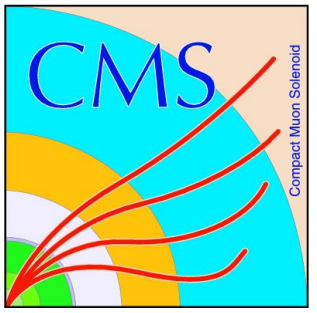
Higgs to di-photons in ATLAS and CMS



SM@LHC Workshop
Freiburg, April 9 2013

Sandro De Cecco

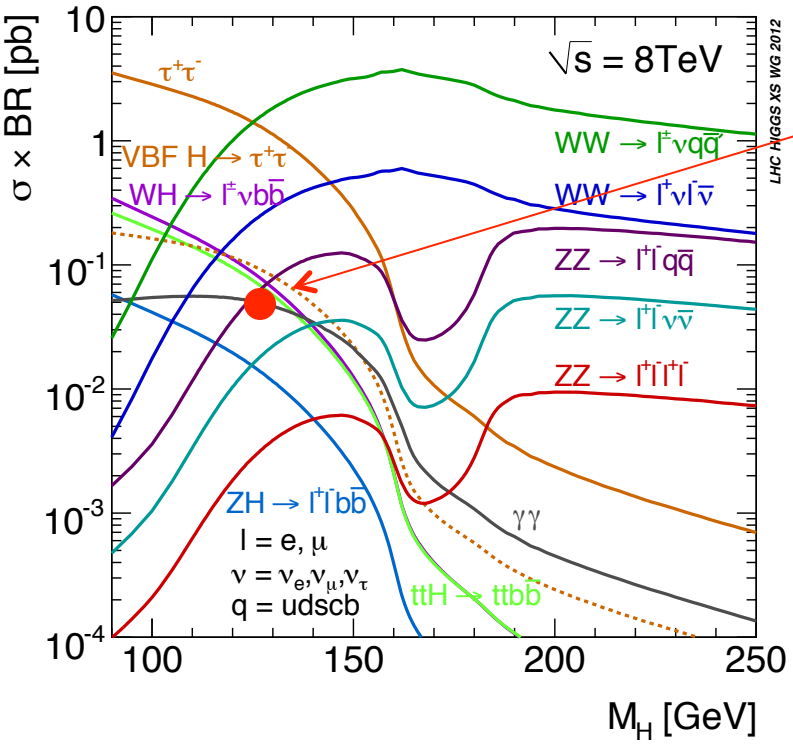
on behalf of ATLAS and CMS collaborations

LPNHE IN2P3/CNRS - Université de Paris Diderot & UPMC
Laboratoire de Physique Nucleaire et des Hautes Energies

Outline

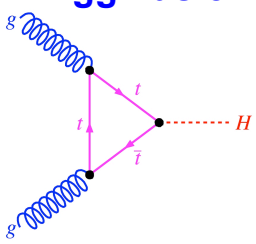
- Introduction:
  - The H → γγ channel at the LHC
- H → γγ analysis updates for winter 2013 with full 2011+2012 data:
  - The **CMS** analysis: "*Updated measurements of the Higgs-like boson at 125 GeV in the two photon decay channel*" (**CMS PAS HIG-13-001**, 21 march 2013)
  - The **ATLAS** analysis: "*Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb−1 of proton-proton collision data*" (**ATLAS-CONF-2013-012**, 5 march 2013)
  - The **ATLAS** spin measurement "*Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7 fb-1 of pp collisions collected at sqrt(s) = 8 TeV with the ATLAS detector*" (**ATLAS-CONF-2013-029**, 10 march 2013)
- ATLAS and CMS results of measurements on Higgs to di-photon channel.
- Summary

The H → γγ channel @ LHC



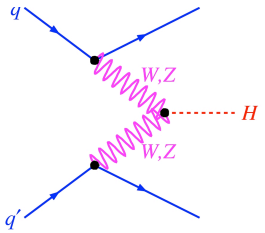
@ mH = 125 GeV, σ x BR = 0.05 pb

gg Fusion



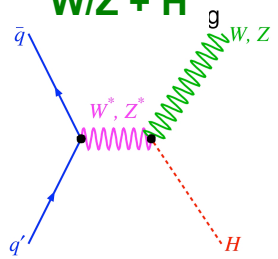
19.5 pb (87%)

Vector Boson Fusion



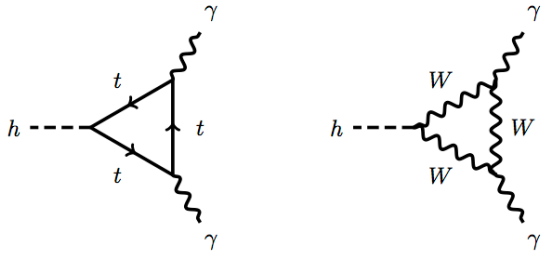
1.6 pb (7%)

W/Z + H



1.1 pb (5%)

H → γγ decay proceeds through W and top loops:



Discovery mode at LHC:

- simple analysis: $m_{\gamma\gamma}$ peak over smooth background
- excellent detector resolution and calibration are needed (EMCAL)
- → precise H mass measurement

sensitive to Vector Bosons and top coupling in both production and decay.

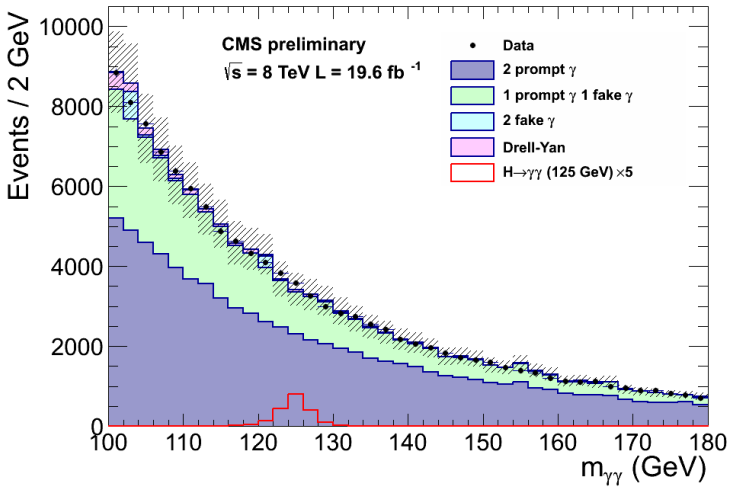
H → γγ analysis updates overview

- H → γγ analysis updates from CMS and ATLAS for winter 2013
  - The **CMS** analysis:
    - Use the full 2012, 8 TeV dataset 19.6 fb^{-1} (last public result with 5.3 fb^{-1}) + 5.1 fb-1of 2011, 7 TeV data
    - Improved energy calibration
    - Performed two analysis in parallel:
      - MVA analysis, baseline (~15% more sensitivity)
      - Cut based approach
    - Improved categorization: New 2 MVA di-jet cats for VBF
  - The **ATLAS** analysis:
    - Use of the full 2012, 8 TeV dataset 20.7 fb^{-1} (last public result with 13 fb^{-1}) + 4.8 fb^{-1} of 2011, 7 TeV data
    - Improved categorization:
      - New E_T^{miss} cat for VH
      - New 2 MVA di-jet cats for VBF

CMS: γγ selection and categories

Pre-selection:

- Photons p_T cuts scaled with $m_{\gamma\gamma}$ ($>m_{\gamma\gamma}/3$; $m_{\gamma\gamma}/4$)
- MVA: single γ ID: BDT for γ/jet discrimination (trained on γ+jet events, inputs: shower shapes and particle flow isolation)
- CiC: cut based single γ identification
- Higgs production vertex selected with BDT (inputs: Σp_T^2 tracks, vtx recoil, conv γ pointing)
- Choose the highest ΣE_T di-photon pair



- irreducible background is 72% of selected γγ pairs (in 100-150 GeV)
- background estimated from SB (not from MC)

Categorization:

Tagged categories, exclusive processes enriched:

VH | VBF/VH | VH

Muon | Electron | Dijet | MET | Untagged

e/μ: p_T > 20 GeV *(not in 7 TeV)*

di-jet BDT 2 cat.: (loose, tight) with VBF purity: 50%,80% *(in 7 TeV: one cutbased di-jet cat)*

MET > 70 GeV *(not in 7 TeV)*

4 untagged categories (0,1,2,3):

- **MVA**: baseline analysis (~15% better expected sensitivity)

- **Cut-in-Categories**: cut based

CMS: untagged categorization

MVA categorisation

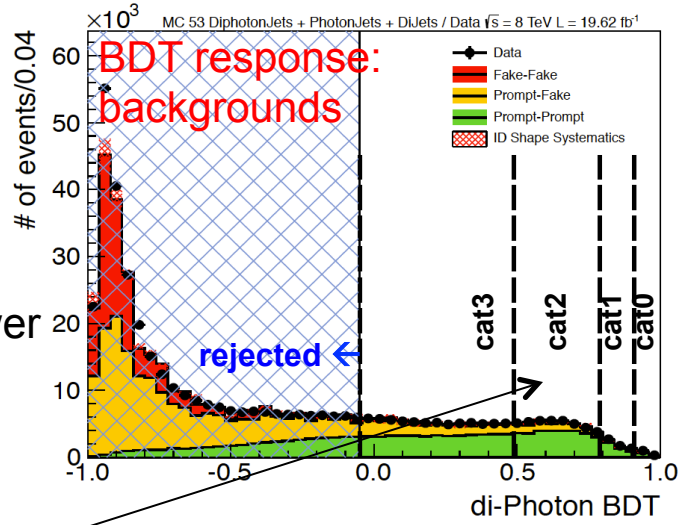
di-γ discriminant: BDT trained on signal MC and background, inputs:

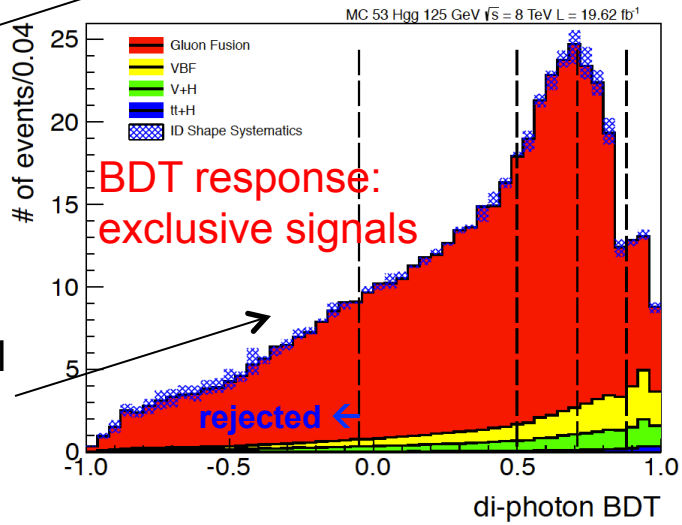
- γγ kinematics
- γ ID MVA score (shower shapes, isolation)
- γγ mass resolution
- validation of inputs on Z→ee and Z→μμγ

→ Define 4 categories (for BDT>-0.05)

- Validation on Z→ee

- different S/B and signal compositions (ggH *vs* VBF, VH, ttH)



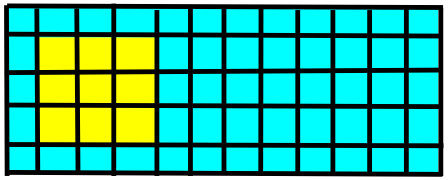


Cut in Categories

- Cut based γ ID, data/MC scale factors from Z→ee and Z→μμγ

- Define 4 categories:
  - Barrel / end-caps
  - converted / unconv. using R_9

$$R_9 = E_{3\times3}/E_{SC}$$

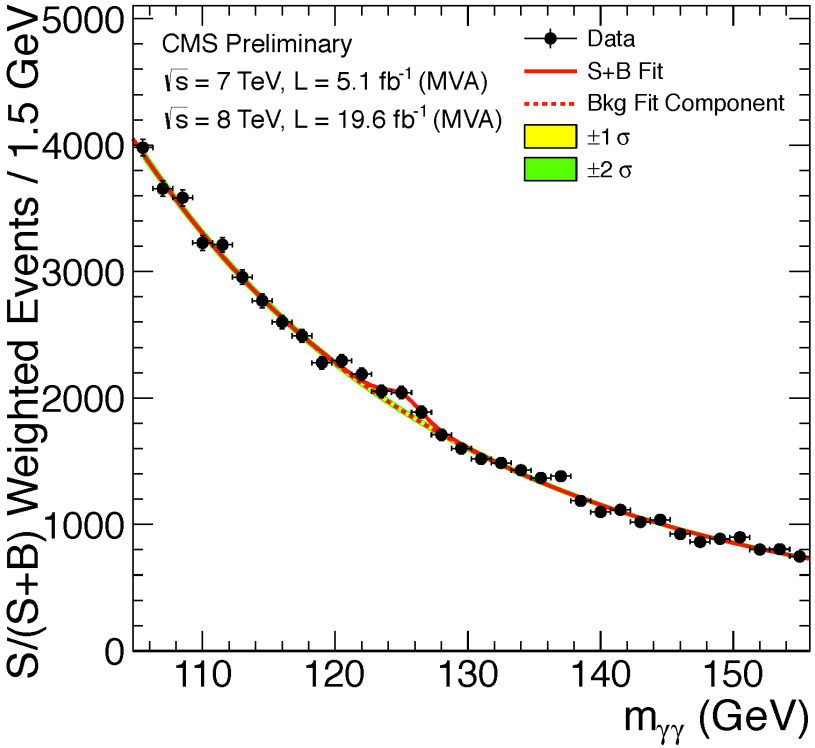


- different mass resolution among categories by construction

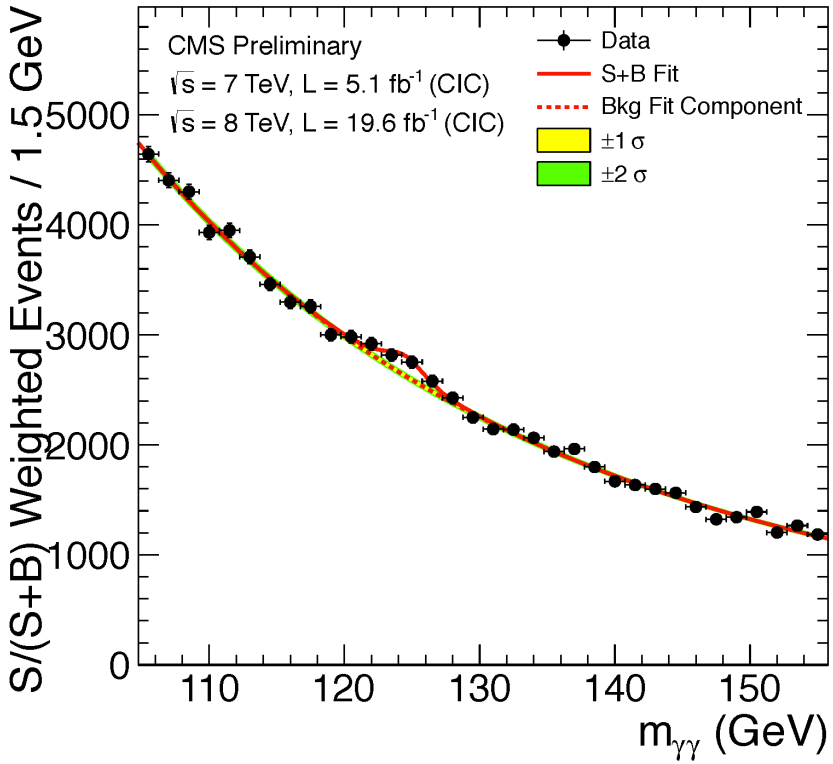
- different S/B

CMS: γγ combined mass plots 7+8 TeV

MVA categorisation



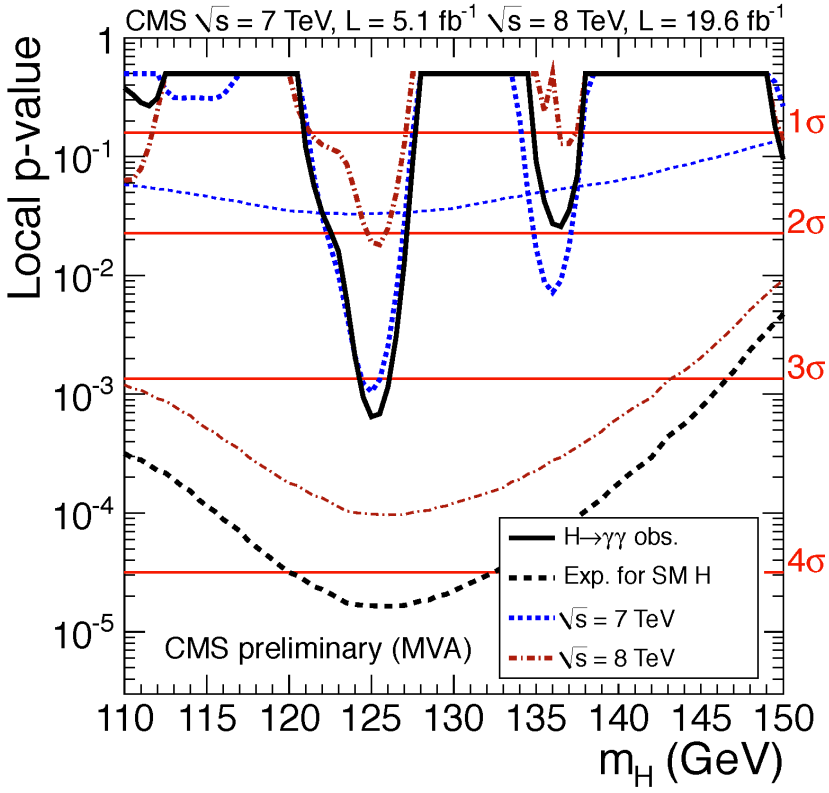
Cut in Categories



- Events are weighted with their corresponding category S/(S+B) for visualization
- Background modeling: fit to data with 3rd to 5th order polynomials (bias<0.2 x stat unc.)

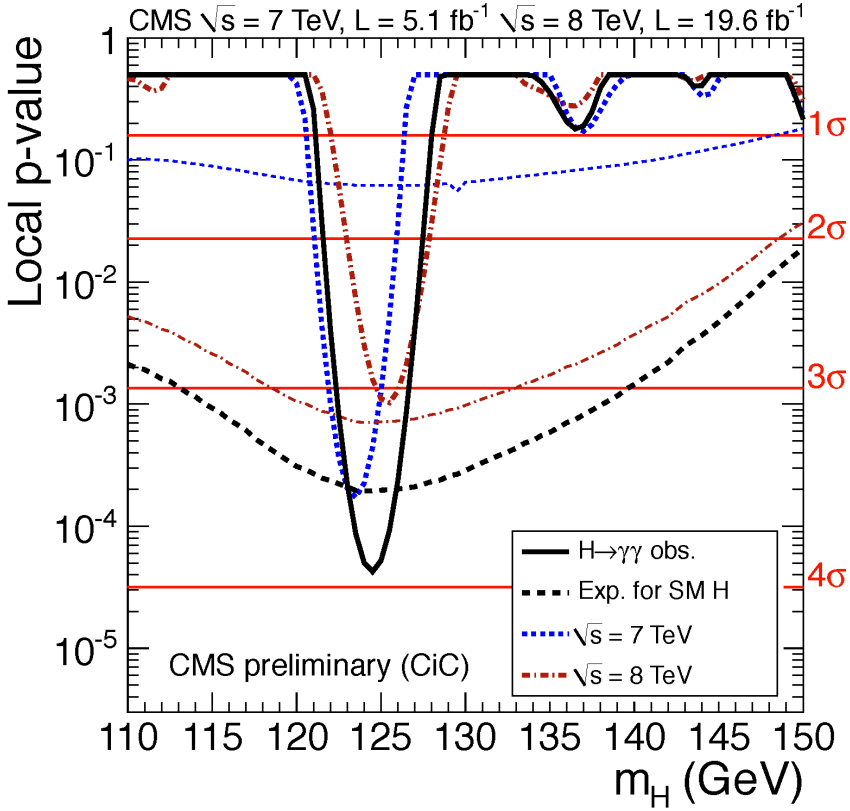
CMS H → γγ analysis: p-values

MVA categorisation



Significance at 125 GeV: 3.2σ (4.2 exp.)

