ATLAS EXPERIMENT

Search for the Higgs boson in the $\mathrm{H} \rightarrow b\bar{b}$ decay mode

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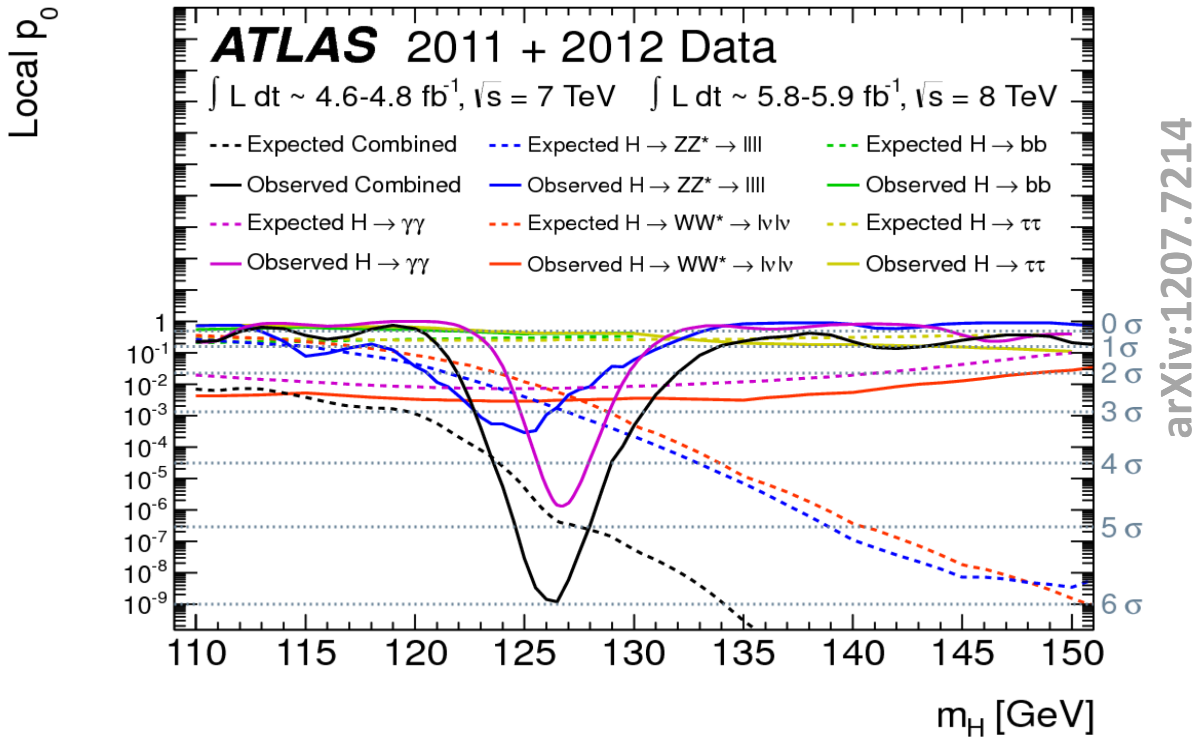
On behalf of **The ATLAS Experiment**

$H \rightarrow b\bar{b}$ decay mode: Motivation

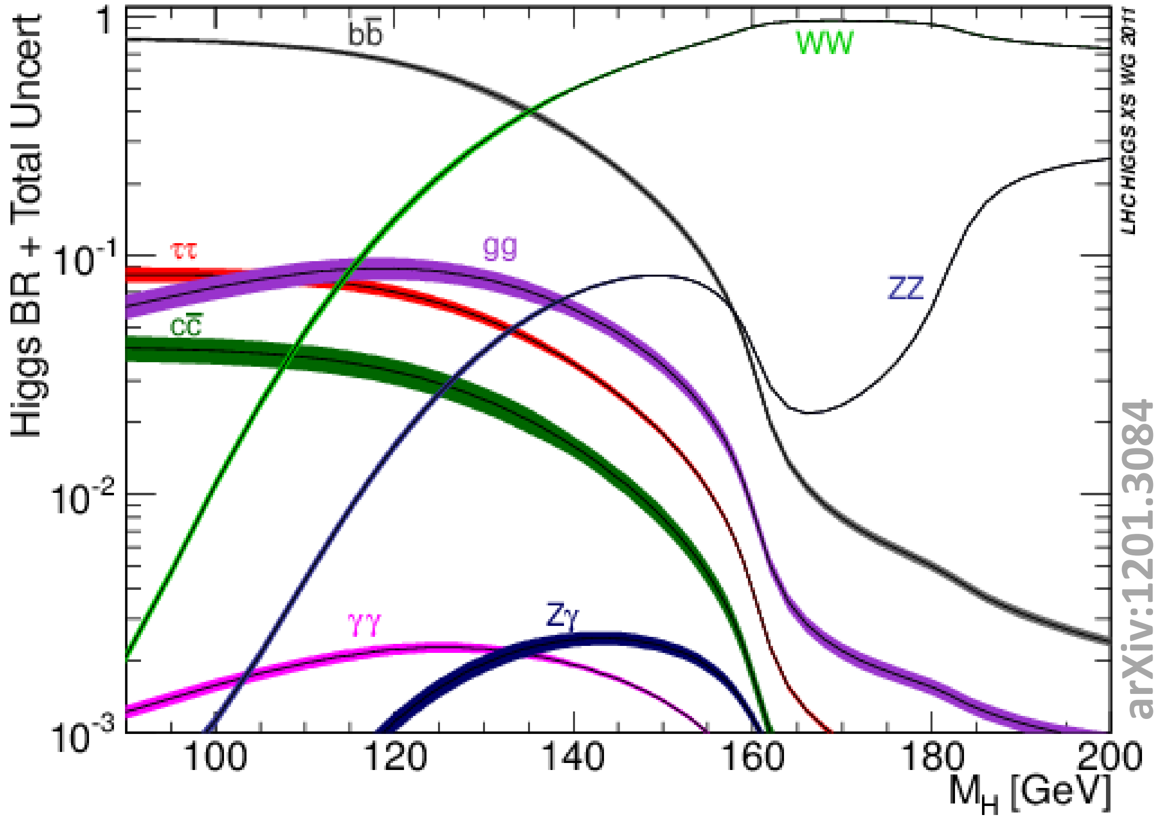
- Observation of a new Higgs-like particle:
  - m = 126 GeV
  - Observed decay into vector bosons: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow W^+W^-$
  - **Not yet observed direct decay into fermions: $H \rightarrow b\bar{b}$ and $H \rightarrow \tau^+\tau^-$**



*p_0 = probability of the background only hypothesis

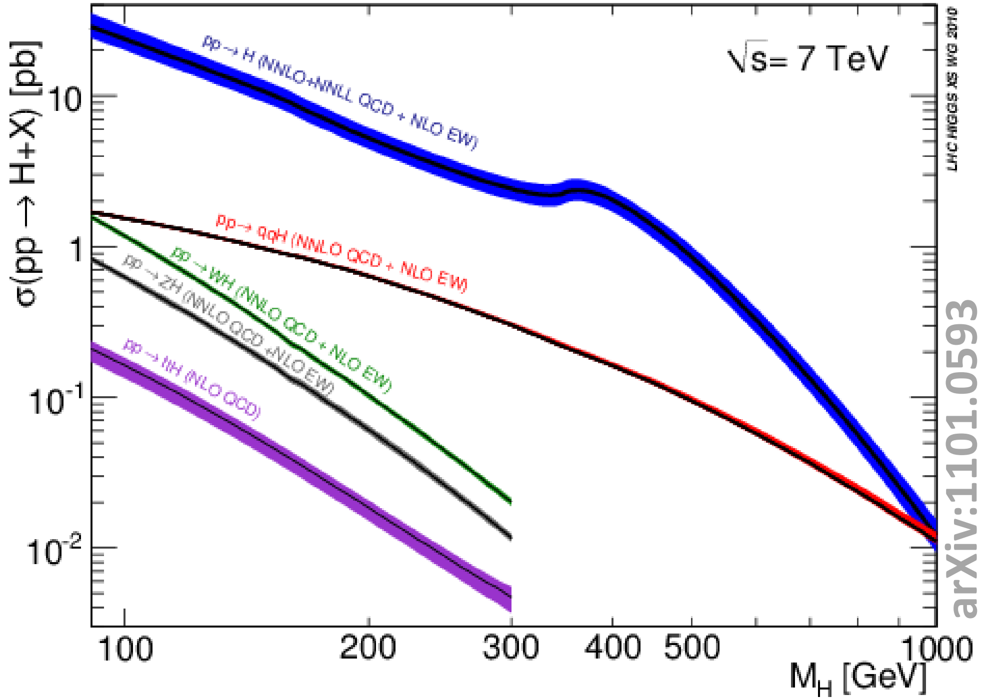
$H \rightarrow b\bar{b}$ decay mode: Motivation

- $H \rightarrow b\bar{b}$:
  - Highest branching ratio at low masses

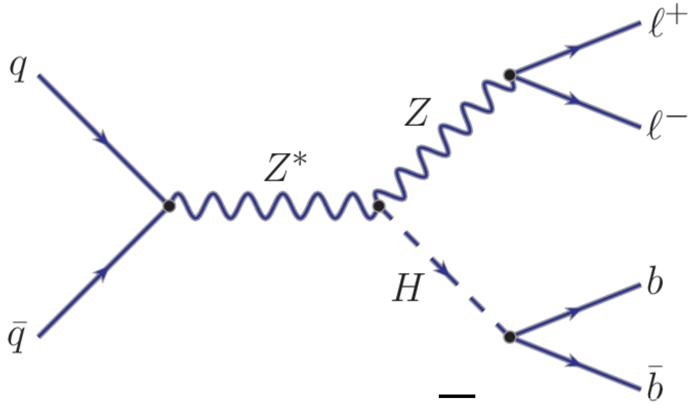


Higgs production

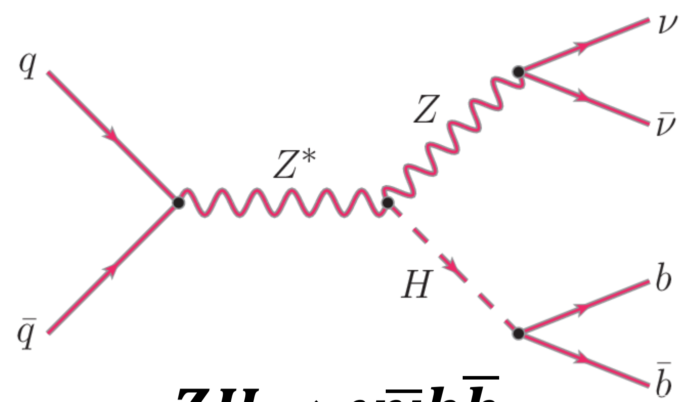
- Direct production:
  - gg fusion and VBF: By far the highest cross-sections
  - Suffers from a huge QCD multi-jets backgrounds
- **Associated production:**
  - $t\bar{t}H$, WH and ZH: smaller cross-section but cleaner signal



