Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a b-quark pair with the ATLAS detector at the LHC

Ricardo Gonçalo (RHUL)
on behalf of Higgs Subgroup 5 (H->bb)

Acknowledgements

- Many thanks to our editorial board for their dedication, many fruitful discussions and thoughtful guidance!

- Editorial board:
  - Chair: Pippa Wells
  - Members: Elzbieta Richter-Was, Christian Weiser, Gavin Hesketh

- Editors:
  - Ricardo Gonçalo, Andrew Mehta, Giacinto Piacquadio, Paul Thompson
- Editors of ZH->ννbb support note:
  - Bill Murray, Song-Ming Wang

- Special thanks to all other members of the analysis team!
  - Especially (but not only!): Benedict Allbrooke, Heather Gray, Carl Gwilliam, David Jamin, Lianliang Ma, Jike Wang

Search for the Standard Model Higgs boson produced in association with a vector boson and decaying to a *b*-quark pair with the ATLAS detector at the LHC

- CDS record: https://cdsweb.cern.ch/record/1425880
- Support material:
  - ZH→llb & WH→lνbb: https://cdsweb.cern.ch/record/1404176/
  - ZH→ννbb: https://cdsweb.cern.ch/record/1418230

A list of supporting internal notes and their authors can be found at:

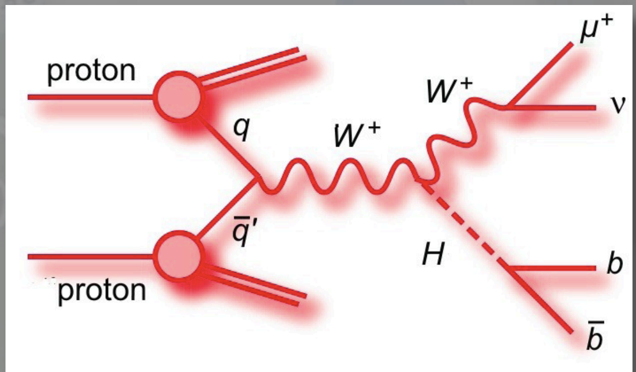
https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/Higgsbb

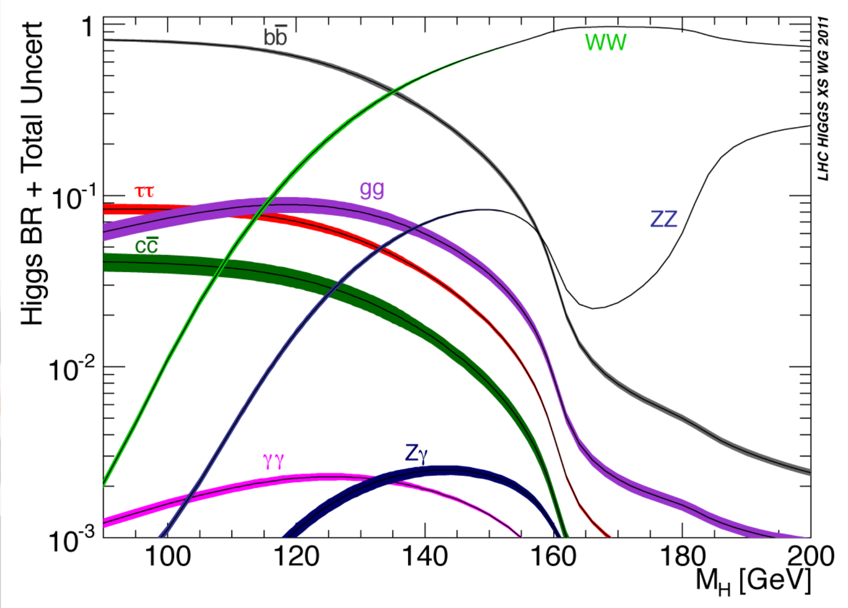
Supporting internal notes

ATL-COM-PHYS-2011-1648 https://cdsweb.cern.ch/record/1404176/
ATL-COM-PHYS-2012-062 https://cdsweb.cern.ch/record/1418230

Comments are due by: February 28, 2012

- This paper:
  - ZH→llb, WH→lvbb and ZH→vvbb
  - 4.6 – 4.7 fb^{-1} analyzed
- H->bb dominant at low mass
  - WH cross section factor ≈2x higher than ZH, but important top background
- Cut-based analyses:
  - Select Z or W or large E_T^{miss} and search for 2 additional b jets
  - Search Higgs in m_{bb} spectrum





m_H (GeV)	$\sigma(WH)$ (pb)	$\sigma(ZH)$ (pb)	Branching Ratios $H \to b\bar{b}$
110	0.8754	0.4721	0.745
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

Datasets

- Full 2011 data from periods B-M
  - 4.7 fb^{-1} e/μ streams (ZH→llb, WH→lνbb)/4.6 fb^{-1} JetTauETmiss (ZH→ννbb)
- Signal (MC11c)
  - ZH→llbb, WH→lνbb, ZH→ννbb simulated in Pythia
  - Normalized to NLO (EW) + NNLO (QCD) from LHC Higgs cross section WG (Yellow Report I)
  - m_H = 110 − 130 GeV in steps of 5 GeV
- Background (MC11c)
  - Z/W+jets: ALPGEN to model l (l and c jets) for Z(W)
  - High statistics Zcc/Zbb(Wbb) using SHERPA(POWHEG)
  - Top: ttbar + single top from MC@NLO
  - Diboson: ZZ/WZ/WW from MC@NLO
- QCD background
  - ZH→llbb multi-jet electron from loose-loose no medium data scaled
  - WH→lνbb electron and muon from anti-isolation data scaled
  - ZH→ννbb from data (ABCD method) – negligible

Lepton Selection: WH→llb, WH→lνbb

- Electrons
  - medium++ (tight++) with pT > 20(25) GeV and |η| < 2.47 for Z(W)
  - Include crack region
  - Trackisolation: Ptracks /pT < 0.1 within R = 0.2
  - For WH: Calo isolation: Pcalo /ET < 0.14 within R = 0.3
  - For WH: Impact parameter cut d0 < 0.1 mm
  - Latest recommended smearing and efficiency corrections
  - Veto in WH: use central loose++ with pT > 10 GeV and forward loose
  - with pT > 20 GeV(|η| < 4.5). Require trk/calo isolation (except forward)

- Muons
  - STACO(Muid) tight with pT > 20(25) GeV and |η| < 2.5 for Z(W)
  - Track isolation (as for electrons); For WH calo isolation
  - Impact paramter cuts d0 < 1(0.1) mm for Z(W)
  - Impact parameter cut against cosmics z0 < 10 mm
  - Latest recommended smearing and efficiency corrections
  - For veto in WH extend to Loose/standalone, pT > 10 GeV and
  - |η| < 2.7. Require track isolation (except standalone)

Jet/E_t^{miss} selection

- Jets – *not updated to last week's recommendations*
  - Anti-kT 4 with pT > 25 GeV and |η| < 2.5 "AntiKt4TopoEMJets"
  - For jet veto in WH pT > 20 GeV and |η| < 4.5
  - Remove events with jets pointing to the bad FEB region
  - Pile-up: reject jets with |JVF| < 0.75 for jets with |η| < 2.5
  - Current JES/JER uncertainty including pile-up, close by and b JES
- b-tagging – *not updated to last week's version*
  - MV1 with w > 0.602 (70% efficiency)
  - Applying corrections and uncertainties derived by b-tagging group.
- MET – *not updated to last week's version*
  - MET RefFinal out-of-the-box
  - Apply pile-up reweighting for each MC run period
  - Additional μ scaling reweighting: scale <μ> by 1.03±0.03

