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

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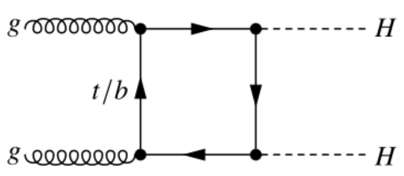
HH Introduction

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

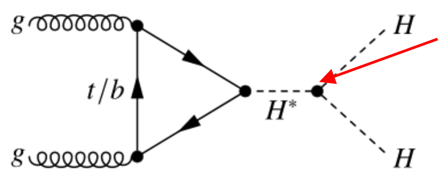
(a) and (b): existing non-resonance production. (in SM ~33 fb @13 TeV)

(c): BSM scenario
Intermediate heavy resonance



(a)

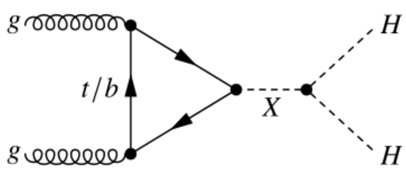
Heavy-quark loop



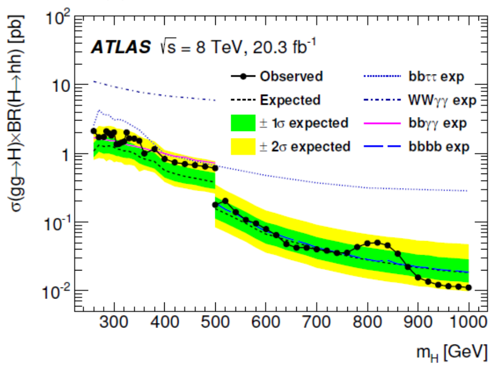
(b)

Higgs self-coupling

λ_{hhh}: Self coupling



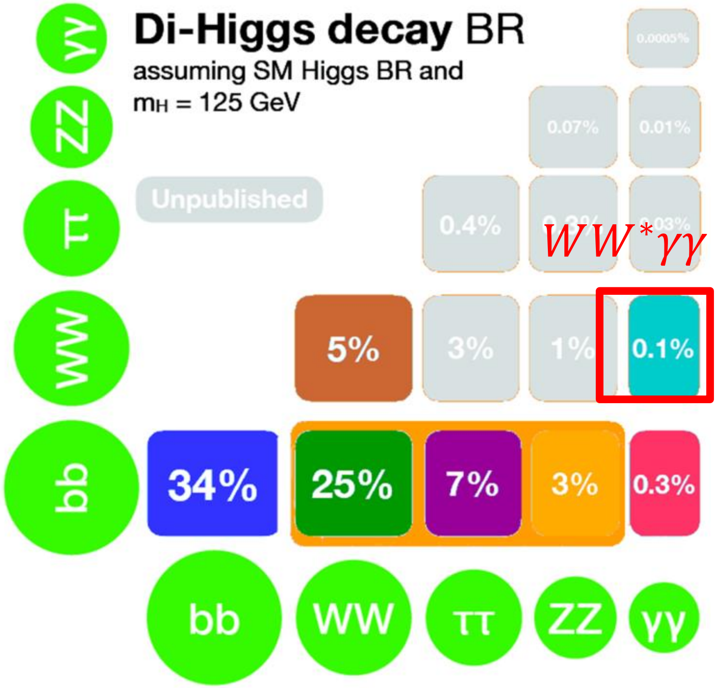
(c)



8 TeV results for HH combination, including $WW^*\gamma\gamma$:
Phys. Rev. D 92, 092004 (2015)

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

Why $WW^*\gamma\gamma$



$Br(HH \to WW^*\gamma\gamma) \approx 10^{-4}$. Limited yields while

- Clean signature diphoton: smooth spectrum provides good background estimation and mass resolution (~1.6GeV).
- Large fraction WW; Higgs boson coupling could be sensitive for BSM.
- Good background rejection from semi-leptonic decay.

