Spin and CP Measurements

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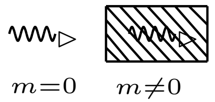
$\mathcal{E}$xperimental $\mathcal{V}$erification of the $\mathcal{H}$iggs $\mathcal{M}$echanism

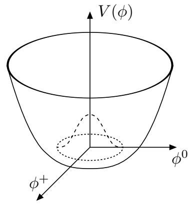
- The production of a new particle with mass $M \approx 125$ GeV
- Is it *the* Standard Model *Higgs* boson? $\Longrightarrow$

<u>Test of the Higgs mechanism</u>

- Discovery – m
- Interaction with a scalar Higgs with $v = 246$ GeV$\neq 0$ $\rightsquigarrow$ $g_{HXX} \sim m_X$



- Spin- and parity quantum numbers – J^{PC}
- EWSB requires Higgs potential – $\lambda_{HHH}, \lambda_{HHHH}$



- Is it the Standard Model Higgs boson, a SUSY Higgs boson, a Composite Higgs boson, ...?

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Quantum numbers of the Higgs boson:** J^{PC} $\quad J$ spin, P parity, C charge conjugation

- **Vast literature:**

Miller eal; Plehn eal; Choi eal; Odagiri; Buszello eal; Ellis eal; Godbole eal; Kramer eal; Berge al; Hagiwara eal; Hankele eal; Gao eal; De Rujula eal; Christensen eal; Englert eal; De Sanctis eal; Bolognesi eal; Boughezal eal; Coleppa eal; Stolarski eal; Alves; Chen eal; Banerjee eal; Freitas, Schwaller; Modak eal; Frank eal; Djouadi eal; Artoisenet eal; Desai eal; Schlegel eal; de Aquino, Mawatari; ...

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

- **Theoretical Tools:**
  - $\ast$ helicity analyses
  - $\ast$ operator expansions

- **Systematic analysis of production and decay processes**

$\mathcal{H}$iggs $\mathcal{B}$oson $\mathcal{Q}$uantum $\mathcal{N}$umbers

- **Systematic analysis of production and decay processes**

  $*$ V^*V decays — Buszello,Fleck,Marquard,van der Bij;Choi eal; Gao eal; De Rujula eal; Bolognesi eal; Englert eal; Boughezal eal

  $*$ $\gamma\gamma$ decays — Ellis, Hwang; Alves; Choi eal

  $*$ $Z\gamma$ decays — Stolarski, Vega-Morales; Choi eal

  $*$ CP-violating decays — Soni, Xu; Chang eal; Godbole eal; Nelson; De Rujula eal: Buszello eal; Freitas, Schwaller

  $*$ Fermionic decays ($\rightarrow$ CP violation) — Kramer eal; Berge eal; Banerjee eal

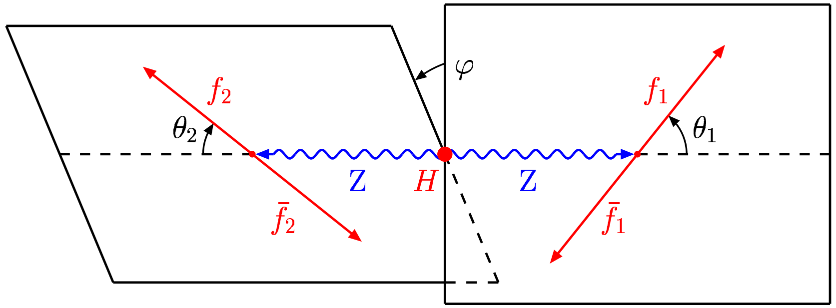
  $*$ Production in gluon fusion, in vector boson fusion — Plehn eal; Hagiwara eal; Buszello, Marquard; Hankele eal; Campanario eal; Del Duca eal; Frank eal

  $*$ Production in Higgs-strahlung — Miller eal; Ellis eal; Englert eal; Frank eal; Djouadi eal; Christensen eal

  $*$ Hadronic event shapes — Englert eal

  $*$ Correlations among branching ratios — Coleppa eal; Ellis eal

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



◇ 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:** $[M_* \equiv M_{Z^*}]$

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

Necessary conditions:

◇ Double polar angular distribution

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

◇ 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

- $\underline{\boldsymbol{M_H < 2M_Z}:}$ $\quad d\Gamma/dM_*^2 \sim \beta$ 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 (<u>sufficient conditions</u>)

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

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

$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\cos\theta_1\cos\theta_2} = \frac{9}{64}(1+\cos^2\theta_1)(1+\cos^2\theta_2)$$

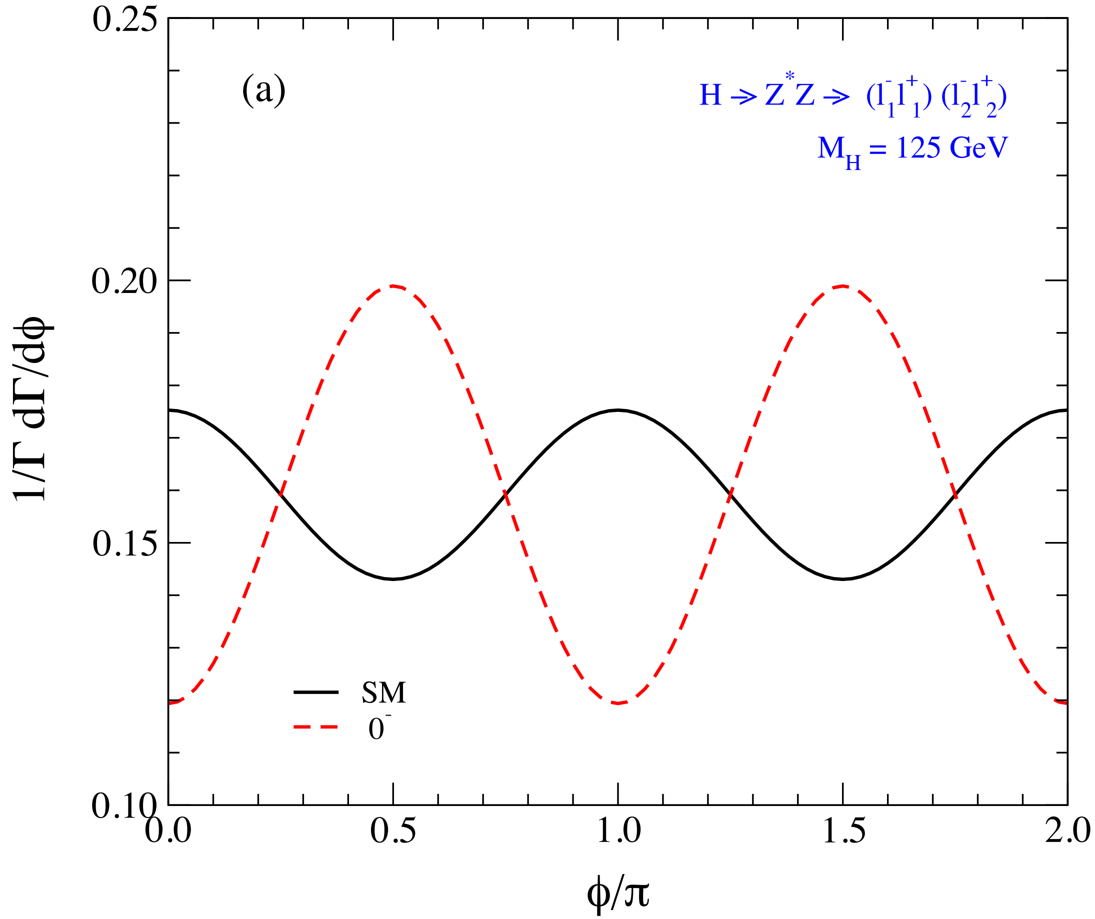
$$\frac{1}{\Gamma_A}\frac{d\Gamma_A}{d\phi} = \frac{1}{2\pi}\left[1-\frac{1}{4}\cos 2\phi\right]$$

