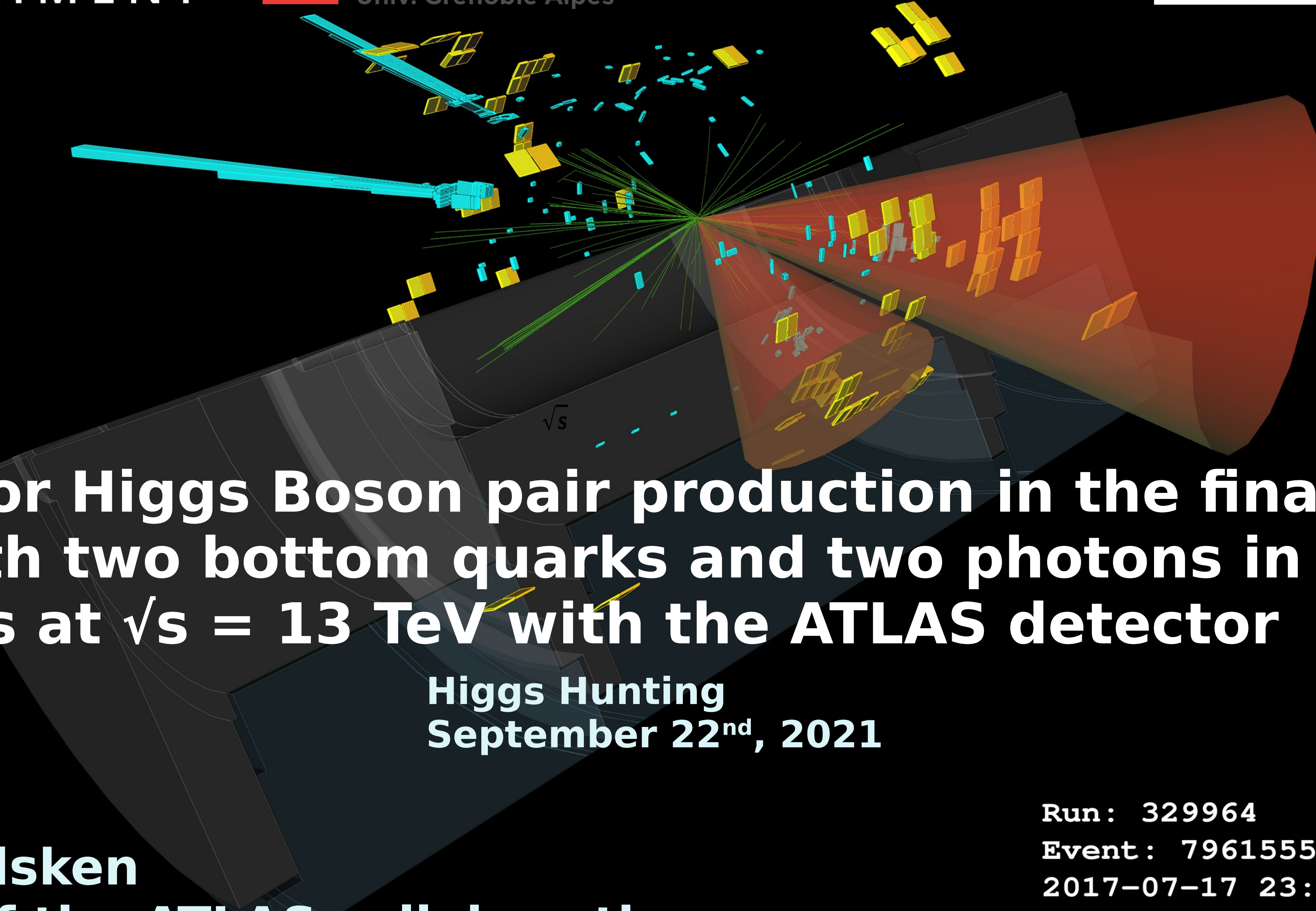
Search for Higgs Boson pair production in the final state with two bottom quarks and two photons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

Higgs Hunting
September 22nd, 2021



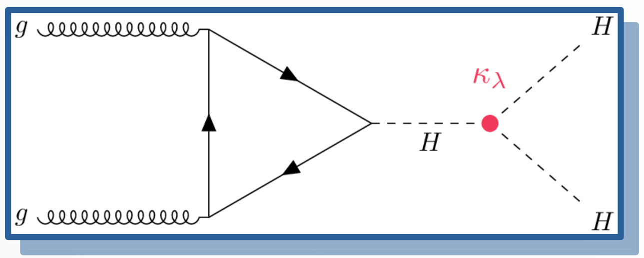
Raphaël Hulsken
On behalf of the ATLAS collaboration

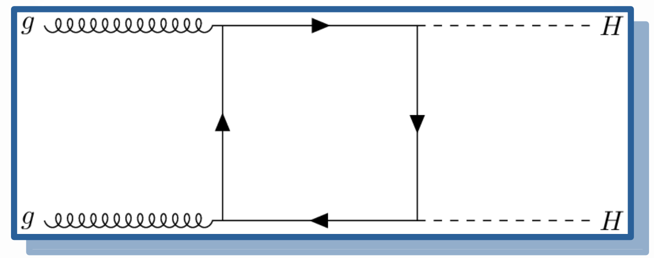
Physics motivations

Non-resonant

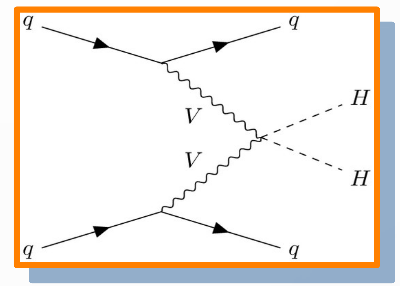
$V(H) = \lambda v^2 H^2 + \lambda v H^3 + \lambda H^4$

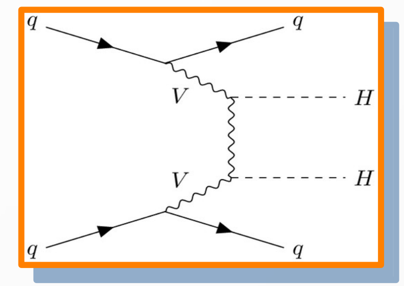
$\kappa_\lambda = \lambda_{HHH} / \lambda_{SM}$

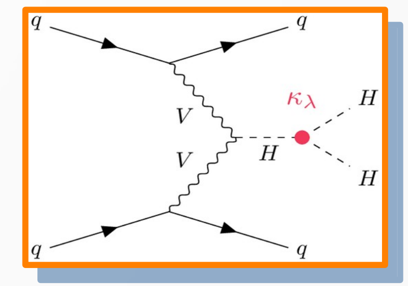




- Tiny SM σ_{HH}^{ggF} due to destructive interference
- **Deviation** can be a **manifestation of new physics**
- Here $\sigma_{HH} = \sigma_{HH}^{ggF} + \sigma_{HH}^{VBF}$



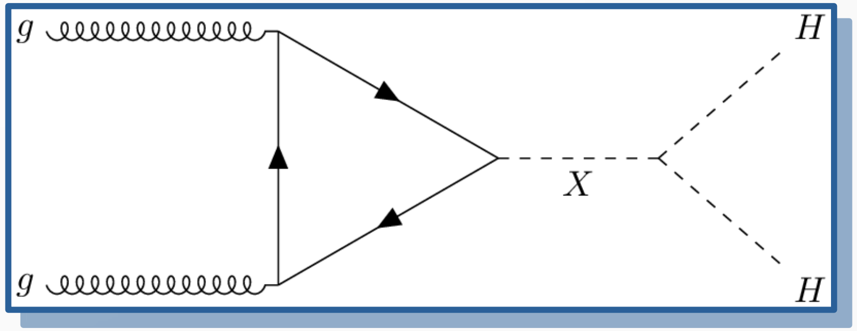




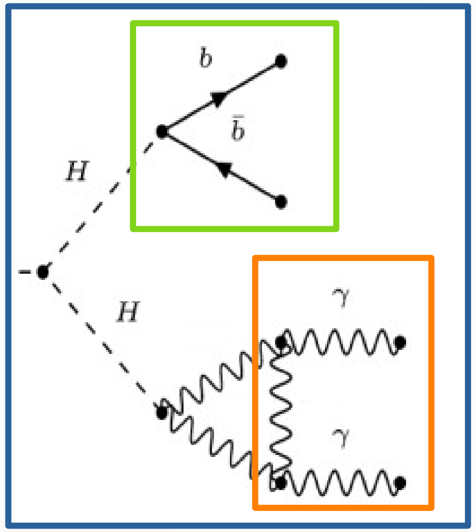
resonant

- Search for a **spin 0** resonance in the 251 GeV ≤ X ≤ 1 TeV range
- Narrow width models such as :
  - **two Higgs doublets**
  - **MSSM**
  - **twin Higgs model**
  - **composite Higgs model**

