HH searches (non-resonant) at ATLAS & CMS

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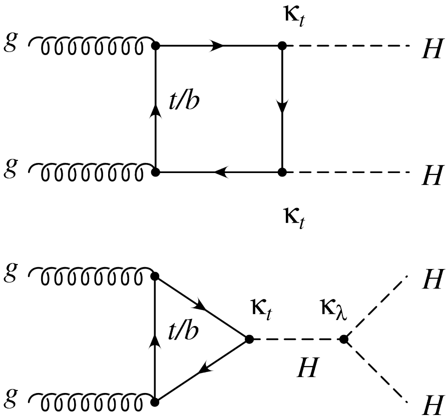
Di-Higgs Searches

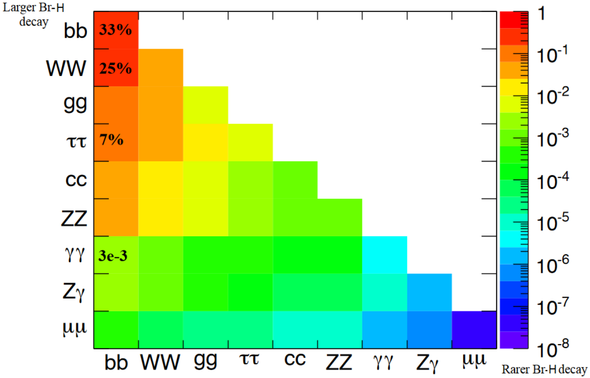
Di-Higgs production is an allowed, rare process in the SM - 33 fb at 13 TeV.

- Standard Model
  - Destructive interference between diagrams.
  - Opportunity to probe the Higgs trilinear coupling directly.
- Beyond Standard Model
  - Non-resonant enhancement in many BSM models.
  - Modifications to $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$.
- Very interesting place to investigate the Higgs sector.



Di-Higgs Final States

- Rich phenomenology.
- ATLAS & CMS have dedicated analysis for each sensitive final state.
- Most sensitive usually have high branching ratio and/or low backgrounds.

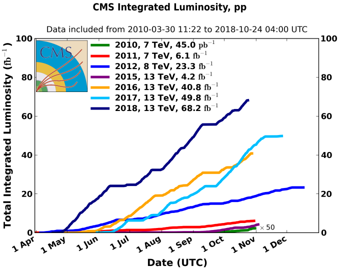


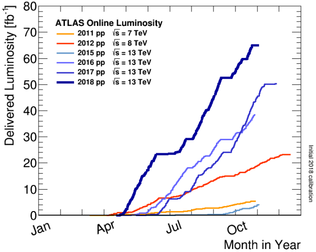
- Will be focusing on recent results with **36 fb^{-1}** of 13 TeV data.

Outline

- Di-Higgs Searches
  - HH→ bb bb
  - HH→ $\tau\tau$ bb
  - HH→ $\gamma\gamma$ bb
  - HH→ WW^* bb
  - Di-Higgs combinations
- Conclusions & Outlook

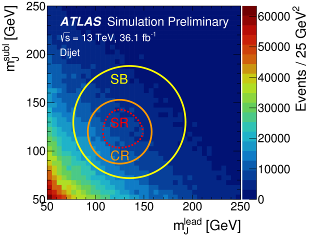
- ATLAS also has searches in the $\gamma\gamma WW^*$ [arXiv:1807.08567] and $WW^* WW^*$ channels [arXiv:1811.11028].

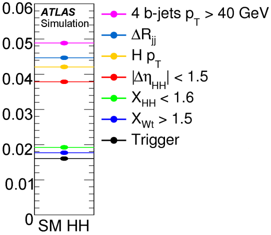


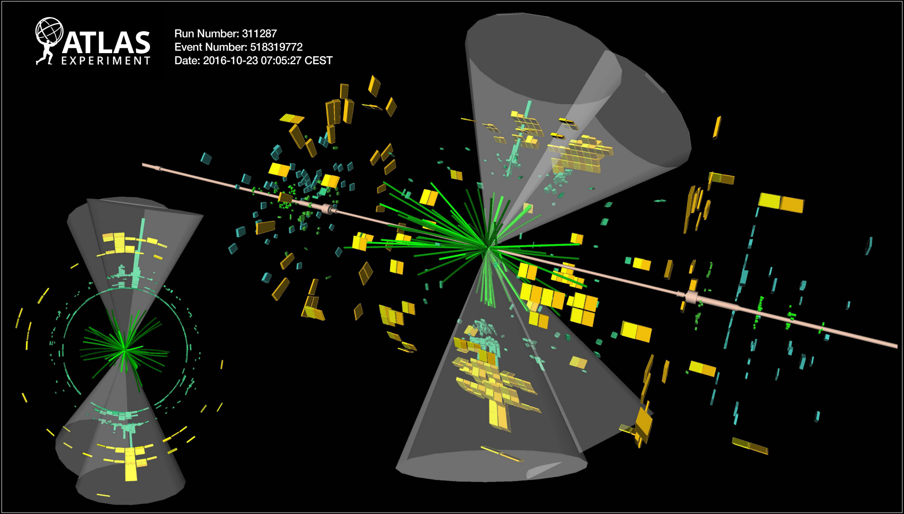


Non-resonant search uses ‘resolved’ channel:

- Construct two Higgs boson candidates from the 4 jets identified most probably to contain a b-hadron.
- Two-b-jet triggers used.
- Dominant background is multijet events, estimated by a data-driven method
  - Shape estimated by a region with fewer b-tagged jets.
- $t\bar{t}$ and multijet normalisation determined simultaneously from 3 enriched data samples.