Cut in Categories



Significance at 124.5 GeV: 3.9σ (3.5 exp.)

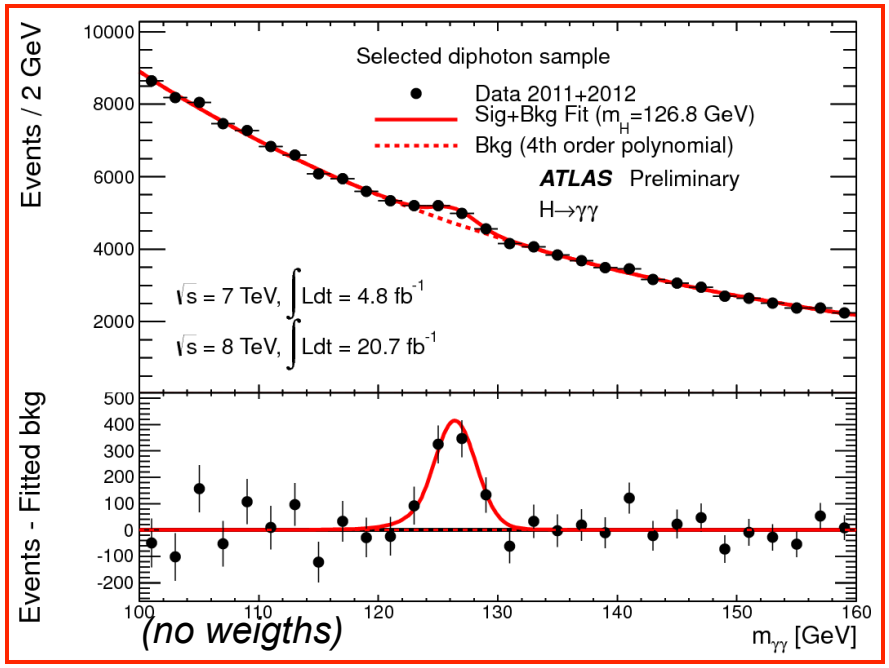
Comparing to published result significance decreased, two effects contributing: re-analysis of 8 TeV data and addition of new data.

ATLAS H → γγ : full 2011+2012 dataset

- Two high E_T (> 40, 30 GeV) isolated photons
  - 142681 events in $100<m_{\gamma\gamma}(\text{GeV})<160$
  - S/B ~ 3% around 125 GeV (in mass window containing 90% signal)

Photon Identification:

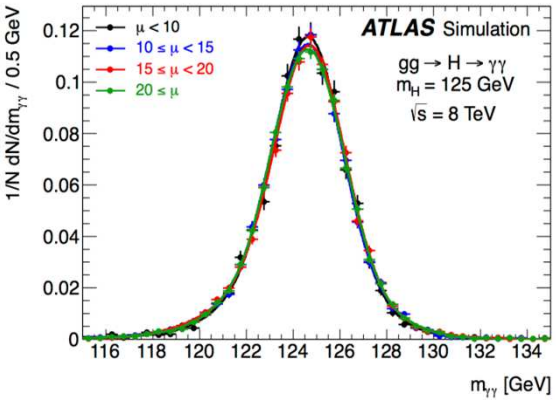
- NN ID for 7 TeV, cut based for 8 TeV. Input are shower shapes.
- Calo + track Isolation requirement stable wrt pile-up.
- Background composition is: 75% γγ irreducible and 25% reducible γ-j+j-j (for 8TeV)



Invariant mass resolution:

- calorimeter pointing (longitudinal segmentation of Atlas Lar ECAL)
- PV reco track based
- good mass resolution overall ~ 1.7 GeV (stable wrt pile-up)

Mass resolution is pile-up robust



Background level estimate: from data sidebands fits.
Photon energy scale & ID efficiencies: from Z→ ee, llγ data & MC

ATLAS H → γγ analysis: categorisation

ATLAS Preliminary

H → γγ

di-photon selection

$p_T(e)>15$ GeV
$p_T(\mu)>10$ GeV

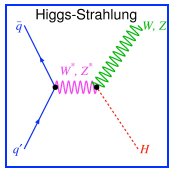
One-lepton
W(→ lν)H, Z(→ ll)H

E_T^{miss} significance
W(→ lν)H, Z(→ νν)H

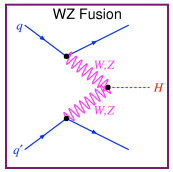
Low-mass two-jet
W(→ jj)H, Z(→ jj)H

High-mass two-jet
VBF

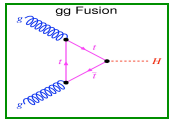
9 p_{Tt}-η-conversion
ggF



VH enriched



VBF enriched



ggF enriched

usual pTt-η-conv categories
same as in published analysis

tight

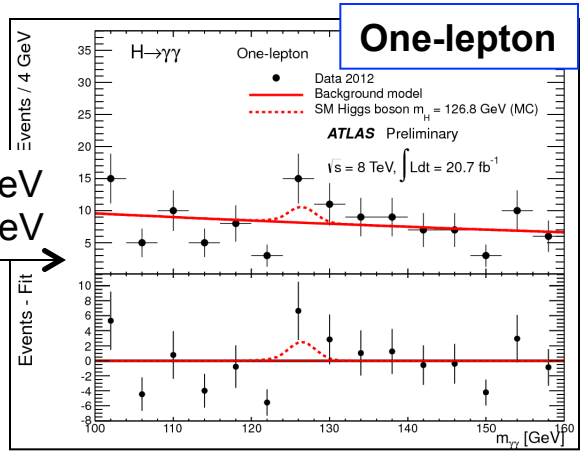
loose

New

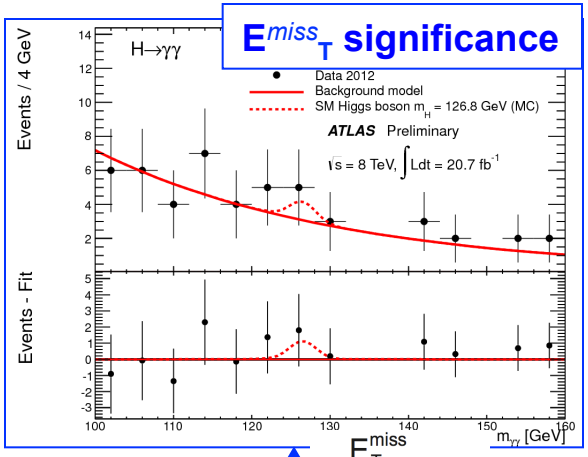
γγ+2jets **MVA VBF** discriminant BDT:
- define 2 cats: loose-tight

New

One-lepton

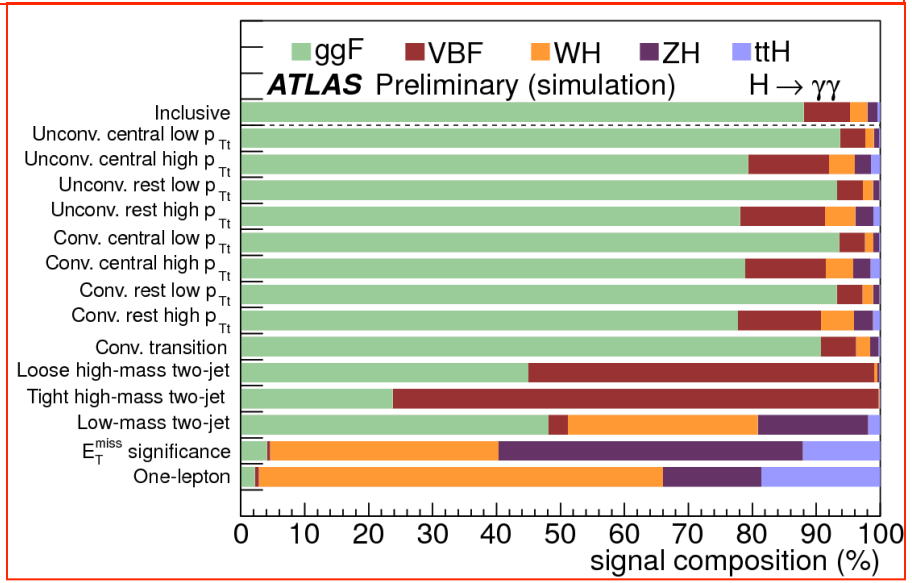


E^{miss}_T significance

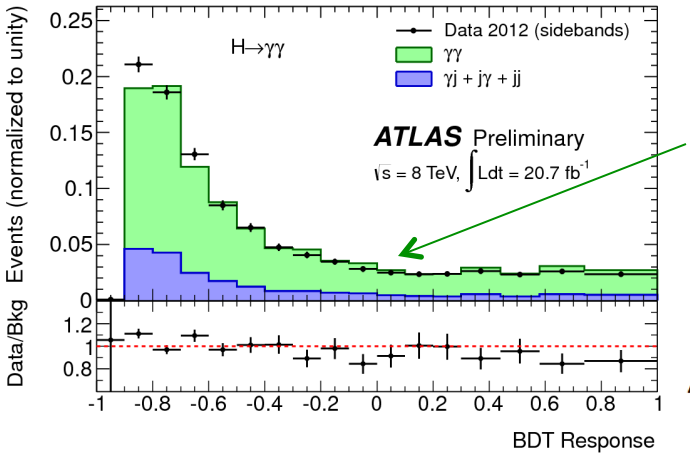


$$\frac{E_T^{miss}}{0.67\times\Sigma E_T} > 5$$

→ Total 14 categories with different mass resolution, S/B and signal composition:



ATLAS H → γγ analysis: VBF categories



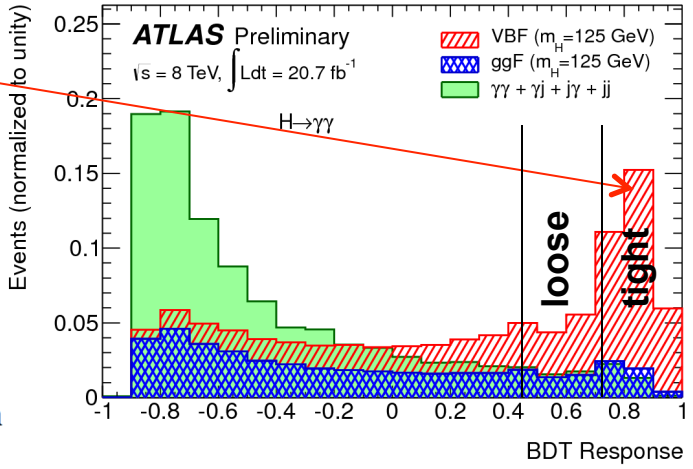
BDT trained on **VBF signal MC** against **backgrounds**: irreducible γγ MC (Sherpa) and red. γj+jj from data non isolated γγ sample.

- Input variables: (mass factorized)

m_{jj} $\Delta\eta_{jj}$ η_{j1} η_{j2} p_{Tt}

$\Delta\phi_{\gamma\gamma;jj}$ $\eta^* = \eta_{\gamma\gamma} - \frac{\eta_{j1}+\eta_{j2}}{2}$ $\Delta R^{\gamma j}_{\mathrm{min}}$

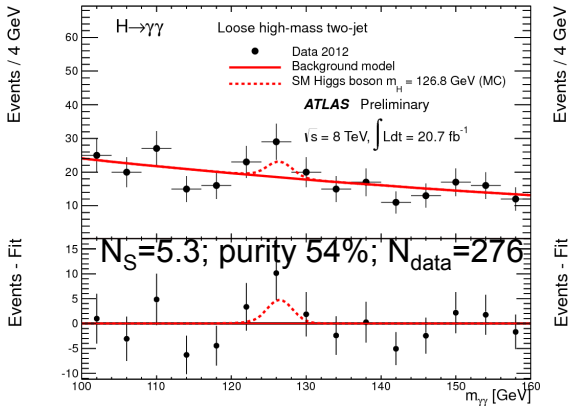
(ggH+jets leakage main systematic)



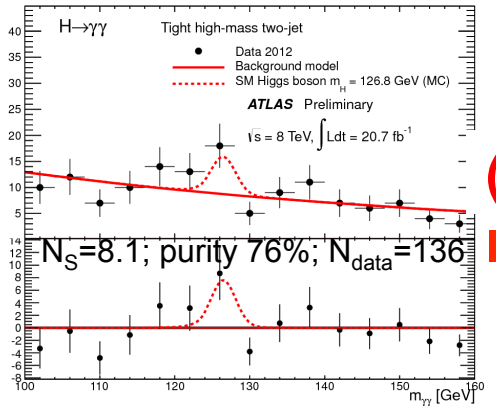
define 2 VBF enriched categories (loose & tight) optimized for μ_{VBF} measurement:

- VBF purities: 54%-76% *(was 68% in published single cutbased dijet tag)*

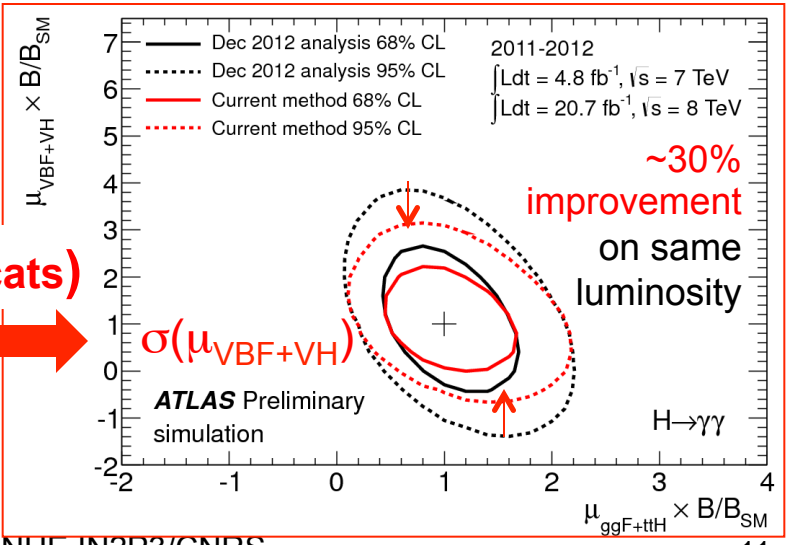
loose BDT high mass di-jet



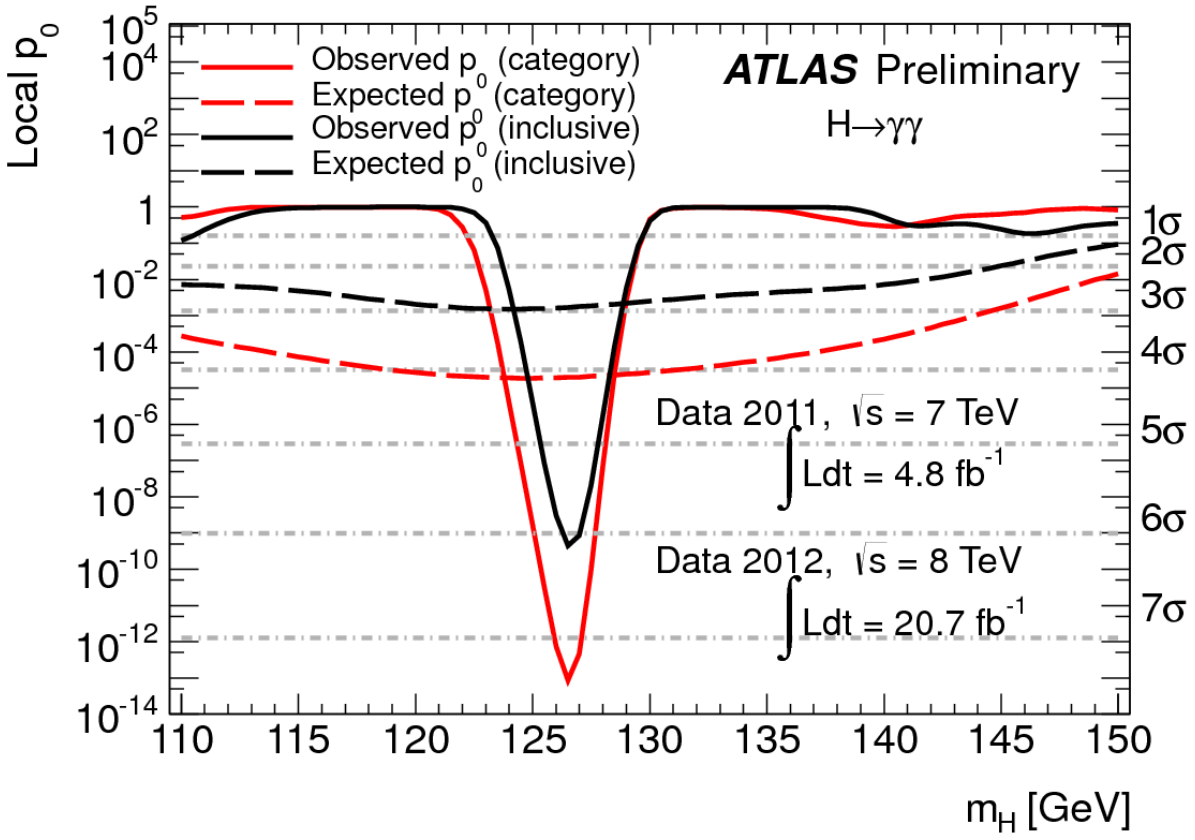
tight BDT high mass di-jet



(+ VH cats)



