Search for the Higgs boson in associated production with a vector boson and decaying to b quarks at ATLAS

Nicolas Morange

Séminaire IPNL,
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The $H \rightarrow b\bar{b}$ search

1. The $H \rightarrow b\bar{b}$ search
2. Performance aspects
3. Building the analysis
4. Statistical analysis
5. Conclusions
The Higgs Landscape today

Observation of a new boson at the LHC in July 2012 at a mass
\( \sim 125 \text{ GeV} \)

- Evidence found first in bosonic channels only
- Now complemented by \( H \rightarrow \tau \tau \) evidence
- Wealth of results on Higgs properties already
- All measurements compatible with SM Higgs boson so far

\( 13 \text{ TeV} | \text{Ldt} = 20.7 \text{ fb}^{-1} \)
\( 8 \text{ TeV} | \text{Ldt} = 4.6 \text{ fb}^{-1} \)
\( 13 \text{ TeV} | \text{Ldt} = 20.7 \text{ fb}^{-1} \)

\( 8 \text{ TeV} | \text{Ldt} = 20.7 \text{ fb}^{-1} \)

\( m_H = 125.5 \text{ GeV} \)

\( V_H(b \bar{b}) \) at ATLAS

\( \lambda_{WZ} \)
\( \lambda_{ZZ} \)
\( \lambda_{ZZ} \)

Total uncertainty
\( \pm 1\sigma \)
\( \pm 2\sigma \)

Combined \( H \rightarrow \gamma \gamma, ZZ^*, WW^* \)
Why still searching for the Higgs?

Measurement of couplings major item of Higgs studies

- Higgs now known to couple to fermions directly ($\tau\tau$ results)
- Need to look for all possible couplings to maximize tests of the SM
- Hence searches for $t\bar{t}H$, $H \rightarrow \mu^+\mu^-$, $HH$, and $H \rightarrow b\bar{b}$
- Indirect constraint on $b\bar{b}H$ coupling from $gg$ fusion. Very loose.

$L = 4.6-5.1\text{ (7 TeV)} + 12-21\text{ (8 TeV) fb}^{-1}$, 68% CL: ATLAS + CMS

$g_x = g_x^{SM} (1+\Delta_x)$
What do we already know?

**Tevatron searches**
- Analysis of final Tevatron data (10 fb$^{-1}$)
- Evidence of 3.1σ for $H \rightarrow b \bar{b}$
- Best-fit: $\hat{\mu} = 1.6$ at 125 GeV

**CMS results**
- Full LHC Run 1 dataset
- Small excess of 2.1σ
- Best-fit: $\hat{\mu} = 1.0$
- CERN-PH-EP-2013-188

**Previous ATLAS analysis**
- Based on 5 fb$^{-1}$ (7 TeV) + 13 fb$^{-1}$ (8 TeV)
- Observed limit 1.8 SM prediction
Looking at BR

- $H \rightarrow b \bar{b}$ largest BR at 125 GeV ($\sim 60\%$)

Taking production modes into account

- $gg$ fusion and VBF very difficult channels: large multijet backgrounds

  ⇒ Next is associated production with vector boson ($W$ or $Z$)

- $V$ boson: easy to trigger, good background rejection
Taking production modes into account

- Total $\sigma \times BR$ same ballpark as bosonic channels
- Final state more complex than $\gamma\gamma$ or $4\ell$
- Analysis performance driven by acceptance, and discrimination against backgrounds
- Naturally divided in 3 channels
Backgrounds

Numerous backgrounds to consider, that will shape the analysis selections

Fake objects
- Fake leptons or MET: multijet
- Mistagged jets: $Z+jets$, $W+jets$, with $c$ or light jets

Same objects in the acceptance
- Additional objects out of acceptance: $t\bar{t}$, $Wb\bar{b}$ in $Z(\nu\nu)H$ search...
- Similar final state: $Zb\bar{b}$, $Wb\bar{b}$, single top, diboson
Performance aspects

1. The $H \rightarrow b\bar{b}$ search
2. Performance aspects
3. Building the analysis
4. Statistical analysis
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**The ATLAS detector**

**Muon Spectrometer:** $(|\eta| < 2.7)$
Air toroid with drift chambers, 
Provides $\mu$ trigger and momentum measurement, 
Resolution $<10\%$ up to $p \sim 1$ TeV.

**Inner Detector:** $(|\eta| < 2.5, B=2T)$
Si Pixels, SCT, TRT 
Precision tracking, 
Vertex reconstruction, 
$e/\pi$ separation 
$\sigma/p_T \sim 3.810^{-4} p_T \oplus 0.015$

**EM Calorimeter:** $(|\eta| < 3.2)$
Pb-LAr, accordion structure 
Provides trigger on $e/\gamma$, 
Identification and measurement 
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

**Trigger System:**
3 levels 
$L1$: calo and muons, 75 kHz dedicated electronics 
$L2$: all detectors, 4 kHz fast reconstruction 
$EF$: all detectors, 300 Hz full reconstruction

