

A stylized, artistic representation of a Higgs boson production process, showing a swirling, spiral-like pattern in shades of gray and black.

Higgs boson pair production

in $WW^*\gamma\gamma$ using 13 TeV 36.1fb^{-1} data
with the ATLAS detector

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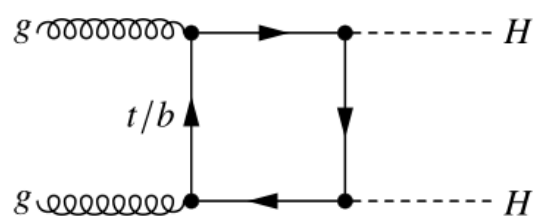
23-27 Oct, 2019

The 5th CLHCP workshop @ DLUT

HH Introduction

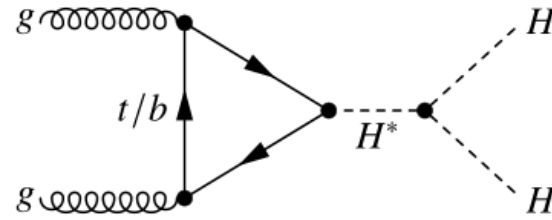
- Searches for new physics are important topics in LHC.
- Higgs pair production could be the sensitive benchmark for new physics.

(a) and (b): existing non-resonance production. (in SM ~ 33 fb @13 TeV)



(a)

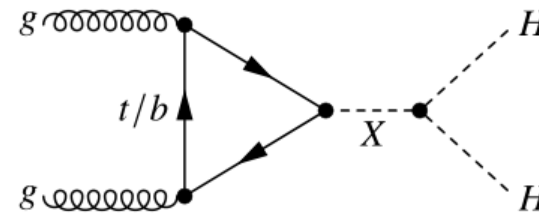
Heavy-quark loop



(b)

Higgs self-coupling

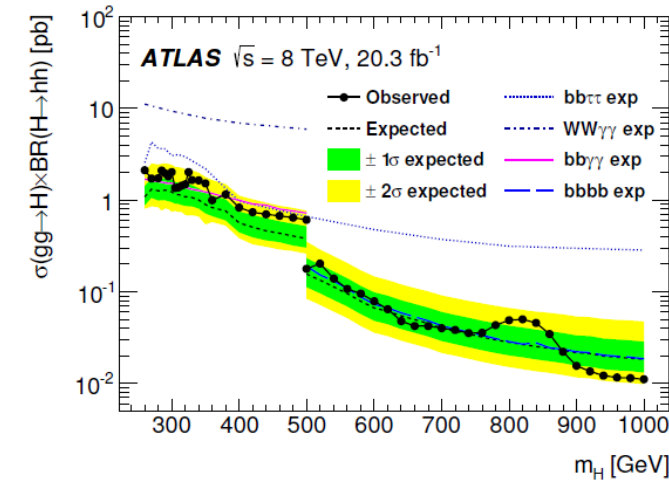
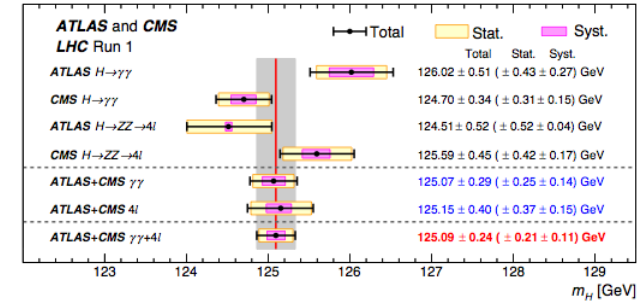
(c): BSM scenario



(c)

Intermediate heavy resonance

- BSM models, like 2HDM (two-Higgs-doublet models), hMSSM, can effectively enhance Higgs pair production.



8 TeV results for HH combination, including $WW^*\gamma\gamma$:

[Phys. Rev. D 92, 092004 \(2015\)](#)

HH combination contains $hh \rightarrow bbyy$, $bbbb$, $bb\tau\tau$ and $WWyy$ in Run1 and $hh \rightarrow bbyy$, $bbbb$, $bbWW$, $WWWW$, $bb\tau\tau$ and $WWyy$ in Run2.

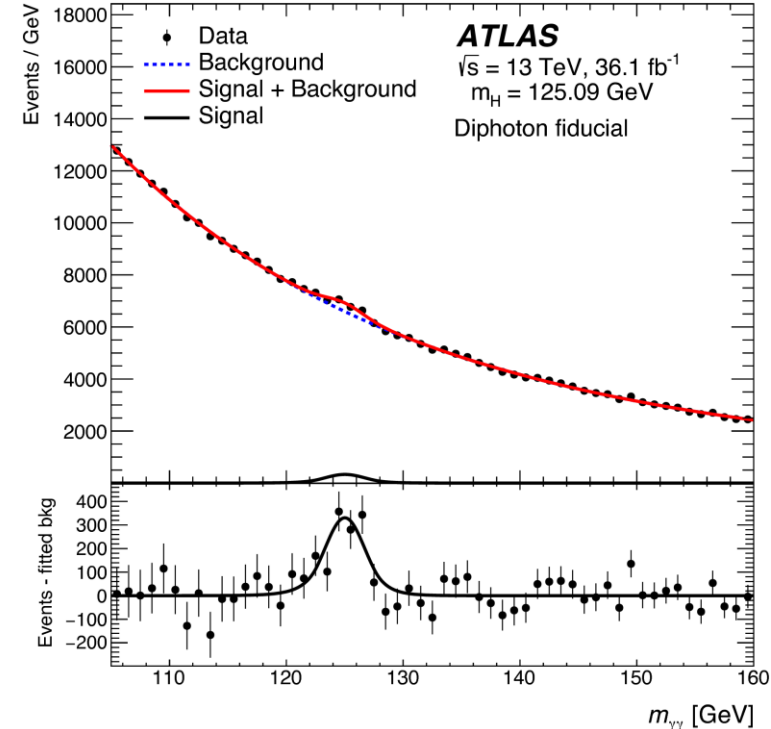
Why $WW^*\gamma\gamma$

$WW^*\gamma\gamma$ do not have the largest branch ratio,
while

- Clean signature diphoton: smooth spectrum provides good background estimation and mass resolution.
- Large fraction WW; Higgs boson coupling could be sensitive for BSM.

