Higgs, LHC Data etc.

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Moriond QCD
And Higgs-Energy Interactions

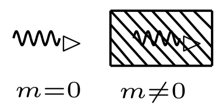
14 March 2013

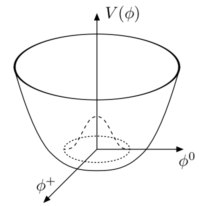
What Have We Seen at the LHC?

* The production of a new particle with mass around $M = 125$GeV
* Is it *the* Standard Model scalar boson *responsible for EWSB*? $\Longrightarrow$

Test of the EWSB mechanism

• Discovery	–	m
• Interaction with the scalar boson with $v = 246$ GeV$\neq 0$	$\rightsquigarrow$	$g_{HXX} \sim m_X$
• Spin and parity quantum numbers	–	J^{PC}
• EWSB: potential w/ non-vanishing VEV	–	$\lambda_{HHH}, \lambda_{HHHH}$





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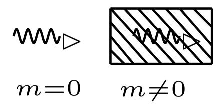

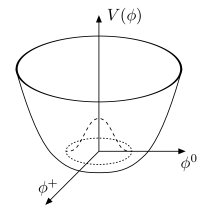

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Basis of Higgs-Spin/Parity Measurements at the LHC

in collaboration with *S. Y. Choi, D. J. Miller and P. M. Zerwas*

- **Literature**

  ∗ LHC Higgs CXN WG, YR3

  ∗ 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]]

- **Further publications:** Hagiwara eal; De Rujula eal; Gao eal; S. Bolognesi eal; J. Ellis eal; Alves; Godbole eal; Plehn eal; Englert eal; Frank eal; Djouadi eal; ...

$\mathcal{P}$rogram

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

- **Theoretical Tools:**
  - ∗ helicity analyses
  - ∗ operator expansions

- **Systematic analysis of production and decay processes**
  - ∗ Z^*Z decays — Choi eal; Gao eal; De Rujula eal; Bolognesi eal
  - ∗ $\gamma\gamma$ decays — Ellis, Hwang; Alves; Choi eal
  - ∗ CP-violating decays — Soni, Xu; Chang eal; Godbole eal; Nelson
  - ∗ Production in gluon fusion, in vector boson fusion — Plehn eal; Hagiwara eal
  - ∗ Production in Higgs-strahlung — Miller eal; Ellis eal

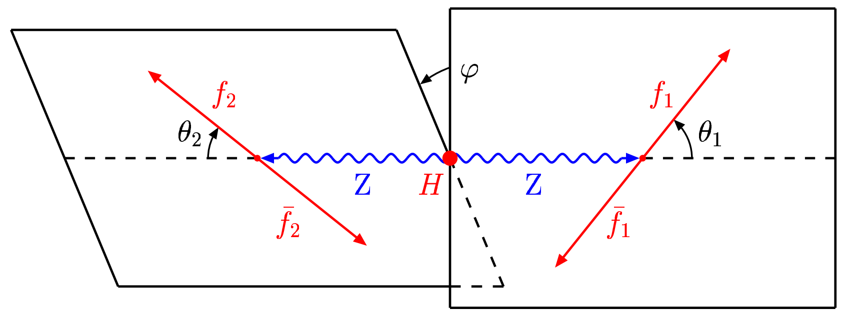
- **Observation in $\gamma\gamma$:** No spin 1 [Landau-Yang]; $C = +1$ [charge invariance]

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

◇ Determination of spin and parity in

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

in H c.m. frame



◇ Helicity methods to generalize to arbitrary spin and parity

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

◇ General tensor for HZZ vertex for each $\mathcal{J}^{\mathcal{P}}$

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

$\mathcal{D}$ifferential $\mathcal{D}$istributions $\mathcal{P}$ure-$\mathcal{S}$pin/$\mathcal{P}$arity $\mathcal{U}$npolarized $\mathcal{B}$oson H^J

◇ **Double polar angular distribution (CP-invariant theory)**

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\cos\theta_1 d\cos\theta_2} = \Big[\sin^2\theta_1 \sin^2\theta_2 \, |\mathcal{T}_{00}|^2 + \frac{1}{2}(1+\cos^2\theta_1)(1+\cos^2\theta_2)\,\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right] + (1+\cos^2\theta_1)\,\sin^2\theta_2\,|\mathcal{T}_{10}|^2 + \sin^2\theta_1\,(1+\cos^2\theta_2)\,|\mathcal{T}_{01}|^2\Big]/\mathcal{N}$$

$\mathcal{N} = (16/9)\sum|\mathcal{T}_{\lambda\lambda'}|^2$ – normalization

◇ **Azimuthal angular distribution (CP-invariant theory)**

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\phi} = \frac{1}{2\pi}\left[1 + |\zeta_1|\cos 2\phi\right]$$

$|\zeta_1| = |\mathcal{T}_{11}|^2/\left[2\sum|\mathcal{T}_{\lambda\lambda'}|^2\right]$

suppressing terms quadratic in $\eta_i = 2v_i a_i/(v_i^2 + a_i^2) \sim 0.02$, 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:**

$$\mathcal{T}_{00} = (M_H^2 - M_*^2 - M_Z^2)/(2M_*M_Z), \qquad \mathcal{T}_{11} = +\mathcal{T}_{-1,-1} = -1, \qquad \mathcal{T}_{10} = \mathcal{T}_{01} = \mathcal{T}_{1,-1} = 0$$

