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Spin and Parity in the HZZ vertex

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- ♢ Introduction
- ♢ PART I : Production $Z^* \to HZ$
- ♢ PART II: Decay $H \to Z^{(*)}Z$
- ♢ Conclusions and summary

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Introduction

Higgs discovery at LHC or Tevatron $\longrightarrow$

Is it the Standard Model Higgs Boson?
Does it cause Electroweak Symmetry breaking?

Must measure:

(i) Quantum Numbers: Spin & CP $\xrightarrow{\text{Ad break}}$

- ♢ Threshold behaviour of Higgs cross-sections
- ♢ Angular correlations in Higgs decays
- ♢ Yang's Theorem: $H \not\rightleftharpoons \gamma\gamma \Rightarrow \mathcal{J}_H \neq 1$

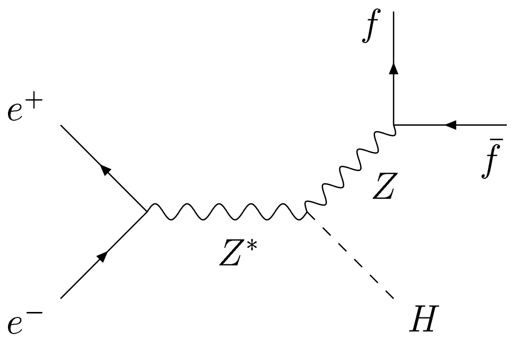
(ii) HVV and $Hf\bar{f}$ Couplings

- ♢ General form of HVV vertex
- ♢ $Ht\bar{t}$ vertex from $t \to Ht$ and top loops in $H \leftrightarrow \gamma\gamma$

(iii) Triple and Quartic Higgs self-couplings

- ♢ Reconstruct the Higgs potential itself

PART I: Higgs-strahlung



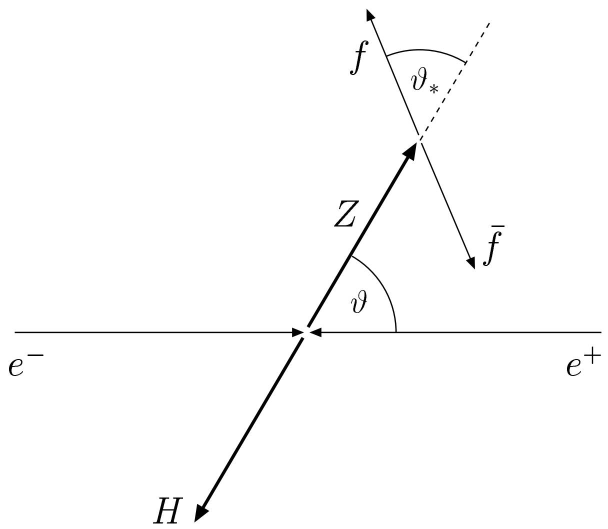
Standard Model

$$\sigma = \frac{G_F^2 M_Z^4}{96\pi s}\,(v_e^2 + a_e^2)\,\beta\,\frac{\beta^2 + 12 M_Z^2/s}{(1 - M_Z^2/s)^2}$$

$[\beta = 2|\vec{p_Z}|/\sqrt{s}]$

- Threshold $\sim \beta$
- Scaling behaviour $1/s$ asymptotically

Angular dependence:



$$\frac{d\sigma}{d\cos\theta\, d\cos\theta_*} \sim \sin^2\theta\sin^2\theta_* + \frac{1}{2\gamma^2}[1+\cos^2\theta][1+\cos^2\theta_*] + \frac{1}{2\gamma^2}\eta_e\eta_f\, 4\cos\theta\cos\theta_*$$

$$\left[\eta_i = \frac{2\, v_i a_i}{(v_i^2+a_i^2)},\ \gamma = E_Z/M_Z\right]$$

- ♢ Note presence of $\sin^2\theta\sin^2\theta_*$ term
  Absent for pseudoscalar

- ♢ No terms like $\sin^2\theta[1+\cos^2\theta_*]$.

A General Model

What would happen if the 'Higgs' had a general spin?

