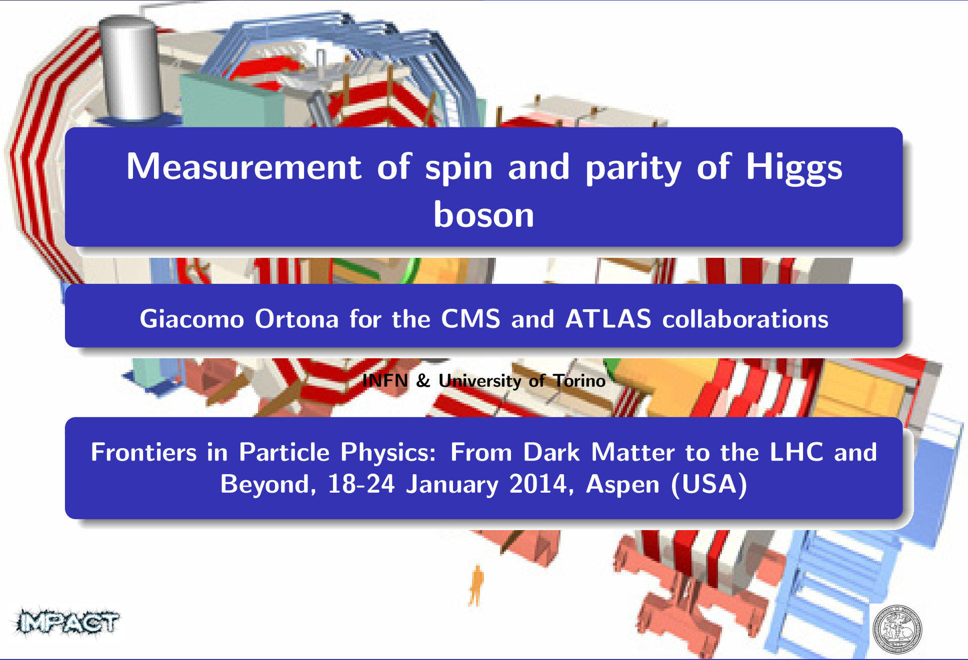


Measurement of spin and parity of Higgs boson

Giacomo Ortona for the CMS and ATLAS collaborations

INFN & University of Torino

Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond, 18-24 January 2014, Aspen (USA)

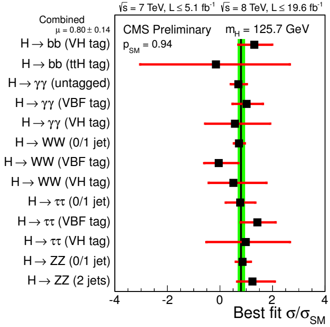
Outline

Motivations

July 2012: new resonance discovered by CMS and ATLAS collaborations

arXiv:1207.7214; arXiv:1207.7235

Couplings and signal strength compatible with the SM Higgs Boson ($\mu = 1.33 \pm 0.20 / \mu = 0.80 \pm 0.14$ measured by ATLAS / CMS) in all channels



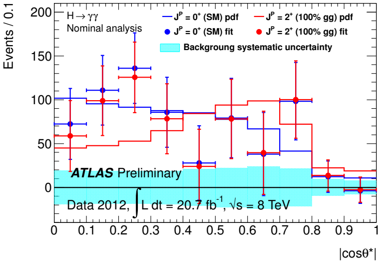
What are the new particle's quantum numbers J^{PC}? SM predicts $J^{PC} = 0^+$

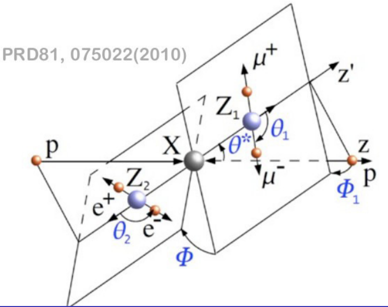
- Observation in diphoton implies C=1 and disfavours J=1 due to Landau-Yang theorem
  - ZZ, WW channels can test spin-1 hypothesis for independent confirmation and mixtures
- Observation in WW favours J=0 (biased selection)
- Observation in ZZ, WW disfavour P=-1

