Search for di-Higgs Production with WW*$\gamma\gamma$

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Di-Higgs 2020: Opportunities and Challenges
T.D. Lee Institute & Shanghai Jiao Tong Univ.
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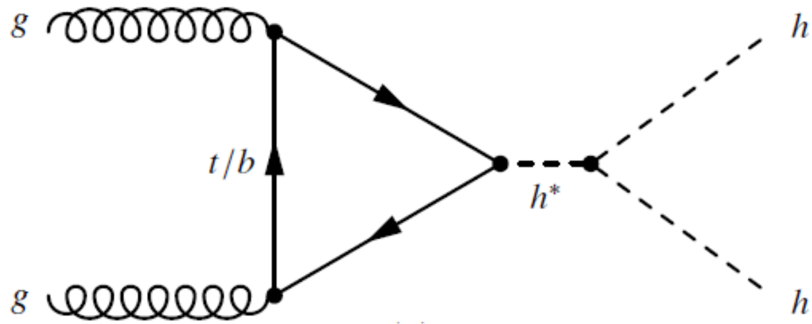
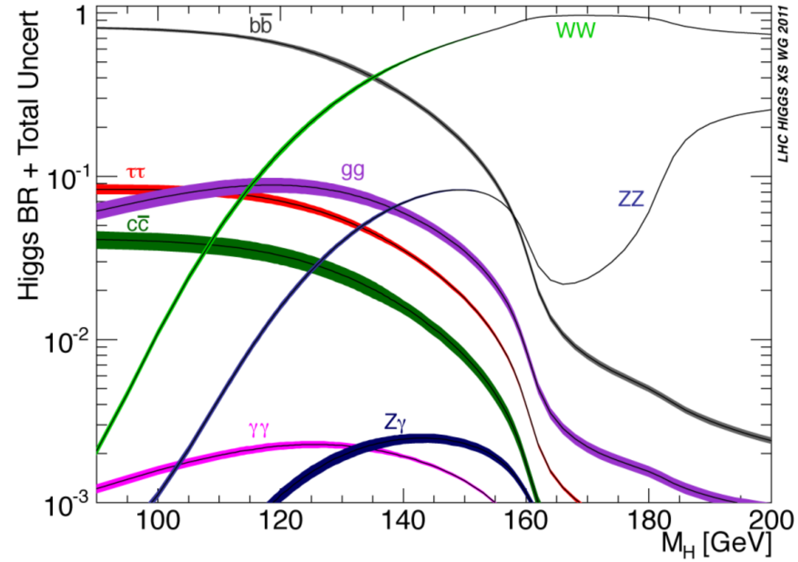
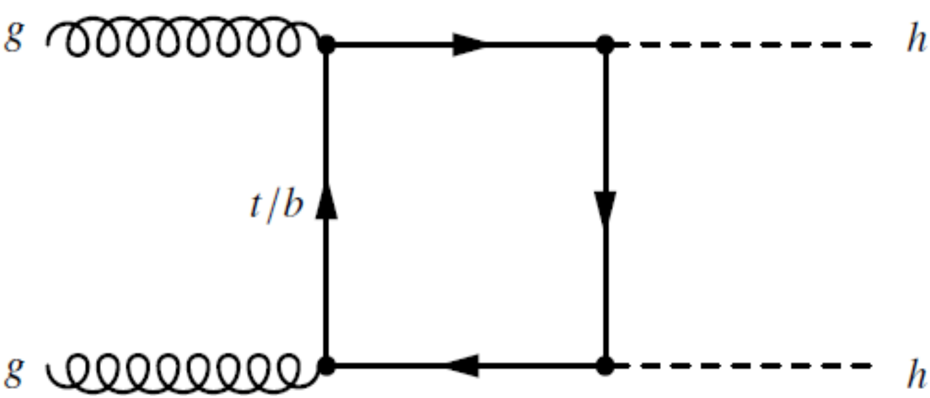
hh analyses



Resonance





Non-resonance

- The bb, WW*, ττ channels have the highest BRs
- γγ has the di-photon mass resonance (bump search)
- SM di-higgs cross-section at at 13TeV, less than 0.1% that of SM Higgs
- Some BSM models (2HDM,KK-Gravitons, new scalar) can enhance the cross-section significantly in some region of phase space.
- WW*γγ can bring you 0Lep, 1Lep, 2Lep subchannel.

hh $\longrightarrow WW^*\gamma\gamma$: working mode

- Theorists always goes ahead of experimentalists.
  - Occasionally, it is not true.
- We cooperated closely with theorists (Hong-jian He's group) and published Pheno. papers about HH channels.
  - JHEP06 (2018) 090 ($WW^*\gamma\gamma$), ", JHEP06 (2018) 090 (WW^*WW^*)
- Propose and lead those analyses in ATLAS:
  - Low statistics prevent $\gamma\gamma$2L
  - Heavy QCD background for $\gamma\gamma$0L(jets)
  - CMS doesn't have dedicated $WW^*\gamma\gamma$ analysis.
    - Multilepton final states

Pheno. Study on $H \longrightarrow hh \longrightarrow WW^* \gamma\gamma$

WW*γγ analyses

- Generator: MG5_aMC
- Showering: Pythia8
- Fast simulation/reconstruction: Delphes

