$ZH \rightarrow ll b\bar{b}$, $WH \rightarrow l\nu b\bar{b}$

"Searches for a Standard Model Higgs boson decaying to a *b*-quark pair with the ATLAS detector at the LHC"

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University of Birmingham

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Higgs Approval Meeting

Introduction

- Analysis of low mass Higgs channels ZH and WH
- ZH uses $llb\bar{b}$ final state. This is same as high mass $H \to ZZ \to llb\bar{b}$ analysed in HSG2 (see previous talk from Carl).
  - Use exactly the same selection, corrections etc. but look for signal above background in $m_{b\bar{b}}$ spectrum. Many control regions similar.
- $WH \to l\nu b\bar{b}$. Benefits from higher production cross section, although larger top background

m_H (GeV)	$\sigma(WH)$ (pb)	$\sigma(ZH)$ (pb)	Branching Ratios $H \to bb$
115	0.7546	0.3598	0.705
120	0.6561	0.3158	0.649
125	0.5729	0.2778	0.578
130	0.5008	0.2453	0.494

Lepton Selection

- Electrons
  - Medium(tight) with $p_T > 20(25)$ GeV and $|\eta| < 2.5(2.47)$ for $Z(W)$
  - Include crack region
  - Object Quality cuts (including removal of bad FEBs in MC)
  - Track isolation: $\sum_{tracks} / p_T < 0.1$ within $\Delta R = 0.2$
  - For WH: Impact parameter cut $d_0 < 0.1$ mm
  - Smearing and efficiency corrections from Egamma EPS recommendations
- Muons
  - STACO(Muid) combined/tagged with $p_T > 20(25)$ GeV and $|\eta| < 2.5(2.4)$ for $Z(W)$
  - Recommended MCP cuts
  - Track isolation: $\sum_{tracks} / p_T < 0.1$ within $\Delta R = 0.2$
  - Impact paramter cuts $d_0 < 1(0.1)$ mm for $Z(W)$
  - Impact parameter cut against cosmics $z_0 < 10$ mm
  - Scaling/smearing and efficiency correction from MCP EPS recommendations

Event Selection

- Common selection
  - Jets and MET object reconstruction as in $H \rightarrow ZZ \rightarrow llbb$ analysis
  - Common GRL, single lepton triggers, vertex requirements, jet cleaning, ...
  - Difference in overlap removal for WH: μ-jet Muons with $\Delta R < 0.4$ to a selected jet are removed
- $ZH \rightarrow llbb$
  - Exactly 2 leptons with $76 < m_{ll} < 106$ GeV
  - Opposite charge required for muons
  - $E_T^{miss} < 50$ GeV
  - b tagger IP3D+SV1, cut > 1.55 (B-Tagging scale factors/errors for advanced taggers available for first time)
  - At least 2 jets, exactly 2 b tagged
- $WH \rightarrow l\nu bb$ selection
  - Exactly 1 lepton and $M_T > 40$ GeV
  - $E_T^{miss} > 25$ GeV
  - b tagger IP3D+SV1, cut > 1.55
  - Exactly 2 jets and both b tagged (reduce top)

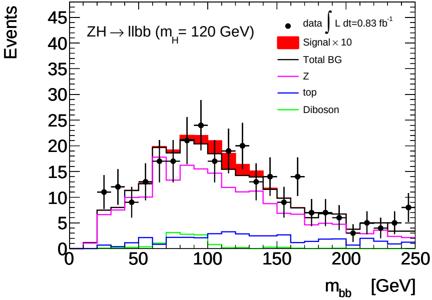
Datasets

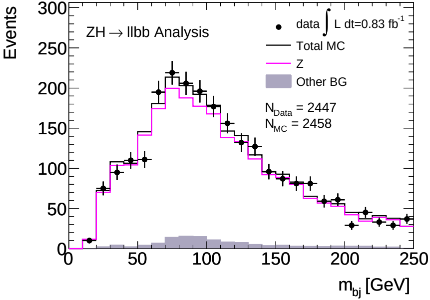
- (ZH) Runs from period B2-H1 using HSG2 Dilepton DAODs
  - Corresponds to 0.83 fb^{-1}
- (WH) Runs from period D1-G5
  - Corresponds to 0.675 fb^{-1} both will include data up to TS for EPS
- Comparing with *mc10b* Monte Carlo (50 ns)
- $ZH \rightarrow llbb$, $WH \rightarrow l\nu bb (m_H = 115, 120, 125, 130\ \text{GeV})$ using Pythia ($m_H = 110, 140$ GeV now available)
- Z (Alpgen+HFOR)
- W (Alpgen+HFOR)
- $t\bar{t}$, single top (MC@NLO)
- $ZZ \rightarrow llqq$, $WZ \rightarrow qqll\ l\nu qq$ (MC@NLO), $WW \rightarrow l\nu qq$ (HERWIG)
- QCD background
  - *ZH* multi-jet electron from loose-loose no medium data scaled, multi-jet muon negelected
  - *WH* electron and muon from anti-isolation data scaled

