SM Higgs boson or not?

Reasonably precise mass : ~125 GeV

$$J^{PC} = 0^{++}\,?$$

Model independent
Clean and transparent
Complementary

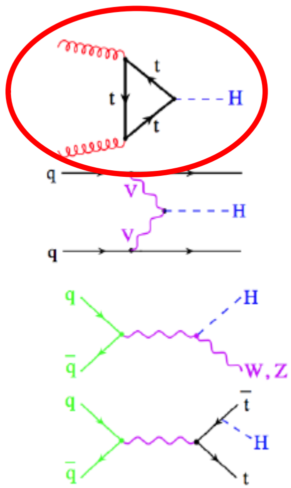
[Assumption]
A single(?) resonance
SM-like production and decay

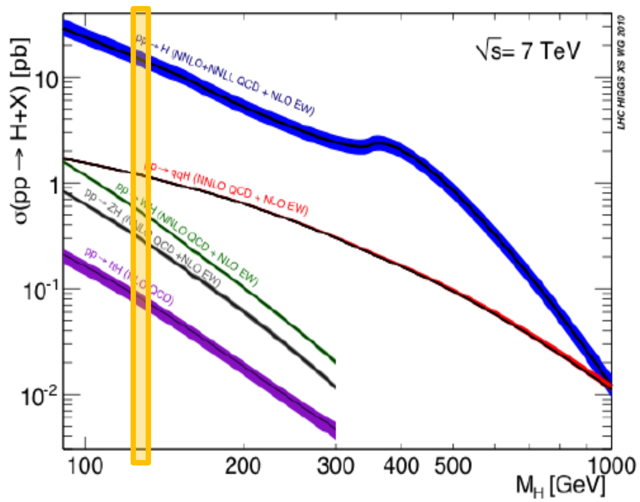
$[gg \rightarrow H]$

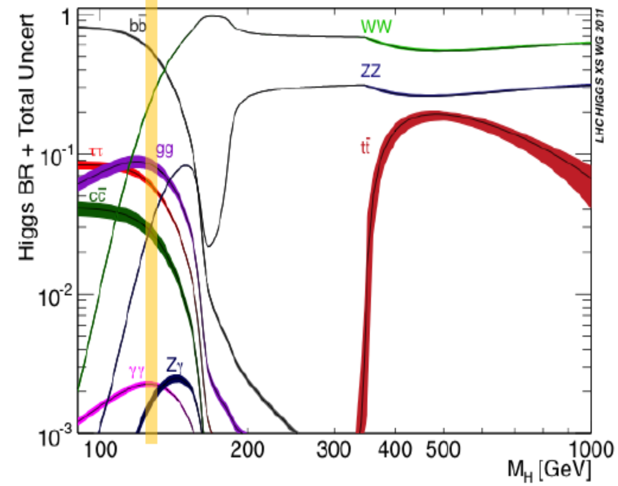
SM Higgs

Production

Decay

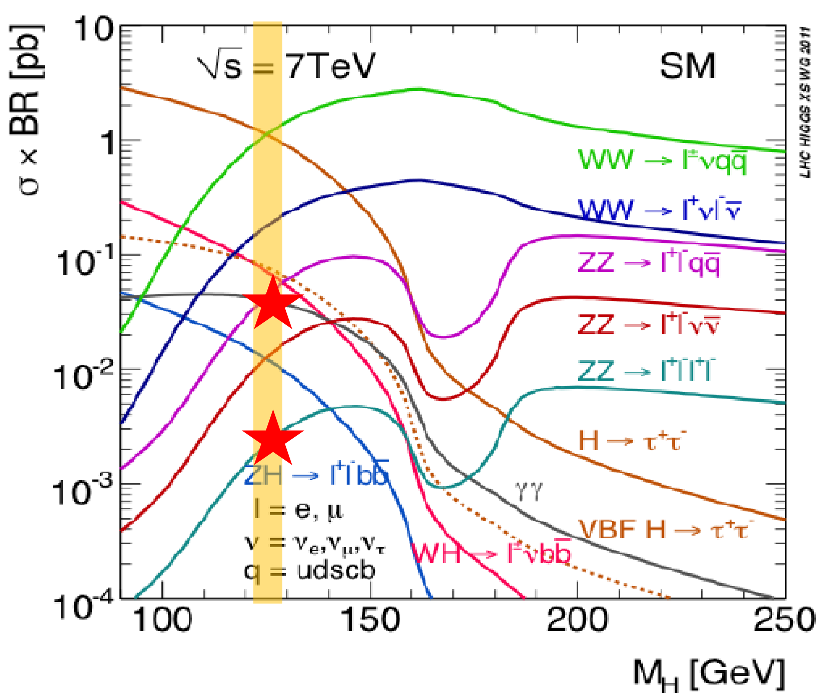






$W \rightarrow l\nu$ (11% each)
$W \rightarrow qq$ (68%)
$W \rightarrow invisible$ (1.4%)

