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

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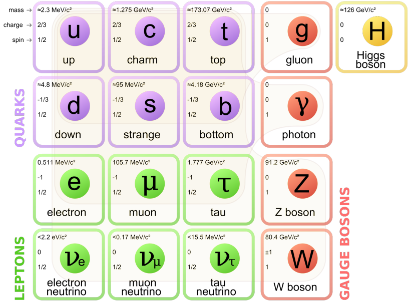
Overview

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

The Standard Model

- Describes matter (fermions) and force carriers (gauge bosons)
- Very successful model
- The discovery of the final piece (Higgs Boson) announced in 2012



Higgs Mechanism

Scalar Boson

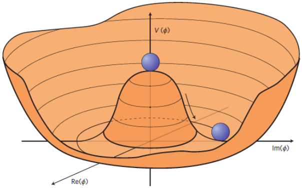
$$\phi = \frac{1}{\sqrt{2}}\binom{\phi^+}{\phi^0}$$

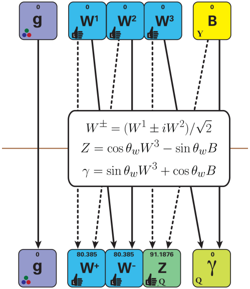
$$\Downarrow \text{ EWSB } \Downarrow$$

$$\phi_0 = \frac{1}{\sqrt{2}}\binom{0}{v};\ \ \phi(x) = \frac{1}{\sqrt{2}}\binom{0}{v+h(x)}$$

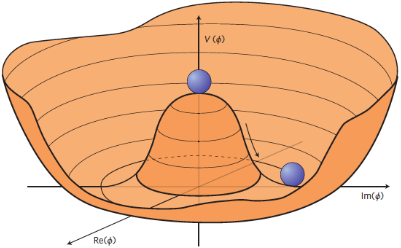
Coupling to Gauge Bosons gives
$W^{\pm},\ Z,\ A(\gamma)$

$$M_W^2 = \frac{1}{4}g^2v^2$$
$$M_Z^2 = \frac{1}{4}(g^2+g'^2)v^2$$
$$M_A^2 = 0$$





Higgs Self-Coupling



Higgs Potential

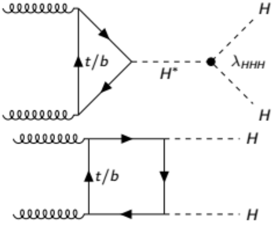
$$V = \mu^2|\Phi^\dagger\Phi| + \lambda(|\Phi^\dagger\Phi|)^2$$

Expand self-coupling around minimum

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

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

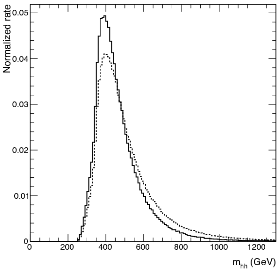
Higgs Self-Coupling



Two dominant double Higgs production diagrams at the LHC

Interfere destructively to give small theoretical cross section

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

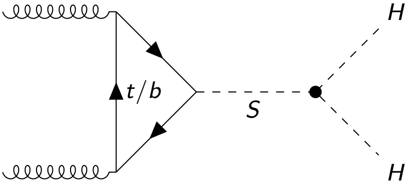


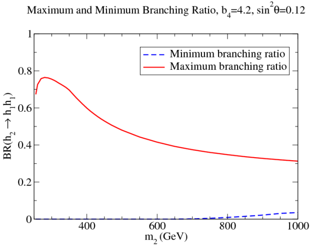
Motivation

Resonant Double 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

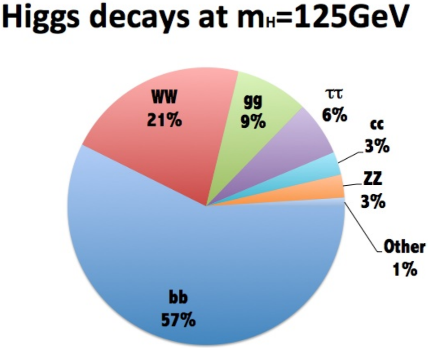
By measuring the HH production rate, we can search for resonant production





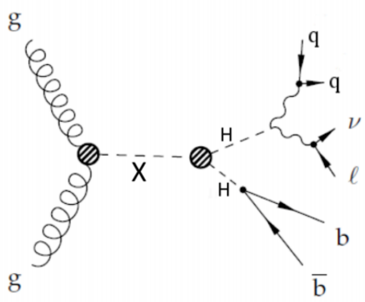
HH $\rightarrow$ b$\bar{\text{b}}$WW* Semi-Leptonic Channel

