Search for Higgs in bosonic channels

Photon 2013

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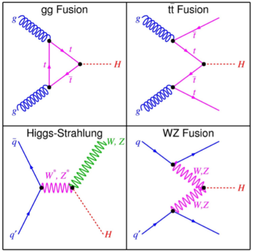
Letizia Lusito

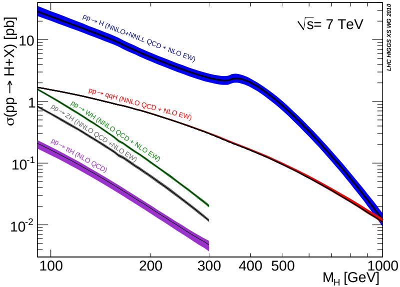
Northwestern University, Chicago, IL

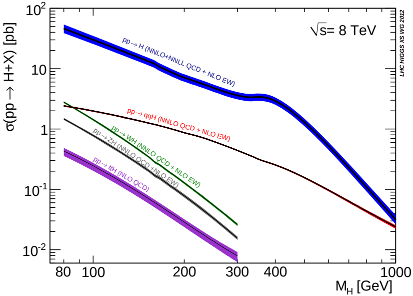
on behalf of the CMS and ATLAS Collaborations

Higgs production at the LHC

- gluon-gluon fusion (gg)
- vector boson fusion (VBF)
- associated production (*WH*, *ZH*)
- *ttH*

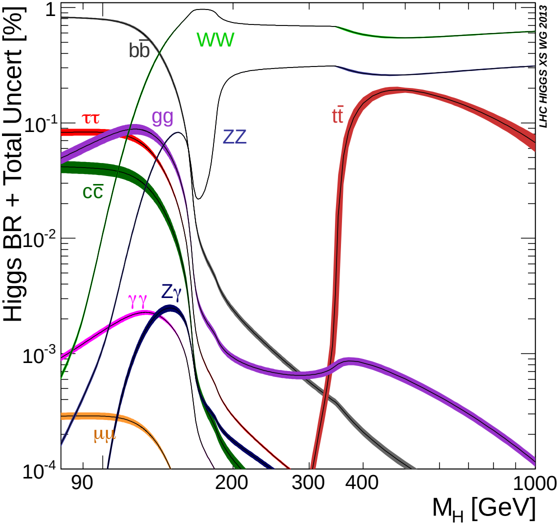






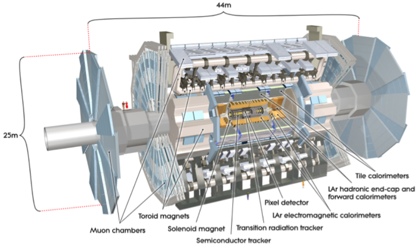
and bosonic decays

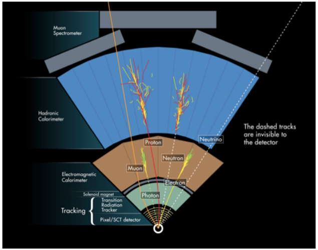
- $H \to WW\ (2\ell 2\nu)$
- $H \to ZZ(^*)\ (4\ell)$
- $H \to \gamma\gamma$
- $H \to Z\gamma$
- Others:
  - $t\bar{t}H \to t\bar{t}\gamma\gamma$ (CMS)
  - $H \to WW\ (\ell\nu q\bar{q})$, (CMS - high mass)
  - $H \to WW\ (e\nu\mu\nu)$, (ATLAS - high mass)
  - $H \to ZZ\ (2\ell 2\nu)$, (CMS - high mass)

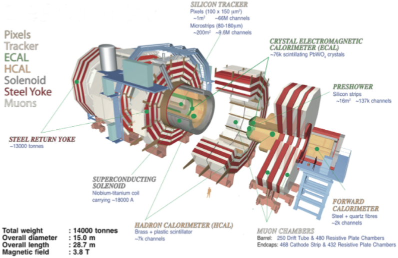


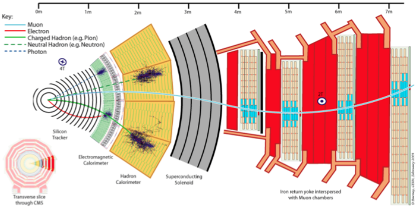
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

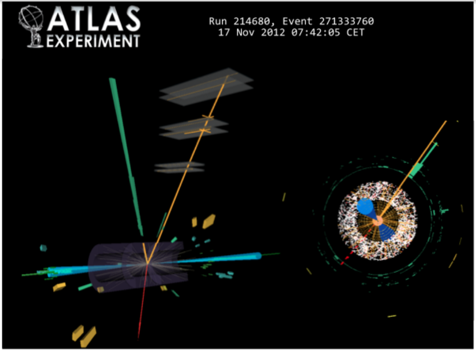
The detectors

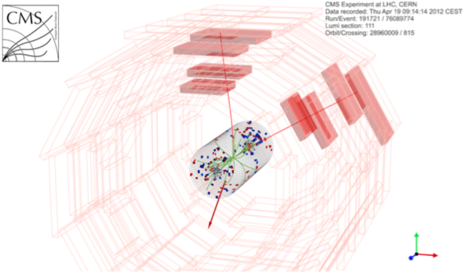










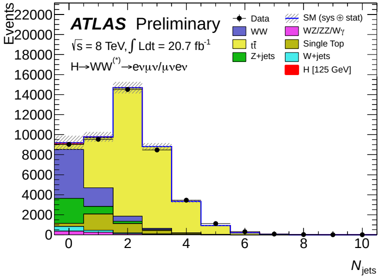


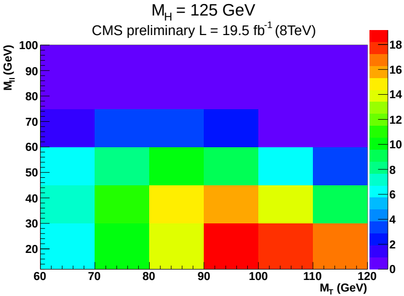
$H \to WW$

ATLAS-CONF-2013-030
ATLAS-CONF-2013-031
CMS-PAS-HIG-13-003
CMS-PAS-HIG-13-008

Experimental strategy

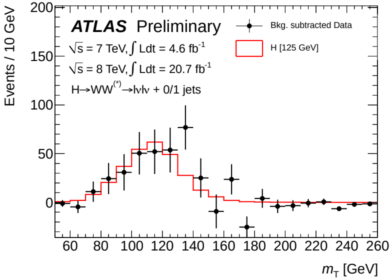
- Large branching fraction
- No mass peak
- 2 opposite-charge leptons + large E_T^{miss}
- Events classified according the exclusive jet multiplicity
- Crucial background estimation with data-driven techniques
  - W^+W^-, top, Drell-Yan, W+jets
  - Uncertainty on background normalization the largest source of systematics
  - CMS: 2D shape analysis of the di-lepton invariant and transverse masses for the different-flavor final state

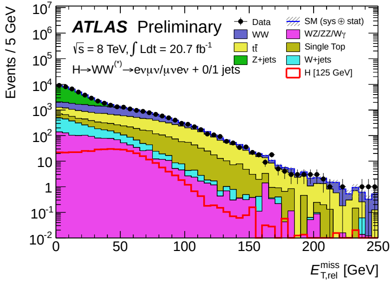


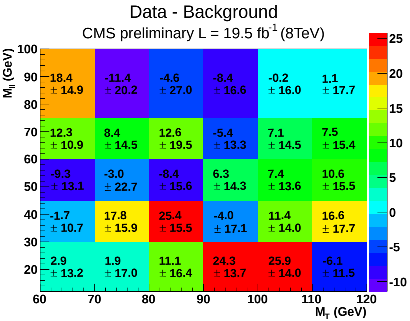


Background estimation and subtraction

- Drell-Yan and multi-jet events suppressed by requiring large E_T^{miss}
- Unfortunately E_T^{miss} sensible to pile-up
- Modification of E_T^{miss} used:
    - projected E_T^{miss} to the nearest lepton (or jet)
- Same-flavor events have even higher Drell-Yan background
    - CMS multivariate analysis
    - ATLAS: soft hadronic recoil
      (recoil momentum of low-p_T-jets opposite to $\ell\ell(j)$ divided by $p_T^{\ell\ell(j)}$)

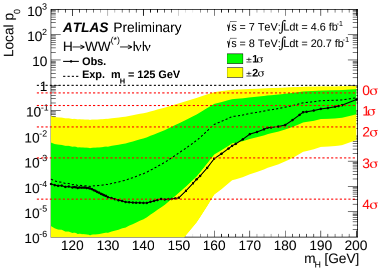


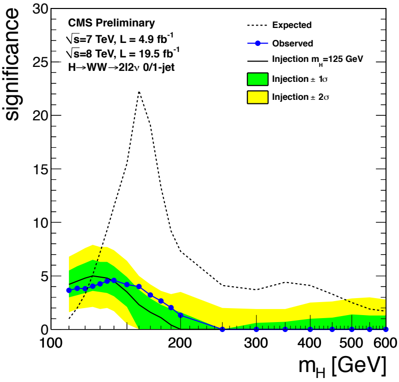




Signal strengths (at 125 GeV)

Excess of events observed above background, consistent with the expectations from a standard model Higgs boson of mass 125 GeV





ATLAS

μ = 1.01 $\pm$ 0.31

Significance

observed= 2.5σ, expected = 1.6σ

CMS

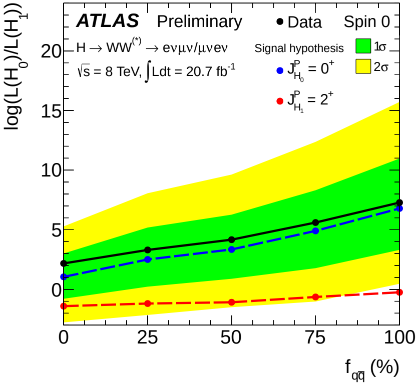
μ = 0.76 $\pm$ 0.21

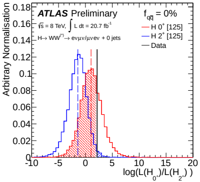
Significance

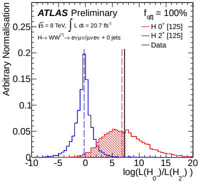
observed = 4.0σ, expected = 5.1σ

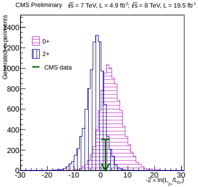
Spin and parity

- $H \to WW$ can distinguish between 0^+ and 2^+
- 2^+ is disfavoured
  - CMS: 1-CL$_s$ = 86%
  - ATLAS: 1-CL$_s$ = 95% for f$_{q\bar{q}}$=0% (only *gg* production), 99% for f$_{q\bar{q}}$=100%
- ATLAS: studies of different mixtures of gluon and quark production