Final state: $\gamma\gamma + l\nu + jj$ selected

- τ from W would be too soft to catch. So for lepton only e/μ.
- Considering large dijet background,
  - Only considering low mass resonance <500GeV
- Considering κ_λ and spin-2 sensitivity
  - which needs high statistics. They are studied in the b-related channels.

Phenomenal study on WWyy potential: Phys.Lett. B755 (2016) 509—522

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

Data Sample

- In this report,
  - Data: 36.1fb^{-1} data collected in 2015 + 2016 used;
  - Signal: Resonant use 4 mass point: m260, m300, m400, m500;

Processes	Generator	Parton shower	Tune	PDF
Non-resonant	MadGraph5_aMC@NLO 2.2.3	Herwig++	UEEE5	CTEQ6L1
Resonant	MadGraph5_aMC@NLO 2.2.3	Herwig++	UEEE5	CTEQ6L1

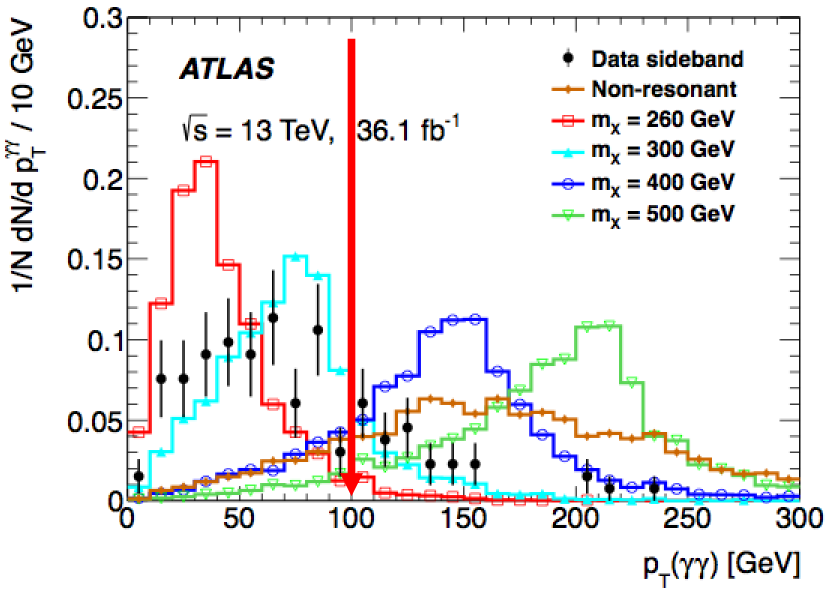
  - Background:
    - Major background could be $\gamma\gamma$+jets(Sherpa), then Single Higgs background;
    - Also the continuum $l\nu jj\gamma\gamma$ sample used to test the shape.

Processes	Generators	QCD order	EW order	PDF	Parton shower	Normalisation
ggF	Powheg NNLOPS	NNLO	NLO	PDF4LHC15	Pythia 8.186	N^3LO (QCD) + NLO (EW)
VBF	Powheg	NLO	NLO	PDF4LHC15	Pythia 8.186	NNLO (QCD) + NLO (EW)
W^+H	Powheg MiNLO	NLO	NLO	PDF4LHC15	Pythia 8.186	NNLO (QCD) + NLO (EW)
W^-H	Powheg MiNLO	NLO	NLO	PDF4LHC15	Pythia 8.186	NNLO (QCD) + NLO (EW)
$q\bar{q} \to ZH$	Powheg MiNLO	NLO	NLO	PDF4LHC15	Pythia 8.186	NNLO (QCD) + NLO (EW)
$ggZH$	Powheg MiNLO	NLO	NLO	PDF4LHC15	Pythia 8.186	NLO NLL (QCD)
$t\bar{t}H$	MadGraph aMC@NLO	NLO	NLO	NNPDF3.0	Pythia 8.186	NLO (QCD) + NLO (EW)

