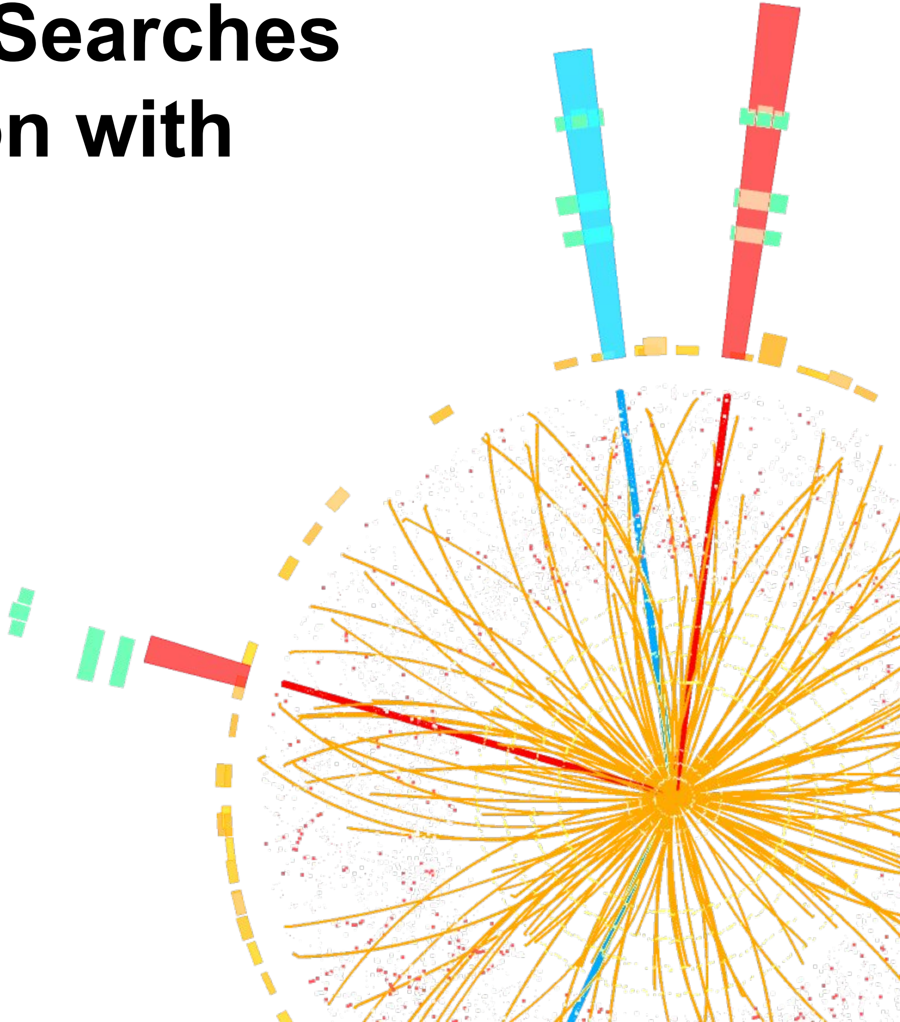
A Tale of Two Theories: Searches For Higgs Pair Production with the ATLAS Detector

November 27th, 2017

THE OHIO STATE UNIVERSITY

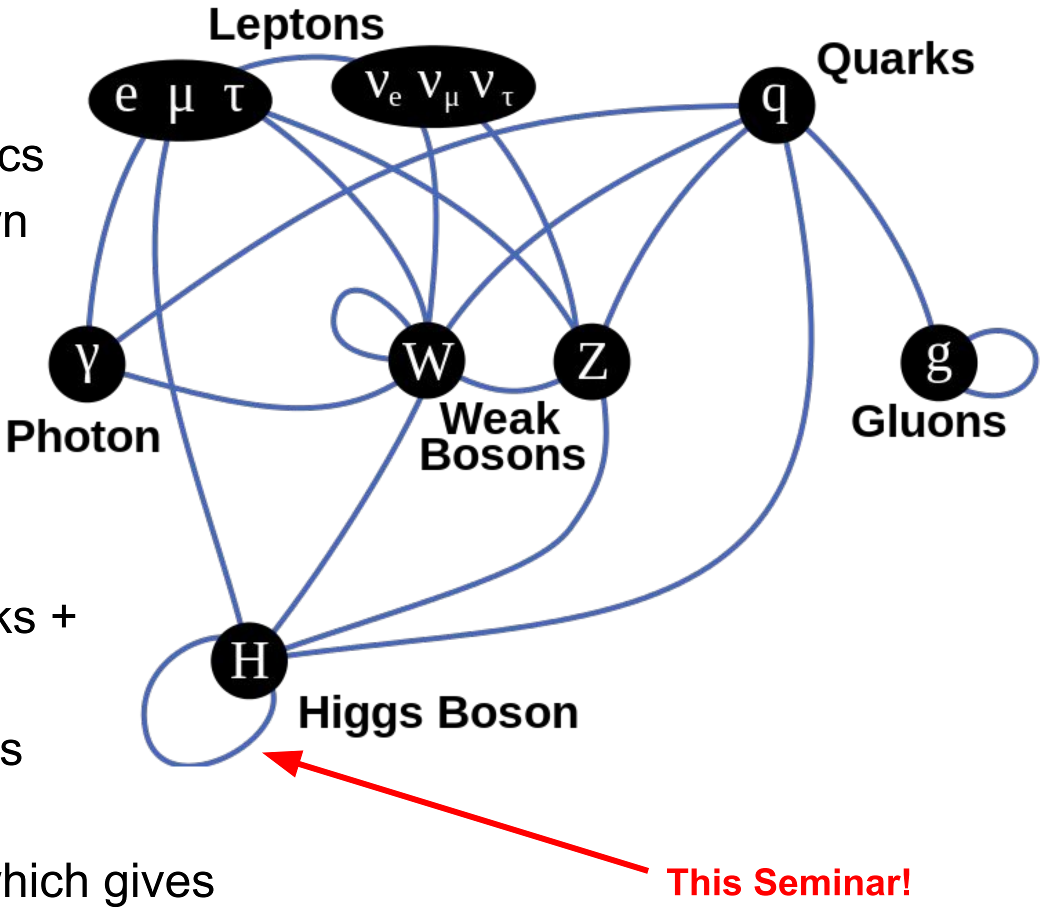
ATLAS EXPERIMENT

Benjamin Tannenwald



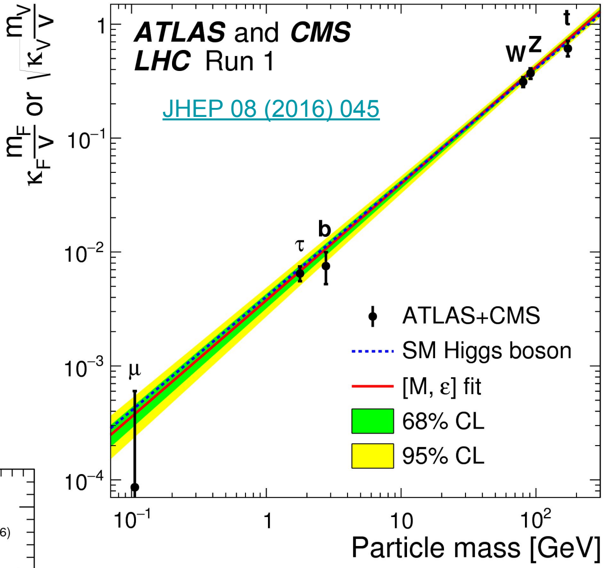
The ‘First’ Theory

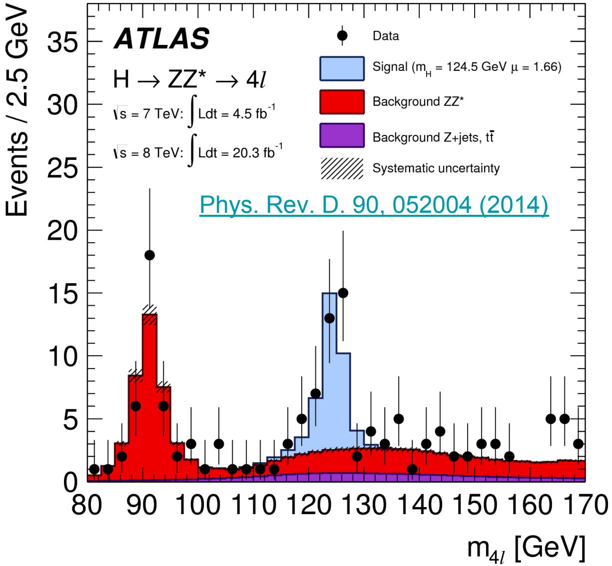
- Standard Model of particle physics
- Describes three of the four known forces (electromagnetic, strong and weak interactions)
- It’s predictions have been tested and found accurate to an impressive degree
- Three families of fermions (quarks + leptons)
- Gluons, photons and W/Z bosons mediate forces (spin-1 bosons)
- Higgs boson is product of field which gives particles their fundamental mass (spin-0 boson)

