The Art of the Impossible

Probing Challenging Higgs Channels at the LHC

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The Discovery of the Higgs at the LHC
The Large Hadron Collider (LHC)

13 TeV data expected in a few weeks!
4 July 2012: Higgs (In)dependence Day

Duration of projects /planning stability:
First LHC workshop 1984!
Discovery in One Slide

- 5+5 fb^{-1}: ~5σ observation
- CMS: five decay modes; γγ, ZZ, WW, bb, ττ
- ATLAS: Only γγ and ZZ(4l), but slightly greater sensitivity
  - Key contributions from members of the Geneva group, e.g. ZZ
- Published in Phys. Lett. B
- Nobel Prize for Higgs and Englert in 2013
• Since the 2012 discovery, focussed has moved to measuring the properties of the Higgs

• Key properties include
  • Mass
  • Width
  • Couplings to fermions and gauge bosons

\[
\frac{\Gamma(H \rightarrow b\bar{b})}{\Gamma(H \rightarrow \tau^+\tau^-)} \approx 3 \frac{m_b^2}{m_{\tau}^2}
\]

• Spin/parity

\[ J^{PC} = 0^{++} \]

• Self-interaction

\[
V = \frac{M_H^2}{2} H^2 + \frac{m_H^2}{2\nu} H^3 \frac{M_H^2}{8\nu^2} H^4
\]
Almost Final Run-1 Coupling Results

Measure coupling strength of each channel

\[ \mu_i = \frac{\sigma_i}{\sigma_{SM}} \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>CMS $m_H = 125$ GeV</th>
<th>ATLAS Preliminary $m_H = 125.36$ GeV</th>
<th>Total uncertainty</th>
<th>Combined $m_H = 125$ GeV</th>
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<td>$H \rightarrow \gamma\gamma$</td>
<td>$\mu = 1.17^{+0.28}_{-0.26}$</td>
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Combined in progress!

arXiv:1412.8662
Designing for Discovery
Expected discovery? No lose theorem

- **Discoveries** are by definition never really expected

- For the LHC, we were very lucky: very strong arguments that we needed to see something

- **Experiment**
  - Higgs mass between **114 and 200 GeV** from LEP, Tevatron and EW constraints

- **Theory**
  - Some mechanism needed to give **mass** to the W,Z bosons
  - **Unitarity violated** if nothing found < 1 TeV
• γγ and ZZ(4l) analyses played a key role in driving the design requirements for ATLAS and CMS, e.g.
  • good diphoton and dimuon mass resolution: <1% at 100GeV
  • ‘wide’ geometric coverage: |η|<2.5
The Unexpected

- The **discovery of the Higgs boson** is by far the greatest achievement of the LHC
  - ATLAS and CMS were designed to and did discover the Higgs boson
- But today I’d like to focus on something a little different
- What was **not predicted, not expected**
- And some things that were even thought to **be impossible** at the LHC
- Goal: Provide some ideas about what happened to make the **impossible possible**
Higgs Production and Decay at the LHC
Reminder: Higgs Production at the LHC

Standard Model is a very predictive theory for the Higgs boson; only unknown parameter is the Higgs mass.

Production rates known to ~10%

arXiv:1412.8662
Higgs Production Mechanisms

**Gluon fusion**
Dominant process
20 pb

**Vector Boson Fusion (VBF)**
Two forward jets and a rapidity gap
1.6 pb

**Associated production with W/Z boson**
Z or W decays leptonically
1 pb

**Associated production with a top pair**
2 b-jets
0.1 pb
Higgs decay

- $H \rightarrow b \bar{b}$ 58%
- $H \rightarrow W^+ W^-$ 22%
- $H \rightarrow \tau^+ \tau^-$ 6.3%
- $H \rightarrow Z^+ Z^-$ 2.6%
- $H \rightarrow t \bar{t}$ 0.2%
Coupling to b-quarks
Coupling to b-quarks

- Higgs decays most often to a pair of b-quarks (~58% BR)
- Obviously an important property to measure
- Also key input to measurements of
  - total width: largest BR
  - coupling to fermions: only bosonic channels for the discovery
Not an easy measurement

