Abstract

The Standard Model Higgs boson searches with the ATLAS experiment at the Large Hadron Collider through its observation in the ZZ(\ast), WW(\ast), gamma-gamma and tau-tau final states are reported.

The Higgs discovery potential of ATLAS for these combined channels is reviewed and discussed, addressing also the statistical procedure used to combine the data.

The expected exclusion limits on the production rate times the branching ratio as a function of the mass and the luminosity are also presented.
Contents

- Present experimental limits
- Higgs production and decay at LHC
- Details on different inclusive decay channels
  - Search for $H\rightarrow \gamma \gamma$ decays
  - Search for $H\rightarrow \tau \tau$ decays
  - Search for $H\rightarrow Z^{(*)}Z\rightarrow 4\ell$ decays
  - Search for $H\rightarrow W^{(*)}W$ decays
- Statistical combination and expected discovery/exclusion

The material for this talk is taken from CERN-OPEN-2008-020
“Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics”

I’ll necessarily leave out some important topics, due to limited time:
APOLOGIES!
**Present limits**

- Higgs mass is unknown, $m_H < 1$ TeV from theoretical arguments (unitarity)
- The Higgs boson has never been observed so far, present experimental results suggest “light” Higgs boson

**LEP direct search:** $m_H > 114.4$ GeV  
http://lepewwg.web.cern.ch/LEPEWWG/

**Recent CDF+DØ direct search (4 fb$^{-1}$):**  
exclude range $160 \div 170$ GeV  
http://arxiv.org/abs/0903.4001

$\Delta \chi^2$ vs $m_H$ [GeV]

- EW fit favours $m_H < 163$ GeV  
(m$H < 191$ GeV if including LEP dir. Search limit)  
http://lepewwg.web.cern.ch/LEPEWWG/ (march 2009)
Higgs production at LHC

- **Gluon fusion**
  (leading process)
  ![Gluon fusion diagram]

- **Vector-boson fusion**, "VBF" (sub-leading, but important for bkg suppression)
  ![Vector-boson fusion diagram]

- **WH, ZH, ttH** associated production (not covered in this talk)

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ATLAS

Cross-section [pb]

\[ \frac{d^2 \sigma}{dy \cos \theta} = C \times \frac{1}{y} \]

At \( \sqrt{s} = 14 \text{ TeV} \)

- \( gg \rightarrow H \)
- \( qq \rightarrow H \) \( qq \)
- \( WH \)
- \( ZH \)
- \( ttH \)
Higgs decays, search channels

- Medium / heavy Higgs (> 130 GeV)
  - \(H \rightarrow W(W)W\)
  - \(H \rightarrow Z(Z)Z\)

- Low-mass (< 140 GeV)
  - \(H \rightarrow bb\) favoured, but affected by large QCD background
  - \(H \rightarrow \gamma\gamma\) and \(H \rightarrow \tau\tau\) decays are used, despite low BR

- Each channel plays an important role, depending on the Higgs mass
$H \rightarrow \gamma \gamma$
H→γγ: signal and main backgrounds

- **Signal:**
  - 2 high-pt photons from a narrow resonance

- **Irreducible background:**
  - Di-photon events from QCD
  - Quark-photon events with extra photon from fragmentation

- **Huge reducible background:**
  - QCD photon-jet with leading $\pi^0 \rightarrow γγ$ (X-section $\sim 10^3 \times$ irred.bkg.)
  - QCD di-jets with with leading $\pi^0 \rightarrow γγ$ (X-section $\sim 10^6 \times$ irred.bkg.)
**H→γγ : jet rejection**

- Keep reducible background (jets) under control!
  - No activity in hadron calorimeter
  - Transverse shape in 1\textsuperscript{st} and 2\textsuperscript{nd} layer of EM calorimeter compatible with EM shower profile
  - No 2\textsuperscript{nd} maximum in 1\textsuperscript{st} layer (strips), to reject jets with leading $\pi^0\rightarrow\gamma\gamma$
  - Track isolation in a cone around the candidate

- High jet rejection:
  - rej $\approx$2500 for quark jets
  - rej $\approx$25000 for gluon jets

- High photon identification efficiency (~80%)
**$H \rightarrow \gamma\gamma$ : direction measurement**

- Invariant mass affected by precision in $\eta, \phi$ measurements:
  \[ M_{\gamma\gamma}^2 = 2 p_{\gamma_1}^t p_{\gamma_1}^t (\cosh \Delta \eta - \cos \Delta \phi) \]

- Primary vertex at LHC has a $z$-spread of $\pm56$ mm: $\eta$ measurement is delicate!

