Spin measurement of the Higgs-like resonance observed in the two-photon decay channel in ATLAS

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Meeting of the APS DPF, Santa Cruz, CA

August 15, 2013

Content

A new particle has been observed in the *γγ*, *ZZ*, and *WW* channels by ATLAS and CMS!

Now it is time to determine what exactly we found…

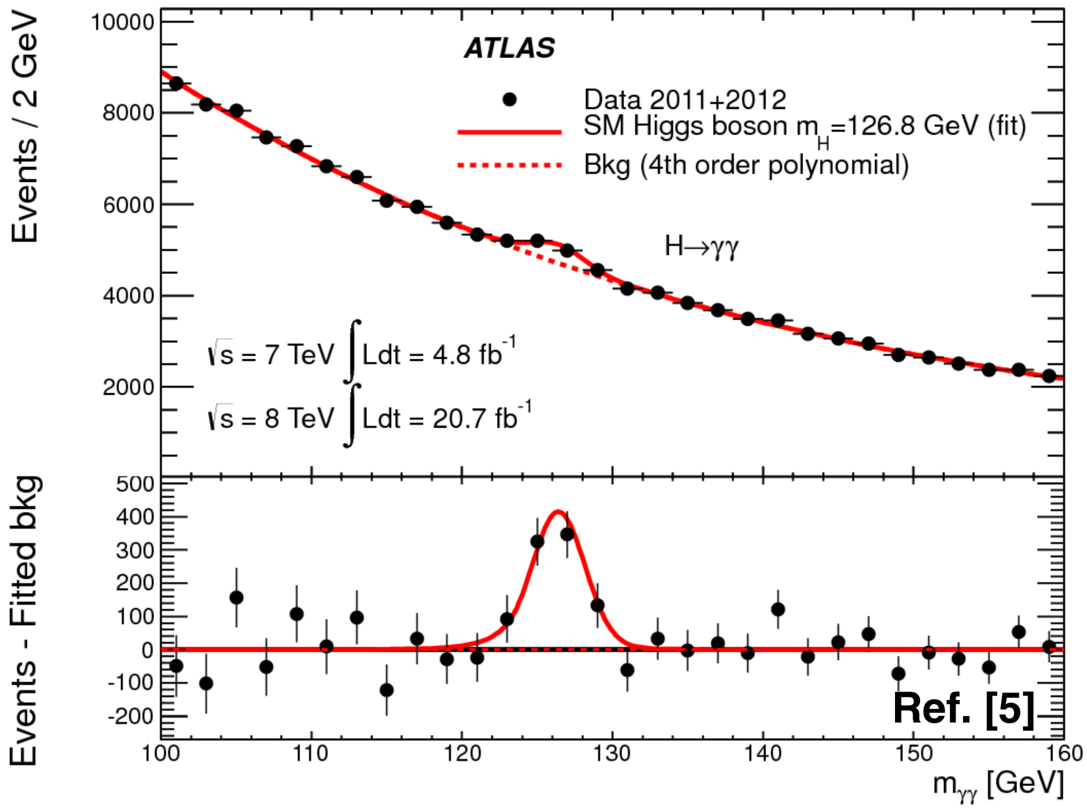
Di-photon decay indicates the new particle is a boson

- Landau-Yang theorem excludes the spin 1 hypothesis
- Other integer spins remain as possibilities

Difficult to reject all spin 2 models

- Separate the standard model ($J^P=0^+$) signal hypothesis from "graviton-like" models ($J^P=2^+$)
- Remaining model dependence lies in the coupling strengths of the spin 2 particle to the SM fields

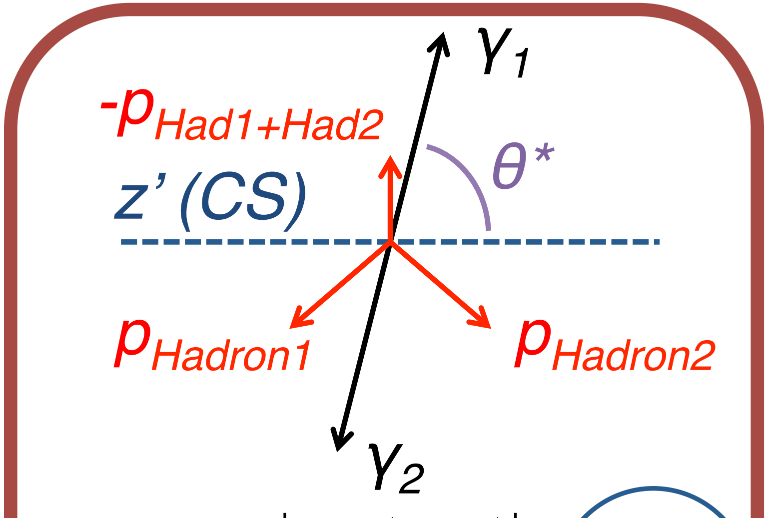
The $H \rightarrow \gamma\gamma$ channel



Separate signal from background with fit to the γγ mass

- Narrow resonance with a large background
- Excellent mass resolution (1.77 GeV)
- Divide events into categories and fit the signal peak (m_H = 126.5 *GeV*)

Spin of the boson creates angular correlation between the decay products (in this case, the two photons)

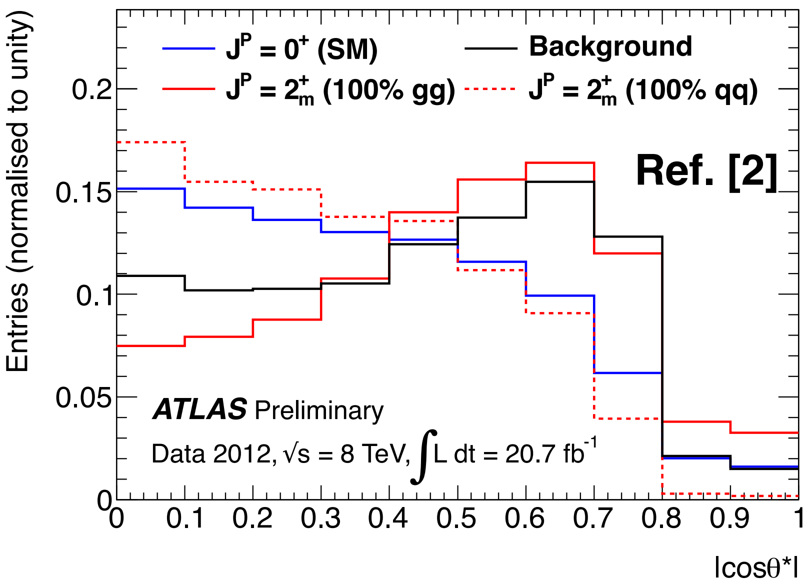


$$\left|\cos\theta^*_{CS}\right| = \frac{\left|\sinh\left(\Delta\eta^{\gamma\gamma}\right)\right|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}}\frac{2p_T^{\gamma1}p_T^{\gamma2}}{m_{\gamma\gamma}^2}$$

Relative p_T cuts on the photons remove most correlation with $m_{\gamma\gamma}$

Collins-Soper frame used to get reference axis z' for $\cos(\theta^*)$

- z-axis bisects angle between the momenta of colliding hadrons
- Minimizes impact of ISR
- Better 0^+ / 2^+ discrimination



