UPPSALA UNIVERSITET

Searches for Higgs boson pair production with ATLAS

Arnaud Ferrari



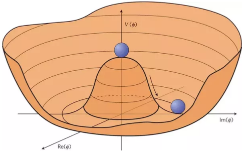
# Searches for Higgs boson pair production with ATLAS


**Arnaud Ferrari (Uppsala University)**
**on behalf of the ATLAS collaboration**


**CIPANP, Palm Springs (USA), 29 May - 3 June 2018**

# The Higgs potential

After discovering the Higgs boson, the ultimate probe of the Standard Model is to fully measure the Higgs potential.




$$V(\Phi) = -\frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4 \stackrel{\Phi\to v+h}{=} \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4$$

mass term $\frac{1}{2}m_h^2 h^2$

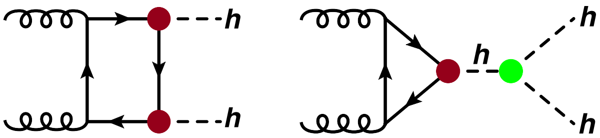
self-interaction terms

→ $v = \mu/\sqrt{\lambda} = 246$ GeV and $\lambda = m_h^2/(2v^2) = 0.13$ fully determine the shape of the Higgs potential.

→ In order to really complete the Standard Model, one must observe $h \to hh$ (and eventually $h \to hhh$ too).

# SM Higgs boson pair production

Gluon-gluon fusion:




Due to the destructive interference between the box and Higgs self-coupling diagrams, the SM Higgs boson pair production cross-section is very small (33.4 fb at 13 TeV).

Other production modes: even smaller cross-sections...

| $\sqrt{s}$ | 8 TeV | 13 TeV | 14 TeV |
|---|---|---|---|
| ggF $hh$ | 10.2 | 33.4 | 39.6 |
| VBF $hh$ | 0.46 | 1.62 | 1.95 |
| $W/Z + hh$ | 0.36 | 0.86 | 0.98 |
| $tt + hh$ | 0.17 | 0.77 | 0.95 |

$\sigma^{hh}_{\text{NLO}}$ in fb (https://arxiv.org/abs/1610.07922)

UPPSALA UNIVERSITET

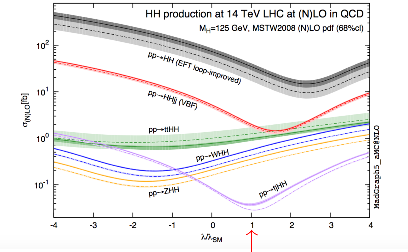
**Searches for Higgs boson pair production with ATLAS**

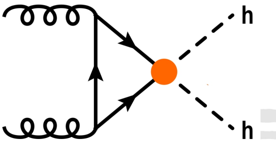
**Arnaud Ferrari**



# BSM Higgs boson pair production

Enhancements of the *hh* production cross-section and modified kinematics (e.g. $m_{hh}$, $p_T^h$) may occur through variations of the Yukawa- or self-coupling, as well as new vertices.

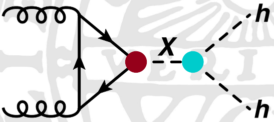



← Phys. Lett. B732 (2014) 142
($\lambda$ = Higgs self-coupling)

Resonant Higgs boson pair production:

- Randall-Sundrum graviton (spin-2): $G \to hh$
- 2HDM heavy Higgs boson (spin-0): $H \to hh$



# Higgs boson pair decays

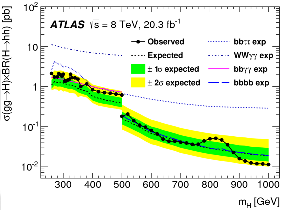
| | bb | WW | ττ | ZZ | γγ |
|---|---|---|---|---|---|
| bb | 33% | | | | |
| WW | 25% | 4.6% | | | |
| ττ | 7.4% | 2.5% | 0.39% | | |
| ZZ | 3.1% | 1.2% | 0.34% | 0.076% | |
| γγ | 0.26% | 0.10% | 0.029% | 0.013% | 0.0053% |

Many final states to explore... In this talk:

- *bbbb*: largest branching fraction
- $bb\gamma\gamma$ & $WW\gamma\gamma$: clean diphoton signature

## Run-1 legacy:

| 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 |

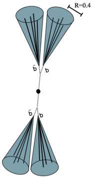


# $hh \rightarrow bbbb$

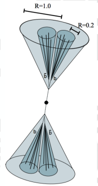
# $hh \rightarrow bbbb$ – event categories

