Search for Non-Standard Model Behavior, including CP Violation, in Higgs production and decay to $ZZ^*$

Jordan Webster; Advisor: Jim Pilcher

2015.05.27
Outline

- LHC and ATLAS
- The Standard Model
- Higgs spin & CP
- \( H \rightarrow ZZ^* \rightarrow 4\ell \) analysis
- Results

Special thanks to...
- Jim, Jeff Dandoy, and Eric Feng, who have all worked closely with me on my thesis analysis
- Mel for advising me on hardware projects
- Woowon and Marcela for being active committee members

Time working on Ph.D. ~6 years
Large Hadron Collider
Multi-layer detector with trackers, calorimeters & muon chambers
For reconstructing electrons, muons, photons, and jets from quark hadronization
The Standard Model (SM) and the Higgs

- Simple & accurate description of elementary particles and their interactions
- Consistent theory of strong, weak & electromagnetic forces
- **Gauge theory:** SU(3)⊗SU(2)⊗U(1)
  - Implies massless matter particles and gauge bosons

  **Matter particles:**
  \[
  \begin{pmatrix}
  v_e \\
  e \\
  \end{pmatrix},
  \begin{pmatrix}
  v_\mu \\
  \mu \\
  \end{pmatrix},
  \begin{pmatrix}
  v_\tau \\
  \tau \\
  \end{pmatrix},
  \begin{pmatrix}
  u \\
  d \\
  \end{pmatrix},
  \begin{pmatrix}
  c \\
  s \\
  \end{pmatrix},
  \begin{pmatrix}
  t \\
  b \\
  \end{pmatrix}
  \]

  **Gauge bosons:**
  \[g, W, Z, \gamma\]

- “Spontaneous symmetry breaking” allows for massive fermions & weak bosons, and predicts additional **Higgs boson**
July, 2012: Higgs-like boson observed in $\gamma\gamma$, $ZZ^*$, and $WW^*$ events by both ATLAS and CMS collaborations

2013 Nobel to Higgs & Englert

All particles in the SM have now been observed, but questions remain:
- Dark matter, Matter-antimatter asymmetry, Neutrino mass / oscillations, hierarchy problem
- Motivation to make **precise measurements** of the Higgs to expose any signs of possible new physics beyond the SM
Higgs boson spin/CP

* SM Higgs is CP-even scalar, $0^+$
* Final state observables can be used to test this hypothesis against other discrete eigenstates, e.g. CP-odd ($0^-$), CP-even with BSM couplings to higher dimensional operators ($0^{+\text{h}}$), graviton-like $2^+$
* ATLAS combination of $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*\rightarrow 4\ell$, $H\rightarrow WW^*\rightarrow e\nu\mu\nu$

![Example Separation between $0^+$ and $0^-$](image)

$0^-$ Excluded at $>99.97\%$ CL
Higgs boson spin/CP

- SM Higgs is CP-even scalar, 0⁺
- Final state observables can be used to test this hypothesis against other discrete eigenstates, e.g. CP-odd (0⁻), CP-even with BSM couplings to higher dimensional operators (0⁺ₜ), graviton-like 2⁺
- ATLAS combination of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

<table>
<thead>
<tr>
<th>Tested Hypothesis</th>
<th>Exclusion confidence level, tested against $0^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>$&gt; 99.97%$</td>
</tr>
<tr>
<td>$0^+_t$</td>
<td>$99.95%$</td>
</tr>
<tr>
<td>$2^+, \kappa_q/\kappa_g=0$</td>
<td>$&gt; 99.99%$</td>
</tr>
<tr>
<td>$2^+, \kappa_q/\kappa_g=1$</td>
<td>$99.99%$</td>
</tr>
<tr>
<td>$2^+, \kappa_q/\kappa_g=2$</td>
<td>$&gt; 99.99%$</td>
</tr>
</tbody>
</table>

- For the 2⁺ model there are no constraints on the quark and gluon couplings so exclusions are calculated for $\kappa_q/\kappa_g = 0, 1, 2$
CP Mixing

Also possible to have a mixture of CP eigenstates

CP violation in the Higgs sector, exists in Two-Higgs Doublet Models

Characterized by couplings in a tree level scattering amplitude for a generic scalar $X$:

$$A(X \rightarrow VV) = v^{-1} \left( g_1 m_V^2 \epsilon_1^* \epsilon_2^* - g_2 f_{\mu \nu}^{* (1)} f^{* (2), \mu \nu} + g_4 f_{\mu \nu}^{* (1)} \tilde{f}^{* (2), \mu \nu} \right)$$

