Higgs and Beyond 2013

(仙台)

$H \rightarrow \gamma\gamma$

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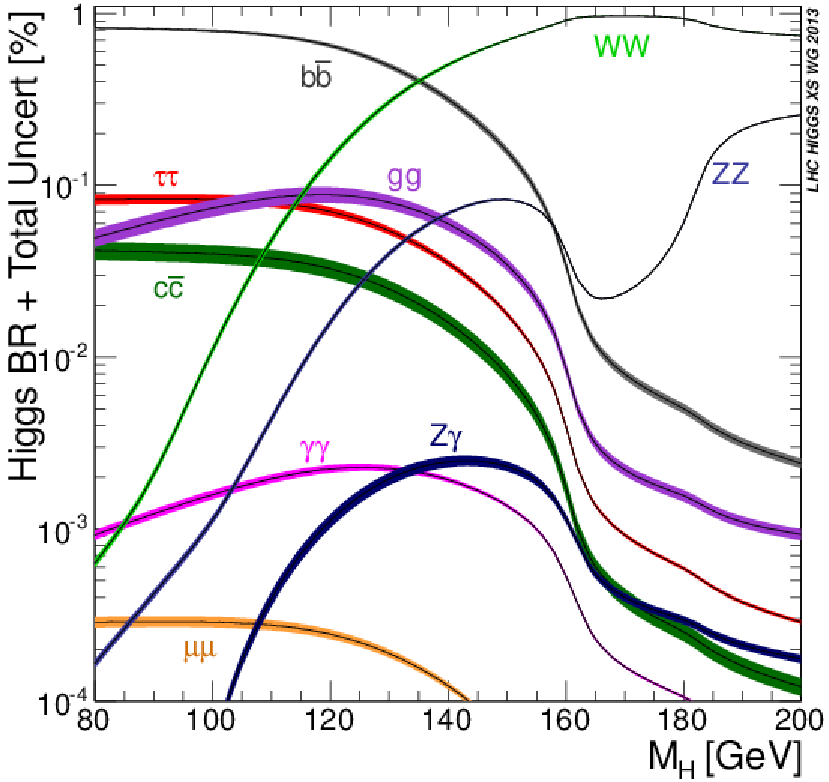
On behalf of the CMS - ATLAS Collaborations

Overview

- The $H \rightarrow \gamma\gamma$ decay mode
- ATLAS and CMS
- Analysis Strategy
- Results

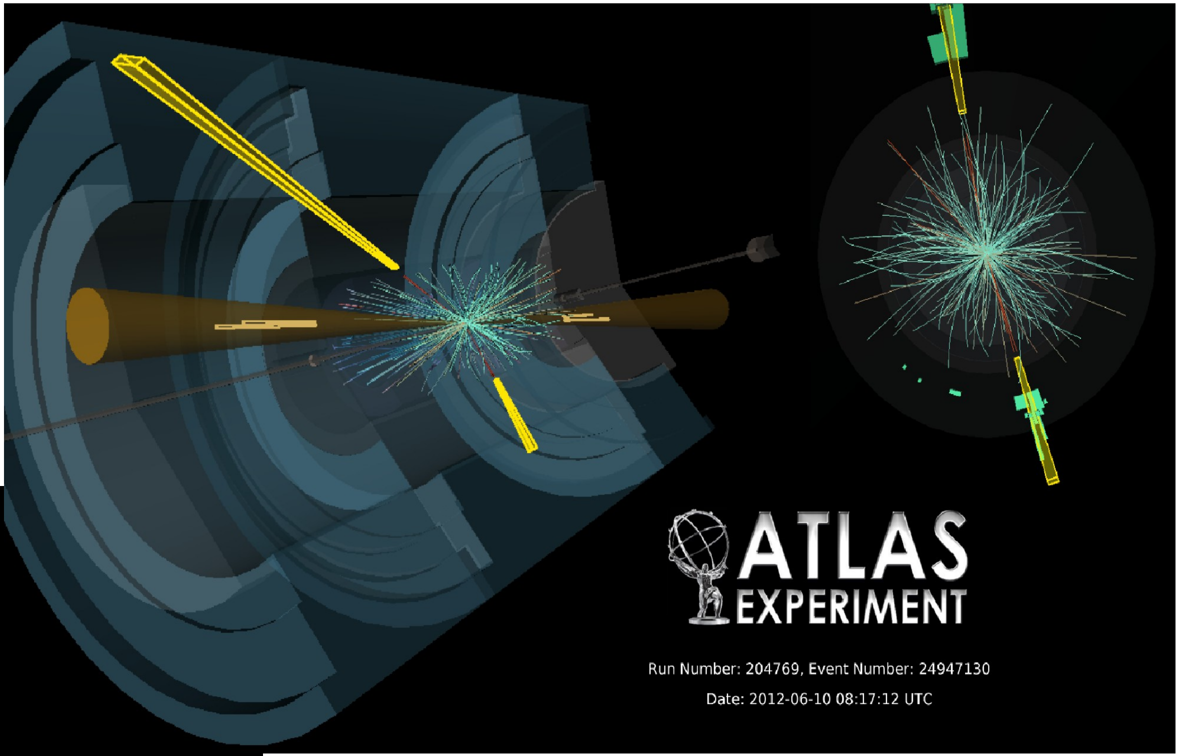
The γγ Channel

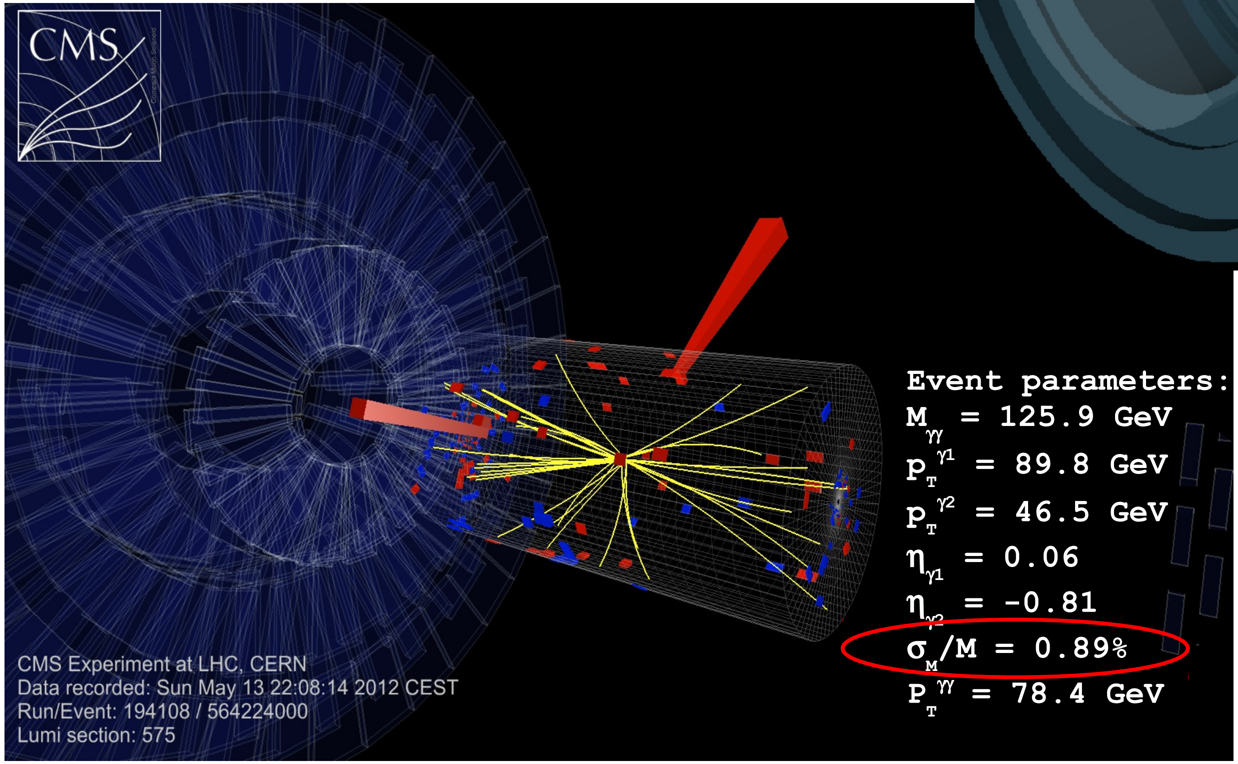
- Small branching ratio (~$2 \cdot 10^{-3}$):
  - High sensitivity at low mass [100-150] GeV with higher statistics than golden $H \rightarrow ZZ$.
- Clear signature: **two isolated photons** with **large transverse momentum** on top of continuous background;
- Large background:
  - γγ from QCD **(irreducible)**;
  - γ+jet with one mis-identified jet as photon;
  - di-jet with two mis-identified jets;
  - Drell-Yan with mis-identified electrons.



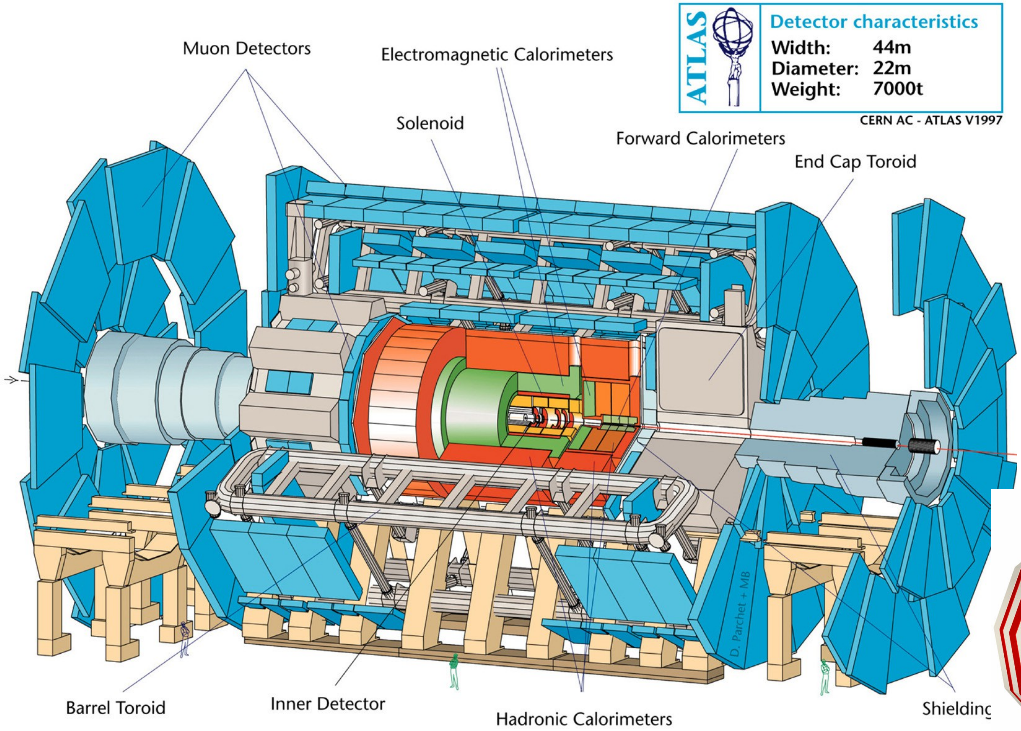
- Sensitivity dependent on experimental diphoton resolution:
  - Good performance of EM Calorimeters (mass resolution **1-2 %** at M_H = 125 GeV);
- Efficient photon reconstruction/identification to reduce reducible background.