- $b\bar{b}WW^*$ 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 $bbl\nu qq$ final state
  - Lepton helps against QCD
  - Neutrino makes reco. more challenging



bblνqq Final State

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



Background

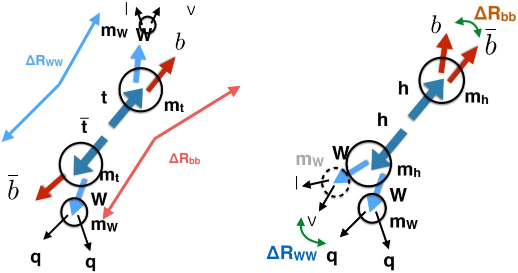
Major

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

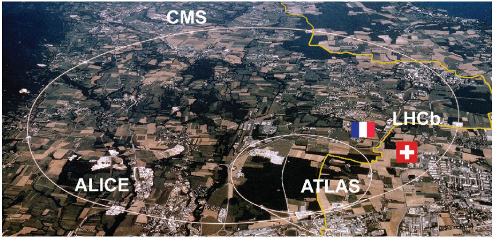
Minor

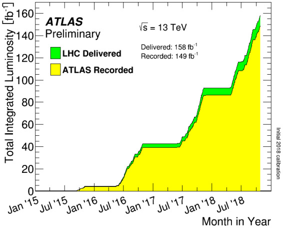
- Z+Jets
- Single Top
- Diboson

$t\bar{t}$ vs signal



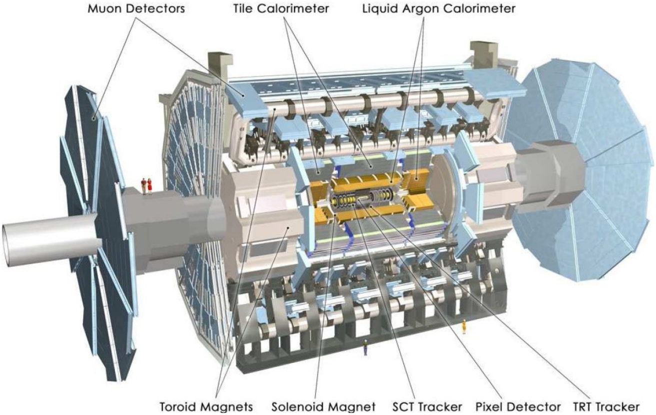
The Large Hadron Collider





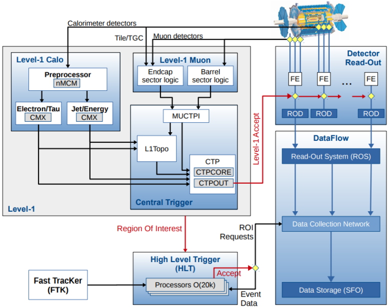
- 13 TeV CoM Proton-Proton Collider
- 27 km Circumference under the French-Swiss border
- 4 primary interaction points, each with a dedicated detector
- Run 2 delivered 158 fb^{-1}

The ATLAS Detector

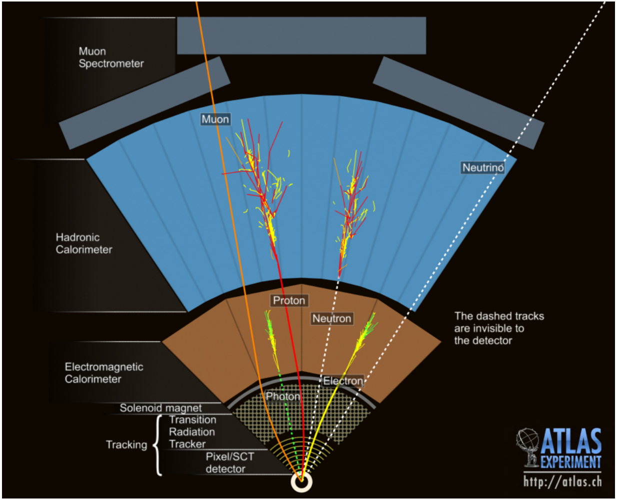


ATLAS Trigger

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

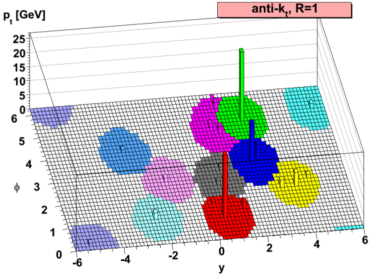


Particles in the Detector



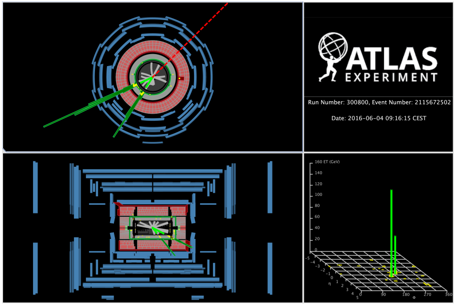
Jets

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



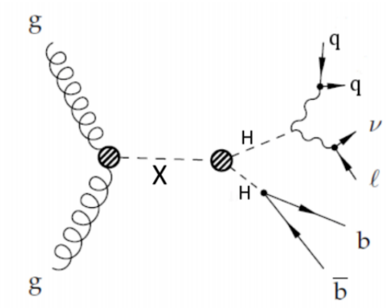
Neutrinos

- Neutrinos do not interact with detector
- Have transverse (perpendicular to beam line) information from $\not{E}_T$
- Need another piece to fully reconstruct 4-momentum
  - This analysis used Higgs mass