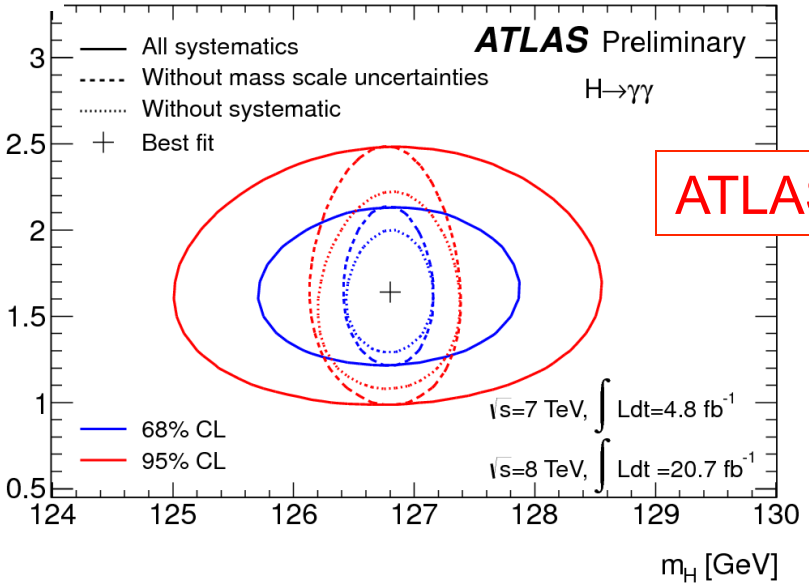
ATLAS H → γγ analysis: excess p-value

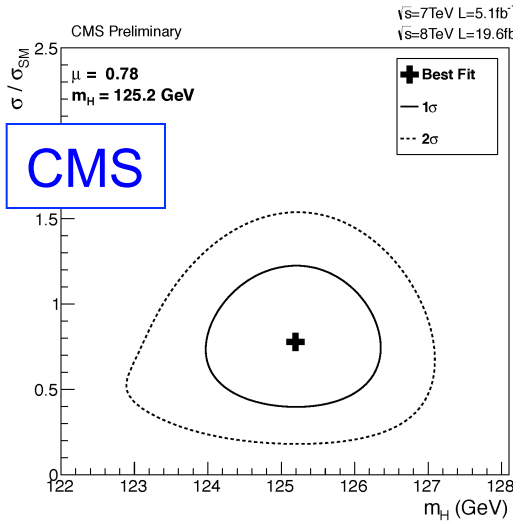


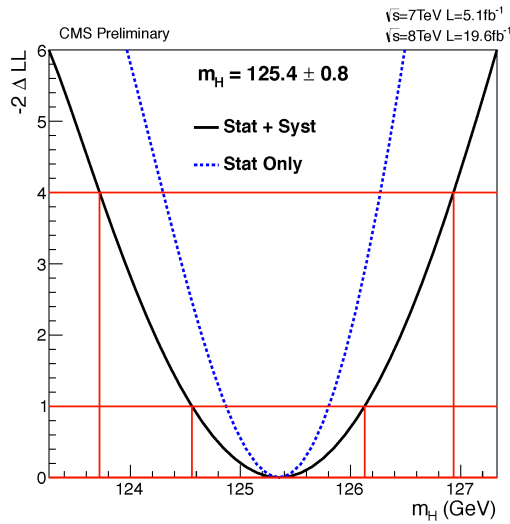
Maximum significance is reached at 126.5 GeV:

- **7.4σ** (4.1 expected) with **14 categories combined**
- **6.1σ** (2.9 expected) **inclusive** γγ sample (no categorization)

$H \rightarrow \gamma\gamma$ results: mass and signal strength







- Mass best fit: **m_H = 126.8 ± 0.2(stat) ± 0.7(syst) GeV**
  - photon energy scale dominant systematic 0.55% total:
    - extrapolated from Z→ee: 0.3%
    - modeling of material: 0.3%
    - Additional uncertainties: 0.32%

- **Signal strength μ = 1.65 ± 0.24 (stat) $^{+0.25}_{-0.18}$ (syst)**
  - consistent across categories
  - 2.3σ from SM Higgs + background hypothesis

- **$\sigma_{fiducial}$ x BR = 56.2 ± 12.5 fb**
  - acceptance cuts: $|\eta|$< 2.37 $p_T\gamma$ > 40/30 GeV
  - inclusive $\gamma\gamma$ (no categories)

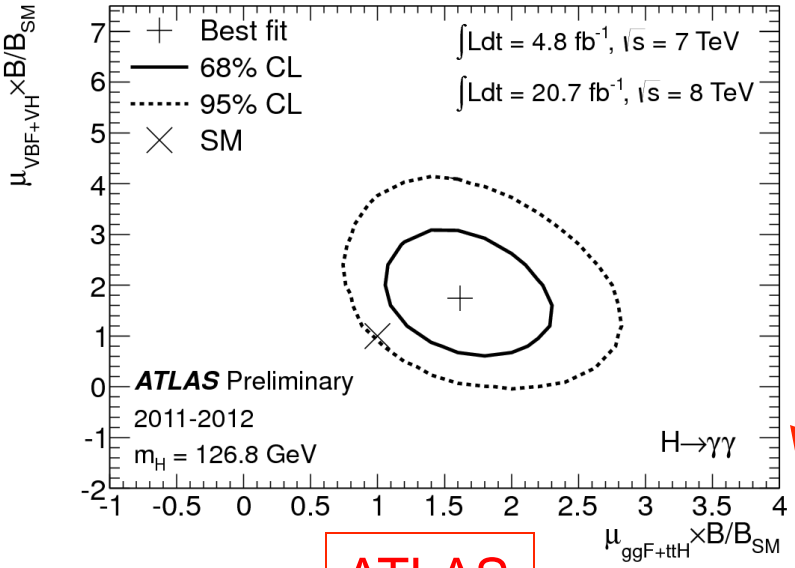
Mass: m_H = 125.4 ± 0.5 (stat) ± 0.6 (syst)

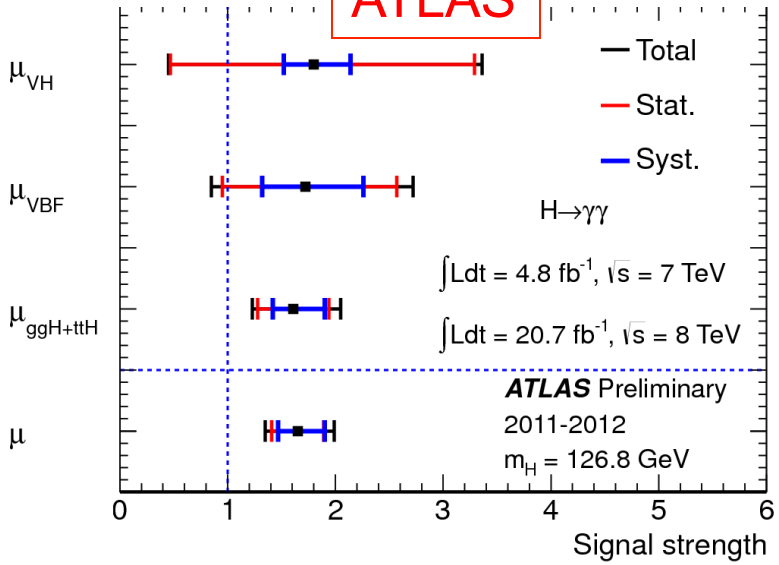
Dominant systematic photon energy scale uncertainty: 0.47%

Signal strength μ :

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

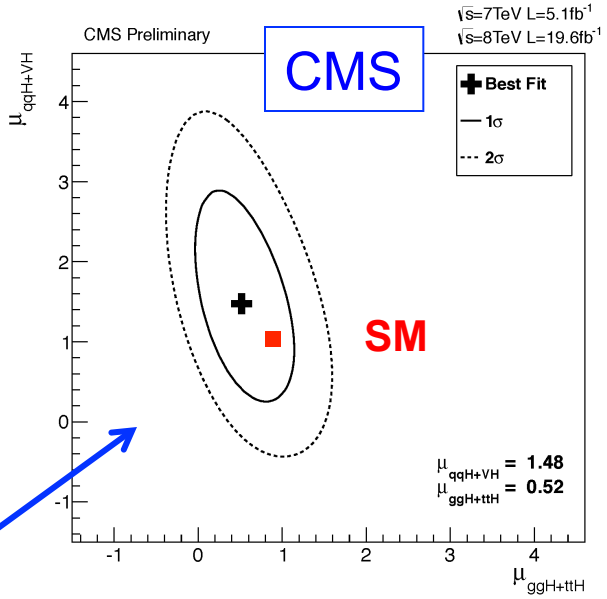
$H \to \gamma\gamma$ results: coupling studies





Production processes associated to coupling to:

- top (ggH, ttH)
- Vector boson (VBF, VH)



CMS:

$\mu_{qqH+VH} = 1.48$

$\mu_{ggH+ttH} = 0.52$

ATLAS:

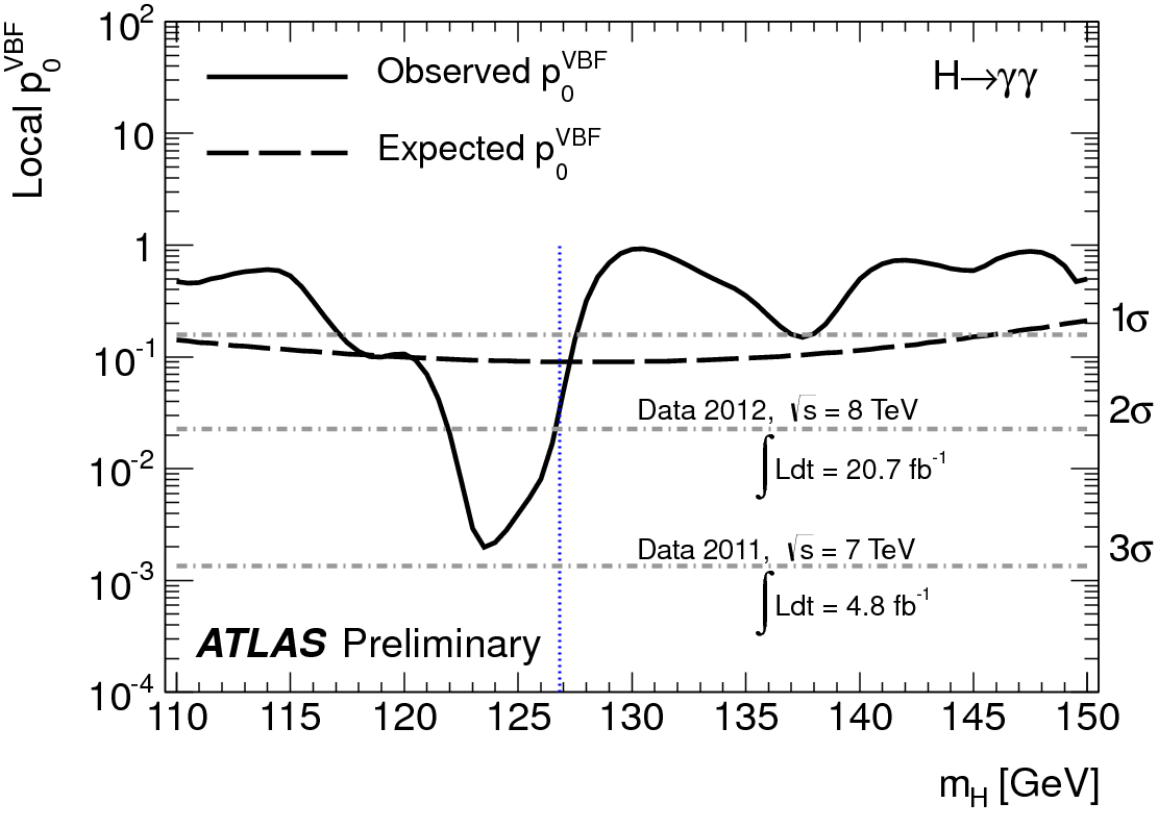
$$\mu_{ggF+ttH} \times B/B_{SM} = 1.6^{+0.3}_{-0.3}(stat)^{+0.3}_{-0.2}(syst)$$