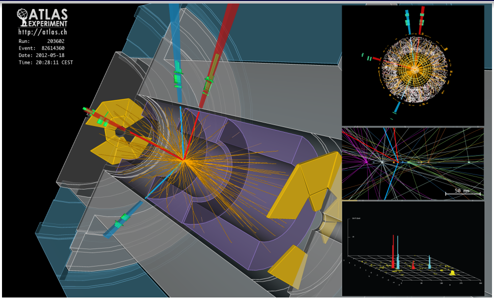


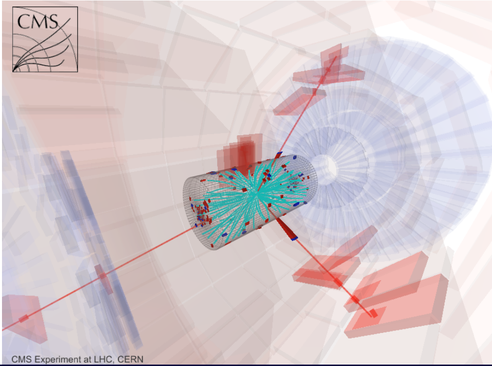






$H \to ZZ(^*)$

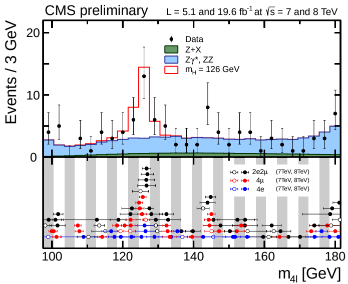


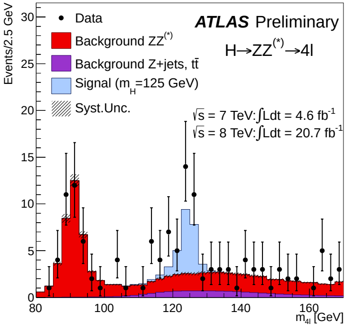


ATLAS-CONF-2013-013
CMS-PAS-HIG-13-002

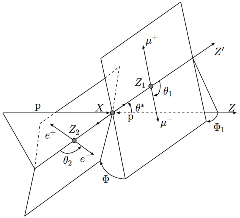
Twin Peaks

- Golden channel: four isolated leptons (e or μ) originating from the same PV
  - High lepton acceptance and ID efficiency down to fairly low pT
  - Good lepton energy/momentum resolution
  - Good control of reducible backgrounds
  - Need to get normalization and shape from data-driven methods
- Fully reconstructed final state
- $\sigma \times$BR $\sim$ 2.8 fb (at 126 GeV)
- Narrow resonance (resolution $\sim$2%)
- Clean final state: S/B $\sim$ 1
- Background:
  - irreducible: EWK $pp \to ZZ \to 4\ell$, well understood
  - reducible: Z+jets, Z+$b\bar{b}$, $t\bar{t}$, smaller than ZZ but sizeable at low $m_{4\ell}$





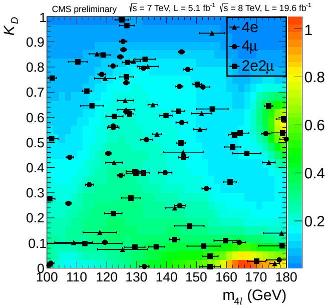
CMS: MELA



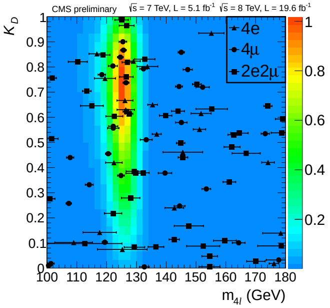
Matrix Element Likelihood Analysis

- kinematic inputs for signal to background discrimination

$$K_D = \frac{P_{sig}(m_{Z_1}, m_{Z_2}, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{P_{sig}(m_{Z_1}, m_{Z_2}, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell}) + P_{bkg}(m_{Z_1}, m_{Z_2}, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}$$



Data vs. background

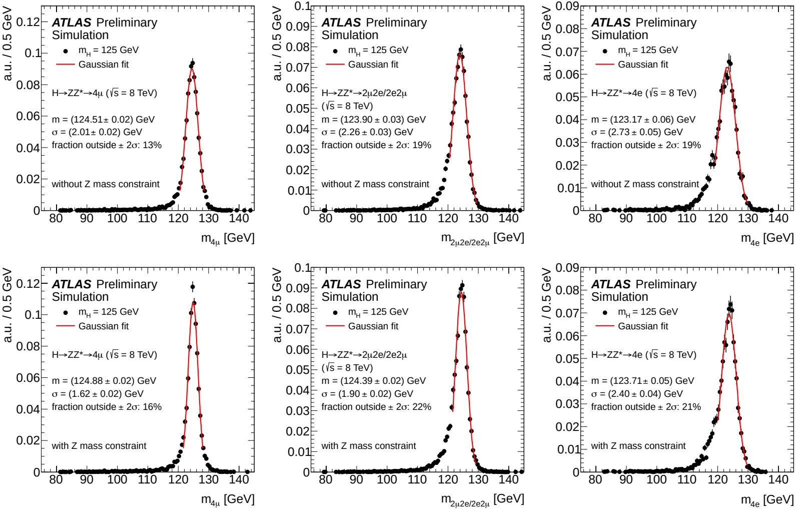


Data vs. signal

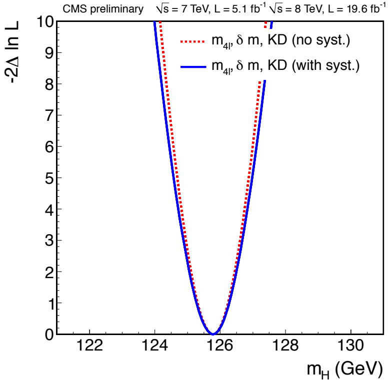
ATLAS: Z-mass constraint

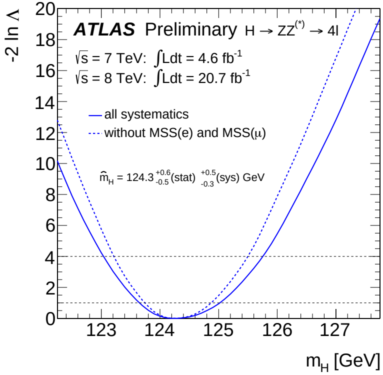
To enhance Higgs mass resolution:

- $m_{4\ell}$ <190 GeV: constraint applied to leading dileptons
- $m_{4\ell}$ >190 GeV: constraint applied to all four leptons



Mass





CMS

$m_H = 125.8 \pm 0.5\ (stat.) \pm 0.2\ (syst.)$

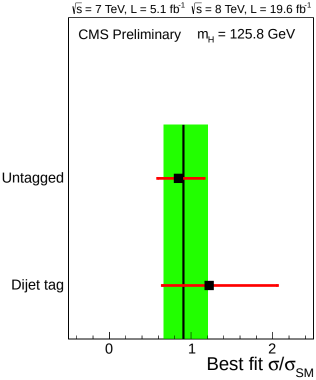
ATLAS

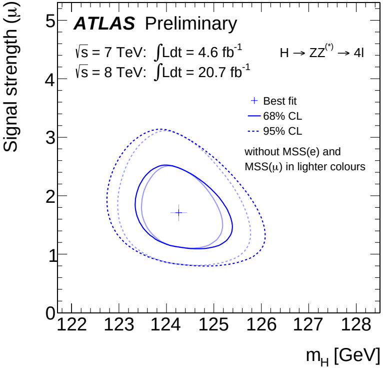
$m_H = 124.3\ ^{+0.6}_{-0.5}\ (stat.)\ ^{+0.5}_{-0.3}\ (syst.)$

Observation of the new boson in the 4ℓ channel alone

Significance of the local excess: 6.7σ (C), 6.6σ (A)

Signal strength





CMS

$\mu = 0.91\ ^{+0.30}_{-0.24}$ at $m_H = 125.8$ GeV

ATLAS

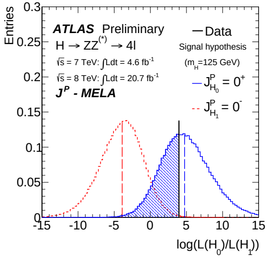
$\mu = 1.7\ ^{+0.5}_{-0.4}$ at $m_H = 124.3$ GeV

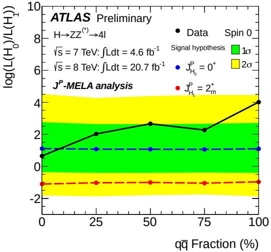
Spin and parity

- Kinematics of the Higgs boson decaying to *ZZ* sensitive to spin and parity
- Probability ratio for two signal hypotheses from kinematic discriminant

$$D_{J^P} = \frac{P_{SM}}{P_{SM} + P_{J^P}} \quad ; \quad q = -2ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

- Different spin-parity models considered, example of numerical results in the Table (from CMS)
  - expected separation when signal strength is pre-determined from the fit to data and
  - expected separation when events are generated with SM expectation for the signal yield (μ=1).
  - observed separation quotes consistency of the observation with 0^+ or J^P
  - CL_s criterion.



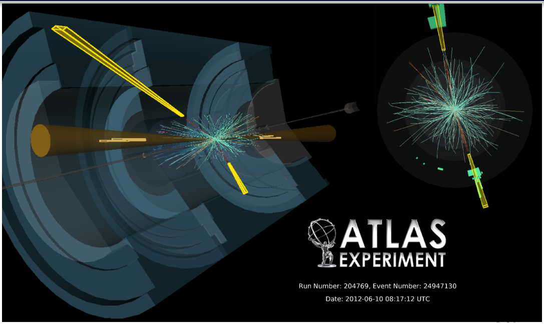


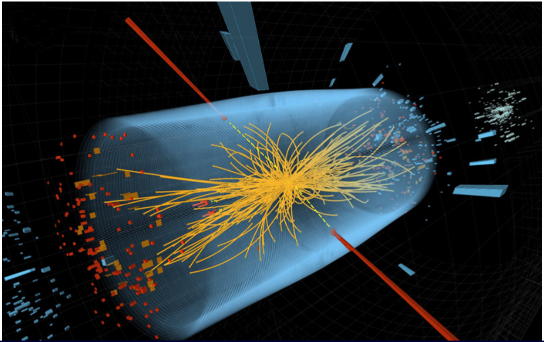
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

ATLAS + CMS

0^-, 1^+, 1^- excluded
2^+ disfavoured
2^- inconclusive (A), 0_h^+ disfavoured (C)