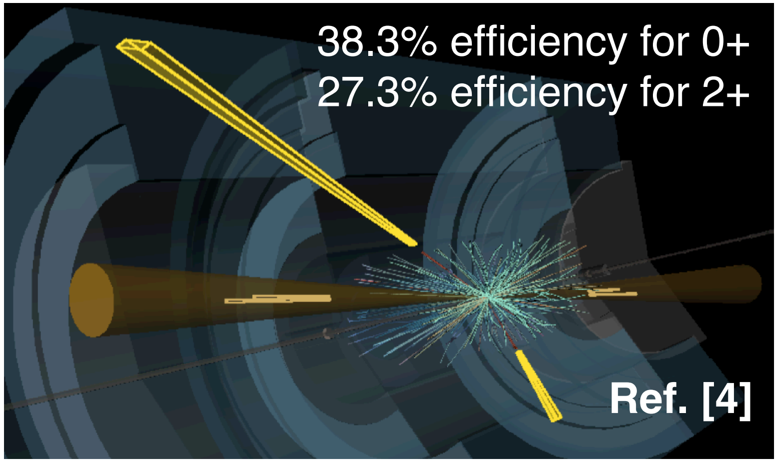
20.7 fb^{-1} of data at $\sqrt{s}$ = 8 *TeV* from the LHC in 2012

Photon reconstruction

- Energy scale calibrations (and smearing for MC) from $Z \rightarrow ee$
- $p_T > 25$ *GeV*
- $|\eta| < 2.37$ excluding $1.37 < |\eta| < 1.56$ (excluding calo. transition region)
- η corrections from electro-magnetic calorimeter pointing.
- Rectangular "tight" ID cuts on calorimeter shower shapes.
- Isolation:
  ΣE_T^{Calo} (Δr=0.4) < 6.0 *GeV*
  Σp_T^{Track} (Δr=0.2) < 2.6 *GeV*

Event selection

- Trigger: EF_g35_loose_g25_loose
- Vertex reconstruction with artificial neural network, using pointing capabilities of the ATLAS EM calo.
- $p_{T,1} / m_{\gamma\gamma} > 0.35$, $p_{T,2} / m_{\gamma\gamma} > 0.25$
- 105 *GeV* $< m_{\gamma\gamma} <$ 160 *GeV*



Signal model from MC

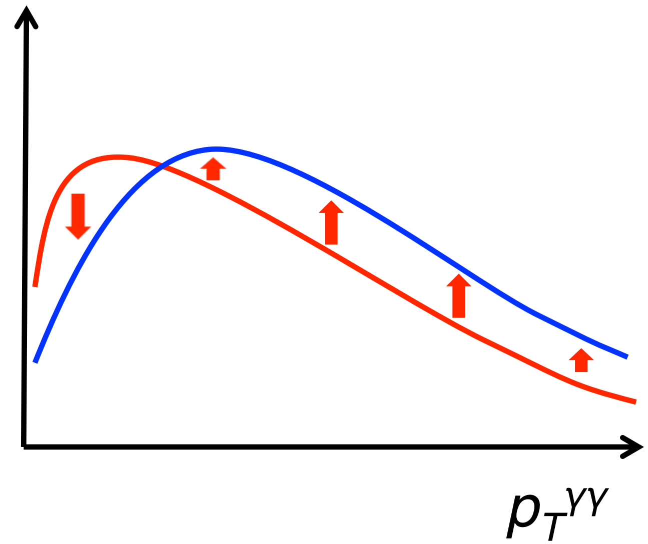
Standard Model Higgs ($J^P=0^+$)

- **NLO predictions** from POWHEG + PYTHIA8 parton showering.
- Tuned to reproduce the re-summed p_T calculation of the HqT program

Spin 2 Model ($J^P=2^+$)

- **LO predictions** from JHU generator + PYTHIA parton showering
- Transverse momentum comes from parton showering in the initial state
- **Large impact of Higgs p_T on cos(θ^*)**
- Reweight p_T to POWHEG prediction:

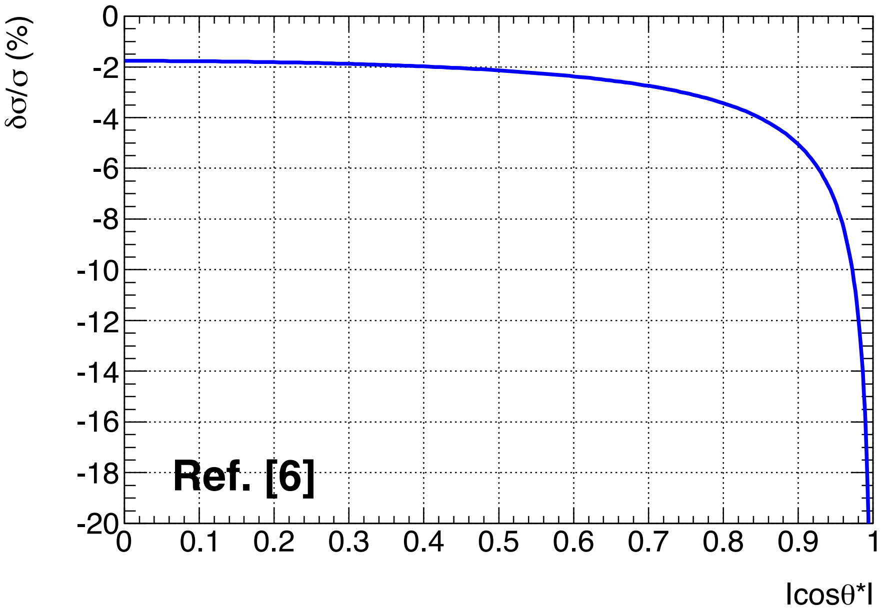
$$w(p_T) = \frac{1}{\sigma_{POWHEG}} \frac{d\sigma_{POWHEG}}{dp_T} \Big/ \frac{1}{\sigma_{PYTHIA}} \frac{d\sigma_{PYTHIA}}{dp_T}$$



A systematic uncertainty for the p_T weights on the 2^+ signal is derived using the difference between the un-weighted and weighted distributions.

Destructive interference between *gg→γγ* non-resonant production and the *gg→H→γγ* process

- Correction calculated in bins of cos(θ^*) and applied as an event weight to modify expected signal yield
- Larger corrections at high values of $|\cos(\theta^*)|$
- A systematic uncertainty is assigned by taking the difference between the $|\cos(\theta^*)|$ shapes with and without the interference correction



Corrections were only computed for the 0^+ model, though there would be (model dependent) interference for 2^+ as well

Events are divided into 3 regions based on the γγ mass

Side-bands: 1D fits in $m_{\gamma\gamma}$

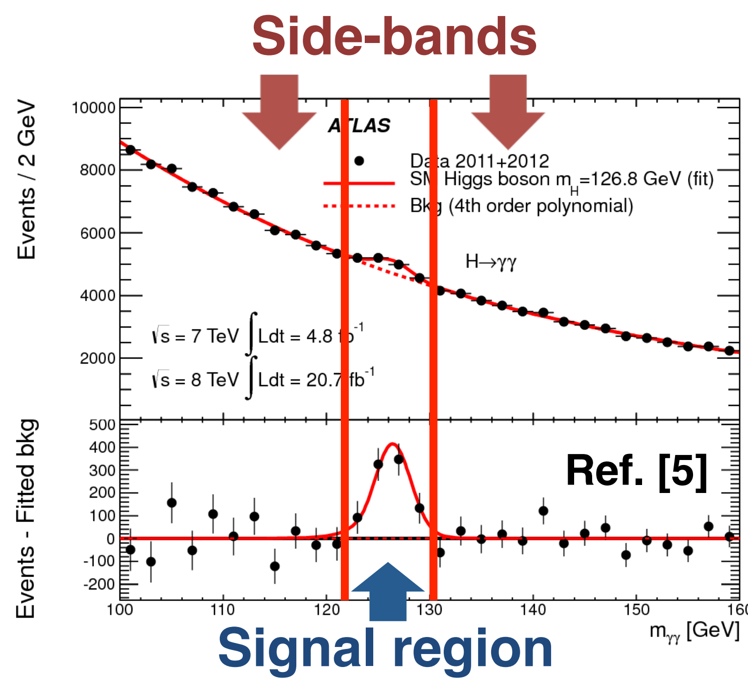
- $105\ GeV < m_{\gamma\gamma} < 122\ GeV$ and $130\ GeV < m_{\gamma\gamma} < 160\ GeV$
- **Background:** a 5th order Bernstein polynomial function
- **Signal:** Crystal Ball + Gaussian function for narrow resonance

