Higgs boson measurements in couplings to τ leptons with the ATLAS experiment

Chris Young, Freiburg

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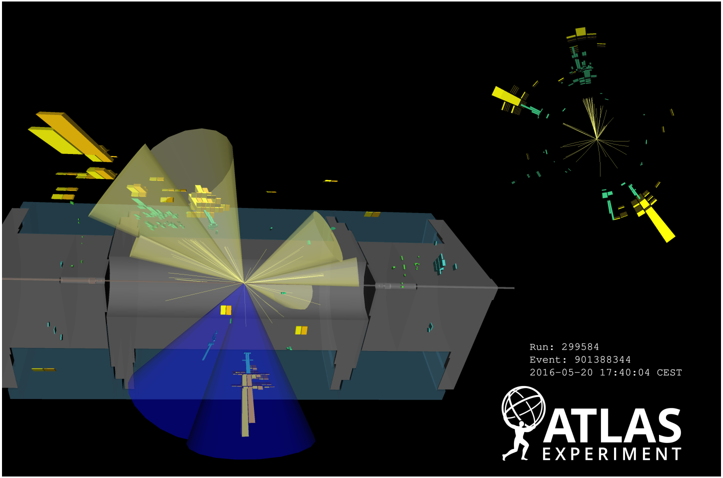
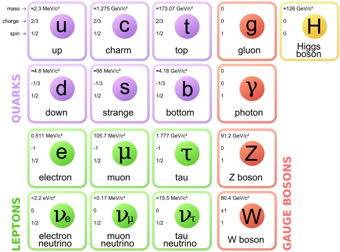


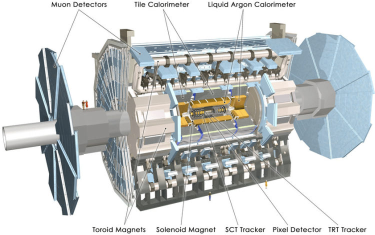
Introduction: The Higgs Boson

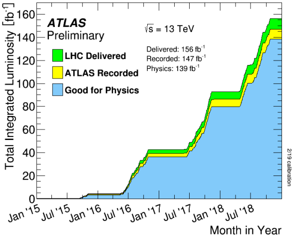
- In 2012 ATLAS and CMS discovered a new boson consistent with the predicted Higgs boson.
- Studying the properties of this new fundamental particle has been a focus of the experiments.
- Measuring the coupling to leptons is an important test of the Higgs mechanism – easiest with τ-leptons.
- $H \to \tau\tau$ – high branching fraction, distinctive signal $\to$ probe production mechanism.



The ATLAS Detector and Datasets

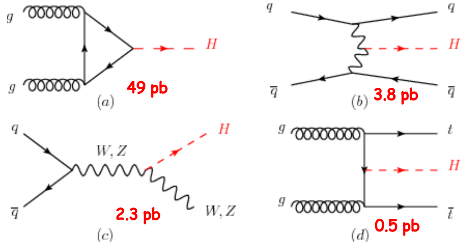
- The ATLAS detector covers nearly the entire solid angle around the collision point and is designed to accurately reconstruct the interacting particles using a inner tracking system, EM and hadronic calorimeters and a muon spectrometer.
- Additionally ($E_{\mathrm{T}}^{\mathrm{miss}}$) can be inferred from an imbalance of visible particles in the transverse plane.
- Run 2; 2015–2018, $\sqrt{s} = 13$ TeV, 139fb^{-1}of data recorded for data analysis.
- The coupling measurement shown here uses this full dataset with some of the later results using a partial dataset while full dataset analyses are still ongoing.