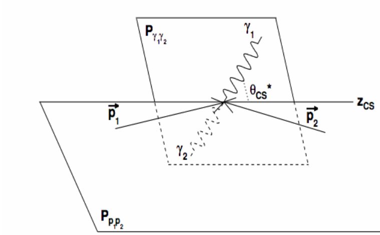
Next step is to test the 0^+ hypothesis against alternative models

Testing spin-parity

- For each channel, find variables that are able to discriminate between the SM and the alternative hypotheses
- We test spin-parity → angles are what we are looking for
- Different channels → different kinematic properties

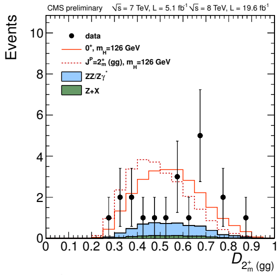


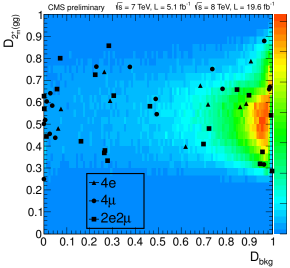


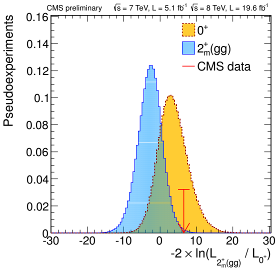


Testing spin-parity: likelihood

- Looking at a single variable is usually not enough to obtain good discrimination
- From simulations (and control regions), obtain the distributions for background, signal and alternative hypotheses events in the space of the discriminating variables $\rightarrow$ likelihood distributions for signals/models
- *Pseudo-experiments* to generate the distribution of the test statistics $q = -2\log\frac{L_{SM}}{L_{JP}}$ under the SM/alternative hypothesis.
- Compare with results observed in the data q_{obs}, $CL_s = \frac{P(q \geq q_{obs}|S_2+B)}{P(q \geq q_{obs}|S_1+B)}$







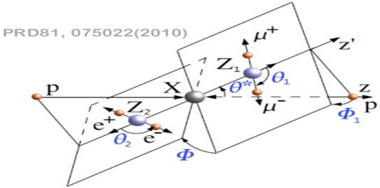
Models tested

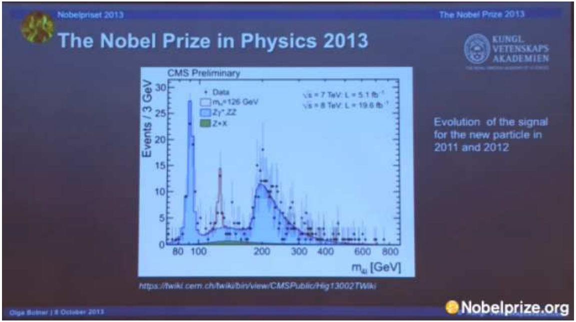
CMS			
J^P	prod	channel	
0^-	any	ZZ,WW	pseudoscalar
0^+_h	any	ZZ	scalar high dim op
1^-	$q\bar{q}$	ZZ	
1^-	any	ZZ	
1^+	$q\bar{q}$	ZZ	
1^+	any	ZZ	
2^+_m	gg	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_m	$q\bar{q}$	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_{m}	any	ZZ,WW,$\gamma\gamma$	grav, min. coupl.
2^+_b	gg	ZZ	RS grav, SM in bulk
2^+_h	gg	ZZ	tensor high dim op
2^-_h	gg	ZZ	pseudo-tensor

ATLAS		
J^P	prod	channel
0^-	any	ZZ
1^-	any	ZZ,WW
1^+	any	ZZ,WW
2^+_m	gg	ZZ,WW,$\gamma\gamma$
2^+_m	$q\bar{q}$	ZZ,WW,$\gamma\gamma$
2^+_m	any	ZZ,WW,$\gamma\gamma$

H → ZZ → 4l

5 angles and 2 masses fully describe the H→ZZ→ 4l decay
Sensitive to spin AND parity.
Main channel to probe the 0^- Hypothesis