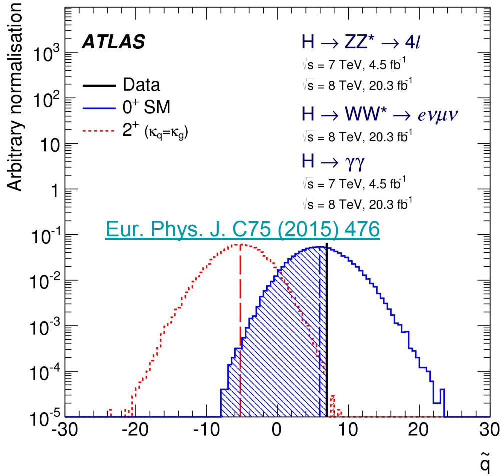


2012: A Higgs Odyssey

- Higgs boson discovered by ATLAS and CMS in 2012
- Many parameters already well measured
  - Mass
  - Spin/CP
  - Couplings to other SM particles
- We are moving from an era focused on Higgs discovery to an era of Higgs exploration
  - Using the Higgs to test new areas of the Standard Model

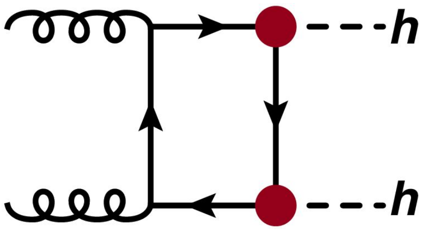




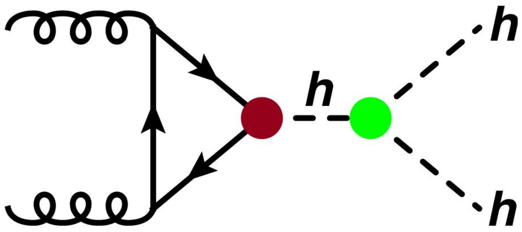


Higgs Pair Production

Heavy Quark Loop

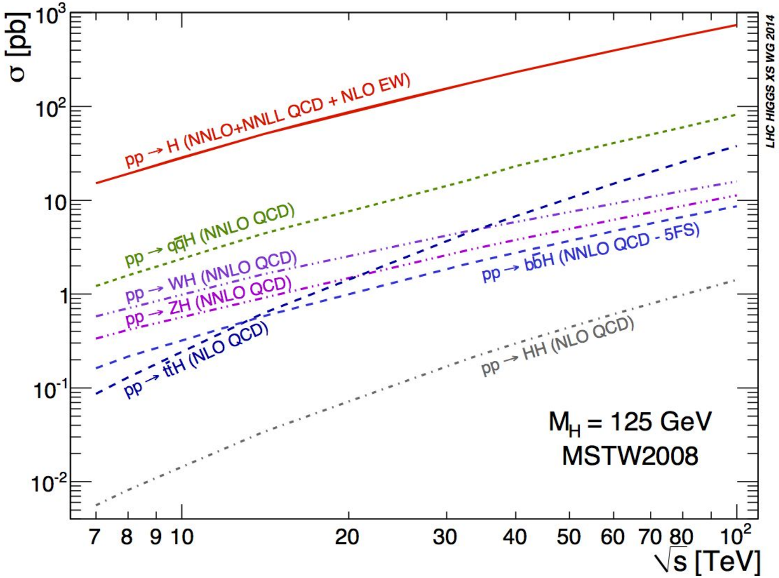


Higgs Self-Coupling



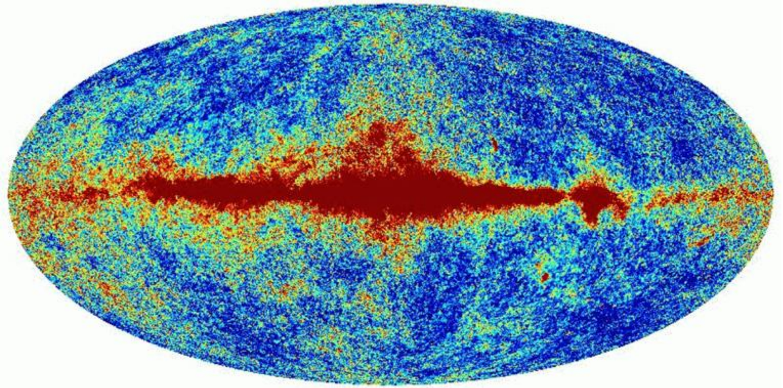
- Both processes lead to non-resonant production of Higgs boson pairs in the Standard Model
- **Quark loop** interactions are proportional to Yukawa Higgs-quark coupling
- **Triple Higgs** interaction is proportional to the unmeasured(**!**) trilinear Higgs self-coupling
  - Strength of coupling well-predicted by the Standard Model

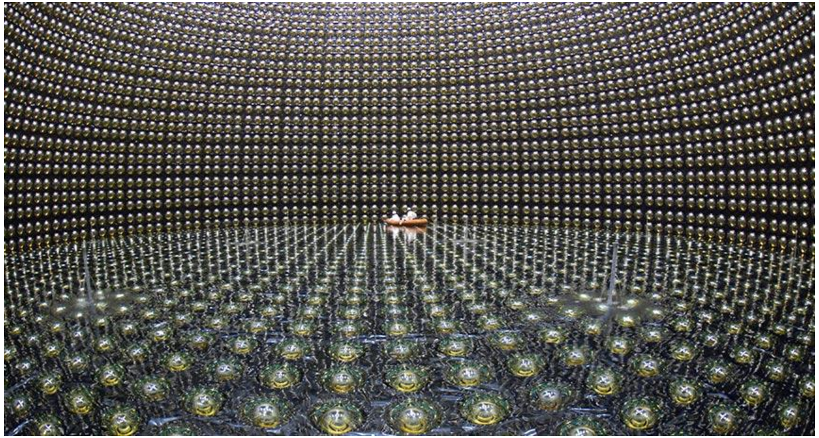
    AND
  - Measurements of the self-coupling are possible at the LHC



So What Else? (I did say two theories...)

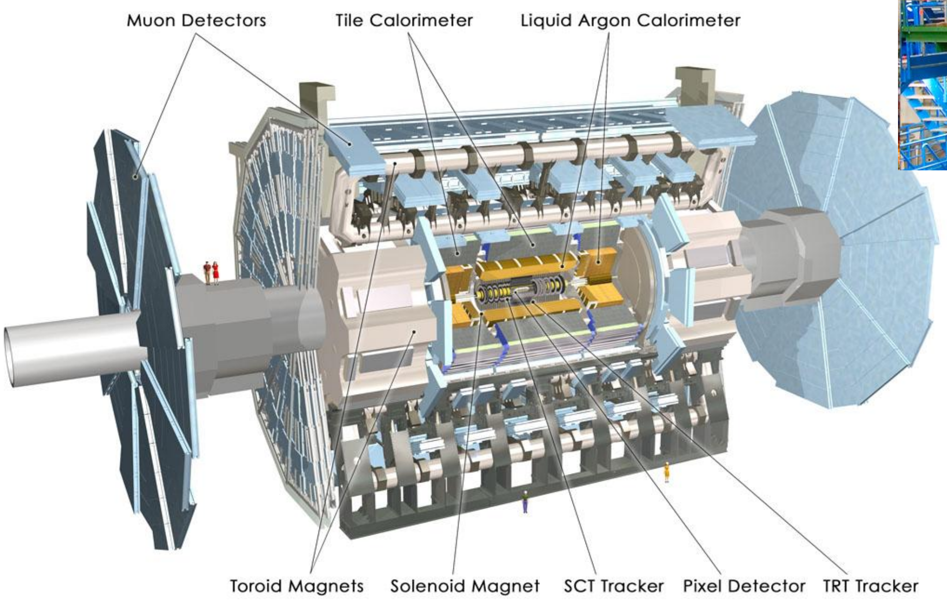
- SM doesn't explain a lot
  - Hierarchy problem
  - Origin of neutrino mass
  - Dark matter?
  - Gravity??
- New theories are needed (and available!) to understand these phenomena