Lepton and jet veto: ZH→ννbb, WH→lνbb

- Veto leptons:
  - Electron : medium , pT>10 GeV, |η|<2.47, pTcone20/pT<0.1
  - Muon : Combined & segmented-tagged STACO, pT>10 GeV, |η|<2.4, pTcone20/pT<0.1
- Veto on any event having an object with:
  - pT > 20 GeV. Veto lepton has wider range than trigger electron
  - (standalone muons, forward electrons).
- Remove any event with:
  - 1 extra lepton with pT > 20 GeV
  - 1 extra opposite sign lepton with pT < 20 GeV
  - > 1 extra leptons
- Remove any event with ≥ 3 jets (veto jet: pT > 20 GeV and |η| < 4.5)
- In ZH→llbb, WH→lνbb: remove overlaps between electrons, muons, jets

Event selection

- Common selection
  - Using WZ+jets GRL (incl. b-tagging)
  - Primary vertex containing at least 3 tracks
- ZH→llb
  - Triggers: single and dilepton triggers
  - Exactly 2 leptons with 83 < mll < 99 GeV
  - Opposite charge required for muons
  - ET^{miss} < 50 GeV
  - At least 2 jets (1 jet with p_T >45 GeV), exactly 2 b tagged
- WH→lνbb
  - Triggers: single lepton trigger
  - 1 lepton and MT > 40 GeV
  - Emiss
  - T > 25 GeV
  - Exactly 2 jets(1 jet with pT >45 GeV) and both b tagged

- ZH→ννbb
  - Trigger: EF_xe70_noMu
  - No lepton (e or μ)
  - Etmiss > 120 GeV
  - Ptmiss > 30 GeV (remove events with fake high Etmiss)
  - 2 or 3 jets, exactly 2 b-tagged jets
  - Leading jet Pt>45 GeV (new)
  - B-tagged jets separated by dR (b1,b2)>0.7 (for 120<Etmiss<200 GeV)
  - Δϕ(Etmiss, Ptmiss) < π/2 (new)
  - Plus optimized angular cuts (table)

	E_T^{miss}(GeV)		
Cuts	120 - 160	160 - 200	> 200
$N\,jets$	= 2	= 2	= 2
$\Delta R(Bjet1, Bjet2)$	< 2.0	< 1.7	< 1.7
$\Delta\phi(V,H)$	> 2.7	> 2.9	> 2.9
$min\_\Delta\phi(E_T^{miss}, jet)$	> 1.8	> 1.8	> 1.8

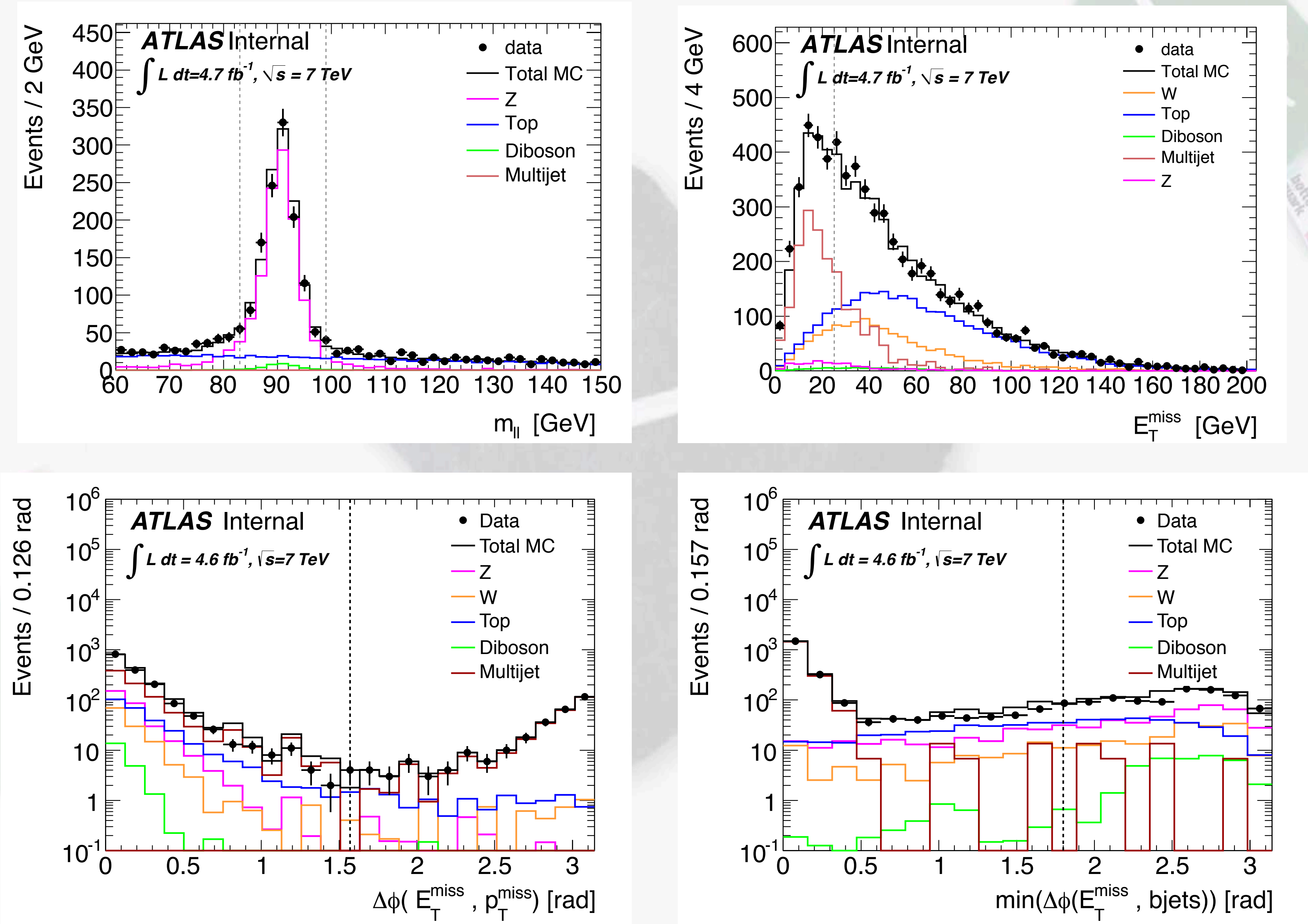
Other aspects of the analysis

- Selected sample is divided into pT(W/Z) categories to increase significance
- Some cuts are optimized for each bin in ZH→ννbb analysis
- Heavily data-driven estimation of backgrounds
- Normalization of main backgrounds transferred from
- ZH→llbb/WH→lνbb analysis to ZH→ννbb analysis
- More info in support material:
  - ZH→llb & WH→lνbb: https://cdsweb.cern.ch/record/1404176/
  - ZH→ννbb: https://cdsweb.cern.ch/record/1418230