$Z \rightarrow ll$ (3.4% each)
$Z \rightarrow invisible$ (20%)
$Z \rightarrow qq$ (70%)



Clean signature

$[H \rightarrow Z^*Z \rightarrow 4\ell]$

$\oplus$

$[H \rightarrow \gamma\gamma]$

Most powerful channels for spin and parity determination

Clean & precise
Fully reconstructed

Only D

$$H \to Z^* Z \to (\ell_1^- \ell_1^+)(\ell_2^- \ell_2^+)$$

$\ell = e, \mu$

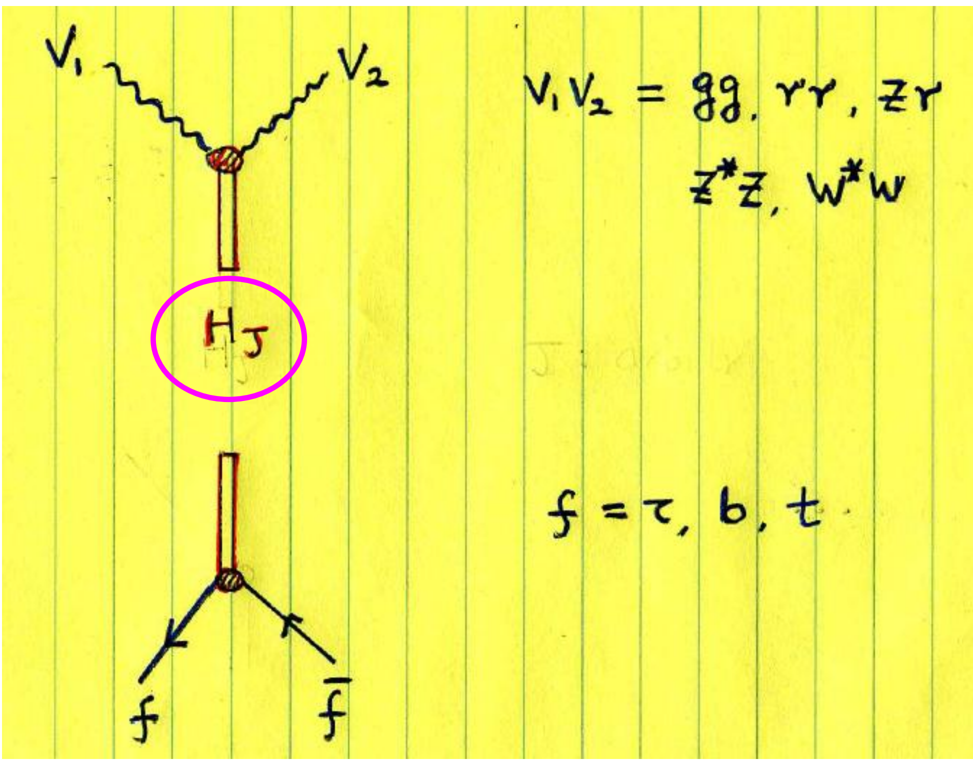
P+D

$$gg \to H \to \gamma\gamma$$

Unambiguous confirmation of SM H

General analysis

General vertex structure



Any integer spin J
Even(+) vs. odd(-) parity

Angular correlations
Invariant mass distribution
Polarization

General description for arbitrary H spin J

[Helicity Formalism]

Traceless and symmetric

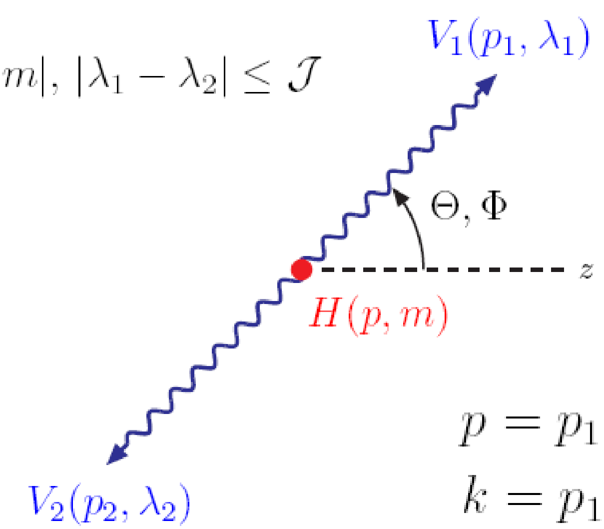
$$\langle V_1(\lambda_1) V_2(\lambda_2) | H(m) \rangle = \epsilon^*_\mu(p_1,\lambda_1)\, \epsilon^*_\nu(p_2,\lambda_2)\, \mathcal{T}^{\mu\nu\beta_1\cdots\beta_J}\, \epsilon_{\beta_1\cdots\beta_J}(p,m)$$