Final State Detector Objects

- electron or muon
- 2 light jets
- 2 b-jets
- $\not{E}_T$

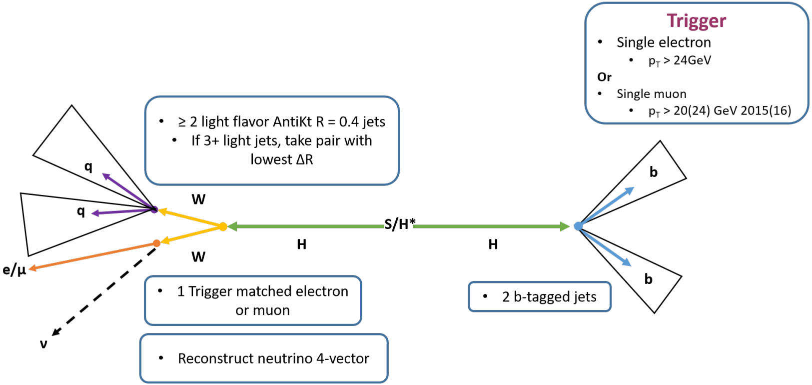


HH $\to$ b$\bar{\text{b}}$WW* Analysis

2 Separate Analyses Presented:

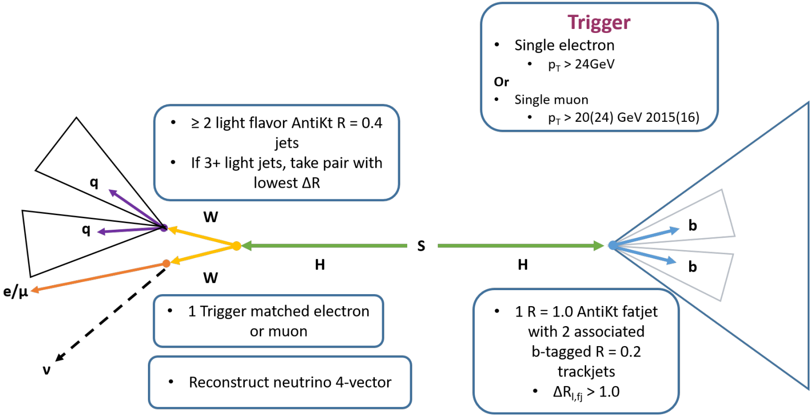
- 2015-2016, 36.1 fb^{-1} Analysis
  - JHEP04(2019)092
- Improvements for full Run 2 analysis

Resolved Event Selection



Designed to target SM production and $m_S < 1300$ GeV

Boosted Event Selection



Designed to target $m_S > 1300$ GeV

Signal Region

Resolved

- $\not{E}_T > 25$ GeV
- Large p_T^{bb}
- Large p_T^{WW}
- $m_{bb} \sim m_H$
- $m_{HH} \sim m_S$

Boosted

- $\not{E}_T > 50$ GeV
- $m_{\mathrm{Large-R\ jet}} \sim m_H$

Resolved Background Determination

$t\bar{t}$

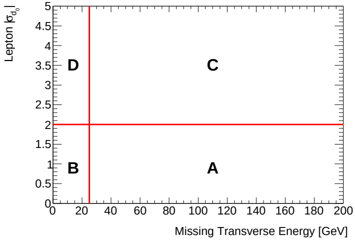
- Normalized in m_{bb} CR
  - Boosted $t\bar{t}$ VR

Other MC Bkg.

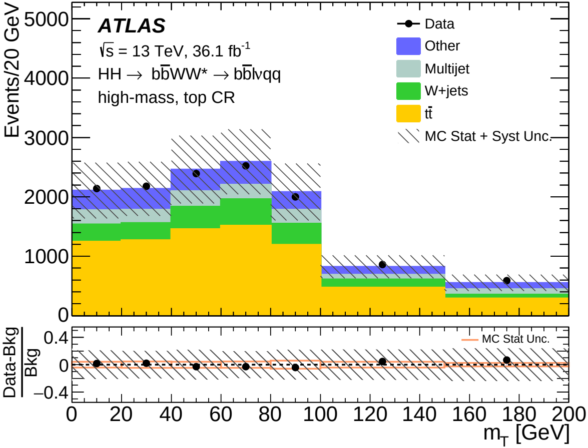
- Modeled using MC and normalized to SM XSec

QCD multi-jet background

- ABCD data driven estimate
  - $N_A = F N_C N_B / N_D$
  - F is a correction factor determined earlier in the cutflow
  - Boosted uses $\not{E}_T > 50$ GeV
    - Takes shape from 1 b-tag C Region

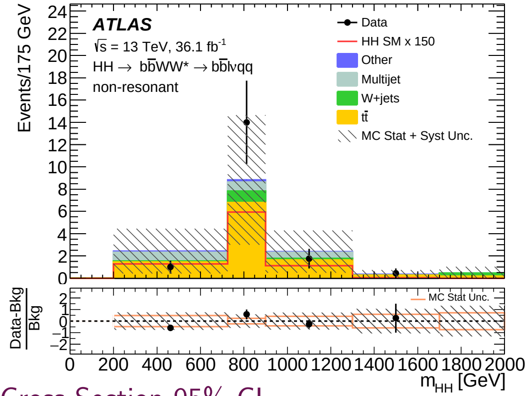


Background Shape Check



$$m_T = \sqrt{2 p_T^l \not{E}_T \times (1 - \cos \Delta\phi)}$$

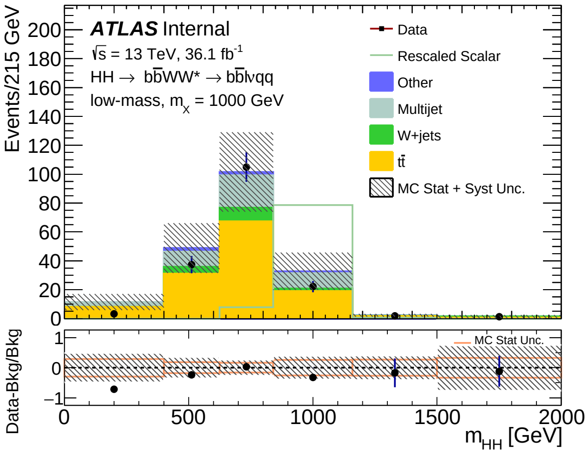
Standard Model Signal Region and Results



