di-Higgs Production at HL-LHC with ATLAS

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Main Analysis Technique for HL-LHC

Truth+Smear Technique

- Generate truth-only 14 TeV events
- Overlay the truth information with jets from the ***pile-up library***:
  - ➡ Pile-up library consists of pile-up jets generated with full simulation (i.e. with detector response simulated)
  - ➡ $\langle\mu\rangle = 140$ or 200
- Reconstruct electron, muons, jets and missing-E_T from truth+overlay
- Smear the p_T and energy of reconstructed electrons, muons, jets and missing-E_T using appropriate ***smearing functions***
- Apply trigger efficiencies
- Apply efficiencies for electron, muon and jet reconstruction

Smearing and efficiency functions:

- dependent on p_T and η
- Functions are based on fully simulated samples samples using upgrade ATLAS detector geometry and high pile-up

- **$HH \rightarrow bbbb$ results extrapolated from Run 2 results**

Jet techniques: pile-up reduction & flavour tagging

- At $\langle\mu\rangle = 200$, 5.5 pileup jets ($p_T > 30$ GeV, $|\eta| < 2.5$) per event
- To reduce sensitivity to pile-up in jets we apply a ***track-confirmation*** requirement:
  - ➡ Jets with $p_T < 100$ GeV (not *b*-jets) must have a jet that matches with a track that comes from the primary vertex.
- Reduces pile-up by factor ~50

- Parametrised *b*-tagging run on *truth-jets*
  - ➡ Provides a 70% working point for b-tagging
  - ➡ mistag rates for light and charm jets
  - ➡ dependent on p_T and η

di-Higgs Overview

- All results for SM-like Higgs boson with $\mathbf{m_H=125\ GeV}$, i.e. decaying like SM Higgs boson
- Results used to constrain the triple Higgs coupling, λ_{HHH} and/or set limits on production
- No combined results

Analysis	Status / Publication
$ttHH,\ HH\to bbbb$	In preparation
$HH\to bb\tau\tau$	ATL-PHYS-PUB-2015-046
$HH\to bbbb$	In preperation

di-Higgs cross section

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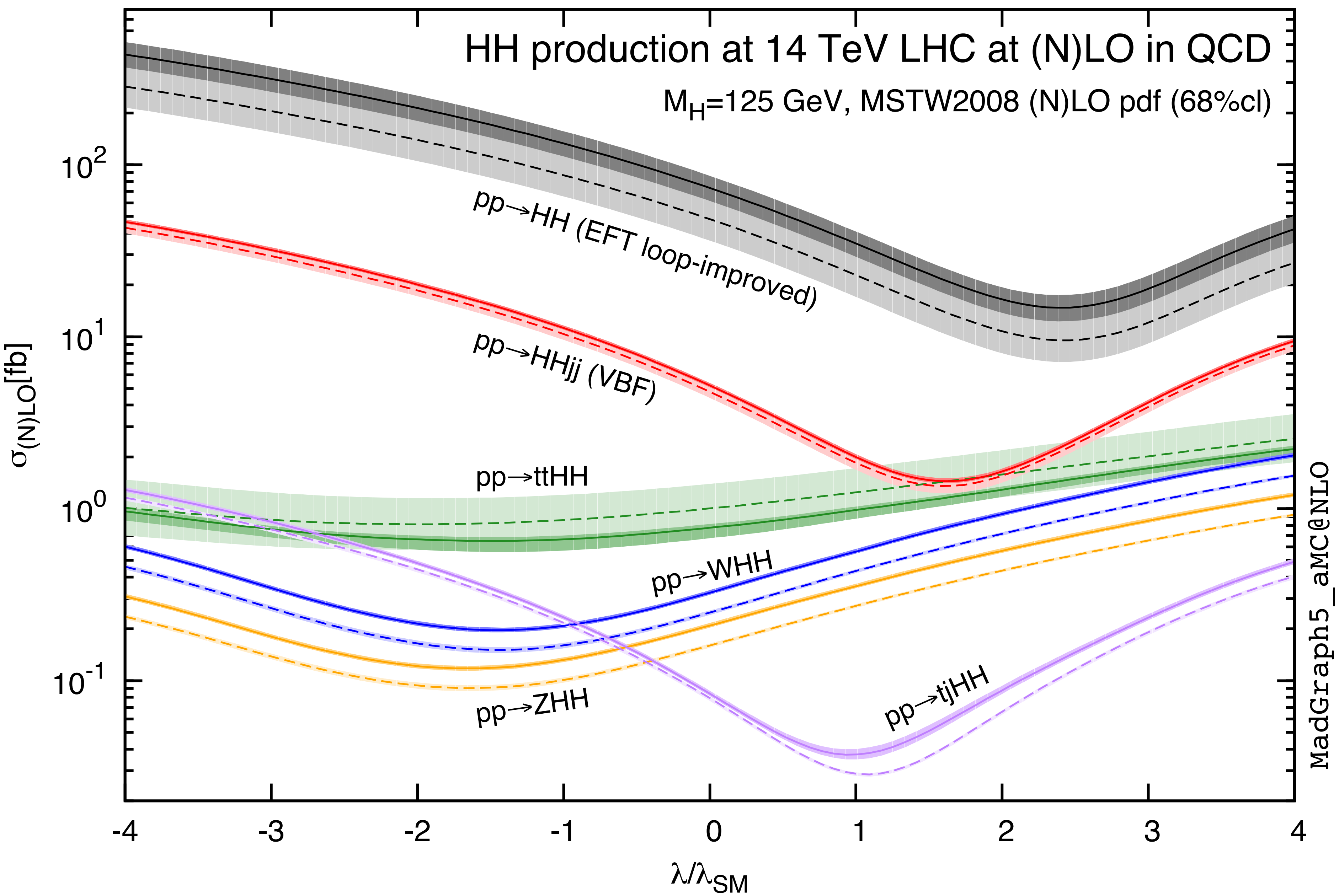

ttHH, HH→bbbb (not yet approved)

