Interplay of Experiment and Theory in Higgs Measurement

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PiTP 2013
Introduction

• Brief Review of Higgs Channels

• Theory and H to WW
  • Review of H to WW Analysis
  • ggH Background Modeling
  • ggH Signal Modeling
  • VBF Background Modeling

• Interpreting Higgs Results
  • Coupling Fits
  • Aside on Higgs to Invisible
  • Advertisement: Differential Distributions
Higgs Production Summary

\[ \sigma (pp \to H+X) [pb] \]

- \( m_H = 125 \text{ GeV} \)
- \( \sqrt{s} = 8 \text{ TeV} \)

- \( \sigma (pp \to H (\text{NNLO} + \text{NNLL QCD} + \text{NLO EW})) \)
- \( \sigma (pp \to q\bar{q}H (\text{NNLO QCD} + \text{NLO EW})) \)
- \( \sigma (pp \to WH (\text{NNLO QCD} + \text{NLO EW})) \)
- \( \sigma (pp \to ZH (\text{NNLO QCD} + \text{NLO EW})) \)
- \( \sigma (pp \to ttH (\text{NLO QCD})) \)

- \( \sigma (pp \to H \to W^+W^- + X) \)
- \( \sigma (pp \to H \to Z\nu\nu + X) \)

- \( ggF \) (vector boson fusion)
- \( VBF \) (vector boson fusion)

Large QCD Uncertainties
Sensitive to new physics in the loop

Small QCD Uncertainties
Distinctive forward jet tags

Access to top coupling
Usually tagged with W/Z decay to leptons (incl. neutrinos)

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Higgs Decay Summary

$m_H = 125$ GeV

Observed:
- $WW$, $ZZ$, and $\gamma\gamma$

Searches:
- $bb$, $\tau\tau$, $Z\gamma$, and $\mu\mu$

Higgs decays at $m_H=125$ GeV

Each decay probes a different Higgs (Yukawa) coupling
$H \rightarrow WW$ vs $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$

The Higgs has been observed in 3 channels: $WW, \gamma\gamma, ZZ$
(with two others on the edge of significance: $\tau\tau, bb$)

$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$ is low background

Signal/Background $\sim 1.5$
\[ H \rightarrow WW \text{ vs } H \rightarrow \gamma\gamma \text{ and } H \rightarrow ZZ \]

The Higgs has been observed in 3 channels: \( WW, \gamma\gamma, ZZ \)
(with two others on the edge of significance: \( \tau\tau, bb \))

\( H \rightarrow \gamma\gamma \) is high background, but resonance allows background to be determined from sideband

Signal/Background \( \sim 1/30 \)
$H \to WW$ vs $H \to \gamma\gamma$ and $H \to ZZ$

$H \to WW \to \ell\nu\ell\nu$ is intermediate background, but there is no mass peak.

We must model all backgrounds in detail.

Selection is complex and its effect on signal has to be modeled.

Use approximate mass variable $m_T$.

Signal/Background $\sim 1/8$.

$H$ to $WW$ relies heavily on theory.
$H \rightarrow WW$ sources of uncertainty

From the ATLAS H to WW conference note

\[ \mu \equiv \frac{\sigma_{\text{observed}}}{\sigma_{\text{SM}}} \]

Table 13: Leading uncertainties on the signal strength $\mu$ for the combined 7 and 8 TeV analysis.

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<td>-4</td>
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<td>+4</td>
<td>-4</td>
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<tr>
<td>Total</td>
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<td>-29</td>
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Main systematics are theory uncertainties
Uncertainty is 50% statistical and 50% systematics
Why bother with $H \rightarrow WW$?

Electroweak fits make it hard to mess with the ratio of $HWW/HZZ$ couplings, can’t we just measure $H \rightarrow ZZ$?

$WW$ uncertainty is smaller than $ZZ$

$$\mu_{WW} = 1.01 \pm 0.31$$

$$\mu_{ZZ} = 1.7^{+0.5}_{-0.4}$$

Difference will be bigger at 13 TeV, **IF** the theory uncertainties can be controlled
Scaling to 13 TeV

LHC Plans to Run at 13-14 TeV for the next ~15 years

• 2015-2016 13 TeV, 100 fb\(^{-1}\)
• 2018-2020 13(?) TeV, 300 fb\(^{-1}\)
• 2022-202(?) 13(?) TeV, 3000 fb\(^{-1}\)