ZH Backgrounds

- Z+jets.
  $Z + b(b\bar{b})$ dominates. Use MC to describe shape. Set normalisation using control region $m_{bb} < 80$ GeV. Cross check using $Z+$ 1-b tag sample.
- Top
  Use MC. Control region from m_{ll} sidebands, b tagged jets, high/low MET (same as $H \rightarrow ZZ$ analysis)
- Multijet
  As per $H \rightarrow ZZ$ analysis. Fit m_{ee} templates obtained using loose-no medium electrons; negligible in muon channel
- Diboson
  ZZ, WZ from theory

ZH: Z+jets Control





$m_{b\bar{b}}$ m_{bj} for 1 b-tag events

Z background template normalised to region $m_{b\bar{b}} < 80$ GeV

m_{bb}: Z MC scaled by 0.84 ± 0.11

m_{bj}: MC consistent with data

Preliminary Systematics

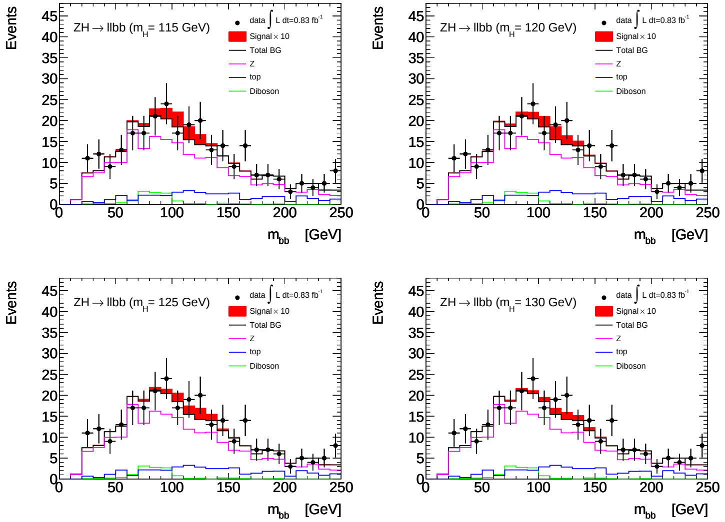
Same as $H \rightarrow ZZ$ except signal and Z+jets

- Luminostiy uncertainty of 4.5% (value/syst will change before EPS)
  - Applied (correlated) to all samples except Z where constrained from data
- Signal Cross Sections uncertainty of 5% (PDF, α_s, μ_f, μ_r)
- Z+jets
  - From statistical error from low m_{bb} control region 14%
  - Apply reco/ID systematics as shape variations only
  - Alpgen/Pythia as shape uncertainty
- Top: 9% theoretical uncertainty
- ZZ: 11% uncertainty + MC@NLO/Pythia as shape uncertainty
  - 5% combined scale/PDF uncertainty $\oplus$ 10% ucertainty from comparing MC@NLO and k-factor-scaled Pythia results
- 11% forWZ, and 100% for QCD

ZH: Effect of Systs. on Signal

Source of Uncertainty	Effect	
	$m_H = 115$ GeV	$m_H = 130$ GeV
Electron Energy Scale	$< 1\%$	$< 1\%$
Electron Energy Resolution	$< 1\%$	$< 1\%$
Muon Momentum Resolution	$< 1\%$	$< 1\%$
Jet Energy Scale (JES)	7%	5%
Jet Energy Resolution	1%	1%
Missing Transverse Energy	1%	$< 1\%$
b-tagging Efficiency	16%	17%
b-tagging Mis-tag Rate	$< 1\%$	$< 1\%$
Electron Reconstruction Efficiency	1%	1%
Muon Selection Efficiency	1%	1%
Lumi	4.5%	4.5%
Cross section	5%	5%

