Spin-parity measurements in CMS/ATLAS

Higgs spin tests

Johannes Mattmann [1] Meng Xiao [2]

[1] Johannes Gutenberg-Universität Mainz

[2] Johns Hopkins University

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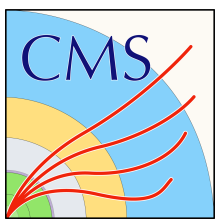

Content

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Introduction

Motivation for spin tests

Are the Higgs boson properties as expected, i.e. $J^P = 0^+$?

- Particle has integral spin, $C = 0$, mass is known
- Unknown: spin and parity
- Landau-Yang theorem forbids spin 1 particle decay to $\gamma\gamma$ (only possible if not only one particle was observed)

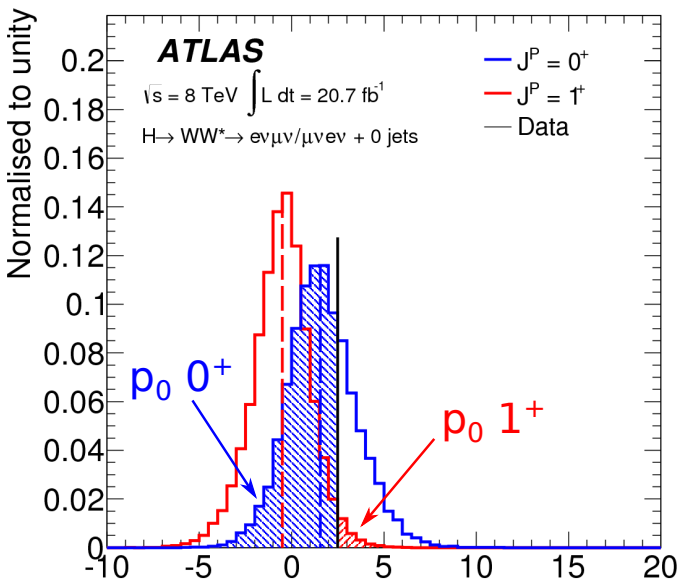
$\rightarrow$ Tests of differenct spin models for spin 1 and 2 performed for $H \rightarrow ZZ \rightarrow 4\ell, H \rightarrow \gamma\gamma, H \rightarrow WW \rightarrow \ell\nu\ell\nu$

How are these tests performed?

- rely on dedicated models (i.e. MC samples) for possible spin/parity states
- per model: identify variables with seperation power, run hypothesis tests against SM

Methodology

- Event selection and systematic uncertainties based on couplings analyses with some extensions (e.g. evt. selection w.r.t. alternative model shapes)
- 3 categories of uncertainties: exerimental (e.g. jet enery scale), theoretical (e.g. bkg. normalization), stats



(from Phys. Lett. B 726 (2013), pp. 120-144)

Hypothesis tests based on toys created from overall p.d.f. including all nuisance parameters

Test statistics: $q = \log \frac{\mathcal{L}(J^P{=}0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$

$$CL_s\left(J^P_{\text{alt}}\right) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

Non-SM models (JHU generator) for spin 1/2 tests

Spin 1: $A(X_{J=1} \to VV) = \underbrace{b_1\left[(\epsilon_1^* q)\,(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)\,(\epsilon_1^* \epsilon_X)\right]}_{\text{vector particle}} + \underbrace{b_2 \epsilon_{\alpha\mu\nu\beta}\epsilon_X^{\alpha}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\tilde{q}^{\beta}}_{\text{pseudo-vector}}$

$\to$ use eff. fraction $f_{b_2} = \frac{|b_2|^2\sigma_2}{|b_1|^2\sigma_1 + |b_2|^2\sigma_2}$ to test mixed spin 1 states

Spin 2:

$$A(X_{J=2} \to V_1 V_2) = \Lambda^{-1}\left[2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}\right.$$
$$+ c_3\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2\left(2c_5 t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2c_6\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}) + c_7\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+ c_8\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha}\tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma$$
$$\left. + \frac{c_{10} t^{\mu\alpha}\tilde{q}_\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*))\right]$$

- c_1 and $c_5 \neq 0$: $J^P = 2^+_{\mathrm{m}}$ - graviton-like model with min. couplings
- $c_1 \ll c_5$: $J^P = 2^+_{\mathrm{b}}$ - graviton in ED model where SM fields can propagate into the bulk
- Other $c_i \neq 0$: $J^P = 2^\pm_{\mathrm{h}}$ - spin 2 models with higher-dim. operators

(see Phys. Rev. D81 (2010) 075022)

Pros and cons of different channels

$H \to \gamma\gamma$

−High background, low number of sensitive variables (little angular information to discriminate between spin states in final state)

+Sufficient number of events recorded

$H \to ZZ$

−Low statistics

+Most sensitive (angular variables + masses fully reconstructable)

$H \to WW$

−Neutrinos in final state → limited resolution

+Large signal yield, angular information from leptons and MET

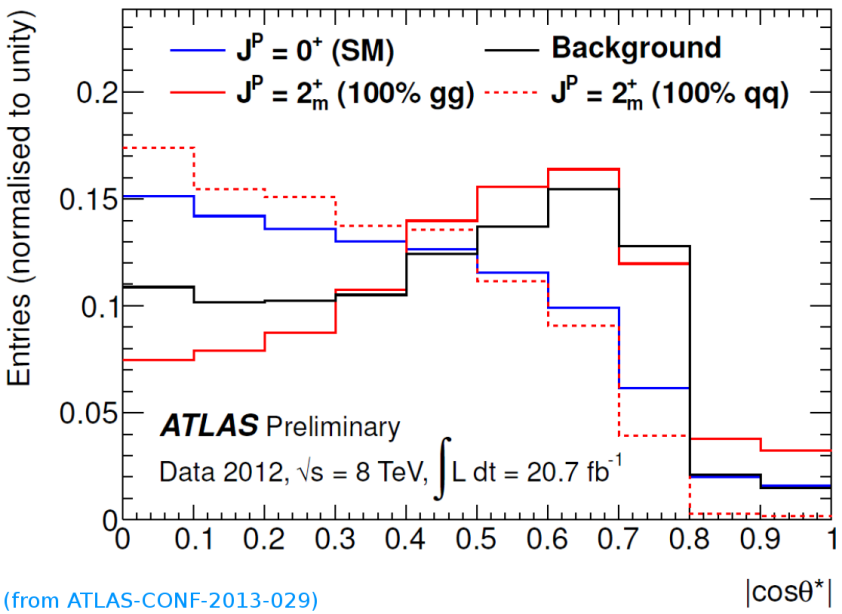
$H \to \gamma\gamma$

General remarks:

- spin 1 not possible
- only minimal couplings tested due to low sensitivity
- main background is non-resonant diphoton production

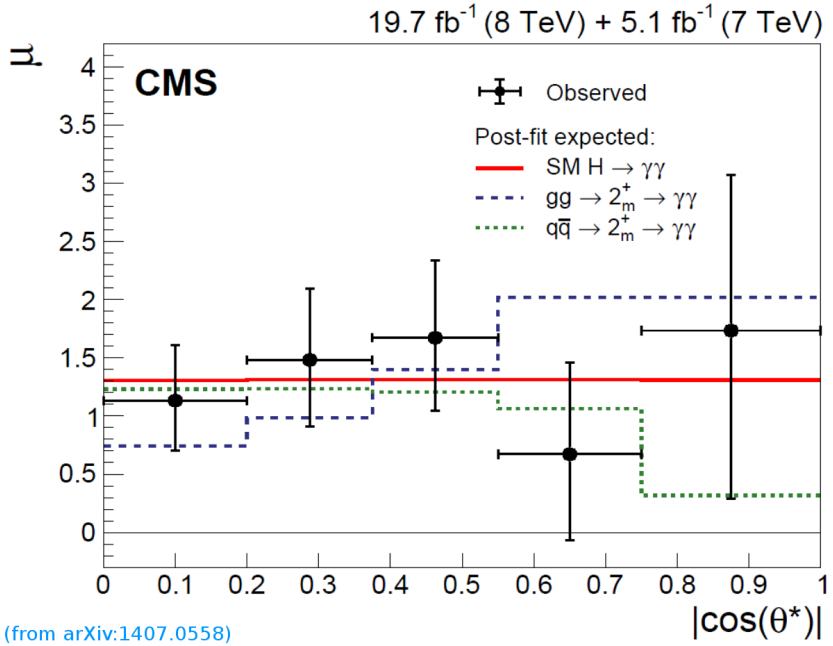
Polar angle of photons w.r.t. z axis identified as sensitive variable:

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



(from ATLAS-CONF-2013-029)

(not flat for 0^+ due to kinematic cuts)



(from arXiv:1407.0558)

Analysis CMS:

- Fit $m_{\gamma\gamma}$ in $|\cos\theta^*|$ bins in different categories

Analysis ATLAS:

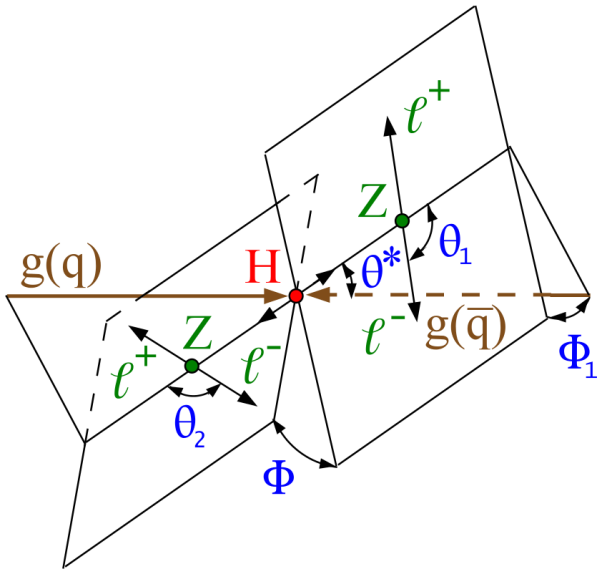
- Simultaneous fit in SR ($m_{\gamma\gamma}$) + two mass sidebands ($m_{\gamma\gamma} \times |\cos\theta^*|$) from which the bkg. shape is derived

$H \to ZZ \to 4\ell$: Analysis strategy

Kinematics can be fully described by 8 variables:

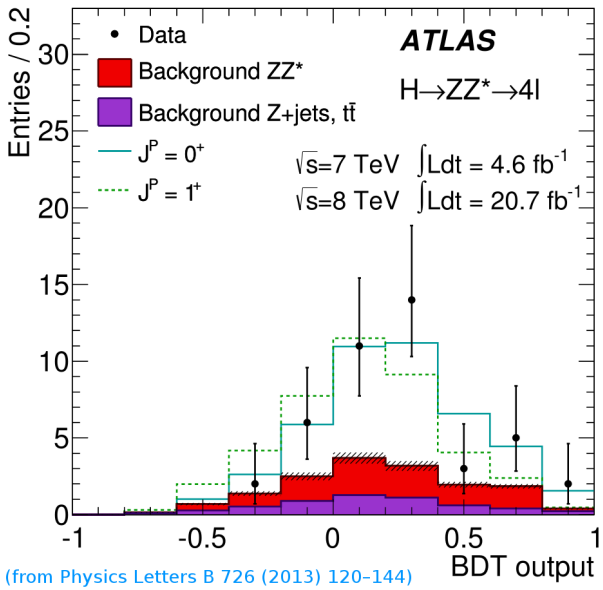
- 3 masses: $m_{Z_1}, m_{Z_2}, m_{4\ell}$
- 5 angles: $\theta^*, \Phi_1, \theta_1, \theta_2, \Phi$

Main backgrounds: ZZ^* (estimated from MC), $Z+$ jets, $(t\bar{t})$, $Zb\bar{b}$ estimated from data in CR



ATLAS Analysis

- 2 masses and 5 angles combined into BDT to discriminate between 0^+ and alternative models
- BDT evaluated in high S/B region in $m_{4\ell}$ (121-127 GeV) and two low S/B regions (115-121 GeV,127-130 GeV)
- Likelihood fit using BDT output as observable

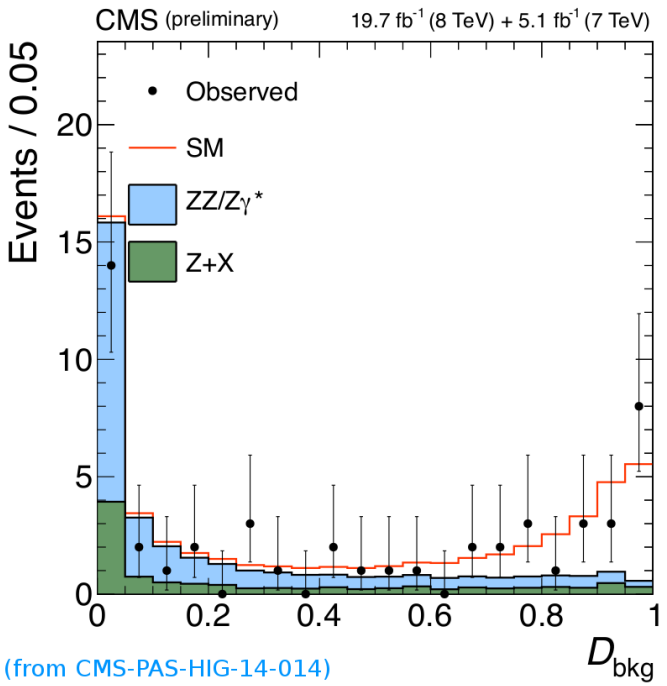


(from Physics Letters B 726 (2013) 120-144)

$H \to ZZ \to 4\ell$: Analysis (continued)

CMS Analysis: Use kinematic discriminants

- Use MELA ($\to$ JHU) (& MEKD) to compute ME from observables, MCFM for bkgs.
- For spin tests: 2 types of discriminants build from probabilities (SM vs. bkg, SM vs. pure other state)
- 2D likelihood fit performed on discriminant distributions



(from CMS-PAS-HIG-14-014)

sig. vs. bkg (ZZ, Z+X)

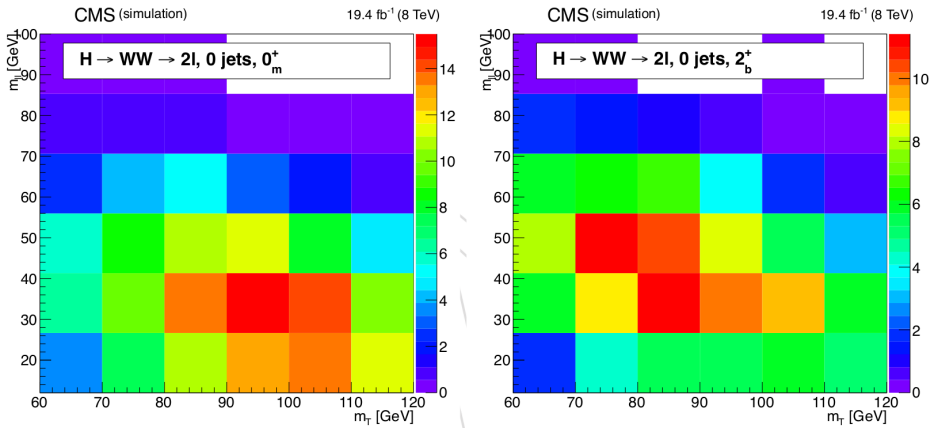
$H \to WW \to \ell\nu\ell\nu$: Analysis

General remarks:

- 2 neutrinos in final state $\to$ kinematics can not be fully reconstructed, use lepton momenta and MET in analyses
- important backgrounds: WW, W+jets, Z+jets, $t\bar{t}$, single top and diboson

CMS Analysis:

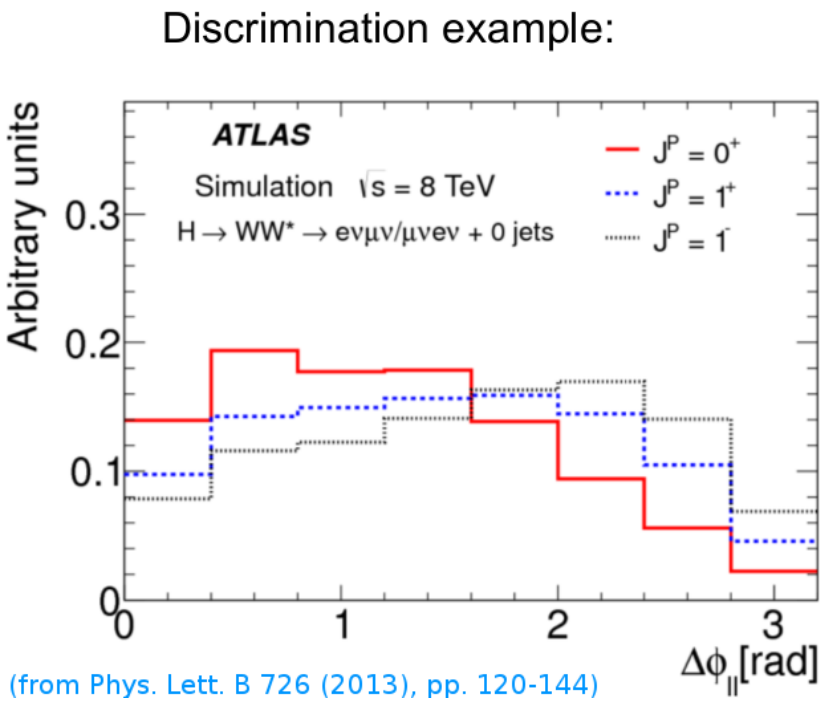
- Use $(m_{\mathrm{T}}, m_{\ell\ell})$ 2D pdf for fitting
- Hypothesis tests SM vs. spin 1 and 2
- Right plot shows 0^+, 2^+_{b}



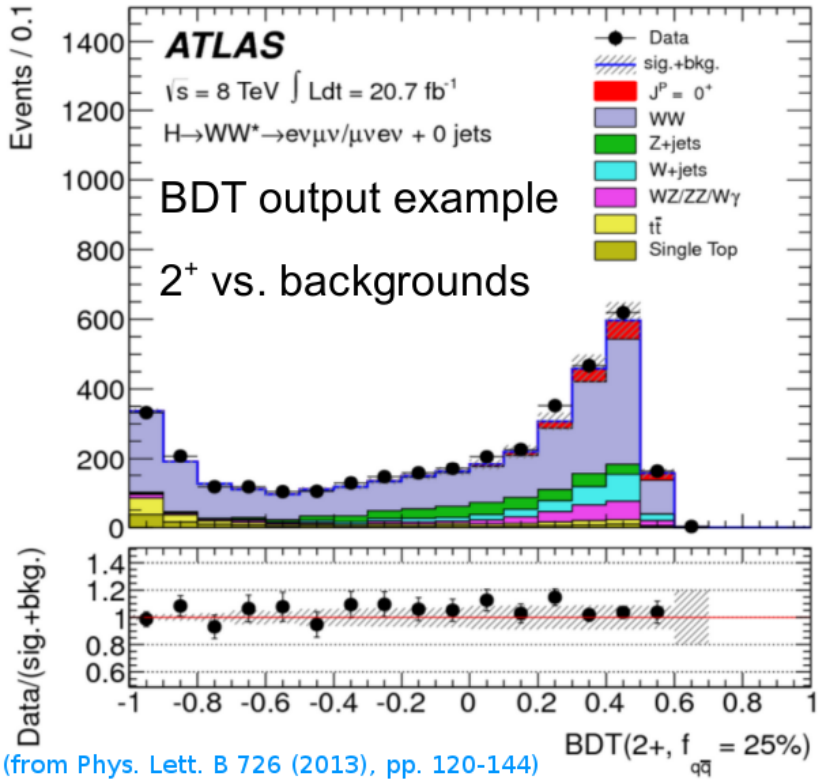
(from JHEP01(2014)096)

$H \to WW \to \ell\nu\ell\nu$: Analysis

ATLAS Analysis:



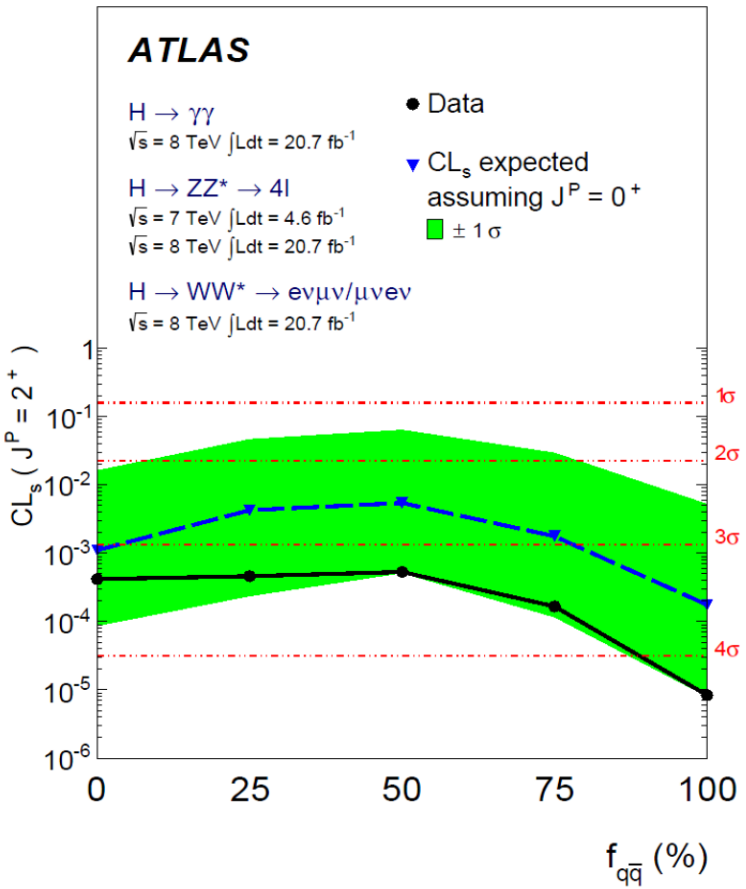
(from Phys. Lett. B 726 (2013), pp. 120-144)



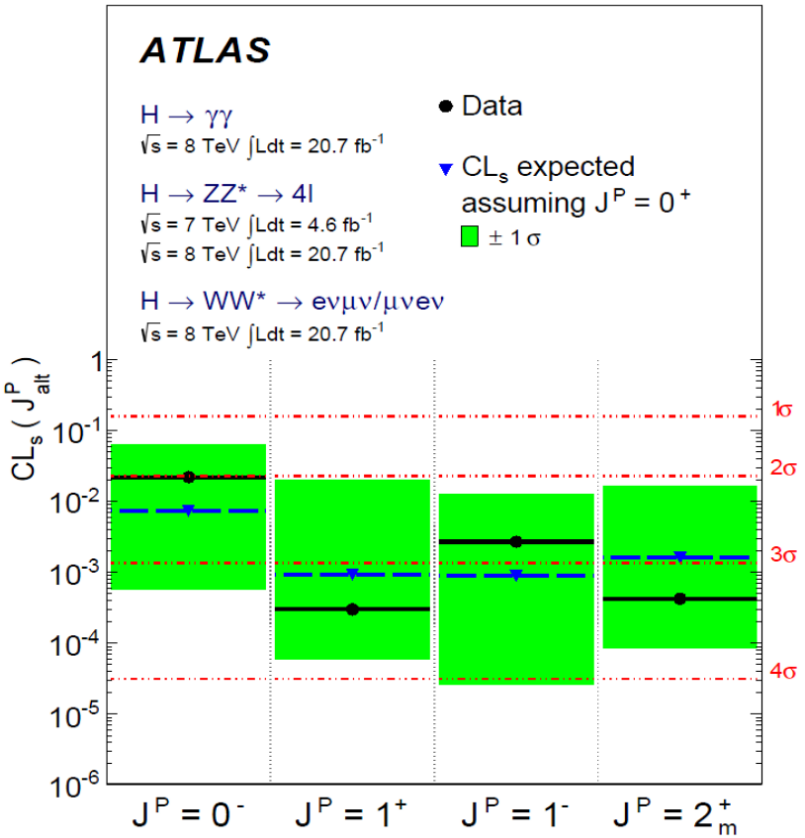
(from Phys. Lett. B 726 (2013), pp. 120-144)

- Main backgrounds estimated from data in control regions
- Two BDT classifiers (0^+ vs. bkg, J^P vs. bkg) to discriminate between hypotheses
- BDT input variables: $m_{\ell\ell}, \Delta\phi_{\ell\ell}, p_{\mathrm{T},\ell\ell}, m_{\mathrm{T}}$
- Unrolled 2D BDT output used for likelihood fit

