Search for the Standard Model Higgs boson through the $H \rightarrow ZZ$ decay channels with the ATLAS detector

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Electroweak Tests of the Standard Model 4 - Higgs

Outline

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- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \nu \bar{\nu}$
- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- q \bar{q}$
- $H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$

3 Summary

Introduction
The Higgs Boson

The Higgs mechanism ...

- ... is the driver of spontaneous break-down of the electroweak symmetry $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$ because of a continuous ground state
- ... gives mass to the $Z/W^\pm$ boson due to gauge couplings
- ... introduces masses for electro-weakly interacting fermions via Yukawa terms

The Higgs boson ...

- ... is the last missing piece of the Standard Model of particle physics
- ... mass m_H below 114.4 GeV (LEP) and in the region $147 < m_H < 179$ GeV (Tevatron) was excluded at the 95% C.L. **before LHC operation**

 $H \rightarrow ZZ$ channels

subsequent decay	additional sub channels	$\mathcal{L} [\text{fb}^{-1}]$	m_H range [GeV]
$\ell^+ \ell^- \nu \bar{\nu}$	$\{ee, \mu\mu\} \otimes$ $\{\text{low pile-up, high pile-up}\}$	2.3 2.4	200 – 280 280 – 600
$\ell^+ \ell^- q \bar{q}$	$\{\text{b-tagged, untagged}\}$	4.7	200 – 300 300 – 600
$\ell^+ \ell^- \ell' \ell' -$	$\{4e, 2e2\mu, 4\mu\}$	4.9 4.8	110 – 600

multi purpose detector at LHC
(pp collisions at $\sqrt{s} = 8$ TeV in 2012;
pp collisions at $\sqrt{s} = 7$ TeV in
2011: analysed here):

- almost 4π solid angle coverage
- silicon pixel/microstrip detector and transition radiation tracker embedded in a $2T$ solenoid field
- lead/liquid-argon and iron/scintillating tile calorimetry system
- muon spectrometer embedded in a $4T$ air-core toroid field

lowest unprescaled triggers are used:

- single object (electron: threshold of 20 and 22 GeV respectively, muon: threshold of 18 GeV)
- di-object (electrons: threshold of 12 GeV each, muons [used by 4ℓ only]: threshold of 10 GeV each)

subsequent decay	muons	electrons	jet
all channels	basic quality requirements track isolation		infrared-safe jet algorithm (anti- k_t with $R = 0.4$) $ \eta < 2.5$ and $E_T > 25$ GeV
$\ell^+ \ell^- \nu \bar{\nu}$	$ \eta < 2.5$ $ \eta < 2.47$ $p_T > 20$ GeV reject lepton with $\Delta R_{j\ell} = \sqrt{(\phi_j - \phi_\ell)^2 + (\eta_j - \eta_\ell)^2} < 0.4$		considered
$\ell^+ \ell^- q \bar{q}$	$p_T > 20$ GeV $ \eta < 2.5$ reject electrons with $\Delta R_{e\mu} < 0.2$ reject jets with $\Delta R_{ej} < 0.4$		at least 75% of the momentum of the associated tracks originate from primary vertex
$\ell^+ \ell^- \ell'^+ \ell'^-$	$p_T > 7$ GeV calorimetric isolation well separated by $\Delta R_{\ell\ell} > 0.1$ impact parameter along beam axis < 10 mm $ \eta < 2.7$ $ \eta < 2.47$ transverse impact parameter < 1 mm		not considered

Remark: $\eta = -\ln \tan(\theta/2)$ with polar angle θ

- exactly 2 opposite charged leptons (veto events with a 3rd lepton with $p_T > 10$ GeV)
- lepton pair is required to be close to the Z pole $|m_Z - m_{\ell^+ \ell^-}| < 15$ GeV
- events with b-tagged jets above 20 GeV are rejected
- backgrounds:
 - irreducible: Standard Model diboson production
 - suppressed by invariant mass requirement: top, W boson, multijet production
 - dominant: inclusive Z production (especially for low Higgs masses)
- splitting of the sample in
 - low pile-up scenario (in average 6 interactions per bunch crossing)
 - high pile-up scenario (in average 15 interactions per bunch crossing)