<table>
<thead>
<tr>
<th>Signal</th>
<th>14 TeV/8 TeV</th>
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<tr>
<td>ggF</td>
<td>2.6</td>
</tr>
<tr>
<td>VBF</td>
<td>2.6</td>
</tr>
<tr>
<td>ttH</td>
<td>4.7</td>
</tr>
<tr>
<td>WH</td>
<td>2.1</td>
</tr>
<tr>
<td>ZH</td>
<td>2.1</td>
</tr>
<tr>
<td>qq to WW background</td>
<td>2.1</td>
</tr>
<tr>
<td>gamma gamma bkg</td>
<td>2.1</td>
</tr>
</tbody>
</table>

In 2016, 4*2.6~10 more signal, 4*2.1~8 more background
Review of H to WW Analysis

Signature: two e or $\mu$ leptons and two neutrinos

Gluon Fusion (ggH) typically gives 0 or 1 jets

Vector Boson Fusion gives 2 or more jets

Many of the lessons in H to WW will apply to other searches where the signal is under significant SM background and does not peak
Review of H to WW Analysis

Just about everything in the hadron collider zoo is a background
Review of H to WW Analysis

W+jets background

- $q\bar{q} \rightarrow W \rightarrow l\nu$ with an associated jet...
- the jet is misidentified as a lepton
- small background, but uncertainty is large
- one of the largest experimental uncertainties

Hard to predict theoretically, because of dependence on fragmentation and detector response
Review of H to WW Analysis

**Z+jets background**

- Different-flavor ($e\mu$) background mainly from $Z \rightarrow \tau\tau$
- Tiny Background

- Same-flavor ($ee$ & $\mu\mu$) background from $q\bar{q} \rightarrow Z/\gamma^* \rightarrow ll$
  - with false missing momentum signature
  - again, a small background, but uncertainty is large

![Graphs showing event yields for different processes](image)

Hard to predict ... see next slide
Challenges in predicting missing energy distributions

We make multiple cuts to suppress $Z/\gamma^* \rightarrow \ell\ell$ and $Z \rightarrow \tau\tau$

Missing Transverse “Energy”

$$\vec{E}_{\text{T}}^{\text{miss}} = \sum_{\text{calorimeter}} \vec{p}_{\text{T}}$$

Missing Transverse Energy Relative

$$E_{\text{T}}^{\text{miss,rel}} \equiv \begin{cases} |E_{\text{T}}^{\text{miss}}| & \text{if } \Delta\phi \geq \pi/2 \\ |E_{\text{T}}^{\text{miss}}| \sin \Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

where $\Delta\phi$ is the angle between $\vec{E}_{\text{T}}^{\text{miss}}$ and the nearest lepton or jet

$E_{\text{T}}^{\text{miss,rel}}$ is less sensitive to mismeasurements of leptons and jets
Challenges in predicting missing energy distributions: Pile-up

• You should think great $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ has $E_T^{\text{miss}}$ and $Z/\gamma^* \rightarrow \ell\ell$ doesn’t, so we are done
• But it’s difficult to measure hadronic energies precisely
• There is still too much left after a reasonable cut for the same-flavor so we have to use the soft recoil system and calibrate it with data
• Made much worse by pile-up:
Challenges in predicting missing energy distributions: Pile-up

Pile-up is hard to model: Soft QCD

These properties are very hard to model

Models are tuned directly to data, but we still find modeling issues which grow with pile-up
Challenges in predicting missing energy distributions: Underlying Event

Underlying event is due to a variety of soft QCD effects

- To use simulation, total amount of energy needs to be simulated in data
- Simulation is tuned to data, but the modeling is limited
Review of H to WW Analysis

Top and Single top

Looks just like WW but with more jets

Single Top Diagrams
Jet Counting Strategy:
• Divide analysis into 0-jet, 1-jet, and 2+-jets
• “controls” top background, but leads to many of the uncertainties

Most of the sensitivity is from 0-jets

Use b-jet “tagging” to suppress top bkg in 1-jet

Specialize the 2+-jets to looking for the VBF signature
Review of H to WW Analysis

WW background

- WW is considered “irreducible”
- It can be partially suppressed using the effect of spin correlations on the angles because the leptons
- It can also be suppressed using kinematics

\[
\text{Gets contributions from both } q\bar{q} \rightarrow WW \text{ and } gg \rightarrow WW
\]

\[ gg \rightarrow WW \text{ will become more important at } 13 \text{ TeV} \]
Review of H to WW Analysis