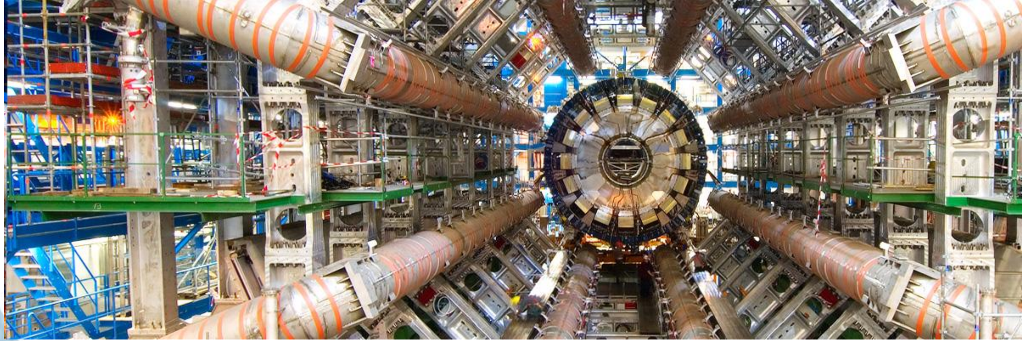


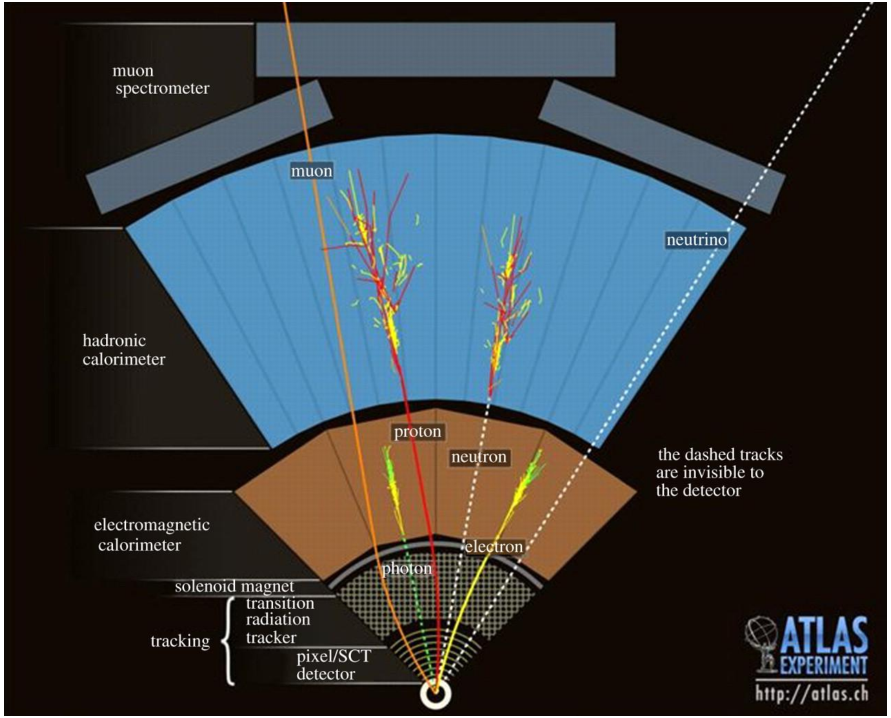


- Precision measurements give us a way to rigorously test Standard Model predictions **AND** let us compare them against the predictions/existence of new theories

ATLAS Detector





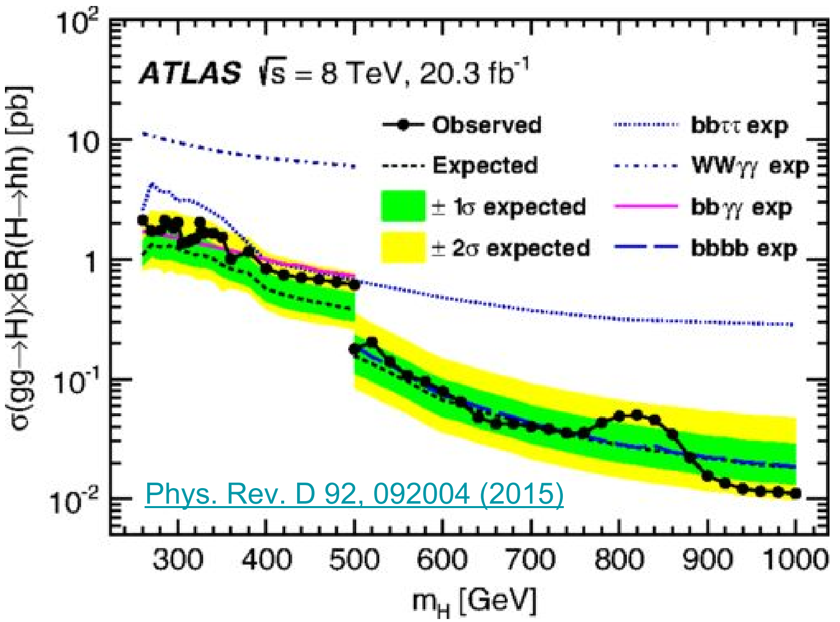


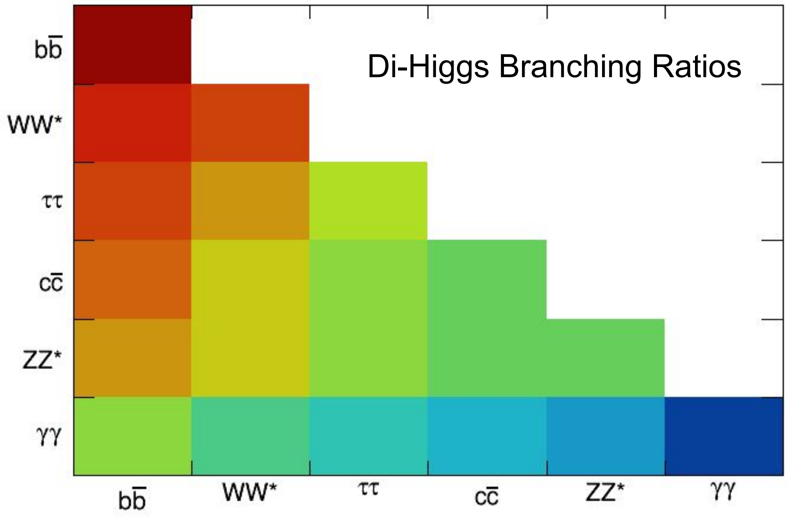
General-purpose detector at the LHC

- Tracking, calorimeters, muon systems
- Designed to reconstruct electrons, muons, photons jets, and missing energy across large range of energies

Di-Higgs Studies with ATLAS

- ATLAS published four searches for Higgs pair production using Run 1 dataset
  - $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, and $\gamma\gamma WW^*$
- Combination yielded results
  - Non-resonant upper limit of ~0.69 pb (70x SM)
  - Resonant upper limit of 0.011 pb for m_H = 1000

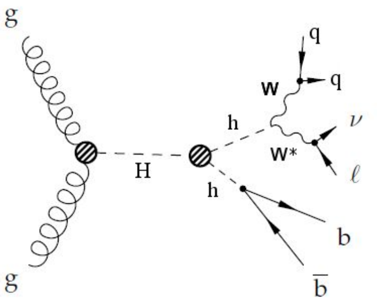


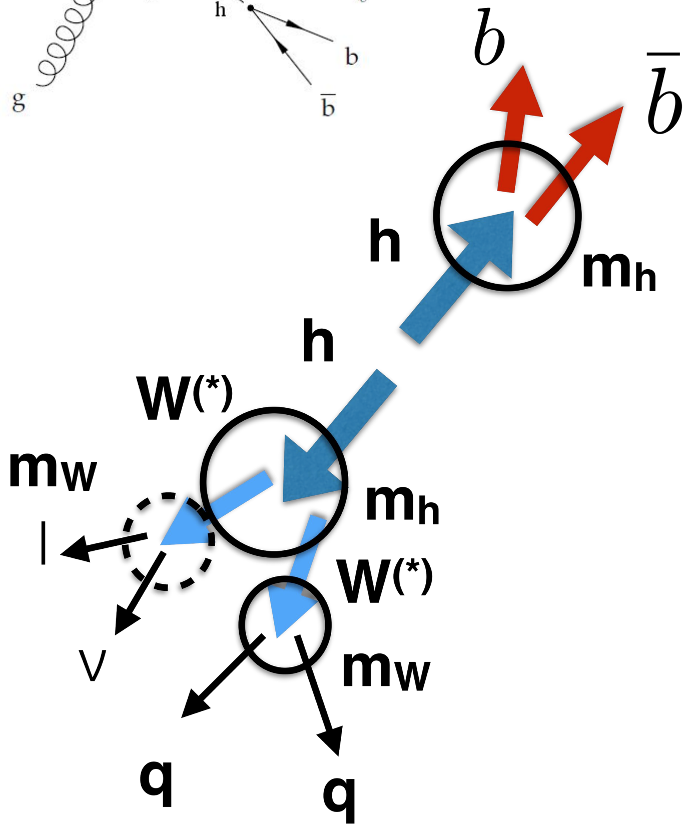


- Effort in Run 2 focusing on improving Run 1 analyses and adding new decay channels
  - Improvements: Multivariate analyses, boosted objects in high p_T regime, and more
  - New channels: **$b\bar{b}WW^*$** and WW^*WW^*