- Must identify Higgs vertex (out of pileup vertices) using:
  - Photon pointing, through multi-layer EM calorimeter (and conversion vertex, if any)
  - $\sum p_t^2$ of tracks for all detected vertices

- Refit photons through identified primary vertex, to get $\eta_1, \eta_2$
**H → γγ**: mass peak

- Invariant mass:
  - Gaussian $\sigma_m < 1.5$ GeV

- Dominated by energy measurement:
  - Resolution:
    - $\sigma_E/E \approx 10%/\sqrt{E} \oplus 0.7%$

- Linearity well within $\pm 0.5%$

$m_H = 120$ GeV

**Low tail due to converted photons**

**Invariant mass:**
- Gaussian $\sigma_m < 1.5$ GeV

**Dominated by energy measurement:**
- Resolution:
  - $\sigma_E/E \approx 10%/\sqrt{E} \oplus 0.7%$

- Linearity well within $\pm 0.5%$
H→γγ : background amount

- Despite good performances:
  - high jet rejection
  - high photon efficiency
  - good mass resolution...
- Yet, Sig/Bkg = 2.5% after analysis cuts!
- Simple event counting is “robust”, but ...
- ... to improve the sensitivity we need to optimize the analysis further! (see next)
**H→γγ : improved analysis**

- Divide events into several categories, based on photons' \( \eta \) and number of jets

\[ \gamma\gamma + 1 \text{ jet} \]

\[ \gamma\gamma + 2 \text{ jets (VBF)} \]

- Use discriminating variables: \( \cos(\theta^*) \) and \( P_{T\gamma\gamma} \)

\[ \cos(\theta^*) : \text{signal} \]

\[ \cos(\theta^*) : \text{background} \]

- Combination with “profile likelihood ratio”

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**Improved analysis**

**Significance at 10 fb\(^{-1}\)**

- Event counting

\( >3.6 \)

\( >2.6 \)

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Marcello Fanti

_Inclusive Higgs searches at ATLAS (SUSY2009)_: 12
Vector Boson Fusion

$H \rightarrow \tau\tau$
VBF $H \rightarrow \tau \tau$ : Event topology

- To reduce background, search is restricted to Vector Boson Fusion (VBF) Higgs production.

- Signal:
  - 2 high-pt jets from quarks, at large $\eta$ ("forward tag jets"), no jets in between.
  - $\tau$-pair from a resonance.
    - Leptonic and hadronic $\tau$ decays are considered ($\ell\ell$, $\ell h$, $hh$ topologies).
    - Missing $E_T$ (neutrinos from $\tau$ decays).

- Background:
  - Irreducible: Z+jets ($Z \rightarrow \tau \tau$).
  - Reducible: W+jets, tt+jets.
VBF $H \rightarrow \tau \tau :$ mass reconstruction

- Despite the presence of neutrinos, invariant mass can be fully reconstructed, by exploiting the precise measurement of missing $P_t$:
  - Assume all $\tau$ decay products are collinear, call $x_i$ the visible momentum fraction of $\tau_i$: ($p_{i\text{vis}} = x_i p_i$)
    - $(m_{\tau\tau}^{\text{vis}})^2 = 2 p_{1\text{vis}}^2 p_{2\text{vis}}^2 (1-\cos \alpha)$
    - $(m_{\tau\tau})^2 = 2 p_1 p_2 (1-\cos \alpha) = (m_{\tau\tau}^{\text{vis}})^2 / (x_1 x_2)$
  - solve for $x_1, x_2$ by imposing missing $P_t$ vector balance (2 unknowns, 2 conditions):
    - $P_t^{\text{miss}} = (1-x_1)/x_1 p_{t1}^{\text{vis}} + (1-x_2)/x_2 p_{t2}^{\text{vis}}$
  - For unphysical solution ($x_i \not\in [0,1]$) reject the event
    - good also for rejecting reducible background
“Bkg-only” and “Sig+Bkg” hypotheses are tested using “profile likelihood ratio” technique