General rules of helicity $\Rightarrow$

$$\langle Z(\lambda_Z) H(\lambda_H) | Z^*(m) \rangle = \frac{g_W M_Z}{\cos\theta_W} d^1_{m,\,\lambda_Z-\lambda_H}(\theta)\, \Gamma_{\lambda_Z\lambda_H}$$

"d functions"
known and
universal

reduced vertex
independent of m

Assume (for this talk) that HHZ vertex is $\mathcal{CP}$-conserving

$$\Rightarrow \Gamma_{\lambda_Z\lambda_H} = n_H\, \Gamma_{-\lambda_Z\,-\lambda_H}$$

normality of H: $n_H \equiv (-1)^{\mathcal{J}}\mathcal{P}$

$$\Rightarrow \text{For odd normality: } \Gamma_{00} = 0$$

SM has:

$$\boxed{\begin{aligned} \Gamma_{00} &= -E_Z/M_Z \\ \Gamma_{10} &= -1 \\ \Gamma_{01} &= \Gamma_{11} = \Gamma_{12} = 0 \\ &\text{with } n_H = +1 \end{aligned}}$$

General (differential) cross-sections in terms of Reduced Vertices:

◊ Total cross-section

$$\boxed{\sigma = \frac{G_F^2 M_Z^6 \, (v_e^2 + a_e^2)}{24\pi s^2 \, (1 - M_Z^2/s)^2} \, \beta \, \Gamma^2}$$

with

$$\boxed{\Gamma^2 = |\Gamma_{00}|^2 + 2\,|\Gamma_{11}|^2 + 2\,|\Gamma_{01}|^2 + 2\,|\Gamma_{10}|^2 + 2\,|\Gamma_{12}|^2}$$

◊ Doubly differential distribution

$$\begin{aligned} \frac{1}{\sigma} \frac{d\sigma}{d\cos\theta \, d\cos\theta_*} = \frac{9}{16\,\Gamma^2} \Big\{ & \sin^2\theta \sin^2\theta_* \, |\Gamma_{00}|^2 \\ & + \frac{1}{2} [1 + \cos^2\theta][1 + \cos^2\theta_*] \left[|\Gamma_{10}|^2 + |\Gamma_{12}|^2 \right] \\ & + \sin^2\theta \, [1 + \cos^2\theta_*] |\Gamma_{11}|^2 + [1 + \cos^2\theta] \, \sin^2\theta_* |\Gamma_{01}|^2 \\ & + \eta_e \eta_f \, 2 \cos\theta \cos\theta_* \left[|\Gamma_{10}|^2 - |\Gamma_{12}|^2 \right] \Big\} \end{aligned}$$

But what are the Γ_{ij}'s?

Most general current:

$$\mathcal{J}_\mu = \frac{g_W M_Z}{\cos\theta_W} T_{\mu\alpha\beta_1\ldots\beta_\mathcal{J}}\, \varepsilon^*(Z)^\alpha\, \varepsilon^*(H)^{\beta_1\ldots\beta_\mathcal{J}}$$

Compare general tensor with helicity formalism

$\longrightarrow$ expressions for Γ_{ij}

Generally find:

◇ Either Γ_{ij} zero

OR

◇ for all $\mathcal{J}^\mathcal{P}$ except 0^+, Γ_{ij} contains a power of β at least as high as:

$$\boxed{\begin{array}{l} \Gamma_{ij} \sim \beta^{|\mathcal{J}-2|} \text{ for } n_H = + \\ \Gamma_{ij} \sim \beta^{|\mathcal{J}-1|} \text{ for } n_H = - \end{array}}$$

Ruling out all $\mathcal{J}^{\mathcal{P}}$ except 0^+

linear β dependence at threshold:

- ♢ Rules out $\mathcal{J}^{\mathcal{P}} = 0^-, 1^-, 2^-, 3^\pm, 4^\pm \ldots$
- ♢ Does not rule out 1^+ or 2^+