Final state: $\gamma\gamma + lv + jj$ selected

- τ from W would be too soft to catch. So for lepton only e/ μ .
- Considering large dijet background,
 - for resonance decay we pick 4 mass points: 260, 300, 400, 500 GeV.
- Considering the κ_λ and spin-2 sensitivity, only spin-0 studied.



Phenomenal study on WWyy potential:

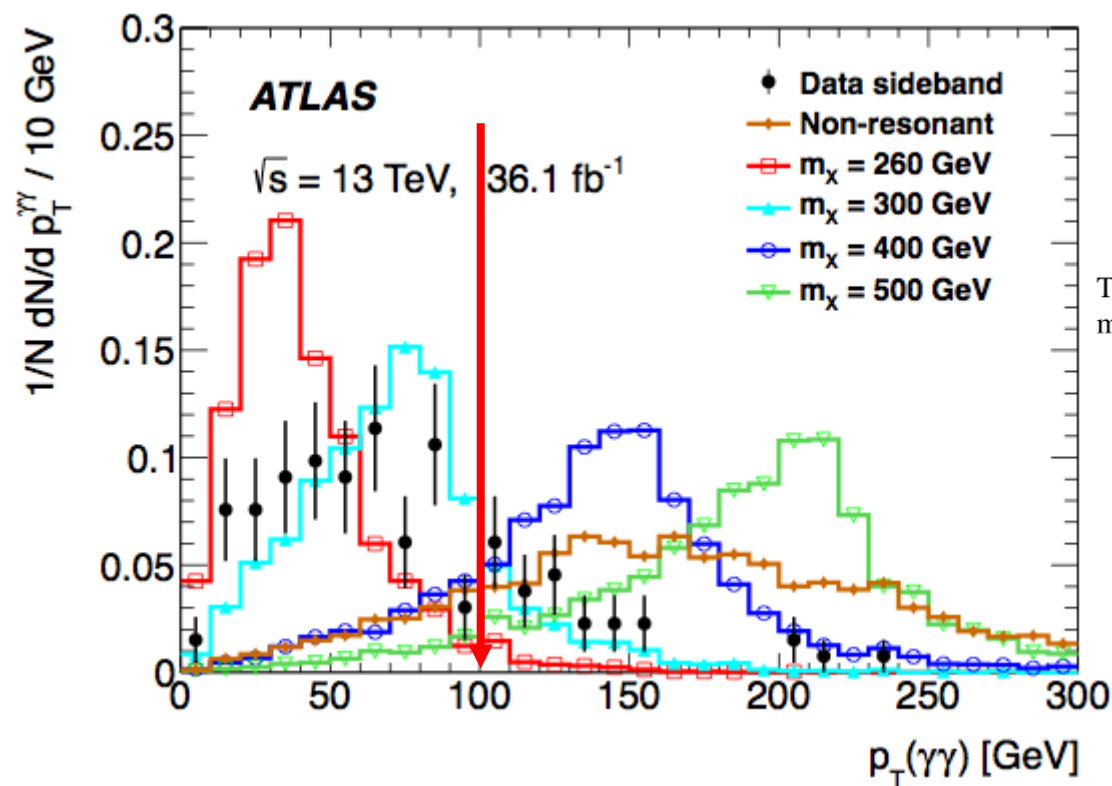
[Phys.Lett. B755 \(2016\) 509—522](#)

$pp \rightarrow \ell\nu\ell\nu\gamma\gamma$	Sum	Selection+Basic Cuts	$M_{\gamma\gamma}, \cancel{E}_T$	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
$pp \rightarrow q\bar{q}\ell\nu\gamma\gamma$	σ_{total}	Selection+Basic Cuts	$M_{\gamma\gamma}, M_{gg}, \cancel{E}_T$	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

Event selection

- Event requirement
 - Trigger, data quality, Good Run List, Primary vertex;
 - b-jet veto: To suppress ttH process; Keep orthogonal with other HH.
- Photon: 2 Tight photons; Tight(PID), FixedCutLoose(Iso)
 - $E_T > 25\text{GeV}$, $|\eta| \in [0, 1.37] \cup [1.52, 2.47]$; $\frac{E_T^{y1}}{m_{yy}} > 0.35, \frac{E_T^{y2}}{m_{yy}} > 0.25$; $m_{yy} \in [105, 160]\text{GeV}$.
- Lepton: At least 1 e/ μ . Medium (PID), Electron: Loose Muon: GradientLoose (Iso)
 - $E_T > 10\text{GeV}$, $|\eta_e| \in [0, 1.37] \cup [1.52, 2.47]$; $|\eta_\mu| < 2.47$
- Jet: At least 2. Anti-kt algorithm, R=0.4
 - $p_T > 25\text{GeV}$, $|\eta| < 2.5$; JVT<0.59.

Selection Optimization



MET seems no separation power so we drop it.

$p_T^{\gamma\gamma}$ would help for the higher mass points and non-resonance.
Cut on 100GeV.

Other cuts value have been tried and the one at 100GeV shows best sensitivity.

Table 3: The combined acceptance and efficiency for non-resonant and resonant with different scalar resonance masses m_X , with and without a $p_T^{\gamma\gamma}$ selection.

