Observation and coupling measurements of the Higgs boson in the diphoton decay channel in ATLAS

Hongtao Yang

University of Wisconsin-Madison

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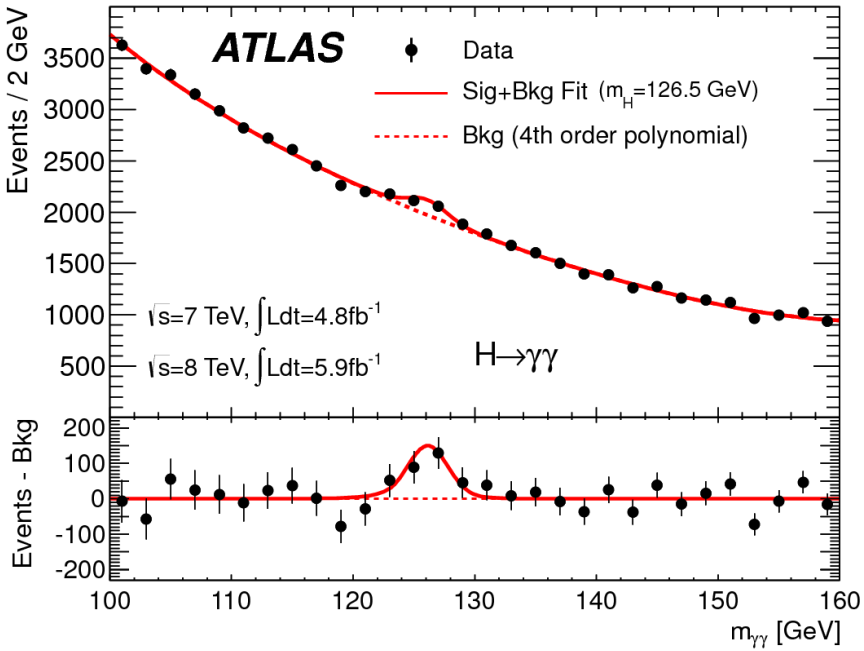
Outline

- Present the post discovery results on observation and coupling measurements in $H \to \gamma\gamma$.
- The results are based on the 4.8 fb^{-1} 7 TeV data and 20.7 fb^{-1} 8 TeV data taken during 2011-2012.



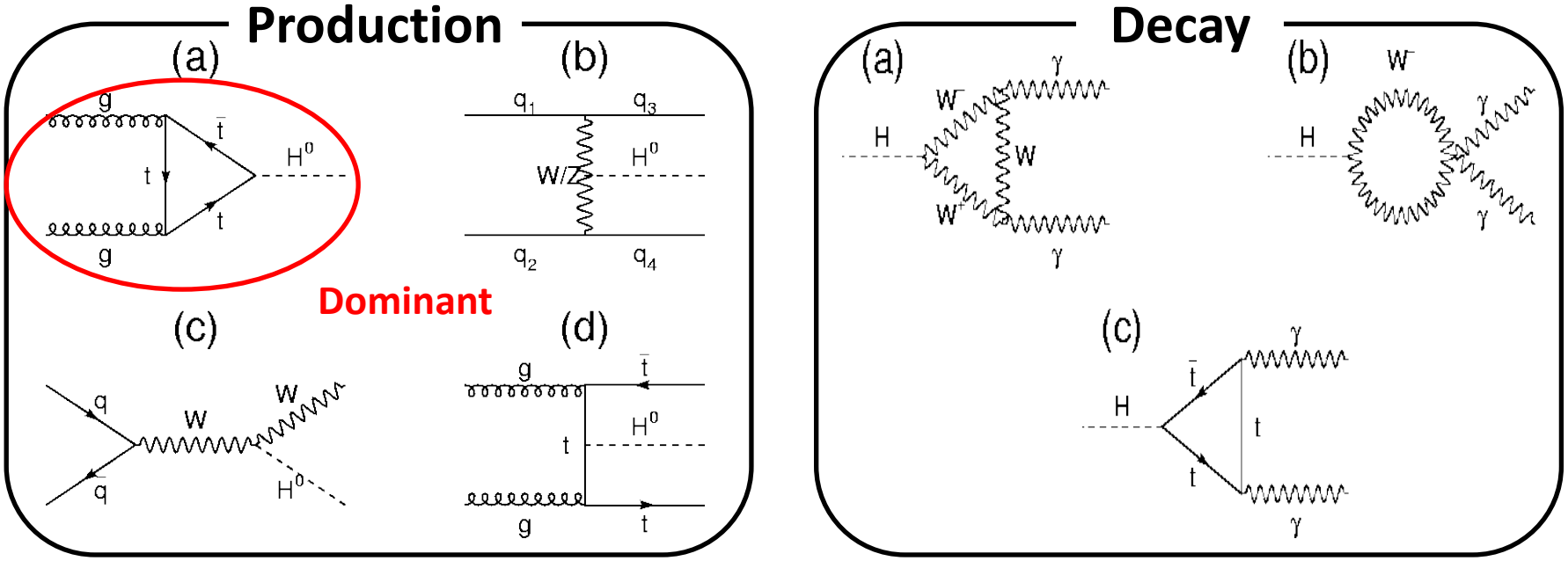
$H \to \gamma\gamma$ contributed an excess of 4.5σ to the discovery of Higgs boson.

ATLAS Higgs group celebrating the discovery of the Higgs-like boson on July 4th, 2012

Phys. Lett. B 716 (2012) 1-29

Production and Decay

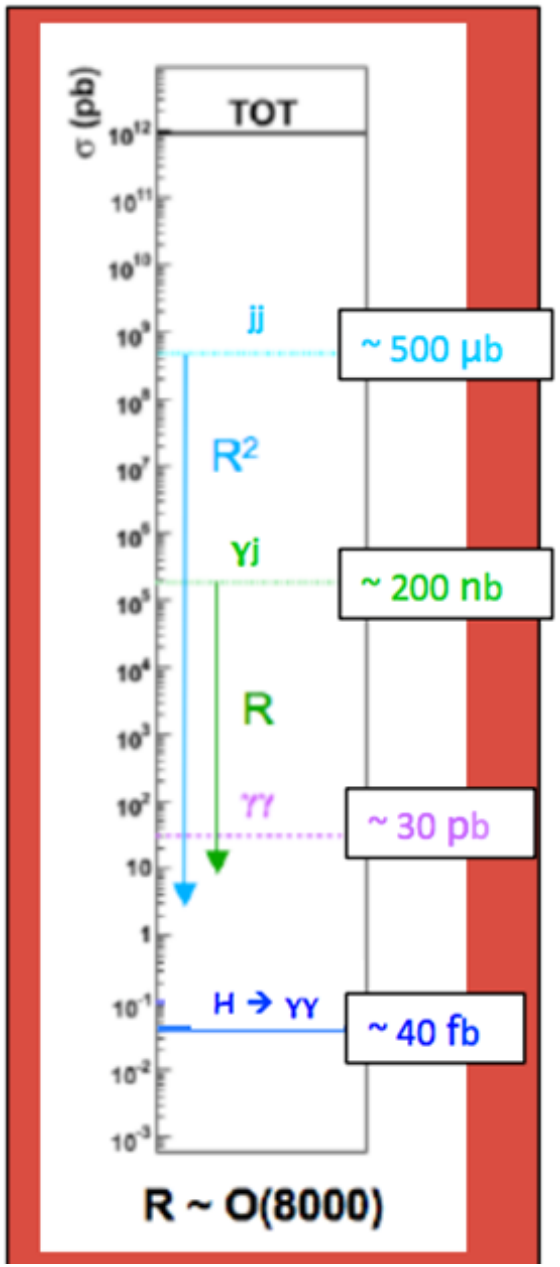
arXiv:1101.0593, arXiv:1201.3084



	Luminosity	Higgs produced	Decayed to diphoton	Selected
7 TeV	4.8 fb^{-1}	~83,000	~190	~80
8 TeV	20.7 fb^{-1}	~458,000	~1000	~420

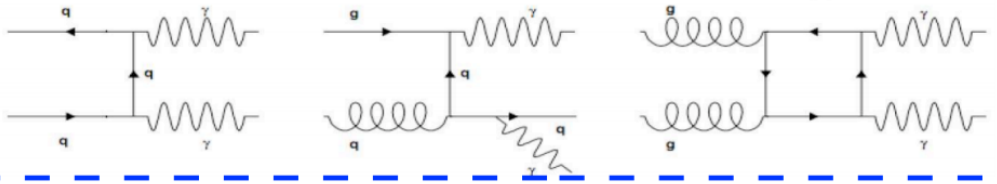
SM expectation assuming m_H = 125.5 GeV

Background

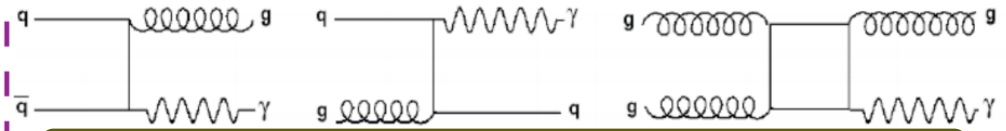


Both photons are not fake

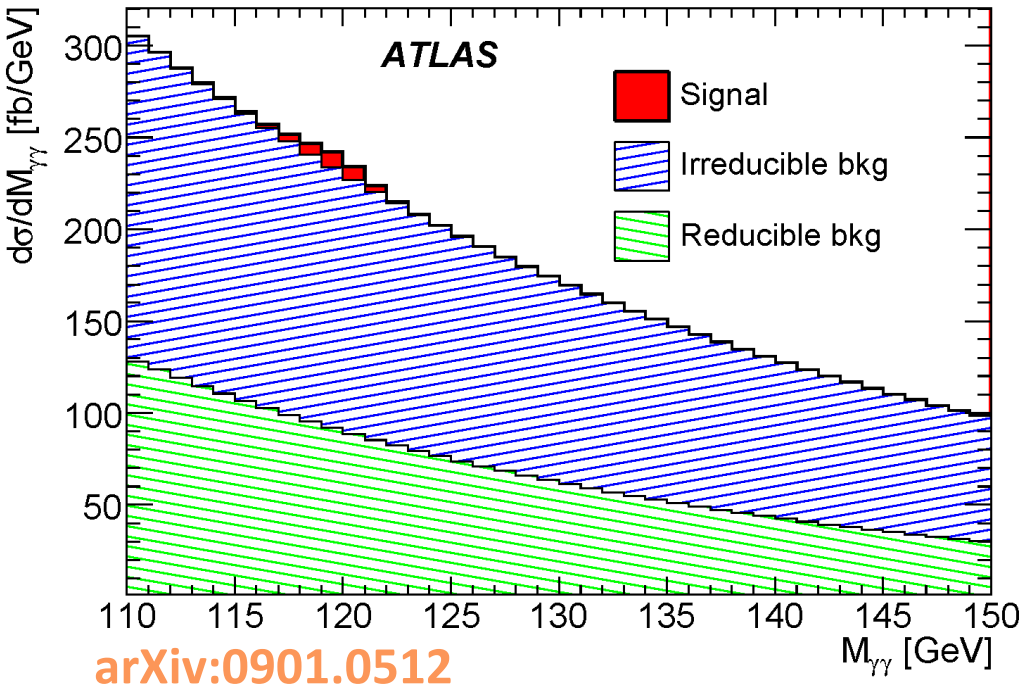
Irreducible background: SM diphoton production



Reducible background: photon+jets production



where a jet is misidentified as a photon (mostly, a pi0)