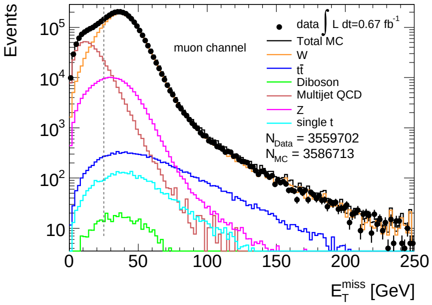
ZH: Preliminary Results m_{bb}



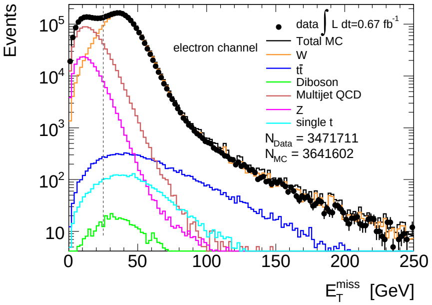
ZH Results Table

Source	expected number				
Z+jets	181.98	$\pm$	5.53 (stat.)	$\pm$	24.10 (sys.)
W+jets	0.00	$\pm$	0.00 (stat.)	$\pm$	0.00 (sys.)
Top	39.70	$\pm$	3.17 (stat.)	$\pm$	8.35 (sys.)
Multijet	0.99	$\pm$	0.33 (stat.)	$\pm$	0.99 (sys.)
ZZ	11.23	$\pm$	1.34 (stat.)	$\pm$	2.87 (sys.)
WZ	0.89	$\pm$	0.23 (stat.)	$\pm$	0.28 (sys.)
Total background	234.79	$\pm$	6.53 (stat.)	$\pm$	26.43 (sys.)
Data	252				
Signal $m_H = 115$ GeV	1.53	$\pm$	0.06(stat.)	$\pm$	0.29 (sys.)
Signal $m_H = 120$ GeV	1.26	$\pm$	0.05(stat.)	$\pm$	0.24 (sys.)
Signal $m_H = 125$ GeV	1.15	$\pm$	0.04(stat.)	$\pm$	0.22 (sys.)
Signal $m_H = 130$ GeV	0.81	$\pm$	0.03(stat.)	$\pm$	0.15 (sys.)

WH: E_T^{miss} in W Events



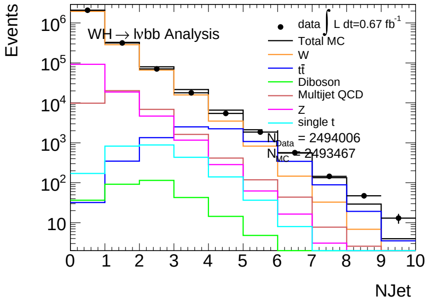
$W \to \mu\nu$



$W \to e\nu$

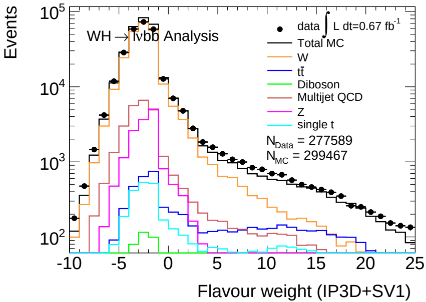
'Multijet QCD' background determined from data gives a good description of selected data at low values of E_T^{miss}

WH: W+jets

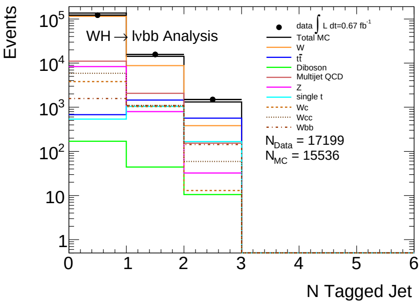


Description of W+jet multiplicity reasonable.
Analysis looks at events with $N_{\mathrm{jet}} = 2$

WH: *b* tagging



IP3D+SV1 weight for $N_{\mathrm{jet}} = 2$ events



Number of *b*-tags (> 1.55)

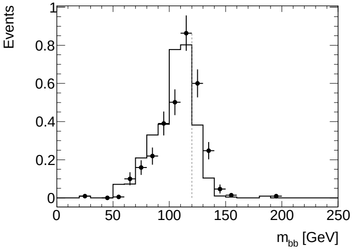
- Flavour weight similarly described for *W* sample as was for *Z*
- *b*-jet multiplicity also reasonably well described
- Note that for *W* channel the 1 *b*-tag sample is mainly *Wcj* and *Wll* and cannot be used as control on *Wb*