Signal region: 2D fits in $m_{\gamma\gamma}$ and cos(*θ**)

- $122\ GeV < m_{\gamma\gamma} < 130\ GeV$
- Multiple of two 1D shapes:

$$f(\cos\theta^*, m_{\gamma\gamma}) = f_c(\cos\theta^*) \cdot f_m(m_{\gamma\gamma})$$

The method assumes no $m_{\gamma\gamma}$-cos(*θ) correlation.**



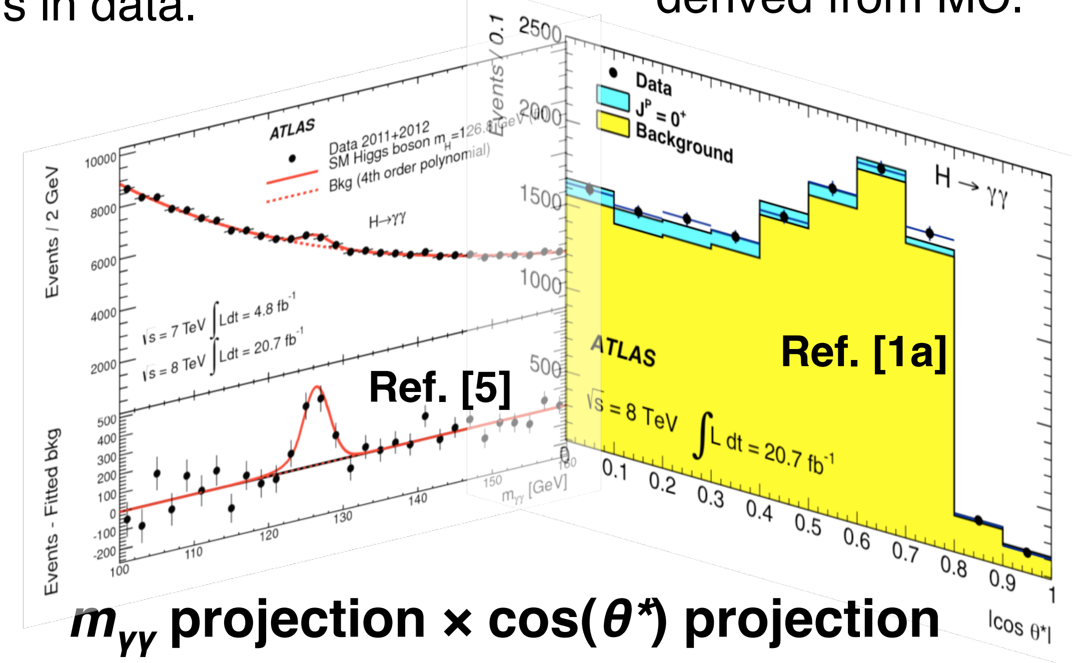
2D fits for signal and background in the signal region are constructed by multiplying two 1D templates

Background fit

- $m_{\gamma\gamma}$ is a 1D analytic 5th order Bernstein polynomial function (fit simultaneously in all regions)
- **cos(θ*)** template from the mass sidebands in data.

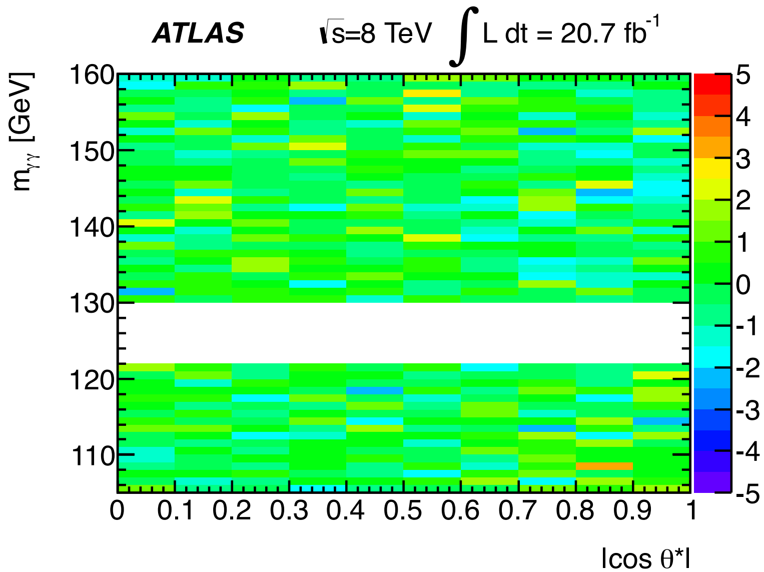
Signal fit

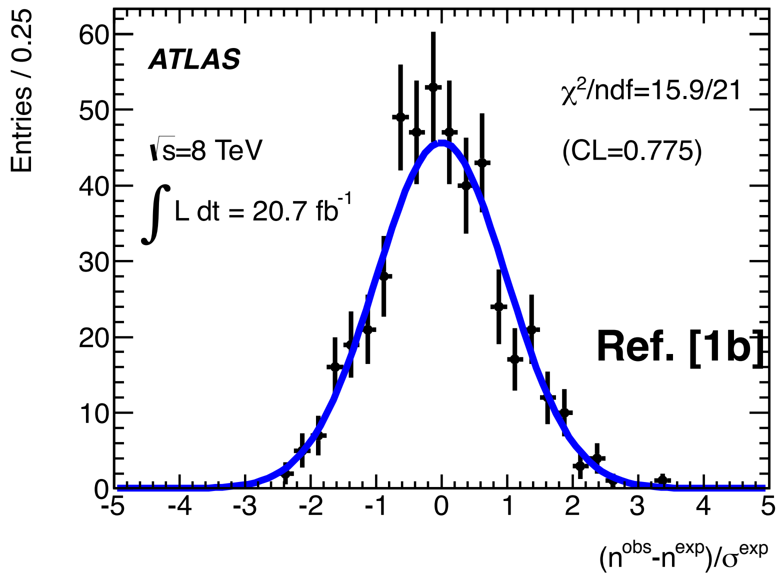
- $m_{\gamma\gamma}$ is an 1D analytic Crystal Ball + Gaussian function (fit simultaneously in all mass regions)
- **cos(θ*)** is a 1D histogram template derived from MC.



$m_{\gamma\gamma}$ projection × cos(θ*) projection

Correlation between $m_{\gamma\gamma}$ and $\cos(\theta^*)$





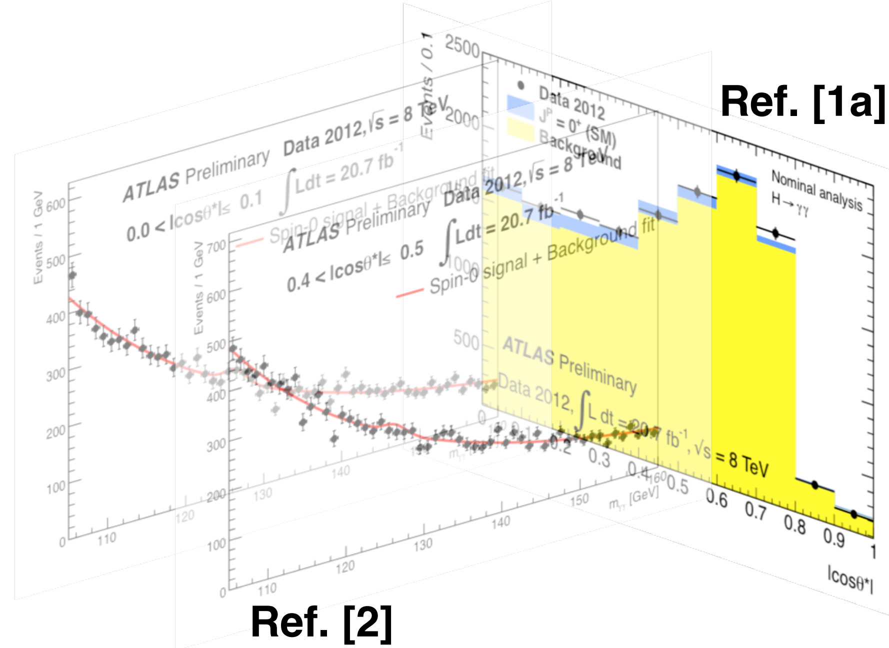
Analysis method #1 assumes no correlation between the two observables → check assumption in data sample

