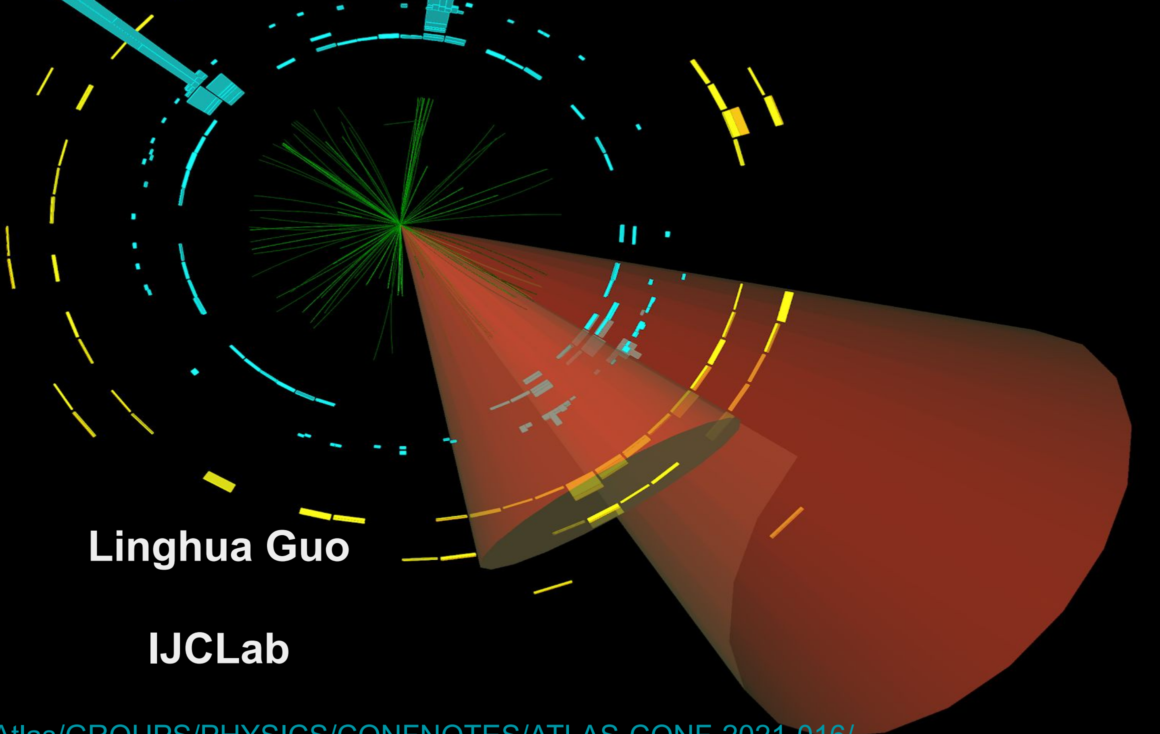
Higgs pair production in bb$\gamma\gamma$ final state with ATLAS at LHC full Run 2

ATLAS EXPERIMENT



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

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Linghua Guo

IJCLab

CONF-note Moriond QCD: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-016/

Motivation for double Higgs production

Higgs potential

Interest: Higgs self coupling

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \left(\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2\right)$$

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After spontaneous symmetry breaking

$$\supset -\left(\lambda v^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4\right)$$

Mass term $m_H = \sqrt{2\lambda v^2}$

Tri-linear term λ_{HHH}

Quartic term λ_{4H}

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Tri-linear term λ_{HHH}

Quartic term λ_{4H}

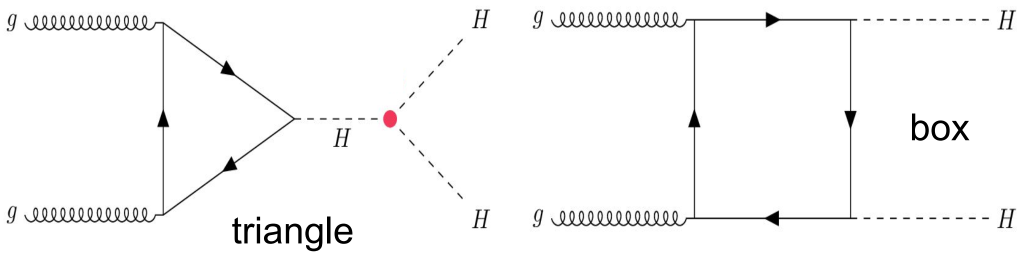
$$\text{with } v \approx 246 \text{ GeV and } m_H \approx 125\,\text{GeV},\ \lambda_{\text{SM}} \approx 0.13$$

- **HHH: with double Higgs production**
- **HHHH (almost out of reach of LHC)**

Main double Higgs production modes

ggF:

σ_{SM}=31.02 fb **at 13 TeV for m_H=125.09 GeV**



Dominant by ggF:

- ➢ Offshell Higgs in triangle
- ➢ Destructive interference

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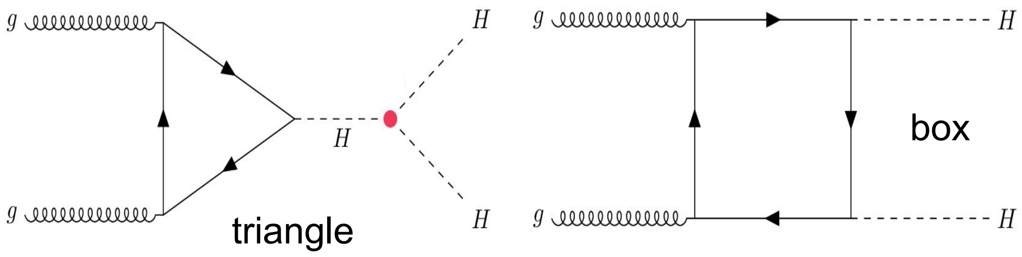
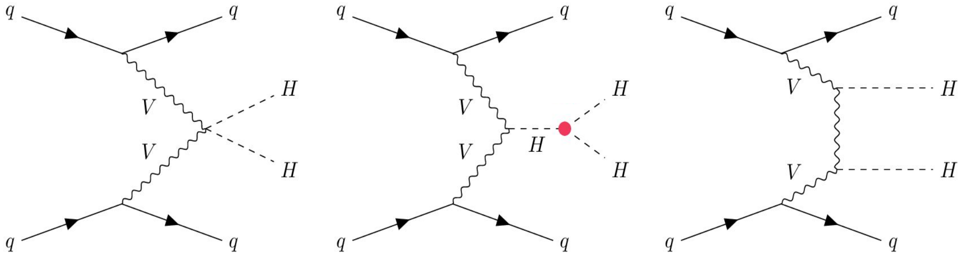


VBF:

σ_{SM}=1.72 fb at 13 TeV for m_H=125.09 GeV



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SM HH cross section:

~ 1k times smaller than 1-H

~ 1σ significance

Life ends up?

Main double Higgs production modes

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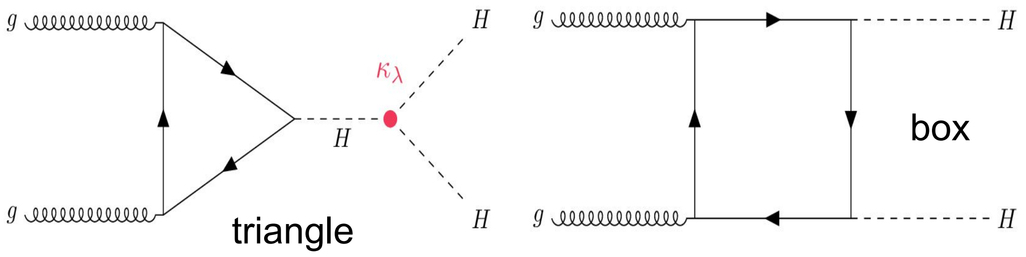

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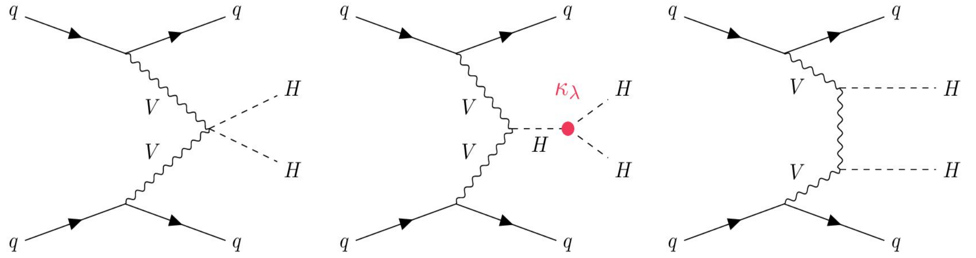

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SM HH cross section:

~ 1k times smaller than 1-H

~ 1σ significance

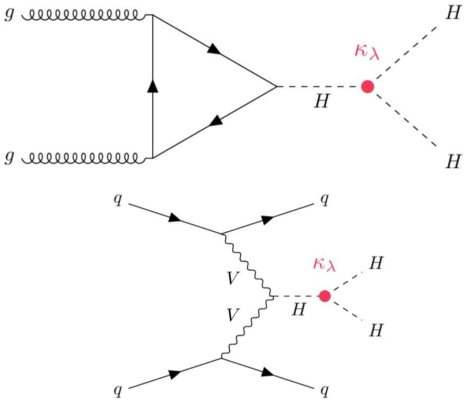
Life ends up?

