$H \to \gamma\gamma$

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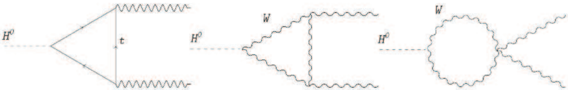
Section 1

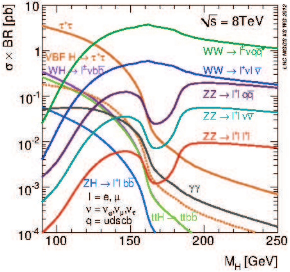
Introduction

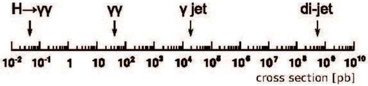
$H \to \gamma\gamma$

The channel



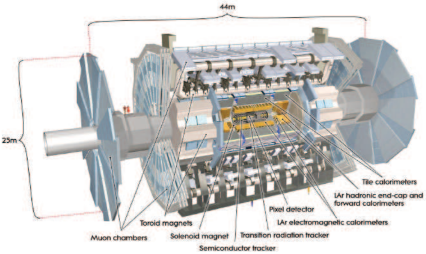
- small branching ratio ($\sim 10^{-3}$)
- simple signature: two isolated photons with large transverse momentum
- very good mass resolution ($1 \div 2\%$ @ 125 GeV)
- huge background
  - $\gamma\gamma$ from QCD (irreducible)
  - γj with one mis-identified jet as photon
  - jj with two mis-identified jets
  - Drell-Yan with electrons mis-identified as photons
- Sensitivity dependent on experimental di-photon mass resolution



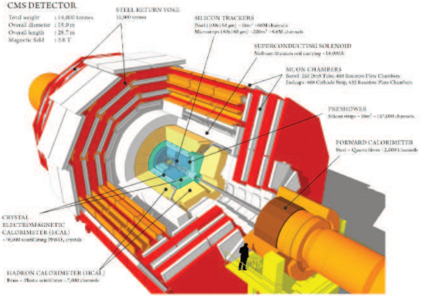


- very high sensitivity in the low mass range

ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

CMS


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

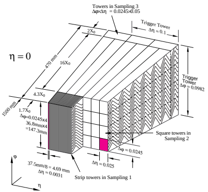
Section 2

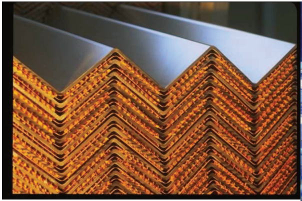
Photon physics

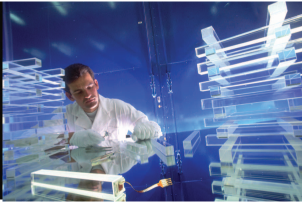
Different calorimeter design

- LAr/Pb sampling calorimeter, $22X_0$
- accordion shape: full azimuthal coverage, fast signal extraction
- longitudinally segmented (strip, middle, back) + presampler
- middle segmentation: 0.025×0.025
- fine η segmentation of strip layer, $\Delta\eta = 0.003$, γ/π^0 separation
- nominal $\sigma/E = \frac{10 \div 17\%}{\sqrt{E/\text{GeV}}} \oplus 0.7\%$

- homogeneous calorimeter
- high resolution $PbWO_4$ scintillating crystals, avalanche photodiodes + endcap silicon preshower
- 0.017×0.017 (barrel), 0.018×0.003 to 0.088×0.015 (endcap)
- lateral segmentation, no longitudinal segmentation
- nominal $\sigma/E = \frac{3\%}{\sqrt{E/\text{GeV}}} \oplus 0.5\%$



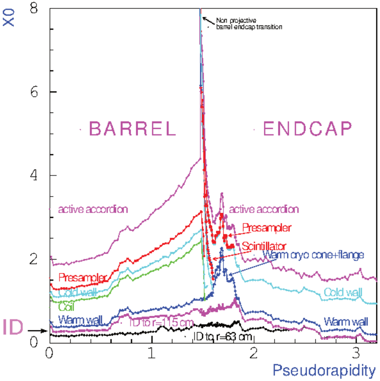


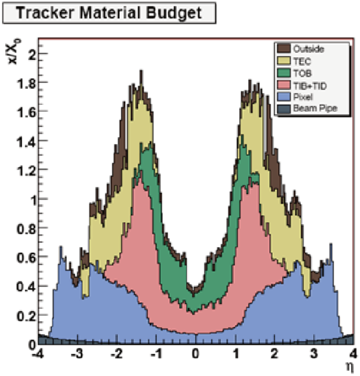


Detectors

material

Limiting the resolution due to energy loss. Need to estimated a correction.