3000 fb^{-1}
$\langle\mu\rangle = 200$

- σ(ttHH) ~ 1 fb
- Use semileptonic final state of tt; single lepton trigger
- Cut-based, no cut on m(bb) due to combinatoric problems

Sample	Generator	σ (fb)	Filter	Events in 3 ab^{-1}	Events Generated
$t\bar{t}HH(HH \to b\bar{b}b\bar{b})$	MadGraph/Pythia8	0.33	-	990	20,000
$t\bar{t}b\bar{b}$ + jets	Sherpa	3750	0.52	5,850,000	6,000,000
$t\bar{t}H(H \to b\bar{b})$ + jets	Sherpa	371	0.55	612,150	600,000
$t\bar{t}Z(Z \to b\bar{b})$ + jets	Sherpa	163	0.55	268,950	300,000

Table 1: Summary of the signal and background samples used in this analysis. The backgrounds samples are generated with a filter requiring a charged lepton (e, μ or τ) with $p_T > 20$ GeV. An additional filter on the $t\bar{t}b\bar{b}$ at the a matrix element level requires b-quarks to have $p_T > 15$ GeV and $m_{bb} > 30$ GeV.

Sample	No cuts	Trigger	One lepton	≥7 jets	≥5 b-tags	$\eta(b_i, b_j)$	≥6 b-tags
$t\bar{t}HH(HH \to b\bar{b}b\bar{b})$	990	513	253	139	29	25	6
$t\bar{t}H(H \to b\bar{b})$ + jets	610,000	500,000	290,000	69,000	1,580	1,200	90
$t\bar{t}Z(Z \to b\bar{b})$ + jets	270,000	220,000	125,000	26,000	600	390	30
$t\bar{t}b\bar{b}$ + jets	5,900,000	4,800,000	2,800,000	460,000	9,700	5,500	400

Table 2: Summary of event selection criteria apply to signal and background events for 3000 fb^{-1}. The background samples are filtered to require a charged lepton with $p_T > 20$ GeV, whereas no filter was required on the signal sample; this leads to a the appearance of a smaller trigger efficiency for the signal sample. $\eta(b_i, b_j)$ refers $\langle\eta(b_i, b_j)\rangle < 1.5$ cut; this column gives the number of events in ≥ 5 b-tag selection; the final column shows the number of events in the ≥ 6 b-tag selection.

- For ≥5 b-tags: 25 signal events, 7100 background

$t\bar{t}HH$, $HH \rightarrow bbbb$ (not yet approved)

- Different background uncertainties considered:

- For ≥5 b-tags

Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{SM}$
0	6.8
5%	20.1
10%	31.7

Significance: 0.30 σ

Table 3: 95% limits on the cross section for $t\bar{t}HH$ production for the $\geq$ 5 b-tag selection, assuming different systematic uncertainties on the backgrounds. The same percentage uncertainty is applied to all the background processes considered.

- For ≥6 b-tags

Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{SM}$
0	7.8
5%	10.4
10%	15.5

Significance: 0.26 σ

Table 4: 95% limits on the cross section for $t\bar{t}HH$ production, for the $\geq$ 6 b-tag selection assuming different systematic uncertainties on the backgrounds. The same percentage uncertainty is applied to all the background processes considered.

$HH \rightarrow bb\tau\tau$

3000 fb^{-1}
<μ> = 140

ATL-PHYS-PUB-2015-046

- $\tau_{LEP}\ \tau_{LEP}$: single lepton trigger —> found to be insignificant
- $\tau_{LEP}\ \tau_{HAD}$: single lepton trigger
- $\tau_{HAD}\ \tau_{HAD}$: di-tau trigger

Table 9: Expected significance for several channel combinations, for a luminosity of 3 ab^{-1}, including the expected uncertainties quoted in the text, using the asymptotic approximation. This table only takes into account the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels.

Channel	Significance	Combined in channel	Total combined
e + jets	0.31	0.43	0.60
μ+jets	0.30		
$\tau_{\text{had}}\tau_{\text{had}}$	0.41	0.41	

Table 10: Combined significances using the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels for different assumptions on the effective coupling λ_{HHH}, assuming the systematic uncertainties as in the text.

$\lambda_{HHH}/\lambda_{\text{SM}}$	Expected Z-value
0	0.84
1	0.60
2	0.40
10	1.14

$HH \rightarrow bb\tau\tau$

3000 fb^{-1}
$\langle\mu\rangle = 140$

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- Using ~current systematics: Background uncertainty of 3% - 5%, signal uncertainty of 11%, lumi uncertainty of 3%