$H \to \gamma\gamma$

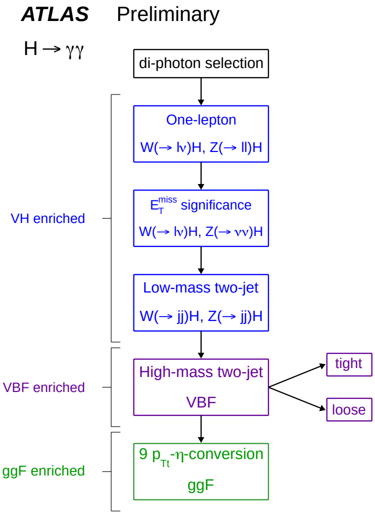




ATLAS-CONF-2013-012
ATLAS-CONF-2013-029
CMS-PAS-HIG-13-001

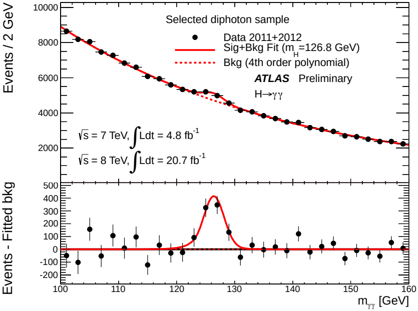
Experimental strategy

- Clean final-state topology
- Good resolution: mass reconstructed with high precision
- Low branching fraction
- Smoothly falling irreducible background (prompt diphoton production + events with jets misidentified as photons)
- CMS:
  - Multi-Variate-Analysis (MVA) techniques for γ identification and event classification
  - fit to the diphoton mass spectrum ("mass-fit-MVA")
  - events divided in classes accordingly to the production mechanism: gluon fusion (87%), VBF (7%) or associated production with a vector boson (5%)
- ATLAS: event classification more complicated (14 mutually exclusive categories for 2012, 10 for 2011 data)

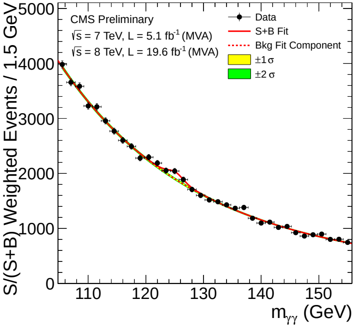


Signal and background modelling

- **Signal**: Crystal Ball + Gaussian (A), sum of two or three Gaussians (C)
  - Function parameters and signal yields as a function of the mass hypotheses
  - simultaneous fit to signal MC samples at different mass to interpolate the signal shape and yield to intermediate mass points where the MC is not available
- **Background**: polynomials or exponential-polynomials (of different orders) in the diphoton mass range from 100 to 160 (A) or 180 GeV (C) for the inclusive sample (but may differ in single categories)
  - Systematic: largest absolute signal component fitted anywhere in (110, 150) mass range

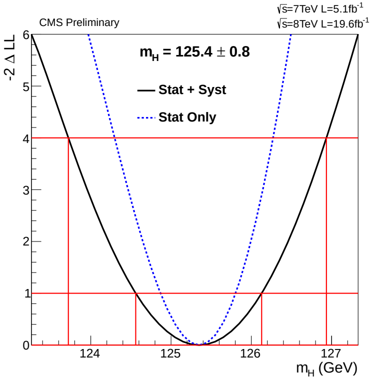


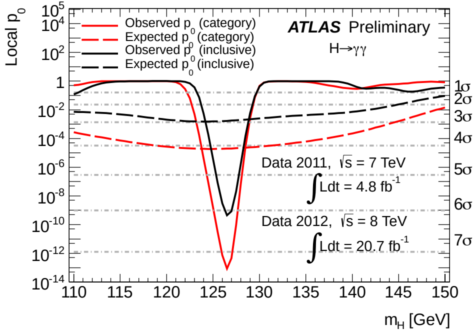
B: residuals of data wrt the fitted background component



Events weighted by the S/(S+B) value of their corresponding category

Mass





CMS

$m_H = 125.4 \pm 0.5\ (stat.) \pm 0.6\ (syst.)$

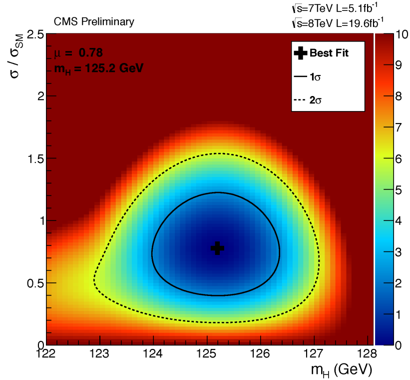
ATLAS

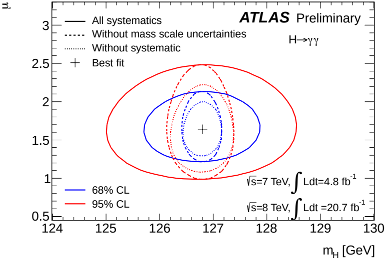
$m_H = 126.8 \pm 0.2\ (stat.) \pm 0.7\ (syst.)$

Signal strenght

2D test statistic "-2 ln Q" for the signal strength, σ/σ_{SM}, versus the Higgs boson mass hypothesis, m_H.

The cross indicates the best-fit pair of values.





CMS

$\mu = 0.78 ^{+0.28}_{-0.26}$ at $m_H = 125$ GeV

ATLAS

$\mu = 1.65 \pm 0.24\ (stat.)\ ^{+0.25}_{-0.18}\ (syst.)$ at $m_H = 126.8$ GeV

Spin & parity (A only)

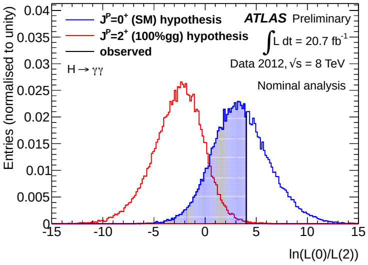
- 8 TeV (20.7 fb^{-1}) data only
- distribution of the polar angle θ^* of the photons wrt the z-axis:

$$cos\theta^* = \frac{sinh(\eta_{\gamma 1} - \eta_{\gamma 2})}{\sqrt{1 + (p_T^{\gamma 1 \gamma 2}/m_{\gamma 1 \gamma 2})^2}} \times \frac{2 p_T^{\gamma 1} p_T^{\gamma 2}}{m^2_{\gamma 1 \gamma 2}}$$

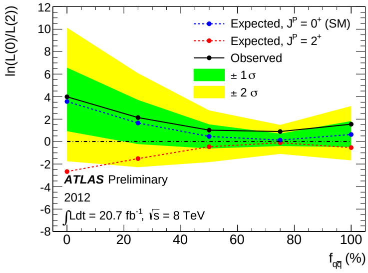
  - $dN/dcos\theta^*$
    - spin-0 particle: uniform
    - spin-2 particle: combination of Wigner functions (different for gg and $q\bar{q}$ production modes)
  - background: peaked in the forward-backward direction
  - separation (in cos θ^*) between the spin-0 and spin-2 hypotheses maximal if the s2 resonance produced by gg
- Fits of the mass spectrum $m_{\gamma 1 \gamma 2}$ and polar angle ($|cos\theta^*|$) (uncorrelated)
- Test statistics q:

$$q = ln \frac{\mathcal{L}_0(\hat{\hat{\theta}}_0)}{\mathcal{L}_2(\hat{\hat{\theta}}_2)}$$

- **2^+ excluded 1-CL$_s$ = 99.3 % at 0% $q\bar{q}$**
- also as a function of the $q\bar{q}$ fraction
- **at 100% $q\bar{q}$: 1-CL$_s$ = 88 %**



coloured areas $\to$ integrals of the expected distributions used for the p-values for the rejection of each hypothesis



$H \to Z\gamma$

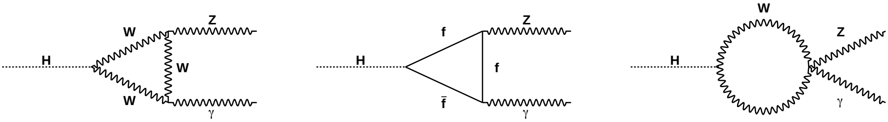
ATLAS-CONF-2013-009

Search for the Standard Model Higgs boson in the $H \to Z\gamma$ decay mode with pp collisions at $\sqrt{s}$ = 7 and 8 TeV

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

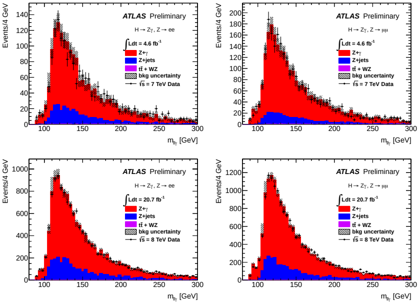
Theoretical motivations



- induced by loops of heavy charged particles
- sensitive to physics beyond the standard model
- Good resolution but small branching fraction

Common experimental strategy

- Dileptons (or even single lepton for ATLAS) unprescaled triggers with p_T threshold as low as possible
- Two opposite-sign, same-flavor leptons (e or μ), consistent with a Z-boson decay and a photon
- All particles isolated
- All particles inside the detector geometric acceptance and with high p_T
- $E_T^\gamma / m_{\ell+\ell-\gamma} > 15/110$ (C)
- $E_T^\gamma > 15$ GeV (A)
- $\Delta R(\ell, \gamma) > 0.3/0.4$
- $m_{\ell+\ell-\gamma} + m_{\ell+\ell-} > 185$ GeV (C)
- $m_{\ell+\ell-} > m_Z$ - 10 GeV (A)
- Dominant backgrounds:
  - SM $Z\gamma$ (irreducible)
  - Final State Radiation in Z decays or Z+jets (reducible)
  - $H \to \gamma\gamma*$ (dilepton pair produced by a photon internal conversion) rejected by $m_{\ell+\ell-} > 50$ GeV



CMS: Event classes

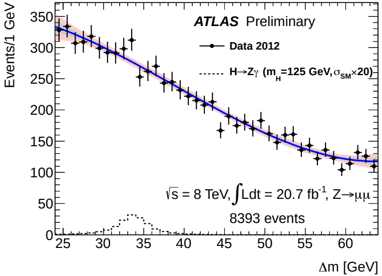
- **WHAT**: 4 classes based on the expected mass resolution and signal-to-background ratio
- **WHY**: sensitivity enhanced by subdividing the selected events into classes
- **HOW**: pseudo rapidity of the leptons and photon and shower shape of the photon

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 > 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 > 0.94$
Data Signal σ_{eff} FWHM	17% 30% 1.9 GeV 4.5 GeV	20% 34% 1.6 GeV 3.7 GeV
	Event class 2	
	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Data Signal σ_{eff} FWHM	26% 28% 2.1 GeV 5.0 GeV	31% 31% 1.9 GeV 4.6 GeV
	Event class 3	
	Photon $0 < \lvert\eta\rvert < 1.4442$ At least one lepton $1.4442 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	26% 23% 3.1 GeV 7.3 GeV	20% 18% 2.1 GeV 5.0 GeV
	Event class 4	
	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	31% 19% 3.3 GeV 7.8 GeV	29% 17% 3.2 GeV 7.5 GeV

