

Search For Double Higgs Production in the $b\bar{b}WW^*$ Channel

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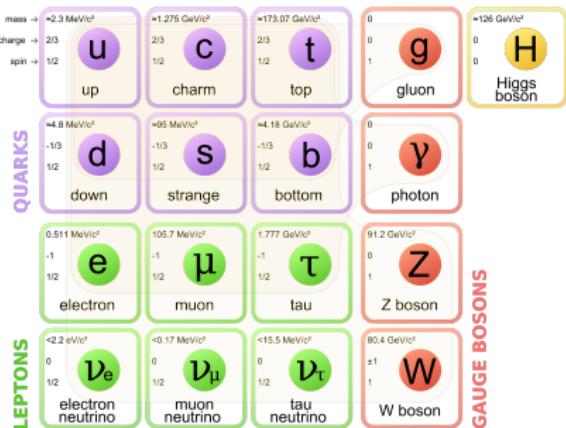
May 24, 2019

Overview

- ▶ The Standard Model
 - ▶ Higgs Physics
- ▶ BSM Di-Higgs Production
- ▶ The LHC and ATLAS
- ▶ $HH \rightarrow b\bar{b}WW^*$ Analysis
- ▶ Improvements to the Analysis
- ▶ Conclusion and Outlook

The Standard Model

- ▶ Describes matter (fermions) and force carriers (gauge bosons)
- ▶ Very successful model
- ▶ Final piece (Higgs Boson) discovered in 2012



Higgs Mechanism

Scalar Boson

$$\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

↓ EWSB ↓

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$$

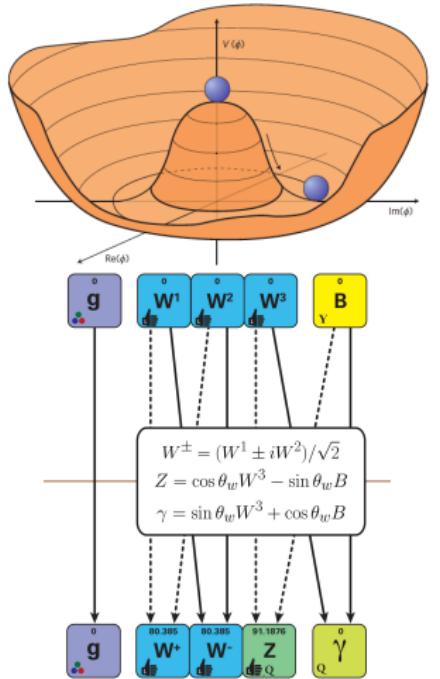
Coupling to Gauge Bosons gives

$$W^\pm, Z, A(\gamma)$$

$$M_W^2 = \frac{1}{4} g^2 v^2$$

$$M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$$

$$M_A^2 = 0$$



Higgs Self-Coupling

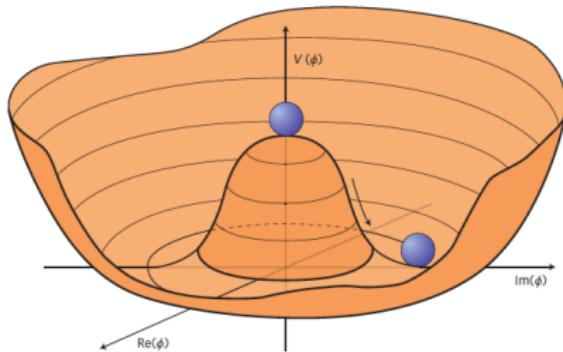
Higgs Potential

$$V = \mu^2 |\Phi^\dagger \Phi| + \lambda (|\Phi^\dagger \Phi|)^2$$

Expand self-coupling around VEV

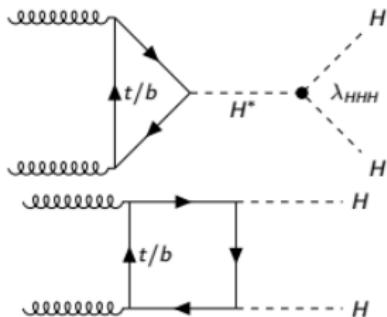
$$V_{\text{self-coupling}} \supset \lambda v \Phi^3 + \frac{\lambda}{4} \Phi^4$$

Tri-linear Higgs coupling strength
 $\lambda_{HHH} \equiv \lambda v$



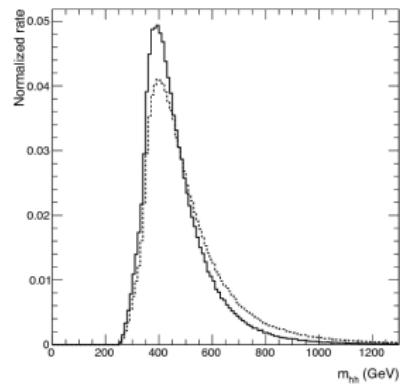
Higgs Self-Coupling

Two Dominant production modes
at the LHC



Interfere destructively to give
small theoretical cross section

SM Theory cross section:
 $\sigma_{HH} \approx 33.53\text{fb}$

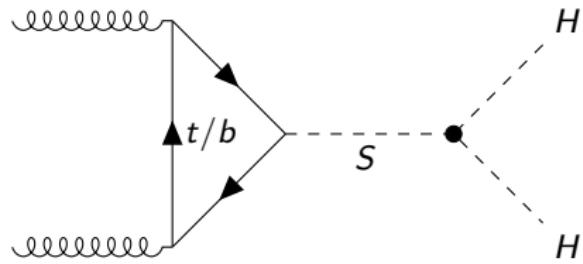


Motivation

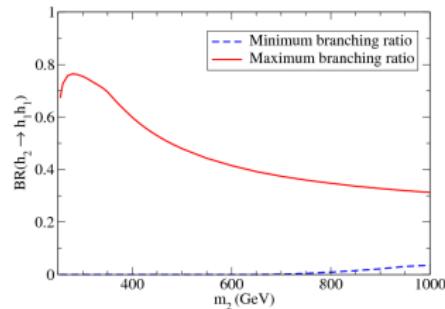
Resonant di-Higgs production

- ▶ A New process could decay to HH
- ▶ E.g. Real Higgs Singlet Extension
 - ▶ Couples to SM Higgs
 - ▶ Large enhancement to HH production rate
 - ▶ Up to 30 times SM

By measuring the HH production rate, we can search for resonant production



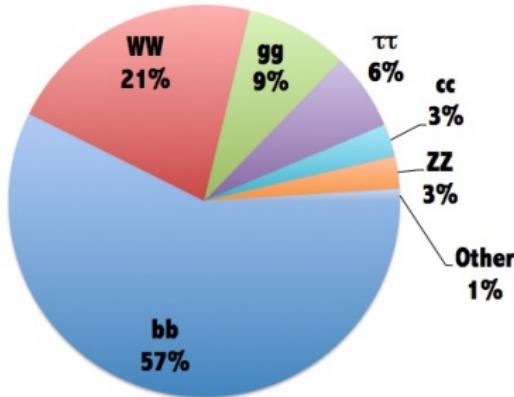
Maximum and Minimum Branching Ratio, $b_4=4.2$, $\sin^2\theta=0.12$



$\text{HH} \rightarrow b\bar{b}WW^*$ semi-leptonic channel

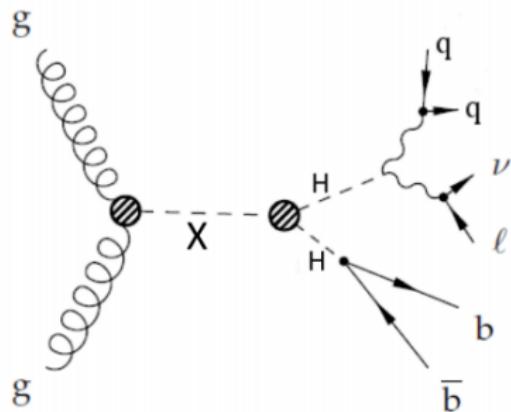
- ▶ $b\bar{b}WW^*$ has the second highest BR behind $b\bar{b}b\bar{b}$
- ▶ W can decay leptonically or hadronically:
 - ▶ Charged lepton + neutrino or
 - ▶ quark + anti-quark
- ▶ Choose $b\bar{b}\ell\nu qq$ final state
 - ▶ Lepton helps against QCD
 - ▶ Neutrino makes reco. more challenging

Higgs decays at $m_H=125\text{GeV}$



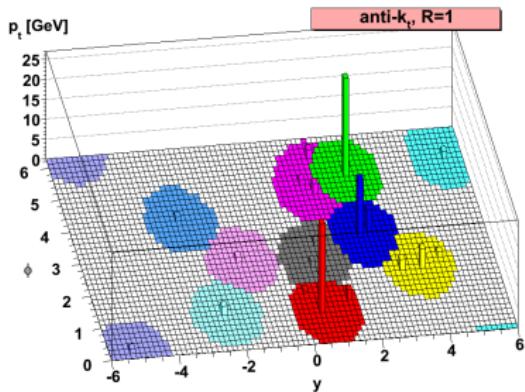
$b\bar{b}l\nu qq$ Final State

- ▶ electron or muon
- ▶ 2 b quarks
- ▶ 2 light flavor quarks
- ▶ neutrino



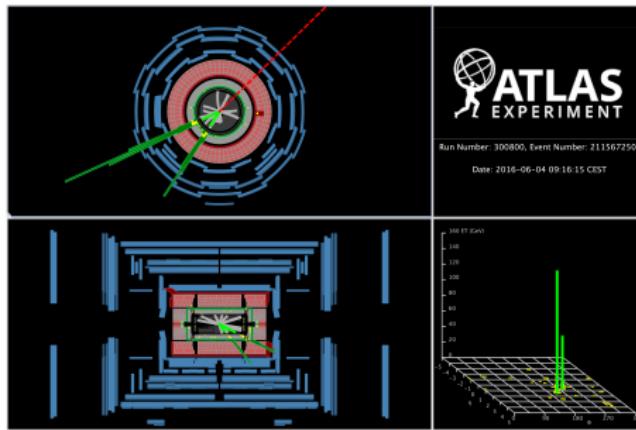
Jets

- ▶ Quarks hadronize before they interact with the detector
- ▶ Gives sprays of energy deposits
- ▶ Energy deposits grouped together into “Jets” by algorithms