**Hadronic Calorimeter:**
Scint/Fe tiles in barrel $(|\eta| < 1.7)$ 
W/Cu-LAr in endcaps $(|\eta| < 4.9)$ 
Provides jet trigger and energy measurement, 
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$ 
Hermetic coverage for MET
A very successful LHC Run1

- 28 fb\(^{-1}\) of data at 7 and 8 TeV delivered
- Excellent efficiency in operations of subdetectors
- \(\sim 25\) fb\(^{-1}\) of data good for physics
- Price is large pileup activity
Jets at ATLAS

**Essential role of jets in $H(b\bar{b})$**

- Reconstructed with AntiKt algorithm, width 0.4
- Calibrated with pileup corrections (jet area techniques)
- Dedicated resolution improvements for $b$-jets in $H \rightarrow b\bar{b}$:
  - Correction for semileptonic decays
  - Correction for the underlying Higgs jet $p_T$ spectrum
  - $\sim 15\%$ gain in resolution

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**ATLAS Simulation**

- **ZH$ \rightarrow \mu\mu b\bar{b}$**
- Resolutions
  - $16.6 \text{ GeV (14.4\%)}$
  - $14.7 \text{ GeV (12\%)}$

- $p_T < 90 \text{ GeV}$

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**ATLAS Simulation**

- **ZH$ \rightarrow \mu\mu b\bar{b}$**
- Resolutions
  - $14.2 \text{ GeV (11.6\%)}$
  - $12.2 \text{ GeV (10\%)}$

- $p_T > 200 \text{ GeV}$
Use of advanced \textit{b}-tagging algorithm

- Use of displaced vertices, impact parameters, decay chains
- MVA combination of available information
- 70\% efficiency, rejections of 5 (\textit{c}-jets) and 150 (light jets)
- Precise calibration with PDF method on $t\bar{t}$ dilepton events
- Rejections calibrated using $D^*$ (for \textit{c}-jets) and ‘negative’ tags (light jets)
Electrons and muons

Essential role for purity and resolution of $W$ and $Z$ bosons

**Electrons**
- Reconstruction with matched track and cluster, $|\eta| < 2.5$
- Identification with track quality and shower shapes
- Several ID criteria used

**Muons**
- 3 types of muons used in the analysis ($|\eta| < 2.5$)
  - matched ID and MS tracks
  - ID track tagged in MS
  - ID track tagged in calorimeters $|\eta| < 0.1$
- High reconstruction efficiency
- Low fake rates
- Incomplete coverage at trigger-level
Reconstruction

- Calorimeter-based
- Clusters belonging to other objects calibrated appropriately
- Additional term for muons

Resolution

- Resolution of MET for soft objects severely affected by pileup
- No longer the case when jets are present
- Low resolution at trigger level ⇒ only high MET triggers available
1. The $H \rightarrow b\bar{b}$ search

2. Performance aspects

3. Building the analysis

4. Statistical analysis

5. Conclusions
Overview of the analysis

**Dataset**
- Use full LHC Run1 data: $4.7\text{ fb}^{-1}$ at 7 TeV and $20.3\text{ fb}^{-1}$ at 8 TeV

**Selections**
- Selection of events with a vector boson
- Reconstruction of Higgs candidates from pairs of $b$-tagged jets

**Statistical analysis**
- Using $m_{b\bar{b}}$ as discriminant variable
- Combination of the channels
- Validation of the analysis on $VZ$
- Results on Higgs production
Preselections

**Triggers**
- single lepton triggers for 1 and 2 leptons
- dilepton triggers for 2 lepton channel
- $E_T^{\text{miss}}$ triggers
  - Limit the 0-lepton search to MET>120 GeV (trigger plateau)
  - Used in 1-lepton to recover from missing muon trigger acceptance

**Selections**
- Charged leptons considered are electrons and muons
- Lepton tightness: different quality cuts, different track and calorimeter isolation requirements

<table>
<thead>
<tr>
<th>Object</th>
<th>0-lepton</th>
<th>1-lepton</th>
<th>2-lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td>0 loose leptons</td>
<td>1 tight lepton + 0 loose leptons</td>
<td>1 medium lepton + 1 loose lepton</td>
</tr>
<tr>
<td>Jets</td>
<td></td>
<td>2 $b$-tags</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\text{jet}_1} &gt; 45$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_T^{\text{jet}_2} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$+ \leq 1$ extra jets</td>
<td></td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>$E_T^{\text{miss}} &gt; 120$ GeV  $\Delta\phi(E_T^{\text{miss}}, b\bar{b}) &gt; 2.8$</td>
<td>$E_T^{\text{miss}} &gt; 25$ GeV</td>
<td>$E_T^{\text{miss}} &lt; 60$ GeV</td>
</tr>
<tr>
<td>Vector Boson</td>
<td>$- $</td>
<td>$m_W &lt; 120$ GeV</td>
<td>$83 &lt; m_{\ell\ell} &lt; 99$ GeV</td>
</tr>
</tbody>
</table>
**Additional selections**

