BEH Overview (ATLAS)

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Overview

• Higgs Boson Production and Decay:
  – Bosonic Decays,
  – Fermionic Production and Decay.

• Higgs Properties:
  – Mass Measurements,
  – Spin / Parity,
  – Width,
  – Higgs Couplings.

• Higgs beyond the Standard Model.

• Conclusion and Summary.
The ATLAS Detector

• Run 1:
  – 2011 at $\sqrt{s}=7$ TeV.
  – 2012 at $\sqrt{s}=8$ TeV.
  – Total $\sim 29$ fb$^{-1}$.

• Run 2:
  – 2015-2018 at $\sqrt{s}=13$ TeV.
  – $\sim 36.1$ fb$^{-1}$ for 2015+2016.
  – $\sim 14$ fb$^{-1}$ for 2017 so far...
Higgs Boson

- The Brout-Englert-Higgs (BEH) mechanism extended spontaneous symmetry breaking to gauge fields.
  - The process generates mass for fundamental particles.
- It also predicted a scalar particle, often referred to as the Higgs boson.
  - However, the mass of the Higgs boson is not predicted in the SM.
- In 2012, CERN announced the discovery!
- Once the Higgs mass is measured, the other parameters become fixed and can be measured and compared to SM predictions. These other parameters are:
  - Mass measurements
  - Spin/Parity
  - Width
  - Higgs couplings.
- Small deviations in the Higgs boson’s properties from those predicted could give hints of new physics.
- The exploration of this new particle is still in early stages.
  - We have collected only ~1% of the anticipated luminosity from the LHC.

Source: AAAS

19th August 2017
Higgs Boson Production

- Run 1 -> Run 2.
  - Increase of Higgs cross-sections.
  - Especially for ttH production (~4x).

- **Gluon Gluon Fusion**
  - The dominant production mode.

- **VBF : Vector Boson Fusion**
  - Second most dominant.
  - Characterized by two forward jets produced along with a Higgs.

- **VH**
  - Composed of a Higgs produced in association with a vector boson.

- **ttH**
  - Higgs produced in association with ttbar pair.
Decay methods

- For a standard model Higgs boson with a mass of ~125 GeV:
  - Decays with the highest branching ratios also have large irreducible backgrounds.
  - However, resolution and S/B are equally critical for the sensitivity.
  - Clean signals for low branching ratio signals:
    - $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4 \ell$ ($\ell$=e,μ).
    - The ‘discovery’ channels.
The discovery of the Higgs in 2012 was announced with bosonic decay channels.

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ^* \rightarrow 4\ell$
  \hspace{1cm} ($\ell = e, \mu$)
- $H \rightarrow WW^*$

See detailed talk: 
*Measurement of cross sections and couplings of the Higgs Boson in bosonic decay channels with the ATLAS detector* Nikita Belyaev

Display of a 4e candidate event. $m_{4\ell} = 124.2$ GeV
Signal is extracted using a maximum-likelihood fit to the diphoton invariant mass.

- Simultaneous fit for a bump on top of a smoothly falling background.

- The main backgrounds for this channel are $\gamma\gamma$, $\gamma$+jets and dijets.
H → ZZ* → 4ℓ and H → WW*

H → ZZ* → 4ℓ:
• High signal to background ratio.
• Extract signal via four-lepton invariant mass.

- The inclusive fiducial cross-section in the H→ZZ*→4ℓ decay channel is:
  - 3.62 +0.53−0.50 (stat) +0.25−0.20 (sys) fb
- Standard Model prediction of:
  - 2.91 ± 0.13 fb.
- Differential fiducial cross-section has also been measured.

H → WW*:
• Second largest branching ratio.

- Latest result with 5.8 fb⁻¹ of Run 2 data.
  - Via VBF and associated WH production.
  - \( \mu_{\text{VBF}} = 1.7 + 1.1 - 0.9 \)
  - \( \mu_{\text{WH}} = 3.2 + 4.4 - 4.2 \)
Want to confirm that the Higgs boson is the one predicted in the SM and therefore testing the direct coupling with fermions is high priority.

