Scalar boson into gamma gamma at LHC:

From the design of the experiments to the measurement of the properties

Louis Fayard
LAL-Orsay
Introduction

Short history of scalar boson and LHC

History of detectors and of $H \rightarrow \gamma\gamma$
  specificities of detectors relevant to $H \rightarrow \gamma\gamma$

Discovery

Properties

Conclusions

Backup (references)
Introduction

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Backup (references)
from detectors to the discovery

\[ \sqrt{s} = 7 \text{ TeV} \int L dt = 0.02 \text{ fb}^{-1} \hspace{1cm} \text{Apr 18, 2011} \]

**ATLAS** Preliminary

\( H \rightarrow \gamma \gamma \) channel

Corfu 8-9-13
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Backup (references)
1950 Ginzburg-Landau (Meissner-Ochsenfeld effect → London penetration length ~ W mass → Pippard coherence length ~ H mass)
1959 Nambu
1960 Goldstone
1961 Schwinger
1962 Anderson
1964 Brout, Englert, Higgs, Guralnik, Hagen, Kibble
1967 Weinberg, Salam Faddeev, Popov
1970 Glashow, Iliopoulos, Maiani, ‘t H

1983 Rubbia, van
1984

1989 construction beginning of
1992 LOI of ‘large’ LHC experiments
1994 TP of ATLAS
1995 discovery of
1996 approval of
1998 approval of
1999 ATLAS Pl

2006 CMS Phys
2008 ATLAS Expected to perform
2010 start-up at 3.5 + 3.5 TeV
2012 4th July discovery of boson
2013 boson like properties

\[
\begin{align*}
\frac{\mu_0^2}{2} \varphi^2 + \frac{\lambda_0}{24} \varphi^4
\end{align*}
\]
10th september 2008 : first beams around
19th september 2008 : incident

14 months of major repairs and consolidation
New Quench Protection system

20th november 2009 : first beams around (again)
december 2009 : collisions at 2.36 TeV cms

January 2010 : decided scenario 2010-11 7 TeV cms

30th march 2010 : first collisions at 7 TeV cms
august 2010 : luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$

may 2011 : luminosity $>10^{33}$ cm$^{-2}$ s$^{-1}$
november 2011 : integrated luminosity $\sim 5$ fb$^{-1}$
13$^{th}$ december 2011 : first ‘signal’ around 126 GeV

march 2012 : start again at 8 TeV
4$^{th}$ July 2012 : evidence for a new boson
(integrated luminosity $\sim 6$ fb$^{-1}$)

(Standard-Model) boson-like properties

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Backup (references)
H → γ γ (historical mode)

Figure 4: Reconstructed mass plots for Higgs boson, $m_H=100\text{GeV}/c^2$
(a) smeared by calorimeter energy resolution of $\Delta E/E = 2\% \sqrt{E} \oplus 0.5\%$
(b) smeared by: calorimeter energy resolution of $\Delta E/E = 7\% \sqrt{E} \oplus 1.0\%$
(c) smeared by: pileup energy from, on average, 10 interactions
(d) smeared by: loss of knowledge of the vertex position ($\sigma_{\text{rad}}=5.5\text{ cm}$)

was studied at the LHC for more than 20 years (and even before at the SSC)
\[ M^2 = 2 E_{\gamma_1} E_{\gamma_2} (1 - \cos \Psi_{12}) \]

Figure 4: Reconstructed mass plots for Higgs boson, \( m_H = 100 \text{GeV/c}^2 \)

(a) smeared by calorimeter energy resolution of \( \Delta E/E = 2\% \sqrt{E} \geq 0.5\% \)

(b) smeared by calorimeter energy resolution of \( \Delta E/E = 7\% \sqrt{E} \geq 1.0\% \)

(c) smeared by pileup energy from, on average, 10 interactions

(d) smeared by loss of knowledge of the vertex position (\( \sigma_v = 5.5 \text{ cm} \))
<table>
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<th>ATLAS</th>
<th>CMS</th>
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<tr>
<td><strong>MAGNET (S)</strong></td>
<td>Air-core toroids + solenoid 4 magnets Calorimeters in field-free region</td>
<td>Solenoid 1 magnet Calorimeters inside field</td>
</tr>
<tr>
<td><strong>TRACKER</strong></td>
<td>Si pixels + strips TRT → particle identification $B=2T \sigma/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$</td>
<td>Si pixels + strips No particle identification $B=4T \sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$</td>
</tr>
<tr>
<td><strong>EM CALO</strong></td>
<td>Pb-liquid argon $\sigma/E \sim 10%/\sqrt{E}$ longitudinal segmentation</td>
<td>PbWO₄ crystals $\sigma/E \sim 2-5%/\sqrt{E}$ no longitudinal segmentation</td>
</tr>
<tr>
<td><strong>HAD CALO</strong></td>
<td>Fe-scint. + Cu-liquid argon ($10 \lambda$) $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$</td>
<td>Cu-scint. ($&gt;5.8 \lambda$ +catcher) $\sigma/E \sim 100%/\sqrt{E} \oplus 0.05$</td>
</tr>
<tr>
<td><strong>MUON</strong></td>
<td>Air $\rightarrow \sigma/p_T \sim 7%$ at 1 TeV standalone</td>
<td>Fe $\rightarrow \sigma/p_T \sim 5%$ at 1 TeV combining with tracker</td>
</tr>
</tbody>
</table>
Exemple of CMS = (Compact Muon Solenoid)