Main bkg is $Z \to \tau\tau$, after mass evaluation

- Data-driven methods to estimate $Z \to \tau\tau$ shape have been studied (see backup slides)
**VBF H$\rightarrow\tau\tau$ : data driven study of Z$\rightarrow\tau\tau$ background**

- $M_{\tau\tau}$ shape and rate affected by large systematics especially for Z with low $p_t$:
  - ($\tau\tau$ almost back-to-back, missing $P_t$ balance may give large tails)

- Need to get $M_{\tau\tau}$ shape and rate from data, but it's difficult to select a pure Z$\rightarrow\tau\tau$ sample from data

- Build an “emulated” Z$\rightarrow\tau\tau$ sample:
  - Don't rely on simulation of Z production (cross-section, kinematics, underlying event, etc), but **trust τ simulation**;
  - Select a pure sample of inclusive Z$\rightarrow\mu\mu$ events from data (easy!)
  - Replace reconstructed $\mu$'s with simulated $\tau$'s (same kinematics)

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**Good agreement between “true” and “emulated” Z$\rightarrow\tau\tau$**
$H \rightarrow Z^{(*)}Z \rightarrow 4\ell$
\[ H \rightarrow Z(*)Z \rightarrow 4\ell : \]

**signal and main backgrounds**

- **Signal:** 4 high-pt leptons (e, \( \mu \))
  - Paired with same flavour, opposite charge
  - 4e, 4\( \mu \), 2e2\( \mu \) final states
  - At least a pair compatible with Z mass (resolve wrong comb's)

- **Irreducible background:**
  - Z pairs from continuum

- **Reducible backgrounds:**
  - Zqq (especially qq \( \equiv \) bb, cc)
  - \( t\bar{t} \), with leptonic W, b decays
  - Require lepton isolation and small impact parameter
$H \rightarrow Z^{(*)} Z \rightarrow 4\ell$ : mass peak

$m_H = 130$ GeV

$H \rightarrow Z^{(*)} Z \rightarrow 4\ell$ : mass peak

$m_H = 160$ GeV

$m_H = 300$ GeV

Selection efficiency (%)

<table>
<thead>
<tr>
<th></th>
<th>4e</th>
<th>4\mu</th>
<th>2e2\mu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>12.5</td>
<td>31.4</td>
<td>19.2</td>
</tr>
<tr>
<td>ZZ bkg</td>
<td>0.05</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Zbb bkg</td>
<td>0.0016</td>
<td>0.0012</td>
<td>0.003</td>
</tr>
</tbody>
</table>

$\sigma_M$ at 130 GeV:

- $4\ell$: $\sigma_M = 2.2$ GeV
- $4\mu$: $\sigma_M = 1.8$ GeV
- $2e2\mu$: $\sigma_M = 1.9$ GeV
**H→Z(*)Z→4ℓ : expected outcome**

- $4e, 4\mu, 2e2\mu$ are combined using “profile likelihood ratio”
- 5 $\sigma$ discovery:
  - With 30 fb$^{-1}$ in 130÷500 GeV mass region
  - Except for $\sim$160÷180 GeV (WW turn-on)
  - With only 5 fb$^{-1}$ around 150 GeV and in 200÷400 GeV region

- Low background, narrow mass peak, “gold-plated channel”
$H \rightarrow W^{(*)}W$
**H → W(*)W → eνμν: topologies**

- **Signal:** full leptonic decay
  - H → W(*)W → eνμν + 0jets (gg-fusion)
  - H → W(*)W → eνμν + 2jets (VBF)
- **Irreducible background:**
  - WW from continuum
- **Reducible backgrounds:**
  - tt → WWbb
  - Z → ττ → eννμνν
  - W+jets
H→W(*)W→eνμν : kinematics