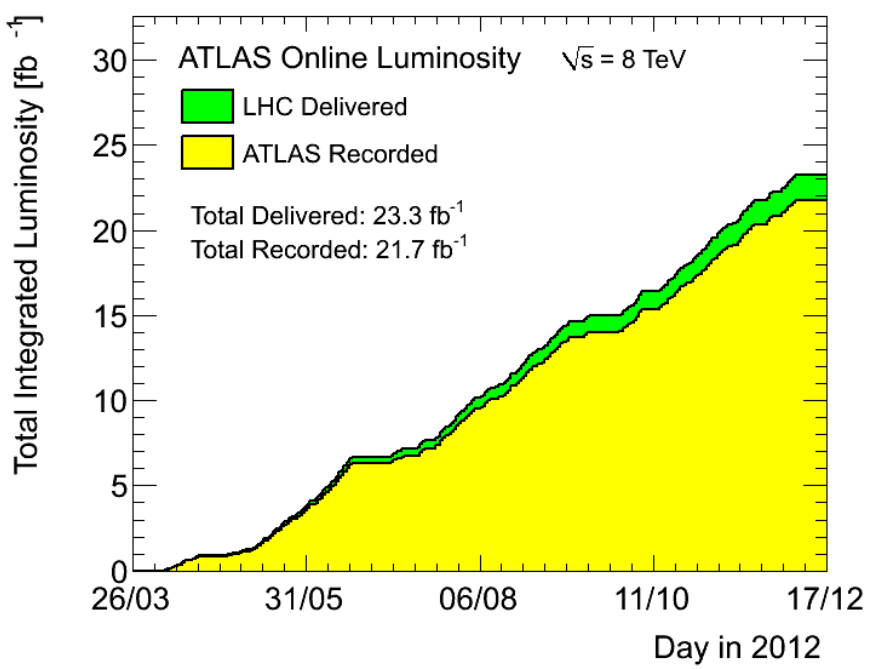


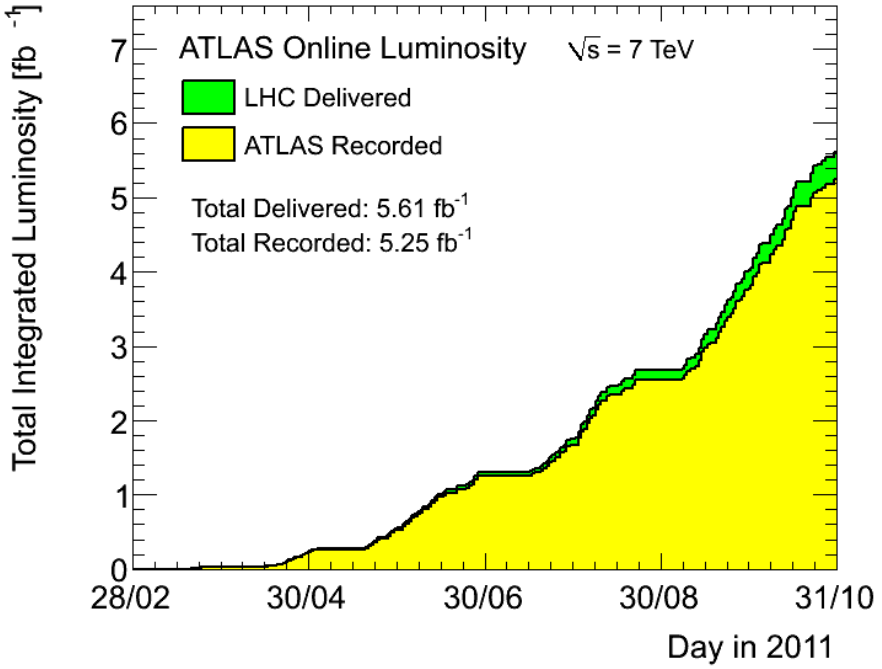
arXiv:0901.0512

Select $H \rightarrow \gamma\gamma$ candidates

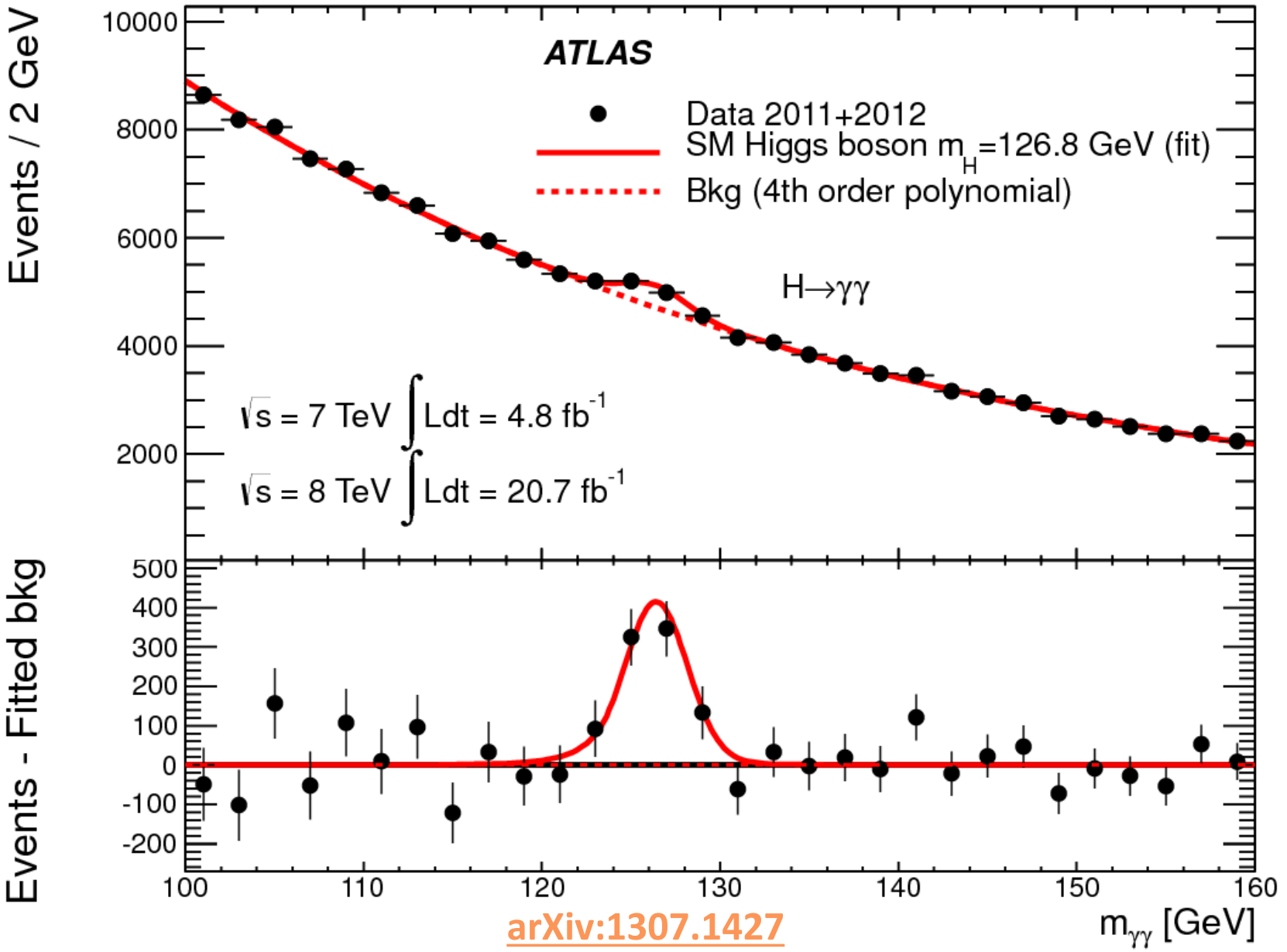
- Very simple diphoton candidates selection:
  - $p_T(\gamma_1,\gamma_2) > 40, 30$ GeV
  - $|\eta| < 1.37$ or $1.56 < |\eta| < 2.37$
  - Isolated photon, passing photon identification criteria

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResults





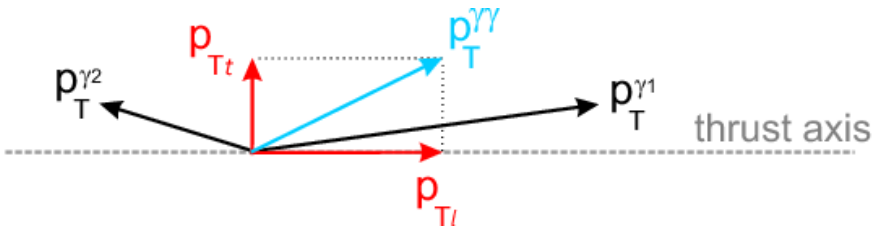
Invariant mass spectrum

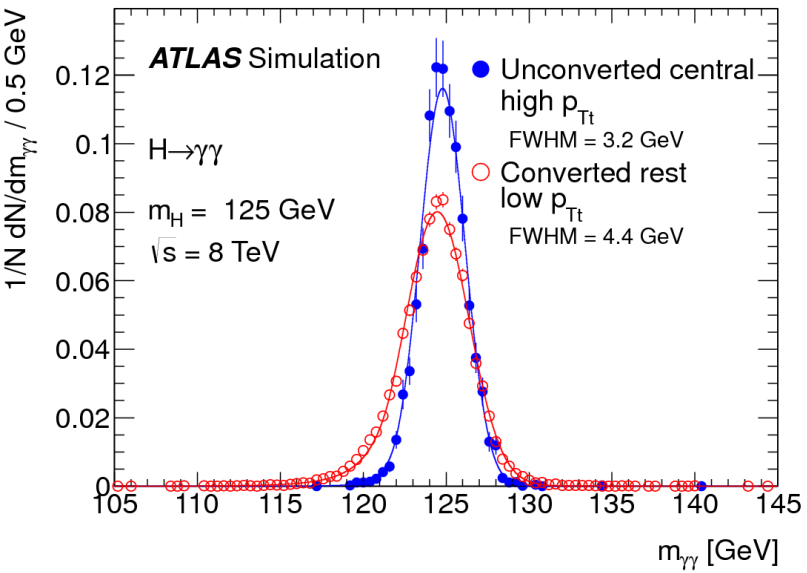


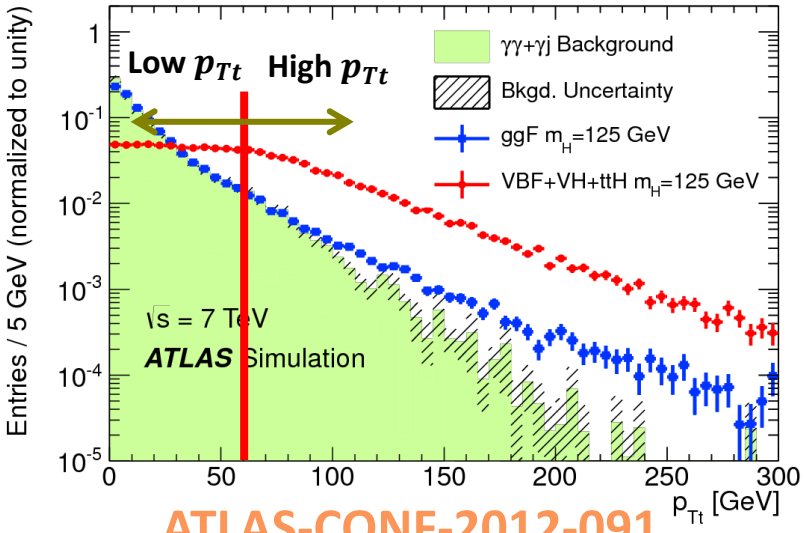
arXiv:1307.1427

Categorization

- **Enhance the sensitivity**: classifying events to categories with different S/B and resolution.
  - Using photon η, photon conversion status and p_{Tt} to define categories.
  - Important for the search



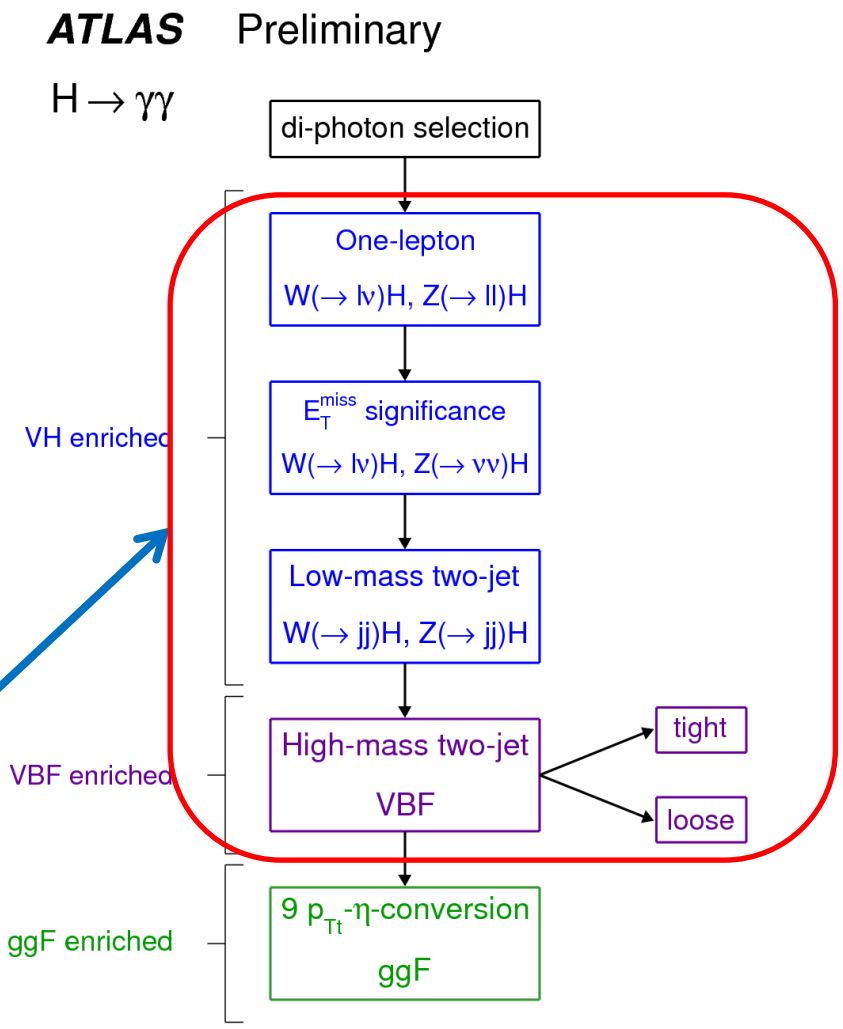




ATLAS-CONF-2012-091

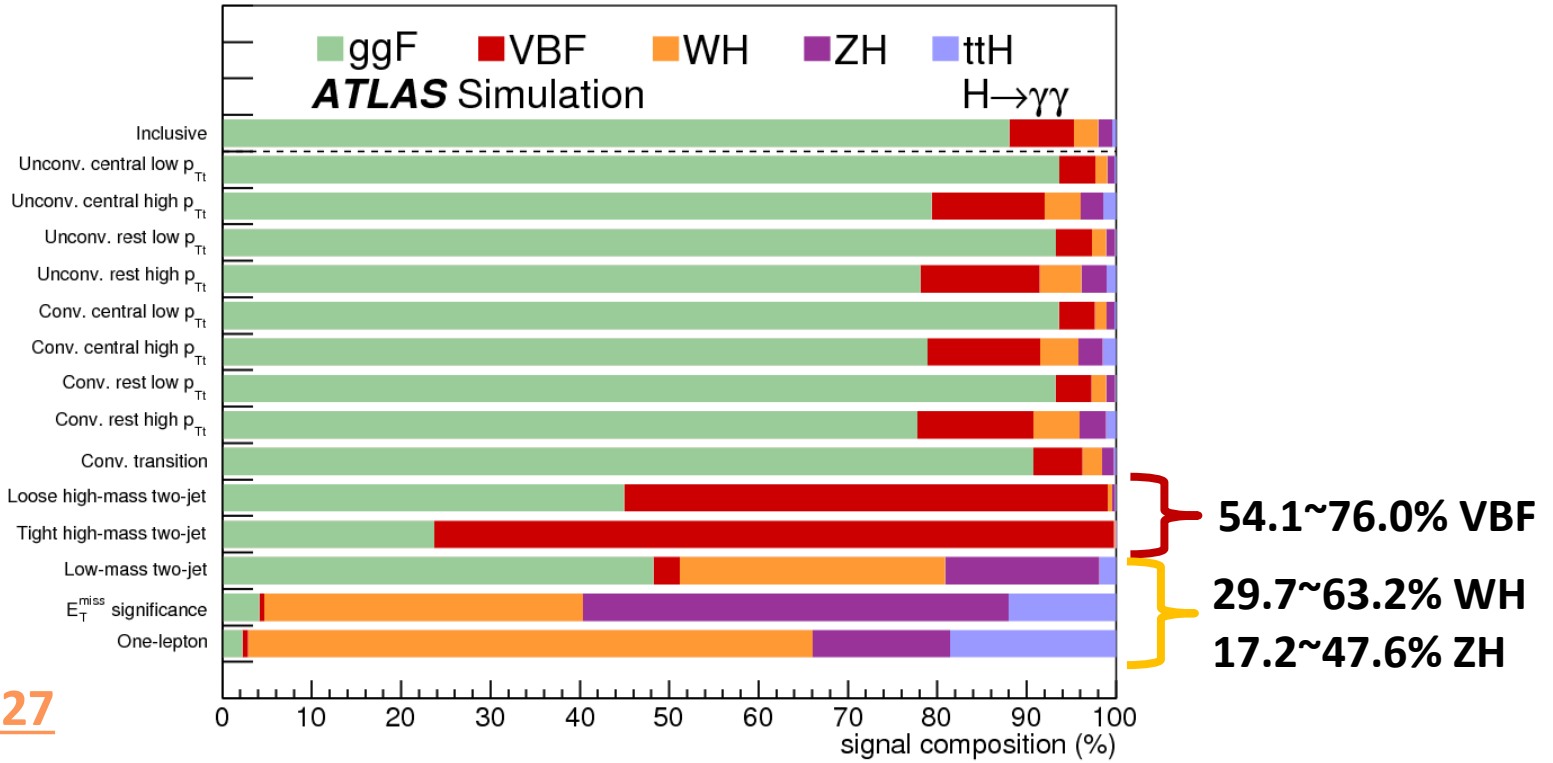
Categorization

- **Enhance the sensitivity**: classifying events to categories with different S/B and resolution.
  - Using photon η, photon conversion status and p_{Tt} to define categories.
  - Important for the search
- **Enhance the sensitivity to particular Higgs boson production modes**: isolate events with distinct topologies.
  - Important for the coupling measurements



