Higgs to 2 photons in ATLAS

Olivier DAVIGNON (LPNHE Paris – UPMC/Paris Diderot/CNRS-IN2P3)

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Introduction

- **Higgs to diphoton searches in ATLAS**
  - ***Jul. 2012:*** **$\gamma\gamma$ + ZZ→4l + WW→lvlv combined discovery of resonance**
  - ***Dec. 2012:*** **observation of the resonance in $\gamma\gamma$ channel alone (6σ)**
  - ***Today*:** moving from discovery mode to **Higgs properties measurements**
    → Improve **sensitivity to exclusive production modes** (vector boson fusion, associate production with a vector boson)

- **$\gamma\gamma$ analysis update**
  - H→ $\gamma\gamma$ analysis of **full 7 + 8 TeV datasets** (4.8 + 20.7 fb^{-1})
  - Quantification of the **significance of the excess**
  - Measurement of the **signal strength and best fitted mass**
  - Measure of the **couplings** using **new categorization of the events**

*Results based on the note presented @ Moriond EW 2013**

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

**unless stated otherwise*

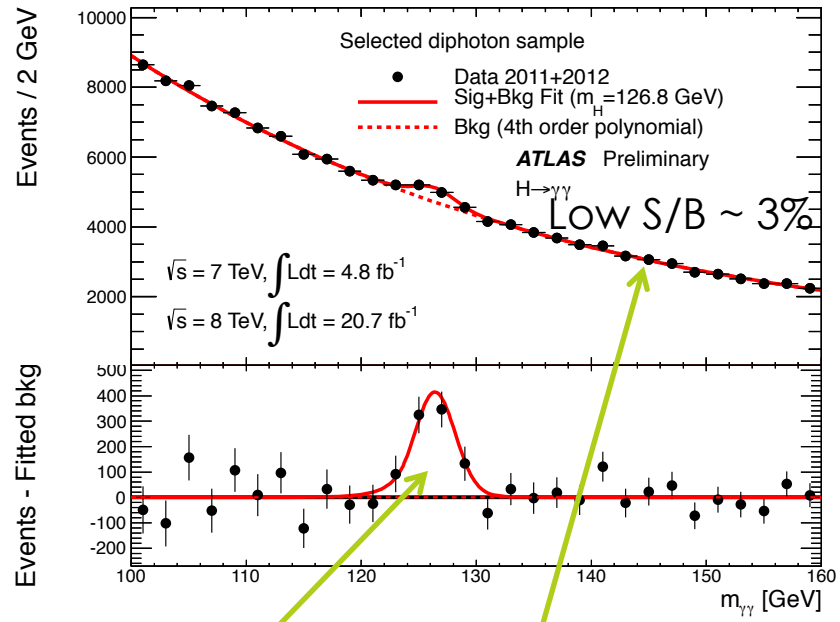
Event selection, signal/bkg models

Event selection

(based on 20.7 fb-1 of 8 TeV and 4.8 fb-1 of 7 TeV data)

See E. Petit's talk

- Diphoton trigger
- *Tight* photons identification criteria
- Isolation requirements
- p_T(leading γ) > 40 GeV, p_T(subleading γ) > 30 GeV
- $M_{\gamma\gamma}$ > 100 GeV and $M_{\gamma\gamma}$ < 160 GeV



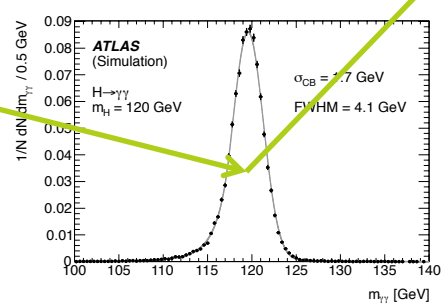
118893 (23788) H→γγ candidates @ 8 TeV (7 TeV)

Mass reconstruction

- Calorimetric energies
- Direction measurement (**See E. Petit's talk**)

Signal $M_{\gamma\gamma}$ resolution

- Fit of MC Higgs signal
- Crystal Ball + Gaussian

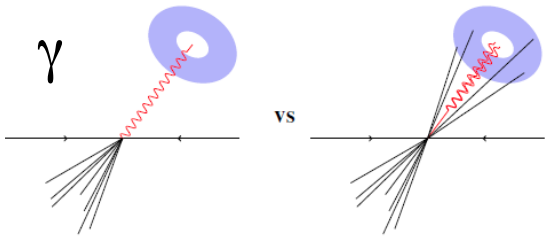


Background modelling

- Fit of $M_{\gamma\gamma}$ in data
- Functional form motivated by MC studies

Data composition

Photon isolation



$\pi^0 \rightarrow \gamma\gamma$
(in jets)

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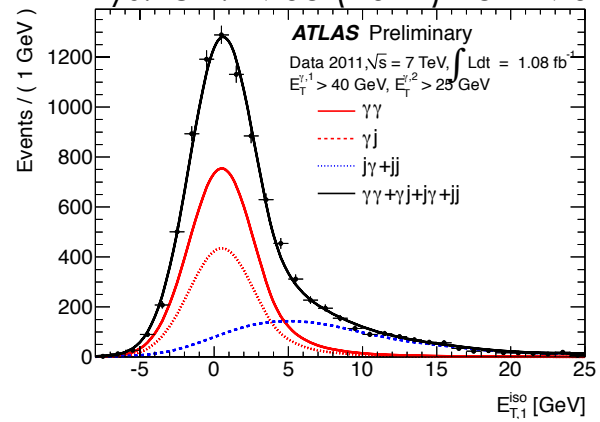


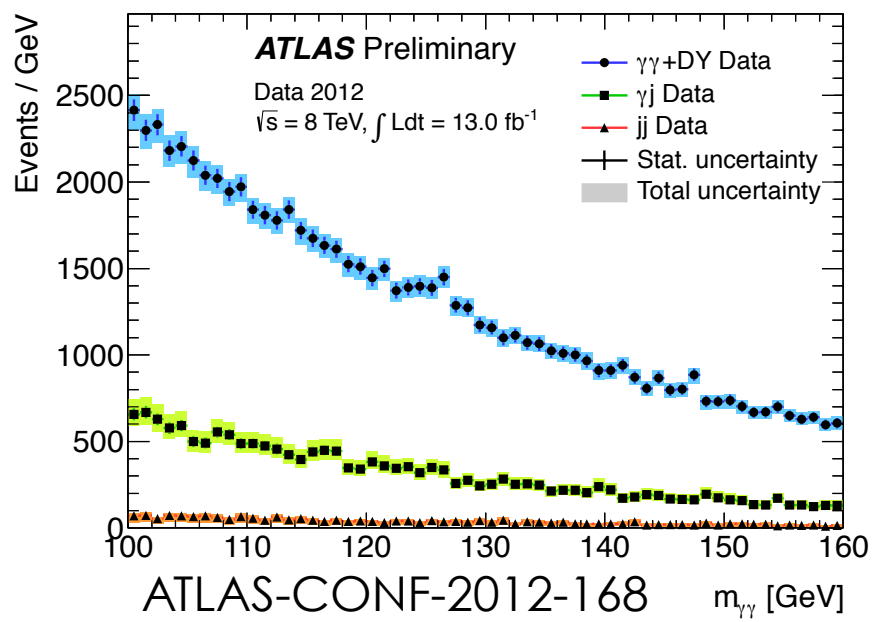
Sample composition

→ **extracted using data driven techniques**

Component	Fraction
γγ	75%
γj+jγ	22%
jj	3%
Drell-Yann	<1%

→ **Gives confidence on bkg rejection**

→ **Helps the understanding of background shapes**



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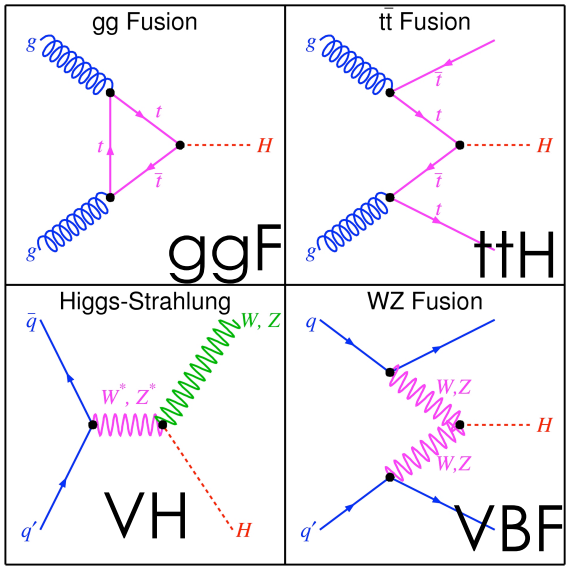
For prompt photons and jets measurements, see **M. Schwoerer's talk**

Exclusive categories

- **Different event topologies**
- → ***Sensitive to different Higgs production mechanisms → Higgs couplings***