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $H \rightarrow bb$
- $ttH$

See detailed talk:

*Measurement of cross sections and couplings of the Higgs Boson in fermionic production and decay modes with the ATLAS detector*

Liaoshan Shi

Candidate $H \rightarrow \mu\mu$ event at $\sqrt{s} = 13$ TeV.
H → ττ and H → μμ

H → ττ
- Two production modes: ggF and VBF
- Three decay modes: \(\tau_\text{lep}\tau_\text{lep}, \tau_\text{lep}\tau_\text{had}, \tau_\text{had}\tau_\text{had}\)
  - Requires good tau identification.
- \(Z \to \tau\tau\) is the main background.

H → μμ
- Allows a direct observation of the Higgs Yukawa coupling to 2\(^{nd}\) generation fermions.
- Clean signal, but low decay rate and a large background from \(Z \to \mu\mu\) (4x SM).
- Channel is statistically limited.

Run 2

Result (Run 1 + 2):
- \(\mu < 2.8\) (2.9) observed (expected).
- Consistent with SM expectation that Higgs coupling is proportional to mass.

Run 1 result (ATLAS):
- \(4.5\sigma\) (3.4\(\sigma\)) observed (expected).

Combined ATLAS & CMS:
- \(5.5\sigma\) (5.0\(\sigma\)) observed (expected).

JHEP 04 (2015) 117

H → bb candidate event
H → bb

- The most common decay for a SM Higgs at 58% but there are large backgrounds which are difficult to separate from signal.

- New result released recently via associated production with a W/Z boson.

- Gives the first evidence from the LHC of H→bb, with a significance, for the BDT Run 2 result, of: $3.5\sigma$ ($3.0\sigma$) observed (expected).

- Combined significance for Run 1 + Run 2: $3.6\sigma$ ($4.0\sigma$) observed (expected).

- Signal strength (combined Run 1 + Run 2): $\mu = 0.90 \pm 0.18\text{(stat.)} + 0.21 - 0.19\text{(syst.)}$

- Measurement of VZ, where $Z \rightarrow bb$ was used as a cross-check, gave a significance of: $5.8\sigma$ ($5.3\sigma$) observed (expected).

[arXiv:1708.03299 [hep-ex]]

Run 2
• Indirect constraints on the top Yukawa coupling to the Higgs can be inferred from ggF production, and from $H \rightarrow \gamma\gamma$ decays.
• Also want to measure direct couplings.

• **ttH Channels:**
  - $H \rightarrow \gamma\gamma$
    • both the hadronic and leptonic $t\bar{t}$ decay channels.
  - $H \rightarrow (WW(\ast), \tau\tau, ZZ(\ast)) \rightarrow$ leptons
    • two – four final lepton states.
  - $H \rightarrow bb$
    • single lepton,
    • opposite-sign dilepton.

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ATLAS-Cong-2016-068

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See detailed talk: *ttH Coupling Measurement with the ATLAS Detector at the LHC* Asma Hadef

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**Run 2**

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**2015+2016**

\[
\begin{align*}
\text{ATLAS Preliminary} & \quad s=13 \text{ TeV, 13.2-13.3 fb}^{-1} \\
\text{ttH} (H\rightarrow\gamma\gamma) & \quad (13 \text{ TeV 13.3 fb}^{-1}) \\
& \quad \text{total} \quad -0.3^{+1.2}_{-1.0} \quad (\text{stat. syst.}) \\
\text{ttH} (H\rightarrow WW/\tau\tau ZZ) & \quad (13 \text{ TeV 13.2 fb}^{-1}) \\
& \quad \text{total} \quad 2.5^{+1.3}_{-1.1} \quad (\text{stat. syst.}) \\
\text{ttH} (H\rightarrow bb) & \quad (13 \text{ TeV 13.2 fb}^{-1}) \\
& \quad \text{total} \quad 2.1^{+1.0}_{-0.9} \quad (\text{stat. syst.}) \\
\text{ttH combination} & \quad (13 \text{ TeV}) \\
& \quad \text{total} \quad 1.8^{+0.7}_{-0.7} \quad (\text{stat. syst.}) \\
\text{ttH combination} & \quad (7-8\text{TeV, 4.5-20.3 fb}^{-1}) \\
& \quad \text{total} \quad 1.7^{+0.8}_{-0.8} \quad (\text{stat. syst.}) \\
\end{align*}
\]
The mass of the Higgs is measured using the two ‘discovery’ channels:
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e, \mu$).
- $H \rightarrow ZZ \rightarrow 4\ell$ is still statistically limited, while $H \rightarrow \gamma\gamma$ is systematically limited.
- Combined Run 2 measurement with 36 $fb^{-1}$.