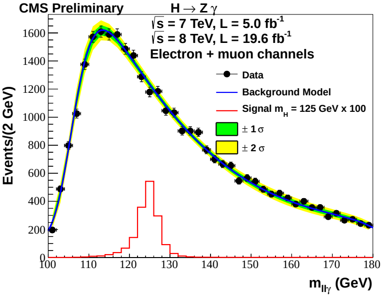
Results

Background-only fits

- ATLAS: $\Delta m = m_{\ell\ell\gamma} - m_{\ell\ell}$, range: (24 - 64) GeV
- CMS: $m_{\ell\ell\gamma}$, range: (100, 180) GeV



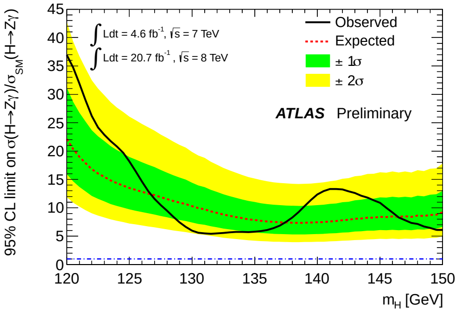
Third-order Chebychev polynomial

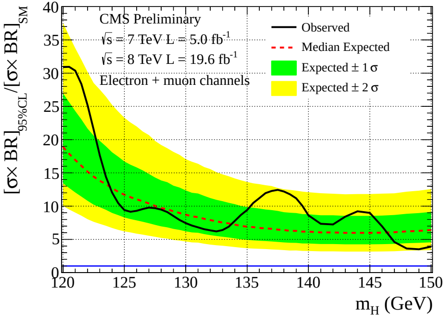


(Step-function X polynomial) $*$ Gaussian

Exclusion limits

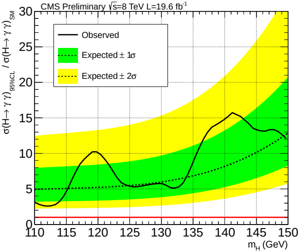
Both experiments are
not yet sensitive
to the expected SM rate

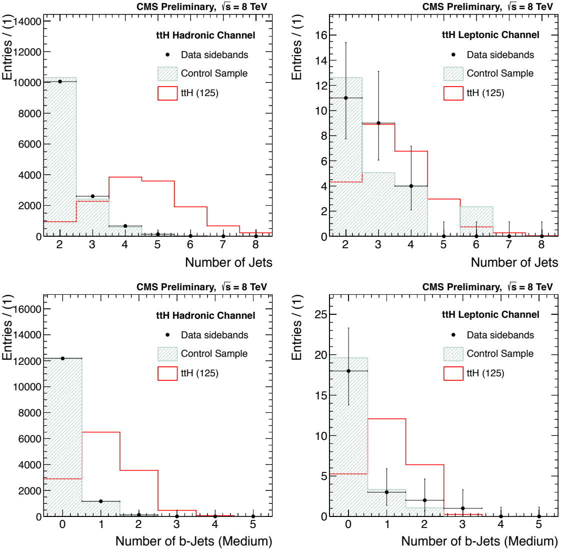




$t\bar{t}H$ with $H \to \gamma\gamma$

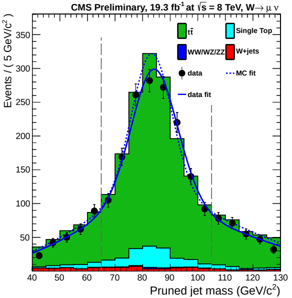
- Analysis performed at 8 TeV only (CMS-HIG-13-015)
- Hadronic (> 2 jets) and leptonic (with e or μ) top decays considered
- No signal excess found

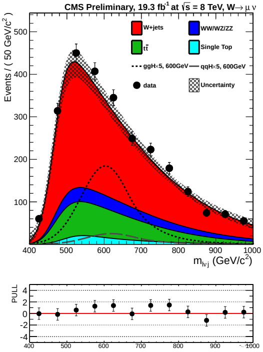


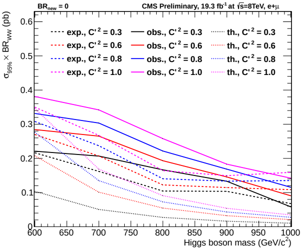


Search for heavy $H \to WW \to \ell\nu q\bar{q}$

- CMS only, $\mathcal{L} = 19.3\ \text{fb}^{-1}$
- High mass regime : $m_H > 600$ GeV
- Interpretation in BSM: two Higgs-like scalar particles, with the lighter with m= 125 GeV
- events with lepton, E_T^{miss} and a "fat" jet that contains all hadronically-decaying W decay products
- jet grooming algorithm + pruning implementation

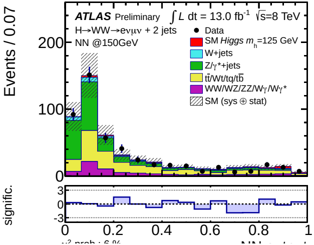


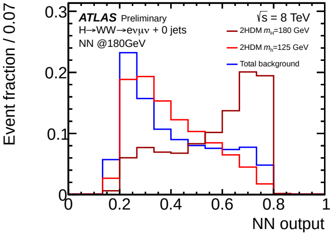


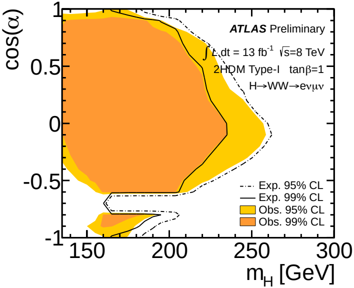


Search for heavy $H \to WW \to e\nu\mu\nu$

- ATLAS only, $\mathcal{L}$ = 13.0 fb^{-1} at 8 TeV
- Interpretation in BSM: Two-Higgs-Doublet (2HDM) scalar particles, with the lighter with m= 125 GeV
- Mass range investigated: 135 - 300 GeV
- 0 or 2 jets categories
- Neural Network based analysis

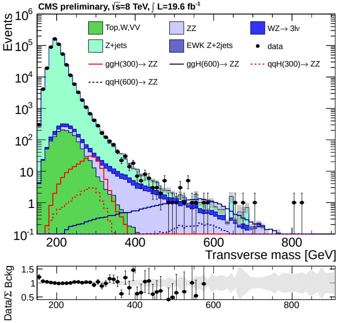


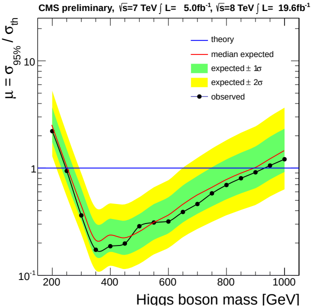


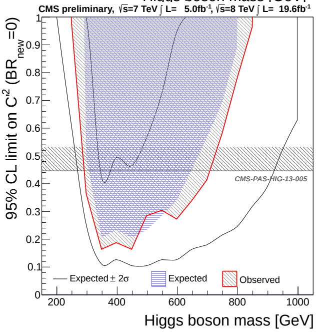


Search for heavy $H \to ZZ \to 2\ell 2\nu$

- CMS only, full 7 + 8 TeV data sample
- Two opposite-sign, same-flavor leptons + E_T^{miss}
- Interpretation in SM Higgs and Higgs singlets in BSM





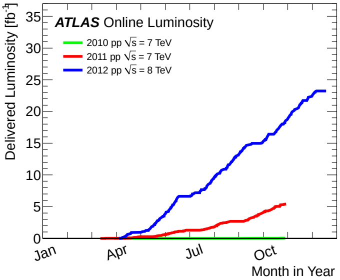


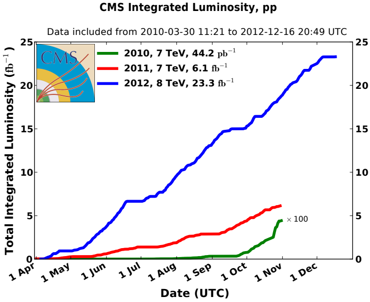
Conclusions

- The CMS and ATLAS collaborations have measured a new boson state with a mass around 125 GeV in an ever increasing number of decays.
- Using the current LHC data both experiments have proven that the new boson is the Higgs boson predicted by the standard model.
- With added data at a larger $\sqrt{s}$, the LHC will continue to probe the Higgs couplings and properties to achieve the highest accuracy probes of this critical piece of EWSB

Backup slides

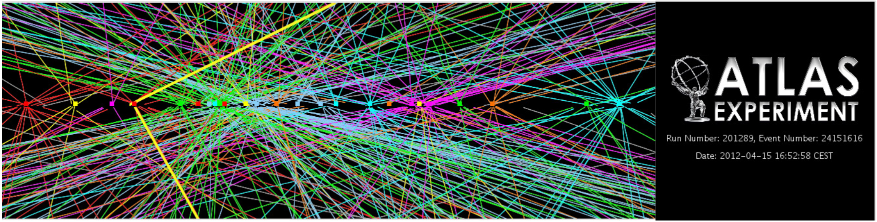
Data taking

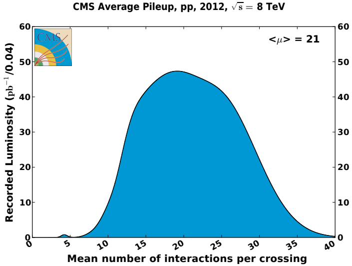




- The LHC as steadily increased the instantaneous luminosity
- Both experiments have been efficiently collecting LHC luminosity

The PileUp challenge





LHC already achieved the design level of pileup

Event display of an event with around 20 pile-up vertices:

(maximum number of vertices goes up to 40)

CMS and ATLAS cope with this high level of pile-up very well

$\langle N_{PU} \rangle = 21$

Muons

- Combined fit to measurements from inner tracker and muon detectors
- Minimal number of hits in the silicon tracker
- High-quality global fit ($\chi^2/ndf < 10$)
- Transverse and longitudinal impact parameter of the muon track relative to the Primary vertex

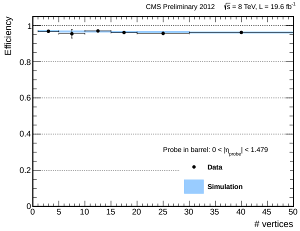
Electrons

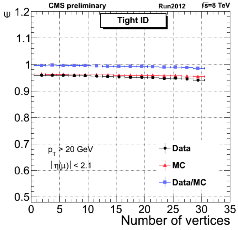
- Tracks reconstructed in the inner tracker with energy compatible with ECAL deposits
- Transverse and longitudinal impact parameters cuts
- Photon conversion rejection

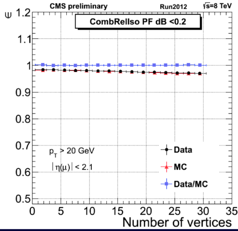
Isolation

- Relative isolation ($\Delta R > 0.3$):

$$I^{\ell}_{Rel} = \frac{E^{\ell}_{CH} + E^{\ell}_{NH} + E^{\ell}_{\gamma}}{p^{\ell}_{T}}$$

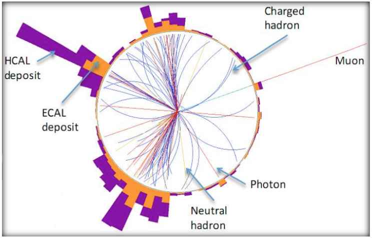






Particle Flow

- Event description in form of mutually exclusive particles identification of all stable particles produced in the event
- Optimal combination of capabilities of each sub-detector $\rightarrow$ most precise measurement of the energy and direction for each particle
- individual measurements combined by a geometrical linking algorithm, e.g. extrapolating a charged-particle track into ECAL and HCAL particle ID on blocks of linked elements

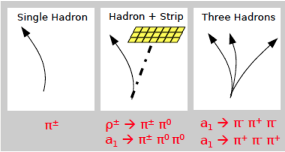


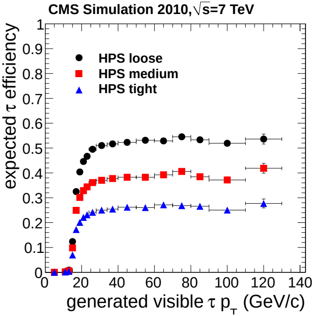
Taus: Hadron Plus Strip (HPS) algorithm

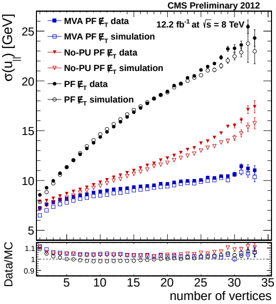
- Complete final state reconstruction of the leptonic and hadronic τ decays
- τ_{had} can have 1-prong or 3-prongs (charged tracks) with up to two ECAL strips for π^0 reconstruction.