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

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

$\#$ Azimuthal Angular Distributions: Parity

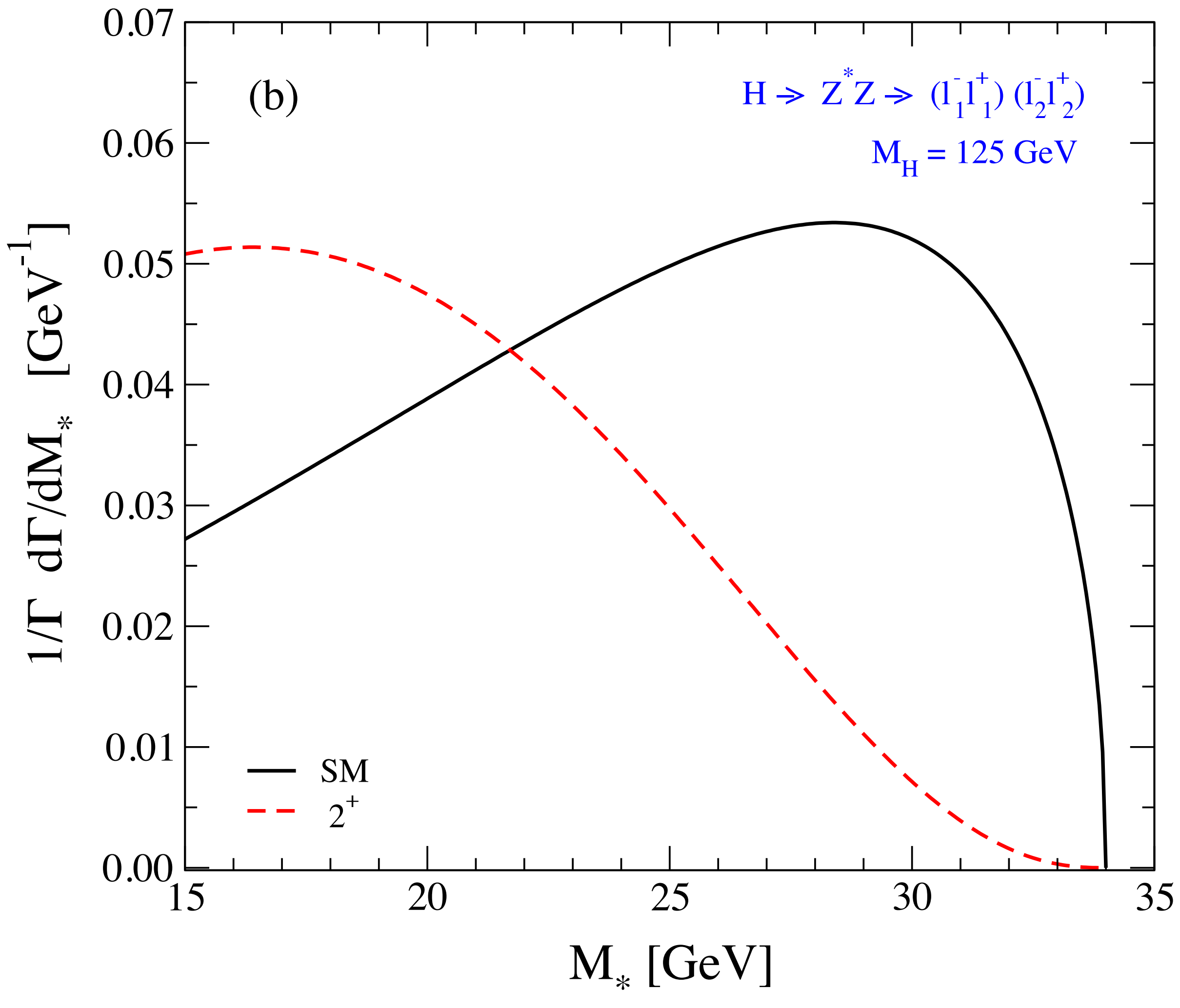
Choi, Miller, MMM, Zerwas



$0^+ : d\Gamma/d\varphi \sim 1 + 1/(2\gamma^4 + 4)\cos 2\phi,\qquad 0^- : d\Gamma/d\varphi \sim 1 - 1/4\cos 2\phi$

$\mathcal{T}$hreshold $\mathcal{B}$ehaviour: $\mathcal{S}$pin

Choi, Miller, MMM, Zerwas



$\mathcal{JHU}$ $\mathcal{M}$onte-$\mathcal{C}$arlo $\mathcal{G}$enerator

- **MC Generator for:** $pp \to qq/gg \to X(q) \to V_1(q_1)V_2(q_2)$

  spin correlations, spin $J = 0, 1, 2$

Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck

- **Parametrisation (example spin 0):**

$$A(X \to V_1V_2) = \Big(\underbrace{a_1\, m_X^2\, g_{\mu\nu} + a_2\, q_\mu q_\nu}_{\text{CP-even}} + \underbrace{a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha\, q_2^\beta}_{\text{CP-odd}} \Big) \epsilon_1^{*\mu} \epsilon_2^{*\nu} / v$$

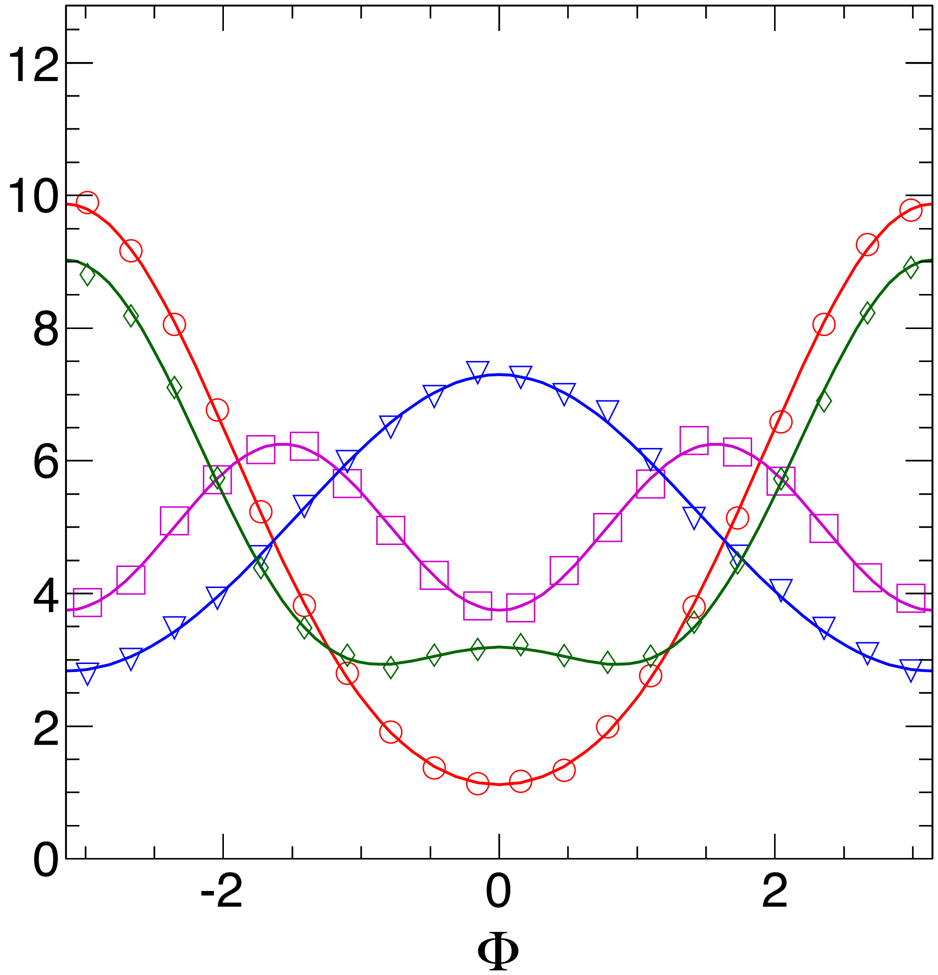
  ◇ a_i $(i = 1, 2, 3)$: momentum-dependent form factors
  (real/imaginary parts $\longrightarrow$ essential for heavier resonances)

  ◇ more general description than effective Lagrangian ($\longleftarrow$ smaller number of terms)

  ◇ assuming momentum-independent form factors $\rightsquigarrow$ effective couplings

$\mathcal{M}$onte-$\mathcal{C}$arlo $\mathcal{S}$imulation

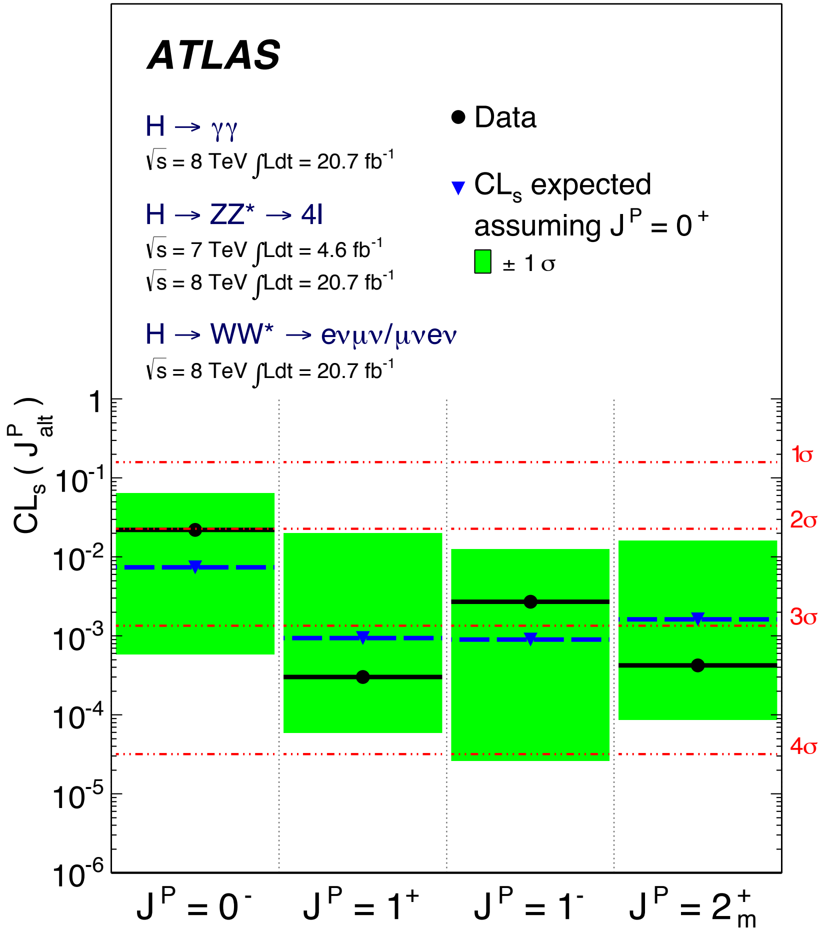
Bolognesi, Gao, Gritsan, Melnikov,
Schulze, Tran, Whitbeck