Result: $m_H = 124.98 \pm 0.19$ (statistical) $\pm 0.21$ (systematic) GeV
Spin / Parity

• Measurement using:
  – $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ and $H \rightarrow \gamma\gamma$ decay processes.
  – Using 25 fb$^{-1}$ at Run 1 ($\sqrt{s}=7$ and 8 TeV).

• Spin:
  – The SM Higgs hypothesis ($JP=0^+$) is tested against alternative spin scenarios:
    • Non-SM spin-0 and spin-2 models with universal and non-universal couplings to fermions and vector bosons.
  – Result: All tested alternative models are excluded in favour of SM Higgs hypothesis at > 99.9 % Confidence Level (CL).

• Parity:
  – Want to test the parity as there can be CP mixtures in various BSM models, such as SUSY.
  – x-axis: observed CP-odd fraction of the event yield $f_{g4}$
    The combination of $H \rightarrow ZZ$ (which dominates) and $H \rightarrow WW$ sets an upper limit of:
    $f_{g4} < 45$ % at 95% CL on the CP-odd component.
Measurements of ZZ and WW final states in the mass range above the $2m_Z$ and $2m_W$ thresholds allow measurement of the off-shell coupling strength of the Higgs.

- Using $20.3 \text{ fb}^{-1}$ at $\sqrt{s}=8$ TeV (Run 1).
- ZZ$\rightarrow$4ℓ, ZZ$\rightarrow$2ℓ2ν and WW$\rightarrow$eνμν final states.

Result: a combination with the on-shell measurements yields, at 95% CL upper limit, an **observed** (expected) total width, $\Gamma_H/\Gamma_{SM}^H$, in the range of: $4.5–7.5$ ($6.5–11.2$).
Couplings

- Coupling strength modifiers, $\kappa$, are used to probe the coupling strengths and test for deviations from the SM expectations.
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ ($\ell = e,\mu$).
- Run 2 with $36.1$ fb$^{-1}$.

No significant deviations from the SM expectations are observed.

**ATLAS-CONF-2017-047**
• Four-lepton candidate event with two electrons and two muons recorded in 2016.
• Only event observed in the doubly-charged Higgs four-lepton signal region.
The Higgs can be used to probe for physics beyond the Standard Model (BSM) if there are anomalous or new Higgs couplings.

- **H → invisible**
  - $pp \rightarrow ZH \rightarrow ll + \text{missing energy}$ with 2015+2016 Run 2 data (36.1 fb$^{-1}$).
  - $\text{BR}(H(125) \rightarrow \text{invisible}) < 67\%$ obs. (39\% exp.) at 95\% CL, assuming SM ZH production rate.

- **Lepton flavour violation**
  - Decay of the Higgs boson to leptons with different flavours.
  - 20.3 fb$^{-1}$ of 8 TeV Run 1 data.
  - Reconstruct the Higgs mass for $H \rightarrow l_{(e, \mu)}\tau_{\text{had}}$ and $H \rightarrow e\tau_{\text{lep}}$.
  - No significant excess observed. Set upper limits at 95\% confidence level:
    - $\text{Br}(H \rightarrow e\tau) < 1.04\%$
    - $\text{Br}(H \rightarrow \mu\tau) < 1.43\%$
    - $\text{Br}(Z \rightarrow \mu\tau) < 1.69 \times 10^{-5}$.

Higgs beyond the SM (2)

- **H → Zγ**
  
  - Produced via loop diagrams:
  
  - Preliminary results at 95% CL upper limit with $m_H = 125.09$ GeV:
    - Cross-section $\times$ BR = 6.6 (5.2) times the SM prediction observed (expected) assuming SM production and decay.

- **H → φγ, H → ργ**
  
  - Probe of the Higgs couplings to light quarks.
  
  - Measurement with 2015+2016 Run 2 data (35.6 fb$^{-1}$).
  