$$\mu_{VBF} \times B/B_{SM} = 1.7^{+0.8}_{-0.8}(stat)^{+0.5}_{-0.4}(syst)$$

$$\mu_{VH} \times B/B_{SM} = 1.8^{+1.5}_{-1.3}(stat)^{+0.3}_{-0.3}(syst)$$

- agreement with SM at 2σ
- improvement of 30% (μ_{VBF}) 45%(μ_{VH}) due to new categorization

ATLAS H → γγ analysis: VBF production

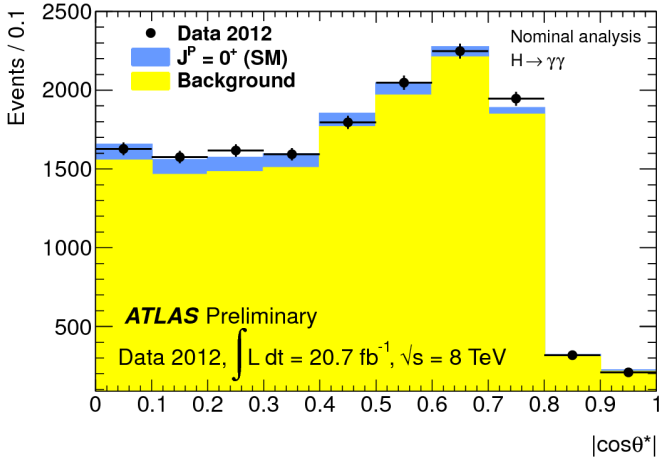


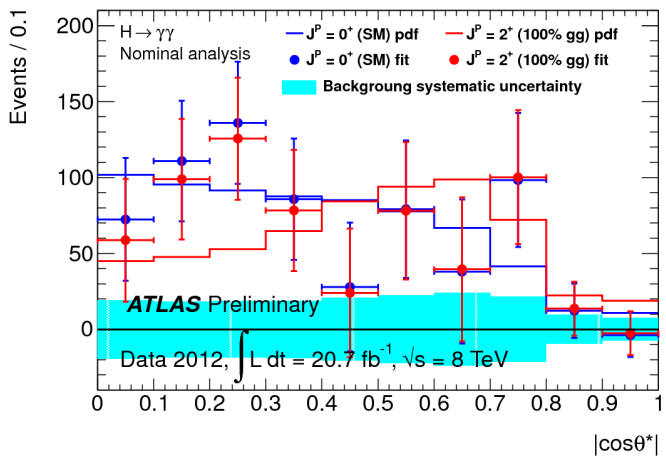
VBF p-value largely driven by tight BDT high mass di-jet category
Significance at best fit mass 126.8 GeV (blue line) is 2σ (~1.2 expected)

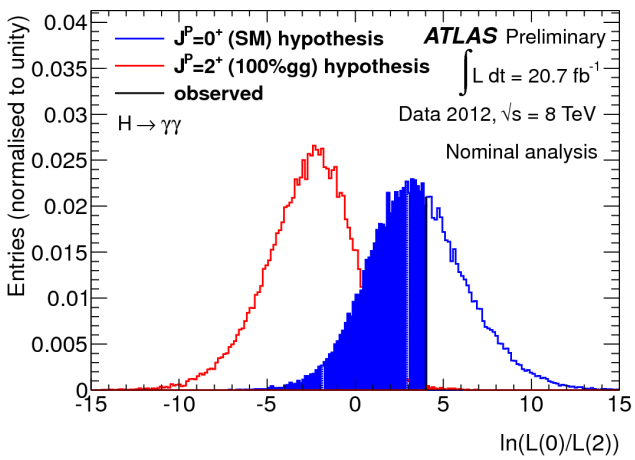
(consistent with backup VBF analysis with re-optimized cut-based selection)

$H \rightarrow \gamma\gamma$ results: spin studies

- Based on 20.7 fb-1 of 8 TeV data. Use of the polar angle cosθ* in the γγ rest frame.
- Inclusive Higgs to di-photon analysis (no categorization).
- Comparing dN/dcosθ* for spin 0 (flat) and spin 2 (1+6cos2θ* +cos4θ* for G-like) hypothesis.
- Shape and normalization of cosθ*background form m_H sidebands data.







- If spin 2 G-like (minimal coupling) resonance produced 100% by gluon fusion, rejection p-values are:
  - **spin 2**: 0.3% (0.5% expected) → (this) spin 2 (100% gg) excluded at 99.3% CL. (If qqbar production fraction is increased, separation is reduced)
  - **spin 0:** 58.8% (1.2% expected) → SM spin 0 hypothesis good agreement with data.

Summary

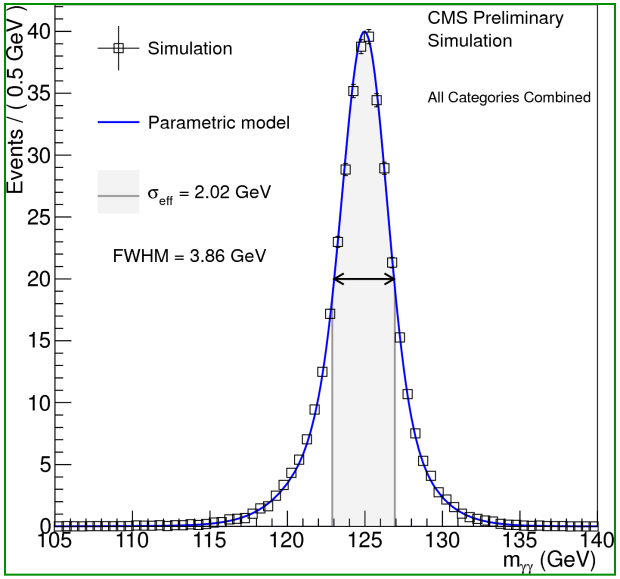
- H → γγ analysis ATLAS and CMS updates summary:
  - Both **ATLAS** and **CMS** updated their H → γγ analysis on the whole 7 TeV + 8 TeV data sample. Categorization are improved on both sides especially toward constraining exclusive production modes (VH, VBF).
  - Higgs mass measured in this channel is systematic dominated and appear to be consistent between the two experiments within systematic uncertainties.
  - Signal strength is close to unity for CMS and at 2.3 sigma from SM hypothesis in ATLAS. Uncertainties are comparable between the two. Sensitivity to exclusive production modes starts to be non marginal. (VBF @ 2 σ in ATLAS)
  - Higgs spin studies has been updated by ATLAS. Standard Model spin 0 hypothesis in good agreement with data.
  - At the level of precision allowed by LHC run 1 data, overall consistency with Standard Model picture seems to emerge in the H → γγ channel.

Backup

CMS: categories, signal model & syst.

Expected signal and estimated background

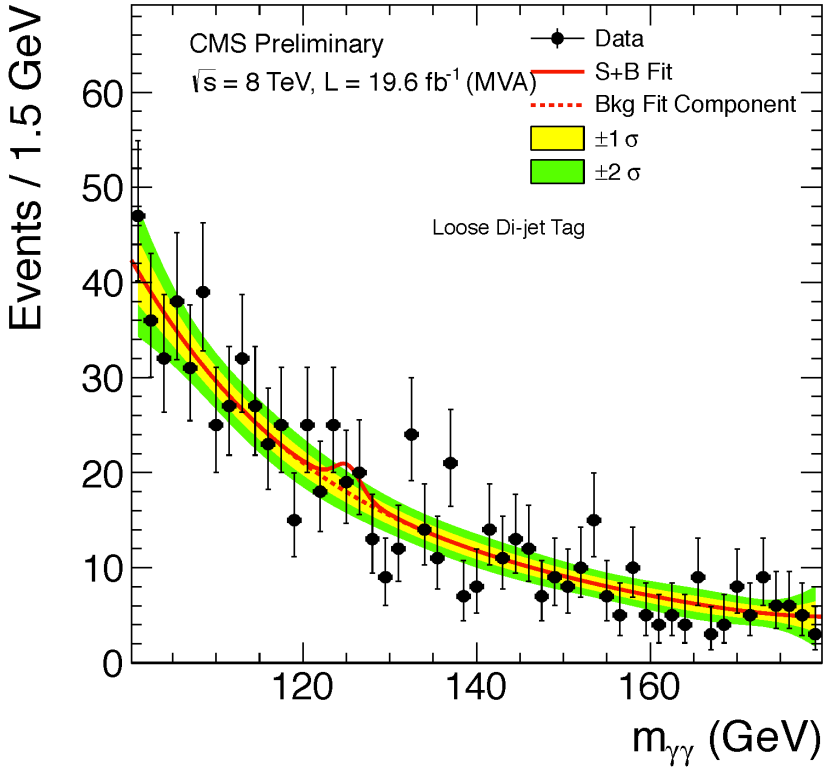
Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 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