- Events selected in the peak [115 – 130]GeV ATLAS, [106 – 141]GeV CMS

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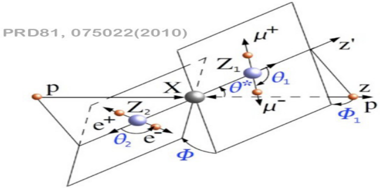
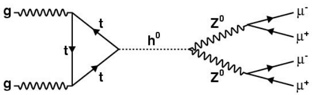
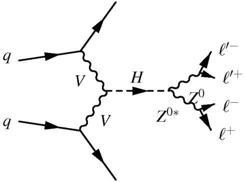




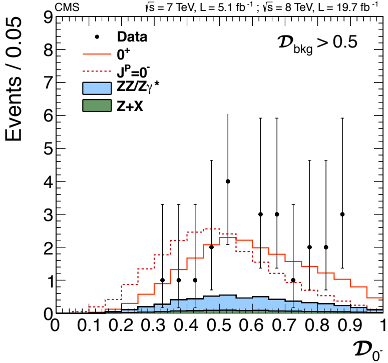


- Events selected in the peak $[115 - 130]$GeV ATLAS, $[106 - 141]$GeV CMS
- Different $q\bar{q}/gg$ production fractions can be tested for spin-2.

H → ZZ → 4l analysis in CMS

- Matrix Element Likelihood approach arXiv:1208.4018, use the discriminant variables:

$$D_{J^P} = \left[1 + \frac{P^{\mathrm{kin}}_{JP}(m_1, m_2, \Omega | m_{4l})}{P^{\mathrm{kin}}_{0+}(m_1, m_2, \Omega | m_{4l})}\right]^{-1}, \quad D_{\mathrm{bkg}} = \left[1 + \frac{P^{\mathrm{kin}}_{\mathrm{bkg}}(m_1, m_2, \Omega | m_{4l}) \times P^{\mathrm{mass}}_{\mathrm{bkg}}(m_{4l})}{P^{\mathrm{kin}}_{0+}(m_1, m_2, \Omega | m_{4l}) \times P^{\mathrm{mass}}_{\mathrm{sig}}(m_{4l})}\right]^{-1}$$



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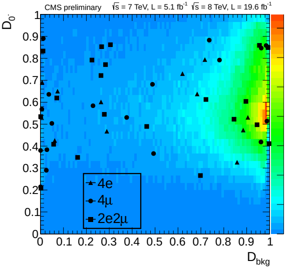
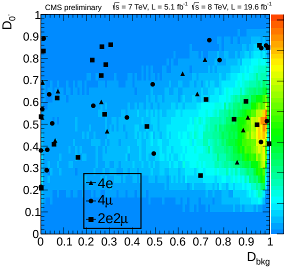
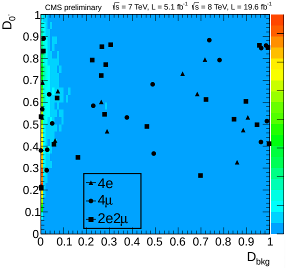
- Build 2D $(D_{J^P}, D_{\mathrm{bkg}})$ templates and Likelihoods for 0^+ and J^P







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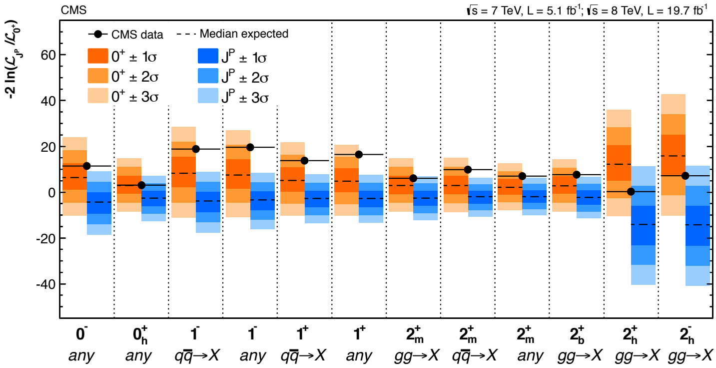
- Build 2D $(D_{J^P}, D_{\rm bkg})$ templates and Likelihoods for 0^+ and J^P
- Tested **and excluded** 9 models + 3 prod independent models $(1^-, 1^+, 2^+)$



