Determination of Higgs Spin and Parity at the LHC

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After the discovery of a new scalar particle by the Large Hadron Collider (LHC) experiments ATLAS and CMS, its properties have to be determined, in order to clarify if it is really the Higgs boson, *i.e.* the particle related to the Higgs mechanism. This requires the measurement of its couplings to the Standard Model (SM) particles, the determination of its spin and parity quantum numbers and finally the extraction of the Higgs boson trilinear and quartic self-couplings. In this contribution it will be shown how spin and parity quantum numbers of the SM Higgs boson can unambiguously be determined at the LHC.

1 Introduction

The discovery of a 125 GeV Higgs boson [1,2] has triggered a large number of investigations on the Higgs boson properties, among which the determination of the spin (J), parity (P) and charge conjugation (C) quantum numbers [3], which are for the SM Higgs boson $J^{PC} = 0^{++}$. The Higgs sector of extensions beyond the SM, like *i.e.* supersymmetry, may additionally contain CP-odd scalar (pseudoscalar) particles or Higgs states which are CP-violating mixtures between CP-even and CP-odd components.

The charge conjugation quantum number $C = +$ follows from the observation of decays into $\gamma\gamma$ for pure states in a C-invariant theory.

The spin/parity quantum numbers can be investigated in a systematic way by analyzing the helicity amplitudes of production and decay processes. They do not only provide necessary and sufficient conditions to assign the J^{PC} quantum numbers of real states but also test possible CP-violating Higgs bosons. On the production side gluon and vector boson fusion and Higgs-strahlung give access to the spin/parity quantum numbers. For the decays systematic analyses have been performed in Z^*Z decays with subsequent leptonic Z^* and Z decays, in $\gamma\gamma$ decays and in CP-violating decays into fermions or massive gauge bosons. In the following the decays into virtual and real Z bosons and into photon final states will be analyzed with respect to the determination of the CP quantum numbers. It will be shown that the spin and parity of the SM Higgs boson can be unambiguously determined and that negative parity assignment and higher spin states can be ruled out by combining angular correlations with threshold distributions.

2 Higgs Boson Decay into ZZ^*

The decay of a general pure spin/parity unpolarized boson state H^J into a pair of a virtual Z^* and a real Z boson which subsequently decay into leptons $l_i^\pm$ ($i = 1, 2$),

$$H^J \to Z^*Z \to (l_1^+ l_1^-)(l_2^+ l_2^-) \,, \tag{1}$$

gives access to the spin/parity quantum numbers of H^J. Denoting the polar angles of the leptons $l_{1,2}^-$ in the rest frame of the virtual and real Z bosons by $\theta_{1,2}$, see Fig. 1(a), the differential decay distribution of the polar angles can be expressed in terms of four independent helicity

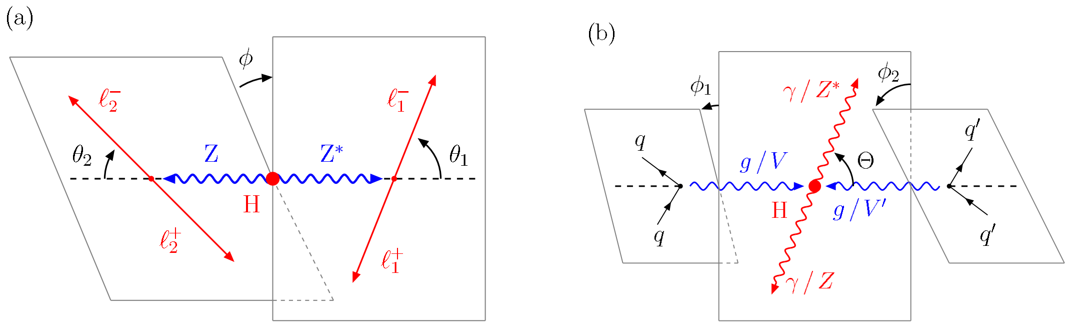

Figure 1: (a) Definition of the polar angles θ_i $(i = 1, 2)$ of the leptons $\ell_{1,2}^-$ in the rest frame of the virtual Z^* and real Z bosons and of the azimuthal angle ϕ for the decay $H^J \to Z^*Z \to (\ell_1^-\ell_1^+)(\ell_2^-\ell_2^+)$. (b) Higgs production through gluon fusion/vector boson fusion ($V = W^\pm, Z$) with subsequent decay into $\gamma\gamma$ and Z^*Z in the Higgs rest frame.

amplitudes [4]

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2} = \mathcal{N}^{-1}\Big[\sin^2\theta_1\sin^2\theta_2\,|\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)[|\mathcal{T}_{11}|^2+|\mathcal{T}_{1,-1}|^2] + (1+\cos^2\theta_1)\sin^2\theta_2\,|\mathcal{T}_{10}|^2 + \sin^2\theta_1(1+\cos^2\theta_2)\,|\mathcal{T}_{01}|^2\Big], \quad (2)$$

fixing the mass squared M_*^2 of the virtual Z^* boson and suppressing the quartic term involving the P-violating parameters which are small for leptonic Z decays. By $\mathcal{N}$ we denote the normalisation factor. Bose symmetry implies for the helicity amplitudes the relations $\mathcal{T}_{\lambda\lambda'} = n_H\mathcal{T}_{-\lambda,-\lambda'}$ and $\mathcal{T}_{\lambda\lambda'}[Z,Z^*] = (-1)^J\mathcal{T}_{\lambda'\lambda}[Z^*,Z]$, with the normality given by $n_H = P(-1)^J$. The azimuthal distribution of the Z-decay planes is given by