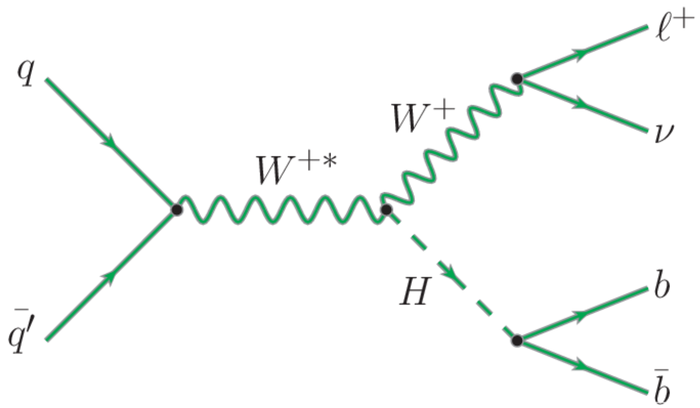
Signal channels



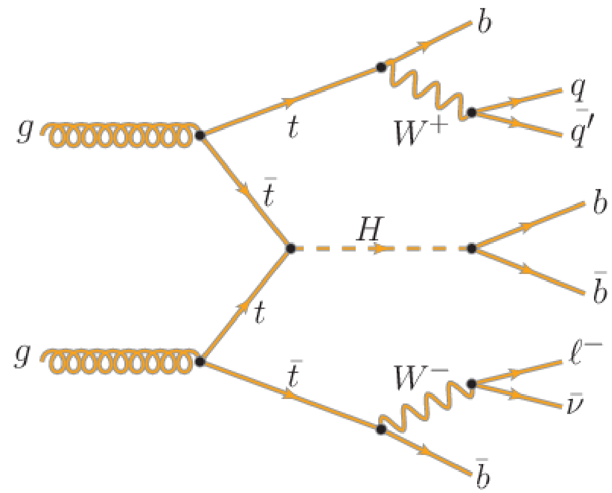
$$ZH \rightarrow llb\bar{b}$$



$$ZH \rightarrow \nu\bar{\nu}b\bar{b}$$



$$WH \rightarrow l\nu b\bar{b}$$



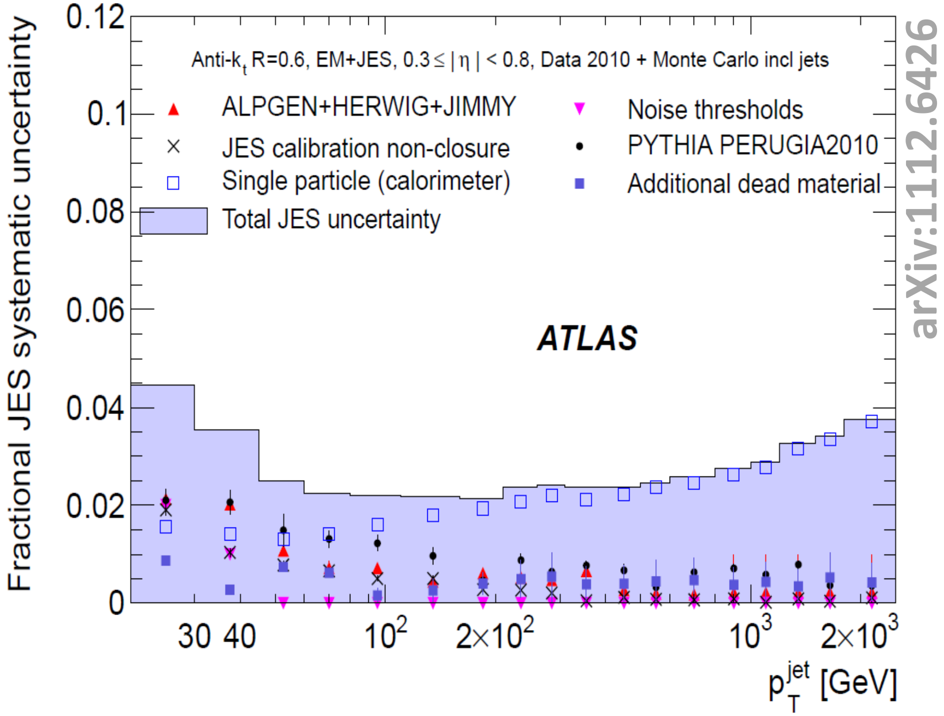
$$t\bar{t}H \rightarrow q\overline{q}'l\nu b\bar{b}b\bar{b}$$

A word about Jets

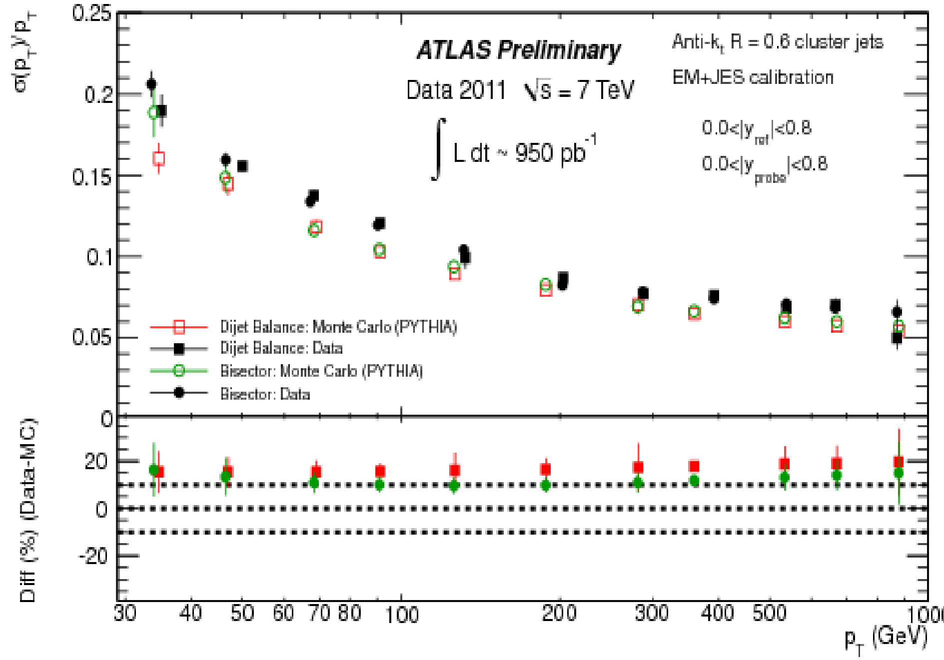
Jet calibration and uncertainties

- Jet reconstruction:
  - Anti-kt (R=0.4) reconstructed at the EM scale with a global calibration to the hadronic scale
  - Use tracks in the jet to reject jets from pile-up

Uncertainties on the energy scale



Jet energy resolution



b-jet identification (b-tagging)

- Spatial tagging:
  - B hadrons have a significant flight path length:
    - E(B) ~ 50 GeV ⇒ L ~ 5 mm
  - Secondary vertex in jets.
  - Tracks with high impact parameter to the primary vertex.
  - Single Neural Network based discriminant
- Performance:
  - b-tagging efficiency: **70%**
  - Light jet rejection*: **~130**
  - c-jet rejection: **~5**

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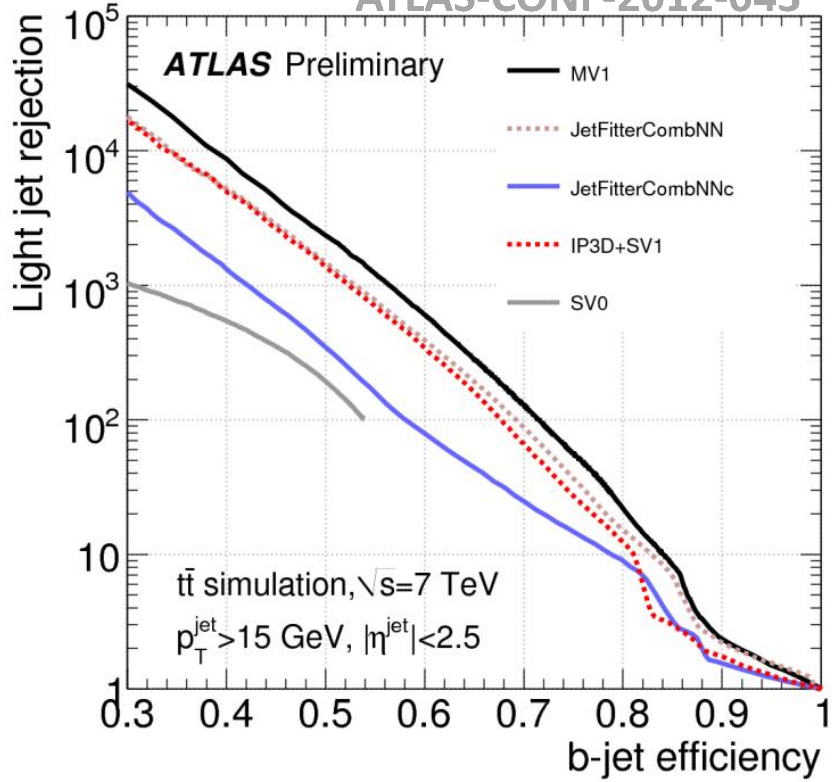
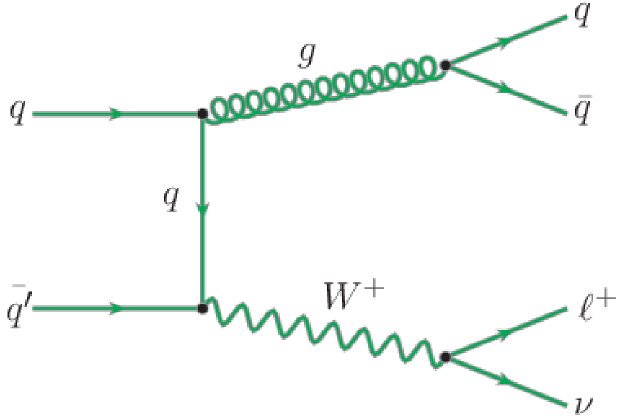


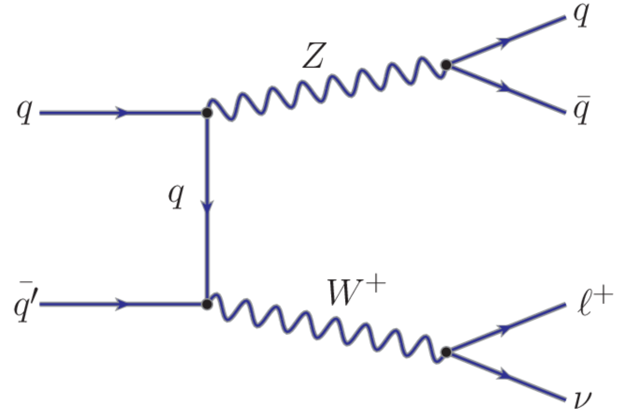
*rejection = 1/efficiency

Analysis:
Selection, backgrounds and limits

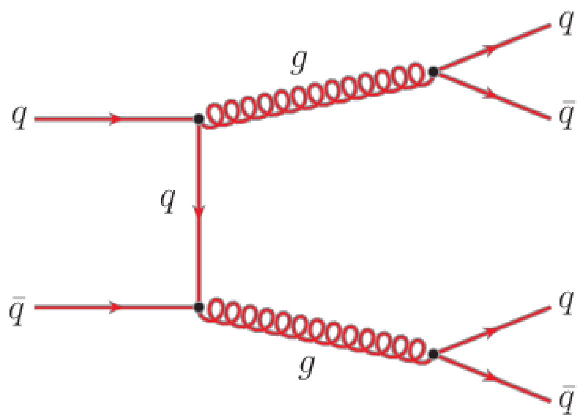
Main backgrounds



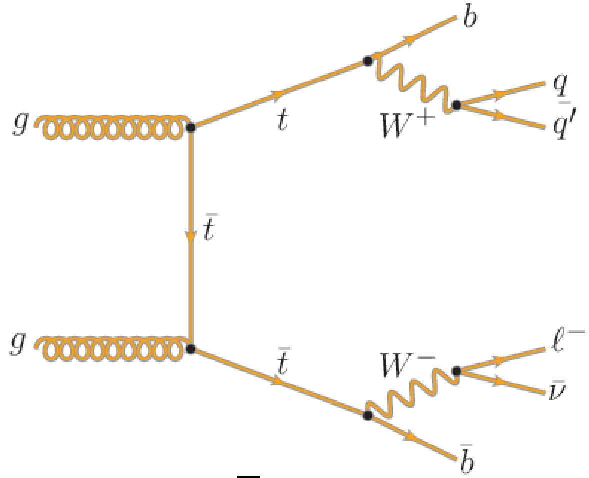
W+jets, Z + jets



Dibosons: WW, WZ, ZZ



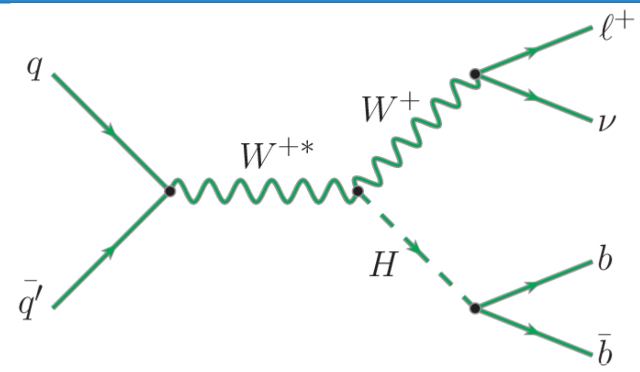
QCD Multi-jets



Top: $t\bar{t}$, single top

Selection: $WH \rightarrow l\nu b\bar{b}$

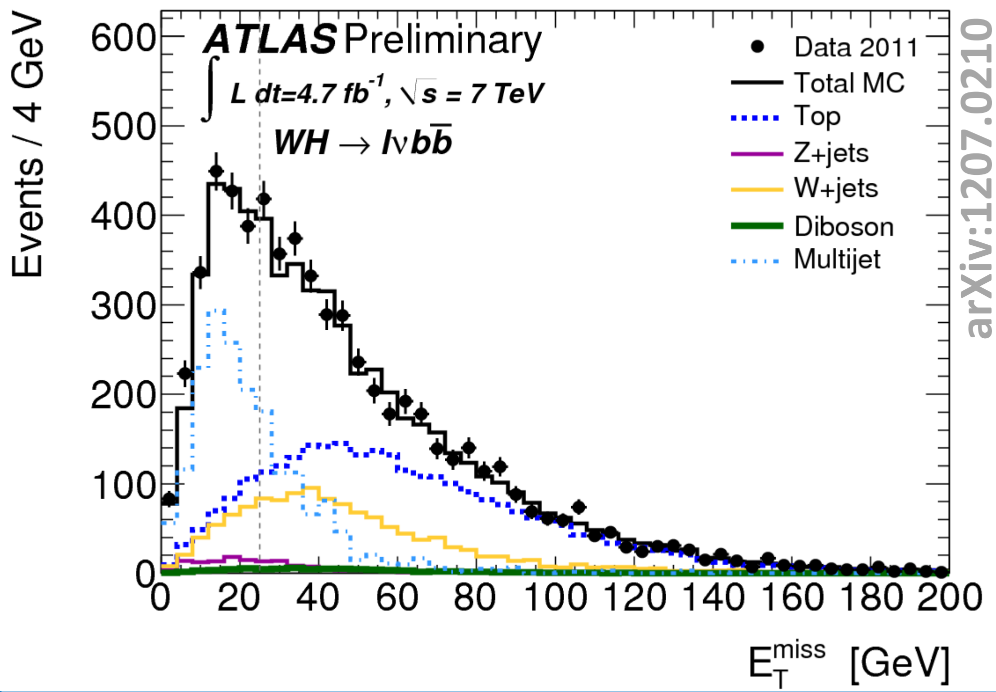
- **Signal definition:**
  - One high p_T isolated lepton (e or μ):
    - Used for the trigger
  - High missing transverse energy
  - 2 high p_T b-tagged jets
  - Veto events with extra leptons or jets