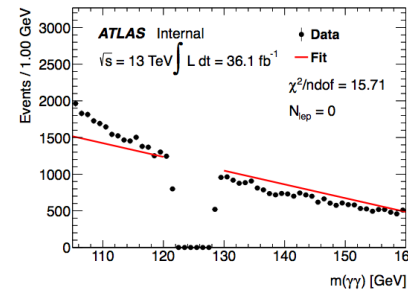
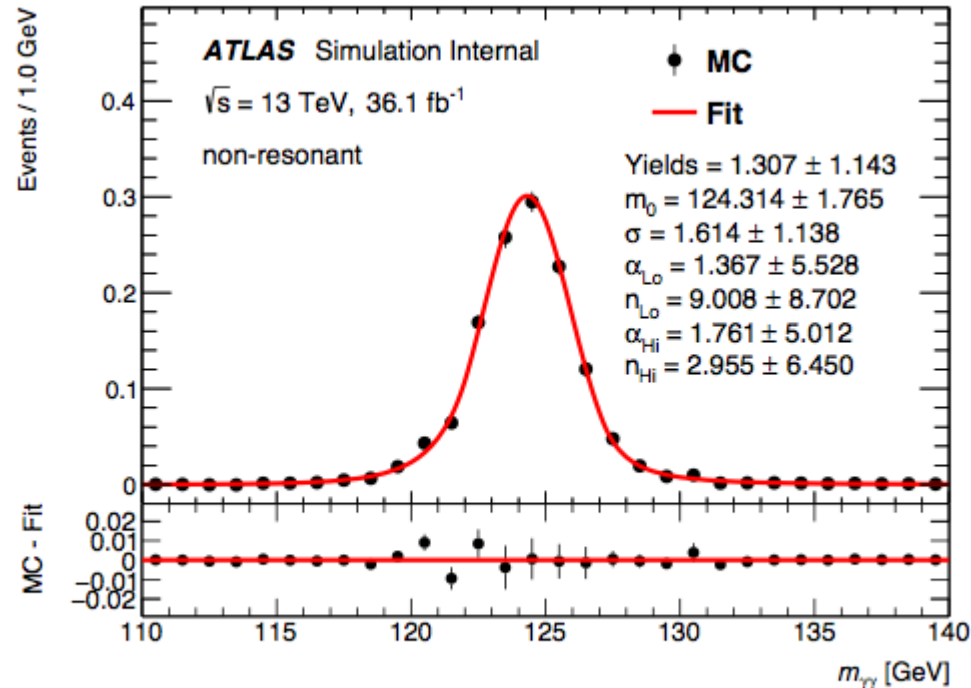
m_X [GeV]	No $p_T^{\gamma\gamma}$ selection			$p_T^{\gamma\gamma} > 100$ GeV		
	260	300	400	400	500	Non-resonant
Acceptance $\times$ efficiency [%]	6.1	7.1	9.7	7.8	10	8.5

Final efficiencies turned to ~ 6 -10% for resonance and 8.5% for non-resonance.

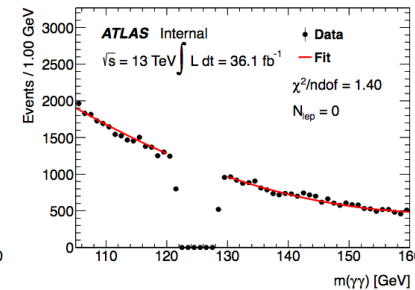
Sideband excluded the Higgs mass region $m_{\gamma\gamma} \in [121.5, 128.5]$ GeV, i.e. $m_H \pm 2\sigma m_{\gamma\gamma}$.

Signal & Background estimation

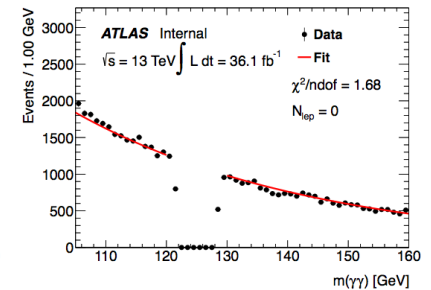
- Signal shape & yields fitted by MC, with double-sided Crystal Ball function.
- SM-1 Higgs background fitted by MC.
- Continuum background use second-order exponential polynomial.
 - Using Spurious signal to estimate the uncertainty.



