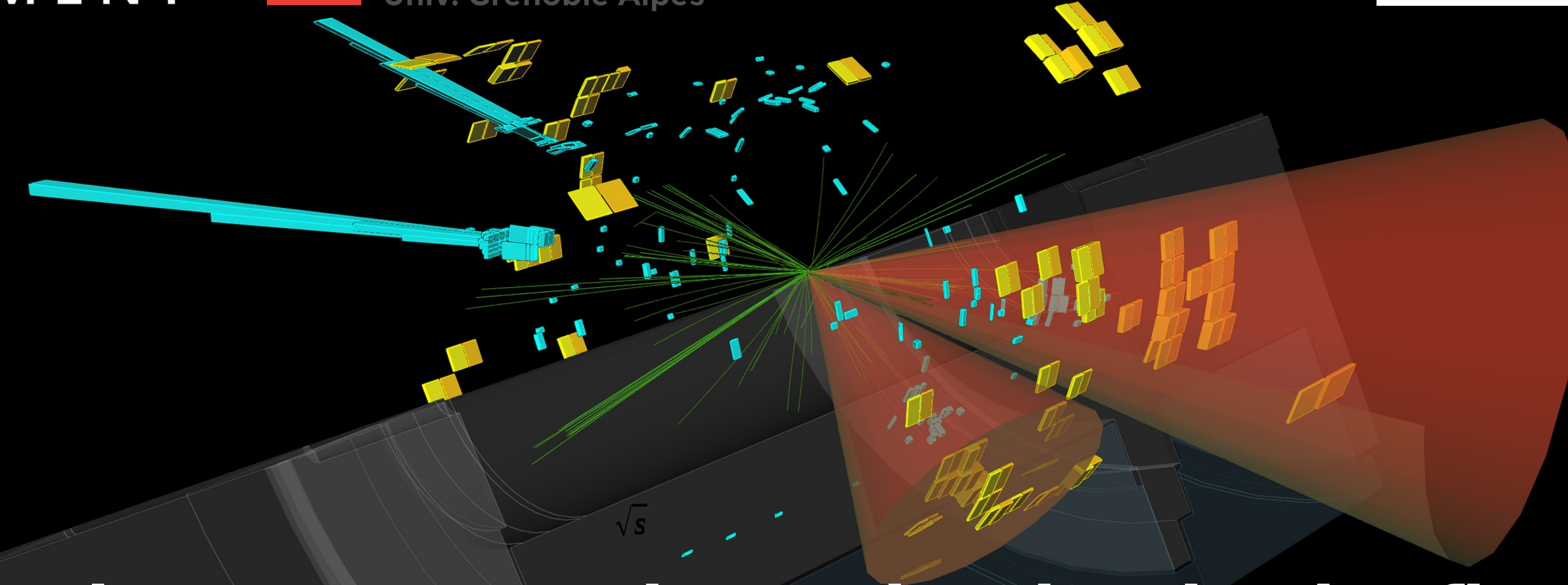
ATLAS EXPERIMENT

UGA Univ. Grenoble Alpes

LPSC Grenoble



Search for Higgs Boson pair production in the final state with two bottom quarks and two photons in pp collisions at √s = 13 TeV with the ATLAS detector

French IRN Terascale
July 5th, 2021

Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

Hulsken Raphaël
On the behalf of the ATLAS collaboration

Paper information

ATLAS CONF Note

ATLAS-CONF-2021-016

March 31, 2021

Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

Searches are performed for non-resonant and resonant di-Higgs boson production in the $b\bar{b}\gamma\gamma$ final state. The data set used corresponds to an integrated luminosity of 139 fb^{-1} of proton–proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector at the CERN Large Hadron Collider. No excess with respect to background expectations is found and upper limits on the di-Higgs boson production cross sections are set. A 95% confidence level upper limit of 130 fb is set on the $pp \to HH$ non-resonant production, where the expected limit is 180 fb. The observed (expected) limit corresponds to 4.1 (5.5) times the cross section predicted by the Standard Model. The observed (expected) limit on the Higgs boson trilinear coupling modifier κ_λ is extracted to be [-1.5, 6.7] ([-2.4, 7.7]) at 95% confidence level. The constraints on κ_λ are obtained over an expected hypothesis excluding $pp \to HH$ production. For the resonant production of a new hypothetical scalar particle X ($X \to HH \to b\bar{b}\gamma\gamma$), limits on the cross section $pp \to X \to HH$ are presented for the narrow-width approximation as a function of m_X in the range 251 GeV $\leq m_X \leq$ 1000 GeV. The observed (expected) limits on the cross section $pp \to X \to HH$ range from 610 fb to 47 fb (360–43 fb) over the considered mass range.

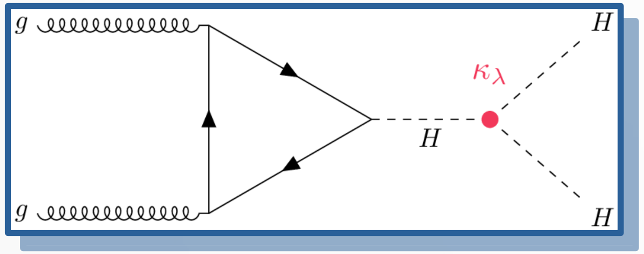
Paper here Published as a conf note for Moriond QCD

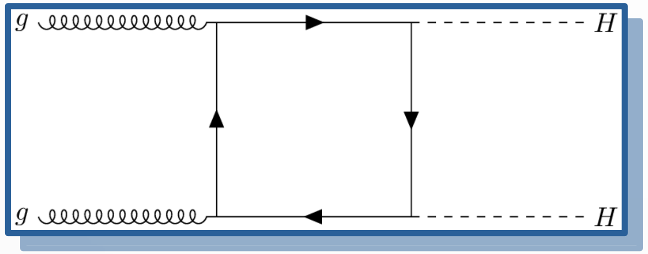
Physics Motivations (non-resonant)

- Study of the Higgs potential

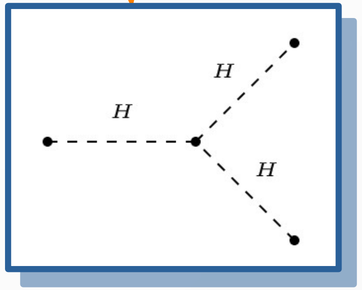
$$V(\phi^\dagger\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$
$$\supset \lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

$\kappa_\lambda = \lambda_{HHH}/\lambda_{sm}$

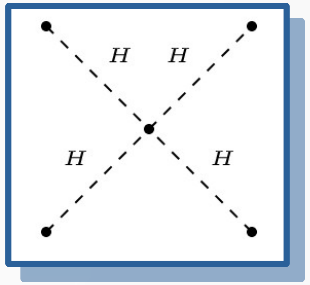




M_H = ~ 125 GeV
v ~ 246 GeV
-> we **know λ** (theo)