$X \to VV$: SM Higgs boson, 0^-, 2^+_m, 2^+_h

ATLAS $\mathcal{R}$esults

ATLAS 1307.1432



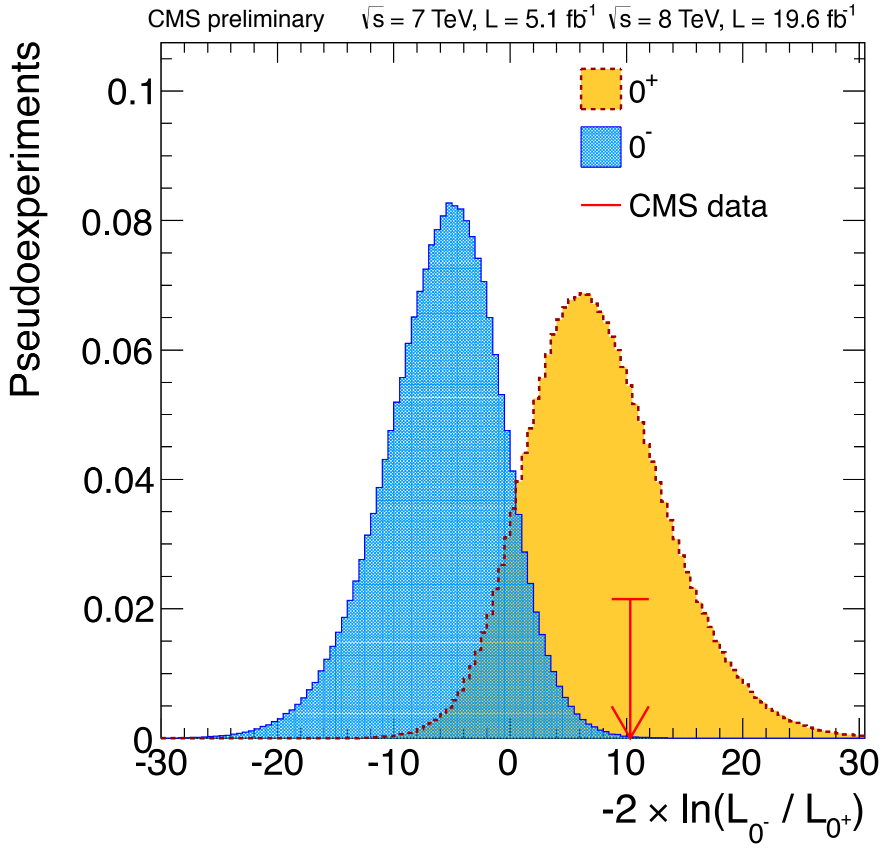
0^- rejected at 97.8% CL ($H \to ZZ^* \to 4l$); $1^\pm$ at $\gtrsim 99.7\%$ CL ($ZZ^* \to 4l$, $WW^* \to l\nu l\nu$)

2^+ rejected at $\gtrsim 99.9\%$ CL ($H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, $H \to WW^* \to l\nu l\nu$), indep gg, $q\bar{q}$

CMS $\mathcal{R}$esults

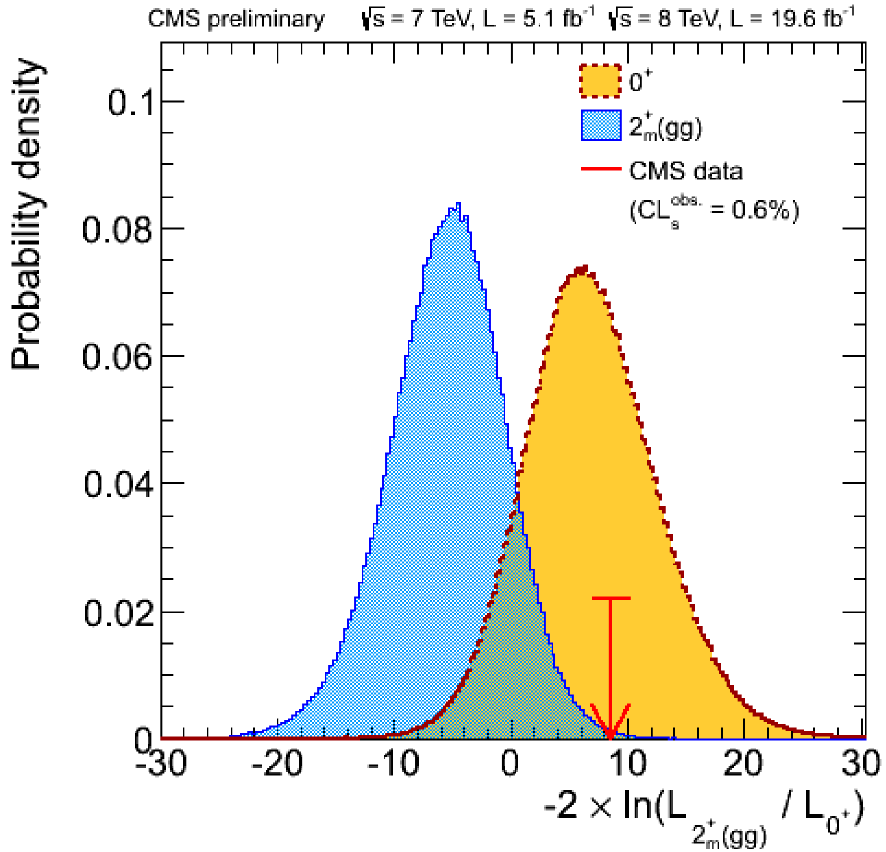
- $\mathbf{0^+, 0^-, 1^+, 1^-, 2^+, 2^-}$ **hypotheses in $H \to ZZ^* \to 4l$** PRL 110 (2013)

CMS-PAS-HIG-13-002



0^- excluded at 95% CL

CMS-PAS-HIG-13-005



$2^+_m(gg)$ excluded at 60% CL

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

$\mathcal{S}$ome $\mathcal{C}$omments

Correlation: between spin/parity and coupling measurements; example

- ◇ observed strong interaction of new particle with EW gauge bosons $\rightsquigarrow$ not pseudoscalar?
- ◇ pseudoscalar interacts w/ gauge bosons through higher-dim operators
- ◇ if significant contributions $\rightsquigarrow$ beyond SM physics at low scale
- ◇ would have been observed experimentally
- ◇ CP non-conserving technicolor models: large admixtures of scalar and pseudoscalar possible

Nevertheless: Experimental test of these arguments is important

Momentum dependence

- ◇ coupling coefficients can be in general momentum-dependent
- ◇ momentum dependence involves ratios of typical momenta in the process to scale of New Physics Λ
- ◇ first approximation: neglect scale dependence

Some Comments

More refined analyses
(more sophisticated parametrisations, kinematic dependences of coupling constants, multi-parameter fits, ...)

- ◇ if introduced minimal couplings cannot describe properties of new particle
- ◇ when more data available

With present data

- ◇ first step: test of different hypotheses
- ◇ extreme spin/parity hypotheses can be excluded
- ◇ small anomalous coupling contributions to Higgs-gauge coupling cannot be excluded

Framework for Higgs characterisation

Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro

- Effective field theory approach: spin 0, spin 1, spin 2
- Simulation of production and decay w/ various spin/parity
- multi-parton tree-level and NLO QCD - both matched w/ parton showers

(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**

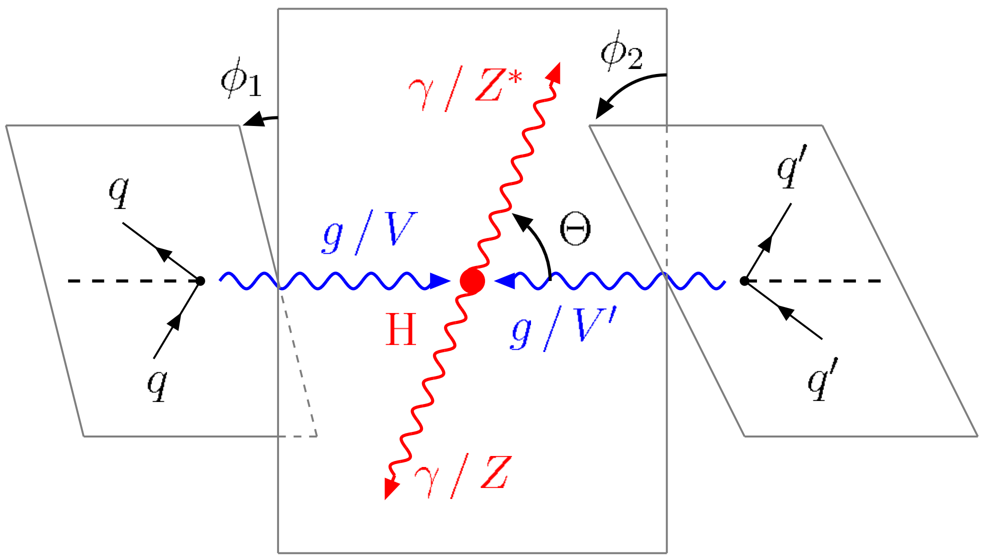
$$\frac{1}{\sigma}\frac{d\sigma(\gamma\gamma)}{d\cos\Theta} = (2J+1)[\mathcal{X}_0^J\mathcal{Y}_0^J\mathcal{D}_{00}^J + \mathcal{X}_0^J\mathcal{Y}_2^J\mathcal{D}_{02}^J + \mathcal{X}_2^J\mathcal{Y}_0^J\mathcal{D}_{20}^J + \mathcal{X}_2^J\mathcal{Y}_2^J\mathcal{D}_{22}^J]$$

$*$ $\mathcal{D}_{m\lambda}^J$ 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)



