Recent Higgs Results from the ATLAS experiment

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On behalf of the ATLAS Collaboration

The Discovery of the Higgs Boson

- Production mechanisms, cross sections and branching ratios of the Higgs at the LHC
- The ATLAS Detector

Higgs Boson “Discovery Channels”

- $H \rightarrow \gamma\gamma$ Channel
- $H \rightarrow ZZ$ Channel
- $H \rightarrow WW$ Channel

Other Higgs channels

- $H \rightarrow \tau\tau$
- $ZH \rightarrow ll + \text{invisible}$
- $H \rightarrow bb$ Channels

Higgs Boson Properties

- Signal Strength and Couplings
- Spin

Higgs Boson Production Modes

- Main production: gluon-gluon fusion
 - Proceeds mainly through the top loop
 - Roughly 10x the production (@ $M_H=125$ GeV) at the LHC than at the Tevatron

- Vector Boson Fusion

- Lower cross section
- Involves direct probe into vector boson coupling constant
- Signature includes two forward high-Pt jets with a large separation in rapidity space
- Analyses use this signature to target this production mode

- $V \rightarrow VH$ (associated production)

- $t\bar{t}$ fusion

- Direct coupling to top quark

<http://sites.uci.edu/energyobserver/2012/11/26/higgs-production-and-decay-channels/>

Guiding principles

- Final states with leptons or photons are easier to distinguish, measure
- Decays to jets are more difficult to separate from QCD background

Discovery Channels

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^* \rightarrow 4l$
- $H \rightarrow WW^*(\rightarrow l\nu l\nu)$

Additional Channels

- $H \rightarrow \tau\tau$
- $H \rightarrow \mu\mu$
- $ZH \rightarrow ll + \text{Invisible}$
- $H \rightarrow b\bar{b}$

- The LHC: Phenomenal Machine Performance
 - Proton-proton collider
 - CM Energies of 7 TeV (2011) and 8 TeV (2012)
 - Delivered $\sim 5 \text{ fb}^{-1}$ in 2011
 - Delivered $\sim 23 \text{ fb}^{-1}$ in 2012
 - Peak instantaneous luminosity: $\sim 8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Challenge in 2012: High pileup conditions
 - Average interactions per bunch crossing increased
 - Must reconstruct and resolve 20 vertices within the space of ~ 100 s of mm
 - Requires careful treatment of missing transverse momentum calculation

The ATLAS detector was built with the discovery of the Higgs in mind

- Identification of electrons and photons against QCD jets
- Precise measurement of particle energy and position
- Excellent calorimetry hermeticity and depth for inferring momentum imbalance (missing transverse momentum)
- Precise muon spectrometry and triggering

The ATLAS detector was built with the discovery of the Higgs in mind

- The Inner Detector

- Provides tracking of charged particles
- 2T magnetic field
- Silicon pixel detector: 80M channels, $10 \times 15 \mu\text{m}$ spatial resolution
- SCT microstrips: 6M channels, $17 \mu\text{m}$ resolution
- TRT: Particle identification of electrons using transition radiation

- The Calorimeter Systems

- Energy measurement and detailed shower shapes for particle identification
- Fine segmentation of the first calorimeter layer to determine the kinematics of photon path
- Full volume coverage to measure missing transverse momentum in an event

- The Muon Spectrometer

- Magnetic field generated by toroidal superconducting air-core magnets
- Separate systems for precise tracking and triggering

The discovery of the Higgs Boson

- Discovery driven by $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$ channels
- How did we get there?
- Is it the Higgs Boson?

What can we measure?

- Test signal strength compatibility with standard model: $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}$
- Measure Higgs couplings - test their compatibility with the SM
- Test particle spin/parity hypotheses (expect that the Higgs is a scalar CP-even particle)
- Probe decays to fermionic final states

$H \rightarrow \gamma\gamma$ Vector Boson Fusion Candidate

$H \rightarrow \gamma\gamma$ Channel

- Dominant production mode is gluon fusion: 87%
- Background
 - Irreducible $\gamma\gamma$ production, and reducible γ -jet production
 - Smooth shape; characterized by analytic functions
- Categorize analysis to separate production modes, backgrounds
 - Separate VBF, WH/ZH, ggF categories
 - Further separation into categories of converted and unconverted photons
 - Increases sensitivity
- Measurements
 - Mass: $126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV
 - Total $\mu = 1.65 \pm 0.24(\text{stat}) + 0.25 - 0.18(\text{syst})$
 - Separate signal strength measurements for $\mu_{\text{ggF}+t\bar{t}H}$, μ_{VBF} , μ_{VH}
- local significance of 7.4σ at $m_H = 126.5$ GeV