• Measuring the b-coupling $ggF$ is basically hopeless
  • $bb$ dijet production cross-section is many orders of magnitude larger
  • no clear trigger
• How about associated production?
• One trigger lepton with $p_T > 20$ GeV (electron) and $p_T > 6$ GeV (muon)
  • No additional lepton with $p_T > 6$ GeV
• Two jets with $p_T > 15$ GeV and $|\eta| < 2.5$
  • No additional jets with $p_T > 15$ GeV and $|\eta| < 5.0$
• 60% b-tagging efficiency
Conclusion: WH(bb) will be very difficult

As shown in Table 19-6, a WH signal might be extracted if one assumes that the various background distributions are all perfectly known. Even in this optimistic scenario, the signal significance is at best 4.7σ for $m_H = 80$ GeV and is below 3σ for values of $m_H$ above the ultimate sensitivity expected for LEP2. These numbers correspond to an integrated luminosity of 30 fb$^{-1}$ expected to be reached over three years of initial operation at low luminosity. It is not clear in all cases how to achieve an accurate knowledge of the various backgrounds from the data.

In conclusion, the extraction of a signal from $H \rightarrow b\bar{b}$ decays in the WH channel will be very difficult at the LHC, even under the most optimistic assumptions for the $b$-tagging performance and calibration of the shape and magnitude of the various background sources from the data itself.
In conclusion, the extraction of a Higgs-boson signal in the $t\bar{t}H, H \rightarrow b\bar{b}$ channel appears to be feasible over a wide range in the low Higgs-boson mass region, provided that the two top-quark decays are reconstructed completely with a reasonably high efficiency. This calls for excellent $b$-tagging capabilities of the detector. Another crucial item is the knowledge of the shape of the main residual background from $t\bar{t}jj$ production. If the shape can be accurately determined using real data from $t\bar{t}$ production, a Higgs-boson signal could be extracted with a significance of more than $5\sigma$ in the mass range from 80 to 130 GeV, assuming an integrated luminosity of 300 fb$^{-1}$. For an uncertainty of $\pm5\%$ on the absolute normalisation of the background shape, the discovery window would be reduced to the range between 80 and 125 GeV.

The prospects of VH(bb) considered to be so dire that ttH(bb) was thought to be the more promising channel

*only 300 fb$^{-1}$ needed!*
• A 2008 paper from Butterworth et al reported a large improvement in significance from focusing on the high $p_T$ Higgs region and using jet substructure techniques.

It is widely considered that, for Higgs boson searches at the Large Hadron Collider, $WH$ and $ZH$ production where the Higgs boson decays to $b\bar{b}$ are poor search channels due to large backgrounds. We show that at high transverse momenta, employing state-of-the-art jet reconstruction and decomposition techniques, these processes can be recovered as promising search channels for the standard model Higgs boson around 120 GeV in mass.
Boost not substructure

- It turns out that the key observation is actually that the signal $p_T$ spectrum of the signal is much harder than the background

- Applying the $p_T$ cut necessary for substructure techniques dramatically improved S/B

- Exploited in the current ATLAS/CMS analyses by explicit $p_T$ categories and as input variables to BDTs

- No gain from substructure at 8 TeV


JHEP01(2015)069
19.2.4 H → bb

19.2.4.1 General considerations

If the mass of the Standard Model Higgs boson is lighter than $2m_W$, the $H \rightarrow bb$ decay mode is dominant with a branching ratio of $\sim 90\%$. The observation of such a characteristic signature would be important for both the Higgs discovery and for the determination of the nature of any resonance observed in this mass region. Since the direct production, $gg \rightarrow H$ with $H \rightarrow bb$, cannot be efficiently triggered nor extracted as a signal above the huge QCD two-jet background, the associated production with a $W$ or $Z$ boson or a $t\bar{t}$ pair remains as the only possible process to observe a signal from $H \rightarrow bb$ decays. The leptonic decays of the $W$ boson or semi-leptonic decays of one of the top quarks provide an isolated high-$p_T$ lepton for triggering. In addition, requiring this high-$p_T$ lepton provides a large rejection against background from QCD jet production. The Higgs-boson signal might thus be reconstructed as a peak in the invariant jet-jet mass spectrum of tagged $b$-jets.

