Search for Di-Higgs Production at ATLAS

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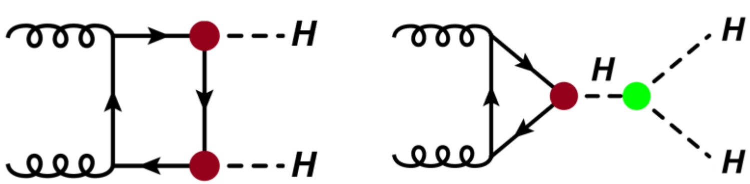
Higgs self coupling

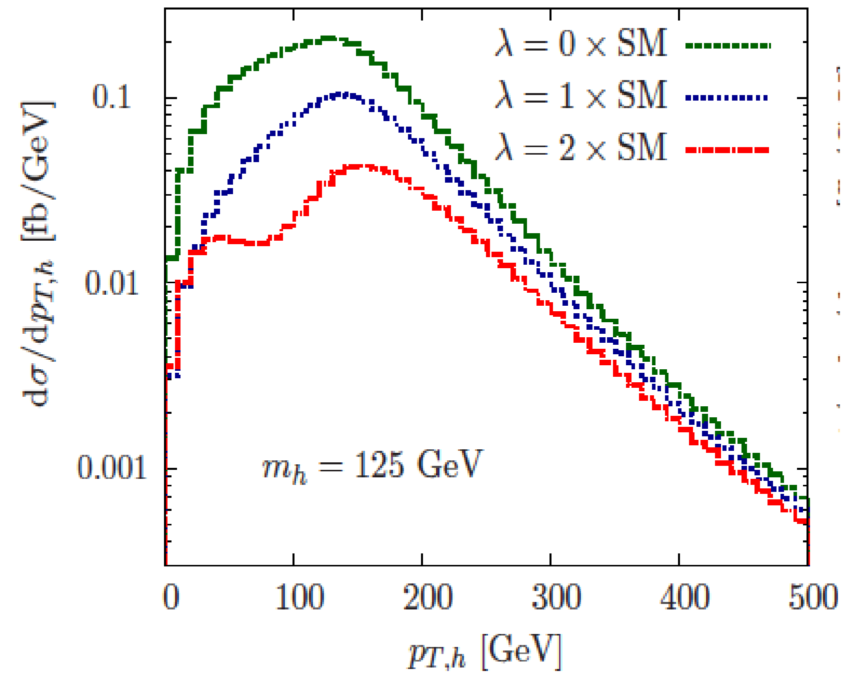
- Di-Higgs makes possible measurement of Higgs self coupling and hence fully reconstruct Higgs potential: $\phi \rightarrow v + h$

$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 = \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

mass term　self coupling terms

- Destructive interference between diagrams reduces cross section

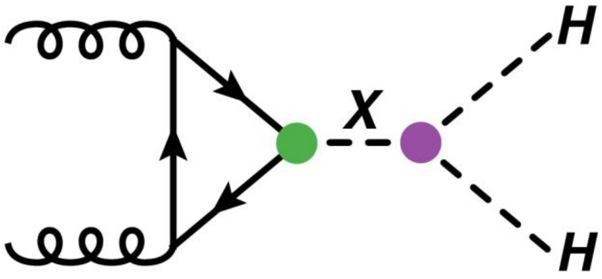




- Measurements of $p_T(H)$ can enhance sensitivity to λ
- Rare process: 33.4 fb^{-1} at 13 TeV

BSM Resonant Higgs Pair Production

Possible production process



- Various models expect a new particle decaying into a Higgs boson pair
- Can reconstruct each Higgs boson and di-Higgs resonance
- Randall-Sundrum graviton (spin 2) $G \rightarrow HH$
- 2HDM CP-even heavy Higgs boson $\mathrm{X} \rightarrow HH$

Which decays?

High branching fractions

Precise $H \rightarrow \gamma\gamma$ mass reconstruction

HH Decay Fractions

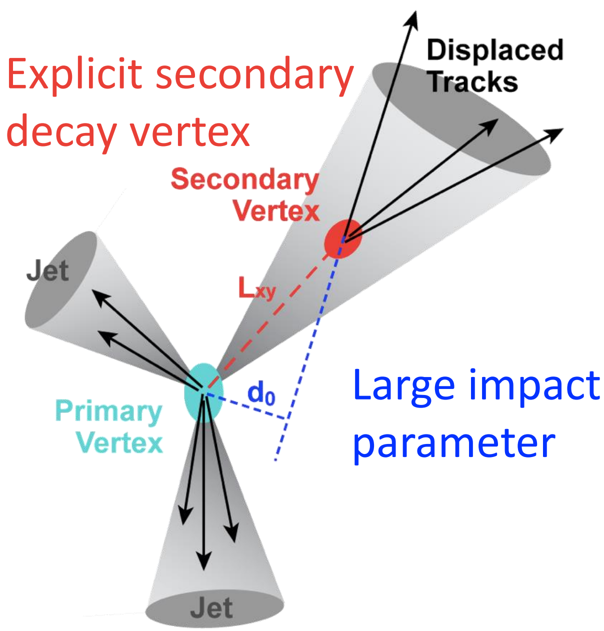
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0005%