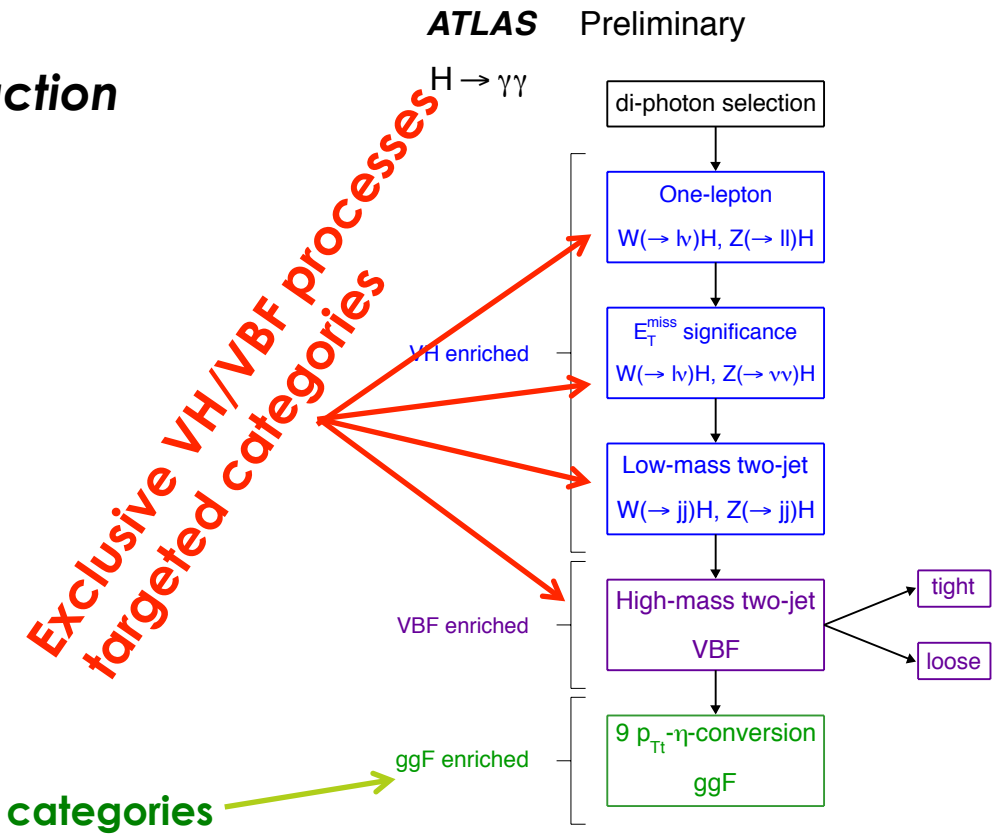
87%



1%

5%

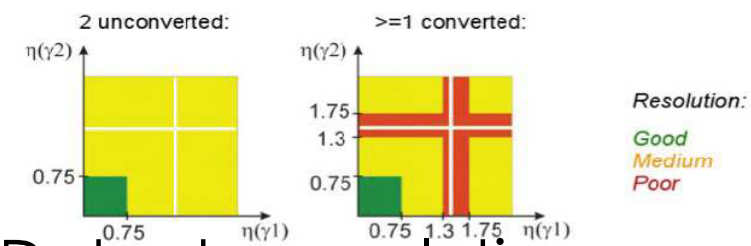
7%

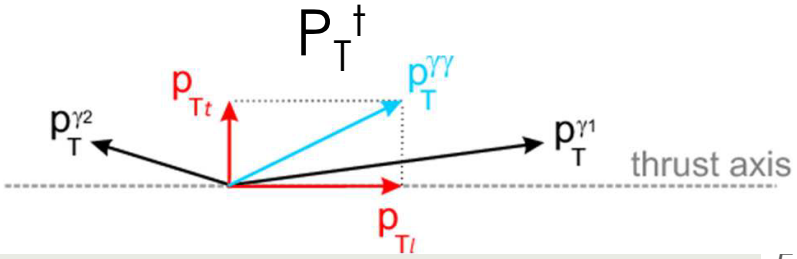


- **Different $M_{\gamma\gamma}$ signal resolution categories**
- → ***Improve expected significance***

Both unconverted:
- Central
- Rest

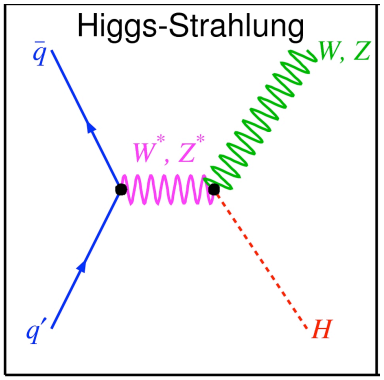
At least one converted:
- Central
- Transition
- Rest





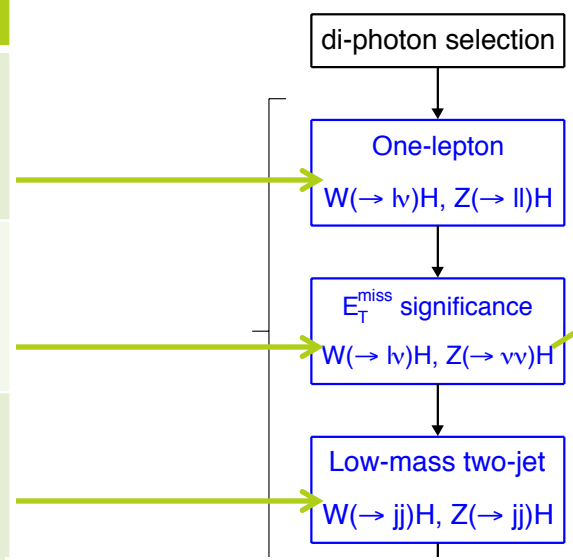
Detector resolution

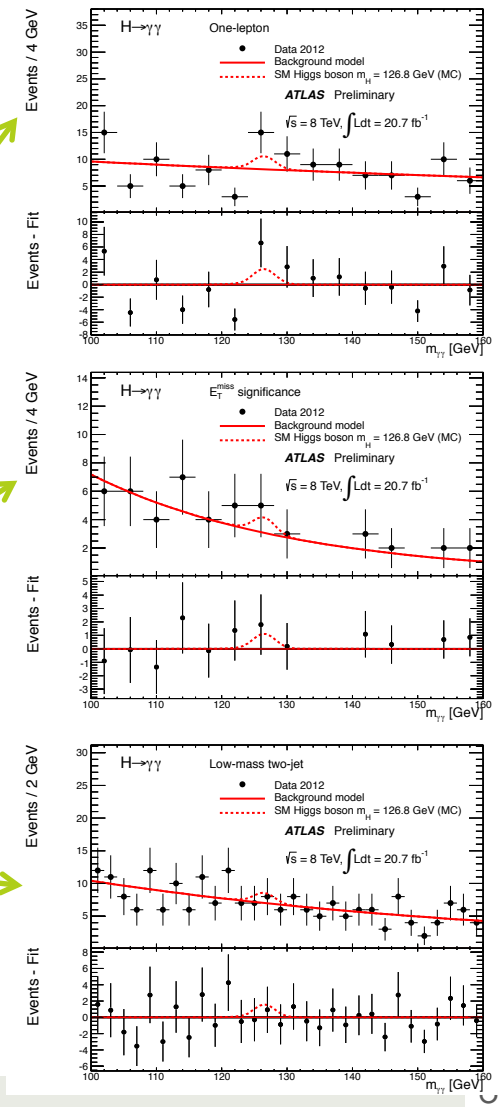
VH enriched categories



- **Associate production with a vector boson [W or Z]**
  - **Boosted Higgs → γγ**
  - **Leptonic (lepton/MET) or hadronic (jj) decay of the vector boson**

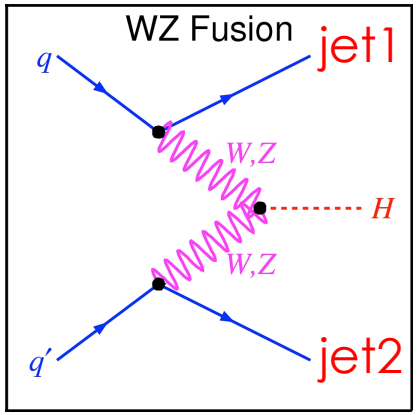
Selection
Electron pT > 15 GeV or muon pT > 10 GeV
MET Significance > 5 $\sigma_{E_T^{miss}} = 0.67\left[GeV^{1/2}\right]\sqrt{\Sigma E_T}$
M(jj) in [60,110] GeV P_T^t > 70 GeV





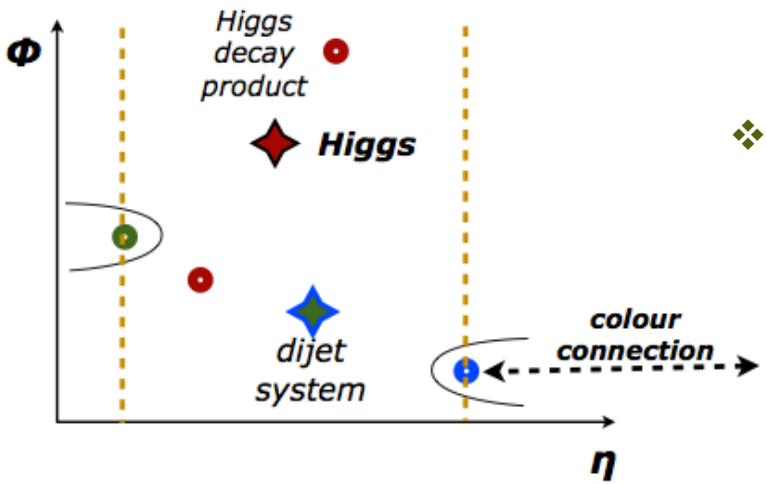
$\sqrt{s}$		8 TeV			
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20

VBF enriched categories (1/3)



- **Vector boson fusion topology**
  - ***No colour exchange at the vertex***
    → *Suppressed central jet activity*
  - ***Forward jets – central photons***
  - ***Boosted Higgs → γγ***