- **eγ precision calorimetry**
  - $H \rightarrow \gamma\gamma, 4\ e$

- **Lead tungstate**
  - 75000 scintillating crystals

**Silicon tracker**
+ vertex (b quark, τ lepton)

**B = 4 T**

**Trigger without dead time**
write > 200 evts /s

**Suppose to work 10 years without decrease of performances**

**Muon spectrometer**

**Hadronic Calorimetry**
Sampling calorimeter with absorber (brass) and plastic scintillators
Jets and $E_T^{miss}$
High level quality control!
history of relative response
E/p history
Validation and tests with $Z \rightarrow ee$

the energy (and the response) of $\gamma$ from $H \rightarrow \gamma\gamma$ is different from the energy (and response) of $e$ from $Z \rightarrow ee$

⚠️

see talk of Cyril Becot next Tuesday

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Muon Spectrometer ($|\eta|<2.7$): air-core toroids ($B \sim 0.5 / 1T$ in barrel/end-cap) with gas-based muon chambers. Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV.

**ATLAS detector**

- **Length**: ~ 46 m
- **Radius**: ~ 12 m
- **Weight**: ~ 7000 tons
- ~10^8 electronic channels
- 3000 km of cables

**Inner Detector ($|\eta|<2.5$, $B=2T$):**
- Si Pixels, Si strips, Transition Radiation detector (straws)
- Precise tracking and vertexing, $e/\pi$ separation
- Momentum resolution: $\sigma/p_T \sim 3.8 \times 10^{-4} p_T$ (GeV) $\oplus$ 0.015 (chamber resolution $\oplus$ MS)

**EM calorimeter: Pb-LAr Accordion**
- $e/\gamma$ trigger, identification and measurement
- E-resolution: $\sigma/E \sim 10%/\sqrt{E}$

**HAD calorimetry ($|\eta|<5$):** segmentation, hermeticity
- Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
- Trigger and measurement of jets and missing $E_T$
- E-resolution: $\sigma/E \sim 50%/\sqrt{E} \oplus 0.03$

3-level trigger reducing the rate from 40 MHz to ~200 Hz.
presampler and longitudinal segmentation of the EM (Liquid Argon) accordion calorimeter

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Outside you have the calorimeters and the muon detector

ATLAS
inner detector

electrons can do some bremsstrahlung in the Inner Detector ⇒ response more complicated

photons can convert ⇒ more complicated than a non converted photon

B = 2T
very good stability

Data 2012, \(\sqrt{s} = 8\) TeV, \(\int L dt = 13.0\) fb\(^{-1}\)

ATLAS Preliminary

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Event display with a $Z \rightarrow \mu^+\mu^-$ with 25 reconstructed vertices recorded April 15th 2012
\[ M^2 = 2 E_{\gamma_1} E_{\gamma_2} (1 - \cos \Psi_{12}) \]

A lot of vertex \( \Rightarrow \) (if the wrong vertex is taken) impact on \( \Psi_{12} \)
ATLAS: uses the longitudinal segmentation in order to get the vertex (and also the track conversion(s) when the photon is converted)

\[ \Rightarrow \text{No degradation of the resolution} \]
CMS: sophisticated kinematical cuts (and the conversions) in order to get 'the' vertex

Fraction of 'good' vertices

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large (non photon) background
due to jets fragmenting mainly into $\pi^0$'s

background ‘photon candidates’ coming from jets are less isolated than real photons
The granularity of the electromagnetic ATLAS detector is very useful to reject the π⁰ background. The opening of photons coming from a π⁰ (p_T=40 GeV) with ΔR > .007 is a good jet rejection essential to reduce γj and jj backgrounds.