Two event topologies depending on the probed mass range:

- Non-resonant and resonant production of $hh \rightarrow bbbb$ with mass up to $\simeq$1 TeV: resolved topology.
- Resonant production of $hh \rightarrow bbbb$ with mass $\gtrsim$1 TeV: boosted topology.




| Topology/ Objects | Resolved (260-1400 GeV) | Boosted (800-3000 GeV) |
|---|---|---|
| Triggers and corresponding $\int Ldt$ (fb$^{-1}$) | Combination of $b$-jet triggers 3.2+24.3 | Single large-$R$ jet trigger 36.1 |
| $N_{\text{jets}}$ | $\geq$4 jets, $R = 0.4$ | $\geq$2 jets, $R = 1.0$ |
| $p_T$ cut | 40 GeV | 450 / 250 GeV |
| $b$-tagging | 70% for all jets | 70% on track-jets with $R = 0.2$ |
| $N_{\text{b-jets}}$ | 4 | 2, 3, 4 |



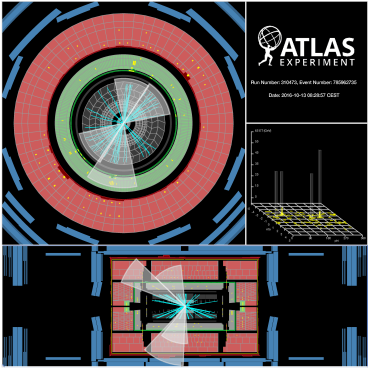
UPPSALA UNIVERSITET

**Searches for Higgs boson pair production with ATLAS**

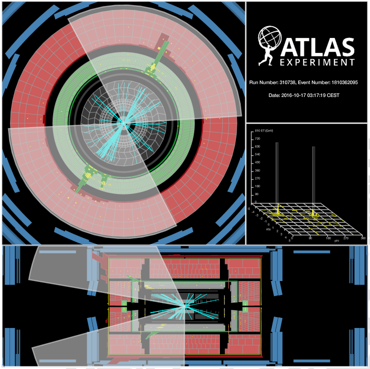
**Arnaud Ferrari**



# $hh \to bbbb$ – event displays




Resolved, $m_{4j} = 272$ GeV

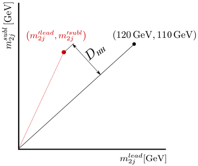



Boosted, $m_{2j} = 3.89$ TeV

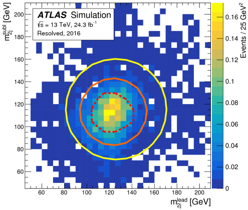
# $hh \to bbbb$ – resolved topology

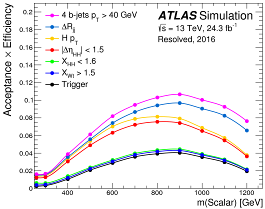
## Event selection:

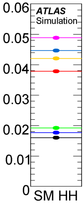
- The four jets with highest *b*-tagging scores are used.
- A selection and pairing of jets into Higgs boson candidates is performed using $\Delta R_{jj}$, $m_{4j}$ and differences in $m_{2j}$.




- $m_{4j}$- and $m_{2j}$-dependent requirements on the $p_T$ and mass of the Higgs boson candidates are applied ⇒ SR centered at (120 GeV; 110 GeV).
- Events where a three-jet-combination is compatible with a top-quark decay are vetoed to reduce the $t\bar{t}$ background contamination.



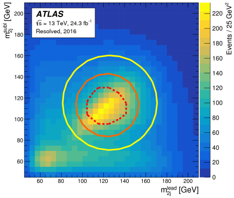
# $hh \to bbbb$ – resolved topology

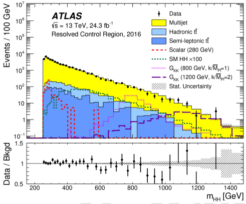
## Multi-jet background (95% in the SR):

- Multi-jet sample: built with the nominal event selection, but $N_b = 2$: one $h$ candidate from the two $b$-tagged jets, one from two non-$b$-tagged jets;
- Weights are applied to the $2b$+$2j$ sample of the SR. They are derived by comparing $2b$+$2j$ and $4b$ samples in a sideband (SB) region:
  - per-non-$b$-tagged-jet factor by comparing jet multiplicities;
  - fitted ratio of $4b$ and $2b$+$2j$ templates (after subtracting $t\bar{t}$) for five variables sensitive to differences in $b$-tagging [iterative].