$\mathcal{G}$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

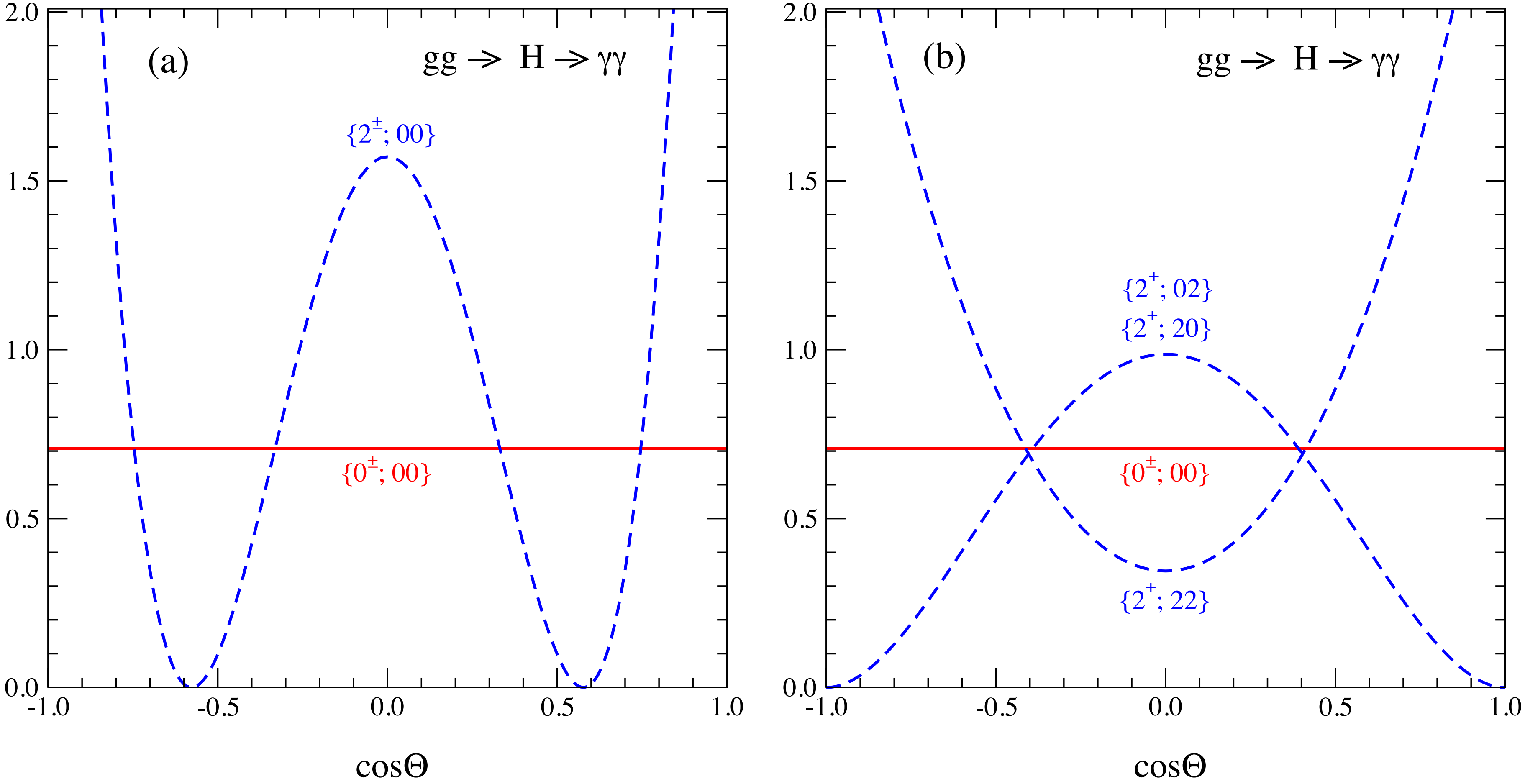
- **Squared Wigner functions** $\mathcal{D}^J_{m\lambda}$ up to $\sim |\cos^{2J}\Theta|$

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

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

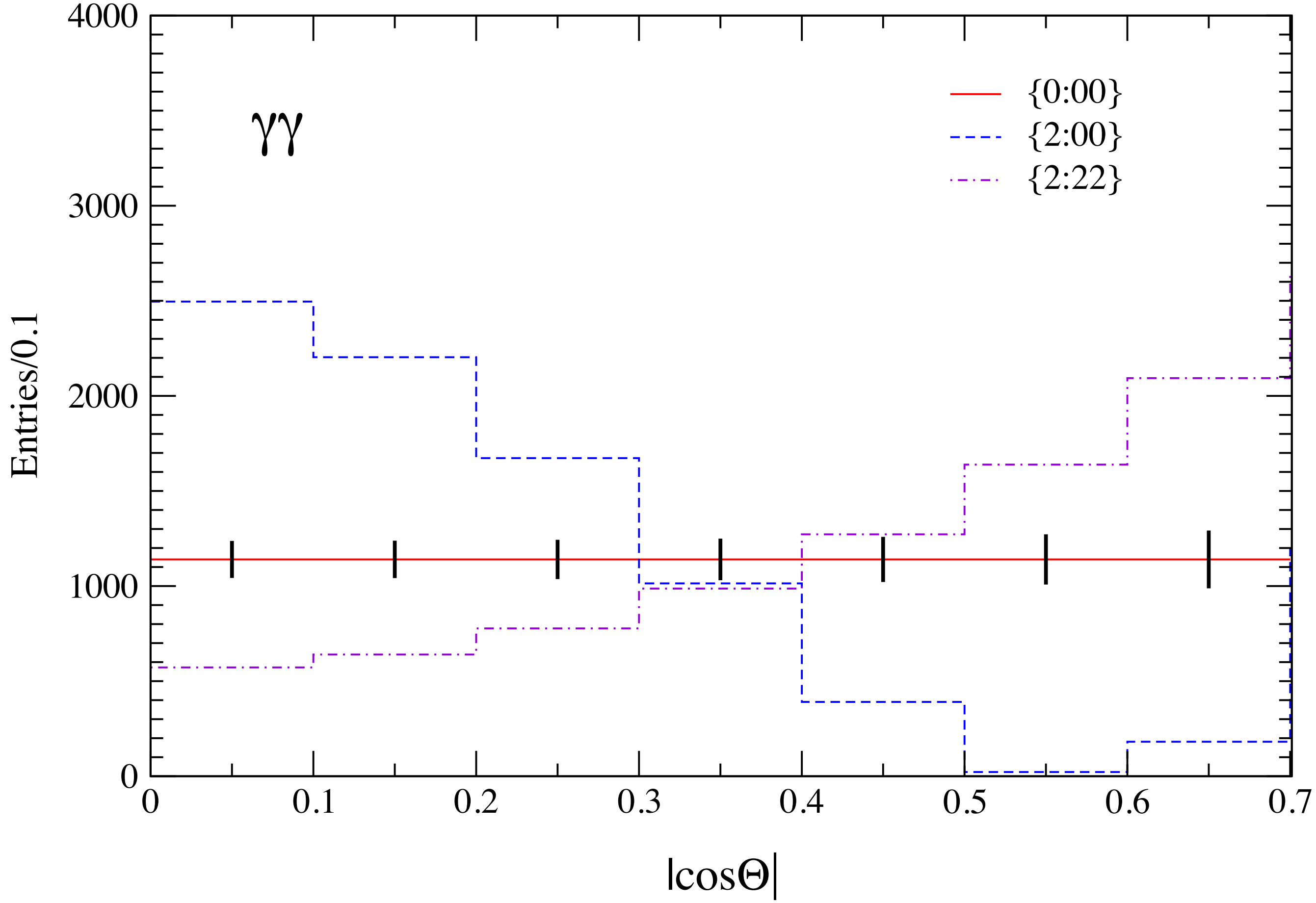
$\mathcal{S}$calar-type, $\mathcal{T}$ensor-type

Choi,Miller,MMM,Zerwas



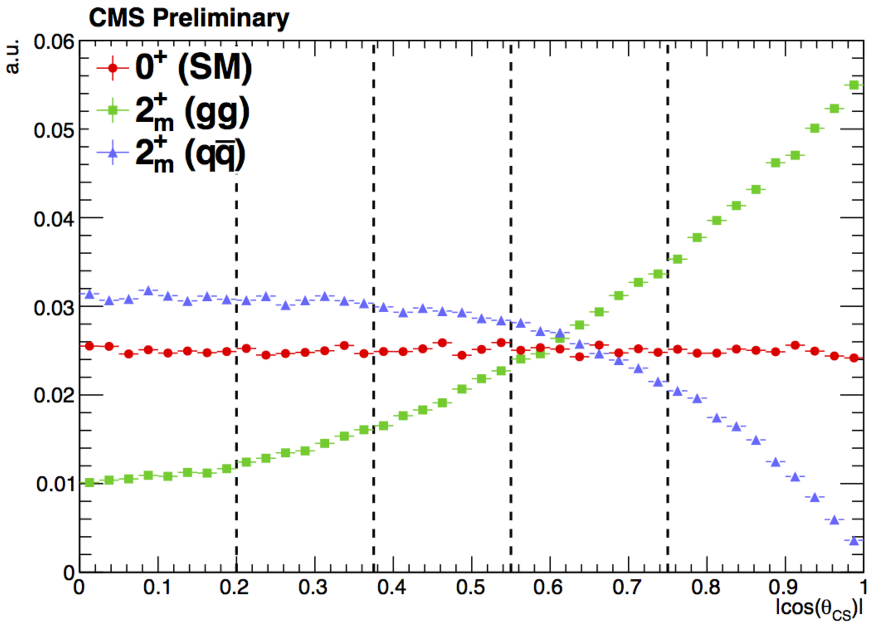
$\mathcal{D}$istinction $\mathcal{S}$calar-type, $\mathcal{T}$ensor-type

Choi,MMM,Zerwas

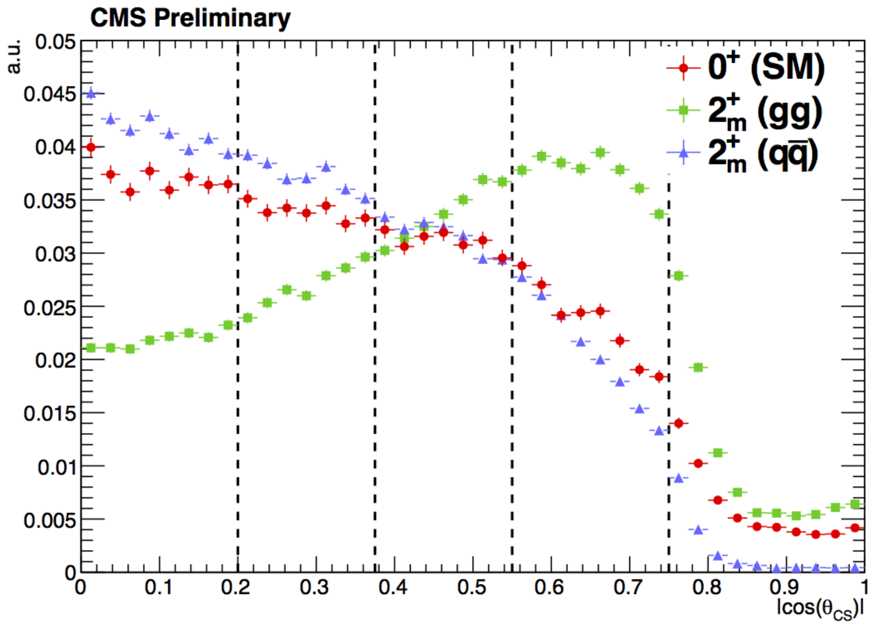


$\mathcal{S}$pin $\mathcal{H}$ypothesis $\mathcal{S}$eparation in $\gamma\gamma$

CMS-PAS-HIG-13-016



before cuts



after cuts

Comparison of SM spin-0 hypothesis with a graviton-like spin-2 hypothesis with minimal couplings: spin-2 model not ruled out w/ present data.