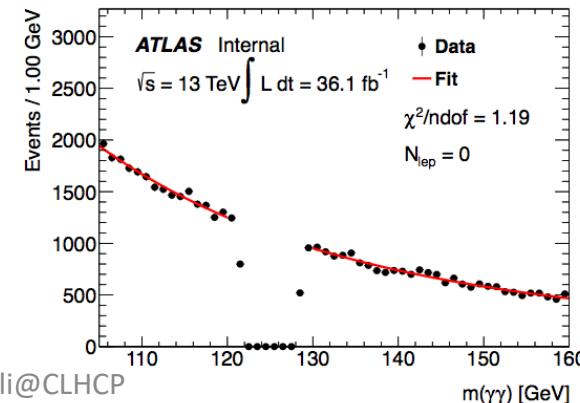
Linear



2rd polynomial

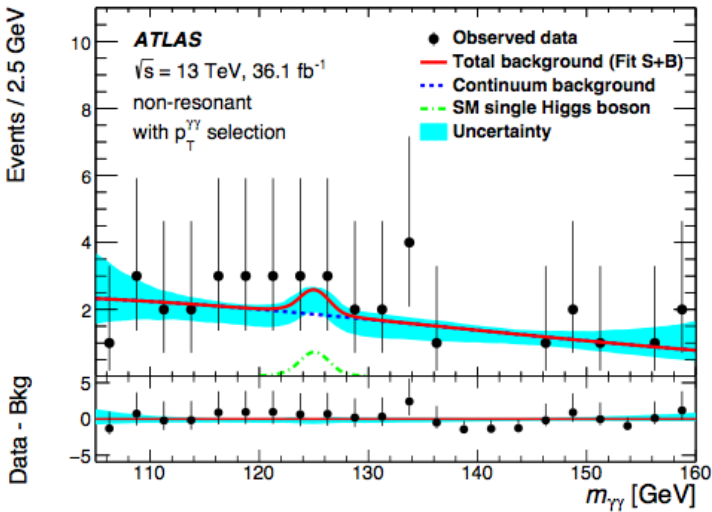
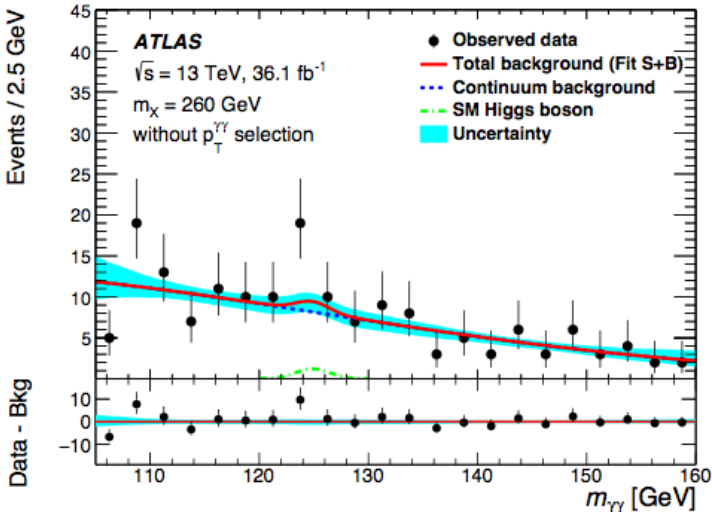


exponential



ExpPoly2

Signal yields



Yields determined from the fit to data by integrating the resulting functional forms over the mass range.

Error here includes both stats and systematic.

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 ± 2.5
Data	33	7

Systematic uncertainty

Source of uncertainties		Non-resonant HH	$X \rightarrow HH$	Single- H bkg $p_T^{\gamma\gamma} > 100$ GeV	Single- H bkg No $p_T^{\gamma\gamma}$ selection
Luminosity 2015+2016		2.1	2.1	2.1	2.1
Trigger		0.4	0.4	0.4	0.4
Event sample size		1.7	2.2	1.6	1.3
Pile-up reweighting		0.5	0.9	0.7	0.6
Photon	identification	1.7	1.4	0.8	0.8
	isolation	0.8	0.7	0.4	0.4
	energy resolution	0.1	0.1	0.2	<0.1
	energy scale	0.2	<0.1	0.2	<0.1
Jet	energy scale	4.0	9.9	2.4	2.6
	energy resolution	0.1	1.6	0.5	1.0
b -tagging	b -hadron jets	<0.1	<0.1	3.8	3.6
	c -hadron jets	1.5	1.0	0.7	0.6
	light-flavour jets	0.3	0.3	0.1	0.1
	extrapolation	<0.1	<0.1	0.1	<0.1
Lepton	electron	0.5	0.7	0.2	0.2
	muon	0.5	0.7	0.3	0.5
Theory	PDF on σ	2.1	-	3.4	3.4
	α_S on σ	2.3	-	1.3	1.3
	scale on σ	6.0	-	0.9	0.9
	HEFT on σ	5.0	-	-	-
	scale on $\epsilon \times A$	2.8	2.5	-	-
	PDF on $\epsilon \times A$	3.0	2.4	-	-
	parton shower on $\epsilon \times A$	7.8	29.6	-	-
	$B(H \rightarrow \gamma\gamma)$	2.1	2.1	2.1	2.1
	$B(H \rightarrow WW^*)$	1.5	1.5	1.5	1.5
Total		13.6	31.8	7.1	6.8

The large parton shower uncertainty 29.6% occurs at $m=260\text{GeV}$, where the jet spectrum at low- p_T is more susceptible to variations.

Statistical model

$$\mathcal{L}(\mu, \theta) = \prod_i [(n_S(\mu, \theta) + n_{SS}) \times f_{DSCB}^1(m_{\gamma\gamma}^i, \theta) + n_{SM-H}(\theta) \times f_{DSCB}^2(m_{\gamma\gamma}^i, \theta) + n_{SM-HH}(\theta) \times f_{DSCB}^3(m_{\gamma\gamma}^i, \theta) + n_{Cont} \times f_{Cont}(m_{\gamma\gamma}^i, \theta)] \prod G(0|\theta, 1)$$

f : Shape function.
 n_{SS} : Spurious signal.
 n_{Cont} : Yields of continuum background.
 θ : Nuisance parameter
 $G(0|\theta, 1)$: Constrain form of NP. (Gaussian).

Spurious signal

- Continuum background modelling uncertainty estimated by **fitting a s+b model to a b-only sample**.
 - Irreducible $\gamma\gamma$ from $\gamma\gamma l\nu jj$ sample
 - $\gamma j, j\gamma, jj$ determined by control region

To scan the largest value of the fitted signal yields as n_{SS} .

