Term Paper

Higgs boson: Spin + CP

Katharina Schleicher

31.07.2013

Albert-Ludwigs-Universität Freiburg

UNI FREIBURG

Table of contents

Introduction

Discovery of new boson July 2012;
Coupling strength compatible with SM $\to$ Investigation of spin- and CP-nature

Spin

- Higgs field is a scalar field $\Rightarrow$ Higgs boson has to be scalar (SM), spin $= 0$
- Spin-1 is ruled out because of the Landau Yang theorem ($H \to \gamma\gamma$)
- Spin-2 particle would not be compatible with a renormalizable theory
- No mixed spin states
- Analysis through longitudinal spin-correlations

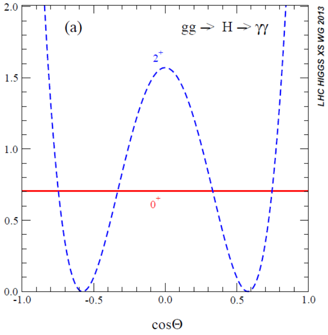
CP

- If CP-symmetric nothing should be changed if particle is replaced by its antiparticle and simultaneously all space coordinates are mirrored
- SM-Higgs boson has CP-eigenvalue $+1$ (CP-even)
- If it is CP-violating it would not be eigenstate but a mixture
- CP-violation already observed (K-mesons) but is not "large" enough to explain the huge dominance of matter against antimatter
- Analysis through transverse spin-correlations

Measurement of spin and CP

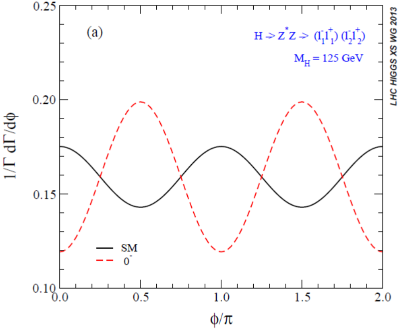
The properties spin and CP manifest themselves in different angular distributions.

For example in the channel $H \to \gamma\gamma$ the distribution in $\cos\theta$



Same CP but different spin.

Or the distribution of Φ in the channel $H \to ZZ^* \to 4\ell$



Same spin but different CP.

All the different spin- and CP-hypotheses

0^+	SM scalar Higgs Boson
0^-	pseudo-scalar
0^+_h	non-SM scalar with higher-dim. operators
1^+	exotic pseudo-vector
1^-	exotic vector
2^+_m	graviton-like tensor with minim. couplings
2^+_b	graviton-like tensor with SM in the bulk
2^+_h	tensor with higher-dim. operators
2^-_h	pseudo-tensor with higher-dim. operators

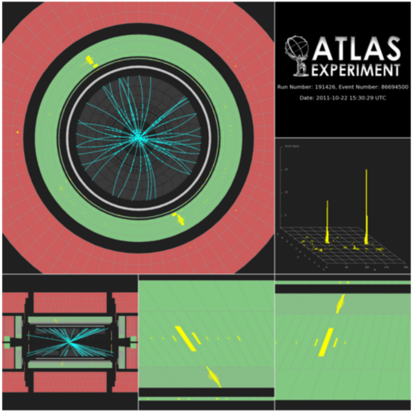
$$A\left(X_{J=0} \to VV\right) =$$
$$v^{-1}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3 f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

Introduction

- $20.7\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$
- Channel with highest significance
- SM 0^+-hypothesis vs. graviton-like 2^+_m-hypothesis

→ Just spin-analysis since photons are stable

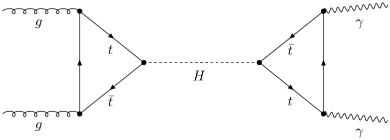
- No spin-1-hypothesis because of the Landau-Yang theorem



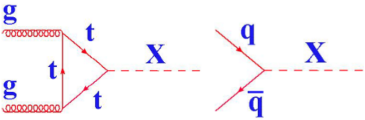
Signal and background

- Signal:

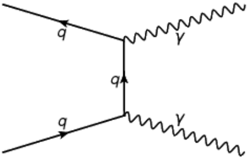
0^+ mainly via ggF

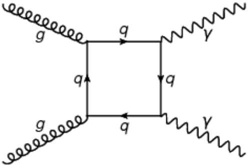


2^+ via ggF or $q\bar{q}$ (different fractions of each will be analysed)



- Main background (irreducible):

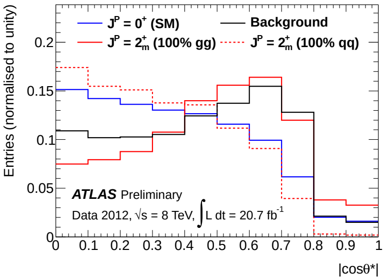




- Reducible backgrounds:
  $\gamma + jet$, $jet + jet$, ...

Sensitive observable

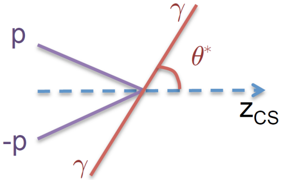
Information about the spin is extracted from the distribution of $|\cos\theta^*|$.



- 0^+ Isotropic decay in rest frame
  - $\Rightarrow$ Distribution expected to be uniform before any cuts
- 2^+ Distribution follows $1 + 6\cos^2\theta^* + \cos^4\theta^*$ for production via gluon-fusion and $1 - \cos^4\theta^*$ for production via $q\bar{q}$-annihilation

Collins-Soper frame

- The Collins-Soper frame is defined in the Higgs-Boson rest frame
- θ^* is the polar angle of the photons with respect to the z-axis of the Collins-Soper frame



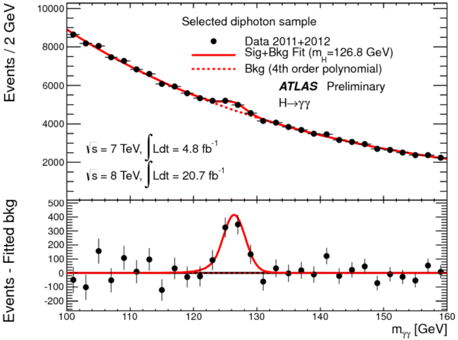
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

Advantage:
Less sensitive to initial state radiation of incoming quarks.

Event selection

- Diphoton trigger with $E_{T,\gamma 1} > 35\,\text{GeV}$ and $E_{T,\gamma 2} > 25\,\text{GeV}$
- $0 < |\eta| < 1.37$ and $1.56 < |\eta| < 2.37$
- $105\,\text{GeV} < m_{\gamma\gamma} < 160\,\text{GeV}$
- $p_{T,\gamma 1}/m_{\gamma\gamma} > 0.35$ and $p_{T,\gamma 2}/m_{\gamma\gamma} > 0.25$

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



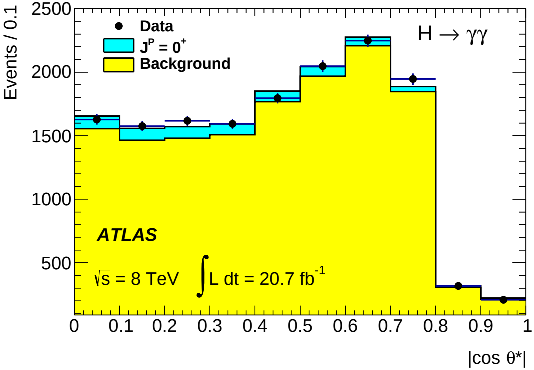
A mass signal region (SR) and side band regions (SBR) are defined for background estimation and separation between signal and bkg.