WH Backgrounds

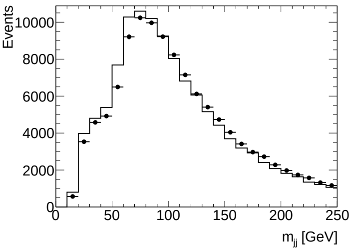
- *W*+jets.
  Low $W + b\bar{b}$ MC stats. Use data driven method - m_{jj} from data as template. Set normalisation using control region $m_{bb} < 80$ GeV (where *Wbb* contributes).
- *Z*+jets.
  Use same normalisation of MC as measured in *Z*+jets control region (see *ZH* analysis)
- Top
  Use MC. Control region from m_{bb} for 3 jet events
- Multijet
  Data templates from QCD enhanced samples (anti-isolation)
- Diboson
  WW, *WZ* from theory

m_{bb} Reconstruction

- The m_{bb} distribution in $H \rightarrow ZZ$ is scaled by 1.05 to improve m_Z reconstruction. Therefore, also for ZH (to improve m_H).
- For WH the m_{jj} distribution is used to model W+jets background.
  - Scale $1.05 \times m_{bb}$ and use $1.05 \times m_{jj}$ histo for modelling background
  - Last week ran all scaling off for W_H
- Scaling improves m_H reconstruction. W+jets template scaled

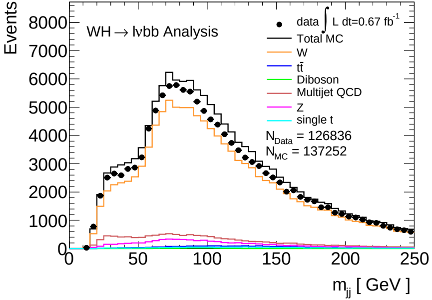


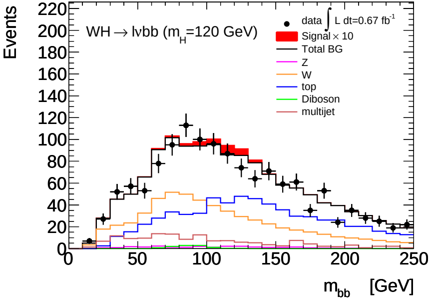
$m_{bb}(m_H = 120$ GeV) unscaled and scaled



m_{jj} from W MC

WH: W+jets Control

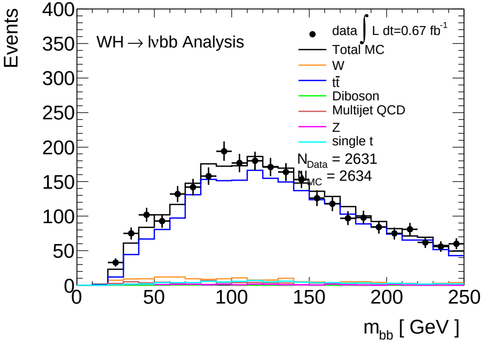




m_{jj} m_{bb}

Data driven W background templates from untagged m_{jj} normalised to region $m_{b\bar{b}} < 80$ GeV
Light data template scaled by 0.00546 ± 0.00052

WH: Top Control



Control region for top

m_{bb} for 3 jet events

Normalisation and shape OK

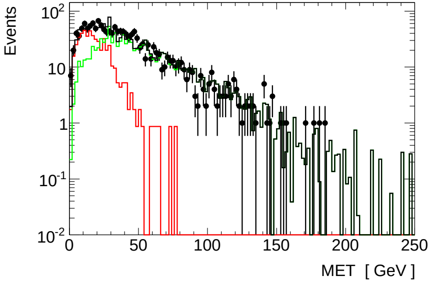
QCD Background Estimation

For both electrons and muons try two QCD enhanced data selections

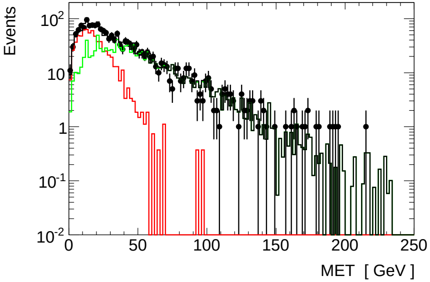
- Anti-isolation selection $0.1 < p_T^{\mathrm{cone}}/p_T < 0.5$ (default).
- Anti-d_0 selection. $0.1 < d_0 < 1\ \mathrm{mm}$ (check).
- Determine QCD Background normalisation for different jet multiplicites etc. by fitting MET distribution (before MET cut) with 2 contributions: MC and data anti-isolation. These describe high and low MET regions respectively.
- QCD control region:
  - $MET < 25$ GeV and $M_T < 40$ GeV
  - Look at invariant mass m_{bb} in this range