Compare the 1D×1D expectation to the observed events

Gaussian distribution of fluctuations away from the $m_{\gamma\gamma}\times\cos(\theta^*)$ expectation → correlations between the two variables are small

Use cos(θ*) to create 10 event categories for the analysis

- Make 1D $m_{\gamma\gamma}$ fits of S+B shapes in in each of the cos(θ*) bins
- Ten simultaneous 1D fits to $m_{\gamma\gamma}$ instead of one 2D fit
- **Signal:** Crystal Ball + Gaussian fit
- **Background:** 2nd order exponential polynomial or 3rd order Bernstein polynomial



Ref. [1a]

Ref. [2]

Spin hypotheses predict different signal yields per category

Similar to 1st analysis

- Can assume de-correlation between $m_{\gamma\gamma}$ and cos(θ*) by simultaneously fitting background shape in each category, but this is not necessary.

Likelihood models

Analysis method 1

2 dimensions in the PDFs entering the likelihood

$\cos(\theta^*)$

$$-\ln L = (n_S + n_B) - \sum_{events} \ln\left[n_S \cdot f_S\left(\left|\cos\theta^*\right|\right) \cdot f_S\left(m_{\gamma\gamma}\right) + n_B \cdot f_B\left(\left|\cos\theta^*\right|\right) \cdot f_B\left(m_{\gamma\gamma}\right)\right]$$

$m_{\gamma\gamma}$

Analysis method 2

1 dimension in the PDFs entering the likelihood, sum over $\cos(\theta^*)$ categories

$$-\ln L = (n_S + n_B) - \sum_{i=1}^{N_{Bins}^{|\cos\theta^*|}} \sum_{events} \ln\left[n_S \cdot \varepsilon_S^i \cdot f_S^i\left(m_{\gamma\gamma}\right) + n_B^i \cdot f_B^i\left(m_{\gamma\gamma}\right)\right]$$

Sum over $\cos(\theta^*)$ categories

$m_{\gamma\gamma}$

Test statistic

Analysis uses likelihood ratio test statistic *q*:

$$q = \log \frac{L(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{L(J^P = 2^+, \hat{\hat{\mu}}_{2^+}, \hat{\hat{\theta}}_{2^+})}$$

- ***L* = maximum likelihood estimator**, evaluated under 0^+ or 2^+ hypothesis.
- $\hat{\hat{\mu}}$ = value of signal strength fitted under the hypothesis
- $\hat{\hat{\theta}}$ = value of nuisance parameters fitted under the hypothesis

Use test statistic *q* distributions (obtained using pseudo-experiments) to calculate p_0 values.

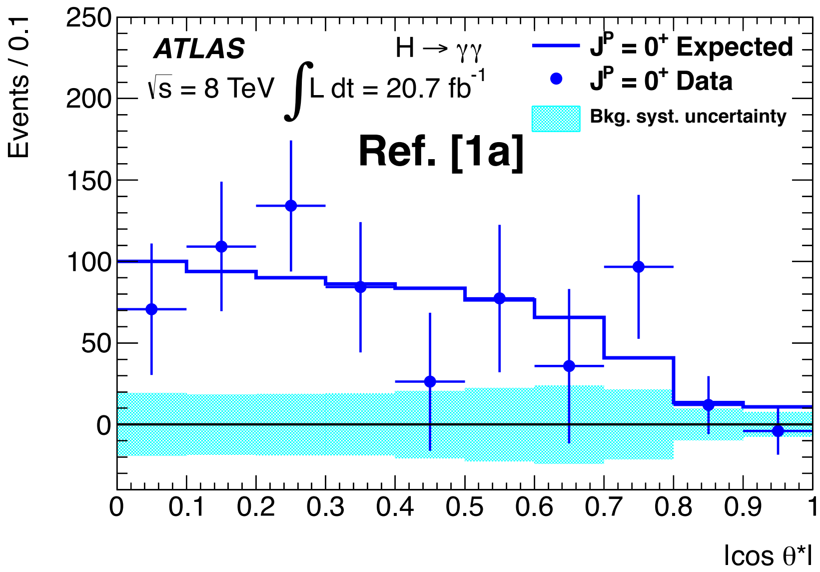
- $p_0(J^P) \rightarrow$ the probability of the data for the J^P signal hypothesis fluctuating to the observed value of the test statistic.

$$p_0(J^P = 2^+) = \int_{q^m}^{\infty} g_{2^+}(q)dq \qquad p_0(J^P = 0^+) = \int_{-\infty}^{q^m} g_{0^+}(q)dq$$

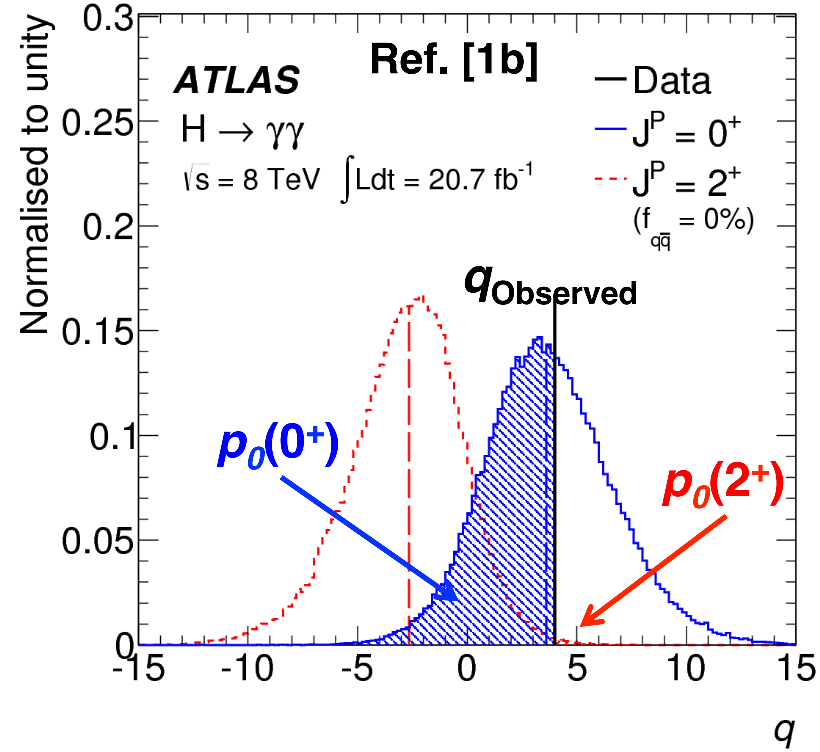
Exclusion confidence level (*CL*) from ratio of p_0 values:

$$CL(J^P = 2^+) = 1 - CL_S(J^P = 2^+) = 1 - \frac{p_0(2^+)}{1 - p_0(0^+)}$$

Analysis results



Profiled signal events vs. expected values for the $J^P = 0^+$ hypothesis.



