Measuring Spin/Parity of the Higgs Boson: Theoretical Basis

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Light Higgs Mass Meeting

CERN

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$\mathcal{P}$rogram

Necessary and sufficient conditions for $J^P = 0^+$ [vis-a-vis SM]

- **Extension of**

  ∗ S.Y. Choi, D.J. Miller, M.M. Muhlleitner and P.M. Zerwas
  "Identifying the Higgs spin and parity in decays to Z pairs"
  Phys. Lett. **B553** (2003) 61 [hep-ph/0210077]

  ∗ S.Y. Choi, M.M. Muhlleitner and P.M. Zerwas
  "Theoretical Basis of Higgs-Spin Analysis in $H \to \gamma\gamma$ and $Z\gamma$ Decays"
  Phys. Lett. **B718** (2013) 1031 [arXiv:1209.5268 [hep-ph]]

- **Other publications:** Hagiwara eal; De Rujula eal; Y. Gao eal; S. Bolognesi eal; J. Ellis eal

- **Theoretical Tools:**

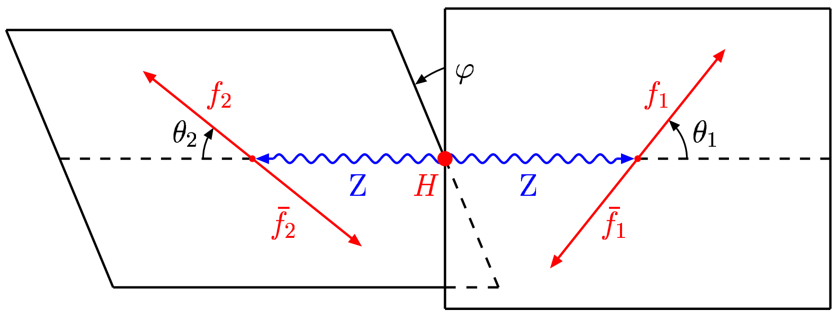
  ∗ helicity analyses
  ∗ operator expansions $\longrightarrow$ two typical examples

(I) $\mathcal{A}$ngular $\mathcal{D}$istributions/$\mathcal{T}$hresholds in $H \longrightarrow VV^* \longrightarrow 4\ell$

◇ Determination of spin and parity in

$$gg \to H \to ZZ^{(*)} \to (f_1\bar{f}_1)(f_2\bar{f}_2)$$

in H c.m. frame



◇ Helicity methods to generalize to arbitrary spin and parity

$$\langle Z(\lambda_1)Z(\lambda_2)|H_{\mathcal{J}}(m)\rangle = \frac{g_W M_Z}{\cos\theta_W}\mathcal{T}_{\lambda_1\lambda_2} d^{\mathcal{J}}_{m,\lambda_1-\lambda_2}(\Theta)e^{-i(m-\lambda_1+\lambda_2)\varphi}$$

◇ General tensor for HZZ vertex for each $\mathcal{J}^{\mathcal{P}}$ $\Rightarrow$ Expressions for reduced vertices $\mathcal{T}_{ij}$

$$\mathcal{J} = \frac{g_W M_Z}{\cos\theta_W} T_{\mu\nu\beta_1\ldots\beta_{\mathcal{J}}}\epsilon^*(Z_1)^\mu \epsilon^*(Z_2)^\nu \epsilon(H)^{\beta_1\ldots\beta_{\mathcal{J}}}$$

$\mathcal{D}$ifferential $\mathcal{D}$istributions

◇ Double polar angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\cos\theta_1 d\cos\theta_2} \sim \sin^2\theta_1 \sin^2\theta_2 \, |\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right]$$
$$+(1+\cos^2\theta_1)\,\sin^2\theta_2\,|\mathcal{T}_{10}|^2 + \sin^2\theta_1\,(1+\cos^2\theta_2)\,|\mathcal{T}_{01}|^2$$
$$+2\,\eta_1\eta_2\cos\theta_1\cos\theta_2\left[|\mathcal{T}_{11}|^2 - |\mathcal{T}_{1,-1}|^2\right]$$

◇ Azimuthal angular distribution ($\mathcal{CP}$ invariant theory)

$$\frac{d\Gamma_H}{d\varphi} \sim |\mathcal{T}_{11}|^2 + |\mathcal{T}_{10}|^2 + |\mathcal{T}_{1,-1}|^2 + |\mathcal{T}_{01}|^2 + |\mathcal{T}_{00}|^2/2$$
$$+\eta_1\eta_2\left(\frac{3\pi}{8}\right)^2 \Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{00}^* + \mathcal{T}_{10}\mathcal{T}_{0,-1}^*)\cos\varphi + \frac{1}{4}\Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{-1,-1}^*)\cos 2\varphi$$