$g_{1,2,4}$ are complex numbers that specify the CP mixture

- $0^+ \rightarrow g_1 = 1$, $g_{2,4} \approx 0$
- $0^- \rightarrow g_4 = 1$, $g_{1,2} \approx 0$

Can measure directly using final state observables in Higgs decays
**CP Mixing**

- $g_{1,2,4}$ are easily mapped to couplings + mixing angle $\alpha$ in an effective Lagrangian, or admixtures $f_{g2}$ and $f_{g4}$

\[ f_{gi} = \frac{|g_i|^2 \sigma_i}{|g_1|^2 \sigma_1 + |g_2|^2 \sigma_2 + |g_4|^2 \sigma_4} \]

- Effective Lagrangian conversion (notation from my abstract/thesis):

\[ g_4/g_1 = (\tilde{\kappa}_{AVV}/\kappa_{SM}) \tan \alpha, \quad g_2/g_1 = \tilde{\kappa}_{HVV}/\kappa_{SM} \]
H→ZZ∗→4ℓ final state

* Considered “golden channel” for the Higgs because of extremely low background and because leptons can be precisely measured

* Con: Low total yield

Diboson production:

* \( \text{BR}(H\rightarrow ZZ^*) \approx 2.8\% \)

* ~10x lower than \( H\rightarrow WW^* \)

* ~10x higher than \( H\rightarrow \gamma\gamma \)
**H→ZZ*→4ℓ final state**

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**Diboson decay:**
- \( \text{BR}(H\to ZZ^*\to 4\ell) \approx 1.3\times10^{-4} \)
  - ~10x lower than \( H\to \gamma\gamma \)
  - and \( H\to WW^*\to e\nu\mu\nu \)
- Low reconstruction efficiency
  - \(~(\text{lepton reconstruction eff})^4\)
H → ZZ* → 4ℓ observables

Lots of useful observables with 4 leptons in final state...

**Sensitivity to g_{1,2,4}**

\[ \cos\theta_1, \cos\theta_2, \Phi, m_{12}, m_{34} \]

\[ m_{4l}, p_{T,4l}, \eta_{4l}, \cos\theta^* \]

**Background separation**

[arXiv:1208.4018]
Signal distributions at parton-level

The scattering amplitude can be used to calculate an analytical matrix-element \( \mathcal{M}(\cos\theta_1, \cos\theta_2, \Phi, m_{12}, m_{34} | g_{1,2,4}) \) that tells us how to expect the data to be distributed for different values of \( g_{1,2,4} \).

\begin{align*}
\text{Signal distributions at parton-level} \\
\text{The scattering amplitude can be used to calculate an analytical matrix-}
\text{element } \mathcal{M}(\cos\theta_1, \cos\theta_2, \Phi, m_{12}, m_{34} | g_{1,2,4}) \text{ that tells us how to expect the data to be distributed for different values of } g_{1,2,4}.
\end{align*}
Simulated data for the measurement

ZZ Background: MC

Reducible backgrounds: Z+jets, ttbar, WZ  Mix of MC and data-driven methods

Signal:

- Production in PowHeg @ NLO; decay with JHU generator at LO
- We need simulated signal for many different CP-mixtures
- Save computer time by using the matrix-element to reweight a single MC sample to any target CP-mixture
- Each event is weighted separately based on the truth-level observables $\vec{x}=(\cos \theta_1, \cos \theta_2, \Phi, m_1, m_2)$

$$w_i = \frac{|\mathcal{M}(\vec{x}_i|\text{target } g_{1,2,4})|^2}{|\mathcal{M}(\vec{x}_i|\text{source } g_{1,2,4})|^2}$$
Simulated data for the measurement

**ZZ Background: MC**

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Mix of MC and data-driven methods

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\[ \mathbf{x} = (\cos \theta_1, \cos \theta_2, \Phi, m_1, m_2) \]

\[ w_i = |M(\tilde{x}_i| \text{source } g_1, g_2, g_4)|^2 \]

\[ \text{Example} \]
(Approximate) Event selection

- Single + di-lepton triggers
- Electrons:
  - $E_T > 7$ GeV
  - $|\eta| < 2.47$
- Muons:
  - $p_T > 6$ GeV
  - $|\eta| < 2.7$
- Require 4 separated leptons with $\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} > 0.1$, 2 OSSF pair
- $50 < m_{12} < 106$ GeV
- $12 < m_{34} < 65$ GeV
- $115 < m_{4\ell} < 130$ GeV (retains 95% of signal)