$$= \mathcal{T}_{\lambda_1\lambda_2}\, d^J_{m,\lambda_1-\lambda_2}(\Theta)\, \mathrm{e}^{i(m-\lambda_1+\lambda_2)\,\Phi}$$

Independent of H helicity m
(Wigner-Eckart theorem)

At most "9" independent terms

$|m|,\ |\lambda_1-\lambda_2| \le \mathcal{J}$



$p = p_1 + p_2$

$k = p_1 - p_2$

$n_H = (-1)^{\mathcal{J}}\, \mathcal{P}$: normality

$\mathcal{CP} \Rightarrow \mathcal{T}_{\lambda_1\lambda_2} = n_H\, \mathcal{T}_{-\lambda_1,-\lambda_2}$

$\mathcal{BS} \Rightarrow \mathcal{T}_{\lambda_1\lambda_2} = (-1)^{\mathcal{J}}\, \mathcal{T}_{\lambda_2\lambda_1}$ $\quad gg,\ \gamma\gamma$

$\mathcal{CP} : n_H = -1 \Rightarrow \mathcal{T}_{00} = 0$

$\mathcal{BS} : J = \mathrm{odd} \Rightarrow \mathcal{T}_{\lambda\lambda} = 0$

General HZ*Z couplings

Massive Z*, Z

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^+	$c_1\,(g^{\mu\beta_1} g^{\nu\beta_2} + g^{\mu\beta_2} g^{\nu\beta_1})$ $+c_2\, g^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$ $+c_3\,[(g^{\mu\beta_1}\, p^\nu - g^{\nu\beta_1}\, p^\mu) k^{\beta_2}$ $+(\beta_1 \leftrightarrow \beta_2)]$ $+c_4\, p^\mu p^\nu k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{00} = \Big\{-c_1\,(M_H^4 - (M_Z^2 - M_*^2)^2)/M_H^2 + M_H^2 \beta^2 [c_2\,(M_H^2 - M_Z^2 - M_*^2)$ $+2c_3\, M_H^2 + \frac{1}{2} c_4\, M_H^4 \beta^2]\Big\}/(\sqrt{6} M_Z M_*)$	1
		$\mathcal{T}_{01} = -[c_1 (M_H^2 - M_Z^2 + M_*^2) - c_3\, M_H^4 \beta^2]/(\sqrt{2} M_* M_H)$	1
		$\mathcal{T}_{10} = -[c_1 (M_H^2 - M_*^2 + M_Z^2) - c_3\, M_H^4 \beta^2]/(\sqrt{2} M_Z M_H)$	1
		$\mathcal{T}_{11} = -\sqrt{2/3}\,(c_1 + c_2 M_H^2 \beta^2)$	1
		$\mathcal{T}_{1,-1} = -2\, c_1$	1
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^-	$c_1\, \epsilon^{\mu\nu\beta_1\rho} p_\rho k^{\beta_2}$ $+c_2\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2}$ $+(\beta_1 \leftrightarrow \beta_2)$	$\mathcal{T}_{00} = 0$	
		$\mathcal{T}_{01} = i\, \beta\, c_1\,(M_H^2 + M_*^2 - M_Z^2) M_H/(\sqrt{2} M_*)$	β
		$\mathcal{T}_{10} = i\, \beta\, c_1\,(M_H^2 + M_Z^2 - M_*^2) M_H/(\sqrt{2} M_Z)$	β
		$\mathcal{T}_{11} = i\, \beta\, 2\sqrt{2/3}\,(c_1 + c_2\, M_H^2 \beta^2) M_H^2$	β
		$\mathcal{T}_{1,-1} = 0$	