$\eta_i = 2v_i a_i/(v_i^2 + a_i^2)$, v_i, a_i electroweak fermion f_i charges

$\mathcal{D}$etermination of $\mathcal{S}$pin and $\mathcal{P}$arity, $\mathcal{N}$ecessary $\mathcal{C}$onditions

- **Standard Model:** Necessary conditions:

◇ Double polar angular distribution

$$\frac{d\Gamma_H}{d\cos\theta_1 d\cos\theta_2} \sim \sin^2\theta_1 \sin^2\theta_2 + \frac{1}{2\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2}\left[(1+\cos^2\theta_1)(1+\cos^2\theta_2)+4\eta_1\eta_2\cos\theta_1\cos\theta_2\right]$$

◇ Azimuthal angular distribution

$$\frac{d\Gamma_H}{d\varphi} \sim 1 - \eta_1\eta_2\,\frac{1}{2}\left(\frac{3\pi}{4}\right)^2 \frac{\gamma_1\gamma_2(1+\beta_1\beta_2)}{\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2+2}\cos\varphi + \frac{1}{2}\,\frac{1}{\gamma_1^2\gamma_2^2(1+\beta_1\beta_2)^2+2}\cos 2\varphi$$

β_i, γ_i $(i=1,2)$: velocity and boost factors

$\mathcal{D}$etermination of $\mathcal{S}$pin and $\mathcal{P}$arity, $\mathcal{S}$ufficient $\mathcal{C}$onditions

- $M_H < 2M_Z$: $d\Gamma/dM_*^2 \sim \beta$ for $\mathcal{J}^{\mathcal{P}} = 0^+$

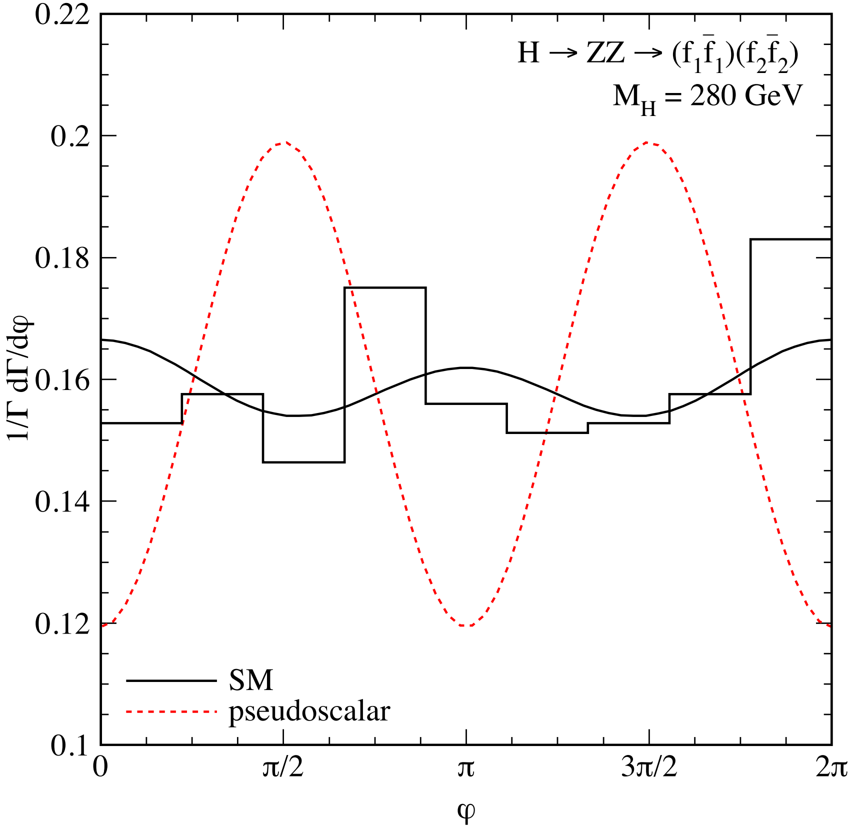
  ◇ $d\Gamma/dM_*^2$ rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm$ [threshold rise $\sim \beta^{2J+1}$]