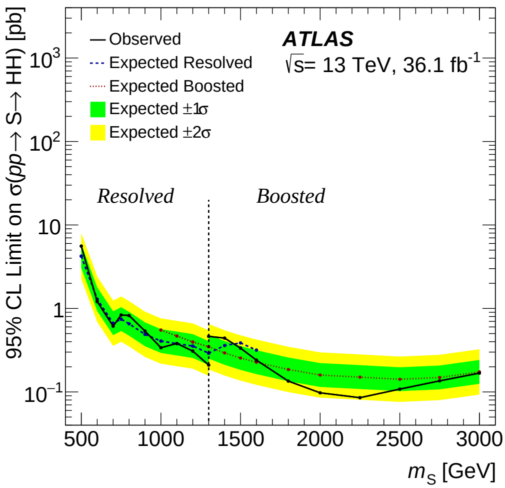
Production Cross Section 95% CL

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

Resonant Production Signal Region

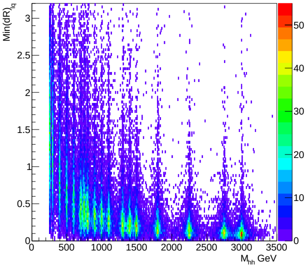


Combined Resonant Production Limit

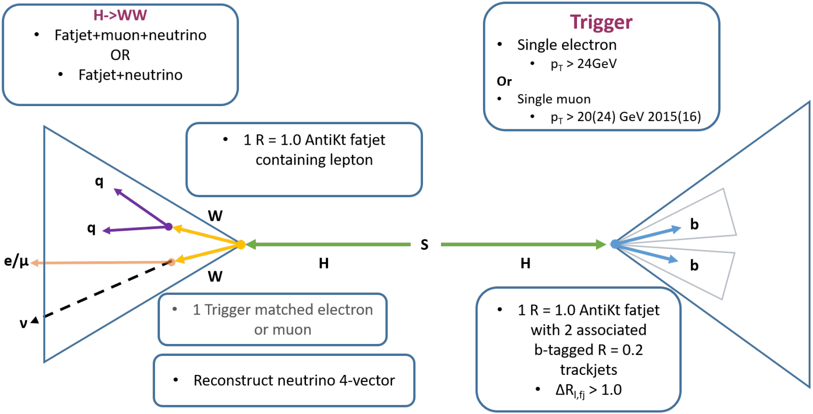


Improvements to the Paper Analysis

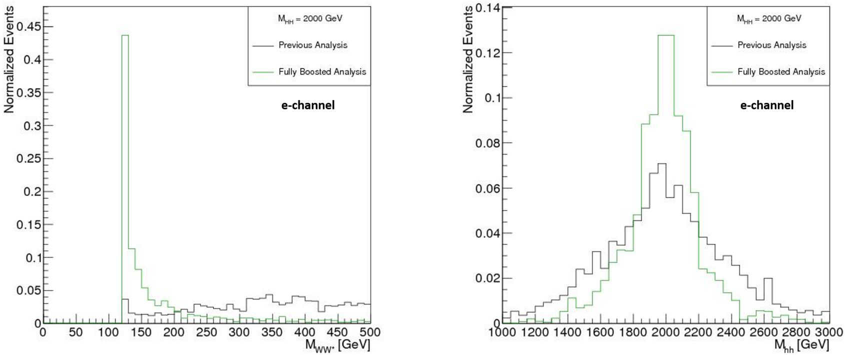
- $H \to WW^*$ becomes boosted around 1 TeV
- Quarks become too close together to use 0.4 jets
- Overlap removal with leptons kill efficiency
- A "Fully-Boosted" selection recovers lost efficiency at high m_S



Fully Boosted Event Selection



Signal Reconstruction

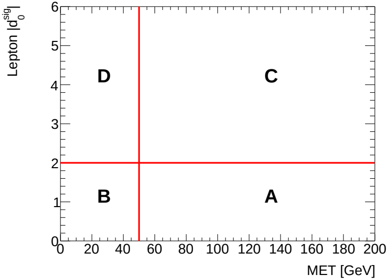


Previous Analysis:

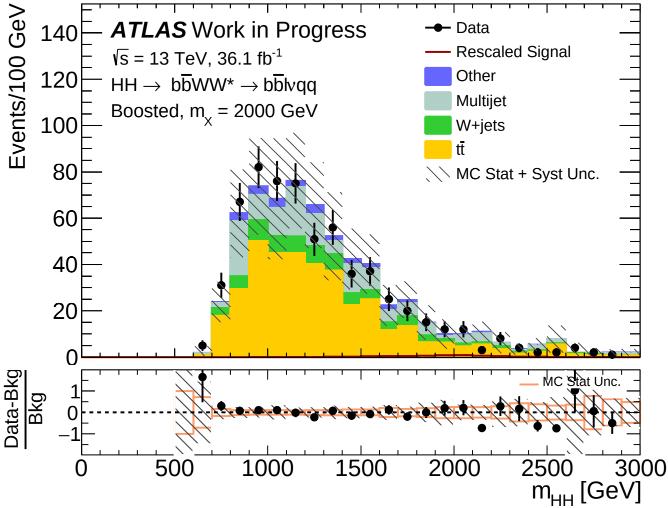
- $H \rightarrow WW = 1$ lepton + 2 AntiKt, R = 0.4 jets + ν

Background Modeling

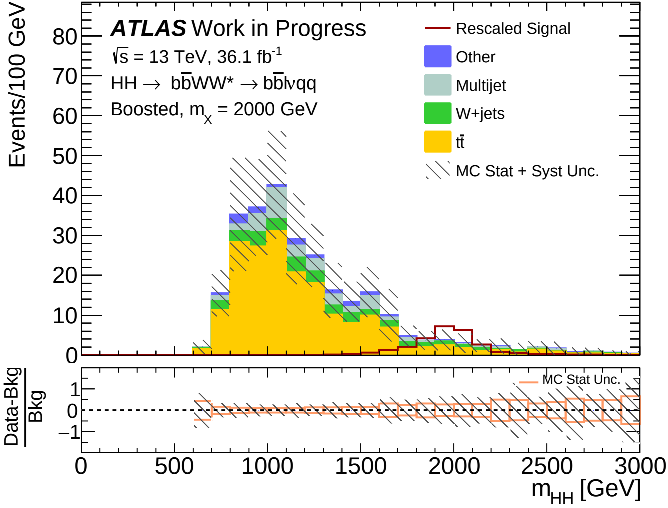
- Same procedure as boosted paper analysis
- ABCD data driven technique for QCD
- Slightly looser selection to increase statistics
- Check shape in mBB validation region



Background Shape Check

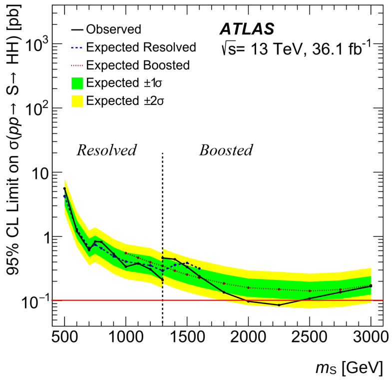


Signal Region m_{HH}

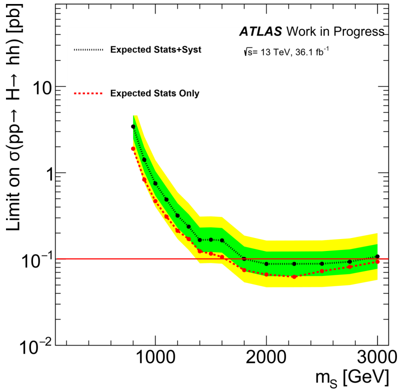


Results

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 factor of $\sim$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 the Matrix Method

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

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

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	*Non-Res*	*m500*	*low-mass*	*high-mass*
$\not\!\!E_T$ (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	mww	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 $\pm$ 52.1	7095.6 $\pm$ 47.5	1940.5 $\pm$ 25.1	122.3 $\pm$ 6.5
QCD	1538.7 $\pm$ 252.7	1359.5 $\pm$ 75.9	392.7 $\pm$ 21.9	20.7 $\pm$ 1.2
W+jets	2259.5 $\pm$ 7.9	1952.1 $\pm$ 7.4	696.6 $\pm$ 4.6	55.5 $\pm$ 1.1
SingleTop	1778.1 $\pm$ 19.4	1601.6 $\pm$ 18.4	405.4 $\pm$ 9.2	29.6 $\pm$ 2.6
Dibosons	170.6 $\pm$ 3.9	147.1 $\pm$ 3.7	46.8 $\pm$ 2.1	3.4 $\pm$ 0.6
Z+jets	403.6 $\pm$ 2.1	307.6 $\pm$ 1.8	95.6 $\pm$ 1.1	7.5 $\pm$ 0.3
Background Sum	14719.1$\pm$ 258.9	12463.5$\pm$ 91.8	3577.5$\pm$ 35.0	238.9$\pm$ 7.2
Xhh2000	25.7 $\pm$ 0.4	24.0 $\pm$ 0.4	9.6 $\pm$ 0.3	2.9 $\pm$ 0.1
Data	14862.0	12450.0	3761.0	250.0

$t\bar{t}$ Normalization Factor

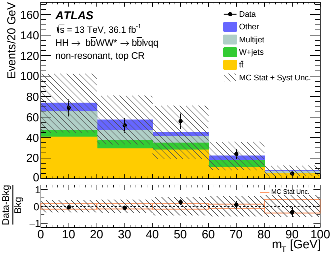
Top background normalization factors in the two CRs.