- In $[120, 130]$, step 0.5GeV

mX260	mX300	mX400	mX500	Non-res
-0.44	-0.46	-0.26	-0.26	-0.26

Results

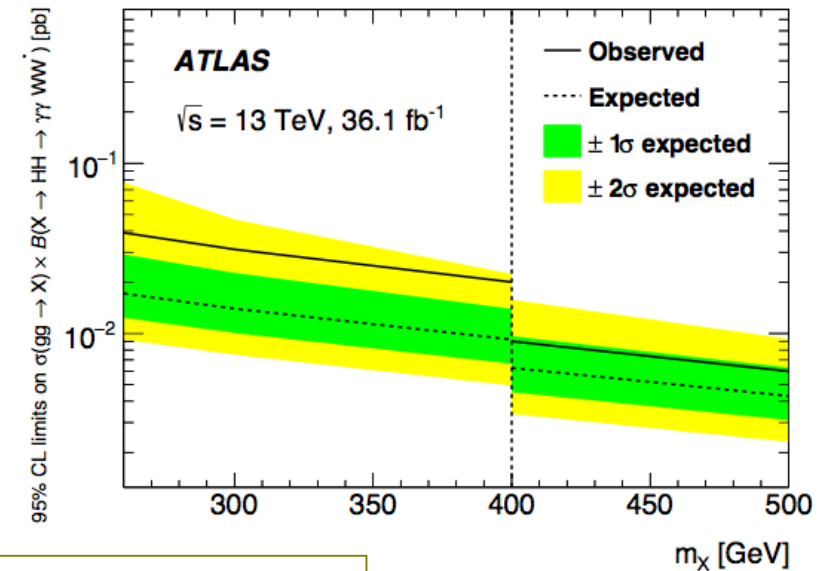
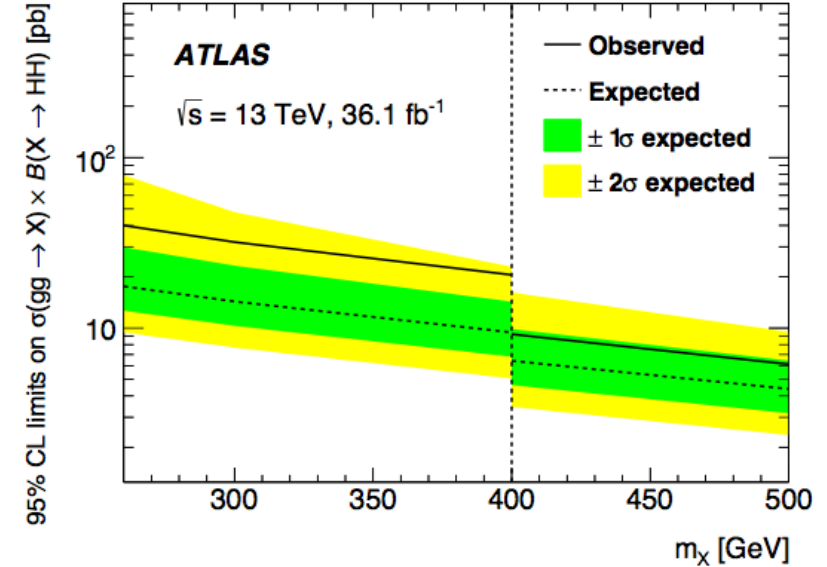
Left/Right: without/with $p_T^{yy} > 100\text{GeV}$ cut.



- Using ATLAS CL_s calculation.
- Due to a slight excess in data, the expected and observed deviation.
- Statistical uncertainty dominates in the final limits, while the impact of systematic uncertainties on these limits is only a few percent.

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.