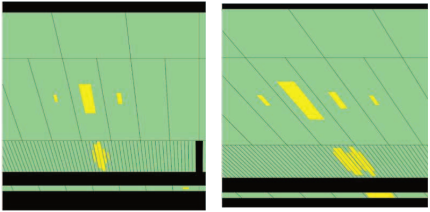


- ATLAS solenoid is located just in front of the barrel ECAL

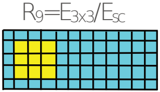
Photon identification

Both ATLAS and CMS exploit the granularity of the detector to reject background based on the shapes of the electromagnetic shower

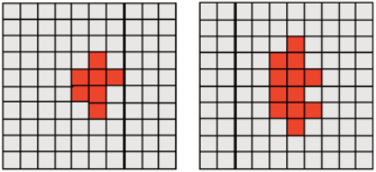
- Identification using
  - hadronic leakage
  - width in the middle layer
  - width in the strip layer
  - presence of second maxima in the strip layer ($\Delta\eta = 0.003 \div 0.006$)
- NN only for 2011
- Systematics: 1.5% - 2.5% (2012)



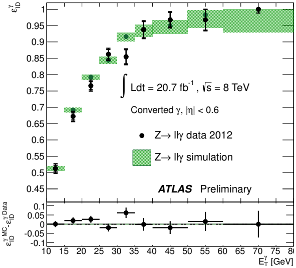
- BDT inputs:
  - isolation
  - cluster shapes ($R_9, \ldots$)
  - preshower energy (endcap)

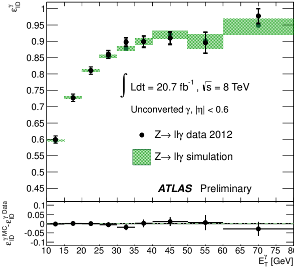


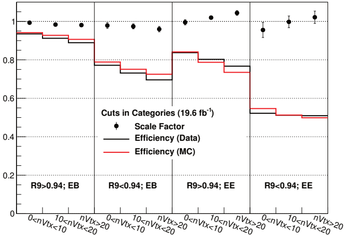
- validated with $Z \to ee$ and $Z \to \mu\mu\gamma$
- Systematics: 1% - 2.5%

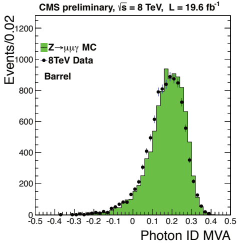


Efficiency





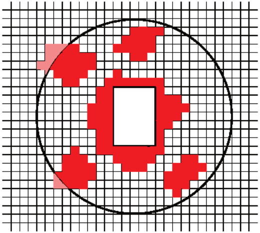




Good agreement data/MC for cut-based ($Z \rightarrow ee$) and MVA ($Z \rightarrow ee\gamma$)

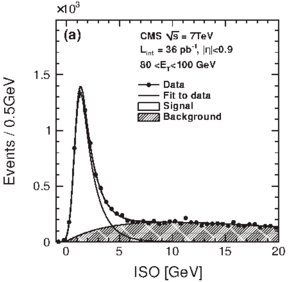
Isolation

- Calorimetric isolation: scalar sum of transverse energy of topoclusters in $\Delta R < 0.4$ except small central region
- Corrected for residual leakage and ambient energy



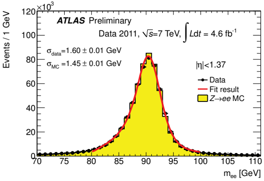
- Track isolation: scalar sum of transverse momenta of all the tracks in a cone around the photon $\Delta R < 0.2$

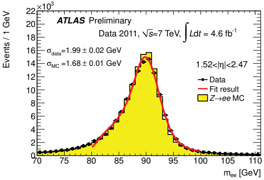
- $\Delta R < 0.3$ cone, using particle flow
- charged candidates from PF, associated to the selected vertex
- charged candidates from PF, associated to the vertex with highest isolation
- electromagnetic neutral candidates
- hadronic neutral candidates
- corrected by MVA for event energy density



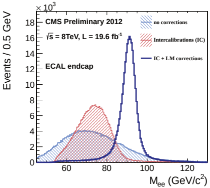
Energy scale and corrections

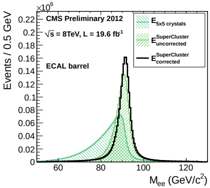
comparison data/MC after corrections:





spread in crystal and photo-detector response, and time-dependent corrections to response loss corrections

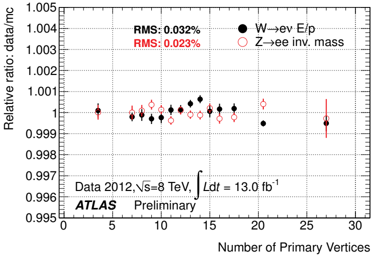


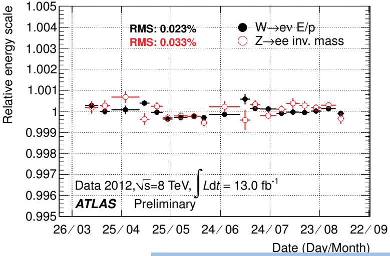


regression correction effect (right)

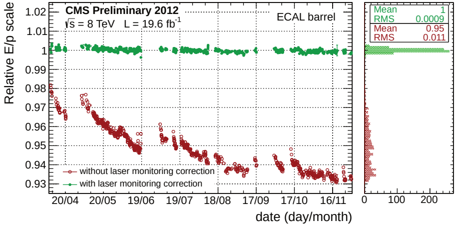
ECAL performance

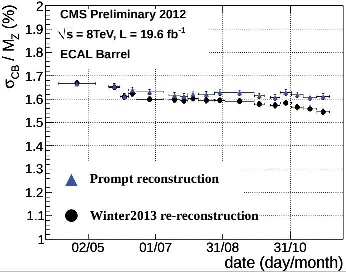
EMC stability < 0.1% vs time and pileup





important correction for CMS





Section 3

Higgs analysis

Moriond analysis

Documentation:

- - ATLAS-CONF-2013-012 (update only 2012, 2011 from ICHEP)
  - CMS-PAS-HIG-13-001 (first update after the discovery for CMS)
- two analyses for CMS: MVA ($\sim$ 15% more sensitivity) / cut-based
- spin analysis, fiducial cross section ($\sigma_{\text{fid}} \times Br = 56.2 \pm 10.5(\text{stat}) \pm 6.5(\text{syst}) \pm 2.0(\text{lumi})\text{fb}$) and VBF evidence ($2.9\sigma$, expected 1.3σ) only from ATLAS

Key points:

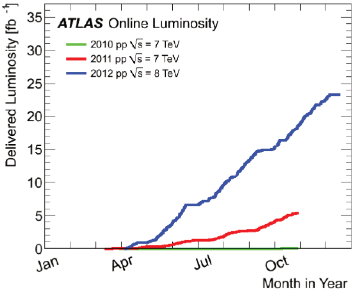
- energy resolution: sensitivity dependent on the resolution
- energy scale: main systematic error on the mass measurement
- vertex identification and pointing: to improve the mass resolution
- photon identification: main systematic on the coupling measurement (except luminosity)
- background parametrisation: important the well describe the background shape
- Data categorization in exclusive categories to increase sensitivity and access VBF / VH modes and in inclusive categories with different resolution and S/B

Data and trigger

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

$+20.7\ \text{fb}^{-1}$ $\sqrt{s} = 8\ \text{TeV}\ (2012)$

Systematics: 1.8% / 3.6%

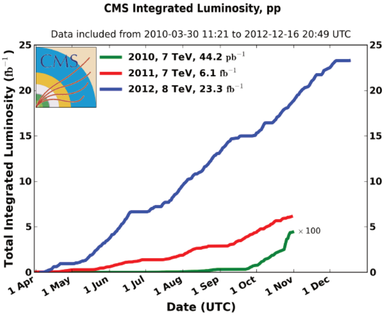


- diphoton trigger, using cluster energies and loose cuts: 20 GeV (2011), 35,25 GeV (2012). Syst: 0.5%

$L = 5.1\ \text{fb}^{-1}$ $\sqrt{s} = 7\ \text{TeV}\ (2011)$

$+19.6\ \text{fb}^{-1}$ $\sqrt{s} = 8\ \text{TeV}\ (2012)$

Systematics: 4.4%



- diphoton trigger, using cluster energies and loose cuts: 26 GeV,18 GeV and 36 GeV,22 GeV. Syst: 1%

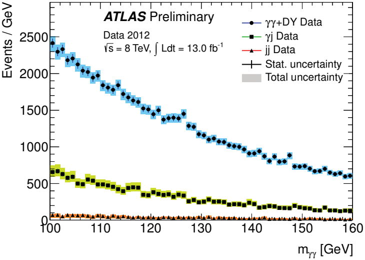
Offline selection

- $|\eta| < 2.37$ except $1.37 < |\eta| < 1.56$
- $p_T > 30, 40\,\text{GeV}$
- cut-based (NN) identification using shower shapes and hadronic leakage in 2012 (2011)
  - efficiency between 85% and 95% (100 GeV)
  - efficiency data-driven measurement on data (2.5%-1.5% uncertainty)
- calorimetric isolation $< 6\,\text{GeV}$
- track isolation $< 2.6\,\text{GeV}$
- 23 788 (118 893) events in $100 < m_H < 160\,\text{GeV}$ $\sqrt{s} = 7\,\text{TeV}$ (8 TeV)

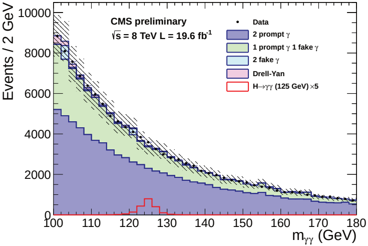
- $|\eta| < 2.5$ except $1.4442 < |\eta| < 1.566$
- $p_T > m_{\gamma\gamma}/3$, $p_T > m_{\gamma\gamma}/4$,
- preselection: hadronic leakage, isolation, loose shower shapes cuts
- BDT identification using:
  - many shower topology variables
  - four isolation definition
  - energy density in the event
- in the cut-based analysis:
  - hadronic leakage
  - shower shape variable
  - isolation
- isolation based on particle flow

Purity

- diphoton purity $75^{+3}_{-4}\%$



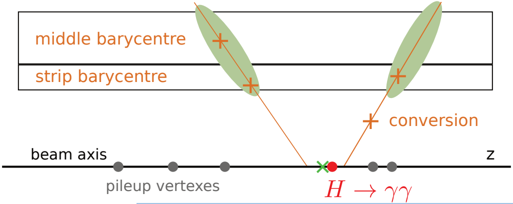
- diphoton purity: 70% from MC in $110 < m_{\gamma\gamma} < 150\,\mathrm{GeV}$