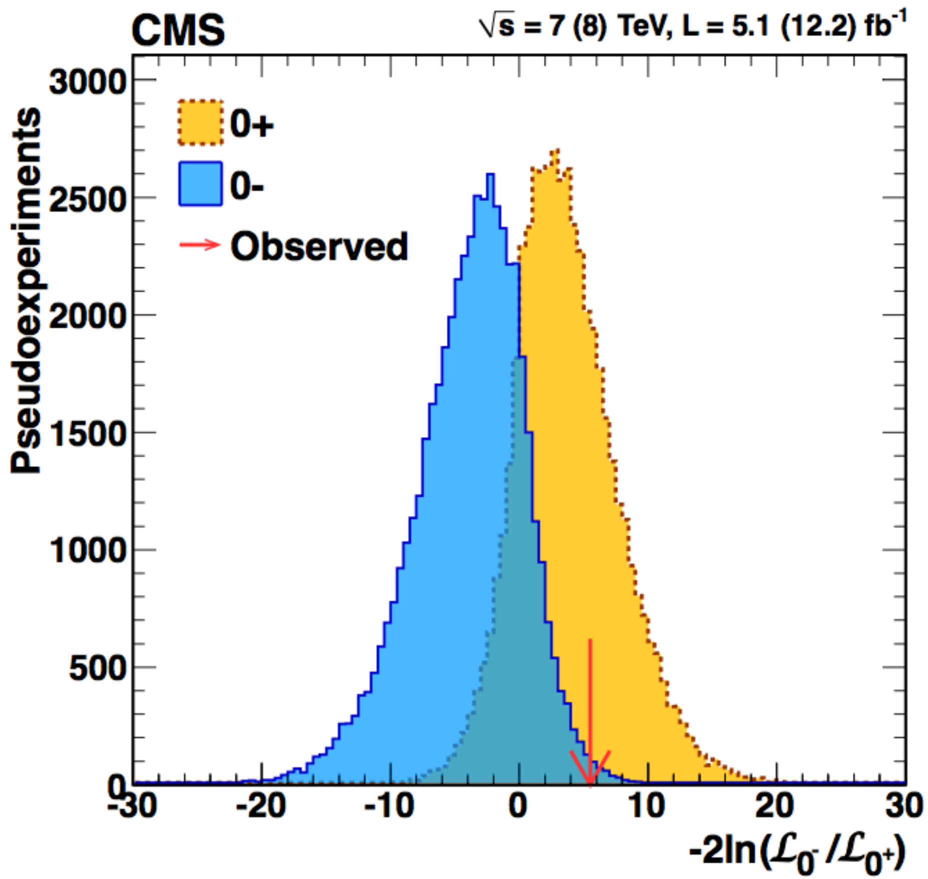
  ◇ $d\Gamma/dM_*^2$ and no $[1+\cos^2\theta_1]\sin^2\theta_2$

  $[1+\cos^2\theta_2]\sin^2\theta_1$ rules out $\mathcal{J}^{\mathcal{P}} = 1^+, 2^+$

  $\Rightarrow$ only 0^+ left (sufficient conditions)