$\mathcal{CP}$ $\mathcal{V}$iolation

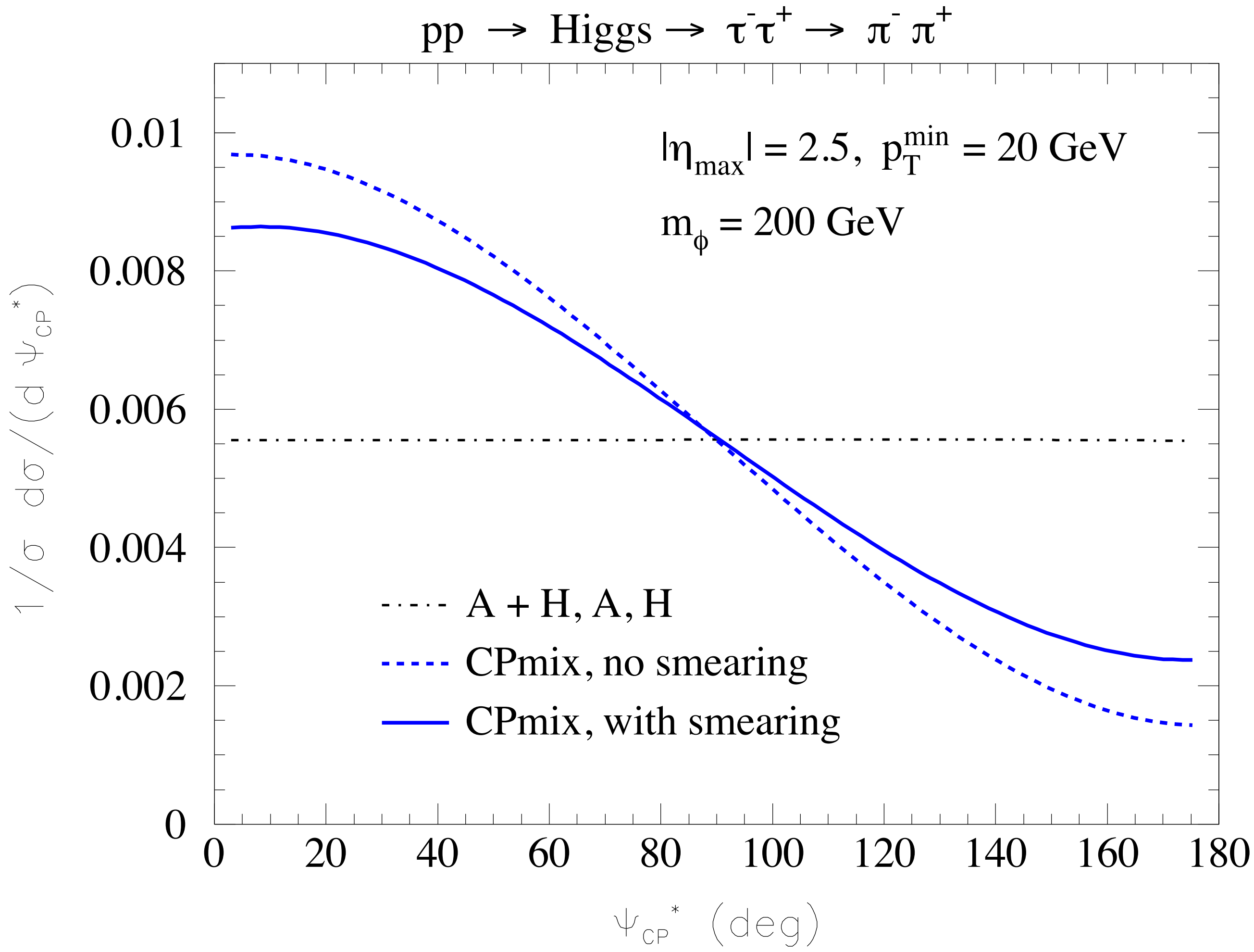
- **CP Violation:**
  - $*$ So far only upper limit on CP-odd component
  - $*$ Test of possible CP-violation:
    - Signal superposition of CP-even and CP-odd state, both close to 126 GeV?
    - Signal from a CP-violating Higgs state?
    - Need observables for identification of CP-violation
- **Fit to signal strengths** Freitas, Schwaller

  $\Phi' = \cos\alpha\, H + \sin\alpha\, A \rightsquigarrow$ constrain $\alpha \lesssim 1.1$ w/ 8 TeV data
- **Fermionic decays $H^J \to f\bar{f} \to a\bar{a}...$**

  polarization of the τ leptons ($\to$ decay distributions) Berge, Bernreuther; Berge, Bernreuther, Ziethe; Berge, Bernreuther, Niepelt, Spiesberger
- **Gauge boson decays: $H' \to Z^*Z$** Godbole, Miller, MMM; Buszello eal
- **Further processes:**
  - $\diamond$ CP violation in $gg \to H' + gg$ Hagiwara eal
  - $\diamond$ CP-violating observables in $pp \to Z/W + H \to ll'b\bar{b}$ Godbole eal; Christensen eal

$\mathcal{CP}$ $\mathcal{V}$iolation in $\mathcal{F}$ermionic $\mathcal{D}$ecays

Berge, Bernreuther



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

- **CP-violating $H'ZZ$ vertex:** Godbole,Miller,MMM

$$V^{\mu\nu}_{H'ZZ} = \frac{igM_Z}{\cos\theta_W}\left[a\, g^{\mu\nu} + b\,\frac{p^\mu p^\nu}{M^2_{H'}} + c\,\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho k_\sigma}{M^2_{H'}}\right]$$

$p = k_1 + k_2, k = k_1 - k_2,$ $\quad k_1, k_2$: 4-momenta of Z^*, Z

- **CP-violation:** simultaneously a, c non-zero, or b, c non-zero (SM: $a = 1, b = c = 0$)

- **Angular correlations and CP-properties**

Angular correlation	Observed quantity	CP
$\mathcal{O}_1 = s^2_{\theta_1} s^2_{\theta_2}$	$\gamma^4 \lvert\tilde{a}\rvert^2$	even
$\mathcal{O}_2 = (1 + c^2_{\theta_1})(1 + c^2_{\theta_2})/4 + \eta_1\eta_2 c_{\theta_1} c_{\theta_2}$	$2\,(\lvert a\rvert^2 + \beta^2\lvert c\rvert^2)$	even
$\mathcal{O}_3 = s^2_{\theta_1} s^2_{\theta_2} c_{2\phi}/2$	$\lvert a\rvert^2 - \beta^2\lvert c\rvert^2$	even
$\mathcal{O}_4 = s^2_{\theta_1} s^2_{\theta_2} s_{2\phi}/2$	$2\beta\,\mathrm{Re}(ac^*)$	odd
$\mathcal{O}_5 = \eta_1 s_{\theta_1} c_{\theta_2} s_{\theta_2} s_\phi + \eta_2 c_{\theta_1} s_{\theta_1} s_{\theta_2} s_\phi$	$-2\kappa\gamma^2\,\mathrm{Im}(ab^*)$	even

Table 1: $c_{\theta_1} \equiv \cos\theta_1$ *etc., and* $\tilde{a} \equiv a + \kappa\, b$ *where* $\kappa = M^2_{H'}\beta^2/[2(M^2_{H'} - M^2_Z - M^2_{Z^*})]$.

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

- **CP-violating $H'ZZ$ vertex:** Godbole,Miller,MMM

$$V^{\mu\nu}_{H'ZZ} = \frac{igM_Z}{\cos\theta_W}\left[a\, g^{\mu\nu} + b\,\frac{p^\mu p^\nu}{M^2_{H'}} + c\,\epsilon^{\mu\nu\rho\sigma}\frac{p_\rho k_\sigma}{M^2_{H'}}\right]$$

$p = k_1 + k_2, k = k_1 - k_2,\quad k_1, k_2$: 4-momenta of Z^*, Z

- **CP-violation:** simultaneously a, c non-zero, or b, c non-zero (SM: $a = 1, b = c = 0$)

- **Angular correlations and CP-properties**

$$O_4 = \frac{[(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot \vec{p}_{1H}][(\vec{p}_{3H} \times \vec{p}_{4H}) \cdot (\vec{p}_{1H} \times \vec{p}_{2H})]}{|\vec{p}_{3H} + \vec{p}_{4H}|^2|\vec{p}_{1H} + \vec{p}_{2H}||\vec{p}_{3Z} - \vec{p}_{4Z}|^2|\vec{p}_{1Z} - \vec{p}_{2Z}|^2/16}$$