Jets & MET

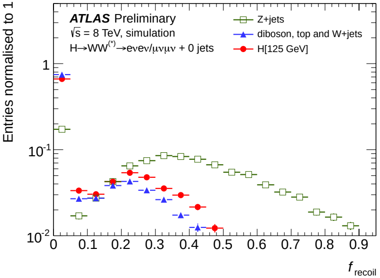
- anti-k_T algorithm jet reconstruction from Particle Flow particles, cone size = 0.5
- $\not{E}_T$ from PF constituents

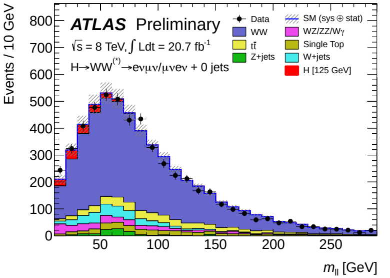


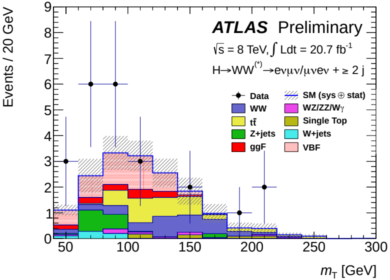


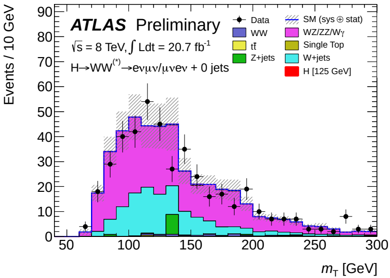


A: $H \to WW$

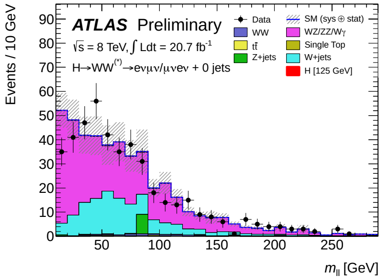

ATLAS Preliminary
√s = 8 TeV, simulation
H→WW(*)→eνeν/μνμν + 0 jets
Z+jets
diboson, top and W+jets
H[125 GeV]
Entries normalised to 1
f recoil

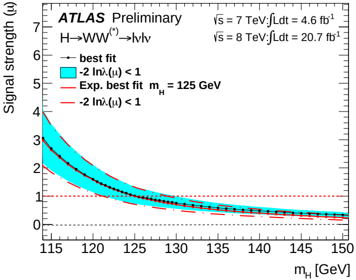

ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→eνμν/μνeν + 0 jets
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
m_ll [GeV]

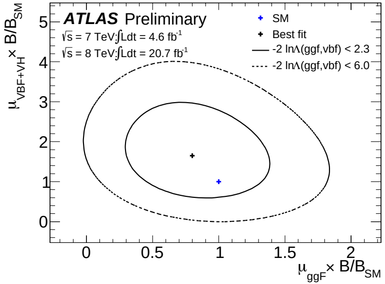

ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→eνμν/μνeν + ≥ 2 j
Data
WW
tt̄
Z+jets
ggF
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
VBF
Events / 20 GeV
m_T [GeV]


ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→eνμν/μνeν + 0 jets
Data
WW
tt̄
Z+jets
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Events / 10 GeV
m_T [GeV]

A: $H \rightarrow WW$



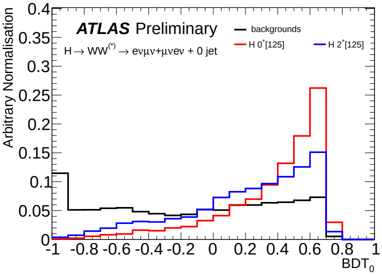




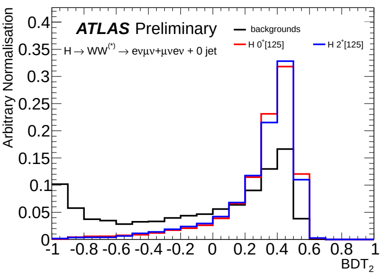
A: $H \to WW$ spin

- $e\mu$ final state only
- no jets
- Other channels not expected to add much in terms of spin sensitivity due to the presence of large backgrounds which cannot be removed without greatly reducing the acceptance of the spin-2 model considered in this analysis.
- 8 TeV only
- multivariate classifier known as a boosted decision tree (BDT)
- specific model graviton- like tensor with minimal couplings
- The 0+ and 2+m hypotheses are tested using a two-dimensional kinematic shape fit.
- The discriminants used in the fit are outputs of two different boosted decision trees (BDT), trained separately against all backgrounds
- Four discriminating variables are used in the BDT classifiers, namely mll, pll, $\Delta\phi$ll and mT.
- A weighted average is taken from all these trees to form a BDT output discriminant with values ranging between -1 and 1.
- Two separate BDT classifiers are developed: one classifier using a 0+ sample as signal and a second classifier using a 2+m sample. The BDT outputs will be referred to as BDT0 and BDT2, respectively.

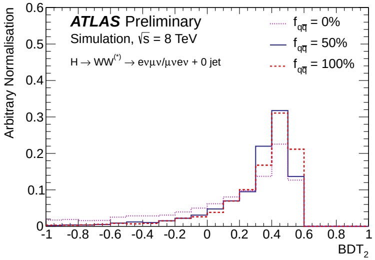
A: $H \to WW$ spin



ATLAS Preliminary
H → WW(*) → eνμν+μνeν + 0 jet
backgrounds
H 0+[125]
H 2+[125]
Arbitrary Normalisation
BDT0



ATLAS Preliminary
H → WW(*) → eνμν+μνeν + 0 jet
backgrounds
H 0+[125]
H 2+[125]
Arbitrary Normalisation
BDT2



ATLAS Preliminary
Simulation, √s = 8 TeV
H → WW(*) → eνμν/μνeν + 0 jet
fqq̄ = 0%
fqq̄ = 50%
fqq̄ = 100%
Arbitrary Normalisation
BDT2

A: $H \to WW$ spin

The statistical analysis of the data employs a binned likelihood $\mathcal{L}(\epsilon, \theta)$ constructed with one parameter of interest ϵ, which represents the fraction of 0^+ signal events in the total signal expectation, such that $\epsilon = 0$ represents the 2^+_m hypothesis and $\epsilon = 1$ represents the 0^+ hypothesis. The overall signal normalisation $\mu > 0$ is included as a nuisance parameter. Template histograms representing the nominal signal and background rates are used to construct $\mathcal{L}(\epsilon, \theta)$. Systematic uncertainties are represented through the nuisance parameters θ, each of which has corresponding auxiliary constraints $\mathcal{A}(\tilde{\theta}|\theta)$. The full likelihood can be written as

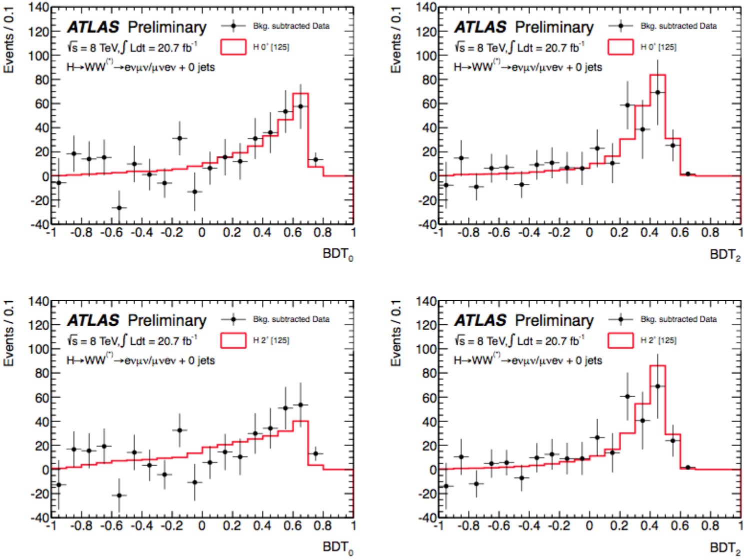
$$\mathcal{L}(\epsilon, \mu, \vec{\theta}) = \prod_i^{N_{bins}} P\left(N_i \,|\, \mu\left(\epsilon S_{0^+,i}(\vec{\theta}) + (1-\epsilon) S_{2^+,i}(\vec{\theta})\right) + b_i(\vec{\theta})\right) \times \prod_j^{N_{sys}} \mathcal{A}(\tilde{\theta}_j|\theta_j)\,, \tag{2}$$

where the treatment of μ as a nuisance parameter is shown explicitly. The product runs over all bins in the two dimensional BDT output distribution. The compatibility between data and the two hypotheses is then estimated using the following test statistic:

$$q = \log \frac{\mathcal{L}(H_{0^+})}{\mathcal{L}(H_{2^+_m})} = \log \frac{\mathcal{L}(\epsilon = 1, \hat{\hat{\mu}}_{\epsilon=1}, \hat{\hat{\theta}}_{\epsilon=1})}{\mathcal{L}(\epsilon = 0, \hat{\hat{\mu}}_{\epsilon=0}, \hat{\hat{\theta}}_{\epsilon=0})}\,. \tag{3}$$

In both the numerator and denominator, the likelihood is maximised over all nuisance parameters to obtain the maximum likelihood estimators $\hat{\hat{\mu}}$, $\hat{\hat{\theta}}$ for a value of $\epsilon = 1$ and $\epsilon = 0$, respectively. Pseudo-experiments for the two hypotheses are used to obtain the corresponding distributions in q and subsequently the p-values which define the expected and observed sensitivities.