Run 1 Results:

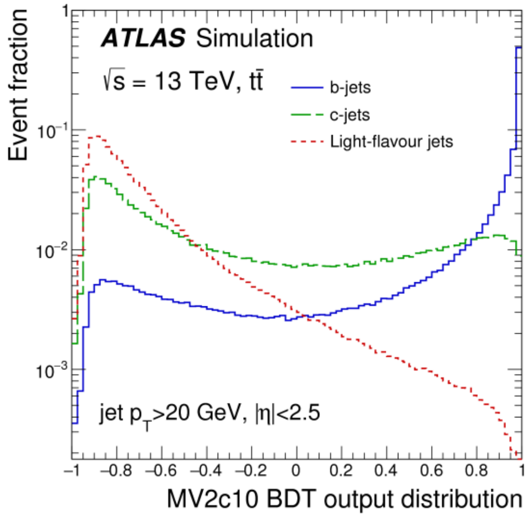
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

b tagging

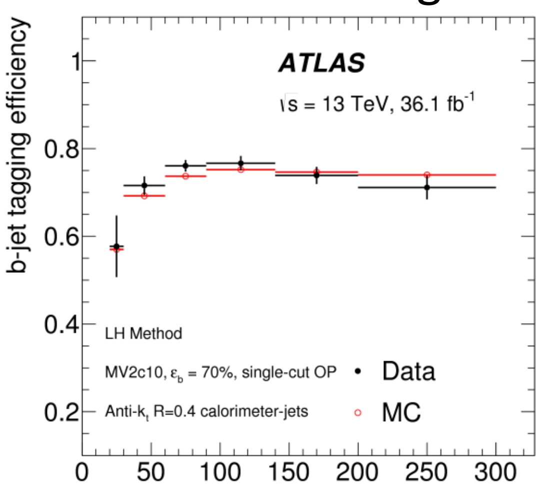
- b-Hadrons decay with a lifetime of cτ ≈ 450μm
- Secondary vertex and lifetime-based ID
- Information combined using MVA algorithms



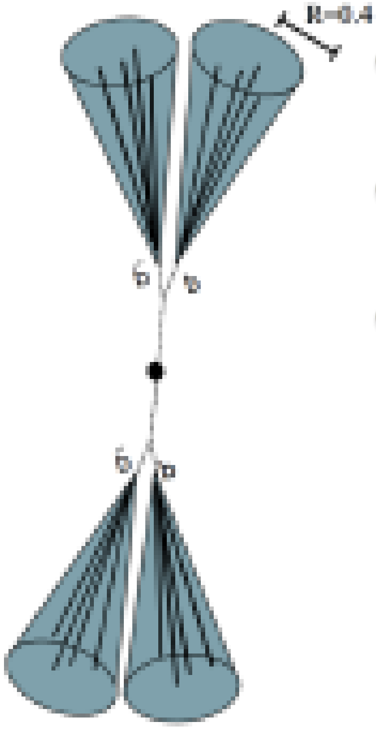
Excellent light and charm rejection



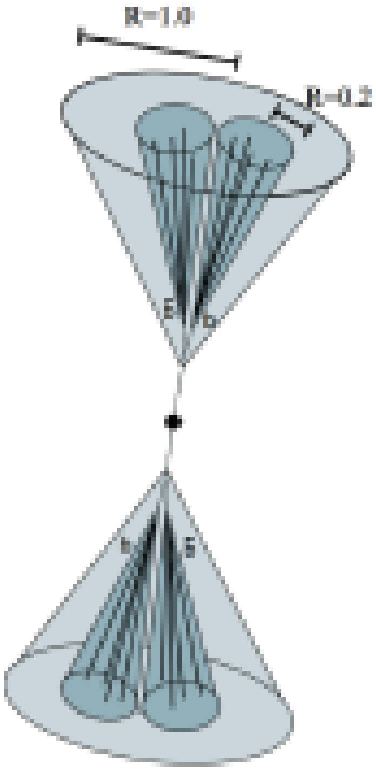
Efficiency measured in situ using $t\bar{t}$ events