Look at 1^+ and 2^+ separately

1^+ : Easy to rule out

- ♢ Yang's Theorem: $H \leftrightharpoons \gamma\gamma \Rightarrow \mathcal{J} \neq 1$
- ♢ odd normality $\Rightarrow$ no $\sin^2\theta \sin^2\theta_*$ correlations
- ♢ linear rise originates from only one term in $T^{\mu\alpha\beta}$
  term non-zero $\Rightarrow \Gamma_{01}$ and Γ_{11} non-zero

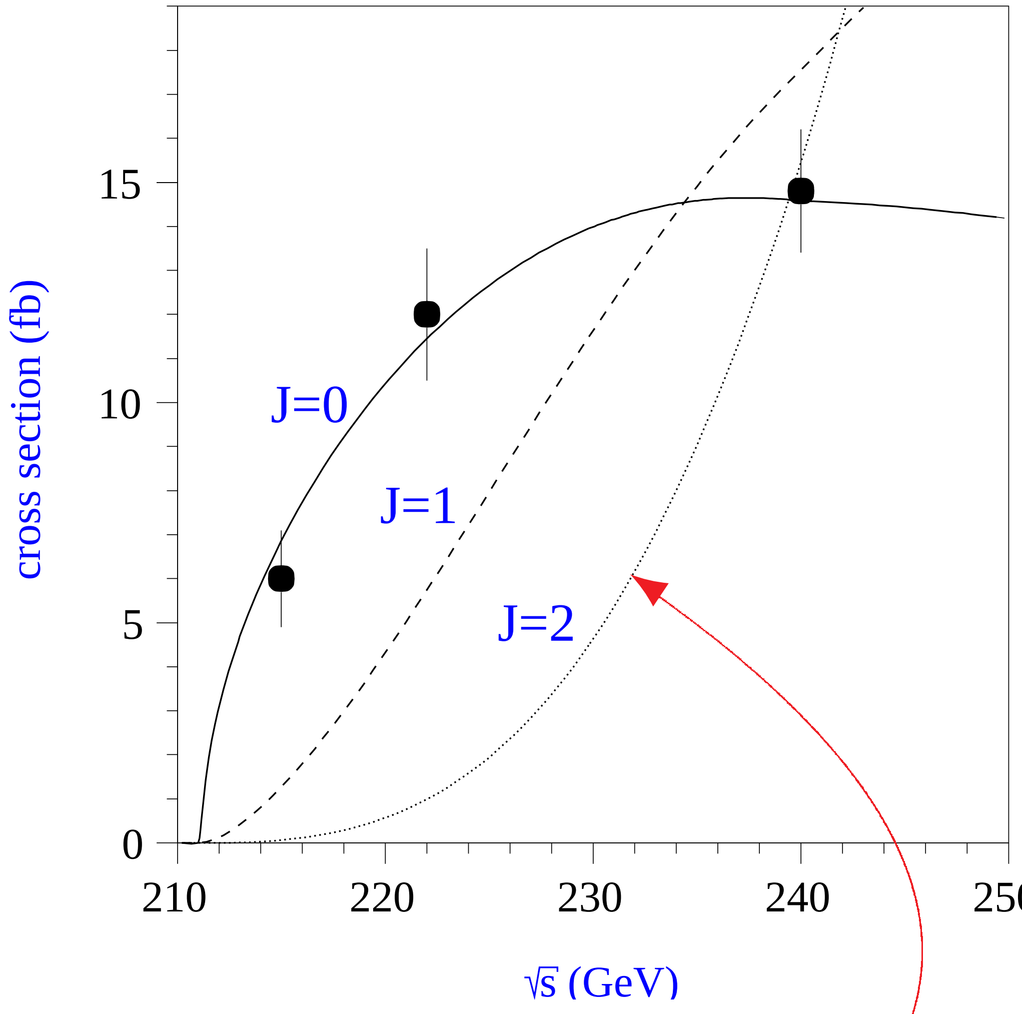
> have non-zero $[1+\cos^2\theta]\sin^2\theta_*$ and
> $\sin^2\theta[1+\cos^2\theta_*]$ angular correlations

2^+ :

- ♢ As for 1^+, linear rise originates from only one term
  term non-zero $\Rightarrow \Gamma_{01}$ and Γ_{11} non-zero