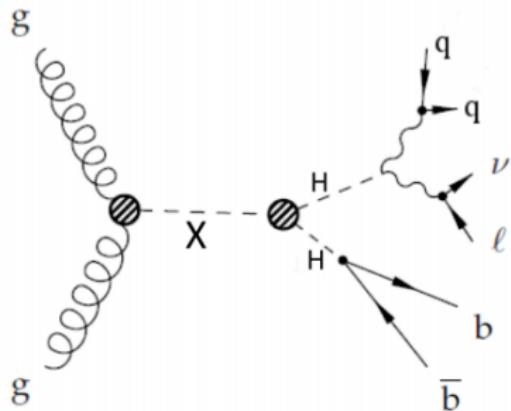
Neutrinos

- ▶ Neutrinos do not interact with detector
- ▶ Have transverse (perpendicular to beam line) information from E_T^{miss}
- ▶ Need another piece to fully reconstruct 4-momentum
 - ▶ This analysis used Higgs mass



$b\bar{b}l\nu qq$ Final State

- ▶ electron or muon
- ▶ 2 light jets
- ▶ 2 b-jets
- ▶ E_T



Background

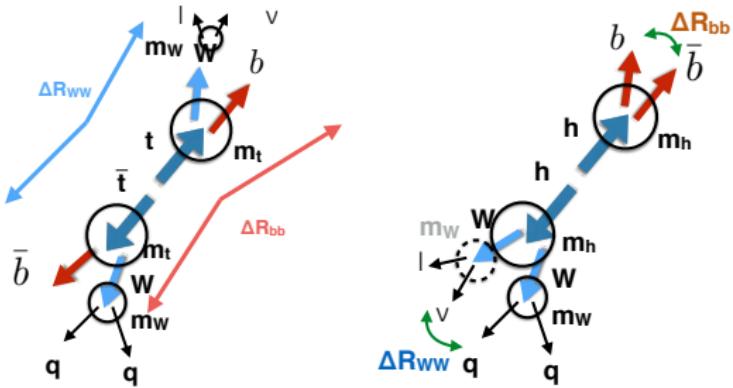
Major

- ▶ $t\bar{t}$
- ▶ W+Jets
- ▶ QCD multijet

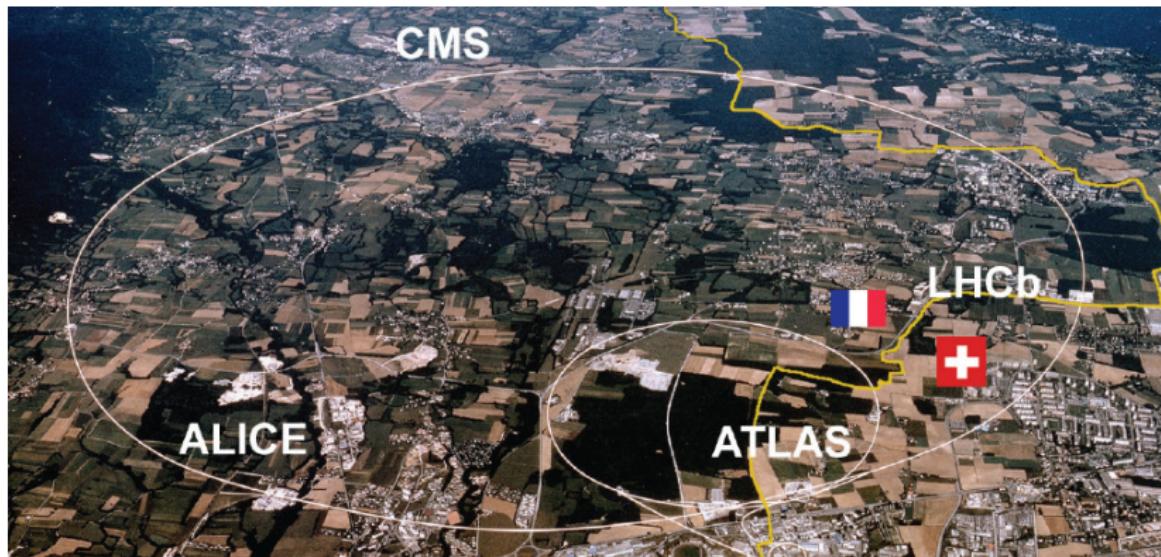
Minor

- ▶ Z+Jets
- ▶ Single Top
- ▶ Diboson

$t\bar{t}$ vs signal

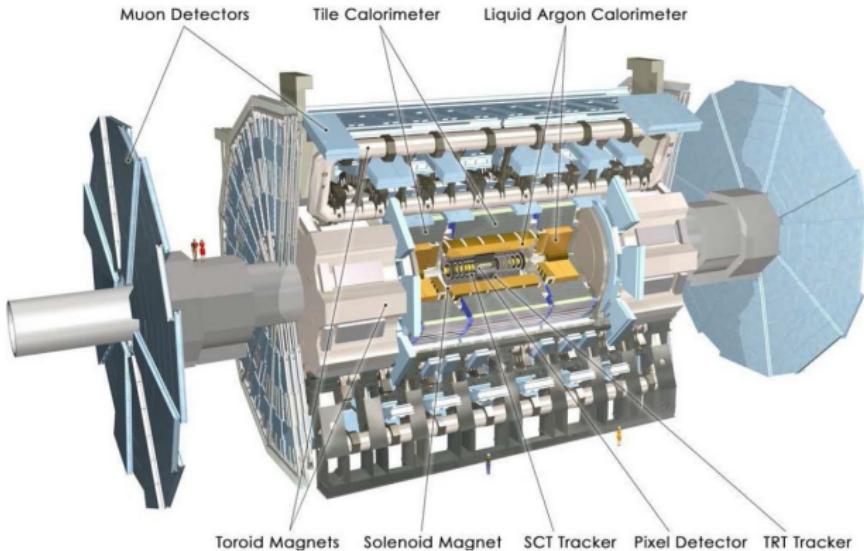


The Large Hadron Collider



- ▶ 13 TeV Proton-Proton Collider
- ▶ 27 Km Circumference under the French-Swiss border
- ▶ 4 primary interaction points, each with a dedicated detector

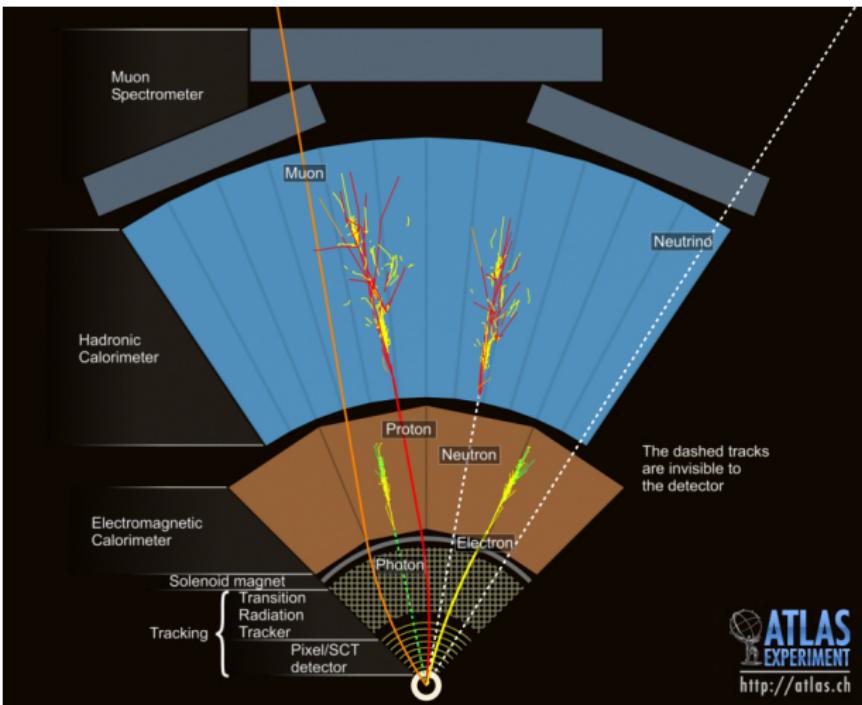
The ATLAS Detector



► General purpose detector

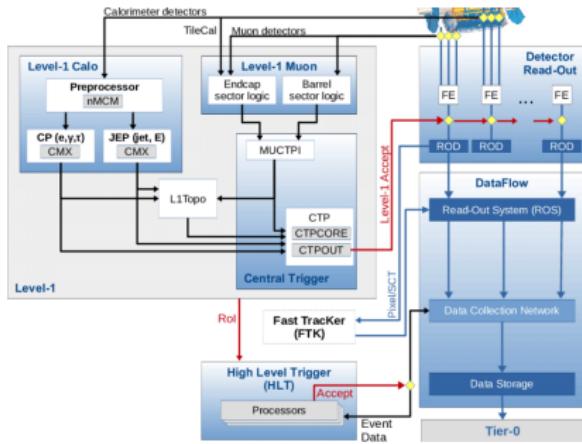
► 3.9 T Toroid

Particles in the Detector



ATLAS Trigger

- ▶ LHC has 40 MHz Collision Rate
 - ▶ ~ 64 TB/s
- ▶ 2 Level Trigger System
 - ▶ Level-1 Trigger (L1)
 - ▶ High Level Trigger (HLT)
- ▶ Reduces rate from 40MHz to ~ 1 kHz (~ 2 GB/s)