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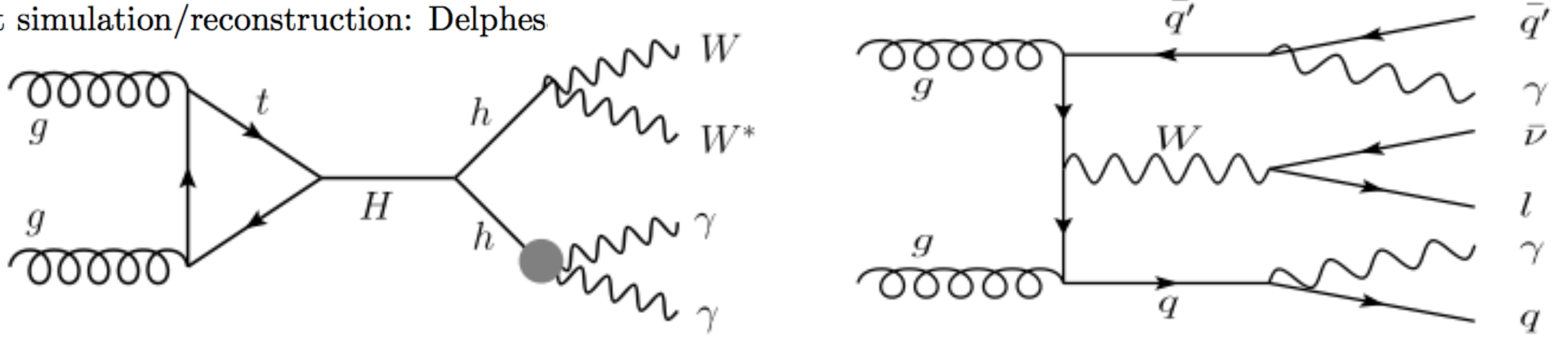


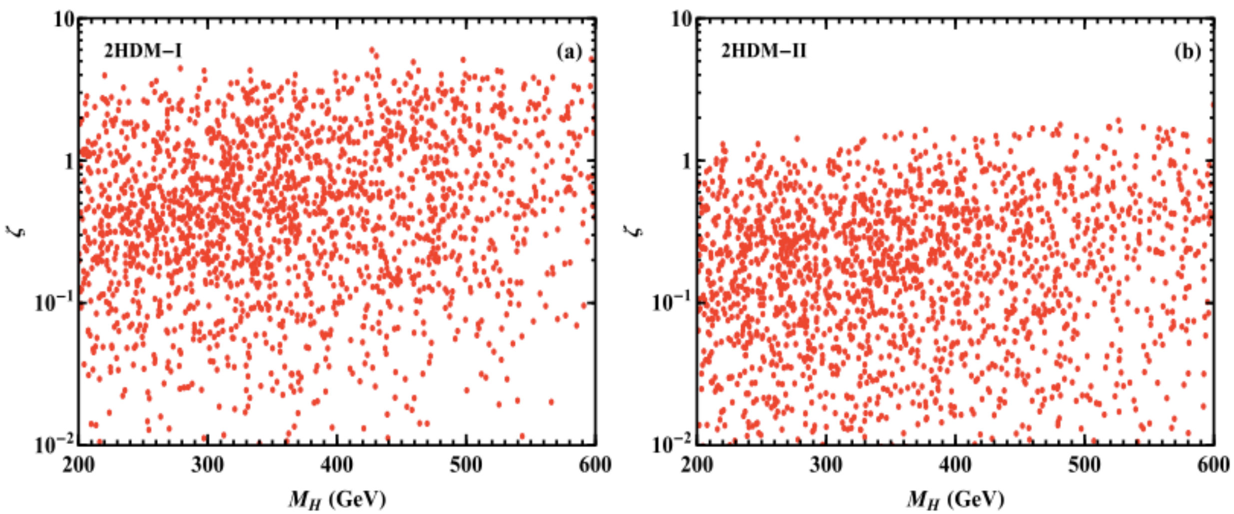


Fig. 1. Parameter space in M_H–ζ plane for 2HDM-I [plot-(a)] and 2HDM-II [plot-(b)], where the red dots present the viable points obeying the consistency requirement of the Higgs potential as explained in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- According to SM Higgs h, one of W has to be off-shell.
- The analyses included two channels according to the decay of WW* (lνqqγγ, lνlνγγ)

Selections of WW(lvlv)γγ analysis (1)

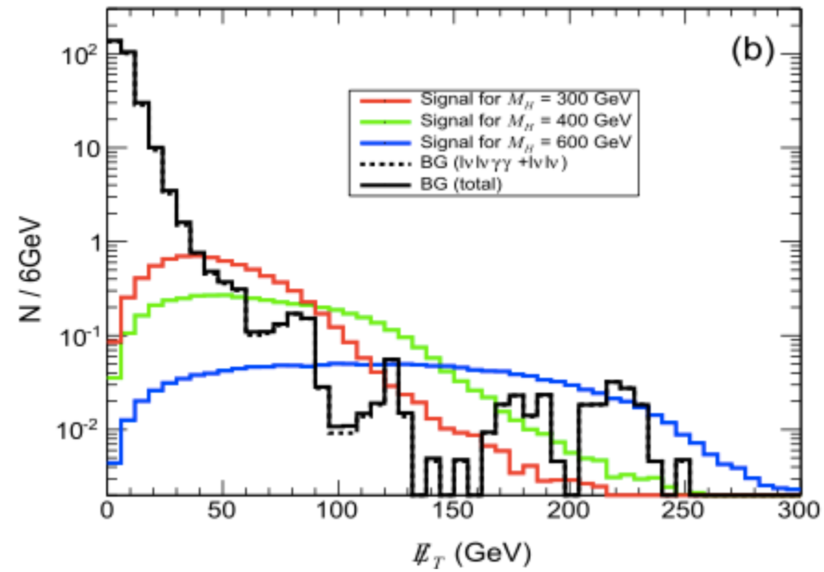
Irreducible backgrounds:

$\ell\nu\ell\nu\gamma\gamma$ and $\ell\ell\gamma\gamma$ and SM Higgs is not negligible.