→ ***Discrimination wrt to background and other signals***



- **8 variables: P_T^t, $\Delta\Phi(\gamma\gamma\text{-jj})$, jets $|\eta|$, η gap between the jets, dijet mass, $\eta^* = |\eta[\gamma\gamma\text{-}(j1+j2)/2]|$ ΔR^{min}(jet/photon)**

8 discriminating variables chosen to train *Boosted Decision Trees (BDT)*

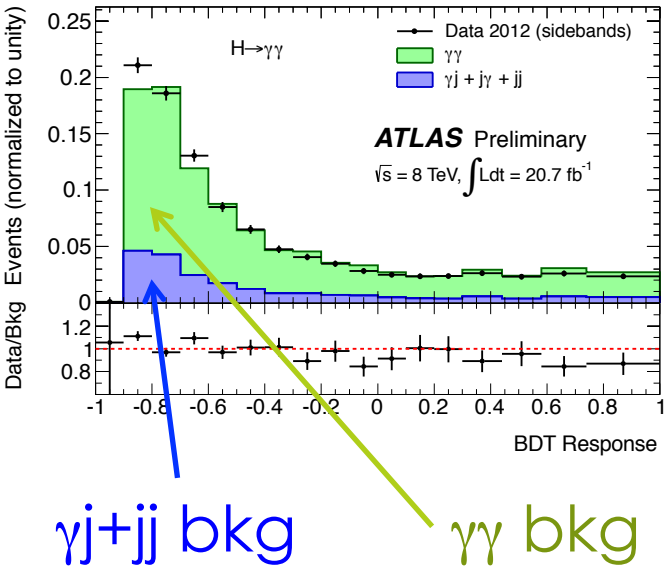
Signal: Vector Boson Fusion MC

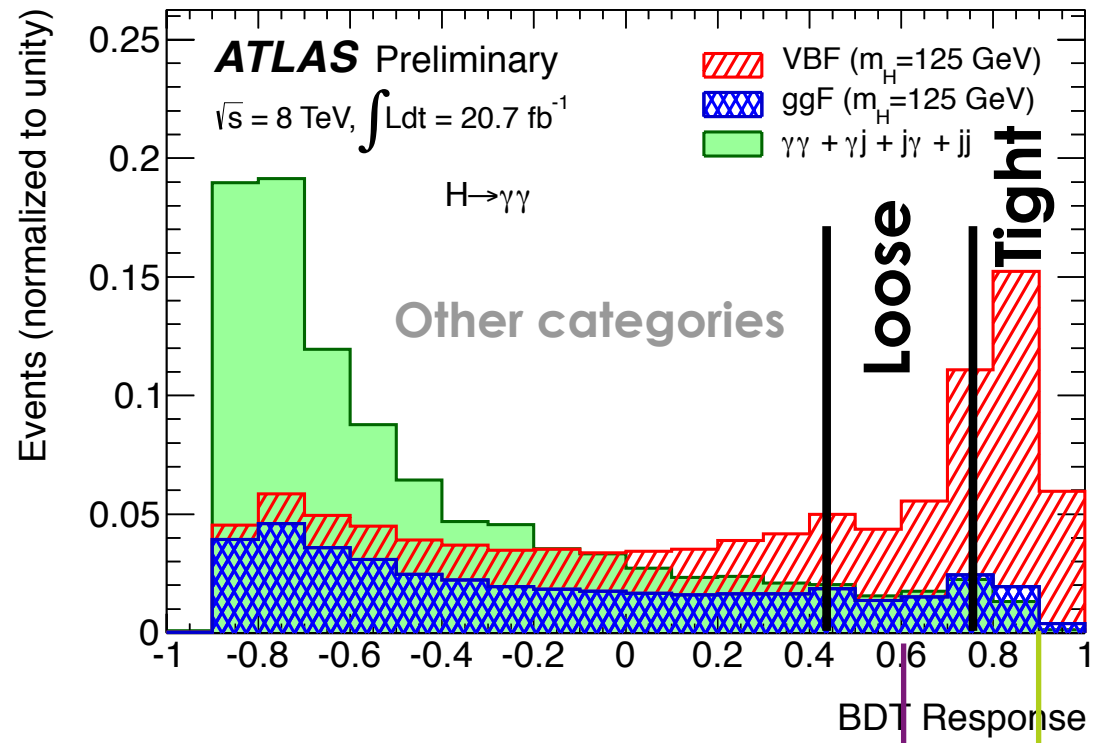
Background:

- γγ MC
- reversed isolation sidebands gj + jj

VBF enriched categories - definition (2/3)

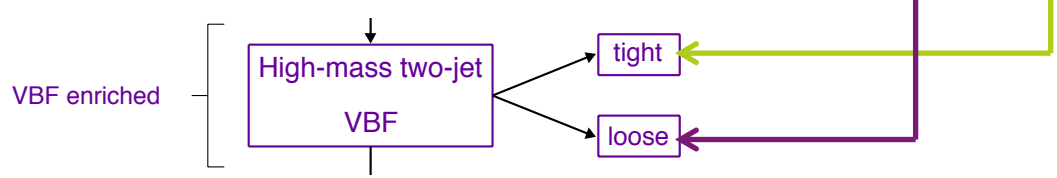
- **Two categories based on multivariate analysis response**





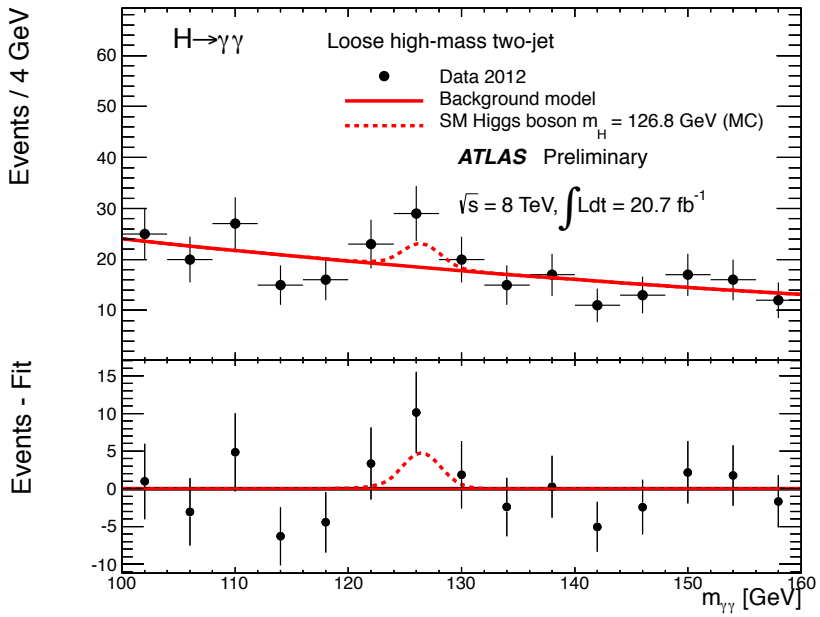
- **BDT discriminant:**
  - **VBF/bkg separation**
  - **VBF/ggF separation**

Category	Signal (%VBF)
Tight	7.3 (76%)
Loose	4.8 (54%)

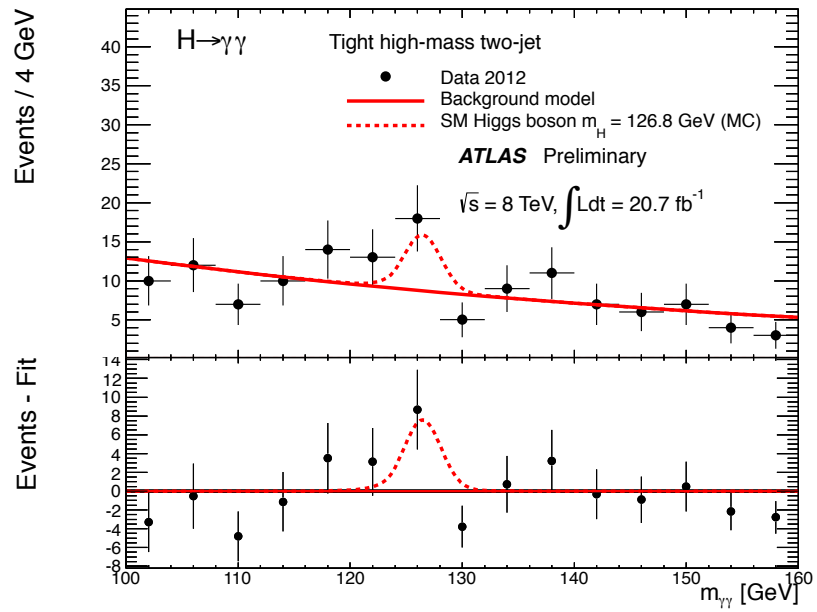


VBF enriched categories (3/3)