Table 1

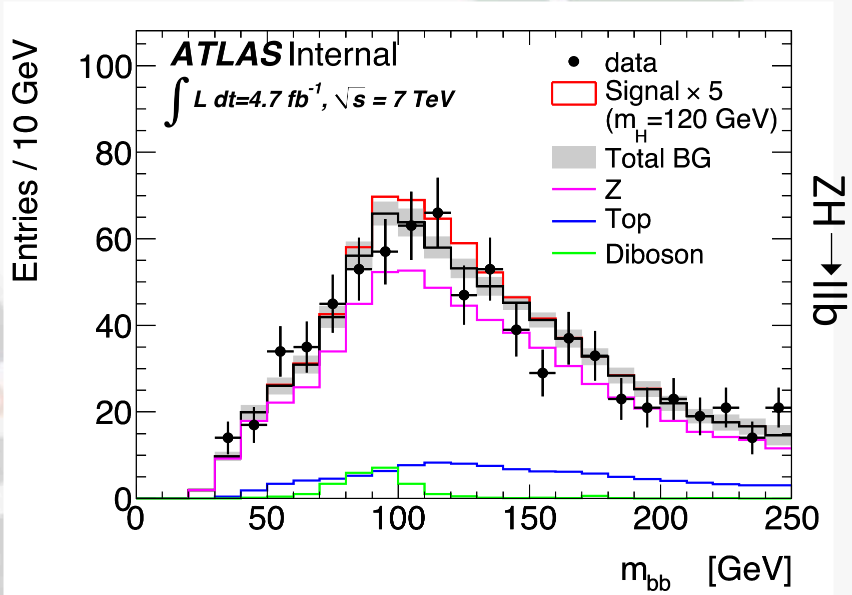
Channel	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^Z [GeV]				$WH \to \ell\nu b\bar{b}$ p_T^W [GeV]				$ZH \to \nu\bar{\nu} b\bar{b}$ E_T^{miss} [GeV]		
Bin	0-50	50-100	100-200	>200	0-50	50-100	100-200	>200	120-160	160-200	>200
Number of events for $80 < m_{b\bar{b}} < 150$ [GeV]											
Data	139	164	62	13	622	597	276	15	103	22	24
Signal	1.4 ± 0.2	2.0 ± 0.3	1.7 ± 0.3	0.4 ± 0.1	4.7 ± 0.9	5.2 ± 1.0	4.1 ± 0.9	1.4 ± 0.3	2.3 ± 0.5	1.3 ± 0.3	1.8 ± 0.5
Bkg	157 ± 15	157 ± 11	70 ± 7	6 ± 2	625 ± 36	620 ± 24	303 ± 13	23 ± 4	93 ± 10	33 ± 5	20 ± 5
Number of events for $90 < m_{b\bar{b}} < 140$ [GeV]											
Data	110	118	49	9	485	456	196	13	76	18	18
Signal	1.3 ± 0.2	1.8 ± 0.2	1.5 ± 0.2	0.4 ± 0.1	4.3 ± 0.8	4.6 ± 0.9	3.7 ± 0.8	1.3 ± 0.3	2.0 ± 0.5	1.1 ± 0.2	1.7 ± 0.4
Bkg	119 ± 12	118 ± 7	48 ± 5	4 ± 1	481 ± 28	453 ± 18	219 ± 10	17 ± 3	65 ± 6	23 ± 4	14 ± 4
Components of the Background Systematic Uncertainties											
B-tag Eff	3.1%	2.8%	2.2%	7.7%	1.4%	1.7%	2.5%	11.3%	4.1%	9.2%	15.6%
Bkg Norm	5.2%	5.0%	5.2%	5.6%	4.0%	2.8%	2.7%	5.5%	2.7%	3.3%	3.7%
JES/MET	1.0%	2.8%	3.5%	3.1%	2.1%	1.6%	1.6%	6.4%	8.2%	10.7%	16.9%
Leptons	0.4%	0.5%	1.1%	3.6%	1.0%	0.4%	0.7%	6.1%	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%	0.8%
Pile Up	0.7%	1.8%	1.5%	6.9%	0.6%	0.7%	1.1%	2.5%	0.7%	2.6%	1.9%
Theory	7.3%	1.7%	7.2%	23.4%	3.1%	1.0%	1.1%	11.9%	3.7%	6.3%	11.1%
Total Bkg	9.6%	6.9%	10.0%	26.6%	5.8%	3.9%	4.4%	19.6%	10.2%	16.0%	25.9%
Components of the Signal Systematic Uncertainties											
B-tag Eff	10.1%	10.6%	12.6%	16.0%	10.0%	10.6%	13.3%	14.6%	13.1%	16.1%	20.8%
JES/MET	6.5%	4.6%	4.0%	3.7%	6.7%	6.8%	7.8%	4.7%	11.0%	5.4%	9.9%
Leptons	1.1%	1.5%	1.5%	3.6%	3.2%	4.2%	5.0%	5.5%	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%
Pile Up	0.7%	1.2%	2.4%	3.4%	1.4%	3.9%	3.2%	3.4%	0.5%	0.8%	2.1%
Theory	5.0%	5.0%	5.0%	5.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%	13.0%
Total Signal	13.6%	13.3%	14.9%	18.3%	18.5%	19.4%	21.4%	21.5%	21.8%	21.7%	26.8%