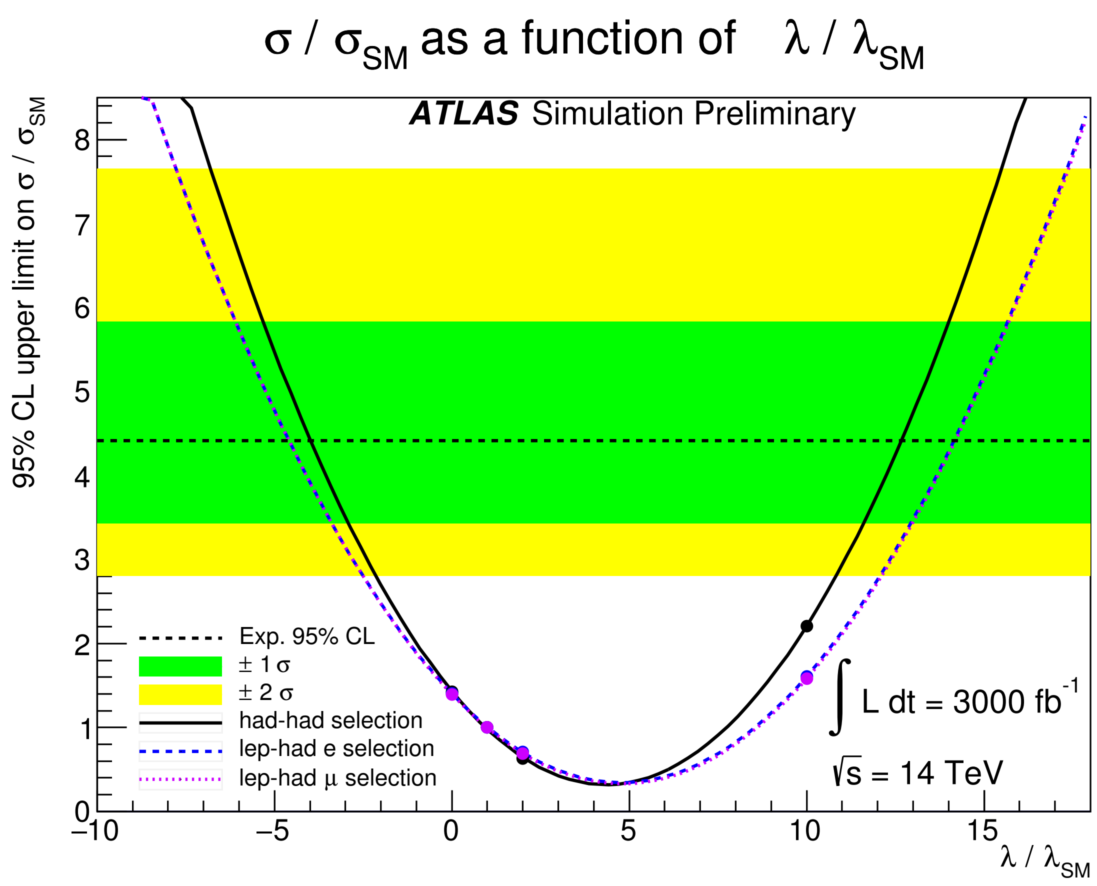


Figure 9: 95% Confidence Level upper limit on the cross section of the $HH \rightarrow bb\tau\tau$ assuming Standard Model couplings is shown in the dashed line with its 68% and 95% error bands. The solid black, dashed blue and dotted violet lines show a fit of the expected number of events normalised by the SM number of events for different λ_{HHH} after the selection for the $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$ electron and muon channels.

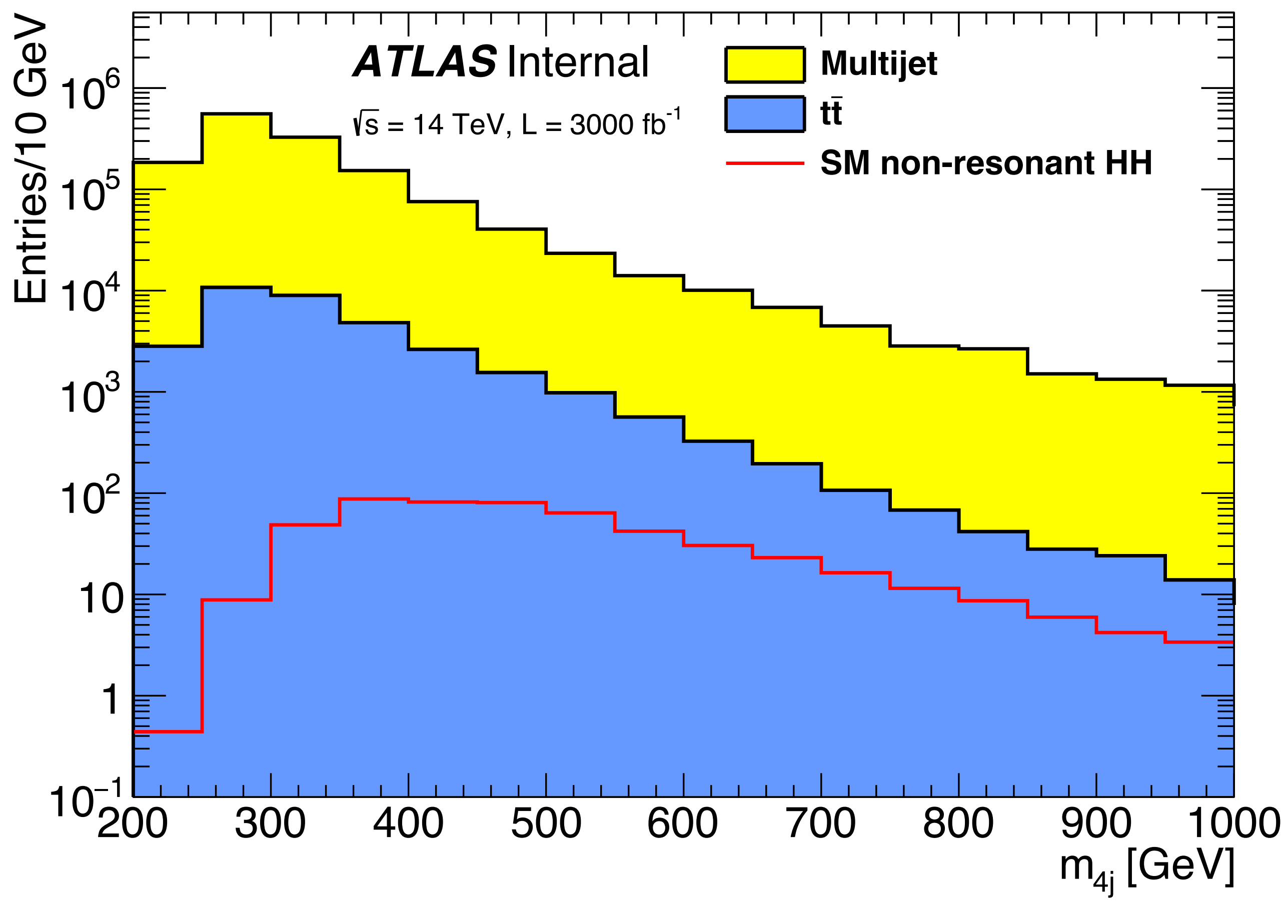
- Limit set of: $-4 < \lambda_{HHH} / \lambda_{SM} < 12$