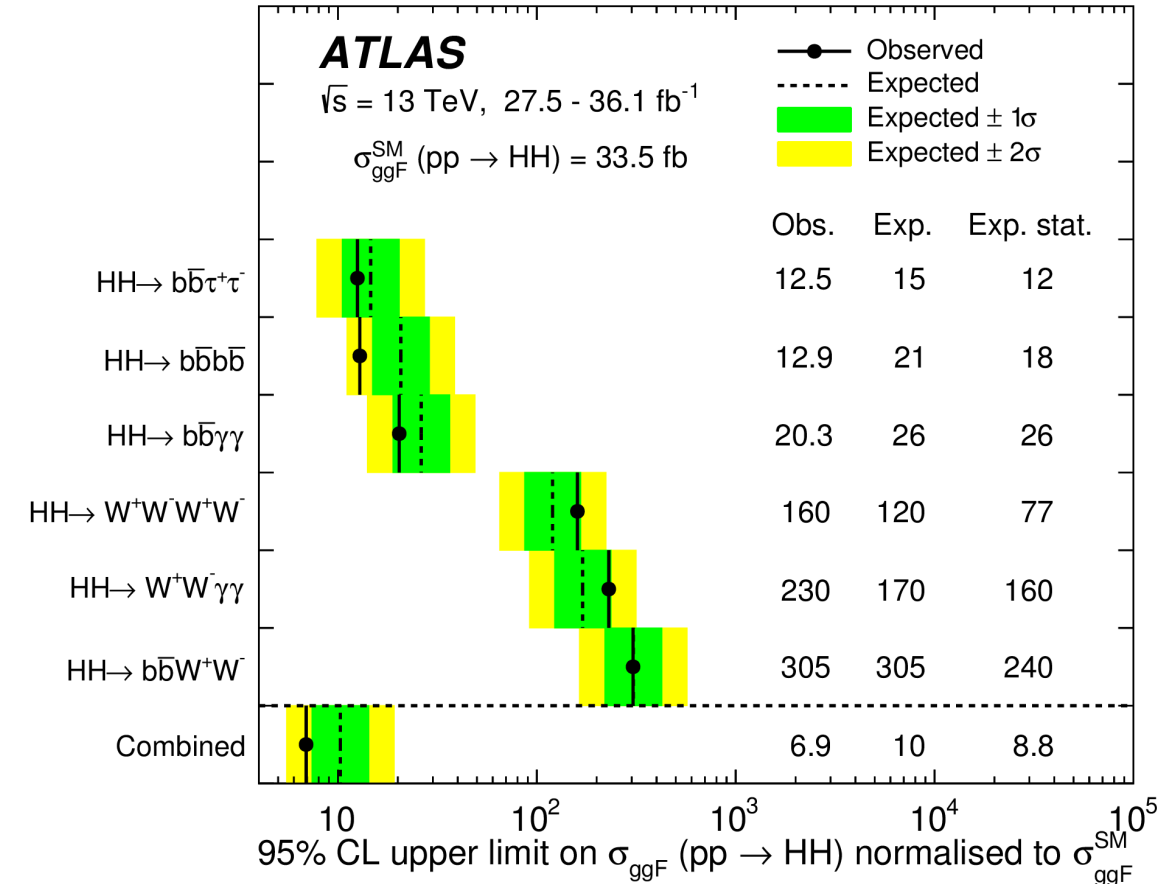
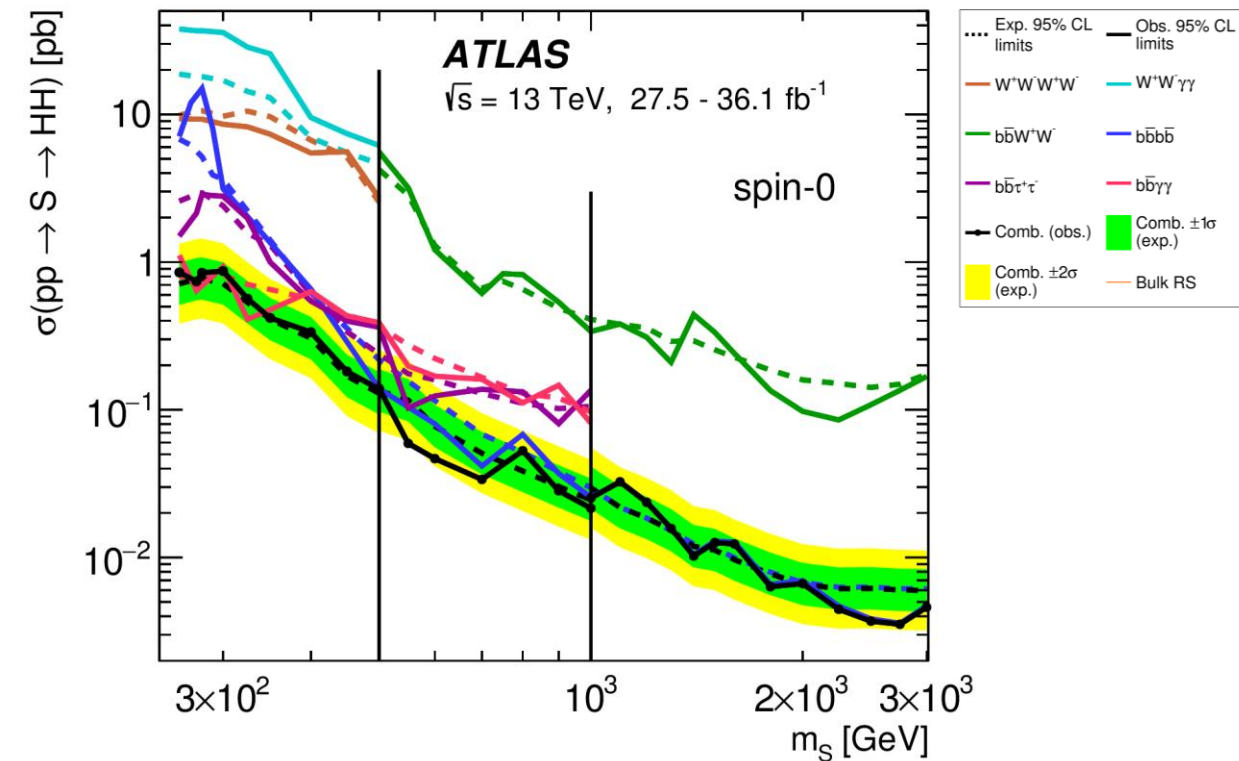
	+2 σ	+1 σ	Median	-1 σ	-2 σ	Observed
Upper limits on $\sigma(HH)$ [pb]	12	8.0	5.4	3.9	2.9	7.7
Upper limits on $\sigma(HH) \times B(\gamma\gamma WW^*)$ [fb]	12	7.8	5.3	3.8	2.8	7.5
Ratios of limits over the SM $\sigma(HH)$	360	240	160	120	87	230



Results published on [Eur. Phys. J. C \(2018\) 78: 1007](#) arXiv:[1807.08567](#).