- **Strategy:**
  - Search for excess in the invariant mass of the two b-jets distribution
  - Split into 4 $p_T(W)$ bins to enhance sensitivity:
    - Different signal to background ration in each bin
    - $[0, 50], [50, 100], [100, 200]$ and $[200, \infty]$

Background estimation: $WH \to l\nu b\bar{b}$

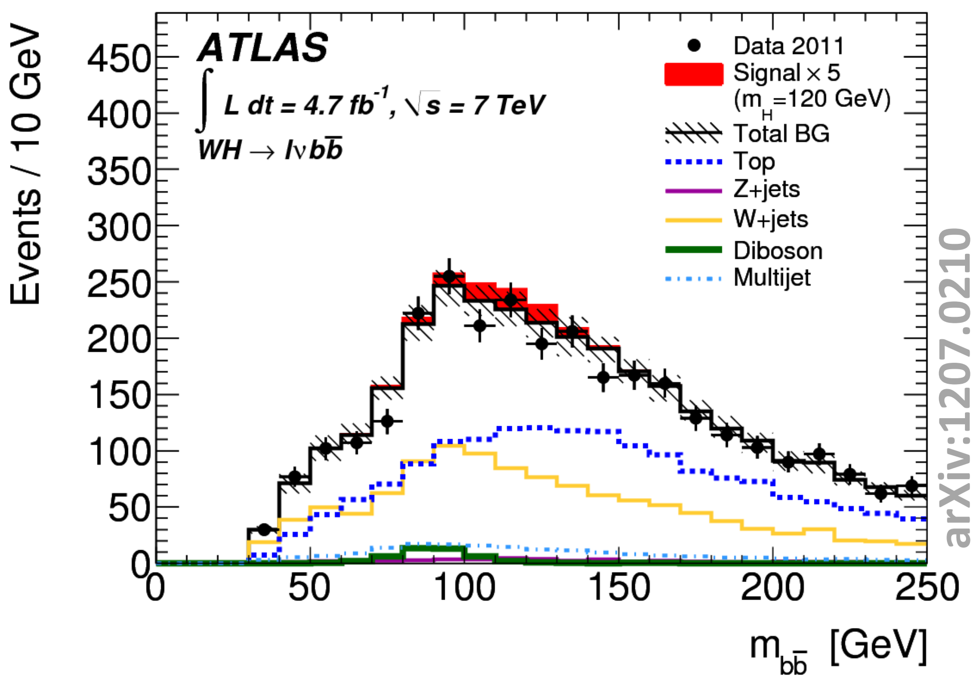
- Top+jets and W+jets:
  - Shape from MC distribution
  - Normalization from control region:
    - $m_{bb} < 80$ GeV & $150 < m_{bb} < 250$ GeV
    - W+3 jets
- QCD Multi-jets: from data
  - E_T^{miss} templates in inverted lepton isolation region for WH→lνb
- Diboson: from MC

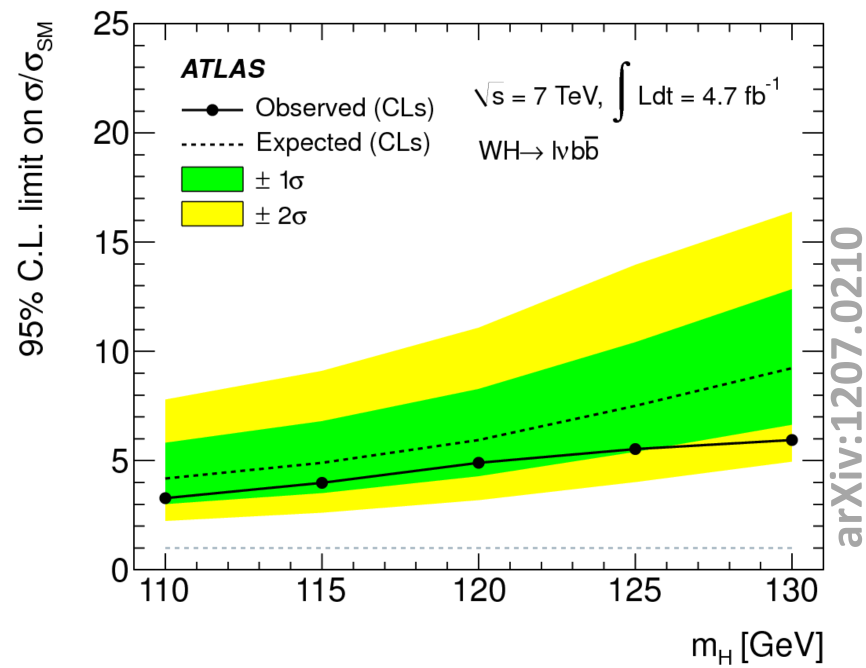


Results: $WH \rightarrow l\nu b\bar{b}$

- Exclusion limits:
  - 3.3 to 5.9 times the SM

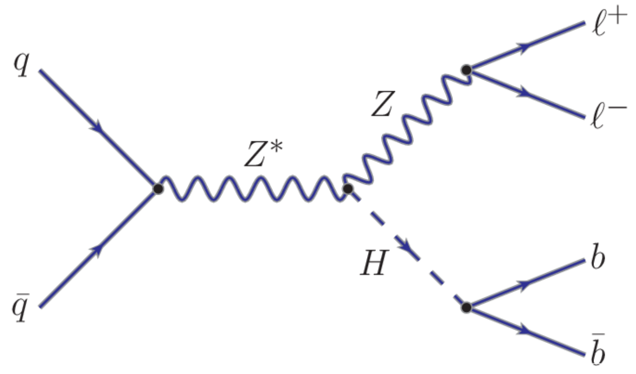
Limits are expressed in terms of the cross-sections divided by the SM prediction





Selection: $ZH \rightarrow llb\bar{b}$

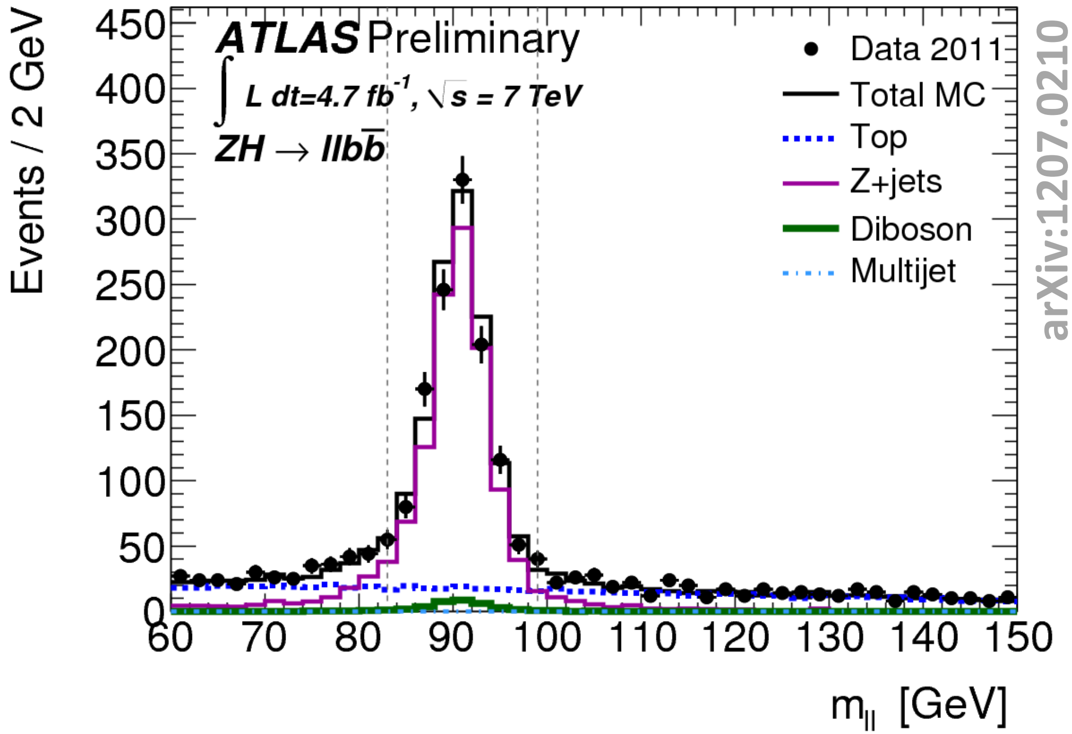
- **Signal definition:**
  - 2 high p_T same flavor isolated leptons:
    - Opposite sign if muons.
    - Used for the trigger
  - Low missing transverse energy
  - 2 high p_T b-tagged jets
  - Compatibility of the di-lepton invariant mass with a Z decay
  - Veto events with extra leptons or jets



- **Strategy:**
  - Search for excess in the invariant mass of the two b-jets distribution
  - Split into 4 $p_T(Z)$ bins to enhance sensitivity:
    - Different signal to background ration in each bin
    - $[0, 50]$, $[50, 100]$, $[100, 200]$ and $[200, \infty]$

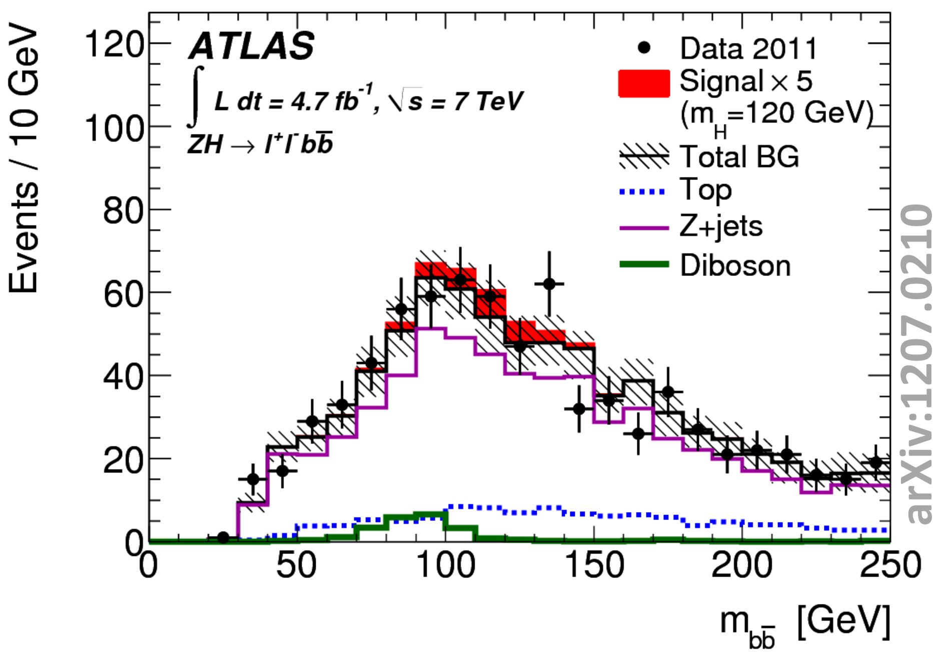
Background estimation: $ZH \rightarrow llb\bar{b}$