Probe real shape of Higgs potential:

Self-coupling modifier

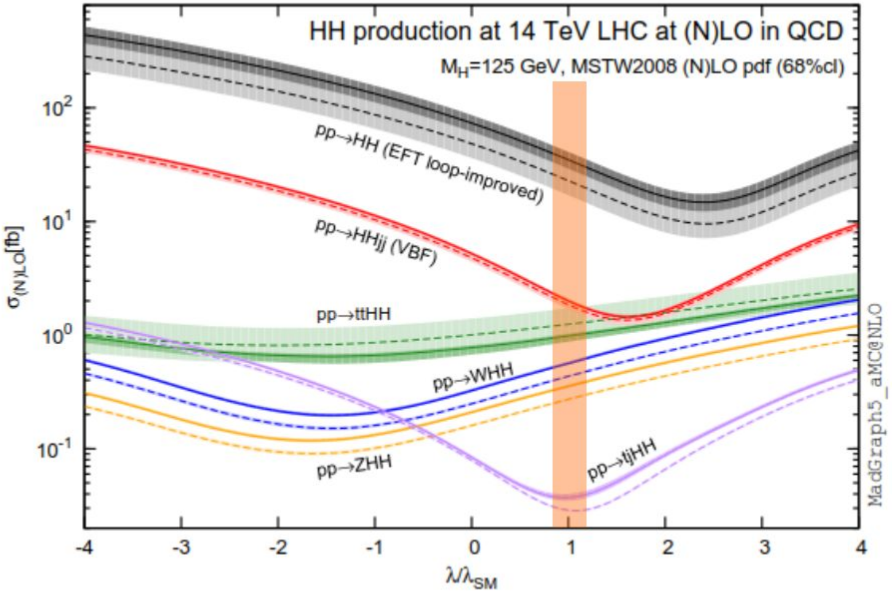
$$\kappa_\lambda = \lambda_{\mathrm{HHH}} / \lambda_{\mathrm{HHH}}^{\mathrm{SM}}$$

Non-resonant analysis: Higgs trilinear coupling

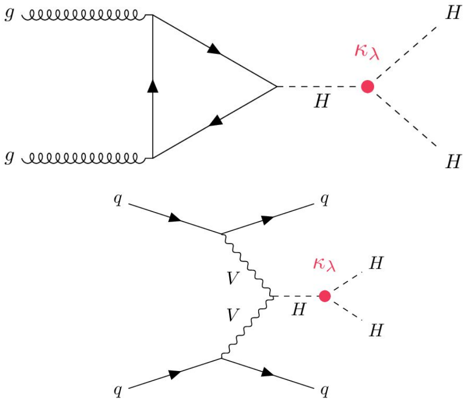


Self-coupling modifier
$\kappa_\lambda = \lambda_{\text{HHH}} / \lambda_{\text{HHH}}^{\text{SM}}$

HH cross section in function of κ_λ



Non-resonant analysis: Higgs trilinear coupling



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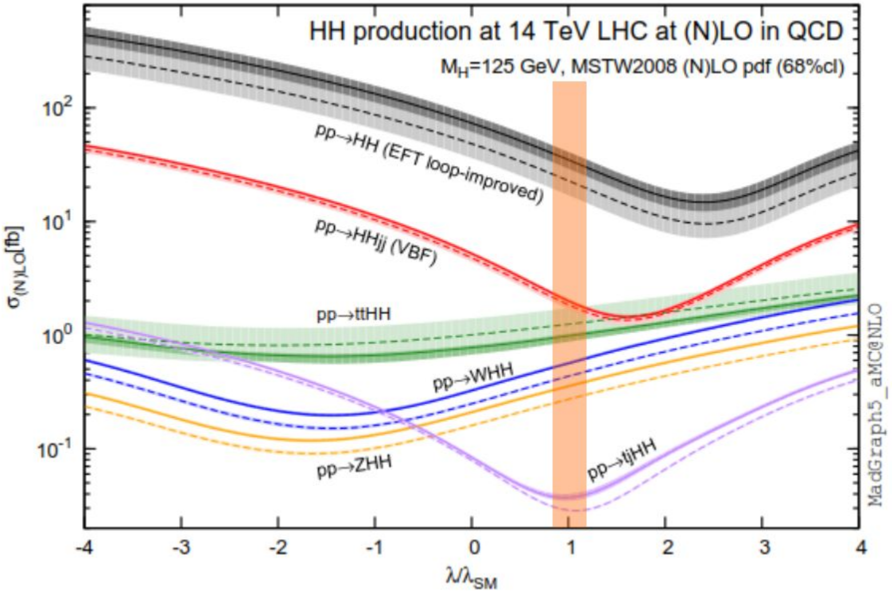
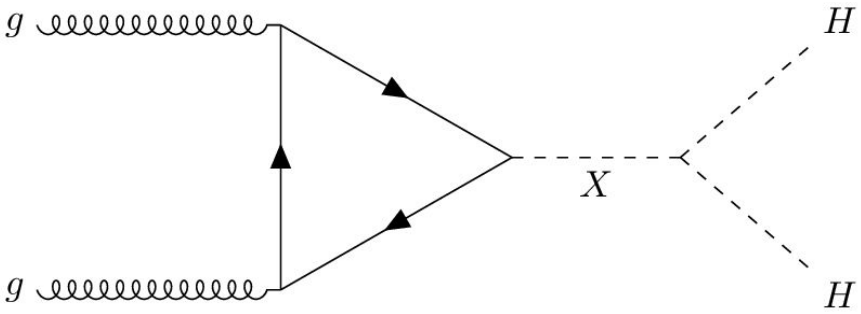
HH cross section in function of κ_λ



Some κ_λ leads to enhancement of HH production might be observable with Run 2 ATLAS data

Search of two on-shell Higgs boson in final state, with **non-resonant peak in m_{HH} spectrum** (off-shell intermediate Higgs)

Resonant analysis: new spin-0 heavy scalar



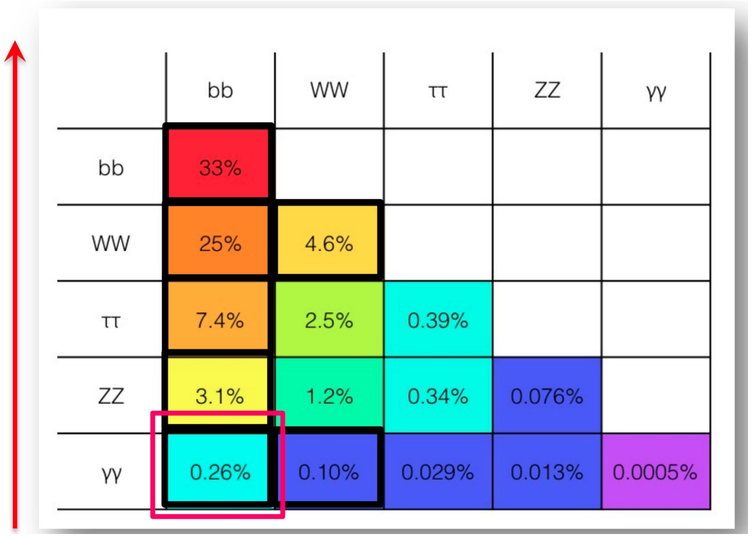
BSM theories predict spin-0:

- Two-Higgs-Doublet Models
- Electroweak Singlet Models

Search of new scalar X decay into two Higgs Boson, with **resonant peak in m_{HH} spectrum** ($m_X > 2m_H$)

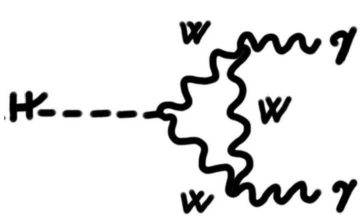
- Different mass hypothesis tested from **251 GeV to 1 TeV**
- Narrow width approximation
- CP even
- Model-independent

Final state signal: HH → bbγγ

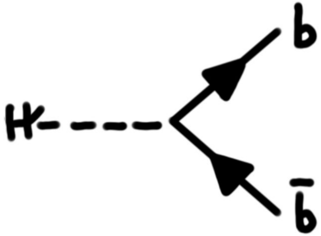


	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

bbbb, bb$\tau\tau$, **bbγγ**, bbWW, ...



Good resolution
Low background

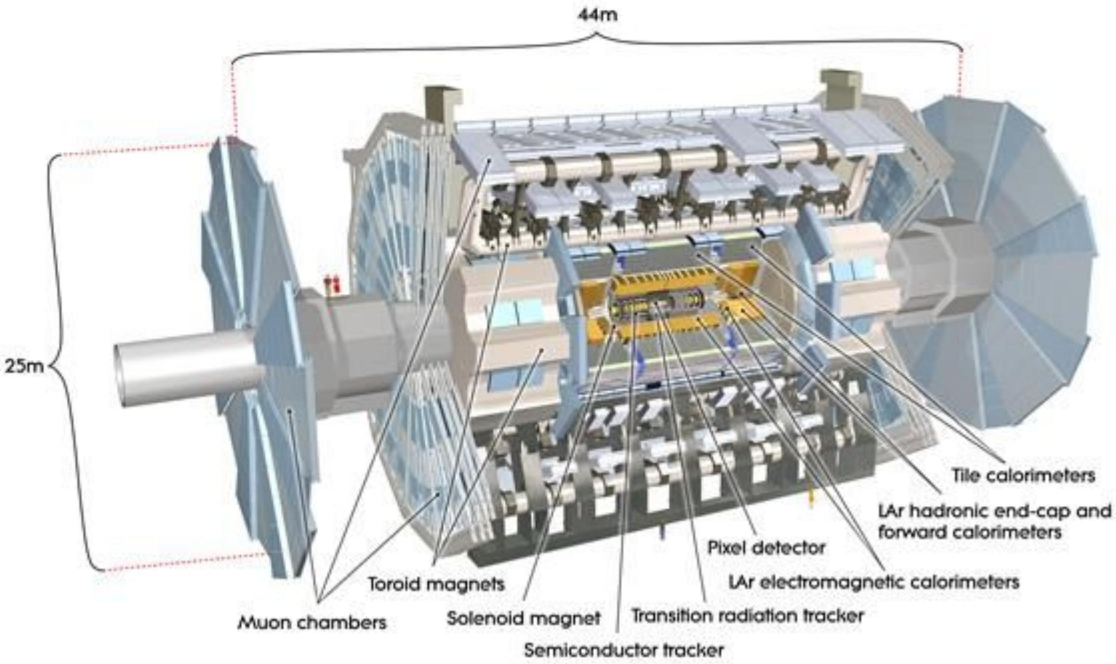


High signal rate

Main background in this channel:

- Dominant: γγ+jets
- Sub-dominant: single Higgs production (ggH, ttH, VBFH, etc.)