  contain such spin 0 resonances



Channel choice

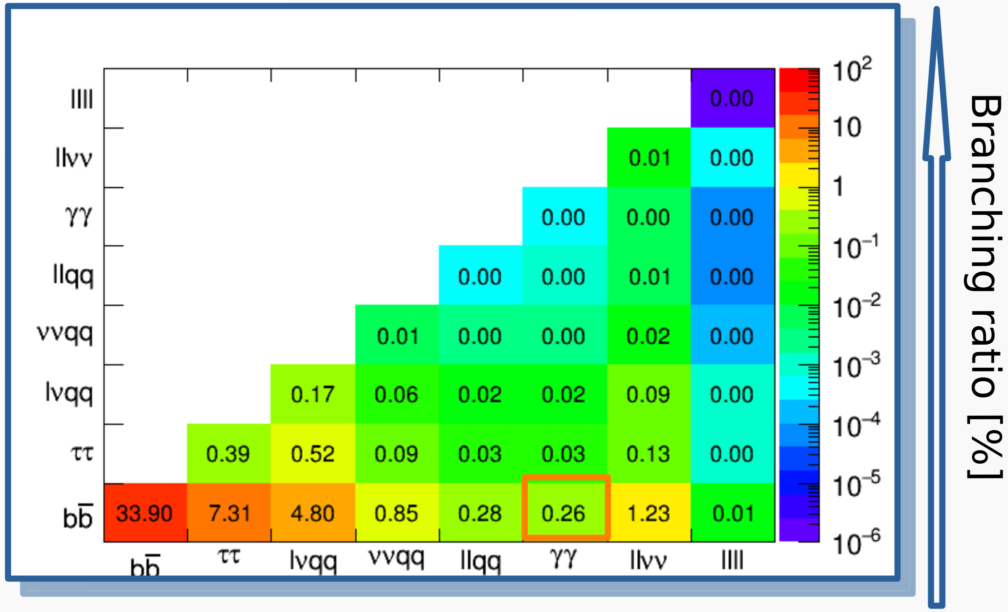


- High H->bb branching ratio

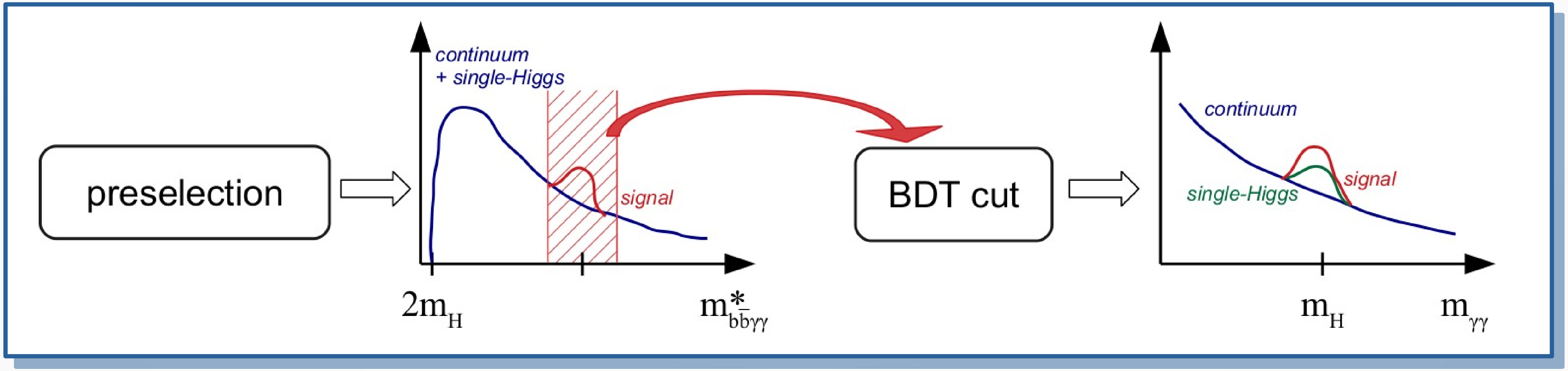
Fully reconstructable final state

- Main backgrounds are di-photon continuum and single Higgs boson (Non-resonant ggF and VBF for resonant analysis)

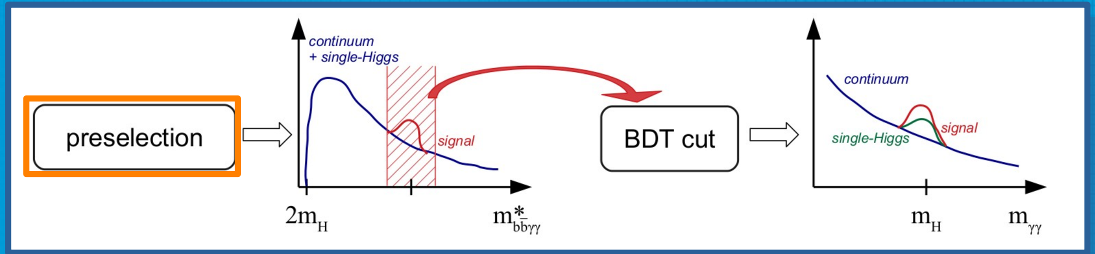
- Excellent $m_{\gamma\gamma}$ resolution (less than 1.9 GeV)
- Good photon identification & reconstruction :
  - good trigger (advantage for low m_{HH})
  - High S/B



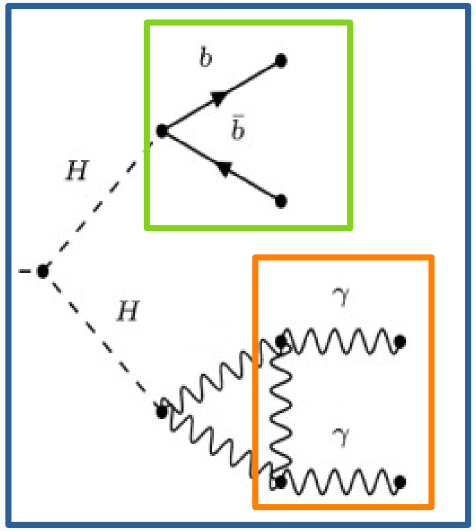
Analysis strategy



Pre-selection



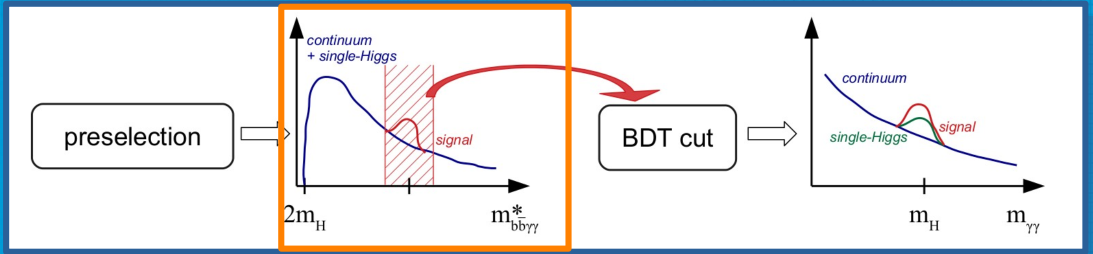
Common pre-selection for resonant and non-resonant analysis



- Di-photon trigger
- $E_T/m_{\gamma\gamma}$ >0.35 (0.25) for leading (subleading) photon
- 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