- Events divided into 4 final states: $4\mu$, $2e2\mu$, $2\mu2e$, $4e$
## Event Yields

**Dataset:** 20.3 fb\(^{-1}\) @ 8 TeV, 4.7 fb\(^{-1}\) @ 7 TeV

<table>
<thead>
<tr>
<th>Final State</th>
<th>Signal</th>
<th>ZZ(^*)</th>
<th>Reducible Bkg</th>
<th>Total Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4\mu)</td>
<td>5.81</td>
<td>3.36</td>
<td>0.97</td>
<td>10.14</td>
<td>13</td>
</tr>
<tr>
<td>(2e2\mu)</td>
<td>3.72</td>
<td>2.33</td>
<td>0.84</td>
<td>6.89</td>
<td>9</td>
</tr>
<tr>
<td>(2\mu2e)</td>
<td>3.00</td>
<td>1.59</td>
<td>0.52</td>
<td>5.11</td>
<td>8</td>
</tr>
<tr>
<td>(4e)</td>
<td>2.91</td>
<td>1.44</td>
<td>0.52</td>
<td>4.87</td>
<td>7</td>
</tr>
<tr>
<td>Combined</td>
<td>15.44</td>
<td>8.72</td>
<td>2.85</td>
<td>27.01</td>
<td>37</td>
</tr>
</tbody>
</table>

\(\sqrt{s} = 8\) TeV

<table>
<thead>
<tr>
<th>Final State</th>
<th>Signal</th>
<th>ZZ(^*)</th>
<th>Reducible Bkg</th>
<th>Total Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>(4\mu)</td>
<td>1.02</td>
<td>0.65</td>
<td>0.14</td>
<td>1.81</td>
<td>3</td>
</tr>
<tr>
<td>(2e2\mu)</td>
<td>0.64</td>
<td>0.45</td>
<td>0.13</td>
<td>1.22</td>
<td>2</td>
</tr>
<tr>
<td>(2\mu2e)</td>
<td>0.47</td>
<td>0.29</td>
<td>0.53</td>
<td>1.29</td>
<td>1</td>
</tr>
<tr>
<td>(4e)</td>
<td>0.45</td>
<td>0.26</td>
<td>0.59</td>
<td>1.30</td>
<td>2</td>
</tr>
<tr>
<td>Combined</td>
<td>2.58</td>
<td>1.65</td>
<td>1.39</td>
<td>5.62</td>
<td>8</td>
</tr>
</tbody>
</table>

\(\sqrt{s} = 7\) TeV

**Events passing selection in data = 45**

**Observed S/B = 2.1 (Expected = 1.2)**
Measurement strategies

* Two approaches done in parallel to cross-check one another, both using of the analytical matrix-element:
  
  * 9D Matrix-Element Method (9DMEM): Fit using 9-dimensional shape of all the useful observables
  
  * Matrix-Element Observable Method (ME-Obs): Collapse the many observables into 3 multivariate discriminants and fit using 3D shape of discriminants
  
  * Boosted Decision Tree (BDT) for background separation
  
  * Matrix-element ratios for sensitivity to $g_{1,2,4}$
9DMEM signal model

- Binned 9D histogram would require unrealistically large number of simulated events!
- **Solution**: slice 9D shape into 4 pieces, neglecting small correlations
- \( m_{4l}, (p_{T,4l}, \eta_{4l}), \cos\theta^* \) & \((\cos\theta_1, \cos\theta_2, \Phi, m_{12}, m_{34})\)

- For the **5D piece**, we start with the parton-level shape from the matrix-element and apply corrections for detector efficiency, acceptance & resolution
- Corrections are 2D and 3D MC histograms divided by matrix-element

\[ \text{ATLAS Internal} \quad 4_{\ell\ell}, \sqrt{s} = 8 \text{ TeV} \]

\[ g_1=g_2=g_4=1 \]
9DMEM background model

- Similar approach for backgrounds, but we have fewer MC events and no validated ME-based parton-level prediction, so there are more neglected correlations:
  - $m_{4l}$, $(p_{T,4l}, \eta_{4l})$, $\cos\theta^*$, $(\cos\theta_1, \cos\theta_2)$, $\Phi$, $(m_{12}, m_{34})$
  - $m_{4l}$ piece is smoothed using Kernel Density Estimation