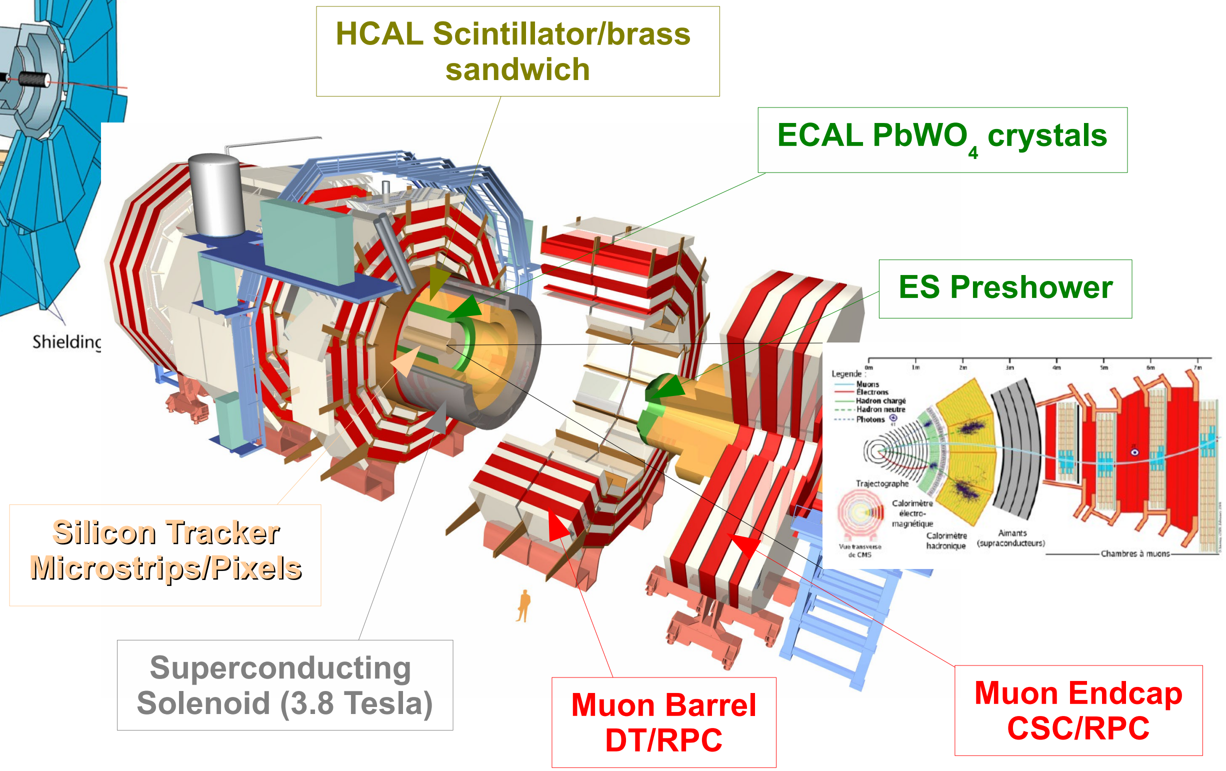
H → γγ Candidates





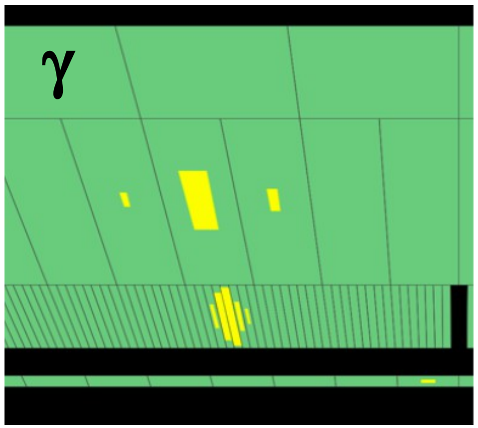
The Detectors

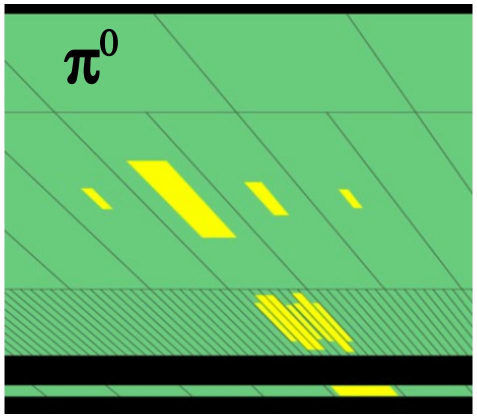




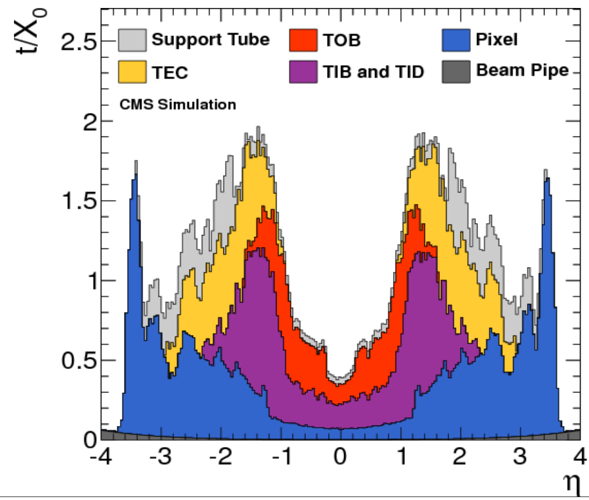
ATLAS and CMS Calorimeter Design

- **ATLAS: LAr/Pb sampling calorimeter** (22 X_0)
  - Accordion shape: **longitudinally segmented** (strip, middle, back) + pre-sampler;
  - Fine η segmentation of strip layer allows γ, π^0 separation;
- Nominal: $\sigma_E / E = \frac{10 \div 17\%}{\sqrt{E}} \oplus 0.7\%$





- **CMS**: homogeneous calorimeter
  - **High resolution PbWO4 scintillating crystals** + endcap silicon pre-shower;
  - **Lateral but no longitudinal segmentation;**
- Nominal: $\sigma_E / E = \frac{3\%}{\sqrt{E}} \oplus 0.5\%$



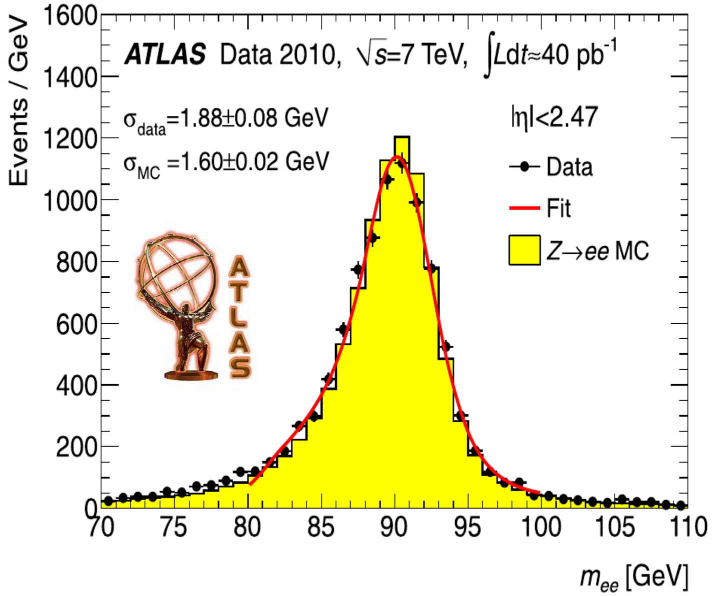
In both experiments detector material limits the resolution due to energy losses: ad hoc energy corrections need to be estimated.

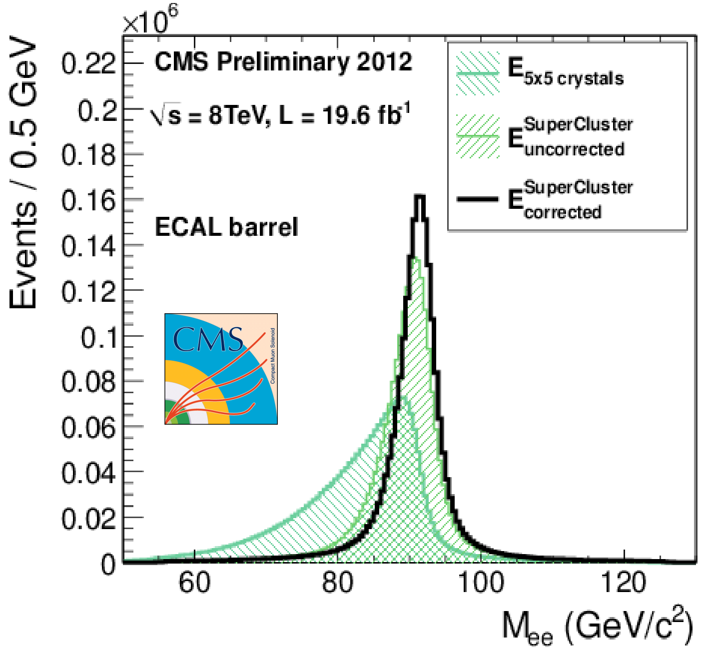
Energy Scale and Corrections

- Corrections are applied to the photon energy:
  - Exploited photon-electron similarities (electron EM cluster treated as photon).

1. A first set of corrections (derived from MC) is applied to correct for energy losses in passive materials, shower containment, pileup...
2. Energy scale in data is corrected to agree with MC.
3. Finally MC energy resolution is corrected through the addition of a constant gaussian term **(smearing)** to match data Z line shape.

- **ATLAS**: eta dependent corrections derived separately for unconverted and converted γ:
  - Photon is converted if conversion vertex found with r < 800mm.
- **CMS**: reconstructed cluster energies corrected based on a multivariate technique (**regression**).



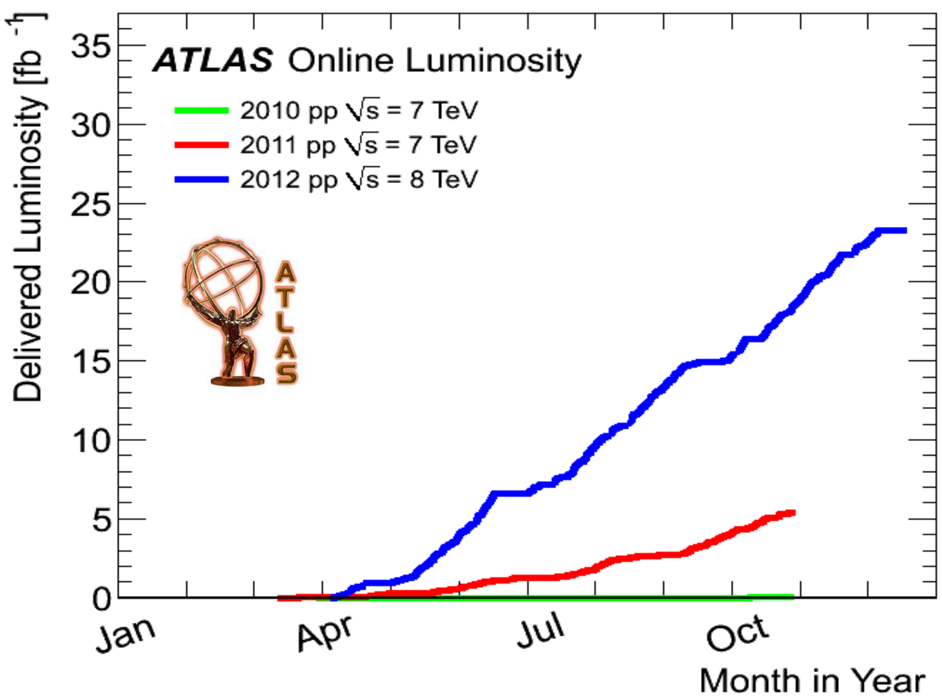


Data and Trigger

- **L = 4.8 fb^{-1} $\sqrt{s}$ = 7TeV (2011)**
- **L = 20.7 fb^{-1} $\sqrt{s}$ = 8TeV (2012)**

  Systematics: 3.6% (1.8%) for 2012 (2011)

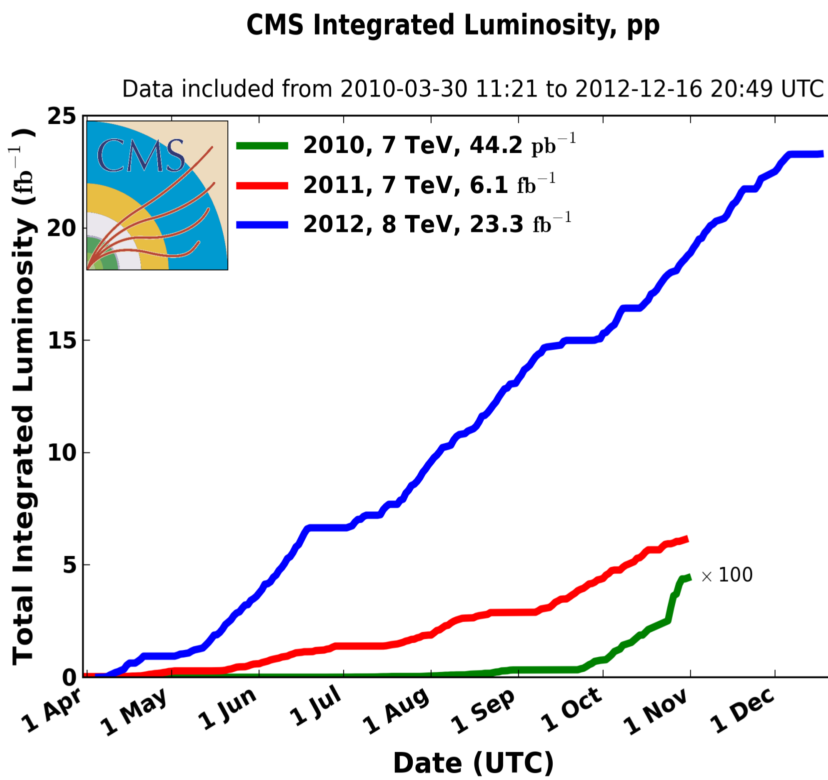
- **Diphoton trigger**: using cluster energies and loose cuts: 20 GeV (2011), 35,25 GeV (2012)



- **L = 5.1 fb^{-1} $\sqrt{s}$ = 7 TeV (2011)**
- **L = 19.6 fb^{-1} $\sqrt{s}$ = 8 TeV (2012)**

  Systematics: 4.4% (2.2%) for 2012 (2011)

- **Diphoton trigger**: using cluster energies and loose cuts: 26,18 GeV and 36,22 GeV.



Analysis Strategy

- **CMS** has two analyses: **MVA (~15% more sensitive)** and **cut-based:**
  - $t\bar{t}H$ exclusive analysis has been recently finalized.
- In addition to the main analysis, **ATLAS** performs also spin analysis and fiducial cross section measurements:
  - **CMS** spin analysis is ongoing.
- Key points:
  - **Energy scale and resolution**: sensitivity dependent on the resolution and energy scale is main systematic error on the mass measurement;
  - **Vertex identification**: not to degrade mass resolution;
  - **Photon identification;**
  - **Background parametrization**: important a good description of the background shape;
- **Both experiments use data categorization**:
  - To increase sensitivity treating differently events with different resolution.

ATLAS-CONF-2013-012, ATLAS-CONF-2013-029 **(update only 2012, 2011 from ICHEP)**
CMS-PAS-HIG-13-001, CMS-PAS-HIG-13-015 **(first updates after the discovery for CMS)**

Offline Selection

ATLAS

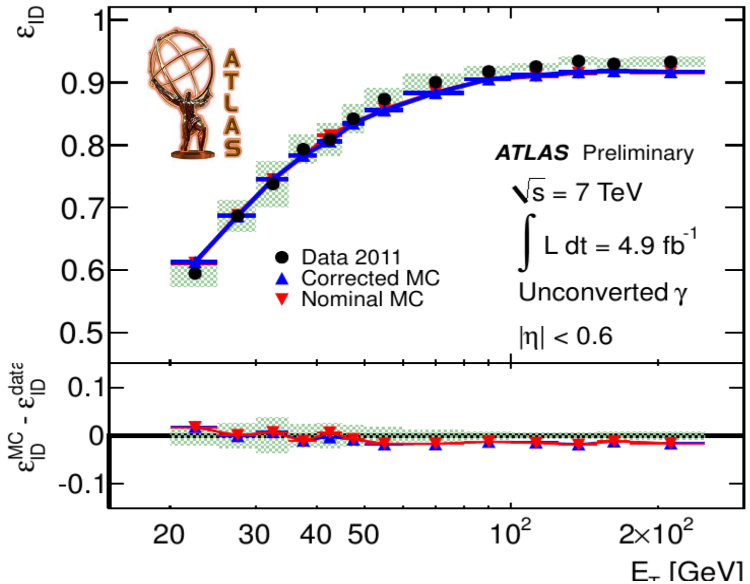
- $|\eta| < 2.37$ (except $1.37 < |\eta| < 1.56$);
- pT > 30,40 GeV;
- Cut-based ID (Neural Network) identification using shower shapes and hadronic leakage in 2012 (2011):
  - Efficiency between 85% and 95% (at 100 GeV);
  - Systematic uncertainty: 2.4%.
- Calorimetric and Track isolation requirements:
  - Systematic uncertainty: 1.0%.