Both the $WH$ and the $t\bar{t}H$ channels have already been studied for the ATLAS Technical Proposal [19-14]. The analysis was complex and it became clear that excellent $b$-tagging capabilities are needed. The major difficulties in extracting a reliable signal from either of these two channels are the combination of a small signal and the need for an accurate control of all the background sources. The analyses have been repeated for this document, using the expected performance of the final ATLAS detector configuration. In the case of the $t\bar{t}H$ channel, the analysis has also been significantly improved. In the new analysis presented here, both top-quark decays are completely reconstructed. This provides a significantly better signal-to-background ratio and a reduction of the combinatorial problem in the $b$-jet assignment to the Higgs boson decay.

Other channels involving $H \rightarrow bb$ decays have been suggested in the literature [19-33]. They have so far not been considered by ATLAS for the following reasons:

- $ZH$ production with $Z \rightarrow \nu\nu$: this channel would provide a rate about six times lower than the $WH$ channel. In addition, although $t\bar{t}$ production does not contribute significantly to the background in this channel, $gg \rightarrow Zbb$ production with $Z \rightarrow \nu\nu$ is only a factor 1.8 smaller in rate than the $Wbb$ background with $W \rightarrow l\nu$, and the signal-to-background ratio would therefore not be significantly improved with respect to the $WH$ channel.

- $ZH$ production with $Z \rightarrow \nu\nu$: it would be difficult to trigger efficiently on such final states. In addition, this channel suffers from potentially very large experimental backgrounds, given the rather low $E_T^{\text{miss}}$ expected for the signal.

- $b\bar{b}H$ production: this process is also difficult to trigger on with high efficiency. However, $b\bar{b}H$ production may be significantly enhanced in supersymmetric extensions of the Standard Model and a detailed study has been carried out in the MSSM framework (see Section 19.3.2.8). This study has shown that, even if the trigger problem is ignored, a signal can only be extracted for large values of $\tan\beta$, where the enhancement is large. Therefore, this channel does not provide any discovery potential for the Standard Model Higgs boson.

In the following, the main features of the analyses of the $WH$ (search for $l\nu bb$ final states [19-34]) and $t\bar{t}H$ (search for $l\nu jjbb$ final states [19-35]) channels are summarised. These analyses have been performed using the fast simulation (see Section 2.5). Crucial aspects of the $b$-tagging performance (see Section 10.6) and of the invariant mass reconstruction of $b$-jet pairs (see Section 9.3) are in agreement with the results obtained from the full detector simulation.
Triggering on MET

• Development of an efficient MET trigger
  • e.g. L1 noise thresholds, L2 MET trigger
• Accurate measurements of the modelling of the turn-on region allowed the ATLAS analysis to extend to 100 GeV (5% uncertainty)
• Clever topological cuts to reduce backgrounds
• Control regions to normalise backgrounds
  • ATLAS: uses signal regions of other VH(bb) channels

Most powerful bb channel!
Final VH(bb) distributions

- Complex analyses using sophisticated multivariate techniques and advanced fit models
- Detailed studies of background modelling
  - Fit model designed to normalise backgrounds

arXiv:1310.3687
VH(bb) Results

ATLAS

$\sqrt{s} = 7$ TeV, $\int L dt = 4.7$ fb$^{-1}$; $\sqrt{s} = 8$ TeV, $\int L dt = 18.9$ fb$^{-1}$

Expected | Observed
--- | ---
ATLAS | 2.6σ | 1.4σ
CMS | 2.1σ | 2.1σ

$\mu = 1.0 \pm 0.8$
$\mu = 0.8 \pm 1.0$
$\mu = 1.1 \pm 0.9$
Coupling to Top Quarks
H→tt coupling

• Top quark **couples** very **strongly** to the Higgs boson
• For \( m_t = 173 \text{ GeV} \)

\[
\lambda_t = \frac{\sqrt{2} m_t}{v} = 0.996 \pm 0.005
\]

• The **top quark**
  • Only quark with a ‘natural mass’
  • Main culprit in the instability of the Higgs mass

\[
(125 \text{ GeV})^2 = m_{H_0}^2 + (-2000^2 + 700^2 + 500^2)(\frac{\Lambda}{10})^2 \text{ [TeV}^2]\]

• Could play a key role in EWSB or as a window to new physics
• Need accurate measurement of the top Yukawa coupling
Direct ttH measurements

- **Indirect constraints** on top-Higgs Yukawa coupling can be extracted from channels using $ggH$ and $\gamma\gamma H$ vertices
  - Assumption: **No new particles**
- $ttH$ production can measure the top-Higgs Yukawa coupling directly
  - Probes **NP contributions** in the $ggH$ and $\gamma\gamma H$ vertices
- **Small production** cross-section at the LHC
  - Need to consider all decay channels to boost sensitivity
How to search for ttH