ATLAS-CONF-2013-012

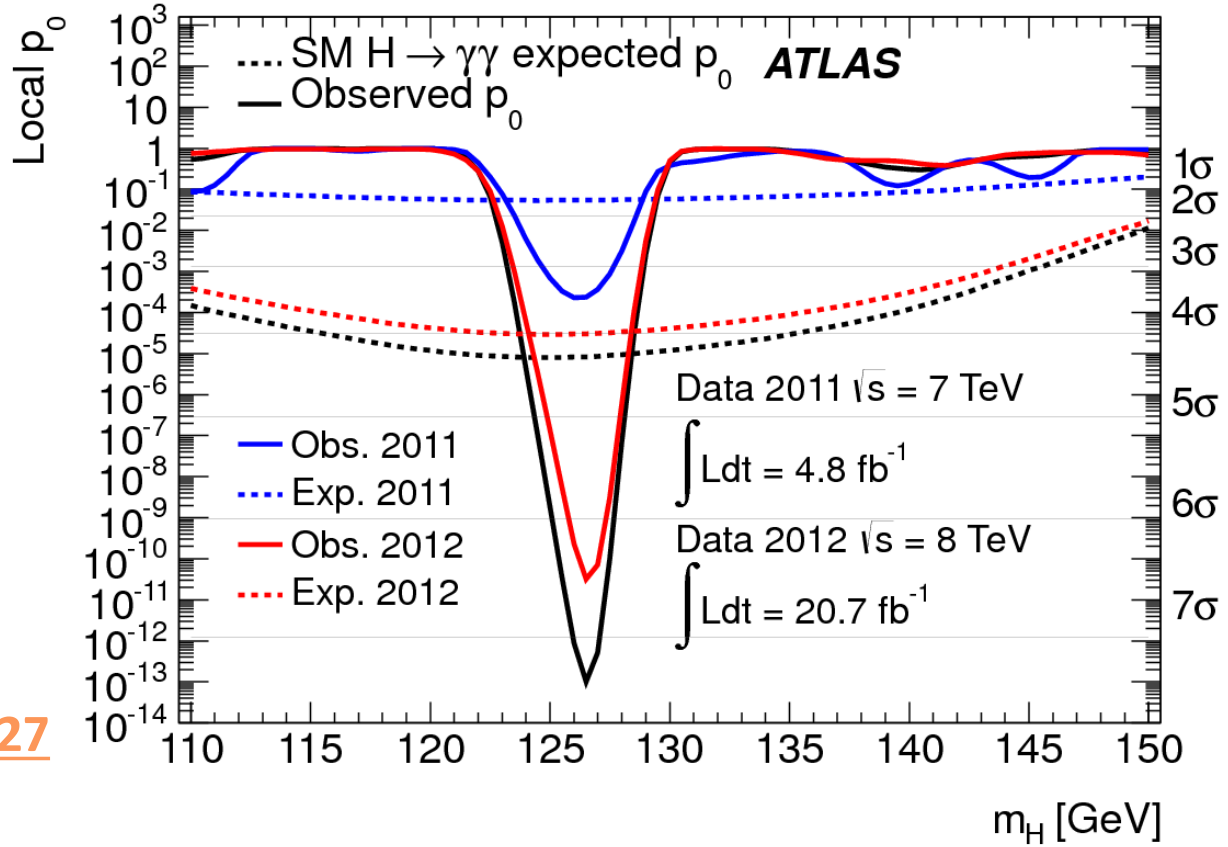
Signal decomposition



arXiv:1307.1427

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

Signal significance



arXiv:1307.1427

	m_H (GeV)	Expected Z (σ)	Observed Z (σ)
7 TeV	126.0	1.6	3.3
8 TeV	126.5	4.0	6.5
Combined	126.5	4.3	**7.4**

Signal strength

- Signal strength (μ) : number of observed signal events over number of expected signal events.
  - For the inclusive production: μ
  - For each Higgs production mode: $\mu_i \times BR/BR_{SM}$ $(i = ggH + t\bar{t}H, VBF, VH\ldots)$
- *Categorization made coupling measurements possible*

N_i: observed signal events in category i.
$S_{i,j}$: SM signal yield in category i for the Higgs boson production mode j.

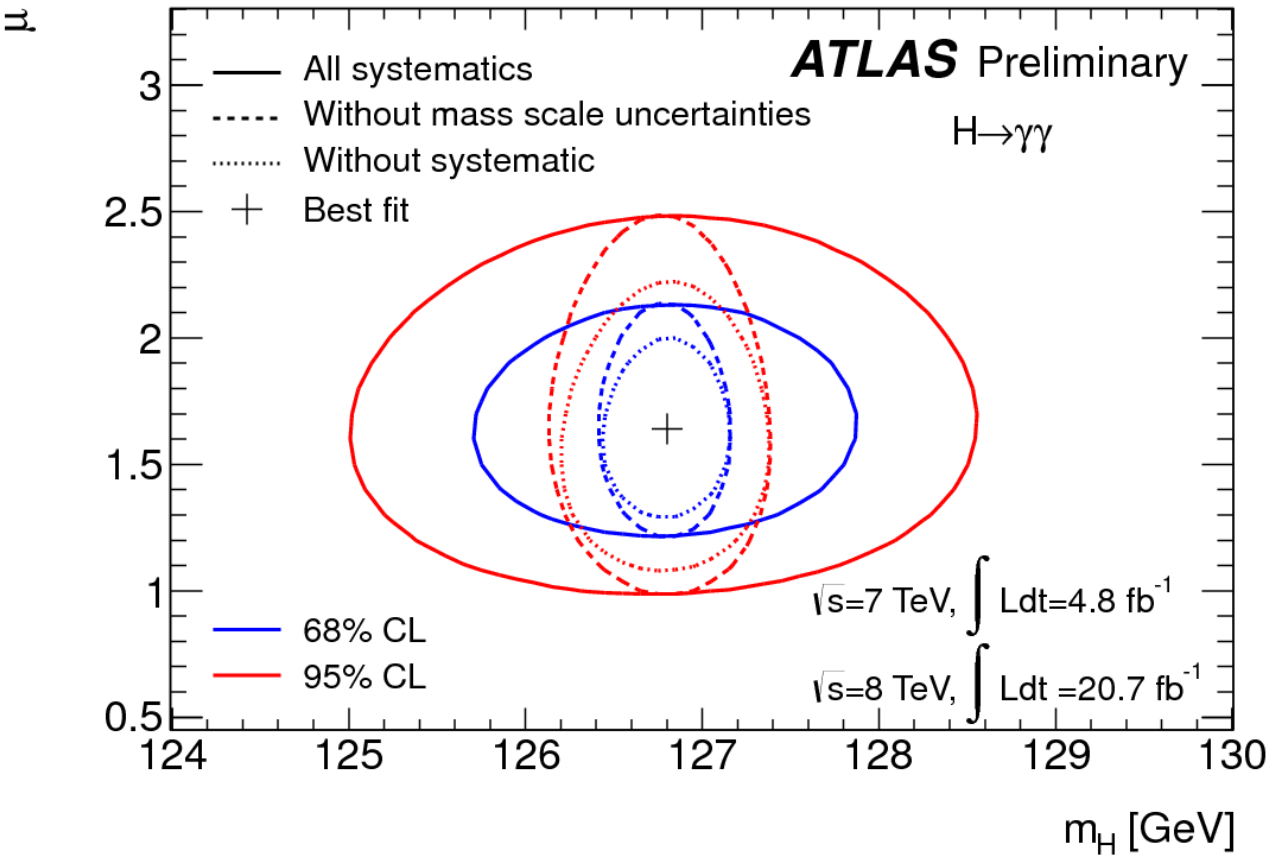
$$N \approx \mu \times S$$

$$\begin{pmatrix} N_1 \\ \vdots \\ N_i \end{pmatrix} \approx \begin{pmatrix} S_{1,1} & \cdots & S_{1,j} \\ \vdots & \ddots & \vdots \\ S_{i,1} & \cdots & S_{i,j} \end{pmatrix} \times \begin{pmatrix} \mu_1 \\ \vdots \\ \mu_j \end{pmatrix}$$

Inclusive
model independent

Categorized
model dependent

Mass measurement



- m_H is extracted from a fit with both signal position and normalization free.
- $\boldsymbol{m_H = 126.8 \pm 0.2\,(stat) \pm 0.7\,(syst)}$ **GeV**
- Dominant uncertainty: mass scale systematics.

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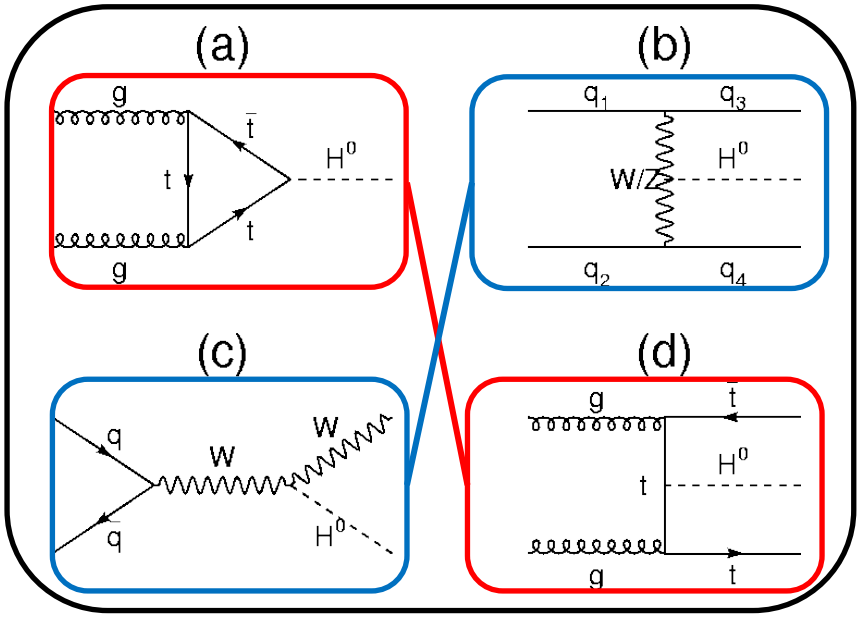
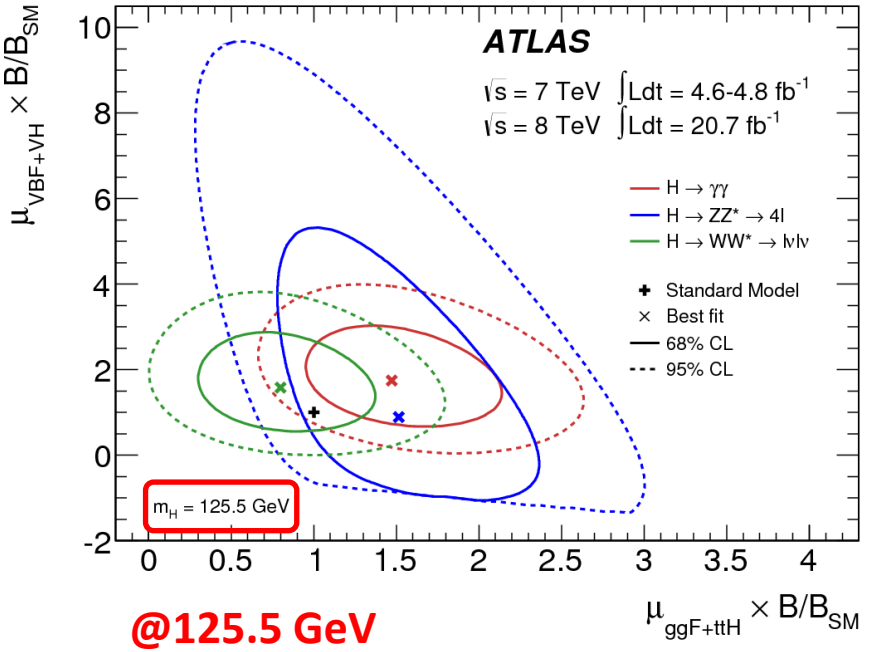
Inclusive signal strength measurement

- $\boldsymbol{\mu = 1.57 \pm 0.22\,(stat)^{+0.17}_{-0.13}(syst)^{+0.17}_{-0.12}(theory)}$ with m_H = 126.8 GeV
  - Theory uncertainty (*theory*): QCD scale, PDF and branching ratio uncertainties.
  - Systematic uncertainty (*syst*): all the other uncertainties.
- The possibility that a SM signal fluctuate to the observation is 3%, corresponding to 1.9σ deviation from the SM S+B hypothesis (@125.5 GeV).