**Rejection of multijet background**

- MJ background: fake MET, fake leptons

<table>
<thead>
<tr>
<th>1-lepton</th>
<th>$p_T^V$ [GeV]</th>
<th>0-160</th>
<th>160-200</th>
<th>&gt;200</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{miss}^T$ [GeV]</td>
<td></td>
<td>&gt;25</td>
<td>&gt;50</td>
</tr>
<tr>
<td></td>
<td>$m_W^T$ [GeV]</td>
<td>40-120</td>
<td></td>
<td>&lt;120</td>
</tr>
</tbody>
</table>

| 0-lepton | $p_T^{miss}$ [GeV] | >30 |
|          | $\Delta \phi(E_{miss}^T, p_T^{miss})$ | < $\pi/2$ |
|          | $\text{min}[\Delta \phi(E_{miss}^T, \text{jet})]$ | > 1.5 |

**Further use of kinematics**

<table>
<thead>
<tr>
<th>$p_T^V$ [GeV]</th>
<th>$\Delta R(b, \bar{b})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-90</td>
<td>0.7-3.4</td>
</tr>
<tr>
<td>90-120</td>
<td>0.7-3.0</td>
</tr>
<tr>
<td>120-160</td>
<td>0.7-2.3</td>
</tr>
<tr>
<td>160-200</td>
<td>0.7-1.8</td>
</tr>
<tr>
<td>&gt;200</td>
<td>&lt;1.4</td>
</tr>
</tbody>
</table>
Results of event selection

Acceptance of selections

- Computed wrt all leptonic decays without phase space restrictions
  - 0-lepton: 2.2%
  - 1-lepton: 3.5%
  - 2-lepton: 8.2%

S/B in mass window 90-150 GeV

- 0.1% to 10%
- Independent of lepton channel
- Depends strongly on $p_T^\ell$ bin.

Events

$\sqrt{s} = 7$ TeV $\int L dt = 4.7$ fb$^{-1}$
$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

0 lep., 2 jets, 2 tags, $160 < p_T^\ell < 200$ GeV

Data/MC

Higgs
Diboson
$tt$
$W+$jets
$Z+$jets

N. Morange (U. of Iowa) Search for $VH(b\bar{b})$ at ATLAS
Séminaire IPNL 07/02/2014

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Backgrounds: composition

0 lepton

- $Zb\bar{b}$ main background
- $t\bar{t}$ and $Wb\bar{b}$ also important

![Graph showing data and MC comparison with various backgrounds]

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV \( \int dt = 4.7\) fb$^{-1}$
- $\sqrt{s} = 8$ TeV \( \int dt = 20.3\) fb$^{-1}$

0 lep., 2 jets, 2 tags

![Graph showing data and MC comparison with various backgrounds]

**ATLAS Preliminary**

- $\sqrt{s} = 7$ TeV \( \int dt = 4.7\) fb$^{-1}$
- $\sqrt{s} = 8$ TeV \( \int dt = 20.3\) fb$^{-1}$

0 lep., 3 jets, 2 tags

N. Morange (U. of Iowa) Search for $VH(bb)$ at ATLAS Séminaire IPNL 07/02/2014 21 / 44
Backgrounds: composition

1 lepton

- $t\bar{t}$ main background
- Single top and $Wb\bar{b}$ also sizeable
- Multijet important at low $p_T^V$.

**ATLAS** Preliminary

$\sqrt{s} = 7$ TeV $\int L dt = 4.7$ fb$^{-1}$

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

1 lep., 2 jets, 2 tags

2 jets

3 lep., 3 jets, 2 tags

3 jets

Data/MC
Backgrounds: composition

2 leptons

- $Zb\bar{b}$ main background
- Some contribution from $t\bar{t}$

![Graphs showing data and MC for different processes with different jet and-tag combinations.

The graphs display data and MC comparison for 2 leptons, 2 jets, 2 tags and 2 leptons, 3 jets, 2 tags. The plots include bars for various processes such as VH(bb), VZ, ZZ, Zb, and their uncertainties. The x-axis represents the $p_T$ in GeV, and the y-axis shows the number of events. The data is compared to the MC predictions with a data/MC ratio shown for each process.]

N. Morange (U. of Iowa) Search for VH(bb) at ATLAS Séminaire IPNL 07/02/2014 23 / 44
Complex analysis, divided into numerous categories

- Signal Regions (SR): $m_{b\bar{b}}$ used as discriminant variable
- Control Regions (CR): only total yields used

<table>
<thead>
<tr>
<th>Channel</th>
<th>Nb $p_T^V$ bins</th>
<th>2jets, 1tag</th>
<th>3jets, 1tag</th>
<th>2jets, 2tags</th>
<th>3jets, 2tags</th>
<th>e-μ CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-lepton</td>
<td>3</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>–</td>
</tr>
<tr>
<td>1-lepton</td>
<td>5</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>–</td>
</tr>
<tr>
<td>2-lepton</td>
<td>5</td>
<td>CR</td>
<td>CR</td>
<td>SR</td>
<td>SR</td>
<td>CR</td>
</tr>
</tbody>
</table>

- e-μ CR: 1 electron, 1 muon, $m_{\ell\ell} > 40$ GeV

Examples

SR: 1lep, 2tag 2jet, $90 < p_T^V < 120$ GeV

CR: 1lep, 1tag 2jet
Statistical analysis

1. The $H \rightarrow b\bar{b}$ search

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Profile likelihoods in statistical analysis

How should systematics be treated?