ATLAS combined results



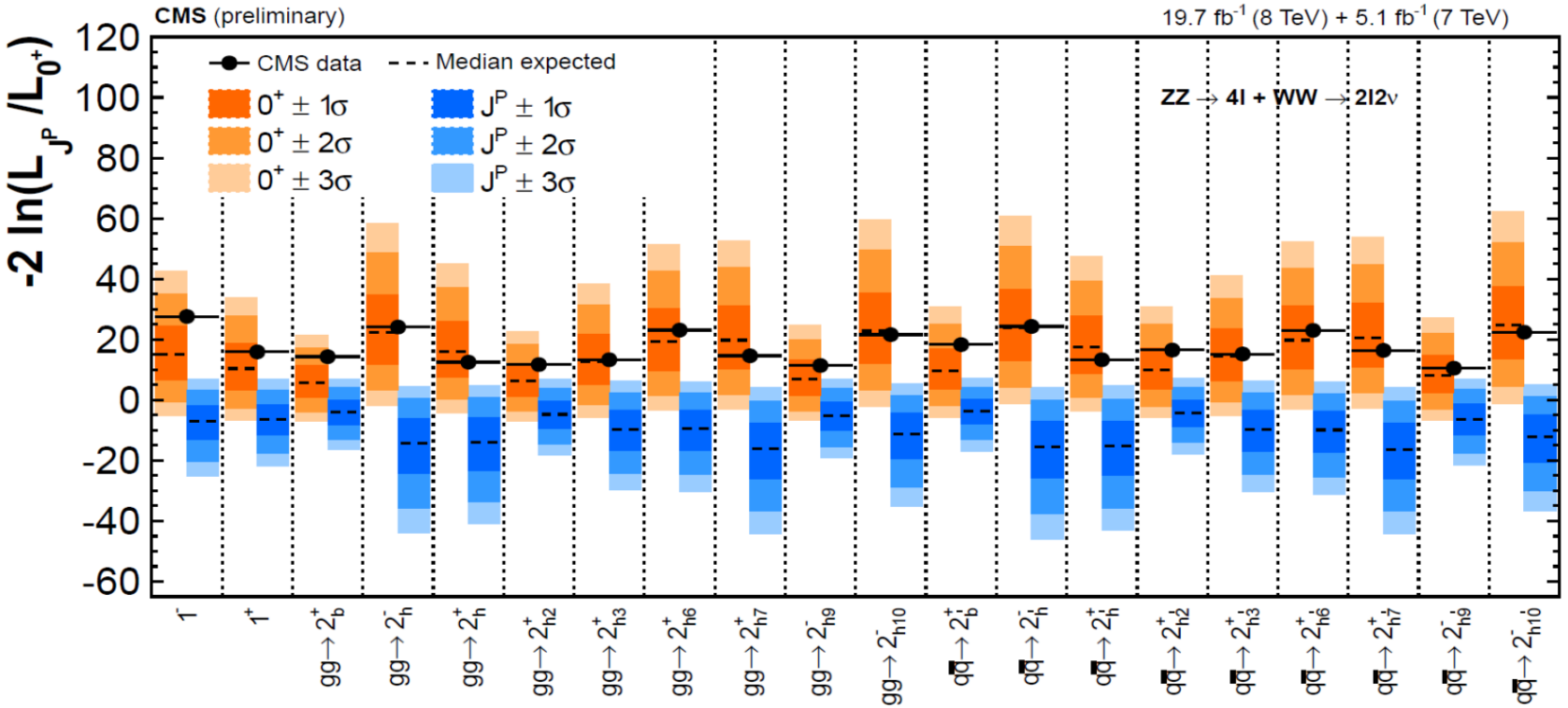
($f_{q\bar{q}} \equiv$ relative fraction of $q\bar{q}$ production)



(both Plots from Phys. Lett. B 726 (2013), pp. 120-144)

- Spin 1 rejected at 99.7 % CL (from *WW* and *ZZ* channel)
- Spin 2 rejected at 99.9 % CL from all 3 channels over whole $f_{q\bar{q}}$ range (2^+_{m} in right plot is 4 % $q\bar{q}$ and 96 % ggF)

CMS combined results

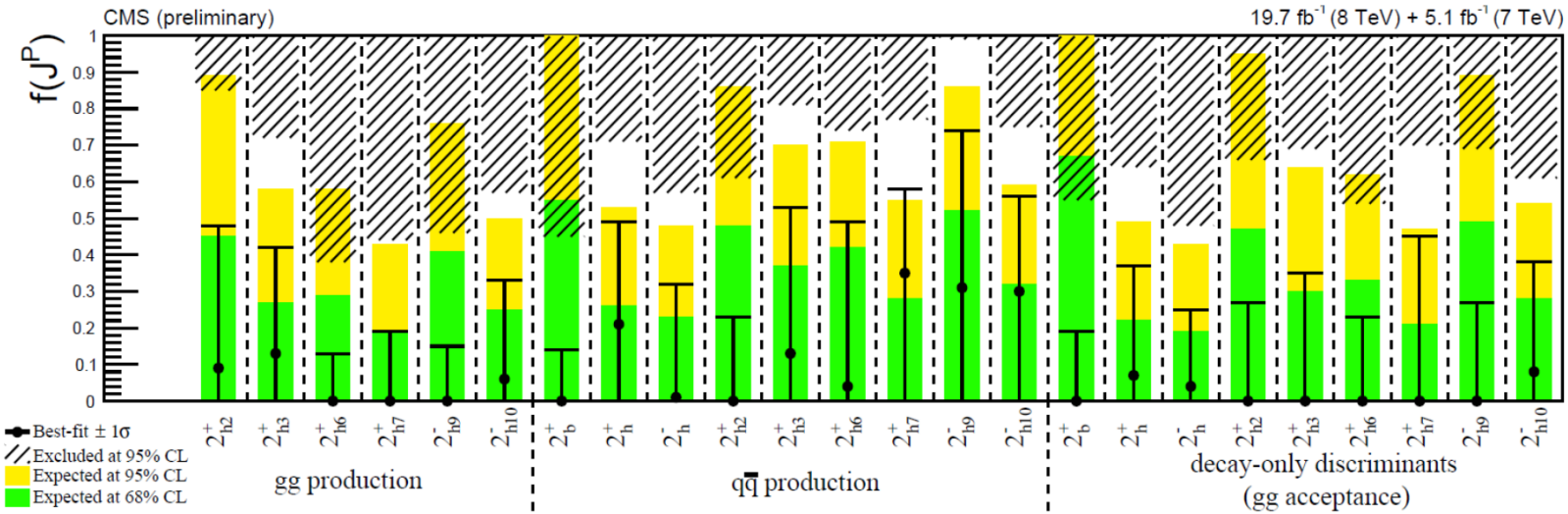


(from CMS-PAS-HIG-14-014)

- Spin 1: only $q\bar{q}$ production (production independent results $\rightarrow$ after next slide),
  spin 2: production-independent test for ZZ, $f_{q\bar{q}}$ dependent test for WW
- Combined results from WW and ZZ $\rightarrow$ all exotic models excluded at 99.9 % CL

CMS: Advanced spin 2 tests in $H \to 4\ell$

Test for 2 near-degenerate but non-interfering states parameter (fractional cross section): $f(J^P) = \frac{\sigma_{J^P}}{\sigma_{0^+} + \sigma_{J^P}}$



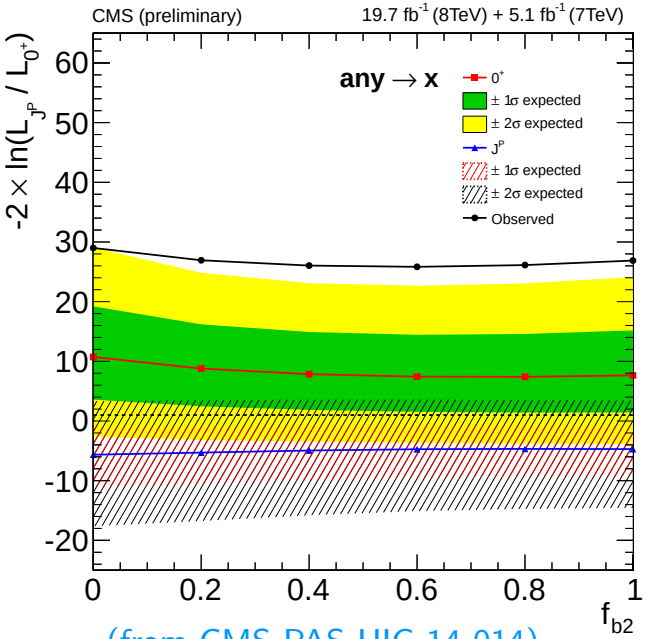
(from CMS-PAS-HIG-14-014)