Event selection

- Event requirement
    - Diphoton Trigger, data quality, Good Run List, Primary vertex;
- Photon: 2 PID Tight, isolated photons;
    - $E_T > 25GeV, |\eta| \in [0, 1.37] \cup [1.52, 2.47]$; $\frac{E_T^{y1}}{m_{yy}} > 0.35, \frac{E_T^{y2}}{m_{yy}} > 0.25$; $m_{yy} \in [105, 160]\mathrm{GeV}$.
- Lepton: At least 1 e/μ, PID:Medium
    - $E_T > 10GeV, |\eta_{\mathrm{e}}| \in [0, 1.37] \cup [1.52, 2.47]$; $|\eta_\mu| < 2.47$
- Jet: At least 2. Anti-kt algorithm, R=0.4
    - B veto: WP70, keep orthogonal with other HH.
    - $p_T > 25GeV, |\eta| < 2.5$; JVT<0.59.

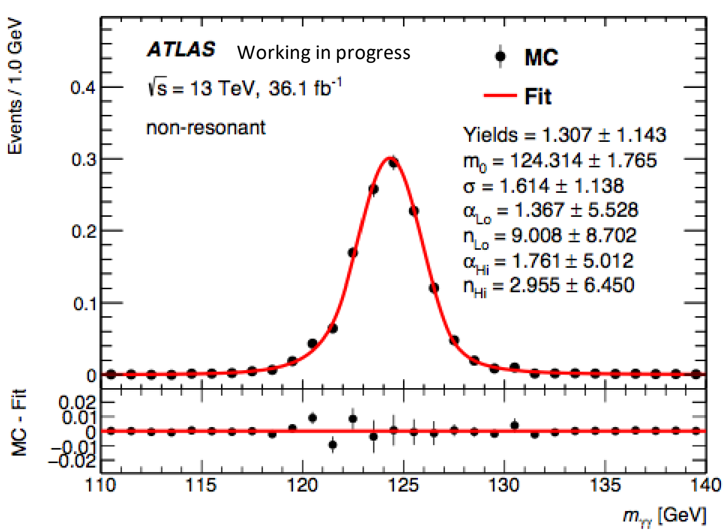
Signal Optimization



MET related variables seem no separation power so we drop it.

p_T^{yy} would help for the higher mass points(m400, m500 and non-resonance), since SM higgs is more boosted.

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

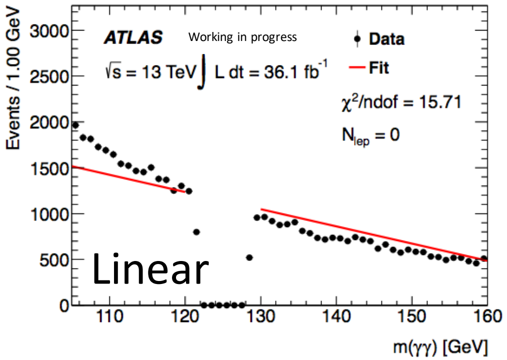


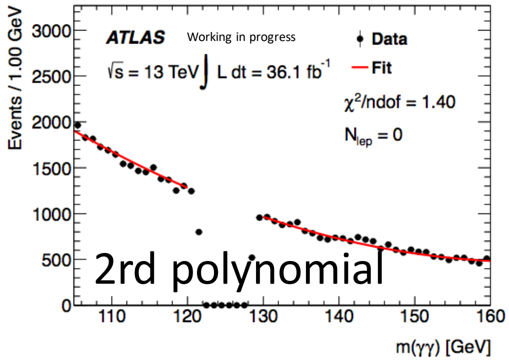
Final efficiencies turned to ~6-10% for resonance and 8.5% for non-resonance.