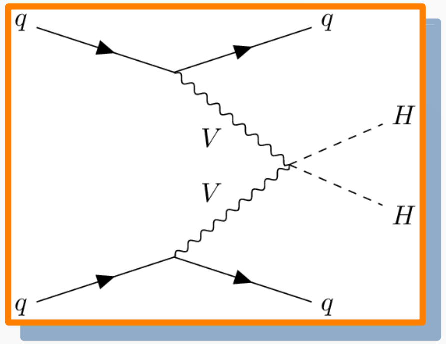


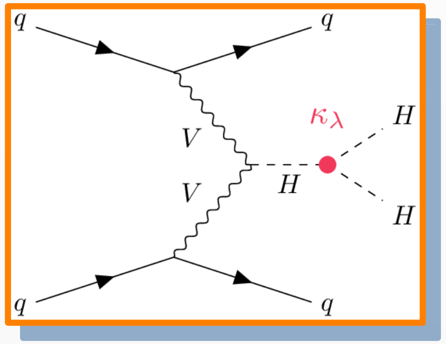
Access through HH pairs

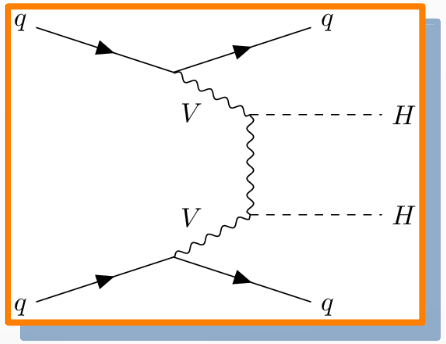


Not accessible yet

- Tiny SM σ_{HH}^{ggF} (31.02 fb at 13 TeV for m_H=125.09) due to destructive interference
- **Deviation** can be a **manifestation of new physics**
- σ_{HH}^{VBF} (31.02 fb at 13 TeV for m_H=125.09)



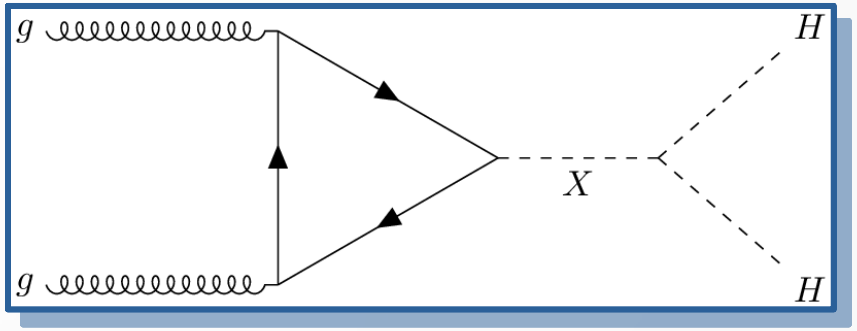




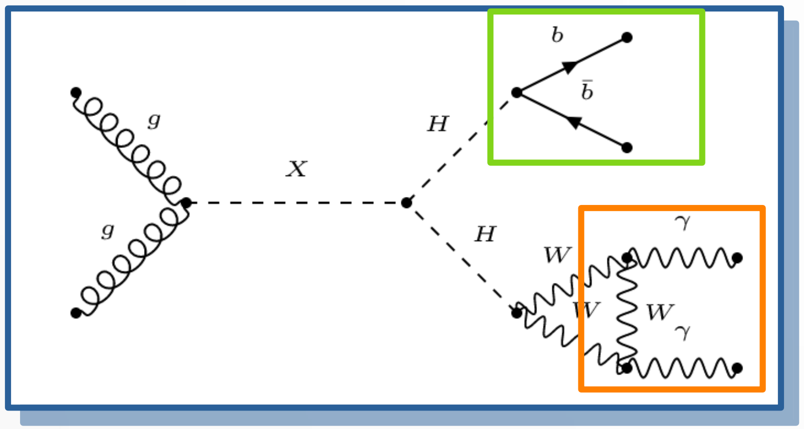
- Here $\sigma_{HH} = \sigma_{HH}^{ggF} + \sigma_{HH}^{VBF}$

Physics Motivations (resonant)

- Search for a **spin 0** resonance in the 251 GeV ≤ X ≤ 1 TeV range
- Narrow width models with **two Higgs doublets. MSSM, twin Higgs models** and **composite Higgs** models contain such doublets
- **Non-resonant** ggF and VBF taken as **background**



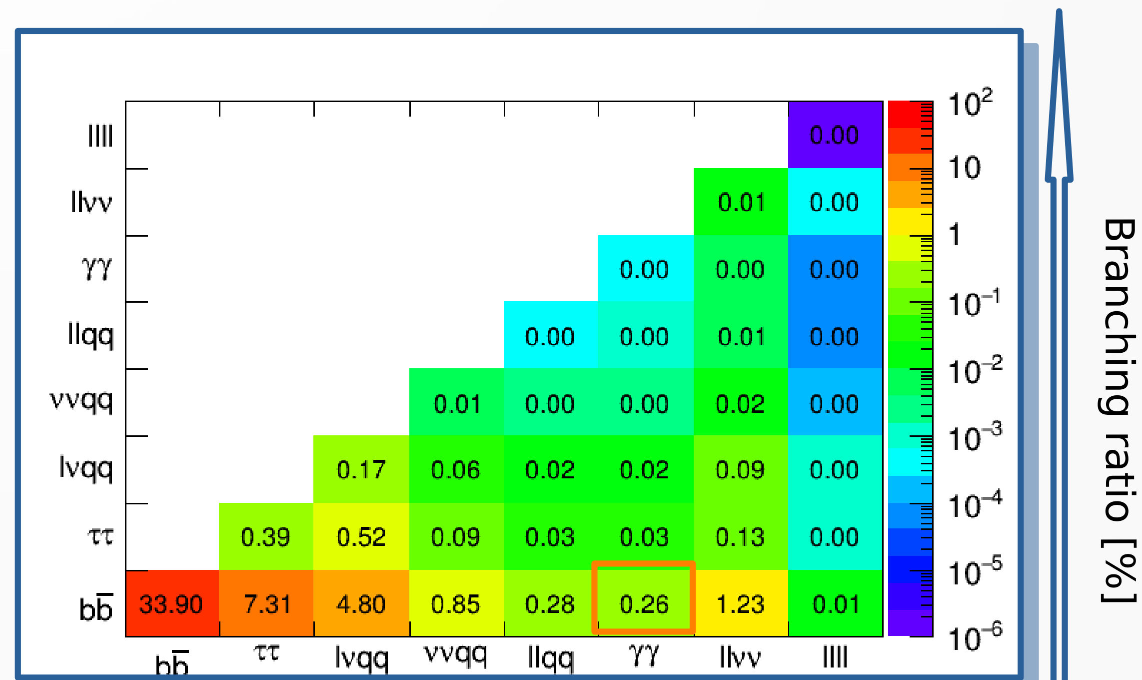
Channel choice



- High branching ratio

- Excellent $m_{\gamma\gamma}$ resolution
- Isolated photons :
  - good trigger (advantage for low m_{HH})
  - High S/B
  - Clean signal