hh → bb̄WW* @ 13 TeV

- Search for non-resonant (SM) and resonant (exotic) di-Higgs production
- Second highest branching fraction after bb̄bb̄
- Analysis in semileptonic decay channel, i.e. bb̄WW* → bb̄ℓvqq’
- Three selection strategies: non-resonant, low resonance mass, and high resonance mass
- Require one charged lepton (e, μ), ≥ 4 jets, = 2 b-tags
- Collaboration between six institutions including Ohio State and Illinois
- First search using this final state





Dataset + Object Selection

- Use 36.1 fb^{-1} of data from 13 TeV proton-proton collisions
- Monte Carlo simulations used for di-Higgs signal, $t\bar{t}$, W+jets, Z+jets, diboson, and single top backgrounds
  - $t\bar{t}$ normalization calculated using data in control region
- Data-driven method used to estimate multi-jet QCD background
- Largest background contributions come from $t\bar{t}$ and multi-jet processes

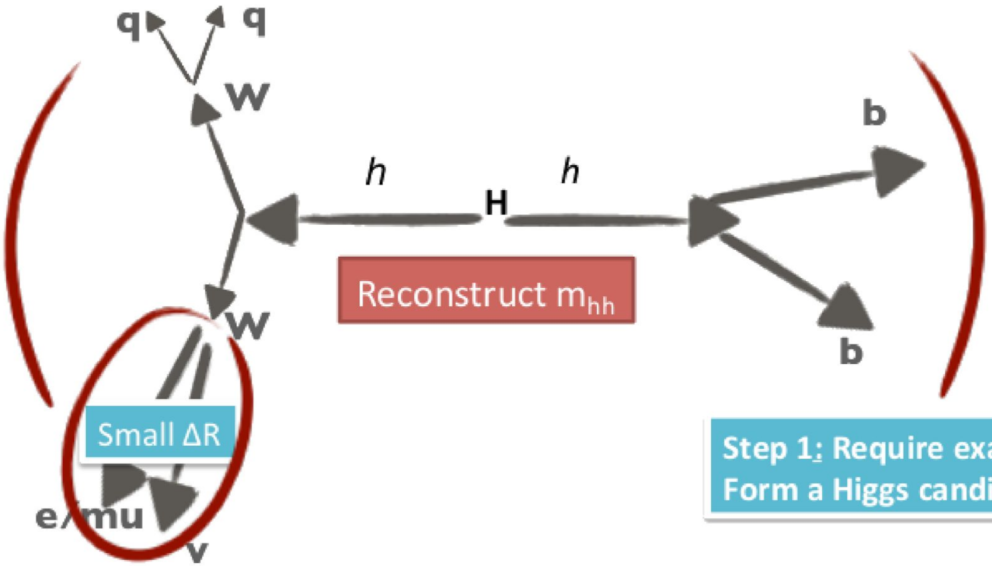
Object Selection
Lepton: p_T > 27 GeV, |η| < 2.5, track-based isolation
Jets: Anti-k_T ΔR=0.4, p_T > 20 GeV, |η| < 2.5, 85% b-tagging eff
MET: MET > 25 GeV

Event Pre-Selection
Lepton trigger, at least one primary vertex with ≥ 5 tracks
= 1 lepton, ≥ 4 jets
Select events with = 2 b-jets

- Create $m_{b\bar{b}}$ control region ($m_{b\bar{b}}$ < 100 GeV, $m_{b\bar{b}}$ > 140 GeV) to validate techniques and optimize search strategies

Event Reconstruction

2. Require a hadronic *W*
Of the 3 highest pT non-b-tagged jets, keep the pair with smallest deltaR

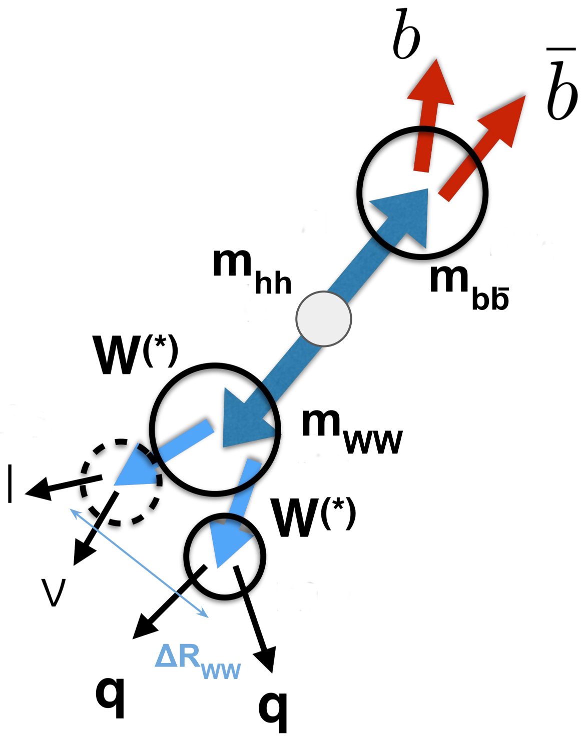


Step 1: Require exactly 2 *b*-jets
Form a Higgs candidate with 2 *b*-jets

Step 3: Reconstruct a leptonic *W*
Solve 2[nd] order equation using MET, lepton, & hadronic *W* using Higgs mass constraint
Keep the solution with smallest deltaR(lep, v) in case of two solutions

Event Selection

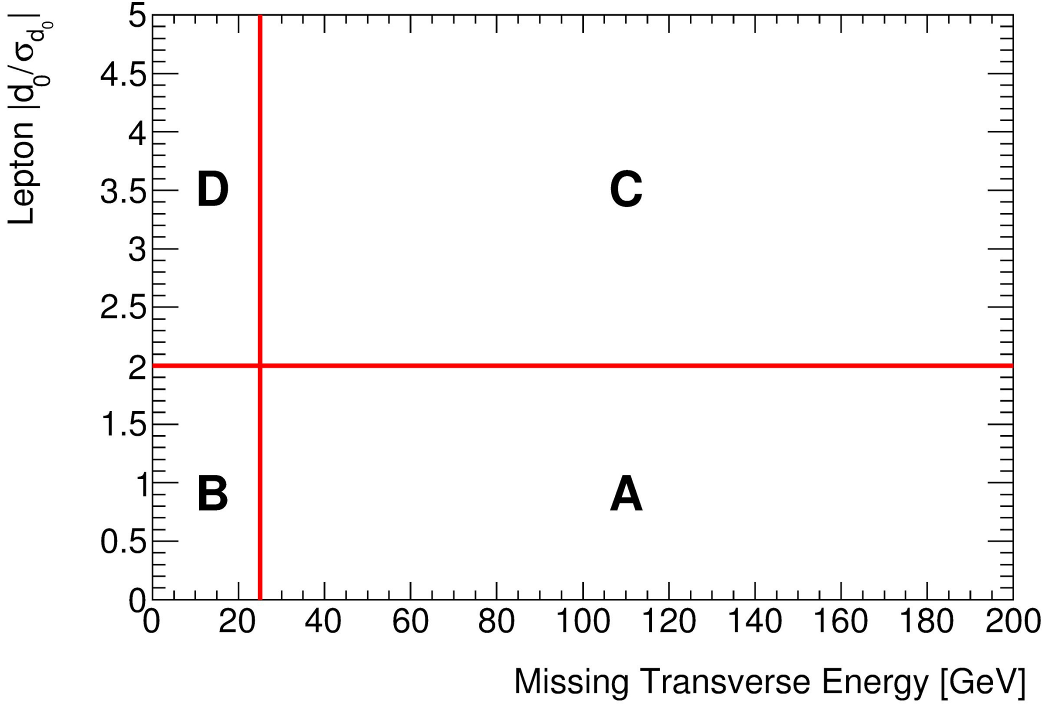
Variable	Non-resonant	Low-mass	High-mass
MET [GeV]		> 25	
p_{T}^{WW} [GeV]		> 250	
$\mathrm{m}_{b\bar{b}}$ [GeV]		$105 - 135$	
m_{WW} [GeV]	< 130	< 130	no cut
$p_{\mathrm{T}}^{b\bar{b}}$ [GeV]	> 300	> 210	> 350
$\Delta\mathrm{R}_{WW}$	no cut	no cut	< 1.5
m_{hh} [GeV]	no cut	$[625, 775]^{\dagger}$	$[1910, 2170]^{\dagger}$