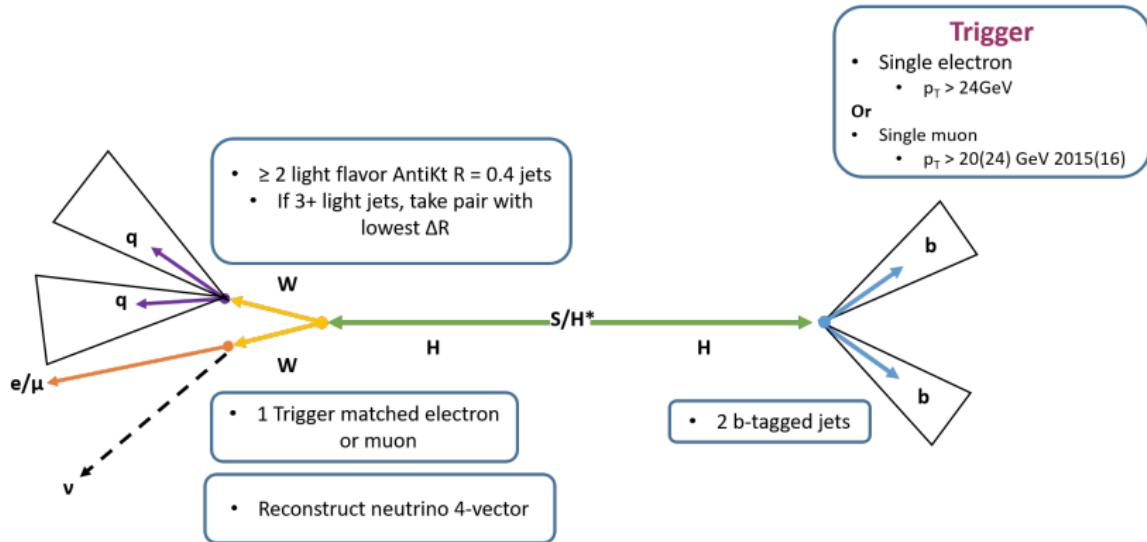


$\text{HH} \rightarrow b\bar{b}WW^*$ Analysis

2 Separate Analyses Presented:

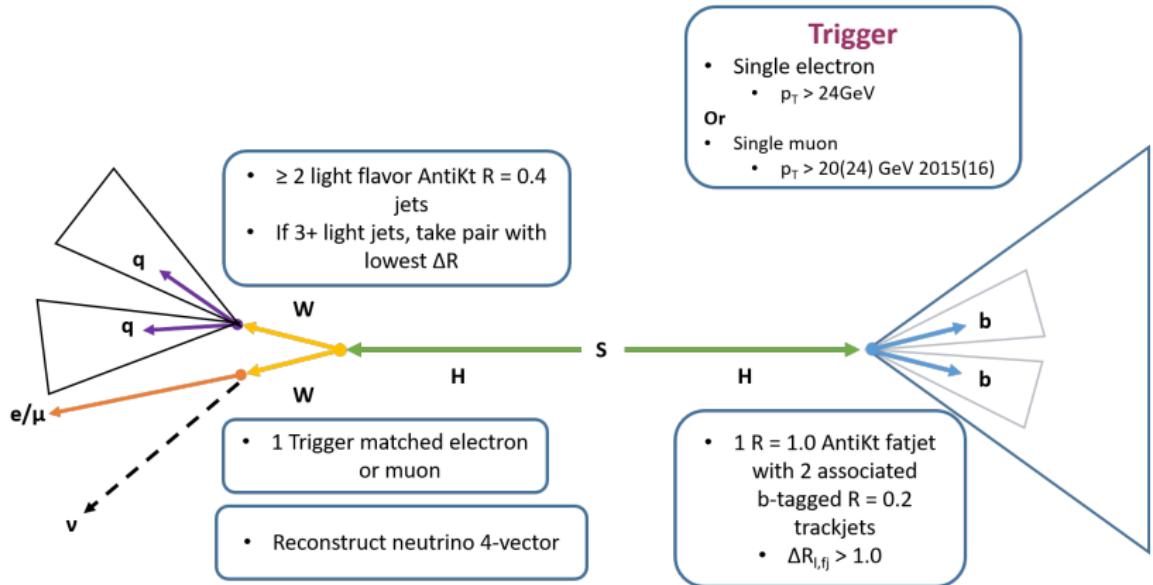
- ▶ 2015-2016, 36.1 fb^{-1} Analysis
 - ▶ JHEP04(2019)092
- ▶ Improvements for full Run 2 analysis

Resolved Event Selection



Designed to target SM production and $m_S < 1300 \text{ GeV}$

Boosted Event Selection



Designed to target $m_S > 1300 \text{ GeV}$

Signal Region

Resolved

- ▶ E_T
- ▶ p_T^{bb}
- ▶ p_T^{WW}
- ▶ $m_{bb} \sim m_H$
- ▶ $m_{HH} \sim m_S$

Boosted

- ▶ E_T
- ▶ $m_{\text{Large-R jet}} \sim m_H$

Resolved Background Determination

$t\bar{t}$

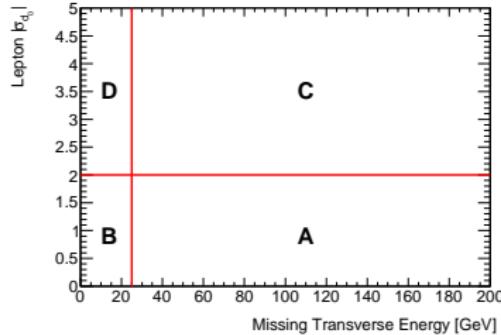
- ▶ Normalized in m_{bb} CR
 - ▶ Boosted $t\bar{t}$ VR

Other MC Bkg.

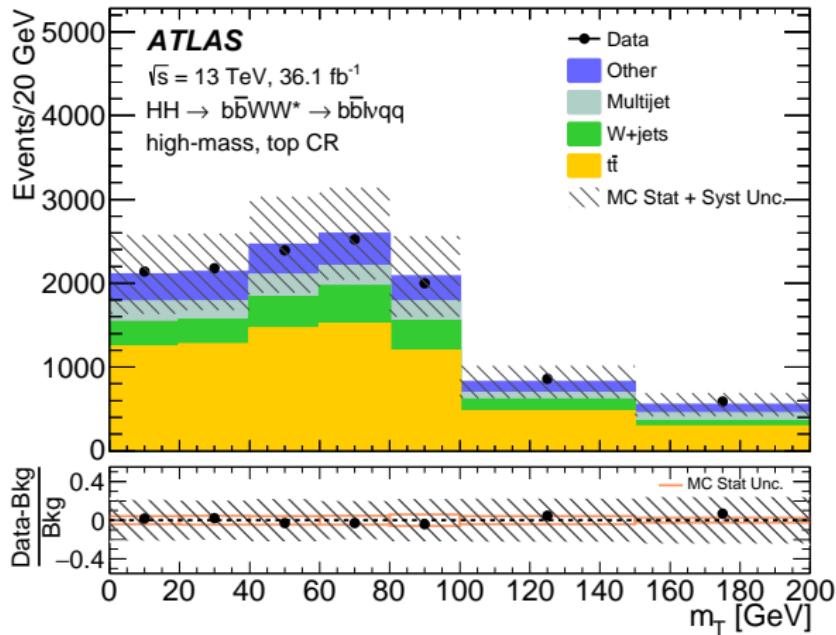
- ▶ Modeled using MC and normalized to SM XSec

QCD multi-jet background

- ▶ ABCD data driven estimate
 - ▶ $N_A = FN_C N_B / N_D$
 - ▶ F is a correction factor determined earlier in the cutflow
 - ▶ Boosted uses $E_T > 50$ GeV
 - ▶ Takes shape from 1 b-tag C Region