Fully reconstructable final state

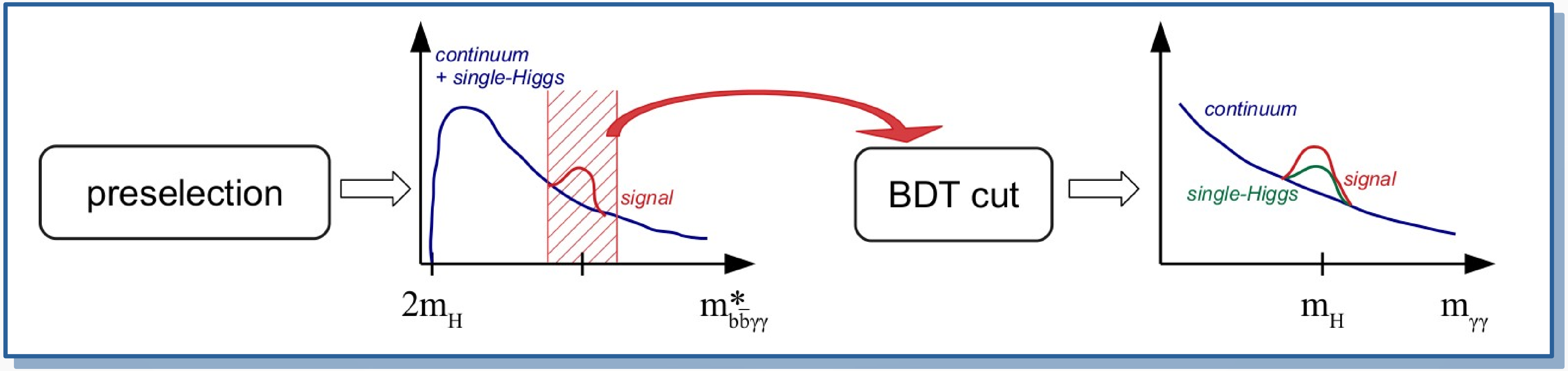


Data and samples

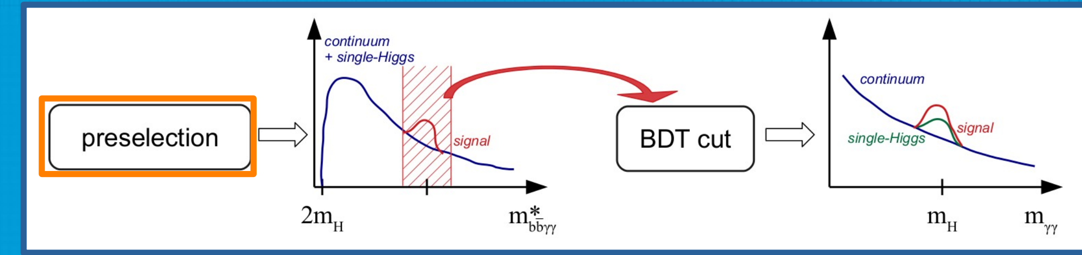
- Full run 2 data (139 fb^{-1})
- ggF HH signal at NLO (κ_λ =1,10) with Powheg-box v2 + Pythia 8
- VBF HH signal at LO (κ_λ =0,1,2,10) with MadGraph5_aMC@NLO + pythia 8
- Spin 0 resonance at LO MadGraph5_aMC@NLO + Herwig
- Single Higgs and continuum background summarized in the table
- PU overlay : Pythia 8.1

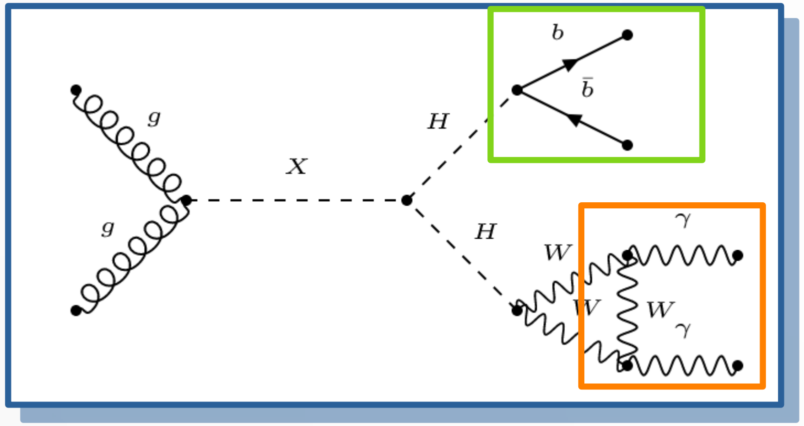
Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS	PDFLHC	Pythia 8.2	AZNLO
VBF	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
WH	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$qq \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$gg \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$t\bar{t}H$	Powheg Box v2	NNPDF3.0nlo	Pythia 8.2	A14
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	NNPDF3.0nnlo	Sherpa v2.2.4	–
$t\bar{t}\gamma\gamma$	MadGraph5_aMC@NLO	NNPDF2.3lo	Pythia 8.2	–

Analysis strategy



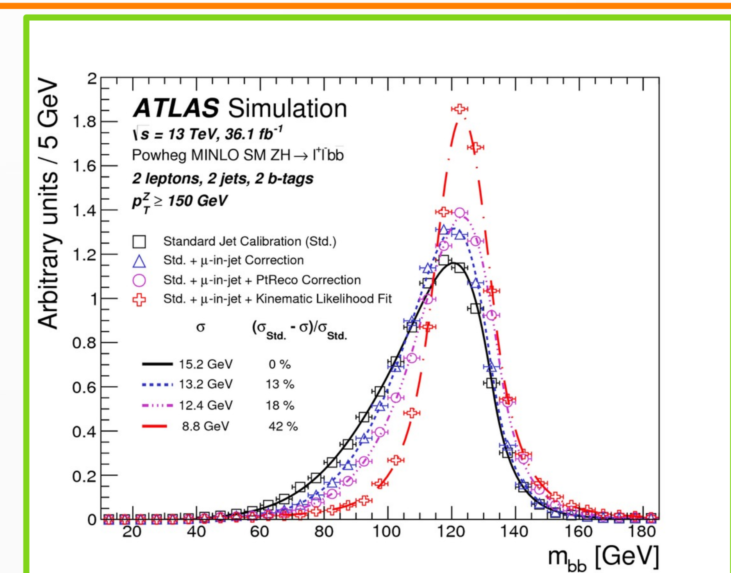
Object and preselection





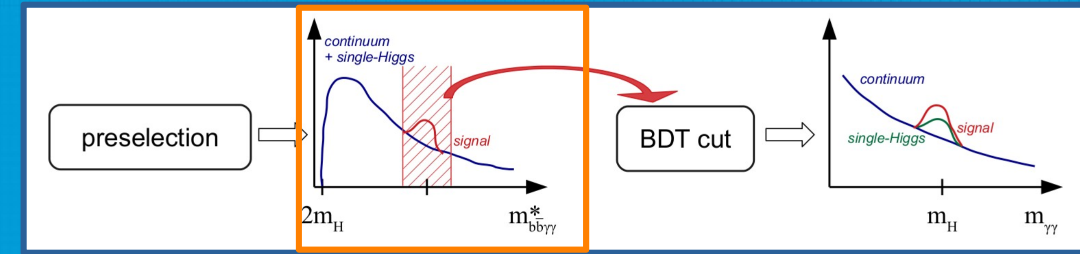
- Tight photon identification
- Isolation criteria in a cone of R =0.2
  - E_T^{iso} <0.065* E_T
  - p_T^{iso} <0.05* E_T
- 105 GeV ≤ $m_{\gamma\gamma}$ ≤160 GeV
- $E_T/m_{\gamma\gamma}$ >0.35 (0.25) for leading (subleading) photon

- Less than 6 central jets
- Pflow jets, anti-kt R=0.4
- Tight JVT applied
- 2 b-jets with DL1r 77 % WP
- B-jet correction applied
  - Muon in jet + P_T-reco