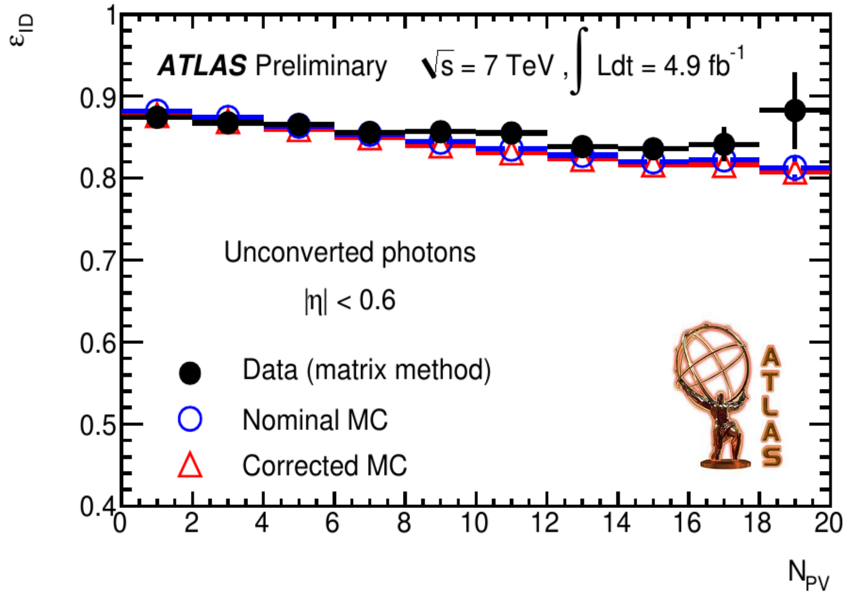
CMS

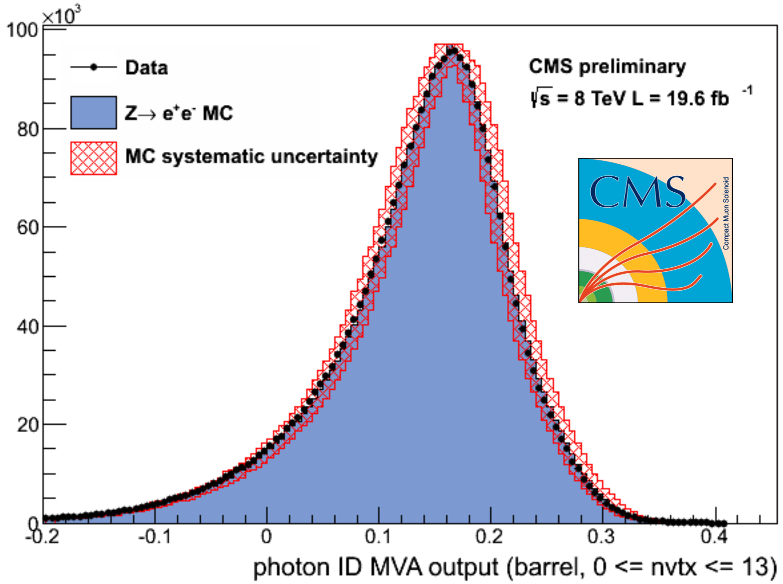
- $|\eta| < 2.5$ (except $1.4442 < |\eta| < 1.566$);
- pT > $m_{\gamma\gamma}/2$, $m_{\gamma\gamma}/4$ GeV.
- MVA photon identification using:
  - Hadronic leakage;
  - Many shower topology variables;
  - Four isolation definition (based on particle flow) corrected for PU.
- Cut-based analysis: identification criteria defined on a similar set of variables:
  - Systematic uncertainty: $1.0 \div 2.6\%$.

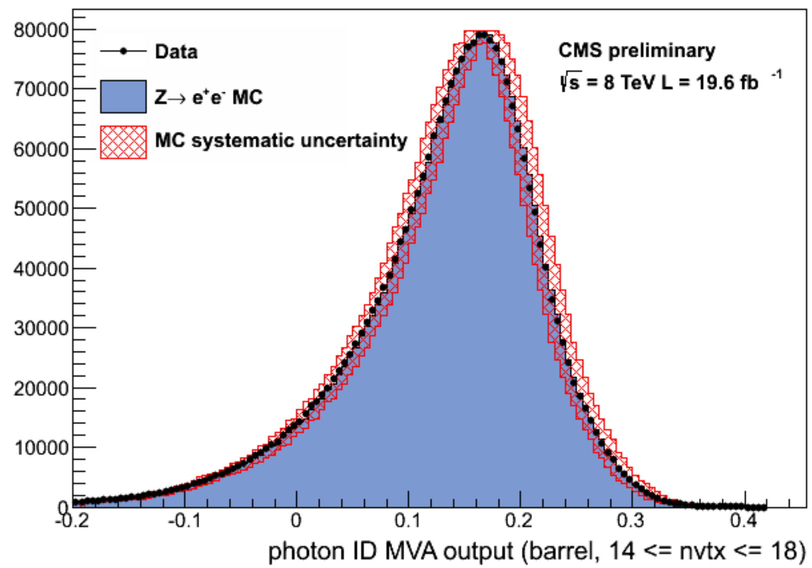
Photon Identification

Photon Identification data/MC scale factors measured using **$Z \to ee$** and **$Z \to \mu\mu\gamma$** events: overall good data/MC agreement.



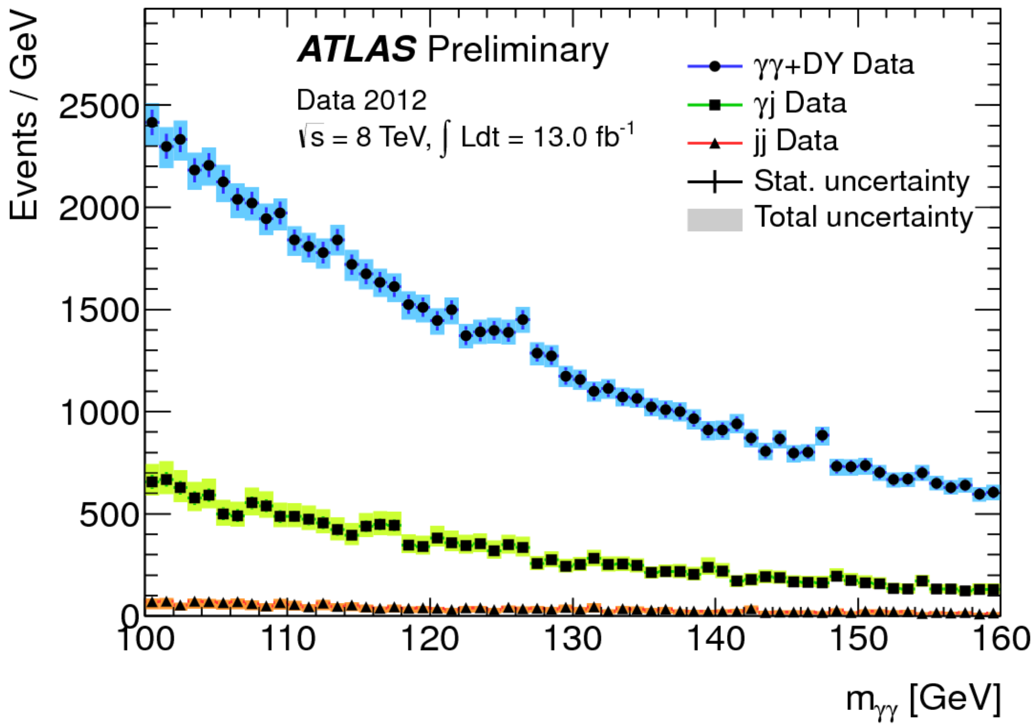


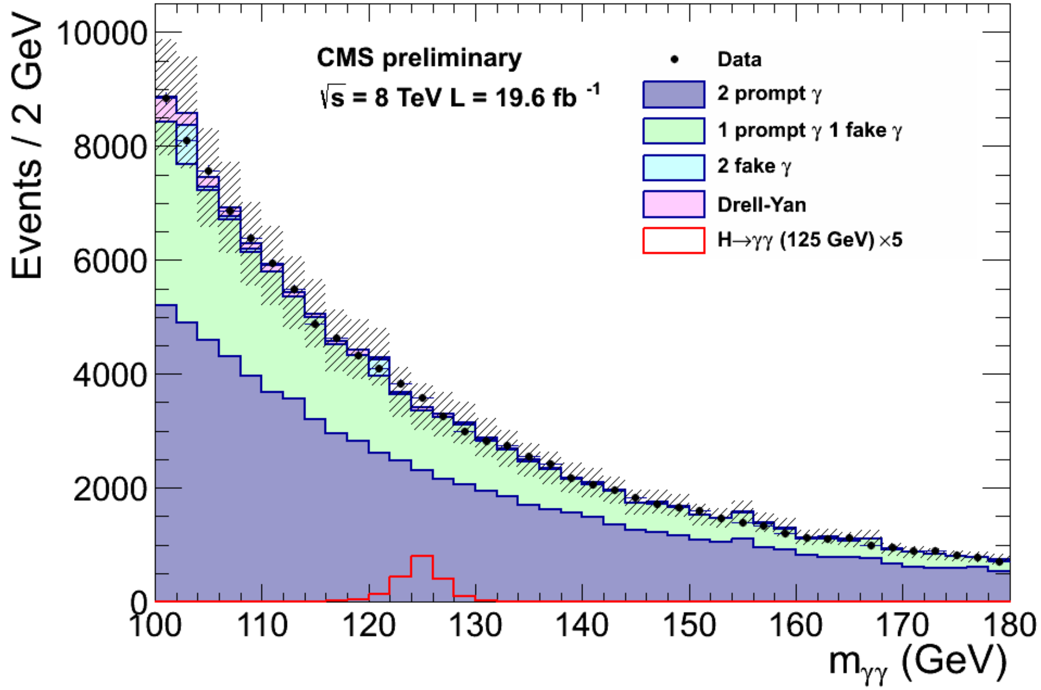




Invariant Mass Spectrum

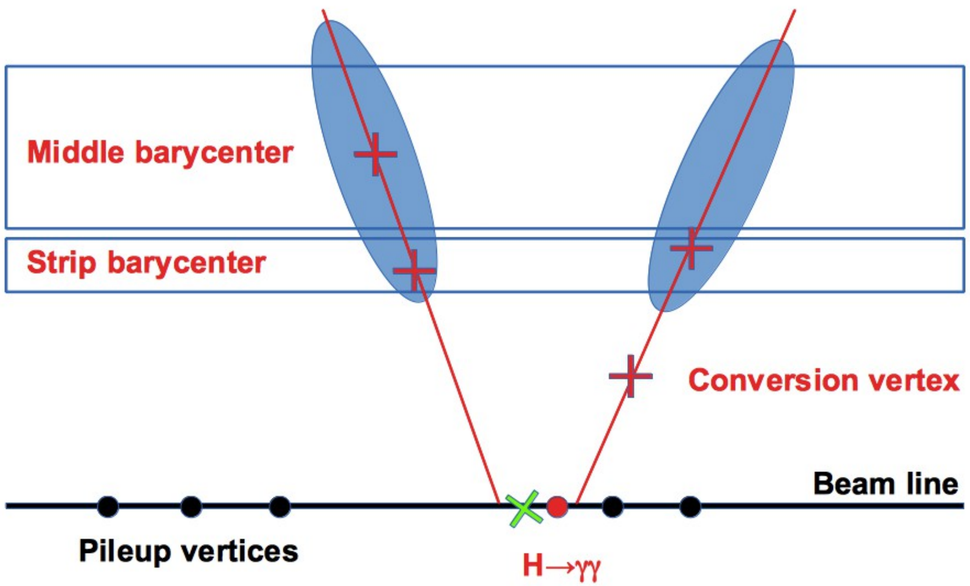
- Diphoton purity: 75%, estimated from data.
- Diphoton purity in 110-150: ~70% (from MC)

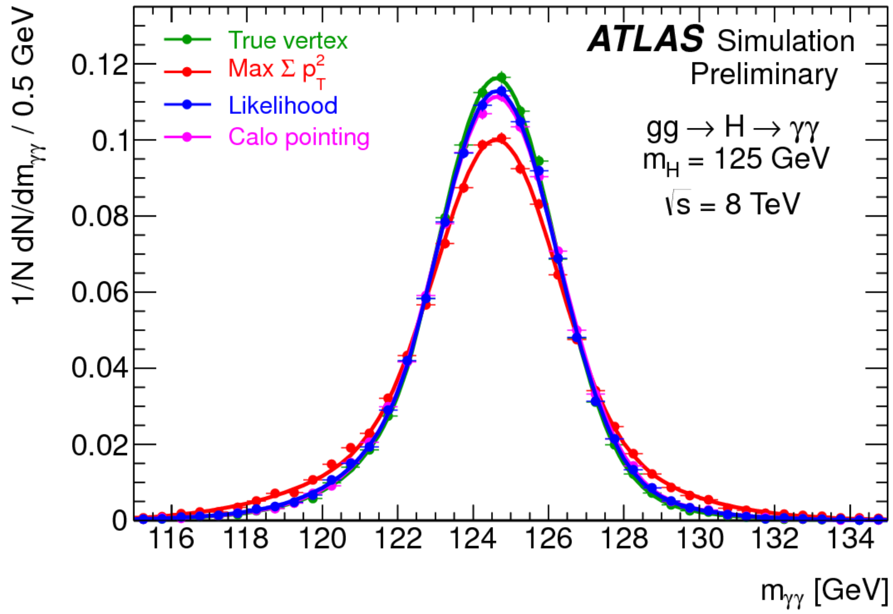




Vertex Determination (ATLAS)

- ATLAS detector has the ability to measure direction with the calorimeter only thanks to its longitudinal segmentation:
  - Unconverted photons vertex are determined using the barycenter of the clusters measured in the first and second layers;
  - Converted photons from the conversion point and the position in the first layer.
- In di-photon events the intersection between their flight lines and the beam line gives the estimate of the z-coordinate of the photon origin (σ_z = 15 (6)mm (using conversion)).