- H → hadrons
  - bb, ττ
- H → leptons
  - WW, ZZ, ττ
- H → γγ

Top Decays

- jets 46%
- μ+jets 15%
- e+jets 15%
- lepton+jets 15%
- jets 15%

Higgs Decays

- hadrons 58%
- photons 58%
- WW 22%
- ττ 6%
- gg 3%
ttH(bb)
bitrarily chosen reference. It is interesting to note that it does not quite yield a substantial significance, even though background uncertainties of 1% and 4% for $t\bar{t}Nj$ and $t\bar{t}b\bar{b}$ are probably substantially better than what will be accessible in reality. This highlights the challenge that is faced in observing $t\bar{t}H$. 

![Graph showing total significance vs $\Delta B/B$ for ATLAS data with 30 fb$^{-1}$]
ttH(bb) Analysis Strategy

- Select **tt-enriched** samples
  - Lepton+jets or dilepton
- **Categorise** events by jet and b-tag multiplicity
- Separate **high** and **low** S/\sqrt{B} channels
- **Constrain systematic uncertainties** from signal depleted categories using profile likelihood fit
Categories

- Cuts are applied to separate selected events into categories
- Often very large gains for Higgs analyses
  - Different S/B: better signal extraction
  - Different background composition: constrain backgrounds
- Both feature exploited for ttH(bb)

**ATLAS Preliminary Simulation**
\[ \sqrt{s} = 8 \text{ TeV}, \int L \, dt = 20.3 \text{ fb}^{-1} \]

- Single lepton
  - \( m_h = 125 \text{ GeV} \)

- Events/bin

- Data

- H (125)
- t\(t\) + light
- c\(c\) + c\(c\)
- b\(b\) + b\(b\)
- Total unc.

- Data/Pred

- 4 j, 2 b
  - S/B < 0.1%
- 4 j, 3 b
  - S/B = 0.2%
- 4 j, ≥ 4 b
  - S/B = 1.3%
- 5 j, 2 b
  - S/B = 0.1%
- 5 j, 3 b
  - S/B = 0.4%
- 5 j, ≥ 4 b
  - S/B = 2.3%
- ≥ 6 j, 2 b
  - S/B = 0.2%
- ≥ 6 j, 3 b
  - S/B = 0.9%
- ≥ 6 j, ≥ 4 b
  - S/B = 3.8%

**ATLAS Preliminary**
\[ \int L \, dt = 20.3 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]

- Single lepton
- Data
- t\(t\) + c\(c\)
- t\(t\) + b\(b\)
- t\(t\) + e\(e\)
- Total unc.
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Many systematic uncertainties: both theoretical and experimental

Background systematics are **larger** than expected **signal yield** (16)

Background uncertainty: ~50%

Expected S/B: ~4%
Proiling Example

- Profile likelihood ﬁts treat systematic uncertainties as nuisance parameters, θ, that can be constrained from data
- Constraints from high-statistics control samples
- Caution: Sufﬁciently sophisticated treatment needed to avoid overconstraints

![Graphs showing data and predictions for ATLAS and CMS with background uncertainties](image)
**ATLAS** \( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}, m_t = 125 \text{ GeV} \)

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</tr>
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</table>
Results

- CMS: Observed (expected) limit @ 125 GeV
  - **4.1 x SM** (3.5 x SM)
- ATLAS: Observed (expected) limit @ $M_H=125$ GeV
  - **3.4xSM** (2.2xSM)

![Graph showing CMS and ATLAS limits](image)

arXiv:1503.05066

CMS-PAS-HIG-14-009
The forgotten leptons
The $t\bar{t}H, H \rightarrow WW(^{*})$ and $WH, H \rightarrow WW(^{*})$ processes have been studied using two- and three-lepton final states. The signal and main backgrounds have been estimated using a full GEANT based simulation of the detector. The estimated accepted cross-sections in fb of signal and background for these processes are $1.9:10$ ($t\bar{t}H$ 2L), $0.8:3.4$ ($t\bar{t}H$ 3L) and $0.3:0.4$ ($WH$ 3L) respectively. The signal is small and clear distinguishing features such as resonance peaks have not been established. The backgrounds are larger and their uncertainties have not been fully controlled. The analysis is therefore very challenging.
ttH Multileptons

- Despite being studied in projections by ATLAS, there were initially no LHC analyses looking for ttH using multilepton channels.
- During 2013, it was realised that these channels would already be quite sensitive with the current dataset.
  - Multilepton analyses began, but after most other analyses.