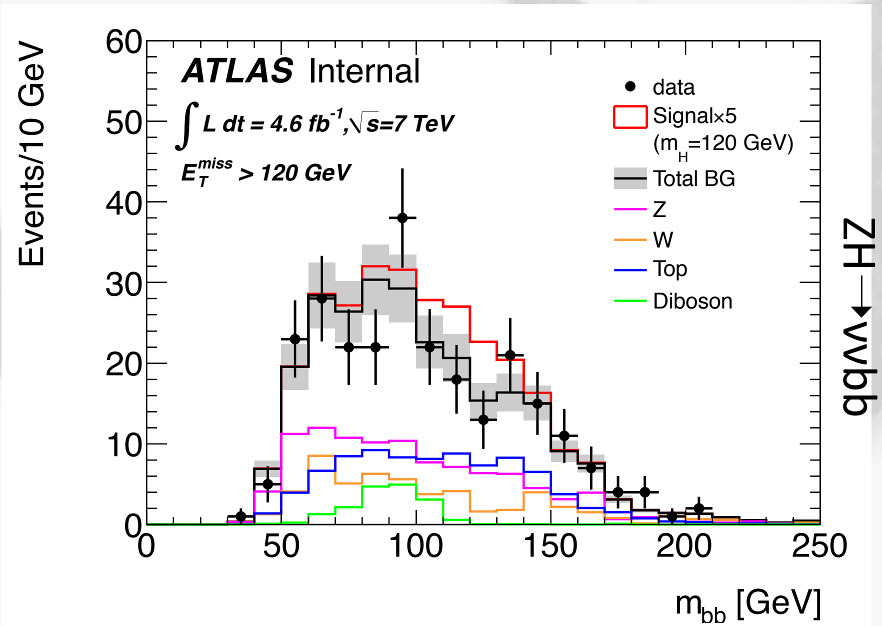
Plots for approval – Fig.1

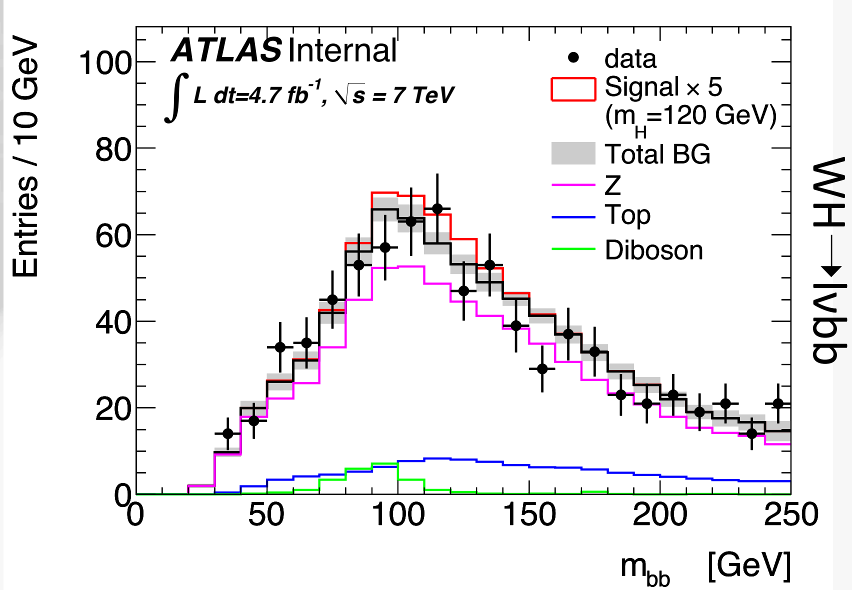


Plots for approval – Figs.2, 3, 4

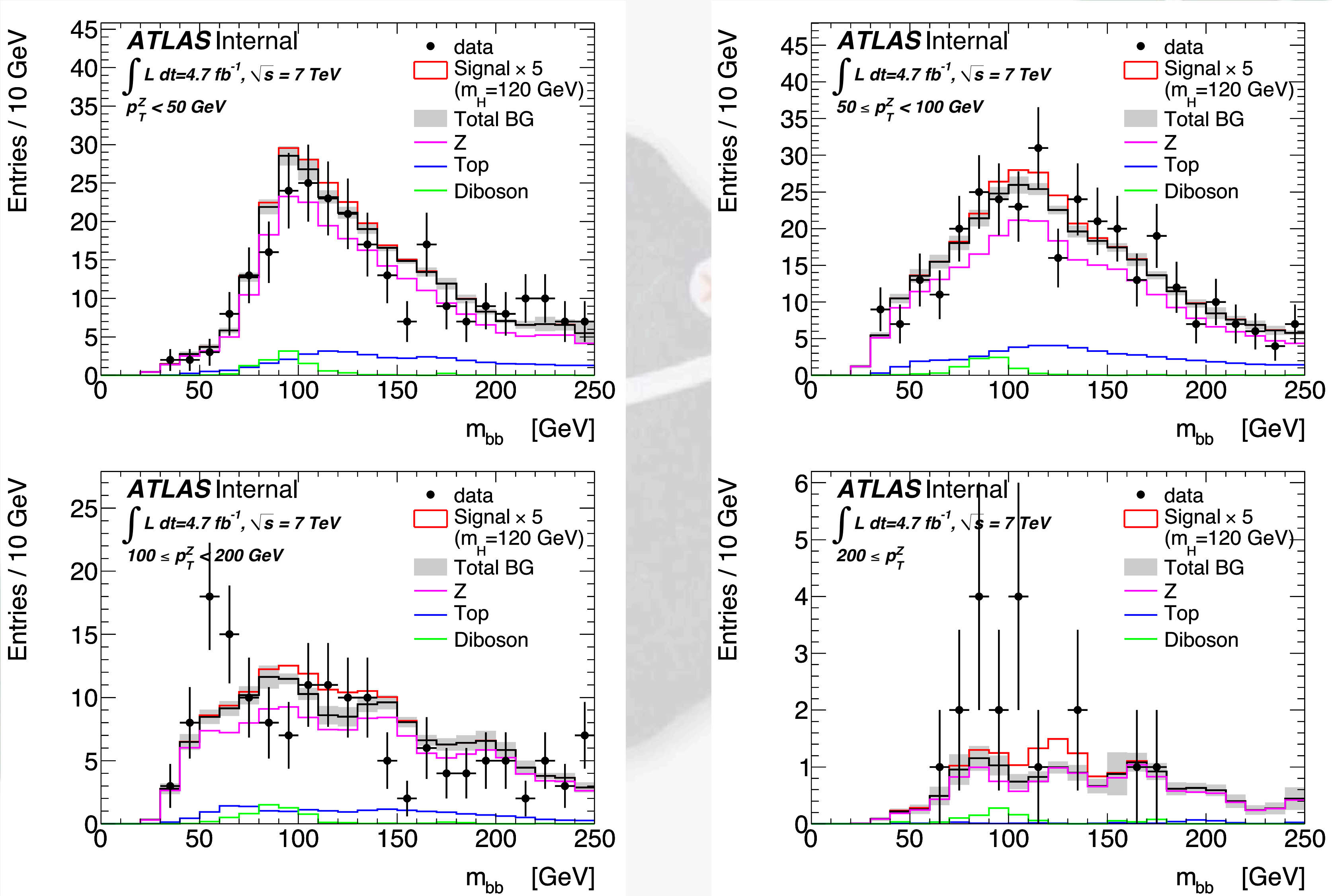
- Inclusive selected sample for each analysis
- Next 3 slides show the same distributions separately in bins of $p_T^{W/Z}$ bins for each analysis