A: $H \to WW$ spin

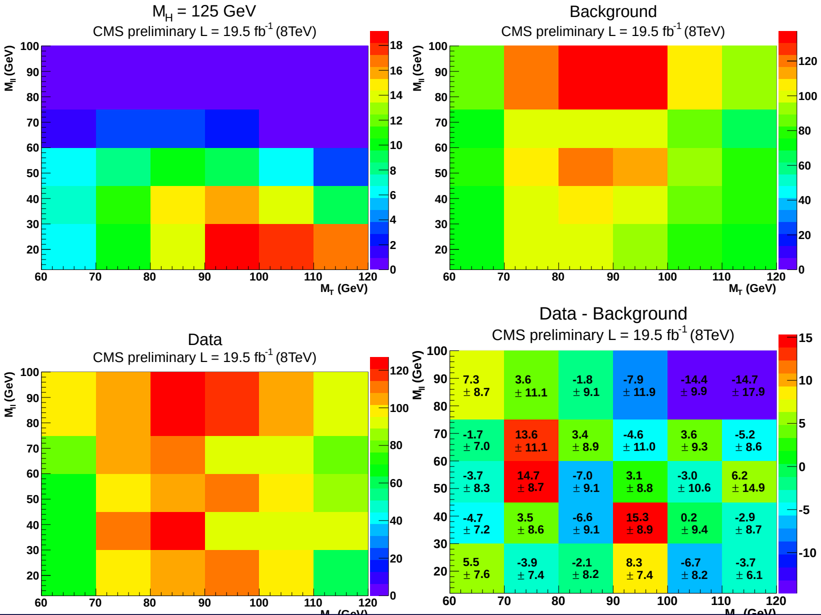


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 20.7 fb^{-1}
H→WW$^{(*)}$→eνμν/μνeν + 0 jets
Bkg. subtracted Data
H 0^{+} [125]
H 2^{+} [125]
Events / 0.1
BDT$_0$
BDT$_2$

A: $H \to WW$ spin

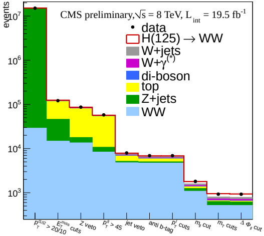
$f_{q\bar{q}}$	$N_{fit}(0^+)$	$N_{fit}(2^+_m)$	exp. $p_0(0^+)$	exp. $p_0(2^+_m)$	obs. $p_0(0^+)$	obs. $p_0(2^+_m)$	1-CL_S (2^+_m)
100%	270^{+100}_{-80}	110^{+110}_{-90}	0.013	0.005	0.543	0.005	0.99
75%	250^{+100}_{-80}	170^{+110}_{-100}	0.034	0.007	0.591	0.005	0.99
50%	250^{+100}_{-80}	230^{+140}_{-100}	0.035	0.012	0.619	0.007	0.98
25%	260^{+110}_{-80}	260^{+130}_{-110}	0.048	0.019	0.613	0.010	0.97
0%	260^{+100}_{-80}	320^{+130}_{-110}	0.091	0.057	0.725	0.014	0.95

C: $H \to WW$

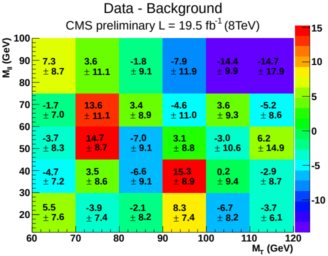


M_H = 125 GeV
CMS preliminary L = 19.5 fb^-1 (8TeV)
Background
CMS preliminary L = 19.5 fb^-1 (8TeV)
Data
CMS preliminary L = 19.5 fb^-1 (8TeV)
Data - Background
CMS preliminary L = 19.5 fb^-1 (8TeV)
M_ll (GeV)
M_T (GeV)
7.3 ± 8.7
3.6 ± 11.1
-1.8 ± 9.1
-7.9 ± 11.9
-14.4 ± 9.9
-14.7 ± 17.9
-1.7 ± 7.0
13.6 ± 11.1
3.4 ± 8.9
-4.6 ± 11.0
3.6 ± 9.3
-5.2 ± 8.6
-3.7 ± 8.3
14.7 ± 8.7
-7.0 ± 9.1
3.1 ± 8.8
-3.0 ± 10.6
6.2 ± 14.9
-4.7 ± 7.2
3.5 ± 8.6
-6.6 ± 9.1
15.3 ± 8.9
0.2 ± 9.4
-2.9 ± 8.7
5.5 ± 7.6
-3.9 ± 7.4
-2.1 ± 8.2
8.3 ± 7.4
-6.7 ± 8.2
-3.7 ± 6.1

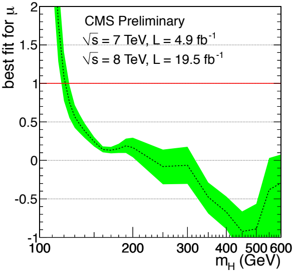
C: $H \to WW$



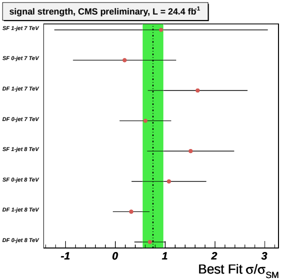
CMS preliminary, √s = 8 TeV, L int = 19.5 fb-1
data
H(125) → WW
W+jets
W+γ(*)
di-boson
top
Z+jets
WW
events



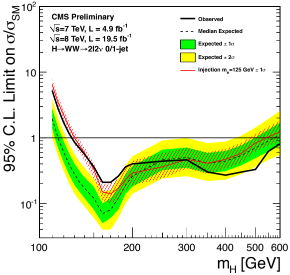
Data - Background
CMS preliminary L = 19.5 fb-1 (8TeV)
7.3 ± 8.7
3.6 ± 11.1
-1.8 ± 9.1
-7.9 ± 11.9
-14.4 ± 9.9
-14.7 ± 17.9
-1.7 ± 7.0
13.6 ± 11.1
3.4 ± 8.9
-4.6 ± 11.0
3.6 ± 9.3
-5.2 ± 8.6
-3.7 ± 8.3
14.7 ± 8.7
-7.0 ± 9.1
3.1 ± 8.8
-3.0 ± 10.6
6.2 ± 14.9
-4.7 ± 7.2
3.5 ± 8.6
-6.6 ± 9.1
15.3 ± 8.9
0.2 ± 9.4
-2.9 ± 8.7
5.5 ± 7.6
-3.9 ± 7.4
-2.1 ± 8.2
8.3 ± 7.4
-6.7 ± 8.2
-3.7 ± 6.1
Mll (GeV)
MT (GeV)



CMS Preliminary
√s = 7 TeV, L = 4.9 fb-1
√s = 8 TeV, L = 19.5 fb-1
best fit for μ
mH (GeV)



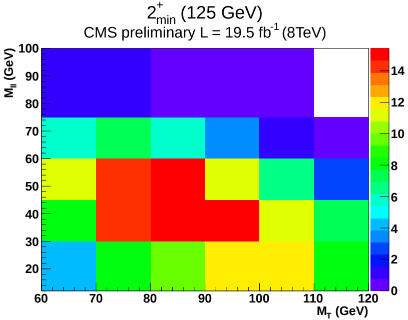
signal strength, CMS preliminary, L = 24.4 fb-1
SF 1-jet 7 TeV
SF 0-jet 7 TeV
DF 1-jet 7 TeV
DF 0-jet 7 TeV
SF 1-jet 8 TeV
SF 0-jet 8 TeV
DF 1-jet 8 TeV
DF 0-jet 8 TeV
Best Fit σ/σSM

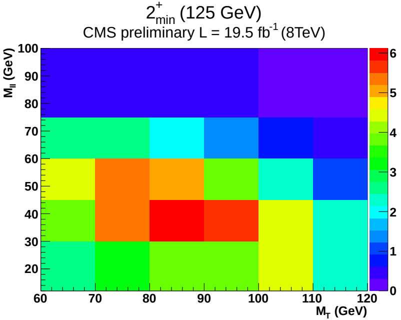


CMS Preliminary
√s=7 TeV, L = 4.9 fb-1
√s=8 TeV, L = 19.5 fb-1
H→WW→2l2ν 0/1-jet
Observed
Median Expected
Expected ± 1σ
Expected ± 2σ
Injection mH=125 GeV ± 1σ
95% C.L. Limit on σ/σSM
mH [GeV]

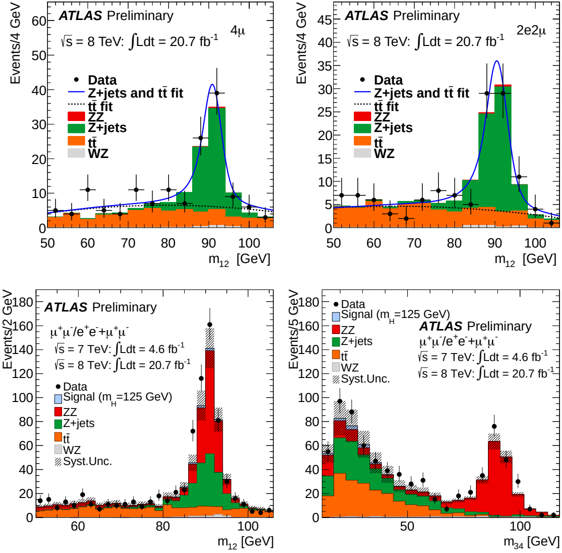
C: $H \to WW$ spin

(0 jet (left), 1 jet (right))