- **Note:** Neglecting more correlations in background than signal could lead to biased measurement. This gets incorporated as a systematic uncertainty, which ends up being negligible.
Reconstructed shapes & data
Projected onto 6 of the 9 observables

0+ Higgs with SM cross-section
ZZ background
Reducible background

Background separation

$g_{1,2,4}$ sensitivity
Fit strategy

- Measure of $g_2/g_1$ & $g_4/g_1$ separately assuming real values & focusing on interval [-10, 10] where we currently have sensitivity
- Profile-likelihood fit
- Signal strength $\mu = \sigma/\sigma_{SM}$ and Higgs mass $m_H$ are free parameters determined by fit
  - Measured values consistent with SM
- Dominant systematics:
  - Theoretical ZZ* background rates from parton distribution function and QCD Scale
  - Reducible background uncertainties from transfer factor method
  - Luminosity uncertainty
- Dominant uncertainties combined have < O(0.5%) impact on expected $g_4/g_1$ 95% CL limits
Validate model by fitting to MC and checking that the measured results are consistent with the injected values

Example: Fitting to $O(100K)$ SM events, reweighted to $10 \times$ the current luminosity:
Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best-fit</th>
<th>Excluded at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected [red]</td>
<td>Observed</td>
</tr>
<tr>
<td>$g_4/g_1$</td>
<td>0.00 $^{+1.49}_{-1.49}$</td>
<td>-0.91 $^{+0.85}_{-0.96}$</td>
</tr>
<tr>
<td>$g_2/g_1$</td>
<td>0.00 $^{+0.82}_{-0.40}$</td>
<td>-0.36 $^{+0.42}_{-0.26}$</td>
</tr>
</tbody>
</table>

* Best-fit signal strength $\hat{\mu} = \hat{\sigma}/\sigma_{SM} \approx 1.7$ assuming 0+
* Results are consistent with SM @ 0
Results

2HDM/Technicolor Models predict $g_4/g_1 \approx O(0.1)$ \cite{arXiv:1307.1347}

SM electroweak corrections predict $g_2/g_1 \approx O(0.01)$

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</table>
Comparison with ME-Obs Method

Comparison to ME-Obs

Results are compatible
Combination with WW*

- Also measured in \( H \rightarrow WW^* \rightarrow e\nu\mu\nu \) channel with slightly less sensitivity
- Fit with two multi-variate discriminants:
  - One for background rejection and one for separating CP-hypotheses
- Combination with ZZ* results from ME-Obs method because it is computationally faster

### Parameter Table

<table>
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<tr>
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<th>Best-fit</th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected [red]</td>
<td>Observed</td>
</tr>
<tr>
<td>( g_4/g_1 )</td>
<td>0.00</td>
<td>-0.68</td>
</tr>
<tr>
<td>( g_2/g_1 )</td>
<td>0.00</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

**Nice consistency with SM**
Two-dimensional 9DMEM Fit

- Also possible to do simultaneous measurement of both parameters
- 9DMEM results within ~1σ of SM prediction (solid black contour):

\[ \sqrt{s} = 7+8 \text{ TeV}, \int L dt = 25 \text{ fb}^{-1} \]

\[ H \to ZZ^* \to 4l \]

9DMEM

ATLAS Internal

\[ \text{Observed} \quad \times \]

\[ \text{Expected } \hat{\mu}, \hat{\theta} \quad \text{+} \]

\[ \text{68\% CL} \quad \text{---} \]

\[ \text{95\% CL} \quad \text{...} \]
Looking Ahead

* We have nice fundamental limits characterizing the WW* and ZZ* final states

* Part of the motivation is to lay the groundwork for future measurements during Run II at the LHC

* Extrapolated expected 95% CL limits from $H \rightarrow ZZ^* \rightarrow 4\ell$ alone:
  - **300 fb$^{-1}$**: $|g_2/g_1| < O(0.5), |g_4/g_1| < O(1.6)$
  - **3000 fb$^{-1}$**: $|g_2/g_1| < O(0.1), |g_4/g_1| < O(0.4)$

* Barely probe current models with $\sim$3000 fb$^{-1}$
Conclusion

First CP-mixing measurement from ATLAS:

<table>
<thead>
<tr>
<th>Channels</th>
<th>95% CL intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BSM CP-odd contribution</td>
</tr>
<tr>
<td>ZZ*-only (9DMEM)</td>
<td>-3.24 &lt; g_4/g_1 &lt; 0.91</td>
</tr>
<tr>
<td>ZZ* + WW*</td>
<td>-2.18 &lt; g_4/g_1 &lt; 0.83</td>
</tr>
</tbody>
</table>