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\phi} = \frac{1}{2\pi}\Big[1+n_H\,|\zeta_1|\cos 2\phi\Big] \quad \text{with} \quad |\zeta_1| = |\mathcal{T}_{11}|^2/\Big[2\sum|\mathcal{T}_{\lambda\lambda'}|^2\Big], \quad (3)$$

again suppressing the terms proportional to the small P-violating parameters. The normality of the Higgs state uniquely determines the sign of the ϕ modulation. Figure 2(a) shows the characteristic behaviour of the azimuthal angle between the Z decay planes. The distributions of the positive (SM) and negative parity decay are mutually anti-cyclic. Such behaviour is also given in jet-jet correlations of electroweak gauge bosons and gluon fusion [3].

In the SM, by angular momentum conservation only two decay helicity amplitudes are non-vanishing, $\mathcal{T}_{00} = (M_H^2 - M_*^2 - M_Z^2)/(2M_*M_Z)$ and $\mathcal{T}_{11} = -1$, so that the angular distributions read [4]

$$\frac{1}{\Gamma_H}\frac{d\Gamma_H}{d\cos\theta_1\cos\theta_2} = \frac{9}{16}\frac{1}{\gamma^4+2}\Big[\gamma^4\sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\Big] \quad (4)$$

$$\frac{1}{\Gamma_H}\frac{d\Gamma_H}{d\phi} = \frac{1}{2\pi}\Big[1+\frac{1}{2}\frac{1}{\gamma^4+2}\cos 2\phi\Big], \quad (5)$$

with $\gamma^2 = (M_H^2 - M_*^2 - M_Z^2)/(2M_*M_Z)$. At the Z^*Z threshold the rise of the distribution in the Z^* invariant mass becomes

$$\frac{d\Gamma[H\to Z^*Z]}{dM_*^2} \Rightarrow \beta \sim \sqrt{(M_H-M_Z)^2 - M_*^2}\,/M_H \quad \text{for} \quad M_* \Rightarrow M_H - M_Z\,. \quad (6)$$

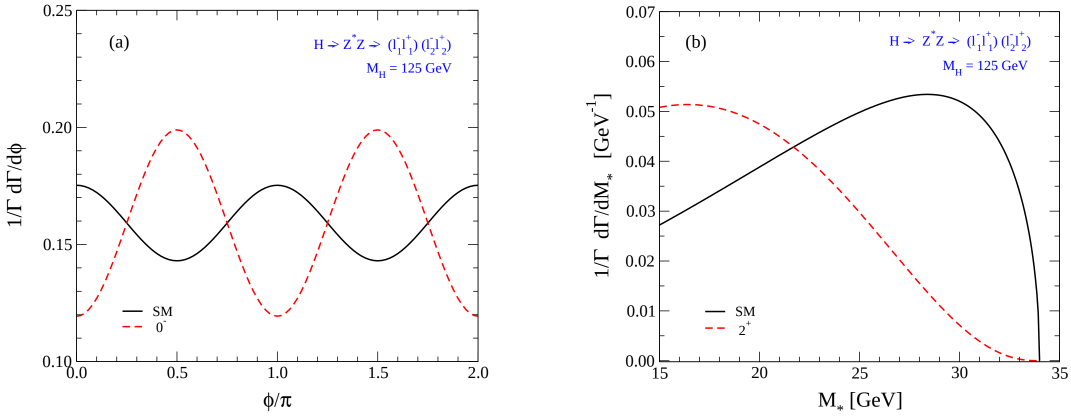

Figure 2: (a) Azimuthal angular distribution between the two Z decay planes for spin = 0 with positive parity in the SM compared with negative parity; (b) Threshold distribution of the decay width $H^J \to Z^*Z$ for the SM and spin-2 even normality bosons, with a Higgs boson mass of 125 GeV.

The necessary conditions for the spin-zero character of the SM Higgs boson are hence given by the observation of the angular distributions associated with the helicity amplitudes $\mathcal{T}_{00}$, $\mathcal{T}_{11}$ and of the steep threshold rise $\sim \beta$. They are also sufficient, as any other spin/parity combination necessarily generates different combinations of threshold power and angular correlations for any pure state, see also [4]. Ambiguities in the angular correlations for higher spin states can be resolved if supplemented by suppression at the threshold. If $(1+\cos\theta_1^2)\sin^2\theta_2$ and $\sin^2\theta_1(1+\cos^2\theta_2)$ polar-angle correlations are absent, there is a pronounced difference in the threshold behaviour of the spin-0 SM and spin-2 even normality bosons with identical 4ℓ angular correlations, *cf.* Fig. 2(b).