Able to exclude the $J^P=2^+$ hypothesis in favor of $J^P=0^+$ at:

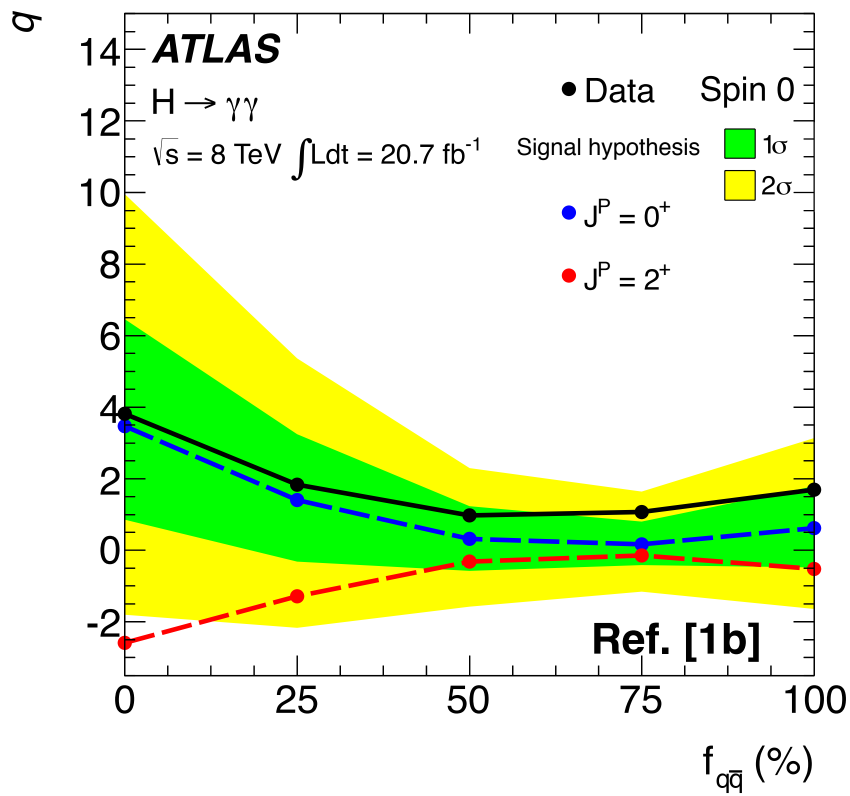
99.3% *CL* (analysis #1)

89.4% *CL* (analysis #2)

Expected distributions of the test statistics $g_{0+}(q)$ and $g_{2+}(q)$ from pseudo-experiments.

Shaded areas correspond to the p_0 values for the hypothesis

Results for various $qq \rightarrow 2^+$ production fractions



f_{qq} (%)	Spin hypothesis	Exp. p-value (%)	Obs. p-value (%)	1-$CL_S(2^+)$ (%)
0	0^+ 2^+	1.2 0.5	58.8 0.3	99.3
25	0^+ 2^+	6.3 5.3	60.2 3.1	92.2
50	0^+ 2^+	24.3 23.4	75.2 7.9	68.0
75	0^+ 2^+	29.4 28.0	88.6 3.4	70.0
100	0^+ 2^+	14.8 13.5	79.8 2.5	88.0

Sensitivity of the analysis is higher for small *qq* production fractions

Signal shape in $\cos(\theta^*)$ for 75% *qq* 2^+ is very similar to *gg* 0^+

Observations favor 0^+ hypothesis over 2^+ at every f_{qq} point

Conclusions

The $H \rightarrow \gamma\gamma$ channel provides a useful tool for studying the properties of the year-old Higgs-like boson.

20.7 fb^{-1} of 8 *TeV* data were used to set limits on graviton-like J^P=2$^+$ models (currently no sensitivity to parity).

Able to exclude the 100% *gg* produced J^P=2$^+$ models in favor of 0$^+$ with 99.3% *CL* with the 1st method (or 89.4% *CL* for the 2nd analysis method).

In comparison (Ref. [3]):
CMS excludes J^P=2$^+$ in favor of 0$^+$ with 39.1% *CL*

ATLAS and CMS Conference Notes and Publications

1a *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*
http://arxiv.org/abs/1307.1432

1b *Evidence for the spin-0 nature of the Higgs boson using ATLAS data (auxiliary plots)*
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2013-01/

2 *Study of the spin of the Higgs-like boson in the two photon decay channel using 20.7fb^{-1} of pp collisions collected at $\sqrt{s}$=8 TeV with the ATLAS detector*
https://cds.cern.ch/record/1527124

3 *Properties of the observed Higgs-like resonance decaying into two photons (CMS)*
https://cds.cern.ch/record/1558930?ln=en

4 *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*
http://cds.cern.ch/record/1523698

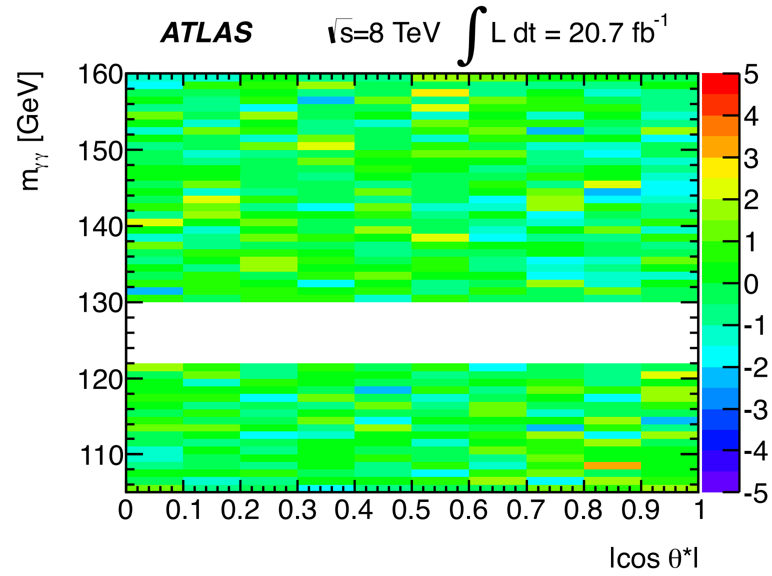
5 *Measurements of the Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC*
http://arxiv.org/abs/1307.1427

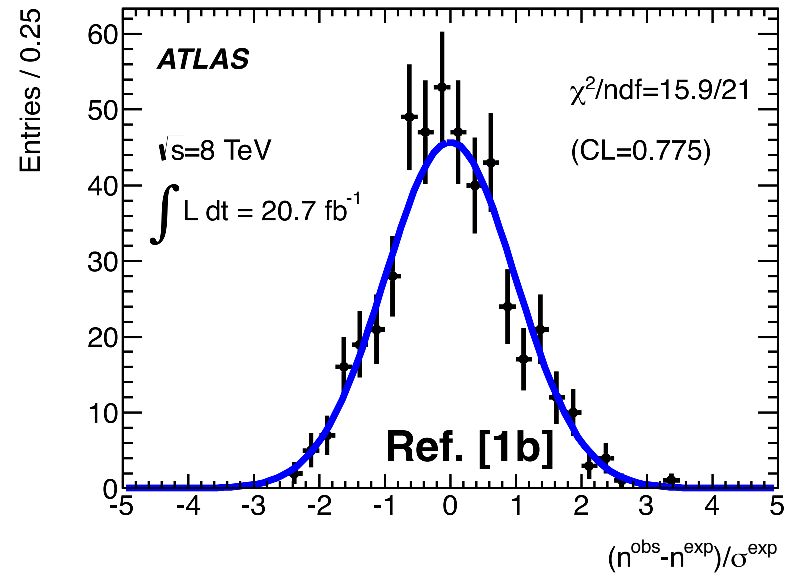
Additional References

6 L. J. Dixon and M. S. Siu, *Resonance continuum interference in the diphoton Higgs signal at the LHC*, Phys. Rev. Lett. **90** (2003) 252001, arXiv:hep-ph/ 0302233 [hep-ph]
http://arxiv.org/pdf/hep-ph/0302233.pdf