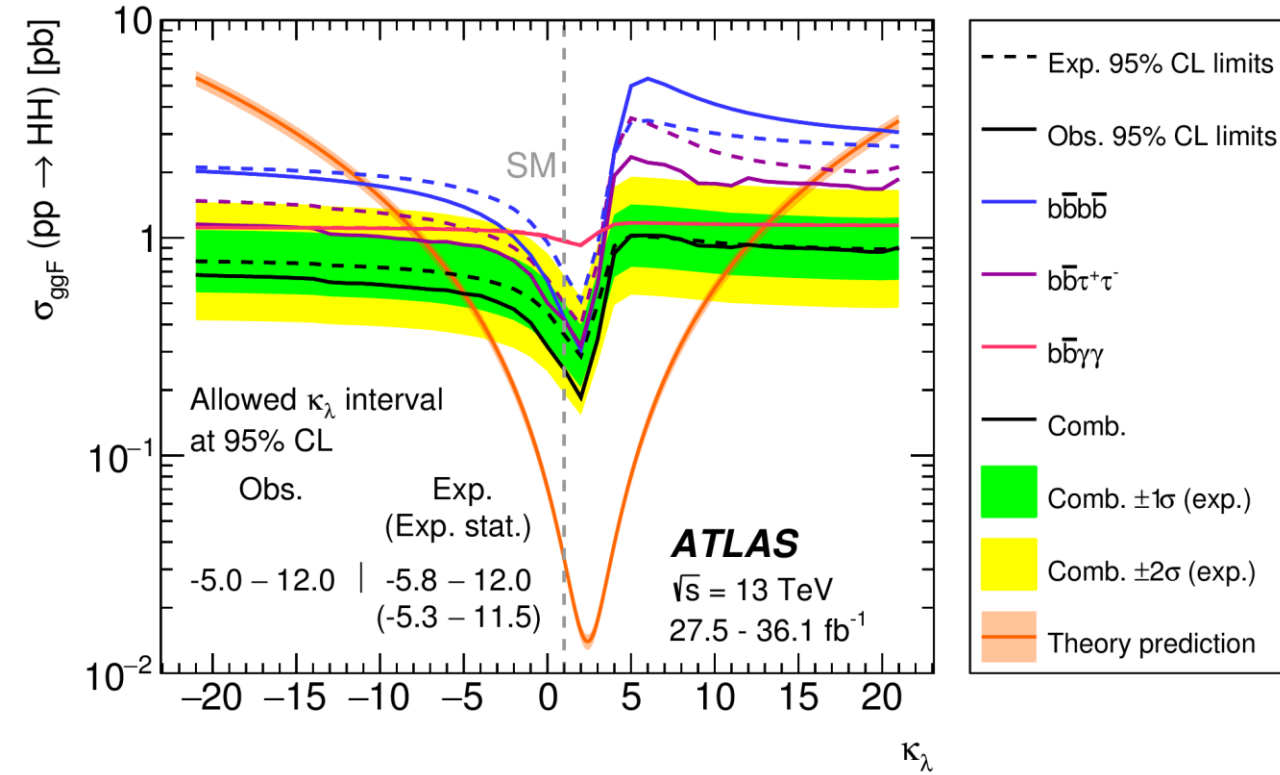
Dihiggs Combination

- $WW^*\gamma\gamma$ becomes one part of HH combination in 36.1fb.
- Latest published on arXiv: [1906.02025](https://arxiv.org/abs/1906.02025).

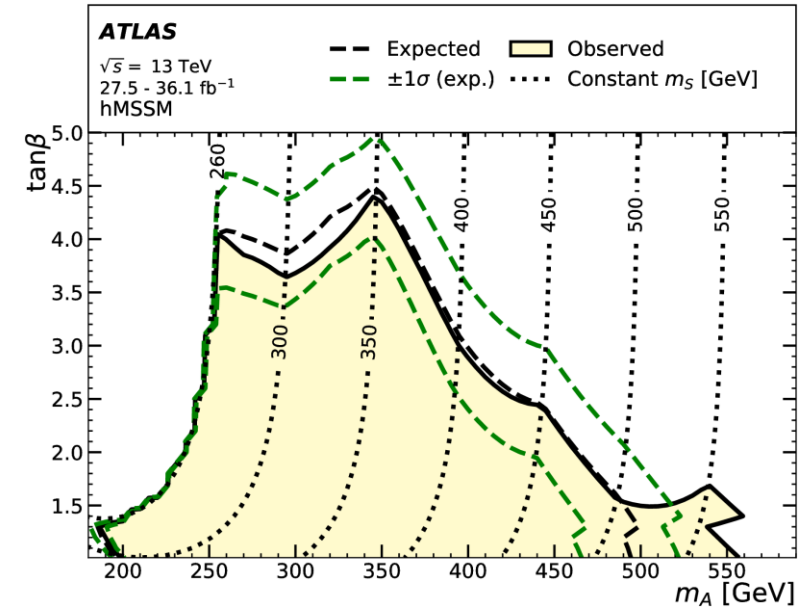
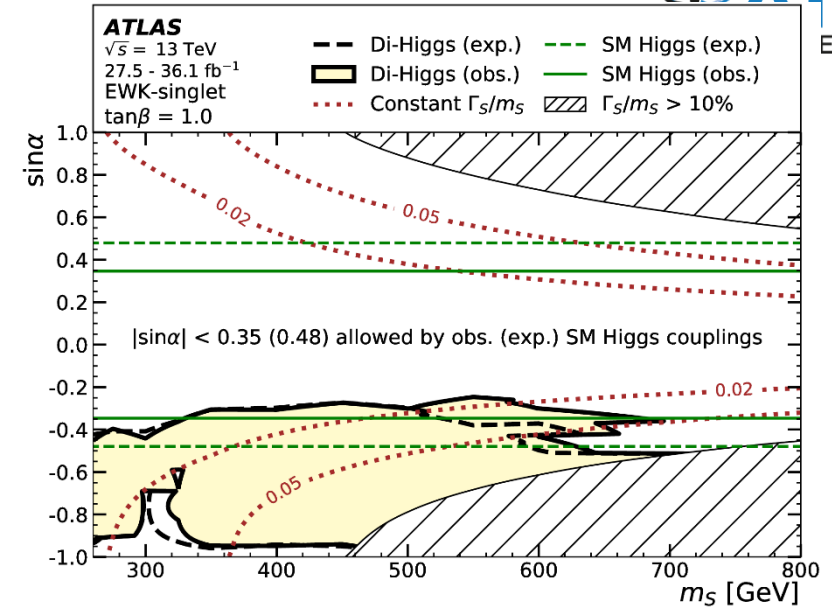


~7 times of SM prediction.

κ_λ and BSM Implication



Current constrain for κ_λ : $-5.0 < \kappa_\lambda < 12.0$
 Expected: $-5.8 < \kappa_\lambda < 12.0$