$HH \to bbbb$ (under approval)

3000 fb^{-1}

- Background very hard to model: therefore we make an extrapolation from Run 2 results
- Assumes the Run 2 detector performance and flavour tagging
- No consideration of extra pile-up

Extrapolated templates for $\int L dt = 3000\ \text{fb}^{-1}$



$HH \to bbbb$ (under approval)

3000 fb^{-1}

Table 2: The number of predicted background events in the signal region compared to the data. The yields for SM non-resonant Higgs pair production are shown. The quoted errors include both the statistical and systematic uncertainties.

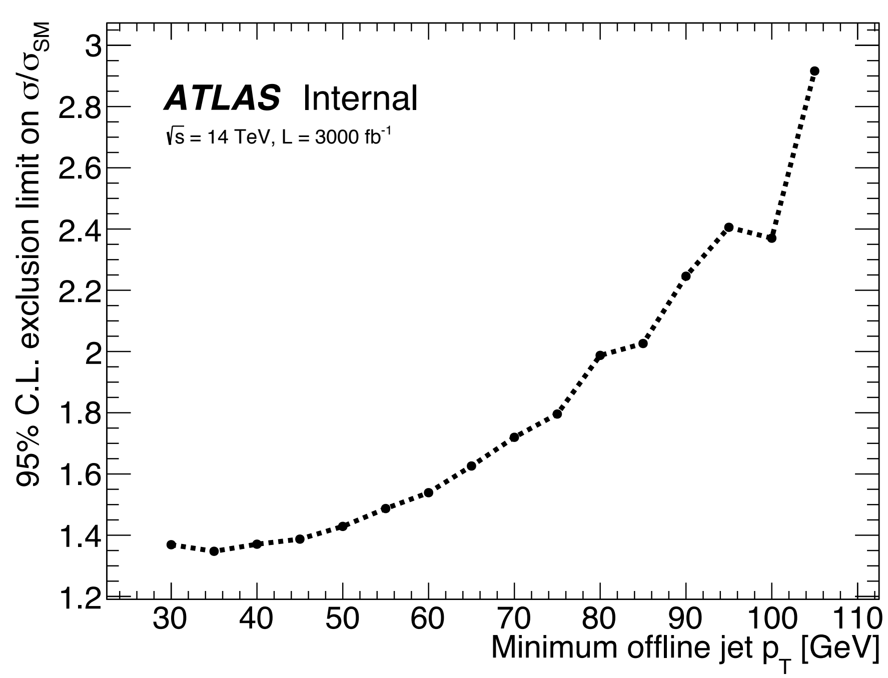
Sample	Yield
Multijet	$3\,670 \pm 200$
$t\bar{t}$	190 ± 110
Total	$3\,860 \pm 230$
Data	3990
SM hh	1.5 ± 0.4