WW suppression using spin correlations

Roughly at rest

$W^+$

\( \rightarrow \)

$W$ products back-to-back

$H$ \( \rightarrow \)

Spin=0

$W$

\( \rightarrow \)

Spins have to add to zero

For each $W$ spins add to one
Review of H to WW Analysis

**WW suppression using spin correlations**

Roughly at rest

<table>
<thead>
<tr>
<th>Spin=0</th>
</tr>
</thead>
</table>

$H \rightarrow$

Spins have to add up to zero

<table>
<thead>
<tr>
<th>W$^+$</th>
</tr>
</thead>
</table>

$W^+ \uparrow \rightarrow e^+$

$W \downarrow \rightarrow \nu$

For each W spins add up to one

<table>
<thead>
<tr>
<th>W$^-$</th>
</tr>
</thead>
</table>

$W^- \downarrow \rightarrow \mu^-$

$\bar{\nu}$
Review of H to WW Analysis

WW suppression using spin correlations

Roughly at rest \( W \) products back-to-back

\[ W^+ \uparrow \rightarrow e^+ \uparrow \nu \uparrow \]

\[ H \rightarrow \]

Spins:

\[ Spin = 0 \]

\[ \text{W products back-to-back} \]

Consequences:

Small angle \( \Delta \phi_{ll} \) between charged-lepton directions
Small invariant mass \( m_{ll} \) of the two charged-leptons

to add to zero
Review of H to WW Analysis

WW suppression using spin correlations

Consequences of spin correlations

Small invariant mass $m_{ll}$ of the two charged-leptons

Small angle $\Delta \phi_{ll}$ between charged-lepton directions
Review of H to WW Analysis

WW suppression approximate mass calculation

\[ m_T = \sqrt{(E_{T}^{\ell\ell} + E_{T}^{\text{miss}})^2 - (p_{T}^{\ell\ell} + p_{T}^{\text{miss}})^2}. \]

This obeys the right basic kinematics

\[ m_T < m_H \]

But width of distribution for both signal and background is broad.
Review of H to WW Analysis

Diboson Backgrounds

- \( q\bar{q} \rightarrow WZ/\gamma^* \rightarrow lll\nu \) with a lost lepton
- \( q\bar{q} \rightarrow Z\gamma^* \rightarrow ll\nu\nu \) is also a small background

- These are generally modeled with simulation
- There is special case \( W\gamma^* \) where the \( \gamma^* \) is nearly massless that is difficult to predict
Modeling of the WW background

Focusing on 0-jet

• Jet requirements add a dependence on the modeling of QCD jet emission

• Signal to background ratio means need to model WW at the 20% * 1/8 = 2.5% level to not be dominated by this uncertainty

• We are claiming 1.6% modeling! Use control regions

Uncertainty on ratio of signal/control is ~ 1.6%
Modeling of the WW background

Uncertainty on ratio of signal/control is $\sim 1.6\%$

WW cross-section uncertainty $\sim 6\%$ using NLO

Example for $10 < m_{ll} < 30$ GeV

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vary factorization and renormalization scales</td>
<td>0.9%</td>
</tr>
<tr>
<td>PDFs</td>
<td>1.5%</td>
</tr>
<tr>
<td>Underlying Event and Parton Shower Models</td>
<td>0.2%</td>
</tr>
<tr>
<td>“Modeling”</td>
<td>1.2%</td>
</tr>
<tr>
<td>• Choice of Generator</td>
<td></td>
</tr>
<tr>
<td>• Different Generators make difference approximations: zero width, massless b-quarks,...</td>
<td></td>
</tr>
</tbody>
</table>
Modeling of the WW background

Why vary the factorization and renormalization scales?

• An all orders calculation wouldn’t depend on these scales, so any dependence is a rough estimate of the uncalculated terms

From Michelangelo Mangano’s slides

**Factorization Theorem**

\[
\frac{d\sigma}{dX} = \sum_{j,k} f_j(x_1,Q_i) f_k(x_2,Q_i) \frac{d\hat{\sigma}_{jk}(Q_i,Q_f)}{d\hat{X}} F(\hat{X} \rightarrow X; Q_i, Q_f)
\]

- Transition from partonic final state to the hadronic observable (hadronization, fragm. function, jet definition, etc)
- Sum over all histories with X in them
Example: ggH signal

