

# Double Higgs production in ATLAS

Seminar at Warwick University

November 29<sup>th</sup> 2018

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# In this talk...

- Double Higgs production
  - SM
  - BSM
  - At the LHC
- Searches in ATLAS
  - Channels included in the combination
- Combined result
- Prospects in HL-LHC

- Not in this talk:
  - more production mechanisms (VBF, ttHH etc)
  - Searches in CMS
  - Channels not included in the combination
  - Prospects beyond HL-LHC

If I missed your favourite topic,  
let's discuss at the end!

# Double Higgs production in the Standard Model (SM)

- Higgs potential:  $V(\varphi) = -\frac{1}{2}\mu^2\varphi^2 + \frac{1}{4}\lambda\varphi^4$
- Expand around the vacuum expectation value:  $V(\varphi) \rightarrow V(v + h)$

- $V(h) = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{1}{4}\lambda h^4 + \dots$

- $V(h) = V_0 + \frac{1}{2}m_h^2 h^2 + \frac{m_h^2}{2v^2} v h^3 + \frac{1}{4} \frac{m_h^2}{2v^2} h^4 + \dots$

$$v = \frac{\mu}{\sqrt{\lambda}} \text{ and } \mu = \frac{m_h^2}{2}$$

Mass term

Higgs  
trilinear self-  
coupling

Higgs  
quadratic  
self-  
coupling

In the SM  $v=246$  GeV and  
 $\lambda=0.13$

**Double Higgs  
production**

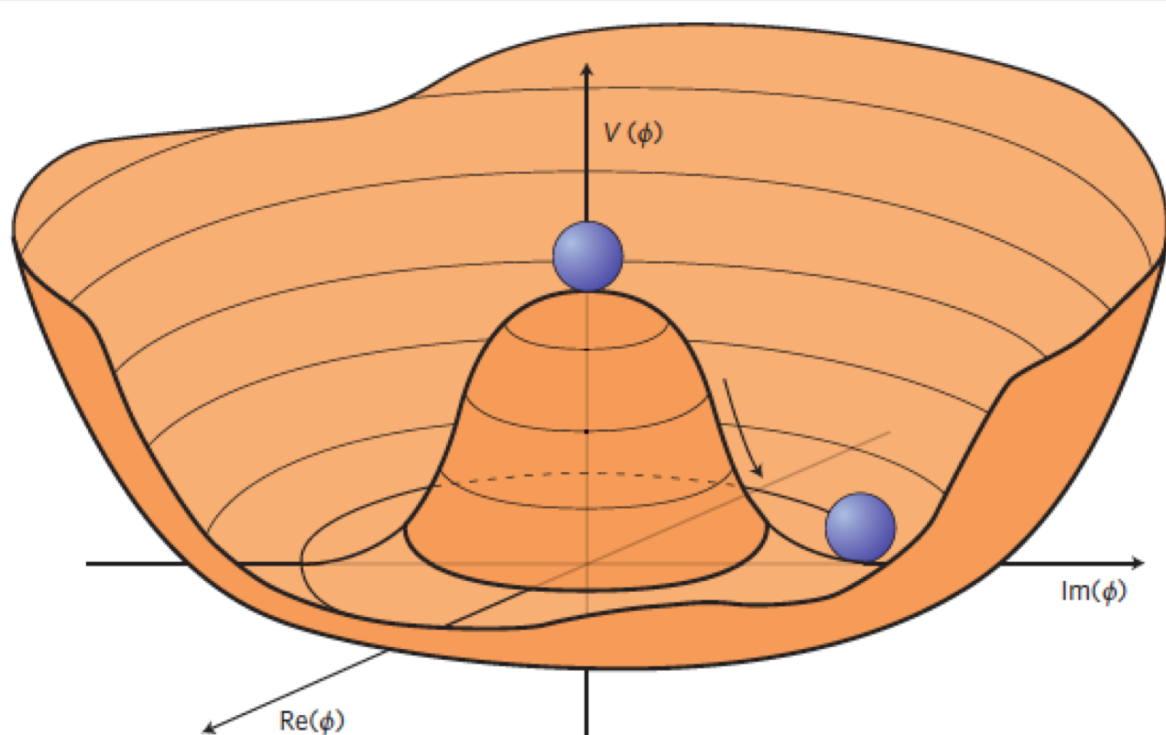
*This is what this talk is about  
(mostly)*

# Double Higgs production in the Standard Model (SM)

- Higgs potential:  $V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$
- Expand around the vacuum expectation value:  $V(\phi) \rightarrow V(v + h)$

•  $V(h)$

•  $V(h)$



$$v = \frac{\mu}{\sqrt{\lambda}} \text{ and } \mu = \frac{m_h^2}{2}$$

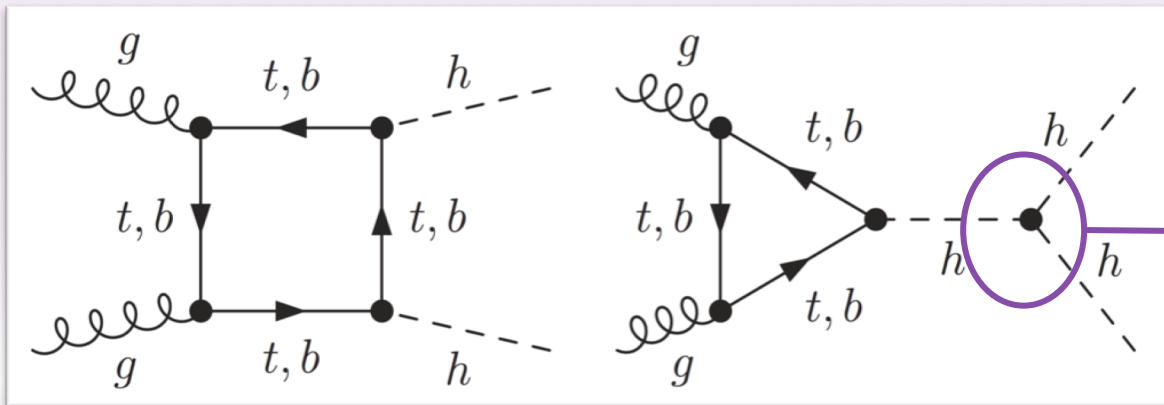
In the SM  $v=246$  GeV and  $\lambda=0.13$

Do  
pr

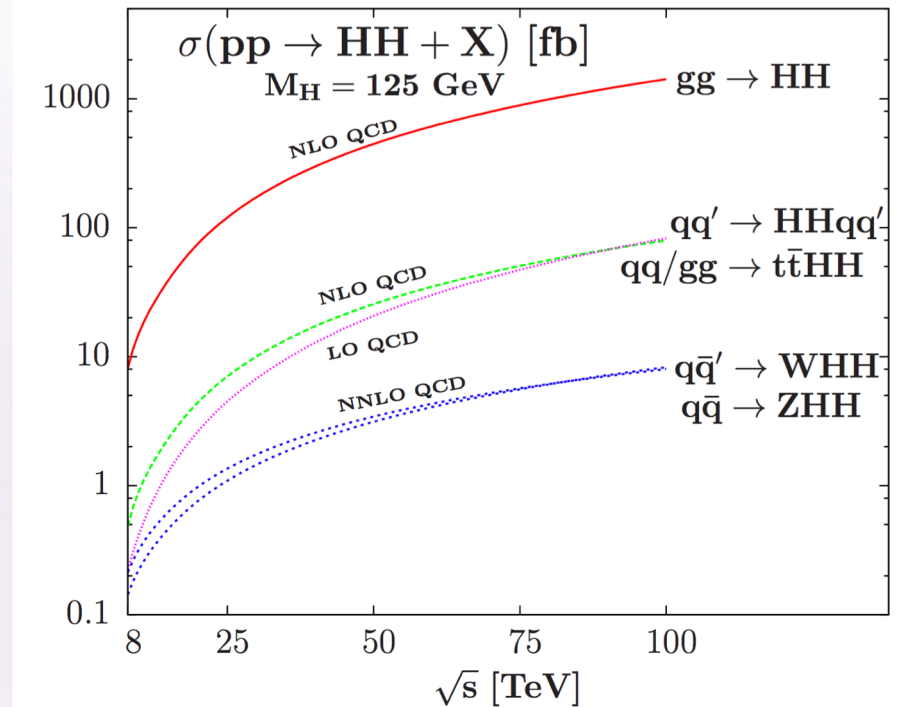
This is wh

# Double Higgs production at the LHC

- At the LHC dominant production mechanism for SM double Higgs production is gluon fusion
- The “box” and “triangle” diagrams interact destructively
- SM cross-section very small !! ~40 fb
- (~1000 times smaller than single Higgs production)

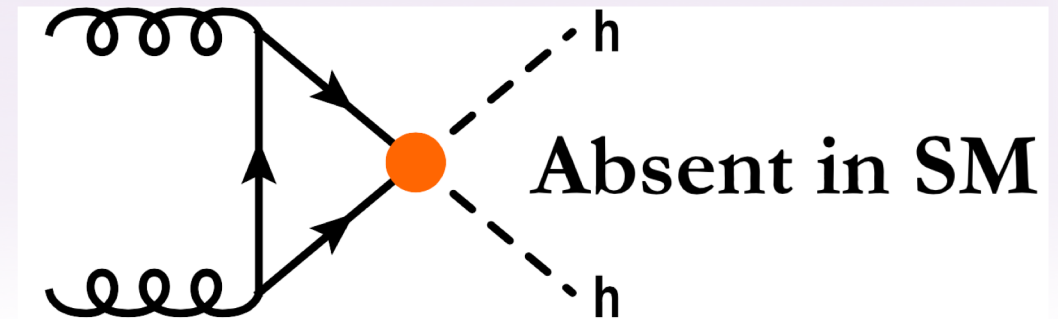
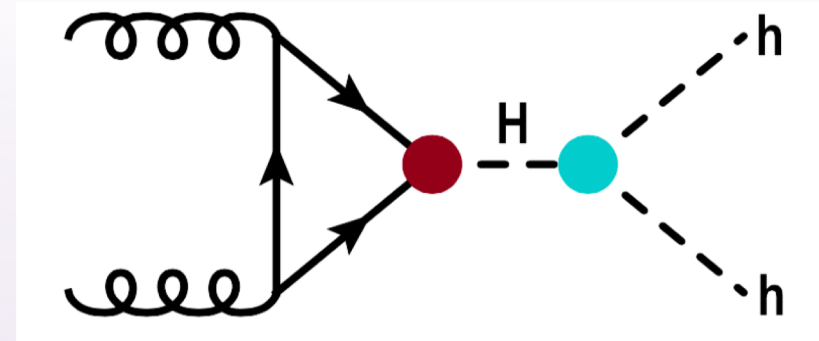


Higgs trilinear coupling



# Double Higgs production at the LHC (2)

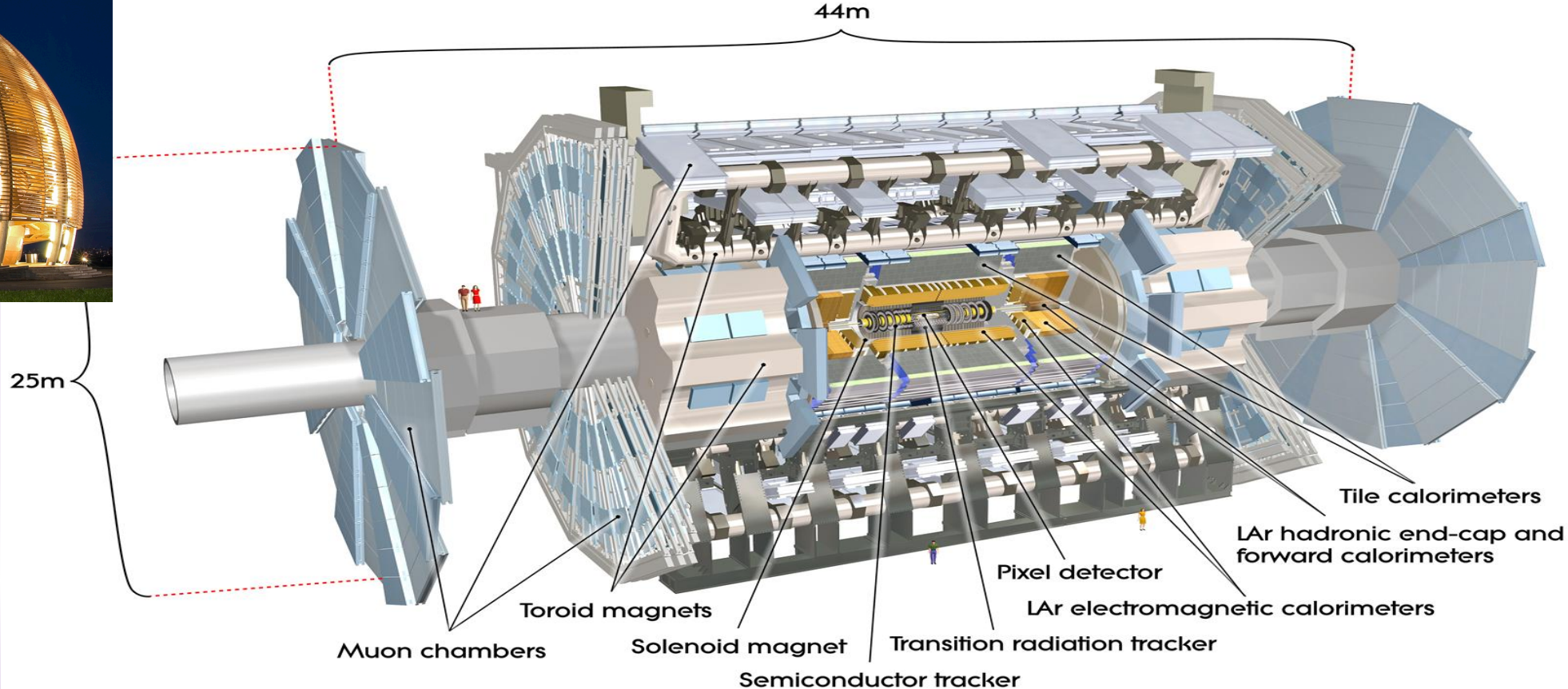
- Beyond the standard model
  - resonant production
  - KK graviton  $G$  predicted in the Randal-Sundrum model
  - 2HDM (the heavy neutral scalar  $H$ )
- Non resonant BSM enhancements
  - Activating  $t\bar{t}h$  vertex, altering  $\lambda_{HHH}$





# The ATLAS detector

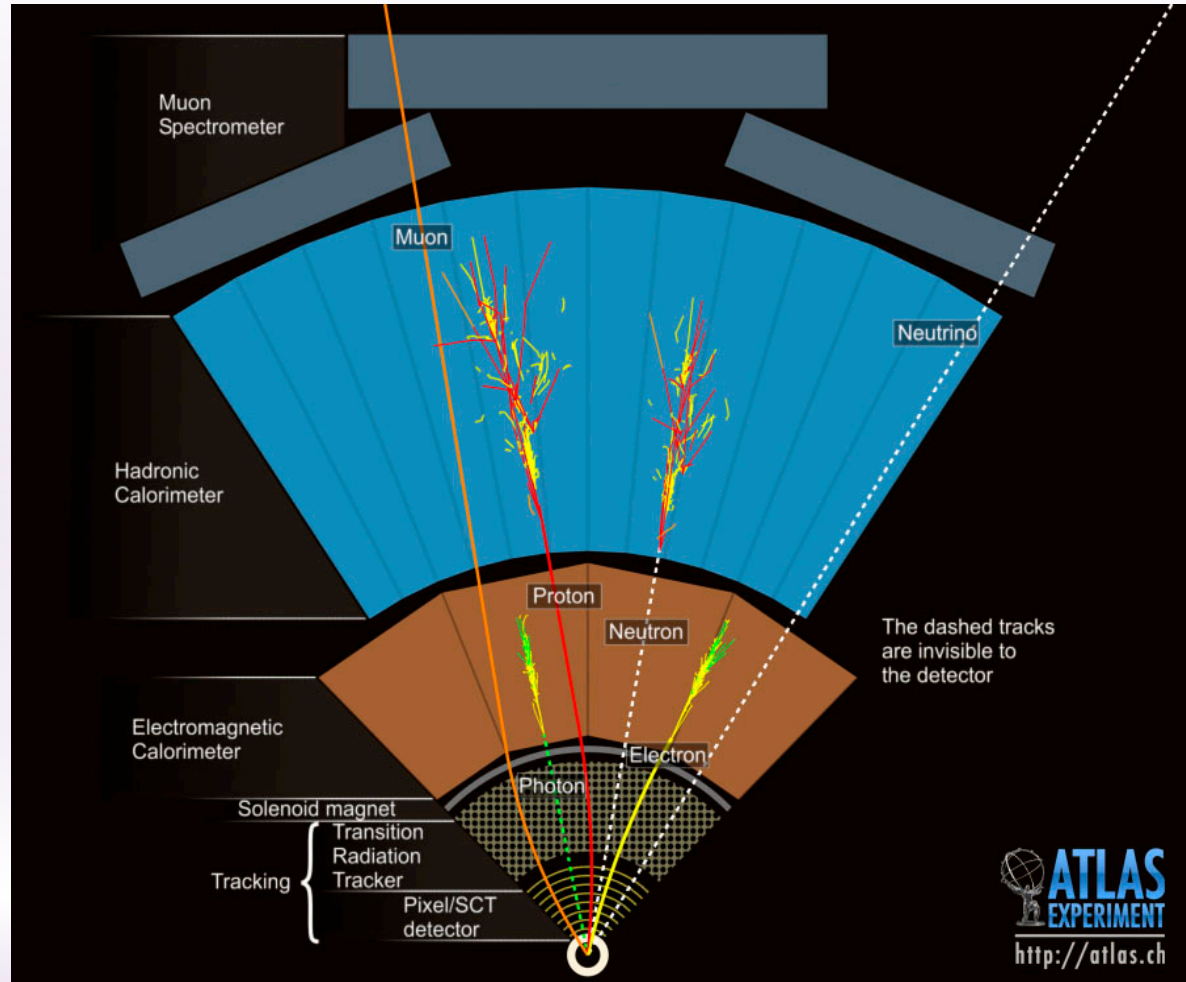
- One of the experiments along the Large Hadron Collider in the Geneva (p-p collisions)