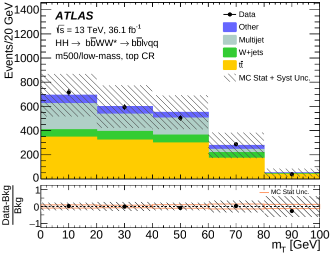
region	NF	$\sigma_{stat.}$	$\sigma_{syst.}$
non-res	1.04	± 0.20	± 0.43
low-mass	1.14	± 0.10	± 0.35
high-mass	1.02	± 0.02	± 0.07

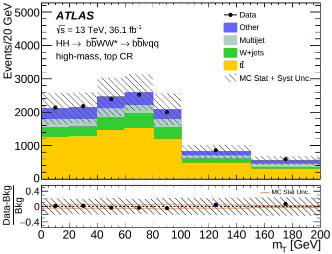
Boosted VR

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

mBBcr


ATLAS
√s = 13 TeV, 36.1 fb-1
HH → bb̄WW* → bb̄lνqq
non-resonant, top CR
Data
Other
Multijet
W+jets
tt̄
MC Stat + Syst Unc.
Events/20 GeV
MC Stat Unc.
Data-Bkg / Bkg
m_T [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
HH → bb̄WW* → bb̄lνqq
m500/low-mass, top CR
Data
Other
Multijet
W+jets
tt̄
MC Stat + Syst Unc.
Events/20 GeV
MC Stat Unc.
Data-Bkg / Bkg
m_T [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
HH → bb̄WW* → bb̄lνqq
high-mass, top CR
Data
Other
Multijet
W+jets
tt̄
MC Stat + Syst Unc.
Events/20 GeV
MC Stat Unc.
Data-Bkg / Bkg
m_T [GeV]

Non-Res SR

SR: $100 < m_{bb} < 140$ GeV					
Sample	mww	bbpt210	bbpt300	wwpt250	mbb
$t\bar{t}$	7461.0 $\pm$ 48.6	162.9 $\pm$ 7.3	27.9 $\pm$ 2.9	18.4 $\pm$ 2.4	15.4 $\pm$ 2.2
QCD	2756.2 $\pm$ 210.5	48.7 $\pm$ 14.2	6.6 $\pm$ 1.9	4.2 $\pm$ 1.2	3.6 $\pm$ 1.6
Wv221	640.8 $\pm$ 12.7	19.1 $\pm$ 1.4	5.0 $\pm$ 0.6	3.1 $\pm$ 0.5	2.3 $\pm$ 0.4
SingleTop	452.2 $\pm$ 9.6	14.3 $\pm$ 1.7	1.7 $\pm$ 0.5	1.0 $\pm$ 0.4	0.6 $\pm$ 0.3
Dibosonsv221	21.6 $\pm$ 1.3	0.6 $\pm$ 0.2	0.4 $\pm$ 0.2	0.0 $\pm$ 0.0	0.0 $\pm$ 0.0
Zv221	262.8 $\pm$ 4.4	3.1 $\pm$ 0.3	1.0 $\pm$ 0.2	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1
Background Sum	11594.7$\pm$ 216.7	248.6$\pm$ 16.1	42.6$\pm$ 3.6	27.0$\pm$ 2.8	22.1$\pm$ 2.8
XhhSM	68.3 $\pm$ 2.4	20.7 $\pm$ 0.9	6.7 $\pm$ 0.4	5.5 $\pm$ 0.3	4.8 $\pm$ 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
Wv221	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
Zv221	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
$t\bar{t}$	7461.0 $\pm$ 48.6	162.9 $\pm$ 7.3	61.5 $\pm$ 4.7	21.9 $\pm$ 2.7	15.3 $\pm$ 2.2
QCD	2756.2 $\pm$ 210.5	48.7 $\pm$ 14.2	14.1 $\pm$ 4.1	5.5 $\pm$ 1.6	4.8 $\pm$ 2.2
Wv221	640.8 $\pm$ 12.7	19.1 $\pm$ 1.4	9.7 $\pm$ 1.1	4.1 $\pm$ 0.8	2.6 $\pm$ 0.6
SingleTop	452.2 $\pm$ 9.6	14.3 $\pm$ 1.7	2.6 $\pm$ 0.7	0.5 $\pm$ 0.2	0.3 $\pm$ 0.2
Dibosonsv221	21.6 $\pm$ 1.3	0.6 $\pm$ 0.2	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1	0.2 $\pm$ 0.1
Zv221	262.8 $\pm$ 4.4	3.1 $\pm$ 0.3	0.6 $\pm$ 0.1	0.1 $\pm$ 0.0	0.1 $\pm$ 0.0
Background Sum	11594.7$\pm$ 216.7	248.6$\pm$ 16.1	88.7$\pm$ 6.4	32.3$\pm$ 3.2	23.3$\pm$ 3.1
Xhh700	9.2 $\pm$ 0.3	7.8 $\pm$ 0.2	5.9 $\pm$ 0.2	5.0 $\pm$ 0.2	4.4 $\pm$ 0.2
Data	11450.0	232.0	75.0	25.0	22.0