• This is actually the single largest systematic uncertainty on $\mu \equiv \sigma_{observed}/\sigma_{SM}$
• I.e. the denominator from theory is bigger than all the experimental errors, but not yet the statistical uncertainty
• We determine the uncertainty from renormalization and scale variation
Modeling the ggH Signal Acceptance

Next two slides from Stewart-Tackmann,(arXiv:1107.2117 [hep-ph])

- $gg \rightarrow H$ is full of gluons $\rightarrow$ lots of strong interactions
- Jet cuts make it significantly harder to calculate acceptance.
- Adding a jet cut adds a new scale into the problem

Inclusive cross-section

$$\sigma_{\text{total}} \simeq \sigma_B \left[ 1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3) \right]$$

Cross-section requiring a jet $p_T > 30$ GeV

$$\sigma_0(p_T^{\text{cut}}) = \sigma_B \left( 1 - \frac{3\alpha_s}{\pi} 2 \ln^2 \frac{p_T^{\text{cut}}}{m_H} + \cdots \right)$$

1-jet cross-section looks schematically like this

$$\sigma_{\geq 1}(p^{\text{cut}}) \simeq \sigma_B \left[ \alpha_s \left( L^2 + L + 1 \right) + \alpha_s^2 \left( L^4 + L^3 + L^2 + L + 1 \right) + \mathcal{O}(\alpha_s^3 L^6) \right]$$

where $L^2 = \ln^2 \left( \frac{p^{\text{cut}}}{Q} \right)$
Modeling the $ggH$ Signal Acceptance

Then 0-jet looks like this:

$$
\sigma_0(p_T^{\text{cut}}) \approx \sigma_B \left\{ \left[ 1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3) \right] - \left[ \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6) \right] \right\}
$$

Cancelation between terms with L and without at roughly the experimental cut

Suggested procedure to fix this gives large uncertainty introduced due to jet cuts
VBF analysis in a slide

The process

Properties

Veto jets between the tagging jets in $Y$
Modeling the VBF Backgrounds

- **ggF+2 jets**
  - 43% uncertainty from QCD scale and PDFs

- **WW+2 jets**
  - 42% uncertainty from QCD scale and PDFs

- **ttbar +2jets**
  - 15% uncertainty for extrapolation from control region
$H \rightarrow WW$ VBF event
A “Higgs” Boson has been Observed

Higgs: Understanding what have we found

Production Mechanisms

Decay Channels

Kinematic Measurements

Combined Fit

Coupling Constants

Properties/Quantum Numbers
Higgs Production Summary

- $m_H = 125 \text{ GeV}$
- $\sqrt{s} = 8 \text{ TeV}$

**Higgs Production Mechanisms**

- **ggF** (gluon-gluon fusion)
  - Large QCD Uncertainties
  - Sensitive to new physics in the loop

- **VBF** (vector boson fusion)
  - Usually tagged with $W/Z$ decay to leptons (including neutrinos)
  - Small QCD Uncertainties
  - Distinctive forward jet tags

**Production Processes**

- $pp \rightarrow H (\text{NNLO} + \text{NNLL} \text{ QCD} + \text{NLO} \text{ EW})$
- $pp \rightarrow qgH (\text{NNLO} \text{ QCD} + \text{NLO} \text{ EW})$
- $pp \rightarrow WH (\text{NNLO} \text{ QCD} + \text{NLO} \text{ EW})$
- $pp \rightarrow ZH (\text{NNLO} \text{ QCD} + \text{NLO} \text{ EW})$
- $pp \rightarrow ttH (\text{NLO} \text{ QCD})$

**Access to Top Coupling**
- $ttH$

**VH**
- $W, Z$

**Higgs Boson**
- $H^0$

---

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$H \rightarrow \gamma\gamma$ Signal

Inclusive: All production modes with $\gamma\gamma$ final state

Signal strength relative to SM: $1.65 \pm 0.24^{+0.25}_{-0.18}$(syst)

ATLAS-CONF-2013-012
Diphoton sample divided into exclusive subsets for different production mechanisms:

- **80-90% leptonic WH and ZH**
- **50% hadronic WH and ZH**
- **54(76)% VBF** for loose(tight)
- **75-95% ggF** depending on category

Most categories not very pure in one production mode.
by Production Channel

\[ H \rightarrow \gamma \gamma \] by Production Channel

**ATLAS**

**H → γγ**

Preprint

Diphoton sample divided into exclusive subsets for different production mechanisms:

- 80-90% leptonic WH and ZH
- Remainder ttH
- 50% hadronic WH and ZH
- Remainder ggF
- 54(76)% VBF for loose (tight)
- Remainder ggF
- 75-95% ggF depending on category