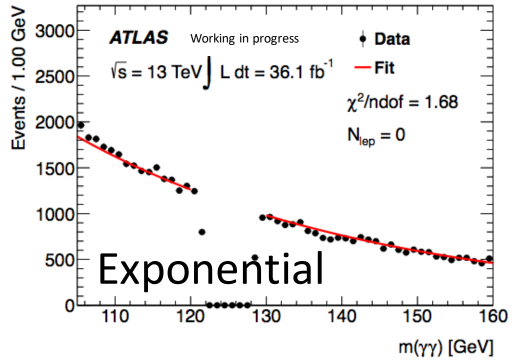
Signal shape modeled by Double-Sided Crystal Ball.

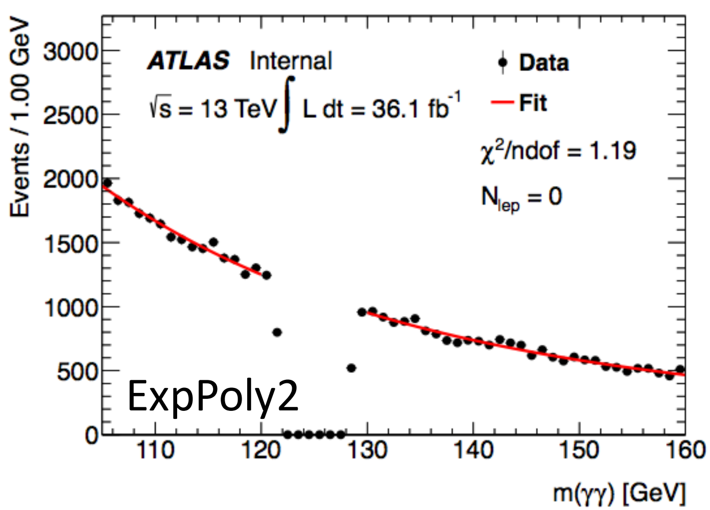
Background estimation

- Background shape: Fitted by 2nd-order exponential polynomial with Minimal χ^2.
  - Uncertainty for background modelling is estimated by Spurious Signal.
    - Fitting a S+B model to a B-only sample.