As external constraints

- Most simple, traditional way
- But sometimes they are overestimated for a given analysis phase space
- Sometimes there are correlations between sources of systematics

In a profile likelihood

- Build a likelihood model that knows about all systematics variations
- Also handles MC stat uncertainties
- Fits of the model to data can alleviate previous issues
- But setup a correct model can be complex
- Approach successfully adopted for numerous analysis at LHC – including all Higgs ones

\[
L(\mu, \theta) = \prod_{bins} P(n_i|E_i(\mu, \theta)) \times A(\bar{\theta}|\theta)
\]
Profile likelihoods in practice

Control of backgrounds through fits
CMS-PAS-HIG-13-019

Prefit: Bkg uncertainty \( \sim 37\% \)

Postfit: Bkg uncertainty \( \sim 7\% \)

Controlling complexity
False constraints of systematics, numerical issues, can arise:

- Not enough freedom (missing systematics)
- Biased evaluation of systematics (limited by MC stat)
- Large correlations

⇒ Building of the fit model must be done with caution!
Introducing the fit model

All categories enter a global fit

- 0 lepton
- 1 lepton
- 2 leptons
- e-μ region

- W+jets
- Z+jets
- Top

- Lots of information on backgrounds and b-tagging in CR
- Needs careful evaluation of modelling systematics
Background Modelling: $V+\text{jets}$

- Mismodelling of $\Delta \phi(jj)$ found in 0-tag regions
  - Correction derived and applied
- Consistent with NLO studies
- Improves agreement in all distributions, incl. $p_T^V$.
- Normalizations of $W+\text{hf}$, $Wcl$, $Z+\text{hf}$, $Zcl$ floated in the fit
  $hf = bb + bc + cc$

$W+\text{jets} \Delta \phi$ before correction

$W+\text{jets} \Delta \phi$ after correction

$W+\text{jets} p_T^V$ before $\Delta \phi$ correction

$W+\text{jets} p_T^V$ after $\Delta \phi$ correction
Background Modelling

**Multijets**

- 0 lepton
  - Control regions from inversion of some $E_T^{\text{miss}}$ cuts
  - Normalization and shapes from the CR
- 1 lepton
  - Shape from CR with inverted lepton isolations
  - Normalizations from the fit
- 2 lepton
  - Estimated in sidebands of $m_{\ell\ell}$
  - Found negligible

**$t\bar{t}$**

- Correction of top $p_T$ at generator level
- Normalization floated in the fit
- Complex background in this analysis: very different phase space regions probed

**Diboson, single top**

- Normalizations and shapes from MC
**Background Modelling systematics**

**Backgrounds**

- Numerous categories of the analysis
  - need to get $m_{b\bar{b}}$, $p_T^V$, 3-to-2 jet ratios and flavour compositions right.
- Systematics on $p_T^V$ through $\Delta \phi$ for $V+\text{jets}$
- MC-based systematics: comparisons of available generators LO or NLO, UE/PS tunes, renormalization scales

<table>
<thead>
<tr>
<th></th>
<th>$m_{b\bar{b}}$</th>
<th>$\Delta \phi$</th>
<th>$p_T^V$</th>
<th>3-to-2-jet ratio</th>
<th>flav. compo.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>MC</td>
<td>–</td>
<td>data</td>
<td>MC</td>
<td>–</td>
</tr>
<tr>
<td>$Z+\text{jets}$</td>
<td>data</td>
<td>data</td>
<td>–</td>
<td>MC</td>
<td>MC</td>
</tr>
<tr>
<td>$W+\text{jets}$</td>
<td>MC</td>
<td>data</td>
<td>data</td>
<td>MC</td>
<td>MC</td>
</tr>
<tr>
<td>Single top</td>
<td>MC</td>
<td>–</td>
<td>MC</td>
<td>MC</td>
<td>–</td>
</tr>
<tr>
<td>Diboson</td>
<td>MC</td>
<td>–</td>
<td>MC</td>
<td>MC</td>
<td>–</td>
</tr>
</tbody>
</table>
Signal Modelling

Modelling

- Associated production is a well-known process
  - Inclusive cross-section at NNLO (QCD) and NLO (EW)
  - NLO EW available differentially in $p_T^V$
- $gg \rightarrow ZH$ contribution not yet included

Uncertainties

- Renormalization and factorization scales, PDF (3.5 %)
- $p_T^V$ dependence of NLO EW corrections (up to 2.6 %)
- Acceptance (comparison LO generators): 10 %
- Total uncertainty $\sim$ 14 %
Sources of Experimental systematics

Complex final state and categorization

**MET systematics**
- Negligible after selections
- Except trigger for MET<160 GeV (5%)

**Lepton systematics**
- Lepton reconstruction/identification efficiencies: %-level
- Lepton energy scales: per-mille effect