arXiv:1307.1427

Coupling with fermions vs. coupling with bosons



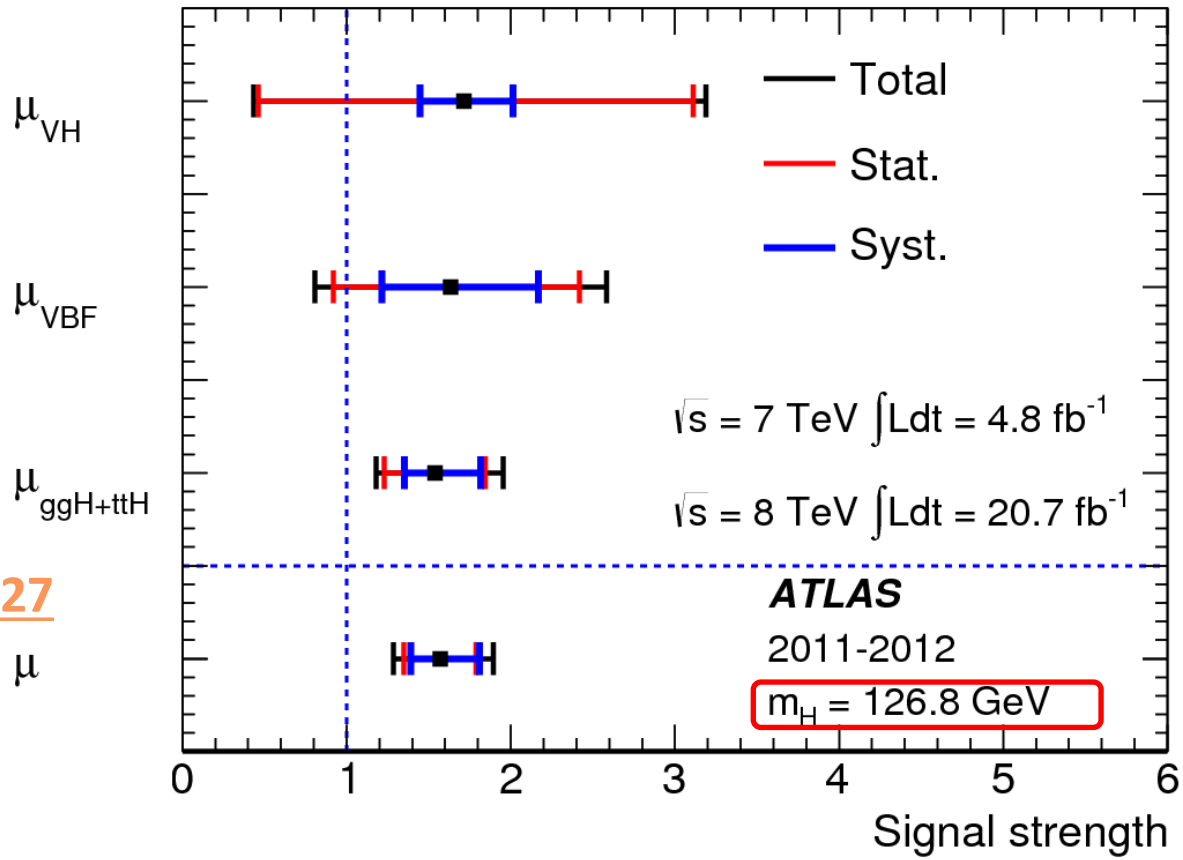


@125.5 GeV

- $ggH + t\bar{t}H$: coupling with fermion (top quark)
- $VBF + VH$: coupling with vector boson
- Consistent with SM within 2σ (Results from $4l$ and WW channels are consistent with SM within 1σ).
- Evaluated @125.5GeV: difference compared with results @126.8GeV is small due to large uncertainty on m_H (700 MeV) in this channel.

arXiv:1307.1427

Coupling measurements results



arXiv:1307.1427

$\mu = 1.57^{+0.32}_{-0.28}$

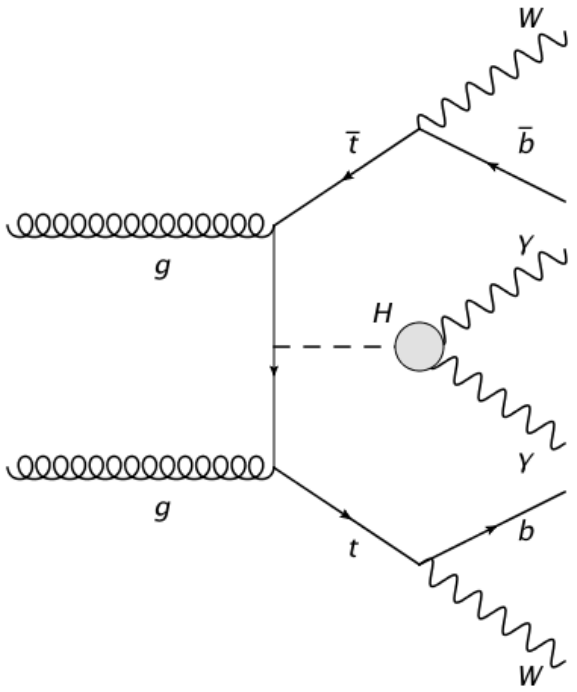
$$\mu_{ggH+t\bar{t}H} \times BR/BR_{SM} = 1.54^{+0.31}_{-0.31}(stat)^{+0.28}_{-0.18}(syst)$$

$$\mu_{VBF} \times BR/BR_{SM} = 1.63^{+0.78}_{-0.71}(stat)^{+0.53}_{-0.42}(syst)$$

$$\mu_{VH} \times BR/BR_{SM} = 1.71^{+1.40}_{-1.25}(stat)^{+0.30}_{-0.27}(syst)$$

Search for $t\bar{t}H$ (New)

- Crucial for understanding the Yukawa coupling between the top quark and the Higgs boson
- Two channels
  - Leptonic: $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow l\nu b + l\nu b/jjb$
  - Hadronic: $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow 4j + b\bar{b}$



ATLAS-CONF-2013-080

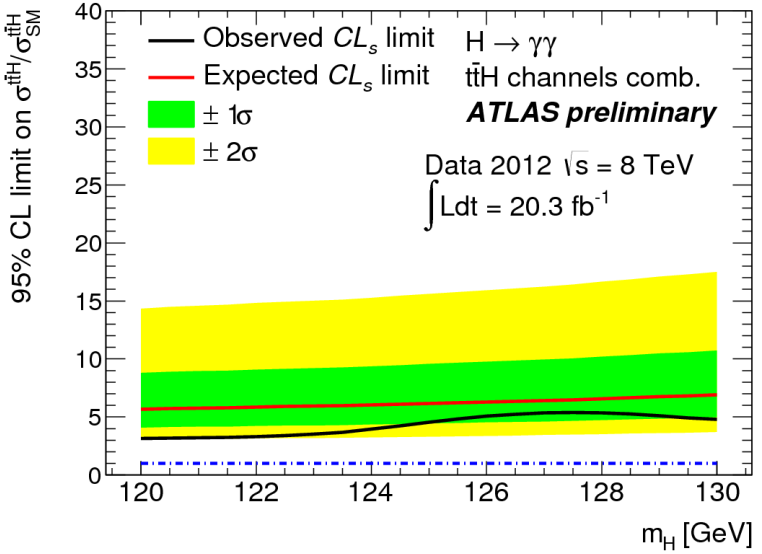
Channel	N_S	$ggH(\%)$	$VBF(\%)$	$WH(\%)$	$ZH(\%)$	$tH(\%)$	$t\bar{t}H(\%)$	N_B	N_S/N_B
Leptonic	0.55	0.6	0.3	7.7	2.4	6.1	82.8	$1.2^{+0.6}_{-0.5}$	0.45
Hadronic	0.36	5.3	1.1	1.1	1.3	0.0	91.2	$1.9^{+0.7}_{-0.5}$	0.19

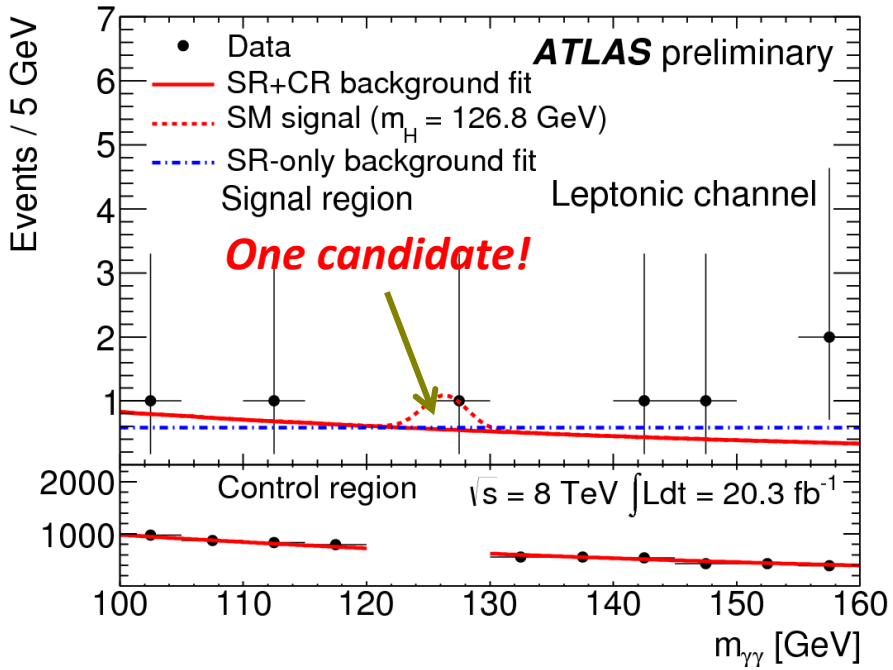
Signal decomposition in the two $t\bar{t}H$ channels

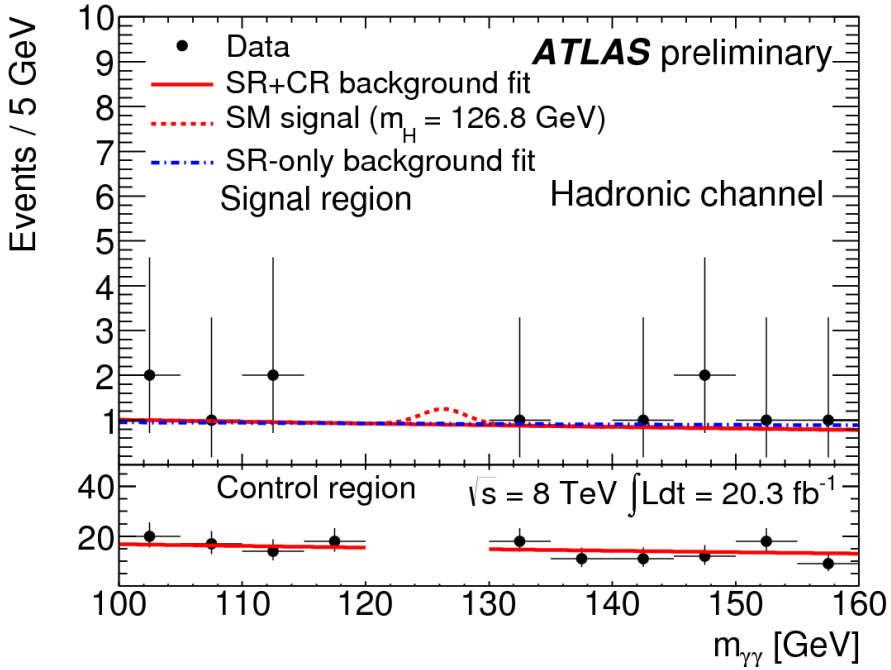
Limit on $t\bar{t}H, H \rightarrow \gamma\gamma$ (New)

- The exclusion limits @ 95% C.L. on $t\bar{t}H, H \rightarrow \gamma\gamma$ production @m_H=126.8 GeV are
  - Observed 5.3×SM
  - Expected 6.4×SM

ATLAS-CONF-2013-080







Conclusion I

- The significance of the newly observed particle in diphoton final state reaches **7.4 σ.**
- The mass of the particle is measured to be $m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)$ **GeV**
- The signal strength @126.8 GeV is

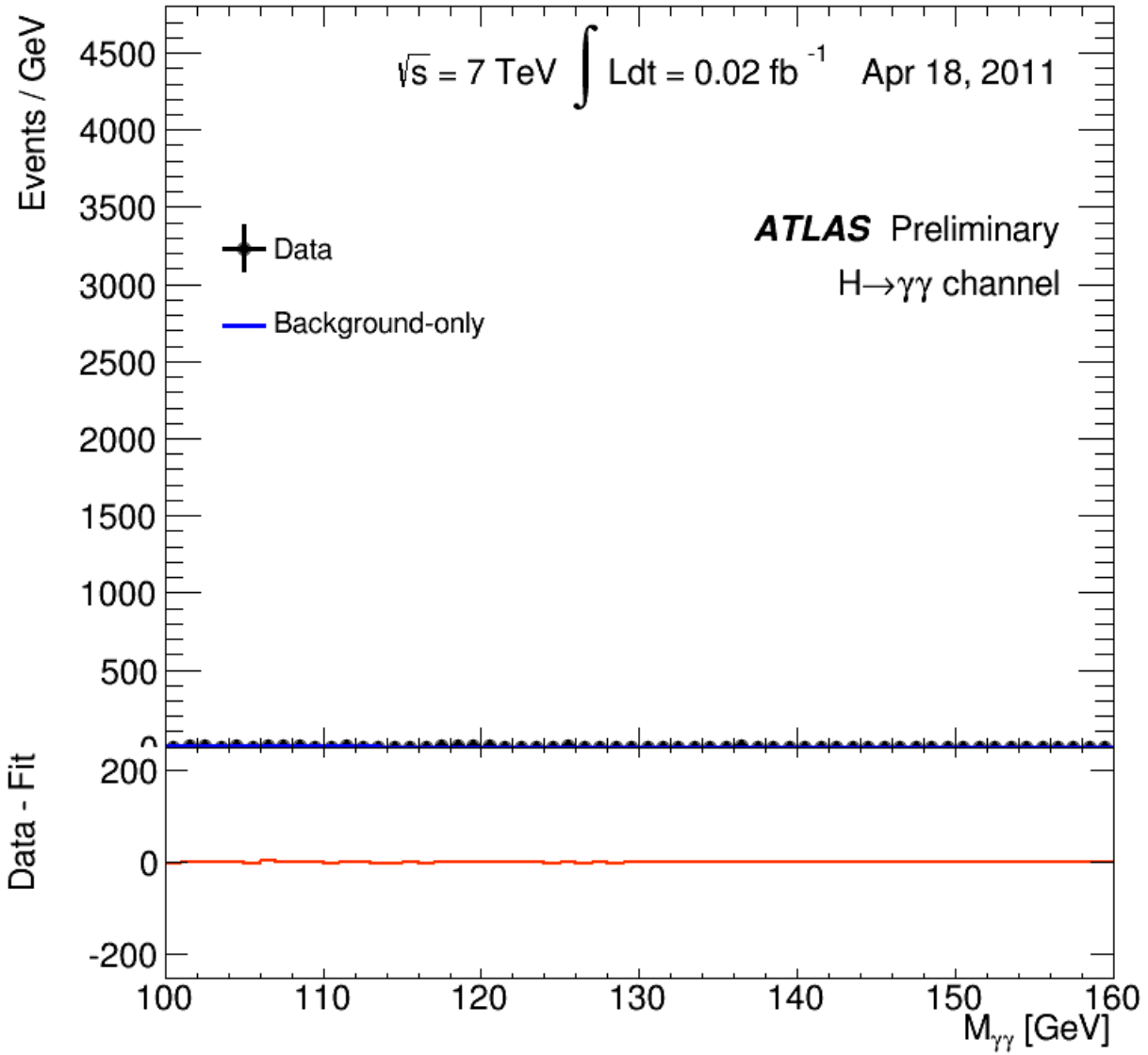
$$\mu = 1.57 \pm 0.22\,(stat)^{+0.17}_{-0.13}(syst)^{+0.17}_{-0.12}(theory)$$

- Tension between data and SM observed. More data will be needed to confirm or dismiss it.