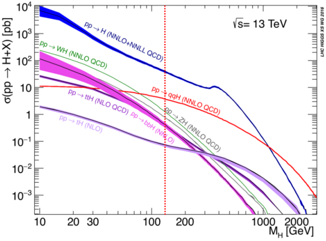




Higgs Production at the LHC

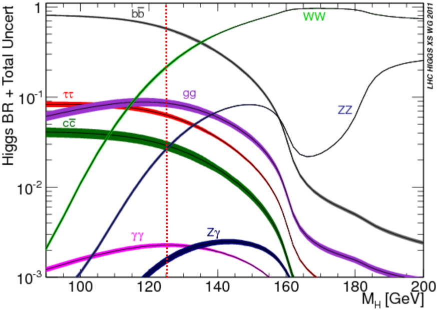
- There are 4 main production mechanisms of the Higgs boson at the LHC.
  1. Gluon-gluon fusion: this has the highest cross-section.
  2. Vector-boson-fusion: characterised by two jets with large $\Delta\eta$, m_{jj}
  3. V-H associated production: a W-boson or Z-boson is present.
  4. ttH production: a $t\bar{t}$ pair is present.
- Measuring all of these independently is an important test of the SM.





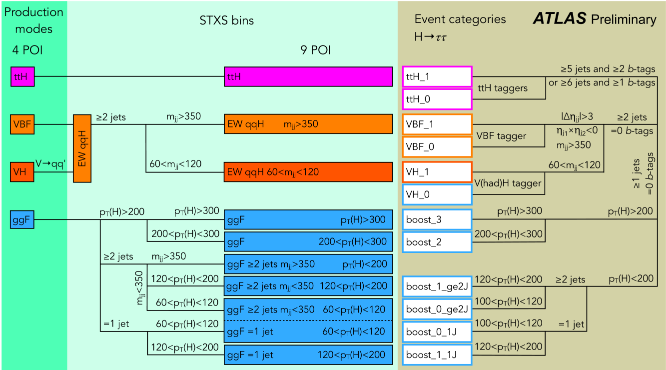
Higgs Boson Decay Channels

- At 125 GeV the Higgs decays to a wide variety of channels.
- 58% of the time it decays to $b\bar{b}$, 2.9% to $c\bar{c}$ and 8.2% to gg but these are very difficult to measure inclusively due to the large backgrounds.
- 21% and 2.6% of the time it decays to WW and ZZ respectively.
- The branching ratio to $\gamma\gamma$ is 0.23% but this is a very distinctive signal.
- **6.27% is the branching ratio to $\tau\tau$.**



STXS (simplified template cross-section) Framework

- We want to test the SM in different phase space as well as production modes.
- The STXS framework is an agreed set of cuts between analyses, experiments and theorists to define fiducial regions so combinations of different channels, with robust coherent theory uncerts., is possible to test the SM across a wide phase space.
- The selections used in the $\tau\tau$ analsis:



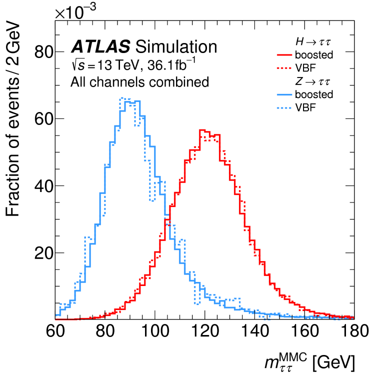
Selecting Events

- Events are selected with two τ candidates - these can either be hadronic decays identified as a τ lepton or an electron or muon, forming 3 channels: $\tau_e\tau_\mu$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$.

	$\tau_e\tau_\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$ ($\tau_e\tau_{\text{had}}$ | $\tau_\mu\tau_{\text{had}}$)	$\tau_{\text{had}}\tau_{\text{had}}$
Charge	Opposite charge	Opposite charge	Opposite charge
Kinematics	$m^{\text{coll}}_{\tau\tau} > m_Z - 25$ GeV $30\text{ GeV} < m_{e\mu} < 100$ GeV	$m_{\text{T}} < 70$ GeV	
b-veto	# of b-jets = 0	# of b-jets = 0	# of b-jets = 0 ($\geq$ 1 or 2 in ttH categories)
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 20$ GeV	$E_{\text{T}}^{\text{miss}} > 20$ GeV	$E_{\text{T}}^{\text{miss}} > 20$ GeV
Leading jet	$p_{\text{T}} > 40$ GeV	$p_{\text{T}} > 40$ GeV	$p_{\text{T}} > 70$ GeV, $\lvert\eta\rvert < 3.2$
Angular	$\Delta R_{e\mu} < 2.0$ $\lvert\Delta\eta_{e\mu}\rvert < 1.5$	$\Delta R_{\ell\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\ell\tau_{\text{had-vis}}}\rvert < 1.5$	$0.6 < \Delta R_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}}\rvert < 1.5$
Coll. app. x_1/x_2	$0.1 < x_1 < 1.0$ $0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.2$	$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.4$