Photon and b-jets with ATLAS



One of the 4 experiments at LHC CERN

proton-proton beam in the center

From innermost to outermost:

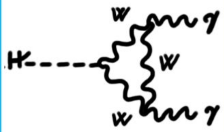
- **Inner tracker**: charged particles
- **ECAL**: e/γ
- **HCAL**: jet
- **Muon chamber**: muons

HH→bbγγ:
Photons reconstructed by tracker and ECAL
Jets reconstructed by tracker and HCAL
(b-tagging with Insertable B-layer)

Common preselection

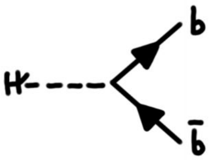
- **Di-photons trigger**: efficiency: 82.9% for SMHH; 69.5% for m_X=300 GeV

  HTL_g35_loose_g25_loose (2015-2016) **HLT_g35_medium_g25_medium_L12EM20VH** (2017-2018)



Two good quality photons:

- Well identified (tight ID)
- With few other particles around the photon (Isolated)
- 105 GeV < $m_{\gamma\gamma}$ < 160 GeV
- γγ vertex
- $E_T/m_{\gamma\gamma}$ > 0.35 and 0.25



Less than 6 central jets (reduce ttH)

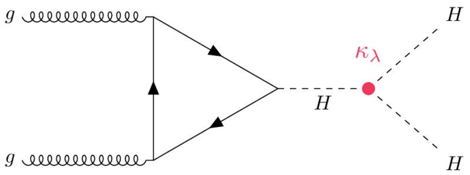
- Particle Flow jets, anti-kt R=0.4, tight JVT

Exact two b-jets:

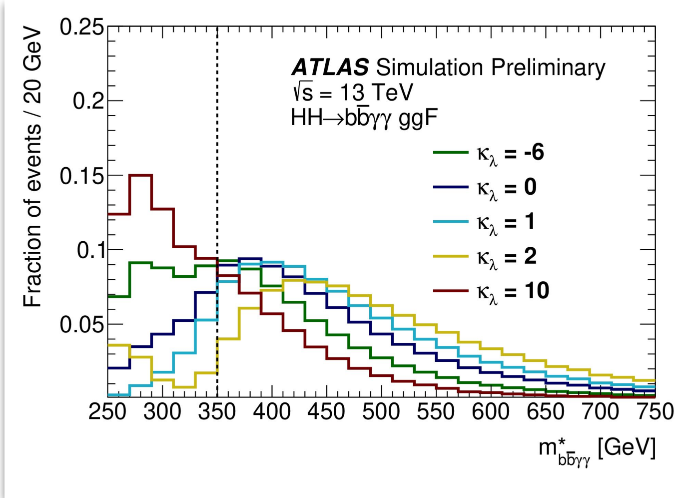
- DL1r 77% working point
- B-jet energy resolution correction (muon in jet, pt-reco)

- **Lepton veto: reduce top background**

Non-resonant: optimization for various κ_λ



$m_{bb\gamma\gamma}$-κ_λ correlation



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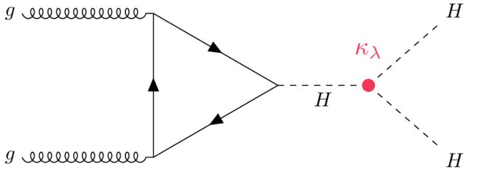
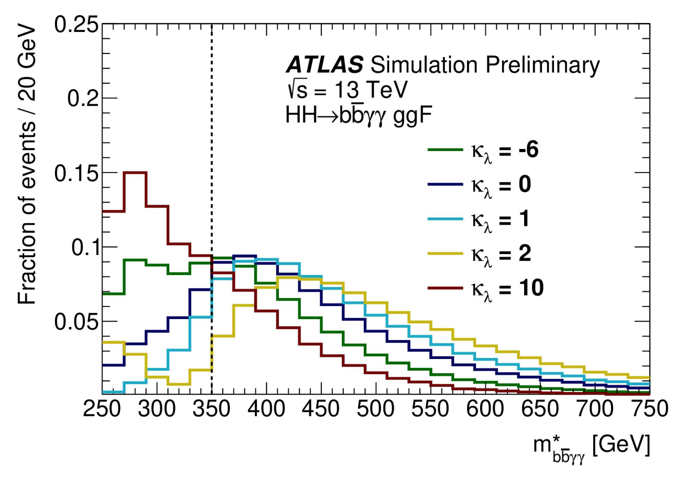
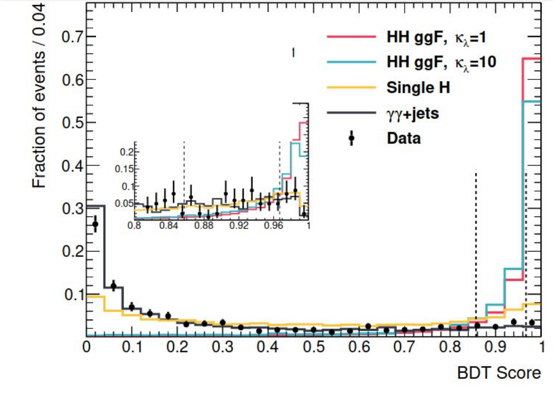


$m_{bb\gamma\gamma}$-κ_λ correlation





(b) High mass region

Big (small) κ_λ prefers small (big) $m_{bb\gamma\gamma}$

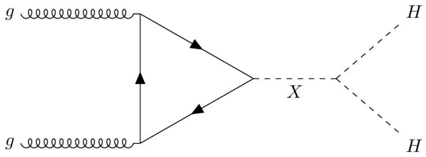
Two Boosted decision tree:

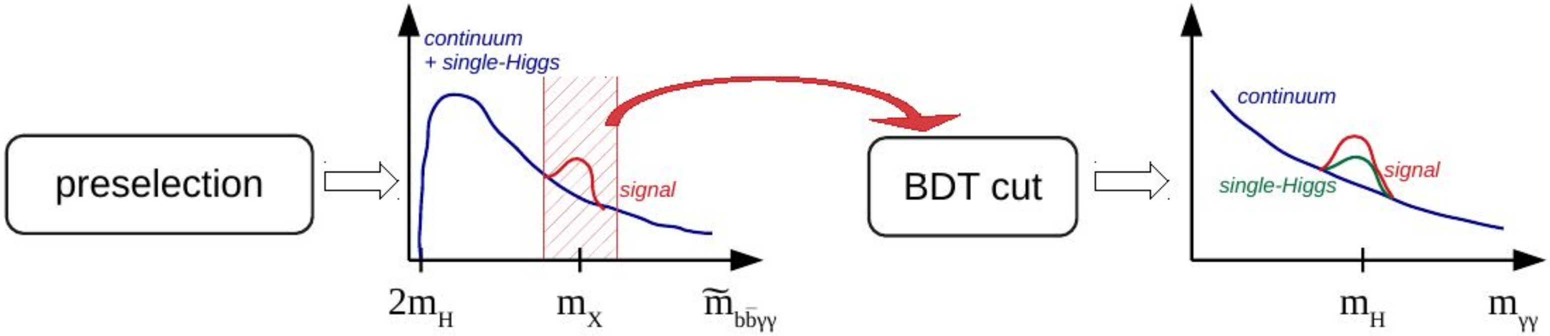
- **High mass** (> 350 GeV): **κ_λ=1** as signal
- **Low mass** (< 350 GeV): **κ_λ=10** as signal

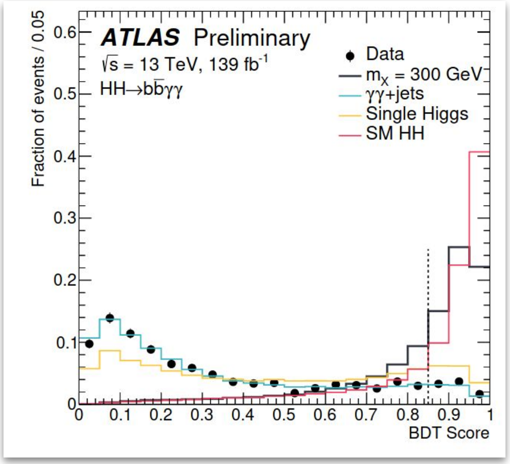
Events are divided into 4 categories by $m_{bb\gamma\gamma}$ and BDT scores

Using $m_{\gamma\gamma}$ as final discriminant variable

Resonant: for various scalar masses







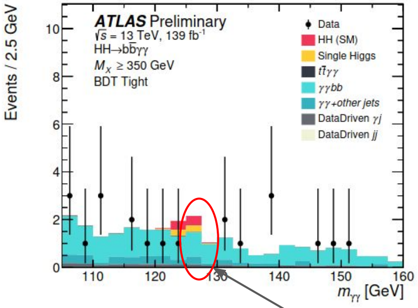
1 common BDT for all m_X to against the bkg

For each m_X, further cut on $m_{bb\gamma\gamma}$ (window near the m_X value)

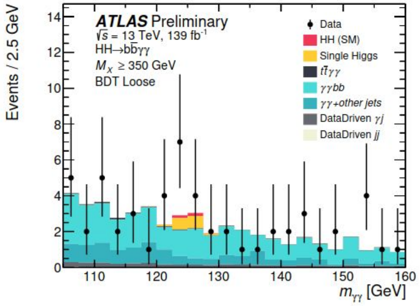
Using $m_{\gamma\gamma}$ as final discriminant variable

Real data and simulation (for illustration)

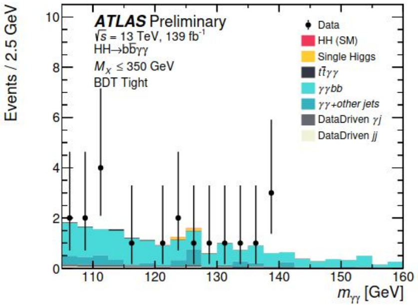
Non-resonant



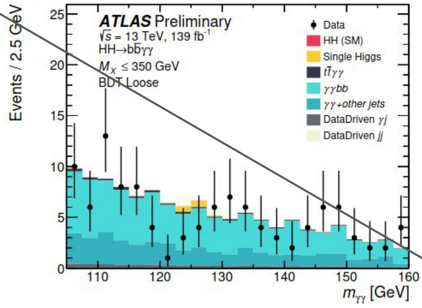
(a) High mass BDT tight selection



(b) High mass BDT loose selection

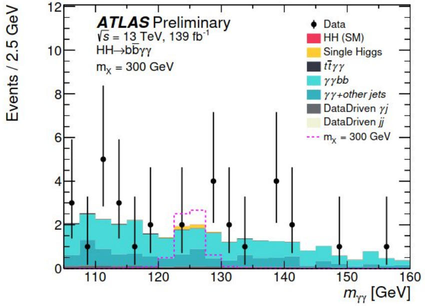


(c) Low mass BDT tight selection

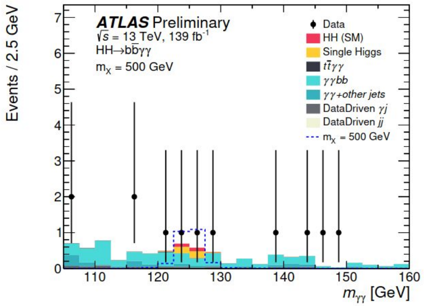


(d) Low mass BDT loose selection

Resonant



(a)