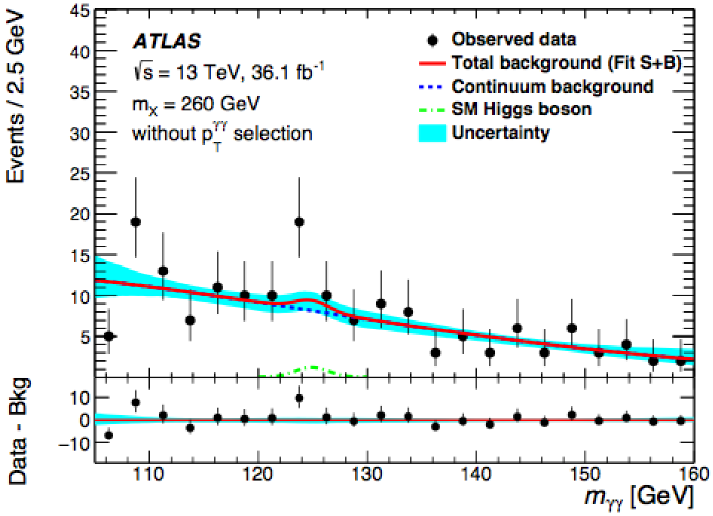


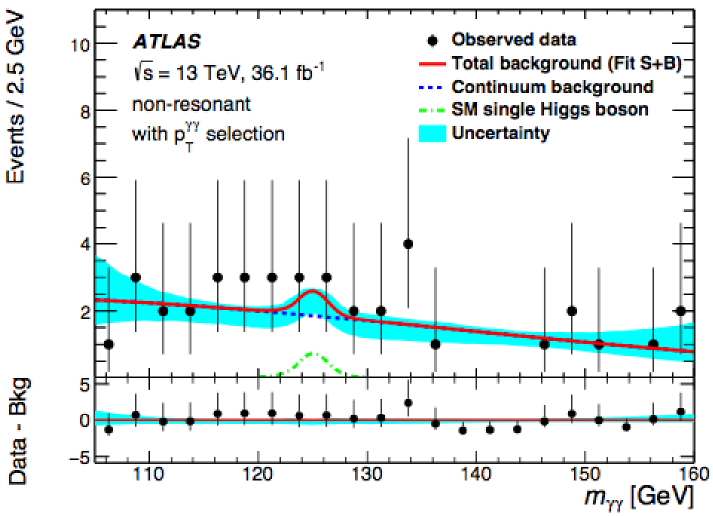




Sideband excluded the Higgs mass region $m_{yy} \in [121.5, 128.5]$GeV, i.e.$m_H \pm 2\sigma m_{yy}$.

Background estimation in signal region





- Background yields determined from the fit to data.
  - Extending the continuum background shape over the signal 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	$X \to HH$	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	-	-
	$B(H \to \gamma\gamma)$	2.1	2.1	2.1	2.1
	$B(H \to WW^*)$	1.5	1.5	1.5	1.5
Total		13.6	31.8	7.1	6.8

Spurious signal uncertainty
- 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

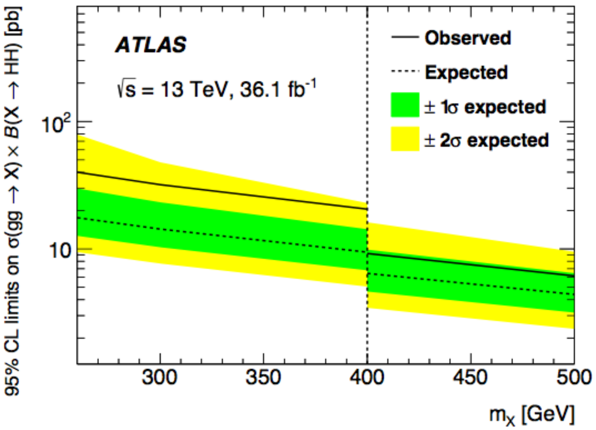
Dominant systematics for non-resonant are:
- Spurious signal
- e/γ energy scale and resolution.

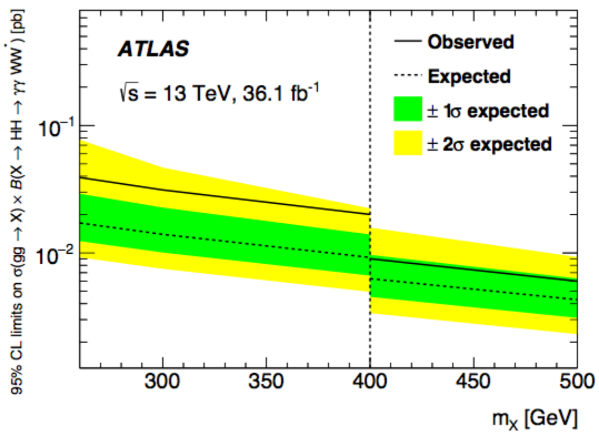
The large parton shower uncertainty 29.6% occurs at m=260GeV, where the jet spectrum at low-pT is more susceptible to variations.

Results

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

- No significant excess observed.
- Expected upper limit on $pp \rightarrow HH$ is 7.7pb for non-resonant; 230(160) times of SM prediction.
  - 17.6pb(m260) to 4.4pb(m500) for resonant.
  - Statistical uncertainty dominates.