SR: $122 - 130\,\text{GeV}$

SBR: $105\,\text{GeV} < m_{\gamma\gamma} < 122\,\text{GeV}$ and $130\,\text{GeV} < m_{\gamma\gamma} < 160\,\text{GeV}$

Distribution of sensitive observable

Sensitive observable in SR:



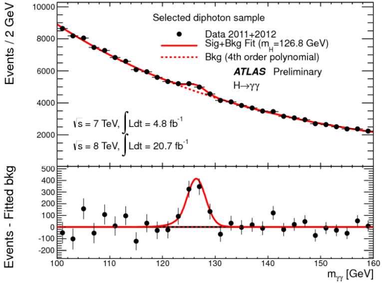
The expected background is very large compared to the expected signal.

$\Rightarrow$ Good estimation of background is important

$\to$ Shape (f_B) and yield (n_B) are needed

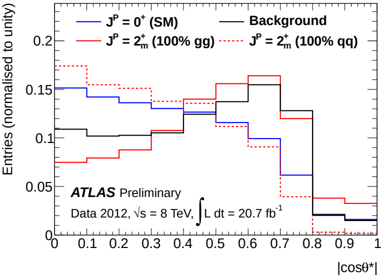
Obtaining the pdf of $m_{\gamma\gamma}$

- Natural width of invariant mass distribution is smaller than experimental resolution
  - $\Rightarrow$ The pdf $f_S(m_{\gamma\gamma})$ is the same for the spin-0 and the spin-2 hypothesis
- $f_S(m_{\gamma\gamma})$ is determined from a fit to the MC simulated distribution
- $f_B(m_{\gamma\gamma})$ is determined from a fifth-degree polynomial fit to the data

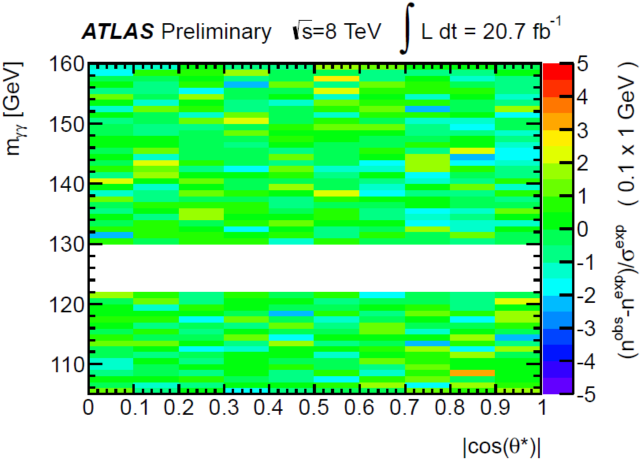


Obtaining the pdf of $|\cos\theta^*|$

- $f_S\,(|\cos\theta^*|)$ is determined from MC for both hypothesis
- $f_B\,(|\cos\theta^*|)$ is determined from the data distribution in $|\cos\theta^*|$ while just considering the events that are in the mass SBR (just possible because of de-correlation between $m_{\gamma\gamma}$ and $|\cos\theta^*|$)



Testing the de-correlation

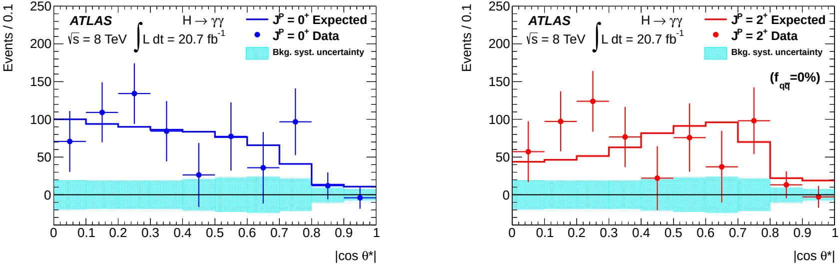


Results

Now everything is done to perform a likelihood-fit (for each hypothesis) and hence to obtain the signal and background estimations.