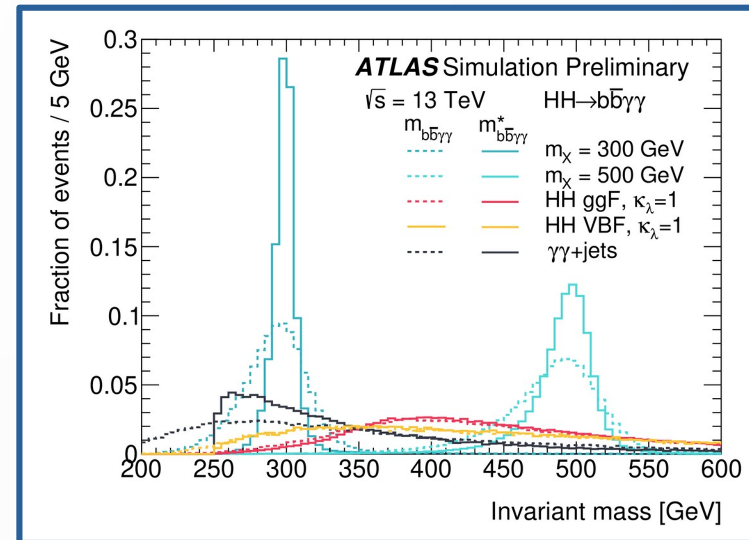
Taken from [Evidence for the H->bb decay with the ATLASdetector]

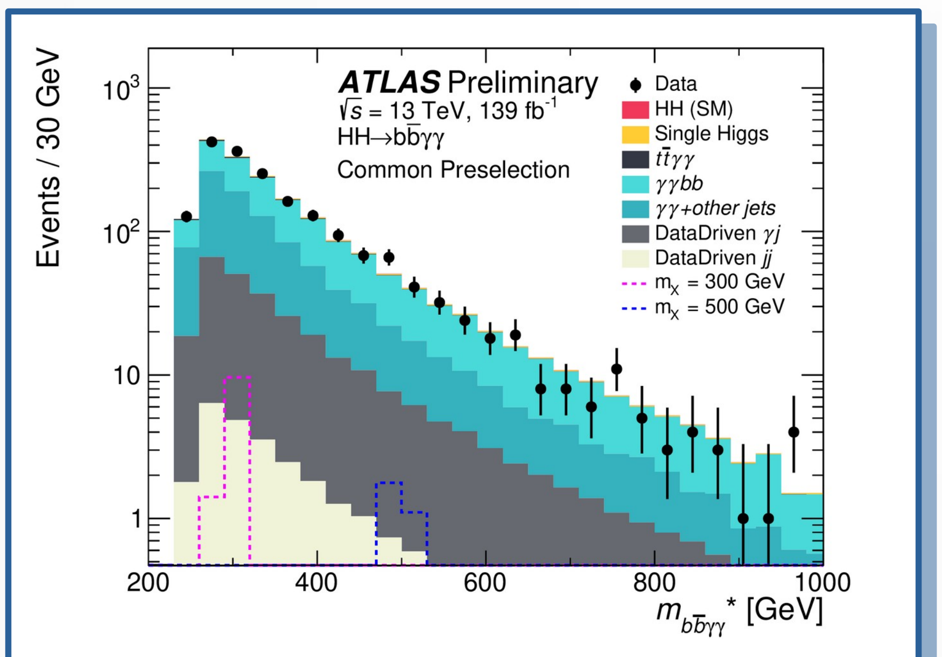
HH invariant mass selection

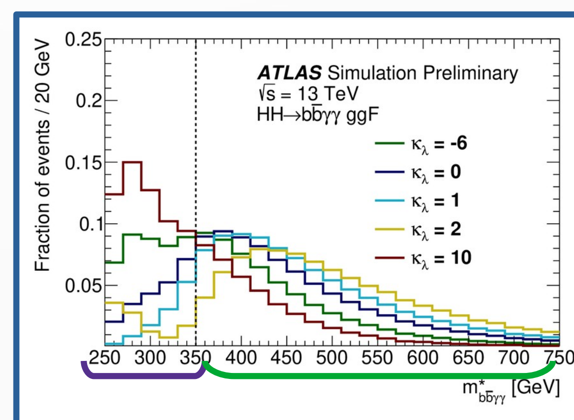


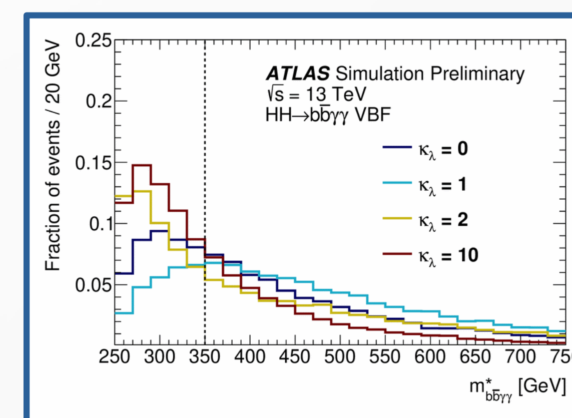
$$m*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250\,GeV$$

- $m^*_{bb\gamma\gamma}$ used in both analysis to **improves resolution**
- **2 category** in Non-resonant analysis :
  -low : < 350 GeV for BSM
  -High : >350 GeV for SM
- Resonant analysis : selection applied on $m^*_{bb\gamma\gamma}$ at **+/-2σ (+/- 4σ)** around the expected **mean signal value** for **each resonance** (at 900-1000 GeV)