# The ATLAS detector

- One of the experiments along the Large Hadron Collider in the Geneva (p-p collisions)
- b-jets are really important for Higgs physics due to the large BR,  $H \rightarrow b\bar{b}$  BR 0.6
- information from the inner tracker are used to identify b-jets

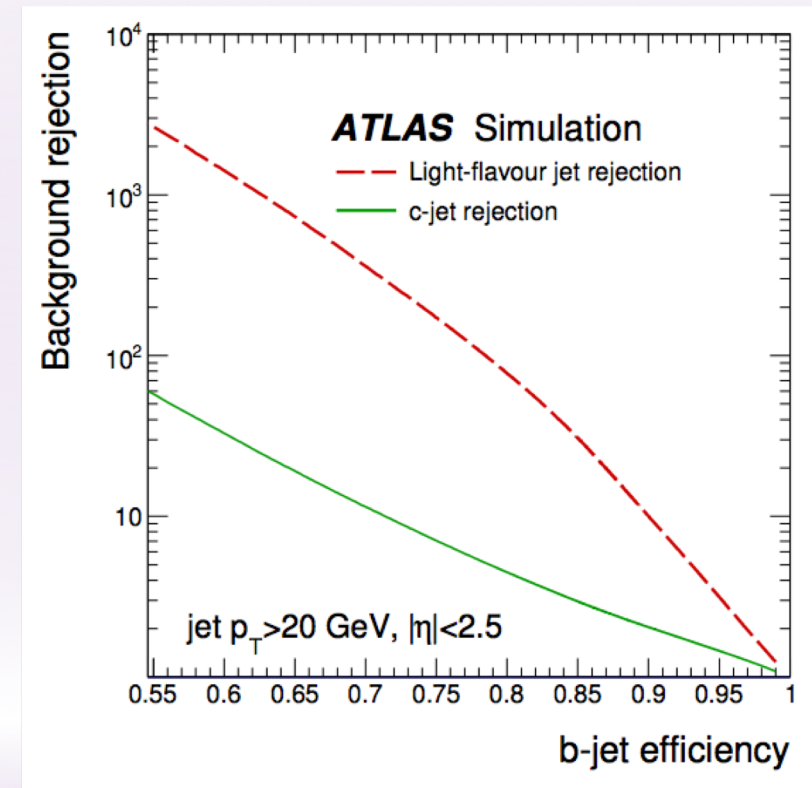
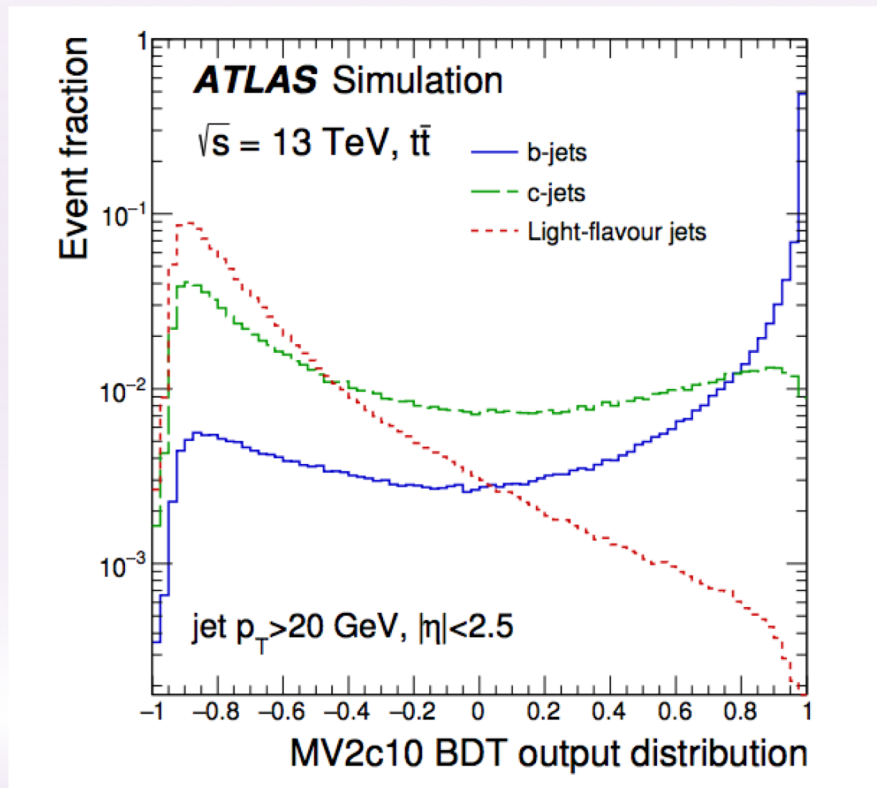


# b-tagging in ATLAS

[JHEP 08 \(2018\) 89](#)

ATLAS is using multivariate “b-tagging” algorithms, such as MV2c10

The analyses use 70%-85% efficiency  
(In HH mostly 70%)



# HH decays

bbbb:  
the highest branching  
fraction, large multijet  
background

bb $\tau\tau$ :  
relatively large  
branching fraction,  
cleaner final state

|                | bb    | WW    | $\tau\tau$ | ZZ     | $\gamma\gamma$ |
|----------------|-------|-------|------------|--------|----------------|
| bb             | 33%   |       |            |        |                |
| WW             | 25%   | 4.6%  |            |        |                |
| $\tau\tau$     | 7.4%  | 2.5%  | 0.39%      |        |                |
| ZZ             | 3.1%  | 1.2%  | 0.34%      | 0.076% |                |
| $\gamma\gamma$ | 0.26% | 0.10% | 0.029%     | 0.013% | 0.0053%        |

WWbb,WWWW  
and WW $\gamma\gamma$  also  
studied!

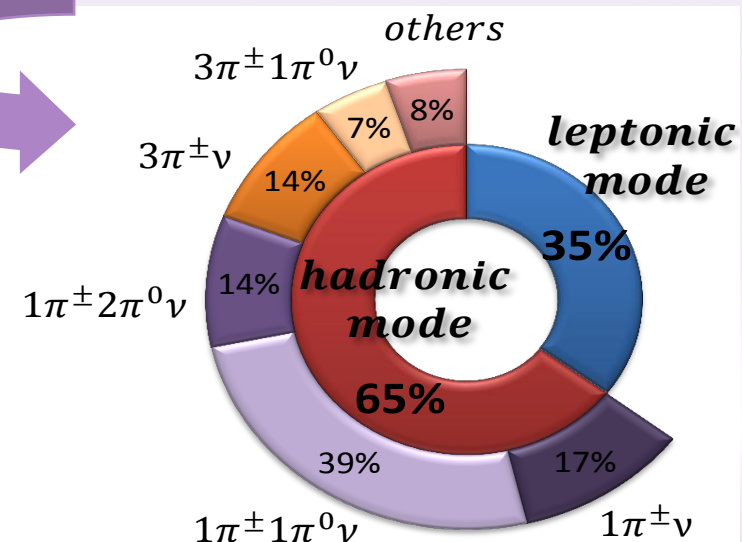
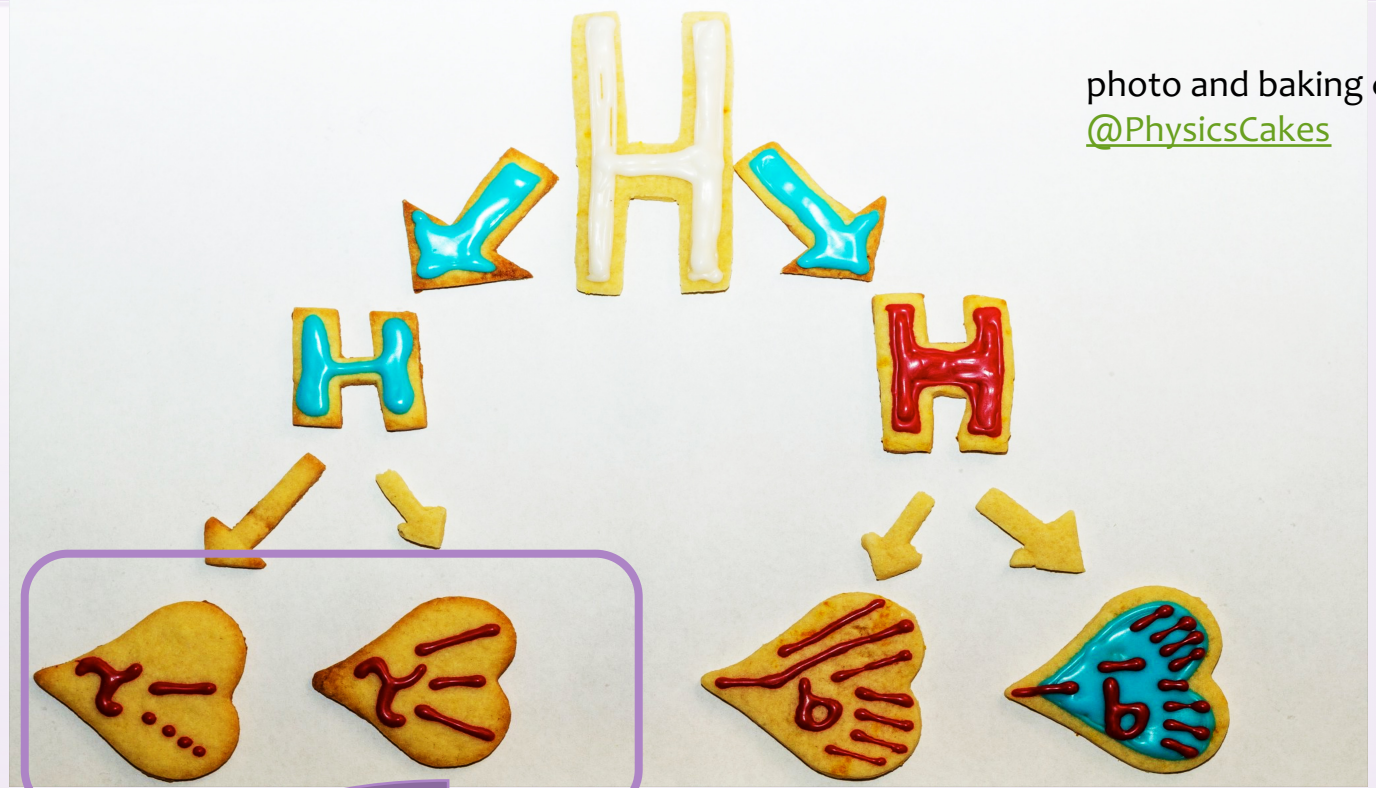
bbyy:  
small branching  
fraction, clean  
signal extraction  
due to the narrow  
 $h \rightarrow \gamma\gamma$  mass peak



# bb $\tau\tau$ final states

- 2 channels
  - $\tau_h\tau_{e/\mu}$  branching ratio 23%
  - $\tau_h\tau_h$  branching ratio 42%
- Final states with 2 b-tagged jets
- Signal hypotheses
  - Non-resonant production (e.g. SM)
  - Resonant production  
Mass points 260 GeV- 1TeV  
Benchmark scenarios:
    - 2HDM heavy scalar
    - Spin 2 Randall-Sundrum graviton (RSG)

photo and baking credit:  
[@PhysicsCakes](#)



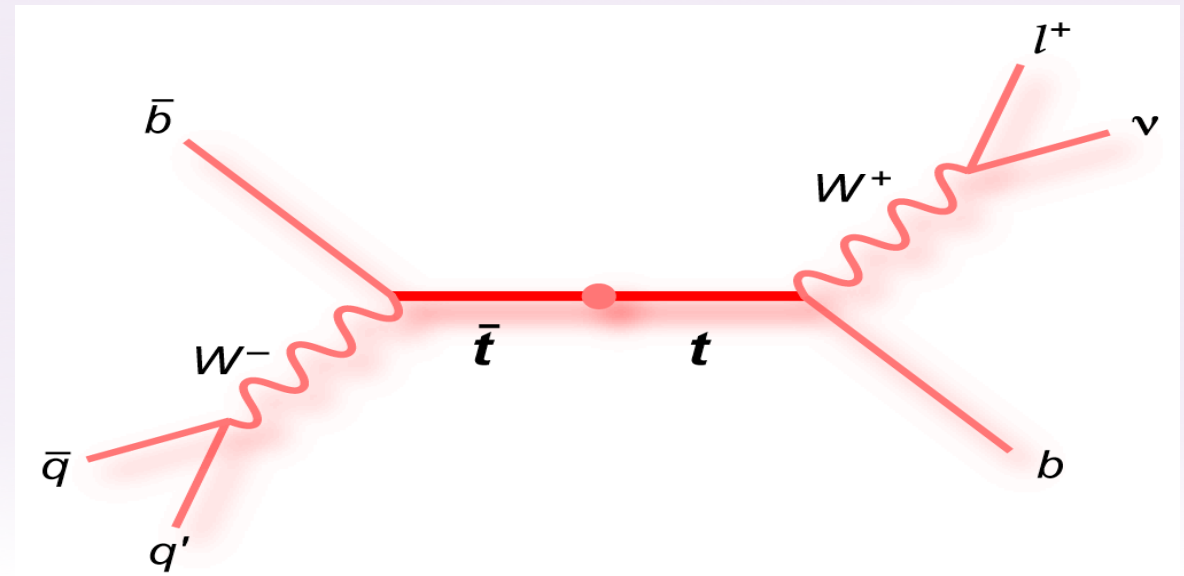
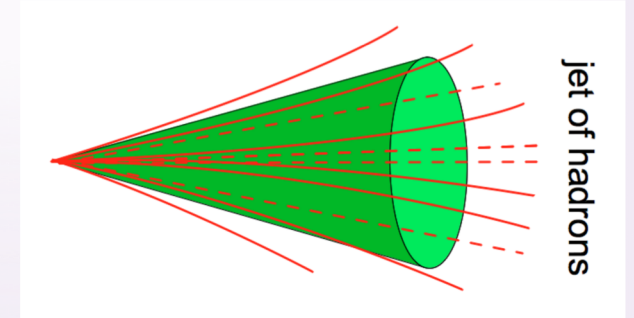
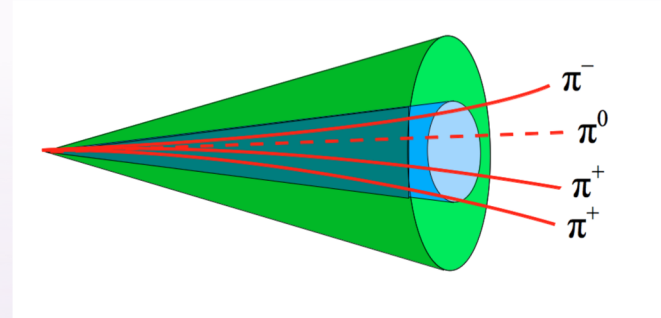


