Recent Higgs Results from the ATLAS experiment

Kurt Brendlinger
On behalf of the ATLAS Collaboration
Outline

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)

• \(tt\)bar fusion
  • Direct coupling to top quark

http://sites.uci.edu/energyobserver/2012/11/26/higgs-production-and-decay-channels/
Higgs Final States

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

- \( H \rightarrow \tau\tau \)
- \( H \rightarrow \mu\mu \)
- \( ZH \rightarrow ll + Invisible \)
- \( H \rightarrow b\bar{b} \)
• The LHC: Phenomenal Machine Performance
  • Proton-proton collider
  • CM Energies of 7 TeV (2011) and 8 TeV (2012)
  • Delivered ~5 fb\(^{-1}\) in 2011
  • Delivered ~23 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 \(\sim 100\)s of mm
  • Requires careful treatment of missing transverse momentum calculation
The ATLAS Detector

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

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, 10x115μm spatial resolution
  • SCT microstrips: 6M channels, 17μm 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 $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$ 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
Recent Higgs Results from the ATLAS Experiment

H→γγ Vector Boson Fusion Candidate

Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC
H→γγ Channel

- Dominant production mode is gluon fusion: 87%
- Background
  - Irreducible γγ 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±0.2(stat)±0.7(syst) GeV
  - Total μ =1.65±0.24(stat)+0.25-0.18(syst)
  - Separate signal strength measurements for μ_{ggF+ttH}, μ_{VBF}, μ_{VH}
- local significance of 7.4σ at m_H = 126.5 GeV
H→ZZ→4e Candidate
H$\rightarrow$ZZ$^*$ Channel

- Decay to an on-shell Z and an off-shell Z
- Cleanest channel - but also very low xsec$\cdot$BR
  - Statistics-limited analysis
  - Largest irreducible bkg: SM ZZ production
  - Peak at 90 GeV is single-resonant Z peak
  - Largest reducible bkg: ttbar, Z+jets
- Separate treatment of 4$\mu$, 2$\mu$2e, 2e2$\mu$ and 4e channels
- Separation into ggF, VBF and VH-like categories
- Measurements
  - Mass Measurement is driven by 4$\mu$, 2e2$\mu$ channels
  - $m_H = 124.3^{+0.6-0.5 \ (stat)}_{-0.5-0.3 \ (syst)}$ GeV
- Signal strength: $\mu = 1.7^{+0.5-0.4}$
- Significance: $6.6\sigma$
H → WW* → lνlν Vector Boson Fusion Cand.

Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
Recent Higgs Results from the ATLAS Experiment

K. Brendlinger

H → WW* → lνlν 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 ttbar, W+jets
- Split analysis into $N_{jet} = 1$, $N_{jet} = 2$
  - Goal is to split backgrounds for higher significance
- VBF channel: $N_{jet} \geq 2$ Measurements
- Signal strength: $\mu = 1.01 \pm 0.31$.
- Significance: $3.8 \sigma$ excess overall
  - VBF channel: $2.5 \sigma$ excess

ATLAS-CONF-2013-013
Recent Higgs Results from the ATLAS Experiment

K. Brendlinger

Higgs Properties

HIGGS PROPERTIES

• Mass Measurement
• Signal Strength and Couplings
• Spin
Signal Strength

- Total signal strength ($\mu$) 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 $\kappa_V$ for vector-boson and and $\kappa_F$ for fermionic couplings
- $\sigma, \text{BR}$ proportional to $\kappa^2$
- Left: couplings $\kappa$ and coupling ratios $\lambda$
Spin Hypothesis Measurement

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:

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

- 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%

ATLAS-CONF-2013-040
Spin Hypothesis Measurement

- **H→γγ Spin**
  - \(|\cos \theta^*|\), where \(\theta^*\) is polar angle with respect to z-axis of the Collins-Soper (CS) frame
  - Use mass as a discriminating variable as well
  - Perform a maximum likelihood fit using two hypotheses

- **H→ZZ Spin**
  - Discriminating variables are decay angles and intermediate Z boson masses
  - Train Boosted decision trees with both hypotheses
  - Other dedicated spin analyses to test for 0+, 0-, 2+, 2- hypotheses

- **H→WW*→lνlν Spin**
  - More stringent cuts to reduce continuum WW and Z/γ* backgrounds
  - Boosted decision trees trained on observable kinematic quantities
- 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 ($\tau_{\text{lep}}$) or hadronically ($\tau_{\text{had}}$) 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 bkgds, production modes
• Results
  • Combined limit: $1.9 \times$ SM prediction
  • Separate limits on VBF and non-VBF categories
  • Search does not use full dataset: $4.7 + 13 \text{ fb}^{-1}$
**H → μμ Channel**

- Only 2nd gen. fermion coupling measurement
- Dominant bkg: Z/γ* → μμ decays
  - Search for possible enhancements to SM
- H → μμ BR Measurements
- Current limit at 95% CL: 9.8x SM prediction
ZH → ℓℓ + Invisible

- H → ZZ → 4ν BR is 4x10⁻² - too small to detect
- Search instead for BSM enhancements
- Event selection:
  - Search for Z decaying to µµ 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 fb⁻¹
H → b¯b (VH, H → b¯b)

• H → b¯b expected to have highest BR: 58%
• Probed using associated production channels
• 3 decay modes:
  • ZH→ννb¯b
  • ZH→llb¯b
  • WH→lvb¯b
• Split into 0-, 1-, 2-lepton categories
• Further categorized by n_{jets} and vector boson p_{T}
• Approaching 1× SM exclusion limit
  • Observed 95% CL: 1.8× SM prediction
  • Search does not use full dataset: 4.7+13 fb^{-1}
Conclusions

“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, ~5x luminosity
- Must contend with even harsher pileup conditions
- Run I: collected ~25 fb$^{-1}$
- Run II: could collect up to ~80 fb$^{-1}$
• $\Delta m_H = 2.3$
  • +0.6-0.7 stat
  • +0.6 sys
• Probability: 1.2% (2.5$\sigma$)
H→ττ Vector Boson Fusion Candidate