The likelihood function for this analysis (de-correlation of $m_{\gamma\gamma}$ and $\cos\theta^*$) is:

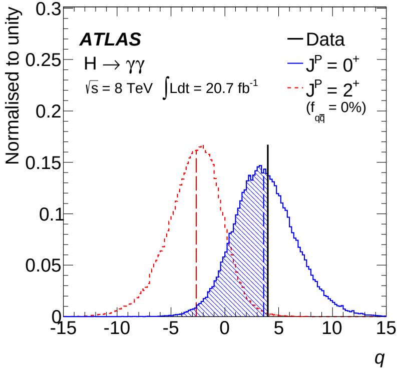
$$\ln\mathcal{L} = -(n_S + n_B) + \sum_{\text{events}} \ln\left[n_S \cdot f_S\left(|\cos\theta^*|\right) \cdot f_S\left(m_{\gamma\gamma}\right) + n_B \cdot f_B\left(|\cos\theta^*|\right) \cdot f_B\left(m_{\gamma\gamma}\right)\right]$$



The distributions of the background-subtracted data in the SR only.

Results

The value for the test-statistic $q = \ln \mathcal{L}_0(\hat{\theta}_0) - \ln \mathcal{L}_2(\hat{\theta}_2)$ of the data can be evaluated (black).



And hence a p-value as well as a Spin-2 exclusion limit (1-$\mathrm{CL_S}(2^+)$) can be obtained.

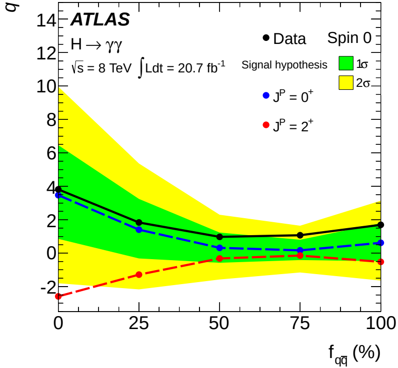
$$p(0^+) = 58.8\,\% \text{ and } p(2^+) = 0.3\,\%.$$

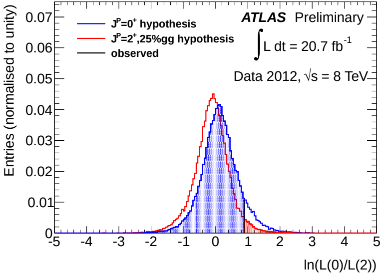
$$p_{\mathrm{exp}}(0^+) = 1.2\,\% \text{ and } p_{\mathrm{exp}}(2^+) = 0.5\,\%.$$

$$1 - \mathrm{CL_S}(2^+) = 1 - \frac{p(2^+)}{1-p(0^+)} = 99.3\,\%$$

Results

Different fractions of $q\bar{q}$.



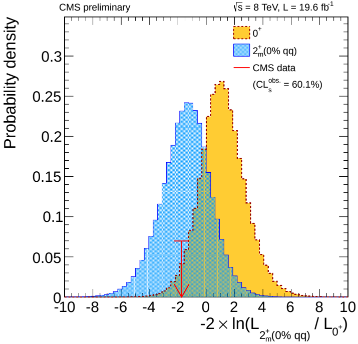


$p(0^+) = 90.2\,\%$ and $1 - \text{CL}_\text{S} = 66.3\,\%$.

Results of CMS

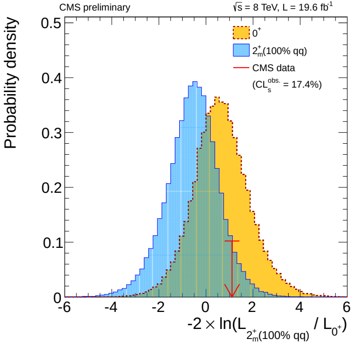
- $19.6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- Used same sensitive variable $|\cos\theta^*|$