## $t\bar{t}$ background (5% in the SR):

- Simulation $\to m_{4j}$ shape for fully-hadronic and semi-leptonic $t\bar{t}$;
- Normalizations of multi-jet events, fully-hadronic and semi-leptonic $t\bar{t}$ by a simultaneous fit of three background-enriched regions of the SB.



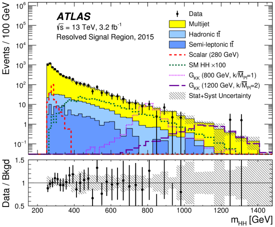



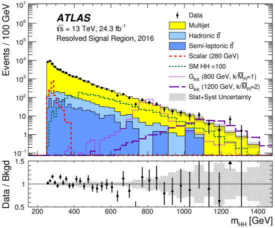
# $hh \to bbbb$ – resolved topology

After the validation of backgrounds in control regions, no significant excess of events is found in the SR:

| Sample | 2015 SR | 2016 SR | 2015 CR | 2016 CR |
|---|---|---|---|---|
| Multijet | 866 ± 70 | 6750 ± 170 | 880 ± 71 | 7110 ± 180 |
| $t\bar{t}$, hadronic | 52 ± 35 | 259 ± 57 | 56 ± 37 | 276 ± 61 |
| $t\bar{t}$, semileptonic | 13.9 ± 6.5 | 123 ± 30 | 20 ± 9 | 168 ± 40 |
| Total | 930 ± 70 | 7130 ± 130 | 956 ± 50 | 7550 ± 130 |
| Data | 928 | 7430 | 969 | 7656 |
| $G_{KK}$ (800 $GeV$) | 12.5 ± 1.9 | 89 ± 14 | | |
| Scalar (280 GeV) | 24 ± 7.5 | 180 ± 57 | | |
| SM $HH$ | 0.607 ± 0.091 | 4.43 ± 0.66 | | |

Largest local deviation at 280 GeV: it is 3.6$\sigma$ for a narrow-width scalar resonance (global significance of 2.3$\sigma$).

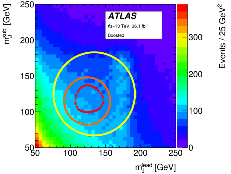


# $hh \to bbbb$ – boosted topology

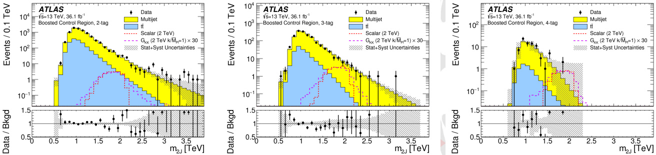
## Event selection:

- The two large-$R$ jets with highest $p_T$ are used, with $|\Delta\eta_{JJ}| < 1.7$;
- $\geq 1$ $b$-tagged track-jet per $J \Rightarrow 2, 3, 4$ $b$-tags;
- Requirements on the jet masses $\Rightarrow$ SR centered at (124 GeV; 115 GeV).




## Background estimation:

- Multi-jet template from "lower-tagged" event selections (i.e. one of the large-$R$ jet has no $b$-tagged track-jet and at least one failing $b$-tagging) + re-weight the kinematics of the non-$b$-tagged $J$ to mimic a $h$ candidate;
- Shape of the $t\bar{t}$ background from simulation;
- Normalization of the backgrounds from binned likelihood fits of the leading large-$R$ jet mass distribution in the sideband region.



UPPSALA UNIVERSITET

**Searches for Higgs boson pair production with ATLAS**

**Arnaud Ferrari**

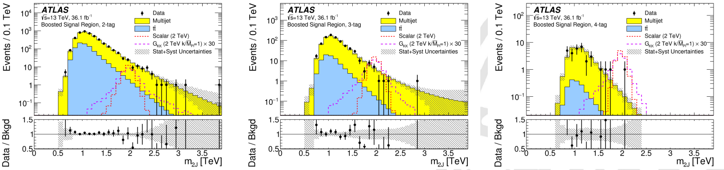


# $hh \to bbbb$ – boosted topology

After the validation of backgrounds in control regions, no significant excess of events is found in the SR:

| | Two-tag | | Three-tag | | Four-tag | |
|---|---|---|---|---|---|---|
| Multijet | 3390 | ±150 | 702 | ±63 | 32.9 | ±6.9 |
| $t\bar{t}$ | 860 | ±110 | 80 | ±33 | 1.7 | ±1.4 |
| Total | 4250 | ±130 | 782 | ±51 | 34.6 | ±6.1 |
| $G_{\mathrm{KK}}$ (2 TeV) | 0.97 ± | 0.29 | 1.23 ± | 0.16 | 0.40 | ±0.13 |
| Scalar (2 TeV) | 28.2 ± | 9.0 | 35.0 ± | 4.6 | 10.9 | ±3.5 |
| Data | 4376 | | 801 | | 31 | |

Discriminant = $m_{2J}$ after correction of the large-$R$ jet momenta by $m_h/m_J$.