S/B weighted $M_{\gamma\gamma}$ spectrum

ATLAS-CONF-2013-029

$H \rightarrow ZZ \rightarrow 4e$ Candidate

ATLAS
EXPERIMENT
<http://atlas.ch>
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST

$H \rightarrow ZZ^*$ Channel

- Decay to an on-shell Z and an off-shell Z
- Cleanest channel - but also very low $\sigma \cdot \text{BR}$
 - Statistics-limited analysis
 - Largest irreducible bkg: SM ZZ production
 - Peak at 90 GeV is single-resonant Z peak
 - Largest reducible bkg: $t\bar{t}$, Z+jets
- Separate treatment of 4μ , $2\mu 2e$, $2e 2\mu$ and $4e$ channels
- Separation into ggF, VBF and VH-like categories
- Measurements
 - Mass Measurement is driven by 4μ , $2e 2\mu$ channels
 - $m_H = 124.3^{+0.6}_{-0.5} \text{ (stat)} + 0.5 - 0.3 \text{ (syst)} \text{ GeV}$
- Signal strength: $\mu = 1.7^{+0.5}_{-0.4}$
- Significance: 6.6σ

$H \rightarrow WW^* \rightarrow l\nu l\nu$ Vector Boson Fusion Cand.

Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET

$H \rightarrow WW^* \rightarrow l\nu l\nu$ analysis

- Presence of two neutrinos prevents full reconstruction of event kinematics
 - Instead look at the transverse mass variable, M_T
- Largest irreducible bkg: SM WW production
 - Other bkg contributions from $t\bar{t}$, W +jets
- Split analysis into $N_{\text{jet}} = 1$, $N_{\text{jet}} = 2$
 - Goal is to split backgrounds for higher significance
- VBF channel: $N_{\text{jet}} \geq 2$ Measurements
- Signal strength: $\mu = 1.01 \pm 0.31$.
- Significance: 3.8σ excess overall
 - VBF channel: 2.5σ excess

HIGGS PROPERTIES

- Mass Measurement
- **Signal Strength and Couplings**
- **Spin**

- Total signal strength (μ) tested in each channel (left)
- Signal strength grouped by common couplings: $ggF+ttH$ and $VBF+VH$ contributions

- Results are compatible with SM within 95% CL bands
- $H \rightarrow \gamma\gamma$ result a bit high

Couplings - Combination and Results

- Define scale factors κ_V for vector-boson and κ_F for fermionic couplings
- σ , BR proportional to κ^2
- Left: couplings κ and coupling ratios λ

General comments on Higgs spin analyses

- The Higgs boson is a scalar particle - spin 0, positive parity
- Test new particle for spin-0, 1, and 2, as well as parity (+,−)
- Spin-1 hypothesis is strongly disfavored due to particle's coupling to diphoton final state (Landau- Yang theorem)
- Define simplified graviton-like spin-2+ tensor, with only red boxes nonzero:

$$\begin{aligned}
 A(H \rightarrow VV) = \Lambda^{-1} & \left[2g_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \right. \\
 & + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f_{\mu\alpha}^{*2} + f^{*2,\mu\nu} f_{\mu\alpha}^{*1}) + g_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f_{\alpha\beta}^{*(2)} \\
 & + m_V^2 \left(2g_5 t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} (\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
 & + g_8 \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f_{\alpha\beta}^{*(2)} + g_9 t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\
 & \left. + \frac{g_{10} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma (\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*)) \right],
 \end{aligned}$$

- A 2+-spin particle can be produced in gluon-gluon fusion and $q\bar{q}$ annihilation processes
 - Test various fractions of production processes $f_{gg}, f_{q\bar{q}}$
 - i.e. f_{gg} increased in steps of 25% from 0% to 100%

