Search for Higgs boson pair production in the final state of $\gamma\gamma WW^{*}(\rightarrow l\nu jj)$ using 13.3 fb^{-1} of pp collision data recorded at $\sqrt{s}$ =13 TeV with the ATLAS detector

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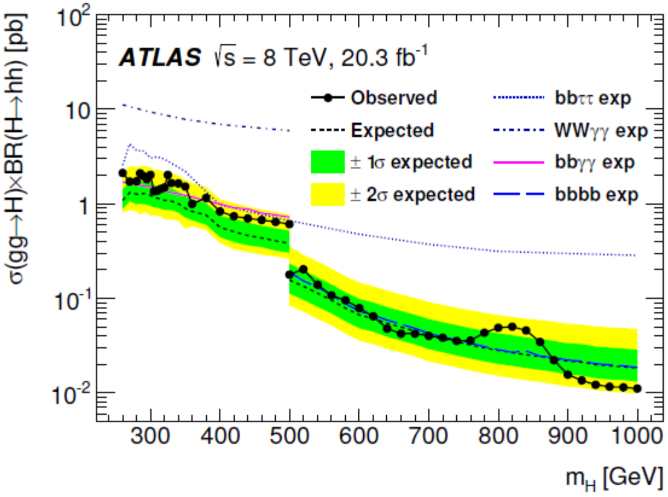
Introduction

- Higgs pair production has a small XS in SM (~33 fb @ 13 TeV) with triangle and box destructive interference.

- BSM can effectively enhance Higgs pair production.
  - non-resonance: altered Higgs self-coupling or ttH coupling. [Fig. (a) and (b)]
  - resonance: BSM resonance decay, such as heavy Higgs and Kaluza-Klein graviton. [Fig. (c)]

- This has been extensively searched with $hh \rightarrow bb\gamma\gamma,\ bbbb,\ bb\tau\tau$ and $WW\gamma\gamma$ in RUN Ⅰ and $hh \rightarrow bb\gamma\gamma,\ bbbb,\ \gamma\gamma WW,\ bbWW,\ bb\tau\tau$ and $\gamma\gamma WW$ in RUN Ⅱ



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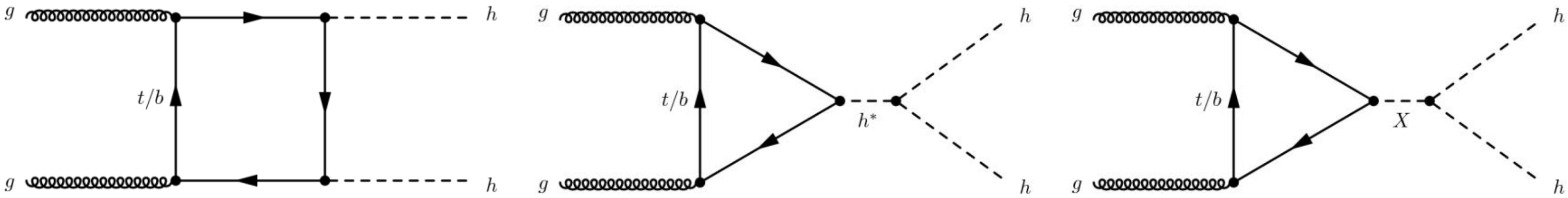


(a) (b) (c)

$hh \rightarrow \gamma\gamma WW^*$ analysis

- **Search for Higgs pair with $\gamma\gamma WW \rightarrow \gamma\gamma l\nu jj$**
  - **Benefit from a clean signature from $h \rightarrow \gamma\gamma$ and a large BR from $h \rightarrow WW$**
  - **Explore non-resonant production**
  - **Explore resonance in low mass region: 260, 300, 400, 500 GeV**

- **Share the same selections in non-resonant and resonant searches**

- **ATLAS-CONF-2016-071**

Selection

Photons

Two well identified and isolated photons with the following p_T and $m_{\gamma\gamma}$ selections:

$\frac{p_T\,(\gamma 1)}{m(\gamma\gamma)} \geq 0.35, \frac{p_T\,(\gamma 2)}{m(\gamma\gamma)} \geq 0.25;$

$m(\gamma\gamma) \in [105, 160]$ GeV.