Granularity of 1st sampling of calorimeter: Δη ~ 0.003
Photon identification with shower shapes

Reminder: opening angle between the two photons of a $\pi^0$ of $p_T = 40$ GeV is $> 0.007$ to be compared with size of strip calo 1st sampling ~0.003

$\pi^0$ candidate passing “loose”, failing “tight” selection

tight selection uses mainly calo 1st sampling
Photon candidate passing “tight” selection

Nice shape in first sampling of EM calorimeter
but there are different categories

very similar ‘effective’ resolutions

slightly better resolution in CMS but more tails
back 21 years ago
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Backup (references)
Hints of signal were already there in 13th December 2011
Corfu 8 - 9 - 13

The 4th July seminar

before

after
during
$\sqrt{s} = 7$ TeV \( \int L dt = 0.02 \) fb\(^{-1} \) Apr 18, 2011

**ATLAS** Preliminary

H\( \rightarrow \gamma\gamma \) channel

![Graph showing event distribution](image)
Evolution of the excess (all channels) with time

ATLAS

$m_H$ [GeV]

Local $p_0$

$\sqrt{s} = 7$ TeV (2011), $\int L dt = 4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV (2012), $\int L dt = 5.9$ fb$^{-1}$

07/11 EPS Prel.
- Observed
- Expected

12/11 CERN Prel.
- Observed
- Expected

Spring 2012 PRD
- Observed
- Expected

04/12 CERN Prel.
- Observed
- Expected

PLB 07/12
- Observed
- Expected

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Several categories are made in order to enhance the sensitivity in order to have different S/B, based on
- number of jets
- different resolutions
- different kinematics giving different S/B

S/B has to be different for various categories
This is needed if we want to gain in statistical significance
if \( \frac{S_1}{B_1} = \frac{S_2}{B_2} \)
then \( \frac{S_1}{\sqrt{B_1}} \oplus \frac{S_2}{\sqrt{B_2}} = \frac{(S_1+S_2)}{\sqrt{(B_1+B_2)}} \)
and one does not gain making categories

(one of) the work of the experimentalist is to find categories with different S/B!
In fact finding and using different categories allows us to « see » the various production modes.
Typical uncertainties on cross-section

- $gg \rightarrow H$: +15 -20% NNnLO
- VBF: 5% NLO
- WH, ZH: 5% NNLO
- $ttH$: 15% NLO

These production cross sections have to be used with the decays $bb$, $\tau\tau$, $WW$, $ZZ$, $\gamma\gamma$
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Backup (references)
A way to have access to H couplings to bosons and fermions.

We are looking $\mu = \frac{\sigma}{\sigma_{SM}}$ SM = SM boson and we can study

$\mu_{ggH} = \frac{\sigma_{ggH}}{\sigma_{ggH_{SM}}}$

$\mu_{VBFH} = \frac{\sigma_{VBFH}}{\sigma_{VBFH_{SM}}}$

$\mu_{WH} = \frac{\sigma_{WH}}{\sigma_{WH_{SM}}}$

In fact $\mu = \frac{(\sigma \cdot B)}{(\sigma \cdot B)_{SM}}$

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Scalar boson decays: example of $H \rightarrow \gamma \gamma$

Interference between

W loop  top loop

$$\Gamma (H \rightarrow \gamma \gamma) = \frac{G_\mu \alpha^2 M_H^3}{128 \sqrt{2} \pi^3} \left| \sum_f N_c Q_f^2 A^H_{1/2}(\tau_f) + A^H_1(\tau_W) \right|^2$$

$\propto 1.8 - 8$
Flow-chart of the event categorisation, giving the order of selection of the different categories.
Figure 10: (left) The diphoton mass spectrum weighted by the ratio of signal-to-background in each event class for the mass-fit-MVA analysis. (right) The background-subtracted weighted mass spectrum.
\[ \mu \text{ slightly above SM} \]
\[ \mu = 1.55^{+0.33}_{-0.28} \]
\[ 7.4 \sigma \]
\[ m_H = 126.8 \pm 0.2 \pm 0.7 \text{ GeV} \]

\[ \mu \text{ slightly below SM} \]
\[ \mu = 0.78^{+0.28}_{-0.26} \]
\[ 3.2 \sigma \]
\[ m_H = 125.4 \pm 0.5 \pm 0.6 \text{ GeV} \]

syst uncertainty : non linearity between Z and H energies and difference between e and \( \gamma \) (see talk of Cyril Becot next tuesday)

errors : \( \pm 0.23 \text{(stat)} \) \( \pm 0.15 \text{(syst)} \) \( \pm 0.15 \text{(th)} \) similar errors
couplings measured in all categories

signal strengths for different subprocesses

start to see evidence for VBF
General good agreement with the Standard Model in particular $\gamma\gamma$ (see lesson of Bruno Mansoulié)
\[ \frac{\mu_{VBF}}{\mu_{ggF+ttH}} = 1.4^{+0.4}_{-0.3} \text{(stat)}^{+0.6}_{-0.4} \text{(sys)} \]