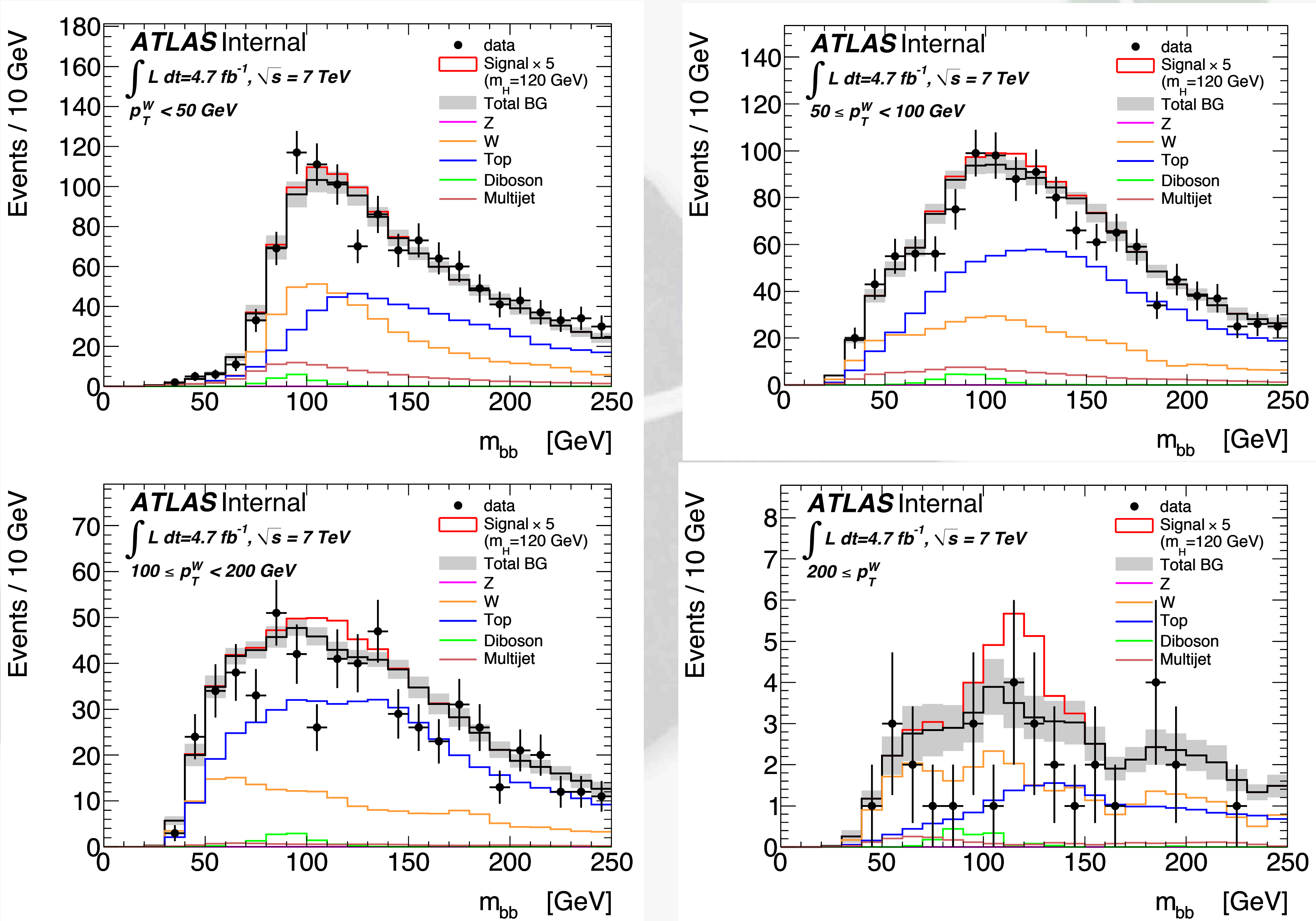




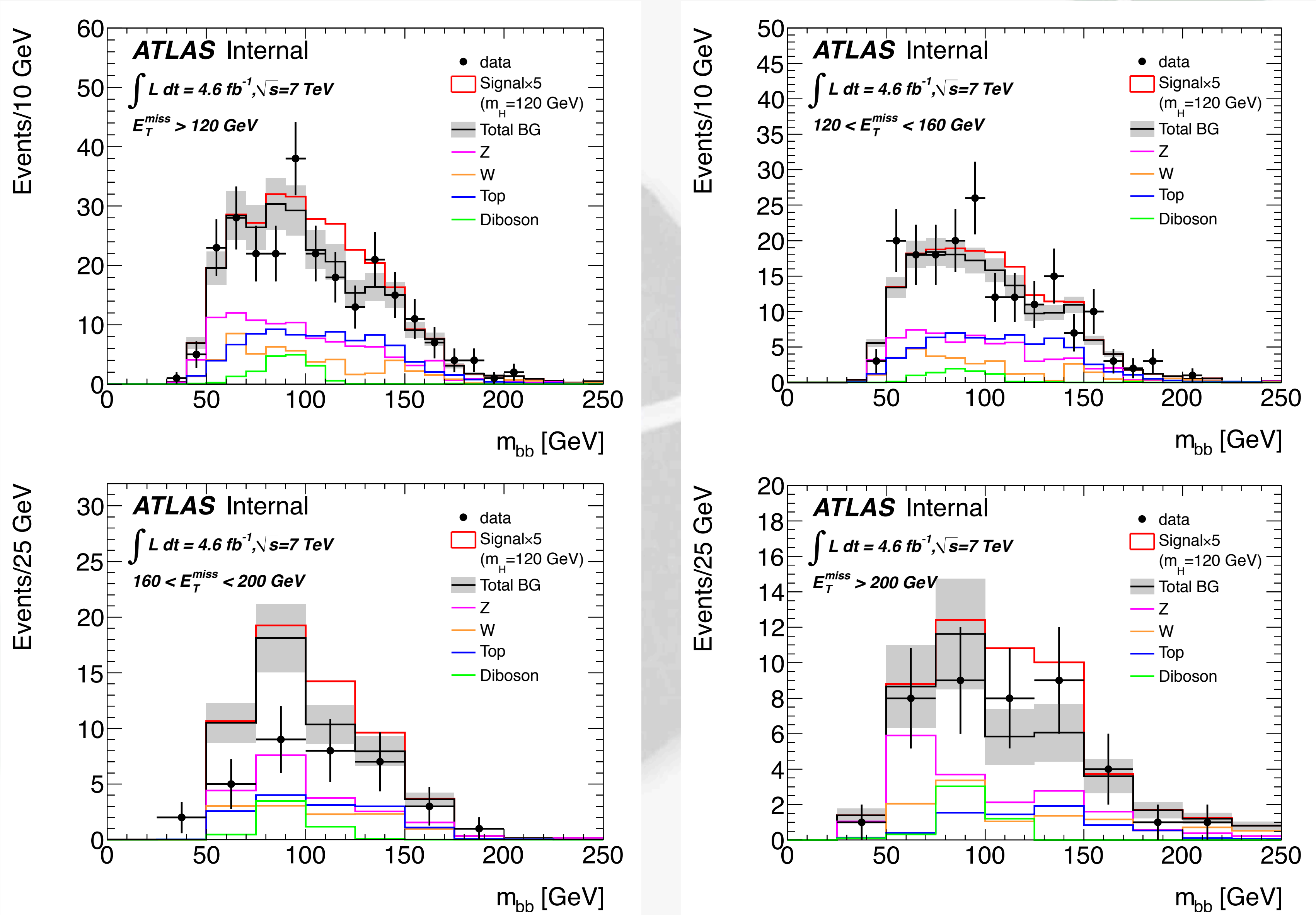
Plots for approval – Fig.2 (ZH→llbb)



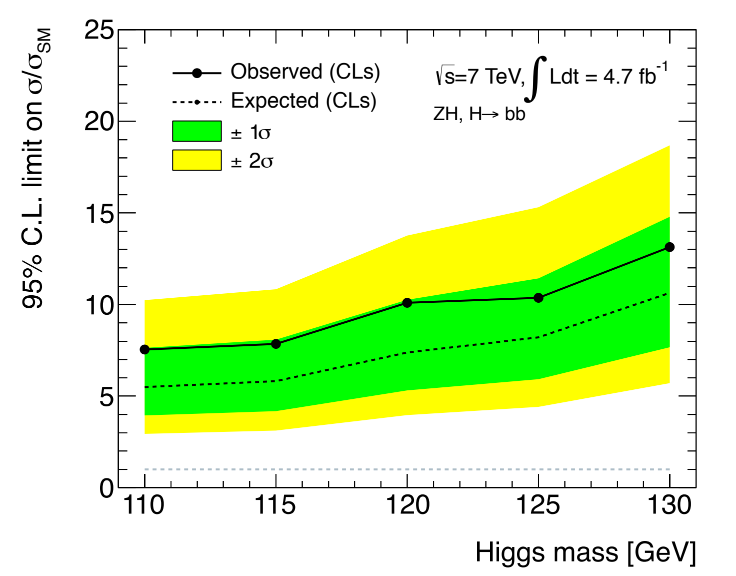
Plots for approval – Fig.3 (WH→lvbb)

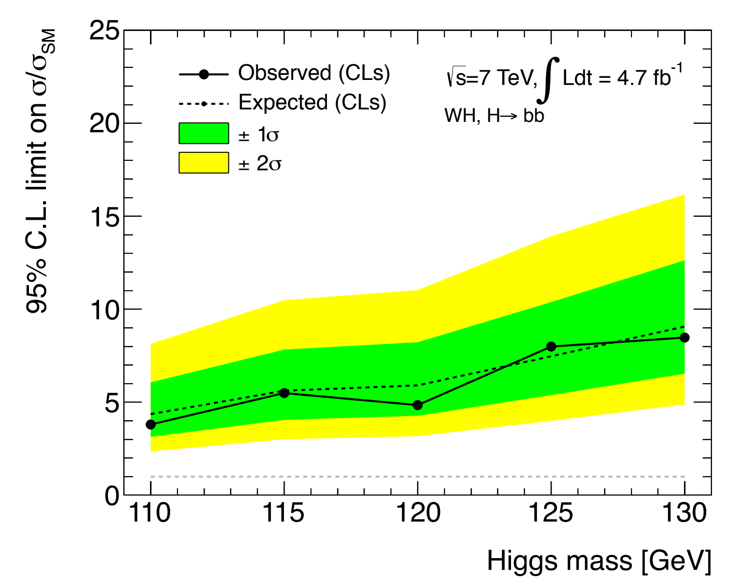


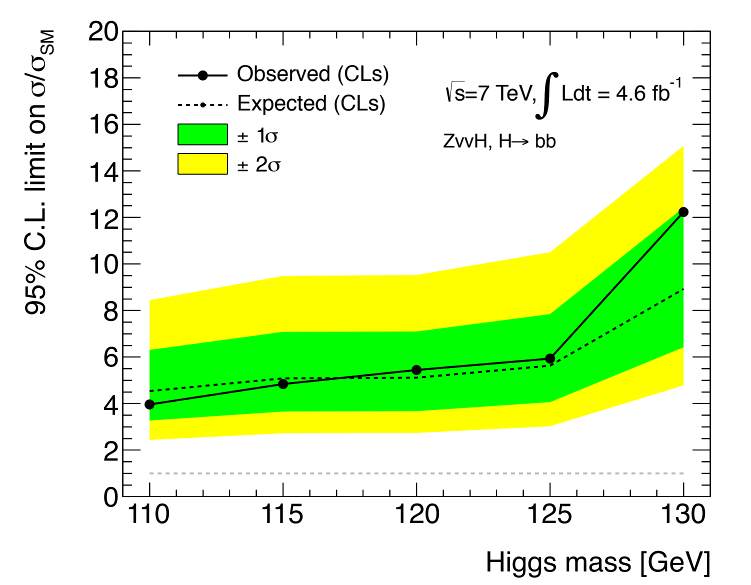
Plots for approval – Fig.4 (WH→lvbb)