- Selection variables differ between analysis strategies
  - Variables and cuts optimized using Poisson significance at end of selection
- † - $\mathrm{m_{hh}}$ cuts are dependent on resonance mass under consideration
  - Windows shown above are for 700 GeV (Low-mass) and 2000 GeV (High-mass)

QCD Estimation

- Multi-jet backgrounds enter event selection due to jets mis-identified as leptons and non-prompt lepton production
- Use a 2D sideband method where the signal region, **A**, has two (independent) cuts inverted to create three independent control regions (**B**, **C**, and **D**)



- Use significance of lepton impact parameter and MET as independent variables

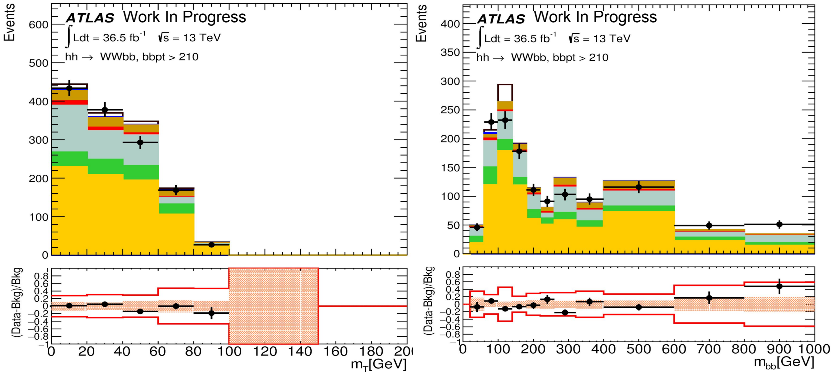
Yield in A region can then be expressed as

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

- Shape in C region taken as shape in A region
- Assume that difference in behavior between B and D regions is identical to difference between A and C regions
  - *R* factor corrects for deviations from this assumption
- Control regions defined early in event selection to validate estimation and modeling

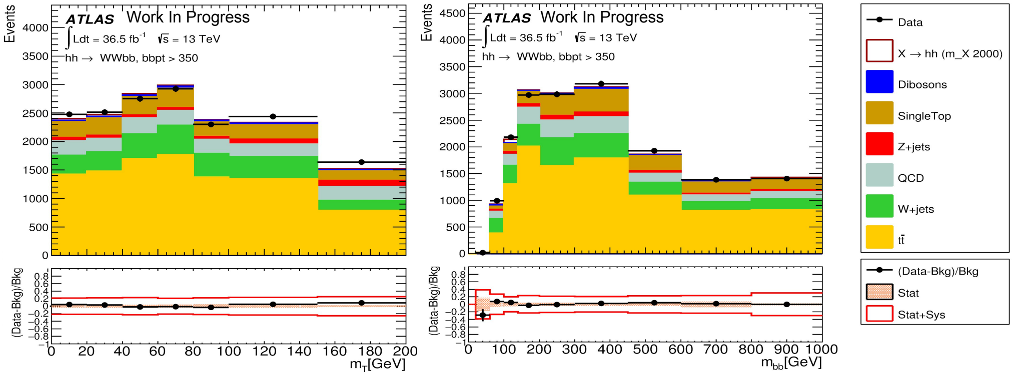
Control Region Kinematics

Non-resonant + Low Resonance Mass



- After requiring $b\bar{b}$ p_T > 210 GeV
- Transverse mass (left) shows agreement including data-driven QCD
- $b\bar{b}$ mass (right) shows backgrounds are well modeled in sideband
- Scaled 700 GeV resonance signal shown to give idea of shape

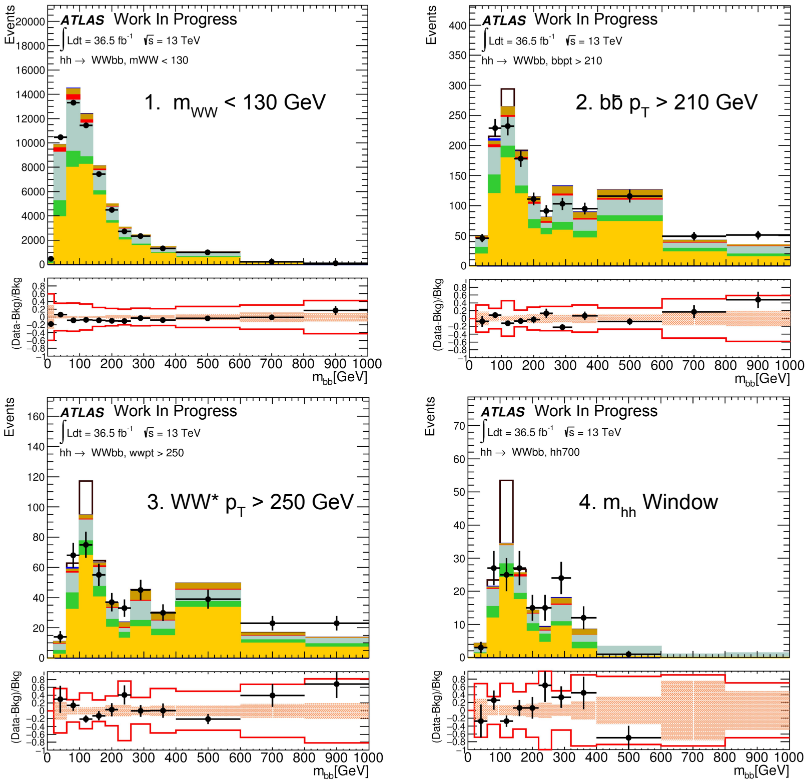
High Resonance Mass



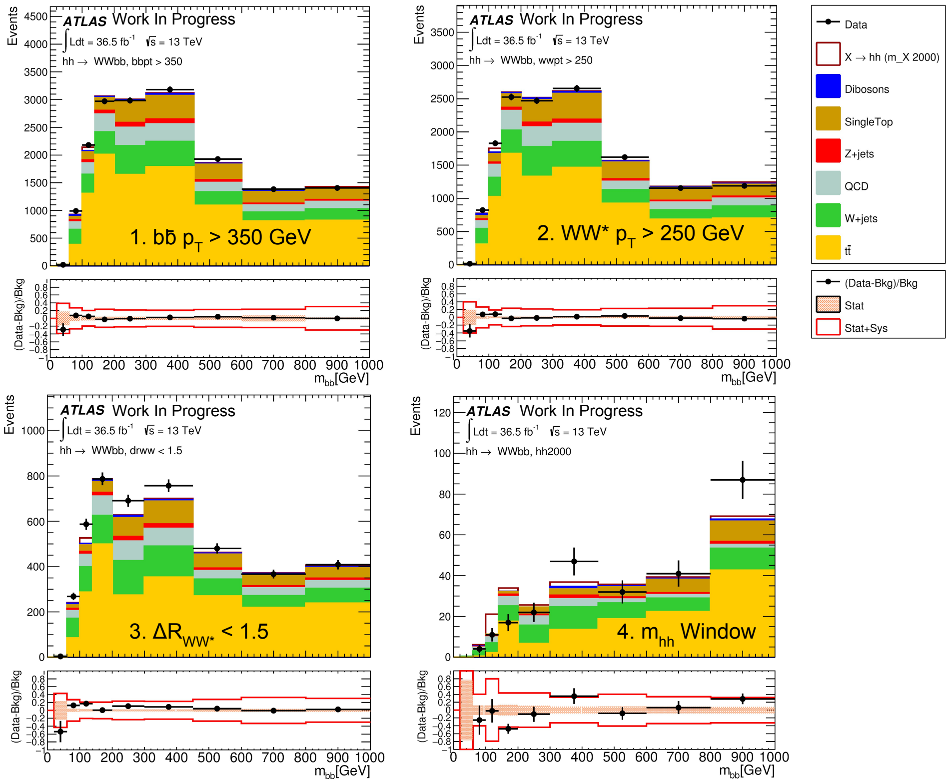
- After requiring $b\bar{b}$ p_T > 350 GeV
- Transverse mass (left) shows agreement including data-driven QCD
- $b\bar{b}$ mass (right) shows backgrounds are well modeled in sideband
- Scaled 2000 GeV resonance signal shown to give idea of shape

