Search for the Higgs Boson in the bb Channel

with 4.7 fb$^{-1}$ of Data Taken in 2011 with the ATLAS Detector

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Terascale workshop on Interpreting Emerging Higgs Data 04/04/12
Why the $t\bar{t}H \rightarrow bb$ Channel Disappeared from Radar Screens?

- Very important to check the Yukawa nature of the Higgs-fermion coupling
- Originally very promising channel $\sim O(H \rightarrow \gamma\gamma)$ in the low luminosity scenario...
- However a very intricate final state... 6 jets (4b), one lepton and MET
  - Very large combinatorial background
  - Very large and uncertain $ttbb$ and $ttjj$ (no obvious control samples)

Very dilute channel at 120 GeV/c$^2$: $s/b \sim 10$
but no definite mass peak

Sensitivity for 30 fb$^{-1}$ (14TeV): $s/\sqrt{b} \sim 2$

**Without systematic uncertainties...**

**None with systematics**

What could be done?

Perhaps experimentally use multivariate techniques or improved $b$-tagging, but...

Mostly needs guidance from theory:

- Simulation to higher orders of $ttbb$ and $ttjj$?
- Overlaps treatment?

... or new ideas ...
The Associated Production W/ZH→bb Channels Never Really Made it to the Radar Screen... Until Recently

Idea:

- Use Higgs only at high $p_T$ to improve acceptance and reduce bkg.
- The Higgs would be a single jet, then investigate the jet structure

Butterworth, Davison, Salam, Rubin

- Use the Cambridge-Aachen jet algorithm Dokshitzer et al. 97' (Clustering based on the R-distances between objects, iterate until $\Delta R > 1.2$)

- Undo the last stage of clustering defining $J_1$ and $J_2$

  If $\max(m_1, m_2) < 2m/3$ then there is a “mass drop”

- If there is a mass drop apply b-tagging

- Then recluster using $R_{\text{filt}} = \min(0.3, R_{J_1,J_2})$
ATLAS has performed this search with full Monte Carlo simulation in three channels...

Z mass peak clearly visible! A combined significance of $\sim 3.0 - 3.7\sigma$ is expected for $30 \text{ fb}^{-1}$ (depending on the systematic uncertainties on main backgrounds)

- Very promising/discovery channel
- bb branching is critical to assess Higgs properties (See talk by T. Plehn)

Revival of the ttH channel also foreseen using a similar technique...

T. Plehn, G. Salam, M. Spannovsky, KA-TP-12-2009

- A similar technique applied requiring at least two fat jets and a lepton (2 or 3 b-tags)
- Combinatorial background not a problem
- Sensitive only at around $100 \text{ fb}^{-1}$ (4-5$\sigma$ sensitivity)

Analyses still need to be performed by experiments with full simulation
Another idea waiting for a word from experiments...

The VBF with an additional photon


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Idea:
- The extra photon will improve trigger efficiency
- Large gluonic $bbjj(\gamma)$ background is suppressed
- Destructive interference reduces the irreducible background when requiring a high $p_T$ photon

Signal reduction by $\sim \alpha$ while background is far more more reduced by $\sim 1/3000$ overall

Interesting but will still need large amounts of luminosity :
About $3\sigma$ at $100 \text{ fb}^{-1}$ and $m_H = 120 \text{ GeV/c}^2$ studies are underway in experiments
Fat-Top-Jet Samples

- Very encouraging first results (top-jet):
Hadronic Top Candidate ($E_T = 356$ GeV, 3 subjets, $M=197$ GeV)
Preamble: Breakthroughs in Phenomenology

Several breakthroughs in the past decade have drastically changed the theory prospective to the hadron collider processes.

- The “Next-to…” revolution:
  - Breakthrough ideas in computation of loops (sewing together tree level amplitudes).
  - NLO generators, blackhat, NLOjet++, Phox, MCFM, etc...
  - NLO generators w/ PS, MC@NLO and POWHEG.
  - NLO+NLL or NNLL, CAESAR, ResBos, HqT
  - NNLO, FEHIP, FEWZ, HNNLO, DYNNLO
  - ...

- NNLO PDFs sets

- Parton Shower (and Matrix Element matching) improvements:
  Pythia, Herwig, Sherpa and CKKW (1.3) and MadGraph (5.0) performing very well (Including description of the Pile Up and the underlying event).