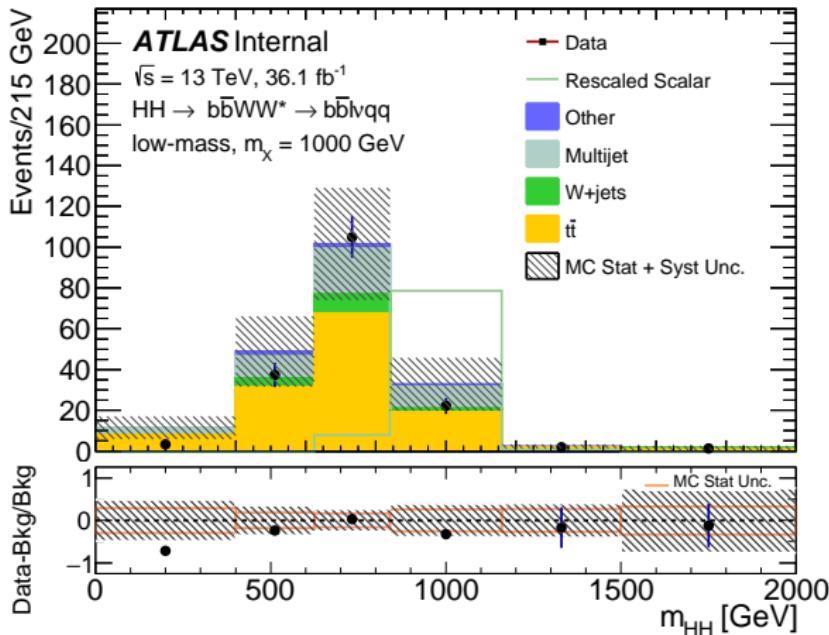


Background Shape Check

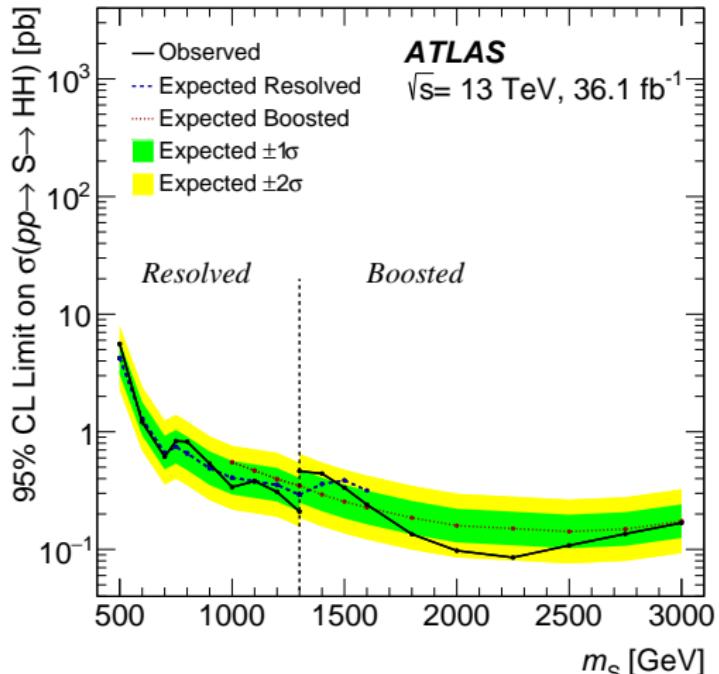


$$m_T = \sqrt{2 p_T^l E_T \times (1 - \cos \Delta\phi)}$$

Results



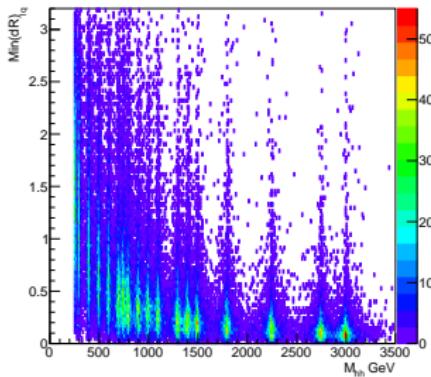
Combined Resonant Production Limit



$$\sigma(pp \rightarrow HH)B(HH \rightarrow b\bar{b}WW^*) < 300_{-80}^{+100} \times SM$$

Motivation

- ▶ $H \rightarrow WW$ becomes boosted around 1 TeV
- ▶ Quarks become too close together to use 0.4 jets
- ▶ Overlap removal with leptons kill efficiency
- ▶ A “Fully-Boosted” selection recovers lost efficiency at high m_S

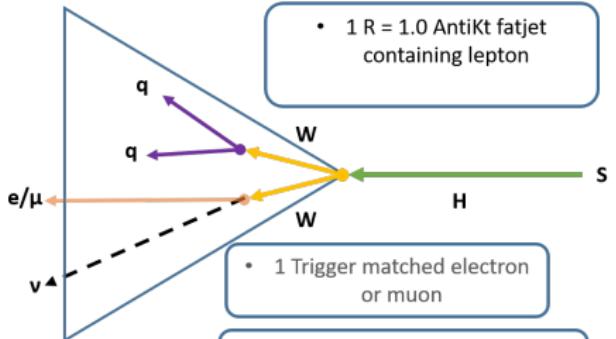


Fully Boosted Event Selection

H->WW

- Fatjet+muon+neutrino
OR
- Fatjet+neutrino

- 1 R = 1.0 AntiKt fatjet containing lepton

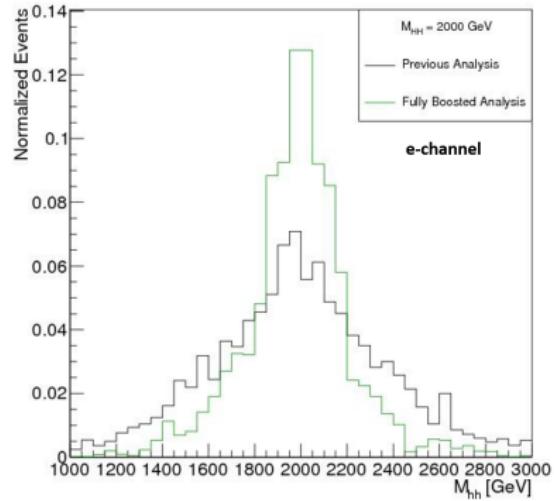
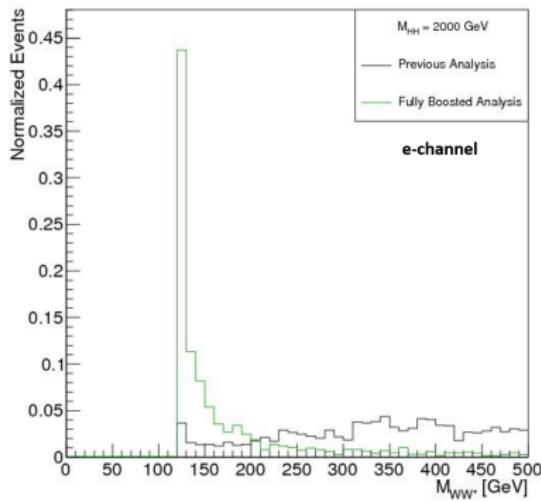


Trigger

- Single electron
 - $p_T > 24\text{ GeV}$
- Or
- Single muon
 - $p_T > 20(24) \text{ GeV} \text{ 2015}(16)$

- 1 R = 1.0 AntiKt fatjet with 2 associated b-tagged R = 0.2 trackjets
- $\Delta R_{l,fj} > 1.0$

Signal Reconstruction

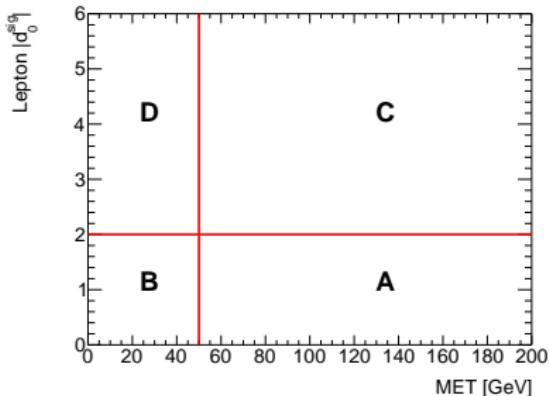


Previous Analysis:

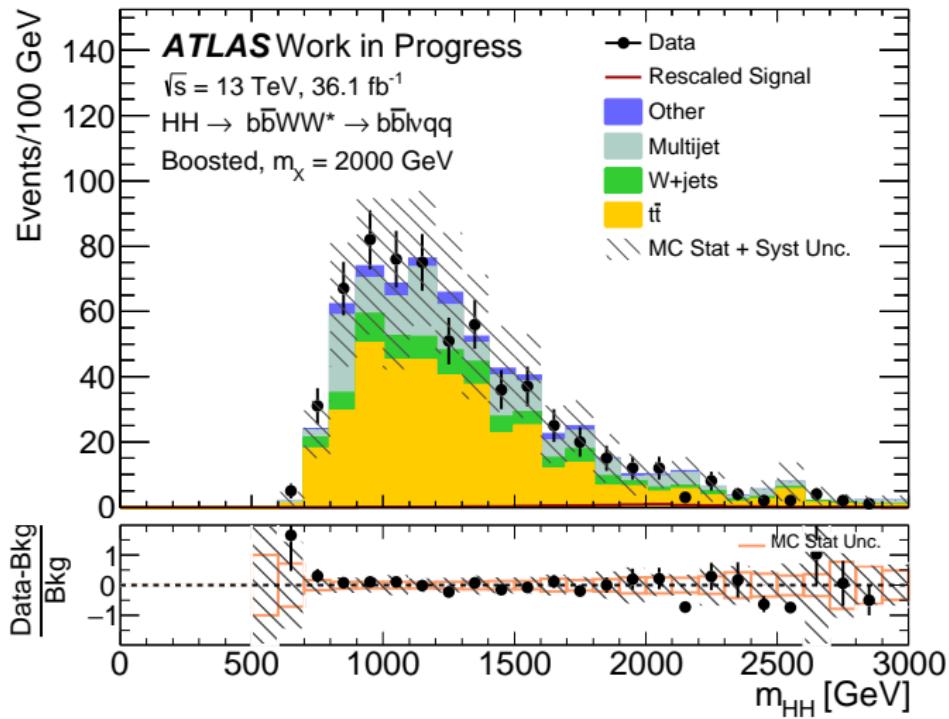
- ▶ $H \rightarrow WW = 1 \text{ lepton} + 2 \text{ AntiKt}, R = 0.4 \text{ jets} + \nu$

Background Modeling

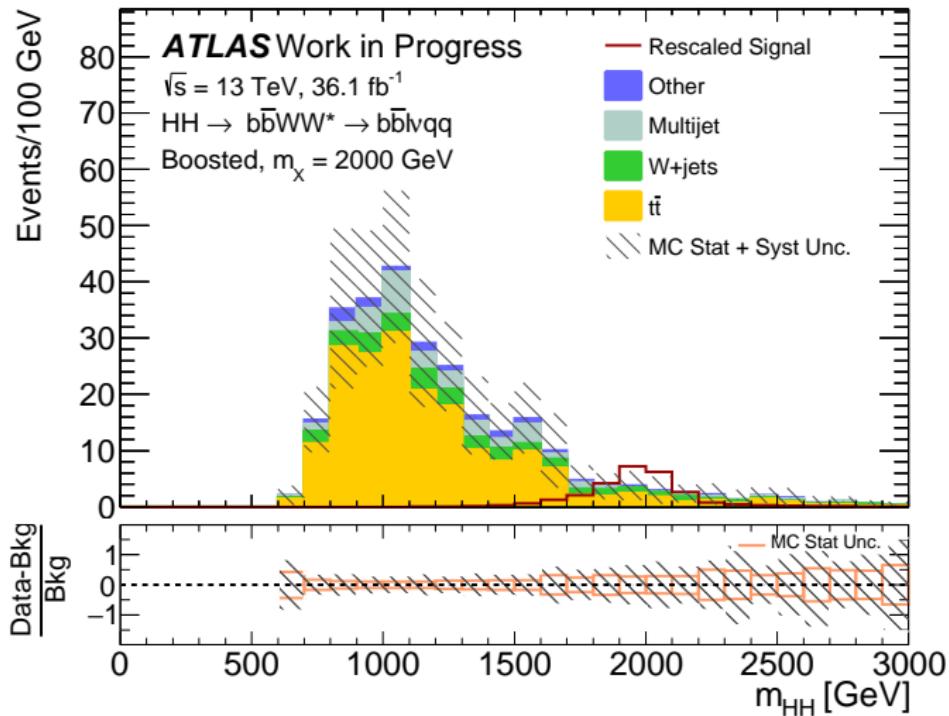
- ▶ Same procedure as boosted paper analysis
- ▶ ABCD data driven technique for QCD
- ▶ Slightly looser selection to increase statistics
- ▶ Check shape in mBB validation region