HH → bbbb

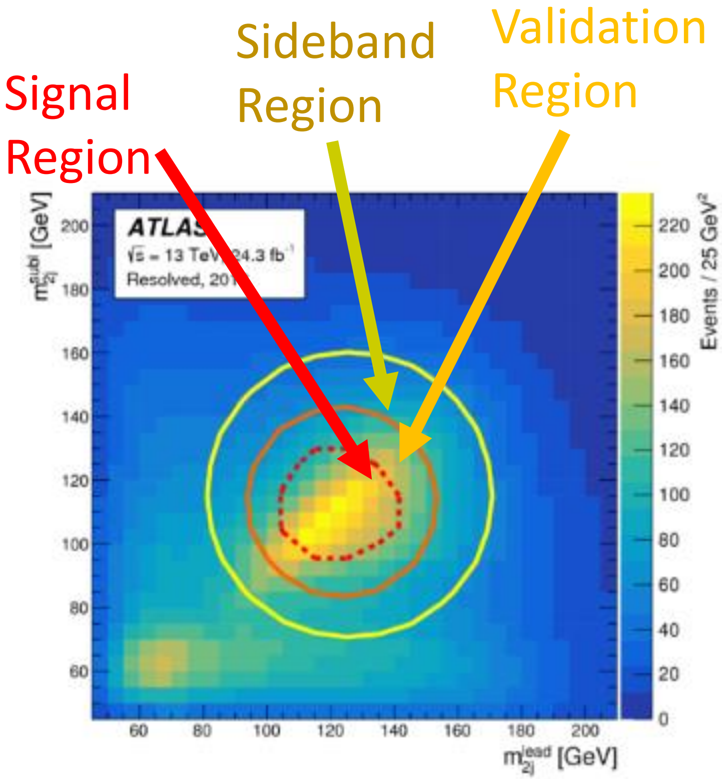


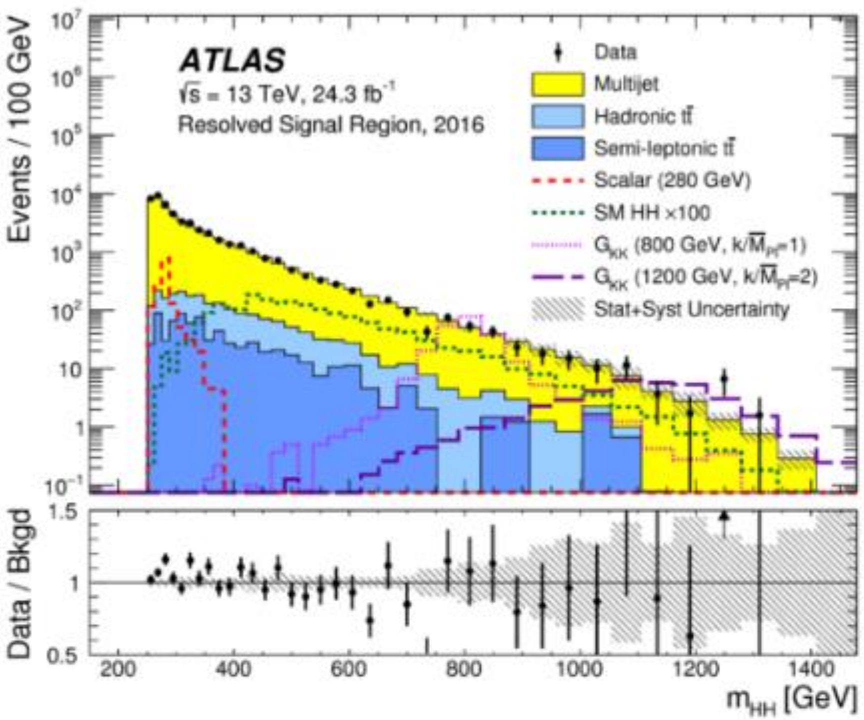
- Data split into resolved and boosted regions
- b jet triggers for resolved and fat-jet trigger for boosted
- Resolved region ($260 < M < 1400$ GeV) has 4 clearly separated b tagged R=0.4 jets
- Boosted region ($800 < M < 3000$ GeV) has 2 R=1.0 fat-jets each containing 1 or 2 tagged R=0.2 track-jets



HH → bbbb : Resolved Analysis

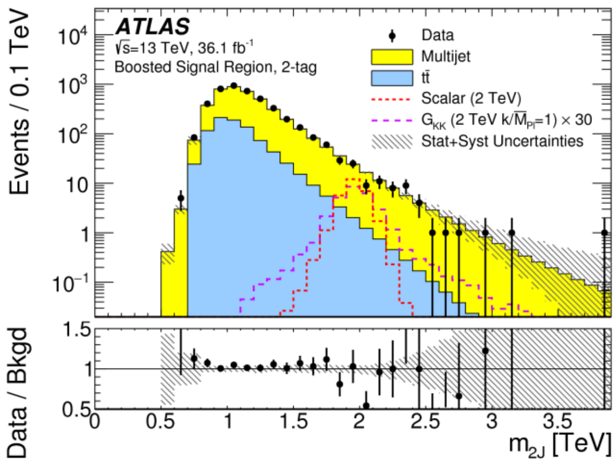
- Main multijet background taken from data using 4 jet, 2 tag events
- Weights applied by comparing 2 tag to 4 tag events in the sideband to account for different jet multiplicities and b-tagging efficiency
- Validation region used for checking background modelling