Loose high mass 2-jet

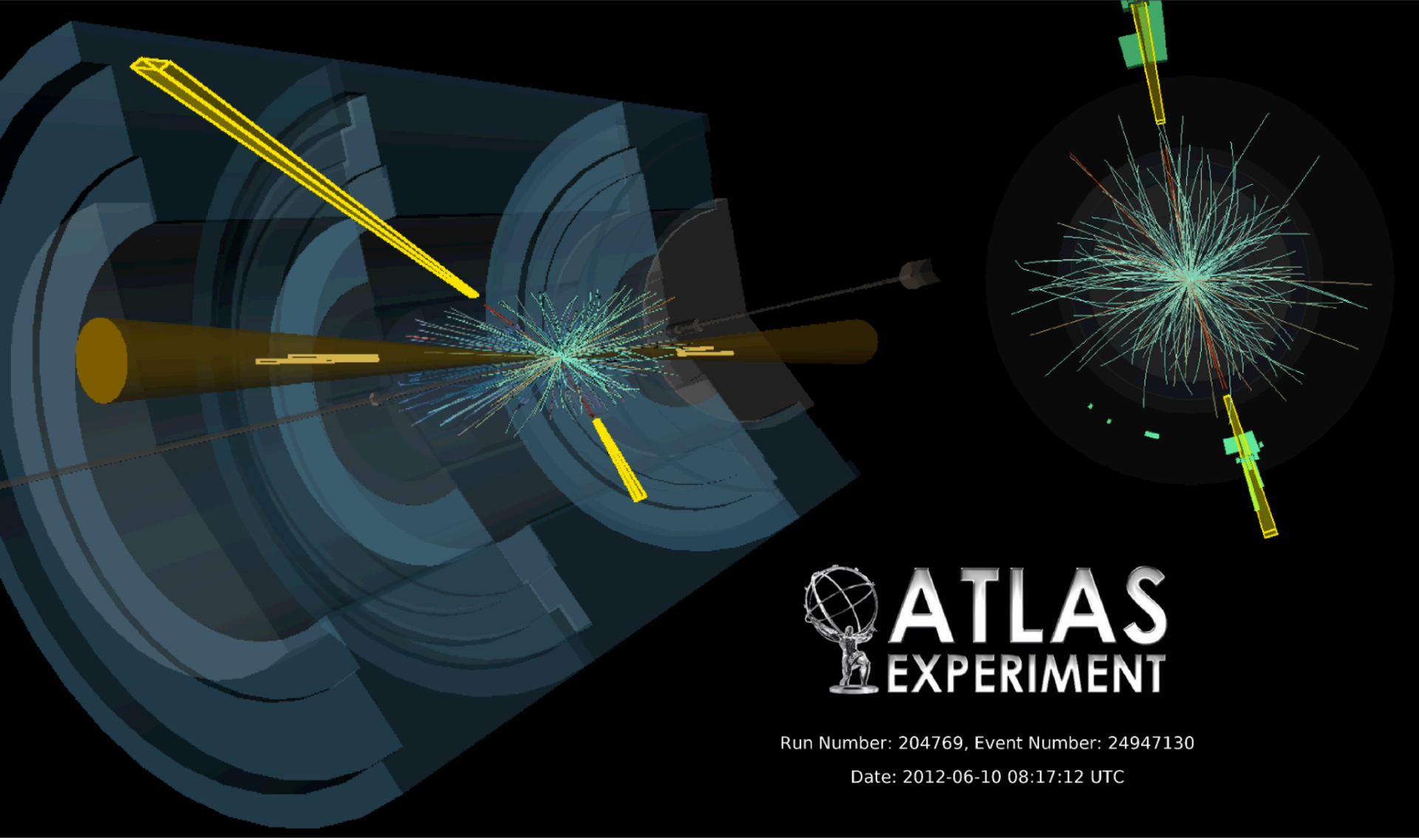


Tight high mass 2-jet



$\sqrt{s}$		8 TeV			
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
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

Favorable S/B



Event display of a VBF H→γγ candidate @ √s=8TeV.

$M_{\gamma\gamma}$ = 126.9 GeV.

M(jj) = 1.67 TeV

$\Delta\eta$(jj) = 5.62

$\Delta\phi$ (gg-jj) = 2.90.

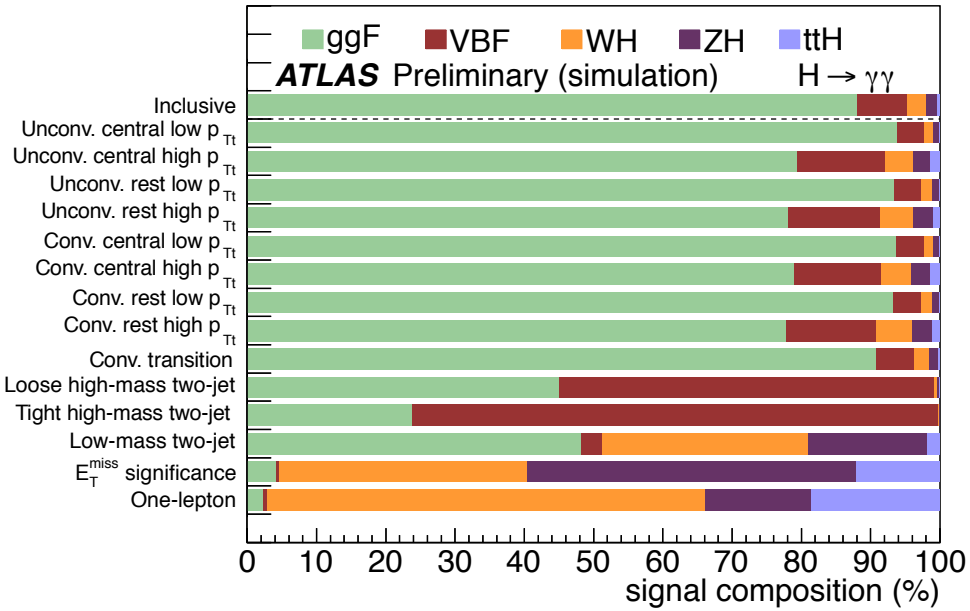
Processes along categories

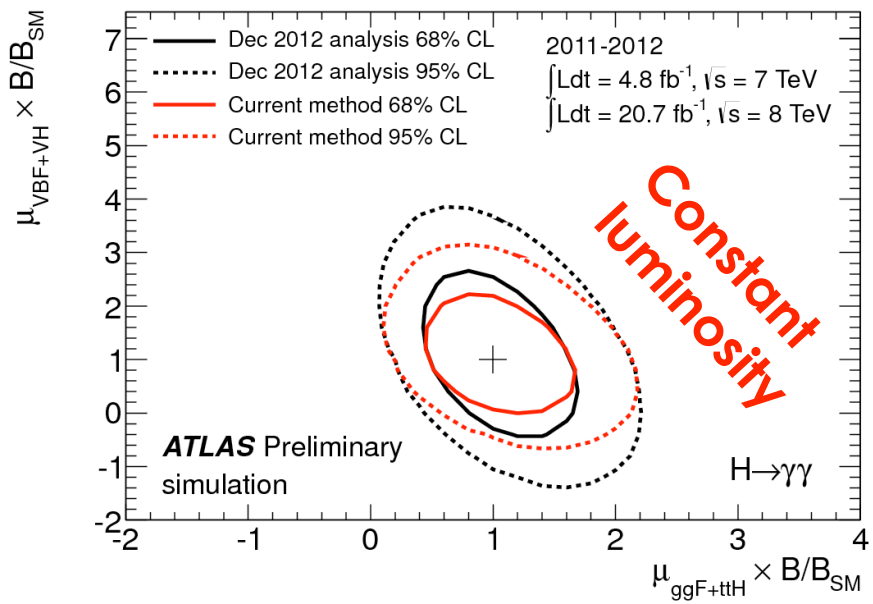
- **The remaining events [ggF enriched] are classified using the 9 P_{Tt}-η-conversion categories**

ggF enriched

9 p_{Tt}-η-conversion

ggF





14 categories for 8 TeV data

Sensitive improvement from from revisited exclusive VH/ VBF categories

Systematic uncertainties

- **All the uncertainties, except luminosity, are taken as fully correlated between 7 and 8 teV. 7 TeV systematics are unchanged wrt latest result*, except luminosity uncertainty which has been updated (now ±1.8%)**

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- **Main uncertainty on signal yield (8 TeV)**

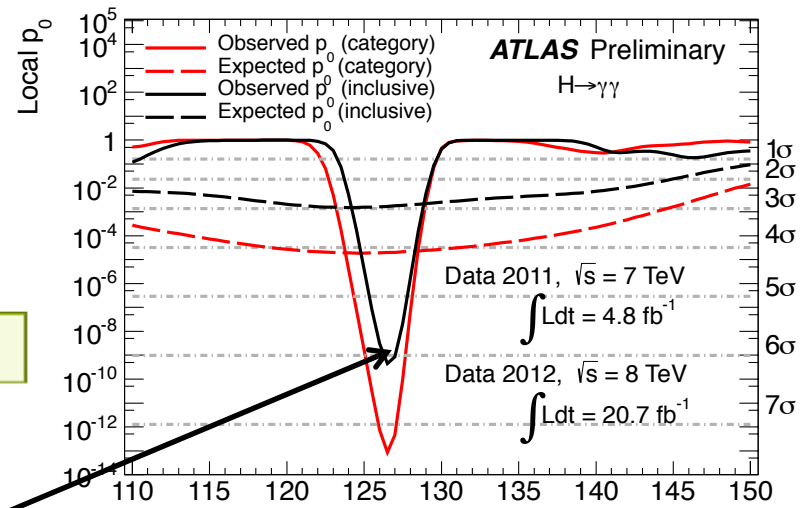
Source of uncertainty	Level
Theory (PDF, scale, α_S)	~12% (average) (up to ~50% for 2-jet categories)
Photon ID	2.4%
Background model	~3% (average)
Luminosity	3.6%

- **Main uncertainties on assignment to categories – migration (8 TeV)**

Source of uncertainty	Level
Higgs pT modelling	Up to ~10%
JES	Up to ~20%
Underlying event	Up to ~13%
Material in front of calo	~4%