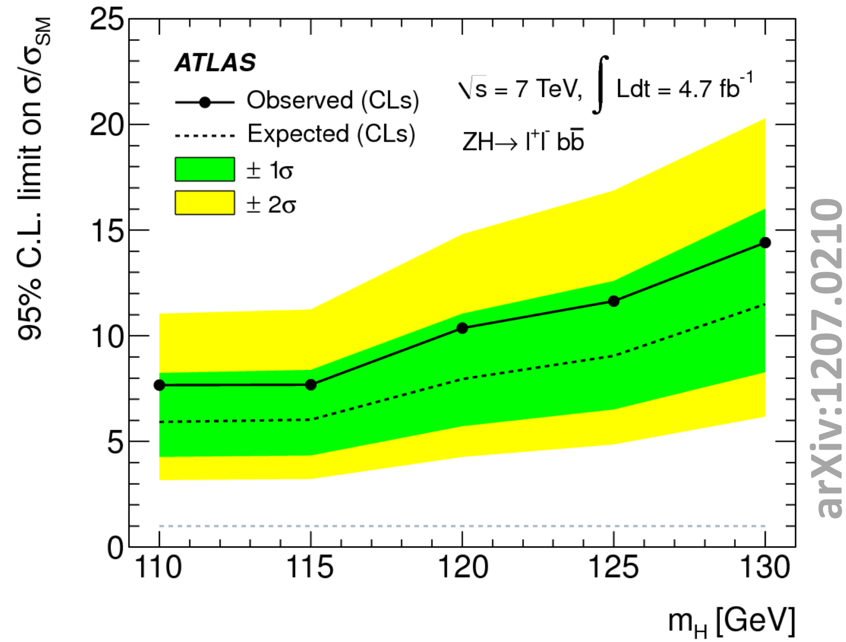
- Top+jets and Z+jets:
  - Shape from MC distribution
  - Normalization from control region:
    - $m_{bb} < 80$ GeV & $150 < m_{bb} < 250$ GeV
    - m_{ll} side-bands
- QCD Multi-jets: from data
  - m_{ll} side-bands
  - Contribution < 1%
- Diboson: from MC



Results: $ZH \rightarrow llb\bar{b}$

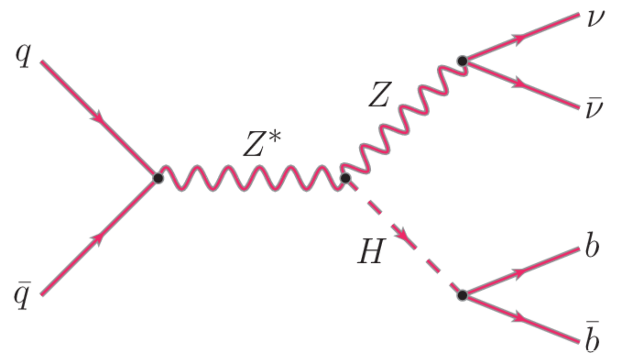
- Exclusion limits:
  - 7.7 to 14.4 times the SM





Selection: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

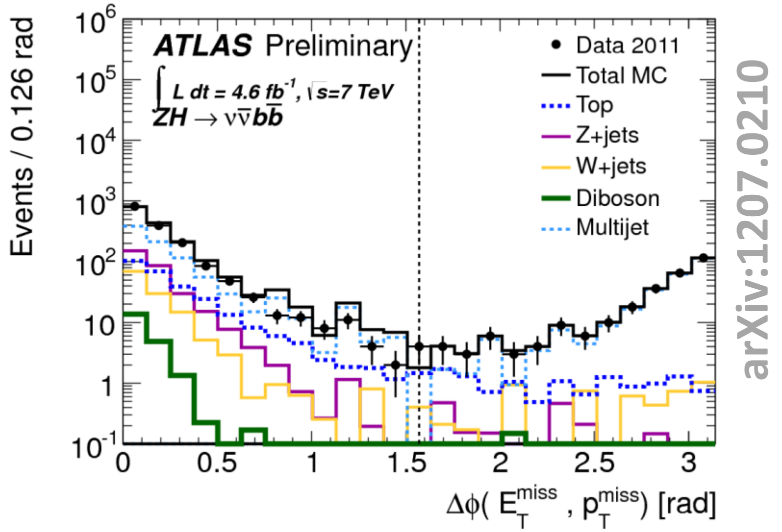
- **Signal definition:**
  - Very high missing transverse energy
    - Used for the trigger
    - Confirmed by a missing momentum measured in the inner detector
  - 2 high p_T b-tagged jets
    - Back to back with the $E_T{}^{miss}$
  - Veto events with extra leptons or jets

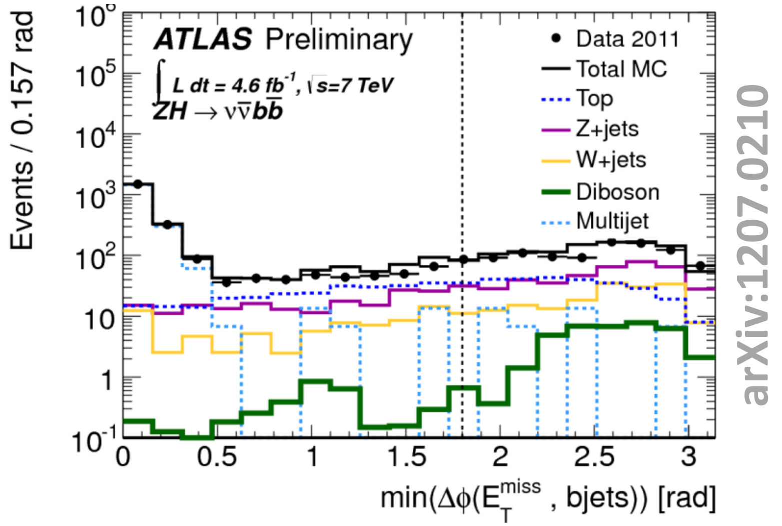


- **Strategy:**
  - Search for excess in the invariant mass of the two b-jets distribution
  - Split into 3 $E_T{}^{miss}$ bins:
    - Different signal to background ration in each bin
    - $[120, 160], [160, 200]$ and $[200, \infty]$

Background estimation: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

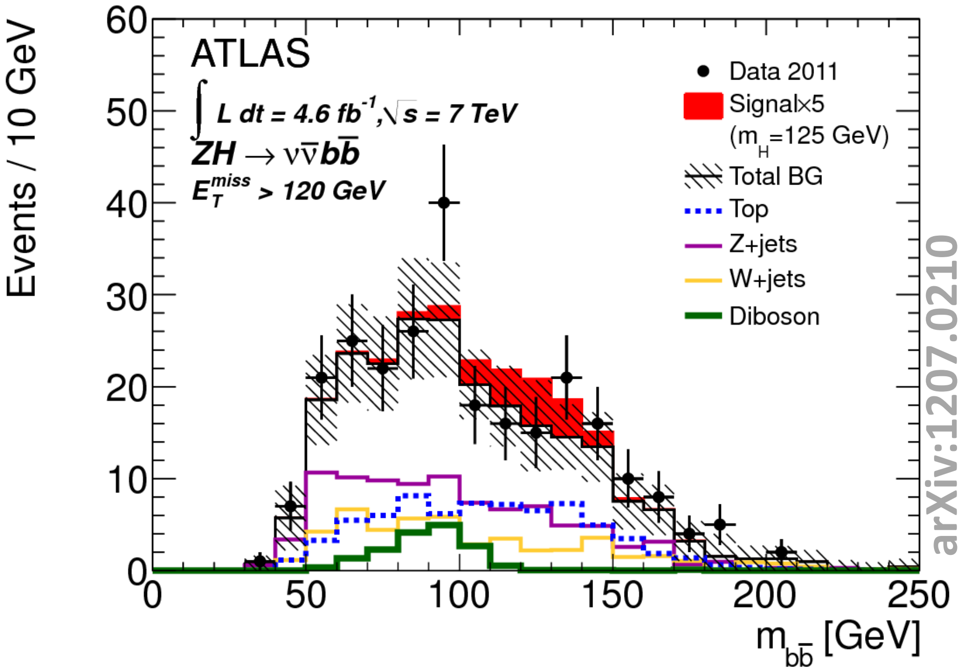
- Top+jets and W,Z+jets:
  - Shape from MC distributions
  - Normalization propagated from the other channels
- Diboson:from MC
- QCD Multi-jets: from data
  - 3 control regions using 2 variables:
    - $\Delta\phi\left(p_T{}^{miss}, E_T{}^{miss}\right) > \frac{\pi}{2}$
    - $\min\{\Delta\phi\left(b, E_T{}^{miss}\right)\} > 1.8$
    - $\min\{\Delta\phi\left(b, E_T{}^{miss}\right)\} < 1.8$

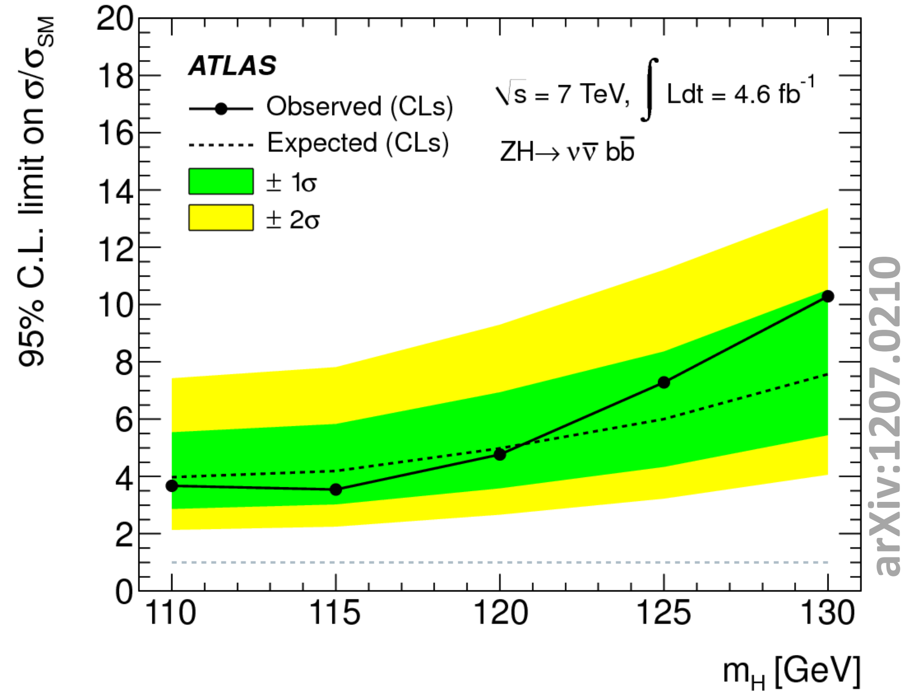




Results: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

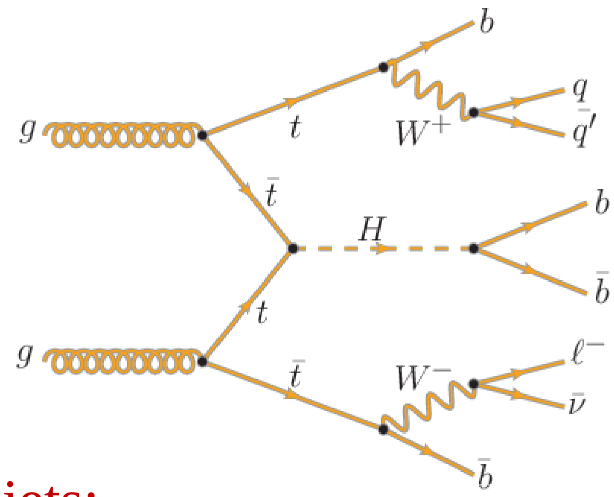
- Exclusion limits:
  - 3.7 to 10.3 times the SM





Selection: $t\bar{t}H \rightarrow q\bar{q}'l\nu b\bar{b}b\bar{b}$

- **Signal definition:**
  - One high p_T isolated lepton (e or μ):
    - Used for the trigger
  - High missing transverse energy
  - At least 4 high p_T jets
- **Strategy:**
  - Events categorized according to the number of b-tagged and non-b-tagged jets:
    - Different signal to background ration in each bin
  - Kinematic likelihood fit to reconstruct the $t\bar{t}$ pair
  - Search for excess in the invariant mass distribution of the remaining two b-jets



Background estimation: $t\bar{t}H \rightarrow q\bar{q}'l\nu b\bar{b}b\bar{b}$

- Top and dibosons: from MC
- W+jets:
  - Shape from MC distributions
  - Normalization from data separating different jet flavors
  - Use W^+/W^- assymmetry:

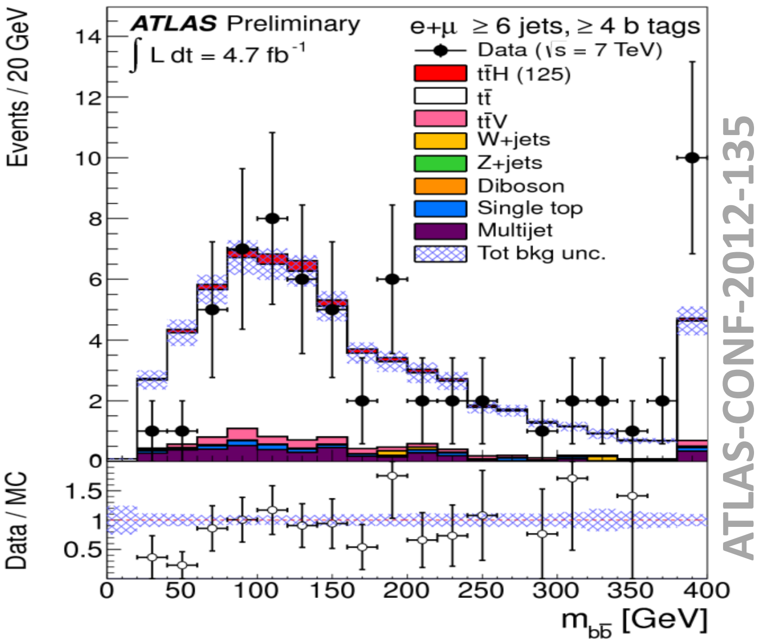
$$N_W = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(N_{W^+} - N_{W^-})_{meas} \text{ where } r_{MC} = \left(\frac{N_{W^+}}{N_{W^-}}\right)_{MC}$$