Production only via ggF



$1 - \mathrm{CL_S}(2^+_m) = 39.1\,\%$

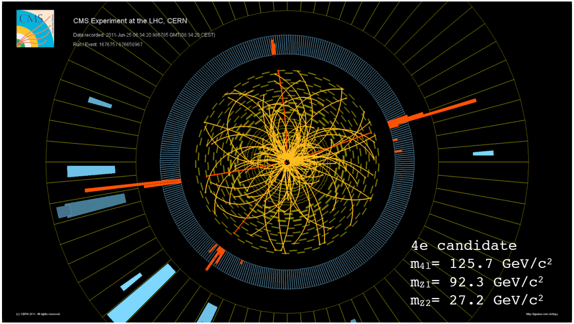
Production only via $q\bar{q}$



$1 - \mathrm{CL_S}(2^+_m) = 83.1\,\%$

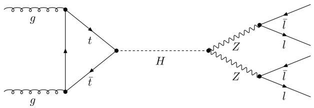
Introduction

- $5.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ and $19.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- Branching fraction is very low, $\mathcal{O}(10^{-4})$
- All decay products visible
- The SM 0^{+}-hypothesis (pure scalar) is compared to 8 alternative hypotheses



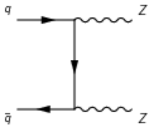
Signal and background

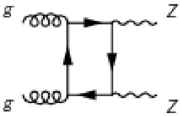
- Signal process $H \to ZZ^* \to 4\ell$:



All decay products are visible!

- Main background (irreducible): Direct ZZ-production via $q\bar{q}$ annihilation and gluon fusion (estimated from MC)

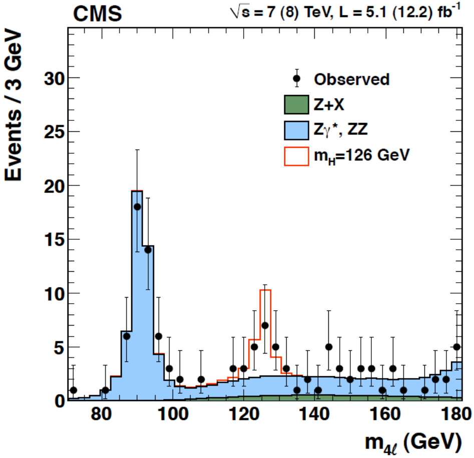




- Subleading background (reducible):
$Z + jets$, $t\bar{t}$, and $WZ + jets$
(estimated from signal-free control regions in data)

Event Selection

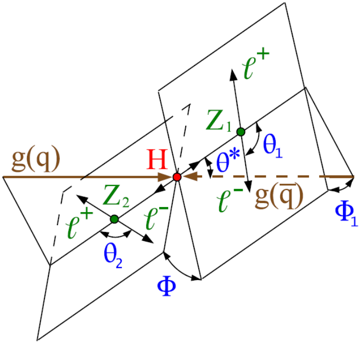
- Two pairs of leptons
- The leptons in a pair must be opposite charged and of same flavour
- $p_T^e > 7\,\mathrm{GeV}$ and $|\eta|^e < 2.5$
- $p_T^\mu > 5\,\mathrm{GeV}$ and $|\eta|^\mu < 2.4$
- $40 < m_{Z1} < 120\,\mathrm{GeV}$
- $12 < m_{Z2} < 120\,\mathrm{GeV}$



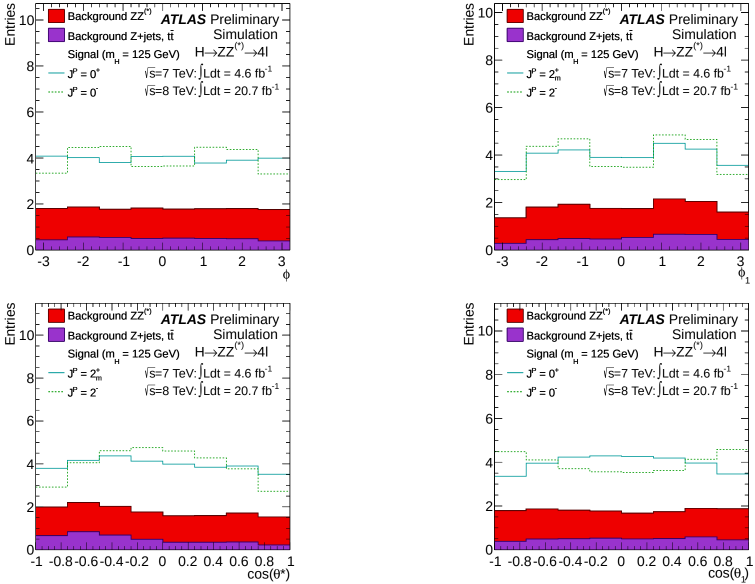
For the following study just events in the mass range $106 < m_{4\ell} < 141\,\mathrm{GeV}$ are used.