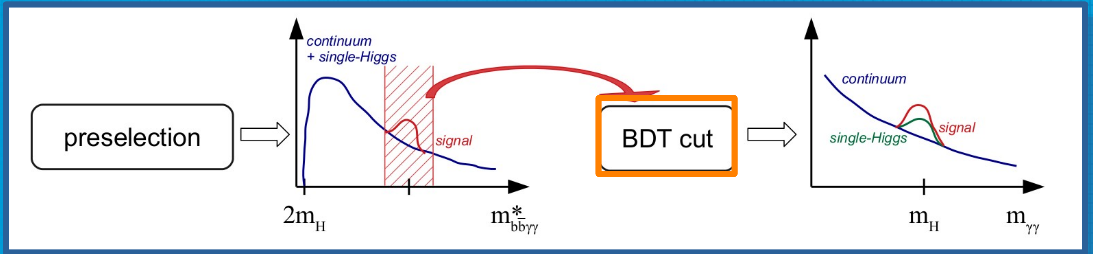






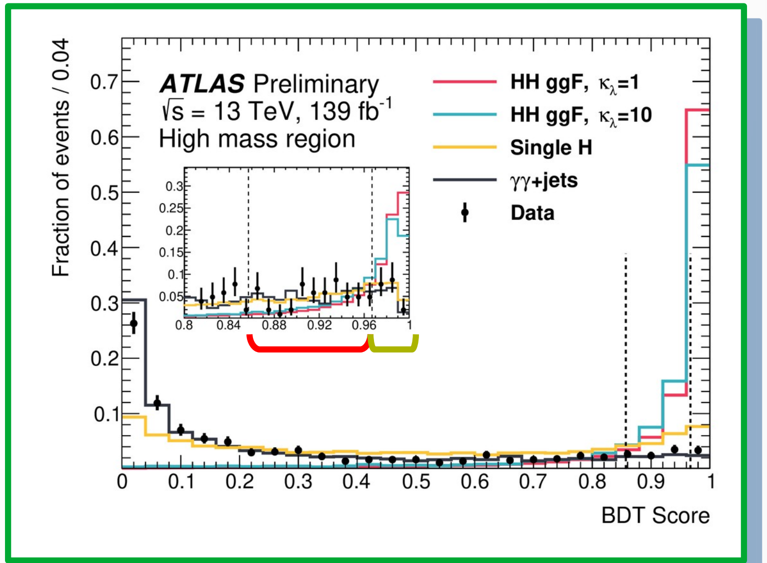


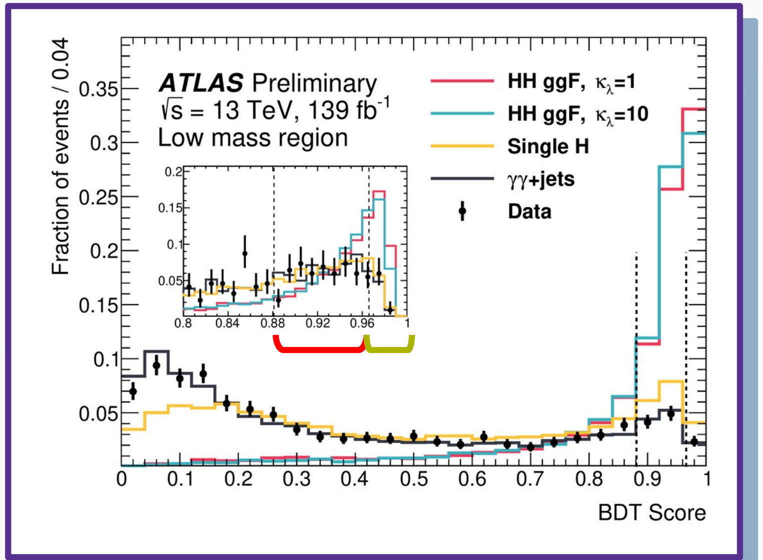
Non-resonant BDT selection



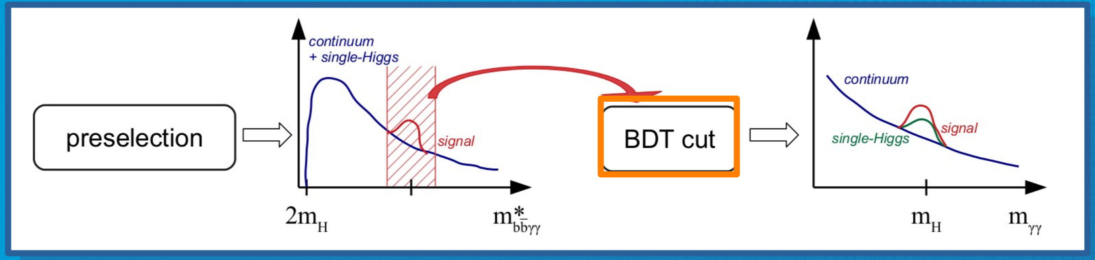
- Low and High mass region are both separated in **2 smaller category**
- **BDT trained** for **each region** to discriminate signal (κ_λ =1,10) from continuum and single Higgs
- Loose and Tight BDT selection
  - Selection taken to **maximize** the **combined** expected significance
- Requirement : at least 9 expected background events in $m_{\gamma\gamma}$ window (outside 120-130) needed to fit data in side-band

Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.967, 1]$
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq 350$ GeV, BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.966, 1]$
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} < 350$ GeV, BDT score $\in [0.881, 0.966]$





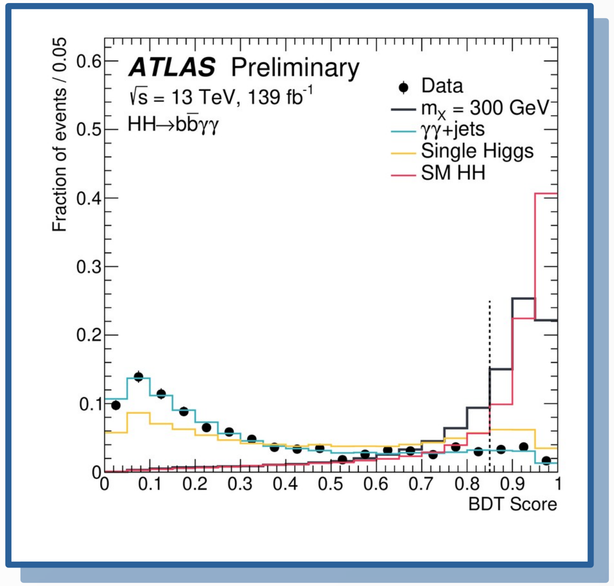
Resonant BDT selection

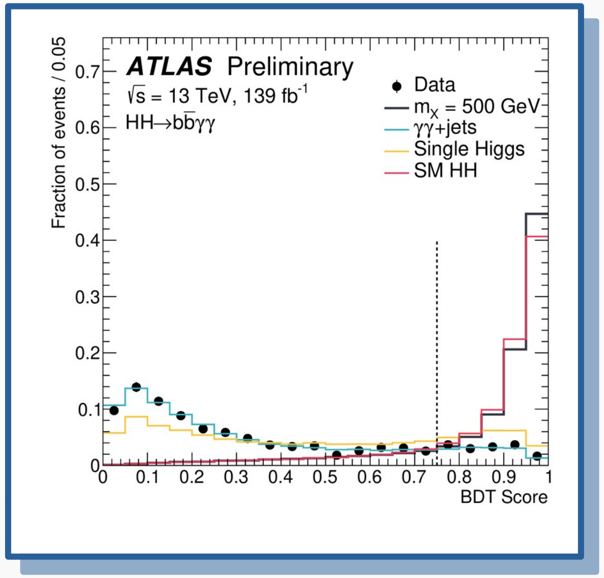


- One BDT for all resonances but **one selection per mass**
- Requirement : at least 9 expected background events in $m_{\gamma\gamma}$ window (outside 120-130) needed to fit data in side-band
- **Two BDT** to separate signal for continuum and from single Higgs background
- Combination of both score into one score BDT_{score} ($C_2 = 1 - C_1$)

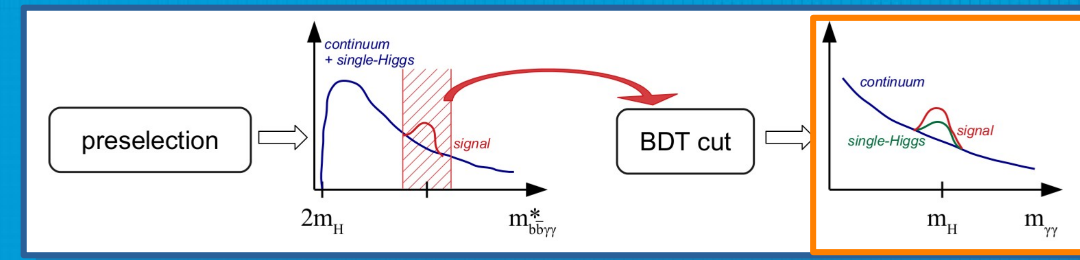
$$BDT_{\text{score}} = \frac{1}{\sqrt{C_1^2 + C_2^2}} \sqrt{C_1^2 \left(\frac{BDT_{\gamma\gamma}+1}{2}\right)^2 + C_2^2 \left(\frac{BDT_{SH}+1}{2}\right)^2}$$