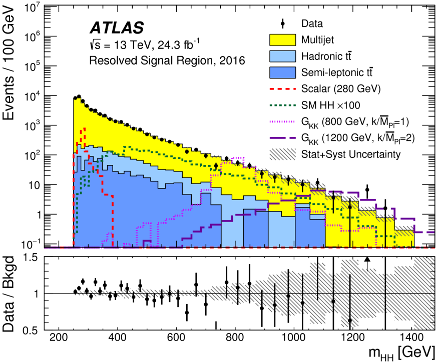






A candidate resolved 4b event in 2016

- Limit on SM non-resonant di-Higgs production stronger than expected, due to deficit about $m_{HH} \sim 400$ GeV.
- Dominant uncertainty in the data-driven background normalisation and shape.
- Observed (exp.) 95% CL upper limit $\sigma(pp \to HH \to bbbb) < 147$ (234) fb. $\sigma_{HH}/\sigma_{HH}^{SM}$ limits:

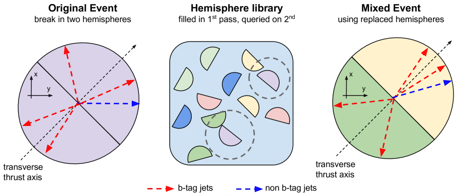


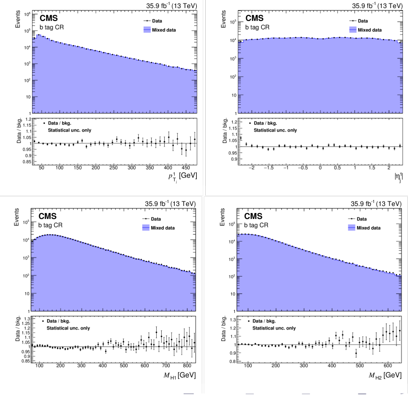
Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
147	126	169	234	339	492

CMS Non-resonant Search for 4b [arXiv:1810.11854]

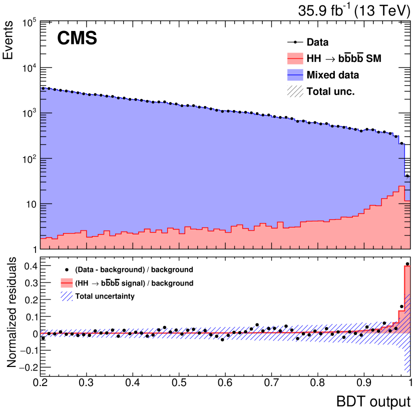
- Final state of 4 identified b-jets.
- B-jet identification and jet substructure techniques.
- Train BDT on jet, HH-decay kinematic and global event variables.
- Background model created by hemisphere mixing technique applied to signal region events, validated in data control regions.





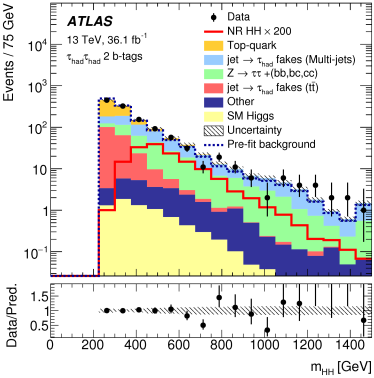
CMS Non-resonant Search for 4b [arXiv:1810.11854]

- Two component fits to the binned BDT discriminant yield an upper limit on signal events and HH cross-section.
- Dominant systematics are those on the shape (30%) and normalisation (8.6%) of the background model.
- BDT discriminant values > 0.2 used for limit setting.
- Observed (Exp.) 95% CL upper limit $\sigma_{HH}/\sigma_{HH}^{SM} = 75$ (37). Cross-section limits (fb):

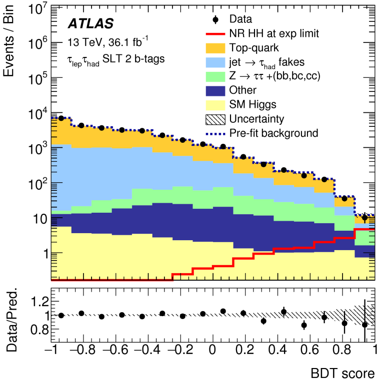


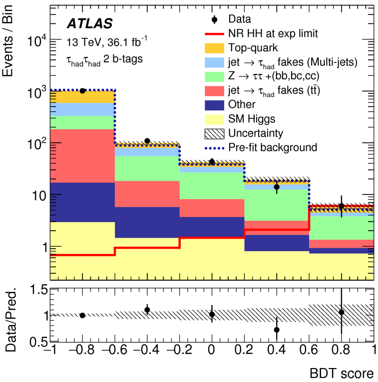
Category	Observed	Expected	-2 s.d.	-1 s.d.	+1 s.d.	+2 s.d.
SM HH → $b\bar{b}b\bar{b}$	847	419	221	297	601	834