Conclusion: for all models, the fraction $f(2^+)$ is consistent with 0

Details on $J = 1$ test; combined results including $H \to \gamma\gamma$

In $H \to ZZ \to 4\ell$:

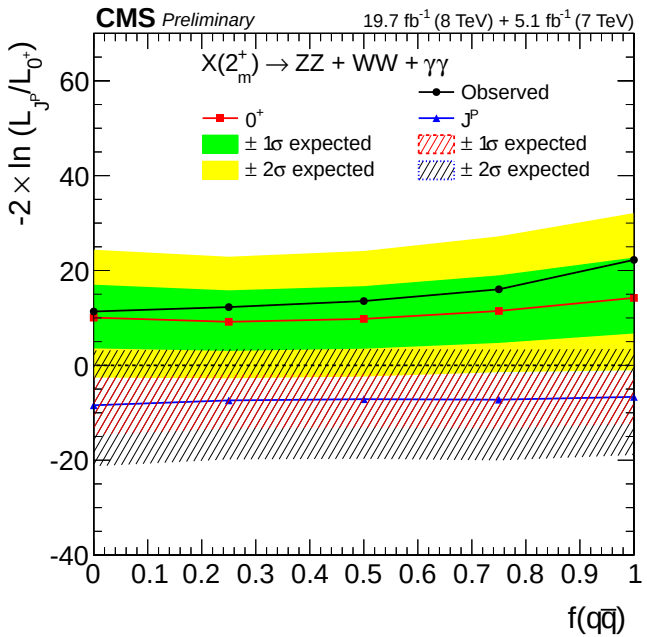
$$f_{b_2} = \frac{|b_2|^2\sigma_2}{|b1|^2\sigma_1 + |b_2|^2\sigma_2}$$



(from CMS-PAS-HIG-14-014)

Hypothesis tests SM vs. mixture of $1^{\pm}$; ($f_{b_2} = 0 \to$ pure vector, $f_{b_2} = 1 \to$ pure pseudo vector state) - prod. independent

Combined limits - Exclusion limits for different production modes, testing 2^+_{min} model:



Summary

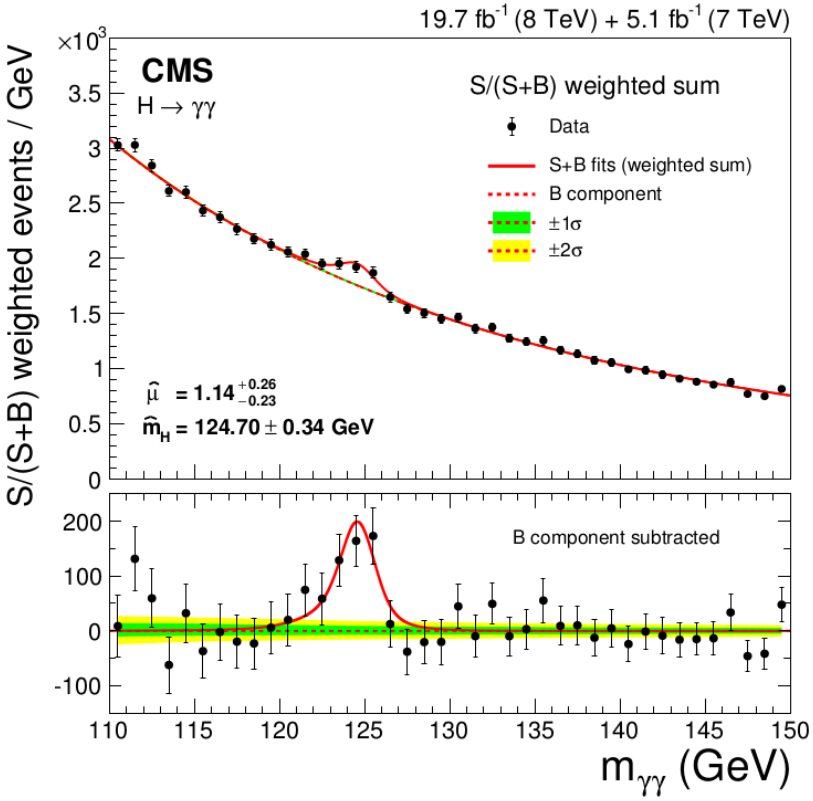
- Results from the bosonic decay channels available from CMS and ATLAS testing alternative spin hypotheses
- Larger variety of spin models and mixing tests published by CMS
- Different approaches taken in the three channels, ME method used by CMS, BDTs used by ATLAS
- Overall similar level of exclusion of the considered models when combining all channels
- Parity and 0^+_{BSM} tests to be discussed in 2nd talk

Backup

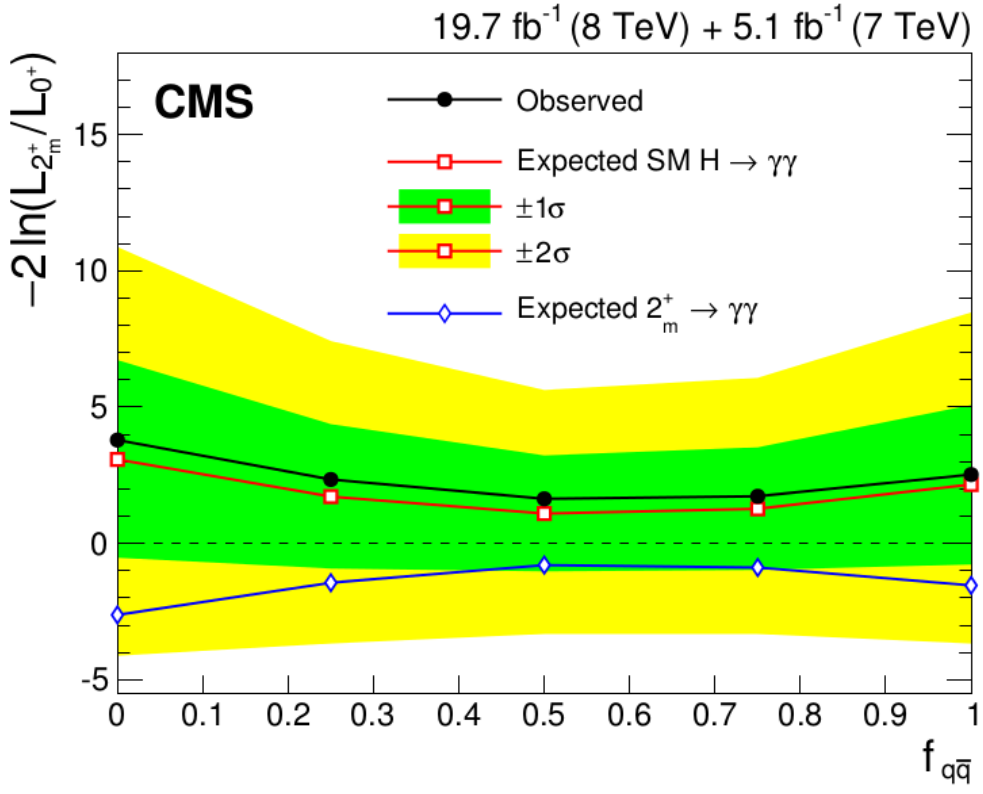
CMS : H → γγ

Result:

$f_{q\bar{q}}$	$1 - CL_s$ expected	observed
0	0.92	0.94
0.25	0.78	0.83
0.50	0.64	0.71
0.75	0.69	0.75
1	0.83	0.85



Diphoton mass spectrum weighted by the ratio S/ (S + B) in each event class, together with the background subtracted weighted mass spectrum. (to illustrate signal region choice)



(from arXiv:1407.0558v1)