QCD Background for $N_b^{\mathrm{jet}} = 2$

- For events with $N^{\mathrm{jet}} = N_b^{\mathrm{jet}} = 2$ fit MET distribution (before MET cut) with two components: QCD dominated template(red), electroweak Monte Carlo(green)
- Reasonable description of MET.
  - Scale factors $\rho_\mu = 0.87 \pm 0.06$, $\rho_e = 0.37 \pm 0.02$



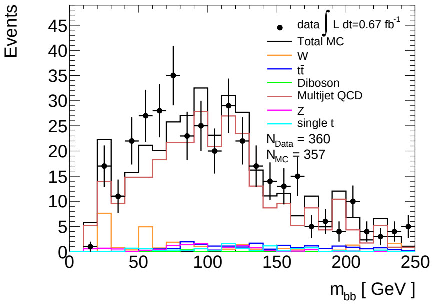
MET for $W\mu\nu$ and $N_b^{\mathrm{jet}} = 2$



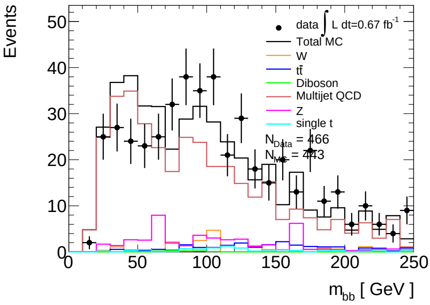
MET for $We\nu$ and $N_b^{\mathrm{jet}} = 2$

Multijet Control Region

- Look at invariant mass m_{bb} in QCD dominated control region: MET$<$ 25 GeV and $M_T < 40$ GeV
  - Model QCD using anti-isolation sample (check using anti-d_0)
  - Use scale factor as determined by fit to MET
- Reasonable description. Uncertainty of 50% applied



m_{bb} for $W\mu\nu$



m_{bb} for $We\nu$

WH Preliminary Systematics

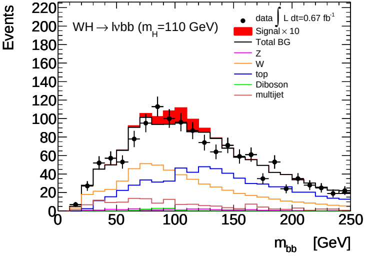
Same as *ZH* plus additional W+jets

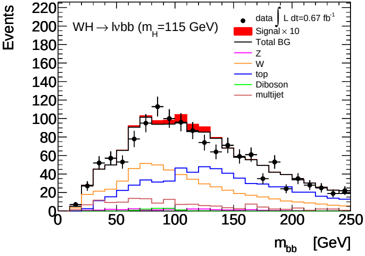
- Luminostiy uncertainty of 4.5% (value/syst will change before EPS)
  - Applied (correlated) to all samples except Z where constrained from data
- Signal Cross Sections uncertainty of 5%
- W+jets
  - From statistical error from low m_{bb} control region 21%
  - Use MC m_{jj} template instead of data as shape uncertainty
- Z+jets
  - See *ZH*
- Top: 9% theoretical uncertainty
- *ZZ*: 11% uncertainty + MC@NLO/Pythia as shape uncertainty
  - 5% combined scale/PDF uncertainty $\oplus$ 10% ucertainty from comparing MC@NLO and k-factor-scaled Pythia results
- 11% for*WZ*, and 50% for QCD

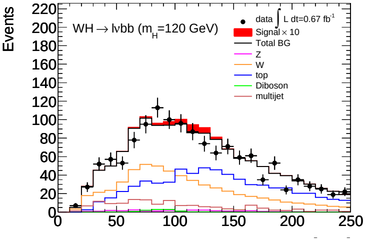
WH: Effect of Systs. on Signal

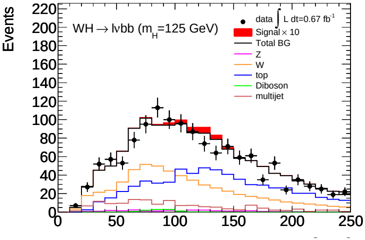
Source of Uncertainty	Effect	
	$m_H = 115$ GeV	$m_H = 130$ GeV
Electron Energy Scale	$< 1\%$	$< 1\%$
Electron Energy Resolution	$< 1\%$	$< 1\%$
Muon Momentum Resolution	$< 1\%$	$< 1\%$
Jet Energy Scale (JES)	$< 1\%$	3%
Jet Energy Resolution	1%	1%
Missing Transverse Energy	1%	2%
b-tagging Efficiency	16%	17%
b-tagging Mis-tag Rate	$< 1\%$	$< 1\%$
Electron Reconstruction Efficiency	1%	1%
Muon Selection Efficiency	$< 1\%$	1%
Lumi	4.5%	4.5%
Cross section	5%	5%