In practice: Dova et al., LC-Note LC-PHSM-2001-055

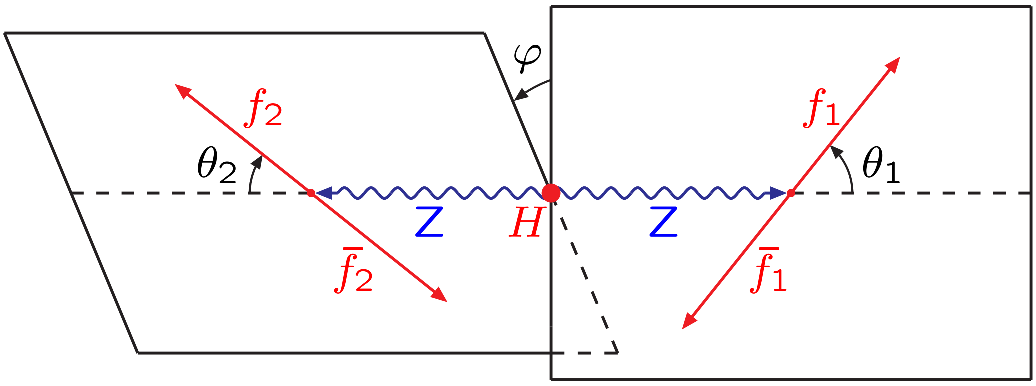
$Z \to l^+l^-$, $M_H = 120$ GeV, $\int \mathcal{L} dt = 20 \text{fb}^{-1}$



Possible $\mathcal{J} = 2$ model with
no $[1 + \cos^2\theta]\sin^2\theta_*$ nor $\sin^2\theta[1 + \cos^2\theta_*]$ correlations

$\boxed{\chi^2 \text{ for spin-1 and spin-2} < 10^{-5}}$

PART II: The Decay $H \to Z^{(*)}Z$



Particularly suited to

$$\begin{array}{ll} gg \to H \to ZZ & \text{LHC} \\ \gamma\gamma \to H \to ZZ & \text{TESLA} \end{array}$$

♢ Again use helicity methods:

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

♢ General tensor for HZ^*Z vertex for each $\mathcal{J}^{\mathcal{P}}$

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

$\Rightarrow$ Expressions for $\mathcal{T}_{ij}$ reduced vertices

◇ Write (differential) cross-sections in terms of $\mathcal{T}_{ij}$

Double polar angle distribution:

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

Azimuthal angle distribution:

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

$M_H < 2M_Z$:

◇ Principle similar to PART I:

Dependence of σ on virtuality of Z^* $\longrightarrow$ Spin of H

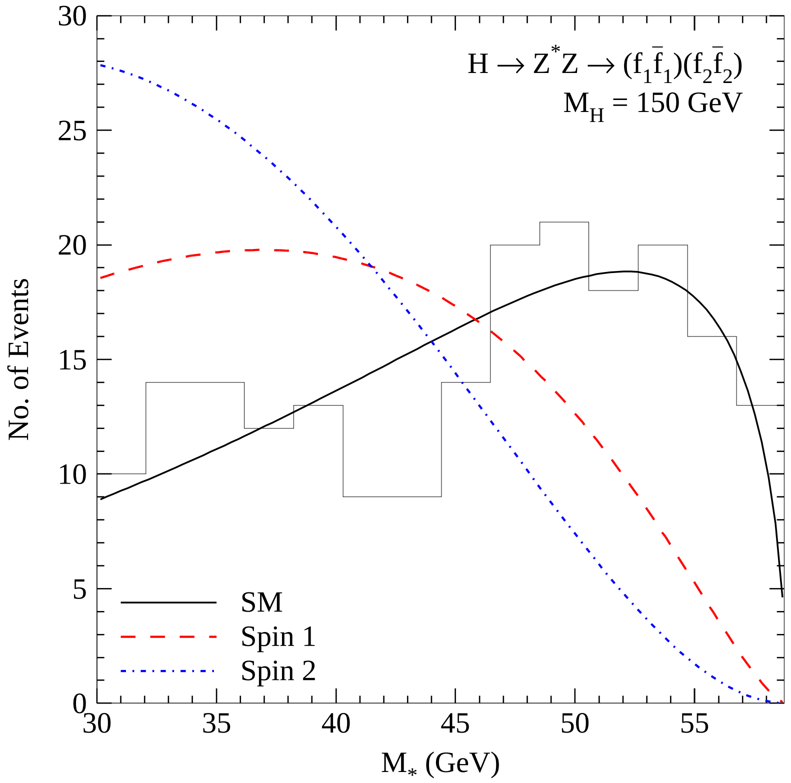
◇ Virtuality (M_*) is not fixed
$\Rightarrow$ don't need to scan in $\sqrt{s}$