Background Shape Check

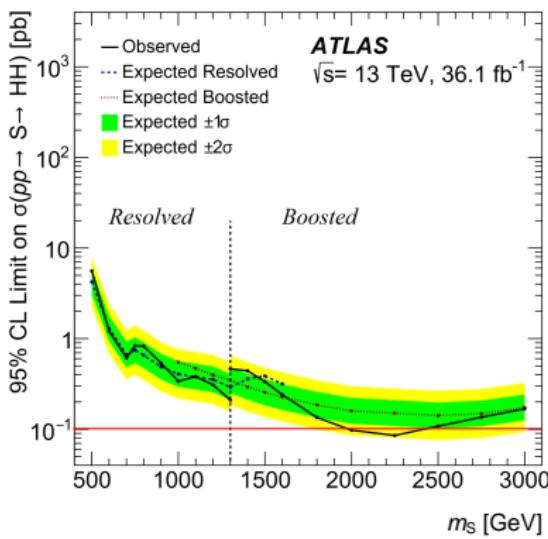


Signal Region m_{HH}

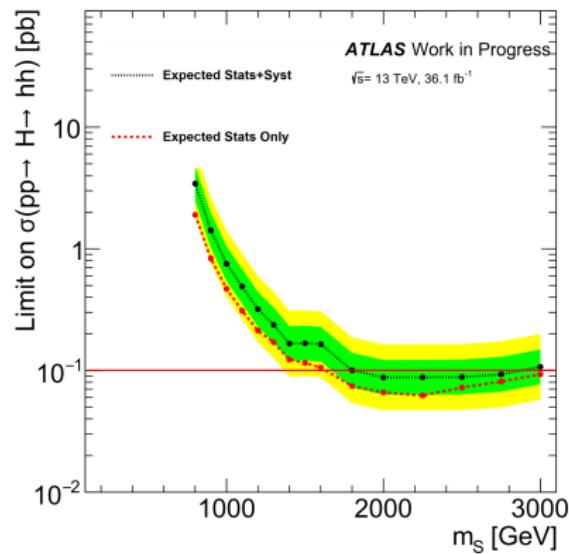


Results

Published Analysis



Improved Fully-Boosted Analysis



Conclusion

- ▶ Set the first limits for HH resonant production over 1 TeV
- ▶ Developed analysis for SM HH production in $b\bar{b} \rightarrow b\bar{b}l\nu qq$ channel
 - ▶ Set limit of 300 X SM cross section
- ▶ Improved the cross section upper limit for high resonant mass by \sim factor of 2

Outlook

- ▶ Move to Fatjet trigger
 - ▶ Lepton ID requirement in derivation limits the high mass analysis
- ▶ Neutrino reconstruction needs improved at high mass
 - ▶ Use $H \rightarrow b\bar{b}$ information
- ▶ ABCD estimate is limited by statistics
 - ▶ Move to alternate QCD estimate like MM

Thank you to my committee:
Stephanie Majewski (Chair)
Tim Cohen
Hank Childs
My Advisor: **Eric Torrence**
And a special thanks to Alison

Questions?

Backup

Neutrino Reconstruction

$$m_H^2 = (p^I + p^\nu + p^{i1} + p^{i2})^2$$

Where p^i is the 4-momentum of particle i

To find p_z^ν , solve:

$$p_E^\nu = E^\nu = \sqrt{p_T^2 + p_z^2} ; p_x^\nu = p_T \cos \phi ; p_y^\nu = p_T \sin \phi$$

Resolved Signal Region

variable	<i>Non-Res</i>	<i>m500</i>	<i>low-mass</i>	<i>high-mass</i>	
E_T (GeV)	> 25	> 25	> 25	> 25	
m_{WW} (GeV)	< 130	< 130	< 130	no-cut	
p_T^{bb} (GeV)	> 300	> 210	> 210	> 350	
p_T^{WW} (GeV)	> 250	> 150	> 250	> 250	
ΔR_{WW}	no-cut	no-cut	no-cut	< 1.5	
m_{bb} (GeV)	105-135	105-135	105-135	105-135	
m_S (GeV)	500	600	700	750	800
m_{HH} (GeV)	480-530	560-640	625-775	660-840	695 - 905
m_S (GeV)	900	1000	1100	1200	1300
m_{HH} (GeV)	760-970	840-1160	925-1275	1010-1390	1095-1505
m_S (GeV)	1400	1500	1600	1800	2000
m_{HH} (GeV)	1250-1550	1340-1660	1430-1770	1750-2020	1910-2170
m_S (GeV)	2250	2500	2750	3000	
m_{HH} (GeV)	2040-2460	2330-2740	2570-2950	2760-3210	

mBBcr

variable	CR1	CR2	CR3
m_{bb} (GeV)	$m_{bb} < 100$ or $m_{bb} > 140$	$m_{bb} < 100$ or $m_{bb} > 140$	$m_{bb} < 100$ or $m_{bb} > 140$
m_{WW} (GeV)	< 130	< 130	no-cut
p_T^{bb} (GeV)	> 300	> 210	> 350

CR1

CR1: m_{bb} Sideband				
Sample	mww	bbpt210	bbpt300	wwpt250
$t\bar{t}$	23776.6 ± 87.2	531.7 ± 13.1	109.9 ± 5.9	63.9 ± 4.6
QCD	13310.5 ± 500.3	250.2 ± 30.6	33.7 ± 4.1	21.4 ± 2.6
W+jets	3938.9 ± 31.1	124.7 ± 3.5	29.3 ± 1.4	17.1 ± 1.1
SingleTop	1605.4 ± 18.0	76.0 ± 3.8	20.1 ± 2.0	13.5 ± 1.7
Dibosons	109.9 ± 2.7	8.3 ± 0.8	2.2 ± 0.4	1.5 ± 0.4
Z+jets	1107.6 ± 8.4	27.1 ± 0.8	6.7 ± 0.4	2.4 ± 0.2
Background Sum	43849.0 ± 509.2	1017.9 ± 33.7	201.9 ± 7.6	119.8 ± 5.7
XhhSM	44.6 ± 2.2	9.1 ± 0.7	1.5 ± 0.2	1.1 ± 0.1
Data	43902.0	1069.0	206.0	138.0

CR2 500

CR2: m_{bb} Sideband				
Sample	mw _w	bbpt210	wwpt150	hh500
t \bar{t}	23776.6 \pm 87.2	531.7 \pm 13.1	432.7 \pm 11.8	35.5 \pm 3.2
QCD	13310.5 \pm 500.3	250.2 \pm 30.6	206.3 \pm 25.3	16.9 \pm 2.1
W+jets	3938.9 \pm 31.1	124.7 \pm 3.5	105.9 \pm 3.3	4.9 \pm 0.6
SingleTop	1605.4 \pm 18.0	76.0 \pm 3.8	64.9 \pm 3.5	2.8 \pm 0.6
Dibosons	109.9 \pm 2.7	8.3 \pm 0.8	6.7 \pm 0.8	0.9 \pm 0.2
Z+jets	1107.6 \pm 8.4	27.1 \pm 0.8	19.0 \pm 0.7	1.5 \pm 0.2
Background Sum	43849.0 \pm 509.2	1017.9 \pm 33.7	835.5 \pm 28.3	62.5 \pm 3.9
Xhh500	3.2 \pm 0.1	0.6 \pm 0.1	0.6 \pm 0.1	0.2 \pm 0.1
Data	43902.0	1069.0	898.0	73.0

CR2 700

CR2: m_{bb} Sideband				
Sample	mww	bbpt210	wwpt250	hh700
t \bar{t}	23776.6 \pm 87.2	531.7 \pm 13.1	175.6 \pm 7.5	49.9 \pm 3.9
QCD	13310.5 \pm 500.3	250.2 \pm 30.6	72.4 \pm 8.9	28.4 \pm 3.5
W+jets	3938.9 \pm 31.1	124.7 \pm 3.5	45.7 \pm 2.1	13.7 \pm 1.4
SingleTop	1605.4 \pm 18.0	76.0 \pm 3.8	28.4 \pm 2.4	6.9 \pm 1.1
Diboson	109.9 \pm 2.7	8.3 \pm 0.8	2.8 \pm 0.5	0.7 \pm 0.2
Z+jets	1107.6 \pm 8.4	27.1 \pm 0.8	5.8 \pm 0.4	2.0 \pm 0.3
Background Sum	43849.0 \pm 509.2	1017.9 \pm 33.7	330.7 \pm 12.1	101.5 \pm 5.5
Xhh700	4.2 \pm 0.2	2.2 \pm 0.1	1.5 \pm 0.1	1.0 \pm 0.1
Data	43902.0	1069.0	367.0	124.0