WH: Preliminary Results m_{bb}

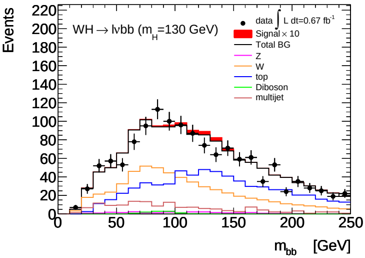


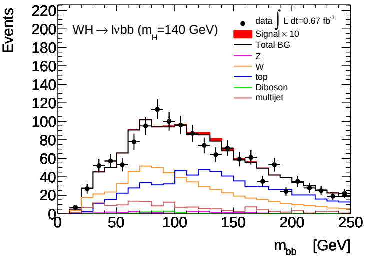






WH: Preliminary Results m_{bb}



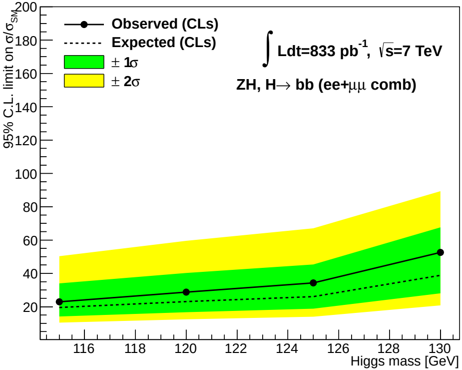


WH Results Table

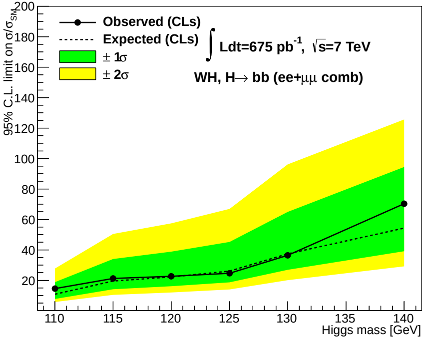
Source	expected number				
Z+jets	23.46	$\pm$	2.18 (stat.)	$\pm$	7.54 (sys.)
W+jets	516.70	$\pm$	1.95 (stat.)	$\pm$	110.66 (sys.)
Top	615.47	$\pm$	11.32 (stat.)	$\pm$	136.73 (sys.)
Multijet	113.08	$\pm$	7.70 (stat.)	$\pm$	56.54 (sys.)
WZ	10.36	$\pm$	1.44 (stat.)	$\pm$	2.49 (sys.)
WW	3.09	$\pm$	0.74 (stat.)	$\pm$	0.83 (sys.)
Total background	1282.16	$\pm$	14.09 (stat.)	$\pm$	191.03 (sys.)
Data	1245				
Signal $m_H = 115$ GeV	3.58	$\pm$	0.21(stat.)	$\pm$	0.62 (sys.)
Signal $m_H = 120$ GeV	3.16	$\pm$	0.17(stat.)	$\pm$	0.56 (sys.)
Signal $m_H = 125$ GeV	2.76	$\pm$	0.14(stat.)	$\pm$	0.52 (sys.)
Signal $m_H = 130$ GeV	2.18	$\pm$	0.11(stat.)	$\pm$	0.41 (sys.)

ZH Preliminary Limits

- Limits obtained using CL_s and the asymptotic formula



WH Preliminary Limits



- Issues with statistical fluctuations in backgrounds (MC stats) causing problems with stability of limits.
  - JES systematic inserted by hand as $\pm 30\%$