CMS ZZ spin-parity summary

J^P model	J^P production	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	any	2.6σ (2.7σ)	-0.9σ	$+3.8\sigma$	0.04%
0^+_h	any	1.8σ (1.9σ)	$+0.3\sigma$	$+1.6\sigma$	10.0%
1^-	$q\bar{q} \rightarrow X$	2.9σ (3.1σ)	-1.5σ	$> 5.0\sigma$	<0.1%
1^-	any	2.7σ (3.0σ)	-1.8σ	$> 5\sigma$	<0.1%
1^+	$q\bar{q} \rightarrow X$	2.4σ (2.6σ)	-1.4σ	$+4.5\sigma$	0.004%
1^+	any	2.3σ (2.4σ)	-2.1σ	$> 5\sigma$	<0.1%
2^+_m	$gg \rightarrow X$	1.8σ (1.9σ)	-0.7σ	$+2.7\sigma$	1.5%
2^+_m	$q\bar{q} \rightarrow X$	1.8σ (1.9σ)	-1.6σ	$+3.8\sigma$	0.16%
2^+_{m}	any	1.5σ (1.6σ)	-1.5σ	$+3.3\sigma$	0.8%
2^+_b	$gg \rightarrow X$	1.8σ (1.9σ)	-1.1σ	$+3.2\sigma$	0.5%
2^+_h	$gg \rightarrow X$	3.9σ (4.1σ)	$+2.0\sigma$	$+1.9\sigma$	3.0%
2^-_h	$gg \rightarrow X$	4.4σ (4.8σ)	$+1.1\sigma$	$+3.3\sigma$	0.05%

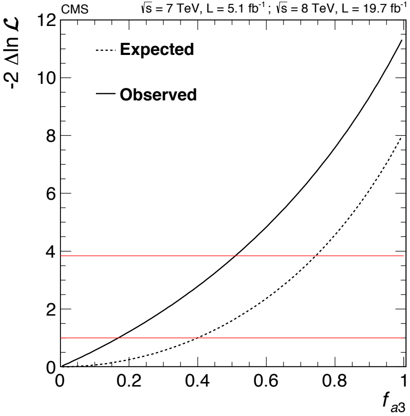
f_{a3} parameter

Most general spin-0 boson decay amplitude:

$$A(H \to ZZ) = v^{-1}\epsilon_1^*\epsilon_2^*\left(a_1 g_{\mu\nu} m_Z^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) = A_1 + \not{A_2} + A_3$$

0^+ dominated by A_1, 0^- by A_3

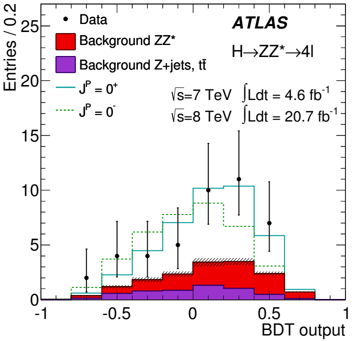
- $f_{a3} = |A_3|^2/(|A_1|^2 + |A_3|^2)$
  if $0 < f_{a3} < 1 \to$ **CP violation**
- Interference is negligible
- The shape of D_{0^-} discriminant depends on the value of f_{a3}. We can use it to measure f_{a3}
- We can set a limit on *CP* violating contributions to *HZZ* coupling



$f_{a3} = 0.00^{+0.17}_{-0.00}$, $f_{a3} < 0.51$ at 95% CL

H → ZZ → 4l analysis in ATLAS

- BDT approach using the 5+2 kinematic variables.
- Split in 4 final states ($4e, 4\mu, 2e2\mu, 2\mu 2e$) to increase sensitivity
- 2 different mass regions: high S/B (121-127) and low S/B (115-121 and 127-130)
- 5 different $q\bar{q}$ fractions tested for spin-2