Limits plots for approval







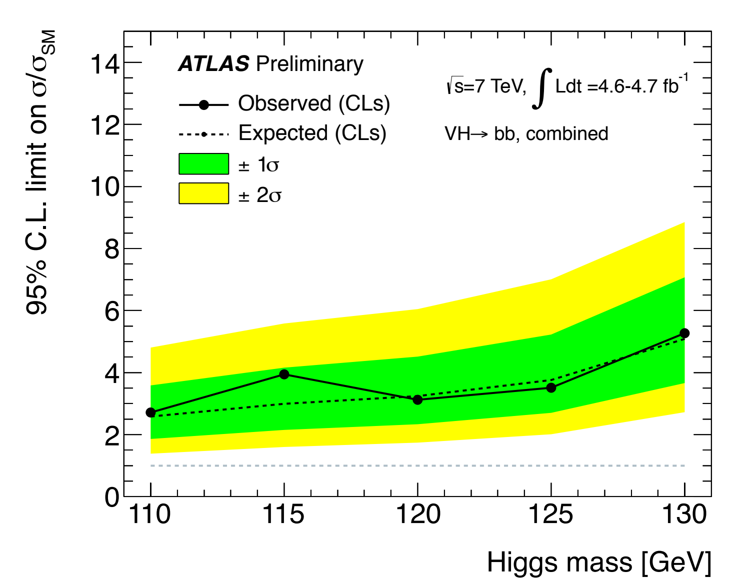


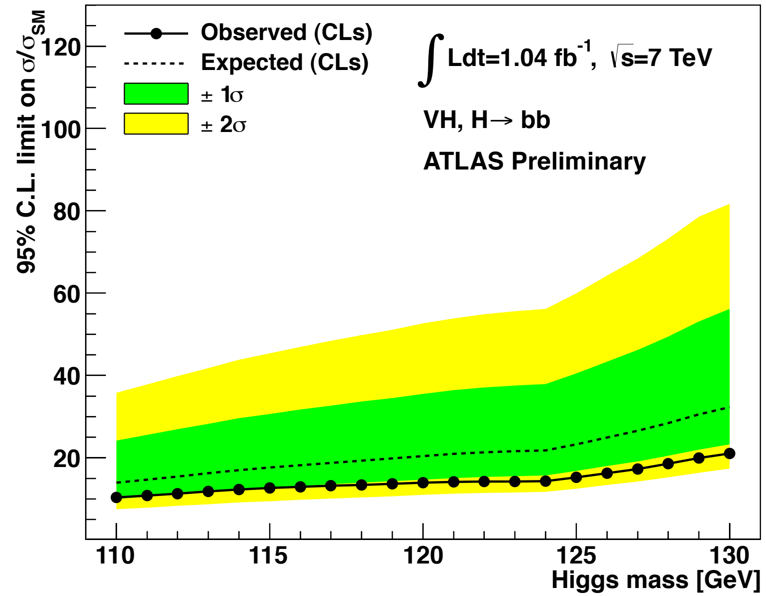
Table 2 – Exclusion Limits

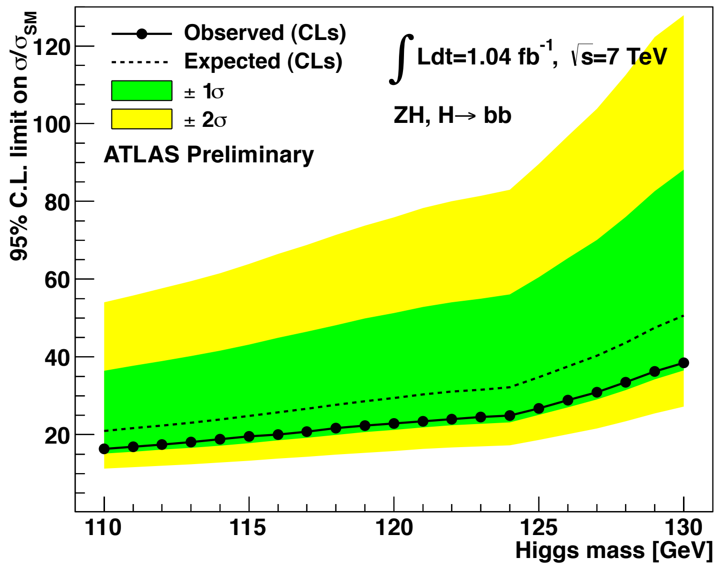
Table 2: The expected 95% C.L. exclusion limits for each channel and the combined exclusion limits for the three channels, in multiples of the SM Higgs boson cross section, as a function of the hypothesized Higgs boson mass.

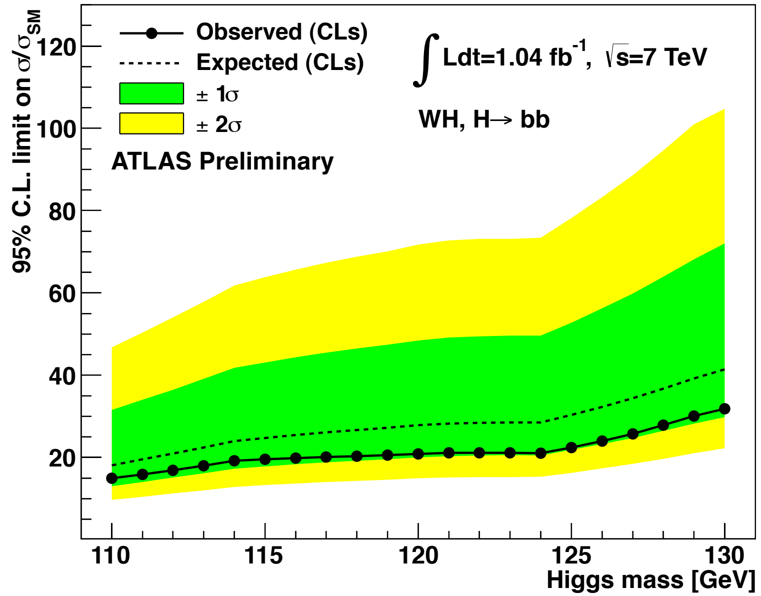
mass	$ZH \rightarrow \ell^+\ell^- b\bar{b}$		$WH \rightarrow \ell\nu b\bar{b}$		$ZH \rightarrow \nu\bar{\nu}b\bar{b}$		Combined	
[GeV]	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.	Exp.
110	7.5	5.5	3.8	4.4	4.0	4.5	2.7	2.6
115	7.8	5.8	5.5	5.6	4.8	5.1	3.9	3.0
120	10.1	7.4	4.9	5.9	5.4	5.1	3.1	3.2
125	10.4	8.2	8.0	7.5	5.9	5.6	3.5	3.8
130	13.1	10.6	8.5	9.1	12.2	8.9	5.3	5.1