- 2 neutrinos ⇒ 6 unknowns ⇒ cannot reconstruct Higgs mass
- Use “transverse mass”:
  \[ M_T = \sqrt{(E_{T,\ell\ell} + E_{T,\text{miss}})^2 - (p_{T,\ell\ell} + p_{T,\text{miss}})^2} \]
  - where:
    \[ E_{T,\ell\ell} = \sqrt{(p_{T,\ell\ell})^2 + m_{\ell\ell}^2} \quad ; \quad E_{T,\text{miss}} \approx \sqrt{(p_{T,\text{miss}})^2 + m_{\ell\ell}^2} \]
    - [if \( m_H < 2m_Z \), \( m_{\ell\ell}^2 \approx m_{\nu\nu}^2 \) : both W's almost at rest in Higgs rest frame]

\[ m_H = 170 \text{ GeV} \]

\[ M_T (e\nu\mu\nu + 0\text{jets}) \]

\[ ATLAS \quad \int L \, dt=10 \text{ fb}^{-1} \]

\[ M_T (e\nu\mu\nu + 2\text{jets}) \]

\[ ATLAS \]

\[ m_H = 170 \text{ GeV} \]

Marcello Fanti

Inclusive Higgs searches at ATLAS (SUSY2009)
H→W(*)W→eνμν : fit to data

- Signal/background hypothesis test: fit data to a likelihood ratio:
  - \( \lambda(m_H, N_s, ...) = L_{s+b}(m_H, N_s, ...) / L_b(...) \)
- Higgs mass \( m_H \) and signal rate \( N_s \) are free parameters; input to fit:
  - \( e\nu\mu\nu + 0 \) jets: \( M_T \) and \( P_T^{WW} \)
  - \( e\nu\mu\nu + 2 \) jets: \( M_T \) and neural net output, based on jet activity

\( m_H \) from fit: \( e\nu\mu\nu + 0/2 \) jets

Significance at 10 fb\(^{-1}\)
(\( e\nu\mu\nu + 0/2 \) jets)
Combined results
Summary of inclusive searches

- $H \rightarrow \gamma \gamma \ (<\ 140\ \text{GeV})$
  - Narrow mass peak, but very low signal/background ratio
- $H \rightarrow \tau \tau \ (<\ 140\ \text{GeV})$
  - Better sig/bkg ratio, but broader mass peak
- $H \rightarrow Z(\ast)Z \rightarrow 4\ell \ (>\ 130\ \text{GeV})$
  - Narrow mass peak on smooth bkg, good significance: “gold-plated”
  - ... but a “hole” in 160-180 GeV mass range
- $H \rightarrow W(\ast)W \rightarrow \ell \nu \ell \nu \ (>\ 130\ \text{GeV})$
  - Highest significance, but no mass peak
Statistical combination of all channels

- Needed, to cover the full mass range and increase the sensitivity to our best
  - use “profile likelihood ratio” (described in Appendix):
  - provide an estimator (p-value) of agreement between data and a given hypothesis (“bkg-only” or “sig+bkg”)

- **Discovery**: falsify no-signal hypothesis
  - Assume “bkg-only” hypothesis; if p-value < $2.87 \times 10^{-7}$ claim for a discovery at 5σ significance!

- **Exclusion**: falsify signal hypothesis
  - Assume “sig+bkg” hypothesis; if p-value < 0.05 exclude signal at 95% confidence level...

- **CAVEAT**: need good knowledge of the background shapes
  - data-driven methods have been studied, based on control (signal-free) regions
Expected exclusion capability

Integrated luminosity of 2 fb⁻¹

95% exclusion for masses 115-460 GeV
Inclusive Higgs searches at ATLAS (SUSY2009)

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Expected discovery potential

Integrated luminosity of 10 fb$^{-1}$

ATLAS
L = 10 fb$^{-1}$

$5\sigma$ discovery in mass range 125-430 GeV

143-179 GeV with 2 fb$^{-1}$

$3\sigma$ evidence in mass range 113-500 GeV

(need 30 fb$^{-1}$ to become “discovery”)

$\gamma \gamma \rightarrow 4l$

$\tau \tau$

$WW0j \rightarrow e\nu\mu\nu$

$WW2j \rightarrow e\nu\mu\nu$
Conclusions:

- Most channels are challenging, good understanding of backgrounds and detector performances are needed!!
- But ATLAS is well prepared for Higgs hunting 😊

... we “only” miss some 10's fb⁻¹ data! 😊
Extra slides
Profile likelihood ratio

- Build a **likelihood function** from a model describing signal and background rates and shapes (for one or several decay channels):

  \[ L(\text{data}|\mu, \Theta) \]