UPPSALA UNIVERSITET

Searches for Higgs boson pair production with ATLAS

Arnaud Ferrari



# $hh \to bbbb$ – results

## Statistical analysis:

- Combination of the resolved and boosted topologies in the range 800-1400 GeV, where they overlap.
- Simultaneous fit of $m_{4j}$ in the 2015 and 2016 dataset for resolved topologies, and of $m_{2J}$ in the 2, 3 and 4 $b$-tag regions for boosted topologies.

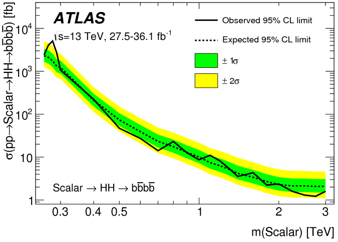
## Non-resonant *hh* production:

Observed 95% CL upper limit on $\sigma_{hh} \times$ BR($bbbb$) at 147 fb.

In units of the SM prediction:

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

## Resonant *hh* production (2HDM interpretation):



UPPSALA UNIVERSITET

**Searches for Higgs boson pair production with ATLAS**

**Arnaud Ferrari**



# $hh \to bb\gamma\gamma$

# $hh \to bb\gamma\gamma$ – event selections

## Two photons

- Di-photon trigger with thresholds at 35 and 25 GeV;
- 2 photons with $E_{\mathrm{T}}/m_{\gamma\gamma}$ above 0.35/0.25 & $m_{\gamma\gamma} \subset [105; 160]$ GeV.

## Jet selection

- $\geq$2 central jets with $p_{\mathrm{T}} > 25$ GeV, reject events with >2 $b$-tags (70%);
- 2-tag: exactly 2 $b$-jets (70%);
- 1-tag: fails 2-tag but has 1 $b$-jet (60%) + BDT to choose the second jet;
- 0-tag $\to$ data-driven estimates of the background shape.

## Additional loose (tight) selection

- Optimised for 260–500 GeV & varied $\lambda$ ($\geq$ 500 GeV & non-resonant);
- Leading jet $p_{\mathrm{T}} > 40\,(100)$ GeV, sub-leading jet $p_{\mathrm{T}} > 25\,(30)$ GeV;
- $m_{jj}$ between 80 (90) and 140 GeV;
- $m_{\gamma\gamma}$ within 4.7 (4.3) GeV of $m_h$ [resonant].

# $hh \to bb\gamma\gamma$ – signal and background models

## Non-resonant $hh$ production

- Analysis strategy: fit the $m_{\gamma\gamma}$ distribution.
- Signal modelling: double-sided Crystal Ball function.
- Single Higgs boson production: simulation, double-sided Crystal Ball function.
- Continuum background modelling: fit to the data with a first-order exponential, which minimises the spurious signal*.

## Resonant $hh$ production

- Analysis strategy: rescale the dijet four-momentum by $m_h/m_{jj}$ and fit the $m_{\gamma\gamma jj}$ distribution around $m_X$.
- Signal modelling: Gaussian core with exponential tails.
- Background modelling: fit to the data, with a functional form chosen to minimise the spurious signal → Novosibirsk (exponential) function for the loose (tight) event selection.

(*) Spurious signal: bias measured by fitting a signal+background model to a background-only sample.

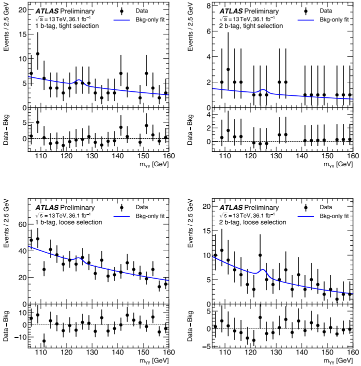
UPPSALA UNIVERSITET





# $hh \to bb\gamma\gamma$ – results

## Non-resonant *hh* production:

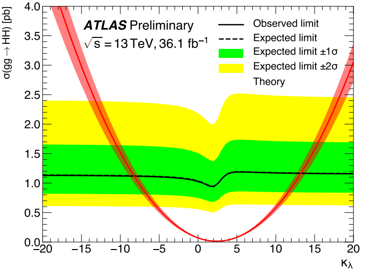



No significant excess.