**Same sign 2-leptons**

**3-leptons**
ttH Multileptons Analysis Strategy

- Cannot easily separate the many relevant decay modes, therefore defined channels defined by **number of leptons**
  - **SS 2-leptons**, 6 jets, 2 b-jets
  - **3-leptons**, 4 jets, 2 b-jets
  - **4-leptons**, 2 jets, 2 b-jets
- Low signal rate, but low background
- Main background is **ttW/Z/γ*; also diboson (WZ and ZZ), ttbar (2/3-leptons)**
- ATLAS used a cut-and-count analyses but additional more categories
- CMS used a **multivariate discriminant** to separate signal and background

### ATLAS Categories

<table>
<thead>
<tr>
<th>Category</th>
<th>Higgs boson decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WW*</td>
</tr>
<tr>
<td>2ℓ0τhad</td>
<td>80%</td>
</tr>
<tr>
<td>3ℓ</td>
<td>74%</td>
</tr>
<tr>
<td>2ℓ1τhad</td>
<td>35%</td>
</tr>
<tr>
<td>4ℓ</td>
<td>69%</td>
</tr>
<tr>
<td>1ℓ2τhad</td>
<td>4%</td>
</tr>
</tbody>
</table>

*Note: The table above shows the fraction of expected candidates for each category, with the main decays contributing to the "Other" column. The contamination from gluon fusion, vector boson fusion, and associated boson decay modes are shown in **Table 1**.*
Multivariate Techniques

- Key component of modern LHC Higgs analyses, BDTs
- Combine discriminating information from kinematic variables
  - Not fully exploited for TDR predictions
- Typically 15-20% improvement per analysis
Single candidate event in the 2l1tau category. Red track - selected muon; green track - selected electron; yellow cone - selected tau; blue cones - selected b-tagged jets; and the white cones - selected non-b-tagged jets. $\mu^+ p_T = 42 \, \text{GeV}$; $e^+ p_T = 16 \, \text{GeV}$; $\tau^- p_T = 52 \, \text{GeV}$. Jet $p_T$ 85, 53, 76, and 26 GeV, first two are b-tagged.
Multilepton Results

The analyses are already very powerful despite low statistics. Both experiments see an excess with respect to SM predictions.
Where do we see the (small) excess?

The four-lepton search. Signal and background normalizations are explained in the text. Events with positive and negative charge are merged in these plots, but they are for the same-sign dilepton search, for the final states $ee$ (left), $e\tau$ (center), and $\mu\mu$ (right). Signal and background predictions are shown.

Figure 11: Distribution of the jet multiplicity (top row) and the BDT discriminant (bottom row) for CMS $t\bar{t}H$, $e\mu$ channel.

Figure 2: The spectrum of the number of jets expected and observed in each signal region. For display purposes, the hatched bands show the total uncertainty on the background prediction in each bin. The non-prompt charge mis-id background spectra are taken from simulation of $Z\gamma$. The data-driven prediction.

Figure 13: Distribution of the BDT discriminant for CMS $t\bar{t}H$, $e\mu$ channel.

Systematic uncertainties are described in the text (in particular the description of the background prediction in each bin. The non-prompt charge mis-id background spectra are taken from simulation of $Z\gamma$. The data-driven prediction). The red line corresponds to the data-driven prediction. Other sources of systematic uncertainty are shown in the figure.

Figure 18: Distribution of the jet multiplicity (top row) and the BDT discriminant (bottom row) for ATLAS $t\bar{t}H$, $e\mu$ channel.

Figure 23: Distribution of the BDT discriminant for ATLAS $t\bar{t}H$, $e\mu$ channel.