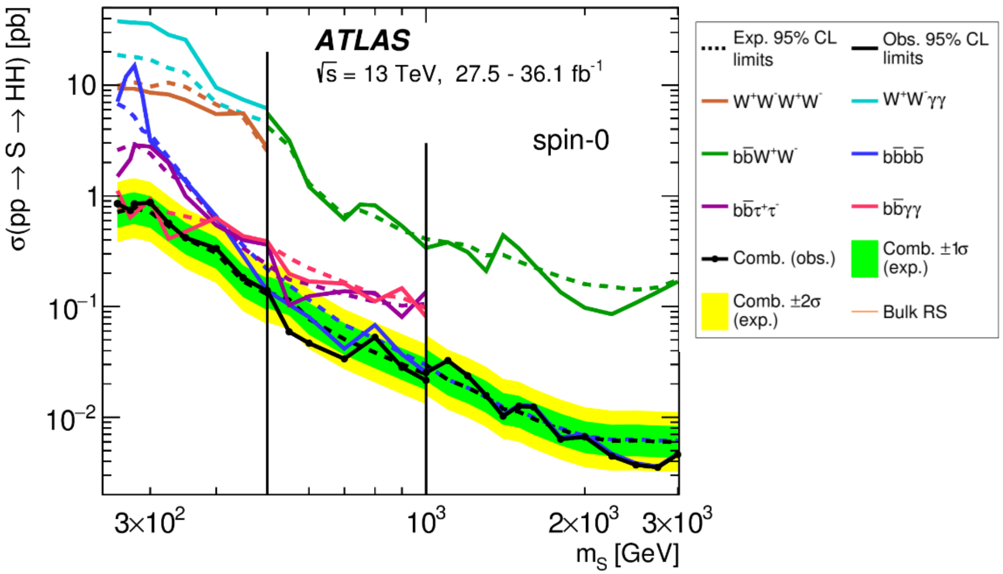
	$+2\sigma$	$+1\sigma$	Median	-1σ	-2σ	Observed
Upper limits on $\sigma(HH)$ [pb]	12	8.0	5.4	3.9	2.9	7.7
Upper limits on $\sigma(HH) \times B(\gamma\gamma WW^*)$ [fb]	12	7.8	5.3	3.8	2.8	7.5
Ratios of limits over the SM $\sigma(HH)$	360	240	160	120	87	230

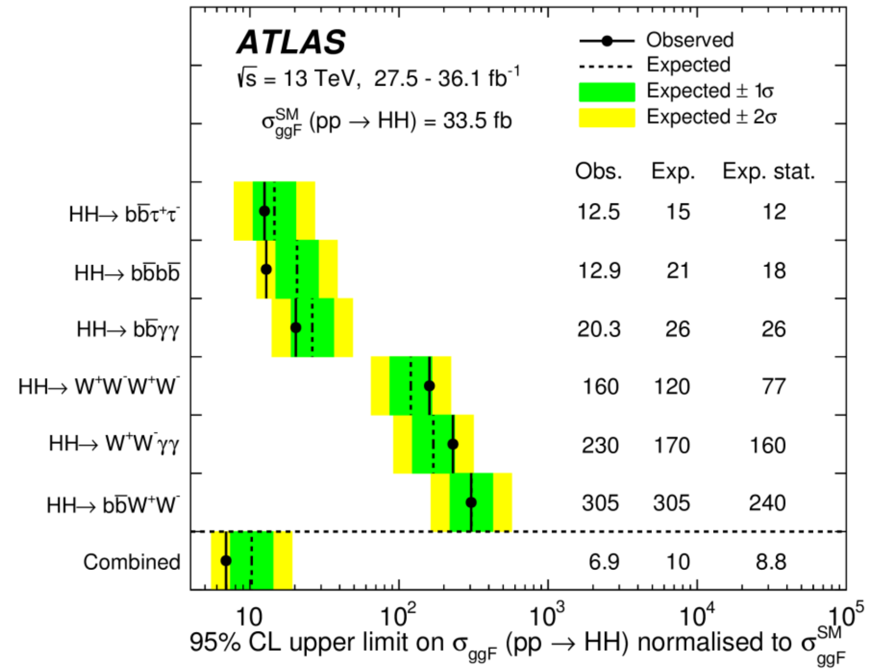
Results published on Eur. Phys. J. C (2018) 78: 1007 arXiv:1807.08567.