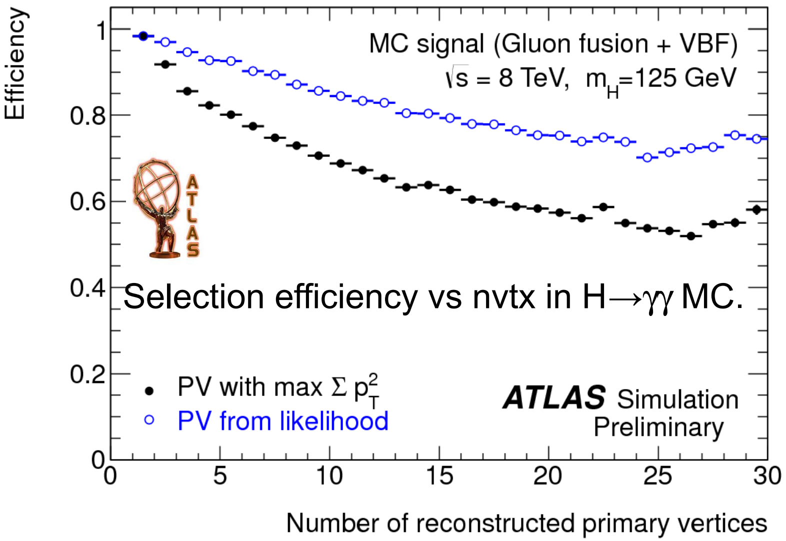
Primary Vertex Selection

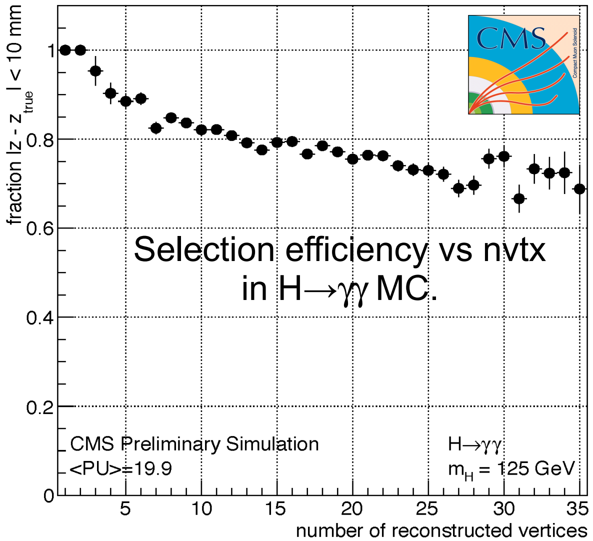
ATLAS

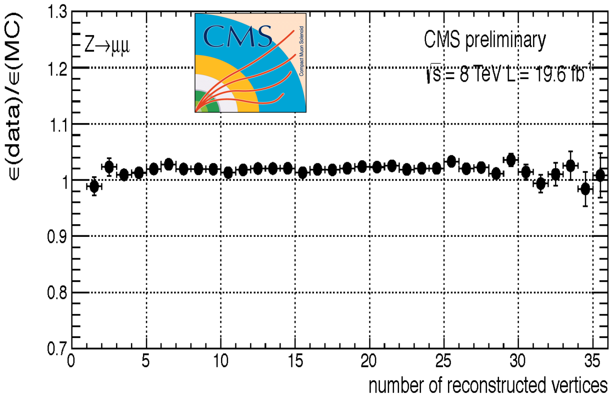
- Neural Network (2012), likelihood ratio (2011):
  - $\Sigma(pT^2)$, $\Sigma(pT)$, $\Delta\phi(\gamma\gamma, vtx)$, pointing+conversion;
- Validated with $Z \rightarrow ee$;
- Efficiency > 75% (within 0.3 mm window).

CMS

- **Selection based on Boosted Decision Tree (BDT)**: conversion, pT-balance, asymmetry;
- Efficiency ~ 80% (within 10 mm window):
  - Comparable with ATLAS.
- Validated with $Z \rightarrow \mu\mu$, γ+jet.



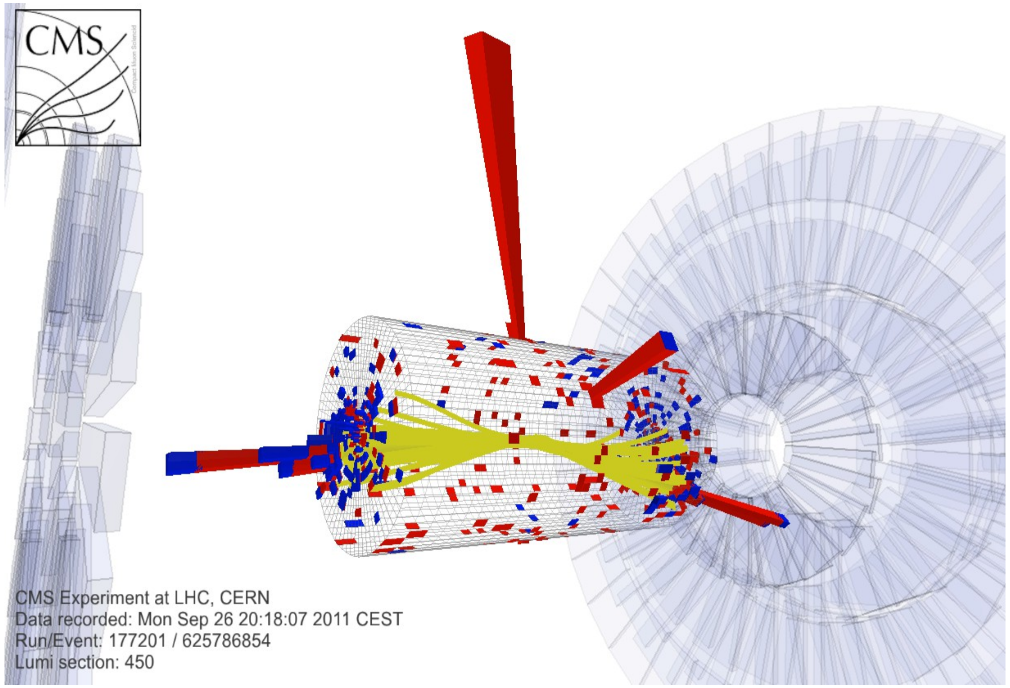




Data/MC scale factor for selection efficiency vs nvtx in $Z \rightarrow \mu\mu$ events.

Event Categorization (Exclusive modes)

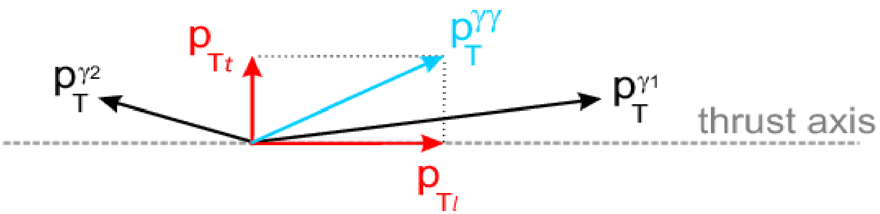
- Exclusive categories are defined with tags targeting to VBF and VH production modes:
  - Low statistics, high purity (S/B ~ 10 – 50 %).

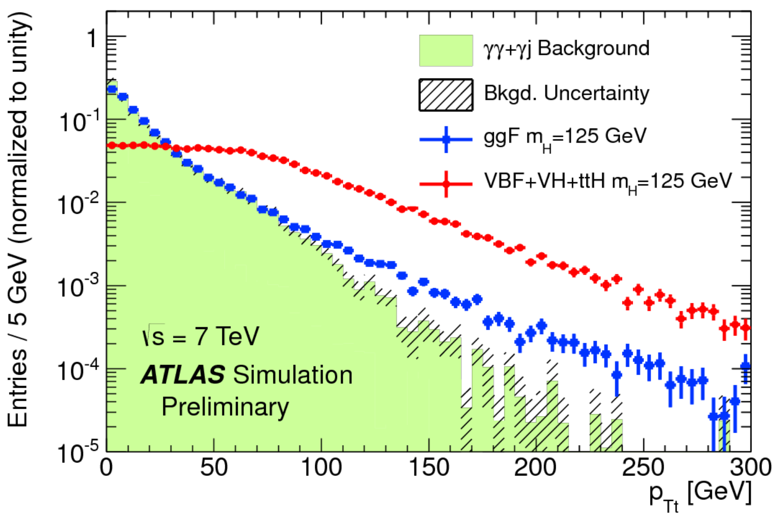


Mode	ATLAS (Tag)	CMS (Tag)
VH	- 1 lepton (e or μ) - ET-miss - Dijet (low mass)	- Electron - Muon - ET-miss
VBF	Dijet (high mass) (two categories based on BDT output)	Dijet (two categories based on BDT output)

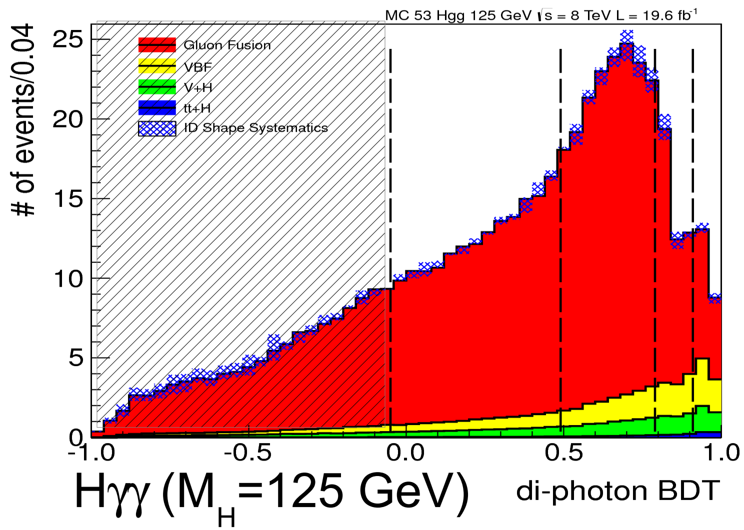
Inclusive Categories

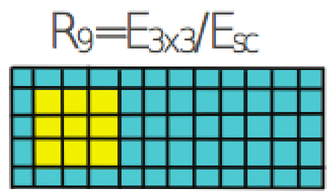
- **Nine categories using:**
  - Conversion status, |η| position;
  - pTt (strongly correlated with the diphoton transverse momentum,
    but better detector resolution).





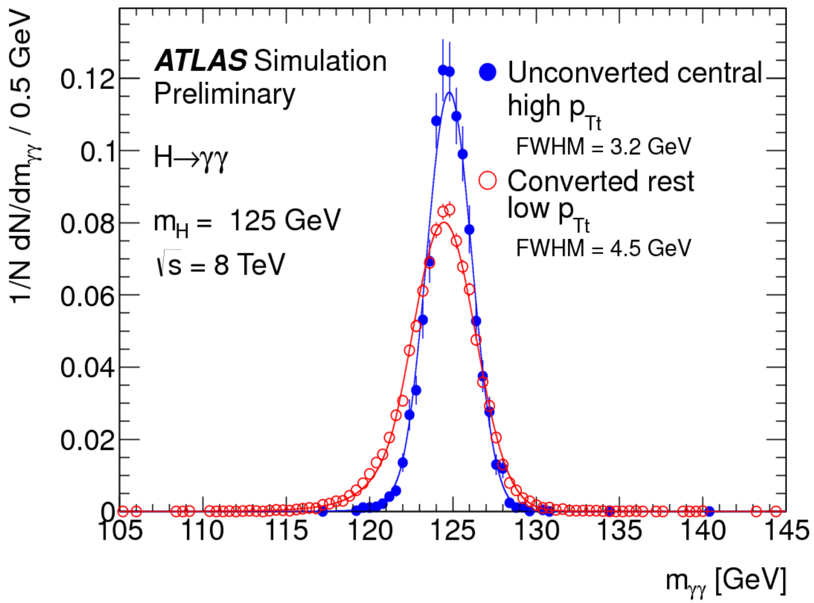
- **MVA, four untagged categories based on BDT discriminant:**
  - Inputs: photon identification, per-event mass resolution, kinematic properties.
- Cut-based: 4 categories using |η| position and shower shape R9 (correlated with conversion status).
- Validation of inputs with Z→ee, Z→μμγ.



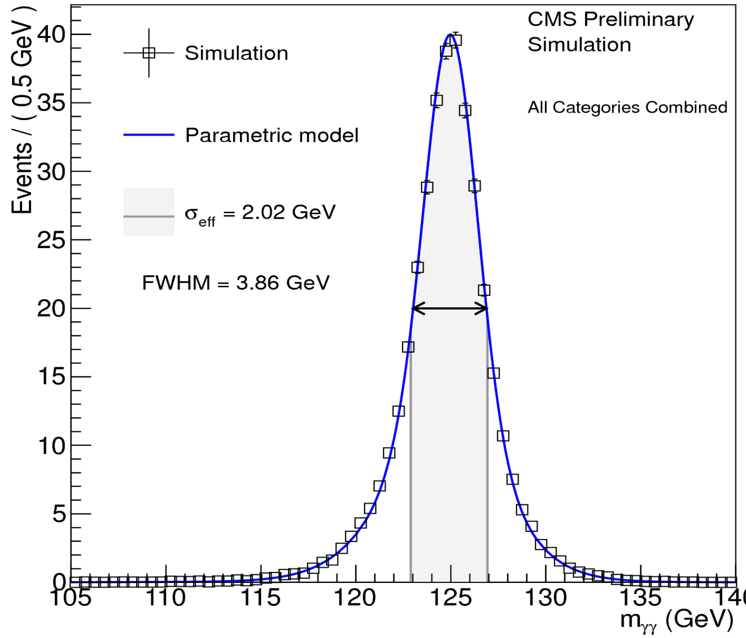


Signal Model

- Fit: Crystal Ball + wide gaussian:
  - Gaussian component <~ 12%.



- Fit: sum of two or three gaussians.



FWHM/2.35	ATLAS(*)	CMS
Overall	1.78 GeV	1.64 GeV
Best Category	1.40 GeV	1.27 GeV
Other Categories	1.50-2.54 GeV	1.39-2.14 GeV

(*) ATLAS quotes just σ_{CB} in the paper. Numbers scaled by the FWHM/σ_{CB} factor from HCP results.

Background Model

- Signal extraction from S+B fits to $m_{\gamma\gamma}$ data, background from analytical functions. Different approaches for the background modeling.