Selections on two leptons and two photons

$$P_T(\gamma), P_T(q) > 25 \text{ GeV}, \quad P_T(\ell) > 15$$

$$|\eta(\gamma)|, |\eta(q)|, |\eta(\ell)| < 2.5 .$$



Treatment of fake backgrounds (negligible)

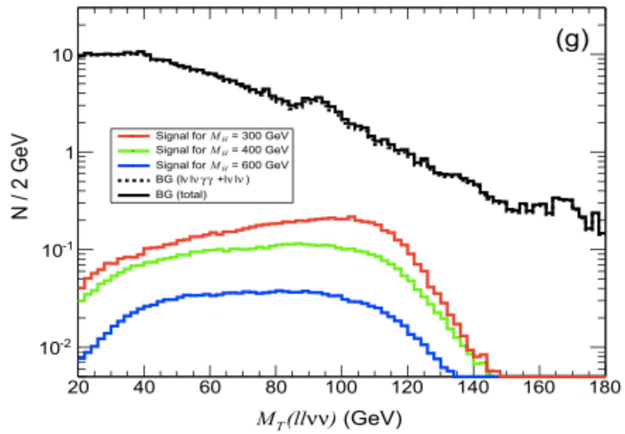
$$\epsilon_{q\to\gamma} \approx 3.6 \times 10^{-4}, \qquad \epsilon_{g\to\gamma} \approx 3.6 \times 10^{-5}$$

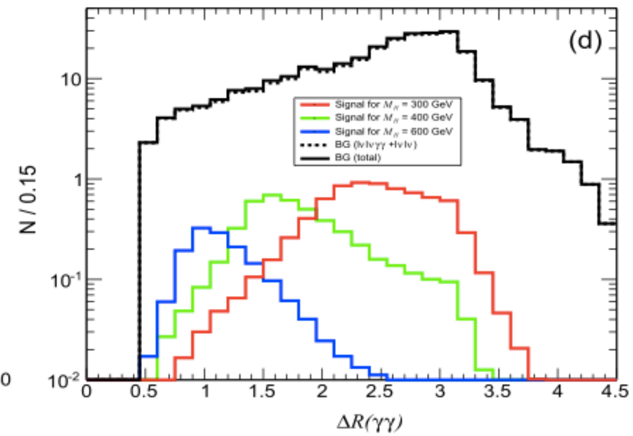
Mass Window and ET missing selections:

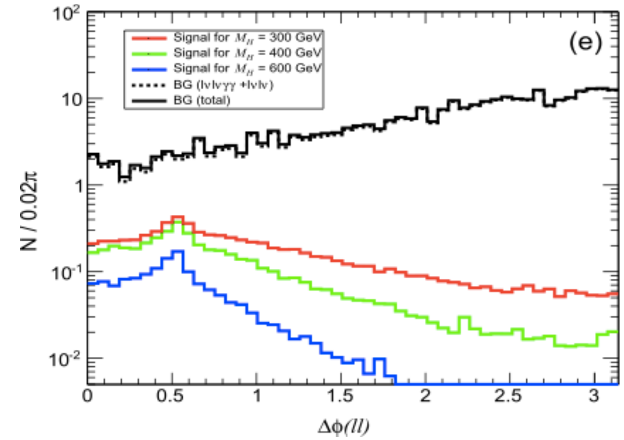
$$120 \text{ GeV} < M_{\gamma\gamma} < 130 \text{ GeV}, \qquad \not{E}_T > 20 \text{ GeV}$$

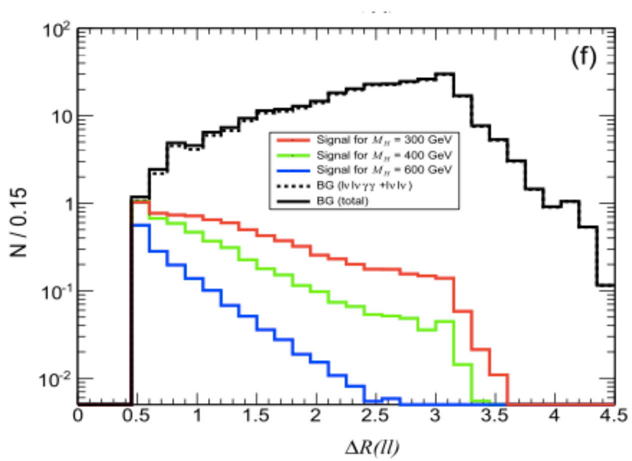
Working point for b veto : eff(b-evto) =22% (ATLAS).

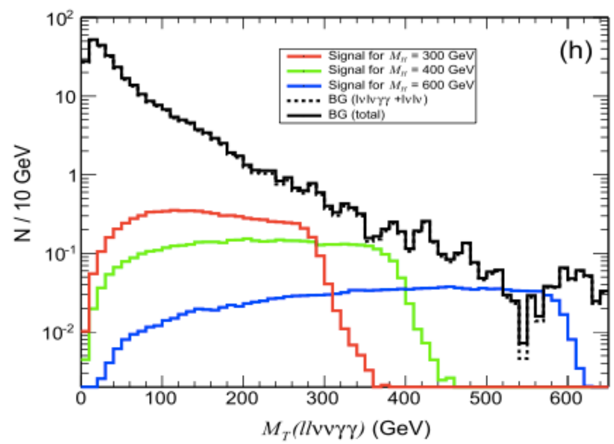
Selections of WW(lνlν)γγ analysis (2)











$M_T(\ell\ell\nu\nu) < 135$ GeV

$\Delta\phi(\ell\ell) < 2.0\,, \quad \Delta R(\ell\ell) < 3.0\,, \quad \Delta R(\gamma\gamma) < 3.8$