**ATLAS**

\[ m_H = 125.5 \text{ GeV} \]

\[ \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.1^{+0.9}_{-0.5} \]

**Total uncertainty**

- \( \sigma(\text{stat}) \)
- \( \sigma(\text{sys}) \)
- \( \sigma(\text{theo}) \)

\( \sqrt{s} = 7 \text{ TeV} \) \( \int L dt = 4.6-4.8 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV} \) \( \int L dt = 20.7 \text{ fb}^{-1} \)

3.3 \( \sigma \) effect
the width of the SM scalar is small \( \Gamma = 4.2 \text{ MeV} \)

compared to the experimental resolution \( \text{FWHM} \sim 4 \text{ GeV} \)

and it is very difficult to obtain

\[
\Gamma \sim \sqrt{\left( \text{FWHM}_{\text{meas}} \right)^2 - \left( \text{FWHM}_{\text{pred}} \right)^2}
\]

still a limit is set for \( \Gamma \) at

6.9 \text{ GeV} \quad 95\% \text{ CL}

There are other (indirect) ways of putting limits (with few hypothesis) on invisible width or invisible branching ratio

- \( \heartsuit \) \( ZH \), \( H \rightarrow \text{inv} \)
- \( \heartsuit \) couplings analysis
search for additional scalar-boson-like states

In this search the observed state around 125 GeV is considered as part of the ‘background’

Once sufficiently away from 125 GeV, we recover the same limit as in the search for a single SM Higgs boson. The \( p \)-value at the most significant excess, where \( m_H=136.5 \) GeV, is found to be 2.93\( \sigma \).
relatively high signal yield ( ~ 620 fitted in ATLAS at \( \sqrt{s} = 8 \text{ TeV} \))

\( \Rightarrow \) can be used to probe the underlying kinematic properties of production and decay

**Methodology:**

- Choose a binning for variable \( X \)
- For each bin get signal yield from \( m_{\gamma\gamma} \) distribution
- Bin-by-bin unfolding (correct yields for acceptance, eff, resolution) \( \Rightarrow d\sigma/dX \)

( for instance \( X = N_{\text{jets}} \) )
No significant deviation from SM predictions

still large uncertainties

$P(\chi^2) = 0.55$ (POWHEG)

$P(\chi^2) = 0.39$ (HRES)
spin 1 excluded by Landau-Yang theorem

different angular distributions

difficult analysis
For spin 2 100% gg production
- compatibility data/SM : **58.8 %**
  ( 0.5 % expected if spin 2 true)
- spin 2 model p-value : **0.3 %**
  ( 1.2 % expected if SM)
⇒ minimal spin 2 strongly disfavoured

large decrease of sensitivity for large q-qbar production fraction
recovered with WW channel
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Backup ( references )
Intense period of discovery, where the channel $H \rightarrow \gamma\gamma$ was very important.

Followed more than 20 years of work on this subject.

After the discovery this channel will be (and is already) used in order to make some measurements which can test the Standard Model.

All the data is analysed. Final results will come soon (waiting for final calibrations).

Very nice (at least for experimentalists) to have several channels ($\gamma\gamma$, $bb$, $ZZ$, $WW$, $\tau\tau$) opened for $mH=125$ GeV.

Several results were not shown, like:
- search for two near-mass degenerate states
- dedicated $ttH$ search
- FCNC $tt$ with $t \rightarrow cH$ ...
Thank you for your attention
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Backup (references and additional plots)
Historical references
For a list of historical references see

Nansi Andari (Orsay, LAL) CERN-THESIS-2012-144
Observation of a BEH-like boson decaying into two photons with the ATLAS detector at the LHC

Early $H\rightarrow \gamma\gamma$ theory references


Early phenomelogical/experimental references (pre-LHC)


C. Barter et al., Detection of $H \rightarrow \gamma\gamma$ at the SSC, Proceedings of the Summer Study on HEP in the 1990’s, june 1988, Snowmass, Colorado

M. Mangano, Production of $WH \rightarrow W\gamma\gamma$, SSC-SDC-90-00113.

Early phenomelogical/experimental references (LHC)

C. Seez and J. Virdee, Photon decay modes of the intermediate masss Higgs, Large Hadron Collider Workshop, Aachen October 1990 ( ed by G. Jarlskog and D. Rein), vol 2 report CERN 90-10 ECFA 90-133 page 474