ATLAS

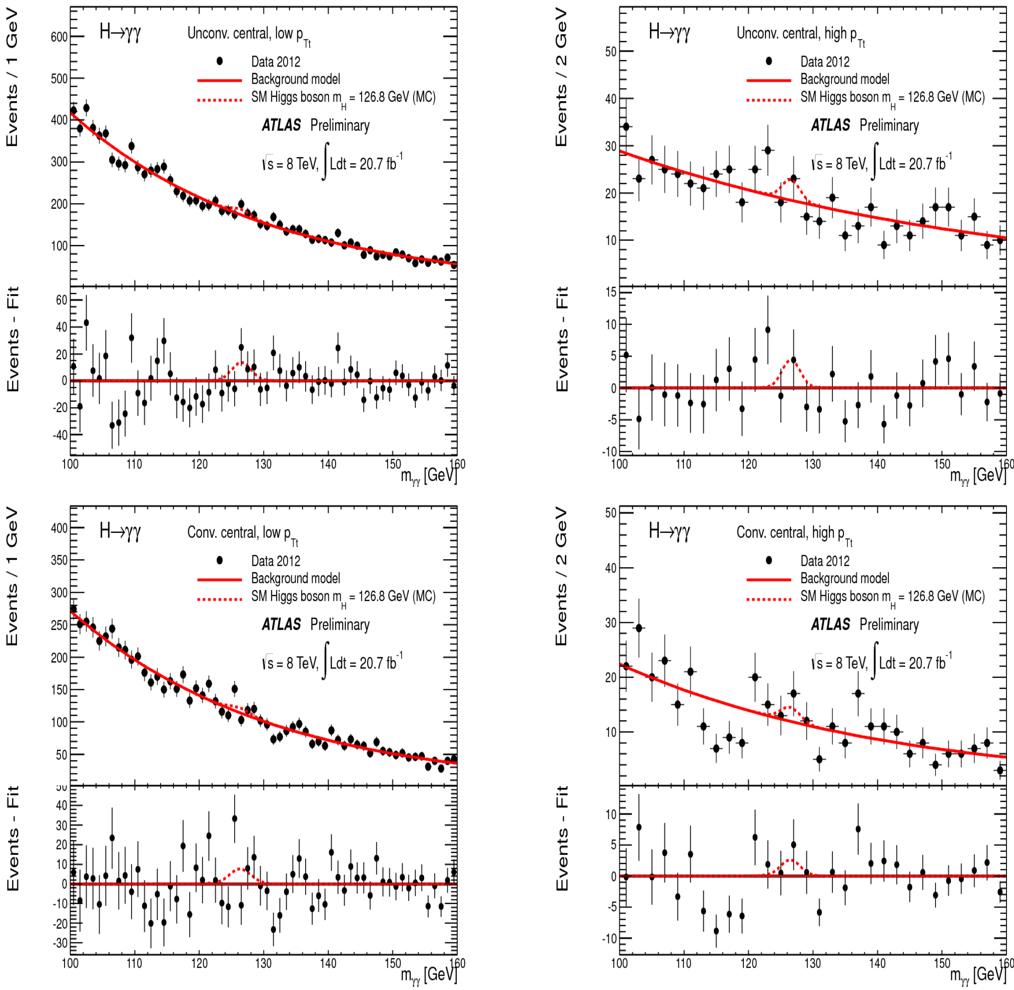
- Based on **high statistic MC** combined according to fraction determined from data;
  - Fitting diphoton mass data distribution between $100 < m_{\gamma\gamma} < 160$ GeV;
- **Spurious signal** defined as the largest absolute signal component fitted anywhere in $110 < m_{\gamma\gamma} < 150$ GeV.
- Function chosen as the one with lowest number of parameters and minimizing the spurious signal which is quoted as systematic.

CMS

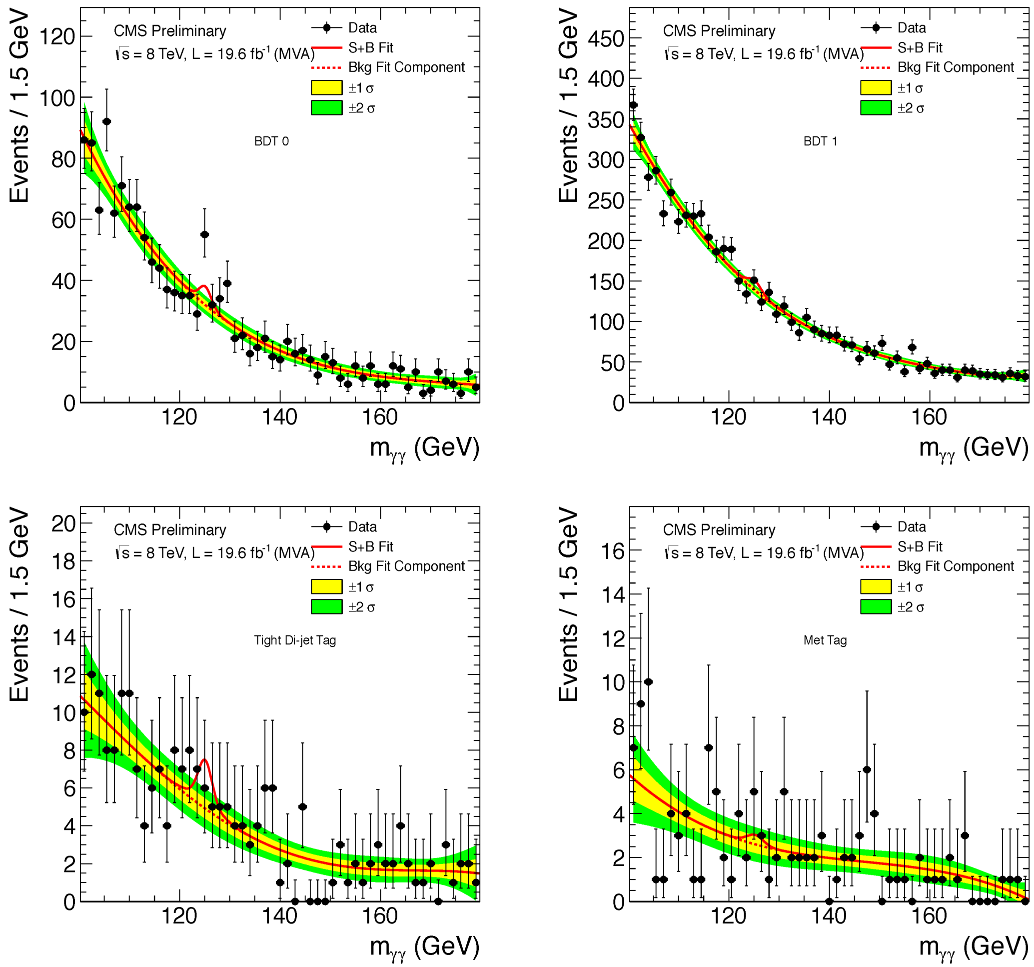
- Determine **truth model from data** using function with high degree of freedom ($100 < m_{\gamma\gamma} < 180$ GeV);
- The functions are **tested on pseudo-data** generated from truth model;
- Find the best function which minimize the bias on the fitted signal strength (<20% background fluctuation in 1 FWHM).

Background Fits

14 (10 in 2011) Categories.



9 (5 in 2011) Categories.



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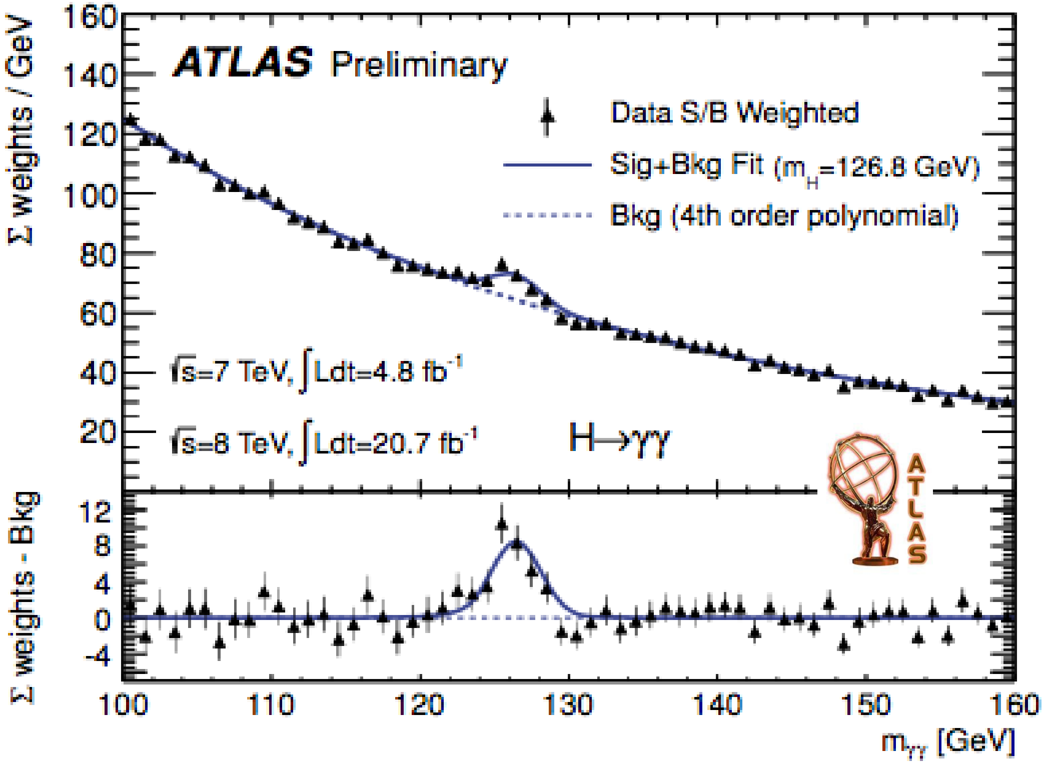
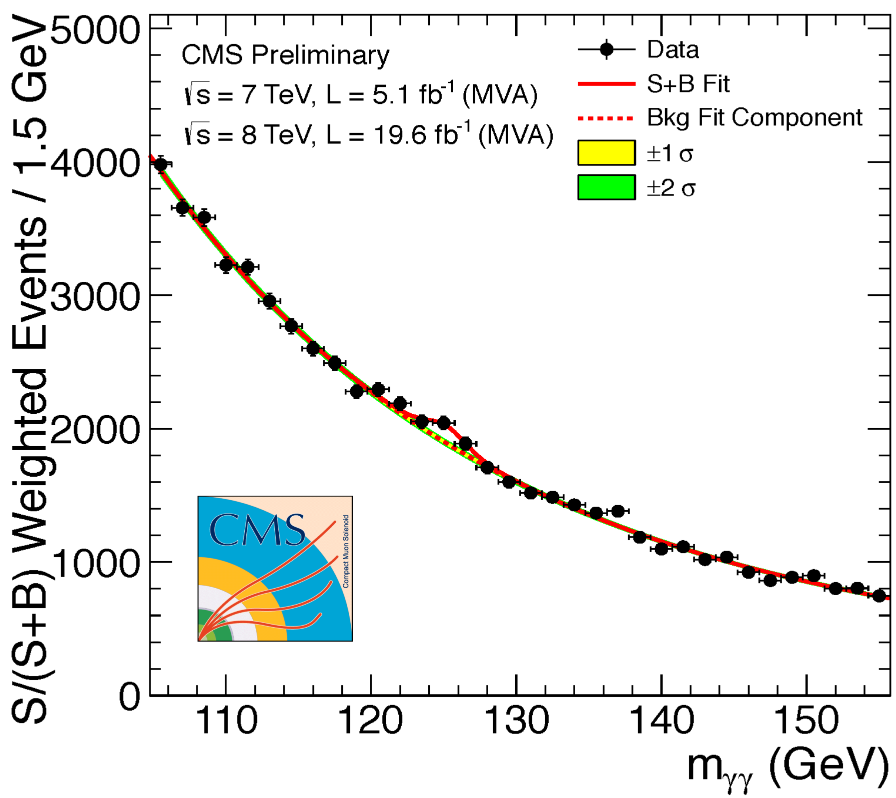
Inclusive Background Fit