**Jet systematics**
- Jet Energy Scale systematics: shift $m_{b\bar{b}}$ but also 3-to-2 jets ratios and $p_T^V$ bins ($E_{miss}^T$).
  - Total size 1–5%
  - Split into various sources
- Jet Energy Resolution: affect $m_{b\bar{b}}$ shapes

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**Diagram:**

- Fractional JES uncertainty
- ATLAS Preliminary
- Data 2012, $\sqrt{s} = 8$ TeV
- Total uncertainty
- Absolute in situ JES
- Relative in situ JES
- Flav. composition, inclusive jets
- Flav. response, inclusive jets
- Pileup, average 2012 conditions

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Sources of Experimental systematics

**b-tagging systematics**
- Affect flavour compositions in 1tag and 2tag regions
- Precise calibration in $t\bar{t}$ events: 3% in most of $p_T$ range
- Uncertainty split into several components
- Larger uncertainty for fake rates of $c$ (8%) and light (20%) jets
- Additional systematics for $V+\text{jets}$: different jet fragmentation in Sherpa

**Luminosity**
- Uncertainty of 2.8% at 8 TeV, 1.8% at 7 TeV
**Statistical analysis**

**Test statistics**

- Following Neyman-Pearson lemma, test statistics is basically log-likelihood ratio
  \[ q_\mu = -2 \log \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})} \]

- \( L(\hat{\mu}, \hat{\theta}) \): unconditional maximum
- \( L(\mu, \hat{\theta}) \): maximum for a given \( \mu \)

**Hypothesis testing**

- Using Wald approximation, \( q_\mu \) distributions are obtained with Asimov datasets
- \( p_0 \) value and CLs limits (\( \frac{p_\mu}{1-p_b} \)) are then computed
Fit results

**Profile likelihood**
- In total 26 SR and 31 CR, per year
- Over 200 nuisance parameters
- A significant fraction of the full ATLAS Higgs combination
- Good agreement MC(postfit)-data obtained in all regions
- Uncertainty on background yields: from $\sim 10\%$ (prefit) to 3\% (postfit).
- Uncertainty on signal yields: $\sim 12\%$.

<table>
<thead>
<tr>
<th>Process</th>
<th>Scale factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$tt$</td>
<td>$1.13 \pm 0.05$</td>
</tr>
<tr>
<td>$Wb$</td>
<td>$0.89 \pm 0.15$</td>
</tr>
<tr>
<td>$Wcl$</td>
<td>$1.05 \pm 0.14$</td>
</tr>
<tr>
<td>$Zb$</td>
<td>$1.30 \pm 0.07$</td>
</tr>
<tr>
<td>$Zcl$</td>
<td>$0.89 \pm 0.48$</td>
</tr>
</tbody>
</table>

**Main sources of uncertainty**
- Leading one is data statistics!
- $t\bar{t}$ modelling: $m_{bb}$ shape, 3 jets to 2 jets ratio, $p_T^V$ shape
- $c$-tagging efficiency
- Signal acceptance
Examples of postfit distributions

**0 lepton**

- ATLAS Preliminary
- $\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$
- 0 lep., 2 jets, 2 tags, $p_T > 200$ GeV

**1 lepton**

- ATLAS Preliminary
- $\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$
- 1 lep., 2 jets, 2 tags, $p_T > 200$ GeV

**2 lepton**

- ATLAS Preliminary
- $\sqrt{s} = 7$ TeV, $L = 4.7$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV, $L = 20.3$ fb$^{-1}$
- 2 lep., 2 jets, 2 tags, $p_T > 200$ GeV

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- 2 lep., 2 jets, 2 tags, $p_T > 200$ GeV
**A crucial check**

- $WZ + ZZ$ as signal
- Higgs at 125 GeV treated as background
- Very good check of validity of modelling and fit
- Measure
  $\mu_{VZ} = \sigma/\sigma_{SM} = 0.9 \pm 0.1\,(\text{stat}) \pm 0.2\,(\text{syst})$
- Significance 4.8$\sigma$ (5.1$\sigma$ expected)
- Compatible between years:
  - $\mu_{VZ} = 0.7 \pm 0.5$ in 2011
  - $\mu_{VZ} = 1.0 \pm 0.2$ in 2012
- Compatible between lepton channels

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**Diboson and Higgs peaks, after subtraction of other backgrounds**
Higgs results

7 TeV
- 2σ deficit in 7 TeV data
- Observed in previous analysis

8 TeV
- ~1σ excess in 8 TeV data

Combination
- No excess observed
- $\mu_H = 0.2 \pm 0.5$ (stat) $\pm 0.4$ (syst)
- Compatible with both $\mu = 0$ and $\mu = 1$
- 35% gain in sensitivity beyond increased stat, wrt previous ATLAS analysis