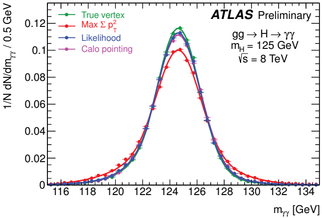


Pointing

ATLAS

- ability to measure direction with the calorimeter only thanks to the longitudinal segmentation
- unconverted photons using the barycentre of the cluster measured in the first and the second layer
- converted photons from the conversion point and the position in the first layer of the accordion
- for each of the two photons the intersection between the flight line and the beam line gives the estimate of the z-coordinate of the photon origin
- a weighted average of the two gives the estimate, with its uncertainty
- $\sigma_z = 15\,\mathrm{mm}$ ($6\,\mathrm{mm}$ using conversion)

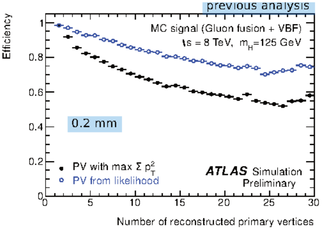




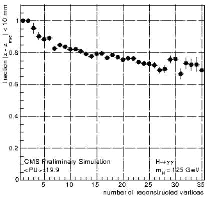
Primary vertex selection

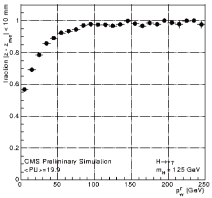
NN (2012), likelihood ratio (2011):

- $\sum_{\text{tracks}} p_T^2$, $\sum_{\text{tracks}} p_T$, $\Delta\phi(\gamma\gamma, \text{vertex})$, pointing+conversion
- validated with $Z \to ee$
- $\varepsilon \gtrsim 75\%$ ($< 0.3\,\text{mm}$)



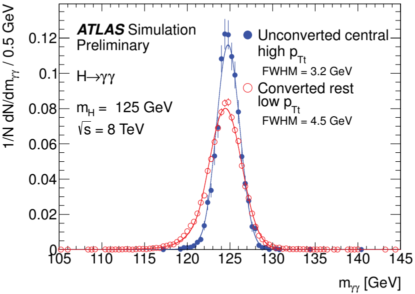
- BDT: conversion, p_T-balance, asymmetry
- $\varepsilon \sim 80\%$ ($< 10\,\text{mm}$)
- validated with $Z \to \mu\mu$, γ-jet
- Another BDT to evaluate prob. of correct choice



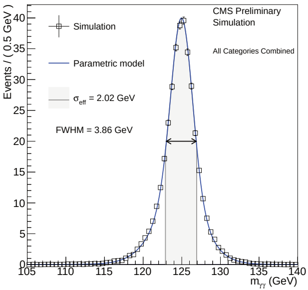


Invariant mass resolution

- Fit: Crystall Ball + wide gaussian
  - gaussian component $\lesssim 12\%$



- Fit: sum of two or three gaussians



FWHM / 2.35:

	ATLAS[1]	CMS
overall	1.77 GeV	1.64 GeV
best cat	1.40 GeV	1.27 GeV
other cats	1.50–2.52 GeV	1.39–2.14 GeV

[1] ATLAS only quotes σ_{CB} in the last public document. FHWM is obtained scaling σ_{CB} for the FHWM/σ_{CB} in HCP note.

Exclusive categories

Data are splitted in exclusive categories to study the coupling of $ggH + t\bar{t}H$ / VBF / VH associate production. Very high purity ($s/b \simeq 10\% \div 50\%$)

- one lepton, to tag VH production with lepton decays of V
- E_T-miss, to tag V decays with neutrinos
- low-mass two-jets category, to tag VH production with hadronic decay of V
- high-mass two-jets category (tight/loose) requiring 2 energetic and well separated hadronic jets, to tag VBF

- muon, to tag VH production with muon decays of V
- electron, to tag VH production with electron decays of V
- E_T-miss, to tag V decays with neutrinos
- dijet (low/high BDT) to tag VBF

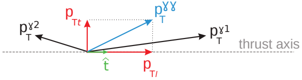
- CMS splits electron / muon
- ATLAS has low-mass two-jets category

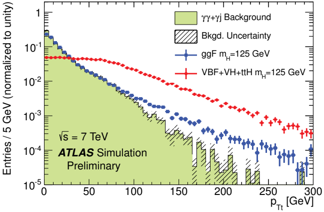
Inclusive categories

cut-based

9 categories using:

- conversion status
- $|\eta|$ position
- $p_{Tt} \gtrless 60\,\mathrm{GeV}$ (strongly correlated with the diphoton transverse momentum, but it has a better detector resolution)

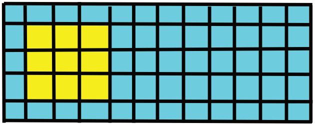




4 categories using:

- barrel / endcap
- shower shape $R_9 \gtrless 0.94$ (correlated with conversion status)

$$R_9 = E_{3x3}/E_{SC}$$

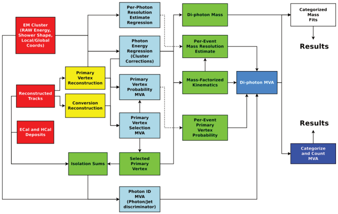


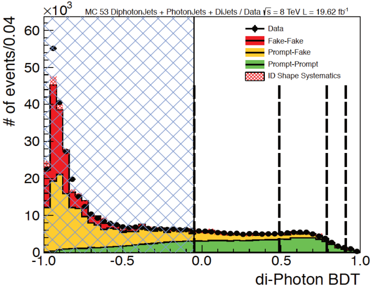
Inclusive categories

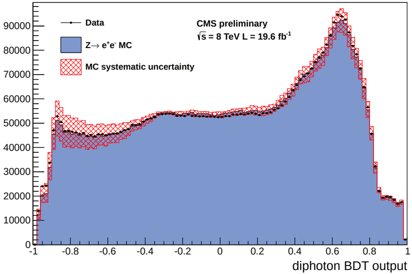
CMS (MVA)