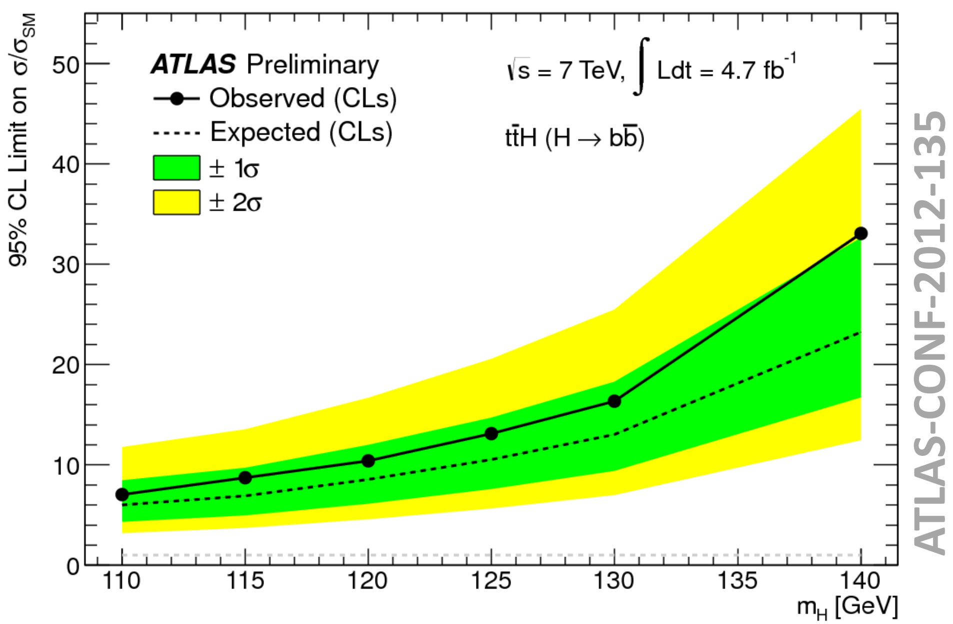
- Multi-jets: from data
  - Using Matrix Method with a tight and a loose lepton samples:

$$N_{loose} = N_{loose\,real} + N_{loose\,fake}$$
$$N_{tight} = \epsilon_{real} N_{loose\,real} + \epsilon_{fake} N_{loose\,fake}$$

Results: $t\bar{t}H \rightarrow q\bar{q}'l\nu b\bar{b}b\bar{b}$

- Exclusion limits:
  - 7.0 to 33.0 times the SM
  - 7.0 to 16.4 times the SM for m_H < 130 GeV





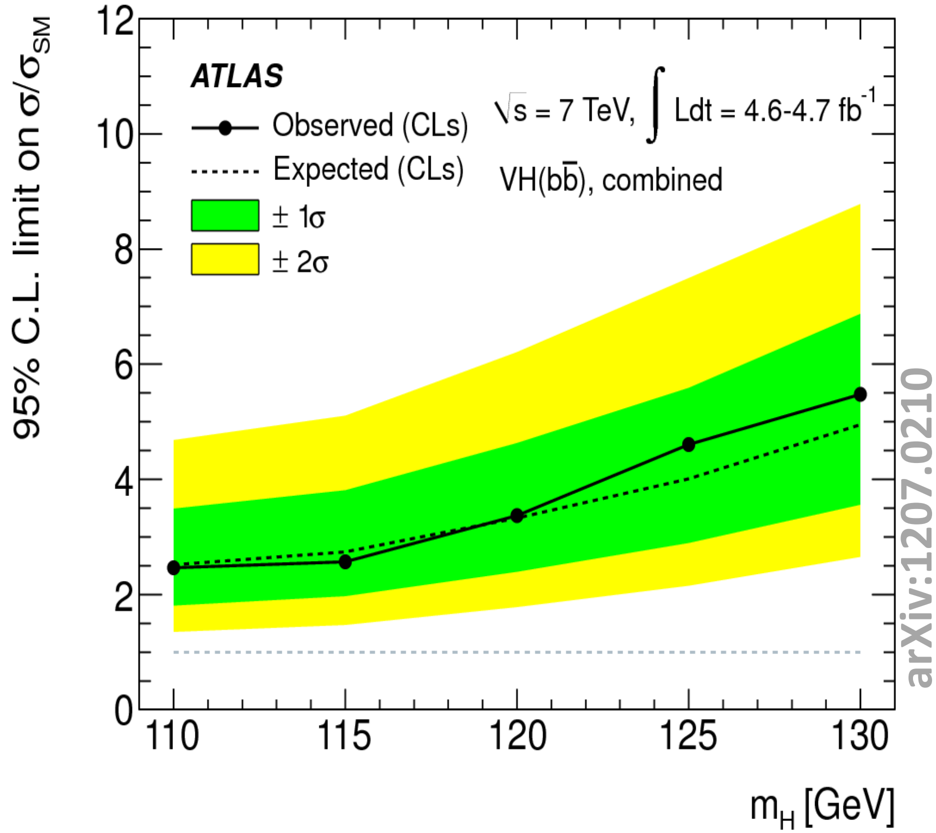
Uncertainties and Combination

Uncertainties

- Main experimental uncertainties:
  - b-jet identification: **0.3 – 5.5%**
  - Jet and E_T^{miss} reconstruction: **1.2 – 12.1%**
  - Background normalization: **1.8 – 4.5%**
  - Other sources: luminosity, pileup, lepton ID, etc… **< 3.4%**
- Theoretical uncertainties:
  - shapes, cross-sections, PDFs, etc…: **0.3 – 14.9%**

Exclusion limit combination

- The combination uses only the VH channels:
  - $WH \rightarrow l\nu b\bar{b}$
  - $ZH \rightarrow llb\bar{b}$
  - $ZH \rightarrow \nu\bar{\nu}b\bar{b}$
- 5 mass hypothesis considered:
  - m_H = 110, 115, 120, 125 and 130 GeV
- Exclusion limits:
  - 2.5 to 5.5 times the SM



Outlook and Conclusion

Ongoing improvements

- Improving m_{bb} resolution:
  - Correcting for the semi-leptonic b-jets decay with muons in jets
  - Inclusive jet corrections at parton level
- Multi-variate approach for signal/background separation: Boosted Decision Tree
  - Preliminary MC based studies show significant improvement

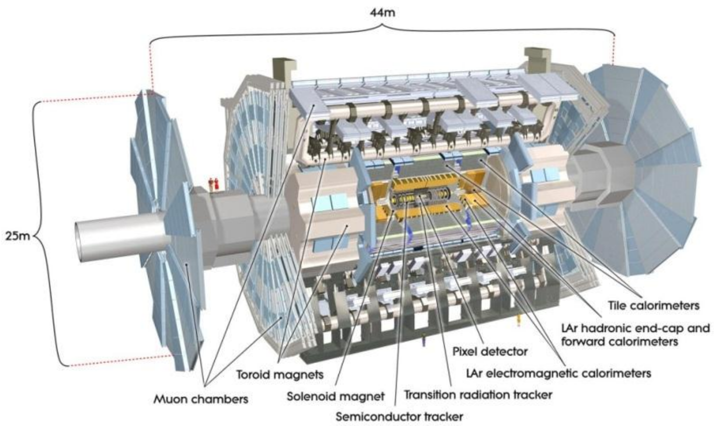
Conclusion

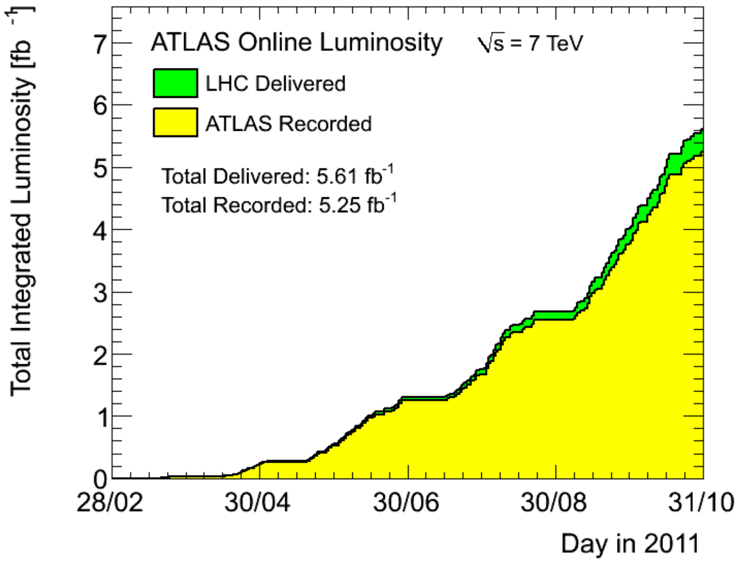
- **Search for Higgs boson decaying into b-quark pair:**
  - Three channels included in the final combination:
    - WH->lνbb, ZH->ννbb, ZH->llbb
    - Results from $t\bar{t}H$ were available at a later stage
  - Combined limit: **σ/σ_{SM}= 2.5-5.5** for m_H < 130 GeV
- **Analysis to be updated soon**
  - Additional data still to come:
    - Already 15 fb^{-1} collected @ 8 TeV
    - LHC will run until early 2013
  - Improved analysis:
    - Improved b-jet energy scale and m_{bb} resolution
    - Analysis based on multivariate techniques

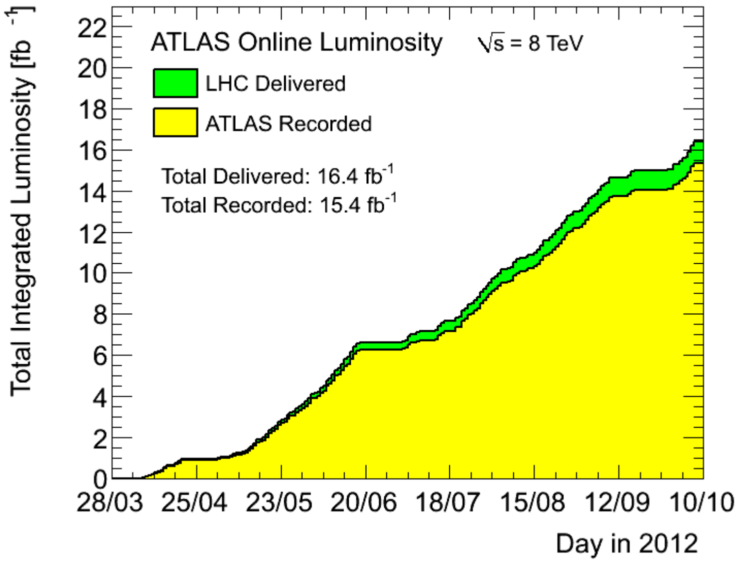
Back-up

ATLAS data taking

- 2011 data taking:
  - 93.5% data taking efficiency
  - $\langle\mu\rangle$ = 9.1 interactions/BC
  - 5.25 fb^{-1} recorded luminosity
- 2012 data taking
  - 93.9% data taking efficiency
  - $\langle\mu\rangle$ = 20 interactions/BC
  - 15.4 fb^{-1} recorded luminosity