- deteriorated transverse missing energy resolution (E_T^{miss}) for high pile-up scenario
- optimized for low ($200 < m_H < 280$ GeV) and high ($280 \leq m_H < 600$ GeV) Higgs mass searches

low mass	high mass
$E_T^{\text{miss}} > 66$ GeV	$E_T^{\text{miss}} > 82$ GeV
$1 < \Delta\Phi(\ell, \ell) < 2.64$	$\Delta\Phi(\ell, \ell) < 2.25$
$\Delta\Phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 1.5$	$\Delta\Phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\text{jet}}) < 0.5$
	$\Delta\Phi(\vec{p}_T^{\text{miss}}, \vec{p}_T^{\ell\ell}) < 1$

- expected exclusion: $280 < m_H < 497$ GeV
- observed exclusion: $319 < m_H < 558$ GeV
- no significant excess observed

(The line at 280 GeV indicates the transition from the low mass to the high mass search region.)

$$H \rightarrow ZZ \rightarrow \ell^+ \ell^- q \bar{q}$$

- exactly two opposite charged leptons (or also same charged for electrons) with an invariant mass of $83 < m_{\ell\ell} < 99 \text{ GeV}$
- less than 50 GeV missing transverse energy E_T^{miss}
- at least two reconstructed jets

number of b-tagged jets	<2	=2	>2
	untagged selection	tagged selection	reject event

- at least one candidate with $70 < m_{jj} < 105 \text{ GeV}$ formed from the three highest- p_T jets (especially requesting $\Delta R_{jj} > 0.7$)
- for high Higgs mass scenarios ($m_H \geq 300 \text{ GeV}$) the two jets must have $p_T > 45 \text{ GeV}$ and $\Delta\Phi_{\ell\ell/jj} < \frac{\pi}{2}$ is required
- backgrounds: inclusive Z production (dominant), top production, Standard Model diboson production

$$H \rightarrow ZZ \rightarrow \ell^+ \ell^- q\bar{q}$$

- expected exclusion: $360 < m_H < 400$ GeV
- observed exclusion: $300 < m_H < 310$ GeV and $360 < m_H < 400$ GeV
- no significant excess observed

(The discontinuity in the limit at $m_H = 300$ GeV is due to the transition between the low- and high- m_H selection.)

Run Number: 182796
Event Number: 74566644
Date: 2011-05-30, 06:54:29 CET

Muon
Electron
Cells: Tiles, EMC
Collection: cega

- $2e2\mu$ candidate event with $m_{4l} = 124.3$ GeV
- masses of lepton pairs are 76.8 GeV and 45.7 GeV

- two leptons with at least 20 GeV transverse momentum
- two lepton pairs with different charge and same flavor are formed to a quadruplet while:
- m_{12} is the invariant mass of the pair closest to the Z boson mass and required to be $|m_Z - m_{12}| < 15$ GeV
- the invariant mass of the other pair m_{34} has to satisfy $m_{\min} < m_{34} < 115$ GeV with

$m_{4\ell}$ [GeV]	≤ 120	130	140	150	160
$m_{\min}$ [GeV]	15	20	25	30	30
$m_{4\ell}$ [GeV]	165	180	190	≥ 200	
$m_{\min}$ [GeV]	35	40	50	60	

- in case of $m_{4\ell} < 190$ GeV the transverse impact parameter significance for the two lowest p_T leptons is required to be < 3.5 (6) for muons (electrons)

- ▶ invariant mass distributions of the second lepton pair m_{34} with the exception of opposite-charge, isolation and impact parameter requirement

- ▶ background sources:

- irreducible: Standard Model $ZZ^{(*)}/Z\gamma^*$ production

(Standard Model ZZ production cross section [ATLAS-CONF-2012-026]: NLO calculation: $\sigma_{ZZ} = 6.5^{+0.3}_{-0.2} \text{ pb}$;

measurement: $\sigma_{ZZ} = 7.2^{+1.1}_{-0.9}(\text{stat})^{+0.4}_{-0.3}(\text{syst}) \pm 0.3(\text{lumi}) \text{ pb}$)

- $Z + \mu\mu$: background from $Zb\bar{b}$ dominates
- $Z + ee$: paramount background is $Z + \text{light jet}$ production

- invariant mass of the four lepton system $m_{4\ell}$
- various signal scenarios superimposed

- width dominated by experimental resolution for $m_H < 350$ GeV
- fraction of $4e$ (4μ) events outside the $\pm 2\sigma$ region is 15% (18%)