Conclusion II

- The coupling measurements results are
  - $\boldsymbol{\mu_{ggH+t\bar{t}H} \times BR/BR_{SM} = 1.54^{+0.31}_{-0.31}(stat)^{+0.28}_{-0.18}(syst)}$
  - $\boldsymbol{\mu_{VBF} \times BR/BR_{SM} = 1.63^{+0.78}_{-0.71}(stat)^{+0.53}_{-0.42}(syst)}$
  - $\boldsymbol{\mu_{VH} \times BR/BR_{SM} = 1.71^{+1.40}_{-1.25}(stat)^{+0.30}_{-0.27}(syst)}$
- The observed exclusion limit on $t\bar{t}H, H \rightarrow \gamma\gamma$ at 95% confidence level @126.8 GeV is 5.3×SM prediction. The expected limit is 6.4×SM.
- More updates expected to come later this year from ATLAS. Stay tuned!

Bonus: Animated Invariant mass spectrum



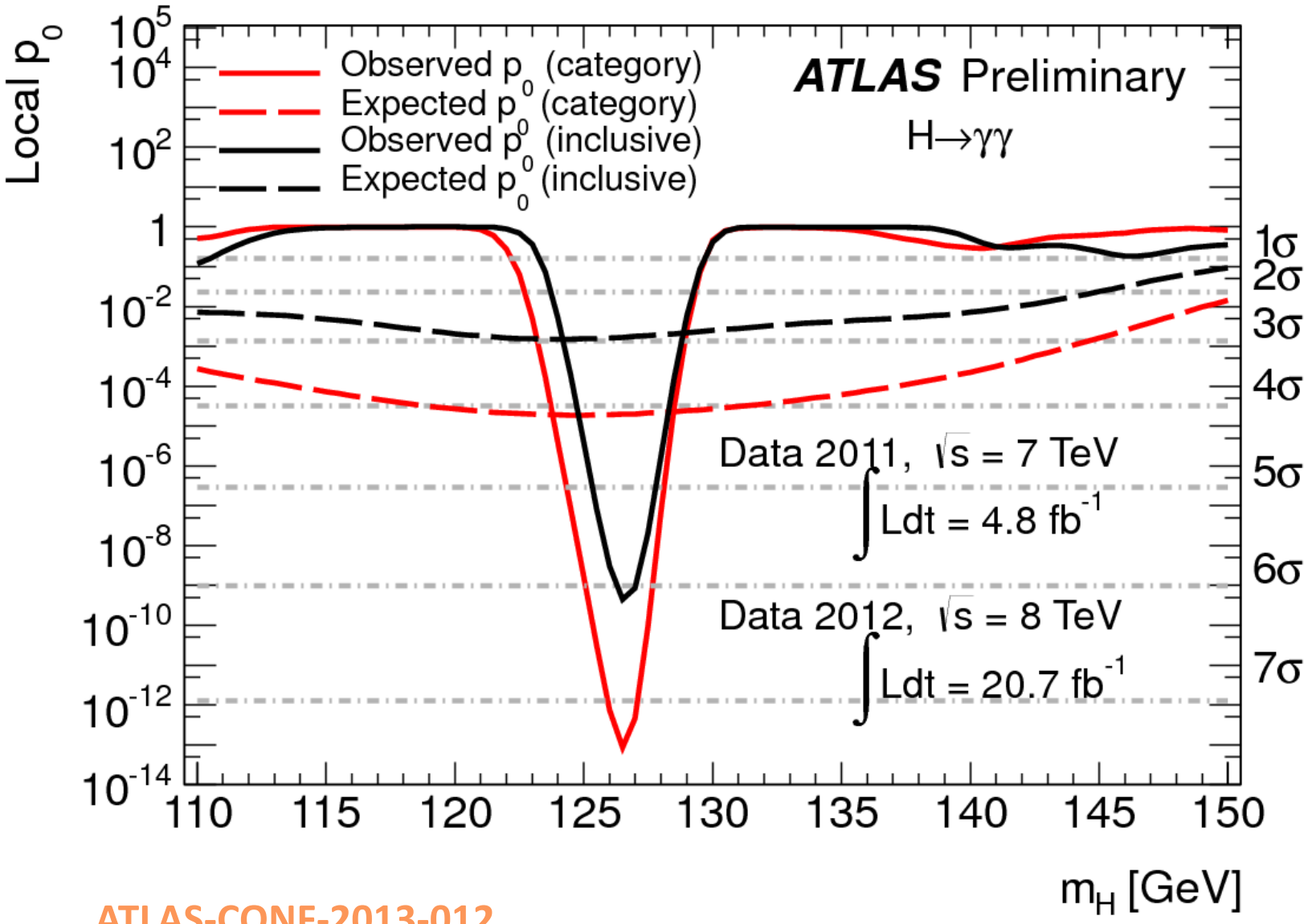
https://twiki.cern.ch/twiki/pub/AtlasPublic/HiggsPublicResults/Hgg-FixedScale-Short2.gif

References

- arXiv:0901.0512: *Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics*
- arXiv:1101.0593: *Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables*
- arXiv:1201.3084: *Handbook of LHC Higgs Cross Sections: 2. Differential Distributions*
- ATLAS-CONF-2012-091: *Observation of an excess of events in the search for the Standard Model Higgs boson in the gamma-gamma channel with the ATLAS detector*
- *Phys. Lett. B 716 (2012) 1-29*: *Observation of a New Particle in the Search for the Standard Moddel Higgs Boson with the ATLAS Detector at the LHC*
- ATLAS-CONF-2013-012: *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*
- arXiv:1307.1427: *Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*
- ATLAS-CONF-2013-080: *Search for ttH production in the H → γγ channel at √s = 8 TeV with the ATLAS detector*

BACK UP

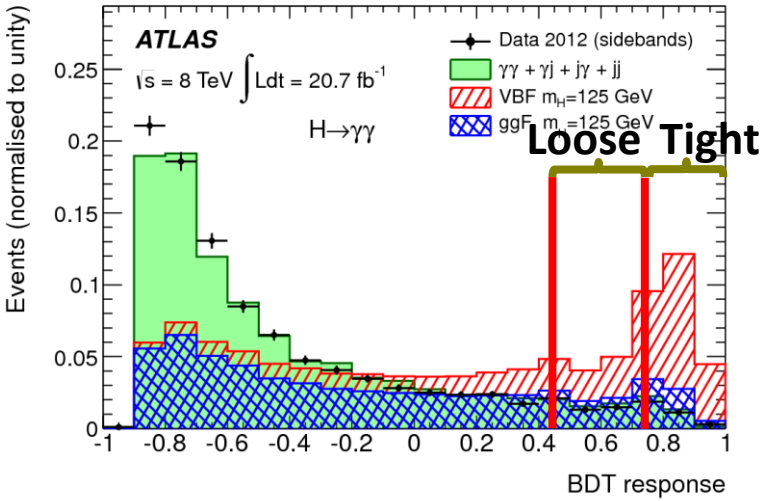
Peak significance in the inclusive spectrum

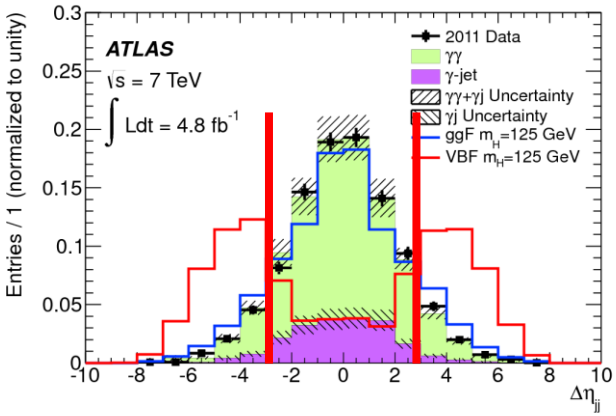


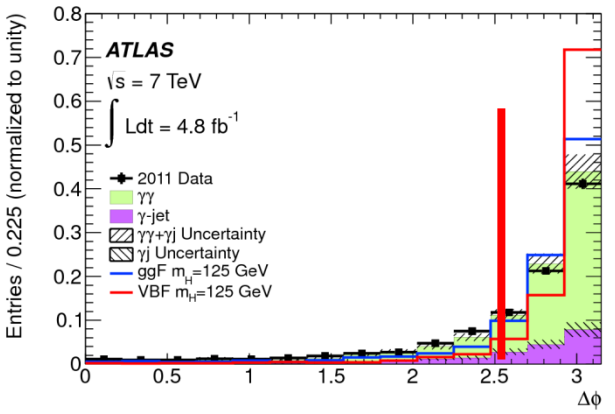
ATLAS-CONF-2013-012

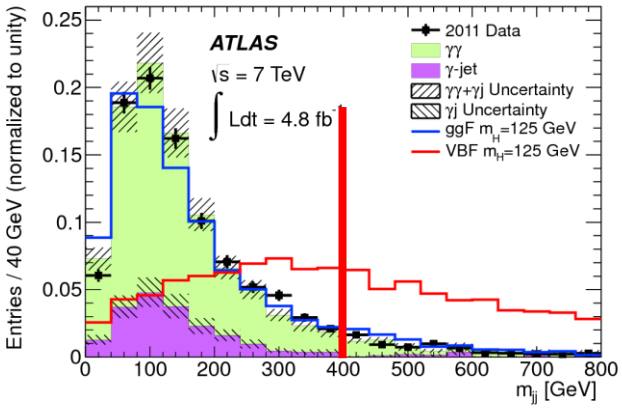
VBF categories

- 7 TeV: $|\Delta\eta_{jj}| > 2.8$, $\Delta\phi_{\gamma\gamma,jj} > 2.6$, $m_{jj} > 400$ GeV.
- 8 TeV: Boost Decision Tree (BDT).
  - Inputs: $\eta_{j1}, \eta_{j2}, \Delta\eta_{jj}, m_{jj}, \eta^* = \eta_{\gamma\gamma} - (\eta_{j1} + \eta_{j2})/2, \Delta\phi_{\gamma\gamma,jj}, \Delta R(\gamma, j)$
  - 2 categories according to BDT score:
    - "Loose": 0.44<BDT<0.74
    - "Tight": BDT>0.74









Phys. Lett. B 716 (2012) 1-29, arXiv:1307.1427

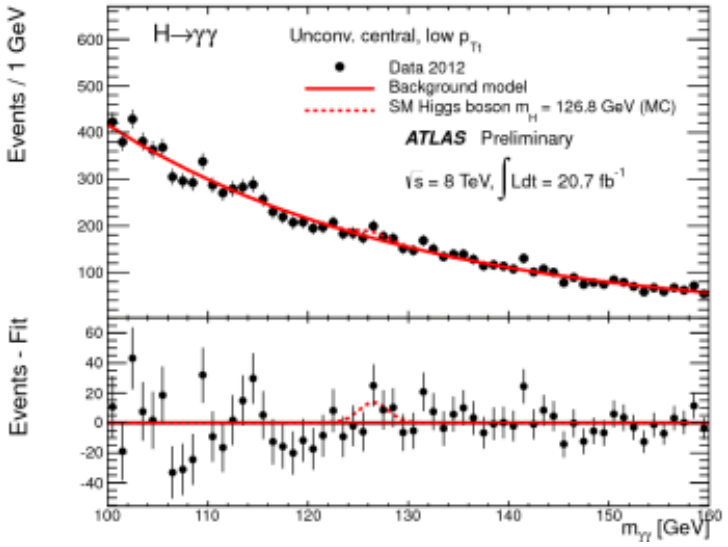
VH categories

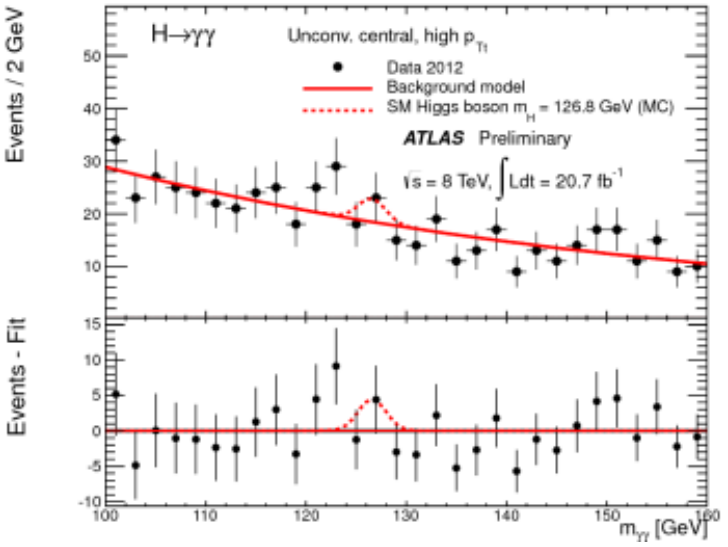
- Lepton category (8 TeV only): $\boldsymbol{VH \rightarrow l\nu/ll\gamma\gamma}$.
  - Requiring an isolated electron or muon candidate.
  - Vetoing events with 84 GeV <$m_{e\gamma}$<94GeV.
- E_T^{miss} category (8 TeV only): $\boldsymbol{VH \rightarrow l\nu/\nu\nu\gamma\gamma}$.
  - Requiring E_T^{miss} significance (defined as $E_T^{miss}/\sigma_{E_T^{miss}}$, where $\sigma_{E_T^{miss}} = 0.67GeV^{1/2}\sqrt{\sum E_T}$) larger than 5.
- Low-mass two-jet category (8 TeV only): $\boldsymbol{VH \rightarrow jj\gamma\gamma}$.
  - 60 GeV < m_{jj} < 110 GeV.
  - $\left|\Delta\eta_{\gamma\gamma,jj}\right| < 1$
  - $p_{Tt} > 70$ GeV

