Search for Higgs boson pair-production in the $b\bar{b}\tau^{-}\tau^{+}$ decay channel with the ATLAS detector

Higgs Couplings 2018 - Tokyo, Japan

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on behalf of the ATLAS collaboration.

ATLAS EXPERIMENT

November 28, 2018

Lancaster University

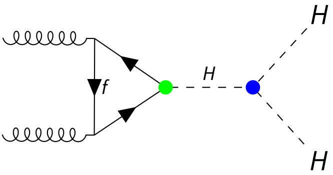
Di-Higgs Production

- Di-Higgs production at the LHC

  Gluon-gluon fusion (ggF)

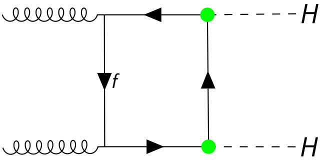
  Vector boson fusion (VBF)

  $pp \rightarrow ttHH$



σ^{SM}_{ggF} = 33.41 fb at $\sqrt{s} = 13$ TeV
(at NNLO with NLO finite top-quark mass effects)

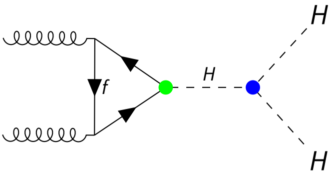
Phys. Rev. Lett. 117, 079901 (2016)



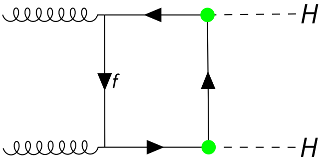
Standard Model production cross-section is small due to destructive interference among ‘box’ and ‘triangle’-diagrams

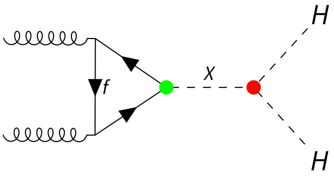
Measuring the Higgs Boson self-coupling, λ_{HHH}, will be the ultimate test of EW symmetry breaking.

Di-Higgs Production



- Beyond Standard Model (BSM) non-resonant enhancements
  - Modifications to λ_{HHH}
  - BSM **Higgs-fermion Yukawa couplings y_f**
  - Introduction of new vertices





- BSM resonant HH production models
  - Heavy Higgs $X \to HH$ (spin=0)
  - Randall-Sundrum Kaluza-Klein graviton $G_{KK} \to HH$ (spin=2)

Strong motivation for HH analyses!

Di-Higgs $\rightarrow b\bar{b}\tau\tau$

$b\bar{b}\tau^+\tau^-$ is a promising di-Higgs final state BR: 7.4%

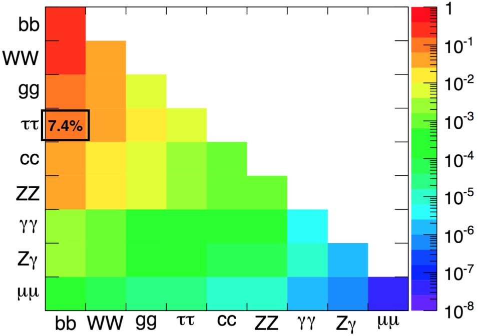
Relatively low multijet background compared to $4b$

Multiple final states considered:

Semi-leptonic $\tau_{lep}\tau_{had}$ (BR: 45.8%)

Fully-hadronic $\tau_{had}\tau_{had}$ (BR: 41.9%)

Phys. Rev. Lett. 121, 191801



Event Selection

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$\tau_{lep}\tau_{had}$

Single lepton trigger (SLT)
OR
Lepton tau trigger (LTT)

- Trigger match to either SLT or LTT
- **Electron/muon and one τ_{had}**
  taus with 1 or 3 tracks (prongs)
- Events passing **SLT**:
  Lepton $p_T > $ 25-27 GeV
  Tau $p_T > $ 20 GeV
- Events passing **LTT**:
  Electron (muon) $p_T > $ 18 GeV (15 GeV)
  Tau $p_T > $ 30 GeV
- Tau $|\eta| < 2.3$

$\tau_{had}\tau_{had}$

Single tau trigger (STT)
OR
Di-tau trigger (DTT)

- Trigger match to either DTT or STT
- **2 opposite sign (OS) τ_{had}**
  taus with 1 or 3 tracks (prongs)
- Events passing **DTT**:
  $p_T > $ 40, 30 GeV
- Events passing **STT**:
  $p_T > $ 180, 140, 100/20 GeV
- Tau $|\eta| < 2.5$ (veto 3rd tau)

b-tagging uses a 70% efficiency working point

Event Selection

$\tau_{lep}\tau_{had}$

Single lepton trigger (SLT)
OR
Lepton tau trigger (LTT)

$\tau_{had}\tau_{had}$

Single tau trigger (STT)
OR
Di-tau trigger (DTT)

Signal Region

$e/\mu + \tau_{had}$ or $\tau_{had} + \tau_{had}$
Opposite sign (OS)

Two b-tagged jets

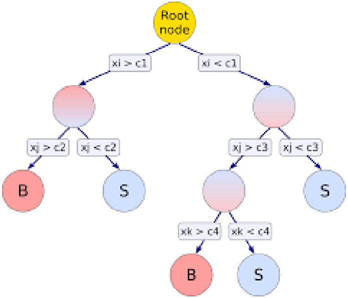
Invariant mass of the di-tau system
(reconstructing using Missing Mass Calculator (MMC) Ref.)
mMMC $>$ 60 GeV

36.1 fb^{-1} data collected with $\sqrt{s} = 13$ TeV

Events are then inputs to a boosted decision tree classifier.