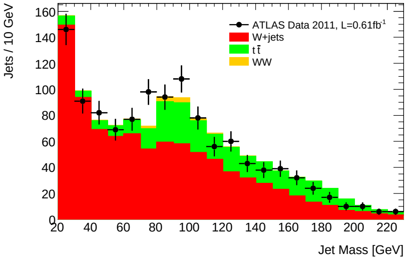
Boosted Higgs Studies

- Approach: take advantage that at high $p_T^H > 200$ GeV, although only 5% of signal the b quarks from $H \rightarrow b\bar{b}$ are highly boosted and different to backgrounds.
- Jet substructure technique used in Higgs senstivity predictions at low mass in ATLAS publication ATL-PHYS-PUB-2010-015
- At high p_T possible to resolve "sub-jets" from within a (wider) jet.
  - Cambridge-Aachen algorithm with $R = 1.2$
  - Undo jet algorithm steps until large drop in mass ($\sim 1/3$)
  - Remaining components reclustered with smaller R value
  - 3 highest p_T sub-jets form heavy particle candidate (discriminator is the jet mass). b-tagging applied to reject light backgrounds.
- Indications are jet substructure at ATLAS is understood ATLAS-CONF-2011-073

WH Boosted Higgs 2011 data

- Data periods D and G, 0.61 fb^{-1}
- Select $We\nu$ and $W\mu\nu$ decays using cuts similar to *WH* analysis and W/Z selection
- Look at $p_T^W > 200$ GeV and $p_T^{\text{jet}} > 180$ GeV
- Calibration from Monte Carlo applied
- Look at jet mass
- No *b*-tagging applied

WH Boosted Higgs Jet Mass



- Monte Carlo(and data) show peak from $t\bar{t}$ events where other W decays hadronically.
  - W+jets has no such peak
  - Difference in data/MC around peak. Useful sample to understand calibration.
- Plot and text added to INT note

Summary

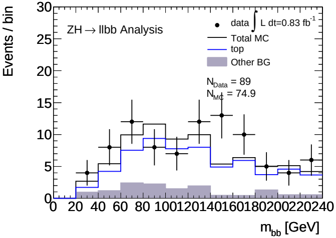
- Advanced *b*-tagging calibrations available in ATLAS for first time this week :)
- Implemented *b*-tagging SFs - results very similar to previous
- Resolving final issues with statistical errors of MC in preliminary WH limits
- First studies of boosted analysis and jet substructure presented. Observed W peak in data consistent with top MC.
- Jet Mass plot added to CONF note as indication of progress towards optimised, more competitive limits from the VH channels.
- Implemented comments from Ed Board to first draft of INT note. Second(Third) draft circulated last Friday(Saturday) with results shown today.

Back Up

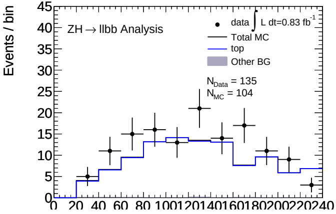
Top Control Region

- $Z \rightarrow ll$ side bands:
  - $60 < m_{ll} < 76$ GeV and $106 < m_{qq} < 150$ GeV
- MC above data but agree within errors
  - Syst error on tagged data: 28%
- Hence MC not scaled at present

tagged ($E_T^{miss} < 50$ GeV)

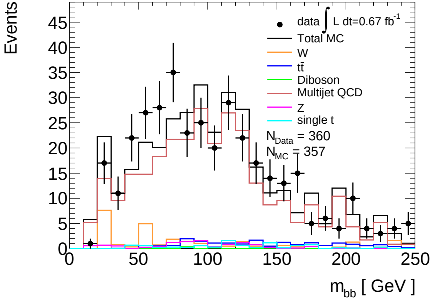


tagged ($E_T^{miss} > 50$ GeV)

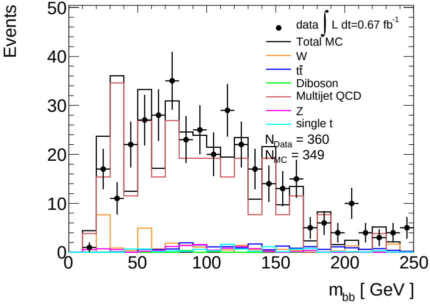


Multijet Control Region - Muons

- Look at invariant mass m_{bb} in QCD dominated control region: MET< 25 GeV and $M_T < 40$ GeV
  - Model QCD using anti-isolation sample, check using anti-d_0
- Dependence on QCD sample. Both reasonable description. Use anti-isolation with 50% uncertainty