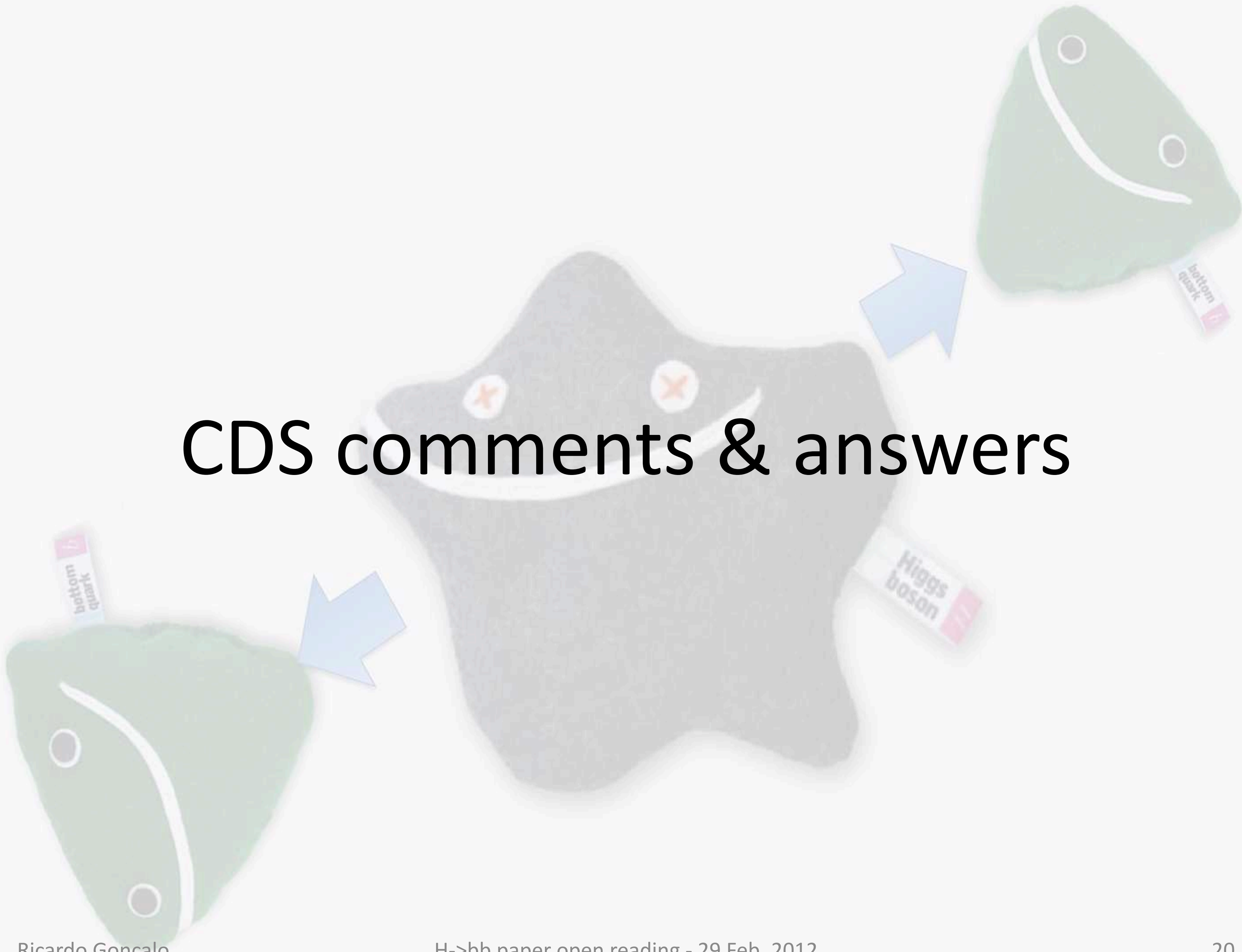
Last public results:

- First H→bb search from the LHC shown at EPS – July 2011
- ZH→llb, WH→lνbb only
- $1fb^{-1}$ @ 7 TeV
- Combined sensitivity: ≈10-20xSM
- Ref.: ATLAS-CONF-2011-103





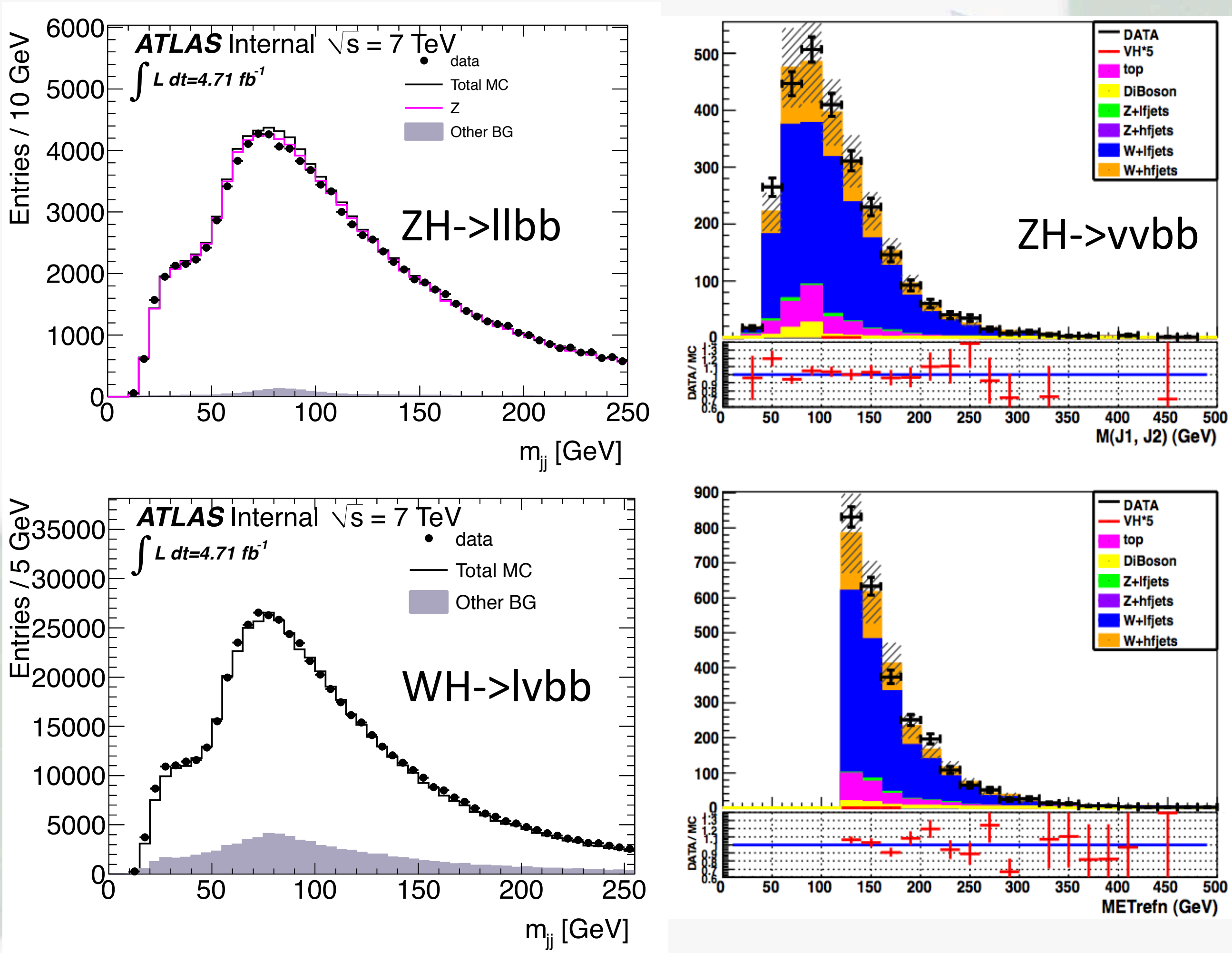




CDS comments & answers

Un-tagged m(j,j) plots

- Added to WH/ZH support note (appendix O.7): https://cdsweb.cern.ch/record/1404176/
- Also in control regions of ZH->vvbb support note: https://cdsweb.cern.ch/record/1418230