- First optimization **maximizing each resonance** with different coefficient and BDT selection
- Search a **common coefficient** allows the significance to varies at most up to 5 % (C_1=0.65 is used) with individual BDT

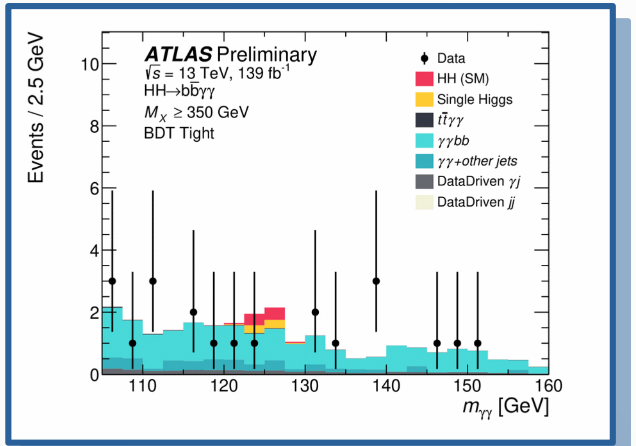


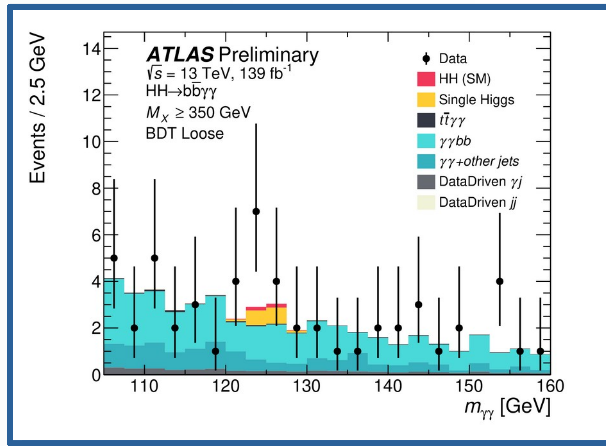


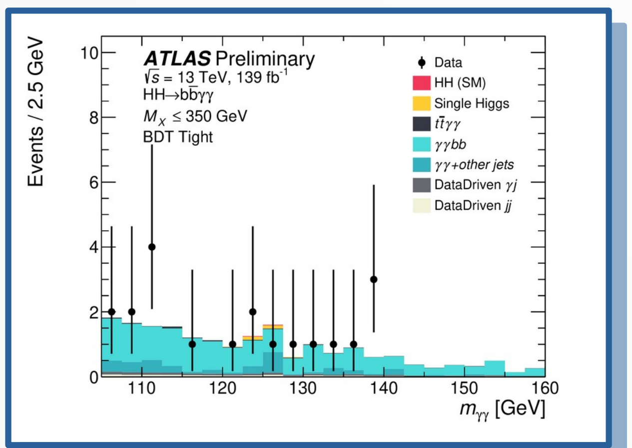
Data/MC comparison

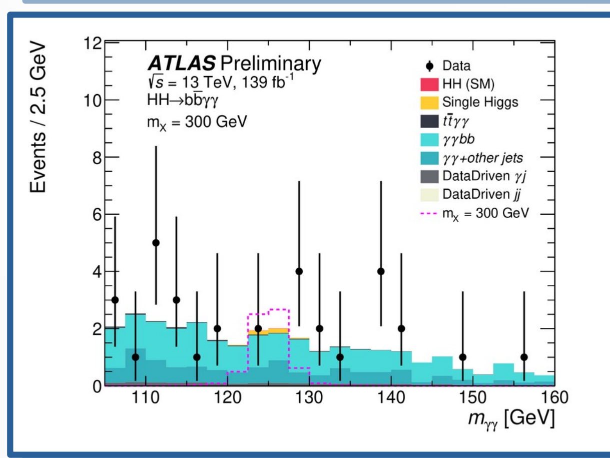


Non-resonant





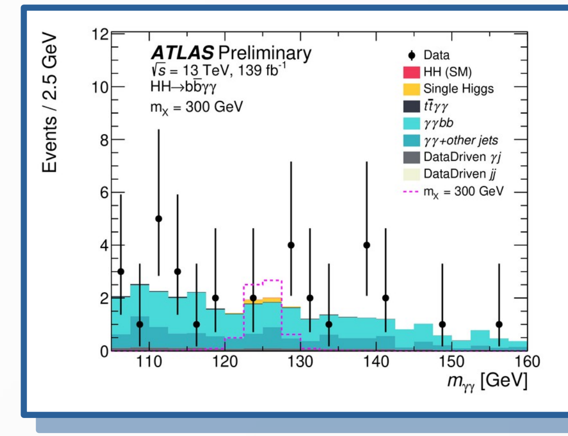


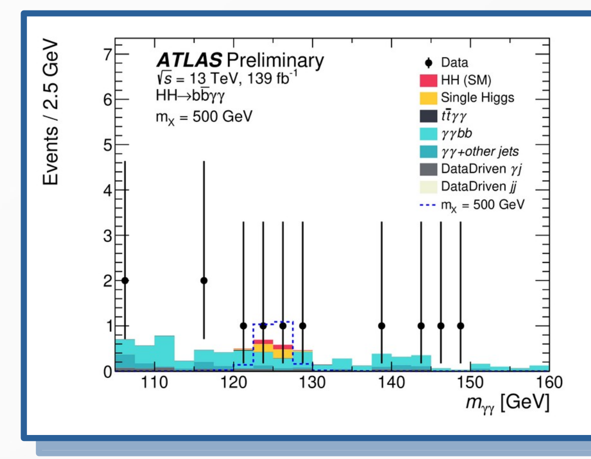


Events dominated by continuum yybb background

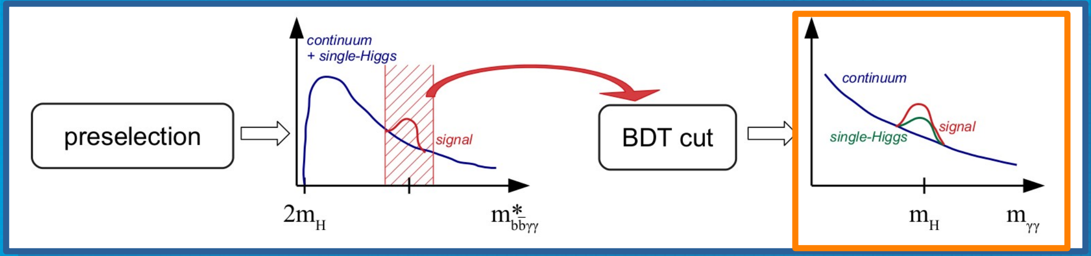
Data-driven method using 2x2D method based on **reverting the isolation and identification** photon criteria (<u>only used for data/MC comparison</u>)