(b)

Use diphoton mass ($m_{\gamma\gamma}$) as final discriminant variable

γγ+jets: dominant background
Single Higgs: ttH, ZH, ggH

For non-resonant, a large deficit observed between 120 and 130 GeV for the most sensitive category (lack of statistics)

Statistical model

Maximum likelihood fit performed on $m_{\gamma\gamma}$∈[105, 160] GeV

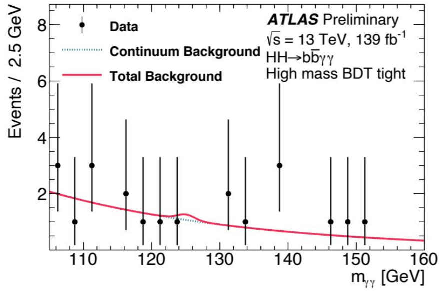
- ★ **Extended Likelihood with auxiliary constraints**

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

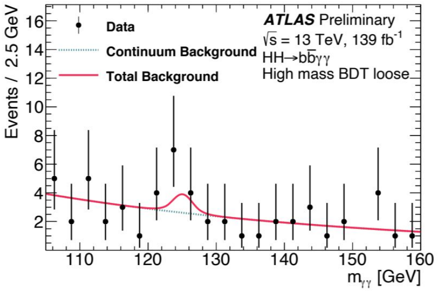
  - Likelihood as product of all categories
  - Parameter of interest: signal strength or HH cross section
  - Poisson term constraining the events in each category
  - Pdf on $m_{\gamma\gamma}$:
    - HH signal and 1-H bkg: Double sided crystal ball function (power+Gaus+power)
    - γγ+jets: exponential function
  - Pre-fit constraint of nuisance parameters (mainly systematics, often Gaussian)

B-only fit with observed data

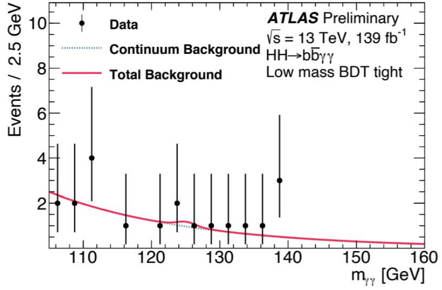
Non-resonant



(a) High mass BDT tight



(b) High mass BDT loose



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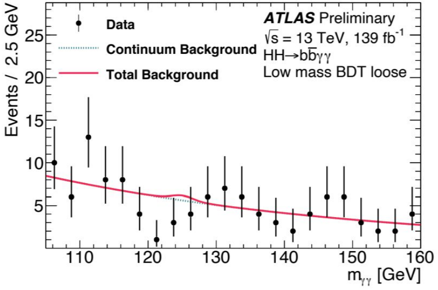

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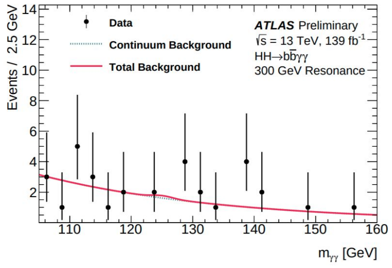
Resonant



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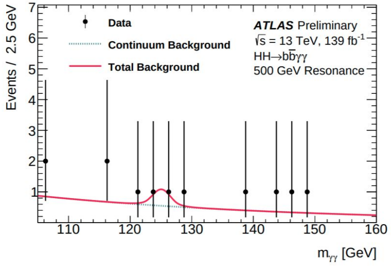


(b)

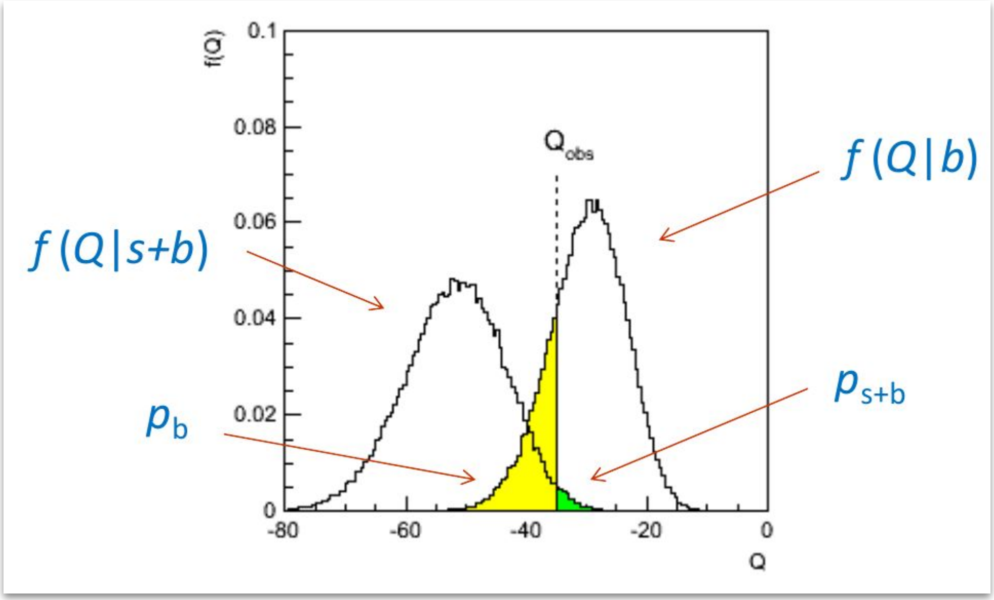
Agreement with b-only model
No clear HH signal
*little bump near 125 GeV correspond to 1-H

What we could do if observing no signal?
Still have constraint on signal (→limit)

Limit setting with CLs method

Consider a test statistic Q, e.g. likelihood ratio, constructing PDF of Q for

- **Null hypothesis** with different signal *s*: **f(Q|s+b)**
- **Alternative hypothesis** with b-only: **f(Q|b)**



Green area: p-value of null, i.e. p_{s+b}
Yellow area: p-value of alternative p_b

$$\mathrm{CLs} = \frac{p_{s+b}}{1 - p_b}$$

For each value of *s*, CLs could be computed
Limit of *s* is the one giving CLs=α
1-α is confidence level, e.g. 95%

Copy from statistic course of Glen Cowan

Non resonant results

No signal observed, asymptotic limits with CLs have been derived for μ_{SMHH} and κ_λ

Upper Limit (95% CL) on μ_{HH} assuming κ_λ=1:

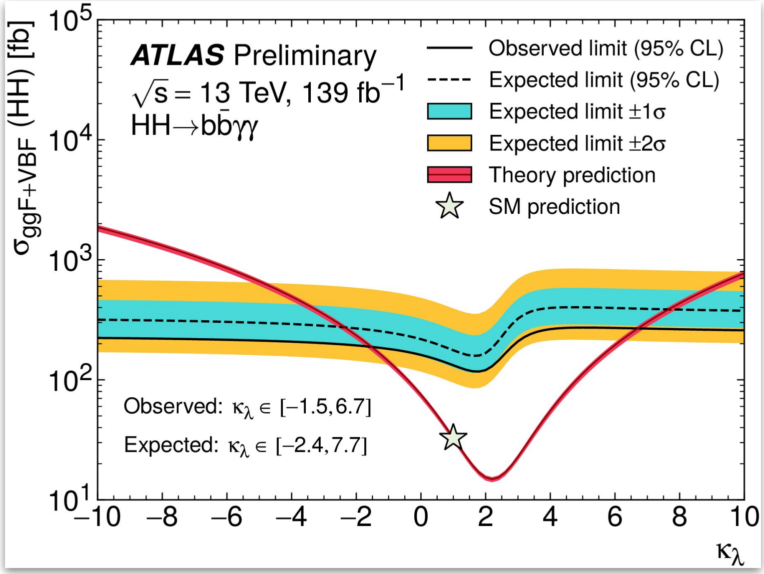
obs: 4.1xSM
exp: 5.5xSM

Statistical dominated, ~3% systematic effect
obs<exp, due to deficits in observed data

Limit (95% CL) on κ_λ:

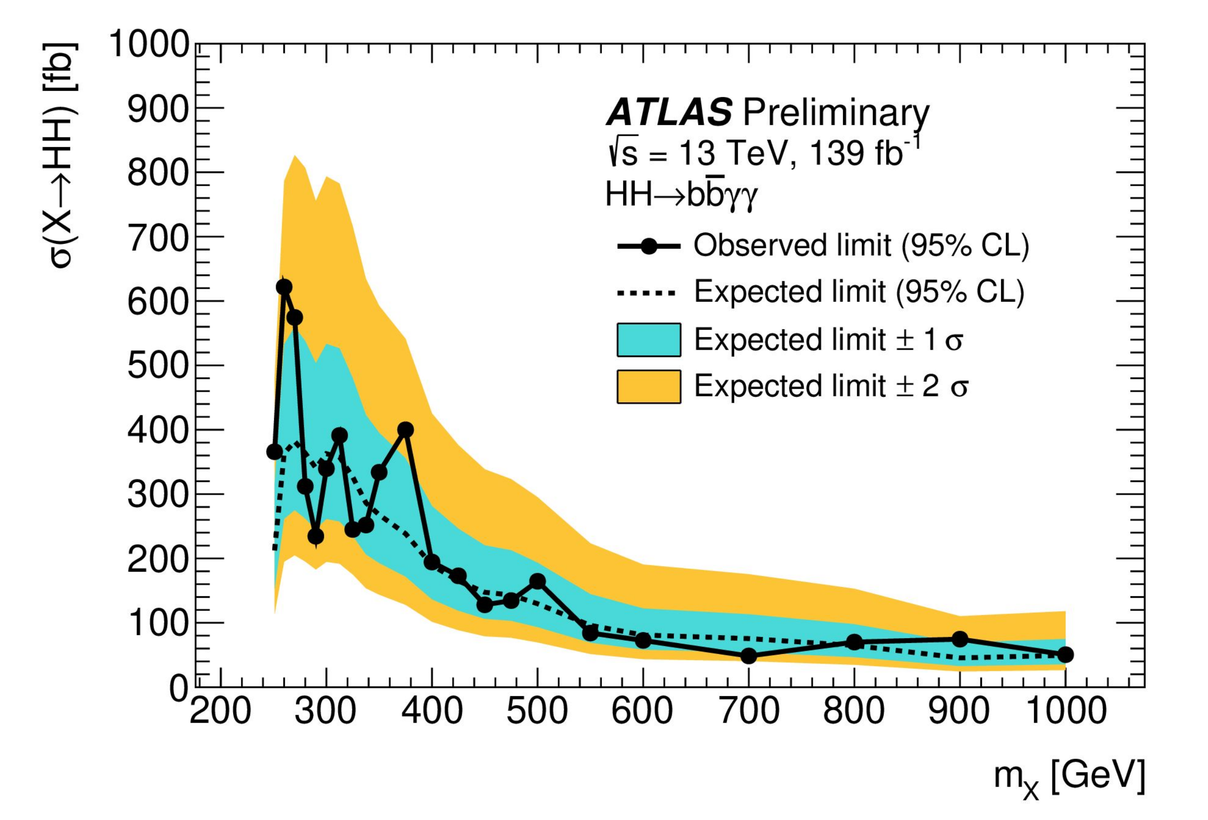
obs: [-1.5, 6.7]
exp: [-2.4, 7.7]

VBF HH contributes to an improvement of 5%



Resonant results

No signal observed, upper limits with CLs on **cross section of each m_X**:



Conclusion

Run 2 ATLAS results 139 fb^{-1}:

Non-resonant:

95% CL limit on $\mu_{HH,\kappa\lambda=1}$:
obs: 4.1xSM
exp: 5.5xSM

95% CL limit on κ_λ:
obs: [-1.5, 6.7]
exp: [-2.4, 7.7]

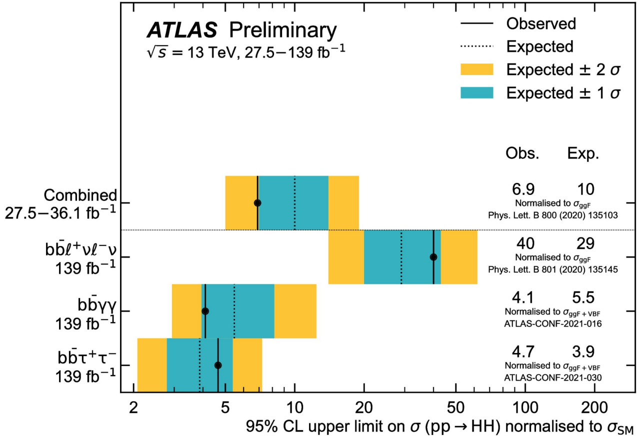
Resonant:

95% CL limit on σ(gg→X→HH):
obs: 610–47 fb
exp: 360–43 fb
for 251 GeV ≤ m_X ≤ 1000 GeV

Result compatible with other HH channels:
http://cdsweb.cern.ch/record/2777013/files/ATL-PHYS-PUB-2021-031.pdf

Comparable with CMS:
https://cds.cern.ch/record/2742937/files/HIG-19-018-pas.pdf?version=1

Extrapolation to HL-LHC (3000 fb^{-1}):
Expect to measure κ_λ with 0.5 uncertainty if equal to 1
https://arxiv.org/pdf/1902.00134.pdf



Backup

Data and MC

- **Full Run 2 data (139 fb^{-1})**: previous study with 36.1 fb^{-1}
- **ggF HH signal (κ_λ = 1,10)** at NLO with **Powheg-Box** v2 + **Pythia 8 + κ_λ reweighting technique**
- **VBF HH signal (κ_λ = 0,1,2,10)** at LO **MadGraph5_aMC@NLO** v2.6.0 NNPDF3.0nlo + **Pythia 8**
  - **Herwig 7** used for parton shower uncertainty
- **Spin 0 signal (251-1000 GeV)** at LO with **MadGraph5_aMC@NLO** v2.6.1 + **Herwig** v7.1.3
- **Background: Single Higgs (ggH, ttH, VBFH, etc.)** and **continuum γγ+jets** :

Single Higgs and continuum bkg MC

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	–

Summary

Run 2 ATLAS results:

Non-resonant:

95% CL limit on $\mu_{HH,\kappa\lambda=1}$:
obs: 4.1xSM
exp: 5.5xSM

95% CL limit on κ_λ:
obs: [-1.5, 6.7]
exp: [-2.4, 7.7]

Resonant:

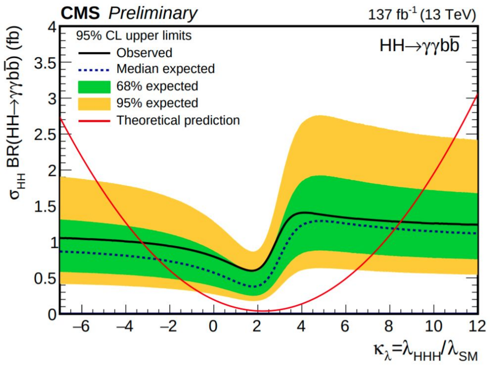
95% CL limit on σ(gg→X→HH):
obs: 610–47 fb
exp: 360–43 fb
for 251 GeV ≤ m_X ≤ 1000 GeV

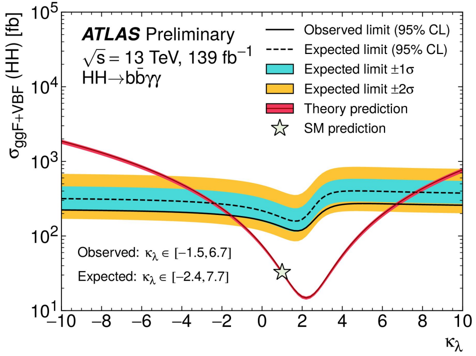
Comparison to CMS:

Full Run 2 CMS results:

Limit of μ_{HH}:
obs: 7.7xSM
exp: 5.2xSM

Limit of κ_λ:
obs: [-3.3, 8.5]
exp: [-2.5, 8.2]

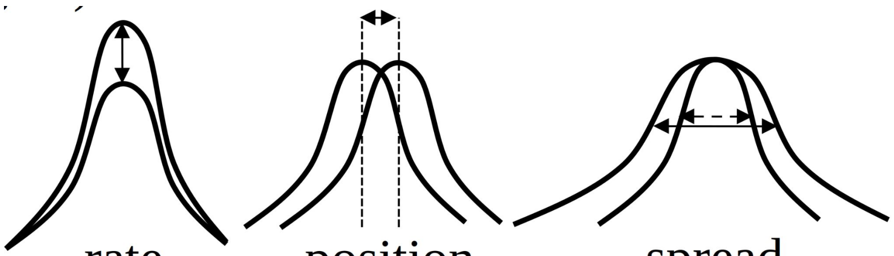




Systematic uncertainties

Systematic uncertainties:

- **Event rate**
- **Shape of $m_{\gamma\gamma}$**
  - signal pdf (DSCB)
  - spurious signal for bkg



Experimental systematics

photon, jets, b-tagging ...

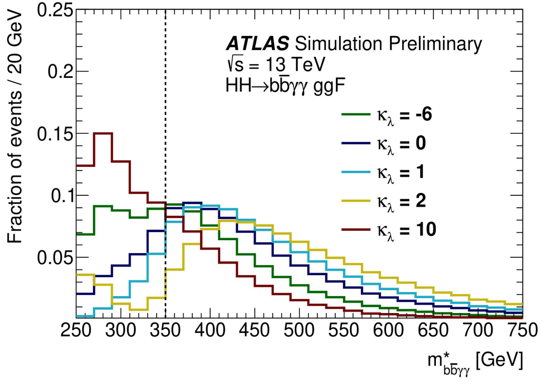
Theoretical systematics

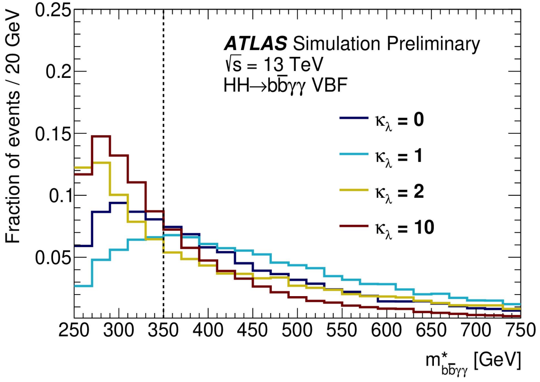
- QCD, pdf+α_s
- HF (100 %) [ggH, VBF, WH]
- BRs, mtop
- Parton Showering (H7 vs Py8)
- κ_λ reweighting syst (O(5 %))

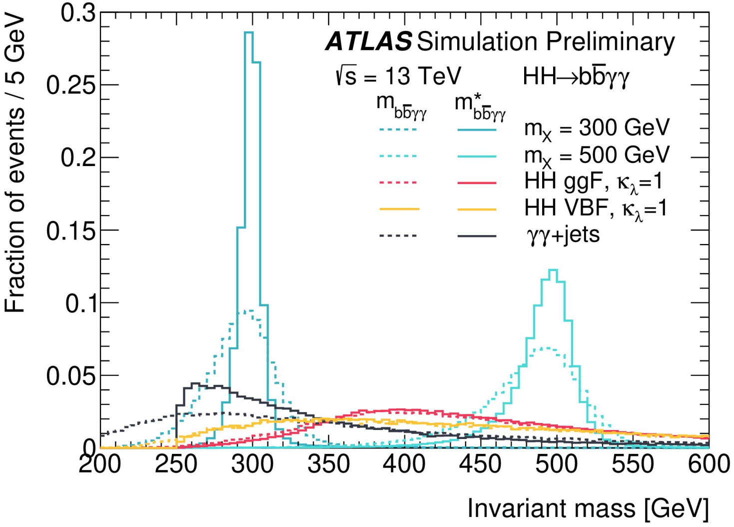
Impact of systematics on limits:

		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

$\kappa_\lambda - m_{\mathrm{HH}}$ correlation: Inspiration for categorization







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

Use mbbyy* to improve the resolution:

Prediction of different κ_λ with reweighting technique

$$A(k_t, k_\lambda) = k_t^2 B + k_t k_\lambda T. \tag{1}$$

The amplitude square is written as:

$$|A(k_t, k_\lambda)|^2 = k_t^4 |B|^2 + k_t^2 k_\lambda^2 |T|^2 + k_t^3 k_\lambda (B^* T + B T^*). \tag{2}$$

The amplitude square can be further expressed in terms of the amplitude squares of three reference samples chosen. In this analysis, the reference samples are chosen to be $k_\lambda = 0, 1, 10$ samples. Since we are only interested in k_λ, k_t is taken as 1.

$$|A(1,0)|^2 = |B|^2, \tag{3}$$

$$|A(1,1)|^2 = |B|^2 + |T|^2 + (B^* T + B T^*) \tag{4}$$

$$|A(1,10)|^2 = |B|^2 + 100|T|^2 + 10(B^* T + B T^*) \tag{5}$$

Using these equations, $|A(k_t, k_\lambda)|^2$ can be expressed in terms of amplitude squares of the three reference samples.

$$|A(k_t, k_\lambda)|^2 = k_t^2 \left[\frac{90k_t^2 + 9k_\lambda^2 - 99k_t k_\lambda}{90} |A(1,0)|^2 + \frac{100k_t k_\lambda - 10k_\lambda^2}{90} |A(1,1)|^2 + \frac{k_\lambda^2 - k_t k_\lambda}{90} |A(1,10)|^2 \right] \tag{6}$$

Description from previous 36.1 fb^{-1} note.

Linear combination of 3 κ_λ samples for generation of other values of κ_λ

Event-level weight applied on m_{HH} kinematics

For current Run 2 analysis, κ_λ =0, 1, 20 are used.

Systematic uncertainty estimated with differences between generated and reweighted samples at κ_λ=10.

Non resonant BDT input 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.

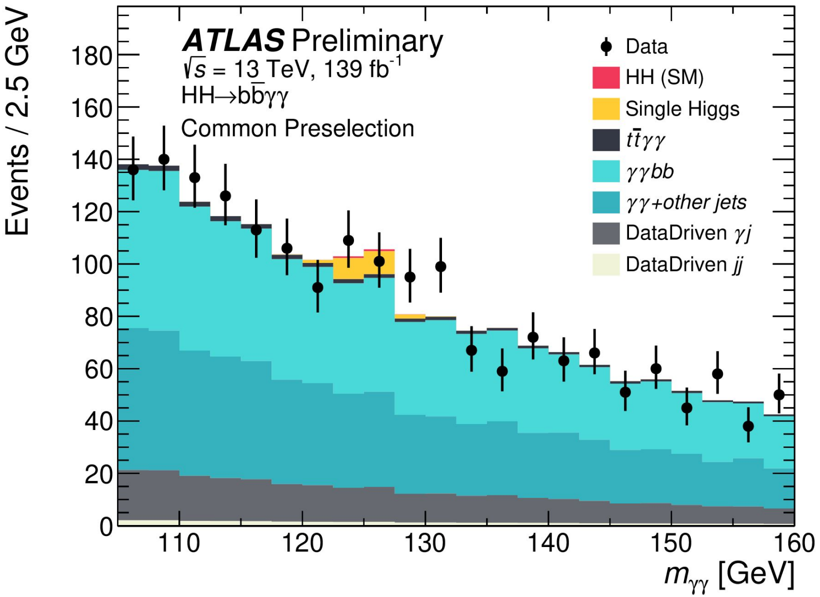
Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
b-tag status	Highest 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
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ 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_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle

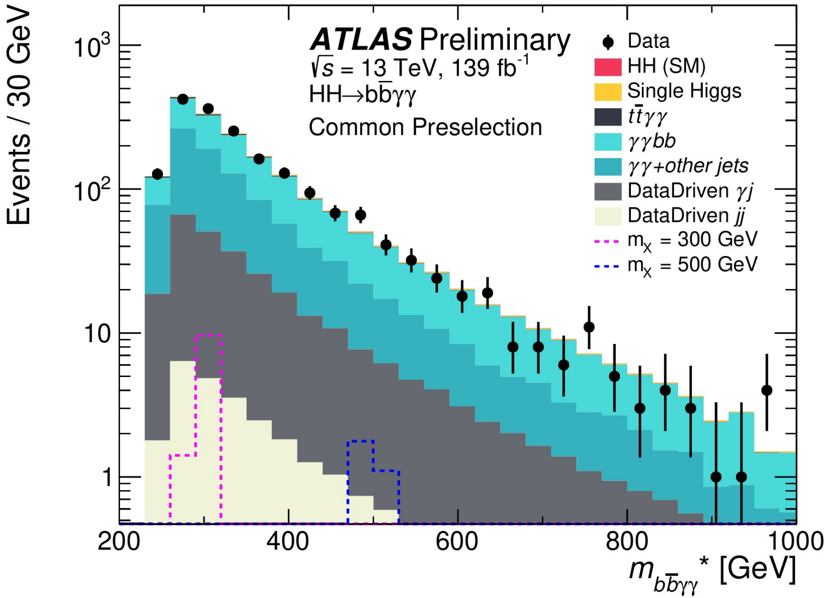
Resonant BDT input variables

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	
$p_T^{\gamma\gamma}$, $y^{\gamma\gamma}$	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

Data vs MC: preselection





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

improve resolution with correlations

Cut flow HH

Non-resonant

Cuts	raw number of events	Yield	Efficiency
N_{xAOD}	1.56e+06	11.3696	100
N_{DxAOD}	1.56e+06	11.3696	100
All events	1.56e+06	11.3685	99.9903
No duplicates	1.56e+06	11.3685	99.9903
GRL	1.56e+06	11.3685	99.9903
Pass trigger	1.30292e+06	9.43463	82.9808
Detecctor DQ	1.30292e+06	9.43463	82.9808
Has PV	1.30292e+06	9.43463	82.9808
2 loose photons	962029	7.00497	61.6112
$e - \gamma$ ambiguity	961632	7.00186	61.5838
Trigger match	913938	6.65969	58.5743
tight ID	799960	5.85507	51.4974
isolation	709300	5.16719	45.4472
$rel.p_T cuts$	638923	4.64775	40.8786
$m_{\gamma\gamma} \in [105, 160]$	638541	4.64498	40.8542
$N_{lep} = 0$	638371	4.71206	41.4442
$N_j > 2$	635973	4.69411	41.2863
N_j central <6	540328	3.94838	34.7274
leading jet 85% WP	521719	3.81785	33.5793
subleading jet 85% WP	269007	2.01101	17.6875
$N_j btag < 3$	263071	1.96522	17.2847
2 b-jet with 77% WP	210794	1.56478	13.7628
DiHiggs invariant mass <350	23434	0.187622	1.6502
DiHiggs invariant mass >350	187360	1.37716	12.1126

Table 152: Cutflow for Non resonant x → hh → γγbb

Resonant

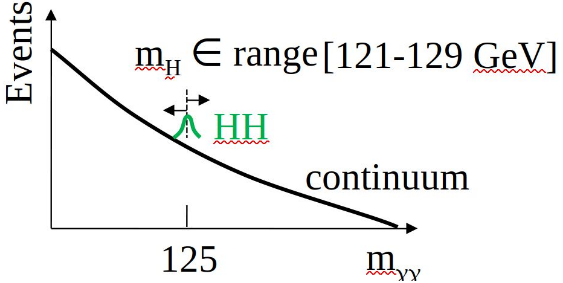
Cuts	raw number of events	Yield	Efficiency
N_{xAOD}	820000	133.994	100
N_{DxAOD}	820000	133.994	100
All events	820000	133.985	99.9927
No duplicates	820000	133.985	99.9927
GRL	820000	133.985	99.9927
Pass trigger	561153	91.8438	68.543
Detecctor DQ	561153	91.8438	68.543
Has PV	561153	91.8438	68.543
2 loose photons	461295	75.6471	56.4554
$e - \gamma$ ambiguity	461105	75.6125	56.4296
Trigger match	415412	68.3971	51.0447
tight ID	354968	58.6712	43.7863
isolation	299286	49.2099	36.7254
$rel.p_T cuts$	270121	44.4441	33.1686
$m_{\gamma\gamma} \in [105, 160]$	269966	44.419	33.1499
$N_{lep} = 0$	269872	45.2723	33.7867
$N_j > 2$	268619	45.0653	33.6322
N_j central <6	201307	33.2857	24.8411
leading jet 85% WP	199795	33.0534	24.6677
subleading jet 85% WP	90129	14.7167	10.9831
$N_j btag < 3$	88730	14.4868	10.8115
2 b-jet with 77% WP	70698	11.289	8.42498
DiHiggs invariant mass selection	70698	11.289	8.42498
BDT selection	40764	6.52261	4.86782
$m_{\gamma\gamma} \in [120, 130]$	38981	6.24486	4.66053

Table 158: Cutflow for resonant x300→ hh → γγbb

Background modeling and spurious signal

S+B fit on b-only MC templates:

-Spurious signal: $N_{sp}=\max|n_{sig}(m_H)|$



- Relaxed Criteria: lack bkg MC statistics

if $N_{sp}>2\Delta n_{sig}^{MC\ stat}$ then $\zeta_{sp}=N_{sp}-2\Delta n_{sig}^{stat\ MC}$

else $\zeta_{sp}=0$

Pass OR of: -$\zeta_{sp}<10\ \%\ N_{signal}$ expected

-$\zeta_{sp}<20\ \%\ \sigma_{bkg}$, ($Z_{sp}<20$ %)