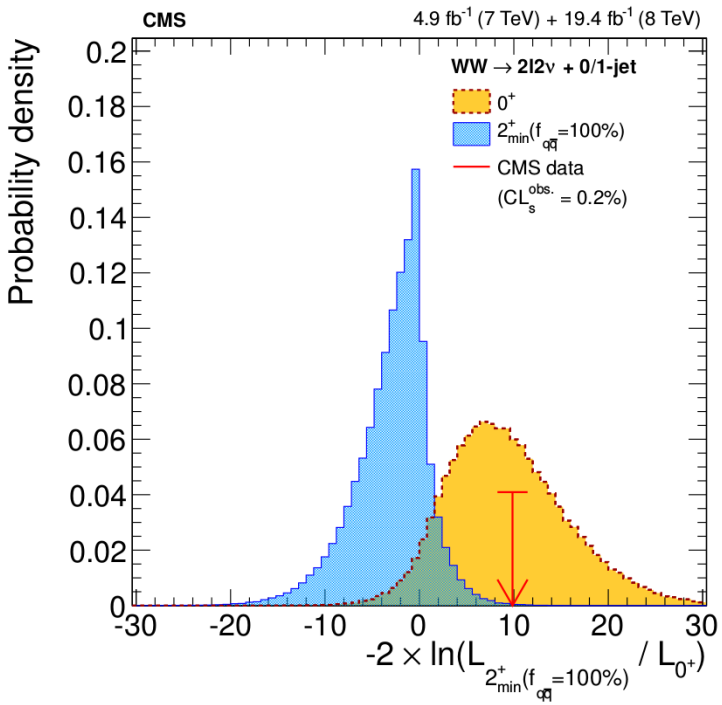
CMS : H → ZZ

J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-1.0σ	$+3.8\sigma$	0.05%
0^+_h	any	1.7σ (1.9σ)	-0.3σ	$+2.1\sigma$	4.5%
1^-	$q\bar{q} \to X$	2.7σ (2.7σ)	-1.4σ	$+4.7\sigma$	0.002%
1^-	any	2.5σ (2.6σ)	-1.8σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.02%
1^+	any	2.0σ (2.1σ)	-2.1σ	$+4.8\sigma$	0.004%
2^+_m	$gg \to X$	1.9σ (1.8σ)	-1.1σ	$+3.0\sigma$	0.9%
2^+_m	$q\bar{q} \to X$	1.7σ (1.7σ)	-1.7σ	$+3.8\sigma$	0.2%
2^+_m	any	1.5σ (1.5σ)	-1.6σ	$+3.4\sigma$	0.7%
2^+_b	$gg \to X$	1.6σ (1.8σ)	-1.4σ	$+3.4\sigma$	0.5%
2^+_h	$gg \to X$	3.8σ (4.0σ)	$+1.8\sigma$	$+2.0\sigma$	2.3%
2^-_h	$gg \to X$	4.2σ (4.5σ)	$+1.0\sigma$	$+3.2\sigma$	0.09%

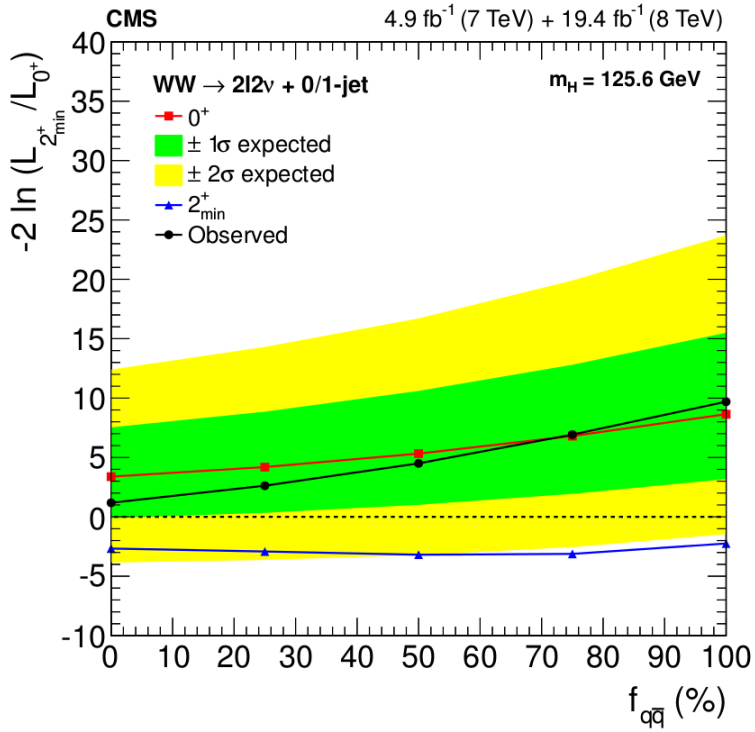
(from PHYSICAL REVIEW D 89, 092007 (2014))

CMS : H → WW

toys distr. in eμ final state,
σ/σ_{SM} from fit to data:



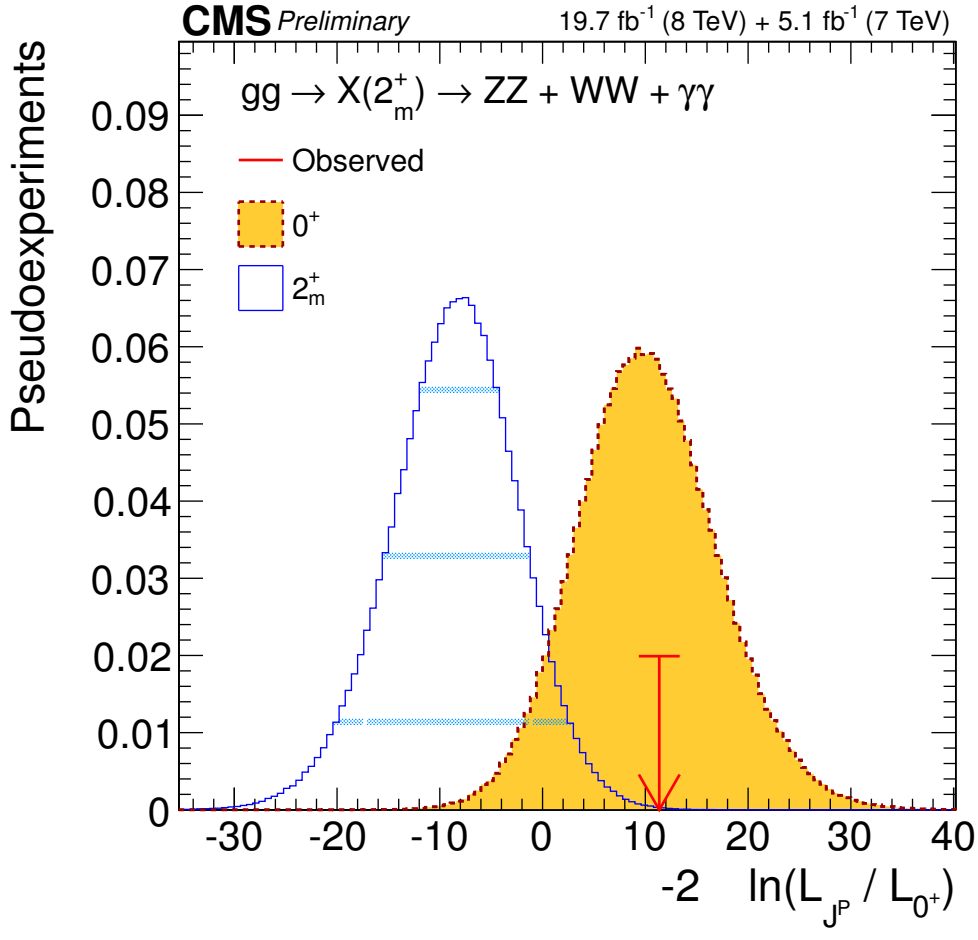
Result:



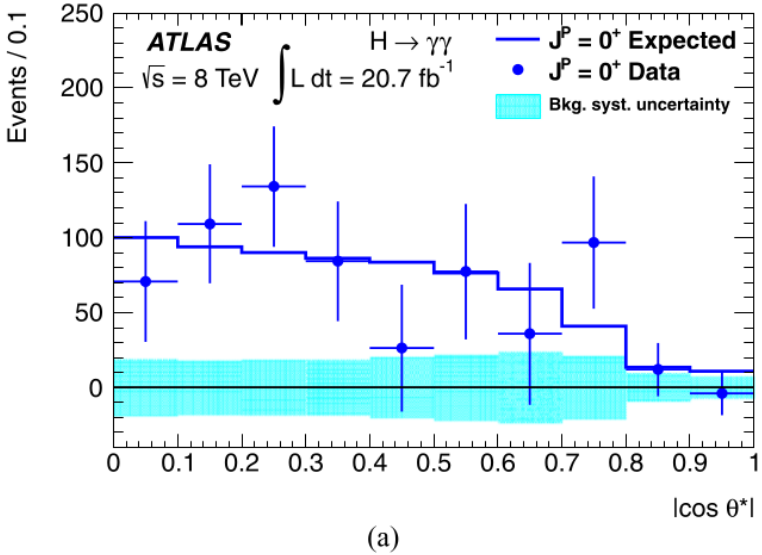
(from JHEP01(2014)096)