Necessary conditions:

◇ Double polar angular distribution

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

◇ Azimuthal angular distribution

$$\frac{1}{\Gamma'}\frac{d\Gamma'}{d\phi} = \frac{1}{2\pi}\left[1+\frac{1}{2}\frac{1}{\gamma^4+2}\cos 2\phi\right]$$

$$\gamma^2 = (M_H^2 - M_*^2 - M_Z^2)/(2M_*M_Z)$$

$\mathcal{D}$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]

  ◇ $d\Gamma/dM_*^2$ 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)

$\mathcal{P}$seudoscalar A with $J^P = 0^-$

- **Differential Distributions:** Parity invariance $\rightsquigarrow$

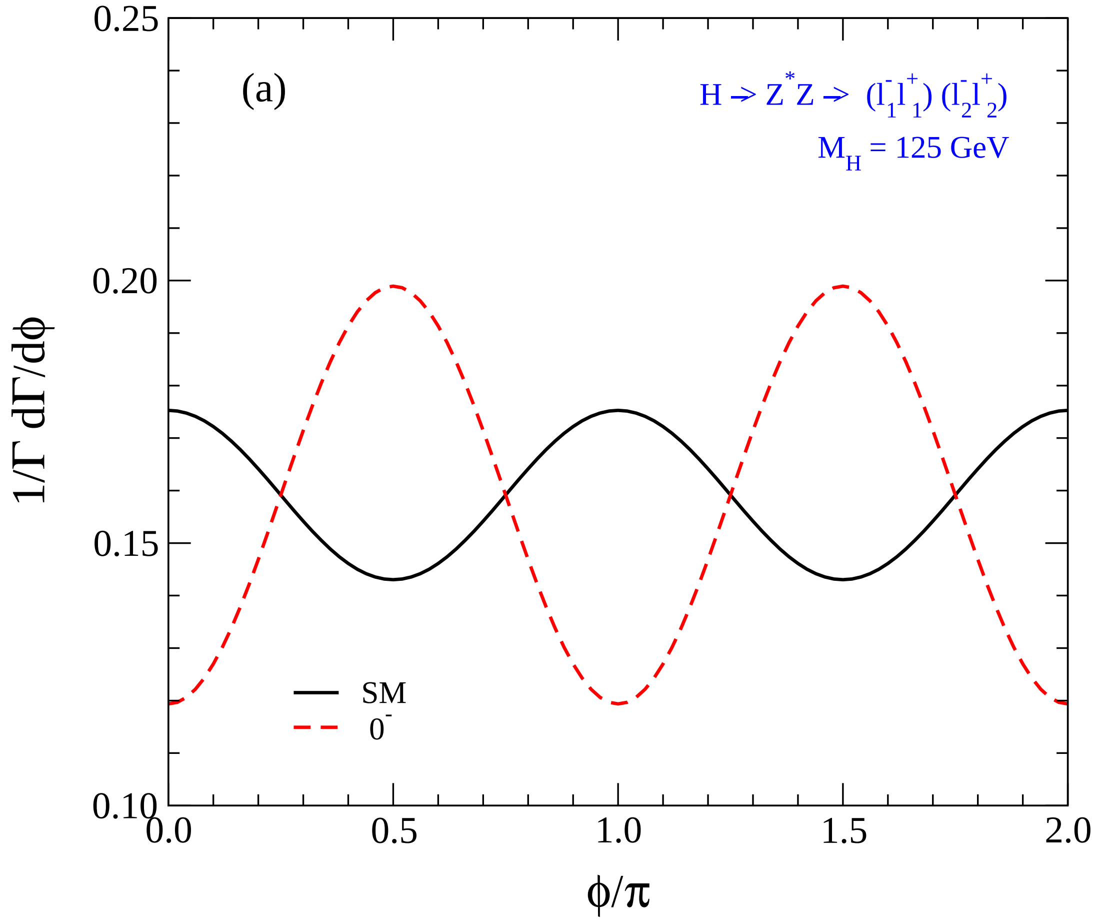
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\cos\theta_1\cos\theta_2} = \frac{9}{64}(1+\cos^2\theta_1)(1+\cos^2\theta_2)$$
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\phi} = \frac{1}{2\pi}\left[1-\frac{1}{4}\cos 2\phi\right]$$

- **Threshold Behaviour:** $d\Gamma_A/dM_*^2 \sim \beta^3$

- **If too small branching ratio $A \to Z^*Z$:** sufficient and necessary conditions of spin/parity
  - Spin 0: isotropic angular distribution in $gg \to A \to \gamma\gamma$ $\longrightarrow$
  - Jets in $gg \to A + gg$ anti-correlated for pseudoscalar (correlated for scalar) Hagiwara eal
  - Exploit fermionic decay channels