60 GeV $< M_T(\ell\ell\nu\nu\gamma\gamma) <$ 320 GeV

In addition,
for M_H>=400 GeV

$\Delta R(\gamma\gamma) < 2.5\,,$

$\not{E}_T > 20$ GeV, $\quad M_T(\ell\ell\nu\nu) < 135$ GeV,

75 GeV $< M_T(\ell\nu\ell\nu\gamma\gamma) <$ 420 GeV,

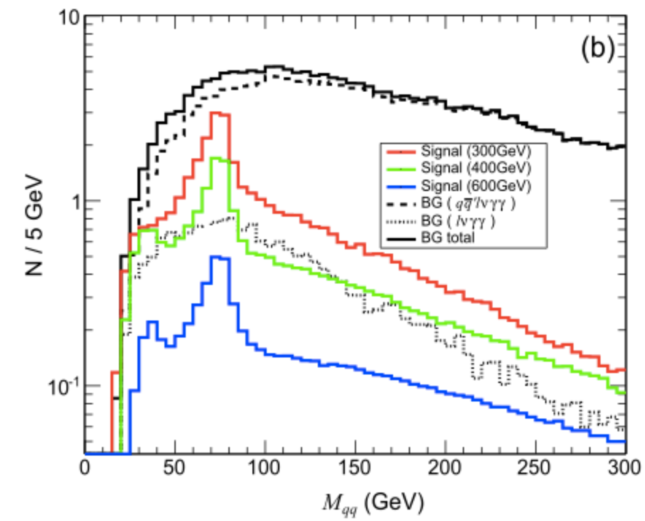
$\Delta\phi(\ell\ell) < 2.0\,, \quad \Delta R(\ell\ell) < 2.2\,,$

$M(\ell\ell) \notin (M_Z - 5\Gamma_Z, M_Z + 5\Gamma_Z)\,.$

Selections of WW(lvqq)γγ analysis (1)

Irreducible backgrounds:

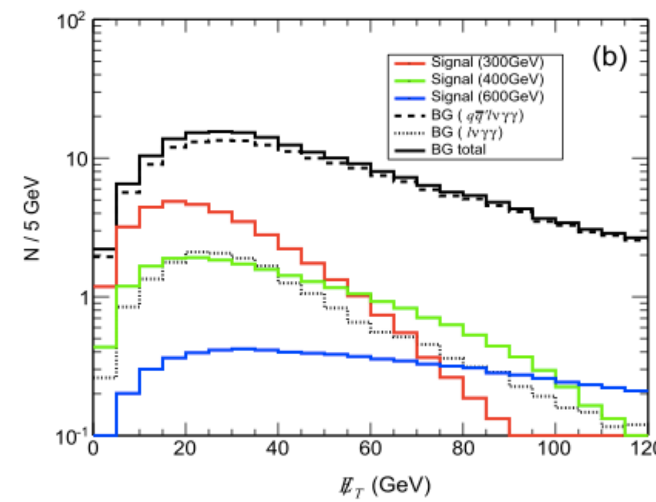
$$pp \to q\bar{q}'\ell\nu\gamma\gamma$$



Selections on one lepton, two photons and two jets

$$P_T(\gamma), P_T(q) > 25 \text{ GeV}, \quad P_T(\ell) > 15 \text{ GeV},$$

$$|\eta(\gamma)|, |\eta(q)|, |\eta(\ell)| < 2.5\,.$$



Treatment of fake backgrounds

$$\epsilon_{q\to\gamma} \approx 3.6 \times 10^{-4}, \qquad \epsilon_{g\to\gamma} \approx 3.6 \times 10^{-5}$$

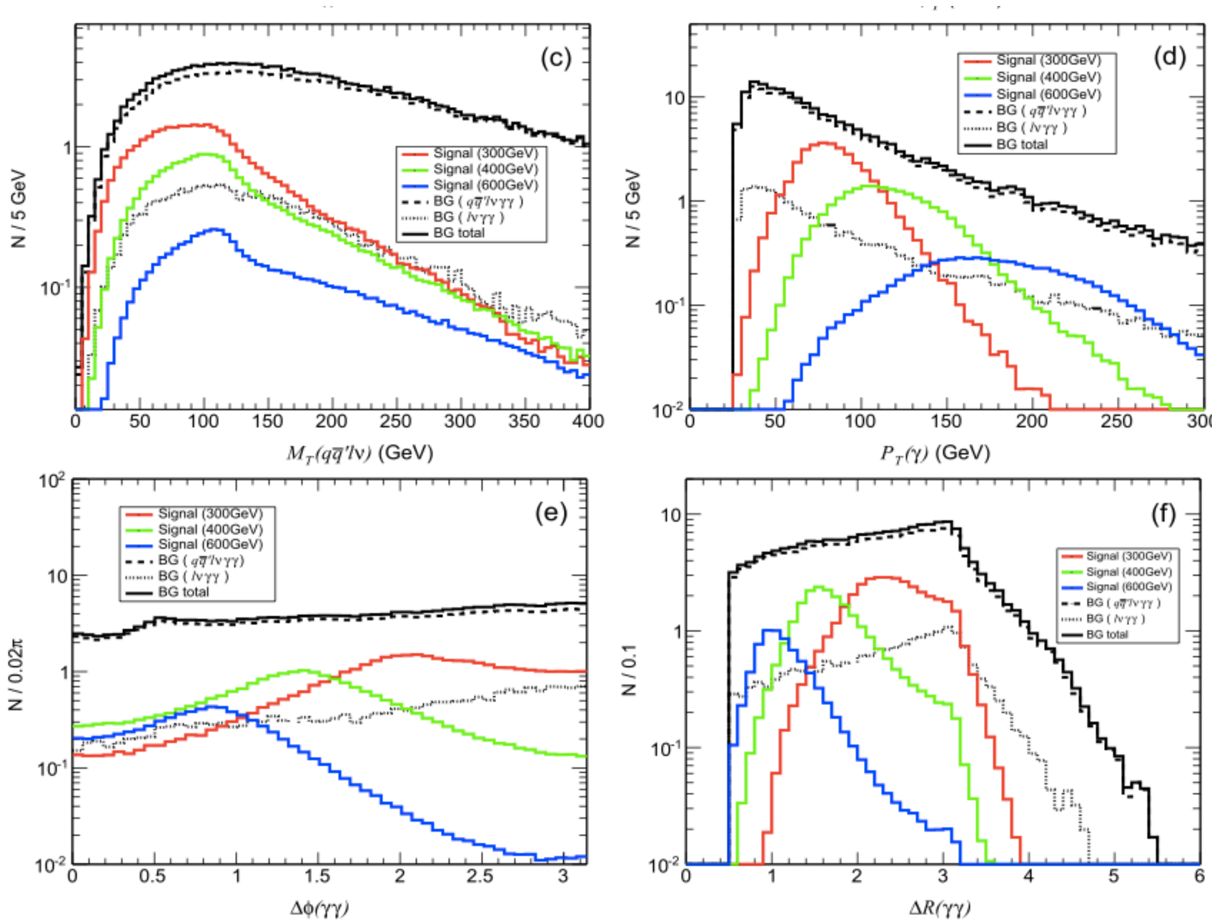
Mass Window and ET missing selections:

$$120 \text{ GeV} < M_{\gamma\gamma} < 130 \text{ GeV}, \qquad 10 \text{ GeV} < \not{E}_T < 80 \text{ GeV}$$

$$M_{qq} < 250 \text{ GeV}$$

Working point for b veto : eff(b-evto) =22% (ATLAS).

Selections of WW(lvqq)γγ analysis (2)



$M_T(q\bar{q}'\ell\nu) < 200$ GeV.

$1 < \Delta R(\gamma\gamma) < 3.8$

For M_H>=600 GeV

$120\text{ GeV} < M_{\gamma\gamma} < 130\text{ GeV}, \quad M_{qq} < 250\text{ GeV},$

$P_T(\gamma) > 120\text{ GeV}, \quad M_T(q\bar{q}'\ell\nu) < 350\text{ GeV}, \quad \not{E}_T > 10\text{ GeV},$

$\Delta\phi(\gamma\gamma) < 1.6, \quad \Delta R(\gamma\gamma) < 1.7.$

Results for wwγγ analyses

$\sigma(pp \to H \to hh \to WW^*\gamma\gamma) = 3$ fb.

M_H = 300 GeV, L = 300 fb $^{-1}$,

$pp \to \ell\nu\ell\nu\gamma\gamma$	Sum	Selection + Basic Cuts	$M_{\gamma\gamma}$, $\not{E}_T$	Final Cuts
Signal (fb)	0.315	0.0165	0.0147	0.0107
BG[$\ell\nu\ell\nu\gamma\gamma + \ell\ell\gamma\gamma$] (fb)	153.3	0.937	0.00394	0.000169
BG[$t\bar{t}h$] (fb)	0.0071	0.000493	0.000452	0.000051
BG[Zh] (fb)	0.175	0.0331	0.00247	0.000065
BG[hh] (fb)	0.00222	0.000132	0.000116	0.000074
BG[Total] (fb)	153.48	0.971	0.00698	0.000359
Significance(Z_0)	0.440	0.289	2.44	4.05

$pp \to q\bar{q}'\ell\nu\gamma\gamma$	$\sigma_{\rm total}$	Selection + Basic Cuts	$M_{\gamma\gamma}$, M_{qq}, $\not{E}_T$	Final Cuts
Signal (fb)	1.32	0.0891	0.0671	0.0533
BG[$qq\ell\nu\gamma\gamma$] (fb)	31.59	0.581	0.0291	0.00672
BG[$\ell\nu\gamma\gamma$] (fb)	143.3	0.0642	0.00454	0.000891
BG[Wh] (fb)	0.42	0.00509	0.00335	0.00139
BG[WWh] (fb)	0.0023	0.000210	0.000127	0.000057
BG[$t\bar{t}h$] (fb)	0.0148	0.00163	0.00111	0.000441
BG[hh] (fb)	0.00462	0.000291	0.000197	0.000155
BG[th] (fb)	0.0129	0.000479	0.000247	0.000104
BG[Total] (fb)	175.35	0.653	0.0386	0.0098
Significance(Z_0)	1.72	1.87	4.86	6.22

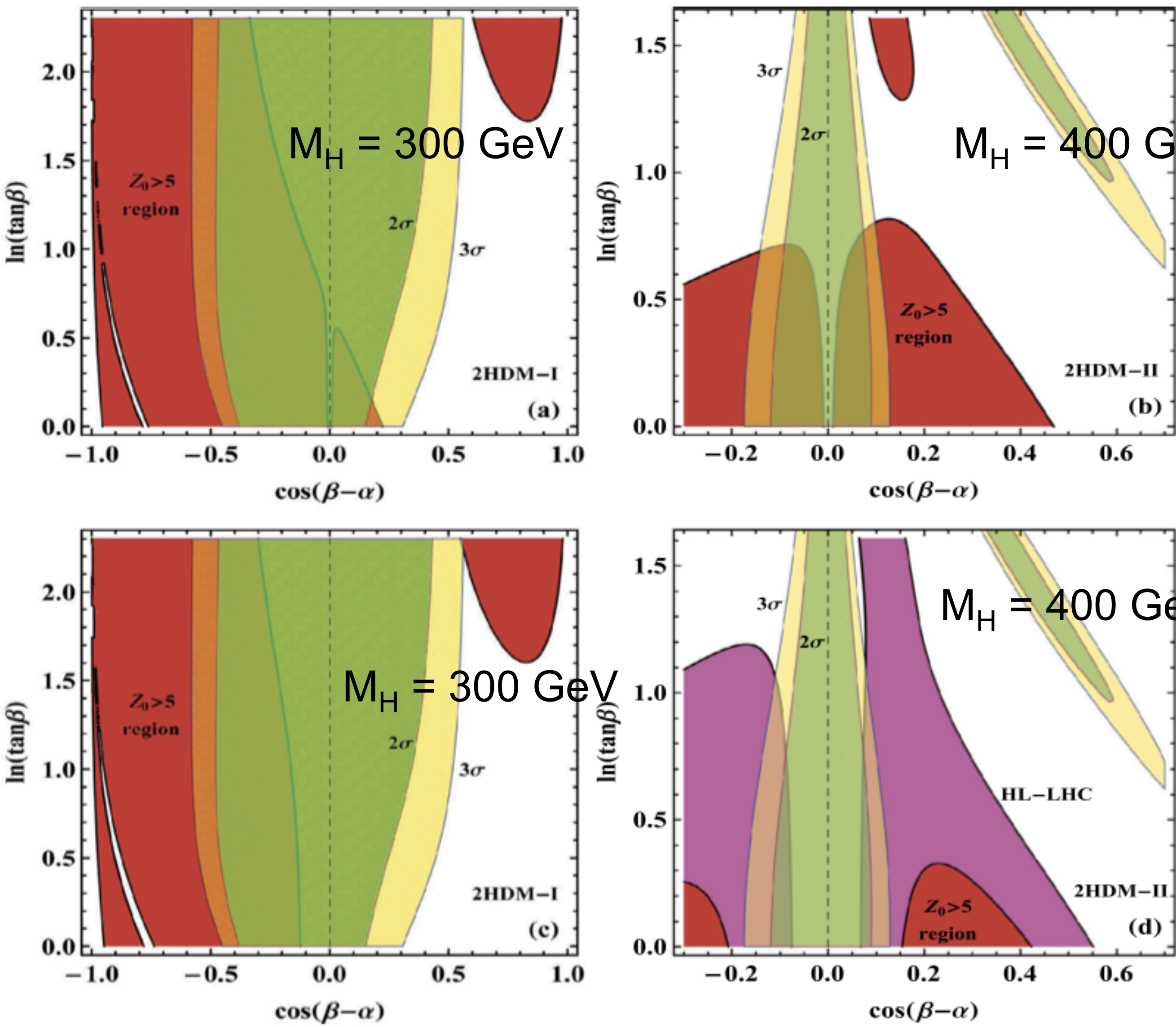
$\sigma(pp \to H \to hh \to WW^*\gamma\gamma) = 1$ fb.