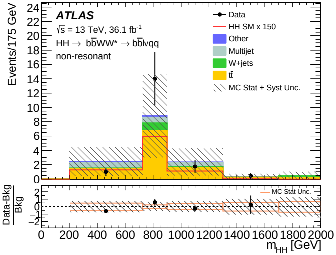
high-mass SR

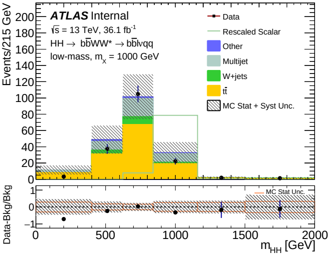
SR: $100 < m_{bb} < 140$ GeV					
Sample	bbpt350	wwpt250	drww15	hh2000	mbb
$t\bar{t}$	1307.8 ± 20.2	1024.9 ± 17.7	287.5 ± 9.4	2.2 ± 0.8	1.4 ± 0.6
QCD	207.2 ± 99.5	191.2 ± 29.0	55.2 ± 8.4	2.9 ± 0.4	2.2 ± 0.5
Wv221	341.3 ± 3.4	291.5 ± 3.2	110.7 ± 2.1	4.8 ± 0.3	3.4 ± 0.3
SingleTop	144.1 ± 5.6	126.6 ± 5.3	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

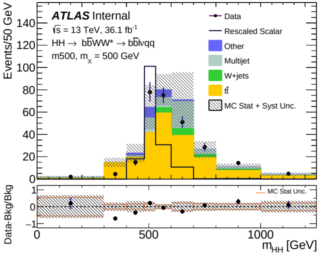
Boosted SR

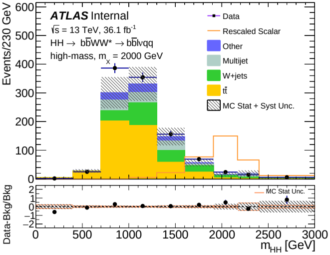
Sample	Yield	Stats Err	Systs Err
$t\bar{t}$	648.7	$\pm$ 16.4	$+177.3(+27.3\%)$ $-169.2(-26.1\%)$
W+Jets	217.0	$\pm$ 6.5	$+104.3(+48.1\%)$ $-100.9(-46.5\%)$
QCD	235.2	$\pm$ 18.9	$+181.8(+77.3\%)$ $-181.8(-77.3\%)$
Single-top	109.2	$\pm$ 6.0	$+86.0(+78.8\%)$ $-85.8(-78.6\%)$
Z+Jets	20.5	$\pm$ 1.1	$+11.2(+54.6\%)$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

Resolved SR m_{HH}

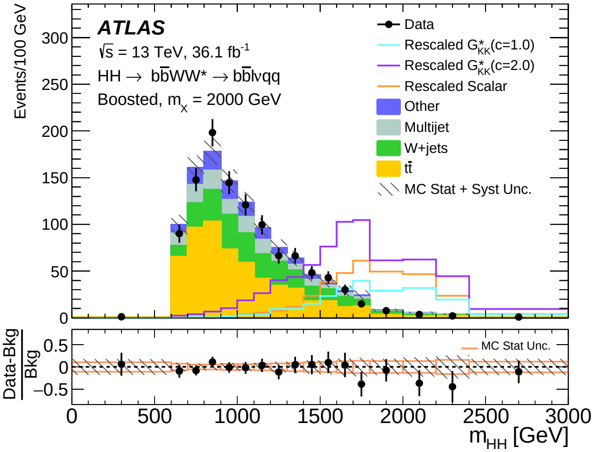




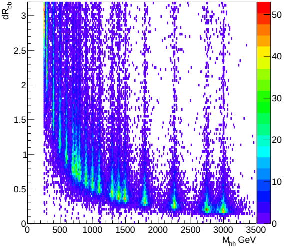


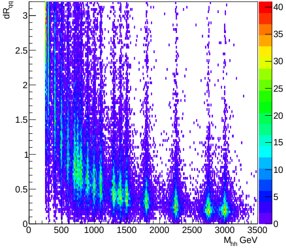


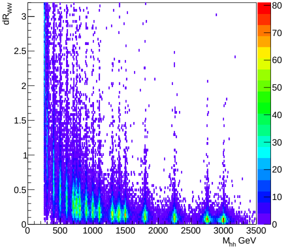
Boosted SR m_{HH}

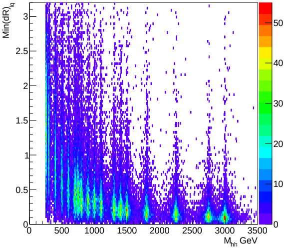


Truth Study









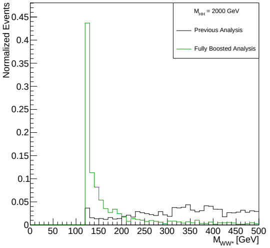
Kinematic Variable Definition

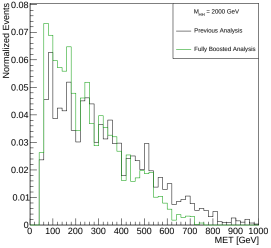
Neutrino reco:

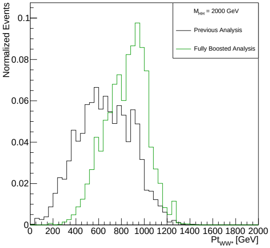
$$m_h^2 = (p^{\nu} + p^{\mathrm{large-R\ jet}})^2$$