**ATLAS Prelim.**

$m_H = 125$ GeV

<table>
<thead>
<tr>
<th></th>
<th>Total uncertainty</th>
<th>$\sigma$(stat)</th>
<th>$\sigma$(sys)</th>
<th>$\sigma$(theo)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VH(bb), 7 TeV</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±1.0±0.9</td>
<td>±0.9</td>
<td>±0.2</td>
<td>±1.5</td>
</tr>
<tr>
<td><strong>VH, 0 lepton</strong></td>
<td></td>
<td>±1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±2.7±0.9</td>
<td>±1.8</td>
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<tr>
<td><strong>VH, 1 lepton</strong></td>
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<td>±1.6</td>
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<tr>
<td>$\mu$</td>
<td>±2.5±0.9</td>
<td>±1.6</td>
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<tr>
<td><strong>VH, 2 leptons</strong></td>
<td></td>
<td>±3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.6±0.4</td>
<td>±3.1</td>
<td></td>
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</tr>
<tr>
<td><strong>VH(bb), 8 TeV</strong></td>
<td></td>
<td>±0.8</td>
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</tr>
<tr>
<td>$\mu$</td>
<td>±0.9±0.7</td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 0 lepton</strong></td>
<td></td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.9±0.9</td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 1 lepton</strong></td>
<td></td>
<td>±0.8</td>
<td></td>
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</tr>
<tr>
<td>$\mu$</td>
<td>±0.7±1.1</td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 2 leptons</strong></td>
<td></td>
<td>±1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.3±1.3</td>
<td>±1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Comb. VH(bb)</strong></td>
<td></td>
<td>±0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.2±0.7</td>
<td>±0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 0 lepton</strong></td>
<td></td>
<td>±0.8</td>
<td></td>
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</tr>
<tr>
<td>$\mu$</td>
<td>±0.5±0.9</td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 1 lepton</strong></td>
<td></td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.5±0.9</td>
<td>±0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VH, 2 leptons</strong></td>
<td></td>
<td>±1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$</td>
<td>±0.4±1.5</td>
<td>±1.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\sqrt{s} = 7$ TeV $\int L dt = 4.7$ fb$^{-1}$

$\sqrt{s} = 8$ TeV $\int L dt = 20.3$ fb$^{-1}$

Signal strength [$\mu$]

N. Morange (U. of Iowa) Search for VH(bb) at ATLAS Séminaire IPNL 07/02/2014 39 / 44
Higgs results: limits

**Limits**

- Observed limit at 125 GeV $1.4\sigma_{SM}$, 1.3 expected in absence of signal
- Observed $p_0$ is 0.36, for 0.05 expected for $\mu = 1$
- Probability, given $\mu = 1$, to be that much background-like: 0.11
- No excess observed over the full mass range analyzed
Conclusions

1. The $H \rightarrow b\bar{b}$ search

2. Performance aspects

3. Building the analysis

4. Statistical analysis

5. Conclusions
Prospects

**Short-term**
- For ATLAS: ongoing final paper for LHC Run1. Numerous improvements wrt analysis shown here

**Medium-term**
- Higgs Spin/CP analysis with $H \rightarrow b\bar{b}$. Results already shown by D0.

**Long-term**
- Precision measurements of $b$-$H$ coupling. 10% or less achievable in LHC lifetime?
**Long-term prospects**

**Ultimate precision conditioned to keep good sensitivity**

- Pileup conditions may be a killer for this analysis
  - Need for detector upgrades
  - Need for improvements in treatment of pileup
  - Need tailored analysis. Use of jet substructure techniques?
First ATLAS results on search for $VH(b\bar{b})$ with full 2011+2012 dataset (ATLAS-CONF-2013-079) has been presented.

Search in 3 channels $Z(\nu\nu)H$, $Z(\ell^+\ell^-)H$, $W(\ell\nu)H$.

Further splitting into $p_T^V$ categories, 2 jet and 3 jet categories.

Price is a very complex fit model.

Result is a non-conclusive $\hat{\mu} = 0.2 \pm 0.7$.

Still room for large improvements. Some are finding their way to the next ATLAS $VH$ paper.

Exciting perspectives on Higgs precision measurements using $VH$. 

### ATLAS Prelim.

<table>
<thead>
<tr>
<th>Process</th>
<th>$m_H = 125.5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.55^{+0.33}_{-0.28}$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4l$</td>
<td>$\mu = 1.43^{+0.40}_{-0.35}$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow l\nu l\nu$</td>
<td>$\mu = 0.99^{+0.31}_{-0.28}$</td>
</tr>
</tbody>
</table>

Combined $H \rightarrow \gamma\gamma$, $ZZ^*$, $WW^*$

$\mu = 1.33^{+0.21}_{-0.18}$

$\hat{\mu} = 0.2 \pm 0.7$

$\hat{\mu} = 1.4 \pm 0.5$

$\hat{\mu} = 0.2 \pm 0.6$

$\hat{\mu} = 1.3 \pm 0.5$

$\hat{\mu} = 0.2 \pm 0.6$

$\hat{\mu} = 1.3 \pm 0.5$

$\hat{\mu} = 0.2 \pm 0.6$
Higgs production

$\sqrt{s}=8\ \text{TeV}$

$\sigma(pp \rightarrow H+X) [\text{pb}]$

$M_{H} [\text{GeV}]$

$80 \quad 100 \quad 200 \quad 300 \quad 400 \quad 1000$

$10^{2}$ $100$ $10$ $1$ $10^{1}$ $10^{2}$

$PP \rightarrow H$ (NLO+NLL QCD + NLO EW)