# bb $\tau\tau$ analysis strategy

<https://arxiv.org/pdf/1808.00336.pdf>

- Main background processes for  $\tau_h\tau_{e/\mu}$  and  $\tau_h\tau_h$ 
  - ttbar
  - QCD
  - Z+bb,cc or bc
  - **jets faking  $\tau_h$**
- Use fake factor (FF) method for the fake  $\tau$  background (jet  $\rightarrow \tau$ )
  - FF is the ratio of the number of fake- $\tau_h$  that pass the  $\tau$  identification to the number that fail
  - contribution from multiple processes  

$$FF_{\text{comb}} = FF_{\text{QCD}} * R_{\text{QCD}} + FF_{\text{ttbar/W+jets}} * (1 - R_{\text{QCD}})$$
  - $R_{\text{QCD}}$  is the fraction of fake-  $\tau_h$  that comes from QCD multijets
  - 1 and 3 track decays treated separately
  - The FF are estimated in control regions.
    - Inverse  $\tau_h$  identification selection in  $\tau_h\tau_{e/\mu}$
    - Region where the  $\tau$  decay products have the same charge and inverse isolation selection in  $\tau_h\tau_h$



# bb $\tau\tau$ Boosted Decision Trees (BDTs)

- Using BDTs, a multivariate method for signal and background discrimination
- Trained especially for different resonant masses.
- The  $\tau_h\tau_h$  channel is trained against all major backgrounds.  
The  $\tau_h\tau_l$  channel is trained only against ttbar

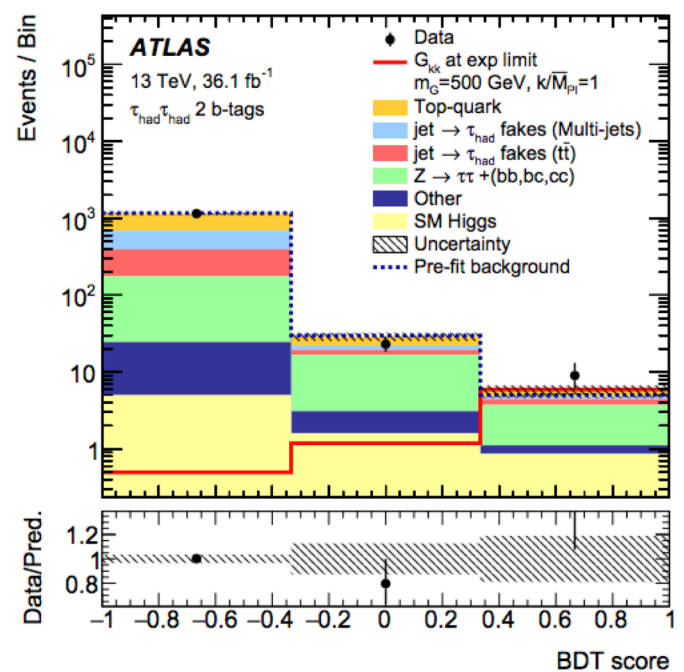
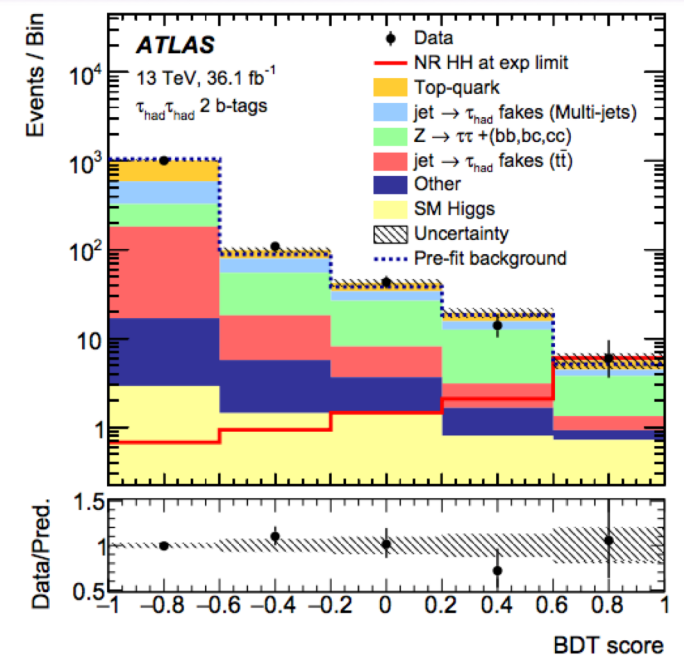
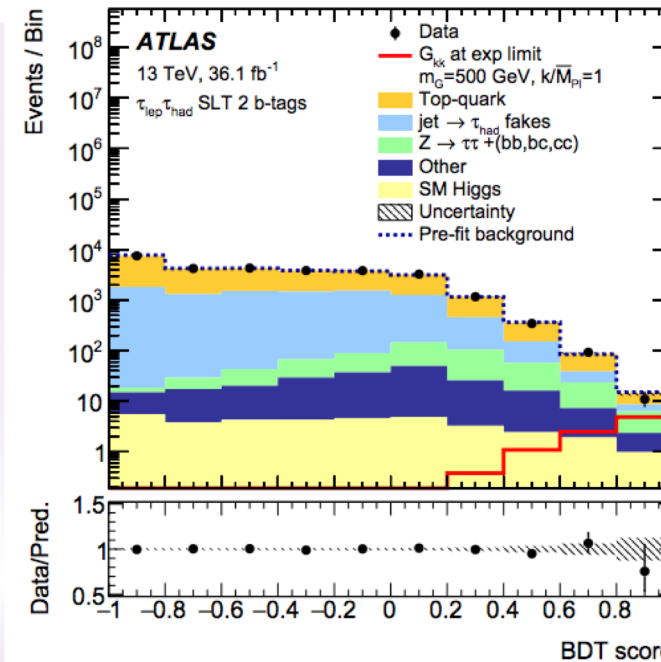
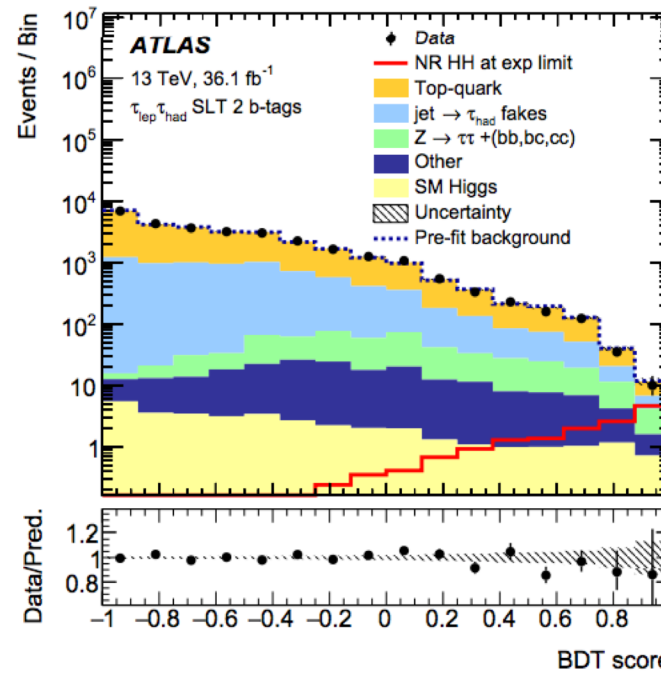
| Variable                          | $\tau_{lep}\tau_{had}$ channel<br>(SLT resonant) | $\tau_{lep}\tau_{had}$ channel<br>(SLT non-resonant & LTT) | $\tau_{had}\tau_{had}$ channel |
|-----------------------------------|--------------------------------------------------|------------------------------------------------------------|--------------------------------|
| $m_{HH}$                          | ✓                                                | ✓                                                          | ✓                              |
| $m_{\tau\tau}^{MMC}$              | ✓                                                | ✓                                                          | ✓                              |
| $m_{bb}$                          | ✓                                                | ✓                                                          | ✓                              |
| $\Delta R(\tau, \tau)$            | ✓                                                | ✓                                                          | ✓                              |
| $\Delta R(b, b)$                  | ✓                                                | ✓                                                          | ✓                              |
| $E_T^{miss}$                      | ✓                                                |                                                            |                                |
| $E_T^{miss} \phi$ centrality      | ✓                                                |                                                            | ✓                              |
| $m_T^W$                           | ✓                                                | ✓                                                          |                                |
| $\Delta\phi(H, H)$                | ✓                                                |                                                            |                                |
| $\Delta p_T(lep, \tau_{had-vis})$ | ✓                                                |                                                            |                                |
| Sub-leading $b$ -jet $p_T$        | ✓                                                |                                                            |                                |

# bb $\tau\tau$ BDT score

NR signal

- The BDT scores are used as the final discriminant for every channel and signal.
- NO CUT is applied on the BDT score.

RSG signal



# bb $\tau\tau$ results

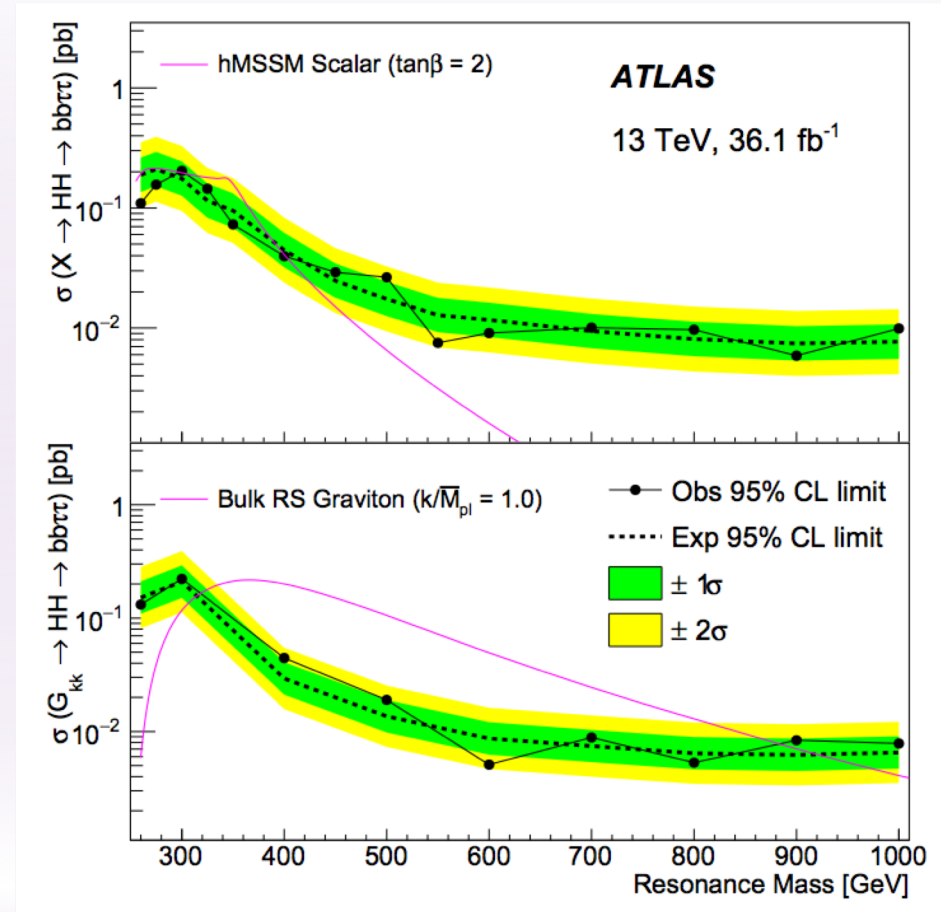
|                                      |                                          | Observed | $-1\sigma$ | Expected | $+1\sigma$ |
|--------------------------------------|------------------------------------------|----------|------------|----------|------------|
| $\tau_{\text{lep}}\tau_{\text{had}}$ | $\sigma(HH \rightarrow bb\tau\tau)$ [fb] | 57       | 49.9       | 69       | 96         |
|                                      | $\sigma/\sigma_{\text{SM}}$              | 23.5     | 20.5       | 28.4     | 39.5       |
| $\tau_{\text{had}}\tau_{\text{had}}$ | $\sigma(HH \rightarrow bb\tau\tau)$ [fb] | 40.0     | 30.6       | 42.4     | 59         |
|                                      | $\sigma/\sigma_{\text{SM}}$              | 16.4     | 12.5       | 17.4     | 24.2       |
| Combination                          | $\sigma(HH \rightarrow bb\tau\tau)$ [fb] | 30.9     | 26.0       | 36.1     | 50         |
|                                      | $\sigma/\sigma_{\text{SM}}$              | 12.7     | 10.7       | 14.8     | 20.6       |

The non-resonant result is:  
observed (expected)

12.7 (14.8)  $\times$  SM prediction

This is the best single channel limit in HH production in the world, ever!

Comparable with the CMS combined result ;)

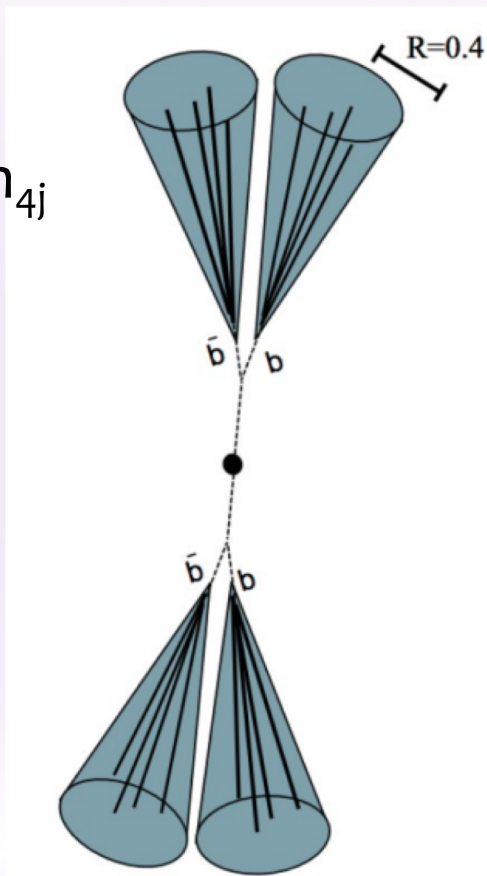




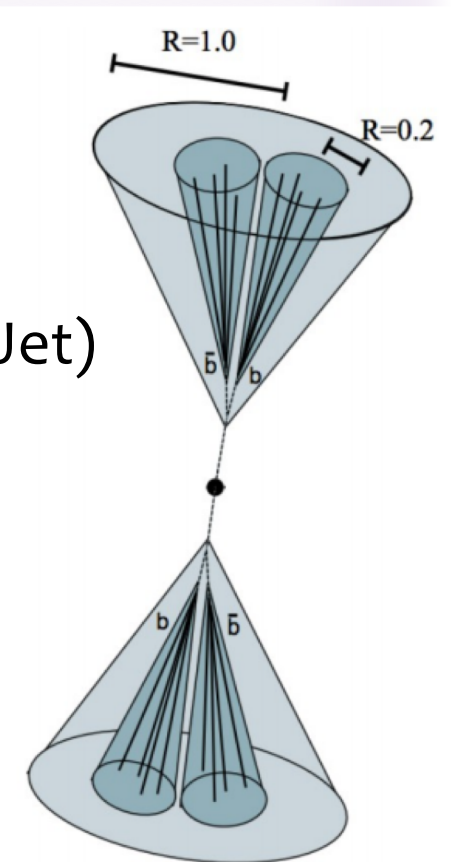
# bbbb final states

<https://arxiv.org/pdf/1804.06174.pdf>

- Resolved
- Reconstruct 4 b-jets  
Final discriminator  $m_{4j}$
- Signal hypotheses
  - non-resonant
  - Resonant signal  
 $m_X$  260-1400 GeV