CR3

CR3: m_{bb} Sideband

Sample	bbpt350	wwpt250	drww15	hh2000
$t\bar{t}$	8568.7 ± 52.1	7095.6 ± 47.5	1940.5 ± 25.1	122.3 ± 6.5
QCD	1538.7 ± 252.7	1359.5 ± 75.9	392.7 ± 21.9	20.7 ± 1.2
W+jets	2259.5 ± 7.9	1952.1 ± 7.4	696.6 ± 4.6	55.5 ± 1.1
SingleTop	1778.1 ± 19.4	1601.6 ± 18.4	405.4 ± 9.2	29.6 ± 2.6
Dibosons	170.6 ± 3.9	147.1 ± 3.7	46.8 ± 2.1	3.4 ± 0.6
Z+jets	403.6 ± 2.1	307.6 ± 1.8	95.6 ± 1.1	7.5 ± 0.3
Background Sum	14719.1 ± 258.9	12463.5 ± 91.8	3577.5 ± 35.0	238.9 ± 7.2
Xhh2000	25.7 ± 0.4	24.0 ± 0.4	9.6 ± 0.3	2.9 ± 0.1
Data	14862.0	12450.0	3761.0	250.0

$t\bar{t}$ Normalization Factor

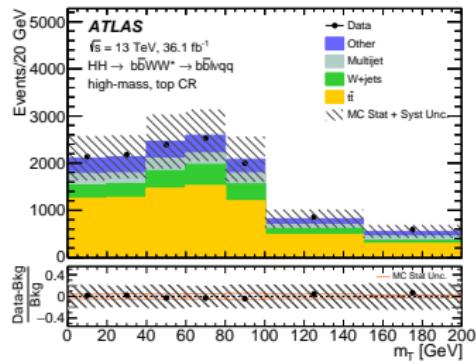
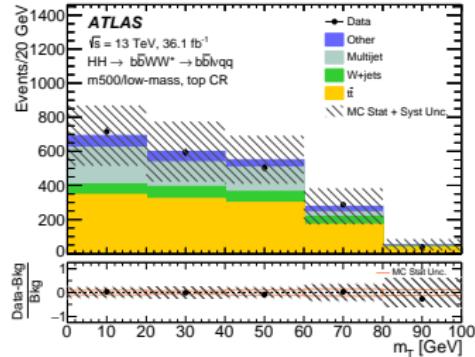
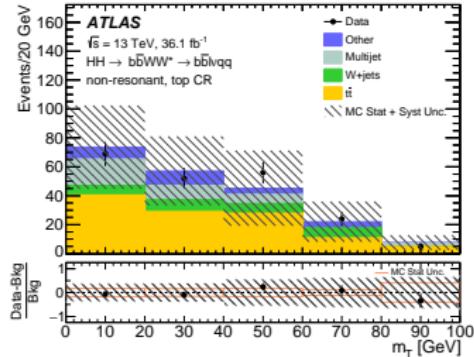
Top background normalization factors in the two CRs.

region	NF	$\sigma_{stat.}$	$\sigma_{syst.}$
non-res	1.04	± 0.20	± 0.43
low-mass	1.14	± 0.10	± 0.35
high-mass	1.02	± 0.02	± 0.07

Boosted VR

Sample	Yield	Stats Unc	Systs Unc
$t\bar{t}$	1005.6	± 20.6	+283.6(+28.2%) -288.8(-28.7%)
W+Jets	565.6	± 10.3	+277.9(+49.1%) -270.0(-47.7%)
QCD	377.9	± 19.6	+328.0(+86.8%) -328.0(-86.8%)
Single-top	161.3	± 7.2	+114.4(+70.9%) -114.4(-70.9%)
Z+Jets	55.9	± 1.6	+27.7(+49.5%) -27.2(-48.6%)
Dibosons	39.7	± 2.6	+23.4(+58.9%) -23.3(-58.7%)
Prediction	2206.0	± 31.2	+593.7(+26.9%) -586.1(-26.6%)
Data	2179	-	-
Data/Pred	0.99	-	-

mBBcr



Non-Res SR

SR: $100 < m_{bb} < 140$ GeV

Sample	mww	bbpt210	bbpt300	wwpt250	mbb
$t\bar{t}$	7461.0 ± 48.6	162.9 ± 7.3	27.9 ± 2.9	18.4 ± 2.4	15.4 ± 2.2
QCD	2756.2 ± 210.5	48.7 ± 14.2	6.6 ± 1.9	4.2 ± 1.2	3.6 ± 1.6
Wv221	640.8 ± 12.7	19.1 ± 1.4	5.0 ± 0.6	3.1 ± 0.5	2.3 ± 0.4
SingleTop	452.2 ± 9.6	14.3 ± 1.7	1.7 ± 0.5	1.0 ± 0.4	0.6 ± 0.3
Dibosonsv221	21.6 ± 1.3	0.6 ± 0.2	0.4 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
Zv221	262.8 ± 4.4	3.1 ± 0.3	1.0 ± 0.2	0.2 ± 0.1	0.2 ± 0.1
Background Sum	11594.7 ± 216.7	248.6 ± 16.1	42.6 ± 3.6	27.0 ± 2.8	22.1 ± 2.8
XhhSM	68.3 ± 2.4	20.7 ± 0.9	6.7 ± 0.4	5.5 ± 0.3	4.8 ± 0.3
Data	11450.0	232.0	47.0	31.0	22.0

m500 SR

SR: $100 < m_{bb} < 140$ GeV					
Sample	mww	bbpt210	wwpt150	hh500	mbb
t \bar{t}	7461.0 \pm 48.6	162.9 \pm 7.3	141.7 \pm 6.8	17.3 \pm 2.2	12.6 \pm 1.9
QCD	2756.2 \pm 210.5	48.7 \pm 14.2	40.2 \pm 11.7	3.3 \pm 1.0	2.9 \pm 1.3
W v 221	640.8 \pm 12.7	19.1 \pm 1.4	15.3 \pm 1.3	0.1 \pm 0.0	-0.2 \pm 0.1
SingleTop	452.2 \pm 9.6	14.3 \pm 1.7	12.2 \pm 1.6	3.6 \pm 0.8	2.8 \pm 0.7
Dibosonsv221	21.6 \pm 1.3	0.6 \pm 0.2	0.5 \pm 0.2	0.1 \pm 0.0	0.1 \pm 0.0
Z v 221	262.8 \pm 4.4	3.1 \pm 0.3	1.9 \pm 0.2	0.5 \pm 0.1	0.4 \pm 0.1
Background Sum	11594.7 \pm 216.7	248.6 \pm 16.1	211.8 \pm 13.7	24.9 \pm 2.5	18.6 \pm 2.4
Xhh500	6.6 \pm 0.2	1.9 \pm 0.1	1.7 \pm 0.1	0.9 \pm 0.1	0.8 \pm 0.1
Data	11450.0	232.0	194.0	32.0	26.0

low-mass SR

SR: $100 < m_{bb} < 140$ GeV					
Sample	mww	bbpt210	wwpt250	hh700	mbb
t̄t	7461.0 ± 48.6	162.9 ± 7.3	61.5 ± 4.7	21.9 ± 2.7	15.3 ± 2.2
QCD	2756.2 ± 210.5	48.7 ± 14.2	14.1 ± 4.1	5.5 ± 1.6	4.8 ± 2.2
Wv221	640.8 ± 12.7	19.1 ± 1.4	9.7 ± 1.1	4.1 ± 0.8	2.6 ± 0.6
SingleTop	452.2 ± 9.6	14.3 ± 1.7	2.6 ± 0.7	0.5 ± 0.2	0.3 ± 0.2
Dibosonsv221	21.6 ± 1.3	0.6 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1
Zv221	262.8 ± 4.4	3.1 ± 0.3	0.6 ± 0.1	0.1 ± 0.0	0.1 ± 0.0
Background Sum	11594.7 ± 216.7	248.6 ± 16.1	88.7 ± 6.4	32.3 ± 3.2	23.3 ± 3.1
Xhh700	9.2 ± 0.3	7.8 ± 0.2	5.9 ± 0.2	5.0 ± 0.2	4.4 ± 0.2
Data	11450.0	232.0	75.0	25.0	22.0

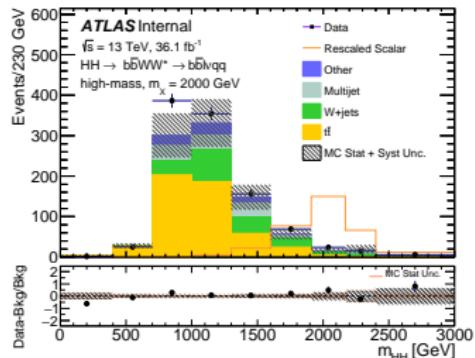
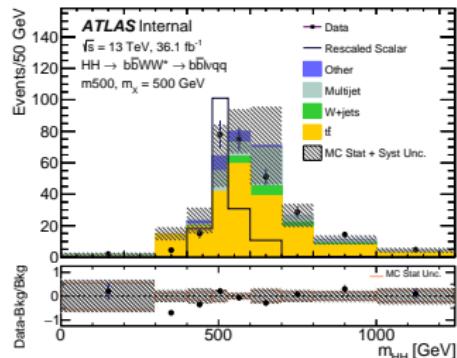
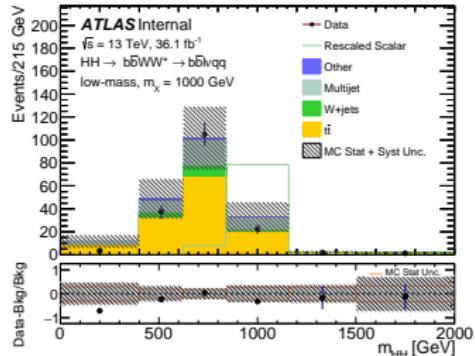
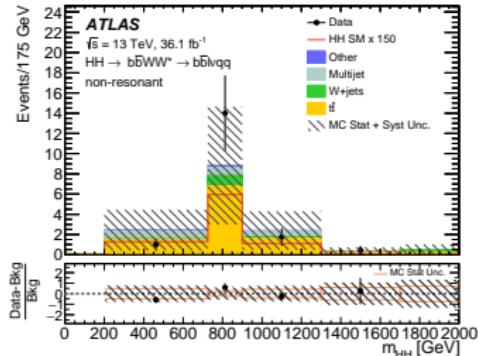
high-mass SR