L. Fayard and G. Unal, Search for Higgs decay into photons with EAGLE, ATL-PHYS-92-001.
The LOI’s of ATLAS, CMS and L3P

B. Mansoulié et al. ATL-CAL-92-008
Study of the rejection of pi-zeros by a cold preshower behind, the coil and cryostat (Dice-A): rapidity dependance, noise dependance
CMS references
CMS-PAS-EGM-10-005
Photon reconstruction and identification at $\sqrt{s} = 7$ TeV

CMS-PAS-EGM-10-006
Isolated Photon Reconstruction and Identification at $\sqrt{s} = 7$ TeV

CMS-PAS-HIG-11-010
Search for a Higgs boson decaying into two photons in the CMS detector (1 $fb$-1
8 categories: $pT$ - converted, non-converted - Barrel, End-Cap)

CMS-PAS-HIG-11-011
SM Higgs Combination (1 $fb$-1)

CMS-PAS-HIG-11-021
Search for a Higgs boson decaying into two photons in the CMS detector (1.7 $fb$-1)

CMS-PAS-HIG-11-023
Combined Standard Model Higgs boson searches with up to 2.3 inverse
femtobarns of pp collision data at $\sqrt{s}$=7 TeV at the LHC (ATLAS + CMS)

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CMS-PAS-HIG-11-030
Search for a Higgs boson decaying into two photons in the CMS detector (5 fb⁻¹)
4 categories: converted, non converted - Barrel, Endcap, local significance of 2.3 σ)

CMS-PAS-HIG-11-032
Combination of SM Higgs Searches (5 fb⁻¹)

Combined results of searches for the standard model Higgs boson in pp collisions
at √s = 7 TeV

Search for the standard model Higgs boson decaying into two photons in pp collisions
at √s = 7 TeV (5 categories, in addition dijet à la VBF, local significance of 3.1 σ)
CMS-PAS-HIG-12-001
A search using multivariate techniques for a standard model Higgs boson decaying into two photons (7 TeV, MVA, local significance of $2.9 \sigma$, 5 categories: 4 from BDT and a dijet one à la VBF)

CMS-PAS-HIG-12-008
Combination of SM, SM4, FP Higgs boson searches (like 12-001, 7 TeV, excludes fermiophobic)

CMS-PAS-HIG-12-002
Search for the fermiophobic model Higgs boson decaying into two photons (7 categories: 4 from converted, non converted – barrel, endcap a dijet tag à la VBF, an electron tag one and a muon tag one)

JHEP 1209 (2012) 111
Search for a fermiophobic Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV (γγ like 12-002, ZZ, WW)
CMS-PAS-HIG-12-015
Evidence for a new state decaying into two photons in the search for the standard model Higgs boson in pp collisions (local significance = 4.1 \sigma, 5 categories at 7 TeV, 6 at 8 TeV, 4 by BDT at 7 and 8 TeV, 1 additional dijet category at 7 TeV, 2 additional dijet categories at 8 TeV)

CMS-PAS-HIG-12-020
Observation of a new boson with a mass near 125 GeV

CMS-PAS-HIG-12-022
Higgs to gamma gamma, Fermiophobic (5+5 fb-1
2011 : 7 categories like in JHEP 1209 (2012) 111
2012 : 9 categories : converted, unconverted –
Barrel-Endcap, 2 dijet categories, 1 e category, 1 \mu category and 1 Etmiss category)

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC (uses 12-015 for \gamma\gamma, mH comb = 125.3 \pm 0.4 \pm 0.5 GeV)
CMS-PAS-HIG-12-045
Combination of standard model Higgs boson searches and measurements of the properties of the new boson with a mass near 125 GeV (\(5 + 13\ \text{fb}^{-1}\), but \(H \rightarrow \gamma\gamma\) \(5 + 5\ \text{fb}^{-1}\) uses Phys.Lett. B716 (2012) 30-61)

CMS-PAS-HIG-12-049
Search for a Light Higgs boson in the Z boson plus a Photon Decay Channel (\(5 + 5\ \text{fb}^{-1}\))

Searches for Higgs bosons in pp collisions at \(\sqrt{s} = 7\) and 8 TeV in the context of four-generation and fermiophobic models (\(\gamma\gamma\) like in Phys.Lett. B716 (2012) 30-61 \(5 + 5\ \text{fb}^{-1}\))

CMS-PAS-HIG-13-006
Search for the standard model Higgs boson in the Z boson plus a photon channel in pp collisions at \(\sqrt{s} = 7\) and 8 TeV (\(5 + 20\ \text{fb}^{-1}\))

JHEP 06 (2013) 081
Observation of a new boson with mass near 125 GeV in pp collisions at \(\sqrt{s} = 7\) and 8 TeV