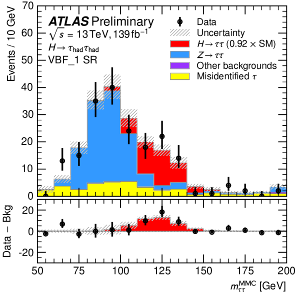
Reconstructing the Higgs Mass

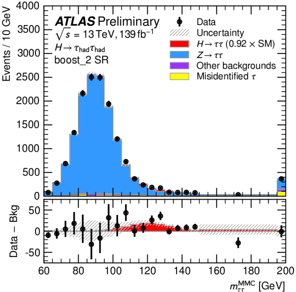
- To reconstruct the Higgs boson mass the visible τ-lepton decay products are combined with the measurement of the $E_{\mathrm{T}}^{\mathrm{miss}}$
- A likelihood fit is used taking into account the decay channels of the τ-leptons, the detector resolution and the τ kinematics to find the most likely neutrino momentum with which to form the mass. [arXiv:1012.4686]

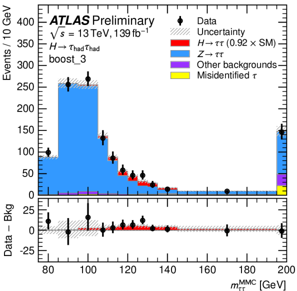


Selecting Events II

- The p_{T}^{H} and the kinematics and multiplicity of the jets in the event are used to split events into ggH (Boost), VBF, VH and ttH categories.
- Machine learning through BDTs using the kinematics of jets, τ-leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$ is then used to split the data into purer/less pure selections in the VBF, VH and ttH categories.
- The p_{T} of the di-tau system is then used along with the number of jets to split the ggH events. The Higgs p_{T} is significantly harder than $Z \rightarrow \tau\tau$ making high p_{T} bins more sensitive.

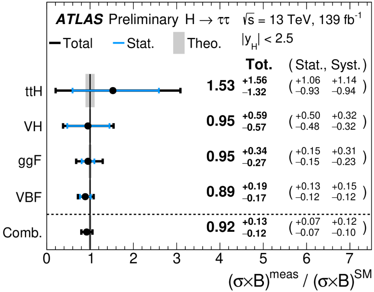






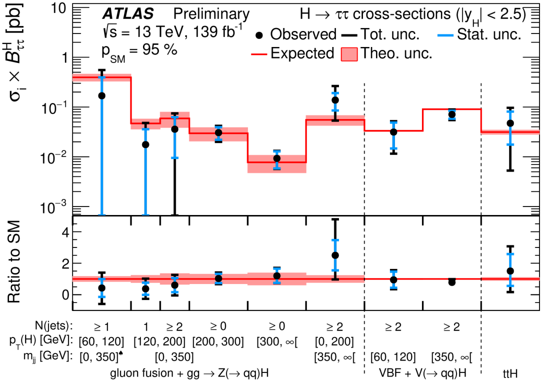
Results: Inclusive and Production Modes

- Fits are performed across the different regions in several setups with different free floating parameters.
- A 1-parameter-or-interest (PoI) fit is performed to extract an overall scaling of the cross-section with respect to the Standard Model.
- The result is found to be compatible with the SM expectation; $\sigma/\sigma_{SM} = 0.92\,^{+0.13}_{-0.12}$.
- Secondly a fit is performed to measure the different production processes separately and all are found to be compatible with the SM expectation.