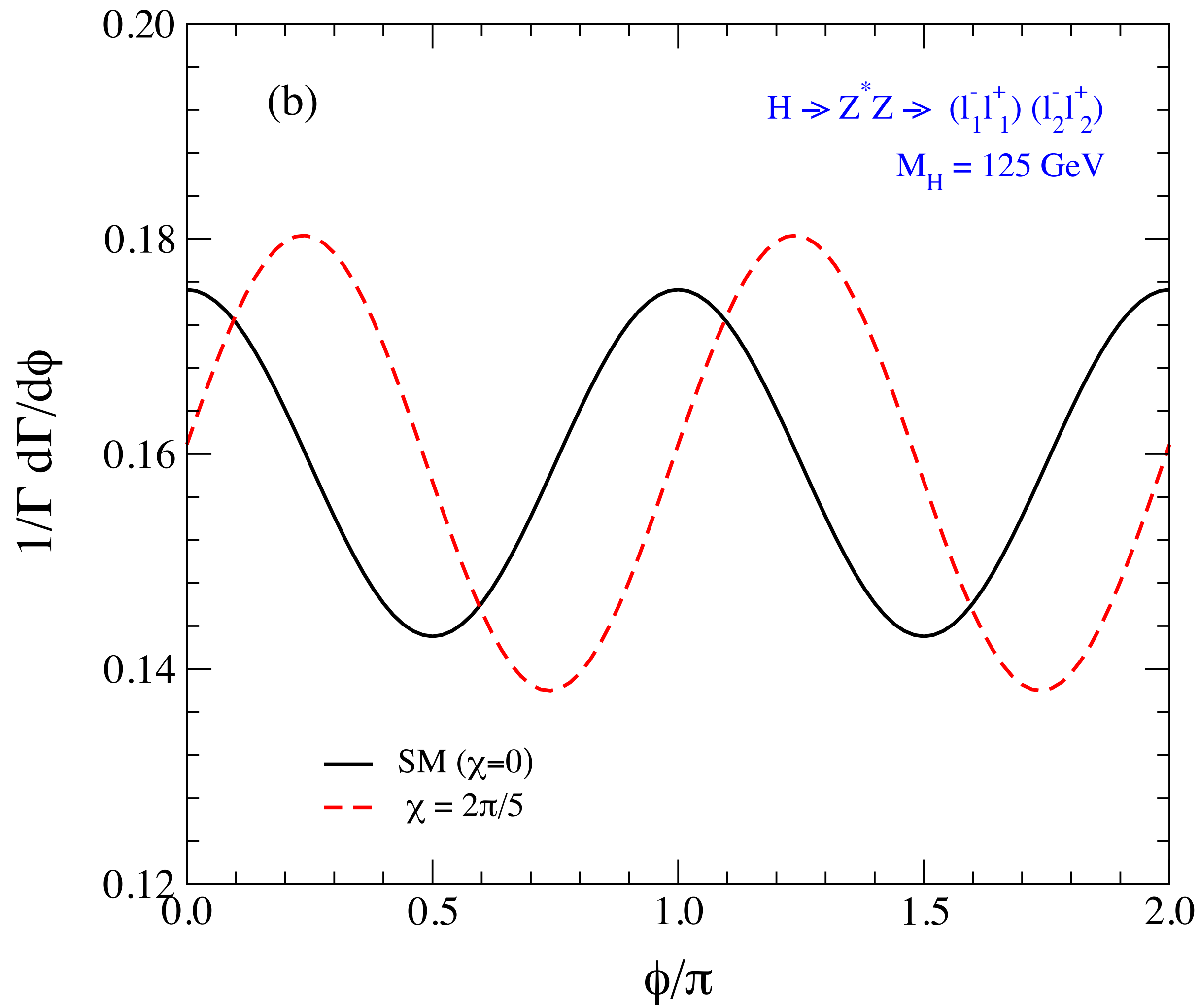
$$\mathcal{A}_4 = \frac{\Gamma(O_4 > 0) - \Gamma(O_4 < 0)}{\Gamma(O_4 > 0) + \Gamma(O_4 < 0)}$$

Achieved significance for Re(c)/a $= 2.7$ (max asymm):

$7+8$ TeV :	$S_{\mathcal{A}_4} = 0.45 - 0.5$	ATLAS-CMS
14 TeV :	$S_{\mathcal{A}_4} = 0.74$	at $\int \mathcal{L} = 100$ fb^{-1}
	$S_{\mathcal{A}_4} = 1.28$	at $\int \mathcal{L} = 300$ fb^{-1}

$\mathcal{CP}$ Violating $\mathcal{W}$ave $\mathcal{F}$unction in $H' \to Z^*Z \to 4l$

Choi,Miller,MMM,Zerwas



$H' = \cos\chi H + \sin\chi e^{i\xi} A$ [plot: $\xi = 0$] Ellis eal; Choi eal

$\mathcal{CP}$ $\mathcal{V}$iolation in $gg \to H' + gg$ with $H' \to \gamma\gamma$

- **CP-violating $H'gg$ vertex:**

$$V_{H'gg} = \cos\chi V_{Hgg} + \sin\chi e^{i\xi} V_{Agg}$$

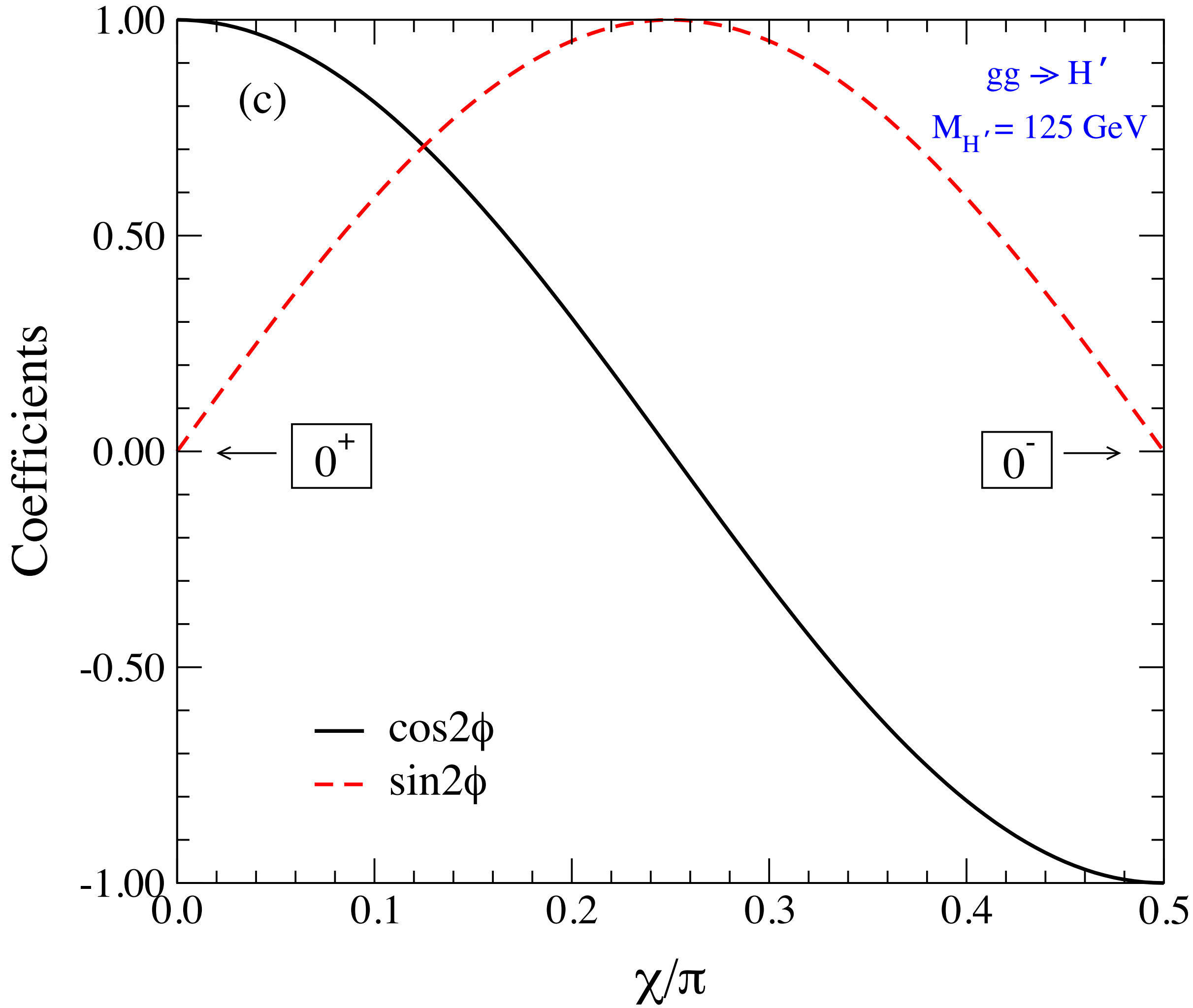
- **Azimuthal angular modulation of the two jets:**

$$\frac{1}{\sigma}\frac{d\sigma}{d\phi} = \frac{1}{2\pi}\left[1 + |\zeta|\left\{\left(c_\chi^2 - \rho_g^2 s_\chi^2\right)\cos 2\phi + \rho_g\, s_{2\chi} c_\xi\, \sin 2\phi\right\}/\mathcal{N}'\right]$$

$|\zeta|$: polarisation parameter, $\mathcal{N}' = c_\chi^2 + \rho_g^2 s_\chi^2$: normalisation, $\rho_g = Agg/Hgg$

$\mathcal{A}$zimuthal-$\mathcal{A}$ngle $\mathcal{D}$istribution

CP-even and CP-odd coefficients in the azimuthal-angle distribution of the two initial two-jet emission planes in $gg \to H' + gg$ ($\rho_g = 1$, $\xi = 0$, $|\zeta| = 1$) Choi,Miller,MMM,Zerwas