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CMS-PAS-HIG-13-001
Updated measurements of the Higgs boson at 125 GeV in the two photon decay channel
\( 3.2 \, \sigma \) \( m_H = 125.4 \pm 0.5 \pm 0.6 \text{ GeV} \)
MVA analysis: 5 categories at 7 TeV, 9 at 8 TeV,
4 by BDT at 7 and 8 TeV, 1 additional dijet category at 7 TeV,
2 additional dijet categories, 1 muon-tag, 1 e-tag and 1 Etmiss tag at 8 TeV
There is also a cut-based analysis described

CMS-PAS-HIG-13-005
Combination of standard model Higgs boson searches and measurements of the properties of
the new boson with a mass near 125 GeV (\( \gamma \gamma \) uses 13-001, \( m_H \text{comb} = 125.7 \pm 0.3 \pm 0.3 \text{ GeV} \))

CMS-PAS-HIG-13-015
Search for \( \text{ttH} \) production in events where \( H \) decays to photons at 8 TeV collisions
(2 analysis: 2 top hadronic
1 hadronic and 1 leptonic)
Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7$ TeV

CMS-PAS-HIG-13-016
Properties of the observed Higgs-like resonance using the diphoton channel (like 13-001. natural width and second Higgs scenario uses MVA analysis, spin uses cut based analysis)

arXiv:1307.5515
Search for a Higgs boson decaying into a Z and a photon in pp collisions at $\sqrt{s} = 7$ and 8 TeV
ATLAS references
Lampl, W ; Laplace, S ; Lelas, D ; Loch, P ; Ma, H ; Menke, S ; Rajagopalan, S ; Rousseau, D ; Snyder, S ; Unal, G

ATL-LARG-PUB-2008-002

Calorimeter Clustering Algorithms : Description and Performance
ATLAS-CONF-2011-004
Measurement of the backgrounds to the Higgs To gammagamma search and reappraisal of its sensitivity with 37 pb-1 of data recorded by the ATLAS detector

ATLAS-CONF-2011-025
Search for the Higgs boson in the diphoton final state with 38 ipb of data recorded by the ATLAS detector in proton-proton collisions at sqrt(s)=7 TeV PCL

ATL-PHYS-PUB-2011-007
Expected photon performance in the ATLAS experiment

ATLAS-CONF-2011-085
Search for the Higgs Boson in the Diphoton Channel with the ATLAS Detector using 209 pb-1 of 7 TeV Data taken in 2011 PCL

Limits on the production of the Standard Model Higgs Boson in pp collisions at $\sqrt{s}=7$ TeV with the ATLAS detector 1st combination H 40 pb$^{-1}$

ATLAS-CONF-2011-135
Update of the Combination of Higgs Boson Searches in 1.0 to 2.3 fb$^{-1}$ of pp Collisions Data Taken at $\sqrt{s} = 7$ TeV with the ATLAS Experiment at the LHC
Search for the Standard Model Higgs boson in the two photon decay channel with the ATLAS detector at the LHC (1 fb⁻¹)

ATLAS-CONF-2011-149
Search for a fermiophobic Higgs boson in the diphoton channel with the ATLAS detector (1 fb⁻¹, pT categories)

ATLAS-CONF-2011-157
Combined Standard Model Higgs boson searches with up to 2.3 fb-1 of pp collision data at sqrt{s} = 7 TeV at the LHC (ATLAS+CMS)

ATLAS-CONF-2011-161
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb-1 of ATLAS data at sqrt(s)=7 TeV (PTt and conversion categories : 9 categories local significance = 2.8 σ)

ATLAS-CONF-2011-163
Combination of Higgs Boson Searches with up to 4.9 fb-1 of pp Collision Data Taken at sqrt(s)=7 TeV with the ATLAS Experiment at the LHC
Combined search for the Standard Model Higgs boson using up to 4.9 fb$^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC

Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV with ATLAS (local significance = 2.8 $\sigma$)

ATLAS-CONF-2012-013
Search for a fermiophobic Higgs boson in the diphoton decay channel with 4.9/fb of ATLAS data at sqrt(s)= 7 TeV (using 9 categories)

ATLAS-CONF-2012-019
An update to the combined search for the Standard Model Higgs boson with the ATLAS detector at the LHC using up to 4.9 fb$^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV

Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector (5 fb-1)
Performance of the ATLAS Electron and Photon Trigger in p-p Collisions at sqrt{s} = 7 TeV in 2011

Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector (10 categories, including a 2 jet – à la VBF – one, 5 (2011) + 6 (2012) fb\(^{-1}\) local significance = 4.5 \(\sigma\))

Observation of an Excess of Events in the Search for the Standard Model Higgs boson with the ATLAS detector at the LHC (WW only 2011)

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC (with WW 2012 \(m_H\) comb = 126.0 ± 0.4 ± 0.4 GeV)