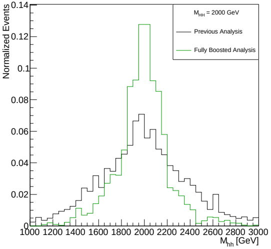
Lepton Channel	Alternative p_T definition
Muon Channel	$p_T^{'} = p_T^{\mathrm{Large-Rjet}}$
Electron channel	$p_T^{'} = \sqrt{(p_x^{\mathrm{Large-Rjet}} - p_x^{\mathrm{electron}})^2 + (p_y^{\mathrm{Large-Rjet}} - p_y^{\mathrm{electron}})^2}$

Reconstructed Variables e-Channel

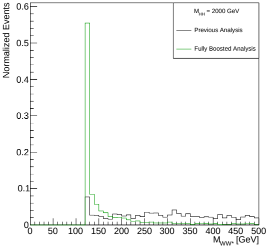


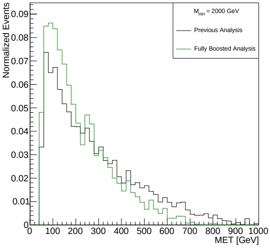


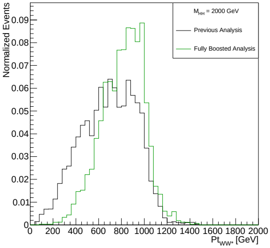


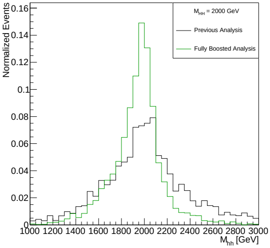


Reconstructed Variables mu-Channel







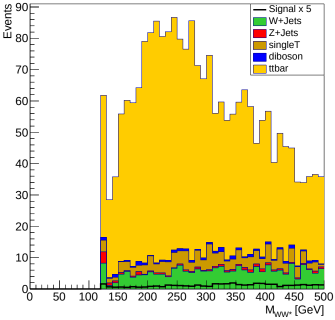


Fully Boosted SR

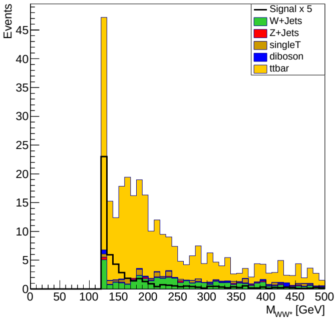
Sample	Yield	Stats Unc
$t\bar{t}$	187.7	$\pm$ 8.8
W+Jets	33.7	$\pm$ 1.9
QCD	34.5	$\pm$ 5.5
Single-top	7.0	$\pm$ 1.3
Z+Jets	4.7	$\pm$ 0.4
Dibosons	3.3	$\pm$ 0.6
Prediction	271.0	$\pm$ 10.7

Electron Reco. m_{WW}

Paper Boosted Analysis

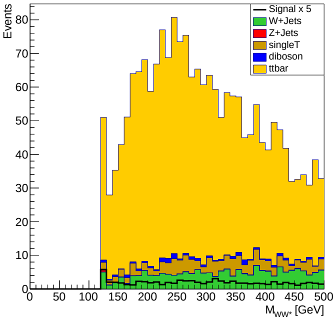


Fully-Boosted Analysis

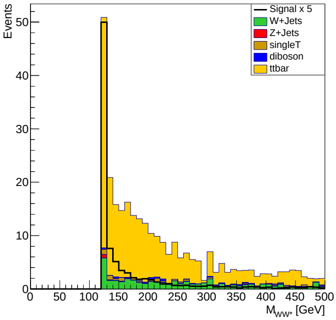


Muon Reco. m_{WW}

Paper Boosted Analysis

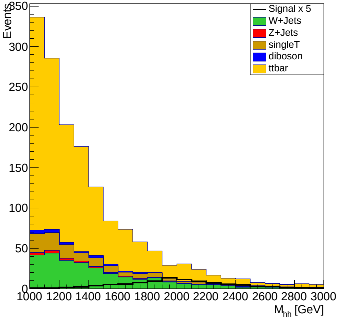


Fully-Boosted Analysis

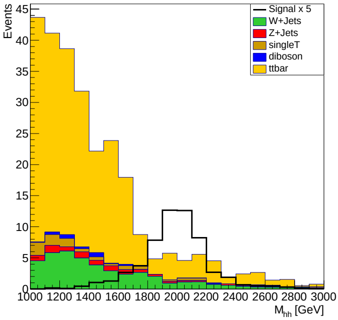


Electron Reco. m_{HH}

Paper Boosted Analysis

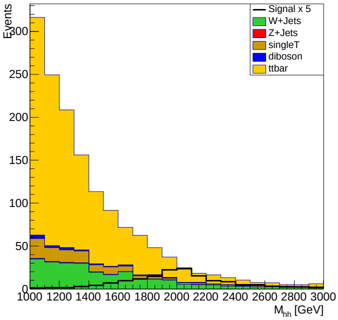


Fully-Boosted Analysis

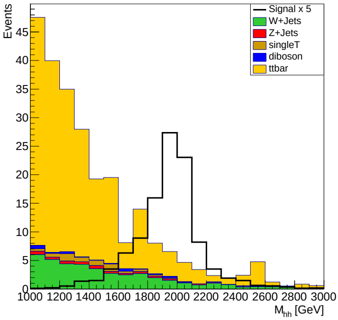


Muon Reco. m_{HH}

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