◇ M_* dependence rules out 0^-, 1^-, 2^-, $3^\pm$, $4^\pm$ ...

◇ M_* dependence and no $[1+\cos^2\theta_1]\sin^2\theta_2$ nor $\sin^2\theta_1[1+\cos^2\theta_2]$ correlations rules out 1^+ and 2^+

◇ 1^+ also ruled out by $H \rightleftharpoons \gamma\gamma$

At the LHC: 203 events in for $300 fb^{-1}$ [Hohlfeld]



Spin-0: Within $0.04\,\sigma$
Spin-1: Disagrees to $7\,\sigma$
Spin-2: Disagrees to $> 20\,\sigma$

$M_H > 2M_Z$:

- ◇ Produce real Z's $\Rightarrow$ use only angular correlations
- ◇ Bose symmetry $\Rightarrow \mathcal{T}_{\lambda_1\lambda_2} = (-1)^{\mathcal{J}}\mathcal{T}_{\lambda_2\lambda_1}$

$\mathcal{J}^{\mathcal{P}} = 0^-, 1^\pm, 2^-, 3^\pm, 4^- \ldots$:

$\mathcal{T}_{00} = 0 \Rightarrow$ no $\sin^2\theta_1 \sin^2\theta_2$ correlations

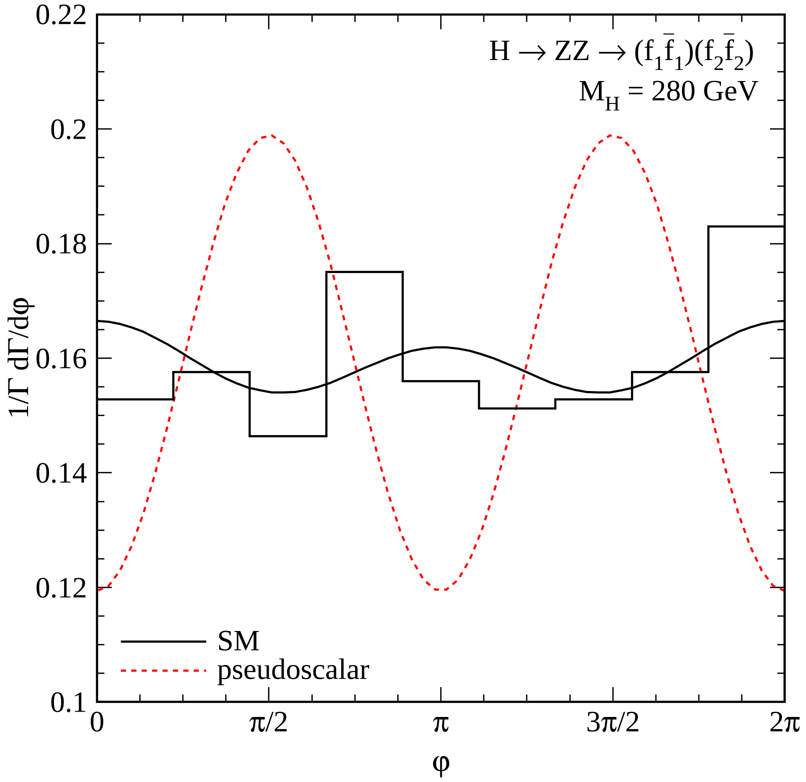
Also, azimuthal distributions different:

$$\frac{d\sigma}{d\varphi} \sim A + \eta_1\eta_2 B\cos\varphi + \frac{1}{4} n_H |T_{11}|^2 \cos 2\varphi$$