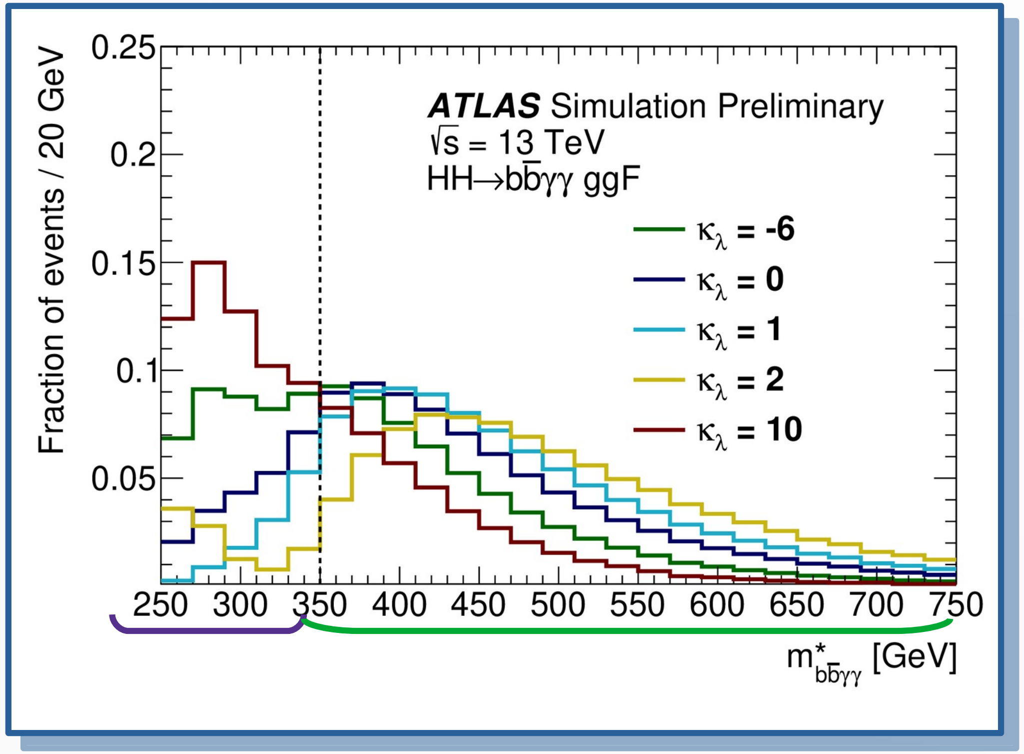
- Less than 6 central jets (|η|<2.5) with P_T>25 GeV
- 2 b-jets with 77 % b-tagging efficiency

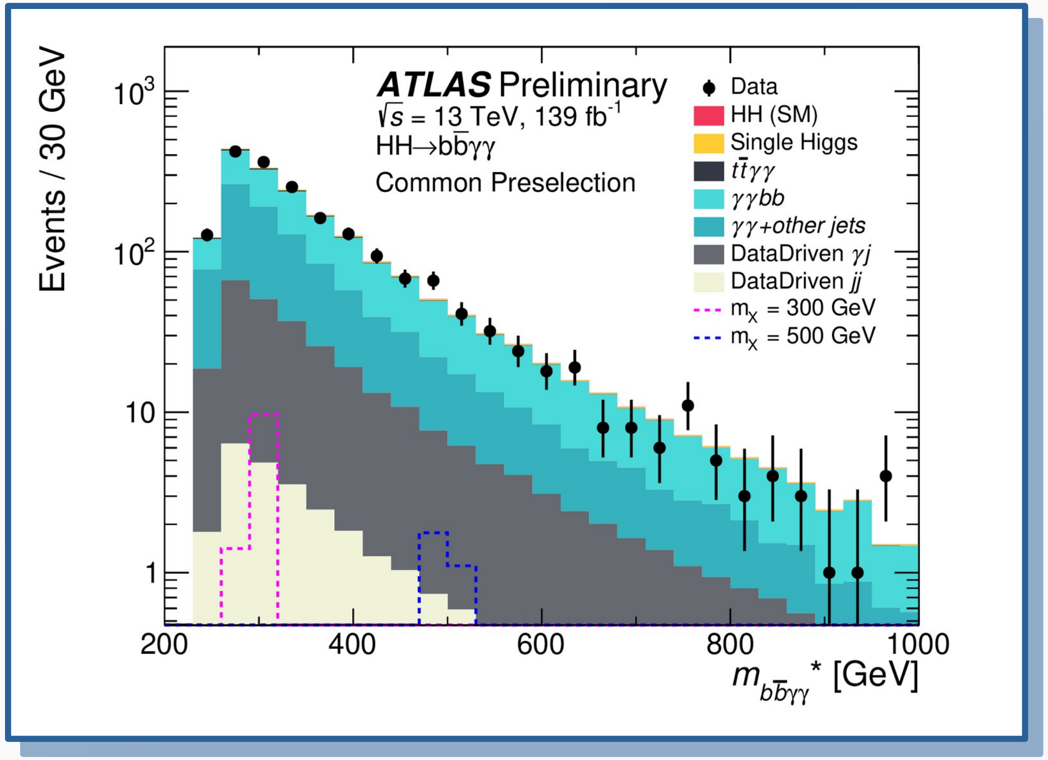
m_{HH} categorization



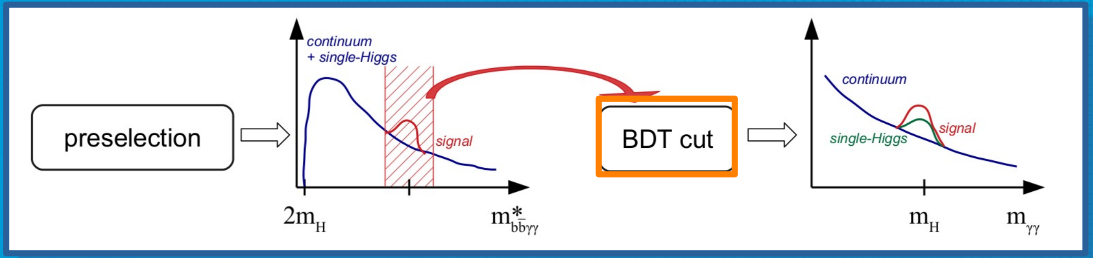
$$m^*_{\bar{b}b\gamma\gamma} = m_{\bar{b}b\gamma\gamma} - m_{\bar{b}b} - m_{\gamma\gamma} + 250$$

- $m^*_{bb\gamma\gamma}$ used in both analysis to **improve 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)