Most categories not very pure in one production mode

1.9% of Sig

3.4% of Sig

95% of Sig

Result is yield in each category

\[ \int Ldt = 20.7 \text{ fb}^{-1} \]

\[ m_H = 126.8 \text{ GeV} \]

**ATLAS** Preliminary

Data 2012, \( \sqrt{s} = 8 \text{ TeV} \)

\[ H \rightarrow \gamma \gamma \]
$H \to \gamma\gamma$ by Production Channel

Involved the $WWH$ and $ZZH$ couplings in SM

Involved the $ttH$ coupling in SM

ATLAS-CONF-2013-012
**$H \rightarrow \gamma\gamma$ differential cross-sections**

ATLAS now has preliminary differential distributions

\[ H \rightarrow \gamma\gamma, \sqrt{s} = 8 \text{ TeV} \]
\[ \int L \, dt = 20.3 \text{ fb}^{-1} \]

**$P_T$ Higgs: p-value=0.39**

**$N_{jets}$: p-value=?**
Grand Combination

We combine all the inputs just discussed into global likelihood fit

Includes correlations of systematics!

Summary of Production Modes

<table>
<thead>
<tr>
<th></th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
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<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$WW$</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
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<tr>
<td>$ZZ$</td>
<td>✓</td>
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<td>✓</td>
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<td>✓</td>
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<td></td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>✓</td>
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ATLAS Preliminary

$W,Z,H \rightarrow bb$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.7$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

$H \rightarrow \tau\tau$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 13$ fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow ll\nu\nu$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

$H \rightarrow \gamma\gamma$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

$H \rightarrow ZZ^{(*)} \rightarrow 4l$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 20.7$ fb$^{-1}$

Combined $\mu = 1.30 \pm 0.20$

$\sqrt{s} = 7$ TeV: $\int L dt = 4.6 - 4.8$ fb$^{-1}$
$\sqrt{s} = 8$ TeV: $\int L dt = 13 - 20.7$ fb$^{-1}$

$m_H = 125.5$ GeV
Inclusion of uncertainties

Each analysis has a table like this....only more complicated
• In order to correctly fit all the data you need to include these correlations

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Evidence of VBF production

3. 1σ evidence of VBF production

*Important* because if you’ve only seen ggF then all measurements are proportional to

\[ \frac{\sigma_{gg}}{\Gamma_{total}} \]

Recall we measure things like this

\[ \sigma_{gg} \times B_{\gamma\gamma} = \sigma_{gg} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{total}} \]
Coupling Interpretation

Several different models depending on assumptions:

• New particles in loops?
• BSM contributions to total width
  (invisible decays, other decays to BSM)?

Both combined in $\kappa_\gamma$
Relationship between measurements and coupling

An individual measurement looks like this

\[ \sigma_{gg} \times \mathcal{B}_{\gamma\gamma} = \sigma_{gg} \times \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\text{total}}} \]

We include this in our fitting

\[ \frac{\sigma_{gg} \times \mathcal{B}_{\gamma\gamma}}{\sigma_{gg,SM} \times \mathcal{B}_{\gamma\gamma,SM}} = \frac{\kappa_g^2 \kappa_{\gamma}^2}{\kappa_H^2} \]

where we define

\[ \Gamma_{\text{total}} \propto \kappa_H^2 \]
Example Fit: change couplings to SM

Many combinations of assumptions you can make

Assume only SM particles, but give fermions one scale factor and bosons another
Example Fit 2: add BSM in loops

Keep SM couplings fixed, but add BSM in loops

Only decays to SM particles

\[ \kappa_g = 1.08 \pm 0.14 \]
\[ \kappa_\gamma = 1.23^{+0.16}_{-0.13} \]

Include invisible or other BSM

\[ \kappa_g = 1.08^{+0.32}_{-0.14} \]
\[ \kappa_\gamma = 1.24^{+0.16}_{-0.14} \]

\( \text{BR}_{\text{invisible or non-SM}} < 0.6 \) at 95\% CL
Higgs to Invisible

We have also searched directly for Higgs to invisible...