Signal Region Plots

Low Resonance Mass



High Resonance Mass



- Show $m_{b\bar{b}}$ across selection for m_X = 700 GeV
- Scaled signals shown to give idea of shape

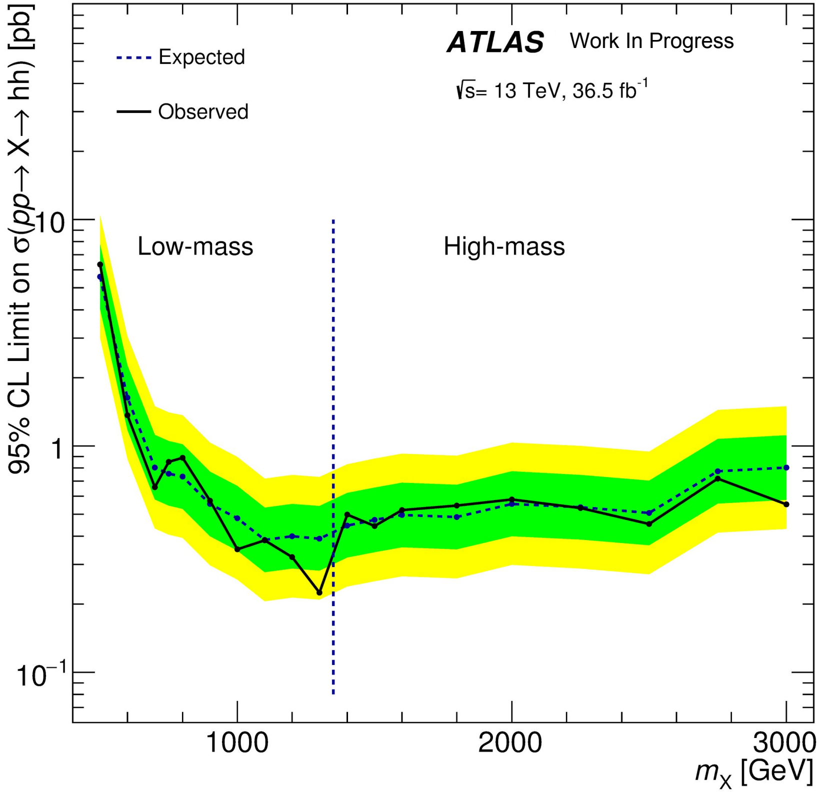
- Show $m_{b\bar{b}}$ across selection for m_X = 2000 GeV
- Scaled signals shown to give idea of shape

$b\bar{b}WW^*$ Upper Limits

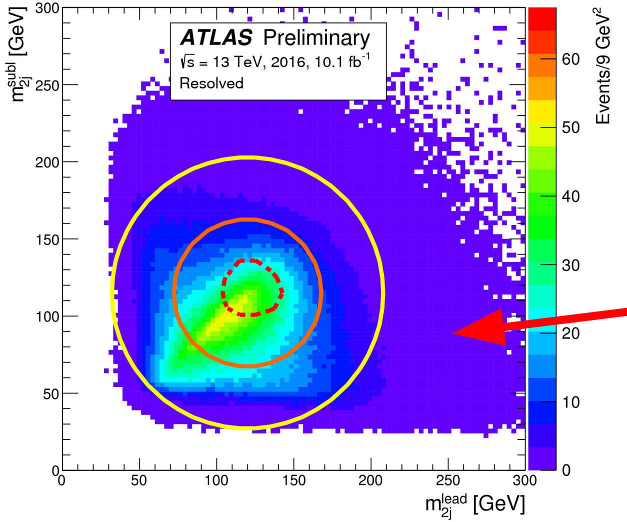
- A simultaneous maximum-likelihood fit is performed using the number of events in the final signal and control regions
- Largest systematics vary by selection strategy
  - Non-resonant: $t\bar{t}$ normalization + ISR/FSR modeling, QCD normalization, jet energy scale, MET resolution
  - Low Resonance Mass: $t\bar{t}$ norm. + parton shower modeling, jet energy scale and resolution, QCD norm., MET resolution
  - High Resonance Mass: W+jets norm. + scale/PDF uncertainties, QCD normalization, jet energy scale and resolution

Resonant: Most stringent observed limit for di-Higgs production from the decay of a spin-0 resonance H is found at ~0.23 pb for a resonance mass of 1300 GeV

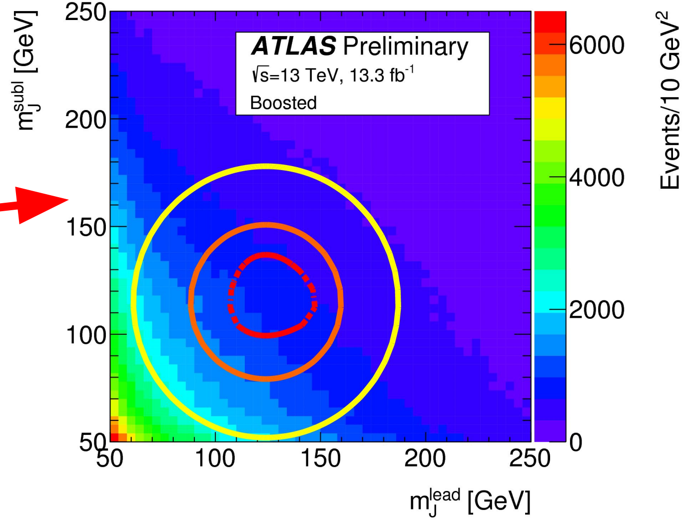
Non-resonant: Observed upper limit for non-resonant di-Higgs production is found to be 12.1 pb (~360 times SM prediction)



hh → bb̄bb̄ @ 13 TeV ATLAS-CONF-2016-049



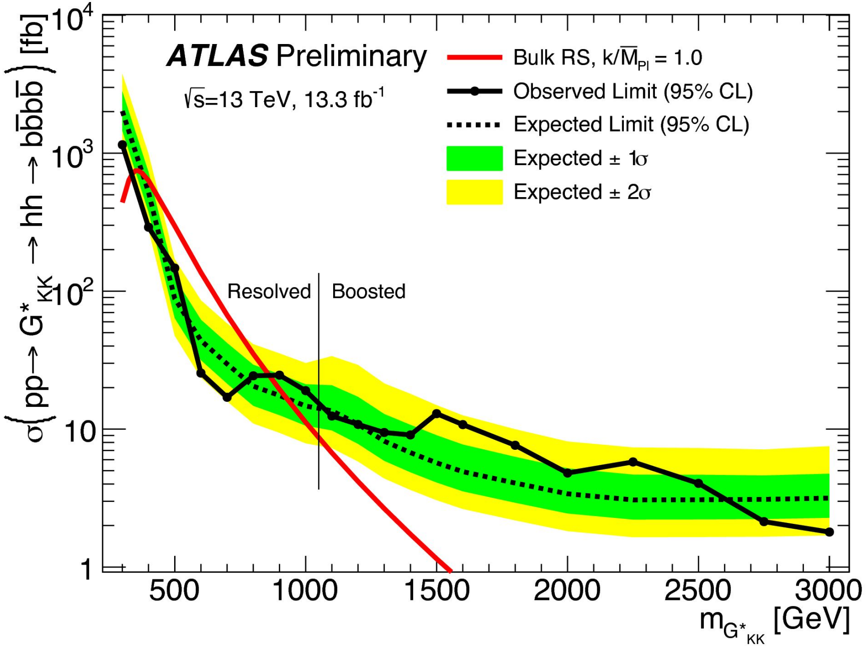
- Uses 13.3 fb-1 of data collected in 2015+2016
- Sets limits on spin-2 production of Higgs pairs over resonance mass range 300-3000 GeV
- Resolved analysis selects ≥ 4 b-jets
  - Keep 4 highest b-tagged jets
  - Pair b-tagged jets based on $m_{b\bar{b}}$ and $\Delta R_{b\bar{b}}$



- Boosted analysis selects 2 high p_T fat jets
  - Leading jet required to have p_T > 450 GeV
  - Require b-tagged track jets in Higgs candidates
- Both analysis use orthogonal sideband and control regions to model backgrounds before fitting in signal region

hh → $b\bar{b}b\bar{b}$ Results ATLAS-CONF-2016-049

- Boosted more sensitive than resolved above resonance masses of 1000 GeV
- Largest background contributions come from tt and QCD multi-jet production
    - Multijet makes up 95% of background in resolved channel
    - Multijet ~85% of bkg in boosted channel