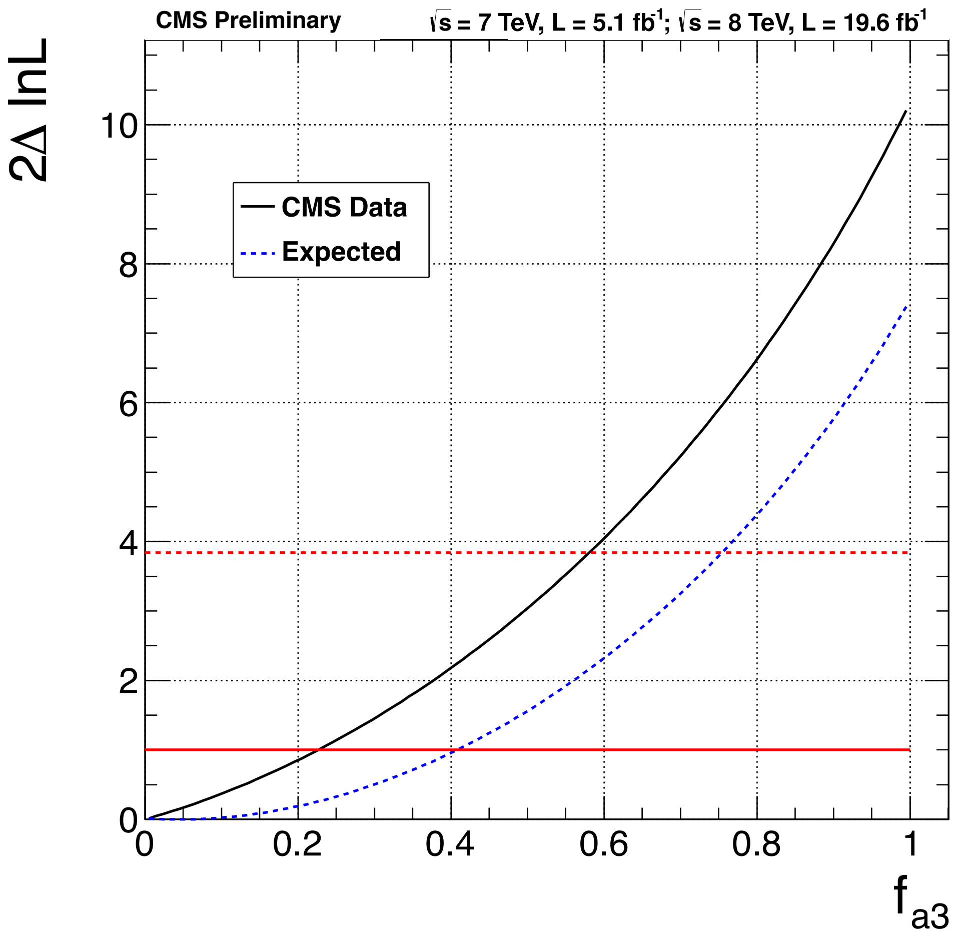
$\mathcal{R}$esults on $\mathcal{M}$ixed $\mathcal{P}$arity

Mixed parity in $H \to ZZ \to 4l$

$$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} (a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma)$$

CP-odd admixture: $f_{a_3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$

CMS



$f_{a_3} = 0.00^{+0.23}_{-0.00}$

$f_{a_3} < 0.58$ @ 95% CL

$\mathcal{C}$onclusions

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

Thank you for your attention!

$\mathcal{C}$omparison with $\mathcal{E}$ffective $\mathcal{L}$agrangian

- **Example:** effective Lagrangian with hVV derivative couplings

$$\Delta\mathcal{L}_{SILH} = \frac{i\bar{c}_W\, g}{2m_W^2}\left(H^\dagger\sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\, g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$+ \frac{i\bar{c}_{HW}\, g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\, g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$

$$+ \frac{i\tilde{c}_{HW}\, g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}^i_{\mu\nu} + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu}$$

- **Compare with:**

$$A(h\to ZZ) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}(a_1 m_h^2 g_{\mu\nu} + a_2 q_\mu q_\nu + a_3\epsilon_{\mu\nu\rho\sigma}q_1^\rho q_2^\sigma$$

$$\begin{aligned}
a_1 &= \frac{m_Z^2}{m_h^2} + (\bar{c}_W + \bar{c}_{WH}) + (\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W - \frac{2(q_1\cdot q_2)}{m_h^2}(\bar{c}_W + \bar{c}_B\tan^2\theta_W) \\
a_2 &= 2(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W) \\
a_3 &= 2(\tilde{c}_{HW} + \tilde{c}_{HB}\tan^2\theta_W)
\end{aligned}$$

J^P	$H^J Z^* Z$ Coupling	Helicity Amplitudes	Threshold
Even Normality $n_H = +$			
0^+	$a_1\, g^{\mu\nu} + a_2\, p^\mu p^\nu$	$\mathcal{T}_{00} = [2a_1(M_H^2 - M_*^2 - M_Z^2) + a_2 M_H^4 \beta^2]/(4M_* M_Z)$	1
		$\mathcal{T}_{11} = -a_1$	1
1^-	$b_1\,(g^{\mu\beta} p^\nu + g^{\nu\beta} p^\mu)$	$\mathcal{T}_{00} = \beta\, b_1 (M_Z^2 - M_*^2) M_H/(2\, M_* M_Z)$	β
		$\mathcal{T}_{01} = \beta\, b_1 M_H^2/(2M_*)$	β
		$\mathcal{T}_{10} = -\beta\, b_1 M_H^2/(2M_Z)$	β
		$\mathcal{T}_{11} = \beta\, b_1\, M_H$	β
2^+	$c_1\,(g^{\mu\beta_1} g^{\nu\beta_2} + g^{\mu\beta_2} g^{\nu\beta_1})$	$\mathcal{T}_{00} = \Big\{-c_1\,(M_H^4 - (M_Z^2 - M_*^2)^2)/M_H^2 + M_H^2\beta^2[c_2\,(M_H^2 - M_Z^2 - M_*^2)$ $+2c_3\, M_H^2 + \frac{1}{2} c_4\, M_H^4 \beta^2]\Big\}/(\sqrt{6} M_Z M_*)$	1
	$+c_2\, g^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{01} = -[c_1(M_H^2 - M_Z^2 + M_*^2) - c_3\, M_H^4 \beta^2]/(\sqrt{2} M_* M_H)$	1
	$+c_3\,[(g^{\mu\beta_1}\, p^\nu - g^{\nu\beta_1}\, p^\mu) k^{\beta_2}$	$\mathcal{T}_{10} = -[c_1(M_H^2 - M_*^2 + M_Z^2) - c_3\, M_H^4 \beta^2]/(\sqrt{2} M_Z M_H)$	1
	$+(\beta_1 \leftrightarrow \beta_2)]$	$\mathcal{T}_{11} = -\sqrt{2/3}\,(c_1 + c_2 M_H^2 \beta^2)$	1
	$+c_4\, p^\mu p^\nu k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{1,-1} = -2\, c_1$	1

Table 2: *The most general tensor couplings of the Bose symmetric $H^J Z^* Z$ vertex and the corresponding helicity amplitudes for Higgs bosons of spin ≤ 2 satisfying the relation $\mathcal{T}_{\lambda\lambda'}[M_*, M_Z] = (-1)^J\, \mathcal{T}_{\lambda'\lambda}[M_Z, M_*]$. Here $p = k_1 + k_2$ and $k = k_1 - k_2$, where k_1 and k_2 are the 4-momenta of the Z^* and the Z bosons, respectively.*

J^P	$H^J Z^* Z$ Coupling	Helicity Amplitudes	Threshold
Odd Normality $n_H = -$			
0^-	$a_1\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma$	$\mathcal{T}_{00}=0$	
		$\mathcal{T}_{11}=i\,\beta\, M_H^2\, a_1$	β
1^+	$b_1\, \epsilon^{\mu\nu\beta\rho} k_\rho$	$\mathcal{T}_{00}=0$	
		$\mathcal{T}_{01}=i\, b_1\, (M_H^2-M_Z^2-3M_*^2)/(2M_*)$	1
		$\mathcal{T}_{10}=-i\, b_1\, (M_H^2-M_*^2-3M_Z^2)/(2M_Z)$	1
		$\mathcal{T}_{11}=i\, b_1\, (M_Z^2-M_*^2)/M_H$	1
2^-	$c_1\, \epsilon^{\mu\nu\beta_1\rho} p_\rho k^{\beta_2}$	$\mathcal{T}_{00}=0$	
	$+c_2\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{01}=i\,\beta\, c_1\, (M_H^2+M_*^2-M_Z^2) M_H/(\sqrt{2} M_*)$	β
	$+(\beta_1 \leftrightarrow \beta_2)$	$\mathcal{T}_{10}=i\,\beta\, c_1\, (M_H^2+M_Z^2-M_*^2) M_H/(\sqrt{2} M_Z)$	β
		$\mathcal{T}_{11}=i\,\beta\, 2\sqrt{2/3}\,(c_1+c_2\, M_H^2 \beta^2) M_H^2$	β
		$\mathcal{T}_{1,-1}=0$	

Table 3: *The most general tensor couplings of the Bose symmetric $H^J Z^* Z$ vertex and the corresponding helicity amplitudes for Higgs bosons of spin ≤ 2 satisfying the relation $\mathcal{T}_{\lambda\lambda'}[M_*, M_Z] = (-1)^J\, \mathcal{T}_{\lambda'\lambda}[M_Z, M_*]$. Here $p = k_1 + k_2$ and $k = k_1 - k_2$, where k_1 and k_2 are the 4-momenta of the Z^* and the Z bosons, respectively.*

$\mathcal{G}$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

$0^\pm$: 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

...