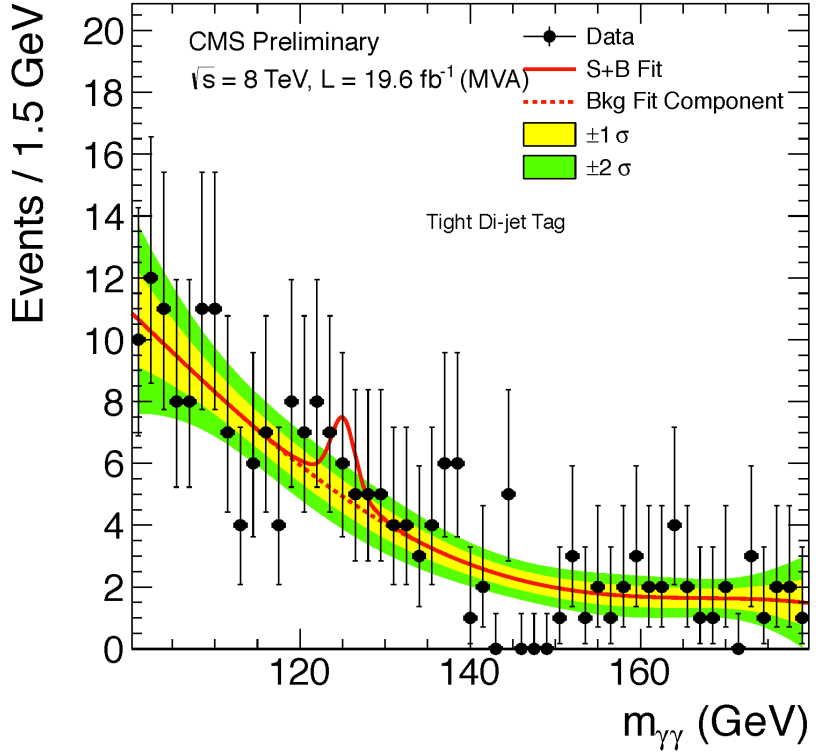
Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.23%, 0.72%	0.93%, 0.36%
	$R_9 < 0.94$ (low η, high η)	0.25%, 0.60%	0.33%, 0.54%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.20%, 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%

CMS: exclusive VBF tagged categories

– $\gamma\gamma$+2 jets VBF MVA similar approach as ATLAS → define 2 categories based on BDT output: Loose and Tight with S/B of 0.2 and 0.5

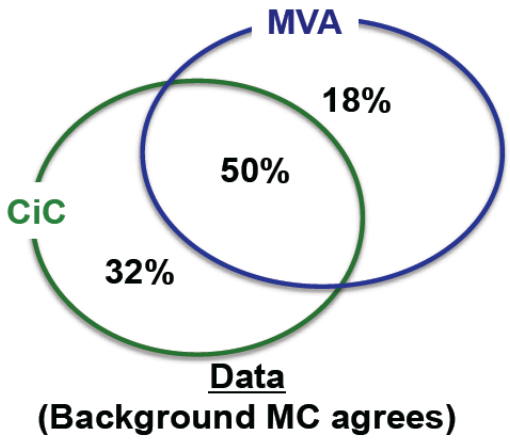


Loose di-jet tag

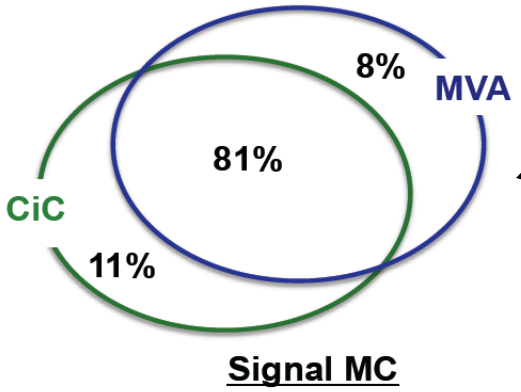


Tight di-jet tag

CMS: compatibility of the 2 analysis



Data
(Background MC agrees)



Signal MC

MVA and CiC results are correlated because of event overlap.

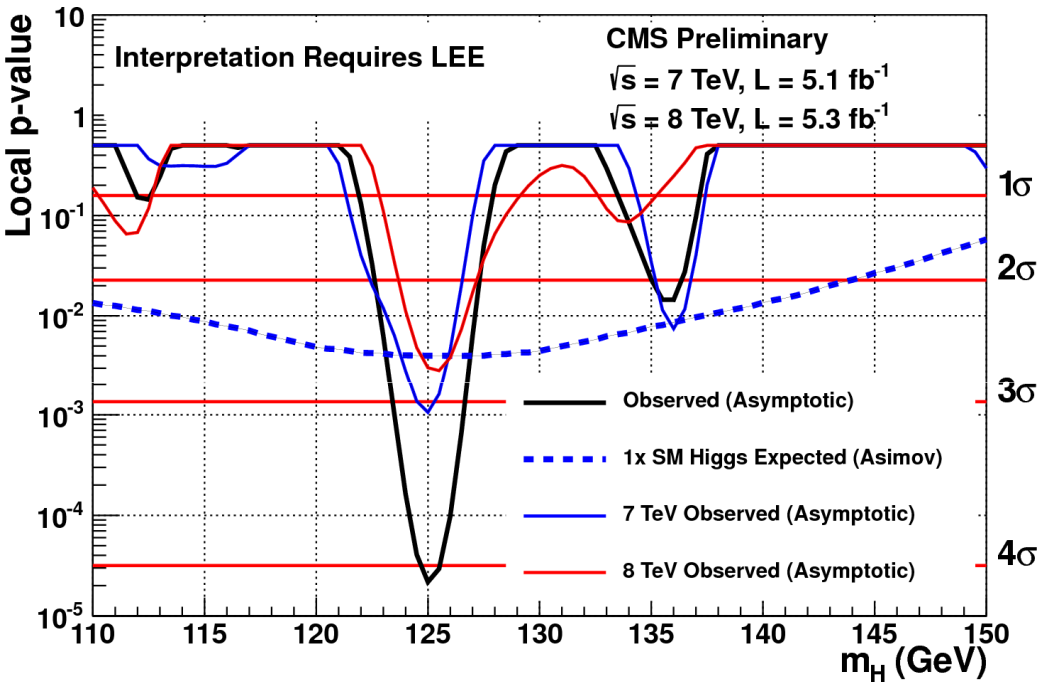
Estimate compatibility including correlations

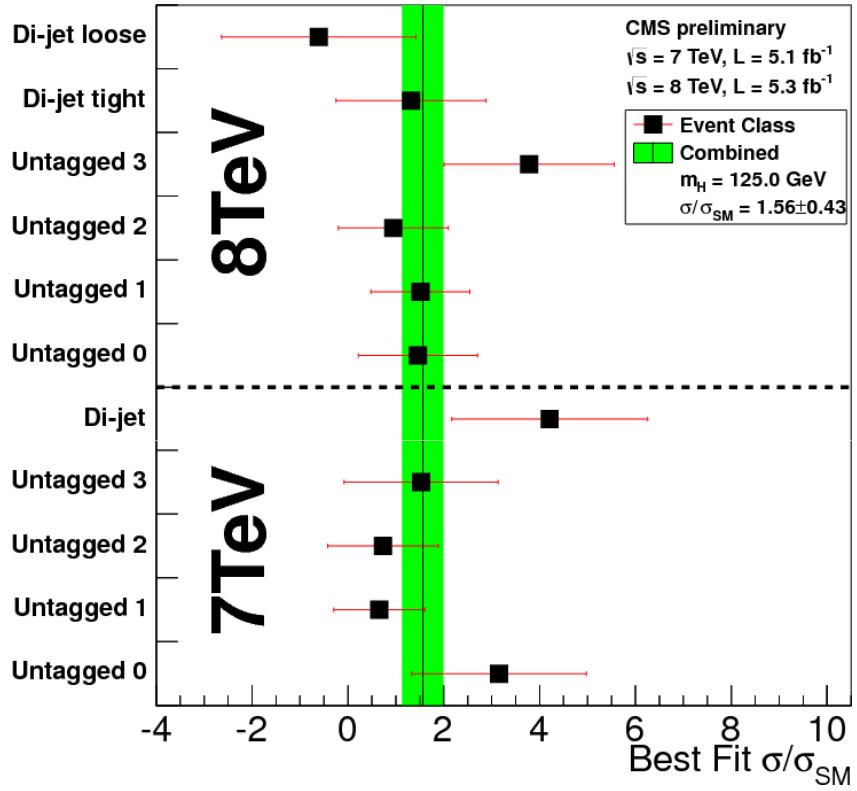
	Compatibility (including correlation)
MVA vs CUT BASED in full dataset	1.5 σ
MVA vs CUT BASED only in 2012 dataset	1.8 σ

within 2 σ

No source of systematic found. Difference appears to be consistent with statistical fluctuation.