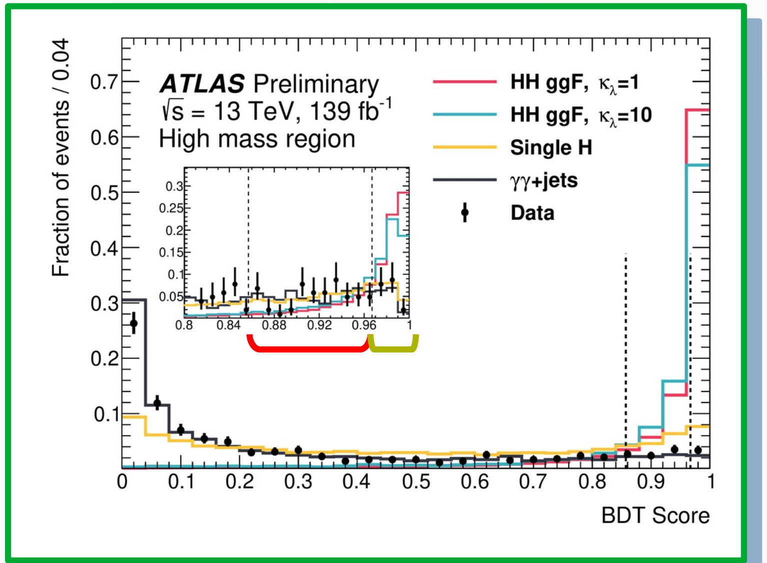


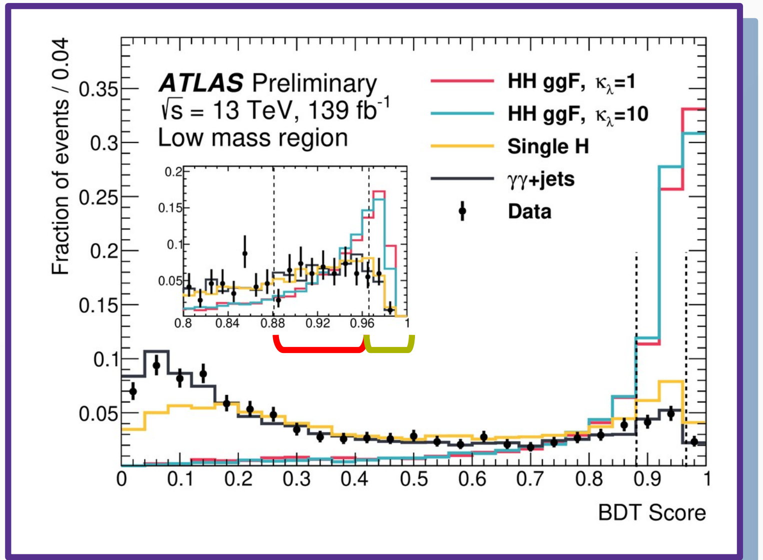
Non-resonant BDT selection



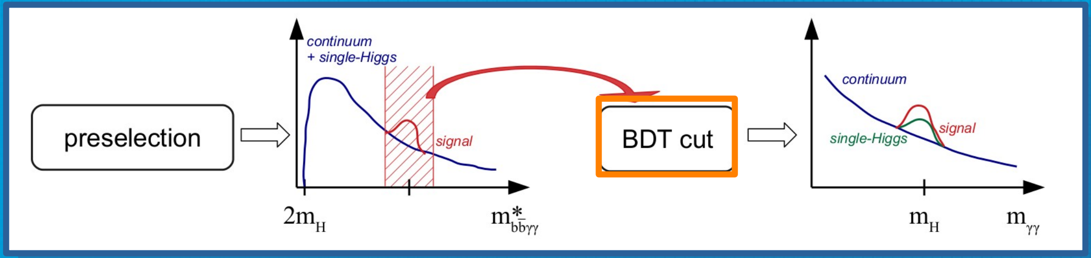
- Low and High mass region are both separated in **2 sub-category**
- **BDT trained** for **each region** to discriminate signal from continuum and single Higgs
- Loose and Tight BDT selection
  - Selection taken to **maximize** the **combined** expected significance

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 $\in [0.881, 0.966]$



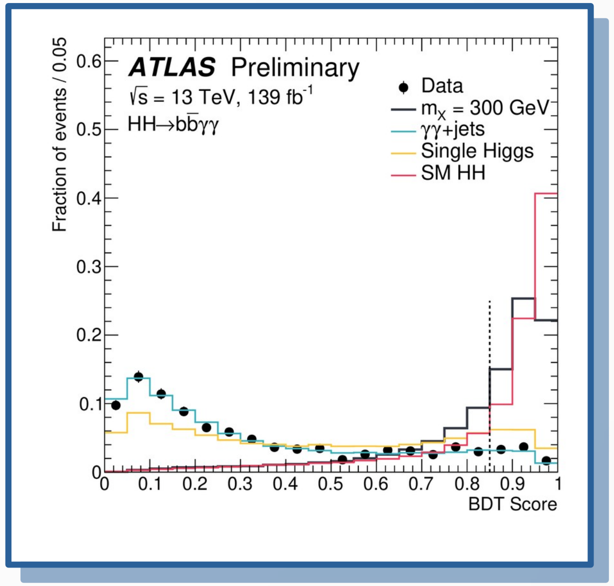


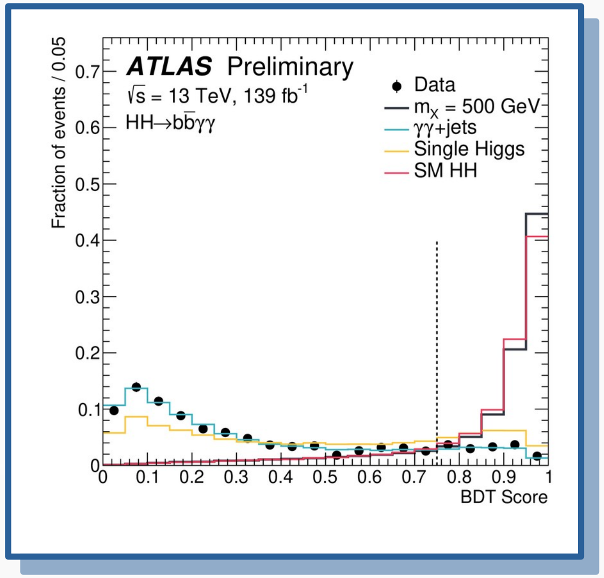
Resonant BDT selection



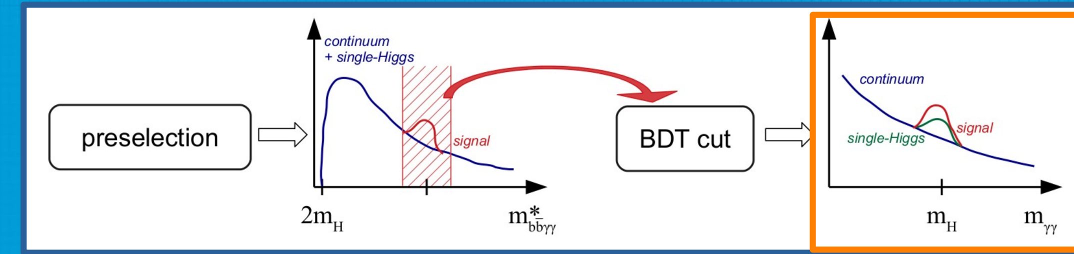
- One BDT for all resonances but **selection depends on the mass**
- **Two BDT** to separate signal for continuum ($BDT_{\gamma\gamma}$) and from single Higgs background ($BDT_{SingleH}$)
- Combination of both score into one score BDT_{tot}

$$BDT_{tot} = \frac{1}{\sqrt{C_1^2 + (1-C_1)^2}}\sqrt{C_1^2\left(\frac{BDT_{\gamma\gamma}+1}{2}\right)^2 + (1-C_1)^2\left(\frac{BDT_{SingleH}+1}{2}\right)^2}$$