Sensitive variables

- Decay of $H \to ZZ \to 4\ell$ sensitive to spin and parity of H
- To distinguish between the different hypothesis five angles in the 4ℓ-rest frame are used
- Together with the two masses m_{Z1} and m_{Z2} these five angles fully describe the kinematic configuration of the 4ℓ-system in its rest frame



Distributions of sensitive variables



Kinematic Discriminants

- Want to construct a discriminant for separation of signal and bkg, $\mathcal{D}_{\text{bkg}}$ and one for separation between different hypotheses, $\mathcal{D}_{J^P}$
- They shall base on matrix-elements
- Therefore pdfs $\mathcal{P}^{\text{kin}}\left(m_{Z1}, m_{Z2}, \vec{\Omega}|m_{4\ell}\right)$ are used which are computed from LO matrix-elements squared
- The following $\mathcal{D}$ are obtained:

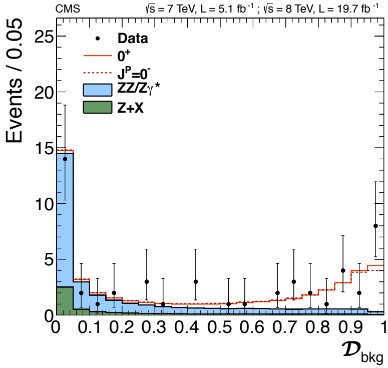
$$\mathcal{D}_{\text{bkg}} = \left[1 + \frac{\mathcal{P}^{\text{kin}}_{\text{bkg}}\left(m_{Z1}, m_{Z2}, \vec{\Omega}|m_{4\ell}\right) \cdot \mathcal{P}^{\text{mass}}_{\text{bkg}}\left(m_{4\ell}\right)}{\mathcal{P}^{\text{kin}}_{0^+}\left(m_{Z1}, m_{Z2}, \vec{\Omega}|m_{4\ell}\right) \cdot \mathcal{P}^{\text{mass}}_{0^+}\left(m_{4\ell}|m_{0^+}\right)}\right]^{-1}$$

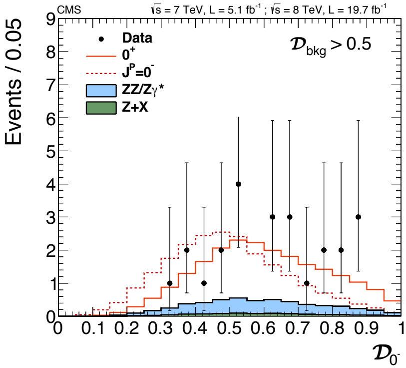
$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{\text{kin}}_{J^P}\left(m_{Z1}, m_{Z2}, \vec{\Omega}|m_{4\ell}\right)}{\mathcal{P}^{\text{kin}}_{0^+}\left(m_{Z1}, m_{Z2}, \vec{\Omega}|m_{4\ell}\right)}\right]^{-1}$$

- All sensitive observables are combined in one discriminant

Kinematic Discriminants

Two example-plots for the $\mathcal{D}$-discriminants are shown.