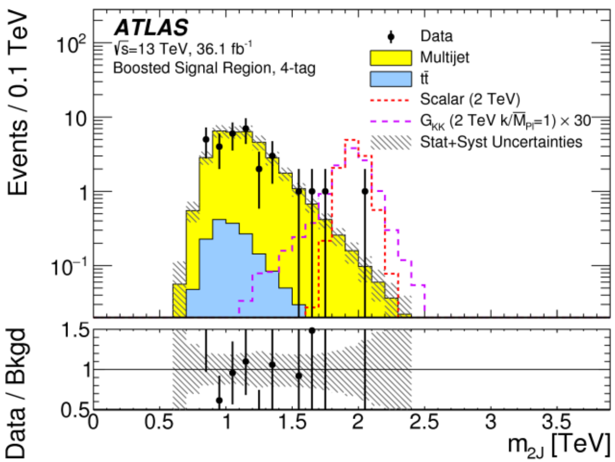


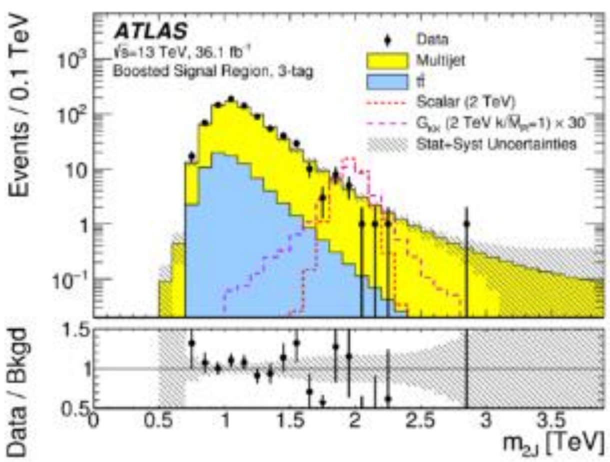


HH → bbbb : Boosted Analysis

- Multijet background taken from lower tagged samples in sideband
- Background modelling checked in the validation region
- 2,3,4 tagged signal regions



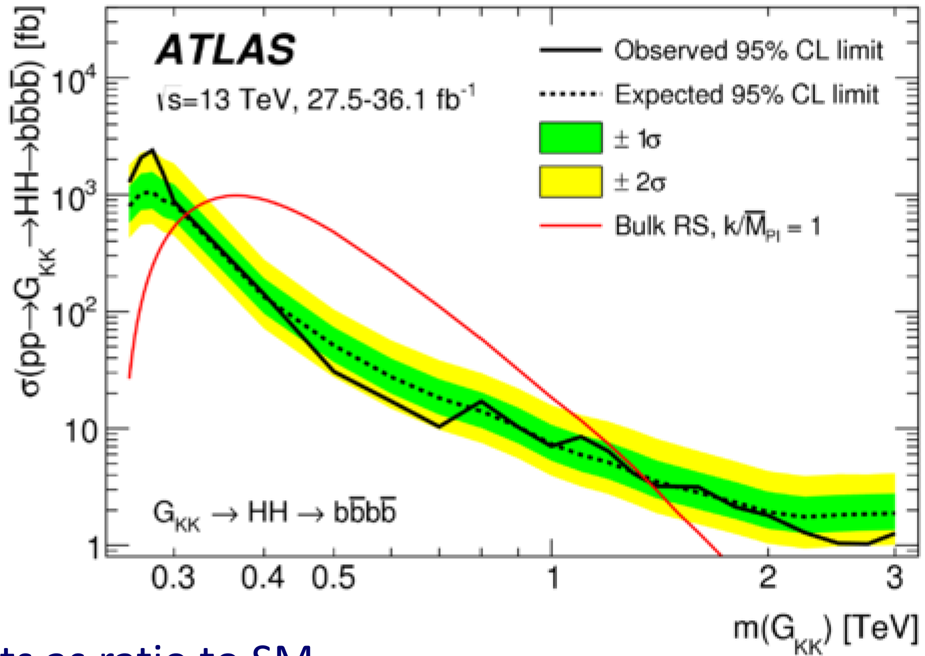




HH → bbbb

- No clear excess observed
- Largest deviation for resonant search is 3.6σ local significance at M=280 GeV (2.3σ global)
- Slightly tighter limits on non-resonant limits than expected.