Mass and signal strength

- **Excess wrt background-only hypothesis:**
  - **Observed 7.4σ** (expected 4.1σ for SM Higgs)

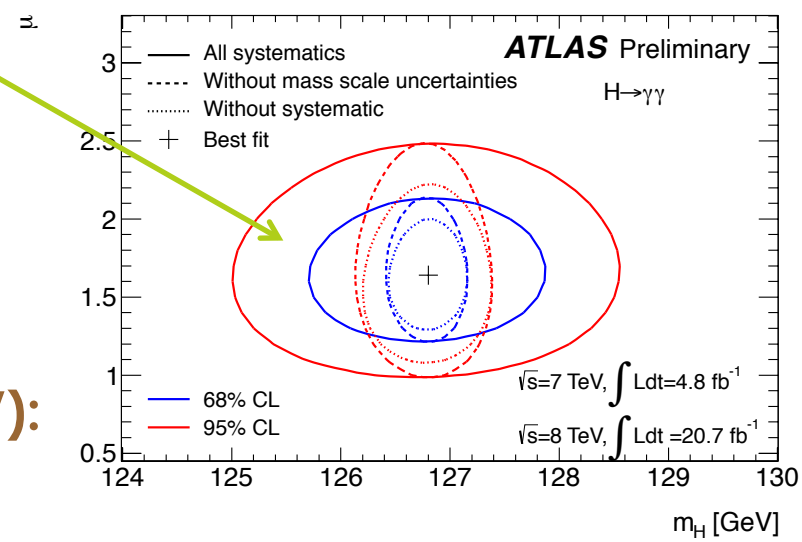


(6σ for inclusive analysis)

- **Best mass fit:**
  - $M_{\gamma\gamma}$ = **126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV**
  - ***Systematics dominated*** – highly dominated by photon energy scale

- **Signal strength $\mu = N_{obs}/N_{SM}$ @ $M_{\gamma\gamma}$ = 126.8 GeV**
  - μ = **$1.65 \pm 0.24\,(\text{stat.})^{+0.25}_{-0.18}$ (syst.)**

2.3σ from SM Higgs + bkg hypothesis



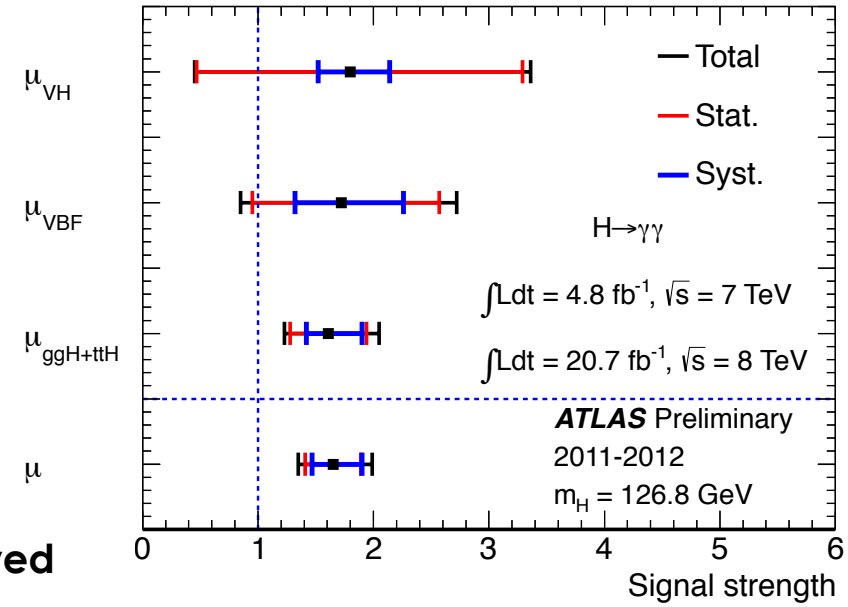
- **Fiducial cross-section (inclusive/8TeV):**
  - σ_{fid} x BR = **56.2 ± 12.5 fb**

[in phase-space: $|\eta| < 2.37$, $E_{\gamma 1}^T > 40$ GeV and $E_{\gamma 2}^T > 30$ GeV]

Signal strengths by processes

- **Fit 3 signal strengths**
  - $\mu_{VH} = 1.8^{+1.5}_{-1.3}$ (stat.) $^{+0.3}_{-0.3}$ (syst.)
  - $\mu_{VBF} = 1.7^{+0.8}_{-0.8}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)
  - $\mu_{ggF+ttH} = 1.6^{+0.3}_{-0.3}$ (stat.) $^{+0.3}_{-0.2}$ (syst.)

    (ttH XS too small for μ_{ttH} to be kept separated)

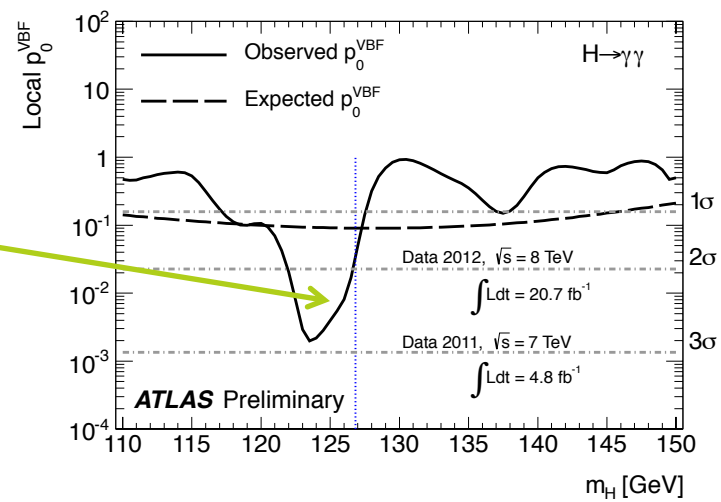


- **The measure of signal strengths has been improved**
- At constant luminosity, the improvement is:
  - **32% on the measure of μ_{VBF}**
  - **27% on the measure of μ_{VH}**

  } w.r.t. previous Dec. Council result

- **Slight excess in VBF p_0**

  (2σ @ $M_{\gamma\gamma}$ = 126.8 GeV)
  - **Significance almost fully driven by MVA-based high-mass 2-jet categories**



Conclusions

- We performed the SM Higgs to diphoton search in ATLAS using the full 7 + 8 TeV datasets (4.8 + 20.7 fb^{-1})

- A 7.4σ excess is observed
- The best fitted mass is $M_{\gamma\gamma}$ = 126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV

- The measured signal strengh is: $\mu = 1.65 \pm 0.24\,(\text{stat.})^{+0.25}_{-0.18}\,(\text{syst.})$

- The signal strength for the different processes were measured:
  - $\mu_{VH} = 1.8^{+1.5}_{-1.3}\,(\text{stat.})^{+0.3}_{-0.3}\,(\text{syst.})$
  - $\mu_{VBF} = 1.7^{+0.8}_{-0.8}\,(\text{stat.})^{+0.5}_{-0.4}\,(\text{syst.})$
  - $\mu_{ggF+ttH} = 1.6^{+0.3}_{-0.3}\,(\text{stat.})^{+0.3}_{-0.2}\,(\text{syst.})$

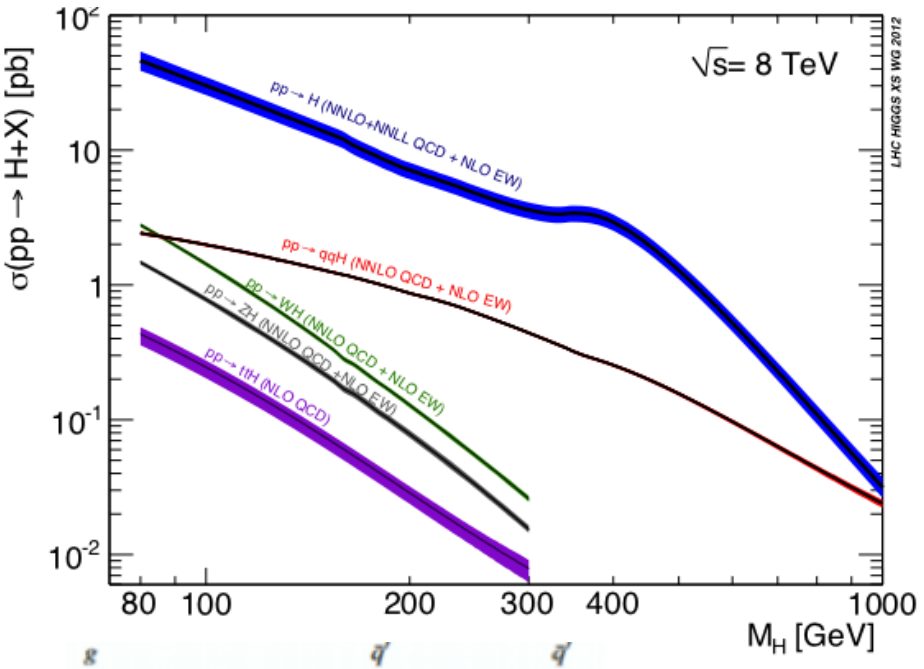
- Combined measures of resonance's mass/couplings:
  → N. Lorenzo-Martinez's talk