$PP \rightarrow VH$ (NLO QCD + NLO EW)

$PP \rightarrow VH$ (NLO QCD)
$\Delta \phi$ correction

ATLAS Preliminary

$E_T = 8$ TeV  $L dt = 20.3$ fb$^{-1}$

1 lep, 2 jets, 0 tag

No $\Delta \phi$ Correction

ATLAS Preliminary

$E_T = 8$ TeV  $L dt = 20.3$ fb$^{-1}$

1 lep, 2 jets, 0 tag

No $\Delta \phi$ Correction

ATLAS Preliminary

$E_T = 8$ TeV  $L dt = 20.3$ fb$^{-1}$

1 lep, 2 jets, 0 tag

With $\Delta \phi$ Correction

ATLAS Preliminary

$E_T = 8$ TeV  $L dt = 20.3$ fb$^{-1}$

1 lep, 2 jets, 0 tag

With $\Delta \phi$ Correction

N. Morange (U. of Iowa) Search for $VH(b\bar{b})$ at ATLAS Séminaire IPNL 07/02/2014 3 / 8
### Diboson results

**ATLAS Prelim.**

<table>
<thead>
<tr>
<th><strong>VZ((b\bar{b})), 7 TeV</strong></th>
<th>$\mu_{VZ}$</th>
<th>Total uncertainty $\pm 1\sigma$ on $\mu_{VZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VZ, 0 lepton</td>
<td>$0.7^{+0.5}_{-0.5}$</td>
<td>$0.3^{+0.4}_{-0.4}$</td>
</tr>
<tr>
<td>VZ, 1 lepton</td>
<td>$1.1^{+0.7}_{-0.7}$</td>
<td>$0.5^{+0.5}_{-0.5}$</td>
</tr>
<tr>
<td>VZ, 2 leptons</td>
<td>$0.7^{+0.4}_{-0.4}$</td>
<td>$0.8^{+0.7}_{-0.7}$</td>
</tr>
<tr>
<td>VZ, 0 lepton</td>
<td>$1.6^{+0.2}_{-0.2}$</td>
<td>$0.1^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>VZ, 1 lepton</td>
<td>$1.2^{+0.3}_{-0.3}$</td>
<td>$0.2^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>VZ, 2 leptons</td>
<td>$0.9^{+0.3}_{-0.3}$</td>
<td>$0.2^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td><strong>Comb. VZ((b\bar{b}))</strong></td>
<td>$0.9^{+0.2}_{-0.2}$</td>
<td>$0.1^{+0.2}_{-0.2}$</td>
</tr>
</tbody>
</table>

- Total uncertainty $\pm 1\sigma$ on $\mu_{VZ}$
- $\sigma$(stat), $\sigma$(sys), $\sigma$(theo)

---

\[ \sqrt{s} = 7 \text{ TeV} \int \mathcal{L}dt = 4.7 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV} \int \mathcal{L}dt = 20.3 \text{ fb}^{-1} \]
More Higgs results

Events after subtraction

$N_{\text{events}} = 600$

$N_{\text{data}} = 500$

$N_{\text{VH(b\bar{b})}} = 400$

$N_{\text{VZ}} = 300$

$N_{\text{uncertainty}} = 200$

Weighted events after subtraction

$N_{\text{weighted events}} = 400$

$N_{\text{weighted data}} = 300$

$N_{\text{weighted VH(b\bar{b})}} = 200$

$N_{\text{weighted VZ}} = 100$

95% C.L. limit on $\sigma_{\text{SM}}$

$0 \pm 1\sigma$

$0 \pm 2\sigma$

$0 \pm 3\sigma$

$0 \pm 4\sigma$

$0 \pm 5\sigma$

$0 \pm 6\sigma$

$0 \pm 7\sigma$

$0 \pm 8\sigma$

$0 \pm 9\sigma$

$0 \pm 10\sigma$

$0 \pm 11\sigma$

$0 \pm 12\sigma$

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$0 \pm 14\sigma$

$0 \pm 15\sigma$

$0 \pm 16\sigma$

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$0 \pm 116\sigma$

$0 \pm 117\sigma$

$0 \pm 118\sigma$

$0 \pm 119\sigma$

$0 \pm 120\sigma$

$0 \pm 121\sigma$

$0 \pm 122\sigma$

$0 \pm 123\sigma$

$0 \pm 124\sigma$
Table 7: Data/MC scale factors for 8 TeV data derived from the control regions, where the first quoted uncertainty is statistical and the second is systematic. The muon and electron channels in $Z(\ell\ell)H$ and $W(\ell\nu)H$ are simultaneously fit to determine average scale factors. For the $Z(\ell\ell)H$ channel only four scale factors are derived, valid for both the low and high $p_T(V)$ boost regions. Because of the limited size of the simulated event samples the scale factors obtained for the $W(\ell\nu)H$ channels are also applied to the $W(\ell\nu)H$ channel.