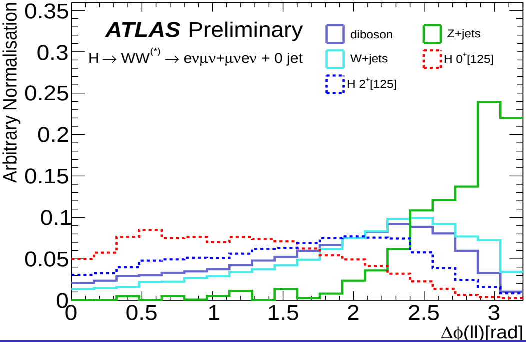


		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060

$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.102	0.082	0.962	0.001	0.026
75%	0.117	0.099	0.923	0.003	0.039
50%	0.129	0.113	0.943	0.002	0.035
25%	0.125	0.107	0.944	0.002	0.036
0%	0.099	0.092	0.532	0.079	0.169

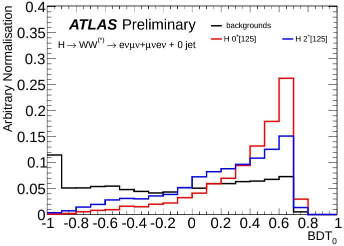
H → WW → 2l2ν

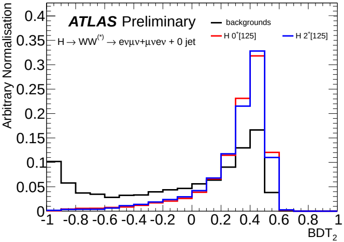
- Low mass resolution due to neutrinos in the final states
- Sensitive to spin-0 vs spin-2 discrimination
- Discriminant variables: $\Delta\Phi_{ll}$, m_{ll}, p_T^{ll}, $m_T = \sqrt{2 p_T^{ll} E_T^{\text{miss}} (1 - \cos \Delta\Phi_{ll - E_T^{\text{miss}}})}$
- Most of the sensitivity from H → WW → $e\nu_e\mu\nu_\mu$



H → WW → 2l2ν at ATLAS

- low signals and high backgrounds, event selection is challenging, for spin analysis softer selection with respect to nominal:
  - MET > 20GeV, 0 jets, $p_T^{ll} > 20$GeV, $m_{ll} < 80$GeV, $\Delta\Phi_{ll} < 2.8$.
- The four discriminating variables are used for the BDT in a MVA

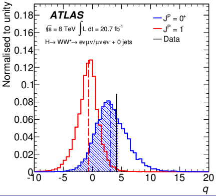




2D fit of the spin-0 and spin-2 BDT discriminants

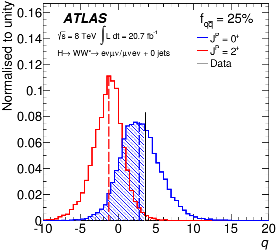
Same approach can be used for spin-1 →

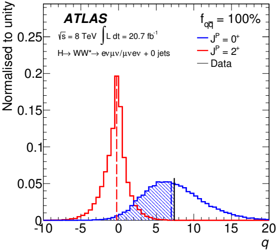
1^+ excluded at 92% CL, 1^- excluded at 98.3% CL

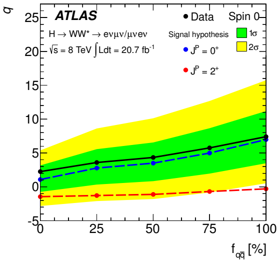


$H \to WW \to 2l2\nu$ at ATLAS: Spin-2 results

Different $q\bar{q}$ fractions tested for spin-2.
Highest rejection for the 100% $q\bar{q}$ case







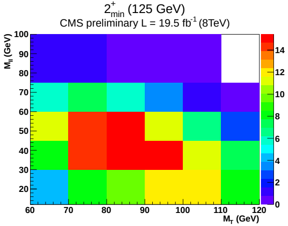
Good agreement between spin-0 and data, 100% $q\bar{q}$ rejected at $> 99\%$ CL

$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.015	0.005	0.552	0.004	0.009
75%	0.035	0.007	0.594	0.005	0.012
50%	0.042	0.013	0.609	0.007	0.017
25%	0.050	0.020	0.614	0.010	0.027
0%	0.092	0.059	0.725	0.014	0.053