CMS: published analysis





Significance at 125 GeV: 4.1σ

Signal strength: μ = 1.56 ± 0.43

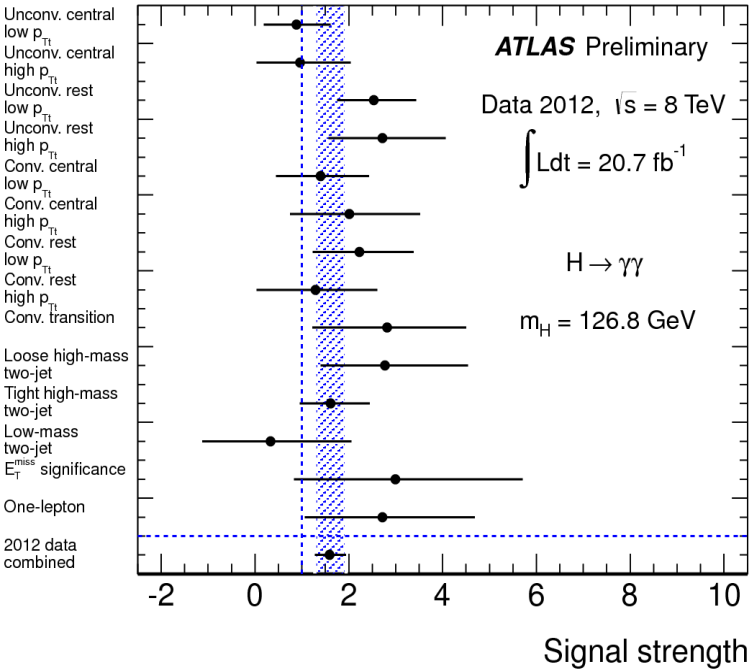
ATLAS: across categories

Mass resolution, S and B exp. and obs. yields

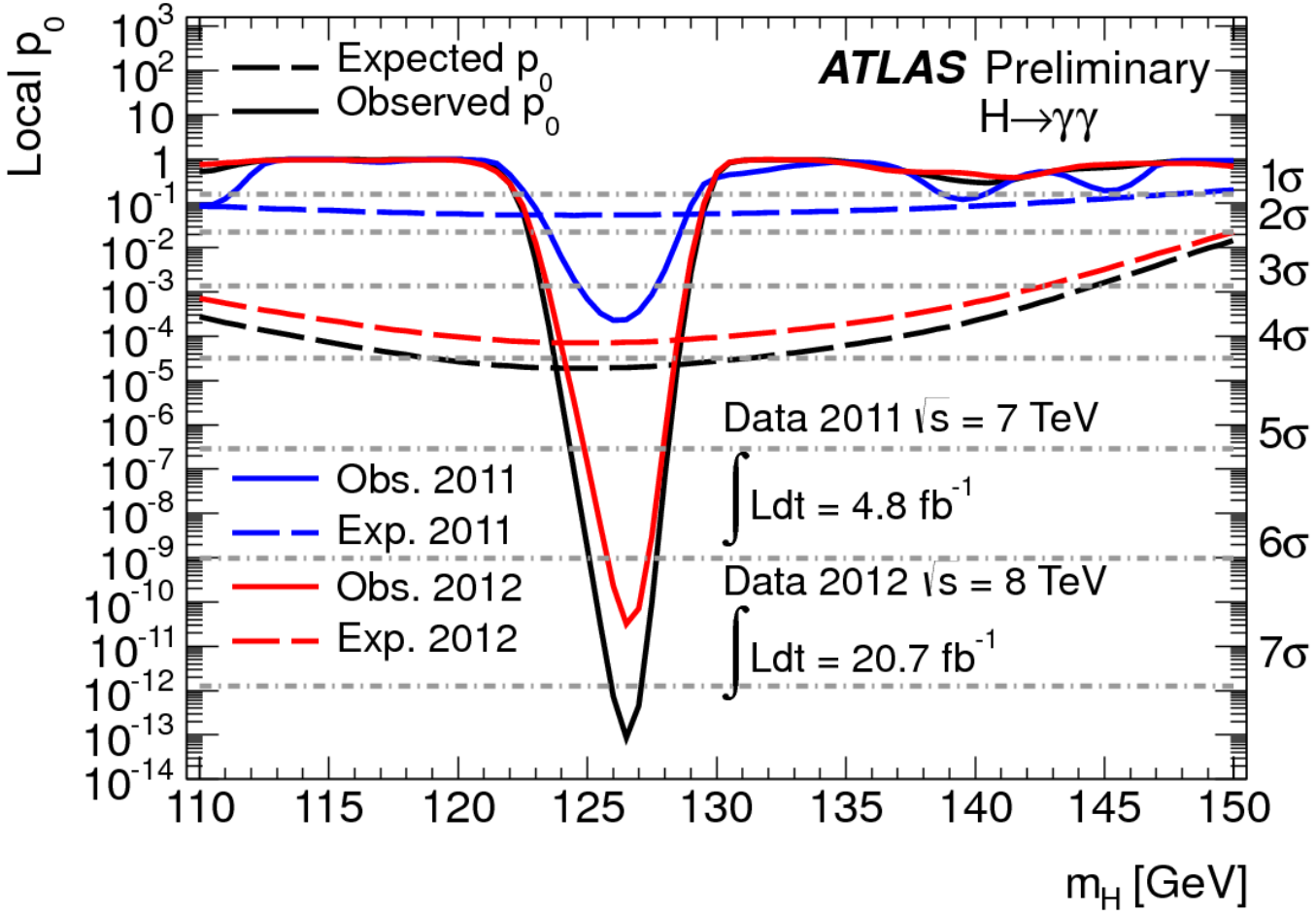
Table 2: Signal mass resolution (σ_{CB}), number of observed events, number of expected signal events (N_S), number of expected background events (N_B) and signal to background ratio (N_S/N_B) in a mass window around $m_H = 126.5$ GeV containing 90% of the expected signal for each of the 14 categories of the 8 TeV data analysis. The numbers of background events are obtained from the background + signal fit to the $m_{\gamma\gamma}$ data distribution.

$\sqrt{s}$	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

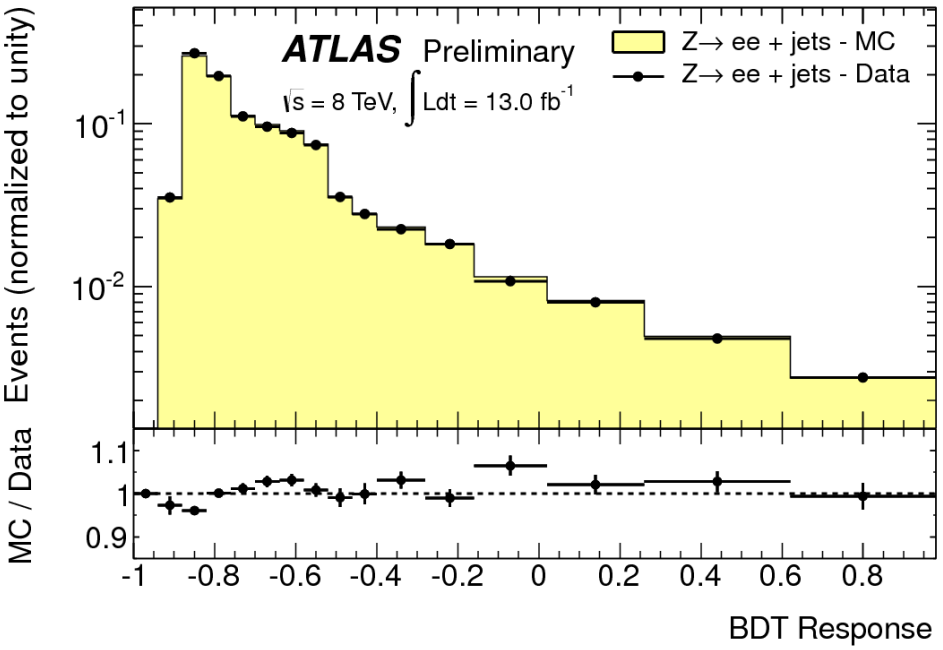
Signal strengths



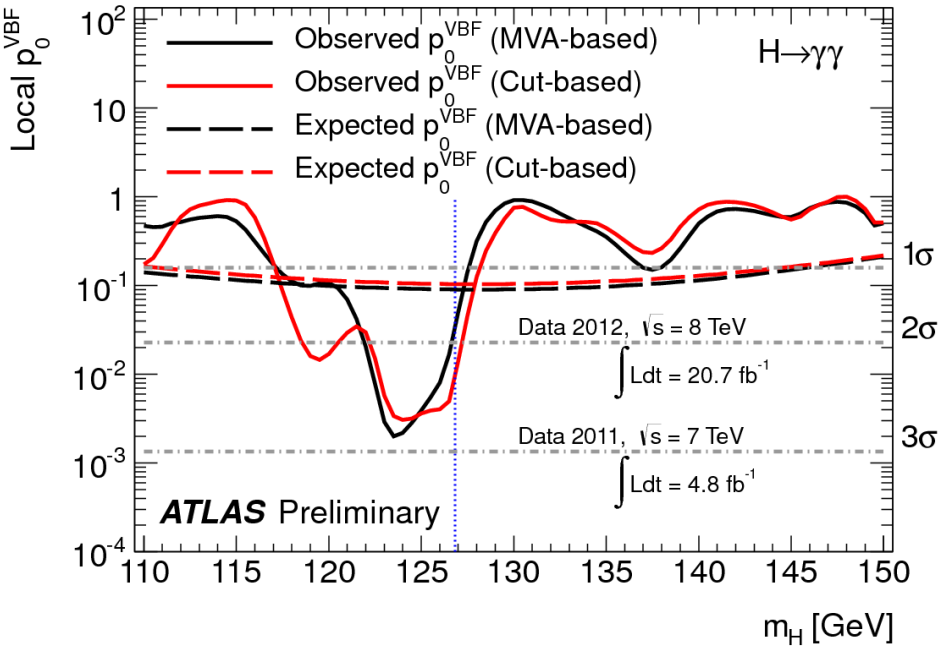
ATLAS: 2011 vs 2012



ATLAS: VBF MVA checks & VBF cutbased



Check of the BDT response in Z+jets data and MC samples. Agrees at a very good level across the whole BDT spectrum.



Baseline MVA VBF analysis (in red) ~10% higher sensitivity is compared to a re-appraised cut-based VBF selection (in black). Observed excesses are consistent.