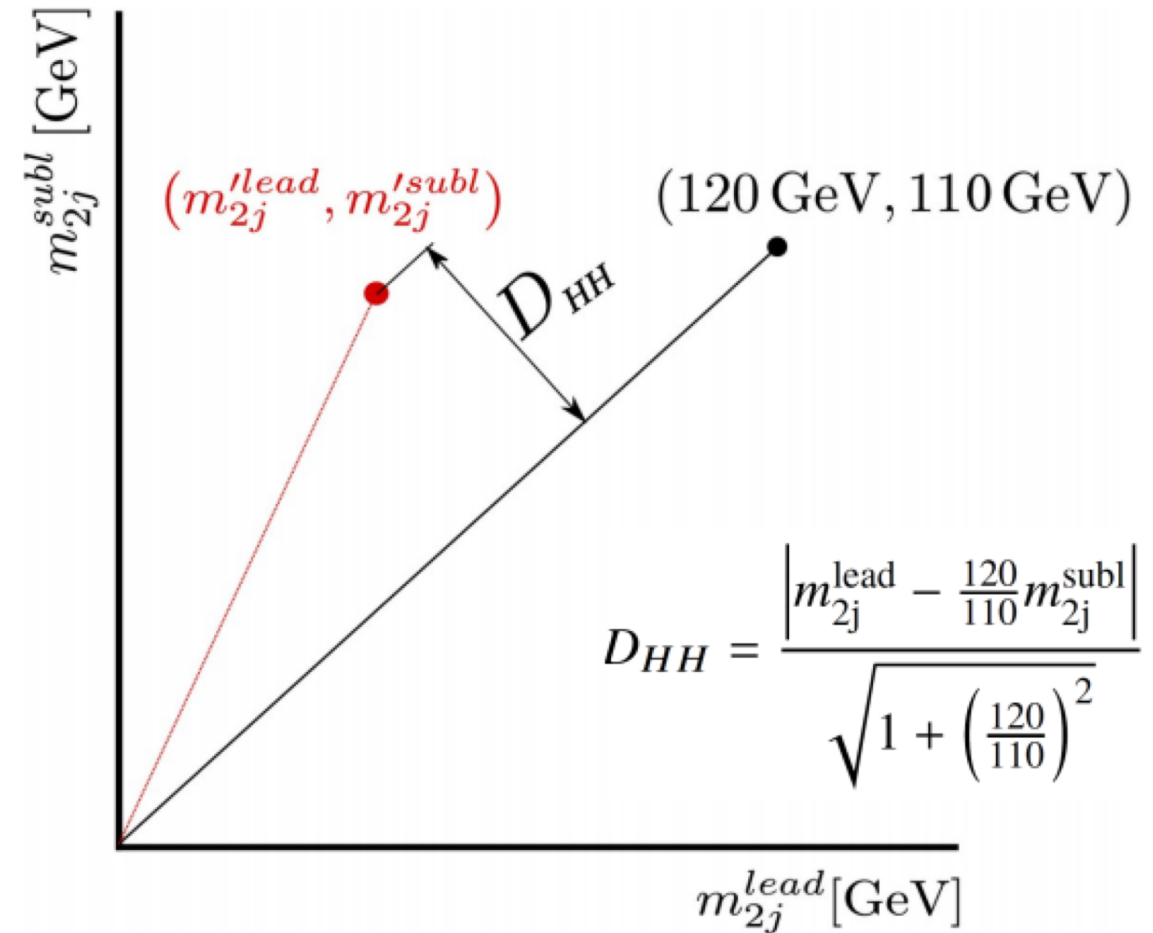


- Boosted
- Cannot resolve the 2 b-jets  
Final discriminator  $m_{jj}$
- Categories : 2, 3, 4 b-tags  
(2-tags: b from a different Jet)
- Signal hypotheses
  - Resonant signal  
 $m_X$  800-3000 GeV



# bbbb: Resolved analysis

- 3 possible combinations-combinatoric background
  - Need the combination most consistent with a HH topology
  - Select hh pair that has the minimal distance to the diagonal line.  
i.e. minimise  $D_{HH}$
  - In simulation, this leads to at least 90% correct pairings



# bbbb: Resolved analysis

Event selection

$$X_{HH} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 110 \text{ GeV}}{0.1 m_{2j}^{\text{subl}}}\right)^2} < 1.6$$

## QCD multi-jets

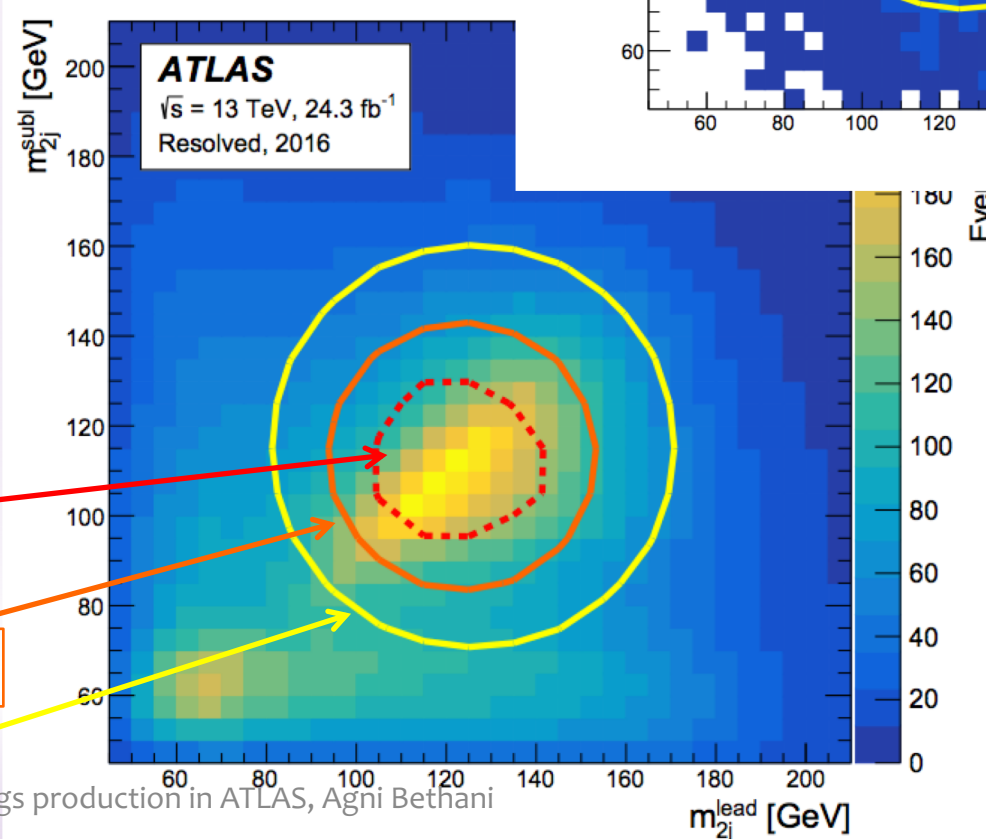
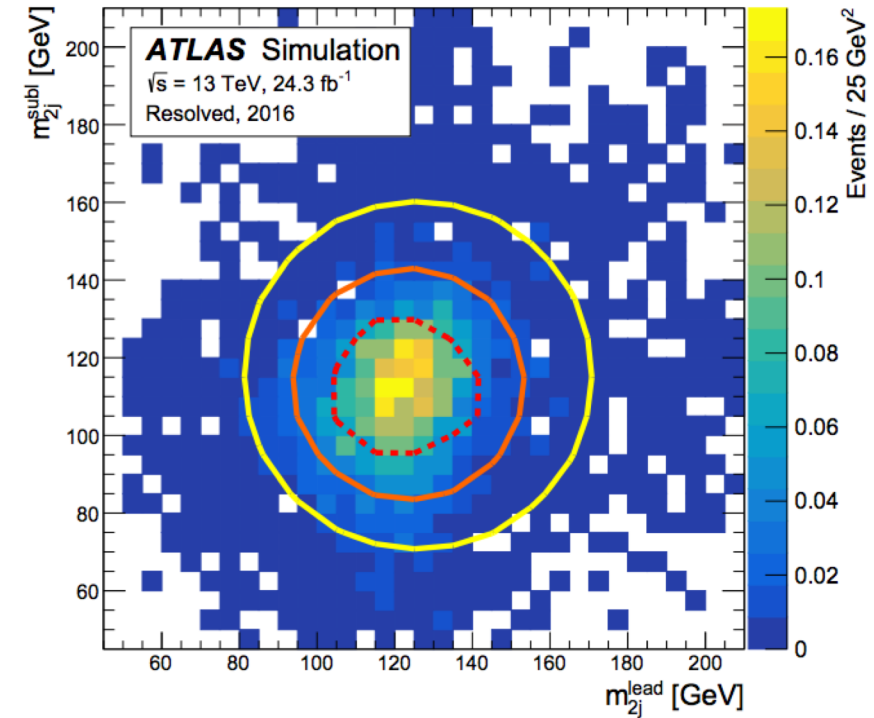
- Use 2-tag sample for shape template
- Weights are applied, estimated in the side band and validated in the control region

## ttbar

- Shape from simulation

## Normalisation

from fit in sidebands



Double Higgs production in ATLAS, Agni Bethani

Signal

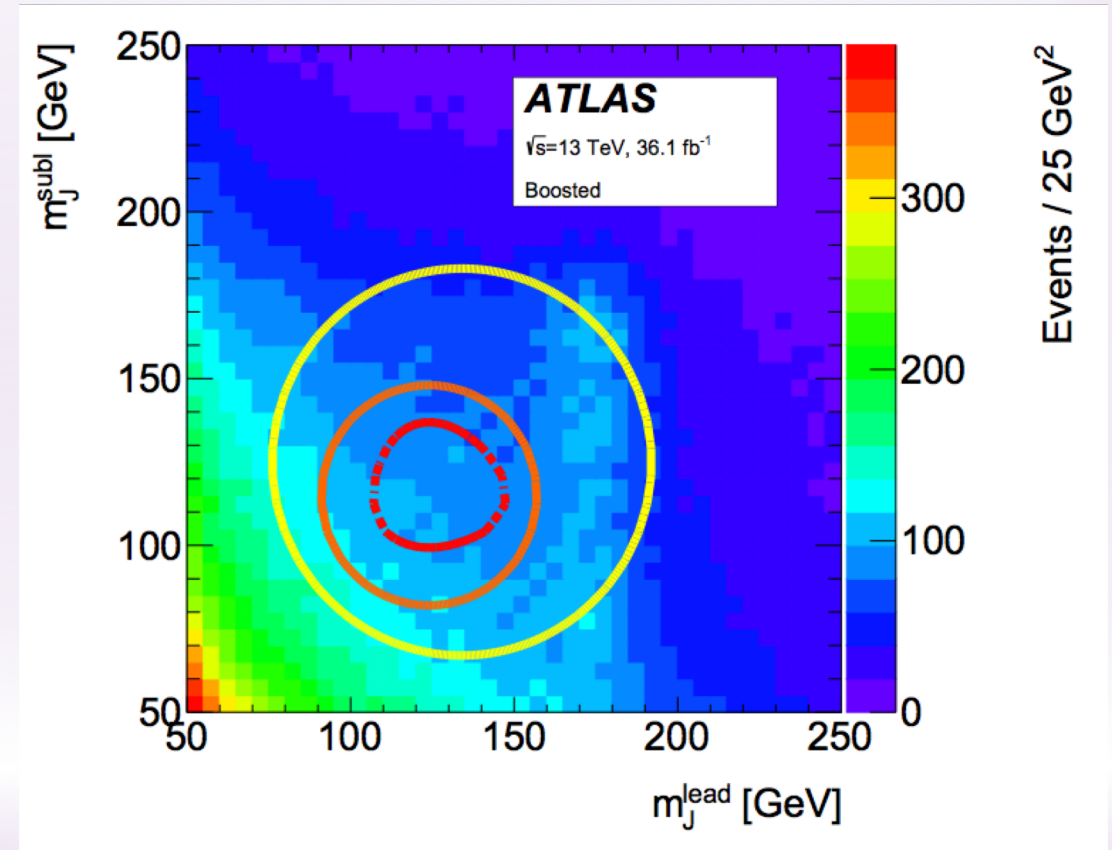
multi-jets

# bbbb: boosted analysis

- The cut  $X_{HH}$  becomes:

$$X_{HH} = \sqrt{\left(\frac{m_J^{\text{lead}} - 124 \text{ GeV}}{0.1 m_J^{\text{lead}}}\right)^2 + \left(\frac{m_J^{\text{subl}} - 115 \text{ GeV}}{0.1 m_J^{\text{subl}}}\right)^2} < 1.6,$$

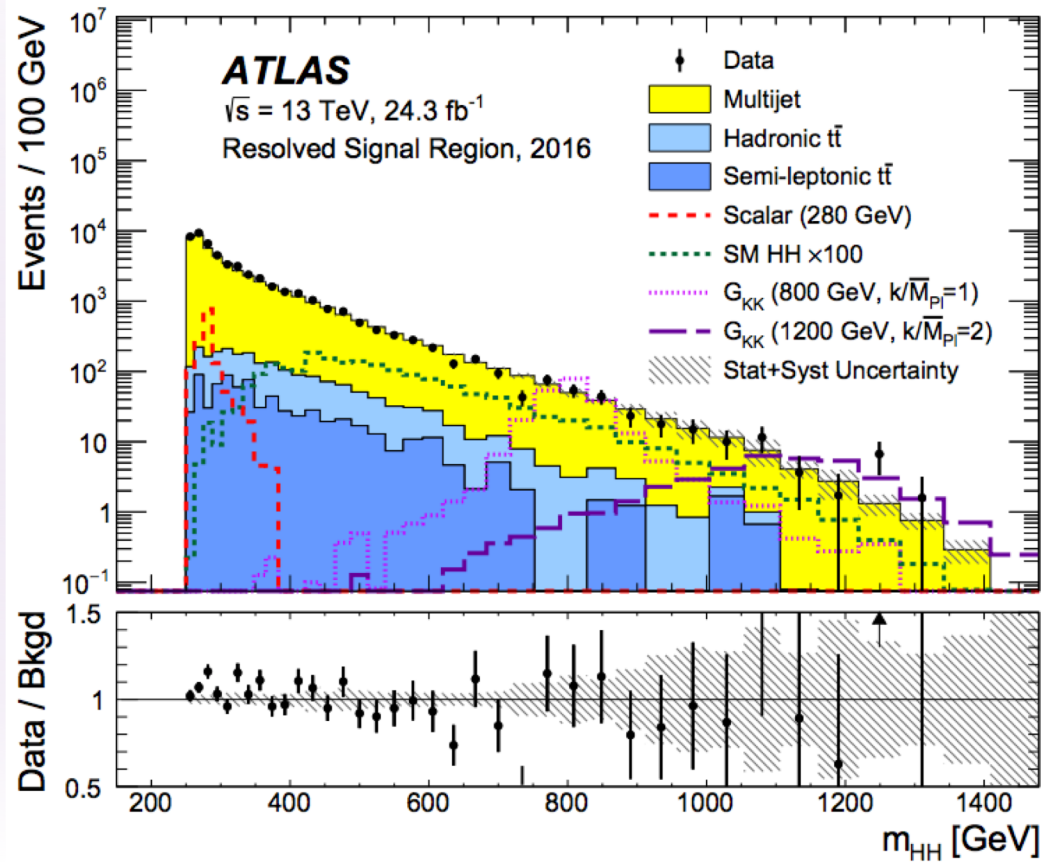
- Shape of multijets using events with less b-tags.  
(e.g. 2 b-tag category using 1 b-tag events)
- $t\bar{t}$  from simulation
- Normalisation from side band