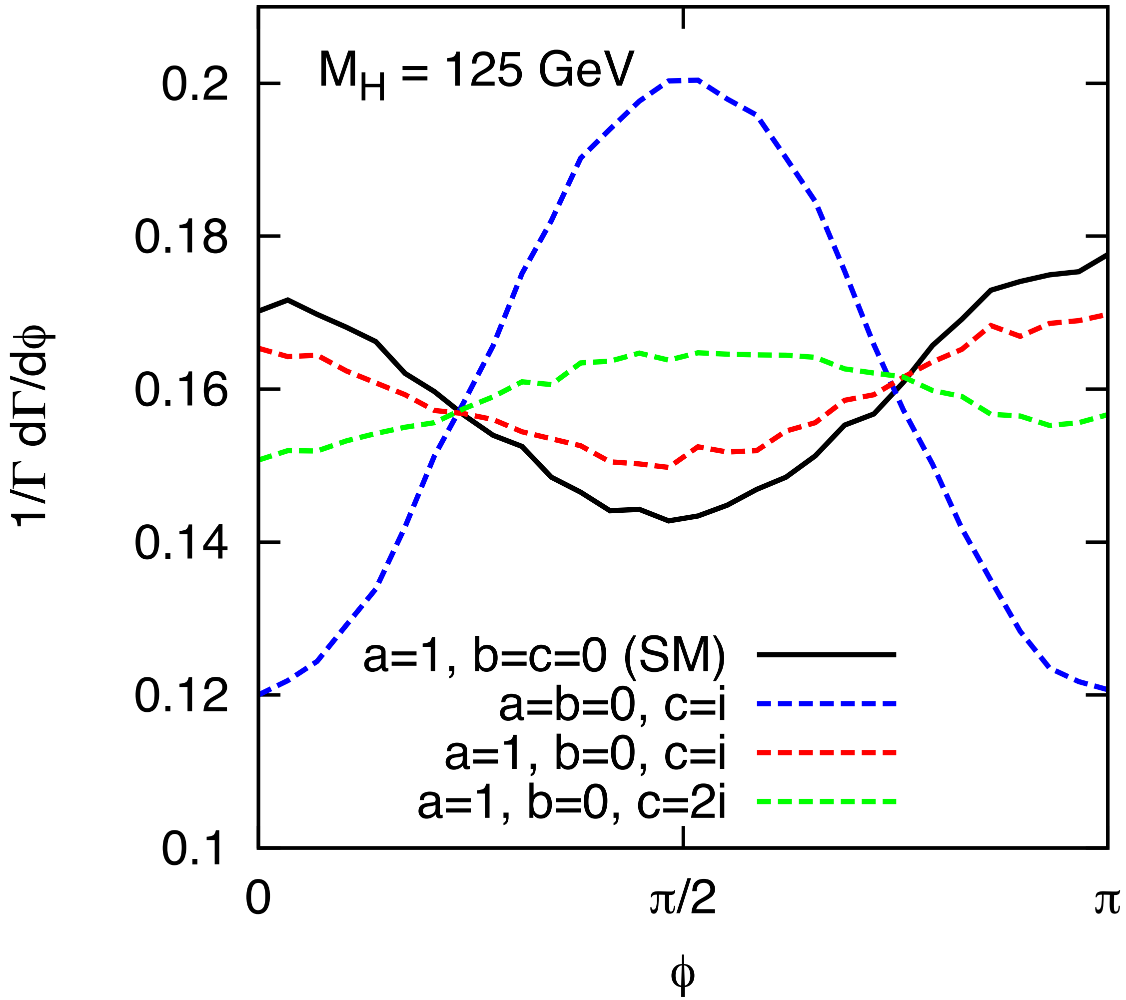
$1^\pm$: forbidden by Landau/Yang

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

3^- : forbidden

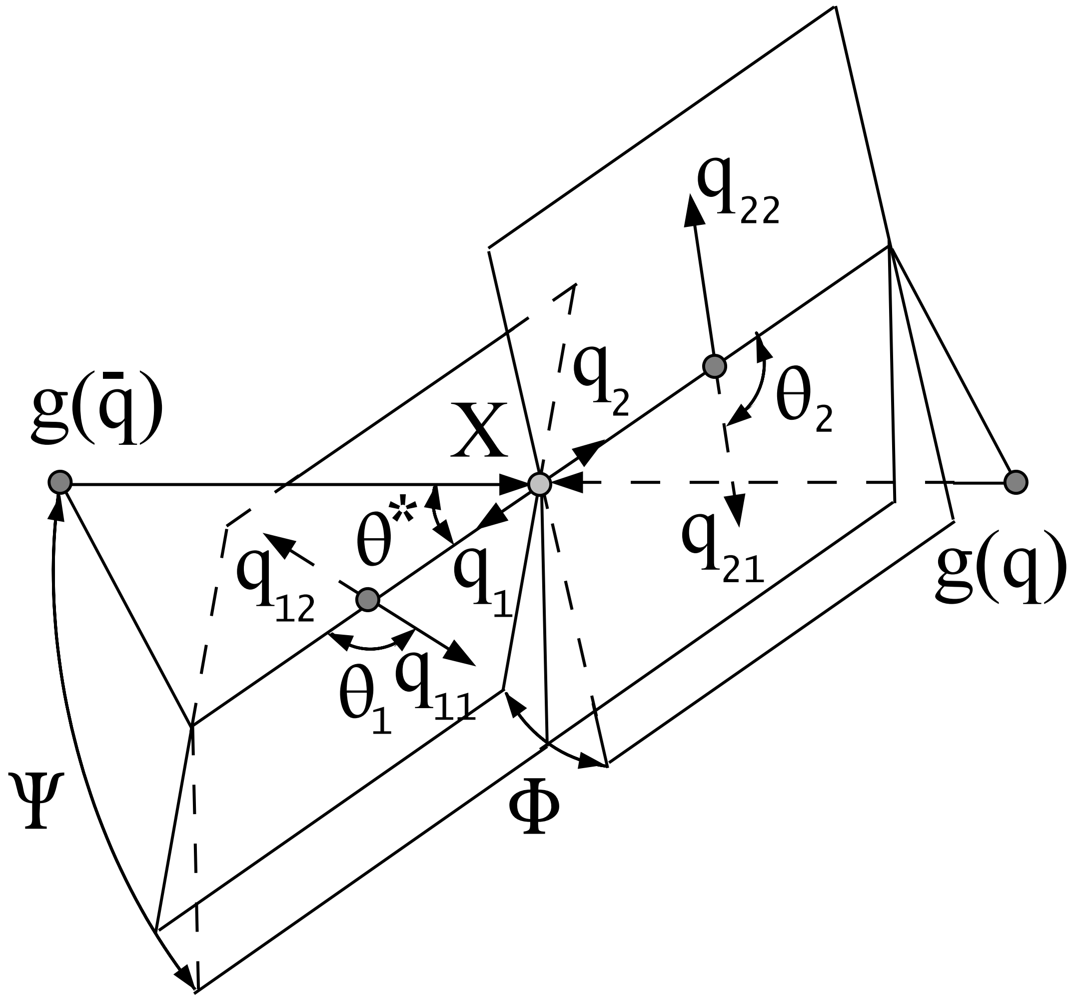
...

Godbole,Miller,MMM



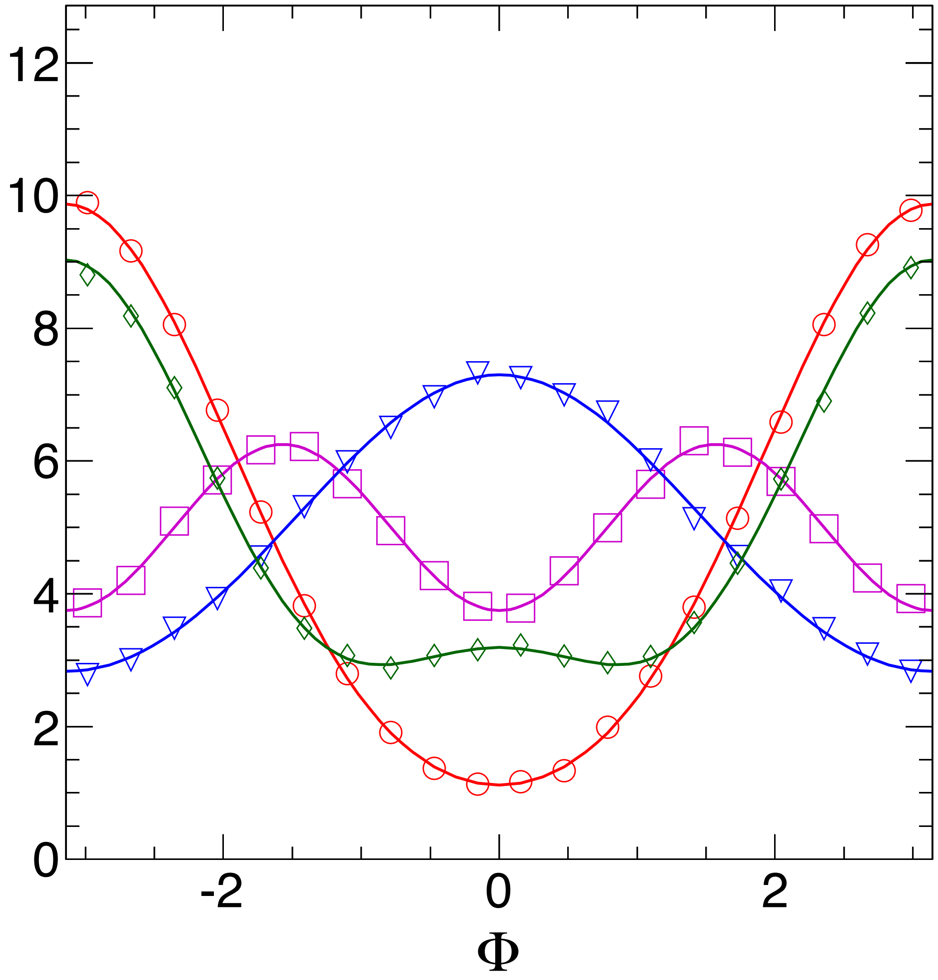
$\mathcal{M}$onte-$\mathcal{C}$arlo $\mathcal{S}$imulation

Bolognesi, Gao, Gritsan, Melnikov,
Schulze, Tran, Whitbeck



$\mathcal{M}$onte-$\mathcal{C}$arlo $\mathcal{S}$imulation

Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck



$X \to VV$: SM Higgs boson, 0^-, 2^+_m, 2^+_h