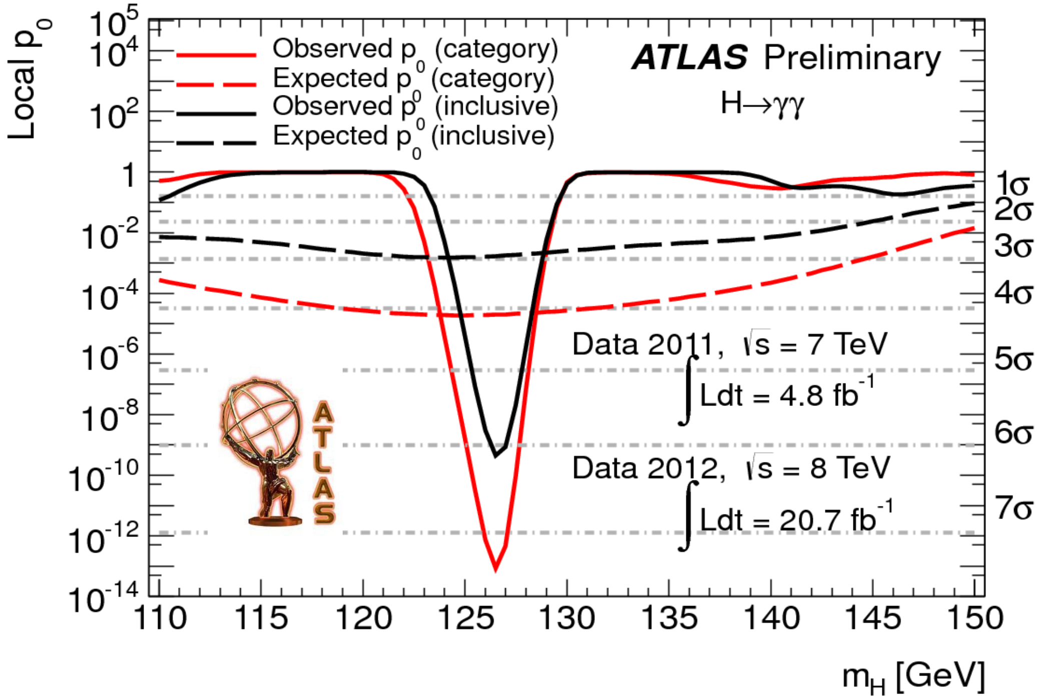


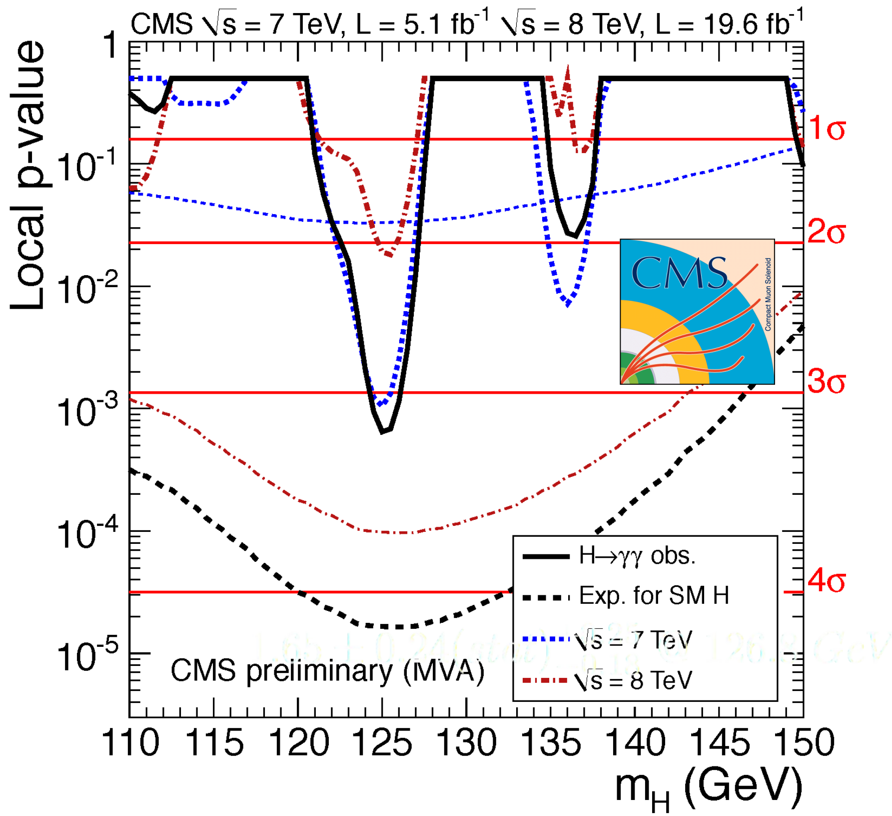
- From inclusive analysis ATLAS estimated the fiducial cross section ($|\eta| < 2.37$):

$$\sigma_{fid} \times BR = 56.2 \pm 10.5\ (\text{stat}) \pm 6.5\ (\text{syst}) \pm 2.0\ (\text{lumi})\ \text{fb}.$$

Results

- Comparable expected significance between ATLAS and CMS MVA analysis.

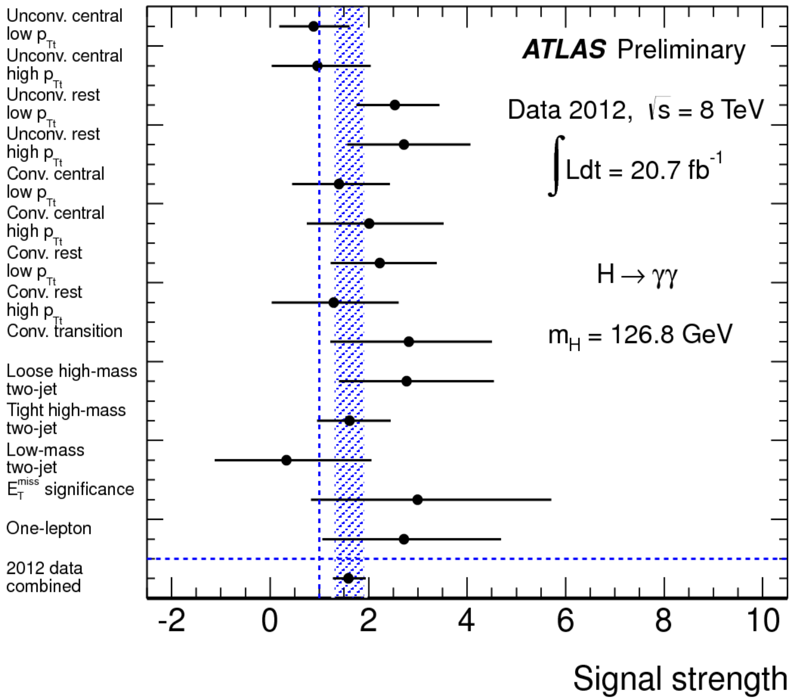


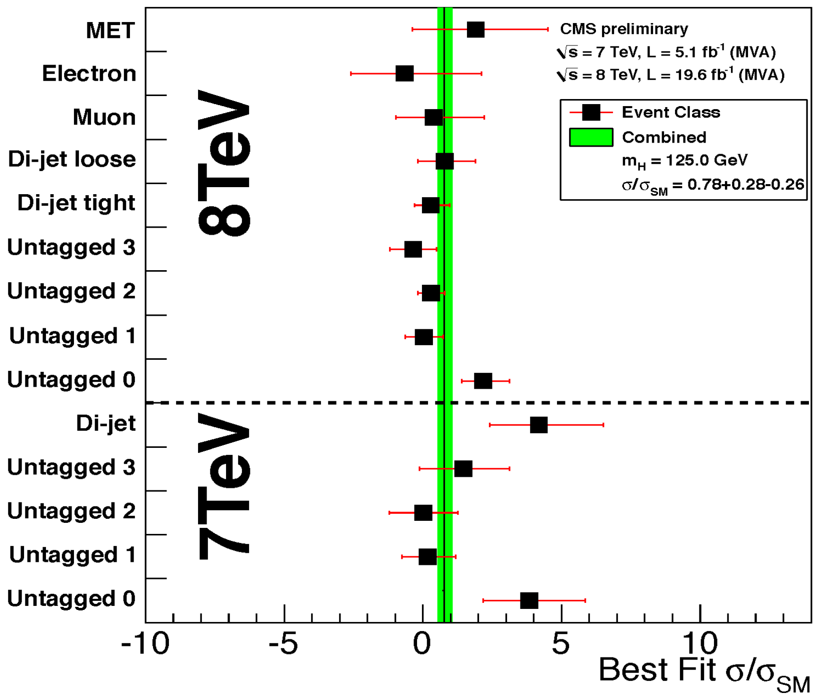


√s = 7+8 TeV	Exp.	Obs.
ATLAS	4.1	7.4
CMS MVA	4.2	3.2

Signal Strength

$\sqrt{s}$ = 7+8 TeV	$\mu = \sigma/\sigma_{SM}$
ATLAS	$1.65^{+0.35}_{-0.30}$ @ 126.8 GeV
CMS MVA	$0.78^{+0.28}_{-0.26}$ @ 125.0 GeV

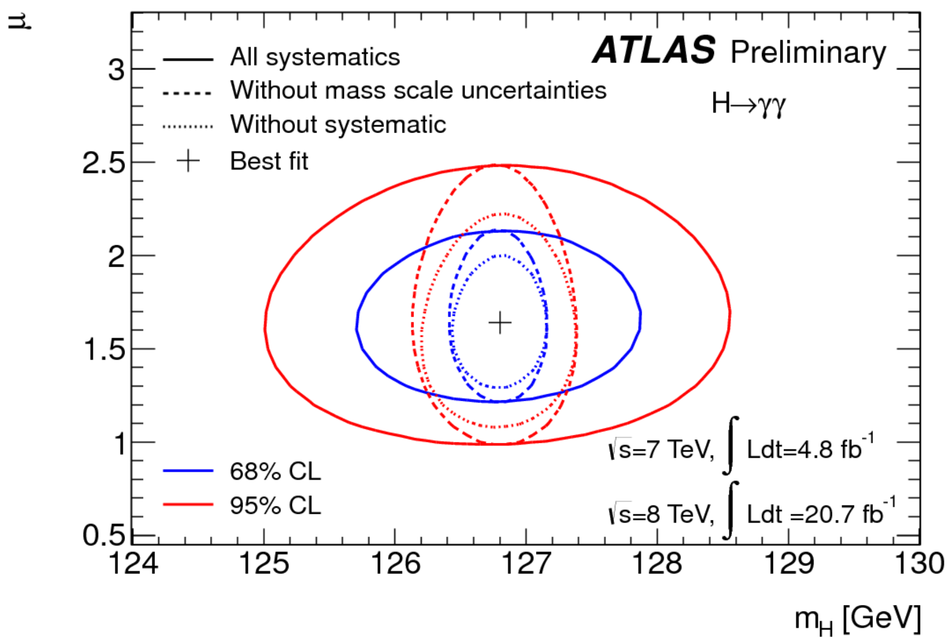




Mass Measurement

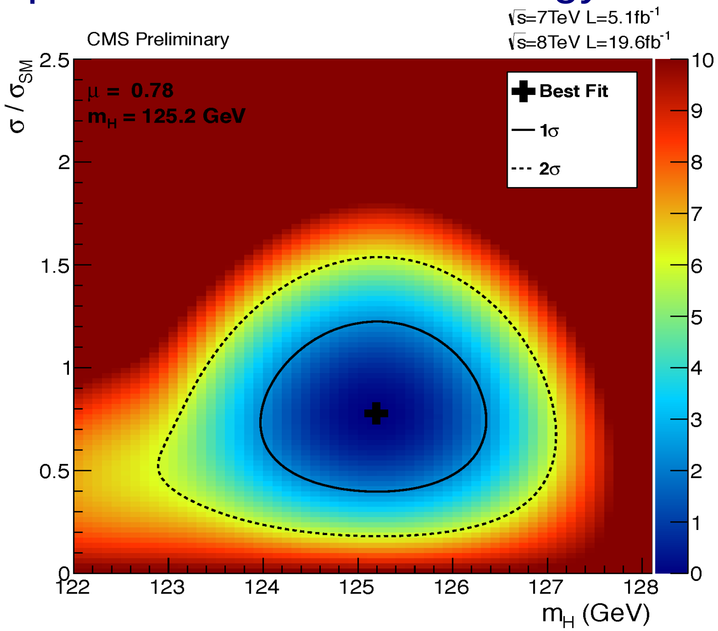
The best-fit for the mass value is
M_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV

- Main uncertainty:
  - extrapolation of photon energy scale from $Z \rightarrow ee$ scale;
  - material modeling.



The best-fit for the mass value is
M_H = 125.4 ± 0.5(stat) ± 0.6(syst) GeV

- Main uncertainty:
  - imperfect simulation of detector response to electrons and γ;
  - mis-modeling of detector linearity in extrapolation from Z to H energy scale.

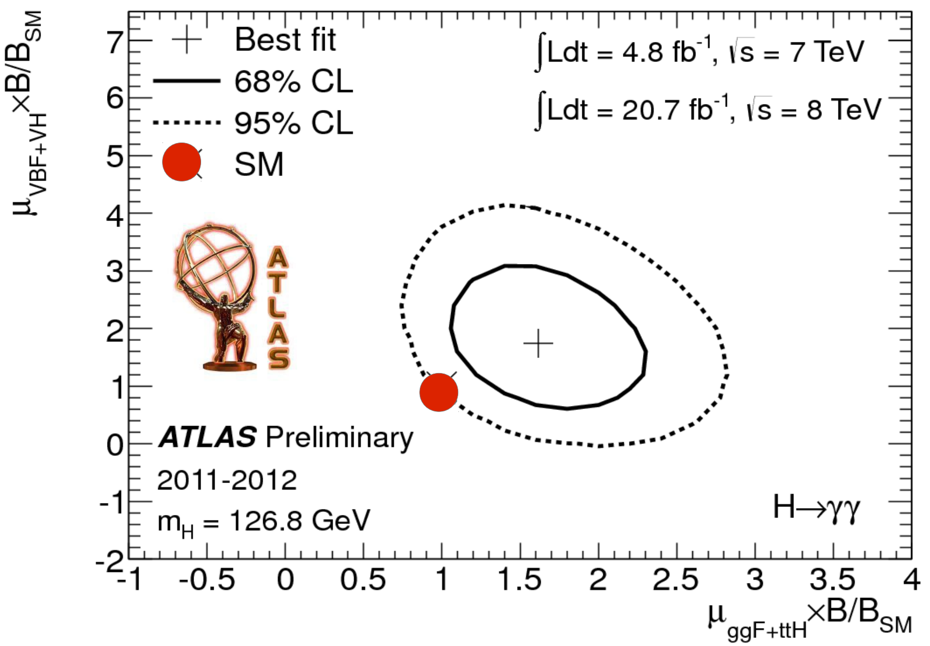


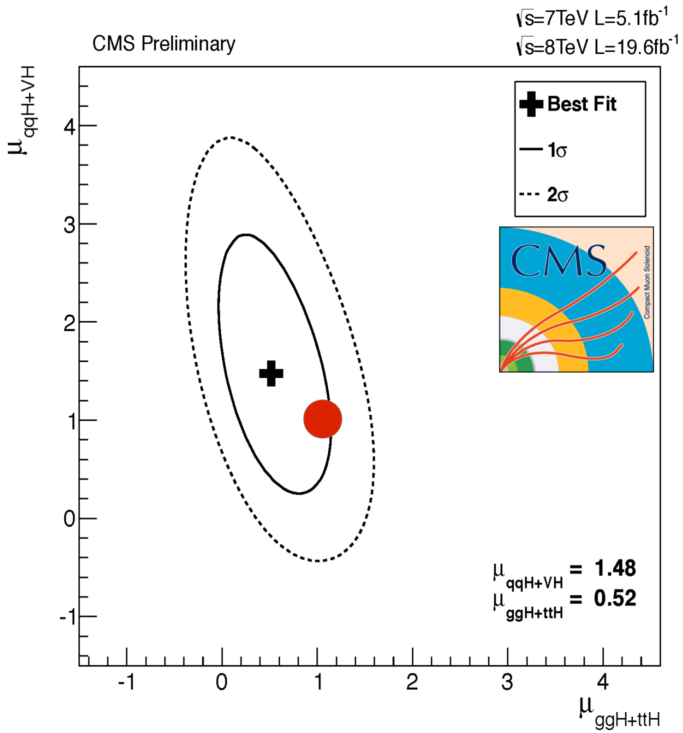
Couplings (RV, RF)

- Higgs production mechanisms can be associated with either top-quark or vector-boson couplings.
- Signal strength associated to each mechanism is determined with a simultaneous fit.