- hypotheses
- γ^* backgrounds
- kinematic quantities
-
- The diagram illustrates the kinematics of the $H \rightarrow ZZ$ decay. A central point X represents the decay vertex. Two planes, representing the decay planes of the Z bosons, are shown. The first plane contains the decay products μ^+ and μ^- , with the decay axis Z_1 and the angle θ_1 between Z_1 and the μ^- direction. The second plane contains the decay products e^+ and e^- , with the decay axis Z_2 and the angle θ_2 between Z_2 and the e^- direction. The angle θ^* is the angle between the two decay planes. The angle Φ is the angle between the two decay planes. The angle Φ_1 is the angle between the Z axis and the Z_1 axis. The angle Φ_2 is the angle between the Z axis and the Z_2 axis. The angle Φ is the angle between the two decay planes. The angle Φ_1 is the angle between the Z axis and the Z_1 axis. The angle Φ_2 is the angle between the Z axis and the Z_2 axis.
- $H \rightarrow ZZ$ Decay

- Results reported in 25% steps of $f_{q\bar{q}}$
- Exclude this specific spin-2+ hypothesis with 99.9+% confidence level
- Combined with information from individual channels: spin 0, even parity particle favored (consistent with SM Higgs Boson)

Additional Decay Modes

- Yet to verify direct coupling to fermions
- Probe for possible new physics via invisible particles coupling to the Higgs
- Featured here:
 - $H \rightarrow \tau\tau$
 - $H \rightarrow \mu\mu$
 - $ZH \rightarrow \ell \ell + \text{Invisible}$
 - $H \rightarrow b\bar{b}$
- Work on other decay modes; searches for high-mass Higgs, etc.

- Taus decay leptonically (τ_{lep}) or hadronically (τ_{had}) in the beampipe
 - Weak tau decay leads to missing energy from neutrinos
- Reconstruct mass by combining visible kinematics with missing energy from neutrinos
 - Missing Mass Calculator
- Analysis split into different final states, categorized to separate bkg, production modes
- Results
 - Combined limit: 1.9x SM prediction
 - Separate limits on VBF and non-VBF categories
 - Search does not use full dataset: 4.7+13 fb⁻¹

$H \rightarrow \mu\mu$ Channel

- Only 2nd gen. fermion coupling measurement
- Dominant bkg: $Z/\gamma^* \rightarrow \mu\mu$ decays
 - Search for possible enhancements to SM
- $H \rightarrow \mu\mu$ BR Measurements
- Current limit at 95% CL: 9.8x SM prediction

$ZH \rightarrow \ell\ell + \text{Invisible}$

- $H \rightarrow ZZ \rightarrow 4\nu$ BR is 4×10^{-2} - too small to detect
- Search instead for BSM enhancements
- Event selection:
 - Search for Z decaying to $\mu\mu$ or ee
 - Dilepton mass requirement to find Z
 - Require >90 GeV Missing Transverse Momentum
 - Additional kinematic cuts
- Place limit on total Higgs branching fraction to invisible at 65%
 - Search does not use full dataset: $4.7 + 13 \text{ fb}^{-1}$

ATLAS-CONF-2013-011

$H \rightarrow b\bar{b}$ ($VH, H \rightarrow b\bar{b}$)

- $H \rightarrow b\bar{b}$ expected to have highest BR: 58%
- Probed using associated production channels
- 3 decay modes:
 - $ZH \rightarrow \nu\nu b\bar{b}$
 - $ZH \rightarrow ll b\bar{b}$
 - $WH \rightarrow l\nu b\bar{b}$
- Split into 0-, 1-, 2-lepton categories
- Further categorized by n_{jets} and vector boson p_T
- Approaching 1x SM exclusion limit
 - Observed 95% CL: 1.8x SM prediction
 - Search does not use full dataset: 4.7+13 fb⁻¹

“Particle consistent with the Standard Model Higgs Boson”

- Further confirmation of Higgs boson
- Probing of properties (spin, couplings, signal strength)
- Measurement of VBF and ggF production modes, properties
- Closing in on fermionic final states

Exciting prospects for further measurements of the Higgs Boson

- End of 2012: LHC shut down
- 2015: 14 TeV beam intensity, $\sim 5\times$ luminosity
- Must contend with even harsher pileup conditions
- Run I: collected $\sim 25 \text{ fb}^{-1}$
- Run II: could collect up to $\sim 80 \text{ fb}^{-1}$

BONUS

Mass Measurement / discrepancy

- $\Delta m_H = 2.3$
 - +0.6-0.7 stat
 - +-0.6 sys
- Probability: 1.2% (2.5σ)

$H \rightarrow \tau\tau$ Vector Boson Fusion Candidate

ATLAS EXPERIMENT

Run Number: 209381, Event Number: 72873013

Date: 2012-08-28 04:17:16 CEST