M_H = 600 GeV, L = 3ab $^{-1}$,

$pp \to \ell\nu\ell\nu\gamma\gamma$	Sum	Selection + Basic Cuts	$M_{\gamma\gamma}$, $\not{E}_T$	Final Cuts
Signal (fb)	0.105	0.00578	0.00540	0.00451
BG[$\ell\nu\ell\nu\gamma\gamma + \ell\ell\gamma\gamma$] (fb)	153.3	0.937	0.00348	0.000092
BG[$t\bar{t}h$] (fb)	0.0071	0.000493	0.000452	0.000028
BG[Zh] (fb)	0.175	0.0331	0.00138	0.000029
BG[hh] (fb)	0.00222	0.000132	0.000117	0.000070
BG[Total] (fb)	153.48	0.971	0.00543	0.000219
Significance(Z_0)	0.464	0.321	3.53	7.76

$pp \to q\bar{q}'\ell\nu\gamma\gamma$	$\sigma_{\rm total}$	Selection + Basic Cuts	$M_{\gamma\gamma}$, M_{qq}, $\not{E}_T$	Final Cuts
Signal (fb)	0.44	0.0260	0.0163	0.0148
BG[$qq\ell\nu\gamma\gamma$] (fb)	31.59	0.581	0.00950	0.00241
BG[$\ell\nu\gamma\gamma$] (fb)	143.3	0.0642	0.00176	0.000395
BG[Wh] (fb)	0.42	0.00509	0.00119	0.000696
BG[WWh] (fb)	0.0023	0.000210	0.000035	0.000035
BG[$t\bar{t}h$] (fb)	0.0148	0.00163	0.000402	0.000237
BG[hh] (fb)	0.00462	0.000291	0.000120	0.000087
BG[th] (fb)	0.0129	0.000479	0.000094	0.000058
BG[Total] (fb)	175.35	0.653	0.0131	0.00392
Significance(Z_0)	1.82	1.75	6.70	9.29

Interpretation



L = 300 fb^{-1}

The pink region corresponds to 3 ab^{-1}

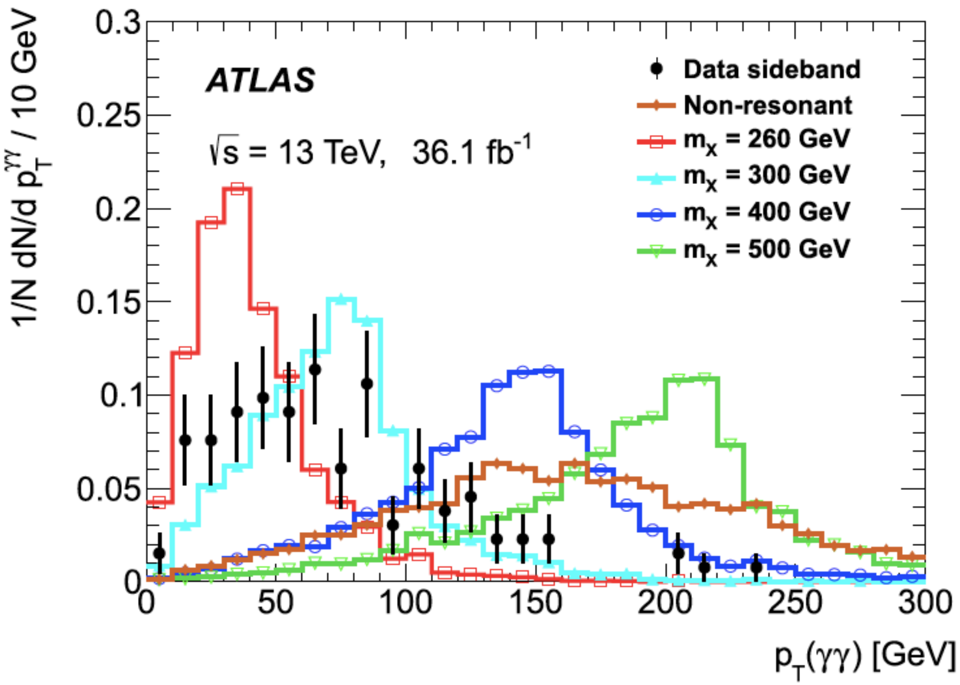
(H$\longrightarrow$)hh$\longrightarrow$WW*$\gamma\gamma$ with ATLAS detector