Appendix

Correlation between $m_{\gamma\gamma}$ and $\cos(\theta^*)$





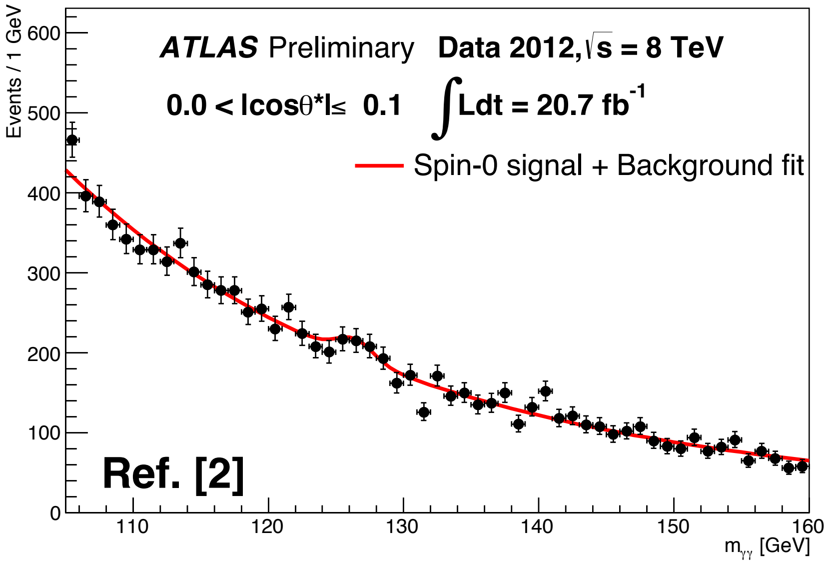
The expected number of events is defined as follows:

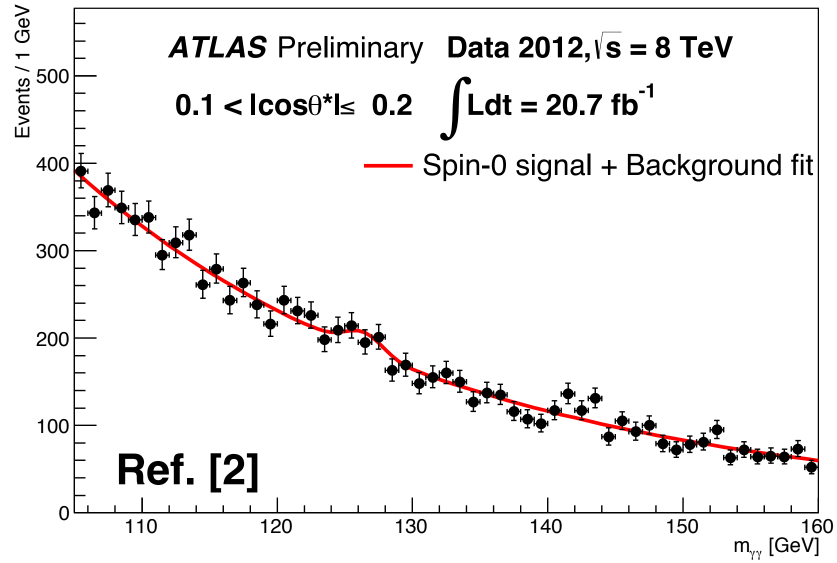
$$n^{exp}[m_{\gamma\gamma}][\cos\theta^*] = \frac{\overbrace{\sum_{m'_{\gamma\gamma}} n^{obs}[m'_{\gamma\gamma}][\cos\theta^*]}^{=n^{obs}[\cos\theta^*]} \cdot \overbrace{\sum_{\cos\theta^{*\prime}} n^{obs}[m_{\gamma\gamma}][\cos\theta^{*\prime}]}^{=n^{obs}[m_{\gamma\gamma}]}}{n^{tot}}$$

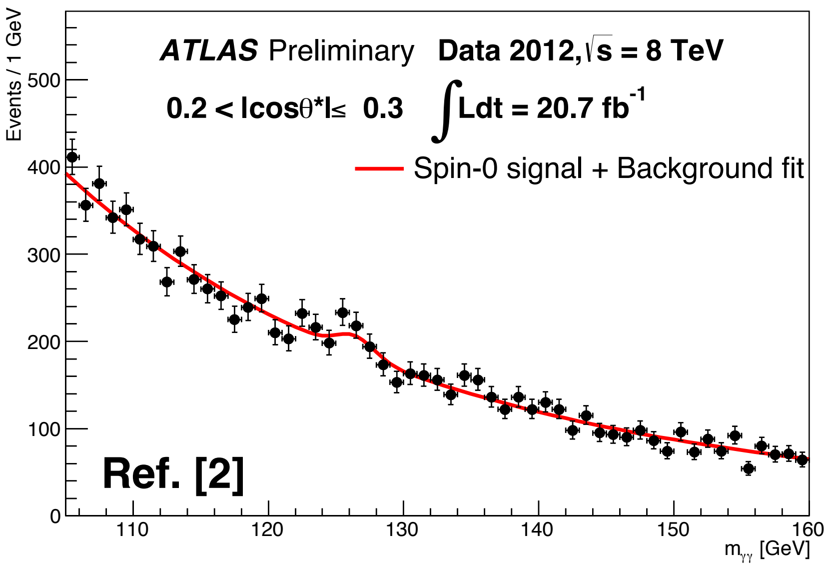
The statistical uncertainty is defined:

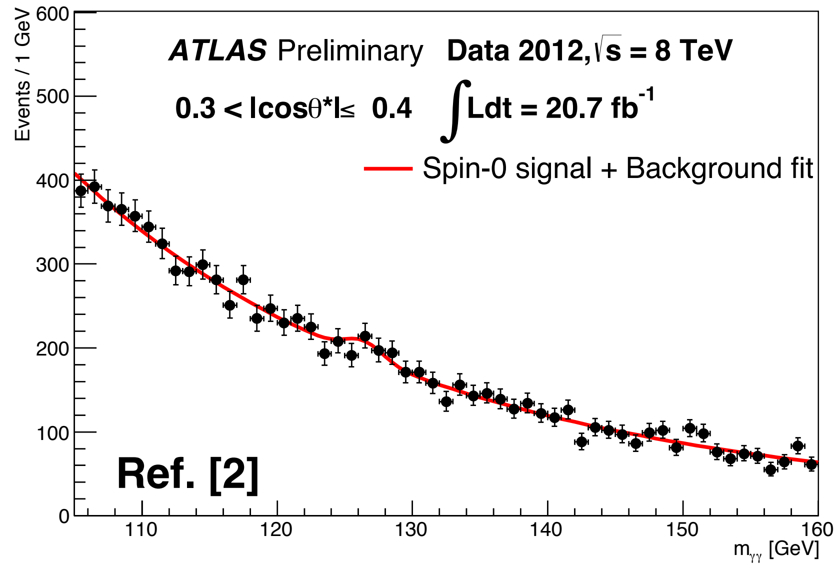
$$\left(\sigma^{exp}[m_{\gamma\gamma}][\cos\theta^*]\right)^2 = n^{exp}[m_{\gamma\gamma}][\cos\theta^*] + \left(n^{exp}[m_{\gamma\gamma}][\cos\theta^*]\right)^2 \cdot \left(\frac{1}{n^{obs}[m_{\gamma\gamma}]} + \frac{1}{n^{obs}[\cos\theta^*]} + \frac{1}{n^{tot}}\right)$$