- Fundamentally characterization of the HVV vertex
- Groundwork for future measurement with many discriminant observables
  - Multi-dimensional fits will become more critical with more data to justify the simultaneous measurement of more parameters
- Small improvement estimated in Run II, but there will be more room for creativity
Backup
### Higgs Properties

Just some of the highlights:

<table>
<thead>
<tr>
<th>Property</th>
<th>Channels</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>ATLAS+CMS: γγ, ZZ</td>
<td>125.09 ± 0.21(stat) ± 0.11(syst) GeV</td>
</tr>
<tr>
<td>xsec (8 TeV)</td>
<td>ATLAS: γγ, ZZ</td>
<td>σ_{pp→H} = 33.0 ± 5.3(stat) ± 1.6(syst) pb (expected ~24 pb)</td>
</tr>
</tbody>
</table>

#### Couplings

- ATLAS: γγ, ZZ, WW, ττ, Vbb, μμ, Zγ, ttH

#### Decay width via off-shell couplings

- ATLAS: ZZ, WW
- CMS: ZZ
  \[ \Gamma_H/\Gamma_{H,SM} < 5.4 \times @ 95\% \text{ CL} \]

#### Spin/CP

- Details in this talk...
### ATLAS Higgs rates in different final states

#### ATLAS Preliminary

**Input measurements**

<table>
<thead>
<tr>
<th>Process</th>
<th>Input measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>μ</strong></td>
<td>± 1σ on <strong>μ</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>1.17±0.27</td>
<td>1.32±0.38</td>
<td>0.8±0.37</td>
<td>1.17±0.27</td>
<td>1.17±0.27</td>
<td>1.32±0.38</td>
<td>1.17±0.27</td>
<td>0.8±0.37</td>
</tr>
<tr>
<td>H → ZZ*</td>
<td>1.44±0.33</td>
<td>1.9±0.4</td>
<td>0.3±0.39</td>
<td>1.44±0.33</td>
<td>1.44±0.33</td>
<td>1.9±0.4</td>
<td>1.44±0.33</td>
<td>0.3±0.39</td>
</tr>
<tr>
<td>H → WW*</td>
<td>1.16±0.21</td>
<td>0.9±0.29</td>
<td>1.26±0.36</td>
<td>1.16±0.21</td>
<td>1.16±0.21</td>
<td>0.9±0.29</td>
<td>1.26±0.36</td>
<td>1.16±0.21</td>
</tr>
<tr>
<td>H → ττ</td>
<td>1.43±0.43</td>
<td>2.0±1.8</td>
<td>1.24±0.59</td>
<td>1.43±0.43</td>
<td>1.43±0.43</td>
<td>2.0±1.8</td>
<td>1.24±0.59</td>
<td>1.43±0.43</td>
</tr>
<tr>
<td>VH → Vbb</td>
<td>0.52±0.40</td>
<td>1.15±0.7</td>
<td>0.06±0.30</td>
<td>0.52±0.40</td>
<td>0.52±0.40</td>
<td>1.15±0.7</td>
<td>0.06±0.30</td>
<td>0.52±0.40</td>
</tr>
<tr>
<td>H → μμ</td>
<td>-0.7±0.7</td>
<td>-0.7±0.7</td>
<td>-0.7±0.7</td>
<td>-0.7±0.7</td>
<td>125.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H → Zγ</td>
<td>2.7±4.3</td>
<td>2.7±4.3</td>
<td>2.7±4.3</td>
<td>2.7±4.3</td>
<td>125.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td>1.5±1.1</td>
<td>1.5±1.1</td>
<td>1.5±1.1</td>
<td>1.5±1.1</td>
<td>125</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS Higgs mass**

- **m_H = 125.36 GeV**

**Colliders**

- **√s = 7 TeV, 4.5-4.7 fb^{-1}**
- **√s = 8 TeV, 20.3 fb^{-1}**
Effective Lagrangian Approach

- Mixture characterized by non-SM couplings in Eff. Lagrangian:

\[
\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{SM} \left[ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^-_\mu \right] - \frac{1}{4} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2} \frac{1}{\Lambda} \left[ c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^-_{\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^-_{\mu\nu} \right] \right\} X_0.
\]

- BSM CP-even contributions

- BSM CP-odd contributions (CP-violation!)