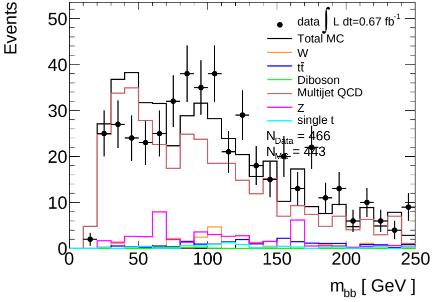
m_{bb}, Multijet from anti-isolation



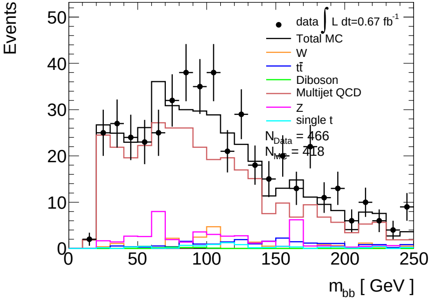
m_{bb}, Multijet from anti-d_0

QCD Control Region - Electrons

- Look at invariant mass m_{bb} in QCD dominated control region: MET$<$ 25 GeV and $M_T < 40$ GeV
  - Model QCD using anti-isolation sample, check using anti-d_0
- Dependence on QCD sample. Both reasonable description. Use anti-isolation with 50% uncertainty



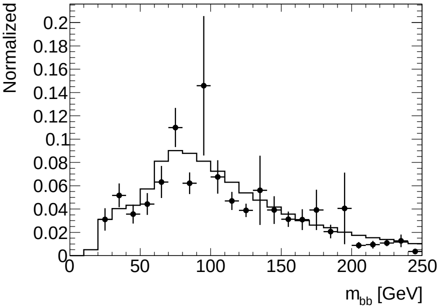
m_{bb}, Multijet from anti-isolation



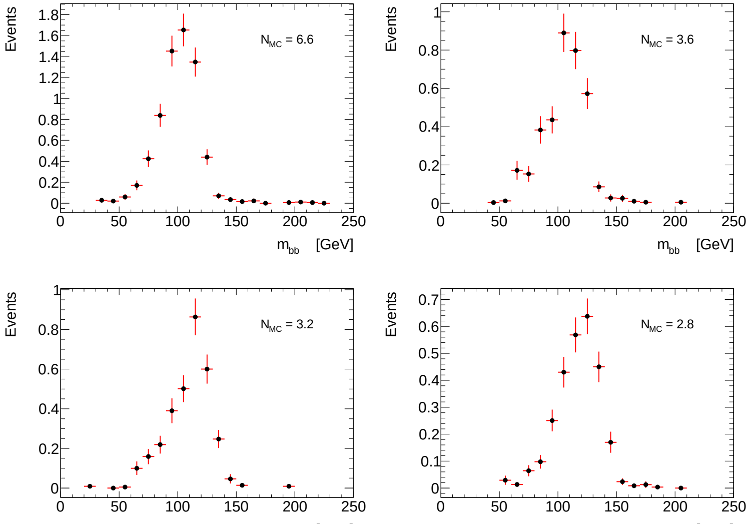
m_{bb}, Multijet from anti-d_0

WH: Backgrounds

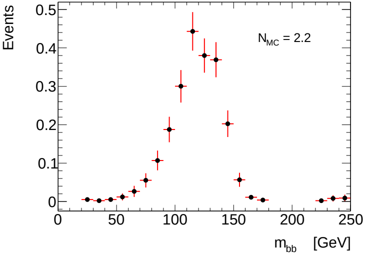
- For *WH*, $Wb\bar{b}$ smaller background than top and MC statistics low
  - Default take shape from untagged m_{jj} data, and normalise this to number of data events $m_{bb} < 80$ GeV
  - Shapes of untagged and tagged m_{jj} distributions consistent within errors



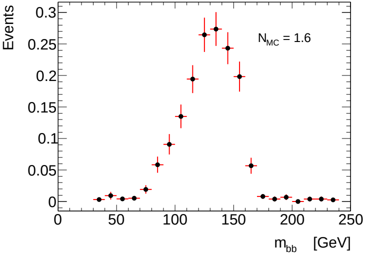
WH: m_{bb}


Events
N_{MC} = 6.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
50
100
150
200
250
m_{bb} [GeV]
Events
N_{MC} = 3.6
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
m_{bb} [GeV]
Events
N_{MC} = 3.2
0
0.2
0.4
0.6
0.8
1
0
50
100
150
200
250
Events
N_{MC} = 2.8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
50
100
150
200
250

WH: m_{bb}



Events
0.5
0.4
0.3
0.2
0.1
0
N_{MC} = 2.2
0
50
100
150
200
250
m_{bb} [GeV]



Events
0.3
0.25
0.2
0.15
0.1
0.05
0
N_{MC} = 1.6
0
50
100
150
200
250
m_{bb} [GeV]