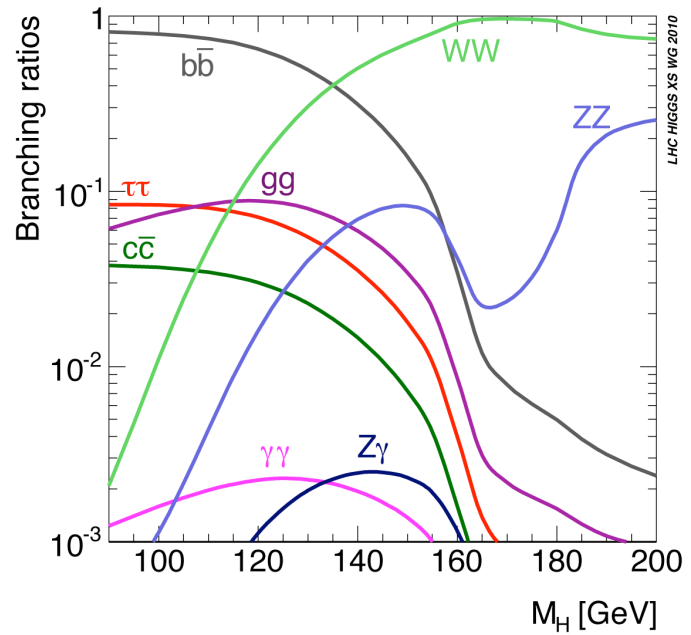
- Resonance's spin/CP properties:
  → C. Maiani's talk

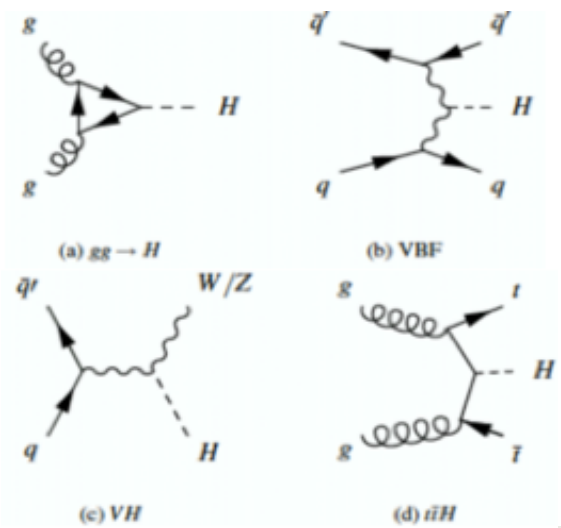
Thank you for your attention!

Backup

Higgs production and decay







In the mass range M_H=[100,160] GeV, the total cross-section for Higgs production is ~10 pb

→ ~87% of gluon fusion

→ ~7% of vector boson fusion

→ ~6% of associated VH/tt production

H→γγ cross section: ~ 50 fb

Background composition (1/2)

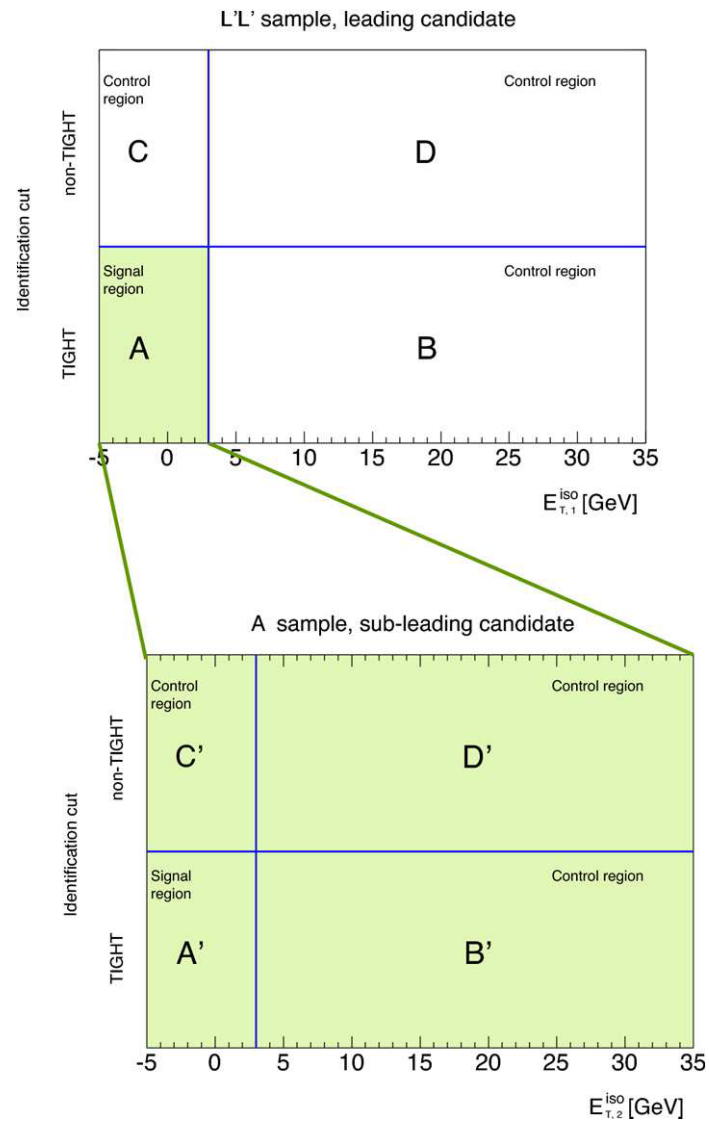
2x2D (ABCD) method

- Extension of the 2D method to the diphoton candidates case
- Preselect events passing the loose section
- Determining number of true leading photons N_A^{sig} from $N_A/N_B = N_C/N_D$

$$N_A^{sig} = N_A - \left[(N_B - c_1 N_A^{sig}) \frac{N_C - c_2 N_A^{sig}}{N_C - c_1 c_2 N_A^{sig}} \right] R^{bkg}$$

- If leading photon is in region A, apply same method to subleading photon, giving the number of true diphoton pairs:

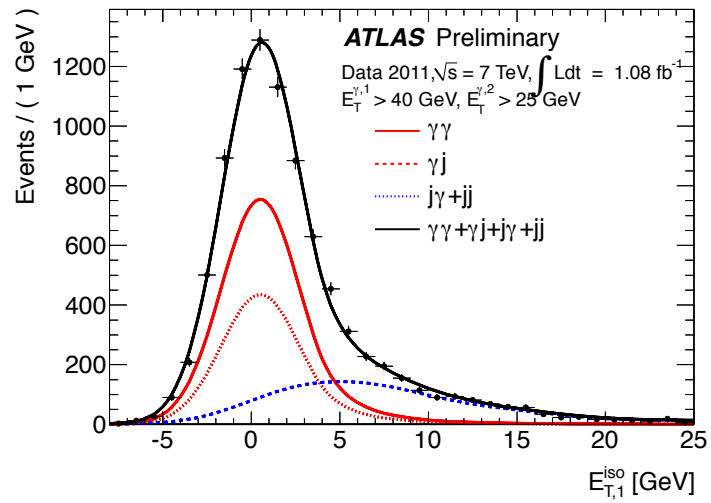
$$N_{\gamma\gamma}^{TITI} = \frac{\varepsilon' \left(\alpha f' N_A^{sig} + (\alpha - 1) N_A^{sig\,'} \right)}{(\alpha - 1)\varepsilon' + \alpha f'}$$



Background composition (2/2)

Isolation template fit method

- **2D simultaneous fit of the isolation distributions for leading and subleading photons**
  - → 4 fractions of (γγ/γj/jγ/jj)
  - → Different component PDFs
  - → Correlations taken into account



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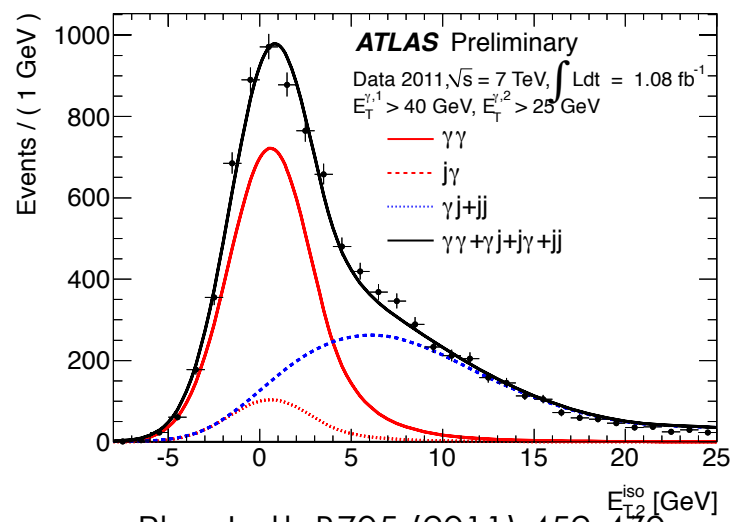
- **PDFs shapes extracted from control regions (reversing photon ID variables) or MC**

- **Gives compatible results with 2x2D**



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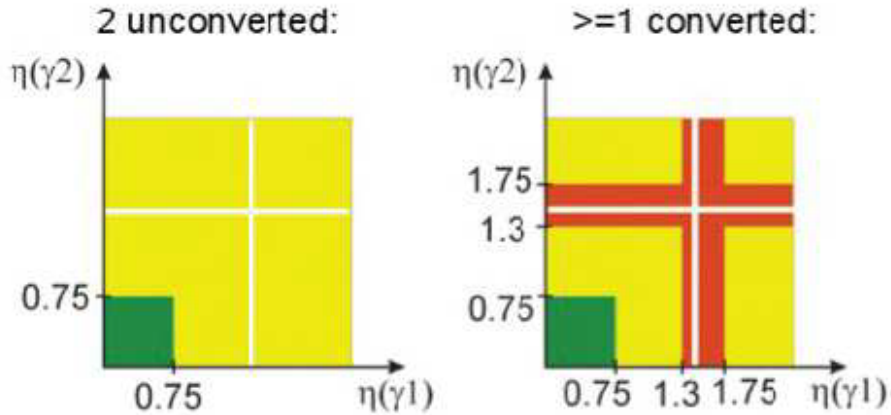
PTt eta-conv categories