10.1 fb^{-1}
p_T (jet) > 30 GeV

3000 fb^{-1}
450 signal
1.1 M background
$S/\sqrt{B} \sim 0.4$

- For HL-LHC, trigger will be 4 jets with p_T > 75 GeV

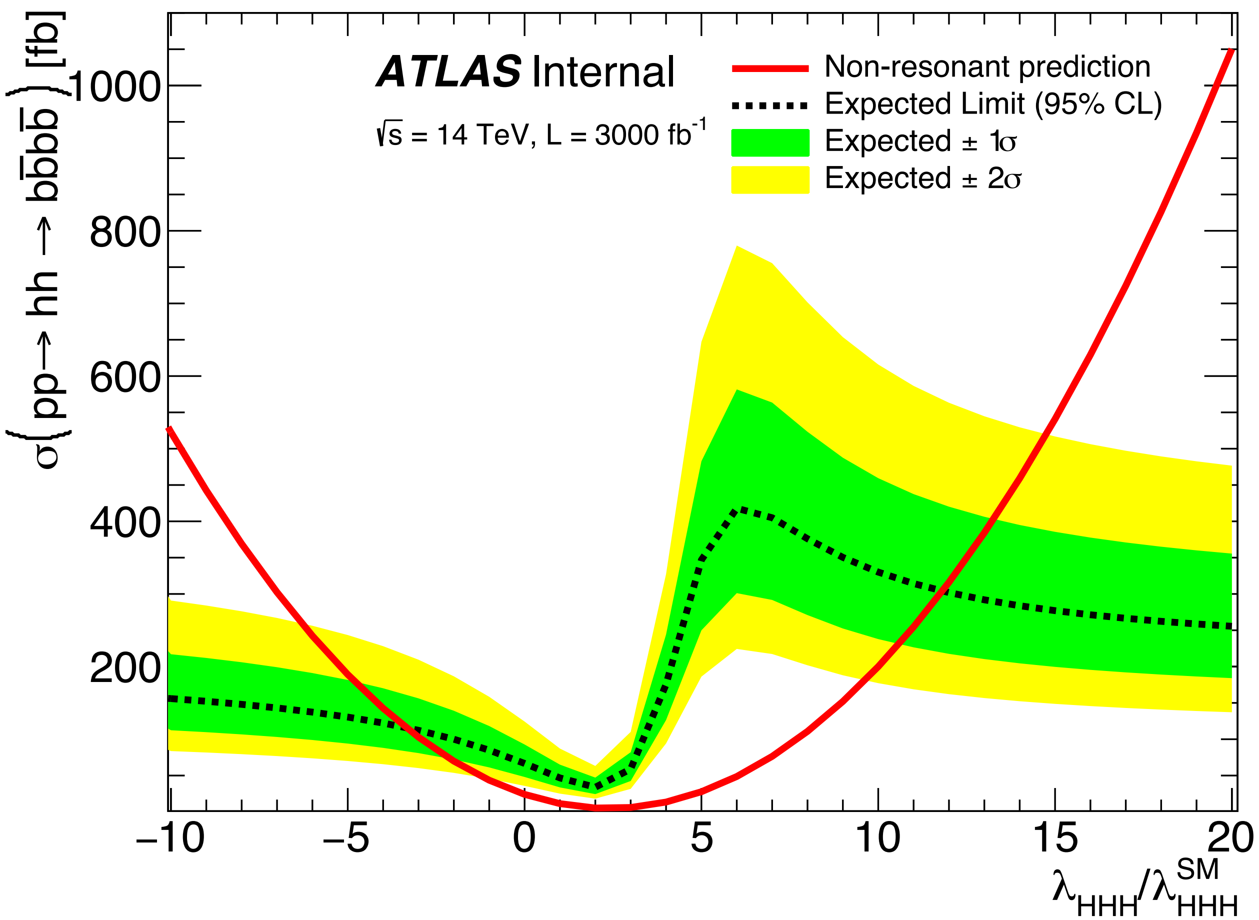
Limits as a function of jet p_T

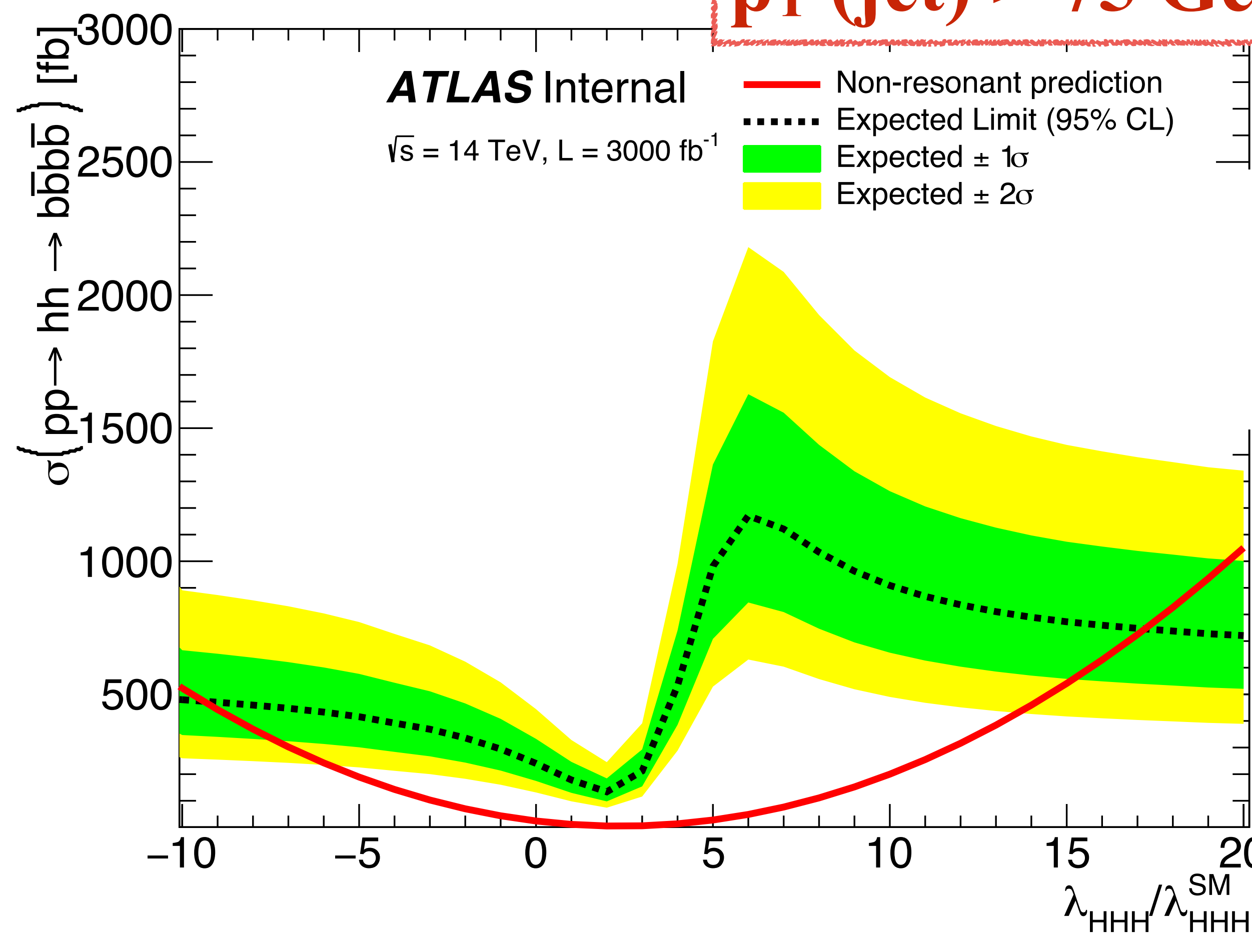


HH→bbbb (under approval)