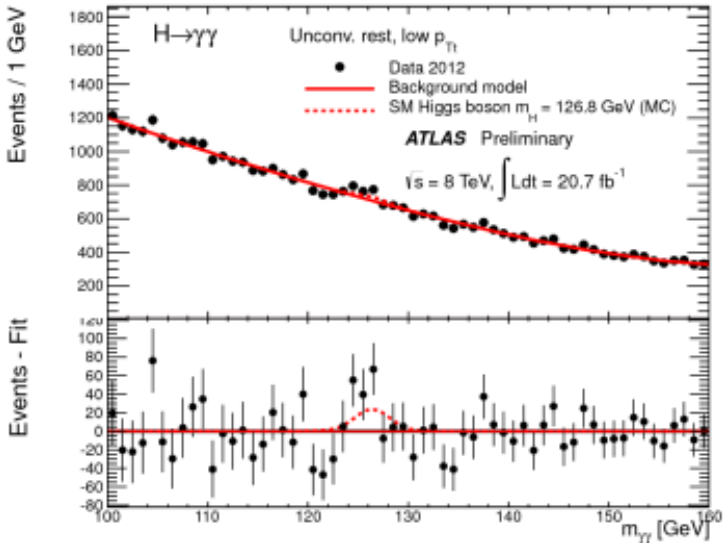
arXiv:1307.1427

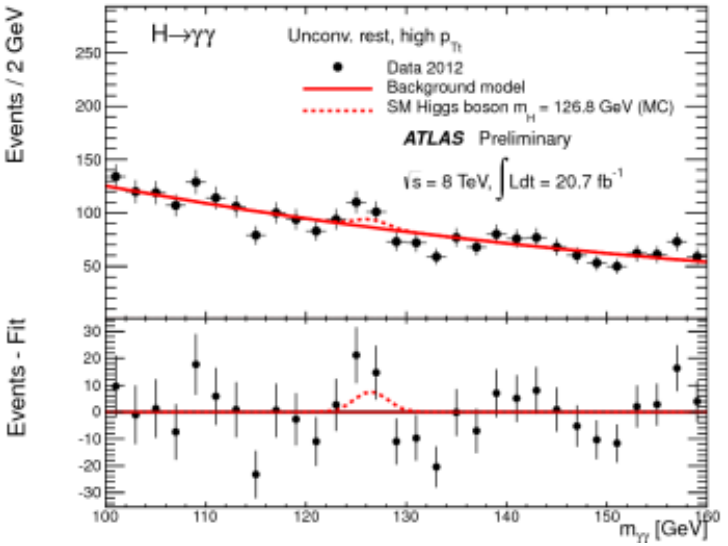
All Categories

Phys. Lett. B 716 (2012) 1-29, ATLAS-CONF-2013-012



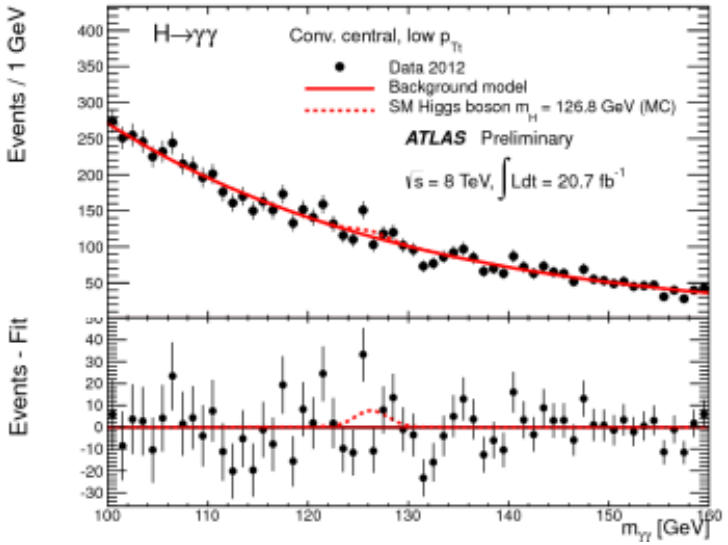


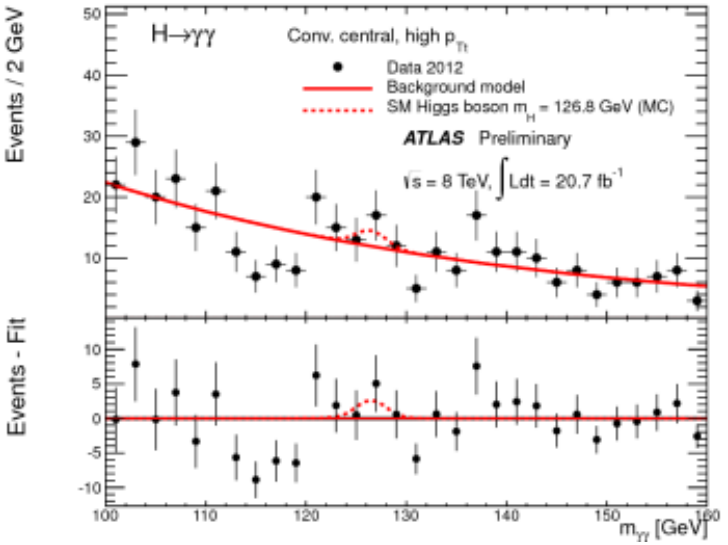


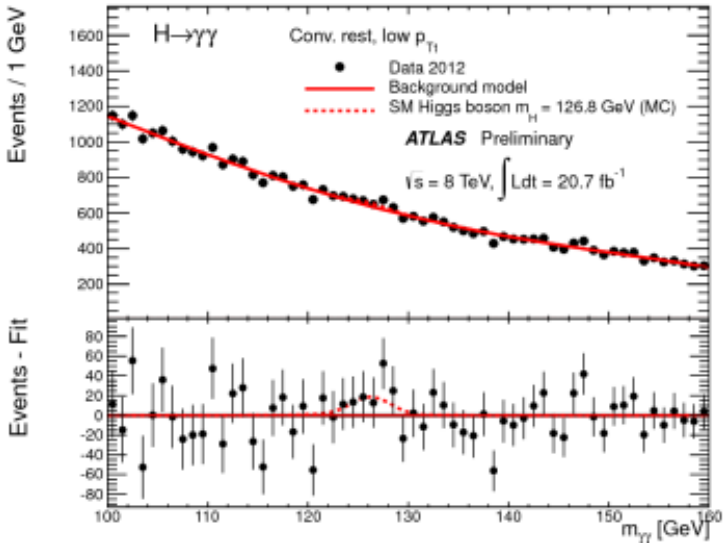


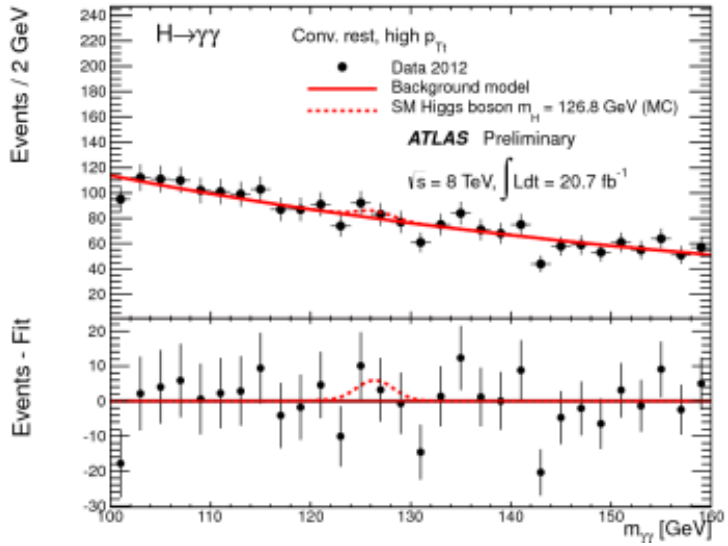
All Categories

Phys. Lett. B 716 (2012) 1-29, ATLAS-CONF-2013-012









All Categories

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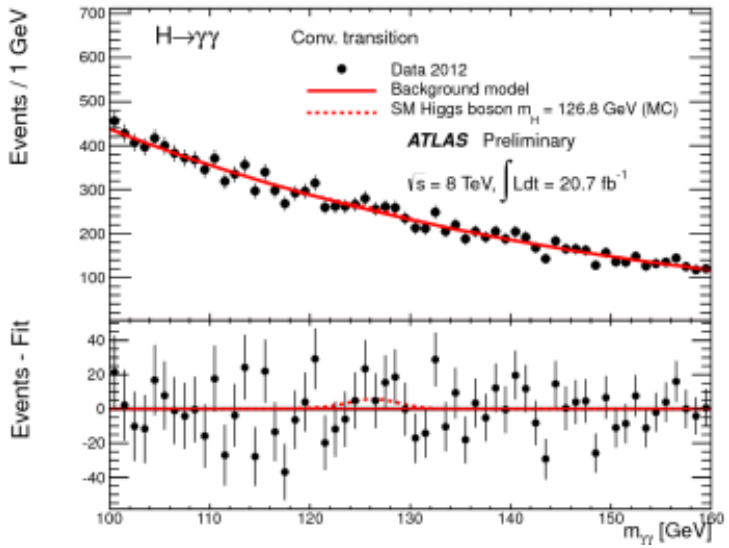

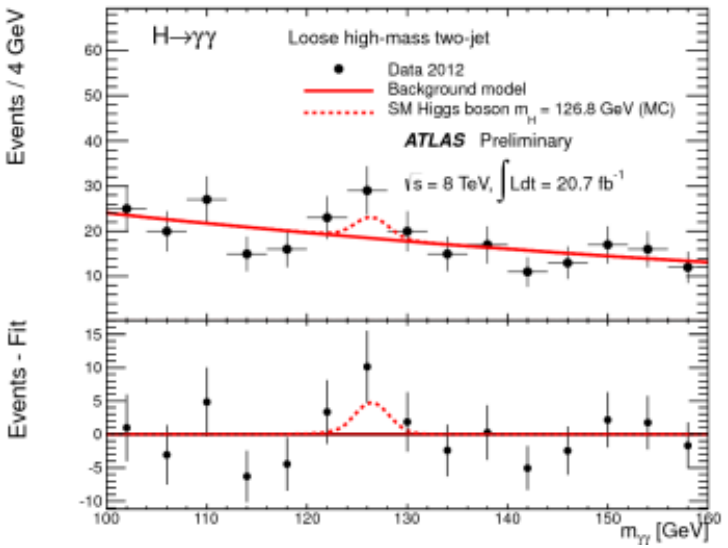

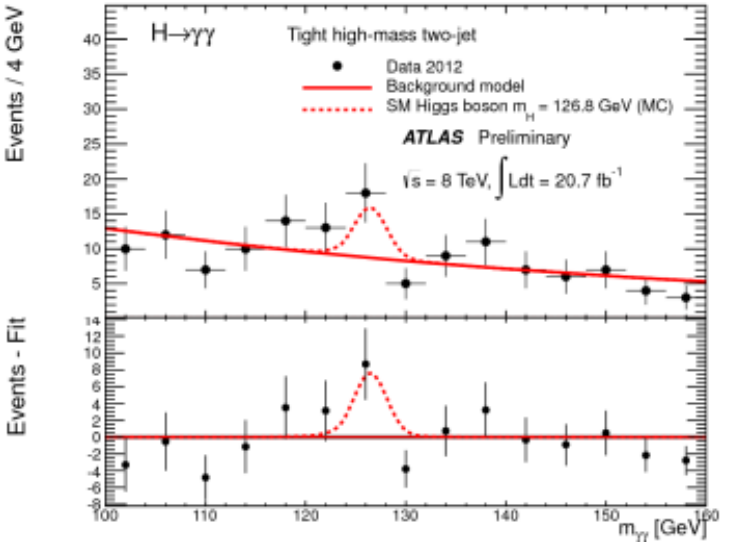

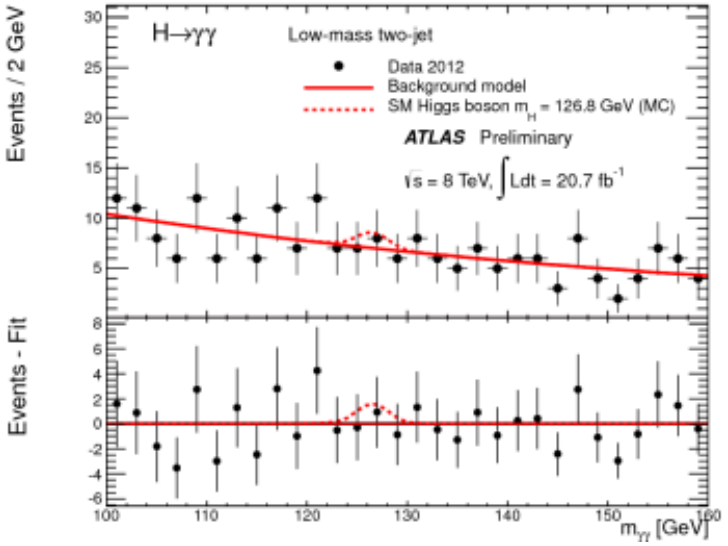

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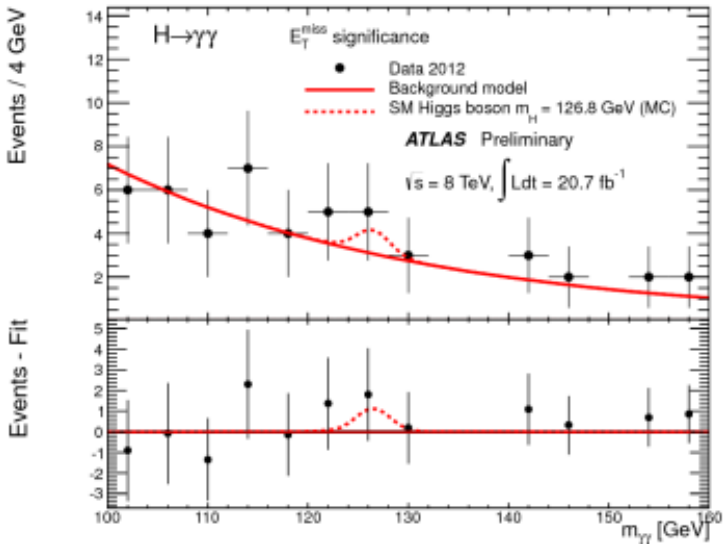