3 Higgs Boson Decay into $\gamma\gamma$

Furthermore, information on any spin of the Higgs boson can be obtained from the combination of Higgs boson production in gluon fusion with the decay into photons [3],

$$gg \to H^J \to \gamma\gamma \,. \tag{7}$$

The information on the spin is given by the distribution in the polar angle Θ of the final state photons with respect to the incoming partons in the Higgs boson rest frame. Both initial state helicities $\mu-\mu'$ and final state helicities $\lambda-\lambda'$ take the values 0 and ± 2 and add up incoherently in the differential distribution

$$\frac{1}{\sigma}\frac{d\sigma[gg\to H^J\to\gamma\gamma]}{d\cos\Theta} = (2J+1)\left[\mathcal{X}_0\mathcal{Y}_0\mathcal{D}^J_{00}+\mathcal{X}_0\mathcal{Y}_2\mathcal{D}^J_{02}+\mathcal{X}_2\mathcal{Y}_0\mathcal{D}^J_{20}+\mathcal{X}_2\mathcal{Y}_2\mathcal{D}^J_{22}\right]\,, \tag{8}$$

with the probabilities for production $\mathcal{X}_{0,2}$ and decay $\mathcal{Y}_{0,2}$ derived from the $gg \to H^J$ production and $H^J \to \gamma\gamma$ decay helicity amplitudes. The squared Wigner functions $\mathcal{D}^J_{m\lambda} = \frac{1}{2}\{[d^J_{m\lambda}(\Theta)]^2 + [d^J_{m,-\lambda}(\Theta)]^2\}$ generally take the non-trivial maximum power of

$$\mathcal{D}^J \sim \cos^{2J}\Theta\,, \tag{9}$$

independently of the helicity indices 0 or 2. The angular distribution of the photon axis hence provides a characteristic signal of the involved Higgs spin. The spin zero of the Higgs boson manifests itself in an isotropic distribution. Any other spin assignment leads to non-trivial polar angular distributions. Figure 3 for the polar angular distributions shows, that while spin-zero Higgs production is isotropic, any other spin assignment entails non-trivial polar angular

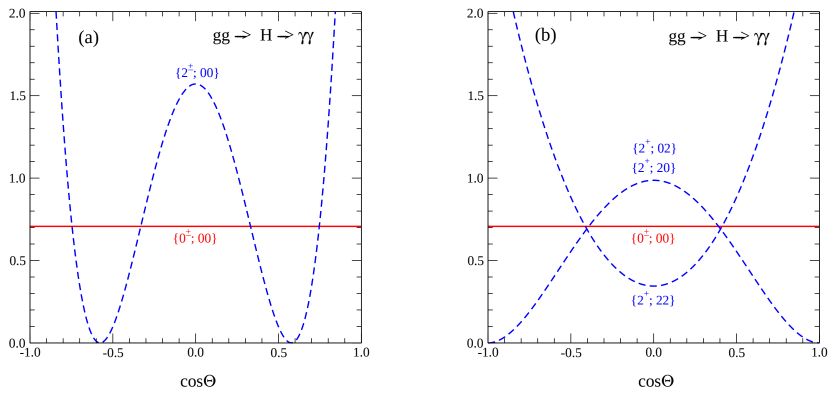

Figure 3: Polar angular distributions of the $\gamma\gamma$ axes in the rest frame of the Higgs boson: the flat SM Higgs signal compared with potential spin-2 distributions; (a) the 'scalar assignment' $\{2;00\}$ and (b) the 'tensor assignment' $\{2;22\}$ and the 'mixed assignments', $\{2;02\}$ and $\{2;20\}$ (all distributions normalized over the interval $|\cos\Theta| \leq 1/\sqrt{2}$). The upper indices denote the allowed parity associated with the distributions in $\gamma\gamma$ decays.

distributions. The figure compares the angular distribution of a SM Higgs boson with $\mathcal{D}^0_{00} = 1$ ($\mathcal{X}_0 = \mathcal{Y}_0 = 1$) with those of spin-2 particles for the 'scalar assignment' $\{2;00\}$ and the 'tensor assignment' $\{2;22\}$. The polar angular distribution can therefore be exploited, whenever a diphoton final state is observed as demanded for a Higgs boson, to determine the spin of the decaying particle and eventually rule out any non-zero spin assignment. Analogously, the decay into ZZ^* can be analyzed if the angular distribution of the ZZ^* axis is measured.

4 Conclusions

It has been shown that spin and parity of the SM Higgs boson can be unambiguously determined at the LHC: The coefficients of the angular distributions of the Higgs boson decay into ZZ^* have to be measured and compared with the unique SM predictions. Additionally the threshold behaviour has to be shown to be linear in the gauge boson helicity as predicted in the SM case. All other states $0^-, 1^\pm, 2^\pm, ...$ are excluded by proving the absence of specific angular correlations (supplemented by high-power threshold factors for even normality states). The observation of isotropic angular correlations between the Z^*Z or $\gamma\gamma$ final state axes and the initial-state parton axis strengthens the conclusion of observing a Higgs boson with spin zero and positive parity.

Acknowledgments

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References

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