$M_{\gamma\gamma}$ distributions in 10 categories for 2nd analysis method

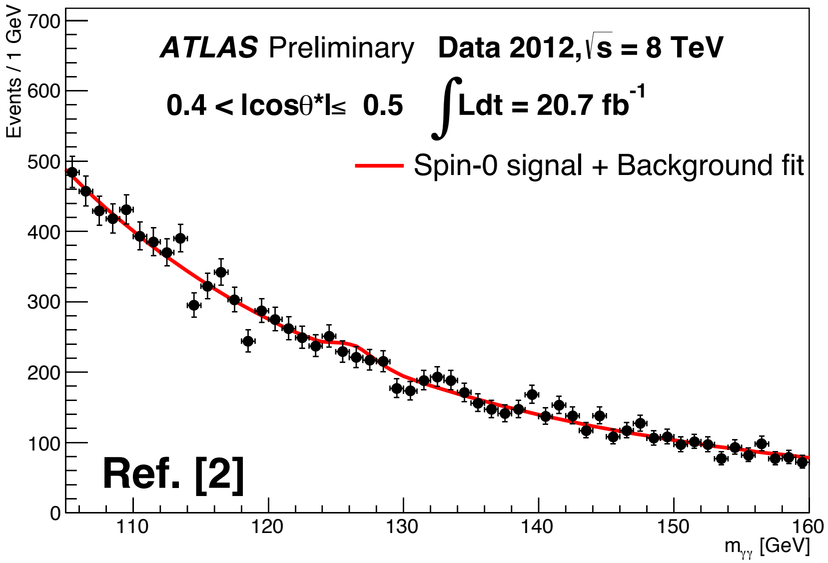


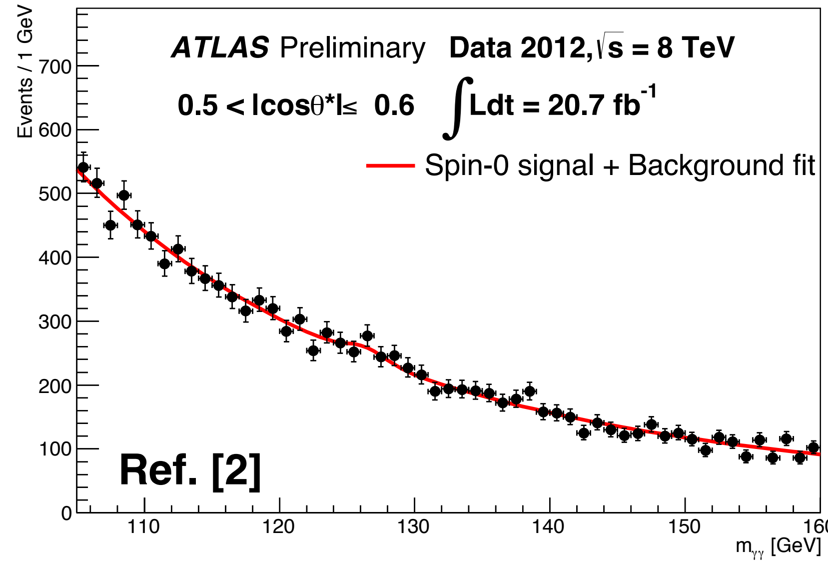


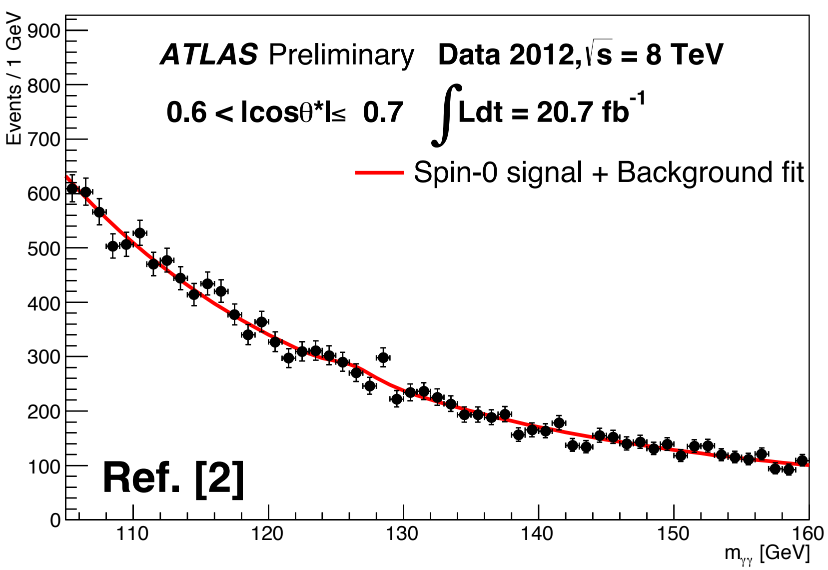


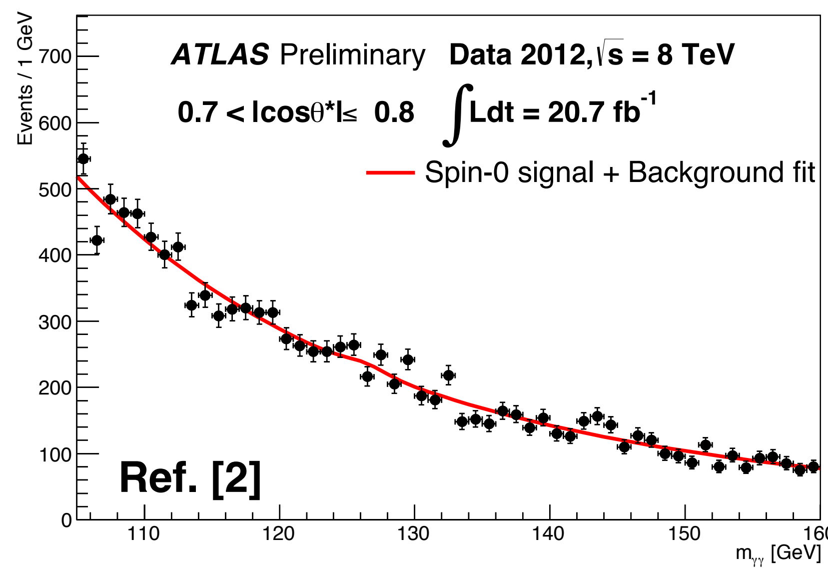


$M_{\gamma\gamma}$ distributions in 10 categories for 2^{nd} analysis method

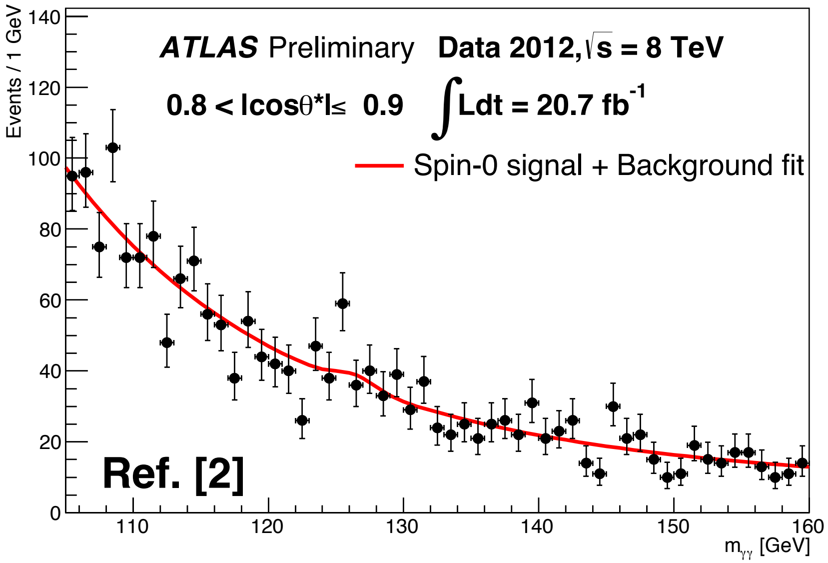


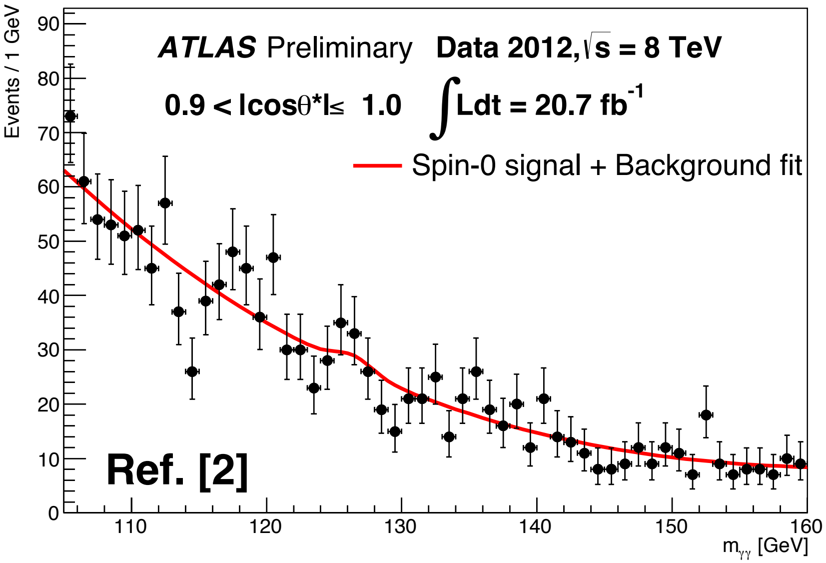






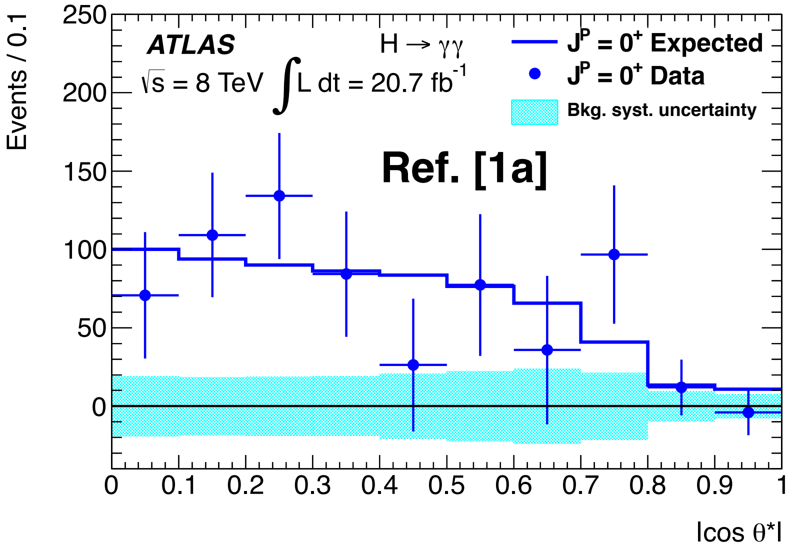
$M_{\gamma\gamma}$ distributions in 10 categories for 2nd analysis method



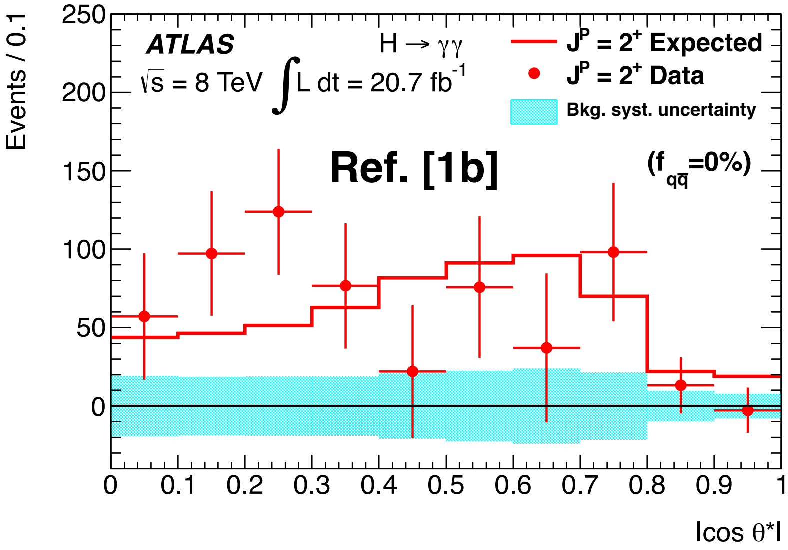


Profiled signal strength vs. cos(θ*)

Fitting the J^P=0⁺ hypothesis



Fitting the J^P=2⁺ hypothesis

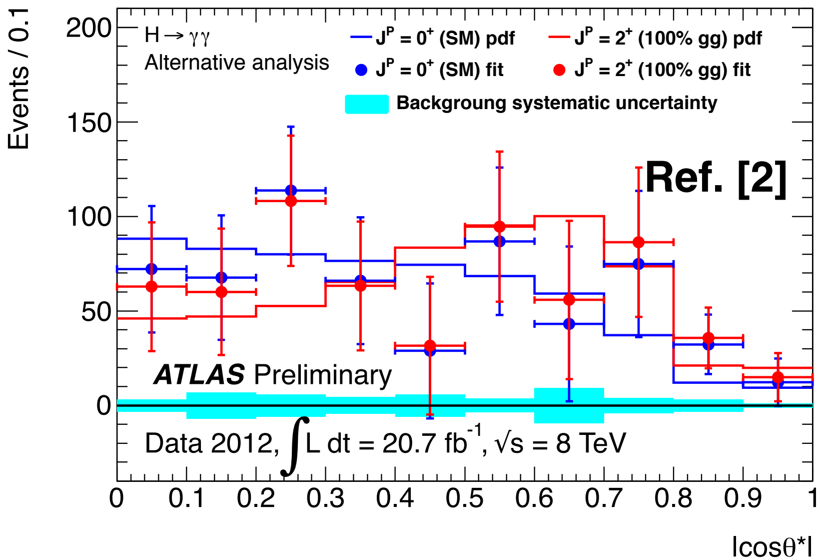


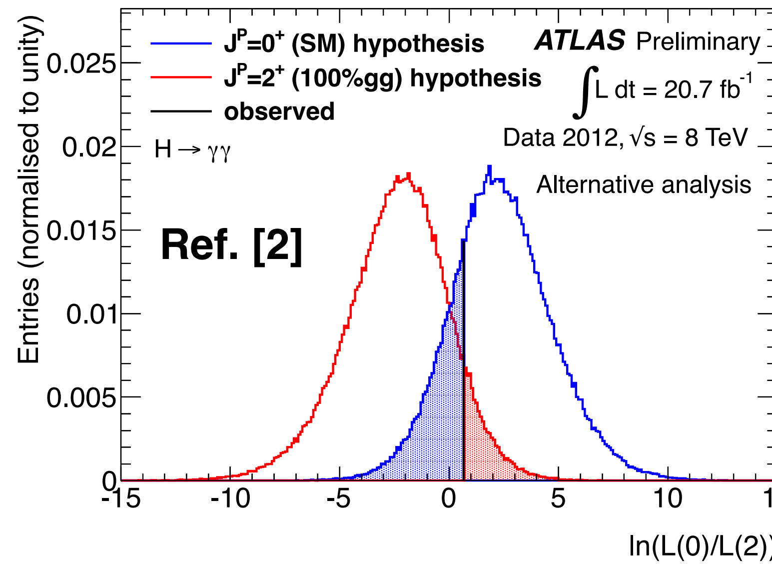
The figures above compare the profiled number of signal events in data (points) to the expected number of signal events (solid line). The results of fitting data are slightly different for the two signal hypotheses since different likelihood models are tested.

Table of Results for 100% *gg* production of 0^+

Analysis	Spin hypothesis	Signal events	Expected p-values (%)	Observed p-values (%)	1-$CL_S(2^+)$ (%)
Analysis 1	0+	690 ± 150	1.2	58.8	99.3
	2+	620 ± 160	0.5	0.3	
Analysis 2	0+	570 ± 120	1.9	21.1	89.4
	2+	590 ± 130	1.7	8.4	

Results for analysis method 2





With analysis method 2, the exclusion is not as strong:

2^+ excluded in favor of 0^+ at 89.4% *CL*

The compatibility of the results from the two analysis methods was studied with pseudo-experiments

10% probability of observing a comparable difference in *p*-values

Toy test statistics for mixed *gg*/*qq* production modes