Four untagged categories based on BDT discriminant

- inputs: kinematic properties, per-event mass resolution, photon identification
- validation of MVA inputs (kinematics, photon ID, mass resolution) with $Z \to ee$, $Z \to \mu\mu\gamma$
- No obvious data/MC discrepancy or pileup dependence







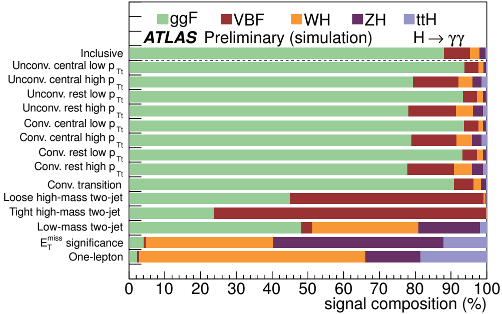
Category purity

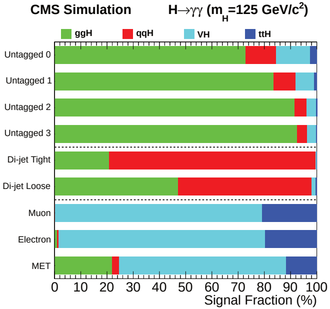
Signal composition

$\sqrt{s}$	8 TeV						
Category	N_D	N_S	$gg \to H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
Loose high-mass two-jet	276	5.3	45.0	54.1	0.5	0.3	0.1
Tight high-mass two-jet	136	8.1	23.8	76.0	0.1	0.1	0.0
Low-mass two-jet	210	3.3	48.1	3.0	29.7	17.2	1.9
E_T^{miss} significance	49	1.3	4.1	0.5	35.7	47.6	12.1
One-lepton	123	2.9	2.2	0.6	63.2	15.4	18.6

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)				
		Total	ggH	VBF	VH	ttH
8 TeV 19.6 fb^{-1}	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%





Signal and background

Expected signal and background considering a window containing 90% of the signal at 126.5 GeV[1]:

category	s	b	s/b	$s/\sqrt{b}$
Unc. Central LowPt	46.6	881	0.053	1.57
Unc. Central HighPt	7.1	44	0.161	1.07
Unc. rest LowPt	97.1	4347	0.022	1.47
Unc. rest HighPt	14.4	247	0.058	0.92
Conv Central LowPt	29.8	687	0.043	1.14
Conv Central HighPt	4.6	31	0.148	0.83
Conv Rest LowPt	88	4567	0.019	1.30
Conv Rest HighPt	12.9	266	0.048	0.79
Conv Transition	36.1	2499	0.014	0.72
Tight HighMass DiJet	7.3	13	0.562	2.02
Loose HighMass DiJet	4.8	28	0.171	0.91
LowMass DiJet	3	21	0.143	0.65
MET	1.1	4	0.275	0.55
Lepton	2.6	12	0.217	0.75
All	355.5	13647	0.026	3.04

category	s	b	s/b	$s/\sqrt{b}$
Untagged0	15.3	99	0.155	1.54
Untagged1	34.02	464	0.073	1.58
Untagged2	135.18	3312	0.040	2.35
Untagged3	143.91	9082	0.016	1.51
DiJetTight	8.28	20	0.414	1.85
DiJetLoose	10.35	76	0.136	1.19
MET	1.53	11	0.145	0.47
Muon	1.26	4	0.297	0.61
Electron	0.81	4	0.188	0.39
All	350.64	13072	0.027	3.07

[1] Quite difficult to compare: ATLAS quotes the number of expected background events in a mass window containing 90% of the signal at 126.5 GeV, CMS the number of expected background events at 125 GeV for 1 GeV. Here scaling CMS numbers to ATLAS using flat background and gaussian signal approximation.

Background model

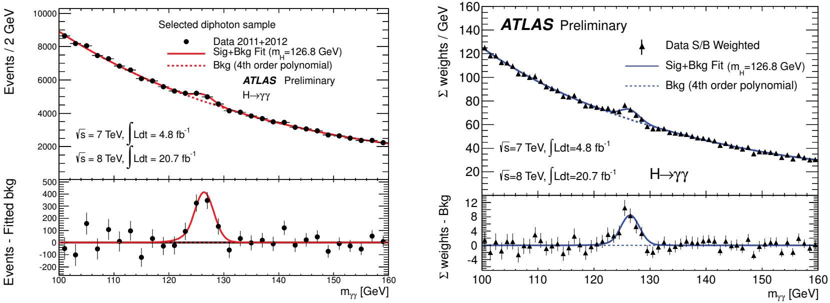
Signal extraction from S+B fits to $m_{\gamma\gamma}$ data, background from analytical functions. Different approach for the background modelling:

- fitting diphoton mass data distribution between $100 < m_{\gamma\gamma} < 160\,\text{GeV}$
- based on high statistics MC combined according to fraction determined from data
- spurious signal defined as the largest absolute signal component fitted anywhere in $110 < m_{\gamma\gamma} < 150\,\text{GeV}$ quoted as systematic

- determine truth model from data using function with high degree of freedom ($100 < m_{\gamma\gamma} < 180\,\text{GeV}$)
- the functions are tested on pseudo-data generated from truth model
- find the best function which minimize spurious signal ($<$ 20% background fluctuation in 1 FWHM)
- no specific systematics is associated to the spurious signal.