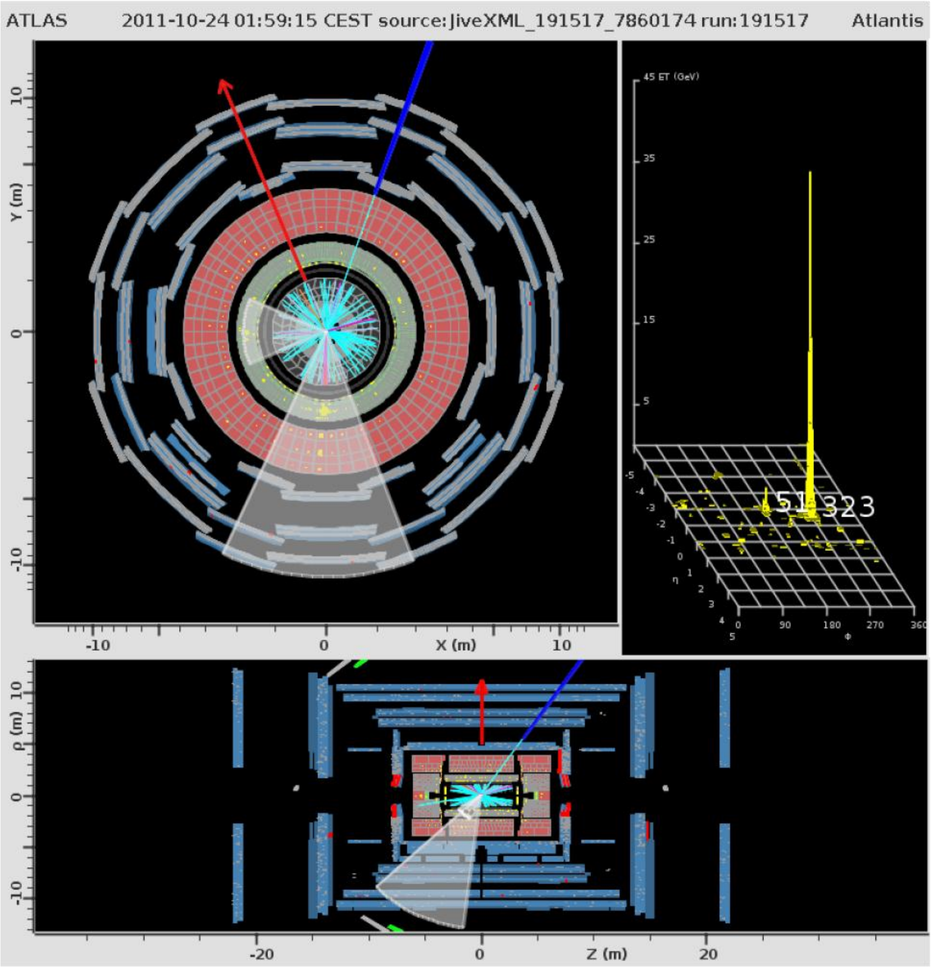






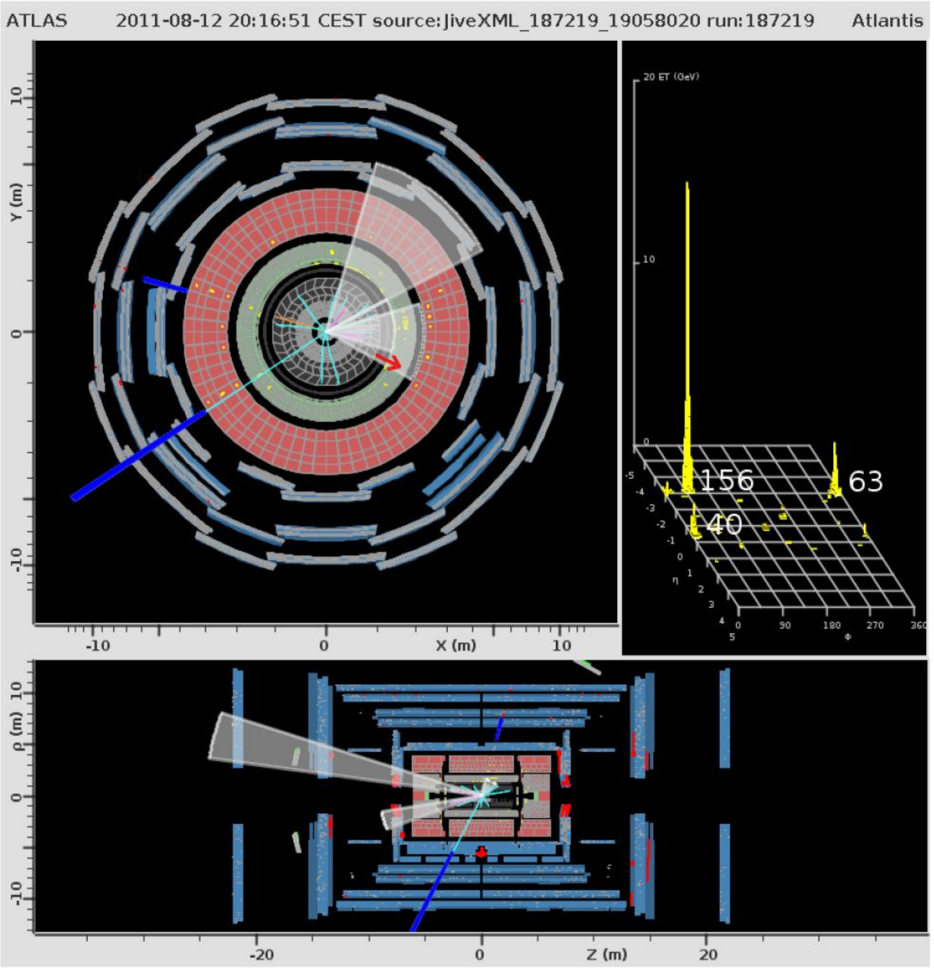
Selection: $WH \rightarrow l\nu b\bar{b}$

- $W \rightarrow l\nu$ system:
  - One charged lepton (e or μ):
    - $p_T > 25$ GeV ;
    - $|\eta(e)| < 2.47$; $|\eta(\mu)| < 2.5$
  - ${E_T}^{miss} > 25$ GeV
  - $M_T(l\nu) > 40$ GeV
  - Extra lepton veto:
    - $|\eta(e)| < 4.5$ and $|\eta(\mu)| < 2.7$
    - $p_T > 20$ GeV
- $H \rightarrow b\bar{b}$ system:
  - 2 b-tagged jets:
    - $|\eta| < 2.5$; $p_T > 45$ and 25 GeV
    - $\Delta R(bb) > 0.7$ if $p_T(l\nu) < 200$ GeV
  - Extra jet veto:
    - $|\eta| < 4.5$; $p_T > 20$ GeV
- Split into 4 $p_T(l\nu)$ bins:
  - $[0, 50]$, $[50, 100]$, $[100, 200]$ and $[200, \infty]$



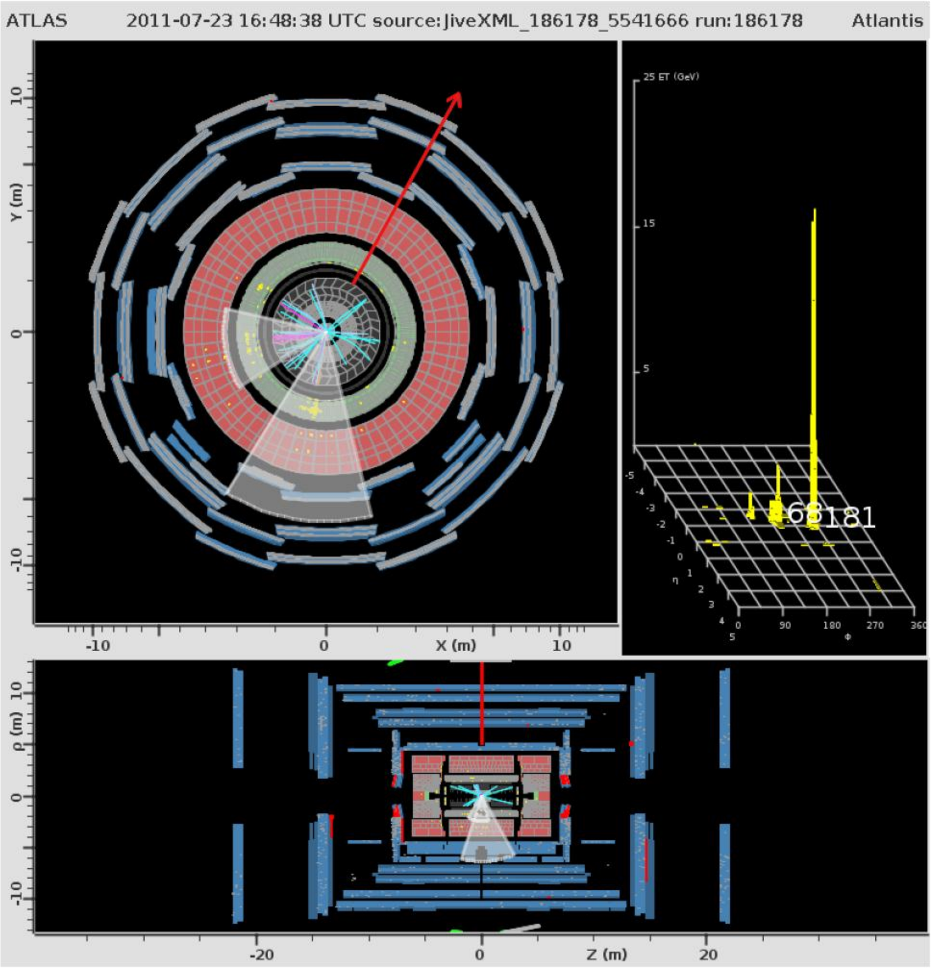
Selection: $ZH \to l^+l^-b\bar{b}$

- $Z \to ll$ system:
  - Two opposite sign leptons (e or μ):
    - $p_T > 20$ GeV
    - $|\eta(e)| < 2.47$; $|\eta(\mu)| < 2.5$
  - $E_T^{miss} < 50$ GeV
  - 83 GeV $< M_{ll} <$ 99 GeV
- $H \to b\bar{b}$ system:
  - 2 b-tagged jets:
    - $|\eta| < 2.5$; $p_T >$ 45 and 25 GeV
    - $\Delta R(bb) > 0.7$ if $p_T(ll) <$ 200 GeV
- Split into 4 $p_T(ll)$ bins:
  - $[0, 50], [50, 100], [100, 200]$ and $[200, \infty]$



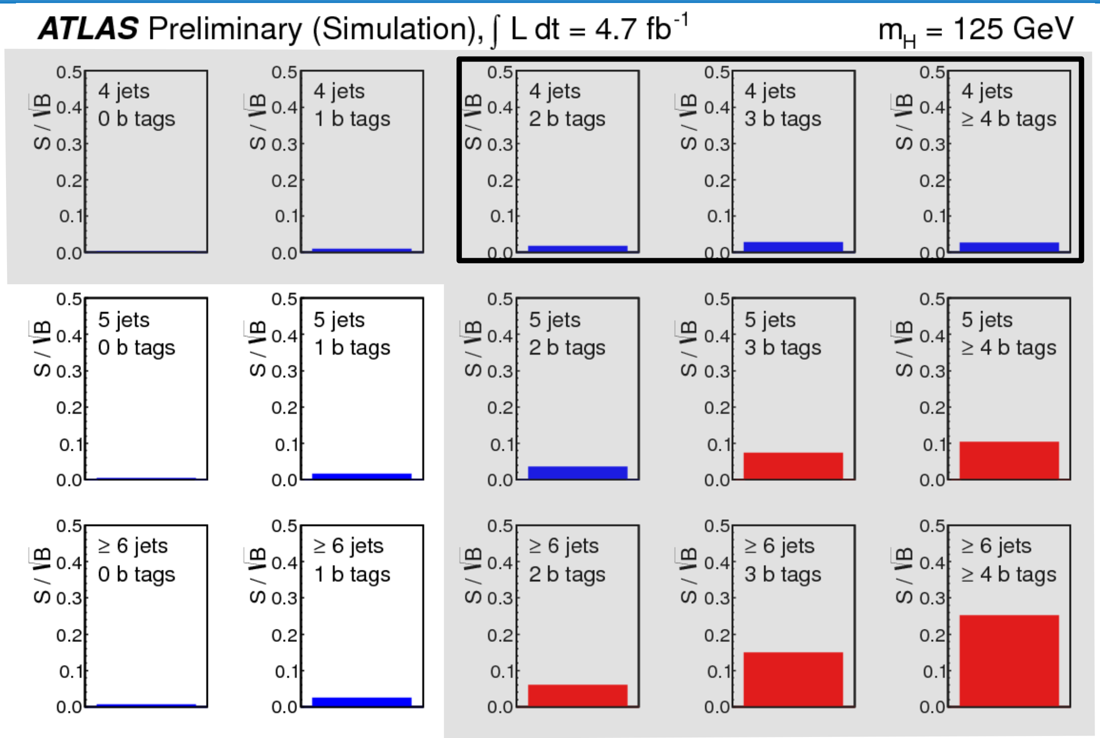
Selection: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- $Z \rightarrow \nu\nu$ system:
  - Transverse missing energy/momentum:
    - $E_T{}^{miss} > 120$ GeV ; $p_T{}^{miss} > 30$ GeV
    - $\Delta\phi(p_T{}^{miss}, E_T{}^{miss}) < \pi/2$
    - $\min\{\Delta\phi(b, E_T{}^{miss})\} > 1.8$
  - Extra lepton veto:
    - $|\eta(e)| < 2.47$ and $|\eta(\mu)| < 2.7$
    - $p_T > 10$ GeV
- $H \rightarrow b\bar{b}$ system:
  - 2 b-tagged jets:
    - $|\eta| < 2.5$; $p_T > 45$ and 25 GeV
    - $0.7 < \Delta R(bb) < 2.0$ if $0 < E_T{}^{miss} <$ 160 GeV
    - $0.7 < \Delta R(bb) < 1.7$ if $160 < E_T{}^{miss} <$ 200 GeV
  - Extra jet veto:
    - $|\eta| < 4.5$; $p_T > 20$ GeV
- Split into 3 $E_T{}^{miss}$ bins:
  - $[120, 160], [160, 200]$ and $[200, \infty]$