General Hγγ and Hgg vertices

Bose symmetry & gauge invariance for massless photons and gluons

Landau, 1948; CN Yang, 1950

$J \neq 1$: $[\pm\pm]$ only $\Rightarrow$ $\mathcal{T}_{\pm\pm} = 0$

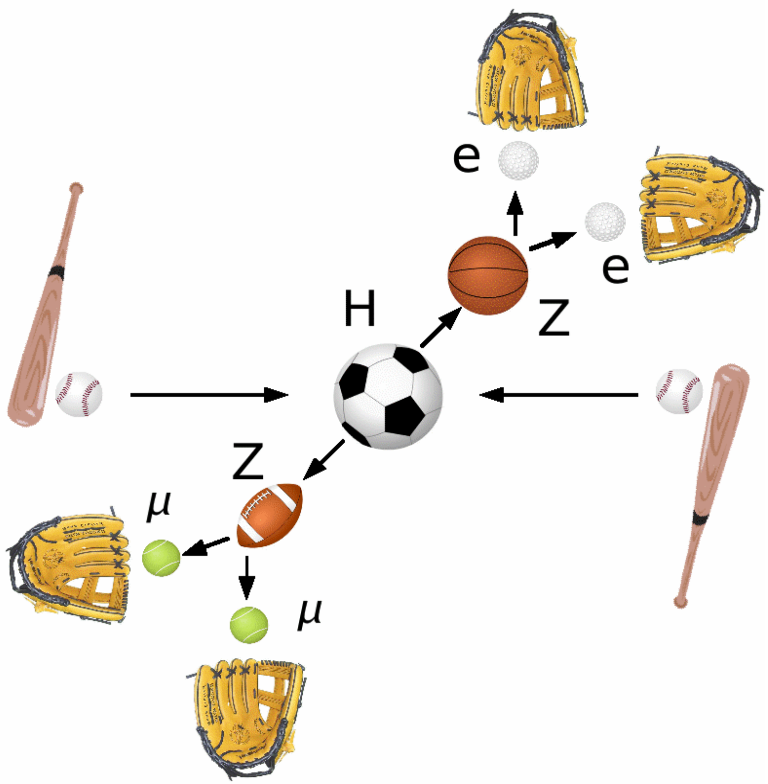
$\mathcal{J}^{\mathcal{P}}$	$H\gamma\gamma$ or Hgg Coupling	Helicity Amplitudes
	Even Normality $n_H = +$	
0^+	$a_1\, g_\perp^{\mu\nu}$	$\mathcal{T}_{11} = -a_1$
2^+	$c_1\, (g_\perp^{\mu\beta_1} g_\perp^{\nu\beta_2} + g_\perp^{\mu\beta_2} g_\perp^{\nu\beta_1})$ $+ c_2\, g_\perp^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{11} = -\sqrt{2/3}(c_1 + c_2 M_H^2)$ $\mathcal{T}_{1,-1} = -2c_1$
	Odd Normality $n_H = -$	
0^-	$a_1\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma$	$\mathcal{T}_{11} = i\, a_1\, M_H^2$
2^-	$c_1\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{11} = i\sqrt{2/3}\, c_1\, M_H^4$