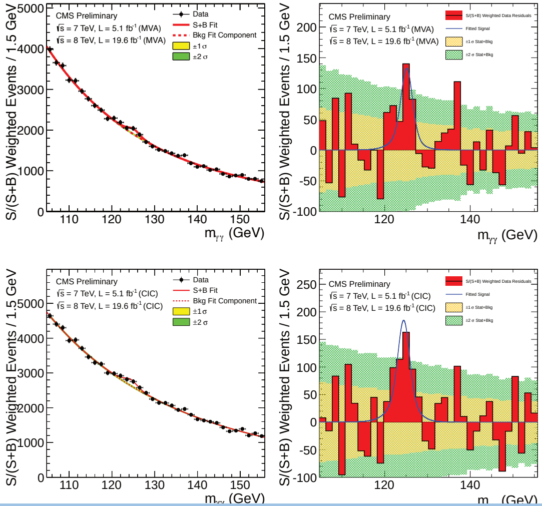
Signal yield

ATLAS (non-weighted/weighted)



Signal yield

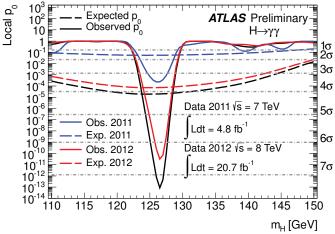
CMS (MVA/cut-based)

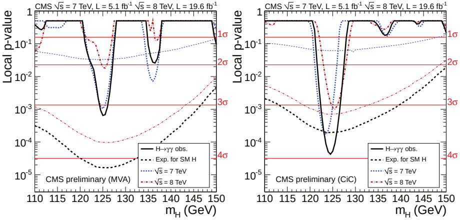


ATLAS-CONF-2013-012,CMS-PAS-HIG-13-001

Results

local p-value

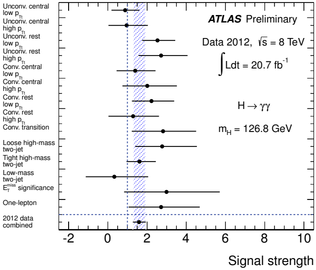


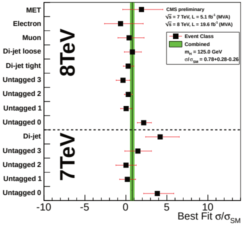


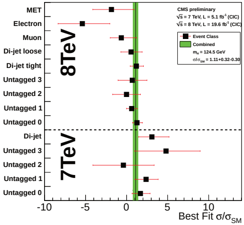
$\sqrt{s} = 7 + 8$ TeV	exp	obs	$\hat{\mu} = \sigma/\sigma_{\text{SM}}$
ATLAS no category	2.9	6.1	
ATLAS	4.1	7.4	$1.65 \pm 0.24(\text{stat})^{+0.25}_{-0.18}$ @ 126.8 GeV
CMS MVA	4.2	3.2	$0.78^{+0.28}_{-0.26}$ @ 125 GeV
CMS cut-based	3.5	3.9	$1.11^{+0.32}_{-0.30}$ @ 124.5 GeV

- Comparable expected significance between ATLAS and CMS MVA analysis
- ATLAS is 2.3 standard deviations from the SM expectation
- ATLAS has worse precision on the observed $\hat{\mu}$
  - there can be an effect related to the background model and treatment of systematics
  - the best would be to compare the expected precision on $\hat{\mu}$

Signal strength per category



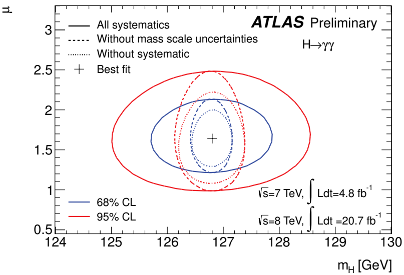


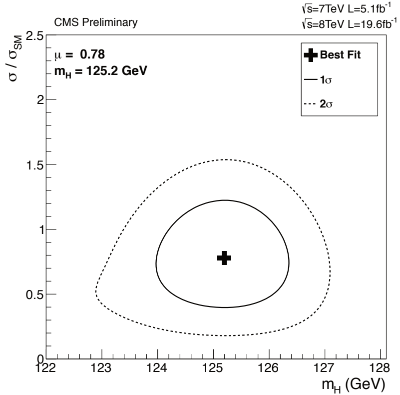


	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

Results

mass





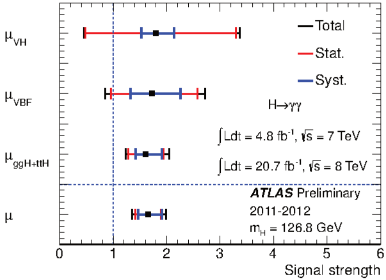
- The best-fit for the mass value is $m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)\mathrm{GeV}$