Boosted Decision Tree

- Discriminate between signal and background using a boosted decision tree (BDT).



- Utilise mass and angular variables to define a final BDT score.

  Full list given in backup

- A BDT is trained for each specific signal sample

  Resonant signals are trained with neighbouring masses to avoid missing signals between MC mass points

Validate background modelling in several control regions (CR)

e.g. selecting same-sign (SS) taus,

0 and 1-tag CRs

Background Modelling

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$\tau_{lep}\tau_{had}$ | $\tau_{had}\tau_{had}$

Top-quark background (True τ_{had})

Taken from Monte Carlo

Normalisation from data in $\tau_{lep}\tau_{had}$ low BDT score region

Fake τ_{had} ($\tau_{lep}\tau_{had}$)

Combined fake-factor method
$t\bar{t}$, W + jets and
multijet events
Data-Driven

Fake τ_{had} ($\tau_{had}\tau_{had}$)

ABCD method for
multijet events
Data-Driven

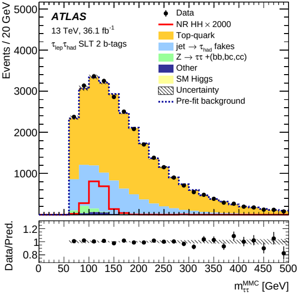
Fake τ_{had} (ttbar)

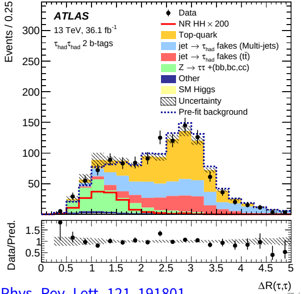
Fake-rate method
for $t\bar{t}$ processes
Data-Driven

$Z \rightarrow \tau\tau$ + heavy flavour jets

Taken from Monte Carlo

Normalisation from data in $Z \rightarrow \mu\mu$ + heavy flavour jets CR





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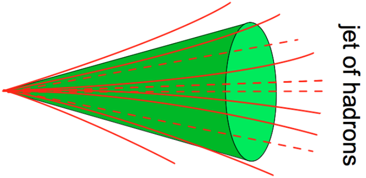
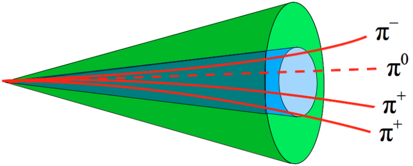
Fake τ_{had} Estimation

Jets can be reconstructed as hadronically decaying τ-leptons





- Data-driven methods are used to estimate jets $\rightarrow$ τ_{had} fakes from various processes.
- The fully hadronic channel employs an ABCD "fake factor" method for multijet processes.

Fake τ_{had} Estimation — ($\tau_{had}\tau_{had}$)

A OS ID-τ	B SS ID-τ
C OS AntiID-τ	D SS AntiID-τ

- ABCD method to estimate the multijet fake background
- Define an anti-ID region where τ-ID is inverted

$$N_A = N_C \times \frac{N_B}{N_D}$$

- Parametrised as a function of leading and sub-leading p_{T}^{τ}

$\tau_{lep}\tau_{had}$ Fake Estimation

- Combined fake factor (FF) method for jet $\rightarrow \tau$ fake background for QCD, W+jets and $t\bar{t}$

$$FF = \frac{N(\tau)}{N(anti-\tau)}$$

where the anti-τ region is defined with the tau-ID inverted

- Fake factors are calculated for each background process in separate CRs

$$FF_{comb} = FF_{QCD} \times r_{QCD} + FF_{t\bar{t}/W+jets} \times (1 - r_{QCD})$$

where r_{QCD} is the fraction of multi-jet events in the anti-τ signal region

Analysis Strategy

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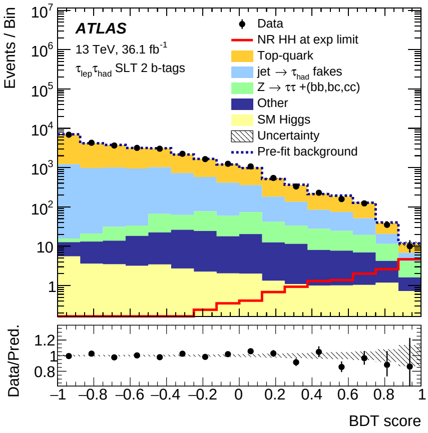
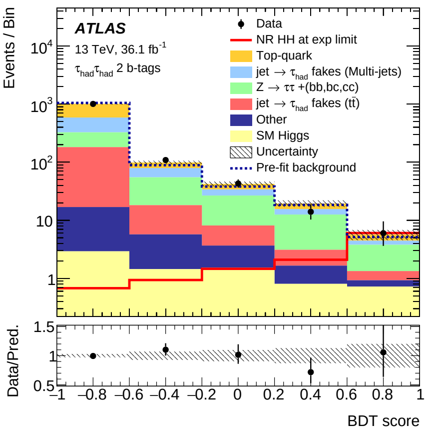
- The BDT score is used in the fitting stage as a final discriminant in three signal regions (lephad SLT, lephad LTT and hadhad STT+DTT):