<table>
<thead>
<tr>
<th>Process</th>
<th>$W(\ell\nu)H$</th>
<th>$Z(\ell\ell)H$</th>
<th>$Z(\ell\nu)H$</th>
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<tbody>
<tr>
<td>Low $p_T(V)$</td>
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<tr>
<td>$W + udscg$</td>
<td>$1.03 \pm 0.01 \pm 0.05$</td>
<td>$0.83 \pm 0.02 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>$W + b$</td>
<td>$2.22 \pm 0.25 \pm 0.20$</td>
<td>$2.30 \pm 0.21 \pm 0.11$</td>
<td></td>
</tr>
<tr>
<td>$W + bb$</td>
<td>$1.58 \pm 0.26 \pm 0.24$</td>
<td>$0.85 \pm 0.24 \pm 0.14$</td>
<td></td>
</tr>
<tr>
<td>$Z + udscg$</td>
<td>$1.11 \pm 0.04 \pm 0.06$</td>
<td>$1.24 \pm 0.03 \pm 0.09$</td>
<td></td>
</tr>
<tr>
<td>$Z + b$</td>
<td>$1.59 \pm 0.07 \pm 0.08$</td>
<td>$2.06 \pm 0.06 \pm 0.09$</td>
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</tr>
<tr>
<td>$Z + bb$</td>
<td>$0.98 \pm 0.10 \pm 0.08$</td>
<td>$1.25 \pm 0.05 \pm 0.11$</td>
<td></td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$</td>
<td>$1.03 \pm 0.01 \pm 0.04$</td>
<td>$1.10 \pm 0.05 \pm 0.06$</td>
<td>$1.01 \pm 0.02 \pm 0.04$</td>
</tr>
<tr>
<td>Intermediate $p_T(V)$</td>
<td></td>
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</tr>
<tr>
<td>$W + udscg$</td>
<td>$1.02 \pm 0.01 \pm 0.07$</td>
<td>$0.93 \pm 0.02 \pm 0.04$</td>
<td></td>
</tr>
<tr>
<td>$W + b$</td>
<td>$2.90 \pm 0.26 \pm 0.20$</td>
<td>$2.08 \pm 0.20 \pm 0.12$</td>
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</tr>
<tr>
<td>$W + bb$</td>
<td>$1.30 \pm 0.23 \pm 0.14$</td>
<td>$0.75 \pm 0.26 \pm 0.11$</td>
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<tr>
<td>$Z + udscg$</td>
<td>$-\phantom{0}$</td>
<td>$1.19 \pm 0.02 \pm 0.07$</td>
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<tr>
<td>$Z + b$</td>
<td>$2.30 \pm 0.07 \pm 0.08$</td>
<td>$1.11 \pm 0.06 \pm 0.12$</td>
<td></td>
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<tr>
<td>$Z + bb$</td>
<td>$1.02 \pm 0.01 \pm 0.15$</td>
<td>$0.99 \pm 0.02 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$</td>
<td>$1.04 \pm 0.01 \pm 0.07$</td>
<td>$0.93 \pm 0.02 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>High $p_T(V)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W + udscg$</td>
<td>$2.46 \pm 0.33 \pm 0.22$</td>
<td>$2.12 \pm 0.22 \pm 0.10$</td>
<td></td>
</tr>
<tr>
<td>$W + b$</td>
<td>$0.77 \pm 0.25 \pm 0.08$</td>
<td>$0.71 \pm 0.25 \pm 0.15$</td>
<td></td>
</tr>
<tr>
<td>$W + bb$</td>
<td>$1.11 \pm 0.04 \pm 0.06$</td>
<td>$1.17 \pm 0.02 \pm 0.08$</td>
<td></td>
</tr>
<tr>
<td>$Z + udscg$</td>
<td>$1.59 \pm 0.07 \pm 0.08$</td>
<td>$2.13 \pm 0.05 \pm 0.07$</td>
<td></td>
</tr>
<tr>
<td>$Z + b$</td>
<td>$0.98 \pm 0.10 \pm 0.08$</td>
<td>$1.12 \pm 0.04 \pm 0.10$</td>
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</tr>
<tr>
<td>$Z + bb$</td>
<td>$1.00 \pm 0.01 \pm 0.11$</td>
<td>$1.10 \pm 0.05 \pm 0.06$</td>
<td>$0.99 \pm 0.02 \pm 0.03$</td>
</tr>
</tbody>
</table>
CMS analysis

N. Morange (U. of Iowa) Search for VH(b\bar{b}) at ATLAS

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CMS analysis

CMS

$\mu_{ZH}$

$\sigma = 7 \text{ TeV}, L = 5.0 \text{ fb}^{-1}$

$\sigma = 8 \text{ TeV}, L = 18.9 \text{ fb}^{-1}$

$pp \rightarrow VH; H \rightarrow b\bar{b}, m_H = 125 \text{ GeV}$

Best Fit

68% CL

95% CL

SM Higgs boson

CMS

$\sigma = 7 \text{ TeV}, L = 5.0 \text{ fb}^{-1}$

$\sigma = 8 \text{ TeV}, L = 18.9 \text{ fb}^{-1}$

$pp \rightarrow VH; H \rightarrow b\bar{b}$

Data

VH

VV

Sub. MC uncert.

VH + VV MC uncert.