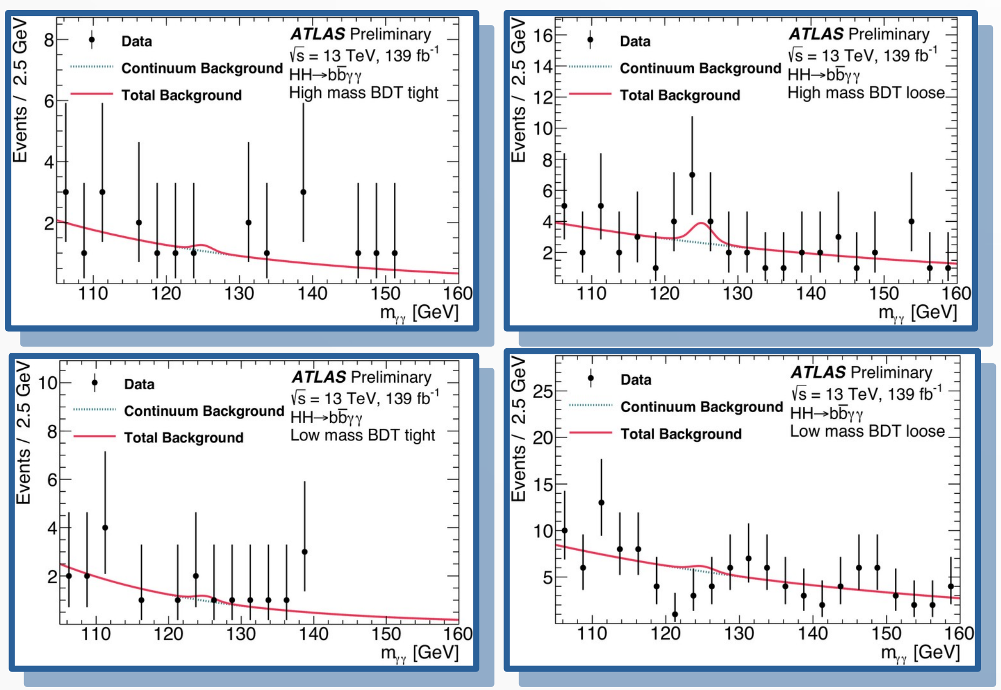


Signal and background modelisation

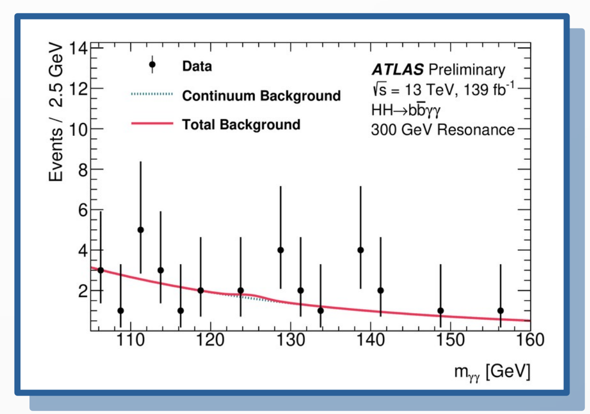


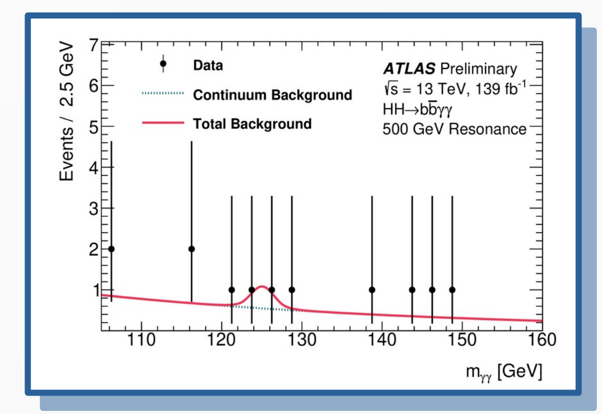
- Fit $m_{\gamma\gamma}$ on for both non-resonant & resonant
- **Signal and single Higgs background** is modeled **from fit on MC** using **Double Sided Crystal Ball** function
- Continuum **background** is modeled from data **side-band fit** using **Exponential** function

Non-resonant



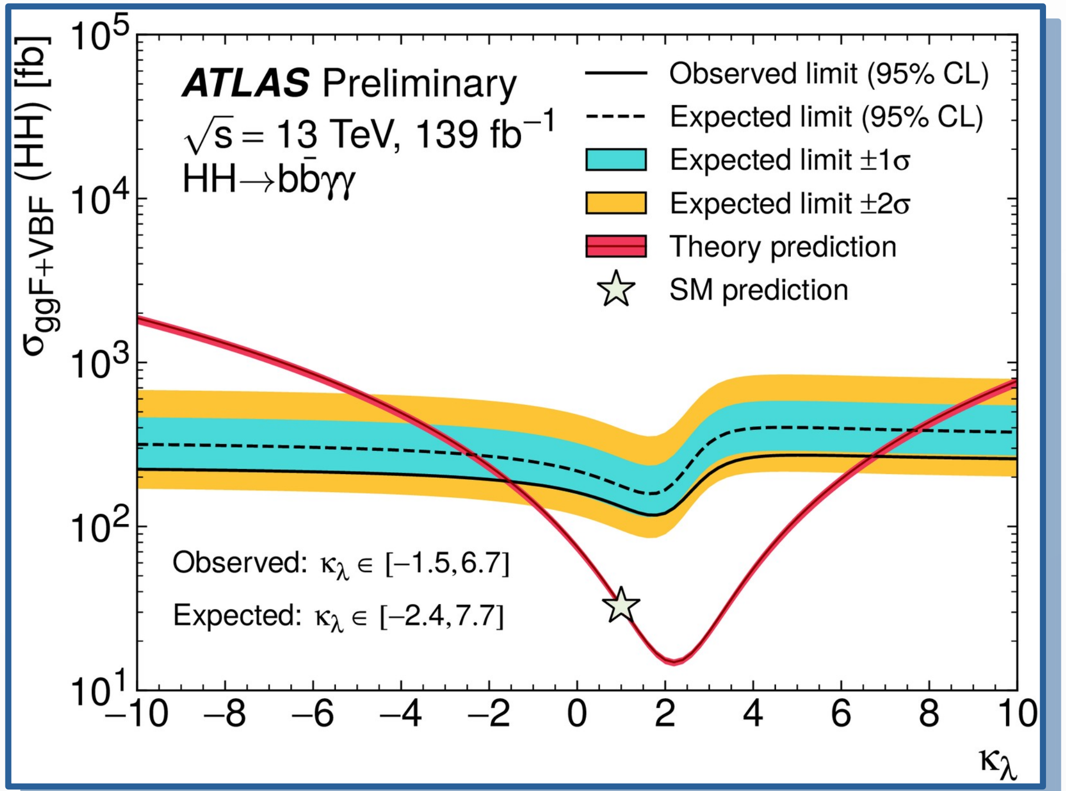
Resonant





Non-resonant results

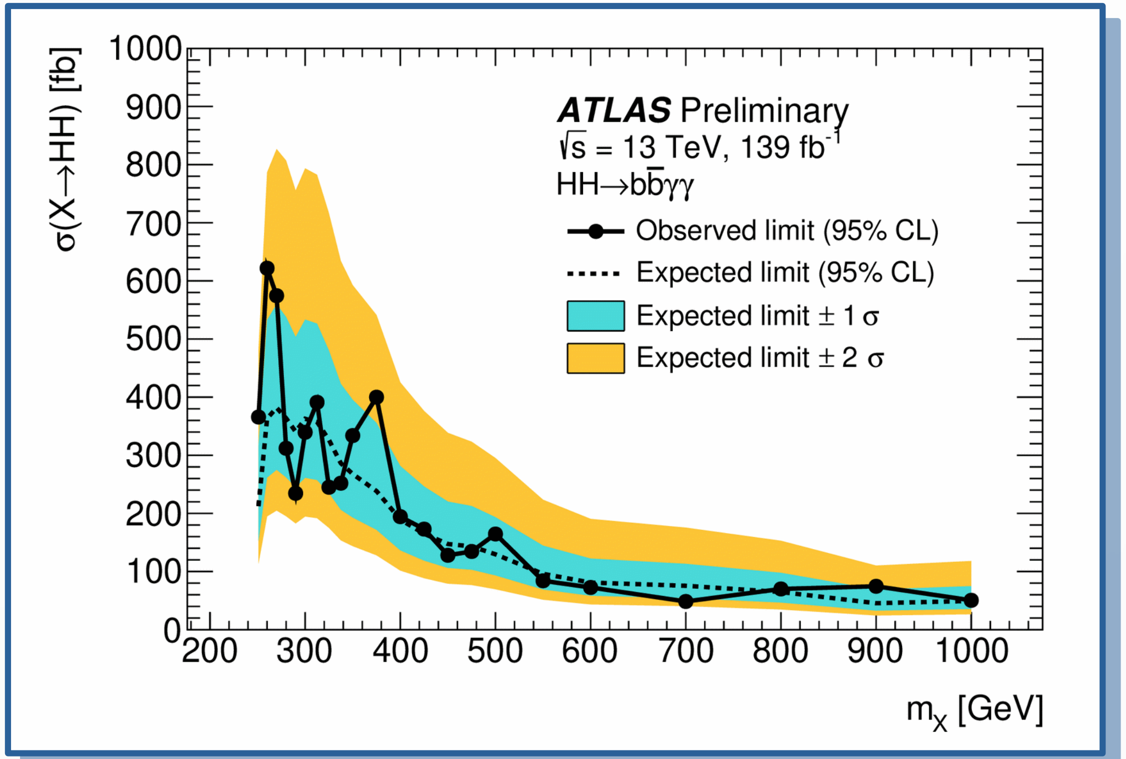
No signal, limits are set via the CLs method



- Observed (Expected) non-resonant HH production of 180 (130) fb : **4.1 (5.5)** times the SM
  - Previous paper, 36 fb^{-1} **results** : 22 (28) times the SM, -8.2 (-8.3) < κ_λ < 13.2 (13.2)
  - Full Run 2 CMS **results** : 7.7 (5.2) times the SM, -3.3 (-2.5) < κ_λ < 8.5 (8.2)

Resonant results

No signal, limits are set via the CLs method



- Observed (Expected) σ upper limits at 95% CL for a scalar resonance vary between **610-47 (360-43) fb** in the 251 GeV ≤ m_x ≤ 1000 GeV mass range.

- Previous paper, 36 fb^{-1} **results**: observed (expected) limits between 1140-120 (900-150) fb in the 260 GeV ≤ m_x ≤ 1000 GeV mass range.