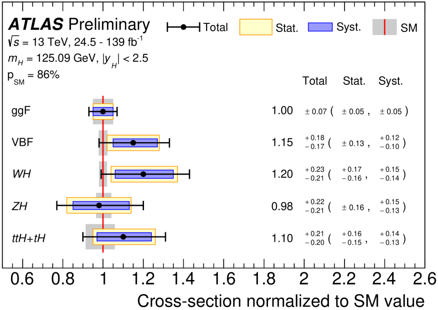
Results: STXS Framework

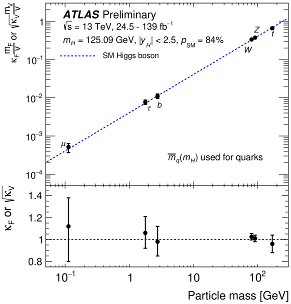
- A 9 PoI fit is used to measure the cross-section in 9 kinematic STXS bins.
- Good agreement is seen across all bins.
- The most precise values are obtained for the most kinematically extreme – high p_{T}^{H} and VBF – bins where the signal-to-background ratio is better.



The Larger Picture: Combinations

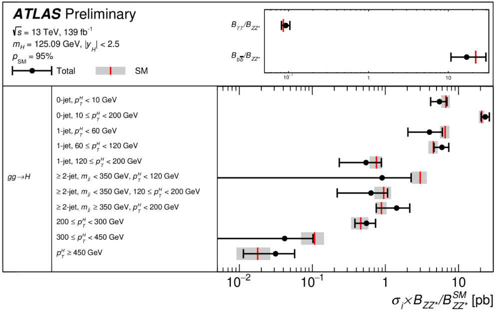
- The Higgs is measured in many decay channels; $\gamma\gamma$, ZZ, WW, $b\bar{b}$, $\tau\tau$, $\mu\mu$...
- These are then combined to give the overall picture of our understanding.
- The latest combination used the previous $\tau\tau$ results with 36fb^{-1} of data.
- Several combinations are performed allowing different free floating parameters, eg. only the different production mechanisms, or a scaling of the coupling to each of the SM particles testing the relationship between particle mass and coupling.





The Larger Picture: Combinations II

- Additionally combinations are performed in the STXS phase space bins.
- Different channels will contribute different amounts in different phases space bins.
- High p_{T}^{H}; $\tau\tau$ and $\gamma\gamma$ results are the most precise and have similar precision.
- VBF production; the latest $\tau\tau$ and WW results have similar precision.
- This shows the importance of this channel for studying Higgs production.
- New combinations will be performed with the latest results from all channels.

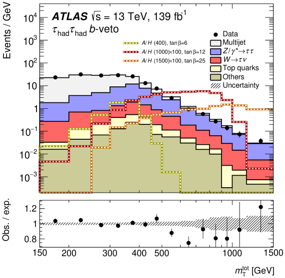


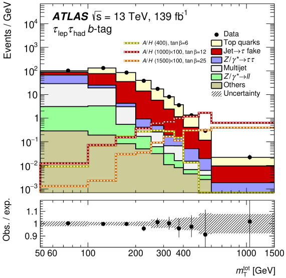
Another Higgs? $A/H \to \tau\tau$

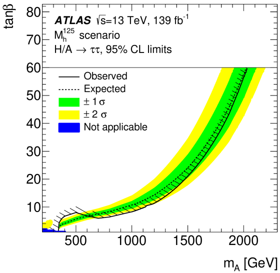
- In many models there are multiple Higgs bosons, and in a large amount of parameter space heavy A/H bosons decay to $\tau^+\tau^-$ with a large branching fractions.
- The primary variable used is;

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{(p_{\mathrm{T,vis}}^{\tau 1} + p_{\mathrm{T,vis}}^{\tau 2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T,vis}}^{\tau 1} + \mathbf{p}_{\mathrm{T,vis}}^{\tau 2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Signals are sometimes produced in associated with b-quarks so seperate *b*-tag and *b*-veto regions are used.
- Data agrees with the SM prediction and MSSM + model independent limits are set.