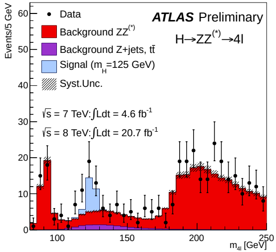


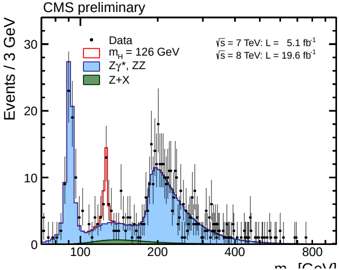


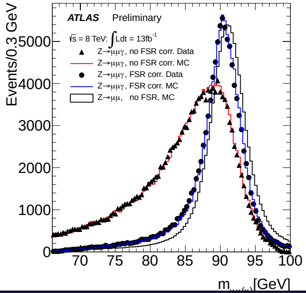
A: $H \rightarrow ZZ(*)$

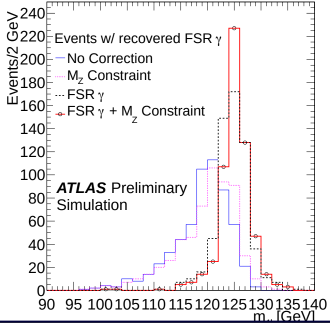


A: $H \rightarrow ZZ(*)$

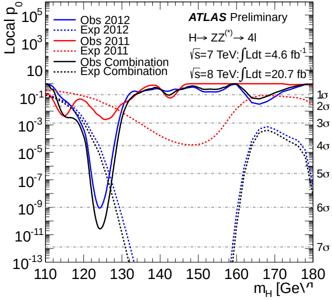


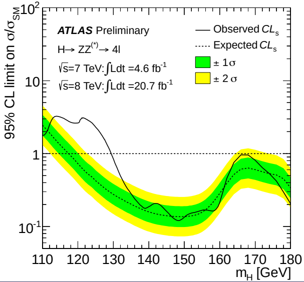


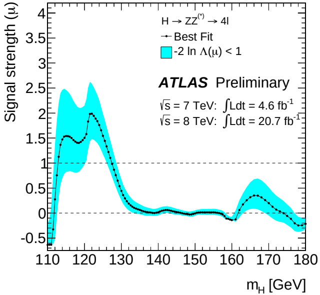




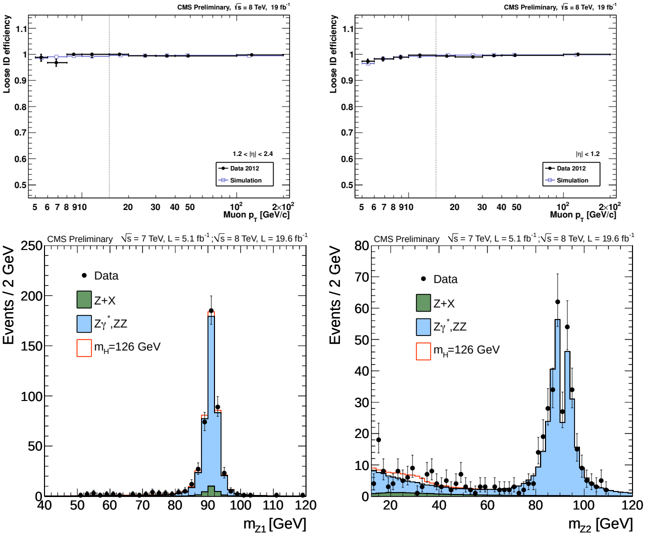
A: $H \to ZZ(*)$


Local p0
Obs 2012
Exp 2012
Obs 2011
Exp 2011
Obs Combination
Exp Combination
ATLAS Preliminary
H→ ZZ(*)→ 4l
√s=7 TeV: ∫Ldt =4.6 fb-1
√s=8 TeV: ∫Ldt =20.7 fb-1
1σ
2σ
3σ
4σ
5σ
6σ
7σ
110 120 130 140 150 160 170 180
mH [GeV]


95% CL limit on σ/σSM
ATLAS Preliminary
H→ ZZ(*)→ 4l
√s=7 TeV: ∫Ldt =4.6 fb-1
√s=8 TeV: ∫Ldt =20.7 fb-1
Observed CLs
Expected CLs
± 1σ
± 2 σ
110 120 130 140 150 160 170 180
mH [GeV]

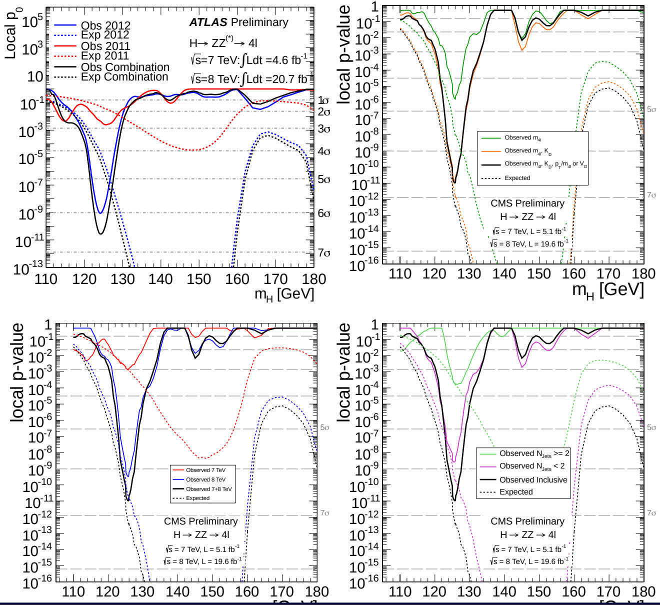

Signal strength (μ)
H → ZZ(*) → 4l
Best Fit
-2 ln Λ(μ) < 1
ATLAS Preliminary
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
110 120 130 140 150 160 170 180
mH [GeV]

C: $H \to ZZ(*)$

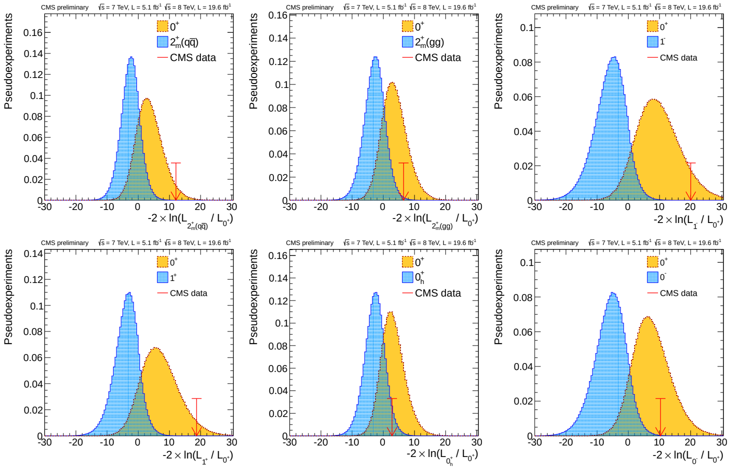


CMS Preliminary, √s = 8 TeV, 19 fb⁻¹
Loose ID efficiency
1.2 < |η| < 2.4
Data 2012
Simulation
Muon p_T [GeV/c]
CMS Preliminary, √s = 8 TeV, 19 fb⁻¹
Loose ID efficiency
|η| < 1.2
Data 2012
Simulation
Muon p_T [GeV/c]
CMS Preliminary √s = 7 TeV, L = 5.1 fb⁻¹ ;√s = 8 TeV, L = 19.6 fb⁻¹
Events / 2 GeV
Data
Z+X
Zγ*,ZZ
m_H=126 GeV
m_Z1 [GeV]
CMS Preliminary √s = 7 TeV, L = 5.1 fb⁻¹ ;√s = 8 TeV, L = 19.6 fb⁻¹
Events / 2 GeV
Data
Z+X
Zγ*,ZZ
m_H=126 GeV
m_Z2 [GeV]

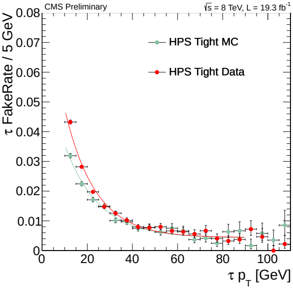
C: $H \to ZZ(*)$

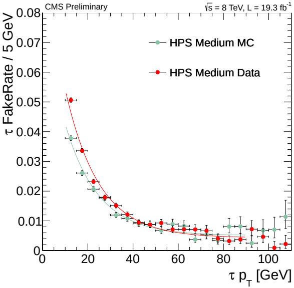

ATLAS Preliminary
$H \to ZZ^{(*)} \to 4l$
$\sqrt{s}$=7 TeV: $\int Ldt$ =4.6 fb^{-1}
$\sqrt{s}$=8 TeV: $\int Ldt$ =20.7 fb^{-1}
Obs 2012
Exp 2012
Obs 2011
Exp 2011
Obs Combination
Exp Combination
Local p_0
m_H [GeV]
1σ 2σ 3σ 4σ 5σ 6σ 7σ
CMS Preliminary
$H \to ZZ \to 4l$
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}
Observed m_{4l}
Observed m_{4l}, K_D
Observed m_{4l}, K_D, p_T/m_{4l} or V_D
Expected
local p-value
m_H [GeV]
5σ 7σ
CMS Preliminary
$H \to ZZ \to 4l$
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}
Observed 7 TeV
Observed 8 TeV
Observed 7+8 TeV
Expected
local p-value
5σ 7σ
CMS Preliminary
$H \to ZZ \to 4l$
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 19.6 fb^{-1}
Observed N_{Jets} >= 2
Observed N_{Jets} < 2
Observed Inclusive
Expected
local p-value
5σ 7σ

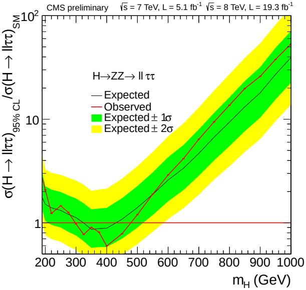
C: $H \to ZZ(*) \to \ell\ell\tau\tau$



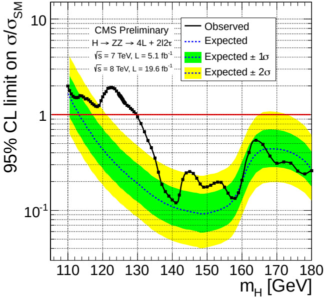
C: $H \to ZZ(*) \to \ell\ell\tau\tau$

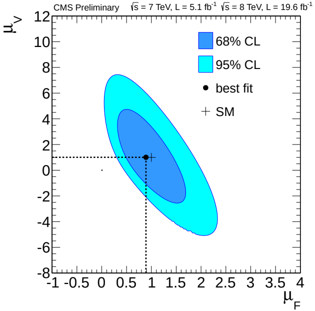




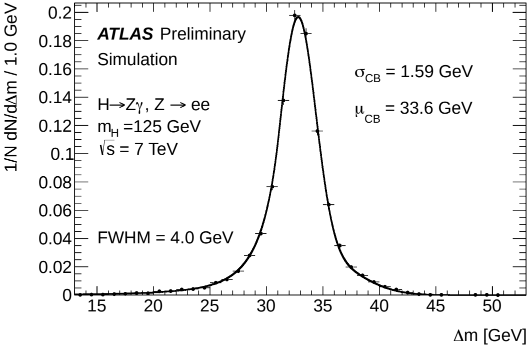


C: $H \to ZZ(*)$


CMS Preliminary
H → ZZ → 4L + 2l2τ
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 19.6 fb-1
Observed
Expected
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σSM
10
1
10-1
110 120 130 140 150 160 170 180
mH [GeV]


CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 19.6 fb-1
68% CL
95% CL
best fit
SM
μV
12
10
8
6
4
2
0
-2
-4
-6
-8
-1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
μF

A: $H \rightarrow Z\gamma$



$H \to Z\gamma$

Table 1: Luminosity and observed data yields used in the analysis. Expected signal yields for a 125 GeV SM Higgs boson.