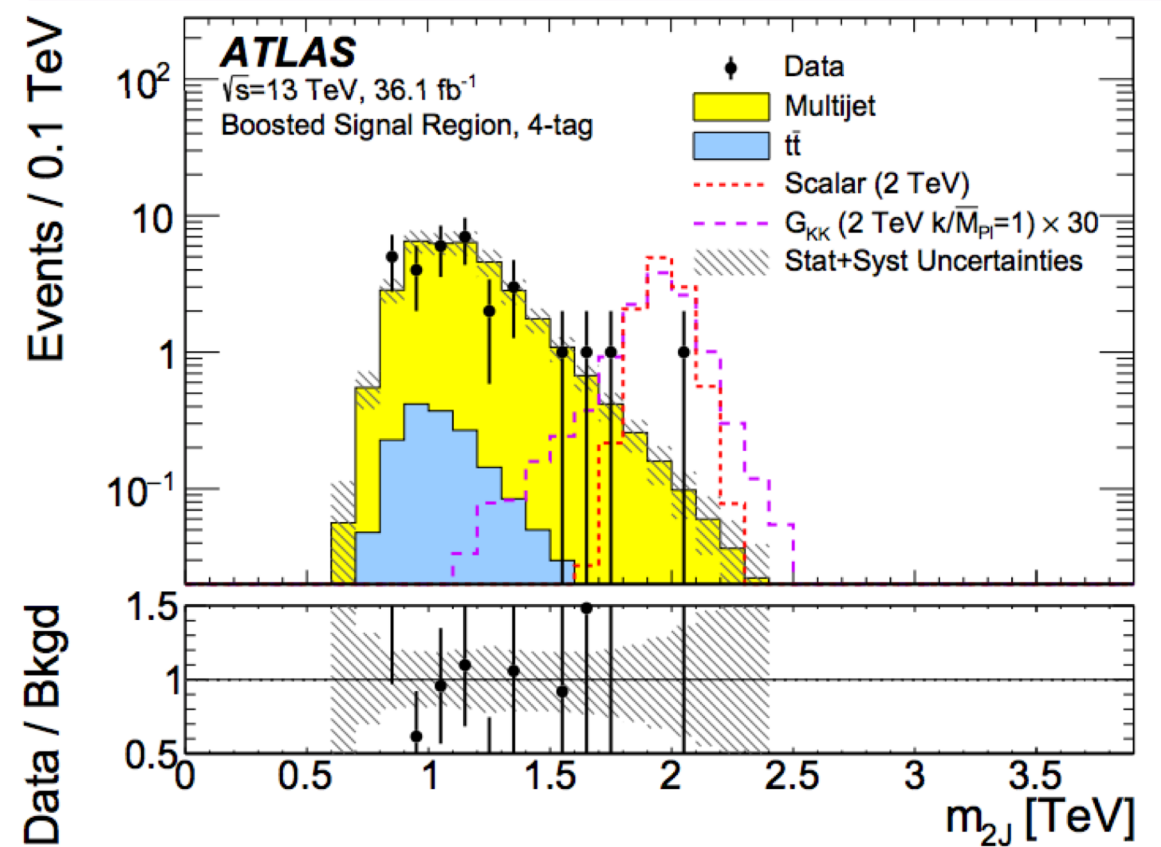


# bbbb discriminants

Resolved 2016 dataset



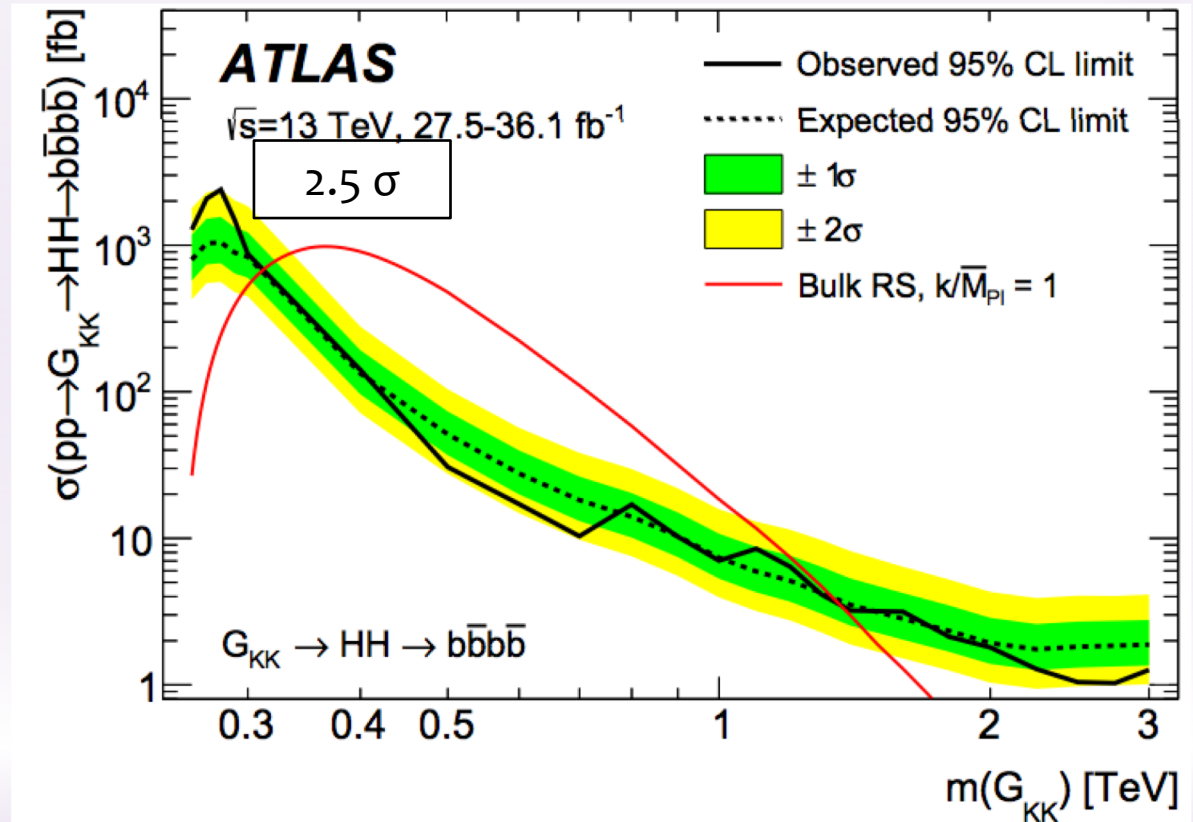
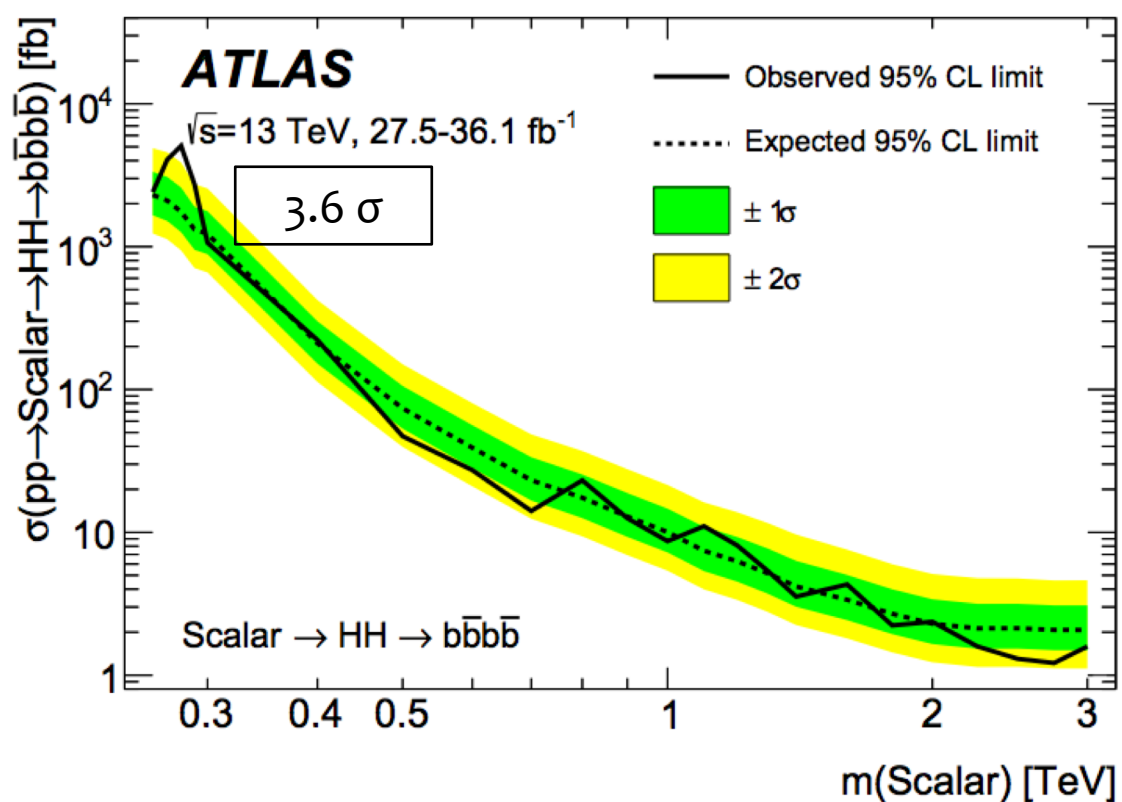
Boosted, 4b-tag category



# bbbb results

Non-resonant limits on  $\sigma/\sigma_{SM}$

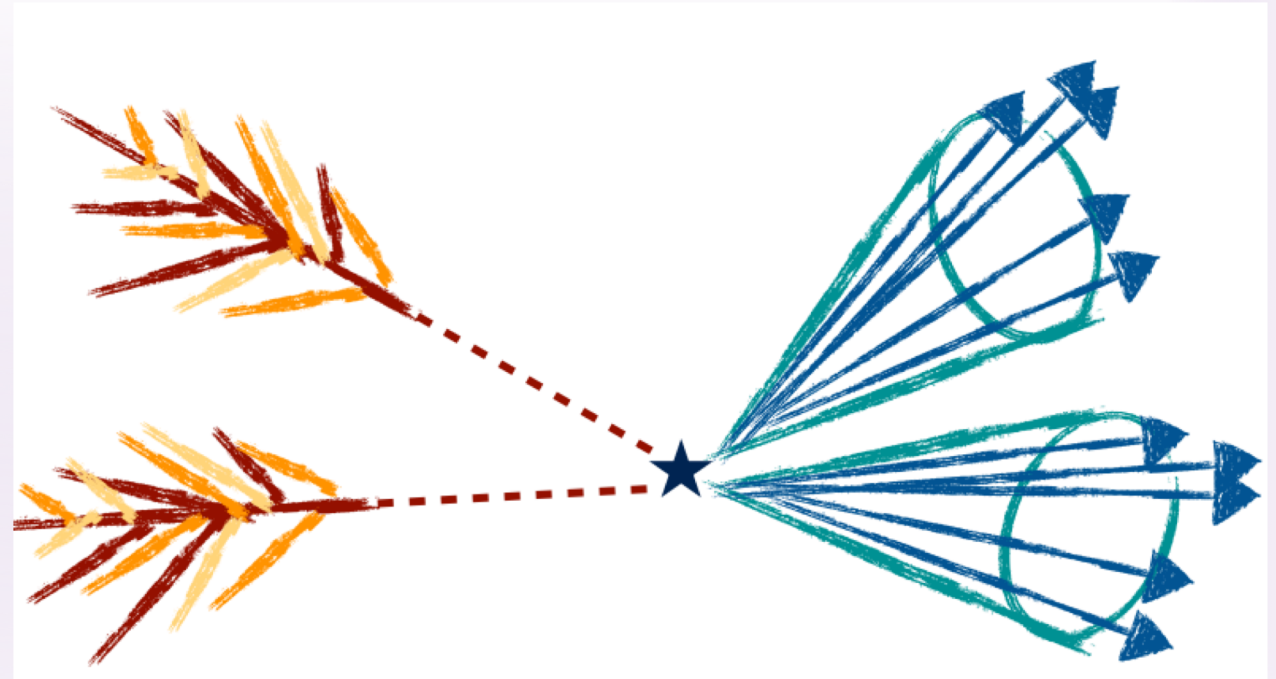
| Observed | $-2\sigma$ | $-1\sigma$ | Expected | $+1\sigma$ | $+2\sigma$ |
|----------|------------|------------|----------|------------|------------|
| 13.0     | 11.1       | 14.9       | 20.7     | 30.0       | 43.5       |



# $b\bar{b}\gamma\gamma$ final state

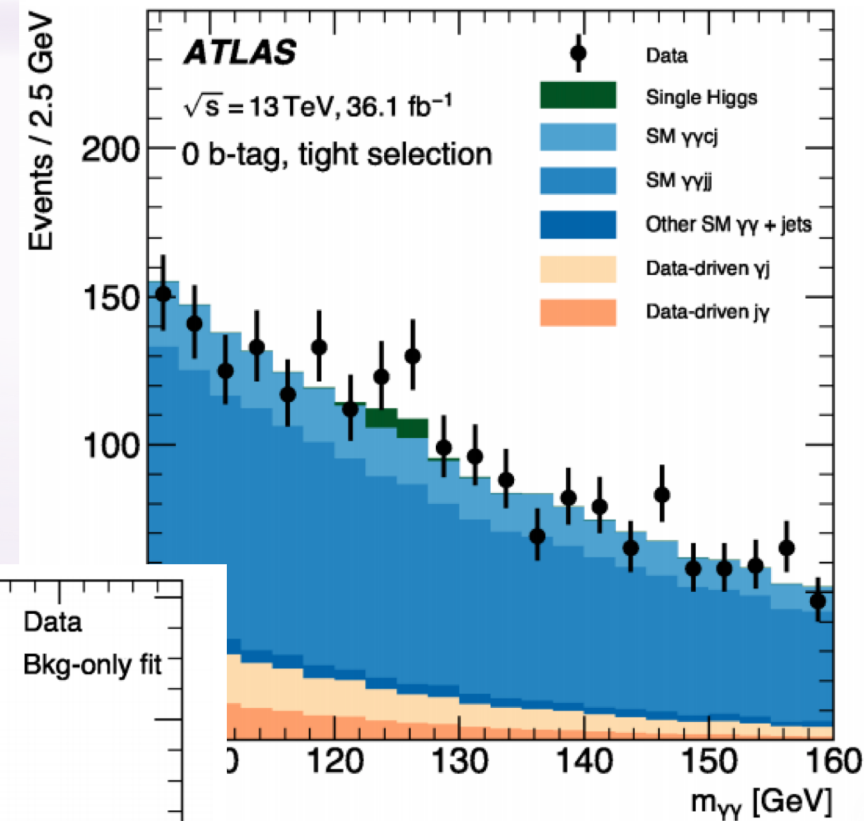
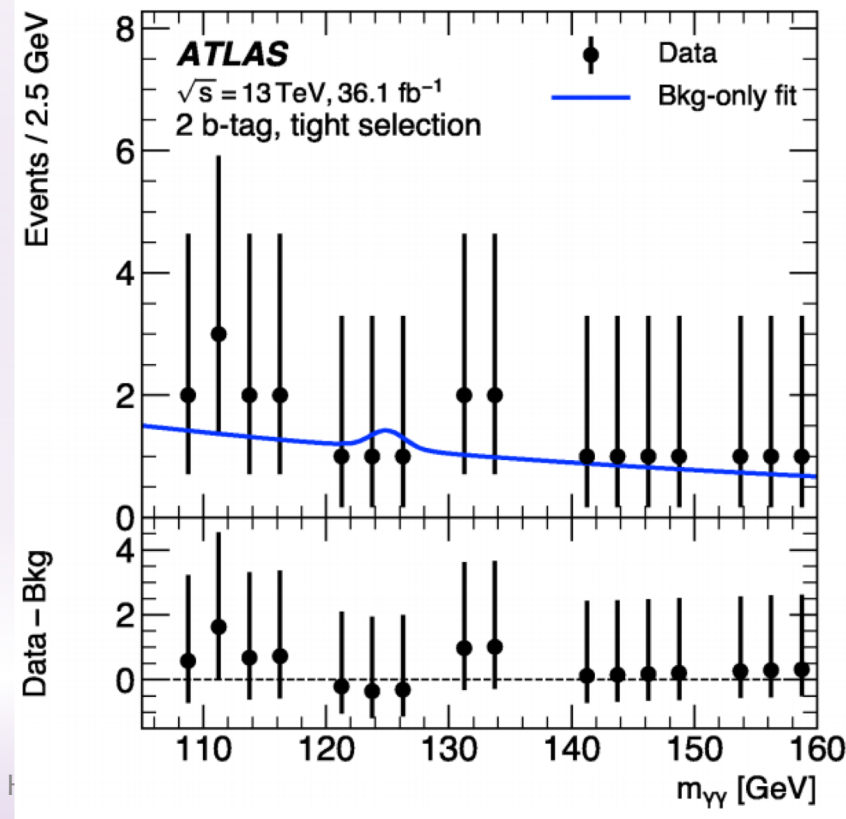
<https://arxiv.org/pdf/1807.04873.pdf>

- 2 photons and jets
- Exploiting 2 b-jet and 1 b-jet categories
  - Additional categories (loose and tight) based on jet  $p_T$
- Non-resonant and resonant signal search
- Resonant mass range 260-1000 GeV



# $b\bar{b}\gamma\gamma$

- Backgrounds:
  - continuum multi-jet
  - multi-photon (gg, gj, jj, w/ j→g, etc.)
  - Single Higgs: ttH, ZH, ggH
- Reweight MC to data in 0 b-tag region
- Background modeling: exponential + double-sided crystal ball
- Signal modeling: double sided crystal ball



Final discriminant  
For non-resonant  
signal



# bb $\gamma\gamma$ results

Non-resonant:

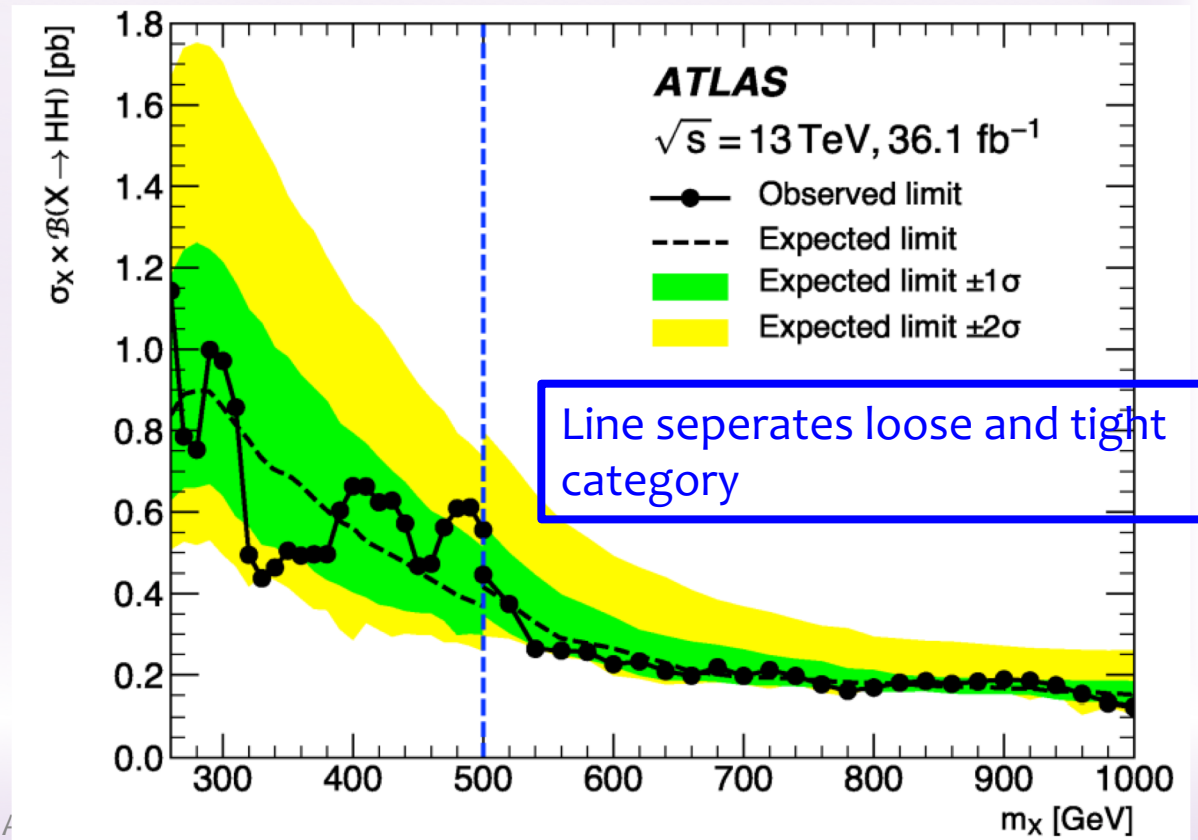
Final discriminant  $m_{\gamma\gamma}$  with  $m_{bb}=125\text{GeV}$

Non-resonant limits on  $\sigma/\sigma_{\text{SM}}$

|                                       | Observed | Expected | $-1\sigma$ | $+1\sigma$ |
|---------------------------------------|----------|----------|------------|------------|
| $\sigma_{gg \rightarrow HH}$ [pb]     | 0.73     | 0.93     | 0.66       | 1.4        |
| As a multiple of $\sigma_{\text{SM}}$ | 22       | 28       | 20         | 40         |

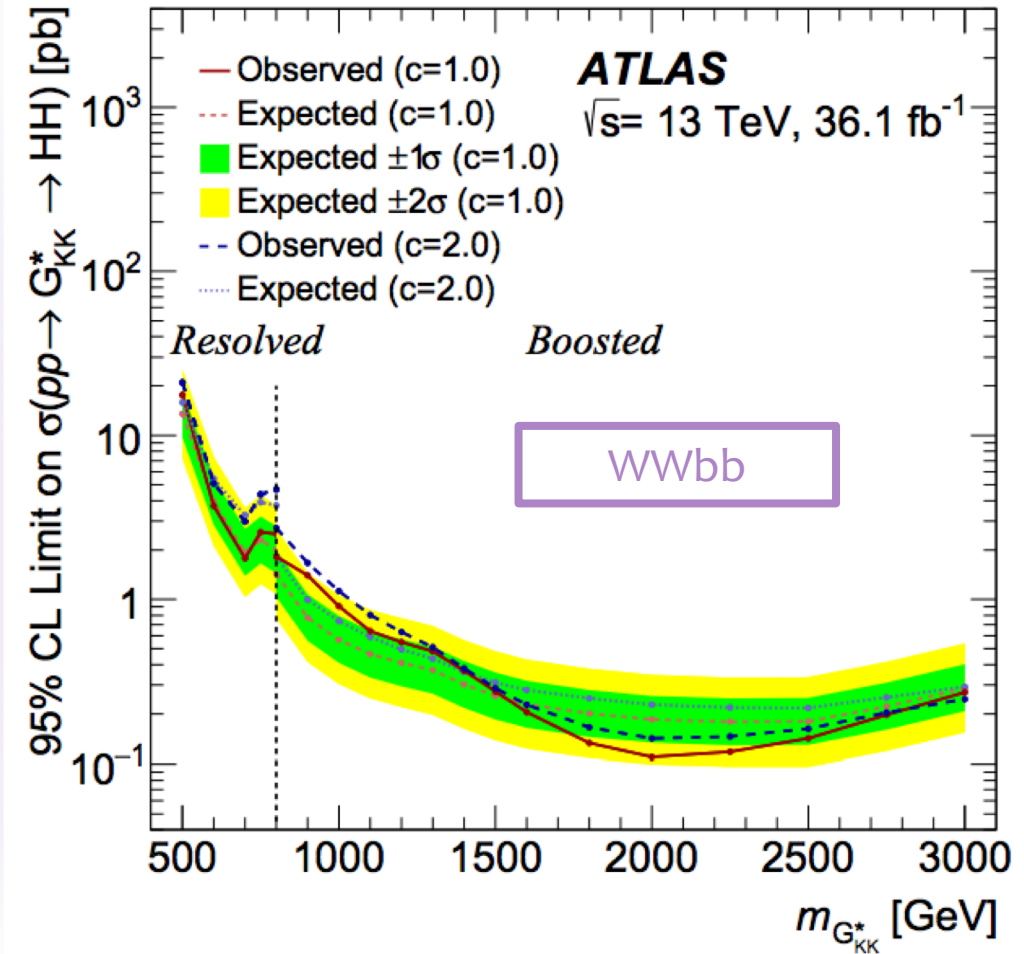
Resonant:

Final discriminant  $m_{\gamma\gamma jj}$  with  $m_{\gamma\gamma}=m_{bb}=125\text{GeV}$



# WWbb, WW $\gamma\gamma$ and WW

- Non included in the combination
- Will become interesting with more data (and energy in the future!)
- Fresh results!
- WWbb <https://arxiv.org/abs/1811.04671>
  - 300 (exp. 300)  $\times \sigma_{SM}$
- WW $\gamma\gamma$  <https://arxiv.org/abs/1807.08567>
  - 230(exp. 160)  $\times \sigma_{SM}$
- WWW on the way too!



# ATLAS combined result

$b\bar{b}\tau\tau$ ,  $b\bar{b}b\bar{b}$  and  $b\bar{b}\gamma\gamma$

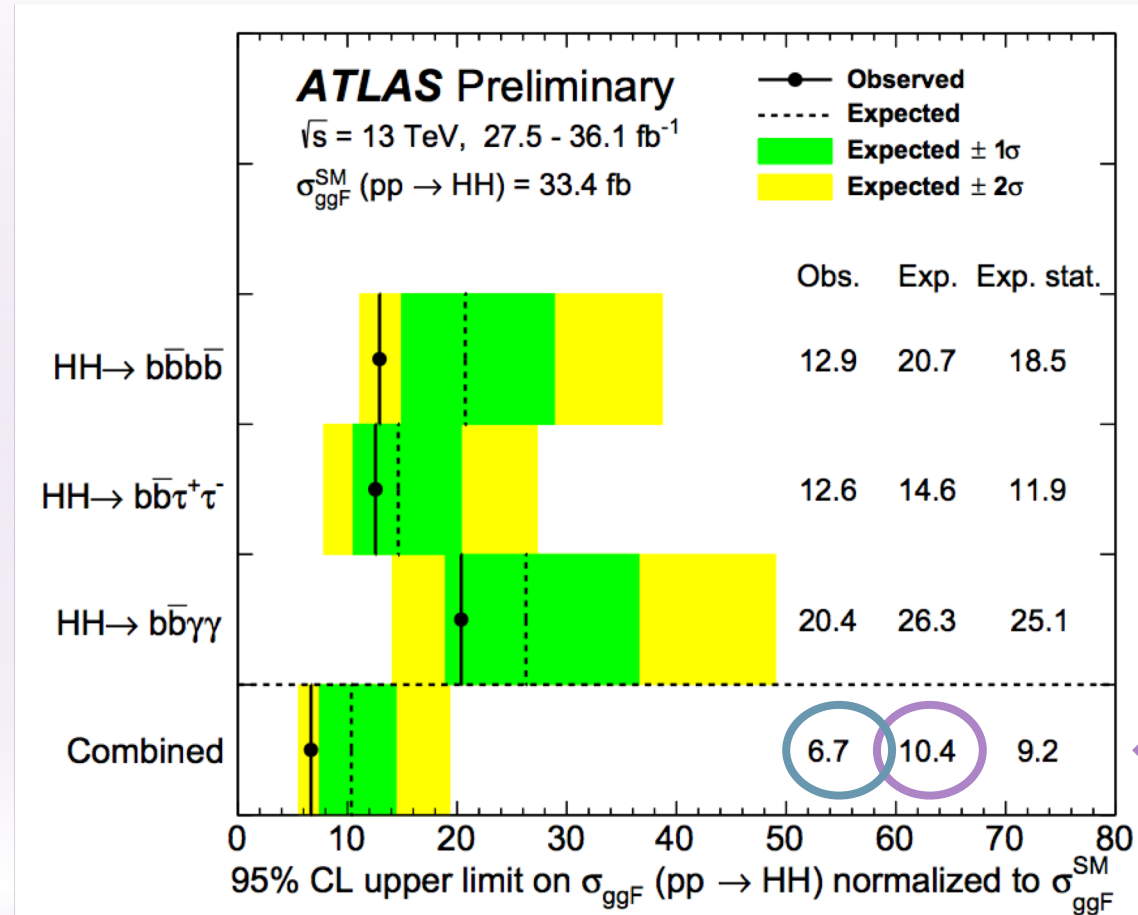
[ATLAS-CONF-2018-043](#)

# HH combination

- $b\bar{b}b\bar{b}$ ,  $b\bar{b}\tau\tau$ ,  $b\bar{b}\gamma\gamma$  are included in the combination.
- integrated luminosity of  $36.1 \text{ fb}^{-1}$
- The combination is realised by constructing a combined likelihood function that takes into account data, models and systematic uncertainties
- All the signal regions considered are orthogonal, or have negligible overlap.
- Instrumental and luminosity uncertainties correlated across the channels.
- The acceptance and the background modeling uncertainties are treated as uncorrelated.
- Theoretical uncertainties on the total signal cross-section are not considered.



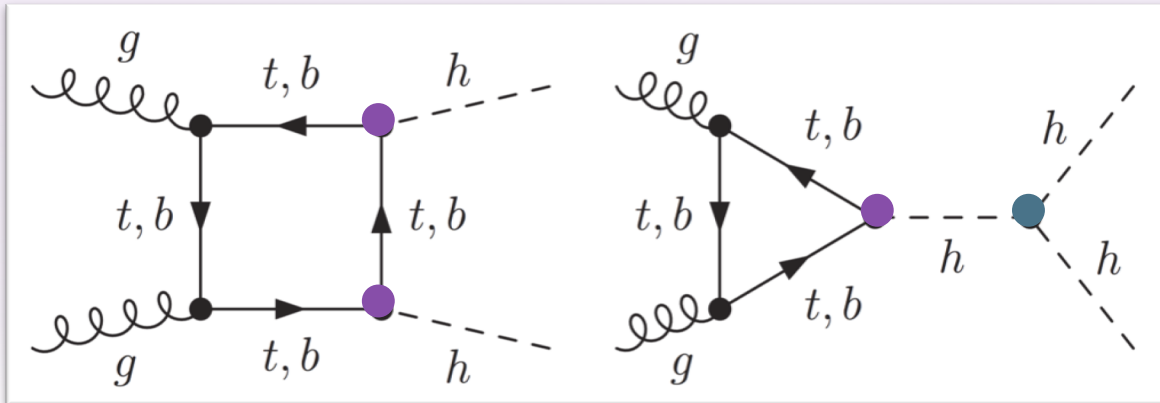
# HH combined result for non-resonant production



# Varying the Higgs coupling

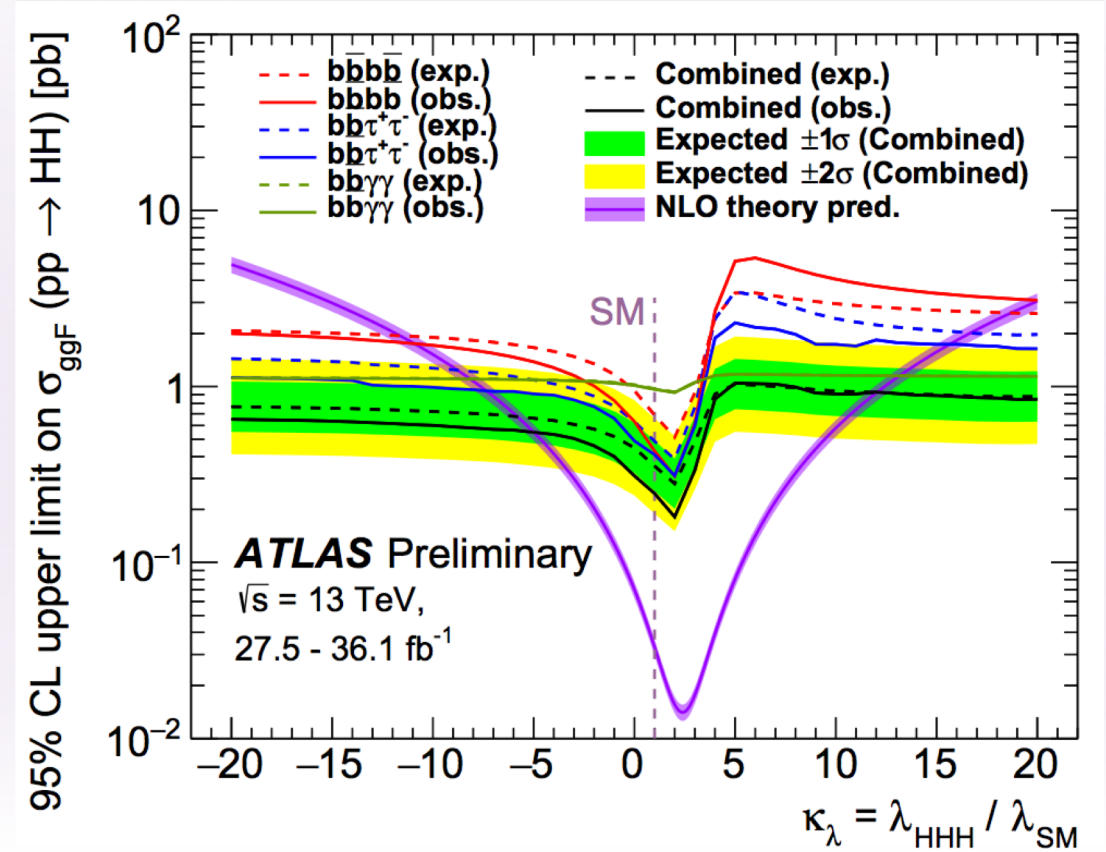
- Using scale factors:  
 $\kappa_t = g_{ttH} / g_{ttH}^{SM}$  and  $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$
- $A(\kappa_t, \kappa_\lambda) = \kappa_t^2 B + \kappa_t \kappa_\lambda T$

We consider  $\kappa_t=1$  (i.e. Higgs-top coupling set to its SM value)