Jets

Anti-kt jets with R = 0.4;

$p_T > 25$ GeV; $|\eta| < 2.5$;

Jet Vertex Tagging algorithm (JVT) used to suppress the pileup jets;

Electrons / Muons

$p_T > 10$ GeV;

Event selection

- Start with the selections aiming at identifying $h \to \gamma\gamma$ events
- At least two central jets
- B-veto (Working Point: 70%)
- At least one lepton
- Tight mass window (TMW), $\left|m_{\gamma\gamma} - 125.09\right| < 2 \times 1.7\ (\sigma_{m_{\gamma\gamma}})$ GeV

- **[SR] Signal Region (above)**
- **[SB] Sideband Region (reverse "Tight Mass Window")**
- **[CR] Control Region (reverse "Tight Mass Window" & $\mathbf{N(lepton) = 0}$)**

Background estimations

- **SM Higgs background is estimated with MC.**
- **Continuum background is estimated with data-driven method.**

$$N_{SR}^{continuum} = N_{SB}^{continuum} \times \frac{\epsilon_{\gamma\gamma}}{1-\epsilon_{\gamma\gamma}}$$

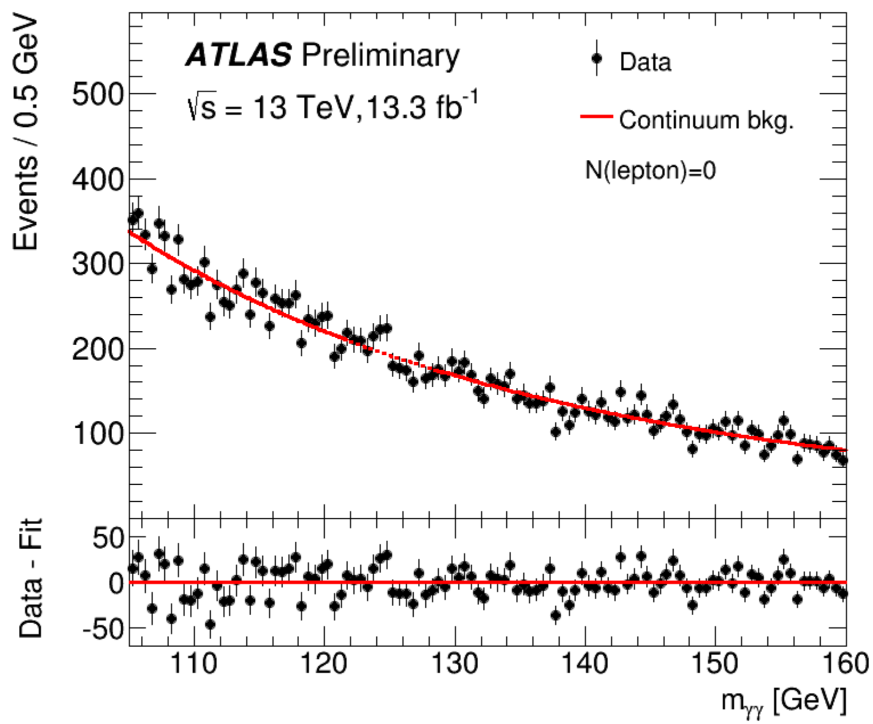
$\epsilon_{\gamma\gamma}$ **is extracted from CR ($N_{lep} = 0$) with a fit.**

$$\epsilon_{\gamma\gamma} = \frac{\int_{TMW} f(m_{\gamma\gamma}) dm_{\gamma\gamma}}{\int_{105}^{160} f(m_{\gamma\gamma}) dm_{\gamma\gamma}}, f(m_{\gamma\gamma}) \rightarrow \text{fit function}$$