- The Jet revolution (Fast Jet): Allowing to compute in reasonable time infra-red safe $k_T$ jets.
Preamble: Important Measurements

ATLAS Overview

Theoretical at NLO

Measurement of di-boson production
Preamble : Important Measurements

W-plus-HF

- W+Heavy flavor is dominated by Charm (Cabibbo favored sg production)
- Makes it a probe of strange content!
- Use the vertex mass to disentangle the W+b in ATLAS

These are very important control samples for the W,Z H to bb analyses!
Basic Selections

Preselections and objects:

1. \( W \) : Only 1 lepton with \( p_T > 25 \text{ GeV} \) (with \( |\eta| < 2.5 \))
2. \( Z \) : 2 leptons with \( p_T > 20 \text{ GeV} \) (with \( |\eta| < 2.5 \))
3. **Jets** are 0.4 anti-\( k_T \) jets (with \( |\eta| < 2.5 \))
4. **MET** : Estimated from
   - Clusters in the calorimeters (with \( |\eta| < 4.9 \))
   - Corrected if the clusters are associated to reconstructed objects (jets, electrons, photons and taus).
   - Muons are included and the clusters in the calorimeter related to them are removed.
5. **MPT** (Missing transverse \( p_T \)) : Vector sum of the transverse momentum of the tracks associated to the primary vertex.
6. **b-tagging** :
   - Secondary vertex reconstruction
   - IP probabilities combination
   Combined with an MVA (70% efficiency for b-jets in \( tt \), 130 b-rejection and 5 c-rejection)
B-Tagging

Performance of the various taggers:

\[ \text{Light jet rejection} \]

\[ \text{c-jet rejection} \]

\[ \text{ATLAS Preliminary} \]

\[ \text{JetFilterCombNN} \]

\[ \text{JetFilterCombNNc} \]

\[ \text{IP3D-SV1} \]

\[ \text{SV0} \]

\[ \text{tt simulation, } \sqrt{s} = 7 \text{ TeV} \]

\[ p_T^{\text{jet}} > 15 \text{ GeV, } |\eta|^{\text{jet}} < 2.5 \]
B-Tagging

Measurement of the B-tagging performance:

- $p_T^{rel}$ method:

- System 8: use three uncorrelated criteria
  - lifetime tagging
  - $p_T^{rel}$ selection $> 700$ MeV
  - Presence of an opposite b-tagged jet

Eight equations with eight unknowns: the number of b and non-b jets passing the 3 selection criteria and originally present in the sample.
B-Tagging

Measurement of the B-tagging efficiency:
3 Main Channels

ZH (llbb) :

1.- Two oppositely charged leptons
2.- 83 GeV < m_{ll} < 99 GeV
3.- MET < 50 GeV to reduce top background

WH (lvbb) :

1.- Single lepton p_T > 25 GeV
2.- MET > 25 GeV
3.- m_T > 40 GeV

WH (lvbb) :

1.- Large MET > 120 GeV
2.- PET > 30 GeV to suppress events which wrongly estimated MET
2.- ΔΦ(MET,MPT) < 90 deg.
Boost Categories

WH and ZH (lv, llbb):

- $p_T^V < 50$ GeV
- $50 \leq p_T^V < 100$ GeV
- $100 \leq p_T^V < 200$ GeV
- $p_T^V \geq 200$ GeV

In this case $\Delta R$ of the jets $> 0.7$

ZH (vv):

- $120 < E_T^{miss} < 160$ GeV
- $160 \leq E_T^{miss} < 200$ GeV
- $E_T^{miss} \geq 200$ GeV
Background Estimates

- **W/Z + jets**: Shape from MC.
- **Top**: Shape from simulation as well.