SR: $100 < m_{bb} < 140$ GeV					
Sample	bbpt350	wwpt250	drww15	hh2000	mbb
$t\bar{t}$	1307.8 ± 20.2	1024.9 ± 17.7	287.5 ± 9.4	2.2 ± 0.8	1.4 ± 0.6
QCD	207.2 ± 99.5	191.2 ± 29.0	55.2 ± 8.4	2.9 ± 0.4	2.2 ± 0.5
Wv221	341.3 ± 3.4	291.5 ± 3.2	110.7 ± 2.1	4.8 ± 0.3	3.4 ± 0.3
SingleTop	144.1 ± 5.6	126.6 ± 5.3	29.2 ± 2.6	0.5 ± 0.3	0.5 ± 0.3
Dibosonsv221	25.9 ± 1.5	21.8 ± 1.3	6.6 ± 0.7	0.0 ± 0.0	0.0 ± 0.0
Zv221	53.8 ± 0.8	40.4 ± 0.7	13.2 ± 0.4	0.8 ± 0.1	0.7 ± 0.1
Background Sum	2080.1 ± 101.8	1696.5 ± 34.6	502.5 ± 13.1	11.2 ± 1.0	8.2 ± 0.8
Xhh2000	21.0 ± 0.4	19.3 ± 0.4	8.4 ± 0.2	3.4 ± 0.1	2.9 ± 0.1
Data	2182.0	1830.0	587.0	11.0	9.0

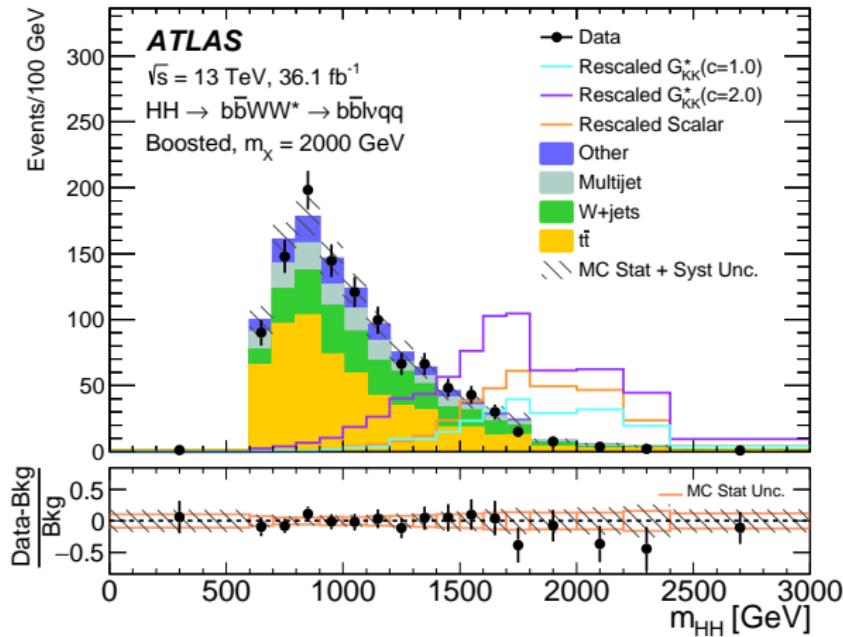
Boosted SR

Sample	Yield	Stats Err	Systs Err
$t\bar{t}$	648.7	± 16.4	+177.3(+27.3%) -169.2(-26.1%)
W+Jets	217.0	± 6.5	+104.3(+48.1%) -100.9(-46.5%)
QCD	235.2	± 18.9	+181.8(+77.3%) -181.8(-77.3%)
Single-top	109.2	± 6.0	+86.0(+78.8%) -85.8(-78.6%)
Z+Jets	20.5	± 1.1	+11.2(+54.6%) -10.9(-52.9%)
Dibosons	24.4	± 1.9	+15.3(+62.6%) -14.7(-60.1%)
Prediction	1255.0	± 26.7	+324.3(+25.8%) -311.3(-24.8%)
Data	1107	-	-
Data/Pred	0.88	-	-

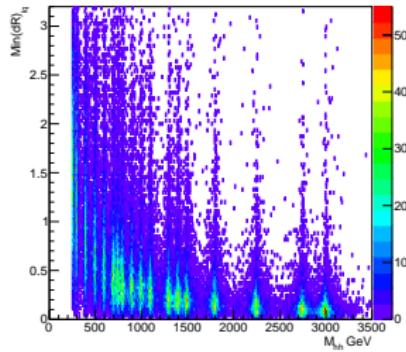
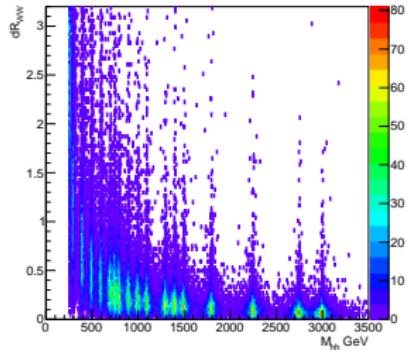
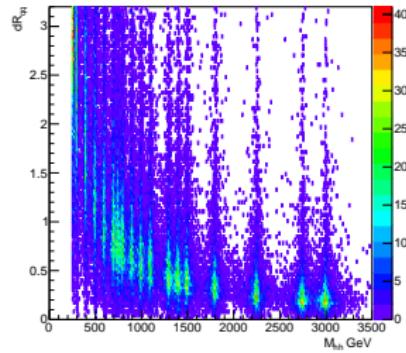
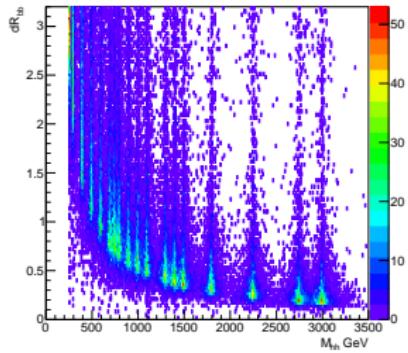
Resolved SR m_{HH}



Boosted SR m_{HH}



Truth Study



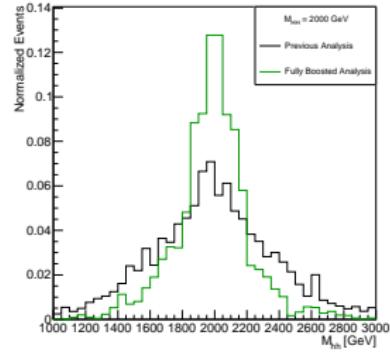
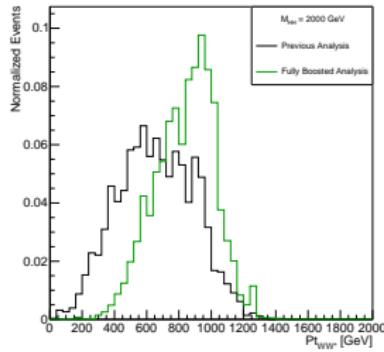
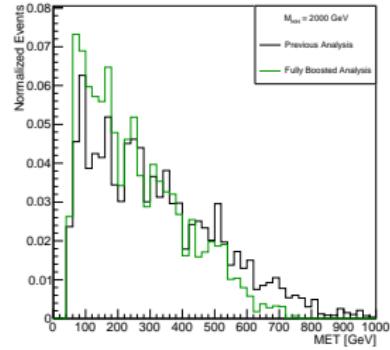
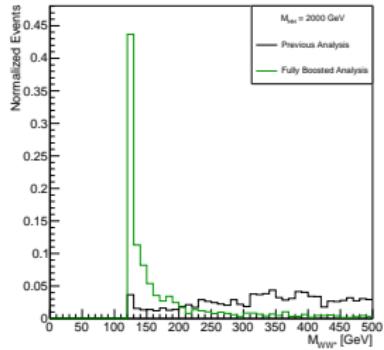
Kinematic Variable Definition

Neutrino reco:

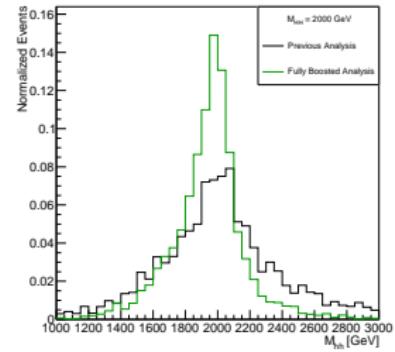
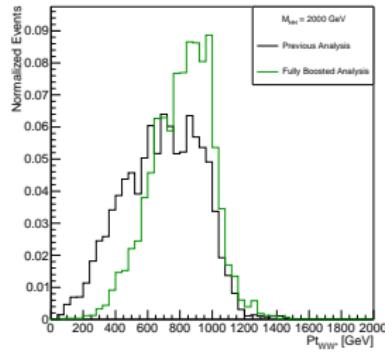
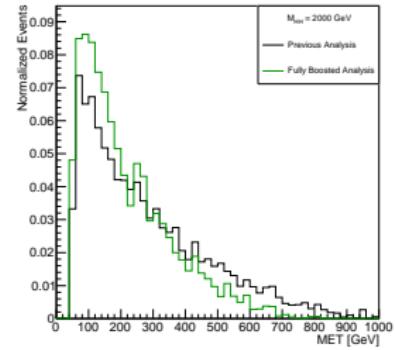
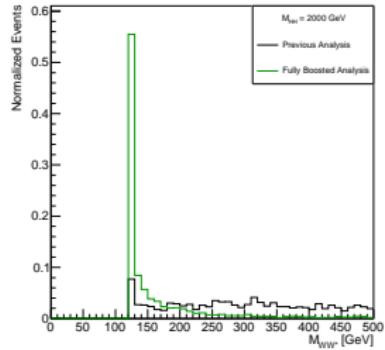
$$m_h^2 = (p^\nu + p^{\text{large-R jet}})^2$$