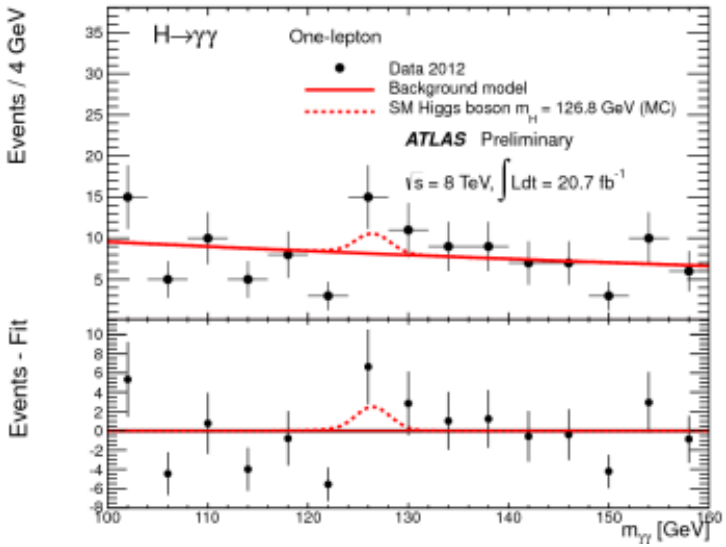

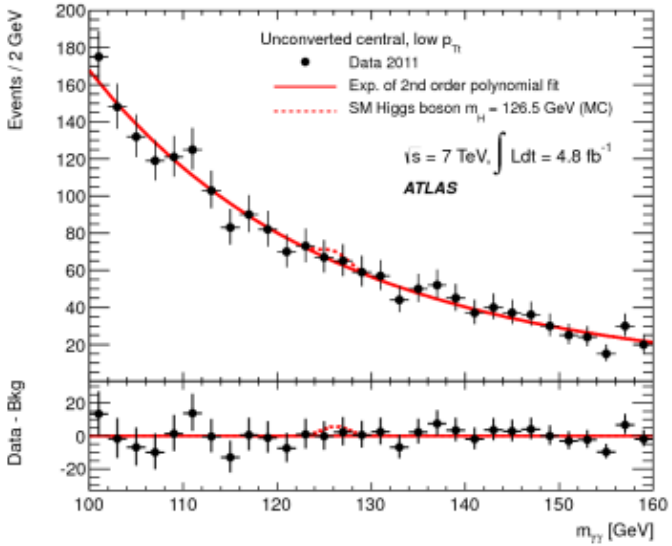

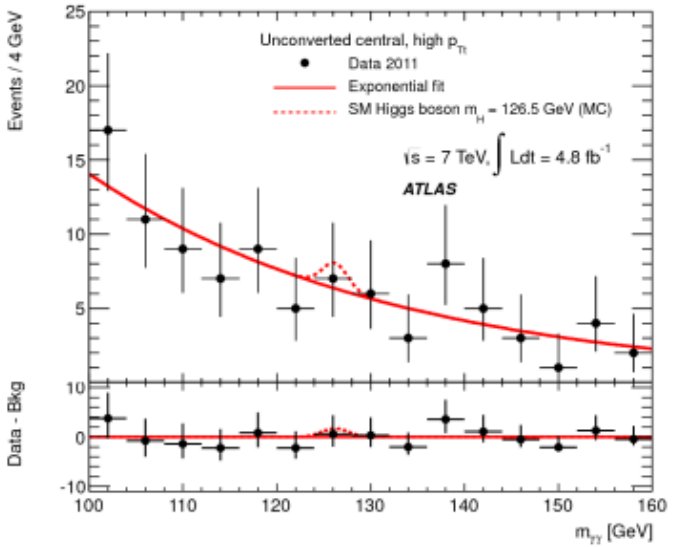

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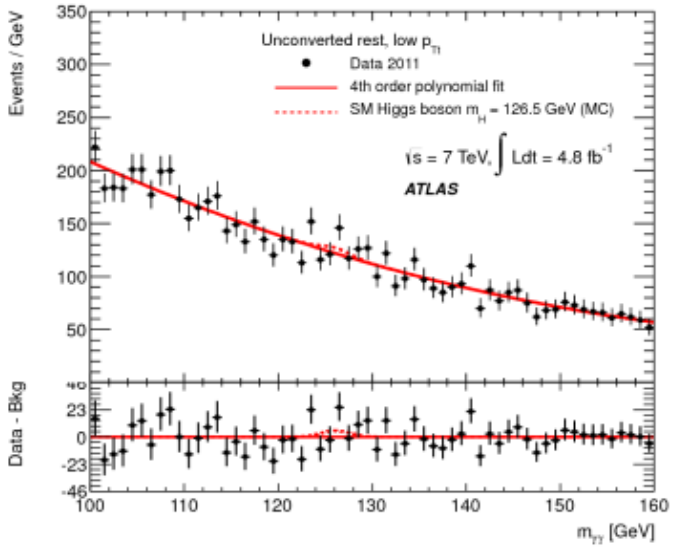

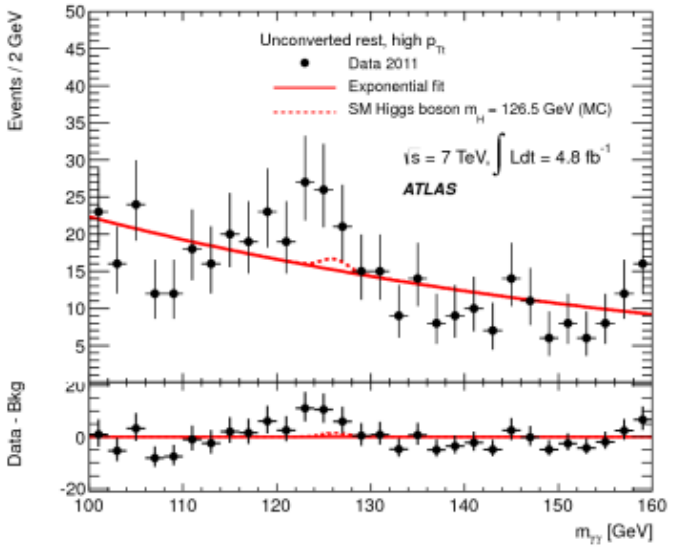

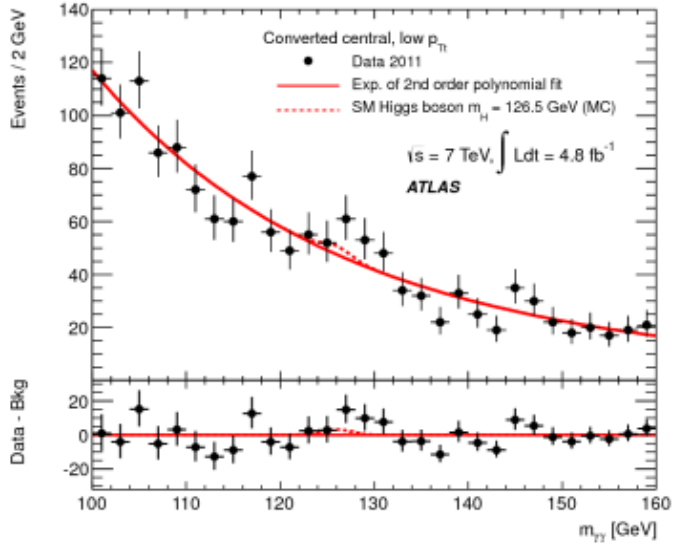

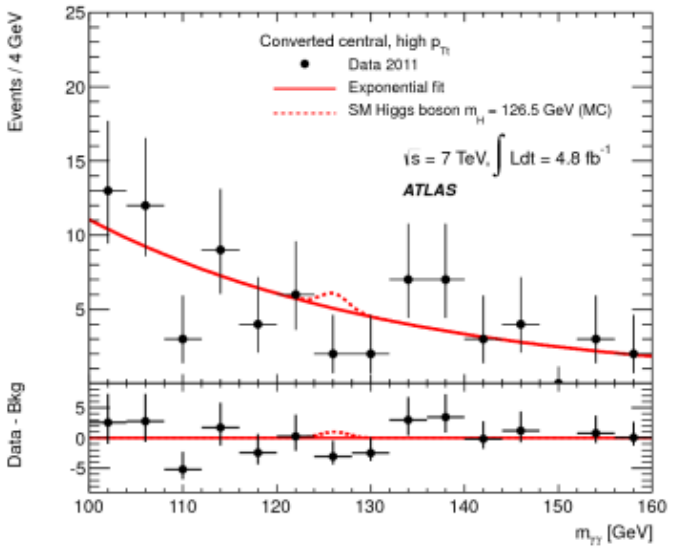

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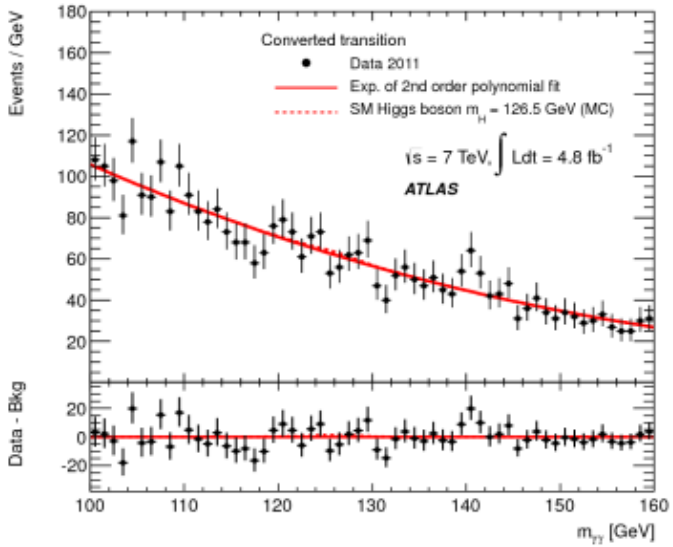
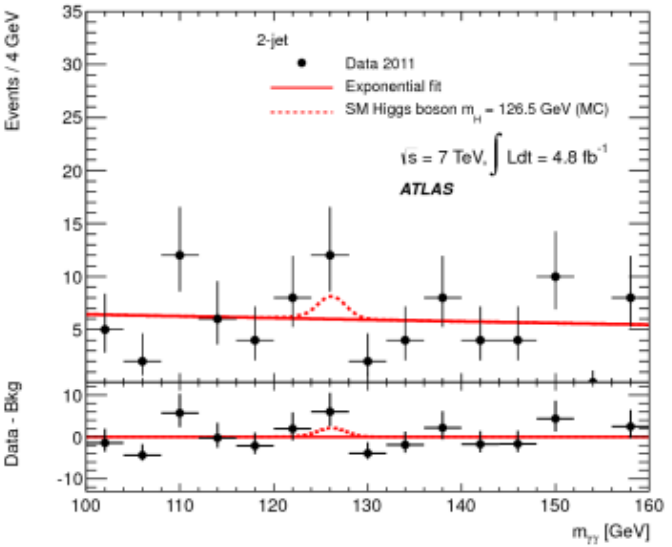
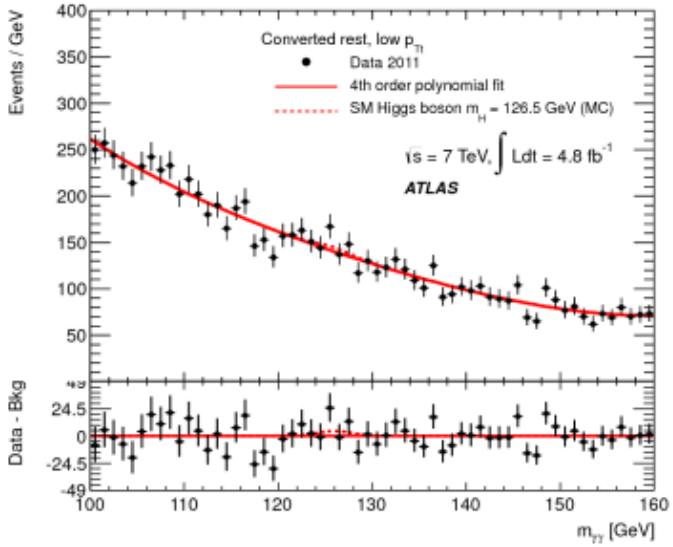
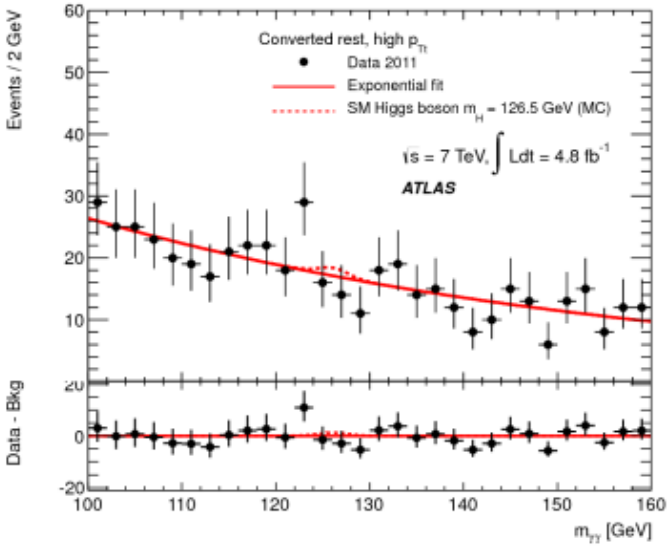
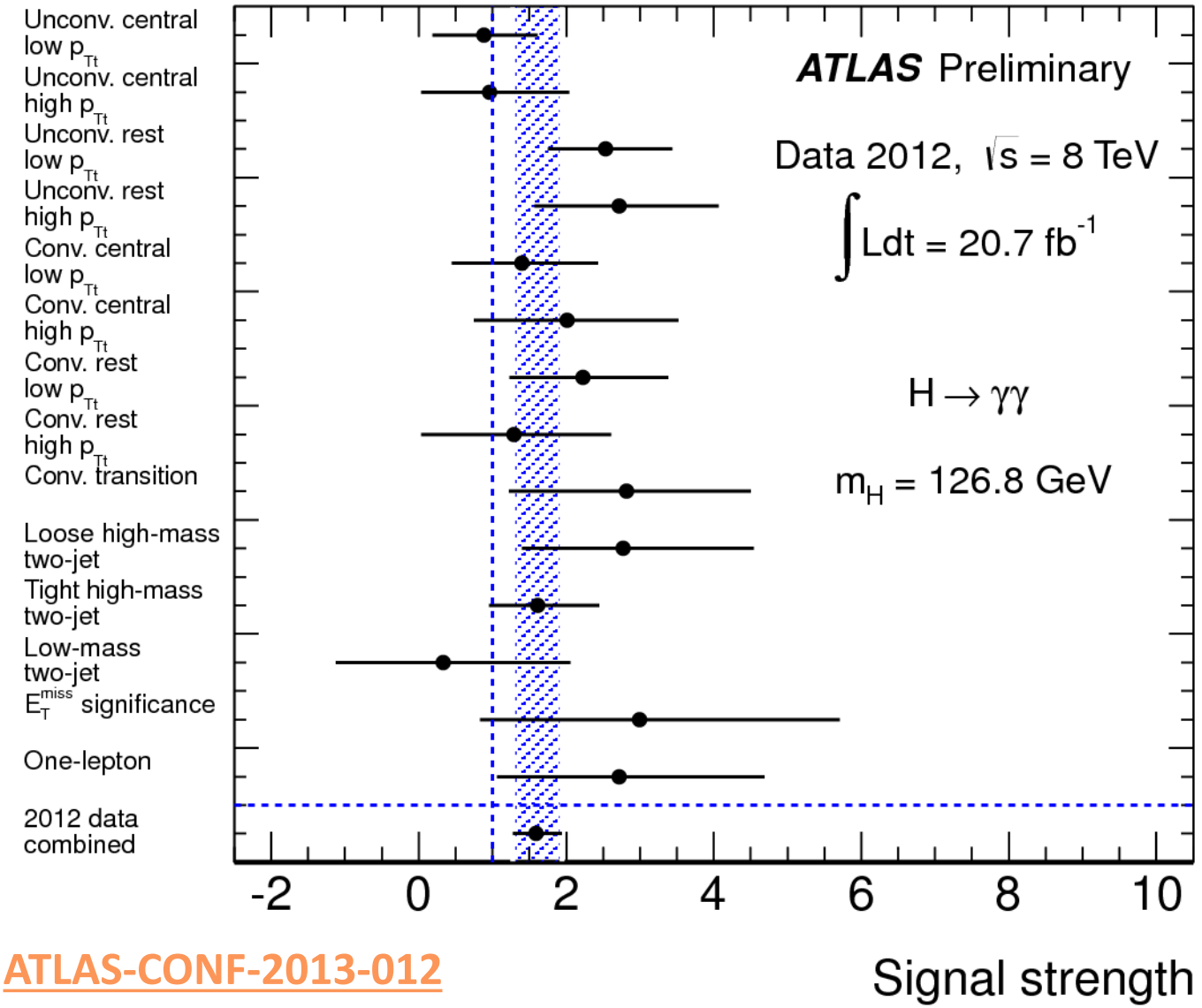