Search channels for $H \rightarrow ZZ$

$$H \rightarrow ZZ \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$$

- expected exclusions:

$$137 < m_H < 158 \text{ GeV}$$

$$185 < m_H < 400 \text{ GeV}$$

- observed exclusions:

$$134 < m_H < 156 \text{ GeV}$$

$$182 < m_H < 233 \text{ GeV}$$

$$256 < m_H < 265 \text{ GeV}$$

$$268 < m_H < 415 \text{ GeV}$$

- largest upward deviations are for $m_H = 125 \text{ GeV}$, 244 GeV and 500 GeV with local significances of 2.1, 2.2 and 2.1 standard deviations

- after considering the look-elsewhere effect these excesses are no longer significant

Conclusion:

- observed exclusion limits for the Higgs mass obtained from $H \rightarrow ZZ$ decay channels were presented

subsequent channel	exclusion limit at the 95%CL	reference
$\ell^+ \ell^- \nu \bar{\nu}$	$319 < m_H < 558 \text{ GeV}$	arXiv:1205.6744 (30th May) submitted to: Physics Letters B
$\ell^+ \ell^- q \bar{q}$	$300 < m_H < 310 \text{ GeV}$ $360 < m_H < 400 \text{ GeV}$	ATLAS-CONF-2012-017
$\ell^+ \ell^- \ell'^+ \ell'^-$	$134 < m_H < 156 \text{ GeV}$ $182 < m_H < 233 \text{ GeV}$ $256 < m_H < 265 \text{ GeV}$ $268 < m_H < 415 \text{ GeV}$	Phys. Lett. B710 (2012) 383-402

- most significant excesses from the expected background before considering the look-elsewhere effect were addressed
- no definite hint for a direct Higgs observation in **only** the $H \rightarrow ZZ$ channels, but also no complete exclusion of a Standard Model Higgs

Outlook:

2012 data analysis will give more exposure due to more statistics and a **potentially 1.5 times higher production cross section** at $\sqrt{s} = 8 \text{ TeV}$ though **pile-up increases as well by a factor of about 1.5**

BACKUP

	inner detector	calorimeter system	muon spectrometer

coverage	$ \eta < 2.5$	$ \eta < 4.9$	$ \eta < 2.7$
resolution	track: <ul style="list-style-type: none"> • resolution: $< 1\%$ • momentum scale: $\sim 0\%$ 	jet energy: <ul style="list-style-type: none"> • resolution: 4% • scale: 3% 	transverse momentum: (in combination with ID): <ul style="list-style-type: none"> • $< 3.5\%$ at $p_T \sim 200$ GeV • $< 10\%$ at $p_T \sim 1$ TeV
efficiency	$\sim 100\%$	-	$(97.0 \pm 0.1)\%$
features	vertex resolution: <ul style="list-style-type: none"> • longitudinal plane $50 \mu\text{m}$ • transverse plane $30 \mu\text{m}$ 	segmented in η and ϕ	3 layers of precision chambers

explanation of limit plots

Explanatory figure (not actual data)

channel / uncertainty	$\ell^+ \ell^- \nu \bar{\nu}$	$\ell^+ \ell^- q \bar{q}$	$\ell^+ \ell^- \ell'^+ \ell'^-$
electron energy scale			0.6% (0.3%) for $4e(2e2\mu)$
electron efficiency			2.3% (1.6%) for $4e(2e2\mu)$ for high m_H
			8.0% (4.1%) for $4e(2e2\mu)$ for low m_H
muon efficiency			0.22% (0.16%) for $4\mu(2e2\mu)$
btagging efficiency		9%	
jet energy scale		3%	
jet energy resolution		4%	
diboson background		same	
inclusive Z production	11%	1.7% for low m_H untagged	
	2.5%	2.2% for high m_H untagged	
		5.5% for tagged	
$Z b \bar{b}$			40%
Z + light jets			45%
inclusive W production	100%		
top quark production	9%	2.7% untagged	
		4.0% tagged	
multijet production in e channel	50%	same	
normalization uncertainty for the signal			
gluon fusion	+14%	15 – 20%	15 – 20%
	–10%		
vector boson fusion	4%	3 – 9%	3 – 9%
theoretical uncertainty on the acceptance			
high mass region	3.4%	3%	2%
low mass region	8.4%	6%	2%
luminosity uncertainty		3.9%	same
high pile-up data	4.1%		
low pile-up data	3.7%		
production cross section uncertainty			
QCD scale for gluon fusion	+12%	same	same
	–8%		
QCD scale for vector boson fusion	1%	same	same
PDF and α_S in gluon-initiated proc.	8%	same	same
PDF and α_S in quark-initiated proc.	4%	same	same
Higgs line shape ($m_H \geq 300$ GeV)	$1.5 \times m_H^3 [TeV]$	same	same