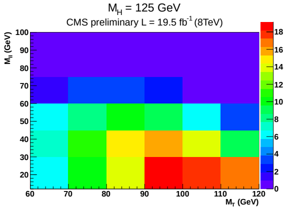
$H \to WW \to 2l2\nu$ at CMS

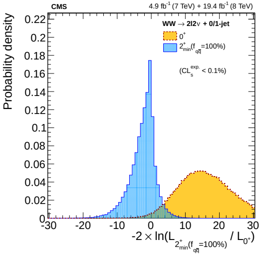
- Used to test 0^+ against 0^- or minimal coupling 2^+_{min} (graviton-like)
- Events are divided in 0 or 1 jet categories.
- Similar to ZZ analysis, 2-dimensional templates based on m_{ll} and m_T distributions
- Different $q\bar{q}$ fractions tested

2^+, 0 jets category

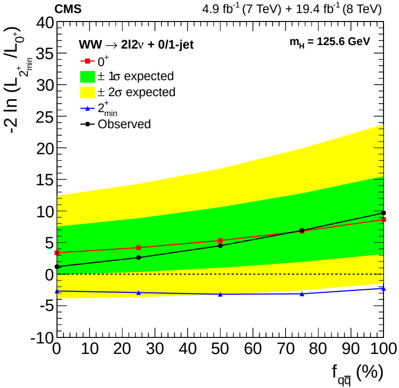


0^+, 0 jets category





H → WW → 2l2ν: CMS results

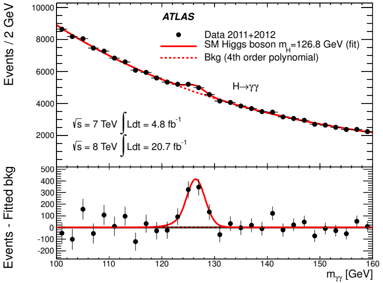


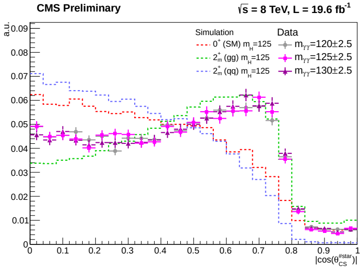
J^P model	J^P production	Expected ($\sigma/\sigma_{SM}=1$)	obs. 0^+	obs. J^P	CL_s
2^+_{min}	$f_{q\bar{q}}$=0%	1.8σ (2.6σ)	+0.6σ	+1.2σ	16.3%
2^+_{min}	$f_{q\bar{q}}$=50%	2.3σ (3.2σ)	+0.2σ	+2.1σ	3.3%
2^+_{min}	$f_{q\bar{q}}$=100%	2.9σ (3.9σ)	-0.2σ	+3.1σ	0.2%
0^-	any	0.8σ (1.1σ)	-0.5σ	+1.2σ	34.7%

Good agreement between 0^+ and data, 100% $q\bar{q}$ rejected at $>$ 99% CL

H → $\gamma\gamma$

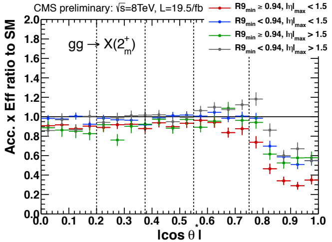
- Decay of spin-1 particles to $\gamma\gamma$ forbidden by Landau-Yang. Observation excludes pure spin-1 states. Test spin-0 vs spin-2 models.
- Main discriminant variables for 0 vs 2 is the **polar angle** θ^*,
  $\cos\theta^* = \frac{\sinh(\Delta\eta_\gamma)}{\sqrt{1+(p_t^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_t^{\gamma 1}p_t^{\gamma 2}}{m_{\gamma\gamma}^2}$
- $\cos\theta^*$ uniform in spin-0, depends on the $q\bar{q}$ fraction for spin-2
- Discrimination power between spin-0 and spin-2 degrades increasing the $q\bar{q}$ fraction. Most sensitive to pure gg production mechanism