H = KK Graviton
$\Rightarrow c_2 = -c_1/M_H^2$

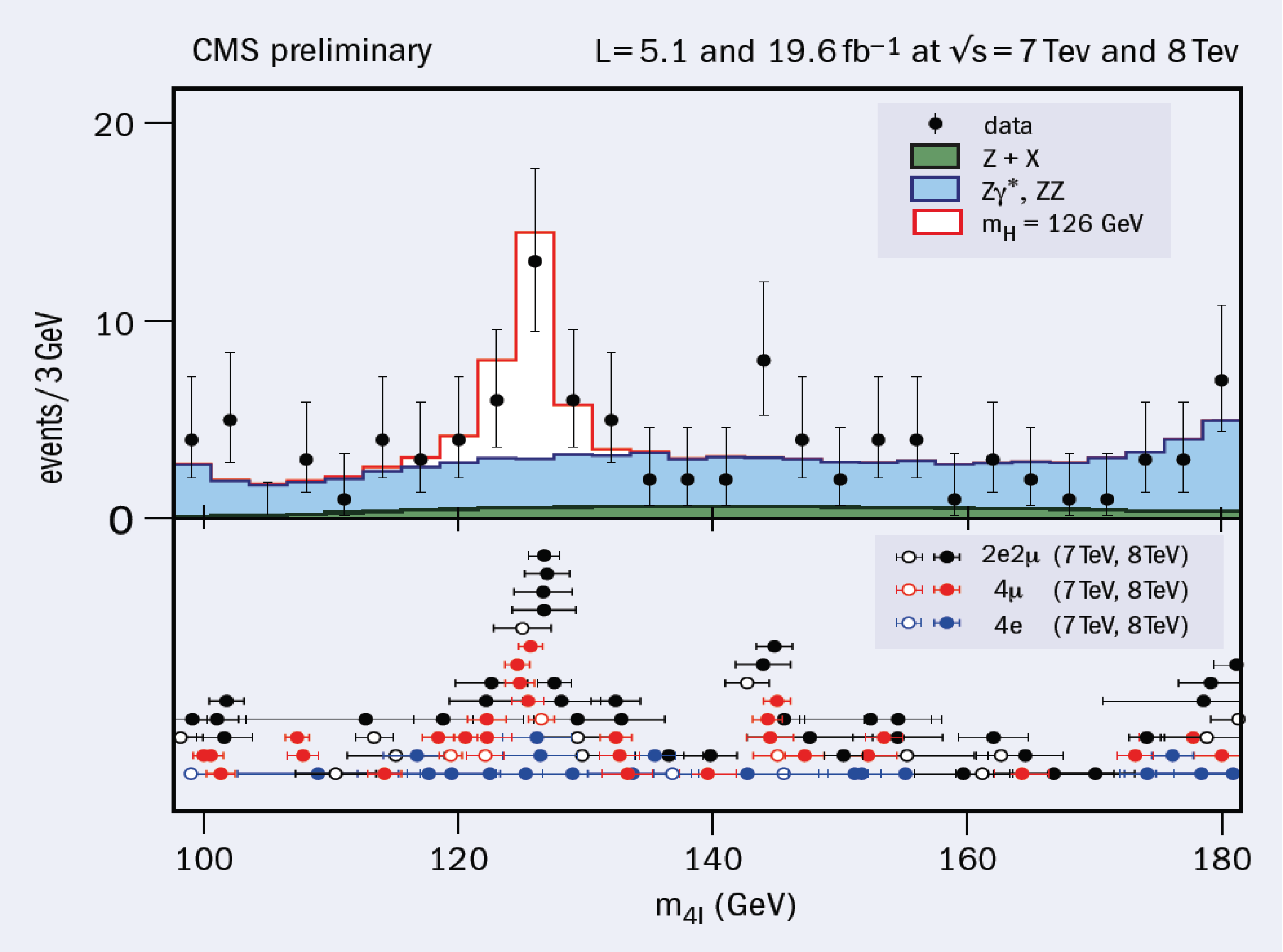
General Tensors for J ≥ 3

$$\mathcal{T}_{\mu\nu\beta_1,\cdots,\beta_J} = \mathcal{T}^{(2)}_{\mu\nu\beta_1\beta_2}\, k_{\beta_3} \cdots k_{\beta_J}$$

$$H \rightarrow Z^* Z \rightarrow (\ell_1^- \ell_1^+)(\ell_2^- \ell_2^+)$$



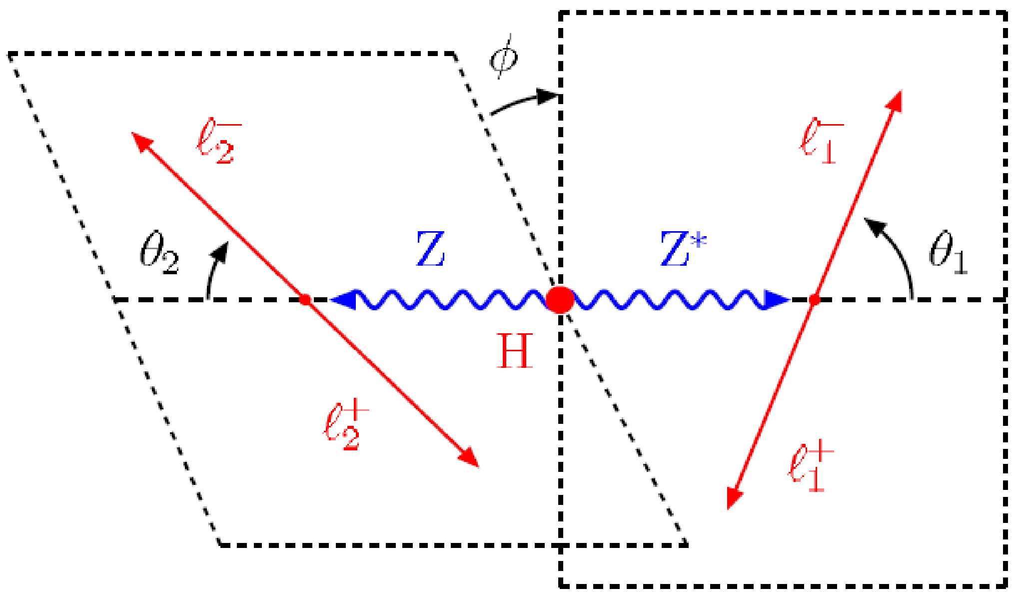
[CERN Courier, 2013-05]