- Select final states with an e/μ and hadronically-decaying τ candidate (τ_{had}) or two τ_{had} candidates, in association with two b-jets and E_T^{miss}.
  - Yields two search channels($\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) with several discriminating kinematic variables.
  - $\tau_{lep}\tau_{had}$ further split by trigger: single lepton / lepton + τ.
  - Dominant backgrounds: $t\bar{t}$ and Z+hf constrained at low BDT score and by enriched control regions.
  - BDT distributions in the 3 signal regions are fit.



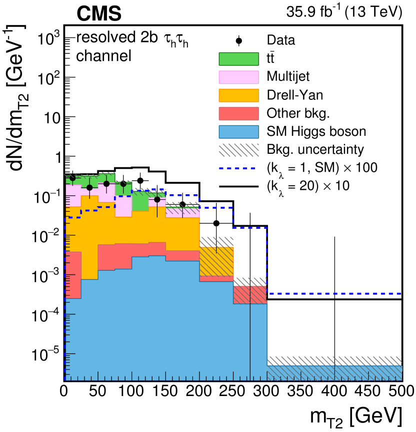
Di-Higgs Search to $\tau\tau$bb - ATLAS [PRL 121 191801]





		Observed	-1σ	Expected	$+1\sigma$
$\tau_{\rm lep}\tau_{\rm had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57	49.9	69	96
	$\sigma/\sigma_{\rm SM}$	23.5	20.5	28.4	39.5
$\tau_{\rm had}\tau_{\rm had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	40.0	30.6	42.4	59
	$\sigma/\sigma_{\rm SM}$	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.1	50
	$\sigma/\sigma_{\rm SM}$	12.7	10.7	14.8	20.6

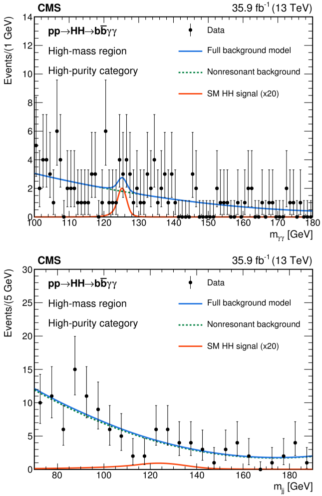
- Select events with 1+ isolated τ_{had} with a second lepton of opposite charge (e/μ or τ_{had}).
- Categorise according to 1/2 b-jets.
- Boosted category for events with a Higgs-*bb* jet candidate.
- BDT discriminant trained on kinematic variables used to reduce the $t\bar{t}$ background in the semi-leptonic channel.



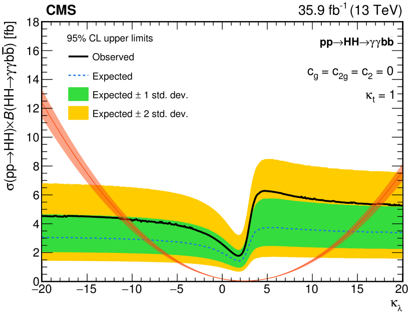
- Z/γ^*+jets and multijet processes estimated with control regions.
- M_{T2} used for signal-background separation - bounded by the top mass for $t\bar{t}$ processes.
- Observed (Expected) 95% CL upper limit $\sigma_{HH}/\sigma_{HH}^{SM} = 30(25)$.

Di-Higgs searches in $\gamma\gamma bb$ - CMS [arXiv:1806.00408]

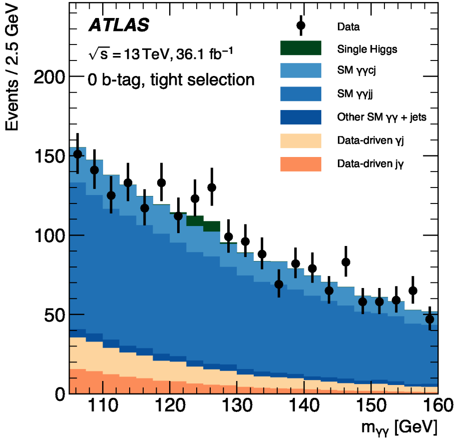
- Perform a 2D fit of the diphoton and di(b)jet invariant mass distributions.
- Estimate the nγ+jet continuum from the mass sidebands.
- Single Higgs production contributes to the background.
- Further event classification according to the HH pair reduced mass, and the purity.
- Signal purity estimated by a BDT using jet b-tagging scores, the HH system helicity angles and H candidate p_T.