CMS : Channel combination

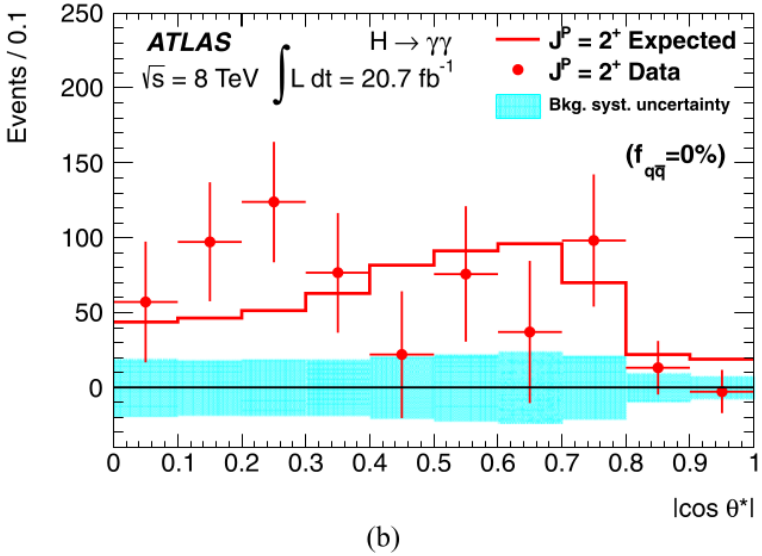
toys distribution including data for all three channels combined



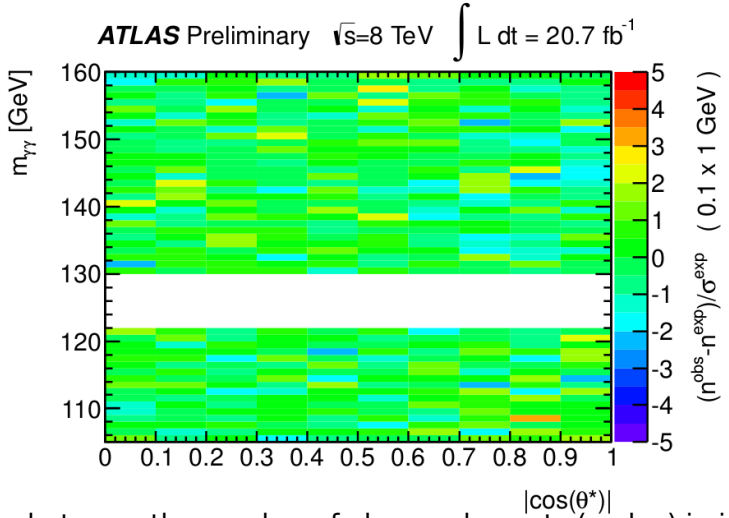
ATLAS : H → γγ



(a)

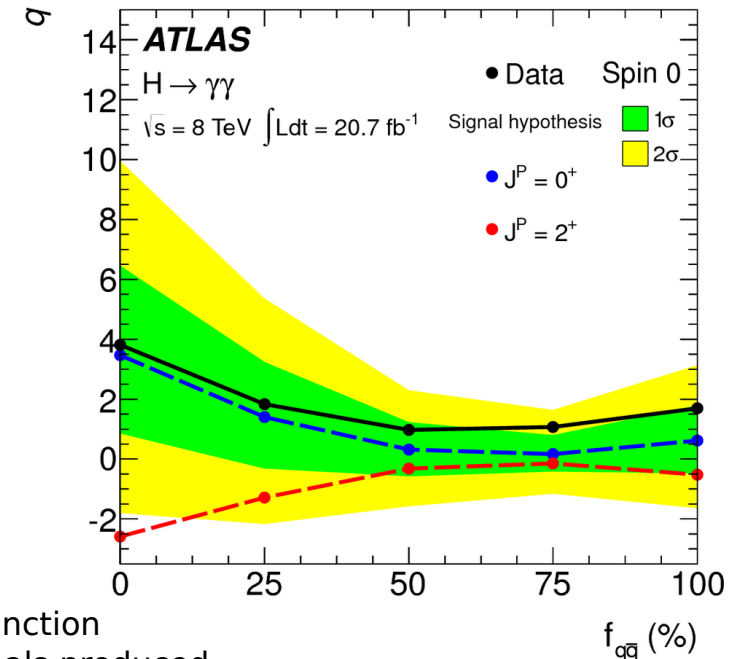


(b)



Difference between the number of observed events (n obs) in intervals of |cos θ*| × $m_{\gamma\gamma}$ = 0.1×1 GeV (excluding the signal region 122 < $m_{\gamma\gamma}$ < 130 GeV) and the number of expected events (n_{exp}) divided by the associated uncertainty (σ_{exp}) as a function of |cos θ* | and the invariant mass $m_{\gamma\gamma}$, in GeV
(from ATLAS-CONF-2013-029)

Result:

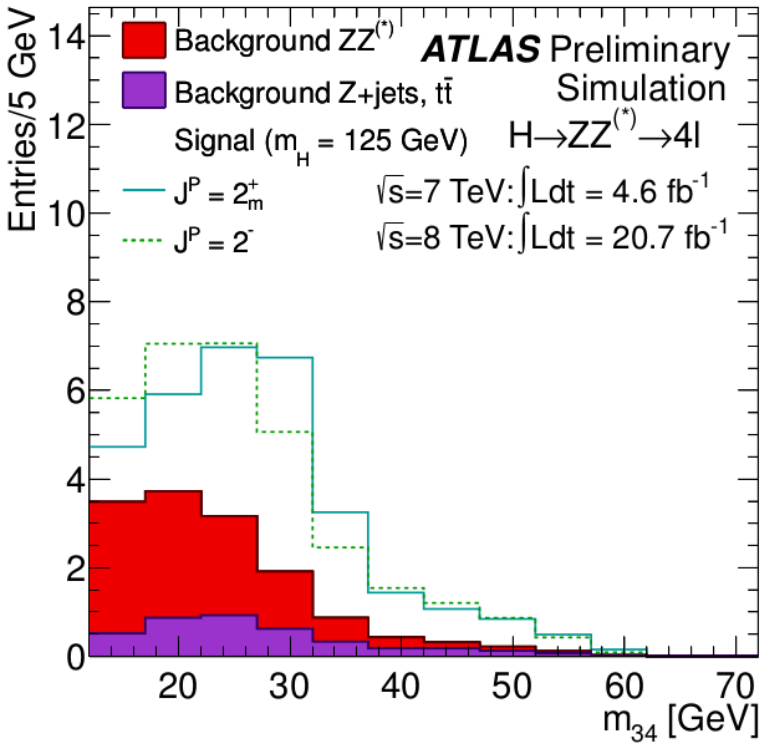


(from Physics Letters B 726 (2013) 120–144)

Distributions of background-subtracted data in the signal region as a function of |cos θ*| . The expected distributions for (a) spin-0 and (b) spin-2 signals produced by gluon fusion, normalised to the fitted number of signal events, are overlaid as solid lines (from Physics Letters B 726 (2013) 120–144)