- Coupling ratios \((\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha\) and \(\tilde{\kappa}_{HVV}/\kappa_{SM}\) measured directly, where \(\tilde{\kappa}_x\) is the non-SM coupling scaled by the vacuum expectation value over 4\(\times\)energy scale for new physics \((\Lambda)\) to be consistent with \(g_4/g_1\) and \(g_2/g_1\)

- E.g.

\[
\begin{align*}
0^+ & \rightarrow (\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha=0, \quad \tilde{\kappa}_{HVV}/\kappa_{SM}=0 \\
0^- & \rightarrow (\tilde{\kappa}_{AVV}/\kappa_{SM})\tan\alpha=1, \quad \tilde{\kappa}_{HVV}/\kappa_{SM}=0
\end{align*}
\]
Matrix-element calculation

Scattering amplitude can be separated into 3 helicity states with amplitudes dependent on $g_{1,2,4}$

\[
\begin{align*}
A_{00} & \quad & A_{++} & \quad & A_{--} \\
\end{align*}
\]

\[
\frac{N_J}{d\Gamma_J(m_1, m_2, \cos \theta^*, \Psi, \cos \theta_1, \cos \theta_2, \Phi)} = \frac{d}{d \cos \theta^* d\Psi d \cos \theta_1 d \cos \theta_2 d\Phi} F_{0,0}^J(\theta^*) \times \left[ 4 |A_{00}|^2 \sin^2 \theta_1 \sin^2 \theta_2 \right. \\
& \quad \left. + |A_{++}|^2 \left( 1 + 2 A_{f_1} \cos \theta_1 + \cos^2 \theta_1 \right) \left( 1 + 2 A_{f_2} \cos \theta_2 + \cos^2 \theta_2 \right) \right. \\
& \quad \left. + |A_{--}|^2 \left( 1 - 2 A_{f_1} \cos \theta_1 + \cos^2 \theta_1 \right) \left( 1 - 2 A_{f_2} \cos \theta_2 + \cos^2 \theta_2 \right) \right. \\
& \quad \left. + 4 |A_{00}| |A_{++}| \left( A_{f_1} \sin \theta_1 \left( A_{f_2} \sin \theta_2 \cos(\Phi + \phi_{++}) \right) \right. \\
& \quad \left. + 4 |A_{00}| |A_{--}| \left( A_{f_1} \sin \theta_1 \left( A_{f_2} \sin \theta_2 \cos(\Phi - \phi_{--}) \right) \right. \\
& \quad \left. + 2 |A_{++}| |A_{--}| \sin^2 \theta_1 \sin^2 \theta_2 \cos(2\Phi - \phi_{--} + \phi_{++}) \right] \right] 
\]
ZZ Background correlations

\[
\begin{align*}
\Phi & \quad 0.004 & 0.005 & 0.003 & 0.006 & -0.001 & -0.008 & 0.003 & -0.001 & 1.000 \\
m_{34} & \quad 0.119 & 0.060 & 0.005 & 0.004 & -0.004 & -0.006 & -0.530 & 1.000 \\
m_{12} & \quad 0.154 & -0.083 & -0.011 & -0.005 & 0.002 & 0.003 & 1.000 \\
\cos\theta_2 & \quad 0.001 & -0.002 & 0.002 & -0.004 & 0.121 & 1.000 \\
\cos\theta_1 & \quad 0.002 & 0.003 & -0.000 & 0.003 & 1.000 \\
\cos\theta^* & \quad -0.004 & -0.000 & 0.038 & 1.000 \\
\eta_{4l} & \quad 0.005 & 0.006 & 1.000 \\
p_{T,4l} & \quad 0.029 & 1.000 \\
m_{4l} & \quad 1.000 \\
m_{4l} & \quad m_{4l} & p_{T,4l} & \eta_{4l} & \cos\theta^* & \cos\theta_1 & \cos\theta_2 & m_{12} & m_{34} & \Phi
\end{align*}
\]

**ATLAS** Internal

\(4\mu, \sqrt{s} = 8\text{ TeV}\)

ZZ Background MC
Impact on the expected likelihood curve (fitting with signal-only model) from removing more correlations in the 5D shape sensitive to $g_{1,2,4}$.
Example of a small functional dependence between $\Phi$ and $\cos\theta_1$ that appears for CP-states “nearby” 0- (also occurs for $\cos\theta_2$ vs. $\Phi$)
Impact from background-rejection observables

\[ m_{4l} \] has largest impact by far out of background discriminants
Asymptotic approximation allows us to infer uncertainty intervals from a single 
-2\ln\Lambda scan, which saves lots of CPU time.