Object definition

Common in most analyses:

Objects	Selections
Photons	TightID EM, trk isolation Lead $P_T/m_{\gamma\gamma}$>0.35, Sub $P_T/m_{\gamma\gamma}$>0.25
Jets	P_T>25 GeV, $\|\eta\|$<2.5 Jet vertex tagger (JVT) selection
Muons	Medium ID P_T>4 GeV, $\|\eta\|$<2.5, $d_0$significance, Z_0 selection B-jet muon correction
Electrons	Loose Likelihood ID, P_T>10 GeV $\|\eta\|$<2.47 excluding the crack region
b-jets	B-tagging selection with eff. 70%

Selections



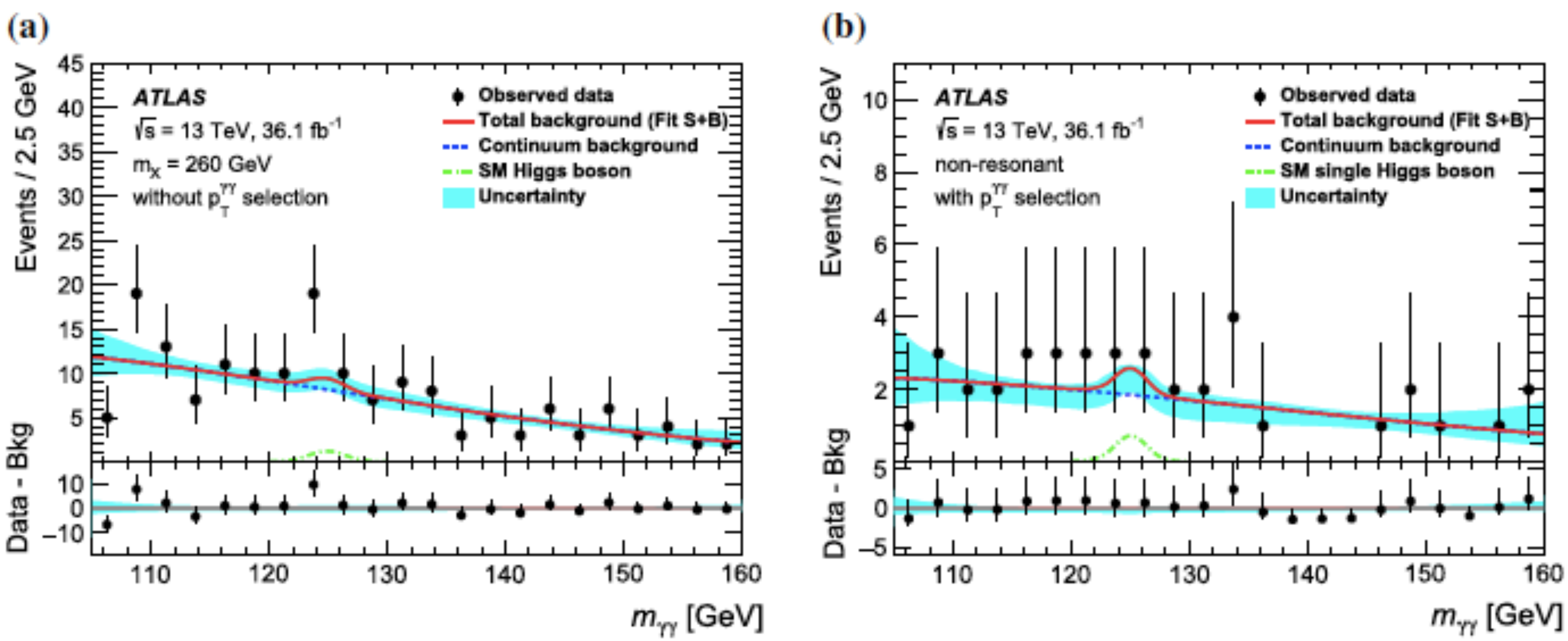
	No $p_T^{\gamma\gamma}$ selection			$p_T^{\gamma\gamma} > 100$ GeV		
m_X (GeV)	260	300	400	400	500	Non-resonant
Acceptance × efficiency (%)	6.1	7.1	9.7	7.8	10	8.5

- At least two central jets
- B-veto.
- At least one lepton with Pt>10 GeV

We found that the analysis is not very sensitive to E_T^{miss}

- For high heavy mass and non-resonance cases, selection of $P_T^{\gamma\gamma}$ can effectively suppress bkg without significant dropping the signal efficiencies.

Background estimation



- Direct fits on the continuum background are implemented w/ and w/o $P_T^{\gamma\gamma}$ selection

Results

Nevent in the mass window: $m_H \pm 2\sigma$

Process	Number of events	
	No $p_T^{\gamma\gamma}$ selection	$p_T^{\gamma\gamma} > 100$ GeV
Continuum background	22 ± 5	5.1 ± 2.3
SM single-Higgs	1.92 ± 0.15	1.0 ± 0.09
SM di-Higgs	0.046 ± 0.004	0.038 ± 0.004
Sum of expected background	24 ± 5	6.1 ± 2.3
Data	33	7

(a)