Distribution nearly independent of hypothesis

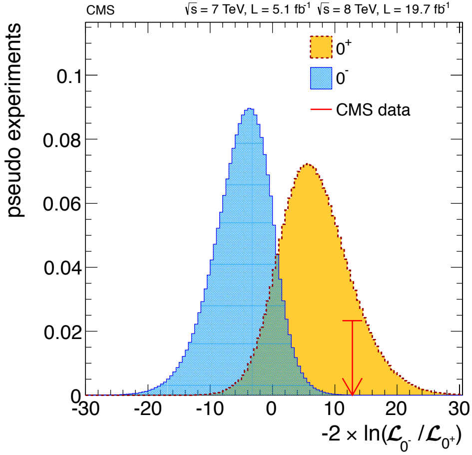
Test statistic

With these discriminants a 2-dim. likelihood-fct. is constructed for each hypothesis and fitted to the data.

$$\mathcal{L}_{2D}^{J^P} = \mathcal{L}_{2D}^{J^P}(\mathcal{D}_{\text{bkg}}, \mathcal{D}_{J^P})$$

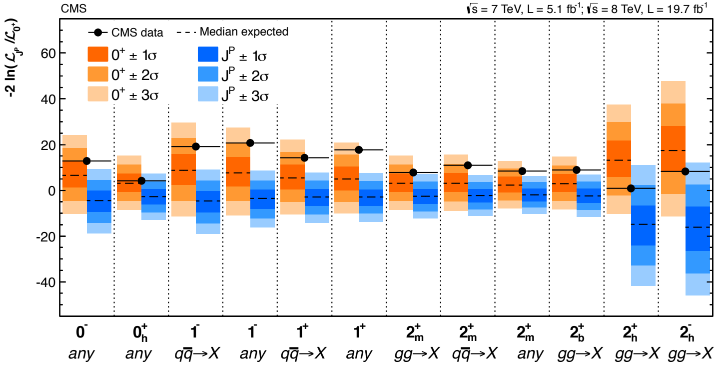
And a test-statistic q is evaluated:

$$\Rightarrow \; q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{0^+})$$



Results

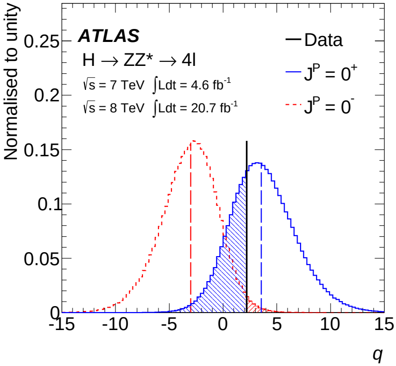
The summary plot for the q-values of all tested hypotheses.



$$1 - \mathsf{CL_S}(0^-, 0_h^+) \geq 95.5\,\% \qquad 1 - \mathsf{CL_S}(1) \geq 99.98\,\% \qquad 1 - \mathsf{CL_S}(2) \geq 97.7\,\%$$

Results of ATLAS

- Considered four alternative hypothesis ($J^P = 0^-, 1^+, 1^-, 2^+$)
- Used same angles and the $Z_{1,2}$-masses as CMS
- Another mass-window: $115 < m_{4\ell} < 130\,\mathrm{GeV}$ (smaller)
- The five angles and two masses are combined by using a BDT



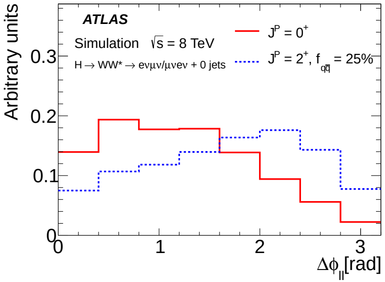
$$1 - \mathrm{CL_S}(0^-) = 97.8\,\%$$
$$1 - \mathrm{CL_S}(1^+) = 99.8\,\%$$
$$1 - \mathrm{CL_S}(1^-) = 94.0\,\%$$
$$1 - \mathrm{CL_S}(2^+) = 96.4\,\%$$

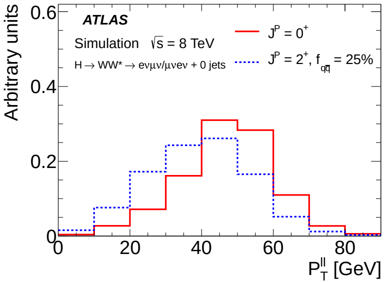
Introduction

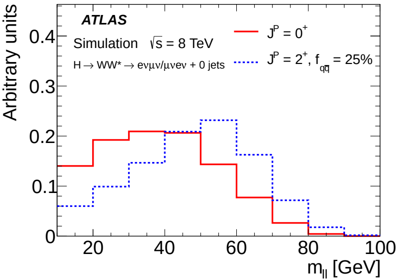
- $20.7\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$
- Better separation from bkg if e and μ
- The SM 0^+-hypothesis is compared to the 1^+-, 1^-- and 2^+_m-hypothesis
- Analysis very similar to ZZ-Analysis
- E_T^{miss} in final state