Tight selection used to set 95% CL limits on the cross section for non-resonant production:

| Observed | $-1\sigma$ | Expected | $+1\sigma$ |
|---|---|---|---|
| 22 | 20 | 28 | 40 |

Loose selection used to set 95% CL limits on the Higgs self-coupling $\longrightarrow \longrightarrow \longrightarrow \longrightarrow$




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

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

UPPSALA UNIVERSITET

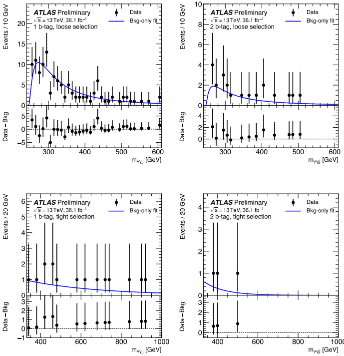
**Searches for Higgs boson pair production with ATLAS**

**Arnaud Ferrari**



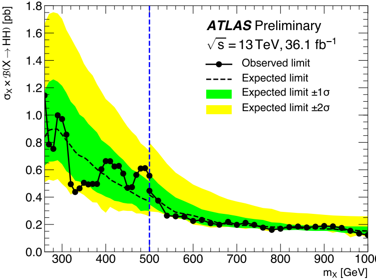
# $hh \to bb\gamma\gamma$ – results

## Resonant *hh* production:




Loose (tight) selection used up to (above) 500 GeV.

Observed 95% upper limits ranging from 1.14 to 0.12 pb.

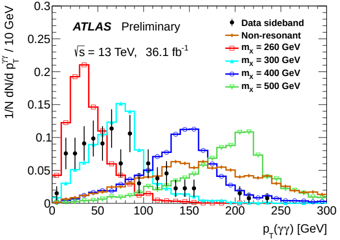


# $hh \to WW\gamma\gamma$

# $hh \to WW\gamma\gamma$ – event selections

## Signal region (SR):

- di-photon trigger with thresholds at 35 and 25 GeV;
- 2 photons with $E_T/m_{\gamma\gamma}$ above 0.35/0.25;
- $|m_{\gamma\gamma} - 125.1 \text{ GeV}| < 3.4$ GeV;
- $p_T^{\gamma\gamma} > 100$ GeV for the high-mass resonant (400–500 GeV) and the non-resonant production modes.




- $W(\ell\nu)W(jj)$: $\geq$1 electron/muon of $p_T > 10$ GeV, $\geq$2 central jets, $b$-veto.

## Sideband (SB): 105 GeV $< m_{\gamma\gamma} <$ 160 GeV & inverted SR cut.

## Background modelling:

- Continuum background from a SB-fit: exponential of a 2nd-degree polynomial, with free-floating shape parameters and normalisation.
- SM single-Higgs events from simulation (double-sided Crystal Ball).
- SM $hh$ events from simulation (double-sided Crystal Ball) $\to$ background in searches for resonant production.

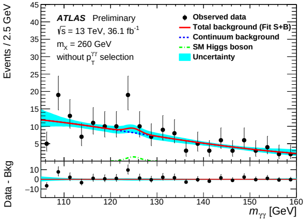
UPPSALA UNIVERSITET

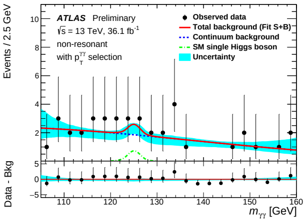
**Searches for Higgs boson pair production with ATLAS**

**Arnaud Ferrari**



# $hh \to WW\gamma\gamma$ – results




## Statistical analysis based on a fit to $m_{\gamma\gamma}$ in the SR:

$$\mathcal{L}(\mu,\theta) = \prod G(\theta|0,1) \prod_i [(n_{\text{signal}}(\mu,\theta) + n_{ss}) \times f^1_{dscb}(m^i_{\gamma\gamma},\theta) + n_{\text{cont.}} \times f_{\text{cont.}}(m^i_{\gamma\gamma},\theta) + n^{\text{SM}}_h(\theta) \times f^2_{dscb}(m^i_{\gamma\gamma},\theta) + n^{\text{SM}}_{hh} \times f^3_{dscb}(m^i_{\gamma\gamma},\theta)]$$

$n_{ss}$: spurious signal obtained by fitting a signal+background model to a background-only sample.