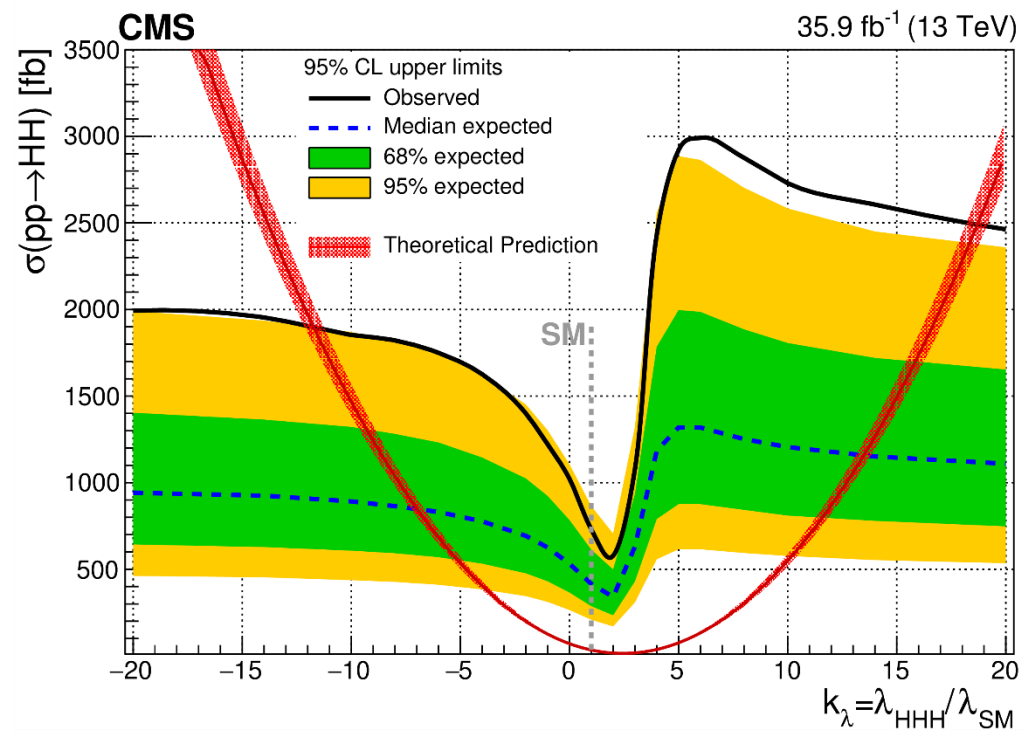
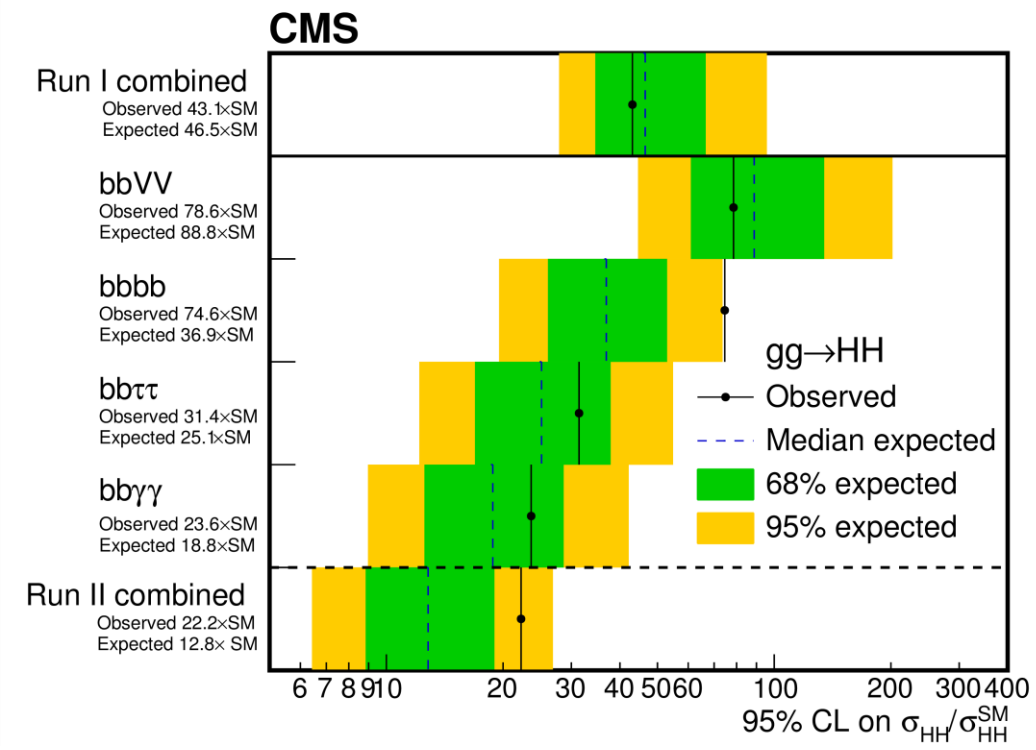


CMS Dihiggs results

CMS contains bbyy, bb $\tau\tau$, bbbb, and bbVV.



- [Phys. Rev. Lett. 122, 121803 \(2019\)](#), arXiv:[1811.09689](#)
- ~22 times of SM while ATLAS 7 times. CMS shows worse performance on b-related channels.



Observed: $-11.8 < \kappa_\lambda < 18.8$
Expected: $-7.1 < \kappa_\lambda < 13.6$

- Now(2019, October), $WW^*\gamma\gamma$ is one part of diHiggs multilepton analyses.
 - Inclusive $\gamma\gamma + ML$ also contains $ZZ^*\gamma\gamma$ and $\tau\tau\gamma\gamma$. Still, $WW^*\gamma\gamma$ is dominant.
 - Now τ information is already available.
 - Singlet Higgs Model could be considered. (Larger WW Br)
 - Analysis with 140fb for 1l and 2l undergoing. Aiming for one note next year.
- HH combination
 - Significance could reach 3σ when $\mathcal{L}$ reach 300fb in the future.

- [Eur. Phys. J. C \(2018\) 78: 1007](#), non-resonant and resonant Higgs boson pair production with a semi-leptonic $WW^*\gamma\gamma$ final state using 36.1fb presented.
 - 95% CL upper limit of **7.7**pb is set on the cross section for non-resonant production.
- Latest ATLAS diHiggs combination results [1906.02025](#) are also shown.
 - for the 95% CL upper limit, **7** times of the SM prediction value can be obtained.
- The analyses with full Run2 data are ongoing.

Backups

Stability check for background model

For different purity and lepton number, on second-order exponential polynomial.