Conclusion

- Non-resonant and resonant searches for HH production in the HH-> $bb\gamma\gamma$ final state are presented
- Both channel are limited by statistics

Non-resonant

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

Compared to previous paper :
~60% improvement from m_{HH} categorization
~20% from BDT strategy
~10% from b-jet corrections

Resonant

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

~30% improvement from BDT strategy compared to the baseline strategy

Best channel for low regime

Presented as a **conf note** for 2021 winter conference

- 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	
$p_{\mathrm{T}}^{\gamma\gamma}$, $y^{\gamma\gamma}$	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

Yields

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

Data and simulation 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

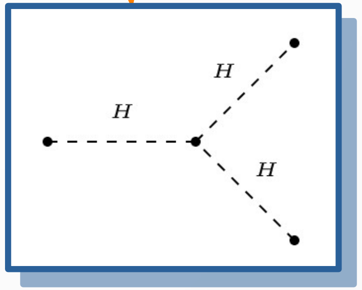
Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS	PDFLHC	Pythia 8.2	AZNLO
VBF	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
WH	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$qq \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$gg \to ZH$	Powheg Box v2	PDFLHC	Pythia 8.2	AZNLO
$t\bar{t}H$	Powheg Box v2	NNPDF3.0nlo	Pythia 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	–

Physics motivations (non-resonant)

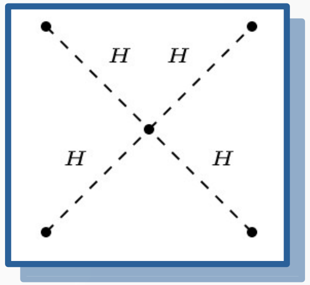
- Study of the Higgs potential

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

$M_H = \sim 125.09$ GeV
v ~ 246 GeV
-> we **know λ** (theo)

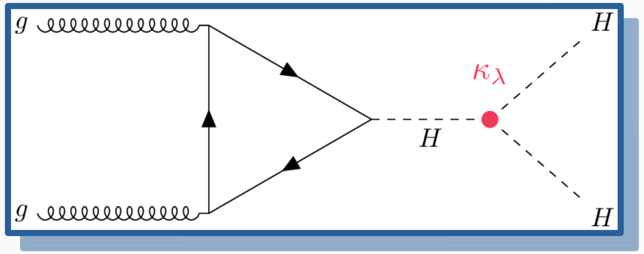


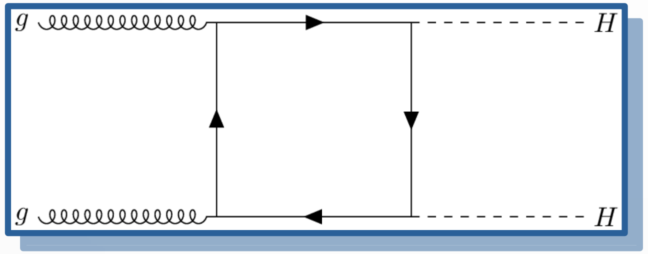
Access through HH pairs



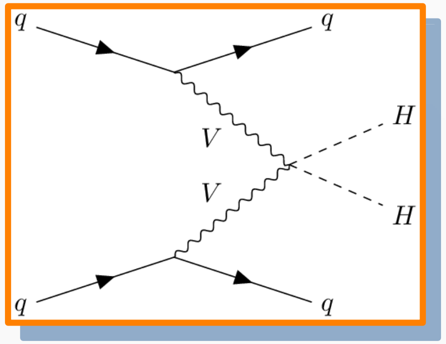
Not accessible yet

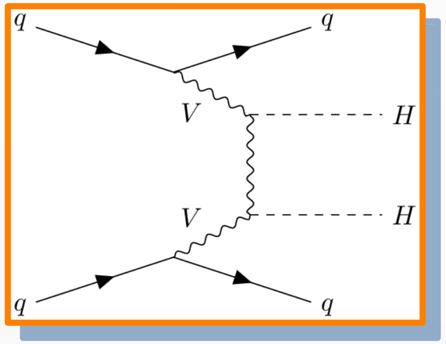
$\kappa_\lambda = \lambda_{HHH} / \lambda_{sm}$

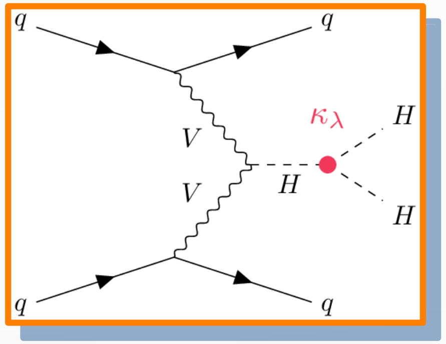




- Tiny SM σ_{HH}^{ggF} (31.02 fb at 13 TeV for m_H=125.09) due to destructive interference
- **Deviation** can be a **manifestation of new physics**
- σ_{HH}^{VBF} (1.7 fb at 13 TeV for m_H=125.09)

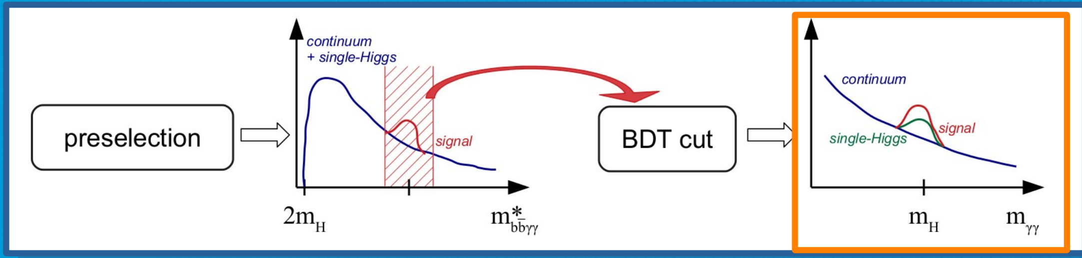




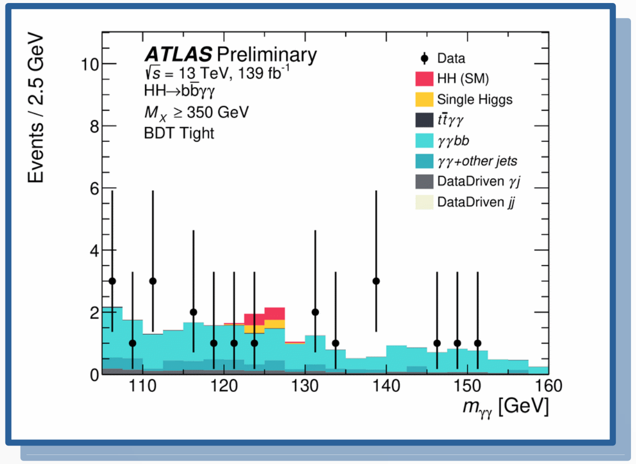


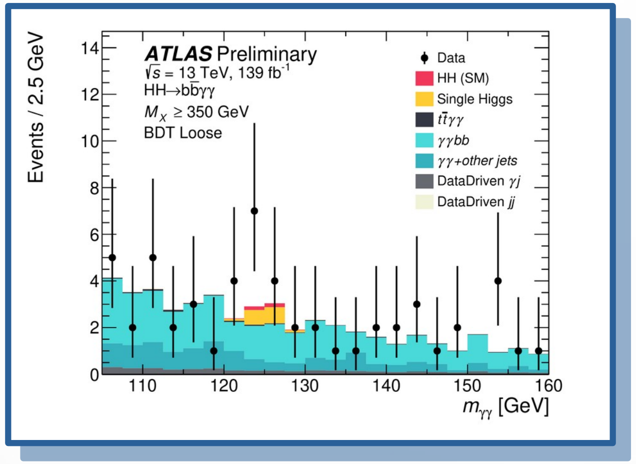
- Here $\sigma_{HH} = \sigma_{HH}^{ggF} + \sigma_{HH}^{VBF}$