Measurements of the photon identification efficiency with the ATLAS detector using 4.9 fb\(^{-1}\) of pp collision data collected in 2011
**ATLAS-CONF-2012-127**
Coupling properties of the new Higgs-like boson observed with the ATLAS detector at the LHC (5+6 fb⁻¹)

**ATLAS-CONF-2012-162**
Updated ATLAS results on the signal strength of the Higgs-like boson for decays into WW and heavy fermion final states (includes 13 fb⁻¹ of 2012 except γγ 5+6 fb⁻¹)

**ATLAS-CONF-2012-168**
Observation and study of the Higgs boson candidate in the two photon decay channel with the ATLAS detector at the LHC (m_H = 126.6 ± 0.3 ± 0.7 GeV local significance = 6.1 σ 5+13 fb⁻¹ 12 categories in 2012 with two 2-jet categories and a one-lepton category)

**ATLAS-CONF-2012-170**
An update of combined measurements of the new Higgs-like boson with high mass resolution channels (m_H comb = 125.2 ± 0.3 ± 0.6 GeV 5+13 fb⁻¹)

**ATLAS-CONF-2013-009**
Search for the Standard Model Higgs boson in the H → Zγ decay mode with pp collisions at √s = 7 and 8 TeV (5+20 fb⁻¹)
ATLAS-CONF-2013-012
Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb$^{-1}$ of proton-proton collision data

(14 categories including two 2-jet high mass, one 2-jet low mass, lepton, $E_{T}\text{miss}$
local significance $=7.4\,\sigma$, $m_H=126.8\pm.2\pm.7\,\text{GeV}$)

ATLAS-CONF-2013-014
Combined measurements of the mass and signal strength of the Higgs-like boson with the ATLAS detector using up to 25 fb$^{-1}$ of proton-proton collision data

($m_H\text{ comb}=125.5\pm.2^{+.5}_{-.6}\,\text{GeV}$)

ATLAS-CONF-2013-029
Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb$^{-1}$ of pp collisions collected at $\sqrt{s}=8\,\text{TeV}$ with the ATLAS detector

ATLAS-CONF-2013-034
Combined coupling measurements of the Higgs-like boson with the ATLAS detector using up to 25 fb$^{-1}$ of proton-proton collision data ($10\,\sigma$)

ATLAS-CONF-2013-040
Study of the spin of the new boson with up to 25 fb$^{-1}$ of ATLAS data
arXiv:1307.1427
Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

arXiv:1307.1432
Evidence for the spin-0 nature of the Higgs boson using ATLAS data

ATLAS-CONF-2013-072
Differential cross sections of the Higgs boson measured in the diphoton decay channel with the ATLAS detector using 8 TeV proton-proton collision data

ATLAS-CONF-2013-080
Search for ttH production in the H → γγ channel at √s = 8 TeV with the ATLAS detector

ATLAS-CONF-2013-081
Search for flavour changing neutral currents in top quark decays t→cH, with H→γγ, and limit on the tcH coupling with the ATLAS detector at the LHC
Condensed matter physics

SSB = Spontaneous Symmetry Breaking: There are symmetries of the Lagrangian that are not symmetries of the fundamental state (vacuum)

1928 (Heisenberg) For $T<T_c$ dipoles are aligned in some arbitrary direction

1950 (Ginzburg Landau): phase transition in superconductivity

1957 (Bardeen, Cooper, Schrieffer) SSB of EM gauge invariance
Particle physics - strong interaction (global symmetry)

1959 (Nambu Jona-Lasinio) : SSB transmitted from condensed matter to particle physics
SSB of (global) chiral symmetry $\rightarrow$ pseudoscalar boson $\pi^0$
massless boson if exact symmetry

1960 (Goldstone) : generalization : SSB of continuous global symmetry $\rightarrow$ massless (Nambu-Goldstone) bosons

$$L = \partial^\mu \phi^\dagger \partial_\mu \phi - V(\phi^\dagger \phi)$$
$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2; \quad \lambda > 0 \text{ and } \mu^2 < 0$$

and massive boson mass $\sqrt{-2 \mu^2}$
$$\sigma = f_0(600)$$
Particle physics - strong interaction (local symmetry)

1964 (Brout, Englert, Higgs, Guralnik, Hagen, Kibble)

SSB of gauge symmetries

The BEH mechanism: no massless particles
massive gauge bosons

mass of gauge boson acquired by ‘eating’ the N-G boson

one massive particle $\sqrt{-2\mu^2}$: BEH boson (or Higgs boson)
Mass of the 4 scalar bosons positive
W and Z mass = 0
fermion masses = 0

$10^{-10}$ s

Mass of one scalar (BEH) boson positive
W and Z mass positive
fermion have their masses
Searching for the intermediate-mass Higgs boson