Resonant





Signal and background modelisation



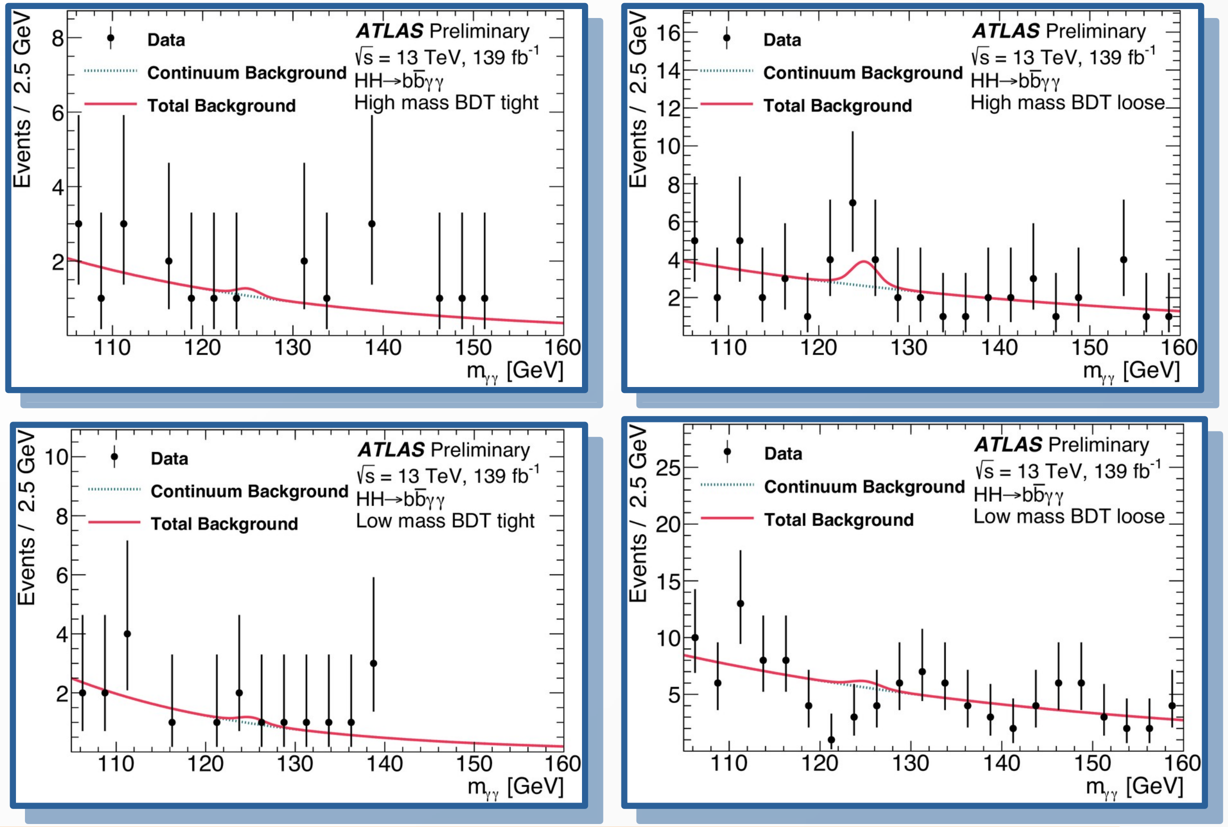
- Fit $m_{\gamma\gamma}$ on for both resonant & non-resonant
- **Signal and single Higgs background** is modeled **from fit on MC** using **DBSC** function
- Continuum **background** is modeled from data **side-band fit**
- Choice of the continuum function done via **spurious signal** method
  - Estimate the **signal bias** by fitting a background only MC template using a signal+background function
  - **Exponential** function chosen due to small bias and small number of free parameters

Statistical analysis

- Maximum likelihood fit in the 105 GeV < $m_{\gamma\gamma}$ < 160 GeV region (simultaneously for all non-resonant category)

$$\mathcal{L} = \prod_c \left(\text{Pois}(n_c | N_c(\boldsymbol{\theta})) \cdot \prod_{i=1}^{n_c} f_c(m^i_{\gamma\gamma}, \boldsymbol{\theta}) \cdot G(\boldsymbol{\theta}) \right)$$

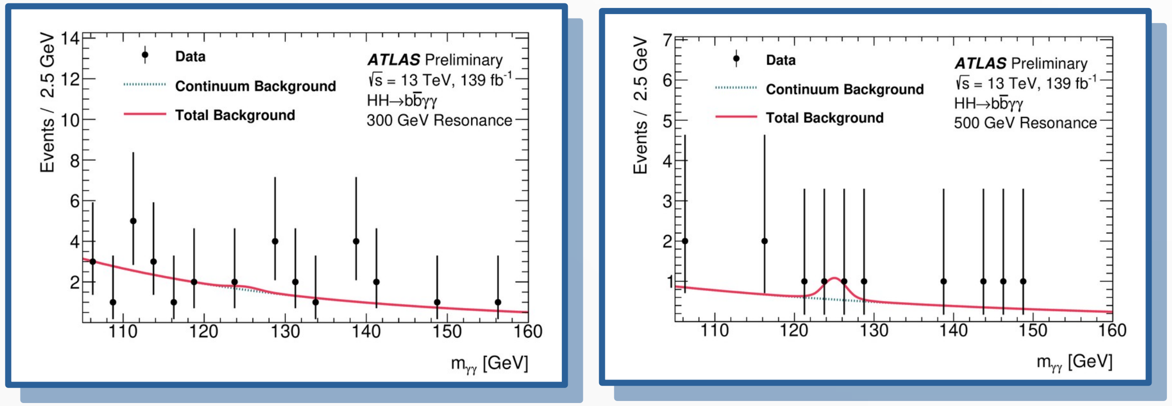
Non-resonant



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

Single Higgs **yield fixed** to SM value (SM signal yield fixed in resonant analysis) while **μ float** in the fit

Resonant



Systematic uncertainties

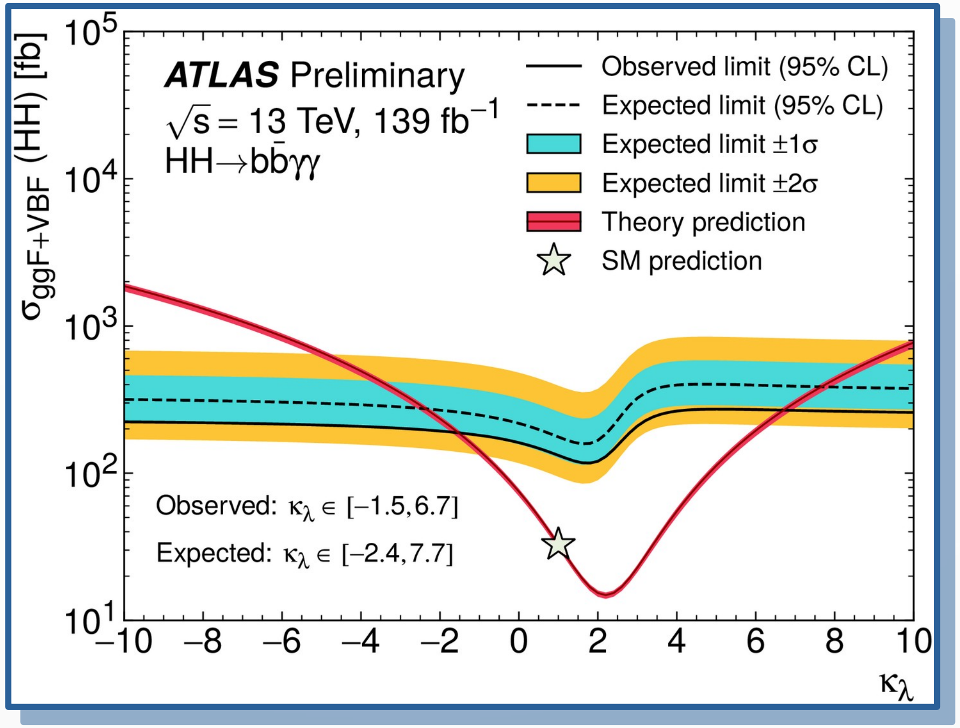
- Both analysis **dominated** by **statistical uncertainty**, systematic uncertainty have relatively low effects
- Only **spurious signal** uncertainty affects **continuum background** as fitted from data
- Other uncertainties affects the resonant and non-resonant signal as well as the single Higgs background