$\epsilon_{\gamma\gamma}$ measurement

- $\boldsymbol{\epsilon_{\gamma\gamma}}$ **is measured in zero-lepton control region with data**
- **The exponential with 2nd order polynomial is used to model background**

$$N_{SB}^{continuum} = 46 \text{ events}$$
$$\epsilon_{\gamma\gamma} = 13.64\%$$
$$N_{bkg}^{continuum} = 7.26 \text{ events}$$



Uncertainties (1)

- **The uncertainties are related to the continuum background.**

- **Statistical uncertainty of events in sideband: 14.7%.**

- **The uncertainties on $\epsilon_{\gamma\gamma}$ measurement**
  - **From lepton multiplicity: 7.4%,**
  - **From fitting functions: 3.8%,**
  - **From sideband definition: 1.2%,**
  - **From statistics : 1.3%.**

Uncertainties (2)

- **Luminosity error, 2.9%, combining errors on luminosity in 2015 and 2016**

- **Theoretical uncertainties**
  - $+2.1/2.0\%$ **on** $\mathbf{br}(h \rightarrow \gamma\gamma)$ **and** $\pm$**1.5% on** $\mathbf{br}(h \rightarrow WW)$**.**
  - **Scale and PDF uncertainties on** $\sigma(gg \rightarrow hh)$ **and cross section of SM Higgs processes. Details are shown as next slide.**
  - **Special 37.5% assigned to Wh process for high jet multiplicity, comparing Pythia8 (parton shower jets) and MadGraph5 (matrix element jets) both with 2 jets inclusively.**

- **Experimental uncertainties:**
  - **Pileup reweighting, photons, jets, leptons, b-tagging**
  - **See next slide.**

Uncertainties (3)