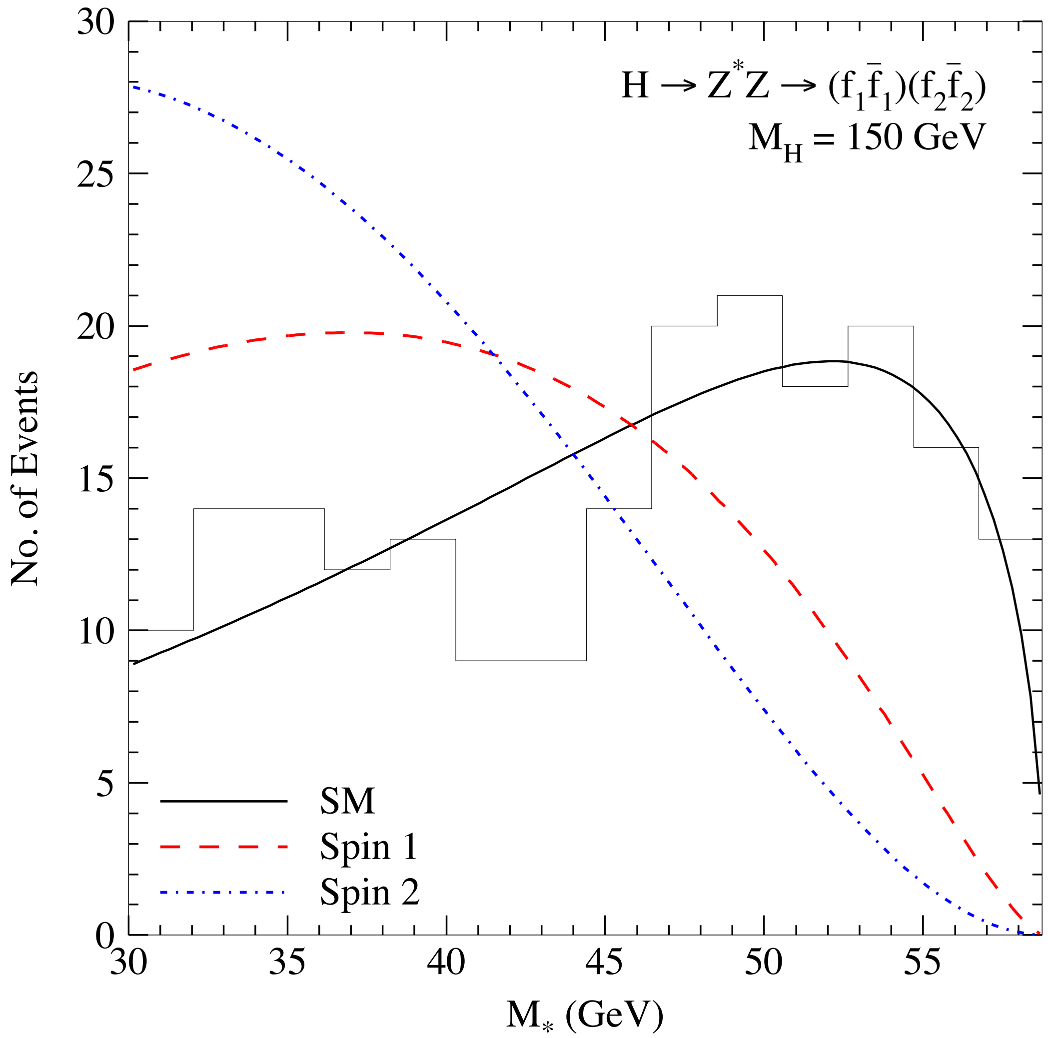
Azimuthal Angular Distributions: Parity





Large masses: $0^+ : d\Gamma/d\varphi \sim$ const., $0^- : d\Gamma/d\varphi \sim 1 - 1/4\cos 2\varphi$

𝒯hreshold ℬehaviour: 𝒮pin



(II) $\mathcal{H}$iggs-$\mathcal{S}$pin $\mathcal{A}$nalysis in $H \to \gamma\gamma$ $\mathcal{D}$ecays

- **Systematic helicity analyses for angular distributions**

$$\frac{1}{\sigma}\frac{d\sigma(\gamma\gamma)}{d\cos\Theta} = (2J+1)[\mathcal{X}_0^J\mathcal{Y}_0^J\mathcal{D}_{00}^J + \mathcal{X}_0^J\mathcal{Y}_2^J\mathcal{D}_{02}^J + \mathcal{X}_2^J\mathcal{Y}_0^J\mathcal{D}_{20}^J + \mathcal{X}_2^J\mathcal{Y}_2^J\mathcal{D}_{22}^J]$$

∗ $\mathcal{D}_{m\lambda}^J$ squared Wigner functions, $m = S_z$ spin component, $\lambda \equiv \lambda_\gamma - \lambda'_\gamma$

∗ $\mathcal{X}$ production helicity probability

∗ $\mathcal{Y}$ decay helicity probability

- **Decays**

'scalar-type assignment': $\mathcal{X}_0^J = \mathcal{Y}_0^J = 1$ and $\mathcal{X}_2^J = \mathcal{Y}_2^J = 0$ $[J \geq 0]$

'tensor-type assignment': $\mathcal{X}_0^J = \mathcal{Y}_0^J = 0$ and $\mathcal{X}_2^J = \mathcal{Y}_2^J = 1$ $[J \geq 2]$

$\mathcal{G}$eneral $\mathcal{S}$pin/$\mathcal{P}$arity $\mathcal{A}$ssignments

- **Selection rules for Higgs spin/parity** from observing the polar angular distributions of a spin-J Higgs state in $gg \to H \to \gamma\gamma$

$\mathcal{P} \setminus J$	0	1	$2, 4, \cdots$	$3, 5, \cdots$
even	1	forbidden	$\mathcal{D}^J_{00}$ $\mathcal{D}^J_{02}$ $\mathcal{D}^J_{20}$ $\mathcal{D}^J_{22}$	$\mathcal{D}^J_{22}$
odd	1	forbidden	$\mathcal{D}^J_{00}$	forbidden