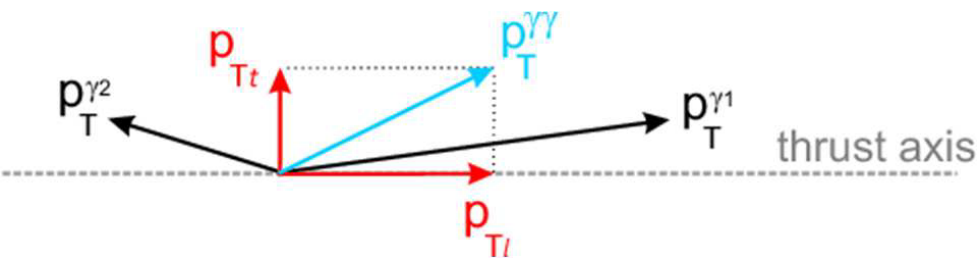
Both unconverted:

- Central
- Rest

At least one converted:

- Central
- Transition
- Rest





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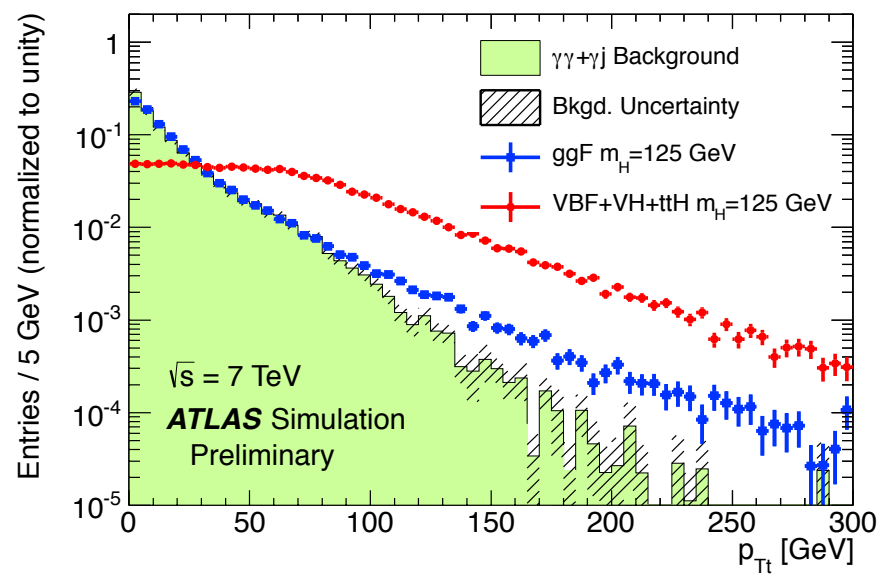
Diphoton momentum perpendicular to the thrust axis



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VBF enriched categories – MVA details

- **New: multivariate analysis (MVA) of the VBF Higgs → $\gamma\gamma$ searches**

- **Strategy:**
  - **Focus on the <u>2-jet signature and topology</u> of the VBF Higgs events**
    → Jets: reconstructed with anti-kT algorithm
  - ***Primary goal*** – build a MVA response which discriminates Higgs signal versus non-resonant backgrounds **(increase S/B)**
  - ***Good side effect*** – discrimination against resonant ggF Higgs*
    (increase VBF purity)
    QCD Higgs production with kinematics close to non-resonant backgrounds
  - **Build exp. significance optimized event categories based on the MVA response**

- **MVA training:**
  - **8 discriminating vars.: $P_T^{\dagger}$, $\Delta\eta(jj)$, $M(jj)$, $\eta(jet1)$, $\eta(jet2)$, $\Delta\Phi(\gamma\gamma\text{-}jj)$, $\Delta R^{min}(g,j)$, η^***
  - **Signal:** PYTHIA VBF Higgs @ 125 GeV
  - **Background:** MC Sherpa $\gamma\gamma$ + reversed isolation sidebands to emulate γj + $j\gamma$ + jj reducible backgrounds
    irreducible and reducible backgrounds weighted to fractions measured in data
  - **Boosted Decision Tree (BDT)**

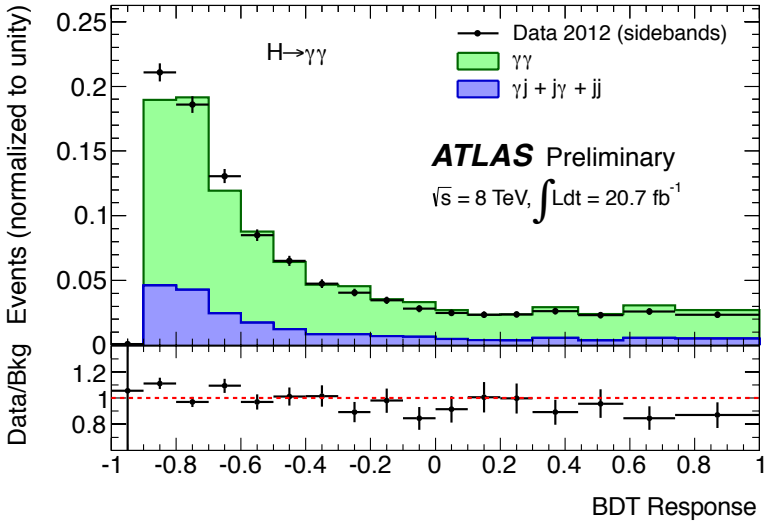
MVA checks

- **Check the MVA response consistency:**

  - **Data sidebands** (excluding $M_{\gamma\gamma}$ signal region) **vs. background sample** (as used in the training)

    → Reasonable agreement

    [NB: the background yield is not extracted from the training sample but from data]

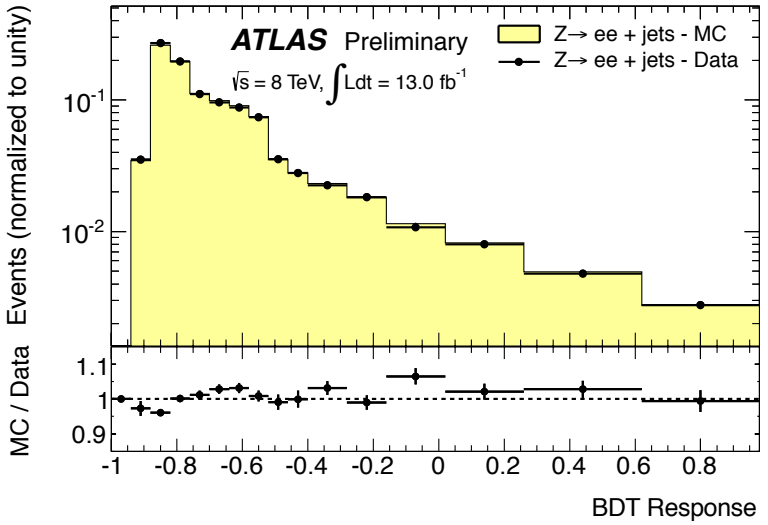


  - High statistics **Z→e⁺e⁻**

    Data vs. Simulation

    → Reasonable agreement

    [Z->ee is background-like]



Categorization summary

$\sqrt{s}$	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_T^{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

In a $M_{\gamma\gamma}$ window containing 90% of the signal

118893 (23788) H→γγ candidates @ 8 TeV (7 TeV)

- S/B ratio changes along categories
- Resolution is different along categories

→ **Gives better expected significance than inclusive analysis**

Background modelling

Category	Parametrisation	Uncertainty [N_{evt}]	
		$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Inclusive	4th order pol.	7.3	12.0
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	4.6
Unconverted central, high p_{Tt}	Exponential	0.2	0.8
Unconverted rest, low p_{Tt}	4th order pol.	2.2	11.4
Unconverted rest, high p_{Tt}	Exponential	0.5	2.0
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.4
Converted central, high p_{Tt}	Exponential	0.3	0.8
Converted rest, low p_{Tt}	4th order pol.	4.6	8.0
Converted rest, high p_{Tt}	Exponential	0.5	1.1
Converted transition	Exp. of 2nd order pol.	3.2	9.1
Loose high-mass two-jet	Exponential	0.4	1.1
Tight high-mass two-jet	Exponential	-	0.3
Low-mass two-jet	Exponential	-	0.6
E_T^{miss} significance	Exponential	-	0.1
One-lepton	Exponential	-	0.3

Signal and background modeling

Signal modeling

- Higgs natural width small along studied mass range (~100 MeV)
- Dominated by detector resolution

→ **Fit on MC of the $M_{\gamma\gamma}$ resolution using a Crystal Ball + Gaussian model**