Azimuthal Angular Distributions: Parity

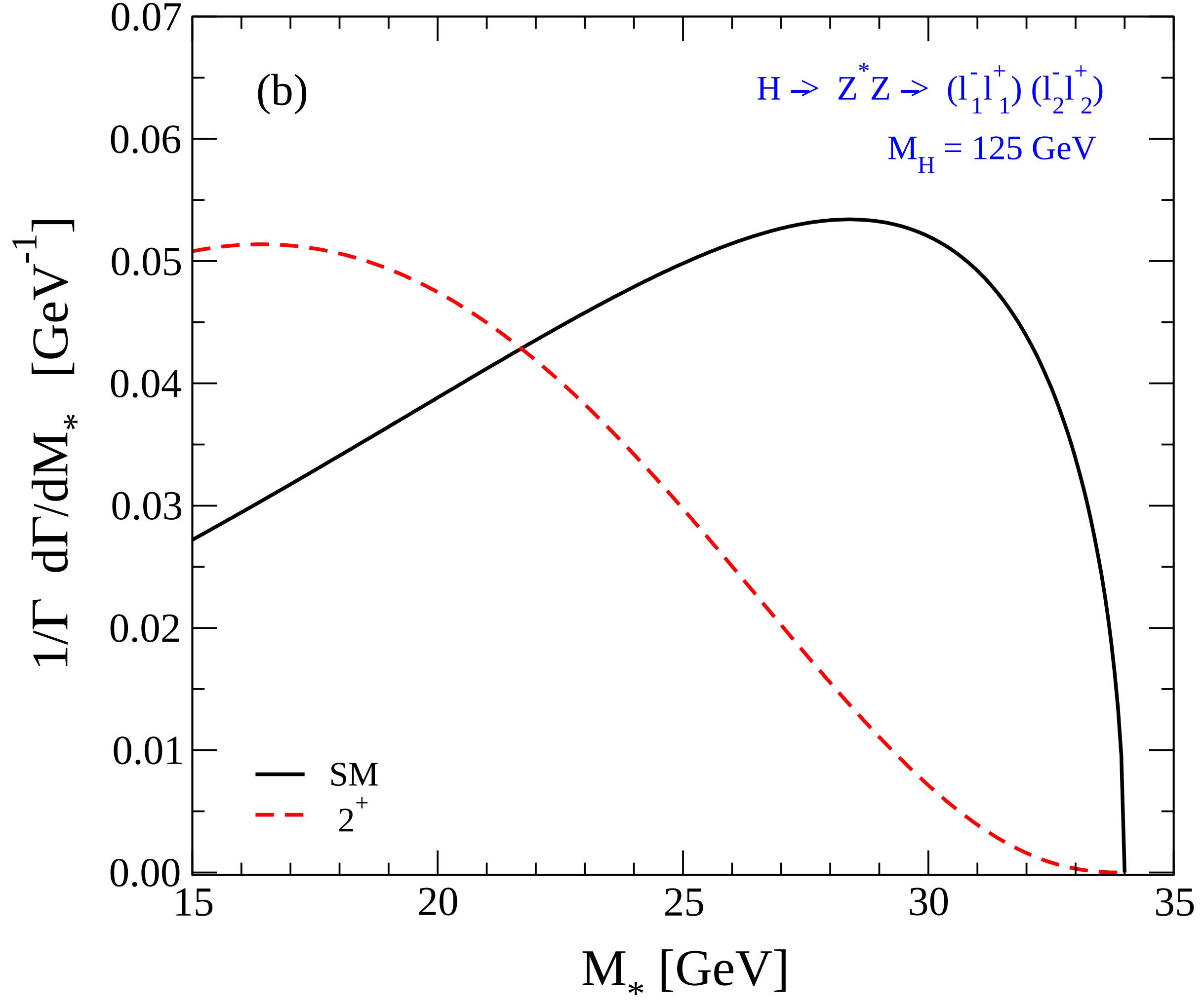
Choi,Miller,MMM,Zerwas



$0^+ : d\Gamma/d\varphi \sim 1 + f_{\mathsf{kin}} \cos 2\phi$, $0^- : d\Gamma/d\varphi \sim 1 - 1/4 \cos 2\phi$