- **Squared Wigner functions** $\mathcal{D}^J_{m\lambda}$ up to $\sim |\cos^{2J}\Theta|$

$$\mathcal{D}^0_{00} = 1$$

$$\mathcal{D}^2_{00} = (3\cos^2\Theta - 1)^2/4 \qquad \mathcal{D}^2_{22} = (\cos^4\Theta + 6\cos^2\Theta + 1)/16$$

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odd	1	forbidden	$\mathcal{D}^J_{00}$	forbidden

$0^{\pm}$: D^0_{00} observed, none else $\rightsquigarrow$ $\pm$ undisc

2^+ : D^2_{00} and $D^2_{22} \neq 0$, both (KK)

2^- : $D^2_{00} \neq 0$, none else

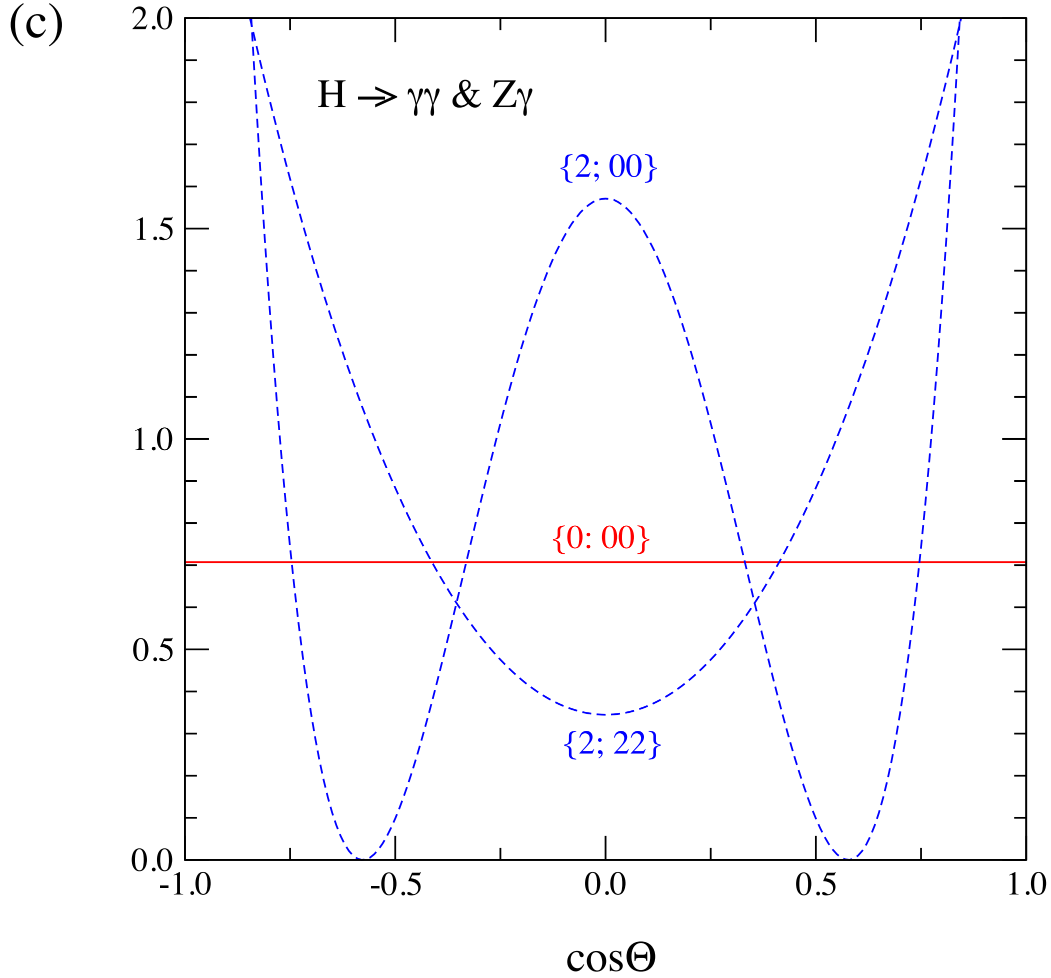
...