$\Rightarrow$ Not all the five angles can be reconstructed

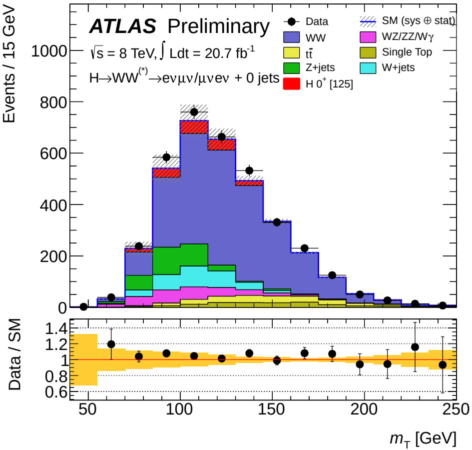
Sensitive variables







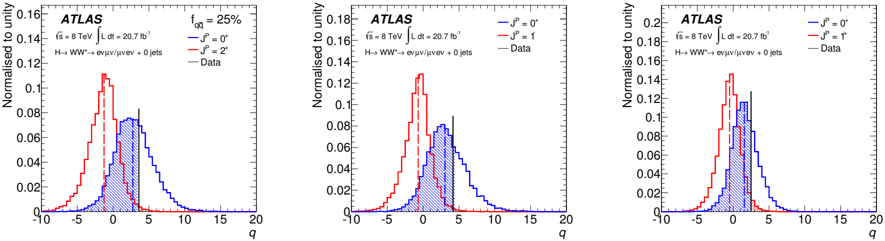
Another variable



For background discrimination.

Results

These three variables plus m_T are used in a BDT again. And a test-statistic q is evaluated.



$1 - \mathrm{CL_S}(2^+) = 98.0\,\%$ | $1 - \mathrm{CL_S}(1^-) = 98.3\,\%$ | $1 - \mathrm{CL_S}(1^+) = 92\,\%$

Combination

For ATLAS the three channels are combined:

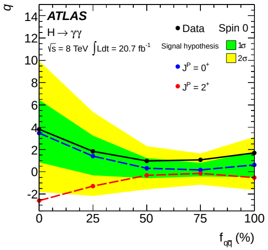
	$\gamma\gamma$	ZZ^*	WW^*
0^-		x	
$1^+/1^-$		x	x
2^+	x	x	x

$$1 - \mathrm{CL_S}(0^-) = 97.8\,\%$$
$$1 - \mathrm{CL_S}(1^+) = 99.97\,\%$$
$$1 - \mathrm{CL_S}(1^-) = 99.73\,\%$$
$$1 - \mathrm{CL_S}(2^+) \geq 99.95\,\%$$

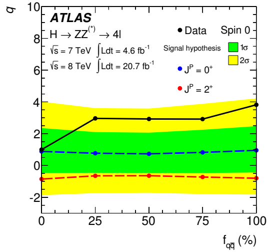
$\Longrightarrow$ All tested alternative hypotheses can be rejected

Combination

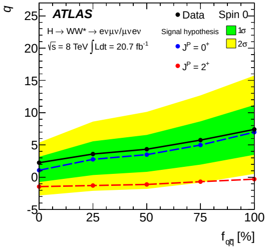
$H \to \gamma\gamma$



$H \to ZZ^* \to 4\ell$



$H \to WW^* \to e\nu_e\mu\nu_\mu$



Conclusion

- All considered alternative hypotheses can be excluded

$\Longrightarrow$ The standard model hypothesis 0^+ is favoured

- Now important: Investigation of CP-mixture states