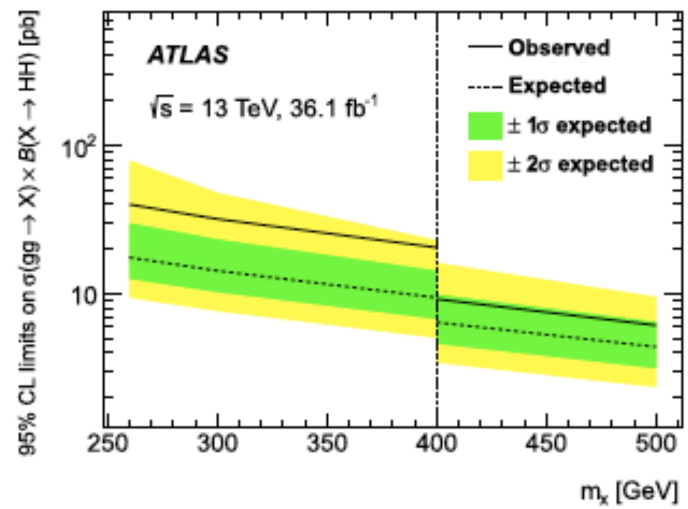


Table 6 The 95% CL upper limits for the non-resonant production and the ratios of the limits to the SM cross-section value of $\sigma(pp \rightarrow HH) = 33.4^{+2.4}_{-2.8}$ fb [17]. The $\pm 1\sigma$ and $\pm 2\sigma$ intervals around the median limit are also presented

	$+2\sigma$	$+1\sigma$	Median	-1σ	-2σ	Observed
Upper limits on $\sigma(HH)$ (pb)	12	8.0	5.4	3.9	2.9	7.7
Upper limits on $\sigma(HH) \times B(\gamma\gamma WW^*)$ (fb)	12	7.8	5.3	3.8	2.8	7.5
Ratios of limits over the SM $\sigma(HH)$	360	240	160	120	87	230

For non-resonance search:

the observed(expected) limits are 230(160)XSM

For the resonance search (mass 275-400 GeV):

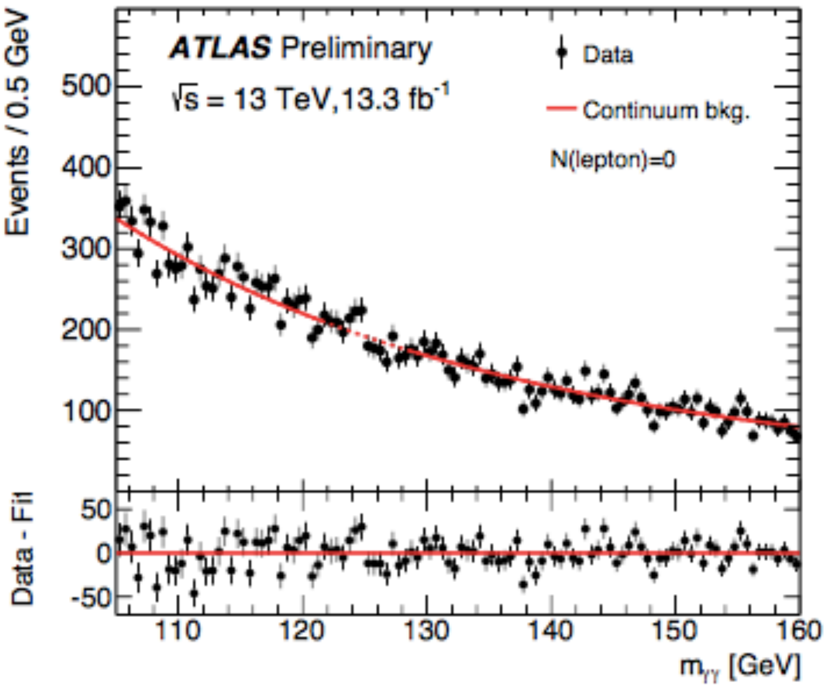
the observed(expected)limit ranges between 6.1-40 (4.4-17.6) pb.

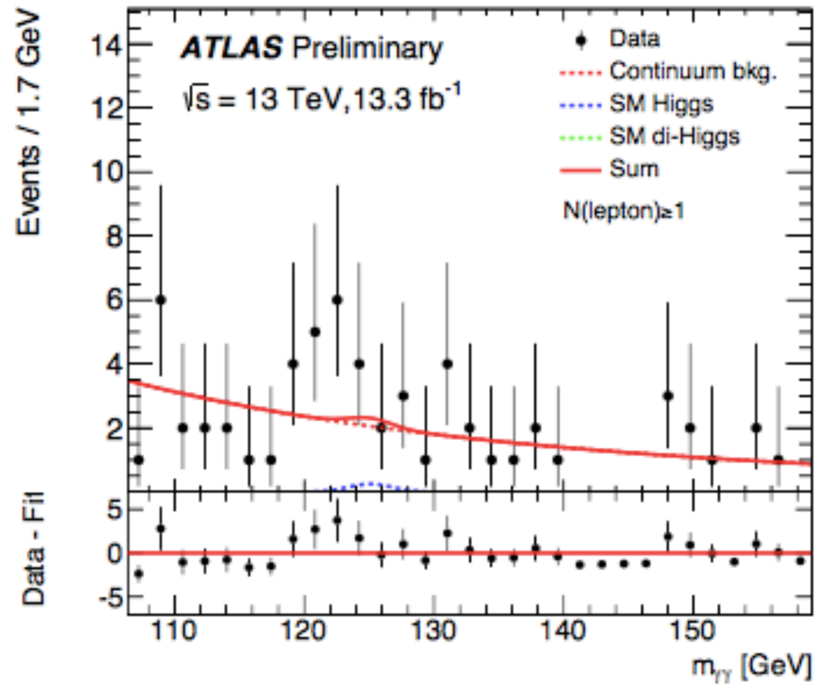
Conclusion

- We work with theorist closely and proposed $H \longrightarrow hh \longrightarrow WW^*\gamma\gamma$ in ATLAS:
  - No obvious excess has been observed.
  - limits have been set with O(10 pb).
  - The best limit for non-resonance is 230(160)XSM.
- Updated results will be come very soon with full RUN2 data.
  - Analysis strategies will be upgraded.
  - DT will be used.
  - 0L, 2L sub-channels will be investigated…

Backup slides

Continuous Background estimation





- With 13.3 fb-1 and due to the lack of statistics in the 1-lepton (right plot), a simultaneous fit with 2nd exponential function on 0-lepton (left plot) and 1-lepton di-photon mass spectra is implemented to extract the continuum bkg.