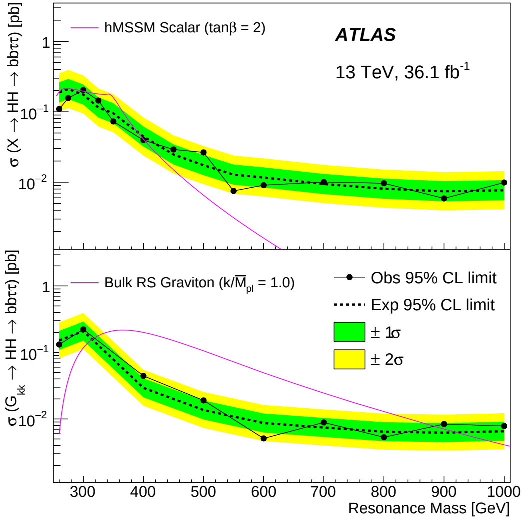




$\tau_{lep}\tau_{had}$ (SLT) $\tau_{had}\tau_{had}$

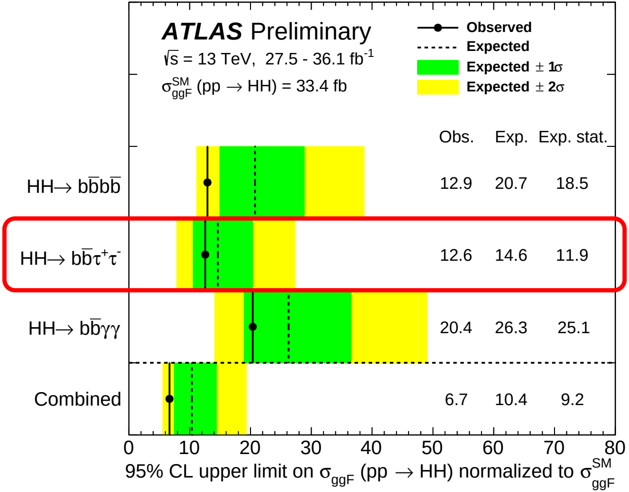
Resonant HH Production

- Observed and expected limits on $\sigma(X \to HH \to b\bar{b}\tau^+\tau^-)$ at 95% CL



Non-resonant HH Production

- Strongest single channel limit on non-resonant HH production ($\int Ldt = 36.1\ \text{fb}^{-1}$) 95% CL upper limit on σ/σ_{SM}



Higgs Self-Coupling λ_{HHH}

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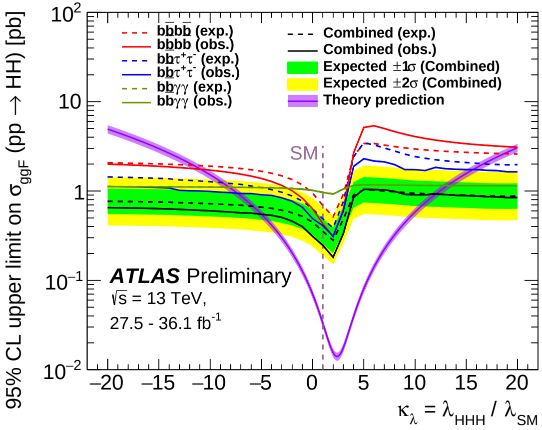

Allowed $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}$ interval		
Obs.	Exp.	Exp. Stat-Only
-7.3 — +15.7	-8.8 — +16.7	-7.8 — +15.4

Summary

- The $b\bar{b}\tau^+\tau^-$ final state is currently the most sensitive single channel for non-resonant di-Higgs production analyses.
- Combination of three most sensitive channels in ATLAS ($bb\tau\tau$, $bbbb$, $bb\gamma\gamma$) excludes *HH* production to be less than 6.7 x SM prediction.
- Work is underway to perform the analysis with the full Run-2 dataset and to introduce additional improvements.

Backup

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 $E_{\text{T}}^{\text{miss}}$	± 3.3
Electron and muon	± 0.5
Theoretical and Modeling Uncertainties	
Top	± 17
Signal	± 9.3
$Z \rightarrow \tau\tau$	± 6.8
SM Higgs	± 2.9
Other backgrounds	± 0.3

BDT Variables

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}	✓		

Variable definitions can be found in the paper