Resonant

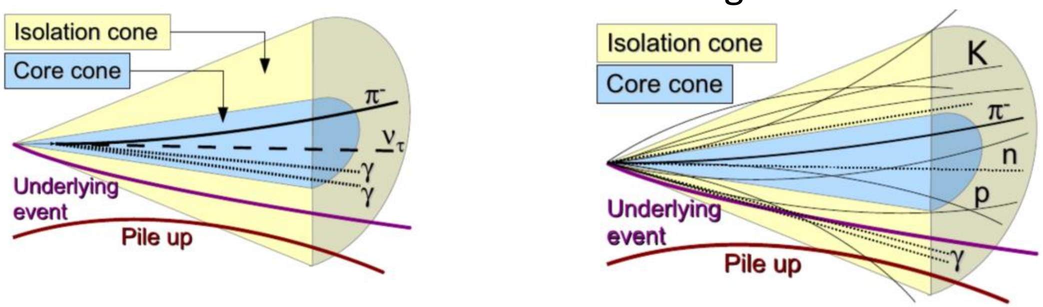


Not resonant. 95% CL limits as ratio to SM

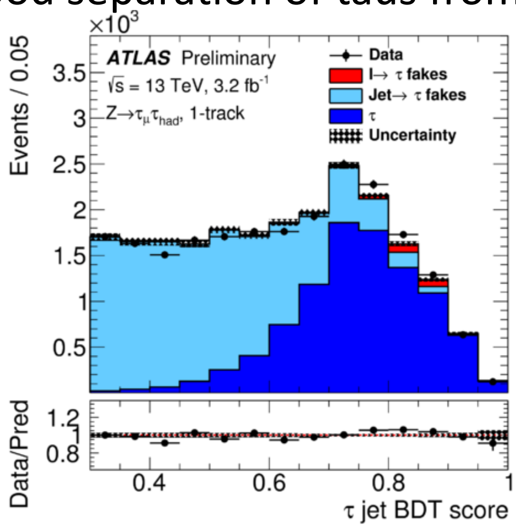
Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
13.0	11.1	14.9	20.7	30.0	43.5

Tau tagging

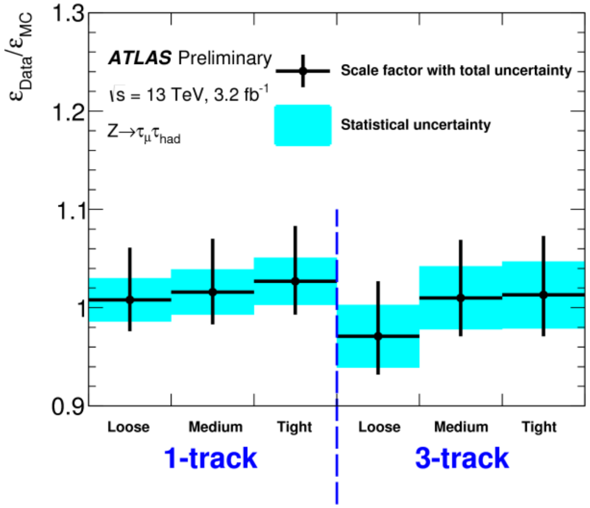
- Hadronic τ id based on
  - collimated jet
  - 1 or 3 tracks
  - Both EM and Had energy
- In situ calibration using Z and events with τs
- Probability of misidentifying jets as τs also measured from data