- High-mass, high purity category dominates for SM non-resonant production.
- Analysis is statistically limited - largest systematic from signal shape functional form.
- Observed (expected) 95% CL upper limit σ(pp$\rightarrow$HH$\rightarrow$ $\gamma\gamma$bb) $<$ 2.0 fb (1.6 fb), 24 (19)x σ_{HH}^{SM}.
- 95% CL limits on coupling: $-11 < \kappa_\lambda < 17$.



- Select events with 2 isolated photons and two jets with an invariant mass compatible with m_H and at least one b-tag.
- Categorise according to the number of b-tagged jets.
- Kinematic selection further optimised for SM non-resonant HH production; second looser selection for non-SM couplings.
- The diphoton mass spectrum is fit.



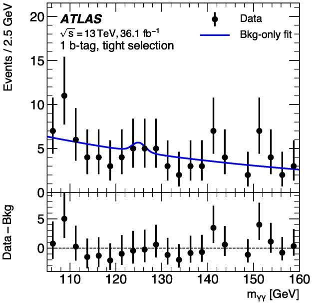
(Control region used for fit function optimisation)

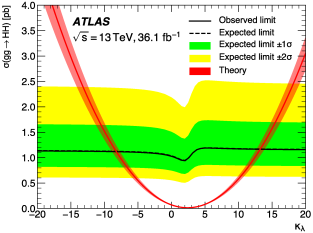
ATLAS Di-Higgs search in $bb\gamma\gamma$ [JHEP 11(2018)040]

- Good agreement between the data and the background expectation.
- Best-fit Higgs boson pair cross-section consistent with zero in loose/tight selection.

	Observed	Expected	-1σ	$+1\sigma$
$\sigma_{gg\to HH}$ [pb]	0.73	0.93	0.66	1.4
As a multiple of σ_{SM}	22	28	20	40

- 95% CL limits on coupling: $-8.2 < \kappa_\lambda < 13.2$, in line with expectation.

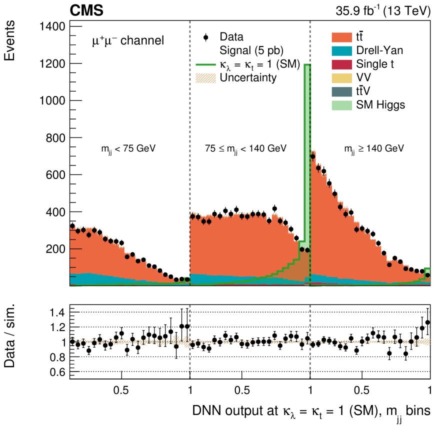




Di-Higgs Searches for bbWW

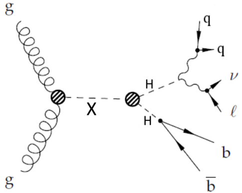
CMS search in the $bbl\nu l\nu$ final state [JHEP01(2018)054]

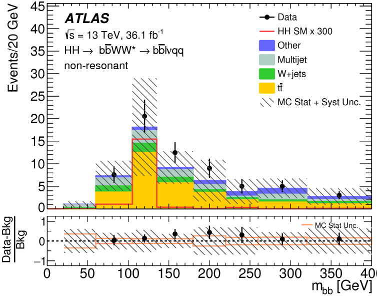
- Covers HH→bbWW→$bbl\nu l\nu$ and HH→bbZZ→$bbl\nu l\nu$ processes.
- Large irreducible background from $t\bar{t}$ and Drell-Yan processes.
- Deep Neural Network used to aid discrimination of signal against background.
- No significant excess over background prediction.
- Observed (exp.) 95% CL upper limit $\sigma(pp \rightarrow HH \rightarrow bbl\nu l\nu) < 72$ (81) fb, 79x (89x) σ_{HH}^{SM}.



ATLAS WWbb search for $bbl\nu qq$ [arXiv:1811.04671]

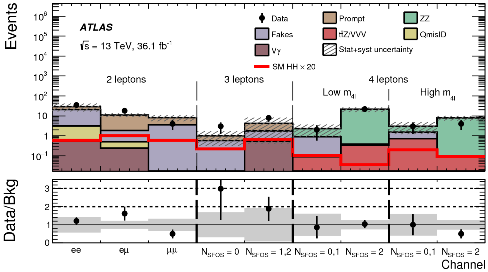
- First ATLAS look at 1-lepton final state.
- Select events passing e/μ triggers, with two b-tagged jets, construct W boson candidate from untagged jets, reconstruct W_{lept} with l+E_T^{miss}.
- Further kinematic requirements suppress $t\bar{t}$; constraints from data control regions.
- Observed 95% CL upper limit σ(pp→HH→bb$l\nu qq$) < 2.5 pb, $\sim$ 300xσ_{HH}^{SM}, (same exp. limit)
- Coupling limit: $-11 < \kappa_\lambda < 17$ at 95% CL.





ATLAS Search in WW^*WW^* [arXiv:1811.11028]

- Search for final states with 2 SS, 3 or 4 leptons.
- Z veto applied in 2-,3-lepton selection.
- Irreducible EW backgrounds dominate.