- Wald test on real blinded data

Stick to natural form : exp

Non-resonant

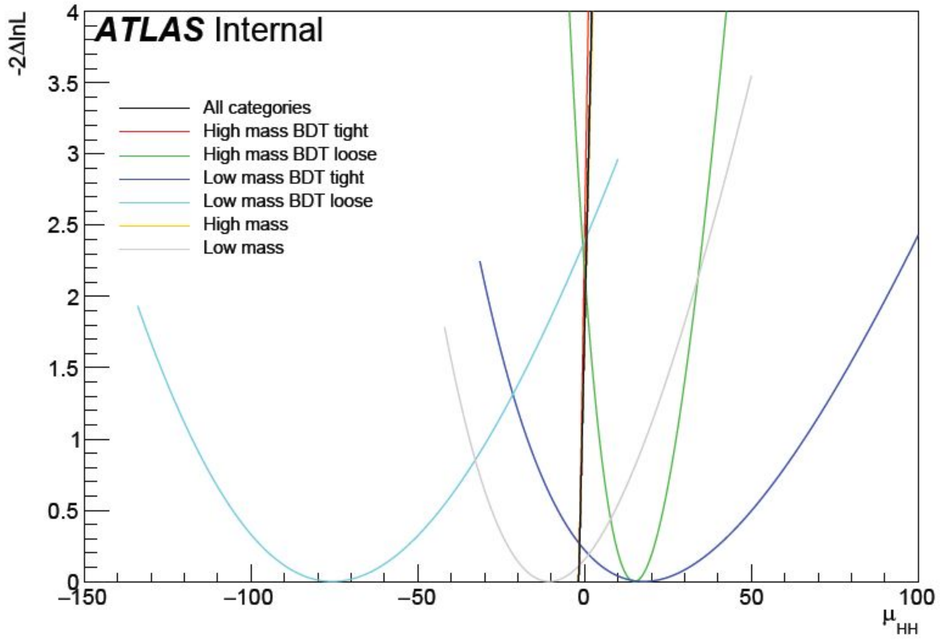
Category	n_{sp}	Z_{spur}	$p(\chi^2)[\%]$
High mass BDT tight	0.688	0.394	68.8
High mass BDT loose	0.990	0.384	30.5
Low mass BDT tight	0.594	0.378	29.8
Low mass BDT loose	1.088	0.272	26.9

Resonant

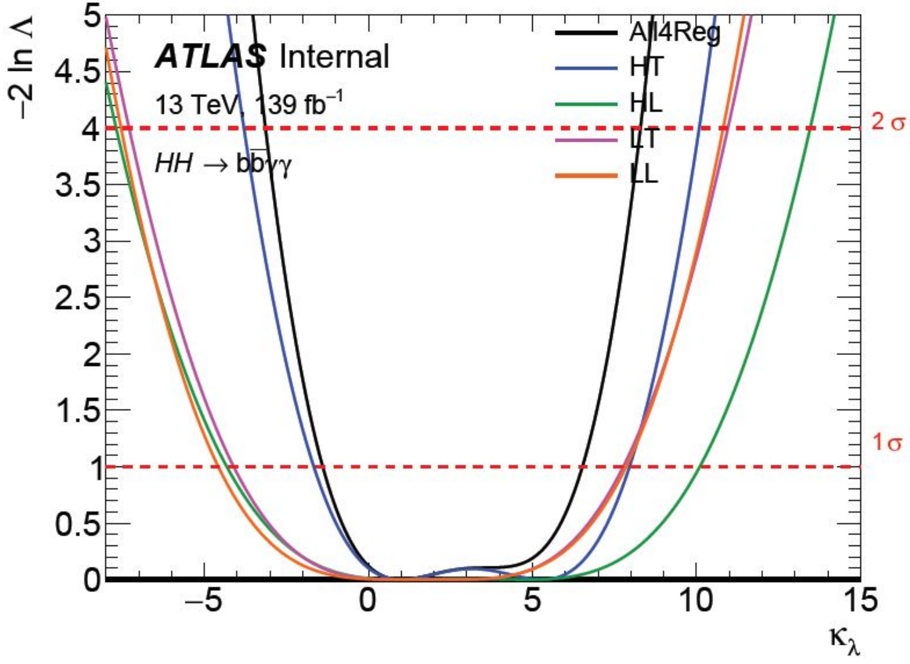
Signal mass [GeV]	n_{sp}	Z_{spur}	$p(\chi^2)[\%]$
251	0.269	0.179	97
260	0.787	0.277	1
270	1.057	0.431	-
280	0.561	0.245	0
290	0.620	0.272	-
300	0.938	0.421	0
312.5	0.538	0.223	-
325	1.075	0.470	0
337.5	0.819	0.399	-
350	0.832	0.457	7
375	0.382	0.303	-
400	0.295	0.182	0
425	0.378	0.310	-
450	0.451	0.421	1
475	0.758	0.594	-
500	0.218	0.178	0
550	0.140	0.155	31
600	0.095	0.115	19
700	0.532	0.397	0
800	0.150	0.152	0
900	0.213	0.286	97
1000	0.269	0.304	71

Non-resonant likelihood scan

Likelihood scan on μ, with κ_λ=1

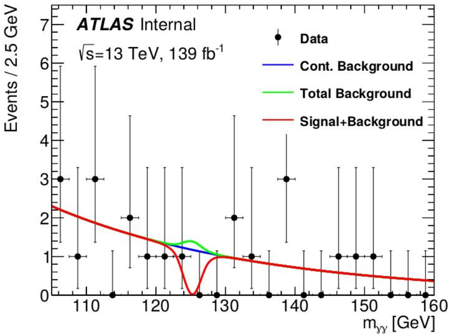


Likelihood scan on κ_λ, with μ=1

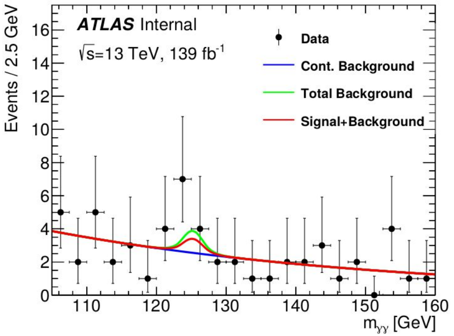


Likelihood performed simultaneously and individually with all the categories

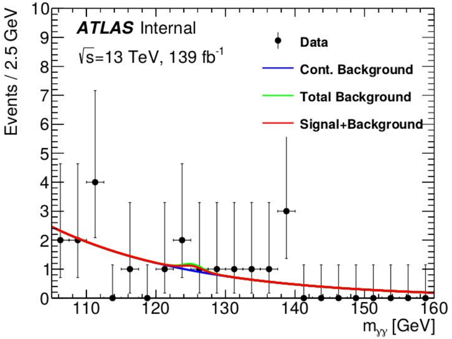
Non-resonant S+B fit



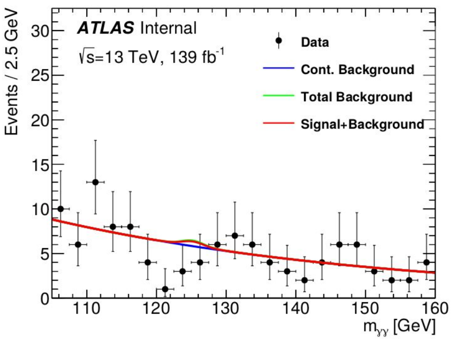
(a) High mass BDT tight



(b) High mass BDT loose



(c) Low mass BDT tight



(d) Low mass BDT loose

Figure 45: The observed data fitted with the signal + background model, in the four non-resonant ggF categories.

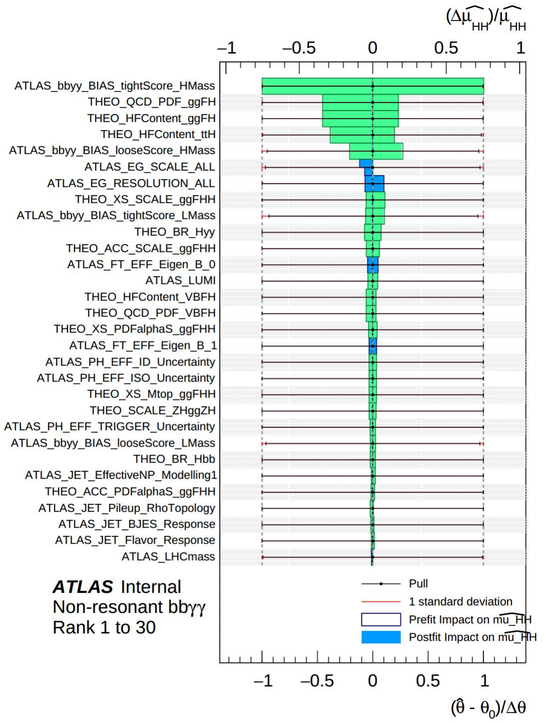
Due to the **large deficit** in the **High mass BDT tight category** (most sensitive), a negative signal strength (**$\mu \approx -2$**) has been observed

Ranking of systematic: expected

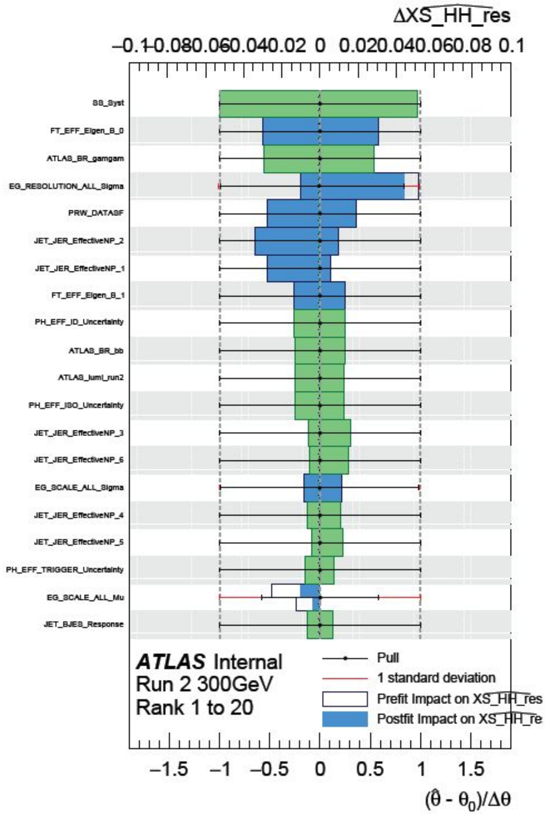
Asimov dataset :
syst. profiled from bkg-only fit
+ add μ_{HH}=1 (SM)