Good separation of taus from background



Data/MC scale factors

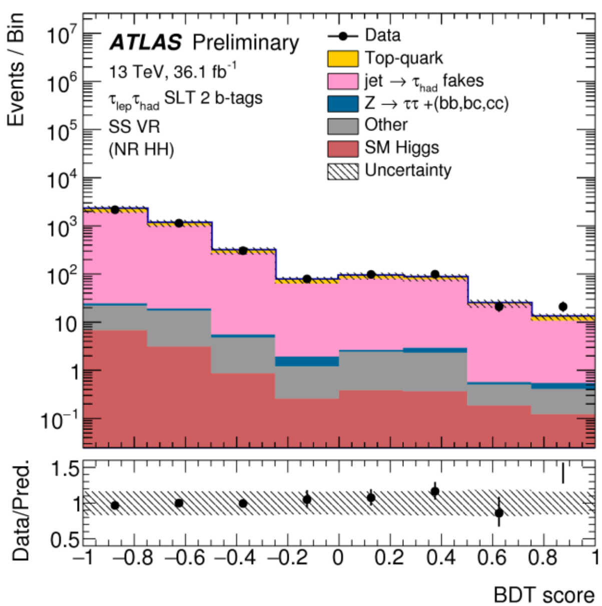


HH → bbττ

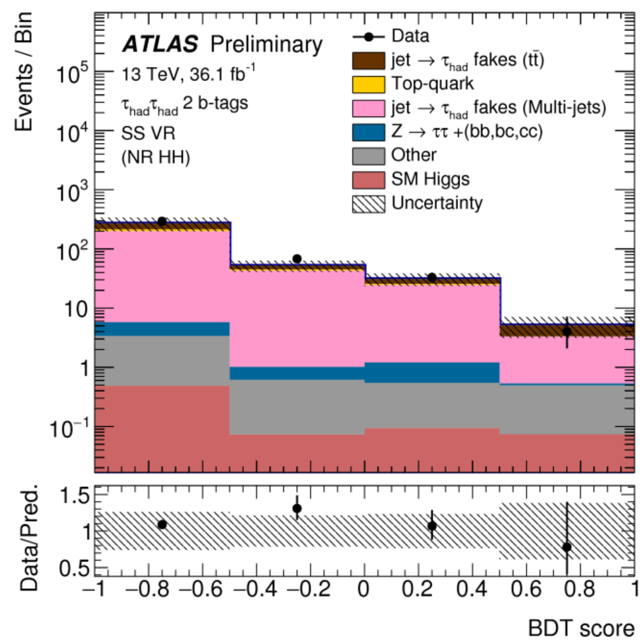
New

- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels analysed
- Major background from $t\bar{t} \rightarrow b\tau\nu b\tau\nu$ taken from Monte Carlo
- $t\bar{t}$ background with jets faking τs taken from data ($\tau_{lep}\tau_{had}$) or from Monte Carlo corrected for jet to τ fake rate as measured from data ($\tau_{had}\tau_{had}$).
- Validate fake τ treatment by looking at same sign control regions
- $Z \rightarrow \tau\tau$+heavy flavour Monte Carlo normalised on $Z \rightarrow \mu\mu$+heavy flavour control region
- Combine kinematic information using boosted decisions trees (next slide)

Same Sign $\tau_{lep}\tau_{had}$

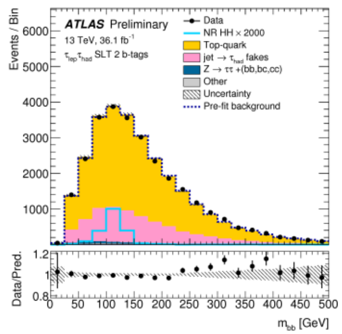


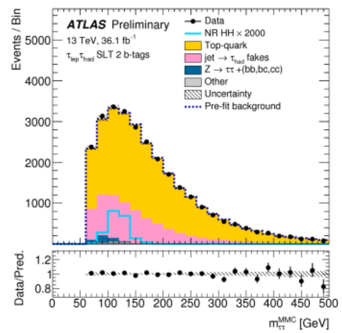
Same Sign $\tau_{had}\tau_{had}$

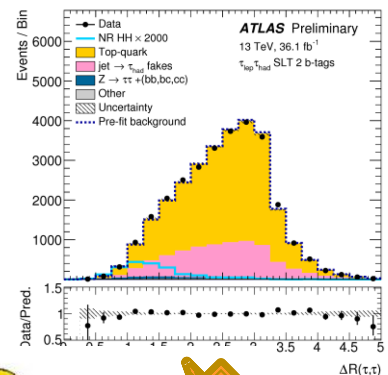


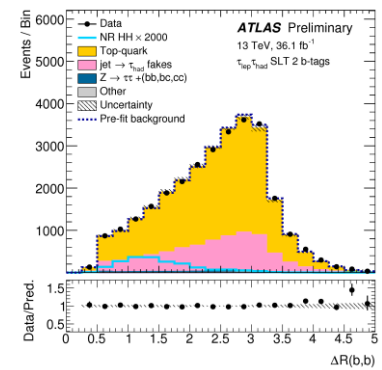
HH → bbττ: Boosted Decision Tree (BDT)

- Combine masses, E_T^{miss} + angular variables to discriminate signal and background

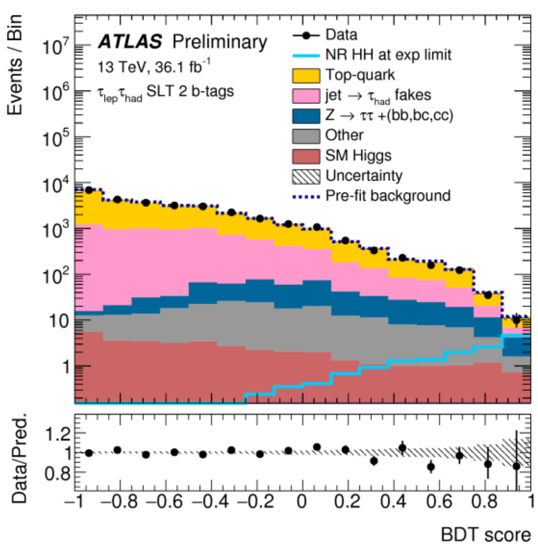


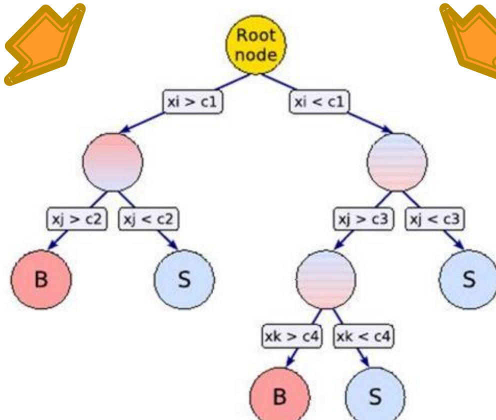




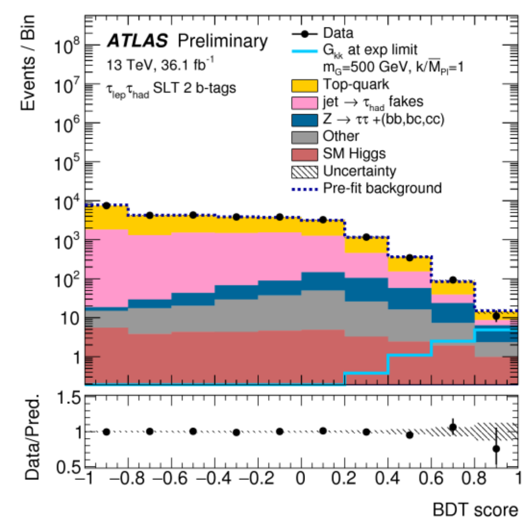


Non-resonant





Resonant e.g. G(500)