$1^{\pm}$: forbidden by Landau/Yang

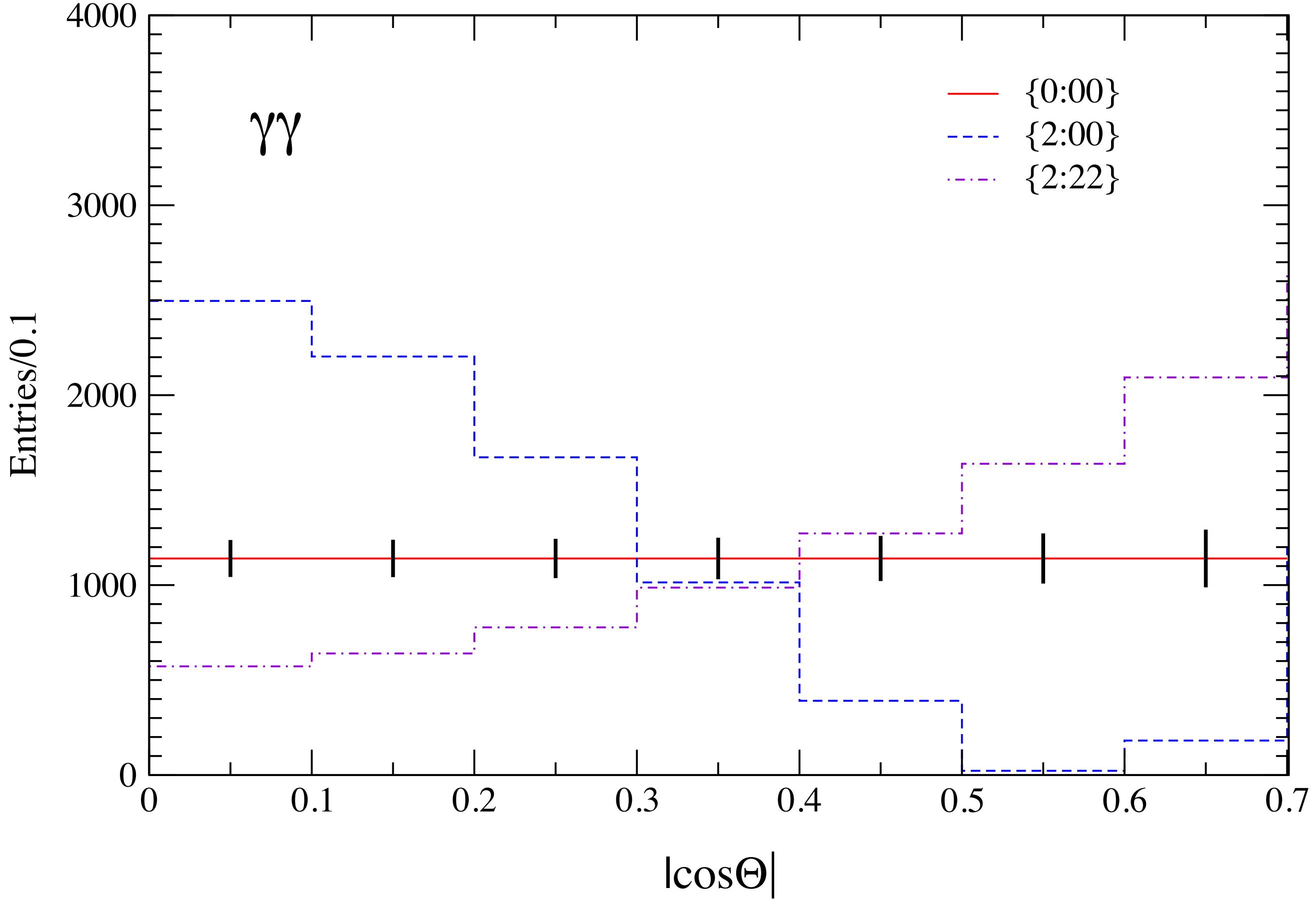
3^+ : $D^3_{22} \neq 0$, none else

3^- : forbidden

...


(c)
H -> γγ & Zγ
{2; 00}
{0: 00}
{2; 22}
2.0
1.5
1.0
0.5
0.0
-1.0
-0.5
0.0
0.5
1.0
cosΘ

$\mathcal{D}$istinction $\mathcal{S}$calar-type, $\mathcal{T}$ensor-type



$\mathcal{F}$uture

Future directions Systematics of spin/parity in vector boson fusion

τ decays

for 0^+ in the SM and 0^- in A [MSSM]

> Straightforward strategies identified for proving $J^P = 0^+$ experimentally under necessary and sufficient conditions.