3000 fb^{-1}

p$_T$ (jet) > 75 GeV





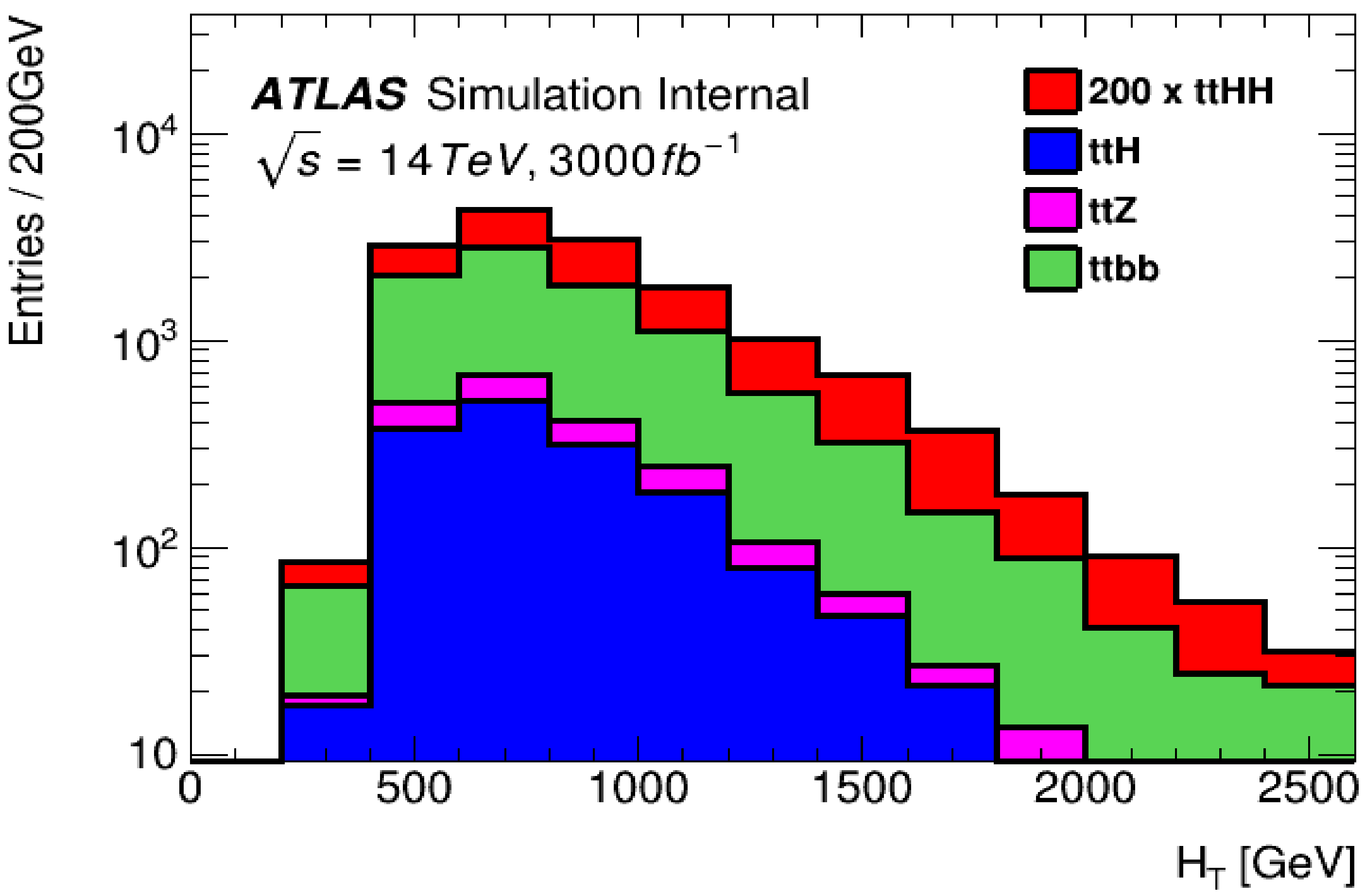
- Statistical uncertainties only: self-coupling constrained to $-3.4 < \lambda_{HHH}/\lambda_{SM} < 12$
- With Run 2 systematic uncertainties, it can be constrained to $-9.5 < \lambda_{HHH}/\lambda_{SM} < 17$

Summary

Analysis	~ Significance	λ_{HHH} (stat only)	λ_{HHH} (~current syst)
$HH \rightarrow bb\tau\tau$	0.6		$-4 < \lambda_H/\lambda_{SM} < 12$
$HH \rightarrow bbbb$	0.4 (pT(jet)>30 GeV)	$-3.4 < \lambda/\lambda_{SM} < 12$ (pT(jet)>75 GeV)	$-9.5 < \lambda/\lambda_{SM} < 17$ (pT(jet)>75 GeV)
$ttHH$, $HH \rightarrow bbbb$	0.3		

Backup

Backup: *ttHH* (not yet approved)



$HH \rightarrow bb\tau\tau$ τ_{HAD} τ_{HAD}

3000 fb^{-1}
<μ> = 140

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Table 3: Expected event yields for the HL-LHC with an integrated luminosity of 3 ab^{-1} in the $\tau_{\text{had}}\tau_{\text{had}}$ selection.