  - No significant excess of events is observed above background, in agreement with SM expectations. Upper limits at 95% CL:
    - $BR(H → φγ) = 4.8 \times 10^{-4}$,
    - $BR(H → ργ) = 8.8 \times 10^{-4}$.

See detailed talk: *Search for neutral and charged BSM Higgs Bosons with the ATLAS detector*

Pawel Bruckman de Renstrom

See detailed talk: *Search for rare and exotic Higgs Boson decay modes and Higgs boson pair production with the ATLAS detector*

Suyog Shrestha
• The highlight of Run 1 was the discovery of a SM Higgs boson.
• Significant aim of Run 2 is to measure the properties of this boson and use it to probe for new physics.
  – Measurements for mass, spin/parity, width and couplings have been presented. Evidence of the Higgs decaying into fermions, such as tau leptons and b quarks, has been shown.
  – So far, no observation of deviations from the SM expectations.
• But: the exploration of this new particle is still in the early stages.
  – We have collected only ~1% of the anticipated luminosity from the LHC.
• Lots of interesting ATLAS Higgs talks at this conference for further details!
Thank you for your attention.
Backup
Large Hadron Collider at CERN (Geneva, Switzerland)
Mass Measurements

• $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^* \rightarrow 4 \ell \ (\ell=e,\mu)$.

• Why these channels?
  – In these channels all of the decay particles can be measured by the ATLAS detector with high precision.
  – Also no missing energy in the final state.

• How are they precise?
  – The key lies in the resolution and calibration of the ATLAS detector. Many different parts are used:
    • the muon momentum is measured in the Inner Detector and the Muon Spectrometer
    • the electron and photon energy is reconstructed in the Liquid Argon electromagnetic calorimeter.
  – Understanding the alignment of the tracking detectors provides the precision of the muon momentum, and the calibration of the calorimeter response is key for electrons and photons.
  – The uncertainty of the muon momentum is known to 0.1–0.5%, depending on the position of the muon, while the uncertainty on the electron (photon) energy scale is 0.02–0.8% (0.4–0.8%) depending on their energy and position.
  – The quality of the alignment and calibration of the data can be seen below, where the abundant Z bosons decay into two muons and into two electrons.
Mass - systematics

- Leading sources of systematic uncertainty on $m_H$ in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel.

- Main sources of systematic uncertainty on $m_{H\gamma\gamma}$.

- Main sources of systematic uncertainty on the combined mass $m_H$.

<table>
<thead>
<tr>
<th>Systematic effect</th>
<th>Uncertainty on $m_H^{ZZ^*}$ [MeV]</th>
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<tbody>
<tr>
<td>Muon momentum scale</td>
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<tr>
<td>Electron energy scale</td>
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<tr>
<td>Background modelling</td>
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<tr>
<td>Simulation statistics</td>
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<table>
<thead>
<tr>
<th>Source</th>
<th>Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]</th>
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<tbody>
<tr>
<td>LAr cell non-linearity</td>
<td>±200</td>
</tr>
<tr>
<td>LAr layer calibration</td>
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<tr>
<td>Non-ID material</td>
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<tr>
<td>Lateral shower shape</td>
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<td>ID material</td>
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</tr>
<tr>
<td>Conversion reconstruction</td>
<td>±50</td>
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<tr>
<td>$Z \rightarrow ee$ calibration</td>
<td>±50</td>
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<td>Background model</td>
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<tr>
<td>Primary vertex effect on mass scale</td>
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<td>Resolution</td>
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<tr>
<td>Signal model</td>
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<tr>
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<td>LAr layer calibration</td>
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<td>Non-ID material</td>
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<td>ID material</td>
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<td>Lateral shower shape</td>
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<td>$Z \rightarrow ee$ calibration</td>
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<td>Muon momentum scale</td>
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<tr>
<td>Conversion reconstruction</td>
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Scan of the negative log-likelihood as a function of $\Gamma_H/\Gamma_{SM}^H$ when profiling the coupling scale factors $\kappa_g$ and $\kappa_V$ associated with the on- and off-shell $gg \rightarrow H$ (*) and VBF production and the $H$ (*) $\rightarrow VV$ decay.
• CONTENT