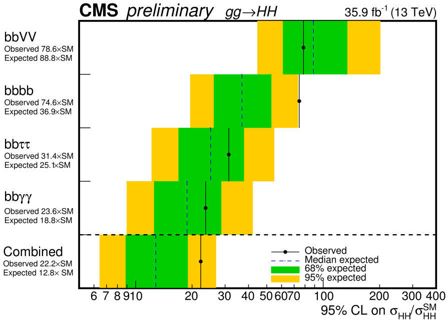
- Non-prompt backgrouds estimated from ‘anti-tight’ selections.
- No significant excess observed.

	Observed limit on $\sigma/\sigma_{\mathrm{SM}}$	Expected limit on $\sigma/\sigma_{\mathrm{SM}}$ Median	$+2\sigma$	$+1\sigma$	-1σ	-2σ
2 leptons	170	150	290	210	100	78
3 leptons	420	270	690	420	200	150
4 leptons	340	400	880	590	290	210
Combined	160	120	230	170	83	62

- ATLAS and CMS have both recently combined their most sensitive di-Higgs channels.
  - ATLAS: bbbb, bb$\tau\tau$, bb$\gamma\gamma$
  - CMS: bb$\gamma\gamma$, bb$\tau\tau$, bbbb, bbWW
- SM Higgs boson decay branching fractions are assumed.

CMS Combination

- Observed upper limit slightly weaker than expectation, due to upward data fluctuations.
- Combined observed (exp.) upper limit: 22.22 (12.8) σ_{HH}^{SM}.

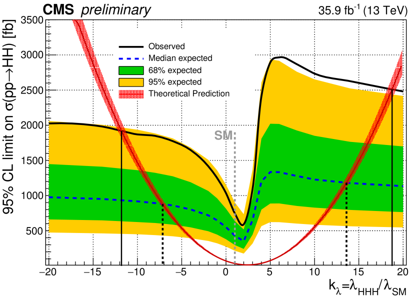


Towards the Higgs Coupling

CMS combinations

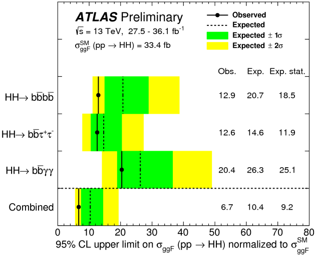
CMS-PAS-HIG-17-030

- Dominant systematics inherited from the channels: $\sim$ 10% (bbbb, bb$\tau\tau$), $\sim$ 5% (bb$\gamma\gamma$).
- Exclusion limits primarily follow the HH production cross-section (e.g. larger c-s for $\kappa_\lambda < 0$, so stronger limit).

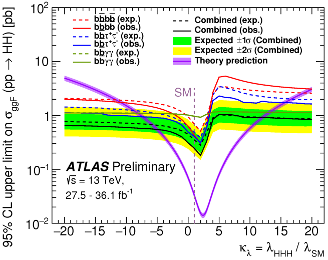


- Minimum at maximal destructive interference between the two diagrams.
- Weaker limits where the m_{HH} spectrum is softer.
- 95% CL observed (expected) limit on κ_λ: $-11.8 < \kappa_\lambda < 18.8$ $(-7.1 < \kappa_\lambda < 13.6)$

- All other couplings set to SM values.
- *HH* →bb$\tau\tau$ BDT trained on $\kappa_\lambda = 20$ for sensitivity across κ_λ.
- *HH* →bb$\gamma\gamma$, less stringent selection used to keep sensitivity to lower p_T^{Higgs} at high κ_λ.
- For each κ_λ value, the kinematic distributions, signal acceptances and the m_{HH} spectrum are computed.

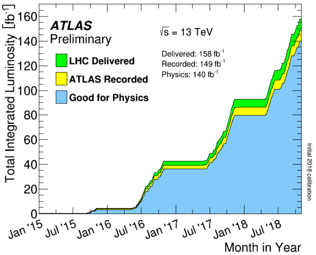


Search channel	Allowed κ_λ interval at 95% CL					
	obs.		exp.		exp. stat.	
$HH \to b\bar{b}b\bar{b}$	−10.9	20.1	−11.6	18.7	−9.9	16.4
$HH \to b\bar{b}\tau^+\tau^-$	−7.3	15.7	−8.8	16.7	−7.8	15.4
$HH \to b\bar{b}\gamma\gamma$	−8.1	13.2	−8.2	13.2	−7.7	12.7
Combination	−5.0	12.1	−5.8	12.0	−5.2	11.4



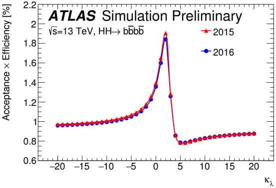
Conclusions and Outlook

- The LHC and the ATLAS and CMS experiments are performing very well during LHC Run-2.
- Wide range of results available using 13 TeV data from 2015 & 2016.
- The di-Higgs programs at ATLAS and CMS are very active across a broad range of final states.
- Not sensitive to SM production yet, but limits from combinations increasingly stringent.