Signal strength in each category (8 TeV only)



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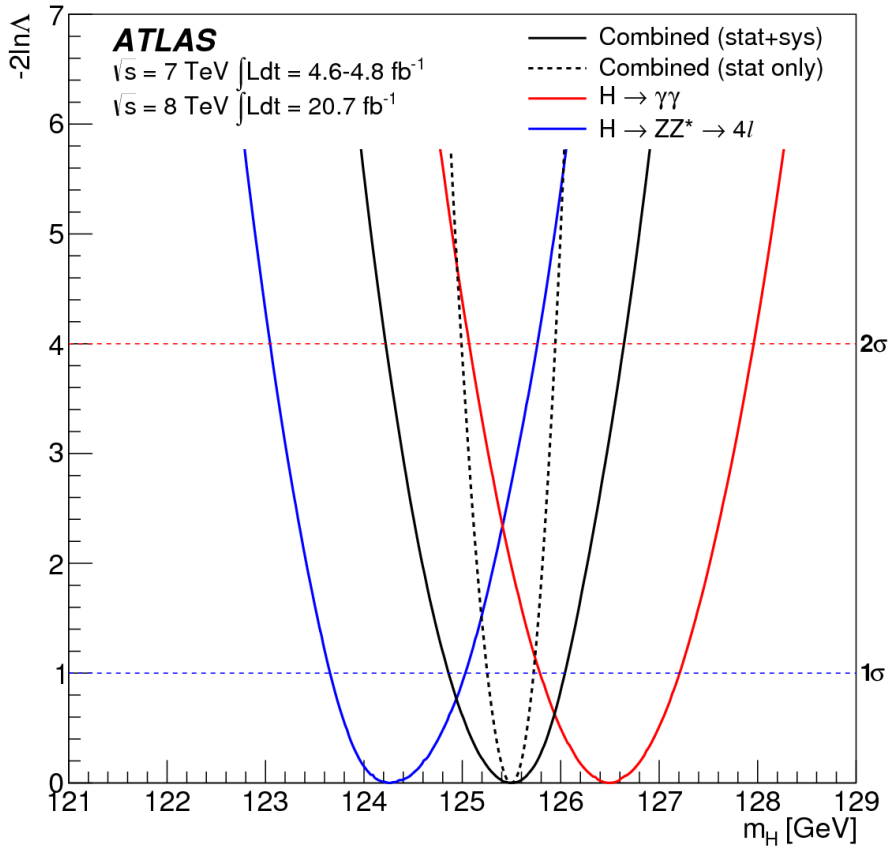
126.8 GeV vs. 125.5 GeV

- 126.8 GeV is the mass of the Higgs boson measured in channel $H \rightarrow \gamma\gamma$ alone
- 125.5 GeV is the mass of the Higgs boson measured combining $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$
- Because of the large uncertainty on m_H in $H \rightarrow \gamma\gamma$ (~700 MeV) channel, using either mass will not result in significant impact on the coupling measurements results
  - $\mu = 1.55$ @ $m_H = 125.5\ GeV$
  - $\mu = 1.57$ @ $m_H = 126.8\ GeV$



arXiv:1307.1427

Limit results for $t\bar{t}H, H \rightarrow \gamma\gamma$

Table 5: Observed and expected 95% CL limits on the $t\bar{t}H$ production cross section times $H \rightarrow \gamma\gamma$ branching ratio relative to the SM expectation at $m_H = 126.8$ GeV.

	Observed limit	Expected limit	$+2\sigma$	$+1\sigma$	-1σ	-2σ
Combined (with systematics)	5.3	6.4	16.2	9.9	4.6	3.4
Combined (statistics only)	5.0	6.0	13.5	8.9	4.3	3.2
Leptonic (with systematics)	9.0	8.4	21.9	13.2	6.1	4.5
Leptonic (statistics only)	8.5	8.0	18.8	12.1	5.7	4.3
Hadronic (with systematics)	8.4	13.6	36.4	21.6	9.8	7.3
Hadronic (statistics only)	7.9	12.6	29.1	18.9	9.1	6.8

Table 6: Observed and expected 95% CL limits on the inclusive Higgs boson production cross section times $H \rightarrow \gamma\gamma$ branching ratio relative to the SM expectation at $m_H = 126.8$ GeV with the $t\bar{t}H$-specific selections.

	Observed limit	Expected limit	$+2\sigma$	$+1\sigma$	-1σ	-2σ
Combined (with systematics)	4.7	5.4	13.7	8.4	3.9	2.9
Combined (statistics only)	4.4	5.0	11.4	7.5	3.6	2.7
Leptonic (with systematics)	7.6	6.9	17.9	10.8	4.9	3.7
Leptonic (statistics only)	7.1	6.4	15.3	9.8	4.6	3.5
Hadronic (with systematics)	7.7	12.5	34.0	19.9	9.0	6.7
Hadronic (statistics only)	7.2	11.4	26.4	17.2	8.2	6.1

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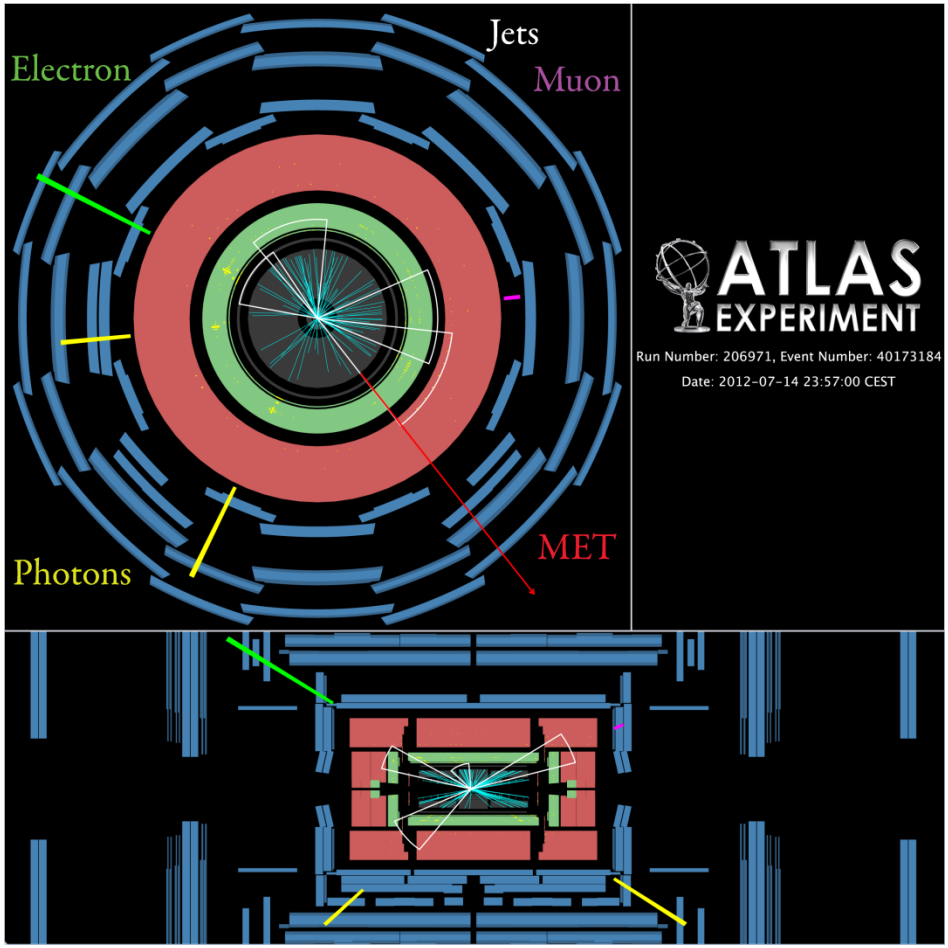
Information about the $t\bar{t}H$ candidate event

- $m_{\gamma\gamma}$ = 126.6 GeV
- Two unconverted photons with transverse momenta of 61 GeV and 39 GeV
- Electron with p_T = 90 GeV
- MET = 43 GeV
- Four jets with transverse momenta of 75 GeV, 71 GeV, 50 GeV, and 39 GeV
- One of the jets is b-tagged jet (jet no. 2) with an additional soft muon inside the jet (7.2 GeV)



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Higgs production cross section @ 7/8 TeV

Cross section (pb)	7 TeV	8 TeV
ggH	14.96	19.07
VBF	1.193	1.558
WH	0.550	0.6691
ZH	0.304	0.3794
$t\bar{t}H$	0.083	0.1256
Total	17.1	21.8

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt7TeV2012update
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV2012update

m_H = 126.5 GeV

Uncertainty on Higgs cross section

Table 3: Cross sections for the Standard Model Higgs boson production with m_H = 126.5 GeV at $\sqrt{s}$ = 8 TeV [57, 58]. The branching ratio to the two photons decay mode is $2.28 \cdot 10^{-3}$ at m_H = 126.5 GeV. Gluon fusion and vector boson fusion cross sections are computed in the complex pole scheme at NNLL+NNLO QCD and NLO EW [58]. Associated production cross section are computed with zero-width-approximation at NNLO QCD and NLO EW. The ttH process cross section is computed with zero-width-approximation at NLO QCD. QCD scale (±Scale) and the PDF+α_s uncertainties are treated as non-correlated [68].

Process	Cross section (pb)	+Scale %	-Scale %	+(PDF+α_s)%	-(PDF+α_s)%
ggF	19.07	+7.2	-7.8	+7.5	-6.9
VBF	1.56	+0.2	-0.2	+2.6	-2.7
WH	0.67	+0.2	-0.6	+3.5	-3.5
ZH	0.38	+1.6	-1.5	+3.6	-3.6
ttH	0.13	+3.8	-9.3	+7.8	-7.8

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Uncertainties on the signal yield

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	

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Background model & uncertainty

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

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Migration uncertainties I

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	
	$E_{\mathrm{T}}^{\mathrm{miss}}$ 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	
	$E_{\mathrm{T}}^{\mathrm{miss}}$ 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 Loose high-mass two-jet: +6.2				Gaussian

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Migration uncertainties II

Dijet angular modelling		Tight high-mass two-jet: +12.1 Loose high-mass two-jet: +8.5			Gaussian
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 Low-mass two-jet	ggF: −1.2 ggF: −2.3	VBF: −0.3 VBF: −2.4	Others: −1.2 Others: −2.3	Gaussian
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

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