- $\mu_{ggF+ttH} = 1.6^{+0.3}_{-0.3}$ (stat) $^{+0.3}_{-0.2}$ (syst);
- $\mu_{VBF} = 1.7^{+0.8}_{-0.8}$ (stat) $^{+0.5}_{-0.4}$ (syst);
- $\mu_{VH} = 1.8^{+1.5}_{-1.3}$ (stat) $^{+0.3}_{-0.3}$ (syst).

- $\mu_{ggH+ttH} = 0.52$
- $\mu_{VBF+VH} = 1.48$

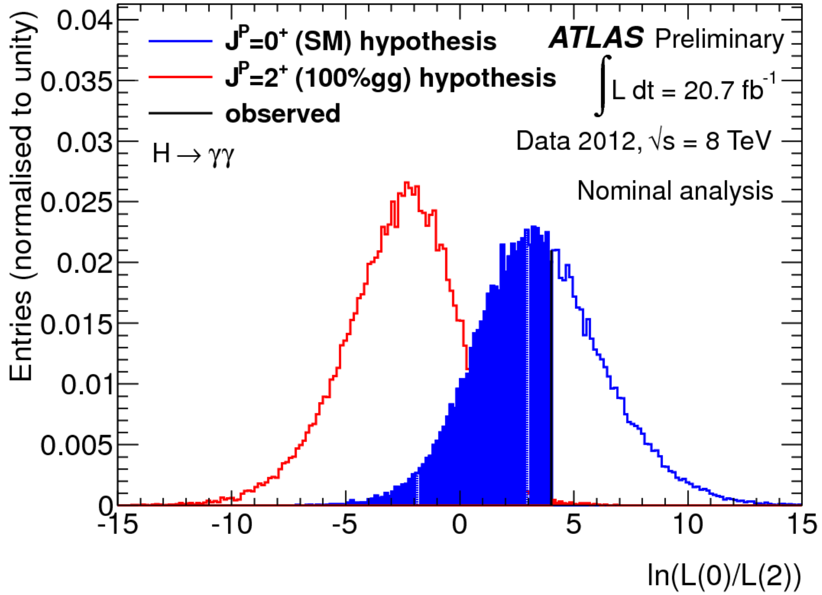


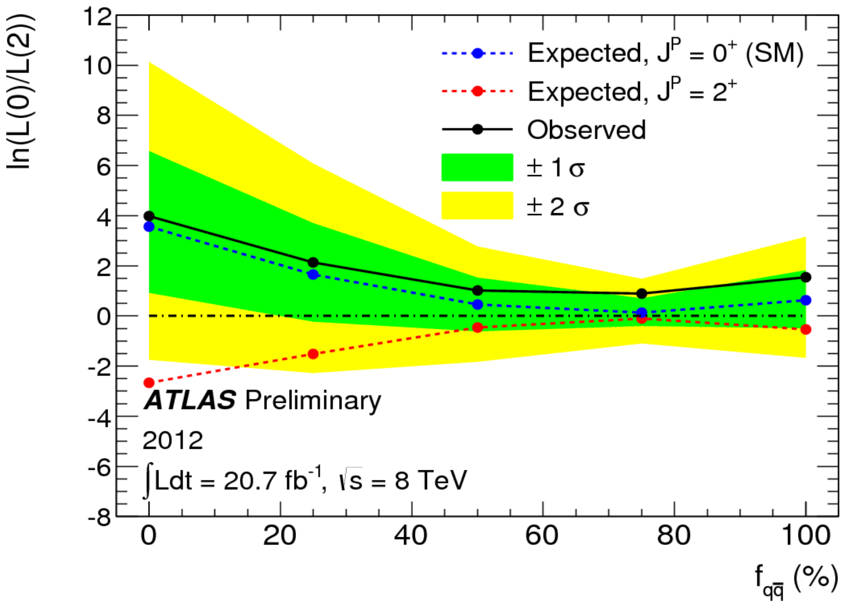


Spin Analysis (ATLAS)

- No event categorization is applied, $p_T/m_{\gamma\gamma}$ cut to avoid correlation with $\cos(\theta^*)$.
- Two methods to discriminate 0^+ from 2^+_m "graviton-like":
  - Statistical analysis using 2D model $|\cos(\theta^*)| \otimes m_{\gamma\gamma}$;
  - Independent fit to $m_{\gamma\gamma}$ in $|\cos(\theta^*)|$ bins.
- Data compatible with 0^+: considering 100% gluon fusion 2^+_m can be excluded at 99.3% C.L.:
  - Limit less stringent if 2^+_m produced also via $q\bar{q}$ annihilation.

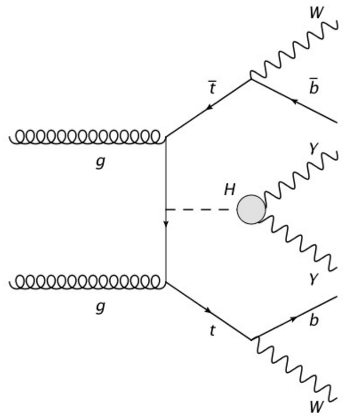
ATLAS-CONF-2013-029



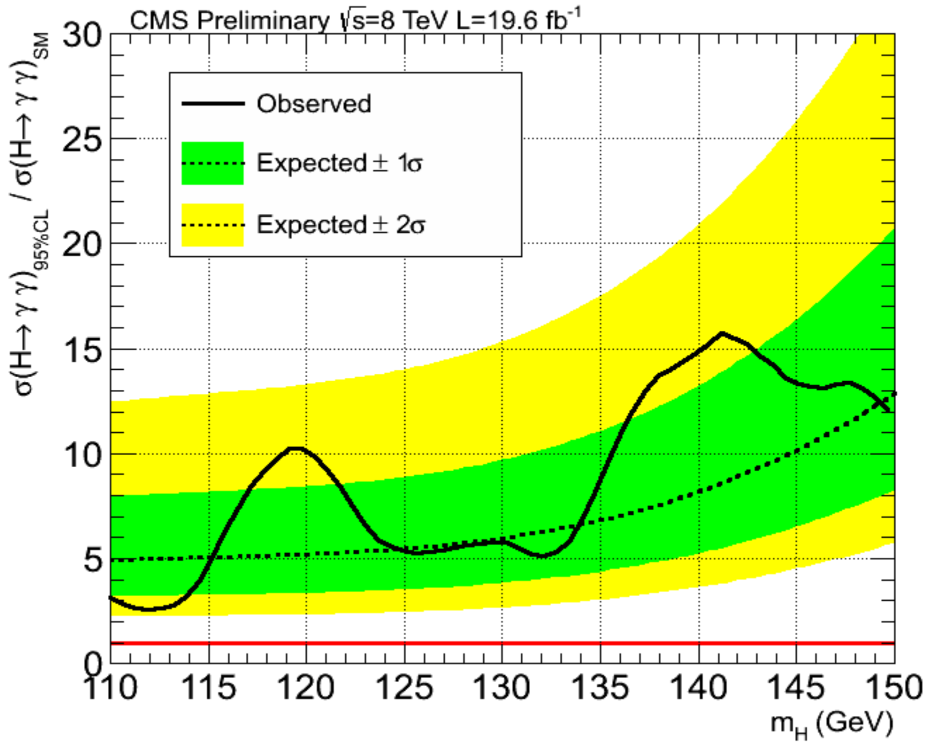


$t\bar{t}$H Exclusive Analysis (CMS)

- First search for $t\bar{t}$H production in $H \to \gamma\gamma$ events:
  - Very small signal yield;
  - Analyzed 19.6 fb^{-1} at 8 TeV.



- To maximize the sensitivity selection criteria optimized for leptonic and hadronic $t\bar{t}$ decays.
- Set observed (expected) 95% C.L. limit on $t\bar{t}$H σ x BR of 5.4 (5.3) corresponding to 1.6 fb for a Higgs boson mass of 125 GeV:
  - Consistent with SM expectation.



CMS-PAS-HIG-13-015

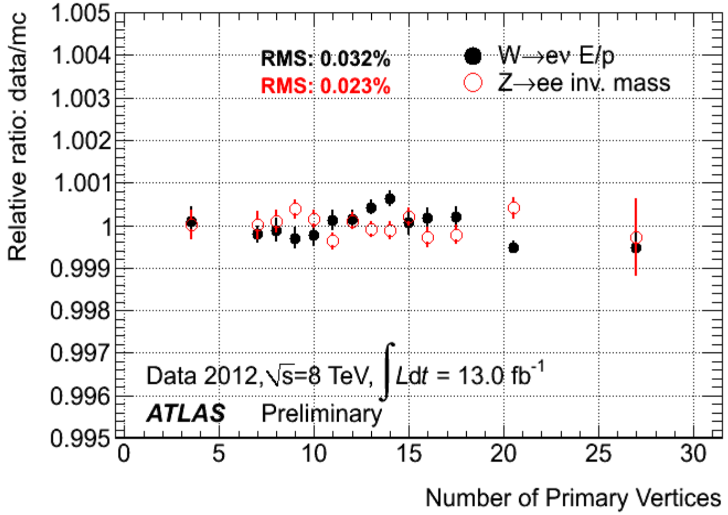
Conclusions

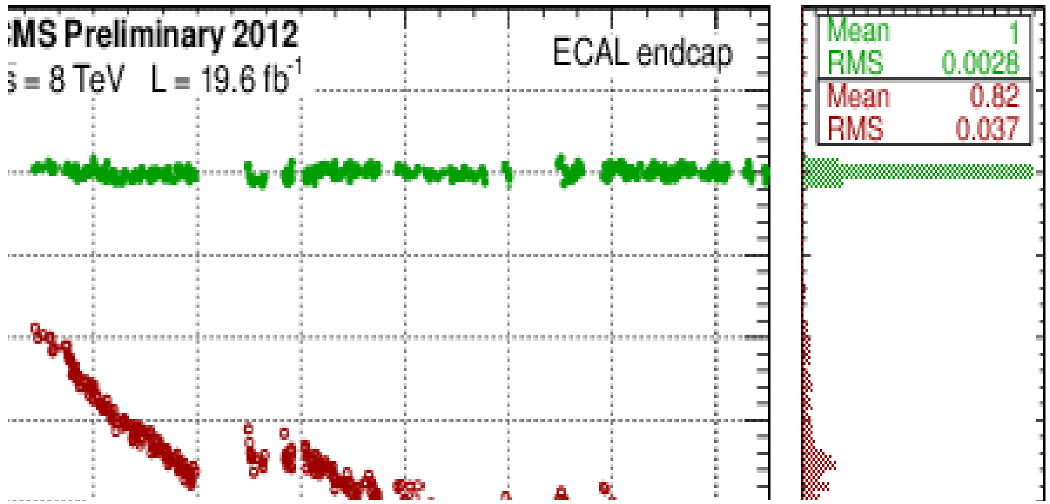
- The results of the $H \to \gamma\gamma$ analysis with both ATLAS and CMS detectors have been presented:
  - The entire 2011+2012 datasets corresponding to ~**25 fb^{-1}** have been analyzed.
- The two experiments show a very similar expected significance:
  - **ATLAS observed σ/σ_{SM}: $1.65^{+0.24}_{-0.24}$(stat)$^{+0.25}_{-0.18}$(syst);**
  - **CMS observed σ/σ_{SM}: $0.78^{+0.24}_{-0.24}$(stat)$^{+0.25}_{-0.18}$(syst).**
- Both ATLAS and CMS have measured the mass of the new boson with high precision (< 1 GeV).
- Measurement of exclusive coupling: an excess with local significance of 2σ is observed by ATLAS for the VBF production mode alone for a mass of 126.8 GeV.
- Spin analysis: ATLAS **disfavour** spin 2^+_m at 99.3% C.L. for 100% gluon fusion production.

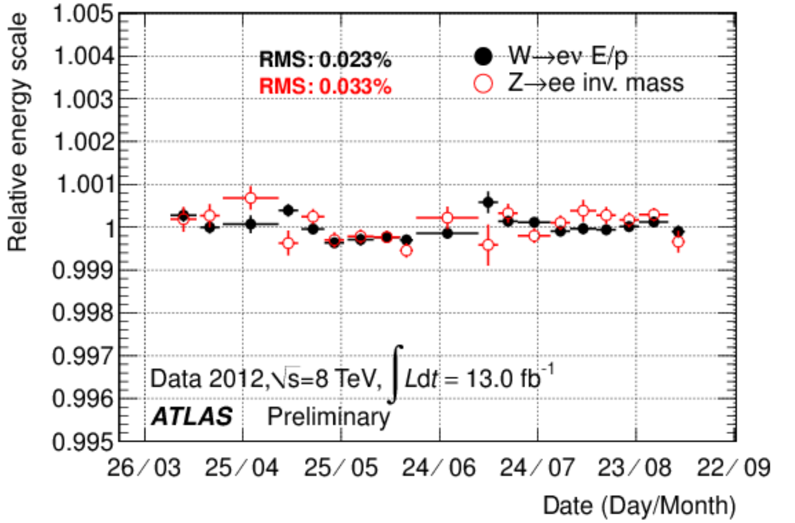
BACK UP

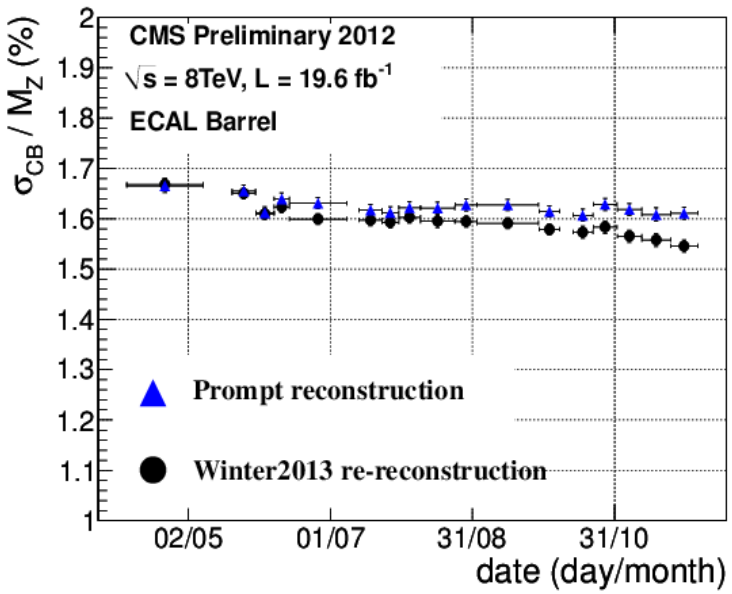
ECAL Performance

CMS transparency corrections.