Sample	Luminosity (fb^{-1})	num. of events $100 < m_{\ell\ell\gamma} < 180$ GeV	num. of events $120 < m_{\ell\ell\gamma} < 150$ GeV	num. of events predicted for $m_H = 125$ GeV
2011 ee	4.98	2268	1041	1.2
2011 $\mu\mu$	5.05	2739	1223	1.4
2012 ee	19.62	12482	5534	6.3
2012 $\mu\mu$	19.62	13392	5993	7.0

Table 3: Separate sources of systematic uncertainties accounted for in the analysis of the 7 and 8 TeV data set. The magnitude of the variation of the source that has been applied to the signal model is shown.

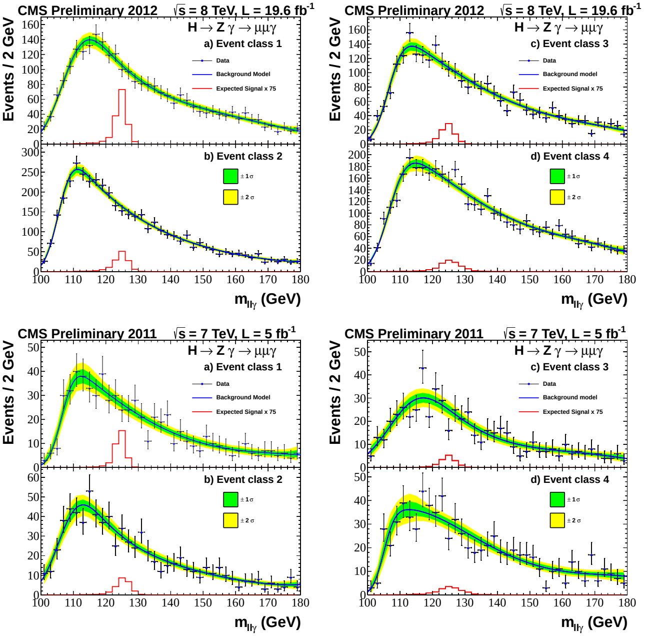
Source	7 TeV	8 TeV
Integrated luminosity	2.2%	4.4%
Theory		
- Gluon-gluon fusion cross section (scale)	+12.5% -8.2%	+7.6% -8.2%
- Gluon-gluon fusion cross section (PDF)	+7.9% -7.7%	+7.6% -7.0%
- Vector boson fusion cross section (scale)	+0.5% -0.3%	+0.3% -0.8%
- Vector boson fusion cross section (PDF)	+2.7% -2.1%	+2.8% -2.6%
- W associate production (scale)	+0.7% -0.8%	+0.2% -0.7%
- W associate production (PDF)	+3.5% -3.5%	+3.5% -3.5%
- Z associate production (scale)	+1.7% -1.6%	+1.9% -1.7%
- Z associate production (PDF)	+3.7% -3.7%	+3.9% -9.7%
- Top pair associate production (scale)	+3.4% -9.4%	+3.9% -9.3%
- Top pair associate production (PDF)	+8.5% -8.5%	+7.9% -7.9%
Branching fraction	6.7%,9.4% -6.7%,-9.3%	6.7%,9.4% -6.7%,-9.3%
Trigger		
- Electron	0.5%	2.0%
- Muon	0.5%	3.5%
Selection		
- Photon Barrel	0.5%	0.6%
- Photon Endcap	1.0%	1.0%
- Electron	0.8%	0.8%
- Muon	0.7%	1.4%
Signal scale and resolution		
- Mean	1.0%	1.0%
- Sigma	5.0%	5.0%
Event migration	5.0%	5.0%
Pileup		
- Electron	0.6%	0.8%
- Muon	0.4%	0.4%

m_H	$Z \to ee$, 7 TeV		$Z \to \mu\mu$, 7 TeV		$Z \to ee$, 8 TeV		$Z \to \mu\mu$, 8 TeV	
[GeV]	ε [%]	S	ε [%]	S	ε [%]	S	ε [%]	S
120	17.1	0.6	22.5	0.7	21.3	4.0	25.8	4.9
125	20.4	0.9	26.5	1.1	24.6	5.9	29.7	7.2
130	23.0	1.1	29.9	1.5	27.3	7.7	32.8	9.3
135	25.1	1.3	32.4	1.7	29.4	9.0	35.1	10.7
140	26.6	1.4	34.1	1.8	30.9	9.5	36.6	11.3
145	27.5	1.4	35.0	1.8	31.7	9.2	37.3	10.8
150	27.9	1.2	35.1	1.5	32.0	8.1	37.2	9.4

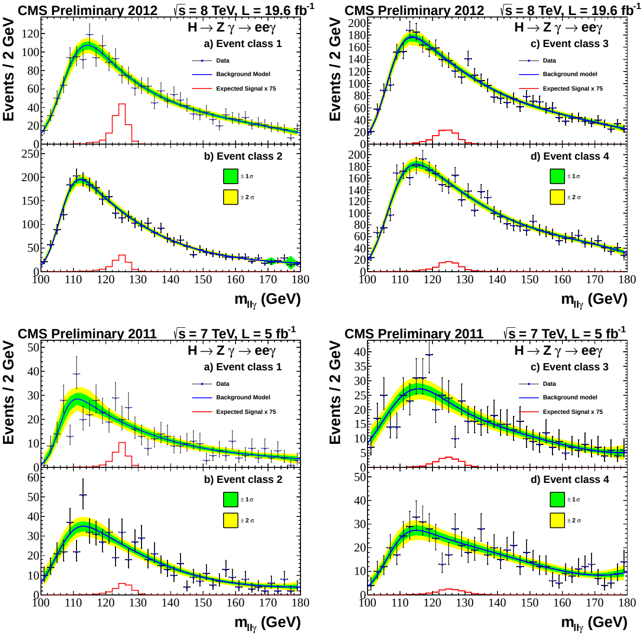
Table 3: Summary of the systematic uncertainties on the signal yield and invariant mass distribution for $m_H = 125$ GeV, at $\sqrt{s} = 8(7)$ TeV.

Systematic Uncertainty	$H \to Z(ee)\gamma(\%)$	$H \to Z(\mu\mu)\gamma(\%)$
Signal Yield		
Luminosity	3.6 (1.8)	3.6 (1.8)
Trigger efficiency	0.4 (0.2)	0.8 (0.7)
Acceptance of kinematic selection	4.0 (4.0)	4.0 (4.0)
γ identification efficiency	2.9 (2.9)	2.9 (2.9)
electron reconstruction and identification efficiency	2.7 (3.0)	
μ reconstruction and identification efficiency		0.6 (0.7)
e/γ energy scale	1.4 (0.3)	0.3 (0.2)
e/γ isolation	0.4 (0.3)	0.4 (0.2)
e/γ energy resolution	0.2 (0.2)	0.0 (0.0)
μ momentum scale		0.1 (0.1)
μ momentum resolution		0.0 (0.1)
Signal Δm resolution		
e/γ energy resolution	5.0 (5.0)	2.4 (2.4)
μ momentum resolution		0.0 (1.5)
Signal Δm peak position		
e/γ energy scale	0.2 (0.2) GeV	0.2 (0.2) GeV
μ momentum scale		negligible

C: $H \to Z\gamma$

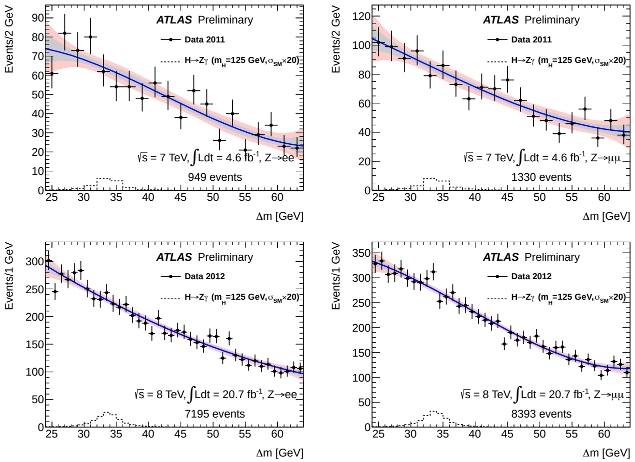

CMS Preliminary 2012 √s = 8 TeV, L = 19.6 fb⁻¹
H → Z γ → μμγ
a) Event class 1
b) Event class 2
c) Event class 3
d) Event class 4
Data
Background Model
Expected Signal x 75
±1σ
±2σ
Events / 2 GeV
m_llγ (GeV)
CMS Preliminary 2011 √s = 7 TeV, L = 5 fb⁻¹

C: $H \to Z\gamma$

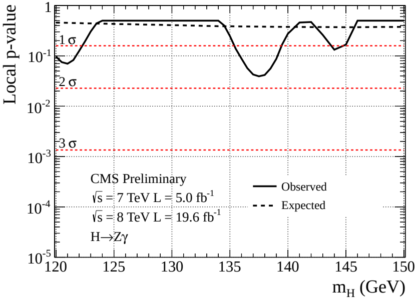


CMS Preliminary 2012 √s = 8 TeV, L = 19.6 fb-1
H → Z γ → eeγ
a) Event class 1
b) Event class 2
c) Event class 3
d) Event class 4
Data
Background Model
Expected Signal x 75
±1σ
±2σ
Events / 2 GeV
m_llγ (GeV)
CMS Preliminary 2011 √s = 7 TeV, L = 5 fb-1

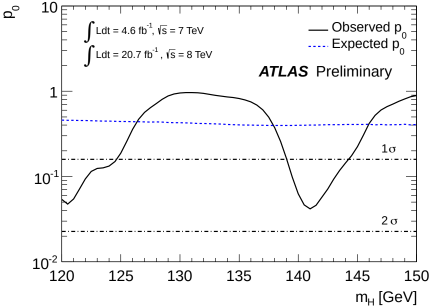
A: $H \to Z\gamma$


ATLAS Preliminary
Data 2011
H→Zγ (m_H=125 GeV,σ_SM×20)
√s = 7 TeV, ∫Ldt = 4.6 fb^-1, Z→ee
949 events
√s = 7 TeV, ∫Ldt = 4.6 fb^-1, Z→μμ
1330 events
Data 2012
√s = 8 TeV, ∫Ldt = 20.7 fb^-1, Z→ee
7195 events
√s = 8 TeV, ∫Ldt = 20.7 fb^-1, Z→μμ
8393 events
Events/2 GeV
Events/1 GeV
Δm [GeV]

$H \to Z\gamma$



Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1 σ
2 σ
3 σ
CMS Preliminary
√s = 7 TeV L = 5.0 fb^{-1}
√s = 8 TeV L = 19.6 fb^{-1}
H→Zγ
Observed
Expected
120 125 130 135 140 145 150
m_H (GeV)



p_0
10
1
10^{-1}
10^{-2}
∫Ldt = 4.6 fb^{-1}, √s = 7 TeV
∫Ldt = 20.7 fb^{-1}, √s = 8 TeV
Observed p_0
Expected p_0
ATLAS Preliminary
1σ
2 σ
120 125 130 135 140 145 150
m_H [GeV]