Z recoiling against nothing

SM source of Z recoiling against nothing

\( \text{BR}_{\text{invisible}} < 0.65 \) (observed) at 95% CL, (0.84 expected)
Higgs to Invisible Interpretation

Implications for dark matter searches if DM to nucleon couplings is entirely Higgs

Based on expected sensitivity ($\text{BR}_{\text{inv}}<0.75$) very close to observed

from arXiv:1109.4398v1 [hep-ph]
Summary

There is an important interplay between theory and experiment
• Theory is an input into Experiment
• Experiment is an input into Theory
• Some important measurements are close to being theory limited

Couplings:
• order 20-30% constraints on vectors, fermions just crossing the sensitivity thresholds
• Interesting sensitivity to dark matter and other BSM

Spin:
• various combinations of $0^-, 1^+, 1^-$, and $2^+$ excluded
$H \rightarrow \gamma\gamma$ Spin

A spin-1 resonance cannot decay to two photons so spin-1 is excluded

Photon spins are not observed

Spin-2 with initial state of $gg$ or $q\bar{q}$ will have different decay kinematics

$\cos \theta^*$ is the angle of photons relative to beam direction with a correction for the boost of the $\gamma\gamma$ system

Selection modified to reduce $m_{\gamma\gamma} - \cos \theta^*$ correlation
$H \rightarrow \gamma\gamma$ Spin

The data are fit for signal and background yields for spin-0 and spin-2.

The ratio of the best fit likelihoods is used as a test statistic to set limits.

Only 8 TeV data are used at this point.

Spin-2 produced by gluon fusion is excluded at 99% CL.
**$H \to ZZ$ Production**

**Signal + VBF, VH, ttH**

Irreducible background: 4 real leptons

Separate VBF and VH categories added

Main Issue is getting the highest efficiency without letting this get out of control

Acceptance:

- $39\%$ $4\mu$
- $26\%$ $2e2\mu/2\mu2e$
- $19\%$ $4e$

$\sqrt{s} = 7$ TeV: $\mathbb{L}dt = 4.6$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\mathbb{L}dt = 20.7$ fb$^{-1}$

**ATLAS Preliminary**

$H \to ZZ^{(*)} \to 4l$

**Events/2.5 GeV**

- Data
- Background $ZZ^{(*)}$
- Background $Z$+jets, $t\bar{t}$
- Signal ($m_H = 125$ GeV)
- Syst. Unc.
$H \rightarrow ZZ$ Spin

Full kinematics measured = 5 angles
Decay products sensitive to $Z$ spins
Two analysis methods:
• BDT with MC for input
• MELA = an analytic probability based on field theory matrix element

Considered $J^P$: $0^+$, $0^-$, $1^+$, $1^-$, $2^+$, $2^-$

0$^-$, 1$^+$ excluded at 97.8% CL
$H \rightarrow WW$ Spin

Discriminating variables: spin-2 looks more like background
$H \rightarrow WW$ Spin

2d binned fit BDT0 vs BDT2

Fit with Spin-0

Test statistic likelihood ratio of spin-0 over spin-2

Exclusion of 2+ varies from 99% for 100% $q\bar{q}$ to 95% for 100% $gg$ production from spin-1
$H \rightarrow WW$ Spin Variables

**ATLAS** Preliminary
Simulation, $\sqrt{s} = 8$ TeV

- $H \rightarrow WW^{(*)} \rightarrow e\mu/\mu\mu + 0$ jets

**ATLAS** Preliminary
Simulation, $\sqrt{s} = 8$ TeV

- $H \rightarrow WW^{(*)} \rightarrow e\mu/\mu\mu + 0$ jets

Arbitrary Normalisation

**ATLAS** Preliminary
Simulation, $\sqrt{s} = 8$ TeV

- $H \rightarrow WW^{(*)} \rightarrow e\mu/\mu\mu + 0$ jets

**ATLAS** Preliminary
Simulation, $\sqrt{s} = 8$ TeV

- $H \rightarrow WW^{(*)} \rightarrow e\mu/\mu\mu + 0$ jets

Arbitrary Normalisation
Spin Combination

Spin results from WW, ZZ, and combined

\[ J^P = 2^+ \text{ excluded at 99.9\% CL independent of } f_{q\bar{q}} \]
$H \rightarrow \gamma \gamma$ VBF BDT

ATLAS Preliminary
$\sqrt{s} = 8$ TeV, $\int L dt = 20.7$ fb$^{-1}$

Events (normalized to unity)

BDT Response
$H \rightarrow \gamma \gamma$ VBF Significance

ATLAS Preliminary

Add S/B numbers
$H \rightarrow \gamma\gamma$ VBF Candidate

VBF Channel has a high purity, S/B $\sim=$