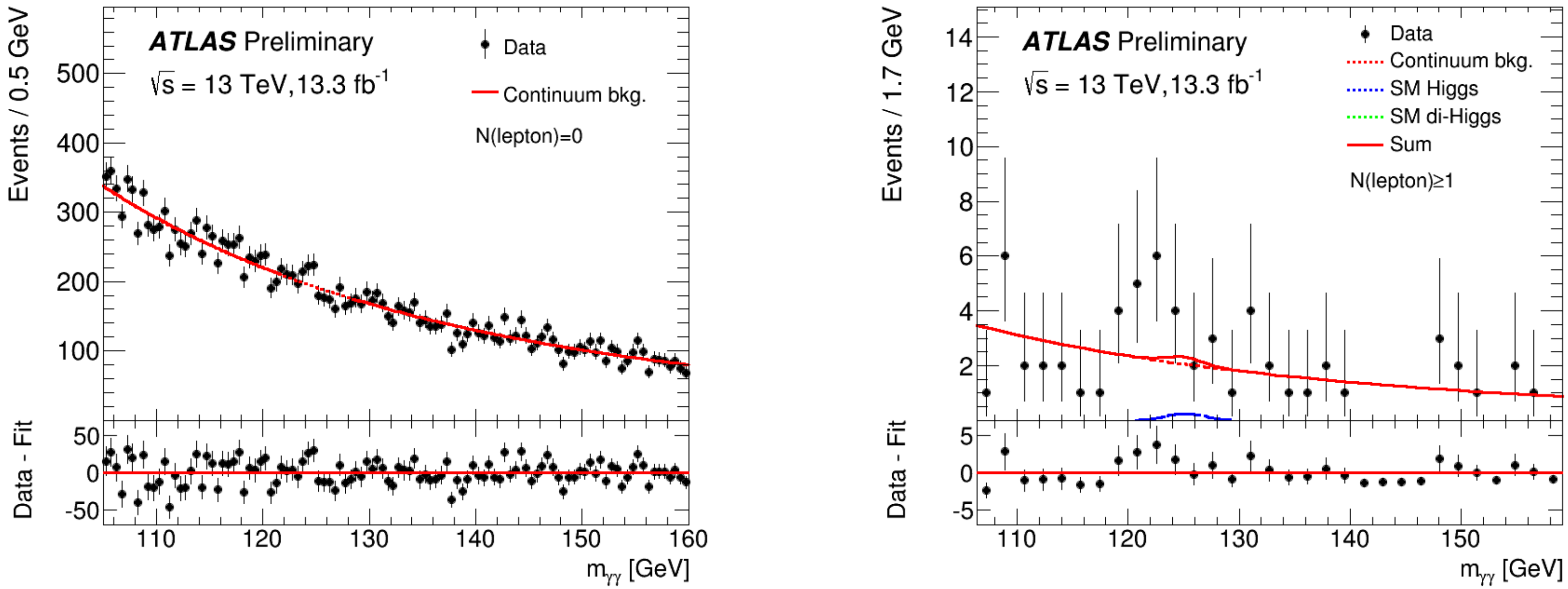
Source of uncertainties		Non-resonant hh	$X \to hh$	Single-h bkg	Cont. bkg
		All numbers are in %			
Luminosity 2015+2016		2.9	2.9	2.9	-
Trigger		0.4	0.4	0.4	-
Pileup re-weighting		0.8	0.2	1.8	-
Event statistics		2.0	1.8	2.7	14.7
Photon	energy resolution	2.0	1.8	1.2	-
	energy scale	4.2	4.1	1.6	-
	identification	4.2	4.2	4.2	-
	isolation	1.0	1.0	1.1	-
Jet	energy resolution	0.8	0.2	8.0	-
	energy scale	3.5	3.5	5.2	-
b-tagging	b-jets	0.06	0.05	5.4	-
	c-jets	0.5	0.5	0.3	-
	light jets	0.4	0.4	0.4	-
	extrapolation	0.006	0.06	0.8	-
Lepton	electron	0.7	0.7	0.7	-
	muon	0.3	0.3	0.6	-
$\epsilon_{\gamma\gamma}$	lepton dependence	-	-	-	7.4
	background modelling	-	-	-	3.8
	sideband definition	-	-	-	1.2
	statistics on $\epsilon_{\gamma\gamma}$	-	-	-	1.3
Theory	PDF	(2.1)	-	2.2	-
	α_S	(2.3)	-	1.5	-
	scale	(6.0)	-	3.7	-
	HEFT	(5.0)	-	-	-
	jet multiplicity	-	-	12.5	-
	BR($h \to \gamma\gamma$)	2.1	2.1	2.1	-
	BR($h \to WW^*$)	1.5	1.5	1.5	-
Total		12.0	8.4	18.6	17.0

Event yields

The signal and background yields in the signal region. Assuming hh production cross section in SM is 33.41 fb and $\mathcal{L}$ = 13.3 $\mathbf{fb^{-1}}$.

Process	Number of events	
Continuum background	7.26	$\pm\,1.23$
SM single-Higgs	0.616	$\pm\,0.115$
SM di-Higgs	0.0187	$\pm\,0.002\,24$
Observed		15