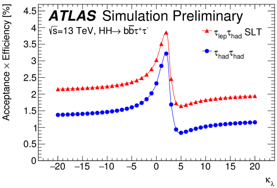


- Much to come in the future, Run-3 and HL-LHC
  - ATLAS and CMS now have ~ 150 fb^{-1} of data recorded from LHC Run-2.
  - Many powerful 13 TeV results to come!

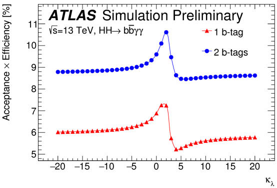
BACKUP SLIDES



HH→bbbb



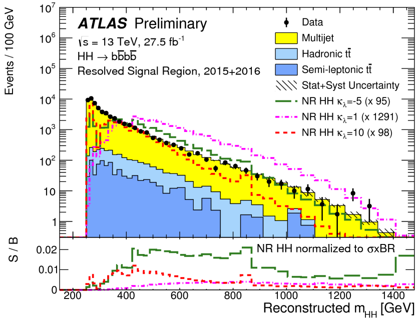
HH→bb$\tau\tau$

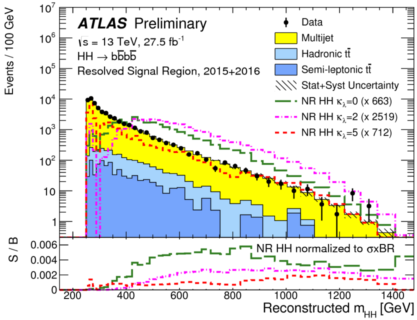


HH→bb$\gamma\gamma$

ATLAS HH→bbbb - 36 fb^{-1} [arXiv:1804.06174]

Varying κ_λ





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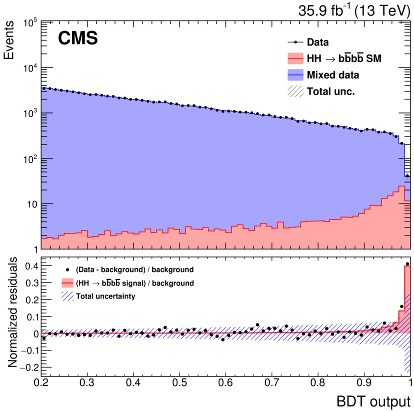
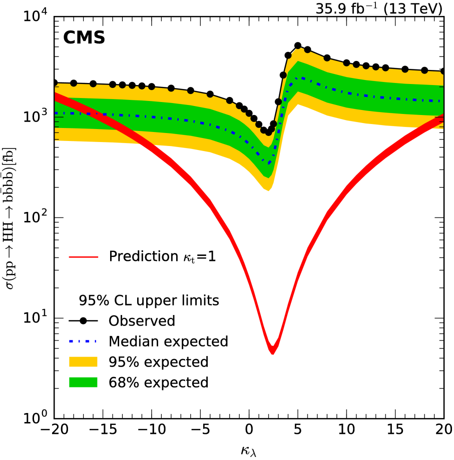
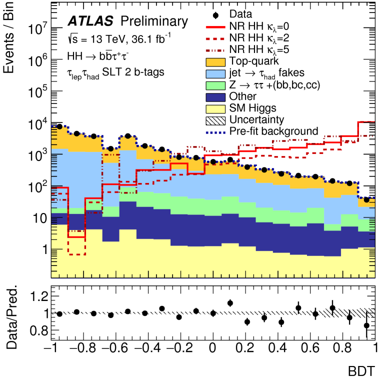
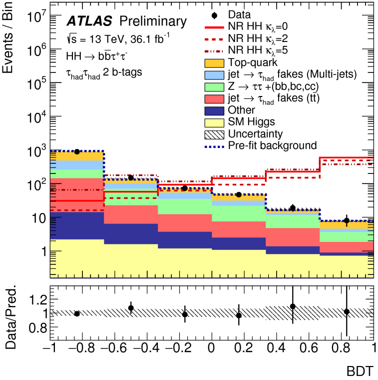




Di-Higgs Search to $\tau\tau$bb - ATLAS [PRL 121 191801]

Varying κ_λ





Variable	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT resonant)	$\tau_{\text{lep}}\tau_{\text{had}}$ channel (SLT non-resonant & LTT)	$\tau_{\text{had}}\tau_{\text{had}}$ channel
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	✓
$E_{\text{T}}^{\text{miss}}$	✓		
$E_{\text{T}}^{\text{miss}}$ ϕ centrality	✓		✓
m_{T}^{W}	✓	✓	
$\Delta\phi(H,H)$	✓		
$\Delta p_{\text{T}}(\text{lep}, \tau_{\text{had-vis}})$	✓		
Sub-leading b-jet p_{T}	✓		

Di-Higgs Search to $\tau\tau$bb - ATLAS [PRL 121 191801]