UPPSALA UNIVERSITET



# $hh \to WW\gamma\gamma$ – results

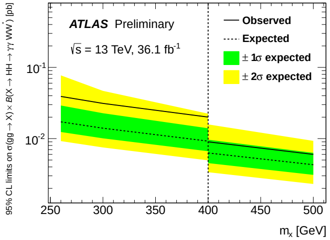
## Limits on non-resonant *hh* production:

| Observed | $-2\sigma$ | $-1\sigma$ | Expected | $+1\sigma$ | $+2\sigma$ |
|---|---|---|---|---|---|
| 230 | 90 | 120 | 160 | 240 | 340 |

## Limits on resonant *hh* production (260–500 GeV):

Observed: 40 to 6.1 pb

Expected: 17.6 to 4.4 pb



UPPSALA UNIVERSITET

**Searches for Higgs boson pair production with ATLAS**

**Arnaud Ferrari**



# Conclusion

- The ATLAS collaboration has recently released three results on searches for Higgs boson pair production, based on 36/fb of 13 TeV data:
  - $hh \to bbbb$: arXiv:1804.06174, submitted to JHEP.
  - $hh \to bb\gamma\gamma$: off the press!
  - $hh \to WW\gamma\gamma$: off the press!
- Non-resonant *hh* production down to 13 times the SM prediction is now excluded (*bbbb*).
- Higgs self-coupling constrained to $-8.2 < \kappa_\lambda < 13.2$ ($bb\gamma\gamma$).

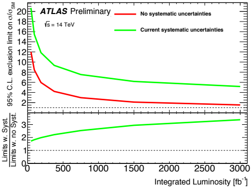
Searches for *hh* production will eventually allow to fully validate the electroweak symmetry breaking in the SM and they already probe BSM physics... Such analyses will be a major highlight of the LHC Run-2, with soon 3 to 4 times more data than presented here!

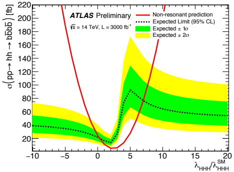
# Back-up

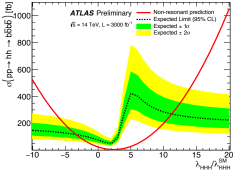
# HL-LHC projections: $hh \to bbbb$

Extrapolation of results in ATLAS-CONF-2016-049. All distributions are corrected to account for the increase 13→14 TeV and 10.1→3000/fb.

Assuming a jet $p_T$ threshold at 30 GeV, and either no or the same systematic uncertainties as in 2016:




Assume that systematic uncertainties $\propto 1/\sqrt{L}$:
$\Rightarrow$ exclude $\sigma_{hh} > 2.2\times$SM @ 95% CL with 3000/fb.

Projections versus the jet $p_T$ threshold:

| Jet Threshold [GeV] | Background Systematics | $\sigma/\sigma_{SM}$ 95% Exclusion | $\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit | $\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit |
|---|---|---|---|---|
| 30 GeV | Negligible | 1.5 | 0.2 | 7 |
| 30 GeV | Current | 5.2 | -3.5 | 11 |
| 75 GeV | Negligible | 2.0 | -3.4 | 12 |
| 75 GeV | Current | 11.5 | -7.4 | 14 |

UPPSALA UNIVERSITET

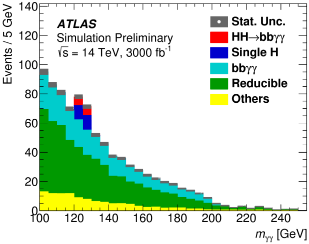
**Searches for Higgs boson pair production with ATLAS**

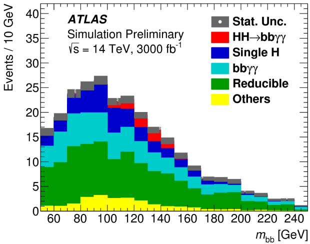
**Arnaud Ferrari**



# HL-LHC projections: $hh \to bb\gamma\gamma$

Study based on 14 TeV simulations with 200 *pp* collisions per bunch-crossing and an upgraded ATLAS detector, including the expected photon and *b*-tagging performance.




$\Rightarrow$ Expected significance of $1.05\sigma$ for SM *hh* production.

$-0.8 < \kappa_\lambda < 7.7$ @ 95% CL with 3000/fb at 14 TeV.