$m_{\gamma\gamma}$ distributions

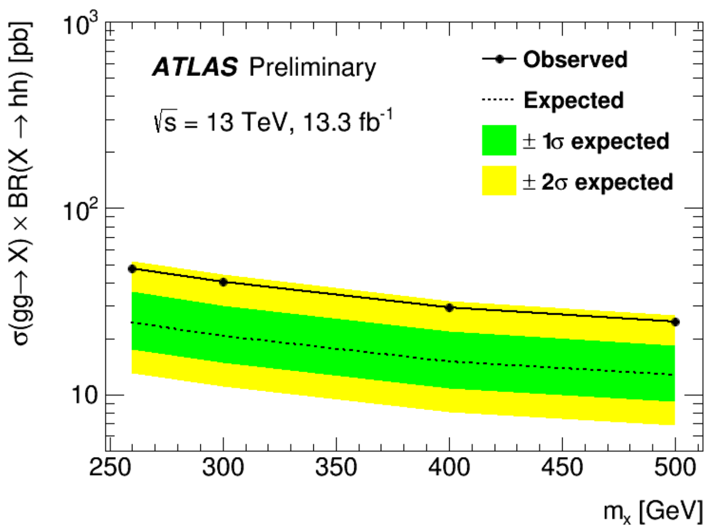


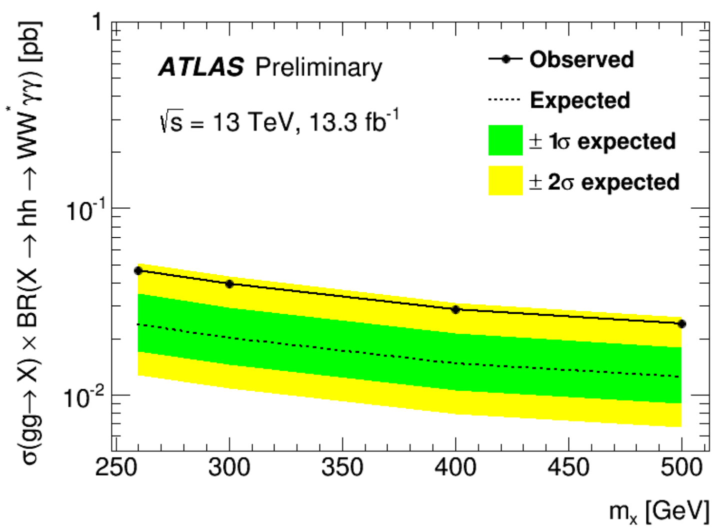
The invariant mass of diphoton system in zero-lepton control region (left) and the one-lepton signal region (right).

Expected upper limits

Histfactory is used to build up the statistical model for an event-counting experiment. Asymptotic approximation is used (was validated with throwing toy MCs).

In the non-resonant search, a 95% CL upper limit is set: the expected limit on $\sigma(gg \rightarrow hh)$ is 12.9 pb, and the observed one is 25.0 pb. For resonant search, the expected limit on the resonant production times the branching fraction of $X \rightarrow hh$ ranges from 24.3 – 12.7 pb and the observed limit ranges from 47.7 – 24.7 pb.





Summary

No significant excess is observed with respect to the SM background-only hypothesis.

A 95% confidence-level upper limit is set.
For non-resonant production, the observed limit is 25.0 pb and expected limit is 12.9 pb.
For resonant production, the observed limit ranges from [47.7, 24.7] pb and the expected limit ranges from [24.3, 12.7] pb.

Backup

$\epsilon_{\gamma\gamma}$ measurement (a)

Test against different lepton multiplicities with MC to quantify the impact on $\epsilon_{\gamma\gamma}$.
MC $jjl\nu\gamma\gamma$ and $jj\gamma\gamma$ are compared.
The difference on the $\epsilon_{\gamma\gamma}$ is 2.2%.

Test against different lepton multiplicities with data control regions to quantify the impact on $\epsilon_{\gamma\gamma}$.
As the MC samples have high diphoton purity, $\epsilon_{\gamma\gamma}$ has been measured with regions by inverting either the photon isolation or the photon identification to check the impact of lepton multiplicities.
The difference on the $\epsilon_{\gamma\gamma}$ is 7.4% and considered as one of uncertainties conservatively introduced by lepton multiplicities.

Test against different sideband region definitions to quantify the impact on $\epsilon_{\gamma\gamma}$.
The difference (1.2%) on $\epsilon_{\gamma\gamma}$ between nominal definition and varied one is considered as one of uncertainties introduced by the SB definition.

$\epsilon_{\gamma\gamma}$ measurement (b)

- Test against various fitting functions of background modeling to quantify the impact on $\epsilon_{\gamma\gamma}$.
- Fitting functions: 0 order polynomial, 1^{st}-order polynomial, 2^{nd}-order polynomial, exponential.

- The largest difference on $\epsilon_{\gamma\gamma}$ to the nominal is taken as uncertainty except comparing the 0 order polynomial due to this function is improper to fit the $m_{\gamma\gamma}$ shape.

- The difference between the 1st order polynomial and nominal fit model is 3.8% and is considered as uncertainty introduced by the choice of fitting functions.