# Constraints on $\kappa_\lambda$

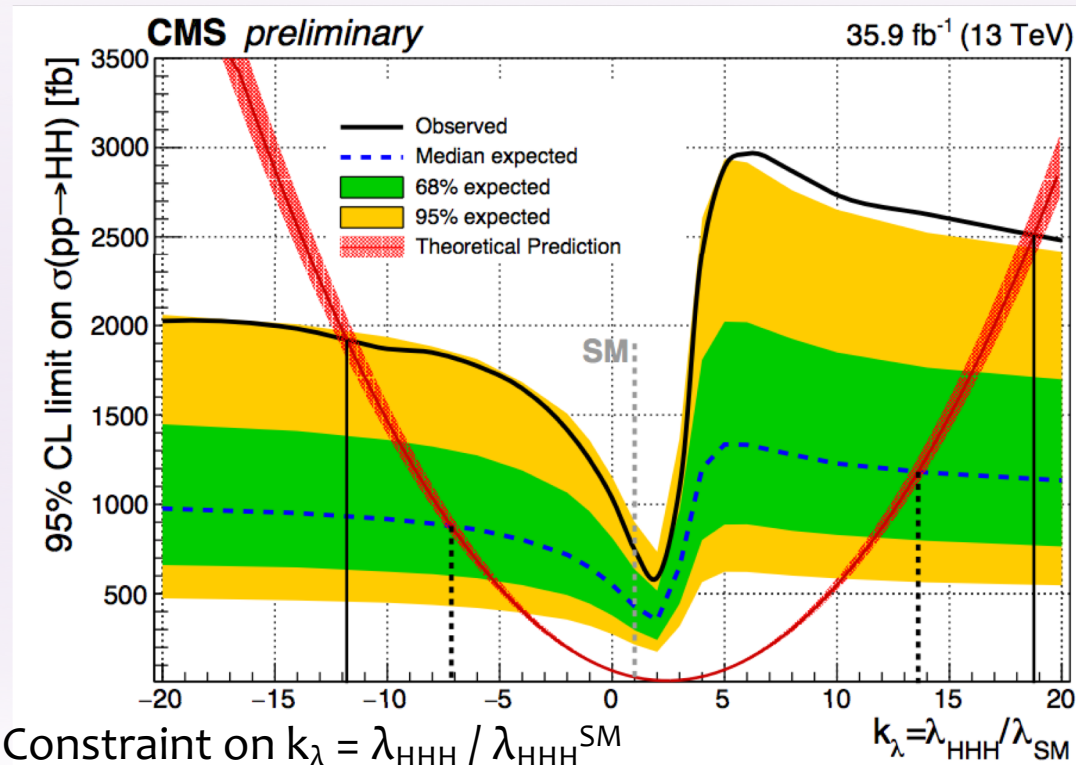
- **4b** **bb $\tau\tau$**  **bb $\gamma\gamma$**  combination
- dashed: expected  
solid: observed
- Observed (expected)  
constraints on scale factor  $\kappa_\lambda$ :  
 $-5.0 < \kappa_\lambda < 12.1$  ( $-5.8 < \kappa_\lambda < 12.0$ )



# Combined CMS result

Combined limit on  $\sigma / \sigma^{\text{SM}}$

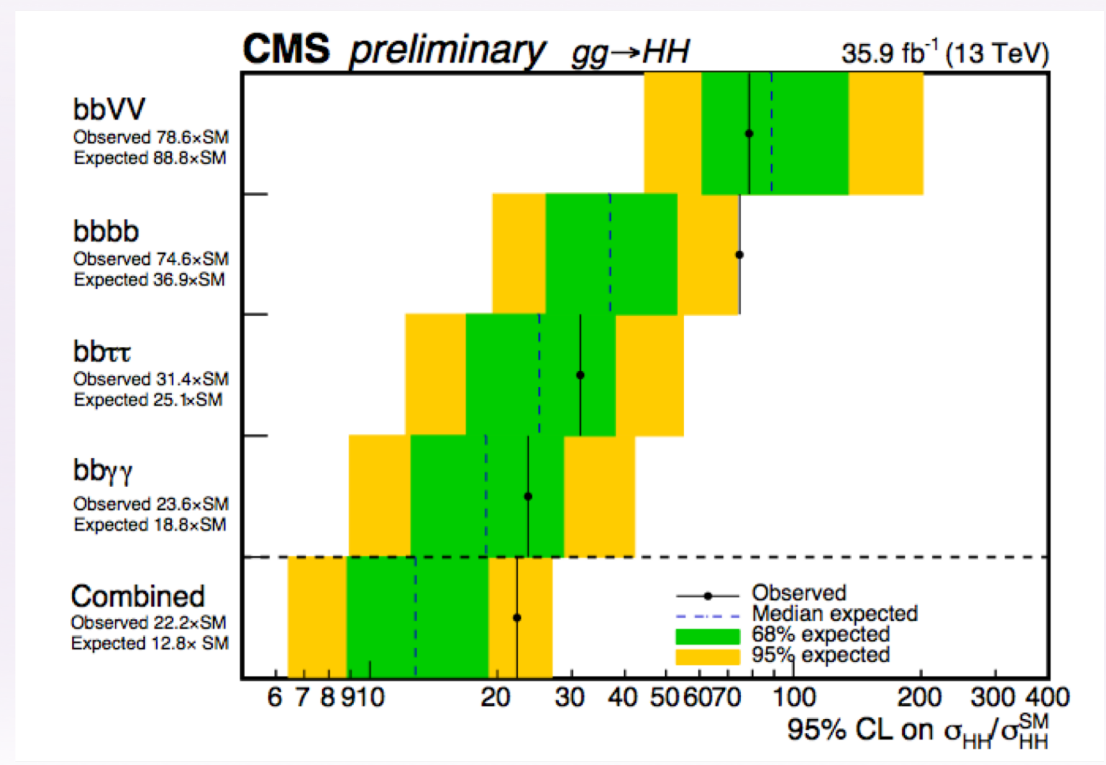
**Observed : 22.2 Expected : 12.8**



Constraint on  $k_\lambda = \lambda_{\text{HHH}} / \lambda_{\text{HHH}}^{\text{SM}}$

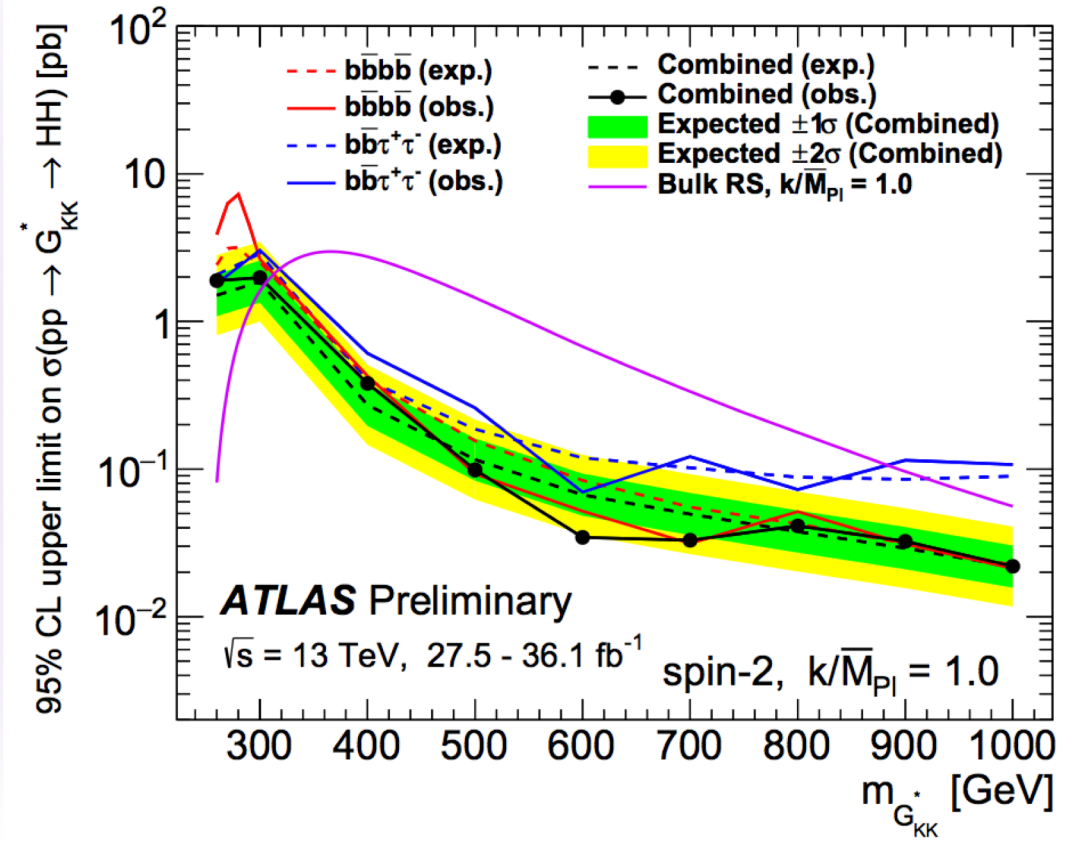
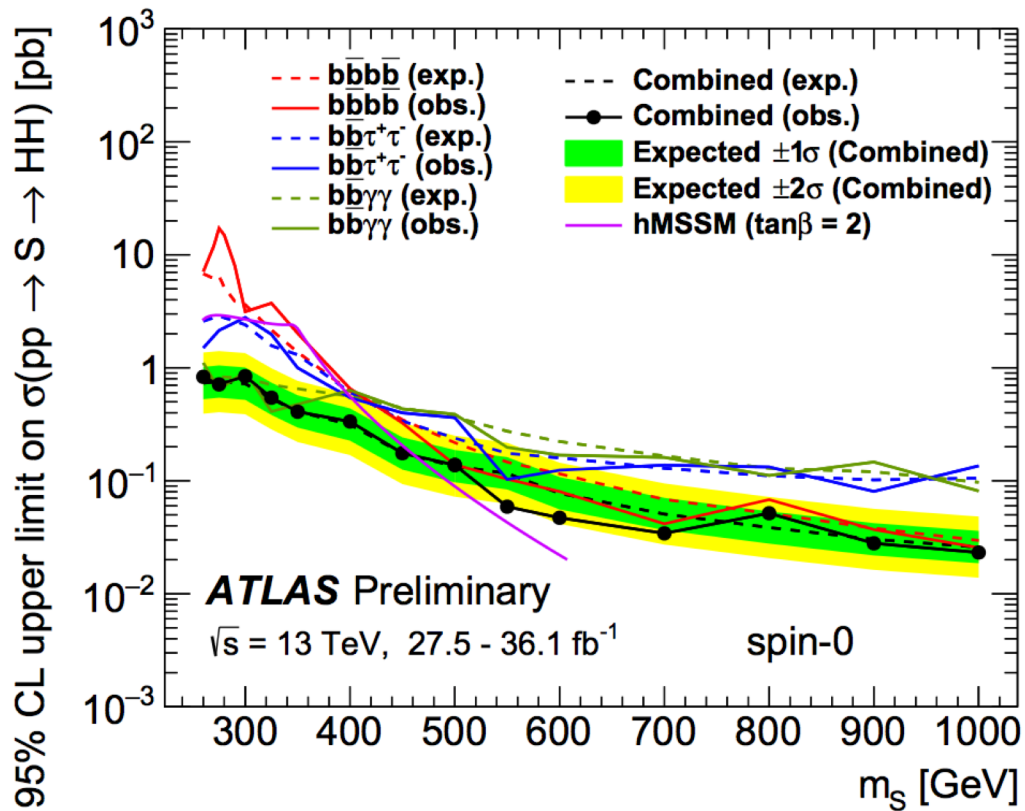
Observed :  $-11.8 < k_\lambda < 18.8$

Expected :  $-7.1 < k_\lambda < 13.6$





# HH combined result for resonant production



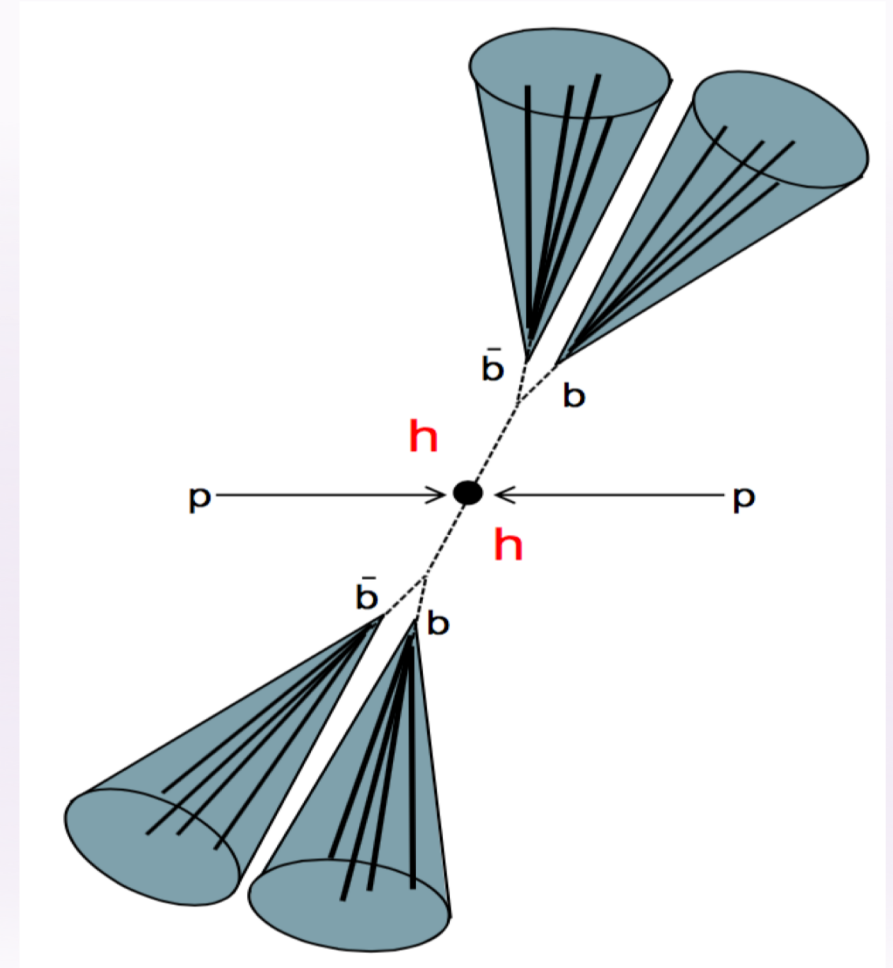
# HL-LHC prospects

- bbbb and bbyy published in ATLAS PIXEL TDR (CERN-LHCC-2017-021)