Yields

	$\tau_{lep}\tau_{had}$ channel (SLT)	$\tau_{lep}\tau_{had}$ channel (LTT)	$\tau_{had}\tau_{had}$ channel
$t\bar{t}$	18.2 ± 4.2	23.2 ± 1.7	4.5 ± 1.4
Single top	6.4 ± 1.3	3.7 ± 1.2	1.06 ± 0.57
Multi-jet fake-τ_{had}	-	-	3.89 ± 0.87
$t\bar{t}$ fake-τ_{had}	-	-	1.9 ± 1.4
Fake-τ_{had}	12.0 ± 2.3	6.6 ± 1.5	-
$Z \to \tau\tau + (cc, bc, bb)$	10.2 ± 2.6	7.7 ± 3.1	12.6 ± 3.6
Other	3.89 ± 0.69	1.51 ± 0.36	1.09 ± 0.32
SM Higgs	1.94 ± 0.43	0.58 ± 0.14	1.54 ± 0.41
Total Background	52.7 ± 4.5	39.5 ± 3.0	26.7 ± 3.5
Data	45	47	20
NR HH	0.49 ± 0.07	0.16 ± 0.02	0.55 ± 0.10

Di-Higgs Search to $\tau\tau$bb - ATLAS [PRL 121 191801]

Systematics

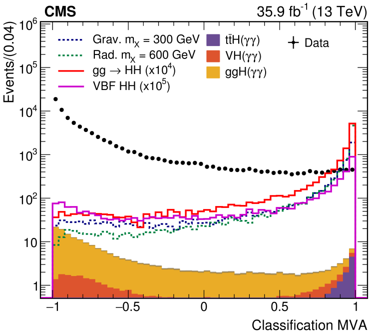
Source	Uncertainty (%)
Total	± 54
Data statistics	± 44
Simulation statistics	± 16
Experimental Uncertainties	
Luminosity	± 2.4
Pileup reweighting	± 1.7
τ_{had}	± 16
Fake-τ estimation	± 8.4
b-tagging	± 8.3
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	± 3.3
Electron and muon	± 0.5
Theoretical and Modeling Uncertainties	
Top	± 17
Signal	± 9.3
$Z \to \tau\tau$	± 6.8
SM Higgs	± 2.9
Other backgrounds	± 0.3

CMS Search for HH→$bb\tau\tau$ [PLB 778(2018)101]

Systematic uncertainty	Value	Processes
Luminosity	2.5%	all but multijet, $Z/\gamma^* \to \ell\ell$
Lepton trigger and reconstruction	2–6%	all but multijet
τ energy scale	3–10%	all but multijet
Jet energy scale	2–4%	all but multijet
b tag efficiency	2–6%	all but multijet
Background cross section	1–10%	all but multijet, $Z/\gamma^* \to \ell\ell$
$Z/\gamma^* \to \ell\ell$ SF uncertainty	0.1–2.5%	$Z/\gamma^* \to \ell\ell$
Multijet normalization	5–30%	multijet
Scale unc.	$+4.3\%/-6.0\%$	signals
Theory unc.	5.9%	signals

ATLAS Di-Higgs search in bb$\gamma\gamma$ [JHEP 11(2018)040]

Source of systematic uncertainty		% effect relative to nominal in the 2-tag (1-tag) category: Non-resonant analysis		Resonant analysis: BSM HH	
		SM HH signal	Single-H bkg	Loose selection	Tight selection
Luminosity		±2.1 (±2.1)	±2.1 (± 2.1)	±2.1 (±2.1)	±2.1 (±2.1)
Trigger		±0.4 (±0.4)	±0.4 (± 0.4)	±0.4 (±0.4)	±0.4 (±0.4)
Pile-up modelling		±3.2 (±1.3)	±2.0 (± 0.8)	±4.0 (±4.2)	±4.0 (±3.8)
Photon	identification	±2.5 (±2.4)	±1.7 (± 1.8)	±2.6 (±2.6)	±2.5 (±2.5)
	isolation	±0.8 (±0.8)	±0.8 (± 0.8)	±0.8 (±0.8)	±0.9 (±0.9)
	energy resolution	-	-	±1.0 (±1.3)	±1.8 (±1.2)
	energy scale	-	-	±0.9 (±3.0)	±0.9 (±2.4)
Jet	energy resolution	±1.5 (±2.2)	±2.9 (± 6.4)	±7.5 (±8.5)	±6.4 (±6.4)
	energy scale	±2.9 (±2.7)	±7.8 (± 5.6)	±3.0 (±3.3)	±2.3 (±3.4)
Flavour tagging	b-jets	±2.4 (±2.5)	±2.3 (± 1.4)	±3.4 (±2.6)	±2.5 (±2.6)
	c-jets	±0.1 (±1.0)	±1.8 (±11.6)	-	-
	light-jets	<0.1 (±5.0)	±1.6 (± 2.2)	-	-
Theory	PDF+α_S	±2.3 (±2.3)	±3.1 (± 3.3)	n/a	n/a
	Scale	+4.3 (+4.3)	+4.9 (+ 5.3)	n/a	n/a
		−6.0 (−6.0)	+7.0 (+ 8.0)	n/a	n/a
	EFT	±5.0 (±5.0)	n/a	n/a	n/a