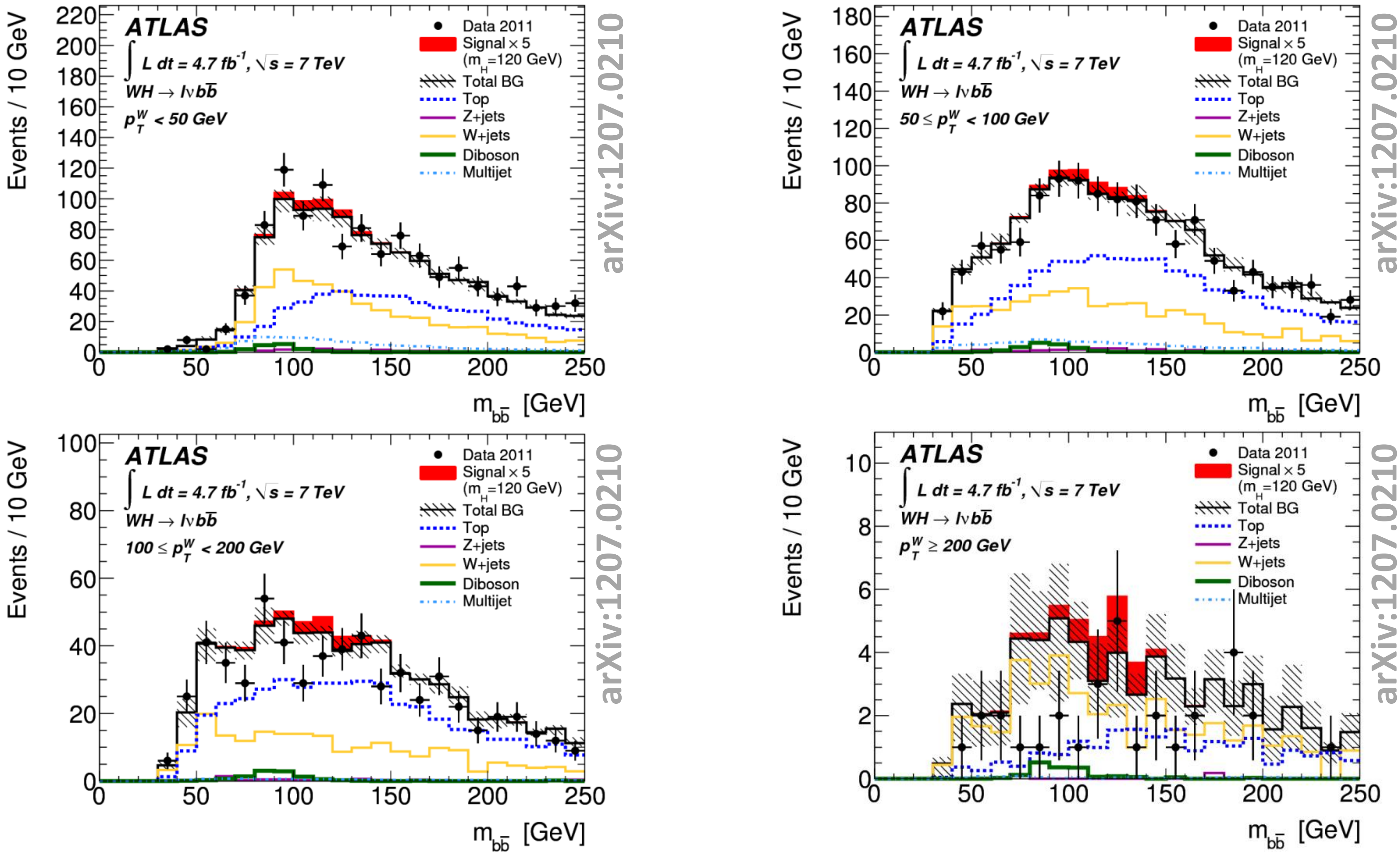
Selection: $t\bar{t}H \rightarrow q\bar{q}'l\nu b\bar{b}b\bar{b}$

- Electron channel:
  - One isolated electron:
    - $p_T > 25$ GeV
    - $|\eta| < 2.47$
  - $E_T{}^{miss} > 30$ GeV
  - $M_T(l\nu) > 30$ GeV
- Muon channel:
  - One isolated muon:
    - $p_T > 20$ GeV
    - $|\eta(\mu)| < 2.5$
  - $E_T{}^{miss} > 20$ GeV
  - $E_T{}^{miss} + M_T(l\nu) > 60$ GeV
- At least 4 jets:
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
- Events categorized according to jet multiplicities:
  - 9 categories used for the analysis

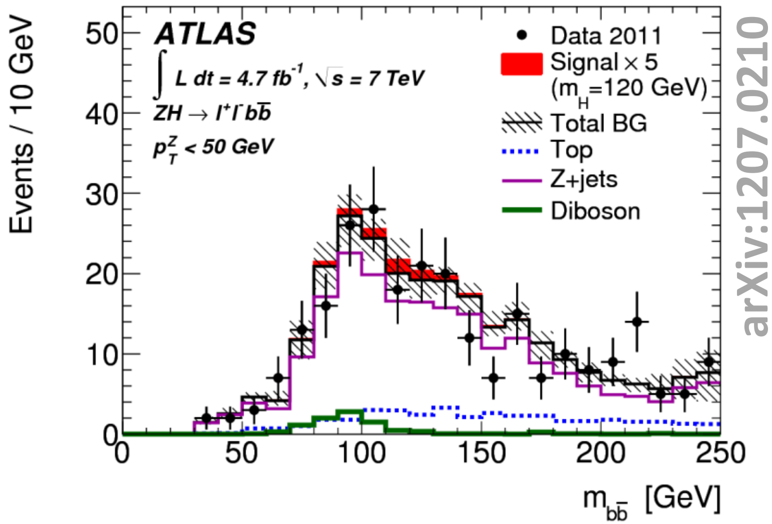


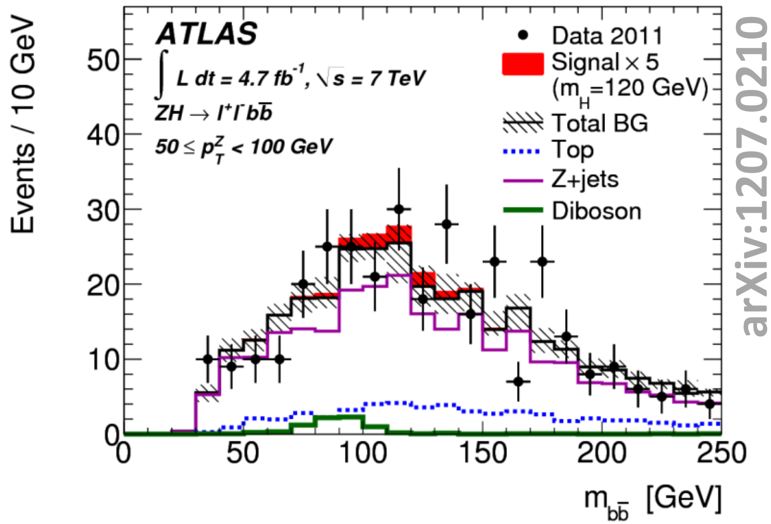
- Kinematic reconstruction:
  - Kinematic likelihood fit to reconstruct the $t\bar{t}$ pair
  - Remaining two b jets are used for H candidate