Rationale behind using different MC generators for different samples

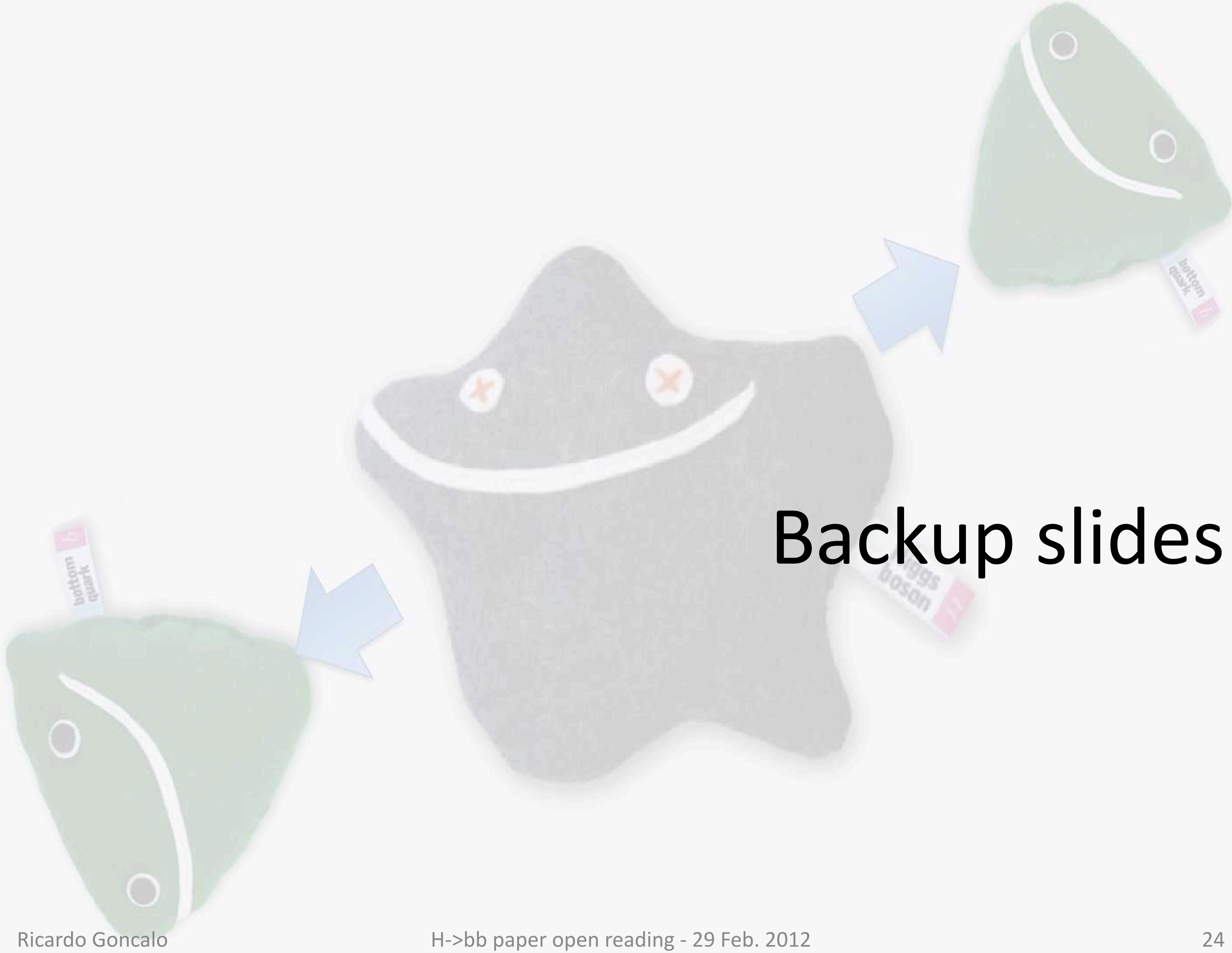
- Alpgen was used for describing V+light jets due to better description of some distributions (e.g. number of jets) – but is very time consuming to produce and use, and requires approximate procedure for removal of heavy-flavour jets
- When appropriate, other generators such as Sherpa were used instead if large statistical samples were needed
- In some cases it was a question of convenience: e.g. large standard MC@NLO top sample
- Powheg was tried for the signal but a large (≈10%) difference in b-tagging efficiency was found – moved to Pythia; Powheg being validated for 2012 analysis in ννbb

Signal contamination

- There is some small contamination expected from other channels
  - E.g. from H->ZZ(*)->llqq on ZH->llbb:
    - Negligible number of events passing ZH->llbb selection (0.06 at most)
- Other sources either small or included in the signal cross section

Higgs mass [GeV]	#events (total)	#events ($80<m_{bb}<150$GeV)
110	0.002	0.002
115	0.005	0.004
120	0.007	--
125	0.04	0.04
130	0.06	0.04

Backup slides



Nice things to do later…

- JES – new recommendations released last week
- MET – new MET code version released last week
- B-tagging – discussion ongoing

Monte Carlo samples

Process	Generator	$\sigma \times BR$
WH	PYTHIA	See Tab. 3
ZH	PYTHIA	See Tab. 3
$W \to \ell\nu$	ALPGEN , POWHEG	10.46 nb [45,46]
$Z/\gamma* \to \ell\ell$	ALPGEN, SHERPA	
$m_{\ell\ell} > 40$ GeV		1.07nb [45,47]
$m_{\ell\ell} > 60$ GeV		0.989 nb [45,47]
WW	MC@NLO+gg2WW	46.23 pb [31,32]
$WW \to \ell\nu qq$	HERWIG	46.23 pb [31,32]
WZ	MC@NLO	
$66 < m_{\ell\ell} < 116$ GeV		18.0 pb [31]
ZZ	MC@NLO, PYTHIA	
$66 < m_{\ell\ell} < 116$ GeV		5.96 pb [31]
Top-quark		
$t\bar{t}$	MC@NLO	166.8 pb [30,36]
t−channel	MC@NLO	64.57 pb [48]
s−channel	MC@NLO	4.63 pb [48]
Wt−channel	MC@NLO	15.74 pb [49]

Table 1 – Nr of events

Channel	$ZH \to \ell^+\ell^- b\bar{b}$ p_T^Z [GeV]				$WH \to \ell\nu b\bar{b}$ p_T^W [GeV]				$ZH \to \nu\bar{\nu} b\bar{b}$ E_T^{miss} [GeV]		
Bin	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]											
Data	139	164	62	13	622	597	276	15	103	22	24
Signal	1.4 ± 0.2	2.0 ± 0.3	1.7 ± 0.3	0.4 ± 0.1	4.7 ± 0.9	5.2 ± 1.0	4.1 ± 0.9	1.4 ± 0.3	2.3 ± 0.5	1.3 ± 0.3	1.8 ± 0.5
Bkg	157 ± 15	157 ± 11	70 ± 7	6 ± 2	625 ± 36	620 ± 24	303 ± 13	23 ± 4	93 ± 10	33 ± 5	20 ± 5
Number of events for $90 < m_{b\bar{b}} < 140$ [GeV]											
Data	110	118	49	9	485	456	196	13	76	18	18
Signal	1.3 ± 0.2	1.8 ± 0.2	1.5 ± 0.2	0.4 ± 0.1	4.3 ± 0.8	4.6 ± 0.9	3.7 ± 0.8	1.3 ± 0.3	2.0 ± 0.5	1.1 ± 0.2	1.7 ± 0.4
Bkg	119 ± 12	118 ± 7	48 ± 5	4 ± 1	481 ± 28	453 ± 18	219 ± 10	17 ± 3	65 ± 6	23 ± 4	14 ± 4

From Summer analysis: WH→lνbb

- Trigger: e (p_T^e>20GeV) or μ (p_T^μ>18GeV)
- Exactly 1 lepton – p_T > 25GeV
- $M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \Delta\phi_{l\nu})}$ > 40 GeV
- E_T^{miss} > 25GeV
- Exactly 2 jets (anti-k_T 0.4; E_T > 25GeV) to reduce top background
- Both jets b tagged