Dihiggs Combination

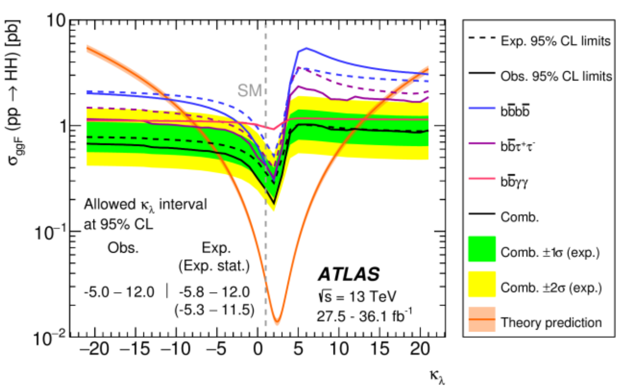
- $WW^*\gamma\gamma$ becomes one part of HH combination in 36.1ifb.
- Latest published on arXiv:1906.02025.

For 4W study, see Shuiting's Poster;





Total: ~7 times of SM prediction.

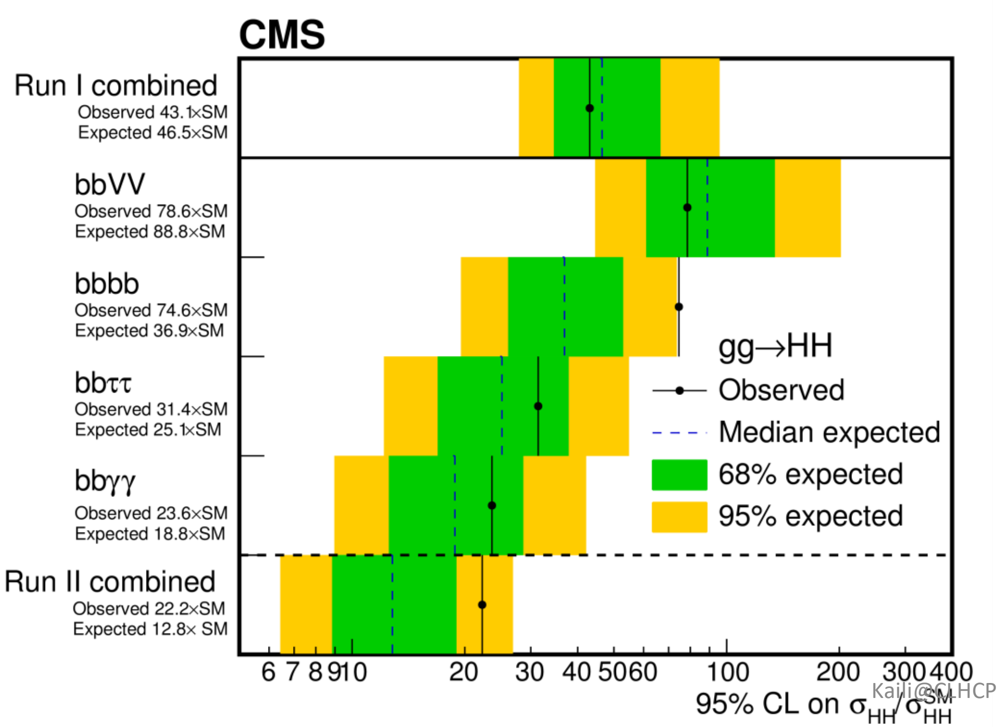


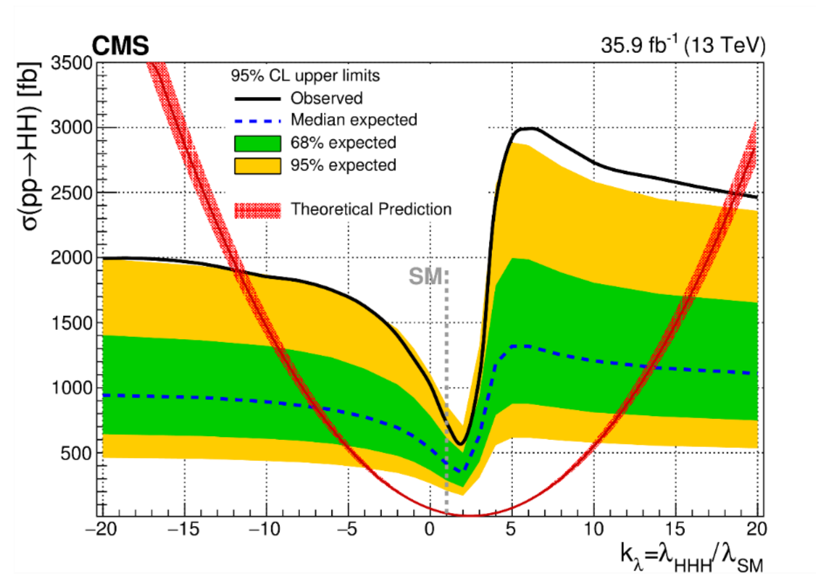
Current constrain for κ_λ: $-5.0 < \kappa_\lambda < 12.0$

Expected: $-5.8 < \kappa_\lambda < 12.0$

CMS results

- CMS dihiggs contains bbyy, bbττ, bbbb, and bbVV.
  - -> VVVV and VVyy not included.
- 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.

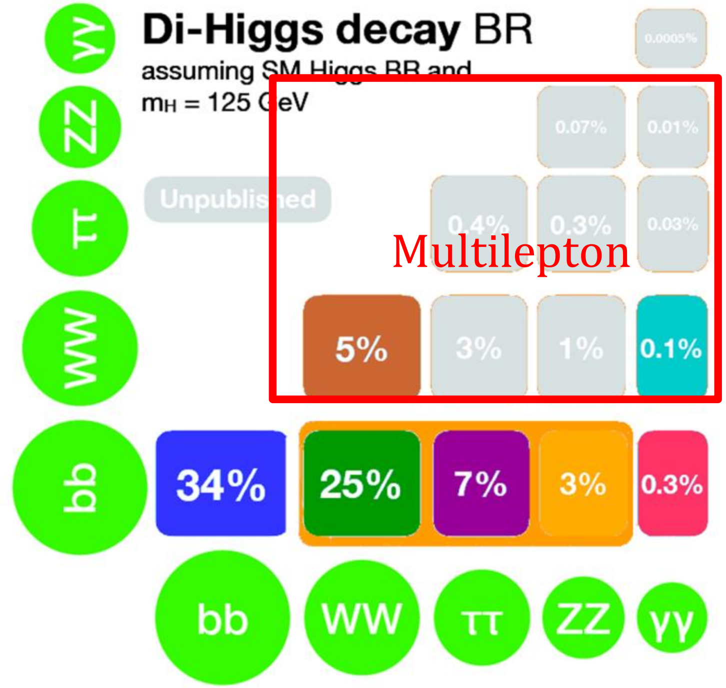




Observed: $-11.8 < \kappa_\lambda < 18.8$
Expected: $-7.1 < \kappa_\lambda < 13.6$

Undergoing

- Now(2019, October), $WW^*\gamma\gamma$ is one part of dihiggs multi-lepton analyses.
  - Full run2 data allows inclusive study for all possible multilepton channels.
  - For $\gamma\gamma + ML$ events, still $WW^*\gamma\gamma$ is dominant.
  - Analysis with full run2 data undergoing, not shown here. Aiming for one note next year.
  - $S(\rightarrow WW/ZZ)H(\rightarrow \gamma\gamma)$ Model also in plan.



Summary

- Eur. Phys. J. C (2018) 78: 1007 , ATLAS non-resonant and resonant Higgs boson pair production with a semi-leptonic $WW^{*}\gamma\gamma$ final state using 36.1ifb presented.
  - No significant excesses found.
  - 95% CL upper limit of 7.7pb is set on the cross section for non-resonant production.
- Lastest 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 multi-lepton analyses with full Run2 data are ongoing.

Backups

Stability check for background model

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