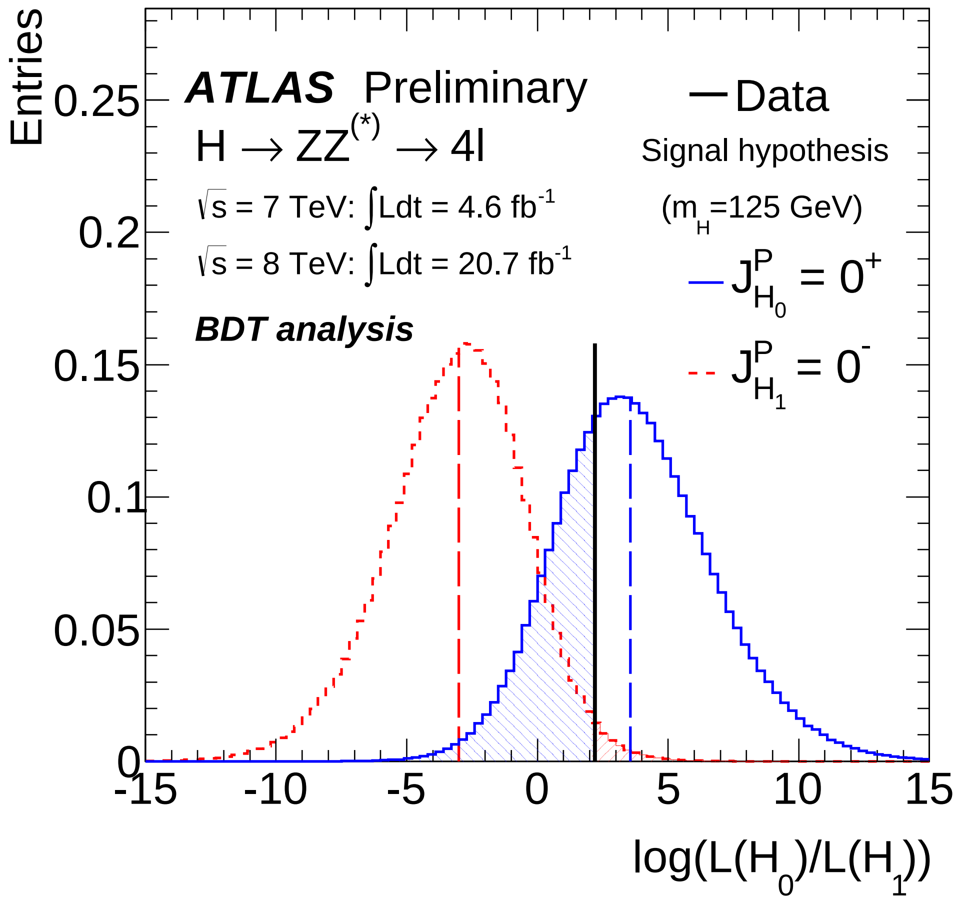
Threshold Behaviour: Spin

Choi,Miller,MMM,Zerwas



ATLAS $\mathcal{R}$esults

- **$0^+, 0^-, 1^+, 1^-, 2^+, 2^-$ hypotheses in $H \longrightarrow ZZ^* \longrightarrow 4l$** ATLAS-CONF-2013-013



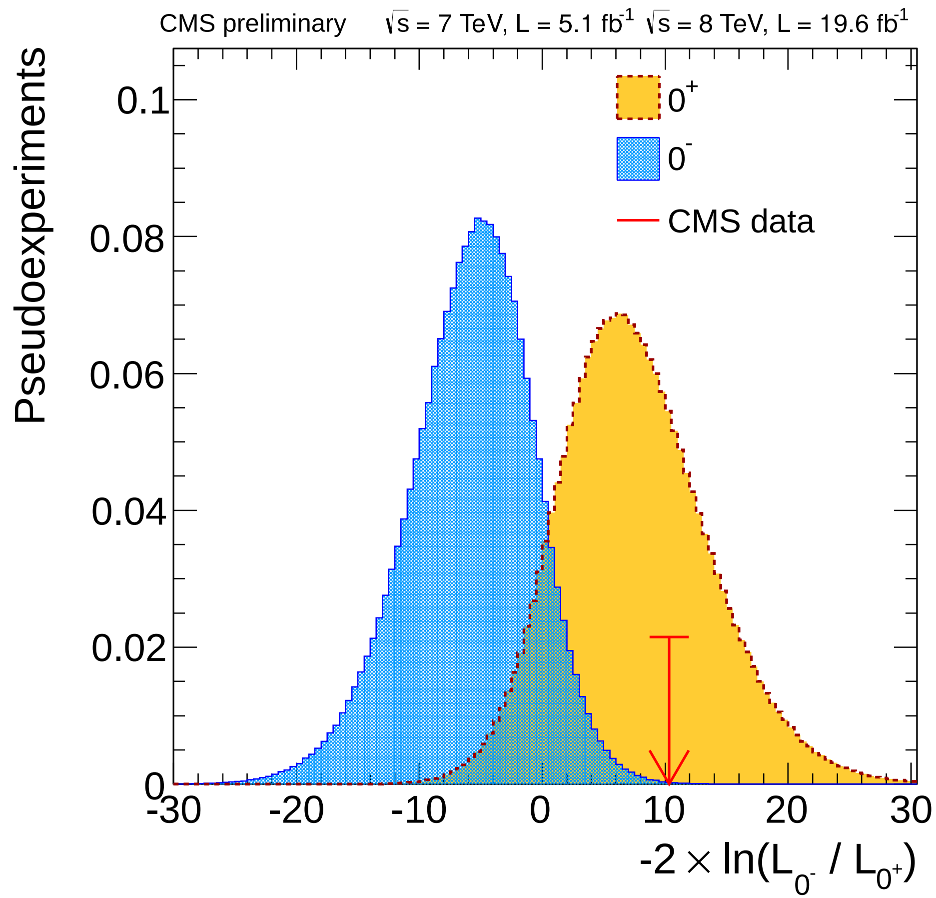
$0^-, 1^+$ states excluded at 97.8% CL in favour of 0^+

- **Spin studies in $H \longrightarrow \gamma\gamma$** ATLAS-CONF-2012-168, $H \longrightarrow WW^* \longrightarrow e\nu\mu\nu$ ATLAS-CONF-2013-031

CMS $\mathcal{R}$esults

- **$0^+, 0^-, 1^+, 1^-, 2^+, 2^-$ hypotheses in $H \longrightarrow ZZ^* \longrightarrow 4l$**

PRL 110 (2013)
CMS-PAS-HIG-13-002



$0^-, 1, 2$ excluded at 95% CL or higher

- **Spin studies in $H \longrightarrow WW^* \longrightarrow l\nu l\nu$** CMS-PAS-HIG-13-003