Lepton Channel	Alternative p_T definition
Muon Channel	$p'_T = p_T^{\text{Large-Rjet}}$
Electron channel	$p'_T = \sqrt{(p_x^{\text{Large-Rjet}} - p_x^{\text{electron}})^2 + (p_y^{\text{Large-Rjet}} - p_y^{\text{electron}})^2}$

Reconstructed Variables e-Channel



Reconstructed Variables mu-Channel

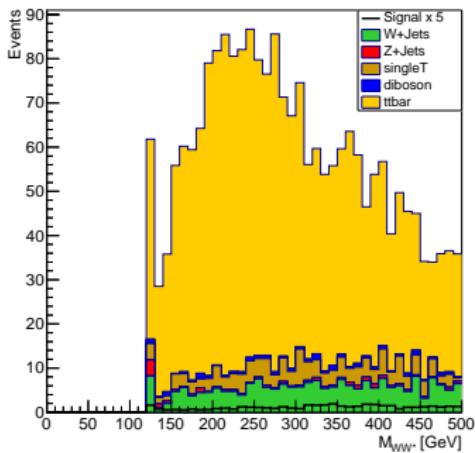


Fully Boosted SR

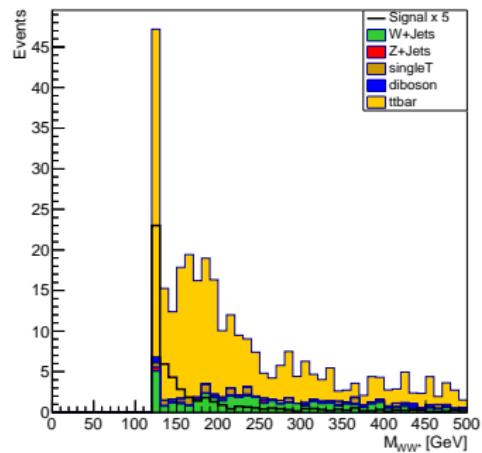
Sample	Yield	Stats Unc
$t\bar{t}$	187.7	± 8.8
W+Jets	33.7	± 1.9
QCD	34.5	± 5.5
Single-top	7.0	± 1.3
Z+Jets	4.7	± 0.4
Dibosons	3.3	± 0.6
Prediction	271.0	± 10.7

Electron Reco. m_{WW}

Paper Boosted Analysis

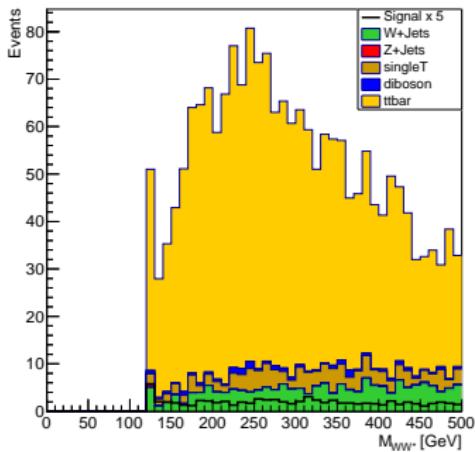


Fully-Boosted Analysis

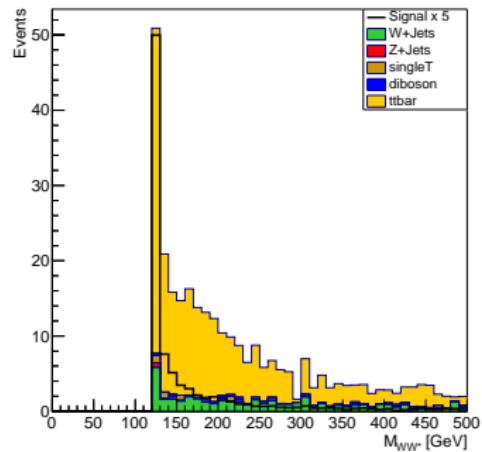


Muon Reco. m_{WW}

Paper Boosted Analysis

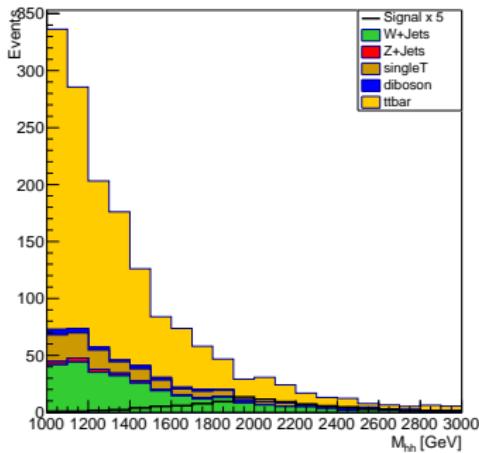


Fully-Boosted Analysis

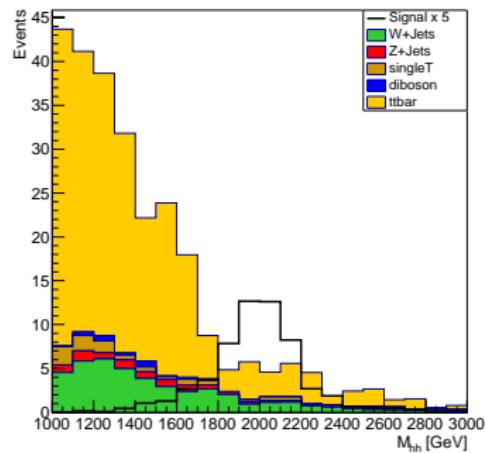


Electron Reco. m_{HH}

Paper Boosted Analysis

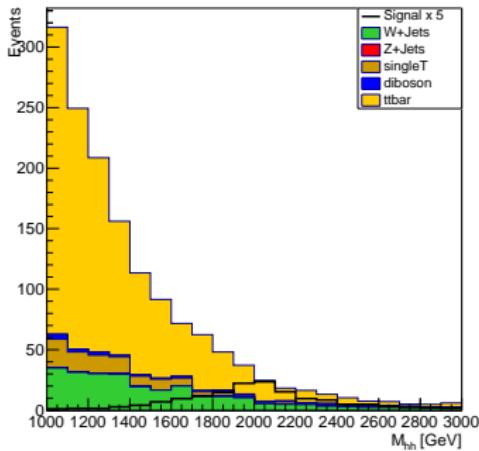


Fully-Boosted Analysis

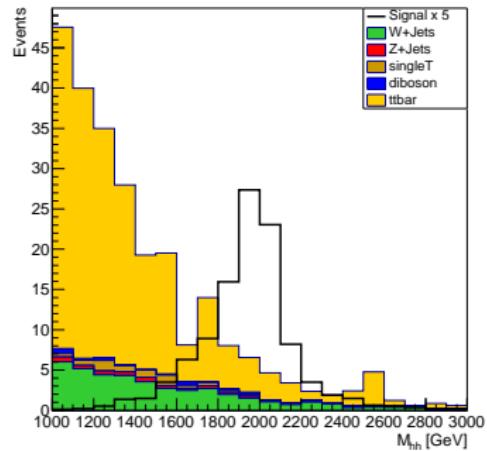


Muon Reco. m_{HH}

Paper Boosted Analysis



Fully-Boosted Analysis



Fully Boosted Systematics Unc.

Uncertainty	Up/Down
SysFT_EFF_Eigen_Light_0_AntiKt2PV0TrackJets_1down	-12.9/12.5
SysFT_EFF_Eigen_C_0_AntiKt2PV0TrackJets_1down	-12.6/12.1
SysFT_EFF_Eigen_C_0_AntiKt2PV0TrackJets_1up	11.3/-11.9
SysFT_EFF_Eigen_Light_0_AntiKt2PV0TrackJets_1up	11.3/-11.9
SysFATJET_Medium_JET_Comb_Baseline_Kin_1up	-6.47/5.95
SysFATJET_Medium_JET_Comb_Baseline_Kin_1down	5.83/-6.43
SysFT_EFF_Eigen_B_0_AntiKt2PV0TrackJets_1down	-3.49/2.97
SysFT_EFF_Eigen_B_1_AntiKt2PV0TrackJets_1down	-3.32/2.8
SysFT_EFF_Eigen_C_1_AntiKt2PV0TrackJets_1down	-2.97/2.45
SysFT_EFF_Eigen_B_0_AntiKt2PV0TrackJets_1up	2.39/-2.94
SysFT_EFF_Eigen_B_1_AntiKt2PV0TrackJets_1up	2.23/-2.78
SysFT_EFF_Eigen_C_1_AntiKt2PV0TrackJets_1up	1.9/-2.45
SysFATJET_Medium_JET_Comb_Tracking_Kin_1down	1.77/-2.38
SysFATJET_Medium_JET_Comb_Tracking_Kin_1up	-2.2/1.68
SysFT_EFF_extrapolation_AntiKt2PV0TrackJets_1up	-2.07/1.59
SysFATJET_JMR_1up	1.41/-1.97
SysFT_EFF_extrapolation_from_charm_AntiKt2PV0TrackJets_1up	-1.62/1.1
SysFT_EFF_extrapolation_AntiKt2PV0TrackJets_1down	0.963/-1.54
SysPRW_DATASF_1down	-1.47/0.94
SysJET_SR1_JET_GroupedNP_1_1down	0.764/-1.33
SysJET_SR1_JET_GroupedNP_1_1up	-1.2/0.678
SysFATJET_JER_1up	0.574/-1.16
SysFT_EFF_Eigen_Light_1_AntiKt2PV0TrackJets_1up	-1.12/0.576
SysFT_EFF_extrapolation_from_charm_AntiKt2PV0TrackJets_1down	0.553/-1.1
SysFATJET_Medium_JET_Comb_TotalStat_Kin_1down	-1.03/0.498
Total Up	27.2
Total Do	27.7