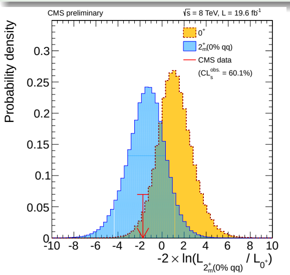


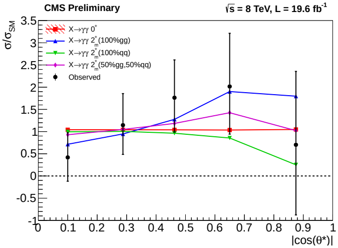


H → γγ in CMS

- Only 8 TeV samples finalized at the moment
- Dataset divided in 5 bins of $\cos\theta^*$ and
- 4 categories of purity ($R9_{\mathrm{min}}$ and $|\eta|_{\mathrm{max}}$)
- Total of 20 fits of $m_{\gamma\gamma}$
- Comparison of 0^+ vs $gg \to 2^+_m$ and $q\bar{q} \to 2^+_m$



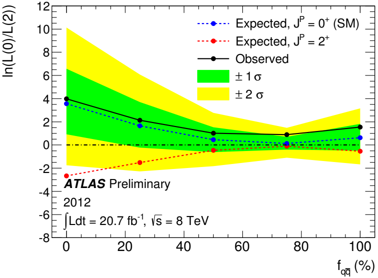




Results are not conclusive yet, updates will arrive soon

$H \to \gamma\gamma$ in ATLAS

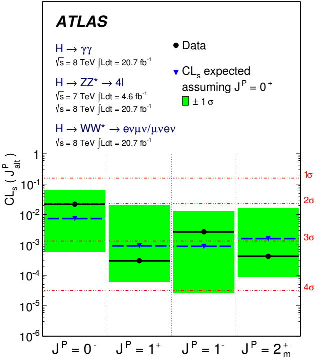
- Good rejection power between 0^+ and 2^+ when 100% gg
- Less powerful in the $q\bar{q}$ case
- background strongly peaked in the forward direction, small S/B
- Cuts optimized to minimize the correlation between $m_{\gamma\gamma}$ and $\cos\theta^*$
  - $\frac{p_T^{\gamma 1}}{m_{\gamma\gamma}} > 0.35$; $\frac{p_T^{\gamma 2}}{m_{\gamma\gamma}} > 0.25$
- Alternative: simultaneous fits of $m_{\gamma\gamma}$ in bins of $\cos\theta^*$ gives compatible results

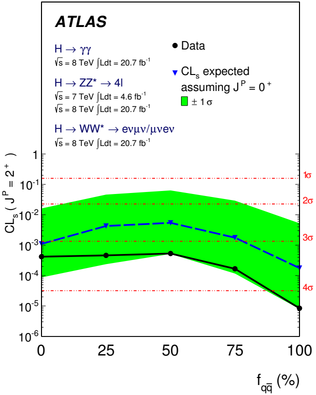


0% $q\bar{q}$ Spin-2 excluded at 99.3% CL

$f_{q\bar{q}}$	Spin-2 assumed exp. $p_0(J^P = 0^+)$	Spin-0 assumed exp. $p_0(J^P = 2^+)$	obs. $p_0(J^P = 0^+)$	obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

Combination: ATLAS





0^- hypothesis is excluded at 97.8% CL in the ZZ channel

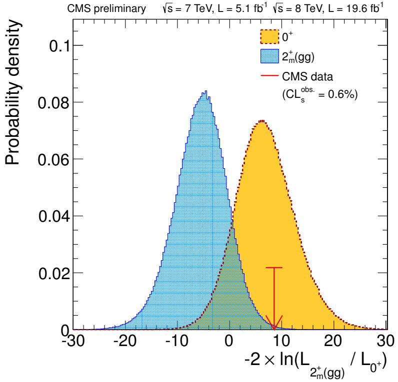
1^+ hypothesis excluded at 99.97% CL by the combined ZZ+WW analysis

1^- hypothesis excluded at 99.7% CL by the combined ZZ+WW analysis

Tested 2^+ excluded at 99.9% CL by the combined ZZ+WW+$\gamma\gamma$ analysis

Results: CMS

- Parity 0^- excluded at 99.96% CL in ZZ channel
- Spin-1 excluded at $> 99.9\%$ in the ZZ channel
- 2_m^+ model excluded at 99.4% by the combined WW+ZZ analysis
- Other spin-2 (2_b^+, 2_h^+, 2_h^-) models excluded at $> 97\%$ CL in ZZ



Mixture studies are the next big goal!