**lvbb**: W+jets and top simultaneous fit of 3-jets (top) sample and $m_{bb}$ sidebands

**llbb**: W+jets and top simultaneous fit of $m_{ll}$ sidebands and $m_{bb}$ sidebands
Background Estimates

- **W/Z + jets**: Shape from MC.
- **Top**: Shape from simulation as well.

llbb : $W + \text{jets}$ and top simultaneous fit of 3-jets (top) sample and $m_{bb}$ sidebands

llbb : $Z + \text{jets}$ and top simultaneous fit of $m_\perp$ sidebands and $m_{bb}$ sidebands
Background Estimates

- W/Z + jets: Shape from MC.
- Top: Shape from simulation as well.

llbb: W+jets and top simultaneous fit of 3-jets (top) sample and $m_{bb}$ sidebands
llbb: Z+jets and top simultaneous fit of $m_{ll}$ sidebands and $m_{bb}$ sidebands
vvbb: W+jets, Z+jets and top from the scale factors derived above
Background Estimates

- **W/Z + jets**: Shape from MC and normalization of W/Z+2jets from <2 tags samples and $m_{bb}$ sidebands
- **Top**: Shape from simulation and normalization from 3-jets sample, $m_{ll}$ sidebands and $m_{bb}$ sidebands
- **Diboson**: from MC (NLO cross sections)
- **Multijet**:
  - lvbb Fit of MET distribution, Template from reversed lepton ID (for the lvbb channel)
Background Estimates

- **W/Z + jets**: Shape from MC and normalization of W/Z+2jets from <2 tags samples and $m_{bb}$ sidebands
- **Top**: Shape from simulation and normalization from 3-jets sample, $m_{ll}$ sidebands and $m_{bb}$ sidebands
- **Diboson**: from MC (NLO cross sections)
- **Multijet**:
  - lvbb Fit of MET distribution, Template from reversed lepton ID (for the lvbb channel)
  - vvbb channel use the $\min(\Delta\Phi(\text{MET}, \text{bjets}))$
The $llbb$ Analysis
The vvbb Analysis

(a) and (b) show the distribution of events as a function of the mass of the_bb system, for different regions of the transverse energy. The plots are derived from ATLAS Preliminary data and include contributions from various backgrounds such as Top, Z+jets, W+jets, and Diboson.
<table>
<thead>
<tr>
<th>Bin</th>
<th>$ZH \to t^+t^-b\bar{b}$</th>
<th>$WH \to t\nu b\bar{b}$</th>
<th>$ZH \to \nu\nu b\bar{b}$</th>
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<tbody>
<tr>
<td></td>
<td>$p_T^Z[\text{GeV}]$</td>
<td>$p_T^W[\text{GeV}]$</td>
<td>$E_T^{\text{miss}}[\text{GeV}]$</td>
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<td></td>
<td>0-50</td>
<td>50-100</td>
<td>100-200</td>
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<tr>
<td>Data</td>
<td>139</td>
<td>164</td>
<td>62</td>
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<tr>
<td>Signal</td>
<td>$1.4 \pm 0.2$</td>
<td>$2.0 \pm 0.3$</td>
<td>$1.7 \pm 0.3$</td>
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<tr>
<td>Top</td>
<td>18</td>
<td>25</td>
<td>7</td>
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<td>W+jets</td>
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<tr>
<td>Z+jets</td>
<td>132</td>
<td>126</td>
<td>58</td>
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<tr>
<td>Diboson</td>
<td>8</td>
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<td>4</td>
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<tr>
<td>Multijet</td>
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<tr>
<td>Total Bkg</td>
<td>$157 \pm 15$</td>
<td>$157 \pm 11$</td>
<td>$70 \pm 7$</td>
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Components of the Background Systematic Uncertainties [%]

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<tr>
<th>Component</th>
<th>B-tag Eff</th>
<th>Bkg Norm</th>
<th>Jets/$E_T^{\text{miss}}$</th>
<th>Leptons</th>
<th>Luminosity</th>
<th>Pile Up</th>
<th>Theory</th>
<th>Total Bkg</th>
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Components of the Signal Systematic Uncertainties [%]

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Number of events for $80 < m_{bb} < 150$ [GeV]
Results

(a)

(b)

(c)

(d)
Conclusions and Outlook

- The search for the Higgs boson in the bb channel in the associated production is now a sensitive channel especially in the very low mass range where it reaches a 95% CL exclusion sensitivity of $\mu_95 = 2.6$ (up to 5.1 at higher mass hypotheses) the observed limits range from 2.7 to 5.3.

- No significant excess is observed in this channel.

- There is still room for improvement (substructure).