Process	Pre-sel	Trig-eff	m_{bb}	$m_{\tau\tau}^{mmc}$	p_{T}^{bb}	m_{T2}
Signal ($\lambda = 0\lambda_{\text{SM}}$)	125	80	49.6	41.5	23	19.1
Signal ($\lambda = 1\lambda_{\text{SM}}$)	72	46.1	29.5	25.1	15.7	13.4
Signal ($\lambda = 2\lambda_{\text{SM}}$)	38.2	24.5	15.9	13.6	9.46	8.49
Signal ($\lambda = 10\lambda_{\text{SM}}$)	545	348	195	151	46.8	29.6
$t\bar{t} \geq 1$ lep	1.01e+05	6.45e+04	1.15e+04	3.42e+03	327	103
bbjj	5.32e+04	3.4e+04	9.61e+03	3.55e+03	522	209
$Z(\tau\tau)$+jets	2.37e+04	1.52e+04	2.77e+03	1.69e+03	423	367
$t\bar{t}$ full had	1.3e+04	8.3e+03	1.47e+03	1.07e+03	< 113	< 113
dijets	3.92e+03	2.51e+03	56.9	< 0.085	< 0.085	< 0.085
$W(\tau\nu)$+jets	1.07e+03	685	165	46.2	< 0.752	< 0.752
ZH	141	90.1	52.2	30.3	13.2	12.4
bbH($\tau\tau$)	317	203	71.7	60.1	25.7	25
others	339	217	29	3.45	0.696	0.427
All backgrounds	1.96e+05	1.26e+05	2.57e+04	9.87e+03	1.43e+03	830

$HH \rightarrow bb\tau\tau$ $\tau_{LEP}\,\tau_{LEP}$

3000 fb^{-1}
<μ> = 140

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Table 4: Expected yields for the electron-electron final state in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel at the HL-LHC for an integrated luminosity of 3 ab^{-1}.

Process	Pre-sel	Trig-eff	m_{bb}	$m_{\tau\tau}^{mmc}$	p_{T}^{bb}	m_{T2}	$\Delta R(b, b)$
Signal ($\lambda = 0\lambda_{SM}$)	79	17.9	11.5	8.4	5.6	4.1	2.1
Signal ($\lambda = 1\lambda_{SM}$)	44	10	6.7	5	3.7	2.9	1.5
Signal ($\lambda = 2\lambda_{SM}$)	23.4	5.3	3.7	2.7	2.2	1.8	1.1
Signal ($\lambda = 10\lambda_{SM}$)	373	83.1	52.3	36.4	15.9	7.4	2.9
$bbH(\tau\tau)$	199	43.1	19.7	14.2	5.5	4.6	2.8
others	1.1e+06	1.2e+04	2.6e+03	1.2e+03	391	244	108
$Z \rightarrow ee+$ jets	8.7e+05	8.9e+04	1.9e+04	7.6e+03	1.5e+03	978	450
$t\bar{t}$	1.5e+07	3.2e+06	6.8e+05	2.0e+05	2.9e+04	7.6e+03	1.7e+03
All backgrounds	1.7e+07	3.3e+06	7e+05	2.1e+05	3.1e+04	8.9e+03	2.2e+03

Table 5: Expected yields for the muon-muon final state in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel at the HL-LHC for an integrated luminosity of 3 ab^{-1}.

Process	Pre-sel	Trig-eff	m_{bb}	$m_{\tau\tau}^{mmc}$	p_{T}^{bb}	m_{T2}	$\Delta R(b, b)$
Signal ($\lambda = 0\lambda_{SM}$)	79	11.2	7.4	6.6	4.5	3.6	1.9
Signal ($\lambda = 1\lambda_{SM}$)	44	6.3	4.4	3.9	2.9	2.3	1.2
Signal ($\lambda = 2\lambda_{SM}$)	23.4	3.4	2.4	2.2	1.8	1.5	0.9
Signal ($\lambda = 10\lambda_{SM}$)	373	47.4	29.9	25.5	10.2	6	2.5
$bbH(\tau\tau)$	199	30.9	13.3	10.4	4.4	3.3	2.1
others	9.3e+05	6.5e+03	1.3e+03	561	184	130	66.4
$Z \rightarrow \mu\mu$+jets	1.0e+06	8e+04	1.9e+04	8.5e+03	1.2e+03	588	375
$t\bar{t}$	1.5e+07	2.2e+06	4.5e+05	1.1e+05	1.5e+04	3.8e+03	734
All backgrounds	1.7e+07	2.3e+06	4.7e+05	1.2e+05	1.7e+04	4.5e+03	1.2e+03

$HH \rightarrow bb\tau\tau$ $\tau_{LEP}\,\tau_{LEP}$

3000 fb^{-1}
<μ> = 140

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Table 6: Expected yields for the electron-muon final state in the $\tau_{\text{lep}}\tau_{\text{lep}}$ channel at the HL-LHC for an integrated luminosity of 3 ab^{-1}.