Dominant systematic :
-spurious signal

Non-resonant



Resonant



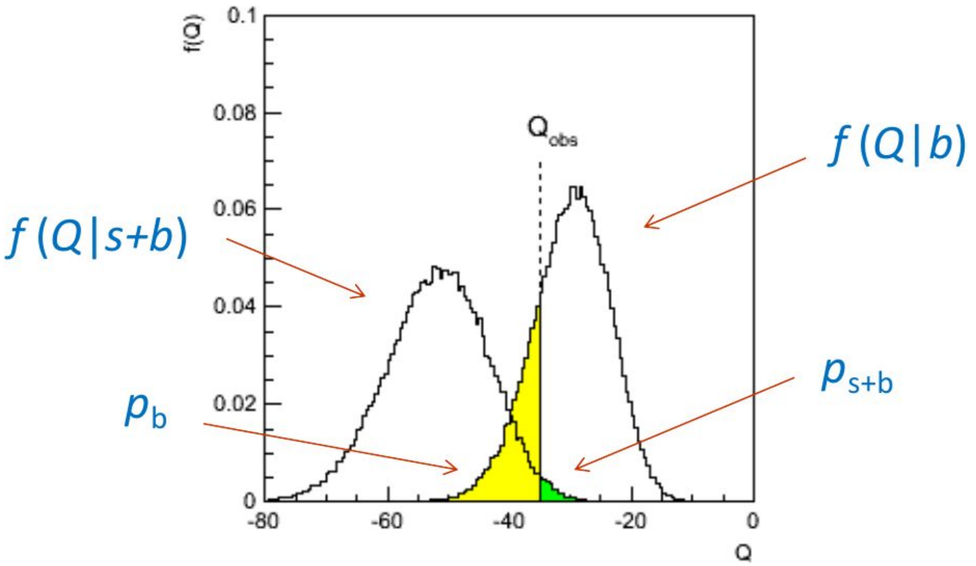
Limit setting with CLs method

$$\mathrm{CLs} = \frac{p_{s+b}}{1 - p_b}$$

Advantage of CLs: not to exclude a hypothesis when pdf of test statistics (Q) are similar between s+b and b

Test statistics used in this analysis

$$\tilde{q}_\mu = \begin{cases} -2\ln \frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0\ , \\ -2\ln \frac{L(\mu,\hat{\hat{\boldsymbol{\theta}}}(\mu))}{L(\hat{\mu},\hat{\boldsymbol{\theta}})} & 0 \le \hat{\mu} \le \mu\ , \\ 0 & \hat{\mu} > \mu\ . \end{cases}$$



Narrow width approximation

$$\frac{1}{(s - M^2)^2 + M^2\Gamma^2} \xrightarrow{\Gamma/M \to 0} \frac{\pi}{M\Gamma}\delta(s - M^2)$$

$$\lim_{\epsilon \to 0} \frac{\epsilon}{\epsilon^2 + x^2} = \pi\delta(x)$$

$$\frac{1}{\Gamma M^3} \frac{\Gamma/M}{(s/M^2 - 1)^2 + (\Gamma/M)^2} \to \frac{1}{\Gamma M^3}\pi\delta(s/M^2 - 1) = \frac{1}{\Gamma M}\pi\delta(s - M^2)$$

Narrow width approx. allows to write the propagator (w/ decay width) as dirac function and 1/decay_width.

Dirac function: on-shell
1/decay_width: cross section of one decay channel = production cross section * BR

Non resonant results: toys vs asymptotic

For **SM HH signal strength μ**, toys have been studied for the validation of asymptotic formula, for both **stat-only** and **full model**

stat-only	**exp**	**obs**
Asymptotic	5.3	3.8
Toys 100k	**5.3**	**4.0**
difference	**0.5%**	**4.4%**

full-model	**exp**	**obs**
Asymptotic	5.5	4.1
Toys 50k	**5.9**	**4.2**
difference	**8.2%**	**3.6%**

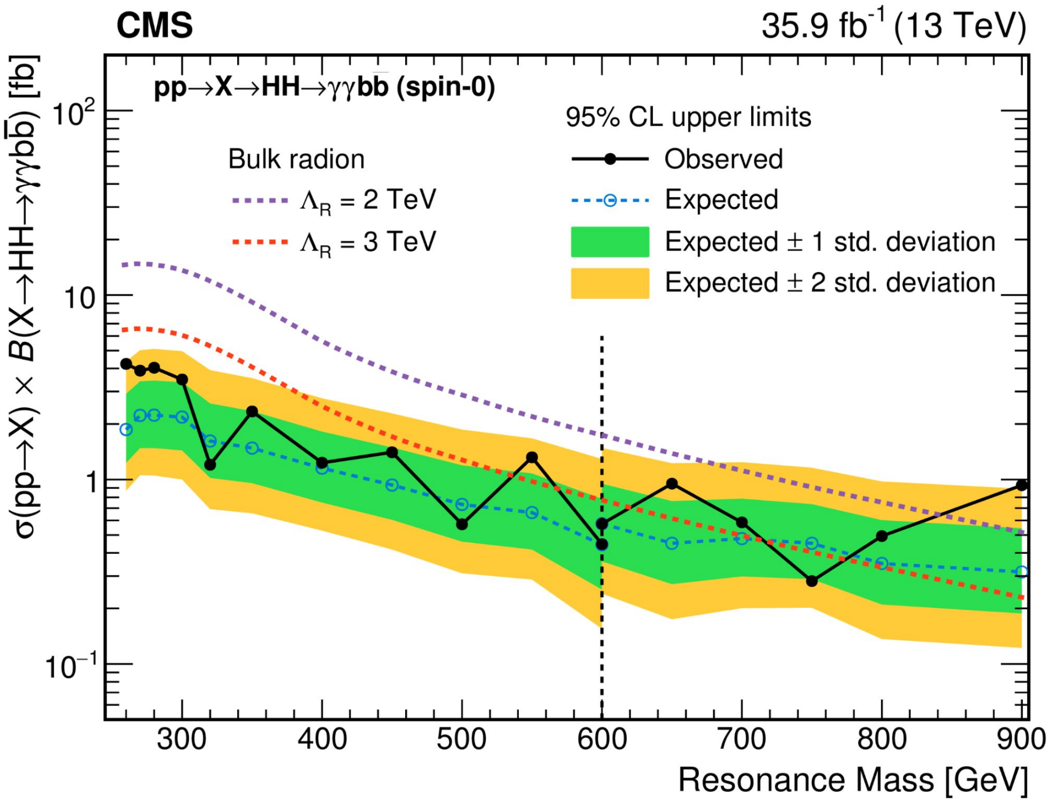
*stat-only limits derived by simply setting all NPs to 0 in the model

stat-only: bias up to 4%
full model: for expected, bias increased to 8%

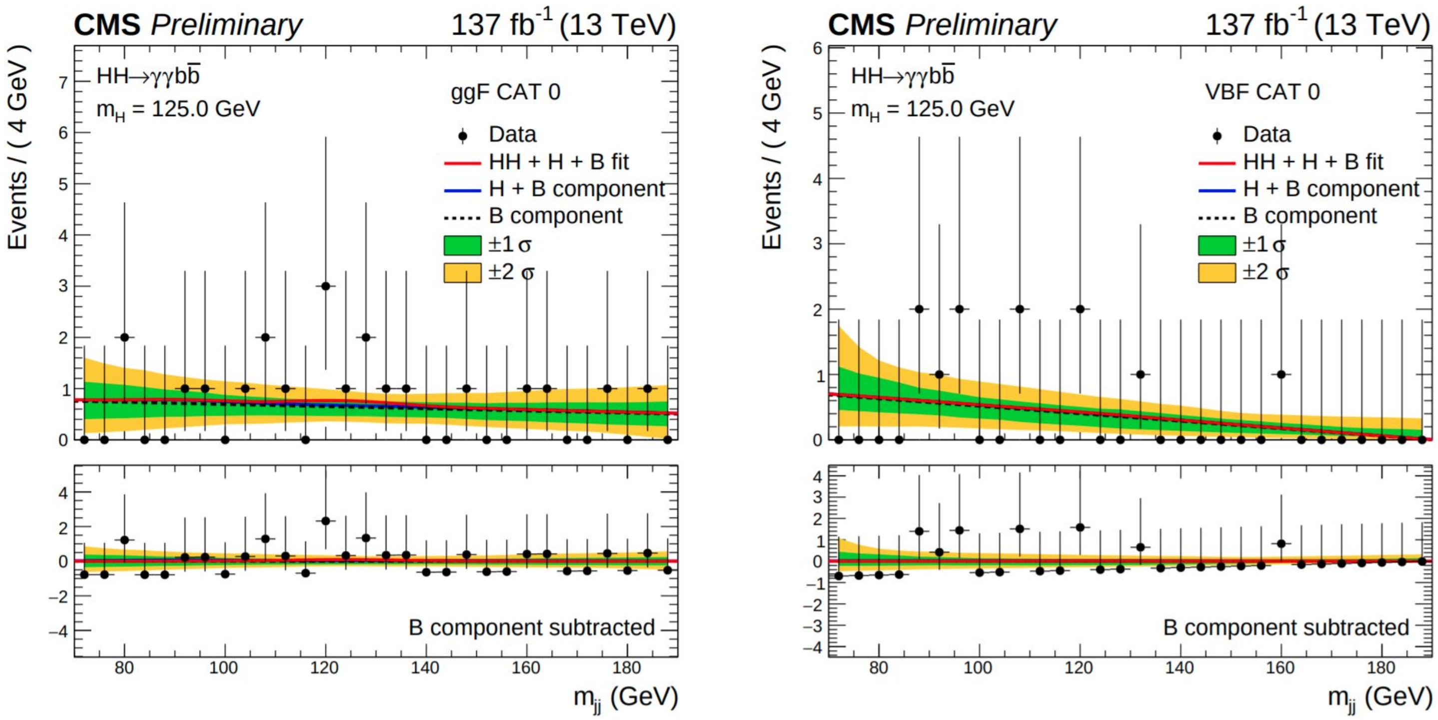
Conclusion: the asymptotic formula works with a bias up to 8%

Resonant search CMS 36 fb^{-1}

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-008/index.html



Up fluctuation of CMS data



(c) ggF CAT 0

(d) VBF CAT 0