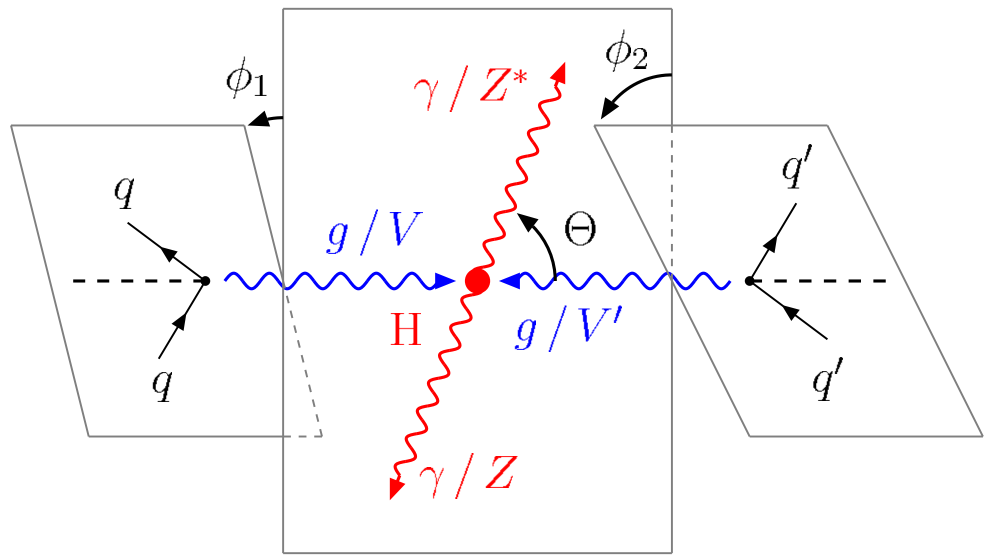
(II) $\mathcal{H}$iggs-$\mathcal{S}$pin $\mathcal{A}$nalysis through $gg \to H^J \to \gamma\gamma$ $\mathcal{D}$ecays

- **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

(b)



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- **Types**

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

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

General Spin/Parity Assignments

- **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 $\sim |\cos^{2J}\Theta|$

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

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

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

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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

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

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

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

...