Process	Pre-sel	Trig-eff	m_{bb}	$m_{\tau\tau}^{mmc}$	p_{T}^{bb}	m_{T2}	$\Delta R(b,b)$
Signal ($\lambda = 0\lambda_{SM}$)	79	34.3	23	18.2	12.3	9.1	4.8
Signal ($\lambda = 1\lambda_{SM}$)	44	19.2	13	10.4	7.7	6	3.2
Signal ($\lambda = 2\lambda_{SM}$)	23.4	10.1	7	5.6	4.6	3.9	2.3
Signal ($\lambda = 10\lambda_{SM}$)	373	165	103	73.5	34.7	18.8	7.44
$bbH(\tau\tau)$	199	82.2	35.6	27.9	16.5	15.1	5.5
others	1.9e+06	2e+04	3.6e+03	1.4e+03	206	160	94.4
$Z \rightarrow \tau\tau$+jets	1.8e+04	7.7e+03	1.4e+03	952	337	238	91.4
$t\bar{t}$	1.5e+07	6.7e+06	1.4e+06	4.2e+05	5.9e+04	1.3e+04	2.6e+03
All backgrounds	1.7e+07	6.7e+06	1.4e+06	4.2e+05	5.9e+04	1.4e+04	2.8e+03

$HH \rightarrow bb\tau\tau$ τ_{LEP} τ_{HAD}

3000 fb^{-1}
$\langle\mu\rangle = 140$

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Table 7: Expected event yields for the HL-LHC with an integrated luminosity of 3 ab^{-1} in the electron and muon channels for the $\tau_{\text{lep}}\tau_{\text{had}}$ selection.

Electron channel

Sample	Pre-selection	e trigger	$m_{\tau\tau}$	m_{bb}	$\sum\Delta\phi$	Δ	m_{T}	$\Delta R(b_1, b_2)$	χ^2	p_{T}^{bb}	m_{T2}
Signal ($\lambda = 0\lambda_{\text{SM}}$)	311	148	104	76.2	44.1	32.4	28.9	24.7	19.6	12.9	10.5
Signal ($\lambda = \lambda_{\text{SM}}$)	170	79.6	56.3	42	26.4	19.9	17.8	16	13	9	7.5
Signal ($\lambda = 2\lambda_{\text{SM}}$)	86	40.3	29	22	14.4	11.3	10.1	9.5	8	6.1	5.3
Signal ($\lambda = 10\lambda_{\text{SM}}$)	1.7e+03	786	532	378	145	93.2	83.3	57.8	39.1	19.8	12
$t\bar{t}$	5.2e+06e+04	2.5e+06e+03	8e+05e+03	2e+05e+03	3.9e+04e+03	2.1e+04	1.7e+04	6.9e+03	3.4e+03	546	261
$Z \rightarrow \tau\tau$+jets	8.5e+04e+03	4.1e+04	2e+04	4.8e+03	1.8e+03	994	924	557	441	215	179
$W \rightarrow \ell\nu$+jets	1.1e+04	7.5e+03	2e+03	304	82.7	54.7	52.4	7.6	7.3	4.9	4.7
others	3.7e+04	1.7e+04	5.2e+03	1.3e+03	217	130	117	54.2	32.6	11.8	9
$bbH(\tau\tau)$	813	400	270	124	57.4	46.8	41.8	33.5	29.4	17.9	15.1
All backgrounds	5.4e+06	2.6e+06	8.3e+05	2.1e+05	4.1e+04	2.2e+04	1.8e+04	7.6e+03	3.9e+03	796	469

Muon channel

Sample	Pre-selection	μ trigger	$m_{\tau\tau}$	m_{bb}	$\sum\Delta\phi$	Δ	m_{T}	$\Delta R(b_1, b_2)$	χ^2	p_{T}^{bb}	m_{T2}
Signal ($\lambda = 0\lambda_{\text{SM}}$)	311	108	84.7	62.5	36.8	27	24.2	20.7	16.2	10.9	9
Signal ($\lambda = \lambda_{\text{SM}}$)	170	59.7	46.7	35	22.7	17.5	15.6	14	11.2	7.8	6.5
Signal ($\lambda = 2\lambda_{\text{SM}}$)	86	30.3	23.6	18	12.2	9.7	8.8	8.2	6.9	5.1	4.5
Signal ($\lambda = 10\lambda_{\text{SM}}$)	1.7e+03	579	444	313	126	83.1	73.9	50.3	34	16.4	10.2
$t\bar{t}$	5.2e+06e+04	1.8e+06e+03	6.1e+05e+03	1.6e+05e+03	3.3e+04	1.8e+04	1.5e+04	6.7e+03	3.4e+03	555	228
$Z \rightarrow \tau\tau$+jets	8.5e+04e+03	3e+04	1.7e+04	4.3e+03	1.9e+03	1e+03	898	517	404	176	151
$W \rightarrow \ell\nu$+jets	1.1e+04	1.6e+03	473	207	42.7	40.4	38.1	38	37.2	2.5	2.4
$bbH(\tau\tau)$	813	275	219	108	45.9	39.5	37.5	31.3	27.1	17.3	15.6
others	3.7e+04	1.3e+04	4.1e+03	1.2e+03	304	175	158	123	98.2	68.8	10
All backgrounds	5.4e+06	1.9e+06	6.4e+05	1.7e+05	3.5e+04	2e+04	1.6e+04	7.4e+03	3.9e+03	819	407

$HH \rightarrow bb\tau\tau$ systematics

3000 fb^{-1}
<μ> = 140

ATL-PHYS-PUB-2015-046

For this approach, we have taken studies performed in the $H \rightarrow \tau\tau$ measurement [41] as a reference for the background estimates using data-driven methods, which claims a background modelling systematic uncertainty of $\sim$ 3% for the $t\bar{t}$ and Z + jets backgrounds. In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, the QCD backgrounds were also assumed to have a 3% background modelling uncertainty. Other backgrounds are expected to use a Monte Carlo based technique and a 5% overall cross section uncertainty was considered. The luminosity uncertainty was taken to be 3% for the signal and the Monte Carlo estimated backgrounds. And finally, the uncertainty for the signal is taken from its theoretical cross section as ±11%.