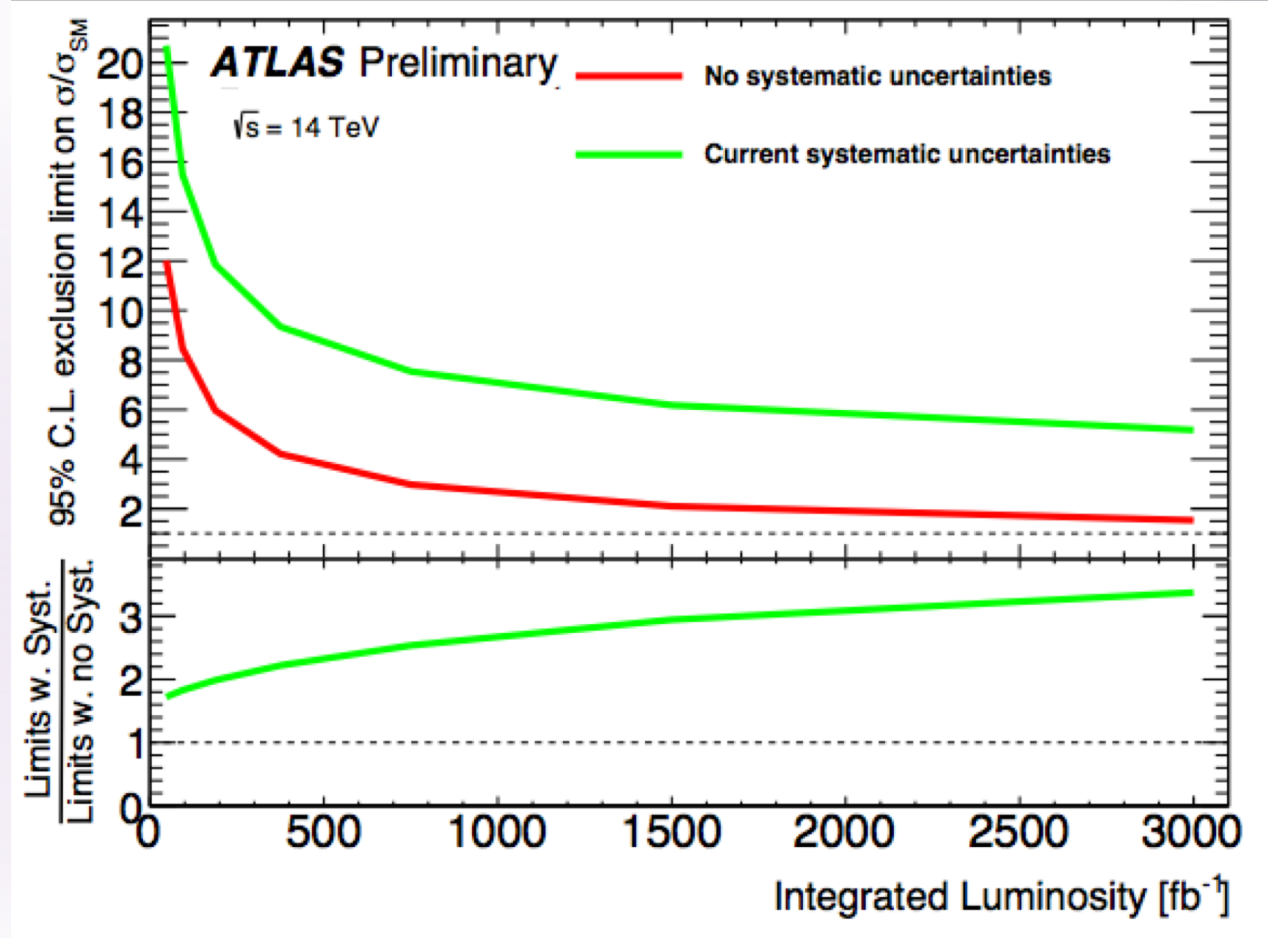
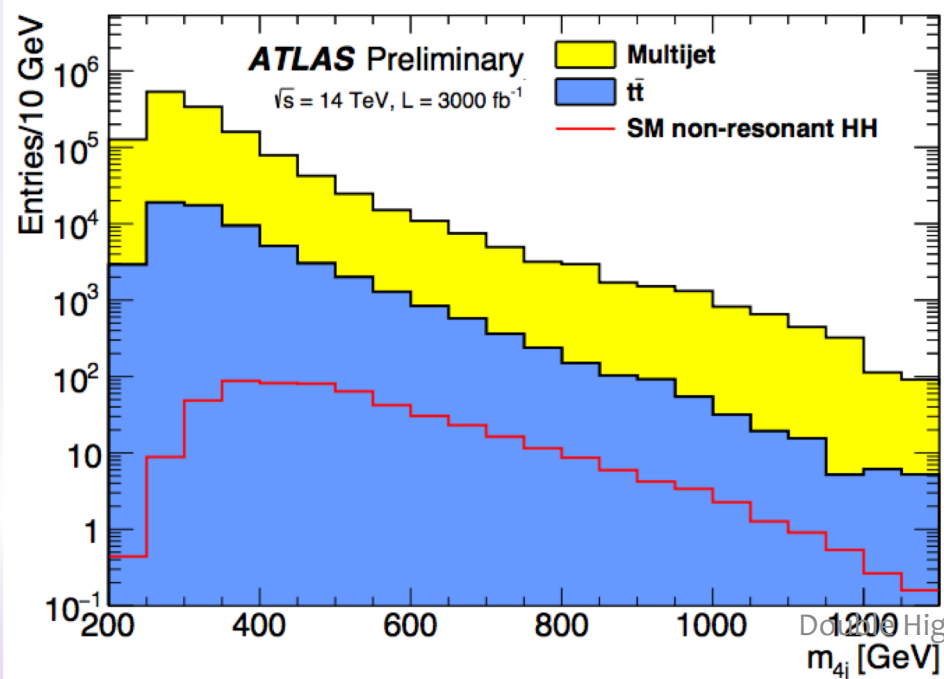
# bbbb at HL-LHC

- extrapolation of the Run-2 result:  
 $L = 24.3 \rightarrow L = 3000 \text{ fb}^{-1}$
- Signal and background distributions scaled by  
 $f = L_{\text{target}}/L_{\text{current}}$
- Background distributions scaled by 1.18 to account for an increase in cross-section
- Normalizations fixed to the best Run-2 fit values
- Pixel TDR detector layout  $\rightarrow$  improved b-tagging performance (8% per b-jet)



# bbbb analysis

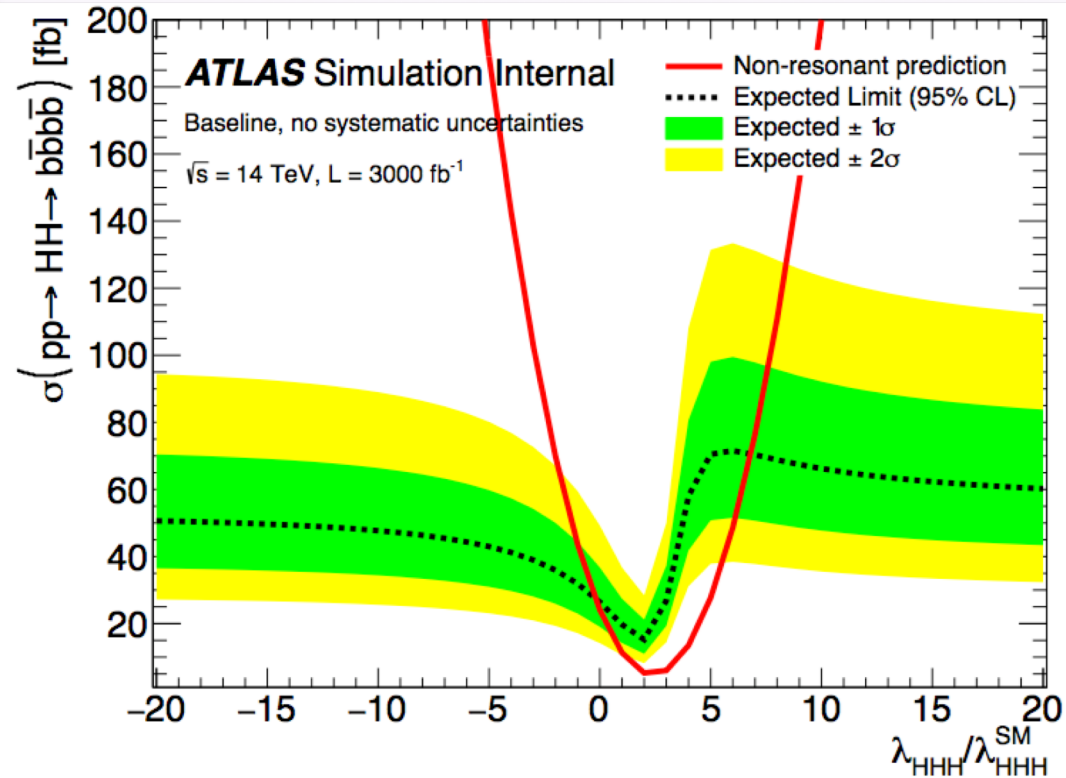
- “Resolved” analysis method used (not boosted reconstruction of four jets)
- Background:  
~ 95% multijet and ~ 5% ttbar
- Extrapolation of the 95% C.L. exclusion limit:  
without systematics:  $\sigma/\sigma_{\text{SM}}=1.5$   
with current level of systematics:  $\sigma/\sigma_{\text{SM}}=5.2$



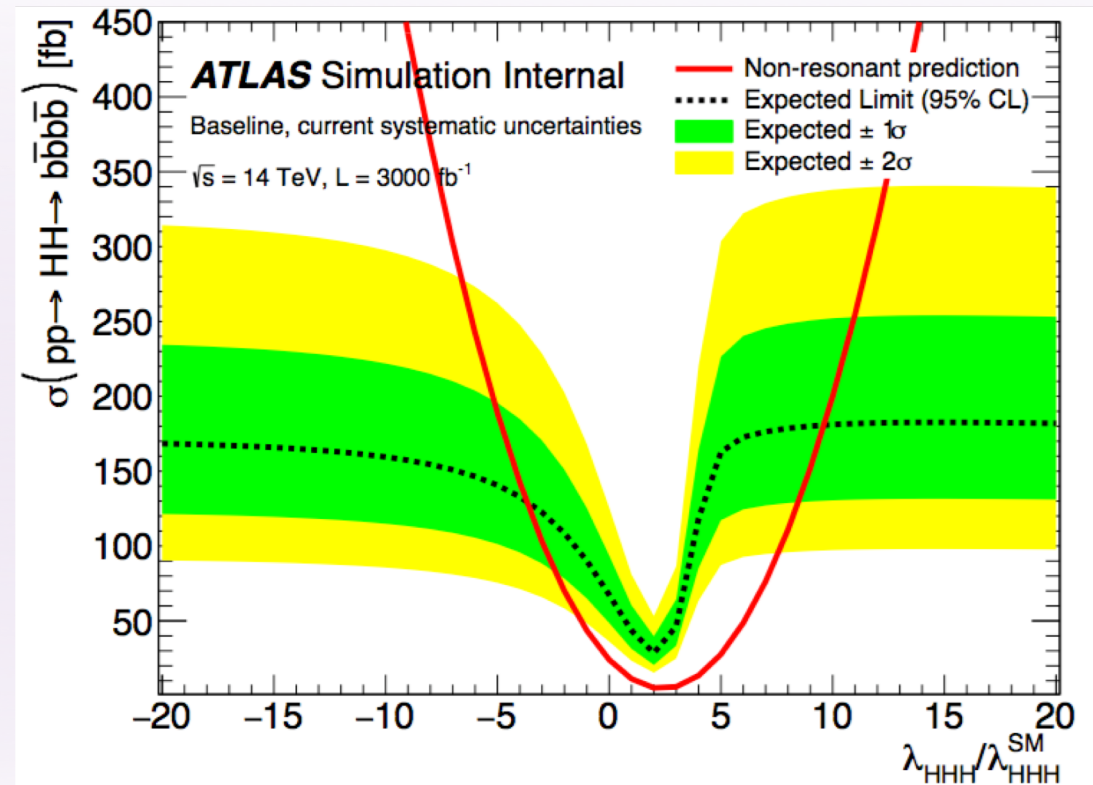


# bbbb results

No systematics



Current systematics



without systematics:  $0.2 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 7.0$

with systematics:  $-3.5 < \lambda_{hhh}/\lambda_{hhh}^{SM} < 11.0$

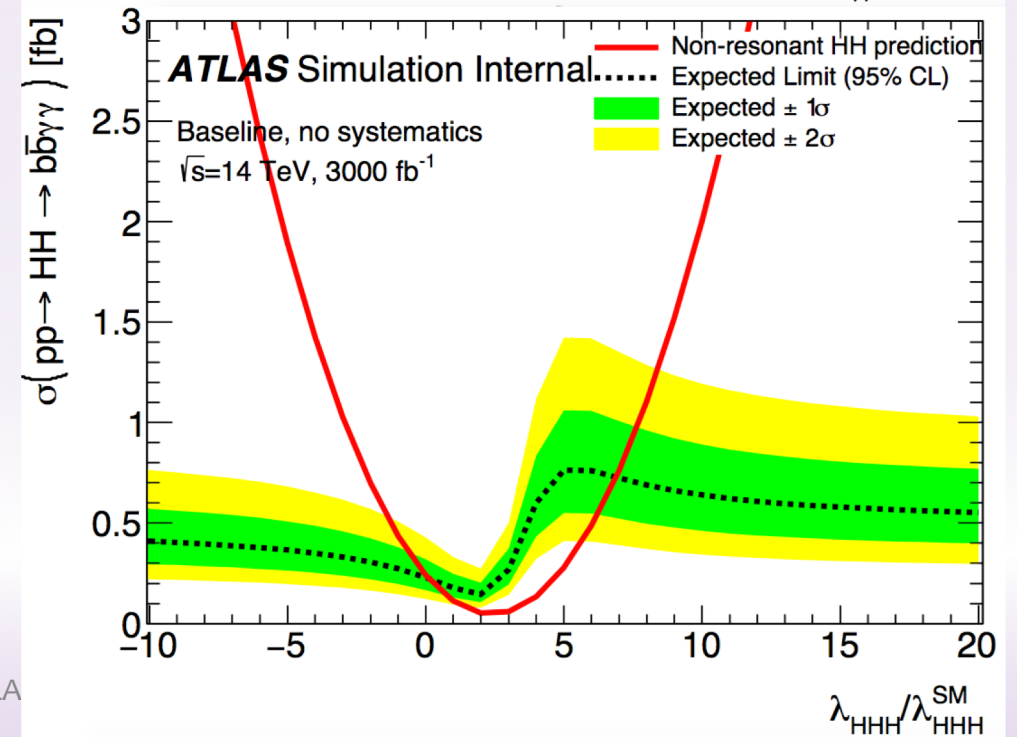
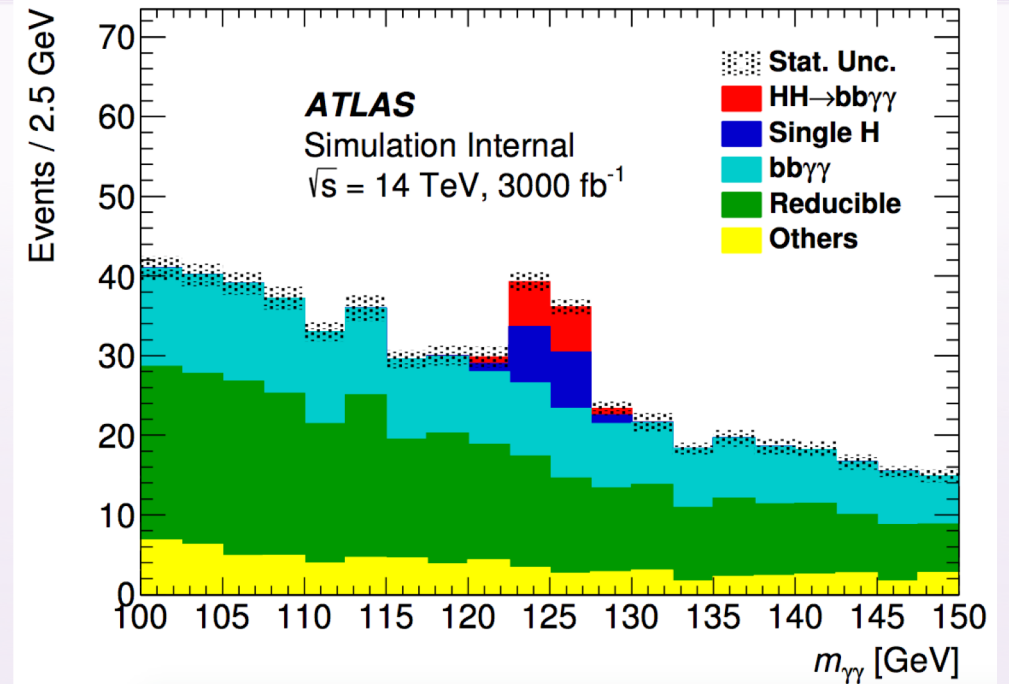
# $b\bar{b}\gamma\gamma$ at HL-LHC

- Study based on  $\sqrt{s} = 14$  TeV Monte Carlo simulations
- The final state particles at truth level are smeared according to the expected detector resolutions assuming a pile-up scenario with 200 overlapping events ( $\langle \mu \rangle = 200$ ).
- The expected efficiencies and fake rates for identifying b-jets and photons are used.
- Upgrade performance functions provide parameterized estimates of ATLAS performance for HL-LHC (resolution, efficiencies, fake rates)

# bb $\gamma\gamma$ results

- processes with multiple jets and photons
- Continuum background (exponential) subtracted
- Fit performed on  $m_{\gamma\gamma}$  distribution
- Signal and single Higgs background modeled as Gaussians

Expected sensitivity is  
no systematics **1.5 $\sigma$**   
Higgs boson self-coupling constrained:  
no systematics: **-0.2 <  $\lambda_{HHH}/\lambda_{HHH}^{SM}$  < 6.9**



# Summary and outlook

- ATLAS provides the best limit on HH production cross-section!  
 $\sigma/\sigma^{\text{SM}} < 6.7$  (expected 10.4)
- $b\bar{b}\tau\tau$ ,  $b\bar{b}b\bar{b}$  and  $b\bar{b}\gamma\gamma$  contribute to the combination
- $b\bar{b}\tau\tau$  is the most sensitive channel providing alone:  
 $\sigma/\sigma^{\text{SM}} < 12.7$  (expected 14.8)
- The CMS combined result is  $\sigma/\sigma^{\text{SM}} < 22.5$  (expected 12.8)
- New results on more channels  $WWb\bar{b}$ ,  $WW\gamma\gamma$  and soon  $WWWW$
- HL-prospects studies performed on  $b\bar{b}b\bar{b}$  and  $b\bar{b}\gamma\gamma$   
(and  $b\bar{b}\tau\tau$  and combined but not public yet. Stay tuned!)
- More channels and production mechanisms to be included for the end of Run2 analyses (~ about a year's time)
- Future colliders will come into play later, with a rich Higgs physics program too!

Thank you for your attention



# Backup material

# Missing Mass Calculator (MMC)

- Algorithm developed for  $\tau$  decays that involve neutrinos
- The algorithm assumes that the missing energy is entirely due to neutrinos and performs a scan on the angles between the neutrino and the visible tau decay products.
- Each solution is weighted according to probability density functions that are derived from simulated  $\tau$  decays.