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(Received 30 September 1985)

We study the feasibility of detecting a neutral Higgs boson $H^0$, with mass between $2m_t \approx 80$ GeV (by assumption) and $2m_W$ at an $e^+e^-$ machine or the Superconducting Super Collider (SSC). Backgrounds to the production at an $e^+e^-$ machine of $H^0$ in association with a $Z$ are calculated with particular emphasis on the case when $m_H \approx m_t$. We present a detailed survey of the signals for and backgrounds to the inclusive or associated production at the SSC of $H^0$ followed by the decay of $H^0$ into one of the available channels. There is no signature which is established to be identifiable at the SSC. Only a few signatures remain to be studied, and the further calculations of most immediate interest are pointed out.

**SEARCH TECHNIQUES FOR CHARGED AND NEUTRAL INTERMEDIATE-MASS HIGGS BOSONS**

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DETECTION OF $H^0 \rightarrow \gamma\gamma$ AT THE SSC

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FIG. 6. Simulated mass distribution for 100 GeV Higgs in detector with extraordinary resolution.

PRODUCTION OF $WH \rightarrow W\gamma\gamma \rightarrow e/\mu\gamma\gamma$

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FIG. 7. Simulated mass distribution for 150 GeV Higgs in detector with extraordinary resolution.
loss in a fill and recovery in interfill
2012 intercalibration precision
CMS Preliminary 2012
\( \sqrt{s} = 8\text{TeV}, L = 19.6\text{ fb}^{-1} \)
ECAL Endcap

\[ \sigma_{\text{CB}} / M_\gamma (\%) \]

- **Prompt reconstruction**
- **Winter2013 re-reconstruction**

Date (day/month):
02/05
01/07
31/08
31/10

Corfu 8-9-13
energy scale corrections
ECAL supercluster energy
efficiency of photons

\[
\int L dt = 20.7 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV}
\]

Unconverted \(\gamma\), \(|\eta| < 0.6\)

- \(Z \rightarrow l\bar{l}\gamma\) data 2012
- \(Z \rightarrow l\bar{l}\gamma\) simulation

\[\eta, E_\gamma\] vs \(E_\gamma\) [GeV]

converted \(\gamma\), \(|\eta| < 0.6\)

- \(Z \rightarrow l\bar{l}\gamma\) data 2012
- \(Z \rightarrow l\bar{l}\gamma\) simulation

\[\eta, E_\gamma\] vs \(E_\gamma\) [GeV]

ATLAS Preliminary

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Corfu 8-9-13

- Simulation
- Parametric model

$\sigma_{\text{eff}} = 1.36$ GeV

FWHM = 2.99 GeV

$\sigma_{\text{eff}} = 2.61$ GeV

FWHM = 5.03 GeV

$\text{BDT}_{\gamma\gamma} \geq 0.91$

$-0.05 \leq \text{BDT}_{\gamma\gamma} \leq 0.49$
Exclusion on $\mu = \sigma / \sigma_{SM}$, $SM = SM$ boson

Everything above the black line is excluded

**ATLAS 2011 - 2012**

$\sqrt{s} = 7$ TeV: $\int_{Ldt} = 4.6$-$4.8$ fb$^{-1}$

$\sqrt{s} = 8$ TeV: $\int_{Ldt} = 5.8$-$5.9$ fb$^{-1}$

95% CL Limit on $\mu$
The dashed line shows the limit we would expect if the data were without any boson. The green and yellow bands show where, without any boson, the limits would be allowed to move at the $1\sigma$ or $2\sigma$ level (depending on the statistical fluctuations of the background).

The fact that the observed limit is above the expected $+2\sigma$ limit is a hint that the data are not well simulated by the backgrounds (statistical fluctuation, mismodeling, signal).
Figure 12: The weighted distribution of the invariant mass of diphoton candidates for the combined 7 TeV and 8 TeV data samples. The weight $w_i$ for category $i$ from [1, 14] is defined to be $ln(1 + S_i/B_i)$, where $S_i$ is the expected number of signal events in a mass window that contains 90% of the signal events, and $B_i$ is the integral in the same window of a background-only fit.
There are other ways of parametrizing the cross sections via couplings (see talk of Bruno Mansoulié)

\[ \sigma \cdot B(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} \]

zero width approximation

**coupling scale factors** \( \kappa_j \)

\[ \frac{\sigma \cdot B(gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma_{SM}(gg \rightarrow H) \cdot B_{SM}(H \rightarrow \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2} \]

\( \kappa_g \) includes \( t \) (and \( b \)) loop but also ‘exotic’ particles
large sensitivity for all qq/gg