[~100 events]

Fully reconstructible kinematic configuration

Only D



$\ell = e, \mu$

Kinematic variables

$$\cos\theta_1 \oplus \cos\theta_2 \oplus \phi \oplus M_*$$

Invariant mass and polar & azimuthal angle distributions

$$\frac{d\Gamma}{dM_*} \propto \frac{M_*^3}{(M_*^2 - M_Z^2)^2 + M_Z^2\Gamma_Z^2} \times [\,\beta\,] \times \sum |\mathcal{T}_{\lambda\lambda'}|^2$$

$\beta \sim \sqrt{(M_H - M_Z)^2 - M_*^2}$ near the end point $M_* \sim M_H - M_Z$ $\longrightarrow$

sharp decrease

Angular correlations

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

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

SM

$$\mathrm{SM}\ :\ \mathcal{T}_{00} = \frac{M_H^2 - M_Z^2 - M_*^2}{2M_Z M_*}, \quad \mathcal{T}_{11} = -1$$

$$d\Gamma/dM_* \sim \beta$$

$\exists\, s_1^2 s_2^2$ correlations

Odd n_H

$$\mathcal{CP}\ :\ \mathcal{T}_{00} = 0 \quad \Rightarrow \not\exists\, s_1^2 s_2^2 \ \text{correlations}$$

Even n_H

$\boxed{1^-}$: every $\mathcal{T}_{\lambda_1\lambda_2} \sim \beta \Rightarrow d\Gamma/dM_* \sim \beta^3$

$\boxed{2^+}$: $\mathcal{T}^{\mu\nu\beta_1\beta_2} \sim g^{\mu\beta_1}g^{\nu\beta_2} + g^{\mu\beta_2}g^{\nu\beta_1}$

Yes $\Rightarrow d\Gamma/dM_* \sim \beta$ with $(1+c_i^2)s_j^2$

No $\Rightarrow d\Gamma/dM_* \sim \beta^5$ w/o $(1+c_i^2)s_j^2$

$J \geq 3$

At least $(J-2)$ momentum factors $\Rightarrow d\Gamma/dM_* \sim \beta^{2J-3}$ with $2J-3 \geq 3$

Unambiguous selection rules for SM Higgs boson

$n_H = +$

$J \neq 2$

Invariant mass spectrum linear in β

Observation of $\sin^2\theta_1 \sin^2\theta_2$

Absence of $(1+\cos^2\theta_1)\sin^2\theta_2$ and $\sin^2\theta_1(1+\cos^2\theta_2)$