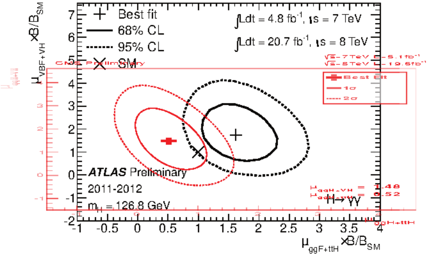
- The best-fit for the mass value is $m_H = 125.4 \pm 0.5(stat) \pm 0.6(syst)\mathrm{GeV}$

Comparable systematics errors

Results

signal strengths





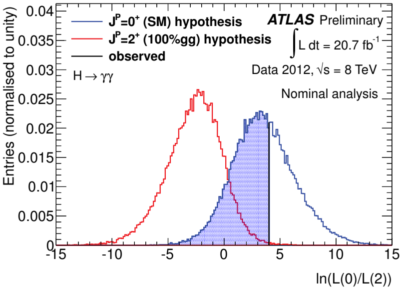
- $\mu_{ggH+t\bar{t}H} = 1.6^{+0.3}_{-0.3}(\text{stat})^{+0.3}_{-0.2}(\text{syst})$
- $\mu_{VBF} = 1.7^{+0.8}_{-0.8}(\text{stat})^{+0.5}_{-0.4}(\text{syst})$
- $\mu_{VH} = 1.8^{+1.5}_{-1.3}(\text{stat})^{+0.3}_{-0.3}(\text{syst})$

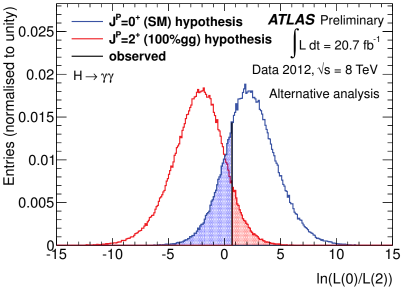
- $\mu_{ggH+t\bar{t}H} = 0.52$
- $\mu_{q\bar{q}H+VH} = 1.48$
- smaller error on $\mu_{ggH+t\bar{t}H}$?

Results

Spin (ATLAS)

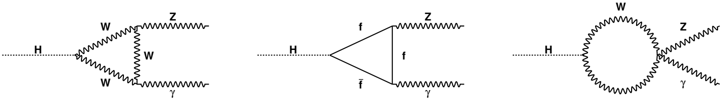
- no categories, $p_T/m_{\gamma\gamma}$ cut instead of p_T to avoid correlation with $\cos(\theta^*)$
- Two methods to discriminate 0^+ / 2^+
  - bidimensional model $|\cos\theta^*| \otimes m_{\gamma\gamma}$
  - independent fit of $m_{\gamma\gamma}$ in $|\cos\theta^*|$ bins





- data compatible with 0^+
- considering 100% gluon fusion: 2^+ excluded 99.3% (89.4%) CL.

$H \to Z\gamma$



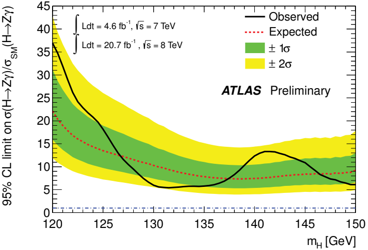
- sensitive to New Physics as $H \to \gamma\gamma$ through the loop, $Br(H \to Z\gamma)/Br(H \to \gamma\gamma)$
- branching ratio similar to $H \to ZZ \to 4l$: $\sigma(pp \to H) \times Br(H \to Z\gamma) \times Br(Z \to ll) \simeq 2.3\,\mathrm{fb}$ @ 8 TeV
- large background: $Z + \gamma$, $Z + \mathrm{jet}$

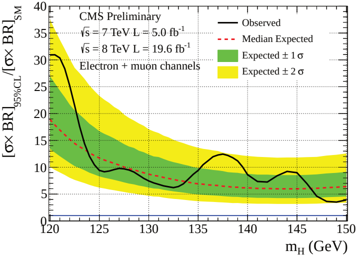
- $4.6 + 20.7\,\mathrm{fb}^{-1}$
- observable: $\Delta m = m_{ll\gamma} - m_{ll}$
- two categories: $\mu\mu/$ ee

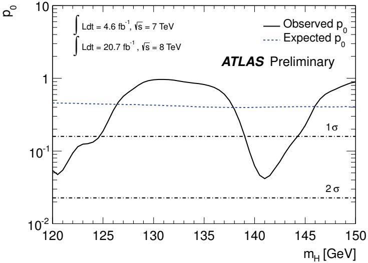
- $5 + 19.6\,\mathrm{fb}^{-1}$
- observable: $m_{ll\gamma}$
- 4 categories (barrel/endcap, R_9) $\otimes ee/\mu\mu$