- CMS already set a limit on CP-odd contribution $f_{a3} < 0.51$ at 95% CL

Conclusions

Summary

- Both CMS and ATLAS results show SM (0^+) state highly favoured against alternative pure J^P states
- The two experiments show good agreement and consistent and complemetary results
- Best knowledge from both experiments allows to exclude all tested hypotheses of 0^-, spin-1 and spin-2 states with CL $>$ 99.9%

Next

- Still some way to go before being able to exclude mixed state
  - But a limit on the fraction of CP-odd contributions to the cross-section $f_{a3} < 0.51$ has already been set by CMS
- In the future, extend the analyses to VBF, VH, ttH, H$\rightarrow \tau\tau$, ...

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References

ATLAS public results:

- $H \to ZZ$
  - ATLAS-CONF-2013-013
- $H \to WW$
  - ATLAS-CONF-2013-031
- $H \to \gamma\gamma$
  - ATLAS-CONF-2013-029
- Combination
  - ATLAS-CONF-2013-040
  - arXiv:1307.1432

CMS public results:

- $H \to ZZ$
  - CMS-PAS-HIG-13-002
  - arXiv:1312.5353
- $H \to WW$
  - CMS-PAS-HIG-13-003
  - arXiv:1312.1129
- $H \to \gamma\gamma$
  - CMS-PAS-HIG-13-016
- Combination
  - CMS-PAS-HIG-13-005

BACKUP

Combination: ATLAS

0^- hypothesis is excluded at 97.8% CL in the ZZ channel

Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

1^+ hypothesis excluded at 99.97% CL by the combined ZZ+WW analysis

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

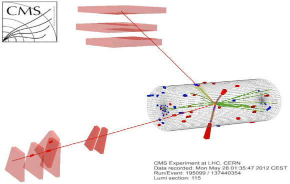
1^- hypothesis excluded at 99.7% CL by the combined ZZ+WW analysis

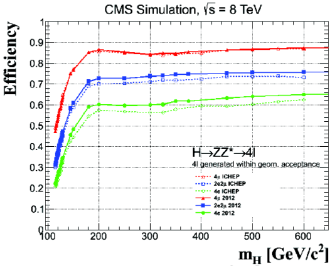
Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

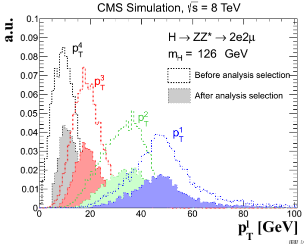
2^+ excluded at 99.9% CL by the combined ZZ+WW+$\gamma\gamma$ analysis

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	$3.0 \cdot 10^{-3}$	$8.8 \cdot 10^{-5}$	0.81	$1.6 \cdot 10^{-6}$	$0.8 \cdot 10^{-5}$
75%	$9.5 \cdot 10^{-3}$	$8.8 \cdot 10^{-4}$	0.81	$3.2 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
50%	$1.3 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	0.84	$8.6 \cdot 10^{-5}$	$5.3 \cdot 10^{-4}$
25%	$6.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	0.80	$0.9 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$
0%	$2.1 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	0.63	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$

H→ZZ→ 4l Kinematics







- Two pairs of OS/SF leptons. Z_1 closest to the Z mass, Z_2 the remaining with highest p_t
- $40 < m_{Z_1} < 120$GeV
  $12 < m_{Z_2} < 120$GeV
- One lepton with $p_t > 20$ GeV/c, another with $p_t > 10$ GeV/c.
- $m_{4l} > 100$ GeV, any $m_{l^+l^-} > 4$ GeV

$\gamma\gamma$ residual correlation