Systematic uncertainties are described in the text (in particular the description of the background prediction in each bin. The non-prompt charge mis-id background spectra are taken from simulation of $Z\gamma$. The data-driven prediction). The red line corresponds to the data-driven prediction. Other sources of systematic uncertainty are shown in the figure.
• Observed (expected) limit @ 125 GeV
  • 4.5 x SM (1.7 x SM)
• Largely driven by excess in Same-Sign 2l channel
Width
• As an highly unstable elementary particle, the **lifetime** of the Higgs is **very short**

• For $m_H = 125$ GeV
  • $\Gamma = 4.07 \times 10^{-3}$ GeV

• Direct experimental measurements probe widths **3 orders of magnitude larger** $\sim 1.6$ GeV (ATLAS, ZZ)

• Thought to be **impossible to measure the width** at a hadron collider
Expectations for width measurements

A measurement of the width is possible only for Higgs boson masses above \( m_H > 2m_Z \) where at the same time the Higgs natural width is becoming large and the detector resolution is improving. A Gaussian width with central values of about 2.3 GeV/c^2 for \( m_H = 200 \) GeV/c^2 and 4.2 GeV/c^2 for \( m_H = 300 \) GeV/c^2 is obtained from the fit, but with a rather large uncertainty of about 50%.

In the CMS TDR the plot showing the expected precision on the width doesn’t even extend below a Higgs mass of 200 GeV ...

**Figure 19-46** Relative precision \( \Delta \Gamma_H/\Gamma_H \) on the measured Higgs-boson width as a function of \( m_H \) assuming an integrated luminosity of 300 fb⁻¹.
Off-shell Higgs Production

- A paper from Kauer and Passerino in 2012 pointed out a peculiar cancellation between the Breit-Wigner trend and the width as a function of $m_{VV}$ enhances the cross-section at high mass

\[
\left(\frac{d\sigma}{dM_{VV}}\right)_{ZWA} = \sigma_{H,ZWA} \frac{M_H \Gamma_H}{\pi} \frac{2M_{VV}}{(M_{VV}^2 - M_H^2)^2 + (M_H \Gamma_H)^2}.
\]

- For ZZ, ~7.6% of the total cross-section is at high mass

<table>
<thead>
<tr>
<th>Process</th>
<th>Total [pb]</th>
<th>$M_{ZZ} &gt; 2M_Z$ [pb]</th>
<th>R [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H \to all$</td>
<td>19.146</td>
<td>0.1525</td>
<td>0.8</td>
</tr>
<tr>
<td>$gg \to H \to ZZ$</td>
<td>0.5462</td>
<td>0.0416</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Measuring the Width

- This can be used to set a constraint on the Higgs width as follows

\[ \sigma_{\text{on-peak}}^{g g \to H \to Z Z} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \text{BR})_{\text{SM}} \equiv \mu (\sigma \cdot \text{BR})_{\text{SM}} \]

\[ \frac{d\sigma_{\text{off-peak}}^{g g \to H \to Z Z}}{dm_{Z Z}} = \kappa_g^2 \kappa_Z^2 \frac{d\sigma_{\text{off-peak,SM}}^{g g \to H \to Z Z}}{dm_{Z Z}} = \mu r \frac{d\sigma_{\text{off-peak,SM}}^{g g \to H \to Z Z}}{dm_{Z Z}} \]

\[ \kappa_g = \frac{g_{ggH}}{g_{ggH}^{\text{SM}}} \]

\[ \kappa_Z = \frac{g_{HZZ}}{g_{HZZ}^{\text{SM}}} \]

\[ r = \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} \]

- Determine \( r \) by measuring ratio of off-peak to on-peak cross-section

Significant interference with the SM VV background at high mass
CMS measurement of the width

- First measured by CMS (Moriond 2014) using the 4l and 2l2v using a matrix element likelihood approach (MELA)
- Combined observed (expected) values
  - \( r < 4.2 \) (8.5) @ 96% CL
  - \( \Gamma < 17.4 \) (35.3) MeV)
- Two orders of magnitude better than direct measurements
• Similar result from ATLAS during 2014
• Additionally, showed the dependence on the $k$-factor for the ZZ background
  • No strong dependence observed
Conclusion

• The first run of the LHC has been a fascinating and exciting time
  • Privileged enough to participate in the discovery of a new elementary particle
• Extensive measurement program is currently ongoing to measure its properties
• The channels used for the discovery were anticipated
  • Benchmark channels for detector design
• This talk has focussed on some results that were not anticipated
  • bb, ttH, width
• Some of these were even thought to be impossible
• Small message for the future: always learn from the past, but don't let the past constrain you
• Clever ideas and innovation can make the impossible possible
First Run-2 collisions (at 900 GeV) last week as seen by ATLAS