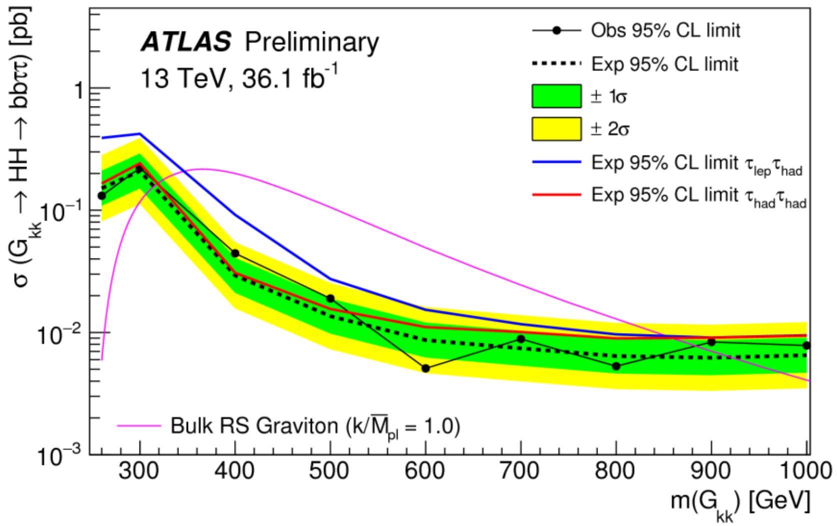


Different training for each mass + non-resonant

HH → bbττ : Results

New

- No excess seen in either channel
- Rules out a wide parameter space in BSM models
- Non-resonant limit is the best individual channel to date

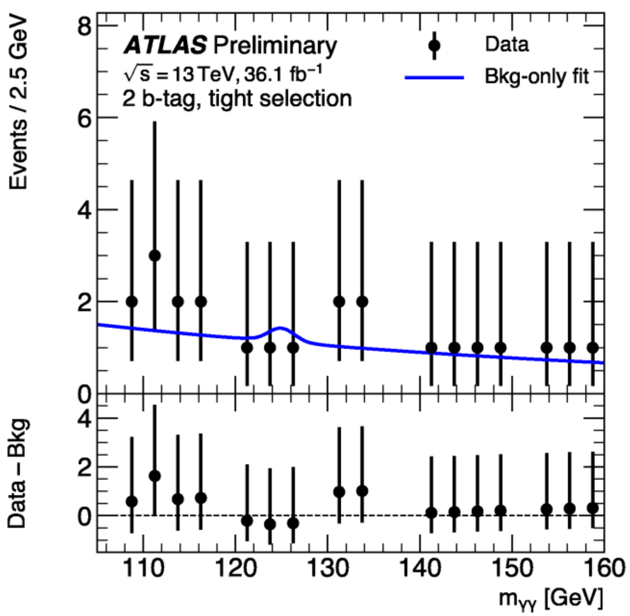


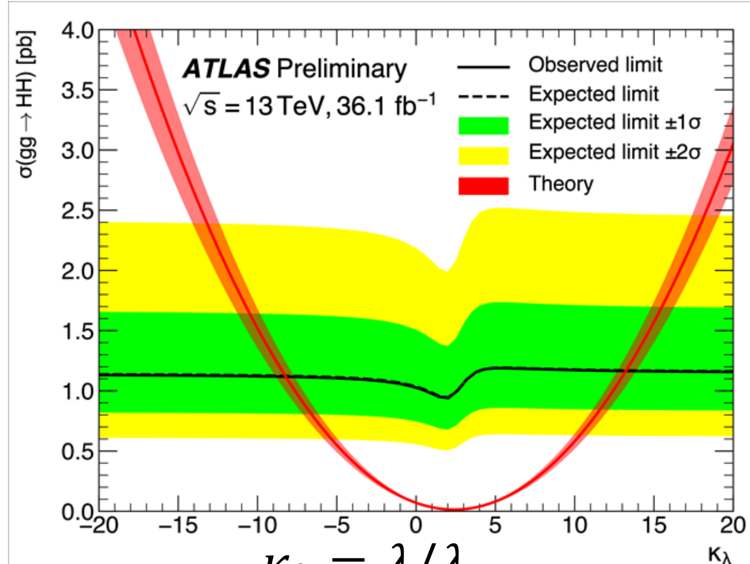
Non Resonant limit

		Observed	-1σ	Expected	$+1\sigma$
$\tau_{lep}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	57.3	49.9	69.2	96.3
	σ/σ_{SM}	23.5	20.5	28.4	39.5
$\tau_{had}\tau_{had}$	$\sigma(HH \to bb\tau\tau)$ [fb]	39.9	30.5	42.4	59.0
	σ/σ_{SM}	16.4	12.5	17.4	24.2
Combination	$\sigma(HH \to bb\tau\tau)$ [fb]	30.9	26.0	36.0	50.1
	σ/σ_{SM}	12.7	10.7	14.8	20.6