  - **Signal strength**: 0 ⇒ bkg-only ; 1 ⇒ sig+bkg

- Build the "**profile likelihood ratio**":

  \[ \lambda(\text{data}|\mu) = \frac{L(\text{data}|\mu, \Theta'')}{L(\text{data}|\mu', \Theta')} \]

- **Maximized by varying** \( \Theta \), at fixed \( \mu \)

- **Maximized by varying** \( \mu, \Theta \) altogether

- **... and its -2log**:

  \[ q_{\mu} = -2 \ln \lambda(\text{data}|\mu) \]

- \( q_{\mu} \) is distributed like a chi-2 with 1 DoF (if \( \mu \)-value under hypothesis is “true”)

- \( q_{\mu} \) easy to evaluate **p-value** (i.e. probability that data be less compatible with assumed \( \mu \)-value, than actually observed)
Standard Model backgrounds

- Cross-sections:
  - Higgs (RED) much below other known particles (BLUE)

- Higgs search needs:
  - Best compromise between “higher” $\sigma \times \text{BR}$ and “lower” background
  - Large statistics!
Photon identification

- EM calorimeter has a longitudinal 3-layer segmentation
- An EM cluster with either of:
  - No associated track
  - Associated track belonging to a conversion (see next slide...)
- Quality cuts to separate photons from hadronic jets
  - No activity in hadron calorimeter
  - Transverse shape in 1\textsuperscript{st} and 2\textsuperscript{nd} layer of EMC compatible with EM shower profile
  - No 2\textsuperscript{nd} maximum in 1\textsuperscript{st} layer (strips), to reject jets with leading $\pi^0 \rightarrow \gamma \gamma$

$$\text{Middle layer: } \Delta \eta \times \Delta \phi = 0.025 \times 0.025$$

$$\text{1\textsuperscript{st} layer (Strips): } \Delta \eta \times \Delta \phi = 0.003 \times 0.1$$

very thin $\eta$ granularity
Converted photons

- Need to consider also converted photons:
  - Appear in ~50% of events
  - Improve signal efficiency
  - Improve precision of direction measurement
- 2-tracks conversion:
  - Track associated to EM cluster belongs to a detected “V-vertex”
- 1-track conversion:
  - Associated track does not have hits in “pixel” detector (inner part of tracker)

2-tracks conversion efficiency falls off rapidly with radius

Some efficiency recovered with 1-track conversions

Note: more recent algorithms provide ~80% efficiency in conversion detection throughout the whole inner tracker
Photon/Electron energy

- Energy resolution:

- Linearity:

  - ±0.5% band

  - ±0.5% band
**Tau identification**

- Tau decays to hadron(s) 65% of the times
  - Mostly 1-prong (sometimes 3-prongs) ⇒ hadronic cluster
  - Possibly with associated neutral hadrons ⇒ e.m. shower component
  - Main background from QCD jets
- Identification seeded by calo-cluster with a track associated
  - Use log likelihood ratio, based on cluster shape and tracks' characteristics
  - Cutoff on LLR chosen to optimize \( s/\sqrt{(s+b)} \)
- Performance:
  - Efficiency \( \sim 50\% \)
  - Gluon-initiated jet rejection: \( \sim 100 \)
  - Quark-initiated jet rejection: \( \sim 40 \)
H→W(∗)W→eνμν:
data-driven background studies

- **Background from Z→ττ:**
  - estimated as for H→ττ search

- **Background from tt → WWbb:**
  - use b-tagged control samples

- **Background from W+jets:**
  - Rely on MC, in-situ determination not studied yet...

- **Background from WW:**
  - Fix shapes and normalization by fitting data in control region \( \Delta \phi > \pi/2 \)

W-spin correlation favours close-by leptons
\[ H \to W(\ast)W \to \ell \nu qq : \text{mass peak} \]

- 1 neutrino \( \Rightarrow \) 3 unknowns
- Use \( p_T^{\text{miss}} \) vector balance and impose 
\( M_{\ell \nu} = m_W \)
- Reconstruct Higgs mass (useful for mass > 250 GeV)

**ATLAS**

Reconstructed \( m_H \)

Fit to pseudo-experiment

**ATLAS**

\[ \int L \, dt = 10 \, \text{fb}^{-1} \]