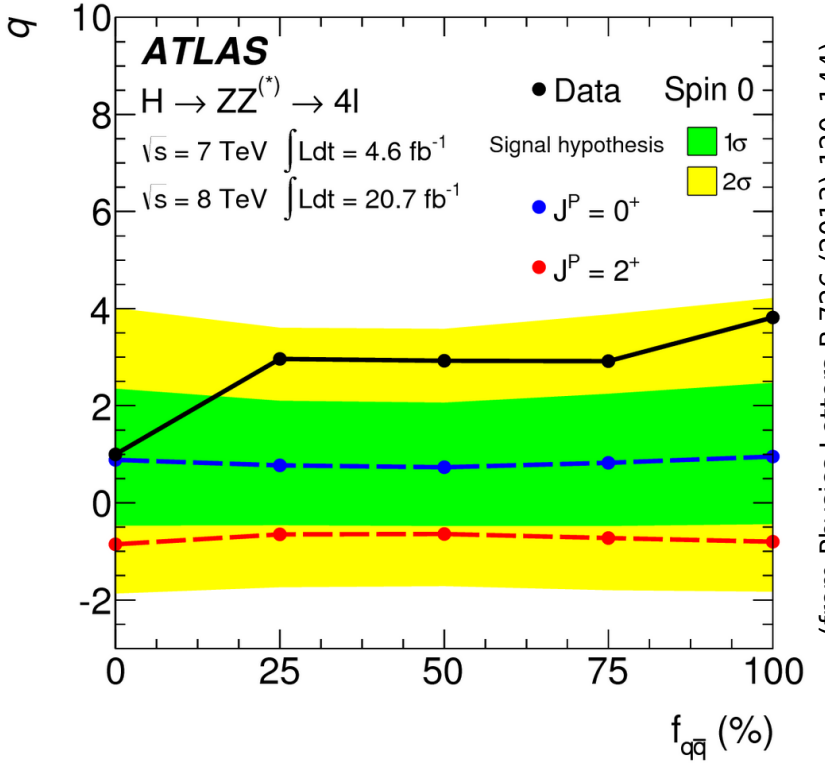
ATLAS : H → ZZ

m_{34} variable distibution (reconstructed Z mass which is further away from the Z peak than m_{12})



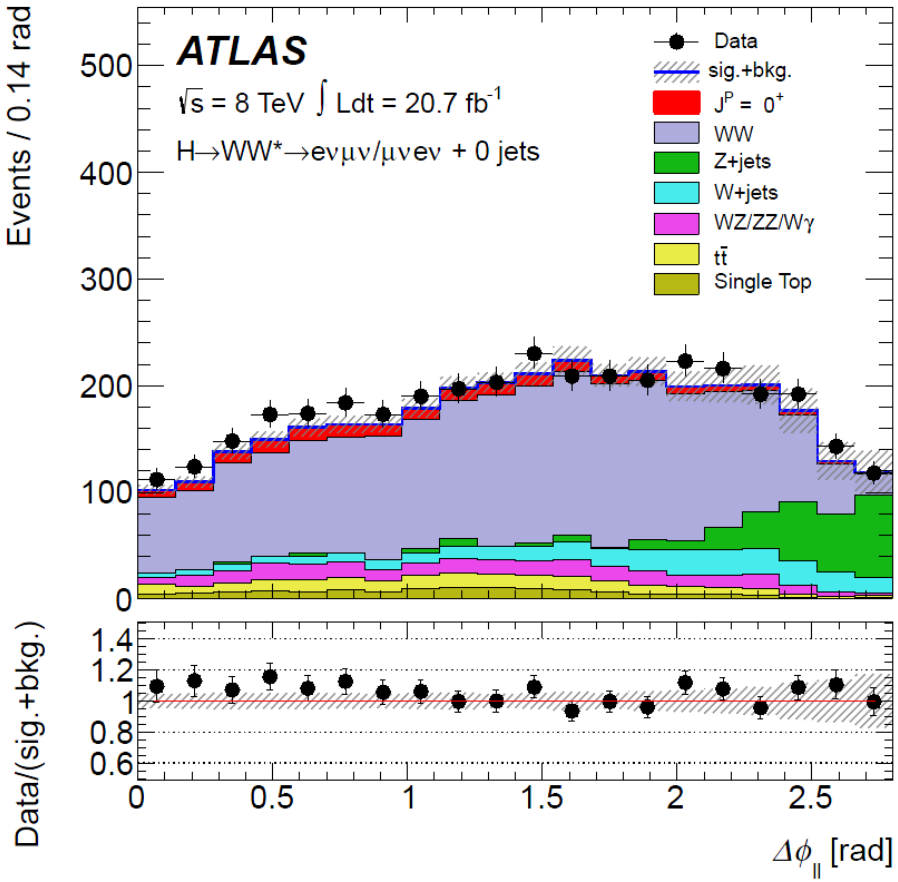
(from ATLAS-CONF-2013-013)

Result:

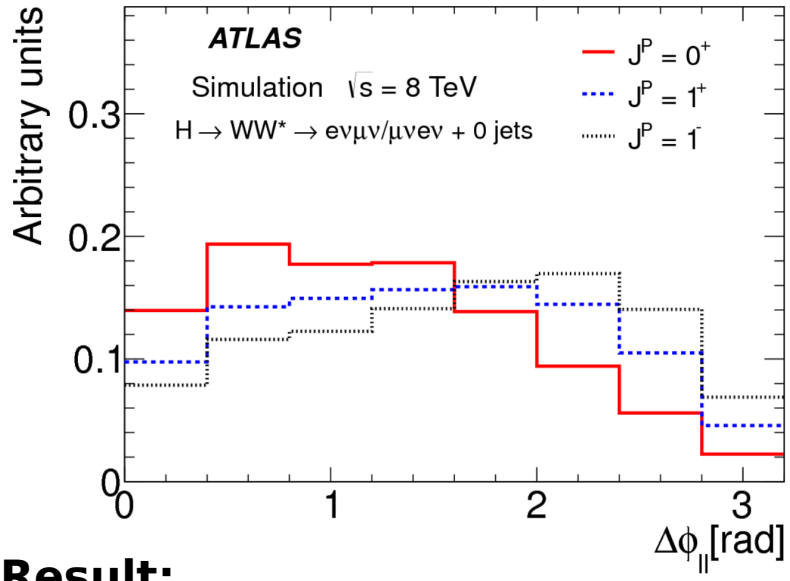


(from Physics Letters B 726 (2013) 120–144)

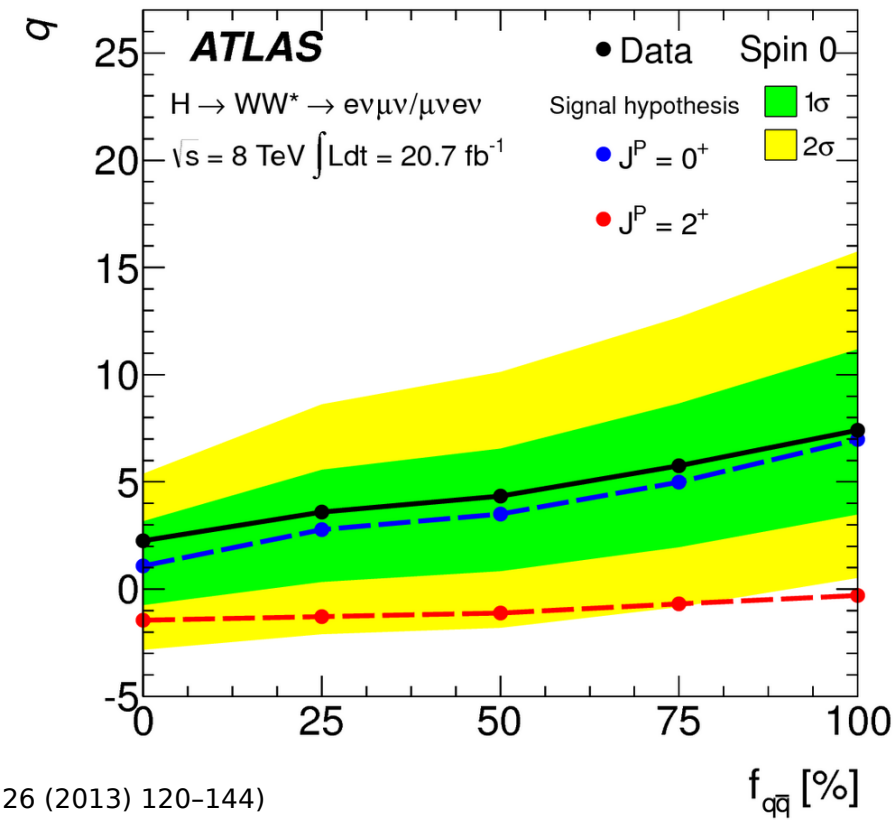
ATLAS : H → WW



stacked backgrounds + (SM) signal, one of the BDT input variables



Result:



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