HH → bbγγ

- 2 photons +2 jets (1 or 2 b-tags)
- Parameterised fit to data distribution to obtain limits
- Set limits on resonant + non-resonant production
- Also set limits on Higgs self coupling
- No significant excess seen
- Observed non-resonant limit 22× SM (28 expected)



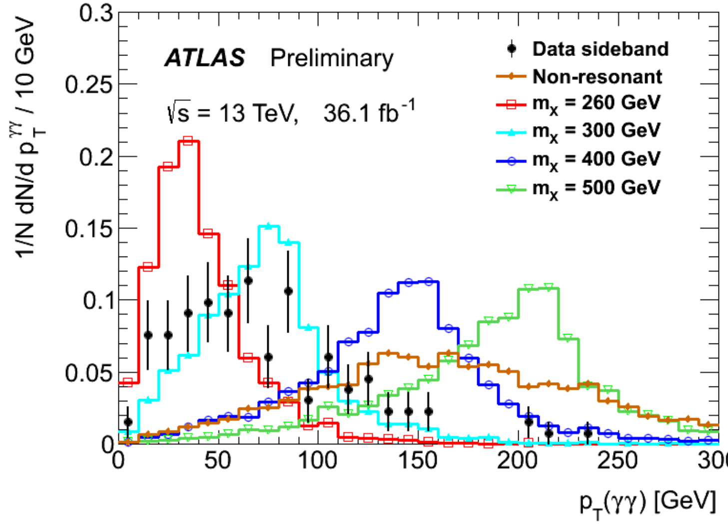


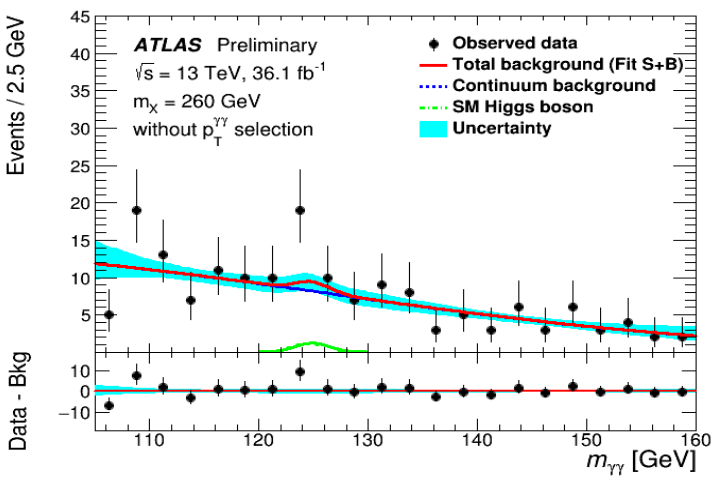
$$\kappa_\lambda = \lambda/\lambda_{SM}$$

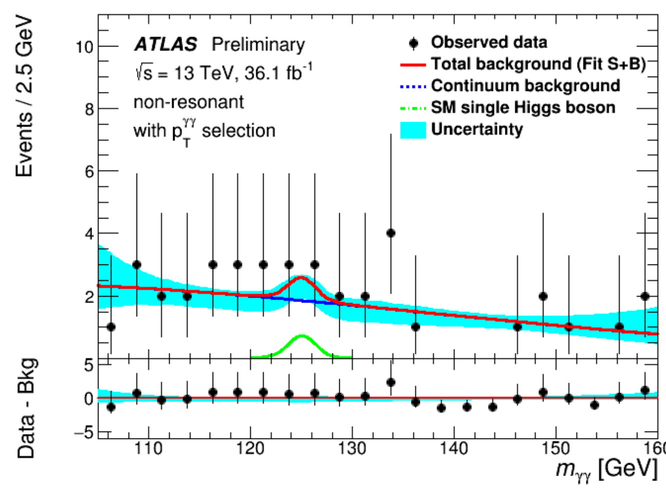
$-8.2 < \kappa_\lambda < 13.2$ @ 95% CL

HH → γγWW*

- 2 photons +1 e or μ + 2 jets
- Parameterised fit to data distribution to obtain limits
- $p_T^{\gamma\gamma} > 100$ GeV for non-resonant and higher mass search
- No significant excess seen
- Observed non-resonant limit 230× SM (160 expected)







Summary

- Searches presented of di-Higgs production in 4 channels using 13 TeV data
- Best limit on non-resonant production is 13 × the SM
- Plenty more results to come → 3-4 × more data from Run II (2017+2018)