High stability ~0.1% vs time and PU conditions.

Signal Yields

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

$\sqrt{s}$	8 TeV						
Category	N_D	N_S	$gg \to H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
Unconv. central, low p_{Tt}	10900	51.8	93.7	4.0	1.4	0.8	0.2
Unconv. central, high p_{Tt}	553	7.9	79.3	12.6	4.1	2.5	1.4
Unconv. rest, low p_{Tt}	41236	107.9	93.2	4.0	1.6	1.0	0.1
Unconv. rest, high p_{Tt}	2558	16.0	78.1	13.3	4.7	2.8	1.1
Conv. central, low p_{Tt}	7109	33.1	93.6	4.0	1.3	0.9	0.2
Conv. central, high p_{Tt}	363	5.1	78.9	12.6	4.3	2.7	1.5
Conv. rest, low p_{Tt}	38156	97.8	93.2	4.1	1.6	1.0	0.1
Conv. rest, high p_{Tt}	2360	14.4	77.7	13.0	5.2	3.0	1.1
Conv. transition	14864	40.1	90.7	5.5	2.2	1.3	0.2
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
All categories (inclusive)	118893	395.0	88.0	7.3	2.7	1.5	0.5

Systematics

Systematic uncertainties	Value(%)	Constraint
Luminosity	±3.6	
Trigger	±0.5	
Photon Identification	±2.4	Log-normal
Isolation	±1.0	
Photon Energy Scale	±0.25	
Branching ratio	±5.9% – ±2.1% (m_H = 110 - 150 GeV)	Asymmetric Log-normal
Scale	ggF: $^{+7.2}_{-7.8}$ VBF: $^{+0.2}_{-0.2}$ WH: $^{+0.2}_{-0.6}$ ZH: $^{+1.6}_{-1.5}$ ttH: $^{+3.8}_{-9.3}$	Asymmetric Log-normal
PDF+α_s	ggF: $^{+7.5}_{-6.9}$ VBF: $^{+2.6}_{-2.7}$ WH: ±3.5 ZH: ±3.6 ttH: ±7.8	Asymmetric Log-normal
Theory cross section on ggF	Tight high-mass two-jet: ±48	Log-normal
	Loose high-mass two-jet: ±28	
	Low-mass two-jet: ±30	

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.23%, 0.72%	0.93%, 0.36%
	$R_9 < 0.94$ (low η, high η)	0.25%, 0.60%	0.33%, 0.54%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.20%, 0.71%	0.88%, 0.12%
	$R_9 < 0.94$ (low η, high η)	0.20%, 0.51%	0.18%, 0.12%
Photon identification efficiency		1.0%	2.6%
Cut-based			
R_9> 0.94 efficiency (results in class migration)		4.0%	6.5%
MVA analyses			
Photon identification BDT		±0.01 (shape shift)	
	(Effect of up to 4.3% event class migration.)		
Photon energy resolution BDT		±10% (shape scaling)	
	(Effect of up to 8.1% event class migration.)		
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency		1.0%	
Global energy scale		0.47%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	30%	
	(Effect of up to 15% event migration among dijet classes.)		
Muon selection			
Muon identification efficiency		1.0%	
Electron selection			
Electron identification efficiency		1.0%	
E_T^{miss} selection			
E_T^{miss} cut efficiency	Gluon-gluon fusion	15%	
	Vector boson fusion	15%	
	Associated production with W/Z	4%	
	Associated production with $t\bar{t}$	4%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+7.6% -8.2%	+7.6% -7.0%
Vector boson fusion		+0.3% -0.8%	+2.6% -2.8%
Associated production with W/Z		+2.1% -1.8%	4.2%
Associated production with $t\bar{t}$		+4.1% -9.4%	8.0%

Fiducial Cross Section (ATLAS)

- Measurement of the production cross section of the new particle (M_H=126.8):
  - Luminosity 20.7 fb^{-1};
  - No categories to be more model independent;
  - Fiducial region: isolated photons in $|\eta|<2.37$ and with $E_T>40,30$ GeV.
- Cross section estimated as:

$$\sigma_{\text{fid}} \times \text{BR} = \frac{N^{\text{signal}}}{C_H \times L_{\text{int}}}$$

N^{signal} = number of signal events extracted from a fit to $m_{\gamma\gamma}$

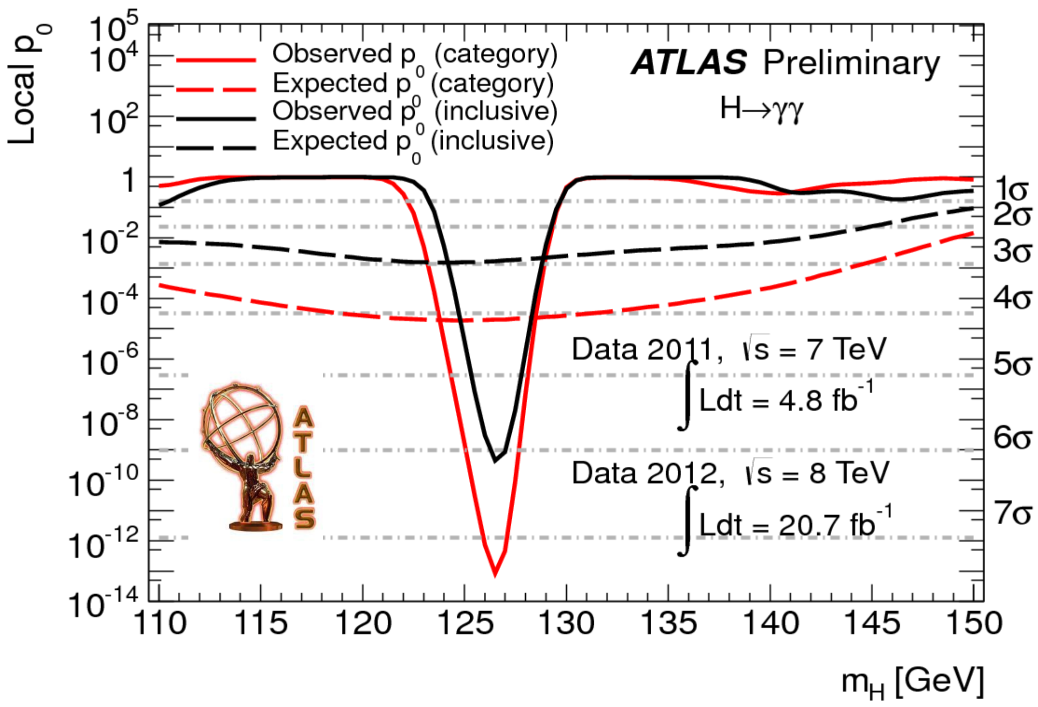
C_H = correction factor for detector effects;

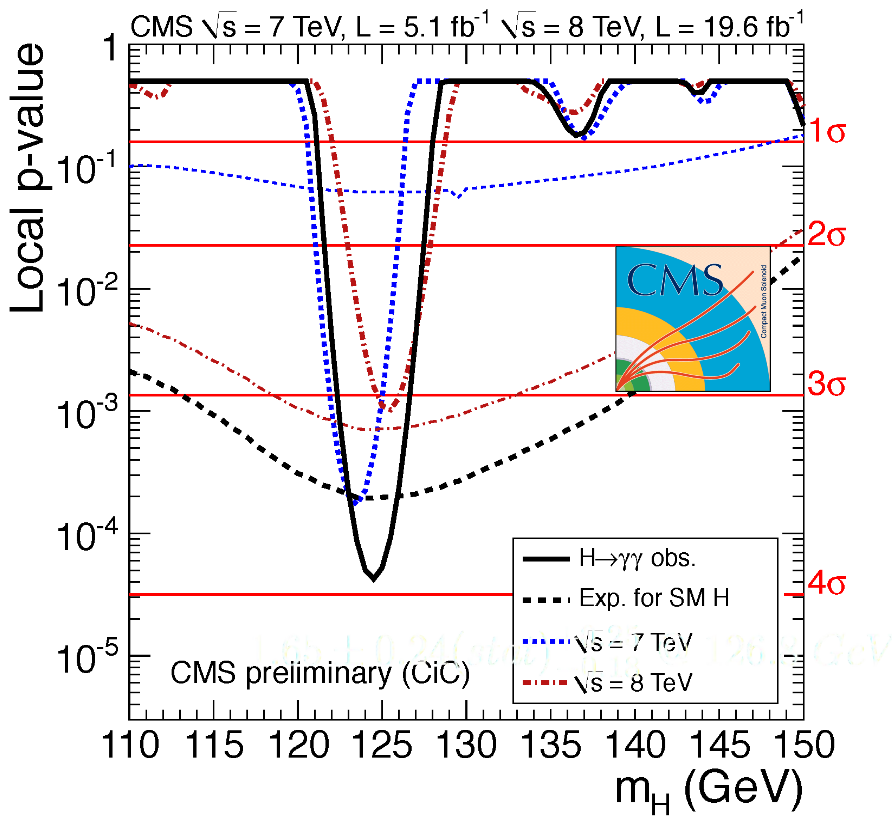
L_{int} = integrated luminosity

- σ_{fid} x BR = 56.2 ± 10.5 (stat) ± 6.5 (syst) ± 2.0 (lumi) fb.

Results (CMS Cut-based)

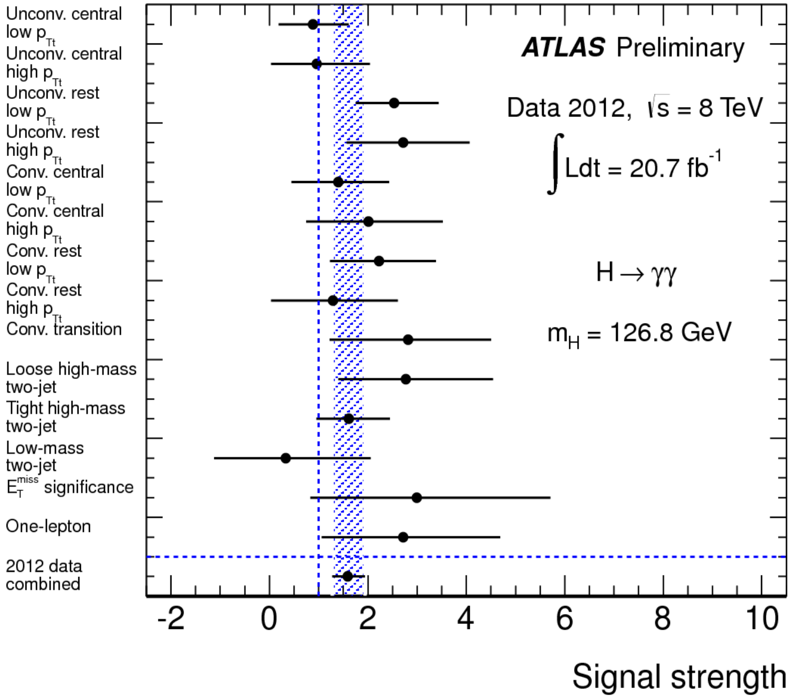
- Comparable expected significance between ATLAS and CMS MVA analysis.

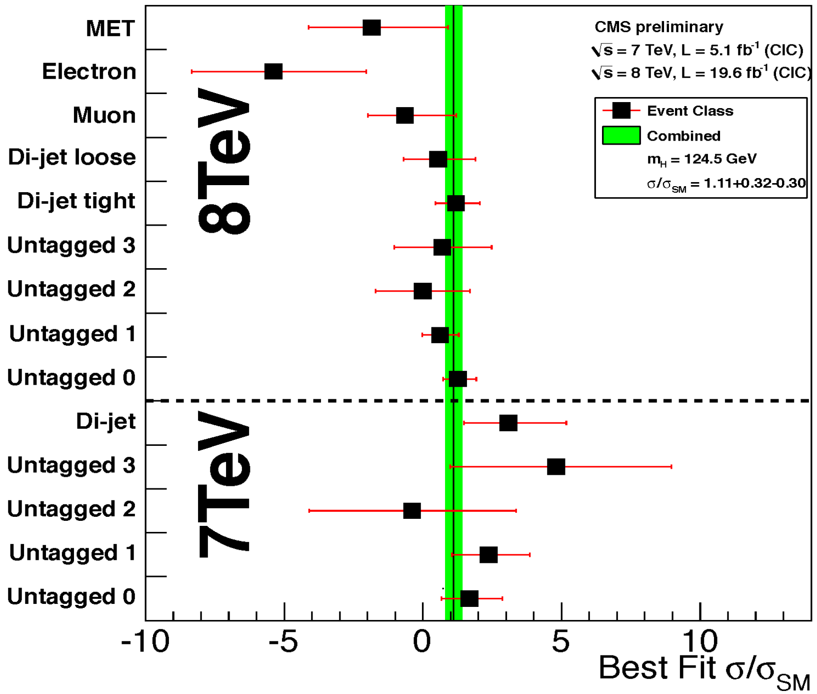




√s = 7+8 TeV	Exp.	Obs.
ATLAS	4.1	7.4
CMS Cut-based	3.5	3.9

Signal Strength (Cut-based)





$\sqrt{s}$ = 7+8 TeV	$\mu = \sigma/\sigma_{SM}$
ATLAS	**$1.65^{+0.35}_{-0.30}$ @ 126.8 GeV**
CMS Cut-based	**$1.11^{+0.32}_{-0.30}$ @ 124.5 GeV**

MVA vs Cut-based (CMS)

- Low signal to background ratio a fundamental feature of $H \rightarrow \gamma\gamma$ channel.
- Uncertainty on signal strength driven by statistical fluctuation of the background, and analysis changes can lead to statistical changes due to fluctuations of which events are selected, and their fluctuations of their mass (recalibration etc..).
- Correlation coefficient between MVA and cut-based signal strength is found to be r=0.76 (estimated with jackknife technique).
- Taking account the correlation the compatibility between the two analysis measurements of signal streng
and 1.8σ
(8

	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	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$