This is only valid if -2\ln\Lambda values at the injection point are distributed like a 
ChiSquare function (typically the case when N\text{events} is large).

**Example profile-likelihood distribution**

- ATLAS Internal
- All Final States, 7+8 TeV
- 1 x Run I
- Injecting $\frac{\kappa_{HV}}{\kappa_{SM}} = 5$

ChiSquare(NDF=1)

95% : Asymptotic

95% : Toys

**Example profile-likelihood distribution from 300 toys with $g_4/g_1=5$**
Compatibility of the two methods

- Same set of checks done for alternative ME-Obs fitting method as well
- How do the expected results compare for the 2 methods?
  - Results compared for 300 SM toys generated from MC:

\[
\frac{K_{AVV}}{K_{SM}} \sim \alpha \tan \Omega_{SM} \kappa_{AVV} \kappa_{SM}
\]

\[
\begin{array}{c}
\text{Correlation} = 0.64 \\
\text{Covariance} = 1.53
\end{array}
\]

\[
\begin{array}{c}
\text{Mean} = -0.07 \pm 0.08 \\
\text{RMS} = 1.33 \pm 0.05
\end{array}
\]

\[
\frac{g_4}{g_1}
\]
Compatibility of the two methods

Gaps at peak expected exclusion near -1.5
Distributions from Toys: $g_2/g_1$

* Example toys for $9DMEM > -1.5$ and ME-Obs $< -1.5$...
Post-analysis

**Distribution of toys used to produce expected uncertainty band for comparison with data**

- **Dashed red**: Median
- **Green band**: 68% interval
- **Yellow band**: 95% interval
Comparison to CMS

- CMS spin/CP combination published in November, 2014
  [arXiv:1411.3441]

- Some differences w.r.t. ATLAS
  - Results reported in terms of admixtures $f_{a2}(=f_{g2})$ and $f_{a3}(=f_{g4})$
  - More data: 7 TeV included for $H \rightarrow WW^* \rightarrow e\nu\nu$
  - Multiple parameters allowed to float at the same time (analogous to a simultaneous fit for $g_4/g_1$ and $g_2/g_1$)
  - More inclusive selection: 50 events passing in $ZZ^*$ final state, 56 expected
Comparison to CMS


### BSM CP-odd fraction (calculated from $g_4/g_1$)

**Experiment & Channels**

<table>
<thead>
<tr>
<th>Channels</th>
<th>BSM CP-odd contribution</th>
<th>BSM CP-even contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS: WW, ZZ</td>
<td>$-2.18 &lt; g_4/g_1 &lt; 0.83$</td>
<td>$-0.73 &lt; g_2/g_1 &lt; 0.63$</td>
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<tr>
<td></td>
<td>$-0.41 &lt; f_{a3} \cos(\phi_{a3}) &lt; 0.09$</td>
<td>$-0.16 &lt; f_{a2} \cos(\phi_{a2}) &lt; 0.12$</td>
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<tr>
<td>CMS: WW, ZZ</td>
<td>$-0.27 &lt; f_{a3} \cos(\phi_{a3}) &lt; 0.28$</td>
<td>$-0.11 &lt; f_{a2} \cos(\phi_{a2}) &lt; 0.17$</td>
</tr>
</tbody>
</table>

---

Approximate 95% exclusions from ATLAS

Fair comparison (signal strengths uncorrelated between WW* and ZZ*)
Fast TracKer Trigger Upgrade
FTK Overview

- Track reconstruction in the trigger is challenging and slow
- FTK is a hardware solution designed to do full track reconstruction at the $O(100 \text{ KHz})$ level 1 output rate
  - helix parameters and $\chi^2$ values get passed to level 2, freeing up resources for more complicated trigger decisions
  - b-jets, $\tau$ leptons, track-MET, etc.
- Parallel pattern matching for hits with Associative Memory (AM)
FTK Design

A potpourri of boards and technologies
FTK Design

Dual HOLA splits ROD data streams for DAQ and FTK
An input mezzanine clusters incoming hits, and the Data Formatter sorts hits into $\eta$-$\phi$ towers (64 FTK towers). Tracks which successfully attach hits in three out of the remaining four layers and pass a second cut are considered the final tracks.