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

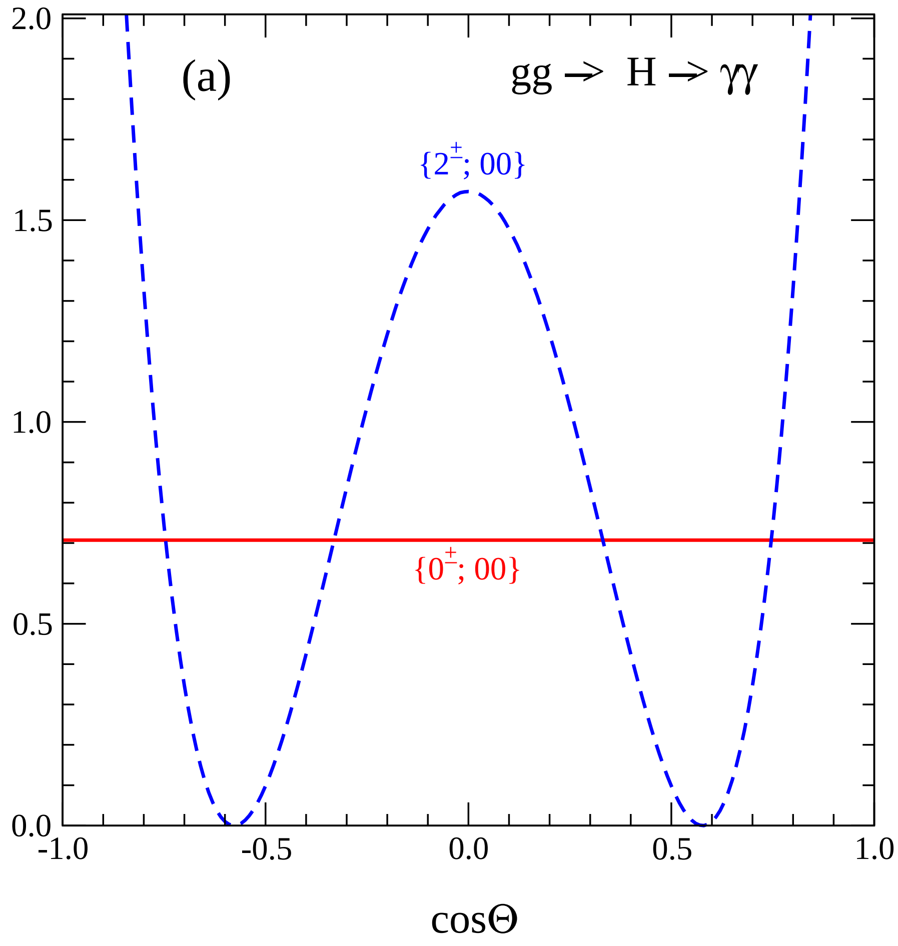
3^+ : $D^3_{22} \neq 0$, none else

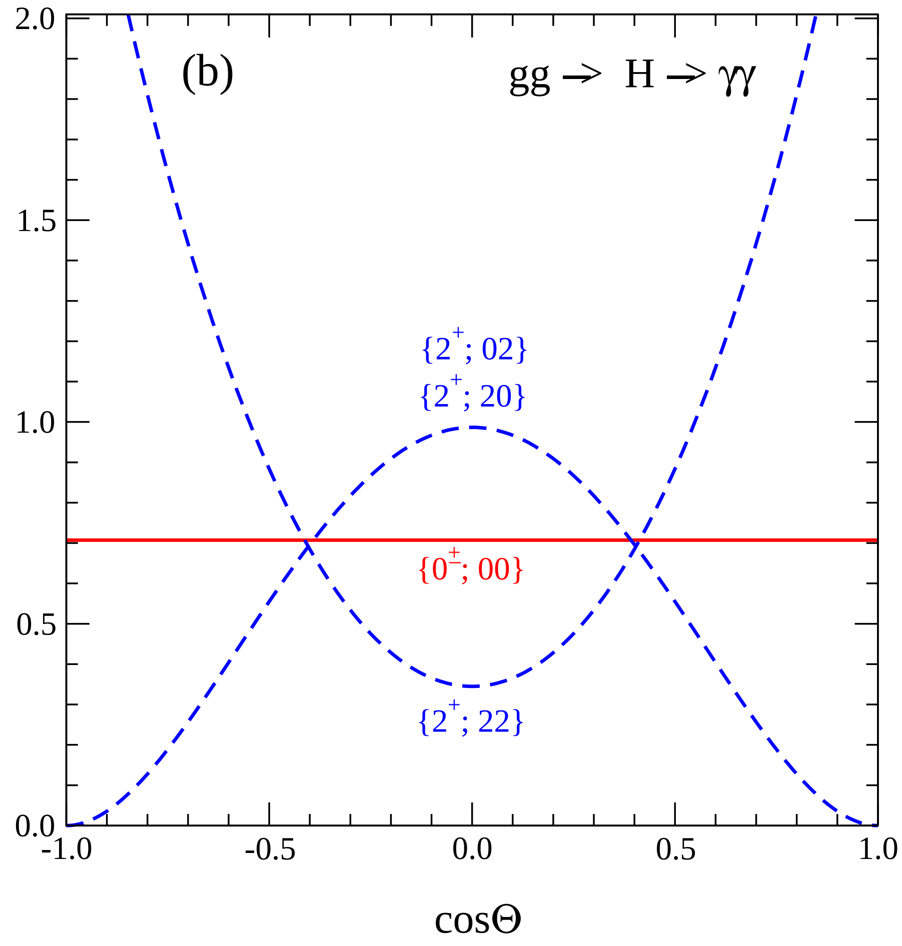
3^- : forbidden

...