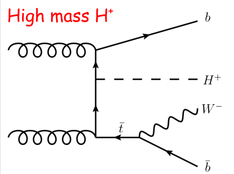


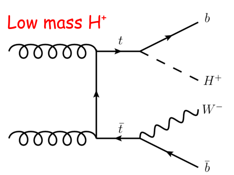


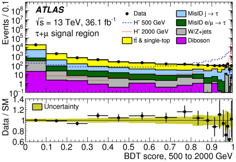
Chris Young, Freiburg

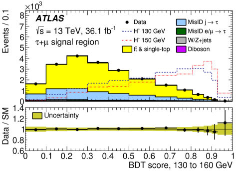
Another Higgs? $H^{\pm} \to \tau^{\pm}\nu_{\tau}$

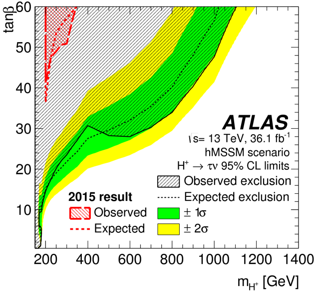
- If there is a charged Higgs then it can be produced in association with t or in t-decays.
- This can dominantly decay; $H^{\pm} \to \tau^{\pm}\nu_{\tau}$.
- A BDT is used to separate signal and background.
- Data agrees with SM prediction and limits are set.

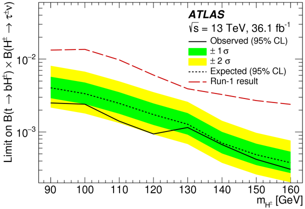






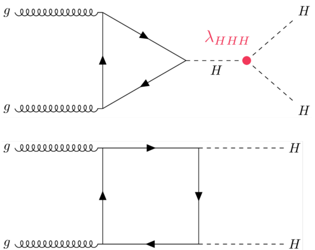


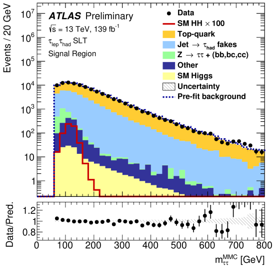


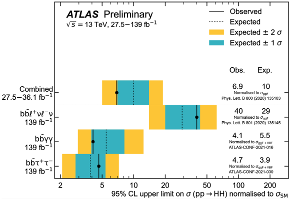


More than one Higgs in an Event? *HH* production

- Di-Higgs production is highly important to test the Higgs self coupling.
- The cross-section for this process is extremely small, 31 fb, so only $\sim$ 4300 events have been produced in ATLAS in Run II.
- The $b\bar{b}\tau^{+}\tau^{-}$ is one of the most promising channels due to its large BR and distinct signal - as the mass of both Higgs bosons can be reconstructed.
- An upper limit on the cross-section of 4.7 (3.9) times the Standard Model prediction is achieved.







Conclusions

- ATLAS has come a long way since the discovery of a new boson in 2012.
- I have shown the latest measurements of the coupling of the Higgs to τ-leptons.
- The production cross-section of $H \to \tau\tau$ is measured to 2.90 ± 0.4 pb consistent with the Standard Model prediction to within 12-13%.
- Different production mechanisms and fiducial phase space regions were also measured using this decay channel consistent with SM predictions.
- These will be important contributions to future combined Higgs measurements.
- ATLAS extensively explores the BSM Higgs sector, but no new Higgs bosons so far.
- Further results using the extensive Run 2 dataset will be released soon, and we eagerly await the larger dataset that will be taken in Run 3 which starts next year...

Links

- All ATLAS Public Results [link]
- ATLAS Higgs Public Results [link]
- $H \rightarrow \tau\tau$ coupling measurement [link]
- Higgs combination [link]
- Search for $A/H \rightarrow \tau\tau$ [link]
- Search for $H^{\pm} \rightarrow \tau\nu$ [link]
- Di-Higgs in $b\bar{b}\tau\tau$ [link]
- Di-Higgs summary plots [link]