Photons		Jets	
Variable	Selection	Variable	Selection
$p_T^{\gamma 1}$	$>m_{\gamma\gamma}/3$	p_T [GeV]	$>25.$
$p_T^{\gamma 2}$	$>m_{\gamma\gamma}/4$	$\Delta R_{\gamma j}$	>0.4
$\lvert\eta\rvert$	<2.5	$\lvert\eta\rvert$	<2.4
$m_{\gamma\gamma}$ [GeV]	$[100, 180]$	m_{jj} [GeV]	$[70, 190]$

Analysis	Region	Classification MVA	$\tilde{M}_X$
Nonresonant	High-mass	HPC: MVA > 0.97 MPC: $0.6 <$ MVA < 0.97	$\tilde{M}_X > 350$ GeV
	Low-mass	HPC: MVA > 0.985 MPC: $0.6 <$ MVA < 0.985	$\tilde{M}_X < 350$ GeV

CMS Search in $\gamma\gamma$bb [arXiv:1806.00408]

Sources of systematic uncertainties	Type	Value (%)
Integrated luminosity	Normalization	2.5
Photon related uncertainties		
Diphoton selection (with trigger uncertainties and PES)	Normalization	2.0
Photon identification	Normalization	1.0
PES ($\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}}$)	Shape	0.5
PER ($\frac{\Delta \sigma_{\gamma\gamma}}{\sigma_{\gamma\gamma}}$)	Shape	5.0
Jet related uncertainties		
Dijet selection (JES+JER)	Normalization	0.5
JES ($\frac{\Delta m_{jj}}{m_{jj}}$)	Shape	1.0
JER ($\frac{\Delta \sigma_{jj}}{\sigma_{jj}}$)	Shape	5.0
Resonant analysis specific uncertainties		
Mass window selection (JES+JER)	Normalization	3.0
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Nonresonant analysis specific uncertainties		
$\widetilde{M}_X$ Classification	Normalization	0.5
Classification MVA (HPC)	Normalization	11–19
Classification MVA (MPC)	Normalization	3–9
Theoretical uncertainties in the SM single-Higgs boson production		
QCD missing orders (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	0.4–5.8
PDF and α_S uncertainties (ggH, VBF H , VH, $t\bar{t}$H)	Normalization	1.6–3.6
Theoretical uncertainty $b\bar{b}$H	Normalization	20
Theoretical uncertainties in the SM HH boson production		
QCD missing orders	Normalization	4.3–6
PDF and α_S uncertainties	Normalization	3.1
m_t effects	Normalization	5

Two-lepton selection

m_X	Channel	$\Delta R_{\ell_2 j}$	$\Delta R_{\ell_1 j}$	$m_{\ell\ell}$ [GeV]	$m_{\ell_1 jj}$ [GeV]
Non-res.	ee	[0.20, 1.40]	[0.20, 1.15]	[55, 270]	[40, 285]
	$\mu\mu$	[0.20, 1.05]	[0.20, 0.75]	[60, 250]	[30, 310]
	$e\mu$	[0.20, 1.15]	[0.20, 0.80]	[75, 250]	[35, 350]

Three-lepton selection

m_X	Variable	$N_{\text{SFOS}} = 0$	$N_{\text{SFOS}} = 1,2$
Non-res.	$\Delta R_{\ell_2\ell_3}$	[2.47, 5.85]	[2.16, 3.50]
	$m_{\ell_2\ell_3}$ [GeV]	[10, 70]	[10, 70]
	$m_{\ell_3 jj}$ [GeV]	[50, 110]	[50, 115]
	$m_{\ell_3 j}$ [GeV]	[15, 50]	[15, 45]

Four-lepton selection

Event selection in the four lepton channel	
4 leptons with $p_T > 10$ GeV and $\sum q_i = 0$	
Trigger	
Trigger matched lepton	
$p_T^{\ell_{\text{matched}}} > 22, 25, 27$ GeV (depending on data period trigger)	
$m_{\ell\ell} > 4$ GeV (for all SFOS pairs)	
$N_{b\text{-tag}} = 0$	
$m_{\ell_0\ell_1} > 10$ GeV	
N_{SFOS} = 0,1 selection	
$\lvert m_{\ell_2\ell_3} - m_Z \rvert > 5$ GeV	
$m_{4\ell} < 180$ GeV	**$m_{4\ell} > 180$ GeV**
N_{SFOS} = 2 selection	
$m_{\ell_2\ell_3} < 70$ GeV, $m_{\ell_2\ell_3} > 110$ GeV	
$m_{4\ell} < 180$ GeV	**$m_{4\ell} > 180$ GeV**
$\Delta\phi_{\ell_2\ell_3} < 2.6$ rad	$m_{\ell_0\ell_1} < 70$ GeV, $m_{\ell_0\ell_1} > 110$ GeV