FTK interfaces to the rest of the HLT through the FLIC, the FTK Level-2 Interface Crate. It formats the FTK track output, now in Raw Data Output (RDO) format, into ROD fragments and sends the data to the ROSs. The track output consists of the helix parameters as determined by FTK, and the FTK cluster information. At $3 \times 10^{34}$ cm$^2$ s$^{-1}$ luminosity with 25 ns bunch spacing there are $\sim 300$ tracks per event found by FTK. There are 100 bytes of data per track leading to a data transfer rate between FTK and the ROSs of 3 GB/s.

FTK track information can be utilized in three different ways at the HLT. First, algorithms may use the track parameters as calculated by FTK. In order to utilize their information, FTK RDOs are converted to HLT input objects which contain the track parameters and Pixel and SCT cluster positions calculated by FTK. There is a time, yet to be measured, to unpack the data and create the input objects used by the HLT algorithms. Some algorithms may require performing a refit of the FTK track using the FTK cluster positions. Updated cluster-position errors are calculated based on the cluster width and then a refit is performed to the FTK cluster positions using the offline Global track fitter [5]. The time required, measured on an Intel(R) Xeon(R) CPU (2.27 GHz), is approximately 2 ms per track. Using a faster fitter with a simple material description (Distributed Kalman Fitter [6]) would reduce this time to roughly 0.5 ms per track, but with slightly worse parameter resolution. The final option is to use FTK track parameters to initiate (seed) HLT tracking. The first two methods require only the information provided by FTK whilst the third method additionally requires Inner Detector RAW data. Performance measurements from the first two methods are presented in this note.

### 2.2 FTK Emulation

FTK has a dedicated simulation framework, TrigFTKSim, to provide functional emulation of the hardware. At present it replicates all of the logical elements of FTK processing, but does not provide a...
FTK Design

AUX calculates course resolution hits ("superstrips") and sends them to AM for pattern matching.
AM sends matched patterns ("roads") to AUX and $\chi^2$ values are calculated with full resolution hits from 8 layers

FTK Design

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SSB performs extrapolation to 12 layers using candidate tracks passing first stage, calculates helix parameters.
FTK Design

FLIC formats output for HLT

Figure 1: Functional sketch of FTK. AM is the Associative Memory, DO is the Data Organizer, FLIC is the FTK-to-Level-2 Interface Crate, HW is the Hit Warrior, ROB is the ATLAS Read Out input Buffer, ROD is a silicon detector Read Out Driver, and TF is the Track Fitter. Second Stage Fit is referred to as the Second Stage Board.

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More detail on the AUX

- Full FTK system contains 128 AUX boards
- 2 “Input” FPGAs + 4 “Processor” FPGAs per board
Track Fitter

- $\chi^2$ values calculated using linear approximation, multiplying hits by pre-stored constants
- 5 Mb of constants stored on each FPGA
- Mixture of fixed and floating point formats
- Calculation is done for all combinations of hits in each road (there are often multiple hits per layer)
- Hits are sometimes missing in layers due to detector inefficiency
  - Solution: If one layer is missing, calculate a “guessed” hit value that minimizes the $\chi^2$
- Design spec: average of 1 fit/ns per FPGA, 200 MHz clock speed
- Functional firmware in place: ~25,000 lines VHDL, ~10 W
  - Ongoing work to increase speed (will be taken over by Karol Krizka)
FTK Installation Schedule

<table>
<thead>
<tr>
<th></th>
<th>IM</th>
<th>DF</th>
<th>AUX</th>
<th>AMB</th>
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<td>32</td>
<td>2</td>
<td>TDR Specs</td>
<td>2018 / Lumi driven</td>
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</table>

- Dual-output HOLA cards installed in 2012-2013
- “Vertical slice” tests done with live data in 2013: just testing HOLAs and pattern matching in slice of detector
- Recent data tests during M7
- **AUX status:** TDR done, PRR early 2015, testing prototypes at Chicago and CERN
Performance in Simulation

- Efficiency evaluated w.r.t. offline for single muons & pions
  \[ \text{Efficiency} = \frac{N_{\text{Off}}(dR_{\text{Off-FTK}} < 0.05)}{N_{\text{Off}}} \]

- Efficiency w.r.t. truth \(~\approx 90\%\) for muons, lower for pions due to more hadronic interactions
Performance in Simulation

- Simple b-tagger built using FTK $d_0$ significance
- b-tag trigger efficiency calculated for three different rejections w.r.t. offline b-tag efficiency
Conclusion

- FTK will be a critical tool for doing physics at high pile-up
- Full detector implementation by 2017
- Start thinking about final states with lots of b’s and τ’s!