→ **Resolution is almost pileup independent**

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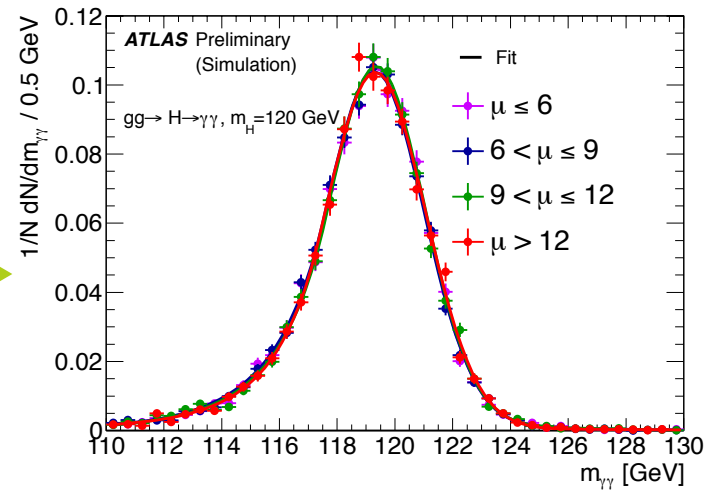


Background modeling

- Background is **extracted** in each category **by fitting the $M_{\gamma\gamma}$ spectra**
- The fitting function is determined on high statistics background MC
- The functional form is chosen as to minimize the corresponding systematic uncertainty

Systematics (signal yields)

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: $^{+0.2}_{-0.6}$	Asymmetric
	ZH: $^{+1.6}_{-1.5}$	ttH: $^{+3.8}_{-9.3}$		Log-normal
PDF+α_s	ggF: $^{+7.5}_{-6.9}$	VBF: $^{+2.6}_{-2.7}$	WH: ±3.5	Asymmetric
	ZH: ±3.6	ttH: ±7.8		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	

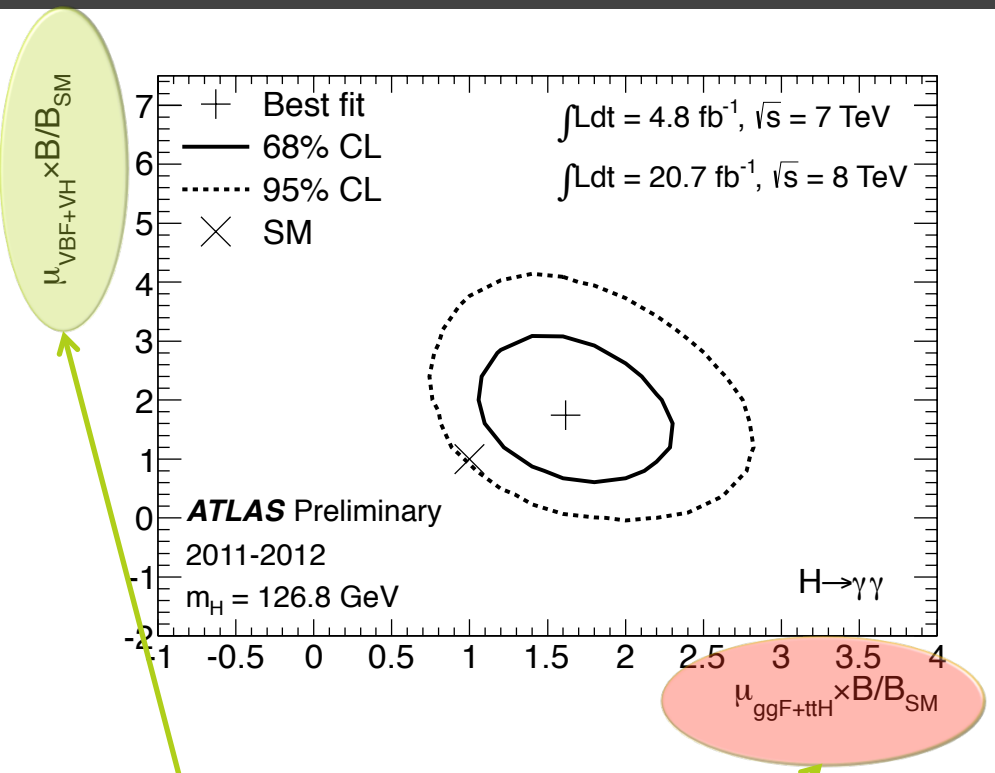
Systematics (migrations 1/2)

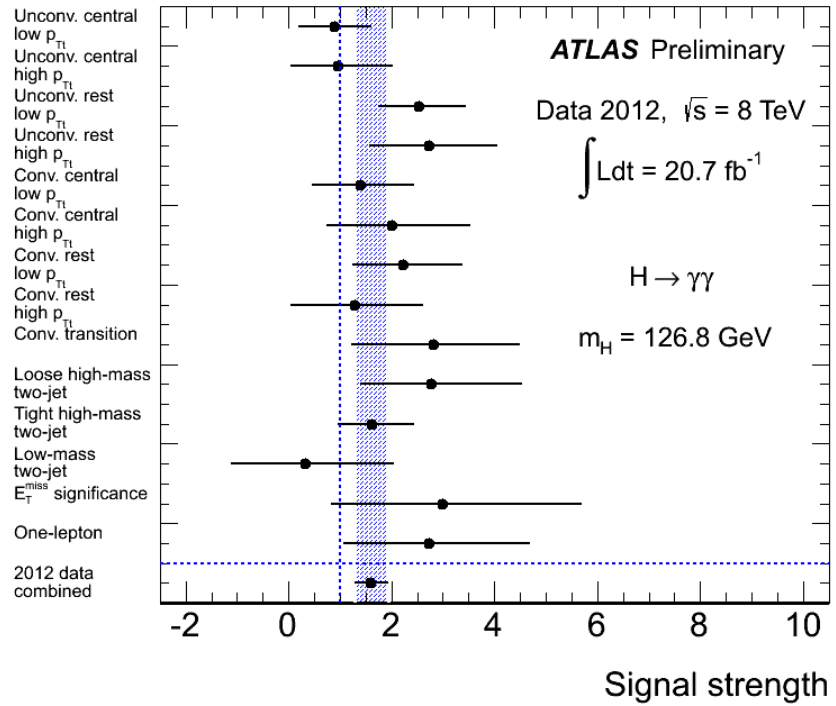
Systematic uncertainties	Category	Value(%)			Constraint
Underlying Event	Tight high-mass two-jet	ggF: ±8.8	VBF: ±2.0	VH, ttH: ±8.8	Log-normal
	Loose high-mass two-jet	ggF: ±12.8	VBF: ±3.3	VH, ttH: ±12.8	
	Low-mass two-jet	ggF: ±12	VBF: ±3.9	VH, ttH: ±12	
Jet Energy Scale	Low p_{Tt}	ggF: −0.1	VBF: −1.0	Others: −0.1	Gaussian
	High p_{Tt}	ggF: −0.7	VBF: −1.3	Others: +0.4	
	Tight high-mass two-jet	ggF: +11.8	VBF: +6.7	Others: +20.2	
	Loose high-mass two-jet	ggF: +10.7	VBF: +4.0	Others: +5.7	
	Low-mass two-jet	ggF: +4.7	VBF: +2.6	Others: 1.4	
	E_T^{miss} significance	ggF: 0.0	VBF: 0.0	Others: 0.0	
	one-lepton	ggF: 0.0	VBF: 0.0	Others: −0.1	
Jet Energy Resolution	Low p_{Tt}	ggF: 0.0	VBF: 0.2	Others: 0.0	Gaussian
	High p_{Tt}	ggF: −0.2	VBF: 0.2	Others: 0.6	
	Tight high-mass two-jet	ggF: 3.8	VBF: −1.3	Others: 7.0	
	Loose high-mass two-jet	ggF: 3.4	VBF: −0.7	Others: 1.2	
	Low-mass two-jet	ggF: 0.5	VBF: 3.4	Others: −1.3	
	E_T^{miss} significance	ggF: 0.0	VBF: 0.0	Others: 0.0	
	one-lepton	ggF: −0.9	VBF: −0.5	Others: −0.1	
η^* modelling		Tight high-mass two-jet: +7.6			Gaussian
		Loose high-mass two-jet: +6.2			
Dijet angular modelling		Tight high-mass two-jet: +12.1			Gaussian
		Loose high-mass two-jet: +8.5			

Systematics (migrations 2/2)

Higgs p_T		Low p_{Tt}: +1.3 High p_{Tt}: −10.2 Tight high-mass two-jet: −10.4 Loose high-mass two-jet: −8.5 Low-mass two-jet: −12.5 E_T^{miss} significance: −2.0 one-lepton : −4.0			Gaussian
Material Mismodelling		Unconv: −4.0	Conv: +3.5		Gaussian
JVF	Loose High-mass two-jet	ggF: −1.2	VBF: −0.3	Others: −1.2	Gaussian
	Low-mass two-jet	ggF: −2.3	VBF: −2.4	Others: −2.3	
E_T^{miss}	E_T^{miss} significance	ggF: +66.4	VBF: +30.7	VH, ttH: +1.2	Gaussian
e reco and identification		one-lepton: < 1			Gaussian
e Escale and resolution		one-lepton: < 1			Gaussian
μ reco, ID resolution		one-lepton: < 1			Gaussian
μ spectrometer resolution		one-lepton: 0			Gaussian

Signal strength [V,t and by category]





VBF+VH

ggF+ttH

→ compatible with SM within 2σ

Fiducial cross-section

Fiducial cross-section

- N_S extracted from signal + background fit on the inclusive $M_{\gamma\gamma}$ spectrum
- Uncertainties are statistical + systematics (mass resolution, background model)

$$\sigma_{fid} \cdot BR = \frac{N_{signal}}{\varepsilon \cdot L_{\text{int}}}$$

- Luminosity uncertainty +/- 3.6%
- ε: acceptance/reconstruction efficiency factors

$$\Rightarrow \sigma_{fid} \cdot BR = 56.2 \pm 12.5 \text{ fb}$$