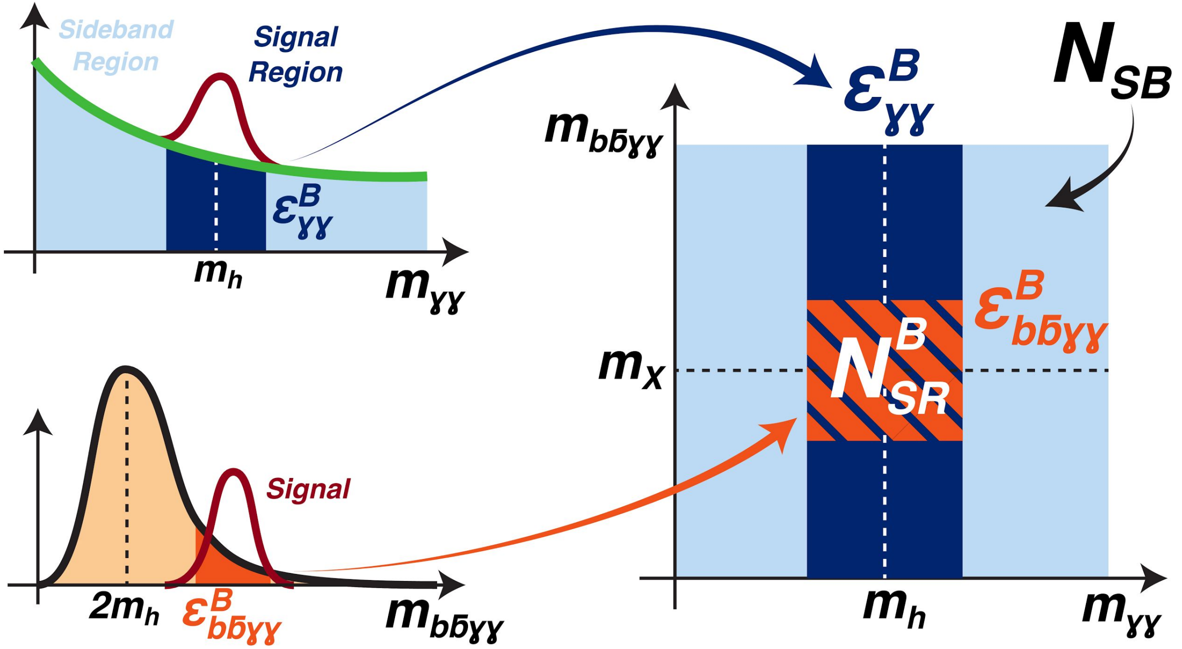


Non-resonant: Observed upper limit for non-resonant di-Higgs production is 330 fb (29 times the SM prediction)

Resonant: Most stringent upper limit for resonant spin-2 di-Higgs production found at ~1.9 fb for a resonance mass of 3 TeV

$hh \to b\bar{b}\gamma\gamma$ @ 13 TeV ATLAS-CONF-2016-004

- Sets limits on spin-0 production of Higgs pairs over resonance mass range 275-400 GeV
- Uses 3.2 fb-1 of data collected in 2015
- Require ≥ 2 isolated photons and = 2 isolated b-jets
- Counting experiment in $m_{\gamma\gamma}$-$m_{b\bar{b}\gamma\gamma}$ plane using mass windows specific for each resonance mass

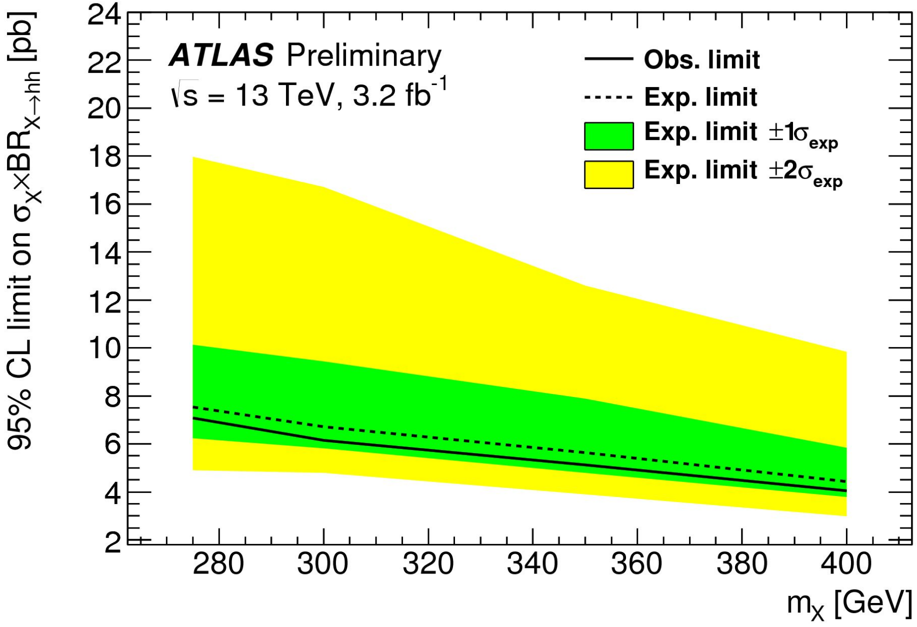


hh → $b\bar{b}\gamma\gamma$ Results ATLAS-CONF-2016-004

- Dominant SM continuum background determined using sidebands and mass window efficiencies in 0 b-tag region
  - $m_{\gamma\gamma}$ efficiency calculated using exponential fit in 0-tag region
  - $m_{b\bar{b}\gamma\gamma}$ efficiency extrapolated from Landau fit to $m_{jj\gamma\gamma}$ spectrum in 0-tag region

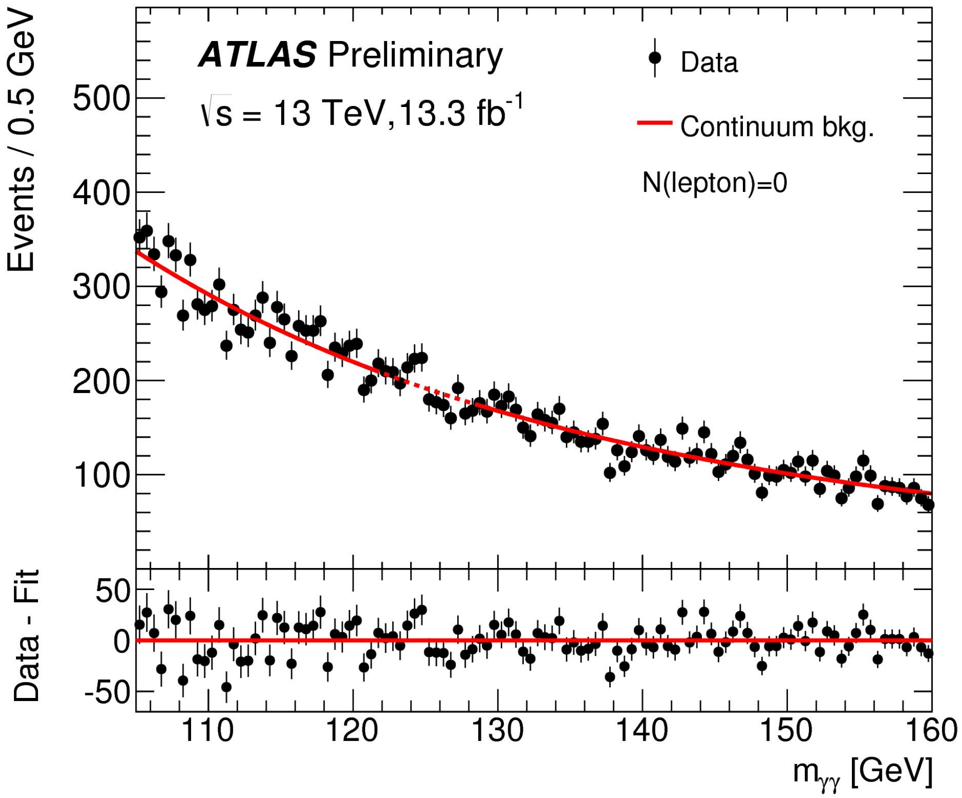
Non-resonant: Observed upper limit for non-resonant di-Higgs production is 3.9 pb (~350 times the SM prediction)