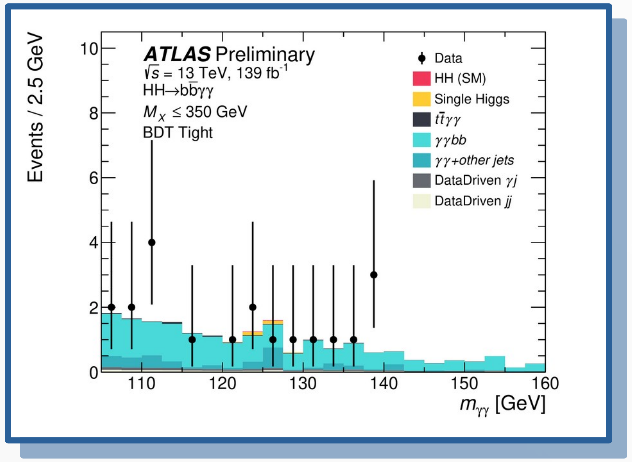
Data/MC comparison

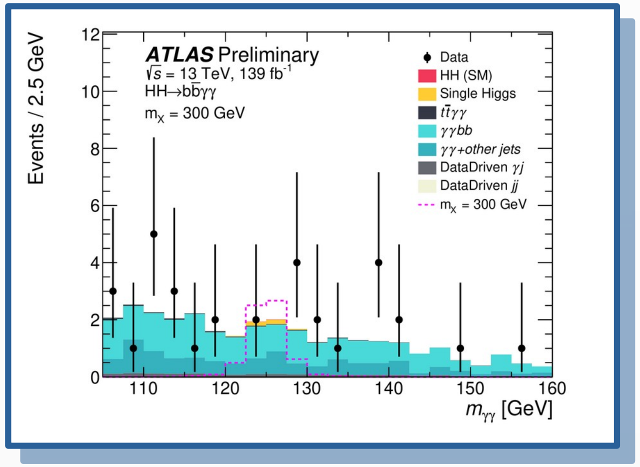


Non-resonant





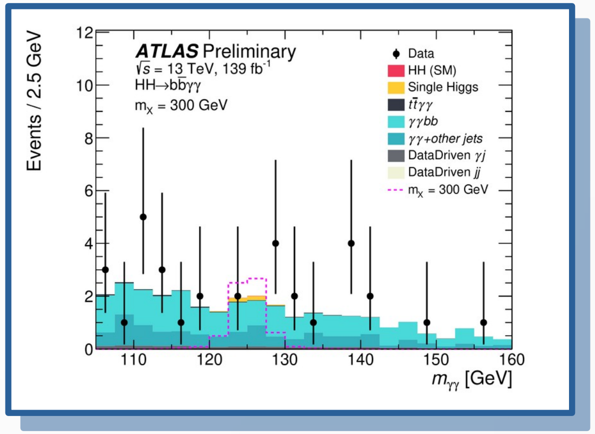


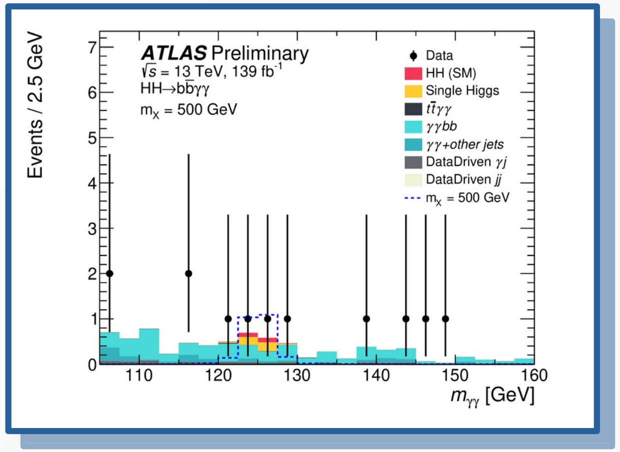


Events dominated by continuum yybb background

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

Resonant



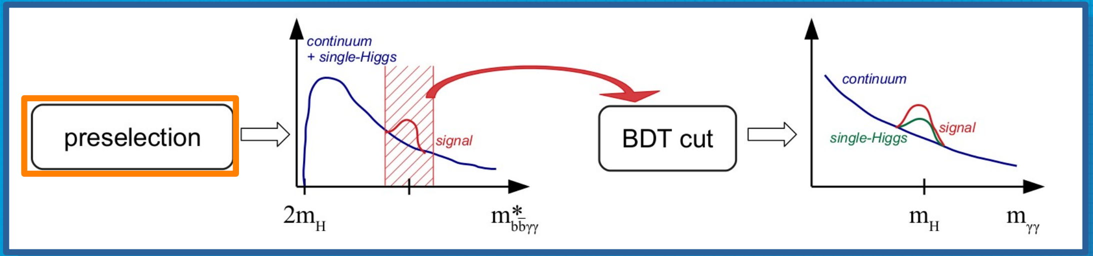


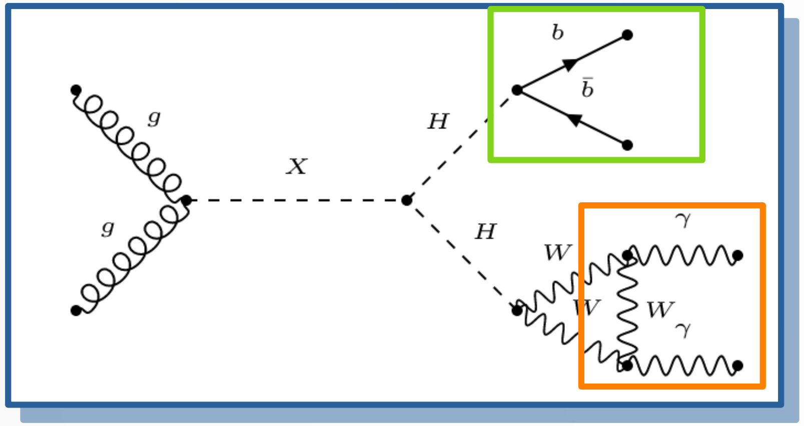
Systematic uncertainties

- 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

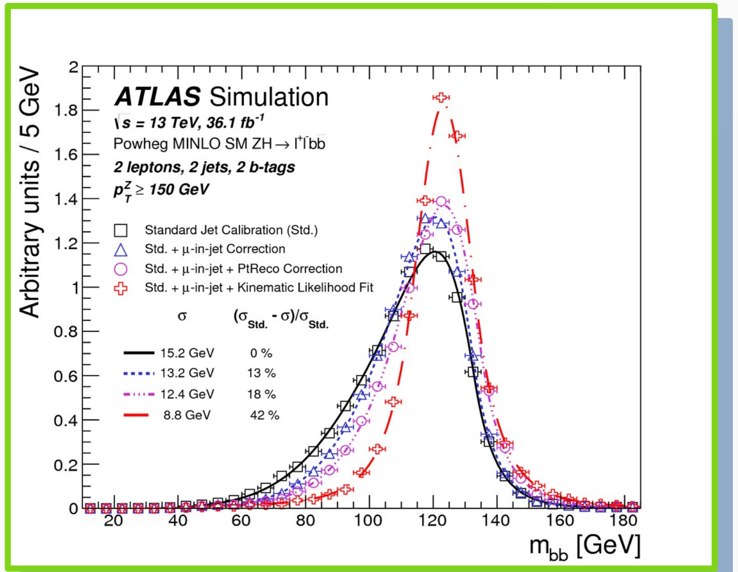
Object and preselection





- 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

Choice of the continuum function

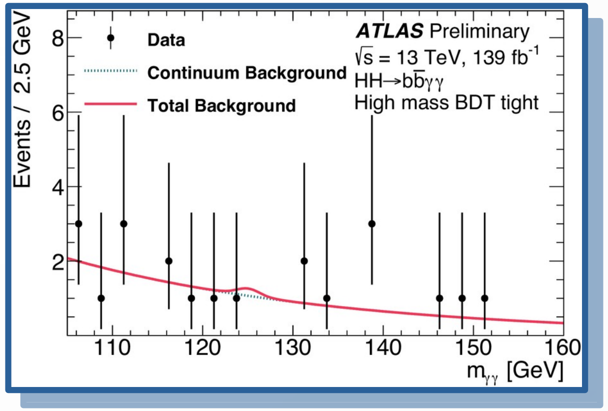
- Choice of the continuum function done via **spurious signal** method
  - Estimate the **signal bias** by fitting a background only MC template using a signal+background function
  - **Exponential** function chosen due to small bias and small number of free parameters