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

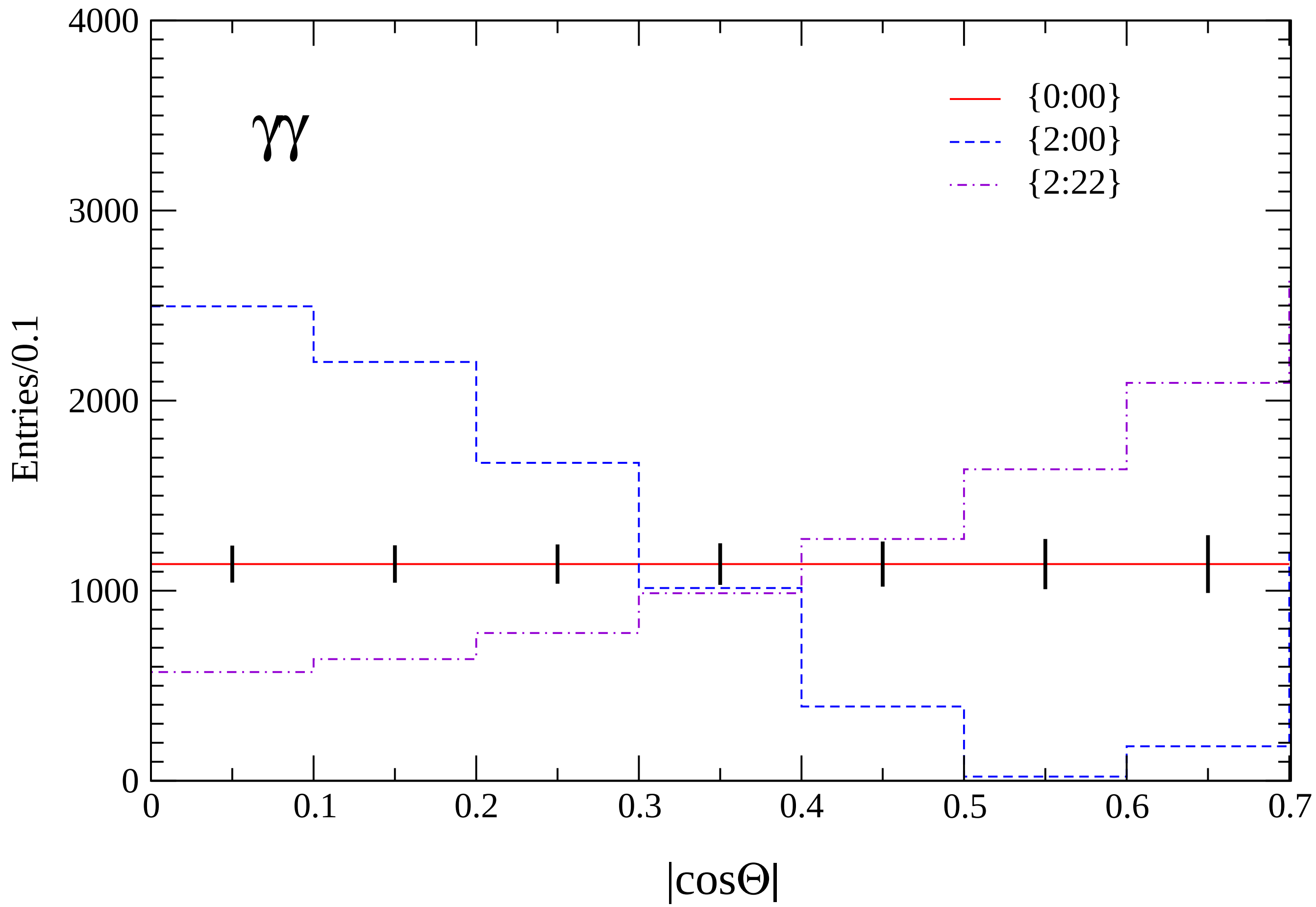
Choi, Miller, MMM, Zerwas





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

Choi,MMM,Zerwas



(III) $\mathcal{F}$urther $\mathcal{A}$nalyses

- **Analoguous analysis:** Angular distribution of Z^*Z axis in Z^*Z final states

- **Parity check in:**
  - Azimuthal corr. between radiation planes in $qq \to VV' + qq \to H, A + qq$ — Plehn eal; Hagiwara eal
  - Correlations of planes in $gg \to H, A+$ 2 jets — Hagiwara eal

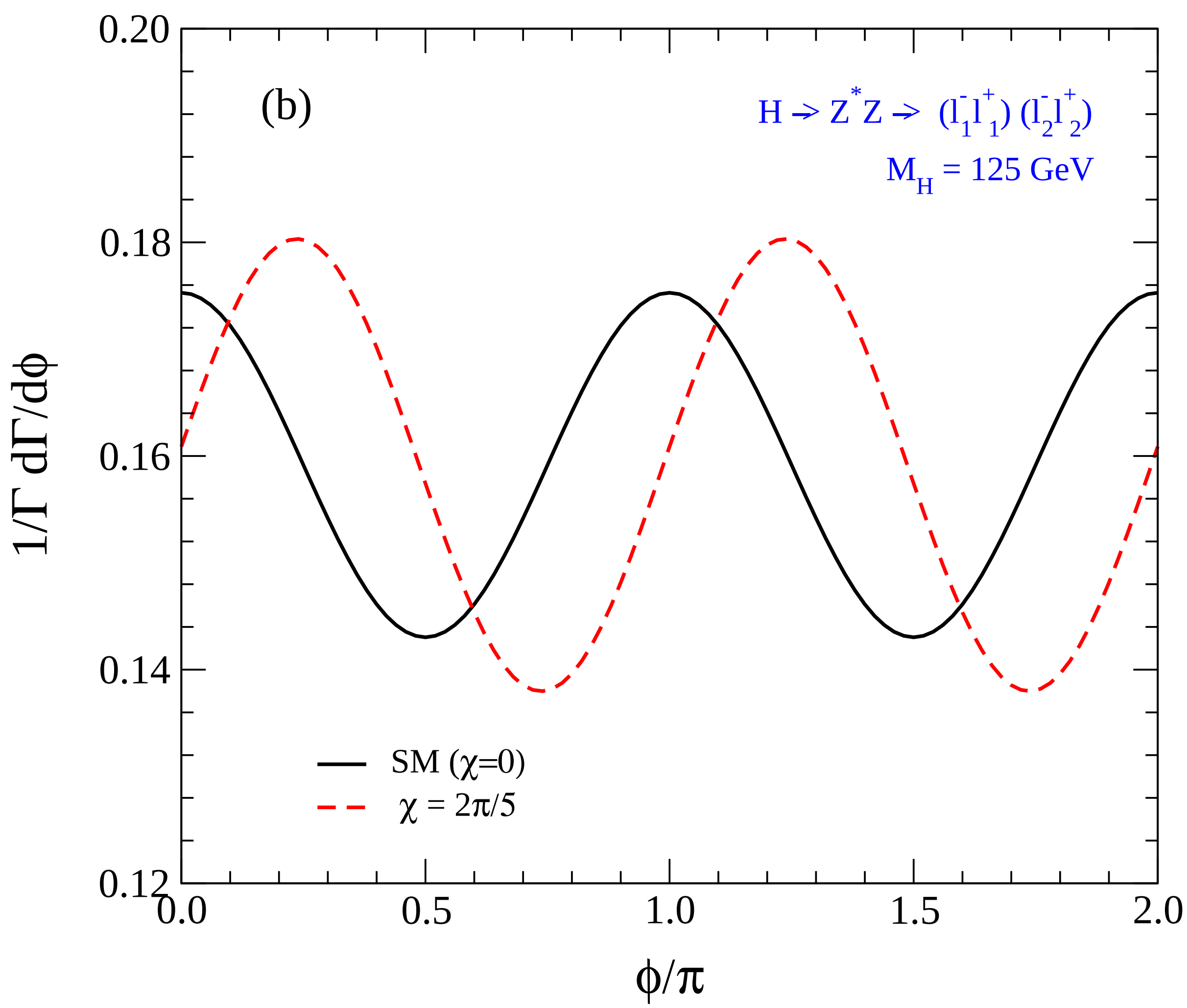
- **Spin/Parity in Higgs-strahlung:** $q\bar{q} \to Z/W + H^J$ — Choi eal; Ellis eal; Englert eal; Frank eal; Djouadi eal