Resonant: Most stringent upper limit for resonant spin-0 di-Higgs production found at ~4.0 pb for a resonance mass of 400 GeV



hh → γγWW* @ 13 TeV ATLAS-CONF-2016-071

- Uses 13.3 fb-1 of data collected in 2015+2016
- Sets limits on spin-0 production of Higgs pairs over resonance mass range 260-500 GeV
- Uses semileptonic decay mode for WW*, i.e. WW* →ℓvqq'
    - Require ≥ 2 photons, ≥ 2 non b-tagged jets, = 0 b-tagged jets, ≥ 1 isolated lepton
- = 0 lepton selection used as control region for data-driven estimation of SM diphoton background

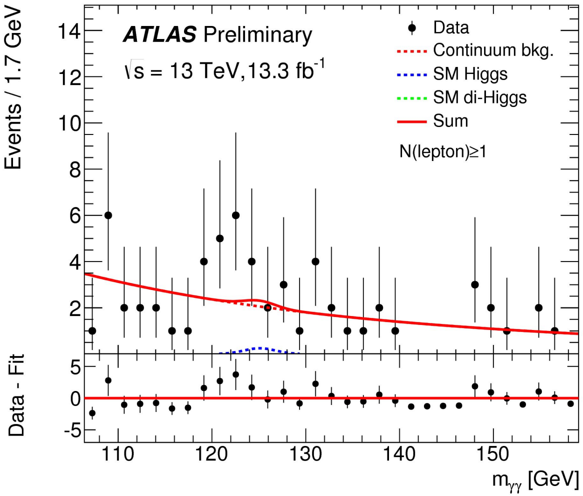


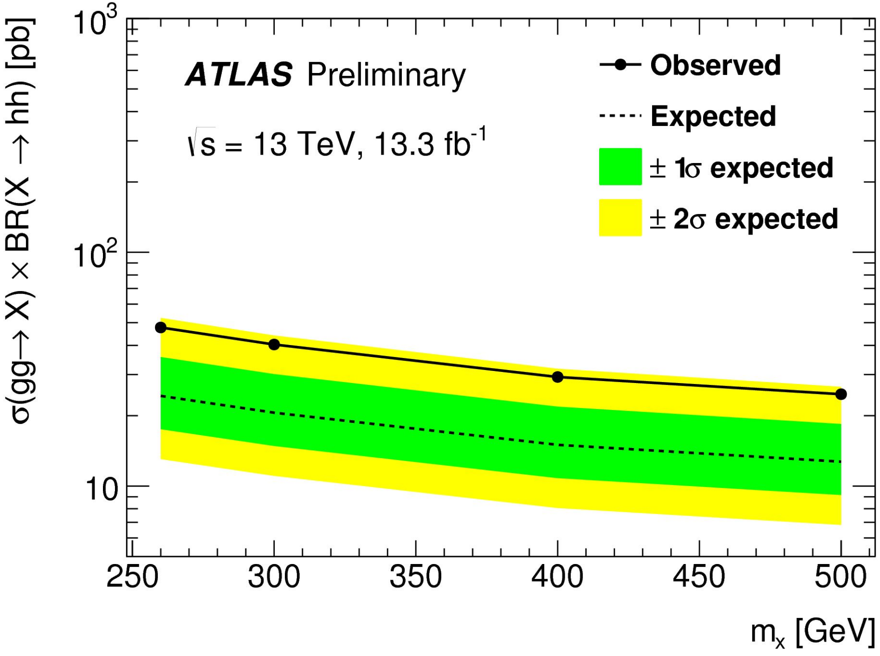
hh → γγWW* Results ATLAS-CONF-2016-071

- Limits set using counting experiment in final signal region
- SM diphoton continuum background is dominant background
  - Estimated using exponential fit to $m_{\gamma\gamma}$ sideband in 0-tag region

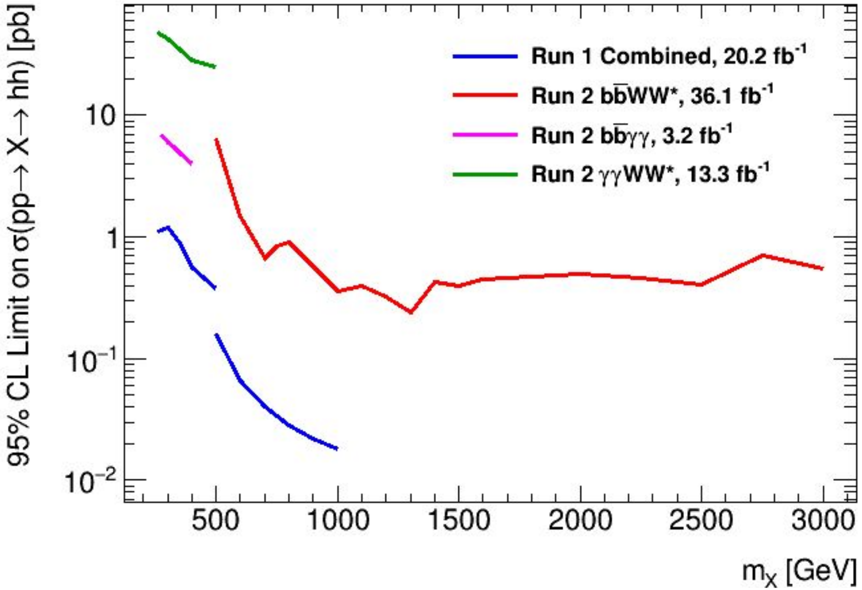
Non-resonant: Observed upper limit for non-resonant di-Higgs production is 25.0 pb (~2200 times the SM prediction)

Resonant: Most stringent upper limit for resonant spin-0 di-Higgs production found at 24.7 pb for a resonance mass of 500 GeV





Where Are We Now?



- Current upper limits for spin-0 resonance analyses shown above
  - Run 2 $b\bar{b}b\bar{b}$ resonance limits presented for spin-2 only
- Best non-resonant upper limit ~29 times SM expectation (from $b\bar{b}b\bar{b}$)
- More channels in progress: $b\bar{b}\tau\tau$, WW^*WW^*
- Use of full dataset will improve limits
- Combination of Run 2 analyses will further improve sensitivity

Future Improvements: $hh \rightarrow b\bar{b}WW^*$

- Add new channels:
  - Fully hadronic $WW^* \rightarrow qq'qq'$: larger branching fraction
  - Fully leptonic $WW^* \rightarrow \ell\nu\ell\nu$: cleaner final state
  - Combining all channels will yield more sensitive measurement
- Boosted regime
  - Look at fat jet + b-tagged track jets to pick up high pT $h \rightarrow b\bar{b}$ decays
  - Use jet substructure variables to recover merged hadronic W decays in $h \rightarrow WW^*$ decays
  - Will drive sensitivity for high resonance masses
- Kinematic fitting
  - Early studies show significant potential for improving S/B
  - Develop background and signal hypotheses, can use individually or in combination
  - Gain dependent on modeling uncertainty, but lots of promise
- Use MVA (e.g. boosted decision trees) to optimize event selection
- Develop/implement new triggers
  - Lepton+jets trigger for low resonance mass/non-resonant analyses
  - Large R-jet trigger for boosted analyses

Future Improvements: General hh

- Use of full Run 2 data set (~120 fb^{-1})
- Add new decay channels of WW^* decays
  - Fully leptonic $\gamma\gamma WW^*$
- Improve b-jet and boosted jet triggers
  - Significant improvement expected for $b\bar{b}b\bar{b}$ analysis
- Non-resonant production:
  - Train boosted decision trees for event selection using multiple values of Higgs self-coupling
- Resonant production:
  - Nearly all channels can extend sensitivity by use of boosted hadronic objects
  - Resolve leptons inside fat jets from $h\to\tau\tau$ and semileptonic $h\to WW^*$ decays
- Full combination
  - $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, and $b\bar{b}\gamma\gamma$ will drive sensitivity at low resonance mass
  - $b\bar{b}b\bar{b}$ will drive high mass sensitivity ($b\bar{b}WW^*$ becomes competitive)

It’s The Best of Times

- Bad news? We haven’t seen any new physics yet.
- Good news? We haven’t seen new physics ***yet***!
- Measurements of the Higgs self-coupling open a new region of the Standard Model
- Upper limits on non-resonant Higgs pair production approaching 10 times the SM prediction
    - Limits also set for wide range of resonant Higgs pair production
- Non-resonant (and self-coupling!) measurement possible with ~1000 fb^{-1}
- <u>This is exciting time:</u> we know there must be new physics, and Higgs is unique new tool for testing SM