- Of course... the overall picture is still consistent.
Backup
The 2011 Dataset

5.6 fb$^{-1}$

Delivered Luminosity

Recent event with 15 Vertices
Luminosity and Beam cross section

\[ \mathcal{L} = \frac{N_p^2 k_b \bar{f}_{rev} \gamma}{4\pi \beta^* \epsilon_n} F \]

Reduction factor W/ Beam crossing angle \( O(0.9) \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010</th>
<th>2011</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(10^{11} \text{ p/bunch}) )</td>
<td>1.2</td>
<td>1.35</td>
<td>1.15</td>
</tr>
<tr>
<td>( k \text{ (N bunches)} )</td>
<td>368</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>150</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>( \epsilon \text{ (\mu m rad)} )</td>
<td>2.4-4</td>
<td>1.9-2.3</td>
<td>3.75</td>
</tr>
<tr>
<td>( \beta^* \text{ (m)} )</td>
<td>3.5</td>
<td>1.5-1</td>
<td>0.55</td>
</tr>
<tr>
<td>( L \text{ (cm}^{-2}\text{s}^{-1}) )</td>
<td>(2 \times 10^{32})</td>
<td>(3.3 \times 10^{33})</td>
<td>(10^{34})</td>
</tr>
</tbody>
</table>

Beam parameters close to nominal in terms of luminosity
What Next? 8 TeV ~ 10% improvement in sensitivity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2010</th>
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<th>2012</th>
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</tr>
<tr>
<td>β* (m)</td>
<td>3.5</td>
<td>1.5-1</td>
<td>0.6</td>
<td>0.55</td>
</tr>
<tr>
<td>L (cm⁻²s⁻¹)</td>
<td>2x10³²</td>
<td>3.3x10³³</td>
<td>~7x10³³</td>
<td>10³⁴</td>
</tr>
</tbody>
</table>

More O(30) PU events!
- In 2012 ~20 fb⁻¹:
  - Confirm (5σ sensitivity)
  - Infirm (exclude at 95% CL with such a large excess)
- Next LS1 preparing for higher energies >12 TeV

2012 Should bring a definite answer to the search of the SM Higgs boson
# The ATLAS and CMS Detectors In a Nutshell

<table>
<thead>
<tr>
<th>Sub System</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td><img src="image" alt="Diagram of ATLAS and CMS Detectors" /></td>
<td><img src="image" alt="Diagram of ATLAS and CMS Detectors" /></td>
</tr>
<tr>
<td><strong>Magnet(s)</strong></td>
<td>Solenoid (within EM Calo) 2T 3 Air-core Toroids</td>
<td>Solenoid 3.8T Calorimeters Inside</td>
</tr>
<tr>
<td><strong>Inner Tracking</strong></td>
<td>Pixels, Si-strip, TRT PID w/ TRT and dE/dx</td>
<td>Pixels and Si-strips PID w/ dE/dx</td>
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<tr>
<td></td>
<td>[ \sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \pm 0.01 ]</td>
<td>[ \sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \pm 0.005 ]</td>
</tr>
<tr>
<td><strong>EM Calorimeter</strong></td>
<td>Lead-Larg Sampling w/ longitudinal segmentation [ \sigma_{E}/E \sim 10%/\sqrt{E} \pm 0.007 ]</td>
<td>Lead-Tungstate Crystals. Homogeneous w/o longitudinal segmentation [ \sigma_{E}/E \sim 3%/\sqrt{E} \pm 0.5% ]</td>
</tr>
<tr>
<td><strong>Hadronic Calorimeter</strong></td>
<td>( \sim 11 \lambda_0 ) [ \sigma_{E}/E \sim 50%/\sqrt{E} \pm 0.03 ]</td>
<td>( \sim 7 \lambda_0 ) Tail Catcher [ \sigma_{E}/E \sim 100%/\sqrt{E} \pm 0.05 ]</td>
</tr>
<tr>
<td><strong>Muon Spectrometer System</strong></td>
<td>Instrumented Air Core (std. alone) [ \sigma_{p_T}/p_T \sim 4% \text{ (at } 50 \text{ GeV)} ] [ \sim 11% \text{ (at } 1 \text{ TeV)} ]</td>
<td>Instrumented Iron return yoke [ \sigma_{p_T}/p_T \sim 1% \text{ (at } 50 \text{ GeV)} ] [ \sim 10% \text{ (at } 1 \text{ TeV)} ]</td>
</tr>
</tbody>
</table>

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