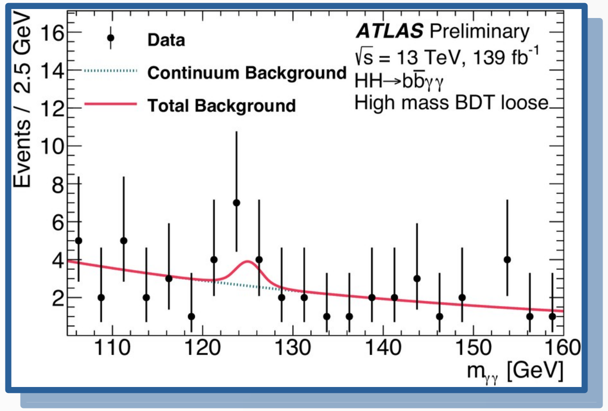
Statistical analysis

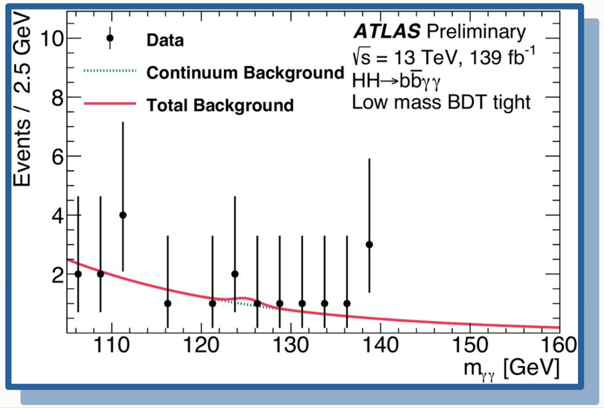
- Maximum likelihood fit in the 105 GeV < $m_{\gamma\gamma}$ < 160 GeV region (simultaneously for all non-resonant category)

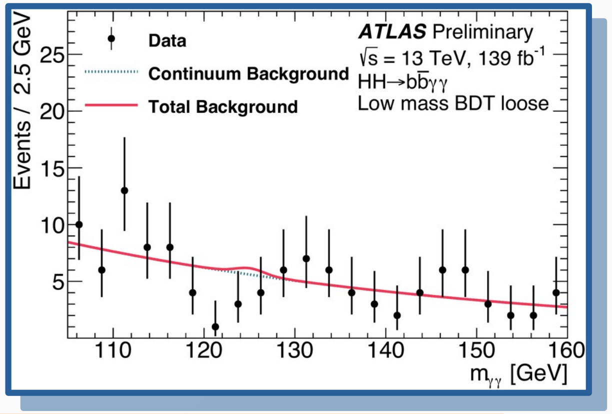
$$\mathcal{L} = \prod_{c} \left(\mathrm{Pois}(n_c | N_c(\boldsymbol{\theta})) \cdot \prod_{i=1}^{n_c} f_c(m^i_{\gamma\gamma}, \boldsymbol{\theta}) \cdot G(\boldsymbol{\theta}) \right)$$

Non-resonant





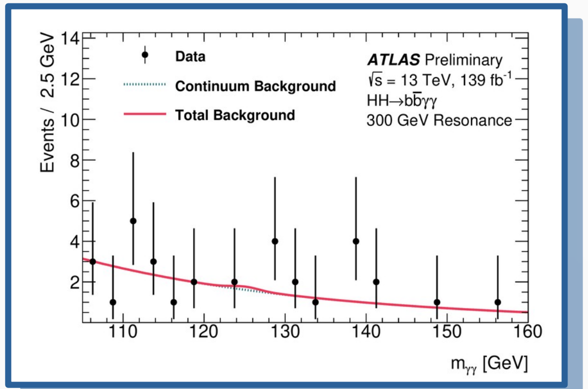


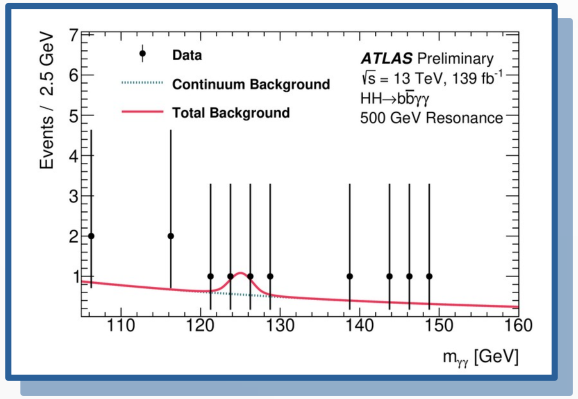


$$N_c(\boldsymbol{\theta}) = \mu \cdot N_{HH,\mathrm{c}}(\boldsymbol{\theta}^{\mathrm{yield}}_{HH}) + N^{\mathrm{res}}_{\mathrm{bkg,c}}(\boldsymbol{\theta}^{\mathrm{yield}}_{\mathrm{res}}) + N_{\mathrm{SS,c}} \cdot \boldsymbol{\theta}^{\mathrm{SS,c}} + N^{\mathrm{non-res}}_{\mathrm{bkg,c}}$$

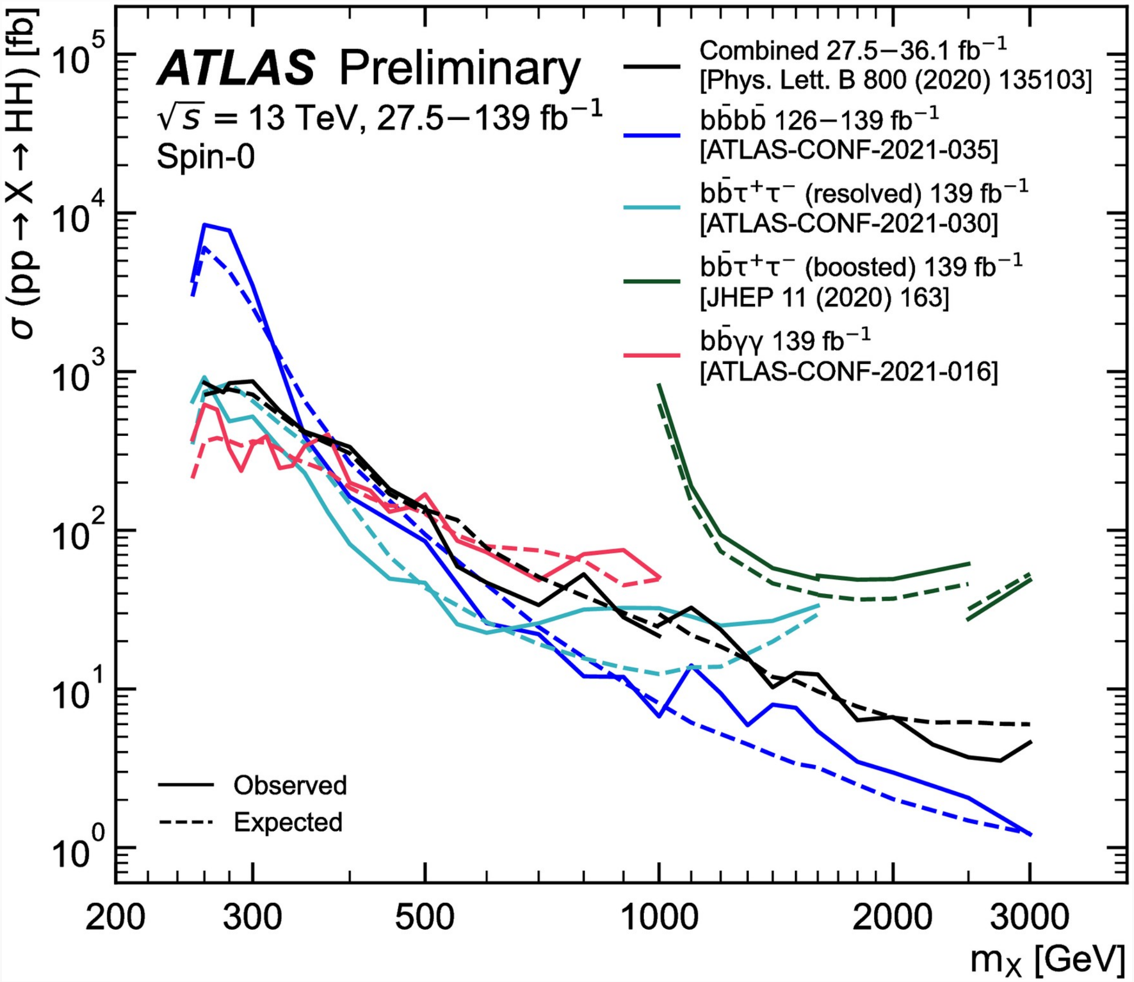
Single Higgs **yield fixed** to SM value (SM signal yield fixed in resonant analysis) while **μ float** in the fit

Resonant





ATLAS resonant results



From CONF note