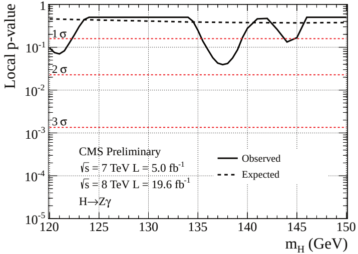
$H \rightarrow Z\gamma$

Results







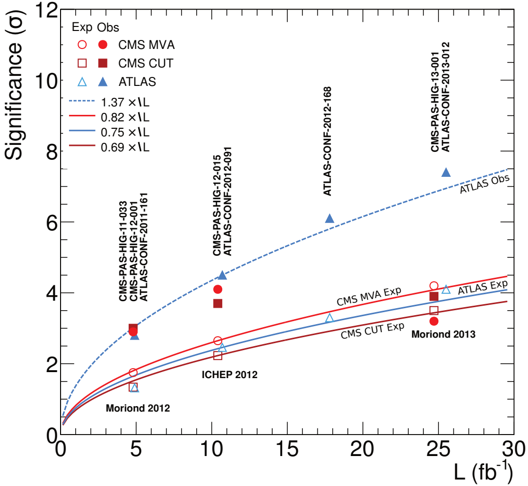


Section 4

Analysis evolution

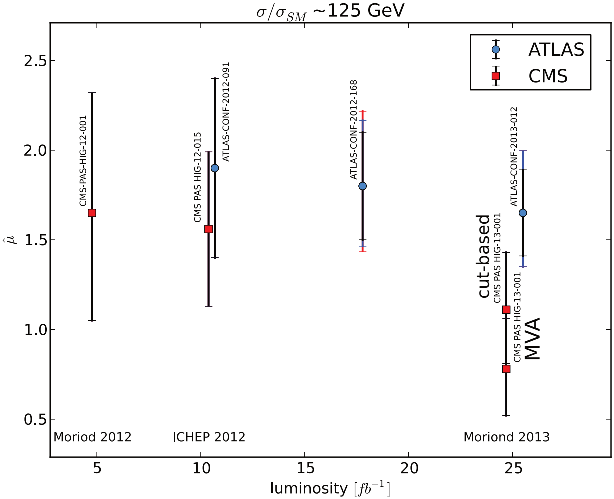
Time evolution

significance



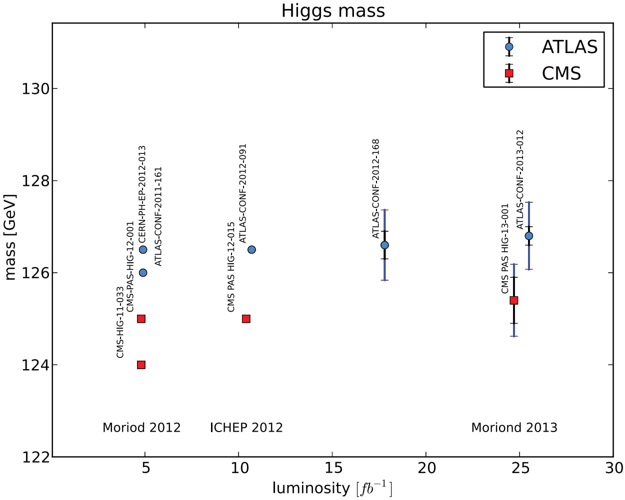
Time evolution

signal strength



Time evolution

mass



Conclusions

- 2011+2012 data have been analysed $\sim 25\,\text{fb}^{-1}$
- very similar expected significance
- observed excess 7.4σ (ATLAS), 3.2σ (CMS)
- observed σ/σ_{SM} 1.65 (ATLAS), 0.78 (CMS)
- ATLAS is 2.3σ above SM, CMS is 0.8σ below
- compatibility ATLAS/CMS? 2σ?
- mass measurement with error $\lesssim 1\,\text{GeV}$
- measurement of exclusive couplings
- spin 2 disfavoured by ATLAS

Invariant mass resolution

Category	σ_{CB}(GeV)
Unconv. central, low p_{Tt}	1.50
Unconv. central, high p_{Tt}	1.40
Unconv. rest, low p_{Tt}	1.74
Unconv. rest, high p_{Tt}	1.69
Conv. central, low p_{Tt}	1.68
Conv. central, high p_{Tt}	1.54
Conv. rest, low p_{Tt}	2.01
Conv. rest, high p_{Tt}	1.87
Conv. transition	2.52
Loose High-mass two-jet	1.71
Tight High-mass two-jet	1.64
Low-mass two-jet	1.62
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	1.74
One-lepton	1.75
Inclusive	1.77

$\sigma_{CB} \sim$ 1.40 ÷ 2.52 GeV

Event classes	Dijet tag	eff (GeV)	FWHM/2.35 (GeV)
8 TeV 19.6 fb^{-1}	Untagged 0	1.36	1.27
	Untagged 1	1.50	1.39
	Untagged 2	1.77	1.54
	Untagged 3	2.61	2.14
	Dijet tight	1.79	1.50
	Dijet loose	1.87	1.60
	Muon tag	1.85	1.52
	Electron tag	1.88	1.54
	$E_{\mathrm{T}}^{\mathrm{miss}}$ tag	1.79	1.64

FW

1.27 ÷ 2.14 GeV

$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)		Background
		eff (GeV)	FWHM/2.35 (GeV)	m = 125 GeV (ev./GeV)
8 TeV 19.6 fb^{-1}	Dijet tight	1.79	1.50	3.4 $\pm$ 0.2
	Dijet loose	1.87	1.60	12.4 $\pm$ 0.4
	Muon tag	1.85	1.52	0.7 $\pm$ 0.1
	Electron tag	1.88	1.54	0.7 $\pm$ 0.1
	E_T^{miss} tag	1.79	1.64	1.8 $\pm$ 0.1