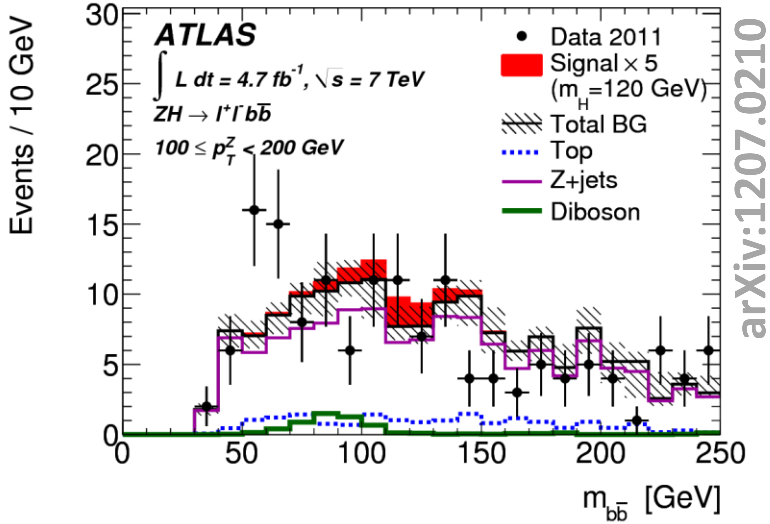
p_T bins: $WH \to l\nu b\bar{b}$

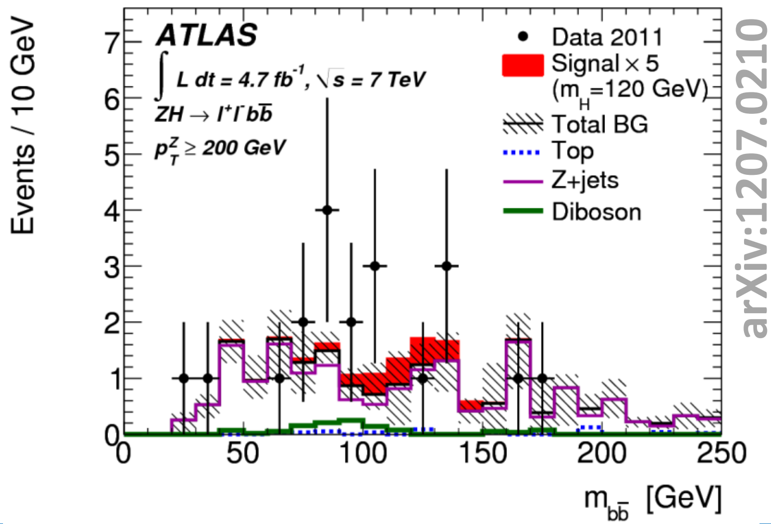


p_T bins: $ZH \rightarrow ll b\bar{b}$

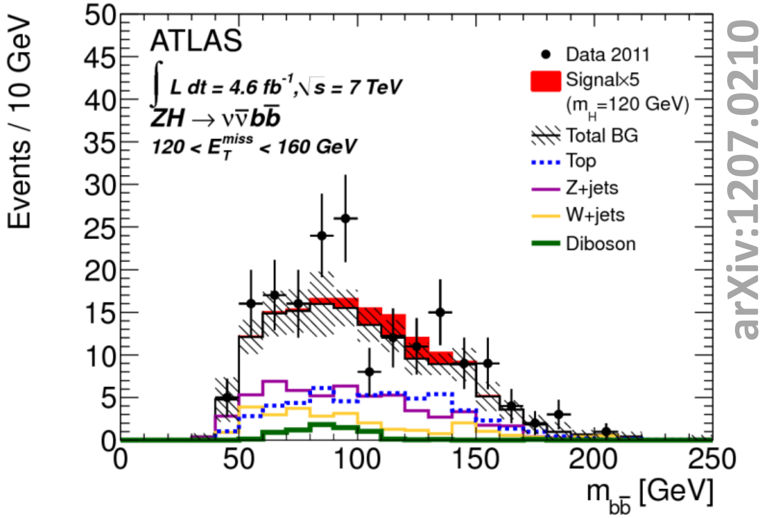


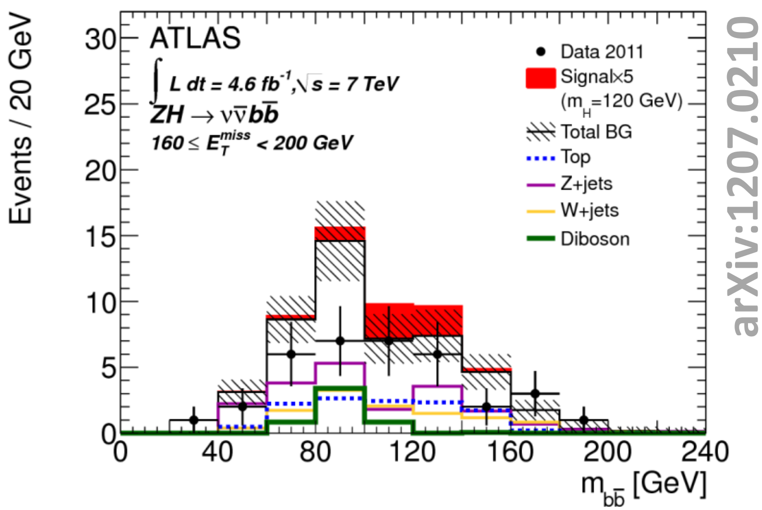


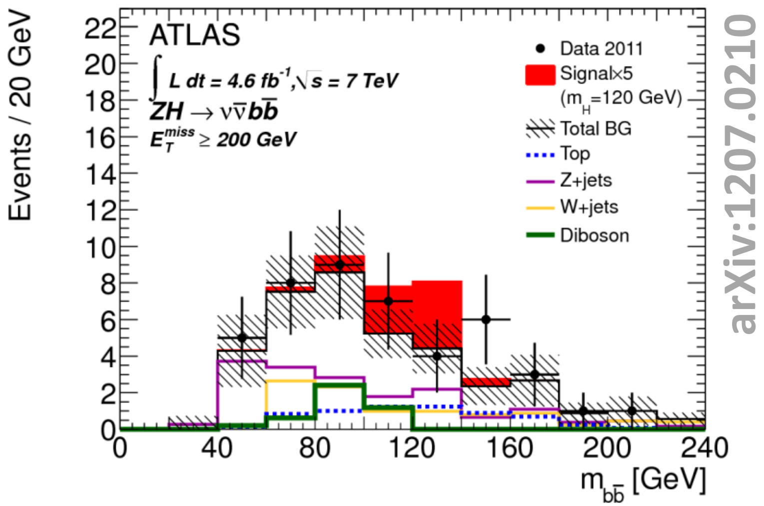




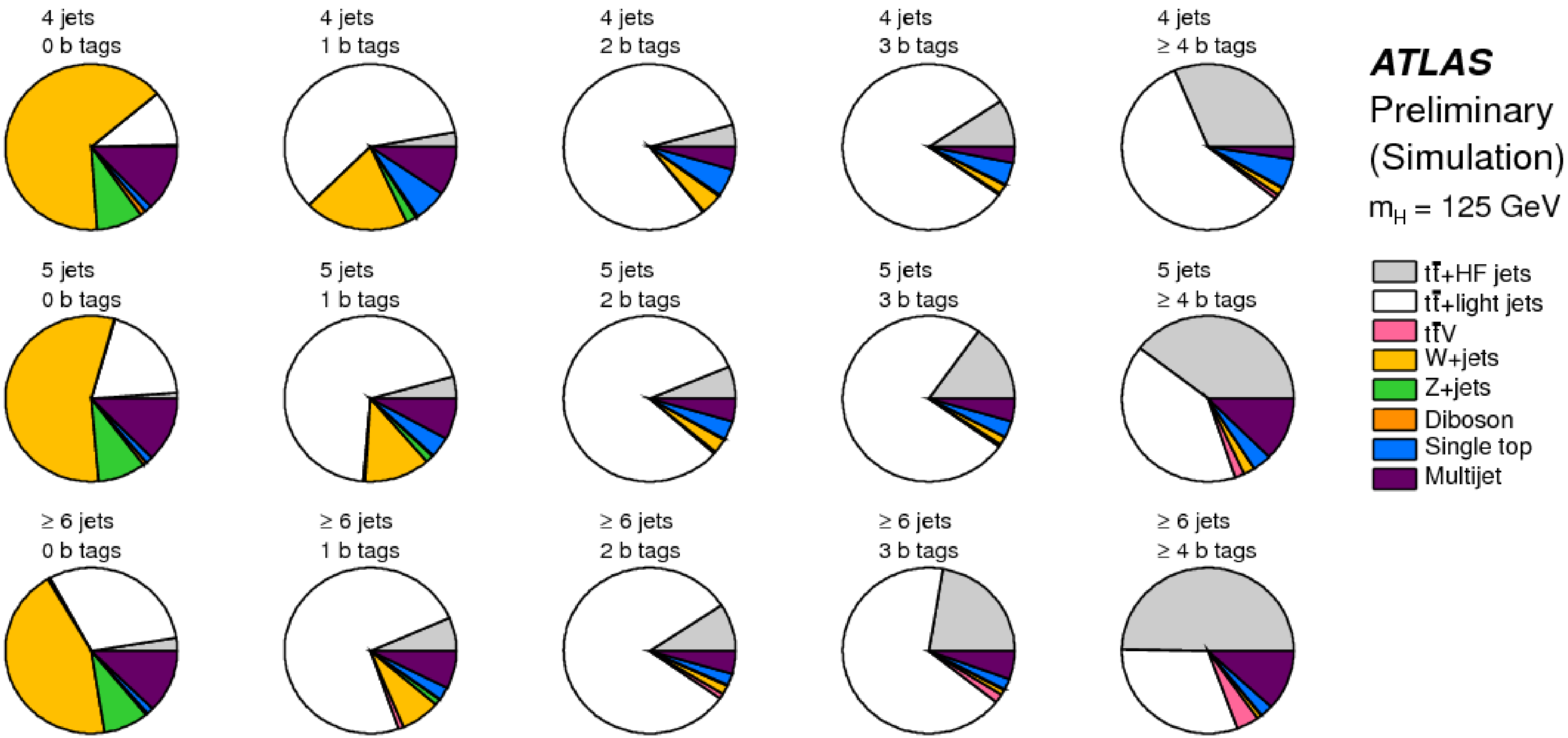
p_T bins: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$







Background composition: $t\bar{t}H \rightarrow q\bar{q}'l\nu b\bar{b}b\bar{b}$



ATLAS EXPERIMENT

Systematics : VH channels

THE UNIVERSITY OF IOWA

Table 1: Number of data, simulated signal, and estimated background events in each bin of p_T^V for the $WH \to \ell\nu b\bar{b}$, $ZH \to \ell^+\ell^- b\bar{b}$ and $ZH \to \nu\bar{\nu}b\bar{b}$ channels. The signal corresponds to a Higgs boson mass of $m_H = 120$ GeV. The number of events is shown for the full signal region ($m_{b\bar{b}} \in [80 \text{ GeV}, 150 \text{ GeV}]$). Background sources found to be negligible are signalled with "–". Relative systematic uncertainties on the hypothesized signal and estimated total background are shown.

bin	$ZH \to \ell^+\ell^- bb$ p_T^V [GeV]				$WH \to \ell\nu bb$ p_T^V [GeV]				$ZH \to \nu\bar{\nu}bb$ p_T^V [GeV]		
	0-50	50-100	100-200	>200	0-50	50-100	100-200	>200	120-160	160-200	>200
Number of events for $80 < m_{b\bar{b}} < 150$ GeV											
signal	1.3 ± 0.1	1.8 ± 0.2	1.6 ± 0.2	0.4 ± 0.1	5.0 ± 0.6	5.1 ± 0.6	3.7 ± 0.4	1.2 ± 0.2	2.0 ± 0.2	1.2 ± 0.1	1.5 ± 0.2
top	17.4	24.1	7.3	0.2	229.9	342.7	201.3	8.2	35.2	8.3	4.1
W+jets	–	–	–	–	285.9	193.6	85.8	17.5	13.2	7.8	4.8
Z+jets	123.2	119.9	55.9	6.1	11.1	10.5	2.8	0.0	31.5	11.9	7.1
diboson	7.2	5.6	3.6	0.7	12.6	11.9	7.8	1.4	4.6	4.3	3.6
multijet	–	–	–	–	55.5	38.2	3.6	0.2	–	–	–
total BG	148 ± 10	150 ± 6	67 ± 4	6.9 ± 1.2	596 ± 23	598 ± 16	302 ± 10	27 ± 5	85 ± 8	32 ± 3	20 ± 3
data	141	163	61	13	614	588	271	15	105	22	25
Components of the relative systematic uncertainties of the background [%]											
b-tag eff	1.4	1.0	0.3	4.8	0.9	1.3	0.9	7.2	4.1	4.2	5.5
BG norm	3.6	3.4	3.6	3.8	2.7	1.8	1.8	4.5	2.7	2.2	3.2
jets/E_T^{miss}	2.1	1.2	2.7	5.1	1.5	1.4	2.1	9.5	7.7	8.2	12.1
leptons	0.2	0.3	1.1	3.4	0.1	0.2	0.2	1.7	0.0	0.0	0.0
luminosity	0.2	0.1	0.2	0.4	0.1	0.1	0.1	0.2	0.2	0.5	0.7
pileup	0.9	1.6	0.5	1.3	0.1	0.2	0.8	0.5	1.6	2.5	3.0
theory	5.2	1.3	4.7	14.9	2.2	0.3	1.6	14.8	2.9	4.0	7.7
total BG	6.9	4.3	6.6	17.3	3.9	2.7	3.4	19.6	9.7	10.6	16.0
Components of the relative systematic uncertainties of the signal [%]											
b-tag eff	6.4	6.4	7.0	13.7	6.4	6.4	7.0	12.1	7.1	8.2	9.2
jets/E_T^{miss}	4.9	3.2	3.5	5.5	5.8	4.6	3.7	3.3	7.3	5.1	6.3
leptons	0.9	1.2	1.7	2.6	3.0	3.0	3.0	3.2	0.0	0.0	0.0
luminosity	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
pileup	0.5	1.1	1.8	2.2	1.2	0.3	0.3	1.6	0.2	0.2	0.0
theory	4.6	3.6	3.3	5.3	4.4	4.7	5.0	8.0	3.3	3.3	5.6
total signal	10.1	9.1	9.6	16.5	11.4	10.8	11.0	16.0	11.8	11.4	13.4

arXiv:1207.0210

Monte Carlo Samples

- Signal:
  - PYTHIA + MRST (LO*) PDFs
  - Cross-section: LHC Higgs Cross Section Working Group report (arXiv:1101.0593)
  - Branching ratios: HDECAY
- W+b: POWHEG + MSTW 2008 NLO PDFs + PYHTIA parton shower
- Z+b, Z+c: SHERPA
- W+c, W+j, Z+j: ALPGEN+HERWIG
- Diboson: HERWIG
- ttbar: MC@NLO + CT10 NLO PDFs + HERWIG
- HERWIG:
  - MRST (LO*) PDFs
  - ATLAS tune AUET2

How to interpret exclusion limits

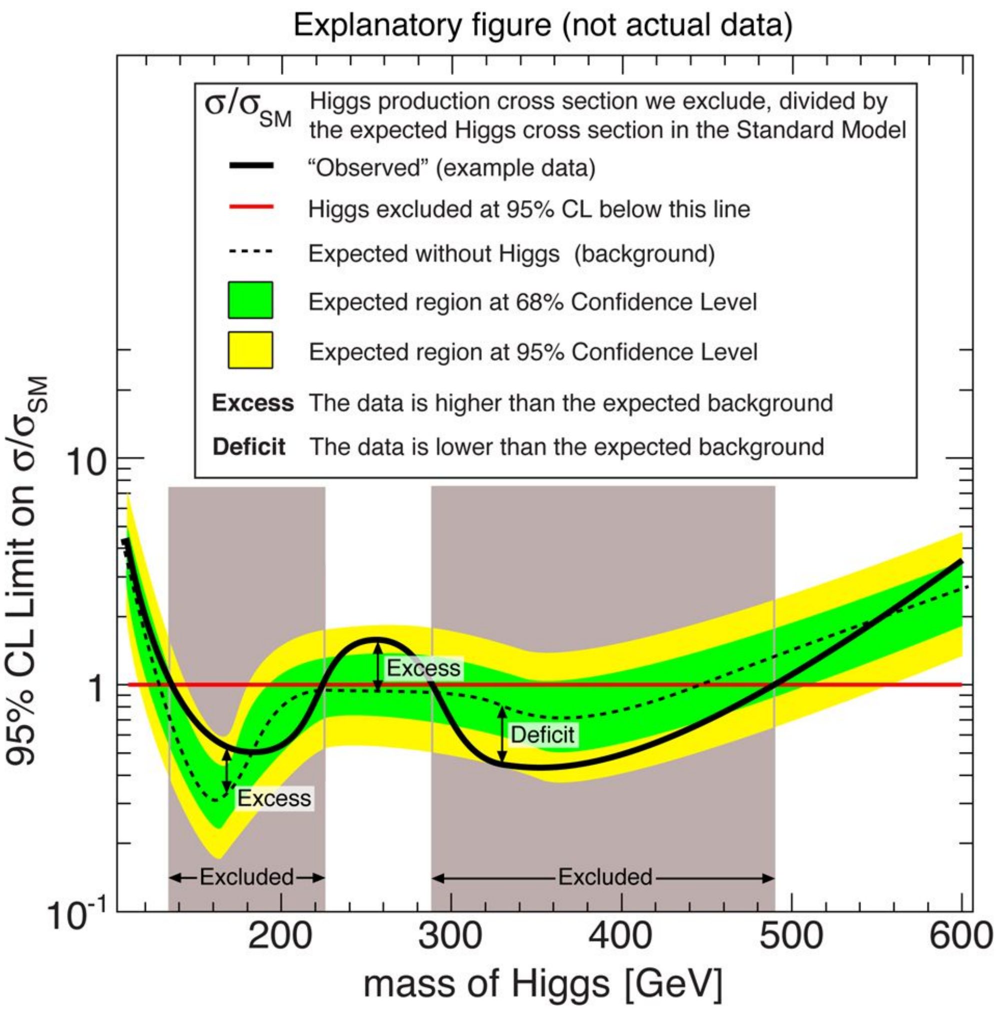


Figure A