Absent for 0^-

[Barger, Cheung, Djouadi, Kniehl, Zerwas]

At LHC: $M_H = 280$ GeV $\rightsquigarrow$ 900 events for $\int \mathcal{L}\, dt = 300$ fb^{-1}



$\mathcal{J}^{\mathcal{P}} = 2^+, 4^+ \ldots$

same (unpolarised) H decay angular correlations as 0^+

◇ turn to $gg \to H \to ZZ$ (ie. corr. with initial state)

◇ general form of tensor $\Rightarrow$

$$\boxed{\frac{d\sigma}{d\cos\Theta} \sim |a_1|^2 \left[P^0_{\mathcal{J}}(\cos\Theta)\right]^2 + 12|a_2|^2 \left[P^2_{\mathcal{J}}(\cos\Theta)\right]^2}$$

form factors from general tensor

Ass. Legendre functions

Θ is polar angle of Z w.r.t. g (in gg c.m.f)

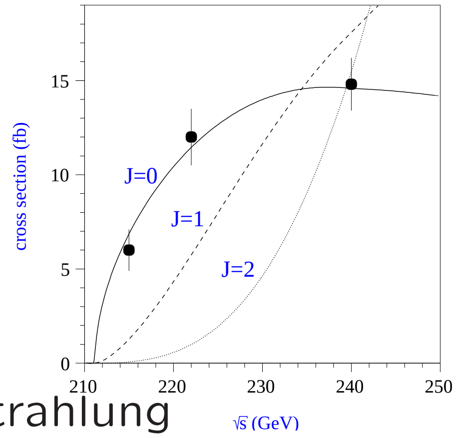
$\boxed{\text{An-isotropic only for } 2^+, 4^+ \ldots}$

Summary & Conclusions

Want to unambiguously determine $\mathcal{J}^{\mathcal{P}}$ of 'Higgs boson'

Production: Higgs-strahlung $Z^* \to ZH$

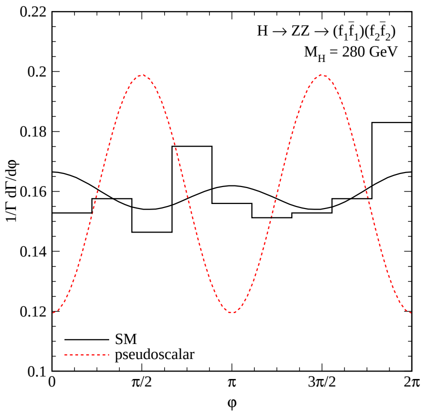
- only 0^+, 1^+, 2^+ has linear β dependence at threshold
- 1^+, 2^+ may be ruled out using angular correlations
- 1^+ also ruled out by $H \rightleftharpoons \gamma\gamma$
- requires scan in $\sqrt{s}$

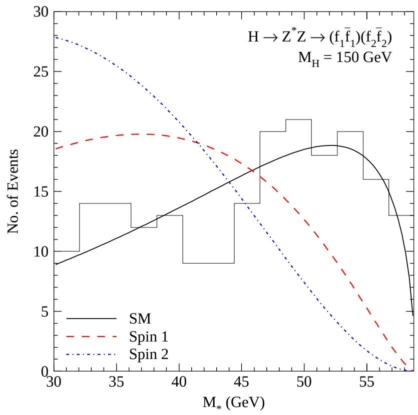


Decay: $H \to Z^{(*)}Z$

For $M_H < 2M_Z$:

- use same method as for Higgs-strahlung
- do not need to scan over $\sqrt{s}$
- consider variation of cross-sections with Z^* virtuality





For $M_H > 2M_Z$:

- real Z's $\Rightarrow$ cannot use dependence on virtuality (or β)
- angular correlations in H decay rule out:

$$\mathcal{J}^{\mathcal{P}} = 0^-, 1^\pm, 2^-, 3^\pm, 4^- \ldots$$

- need correlations with initial state to rule out:

$$\mathcal{J}^{\mathcal{P}} = 2^+, 4^+ \ldots$$