- **Fermionic decays:** Angular correlations among fermion decay products in $H^J \to f\bar{f} \to a\bar{a} \dots$ — Kramer eal; Berge eal

- **CP-violating H':**
  - In $H' \to Z^*Z$, hopefully — Godbole,Miller,MMM
  - Alternatively in Higgs + 2 jets

$\mathcal{CP}$ $\mathcal{V}$iolation in $H' \to Z^*Z \to 4l$

Choi,Miller,MMM,Zerwas



$$H' = \cos\chi H + \sin\chi e^{i\xi} A$$

Ellis eal; Choi eal

Conclusions

* Angular helicity analyses and threshold effects in particle decays into VV', $\gamma\gamma$, $f\bar{f}$
* Initial-final state angular correlations in Higgs decays into $\gamma\gamma$, VV' in gluon fusion
* Azimuthal angle correlation in gluon fusion + 2 jets, vector boson fusion

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

* CP-violation: - in $H' \rightarrow Z^*Z$
  - in azimuthal distributions of decay planes in vector boson fusion, gluon fusion, fermion decays

Thank you for your attention!

(III) $\mathcal{F}$urther $\mathcal{A}$nalyses - Continued

- **CP-violating spin-0 Higgs boson:**
  - In $Z^* Z$ decays

$$V^{\mu\nu}_{H'ZZ} = i g_Z M_Z \left[a\, g^{\mu\nu} + b\, \frac{p^\mu p^\nu}{M_H^2} + c\, \epsilon^{\mu\nu\rho\sigma} \frac{p_\rho k_\sigma}{M_H^2} \right]$$

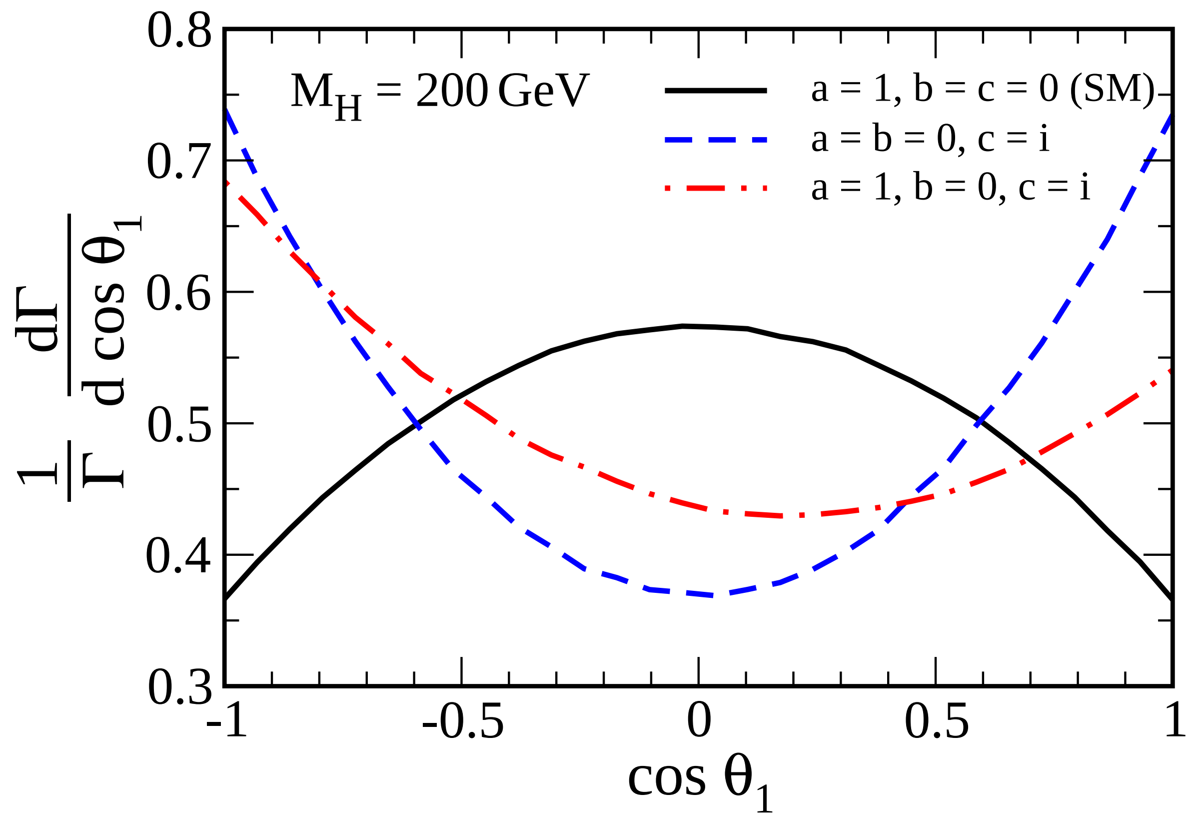
CP-violation: $c \wedge a$ and/or b non-zero

- CP-sensitive asymmetries — Godbole eal
- Azimuthal angular modulation of the two jets in $gg \to H' + gg \to \gamma\gamma + gg$
- Azimuthal angle-correlation between the two τ decay planes in $H' \to \tau^- \tau^+ \to a^- b^+ ...$

Higgs boson quantum numbers

angular distribution in $\cos\theta$

Godbole,Miller,MMM



Higgs boson quantum numbers

angular distribution in ϕ

Godbole,Miller,MMM