		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

Non-resonant results

No signal is observed, exclusion limits are set via the Cls method with asymptotic approximation

- Expected (Observed) non-resonant HH production of 180 (130) fb : **5.5 (4.1)** times the SM

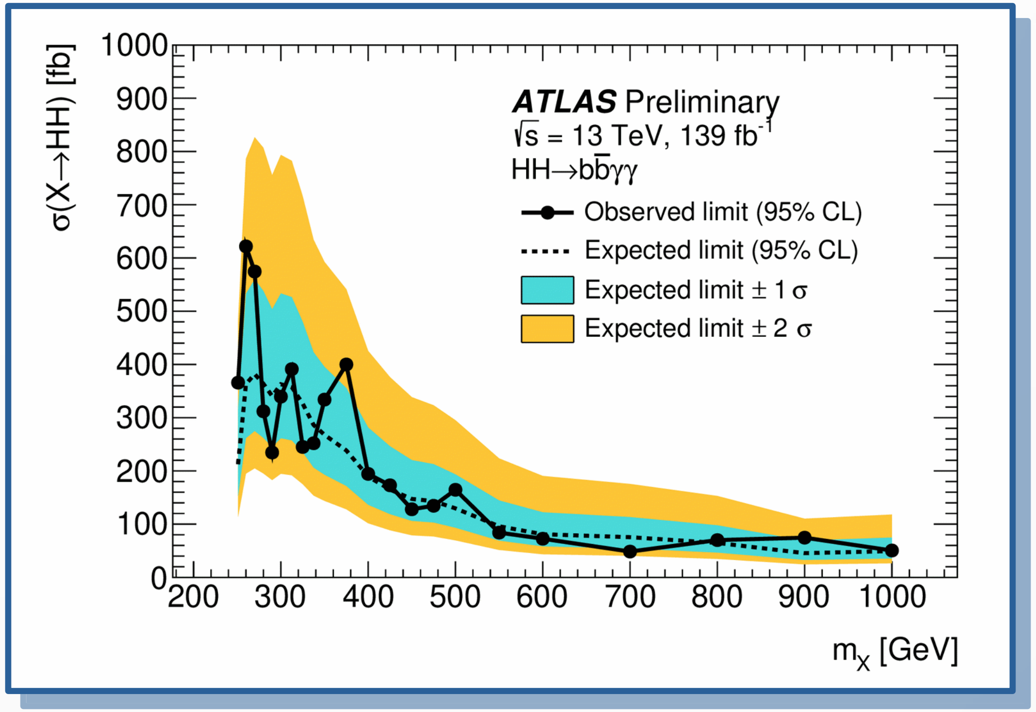


- Previous paper, 36 fb^{-1} **results** : 28 (22) times the SM, -8.3 (-8.2) < κ_λ < 13.2 (13.2)
- Full Run 2 CMS **results** : 5.2 (7.7) times the SM, -2.5 (-3.3) < κ_λ < 8.2 (8.5)

Resonant results

No signal is observed, exclusion limits are set via the Cls method with asymptotic approximation

- Expected (Observed) σ upper limits at 95% CL for a scalar resonance vary between **360-43 fb (160-47 fb)** in the 251 GeV ≤ m_x ≤ 1000 GeV mass range.



- Previous paper, 36 fb^{-1} **results**: expected (observed) limits between 0.9 pb (1.1 pb) and 0.15 (0.12) in the range 260 GeV ≤ m_x ≤ 1000 GeV

Conclusion

- Resonant and non-resonant searches for HH production in the HH-> bb$\gamma\gamma$ final state are presented

Non-resonant

5.5 (4.1) times the SM
-2.4 (-1.5) < κ_λ < 7.7 (6.7)

~60% improvement from m_{HH} categorization
~20% from BDT strategy
~10% from b-jet corrections

Resonant

360-43 fb (610-47) in the 251 GeV ≤ m_X ≤ 1000 GeV mass range

~30% improvement from BDT strategy

Best channel for low regime

- Thanks for your attention !

Variable in BDT non-resonant analysis

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. (**??**)
Missing transverse momentum-related variables	
$E_{\mathrm{T}}^{\mathrm{miss}}$ and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

Variable in BDT resonant analysis

Variable	Definition
Photon-related kinematic variables	
$p_T^{\gamma\gamma}$, $y^{\gamma\gamma}$	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	
$m_{b\bar{b}}$, $p_T^{b\bar{b}}$ 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 $N_{b-\text{jets}}$	Number of jets and number of b-tagged jets
H_T	Scalar sum of the p_T of the jets in the event
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

Number of events

Non-resonant analysis

	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	4.9 ± 1.1	9.5 ± 1.5	3.7 ± 1.0	24.9 ± 2.5
Single Higgs boson background	0.670 ± 0.032	1.57 ± 0.04	0.220 ± 0.016	1.39 ± 0.04
ggF	0.261 ± 0.028	0.44 ± 0.04	0.063 ± 0.014	0.274 ± 0.030
$t\bar{t}H$	0.1929 ± 0.0045	0.491 ± 0.007	0.1074 ± 0.0033	0.742 ± 0.009
ZH	0.142 ± 0.005	0.486 ± 0.010	0.04019 ± 0.0027	0.269 ± 0.007
Rest	0.074 ± 0.012	0.155 ± 0.020	0.008 ± 0.006	0.109 ± 0.016
SM HH signal	0.8753 ± 0.0032	0.3680 ± 0.0020	$(49.4 \pm 0.7) \cdot 10^{-3}$	$(78.7 \pm 0.9) \cdot 10^{-3}$
ggF	0.8626 ± 0.0032	0.3518 ± 0.0020	$(46.1 \pm 0.7) \cdot 10^{-3}$	$(71.8 \pm 0.9) \cdot 10^{-3}$
VBF	0.01266 ± 0.00016	0.01618 ± 0.00018	$(3.22 \pm 0.08) \cdot 10^{-3}$	$(6.923 \pm 0.011) \cdot 10^{-3}$
Alternative $HH(\kappa_\lambda = 10)$ signal	6.36 ± 0.05	3.691 ± 0.038	4.65 ± 0.04	8.64 ± 0.06
Data	2	17	5	14

Resonant analysis

	$m_X = 300$ GeV	$m_X = 500$ GeV
Continuum background	5.6 ± 2.4	3.5 ± 2.0
Single Higgs boson background	0.339 ± 0.009	0.398 ± 0.010
SM HH background	$(20.6 \pm 0.5) \cdot 10^{-3}$	0.1932 ± 0.0015
$X \to HH$ signal	5.771 ± 0.031	5.950 ± 0.026
Data	6	4

Cross section distribution as function of k_λ or k_V