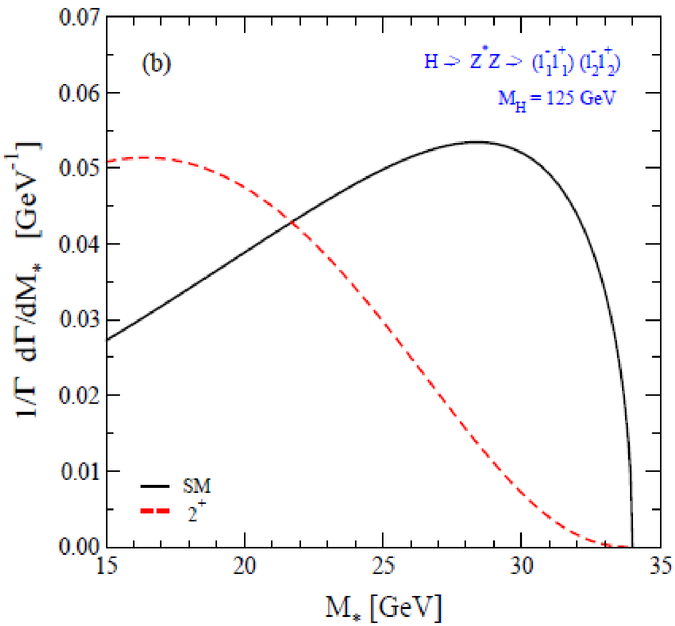
$[\,0^+,\,1^+,\,2^+\,]$

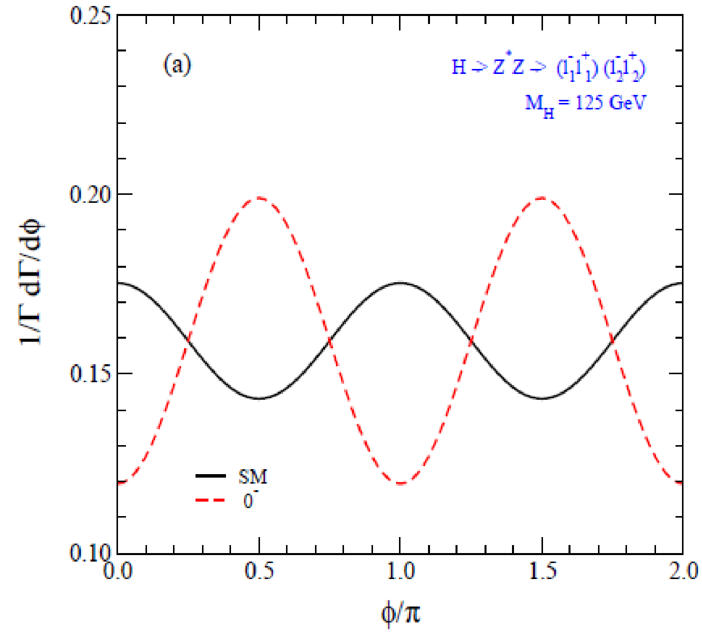
$\downarrow$

$[\,0^+,\,2^+\,]$

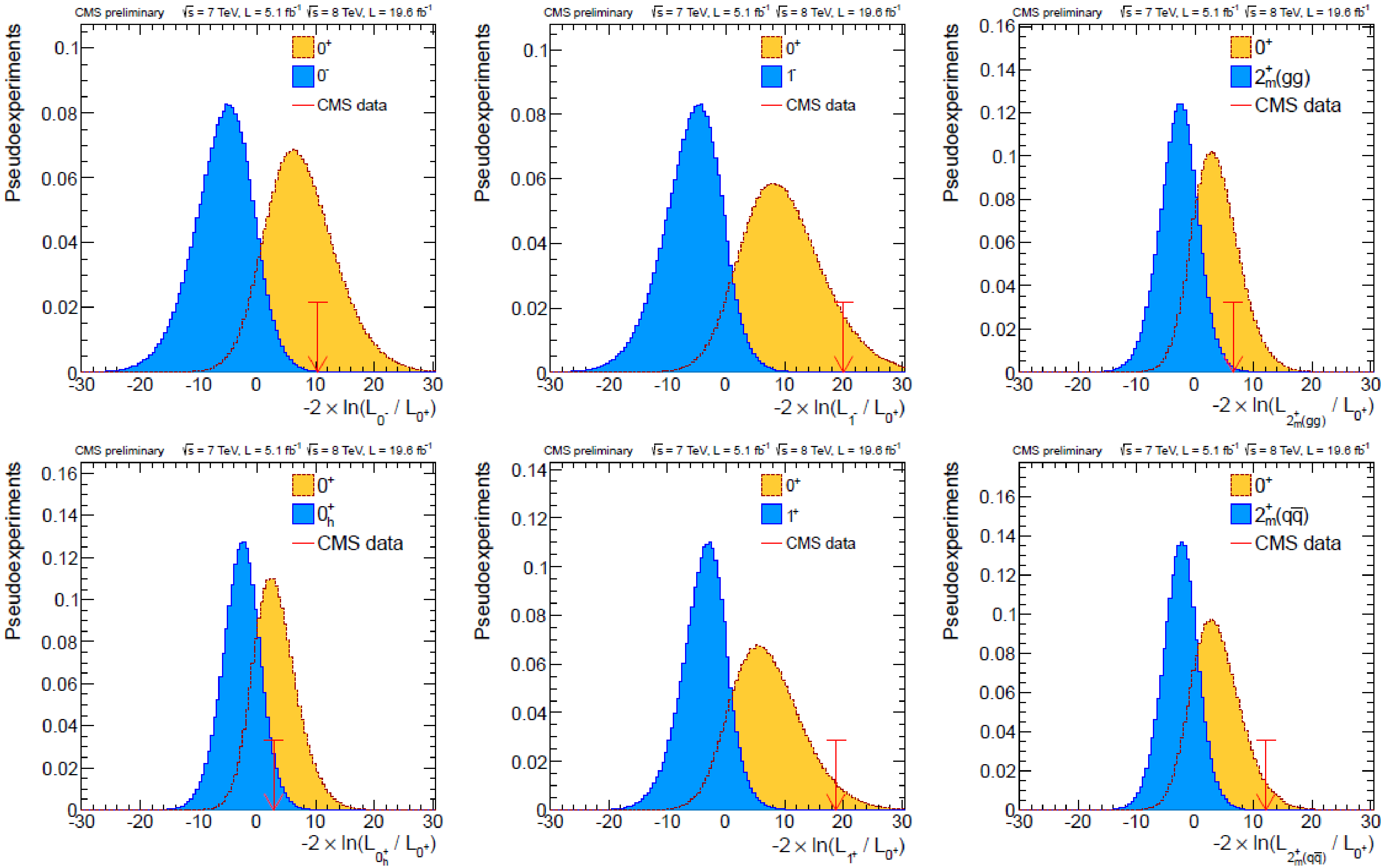
$\downarrow$

$\boxed{0^+}$





[HIG-13-002 @ CMS]



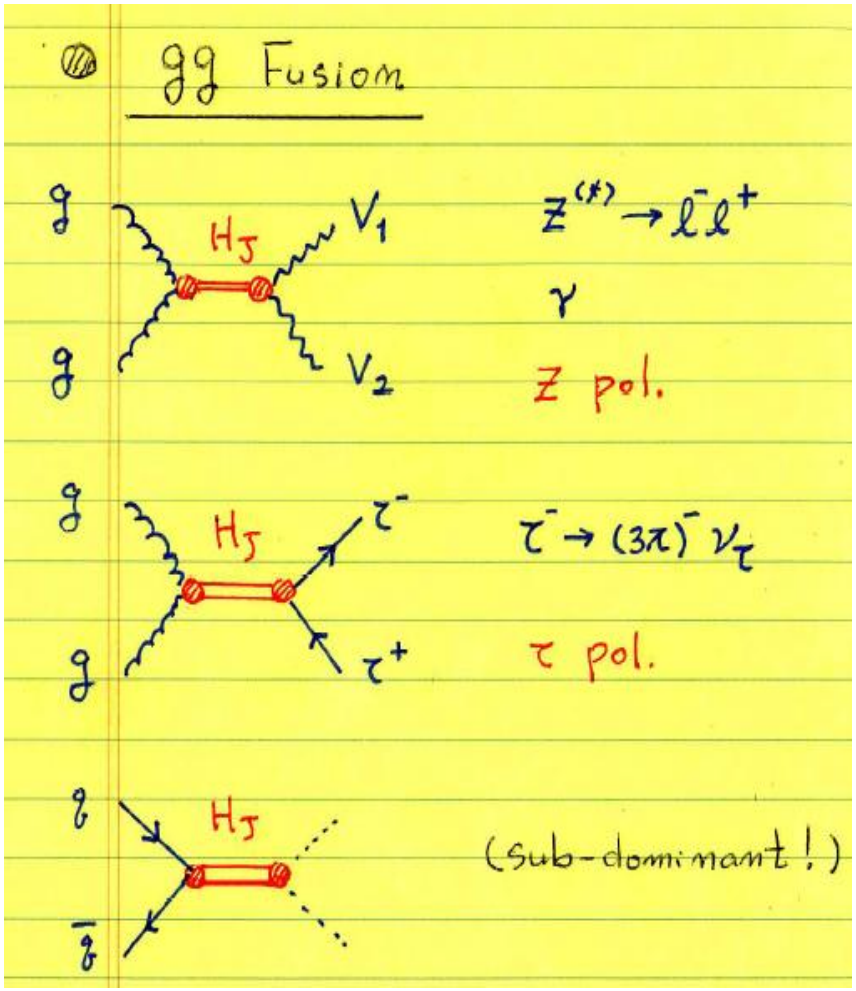
0^- and 2^+ excluded at 99.84 % and 98.5 % CL in favor of 0^+

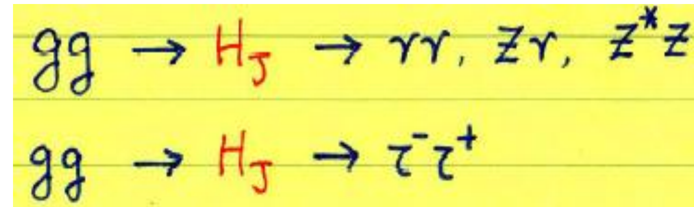
Summary of spin/parity hypothesis tests

[CERN Courier, 2013-05]

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Powerful and complementary processes





Production angle
Z momentum
Z polarization
Z* invariant mass

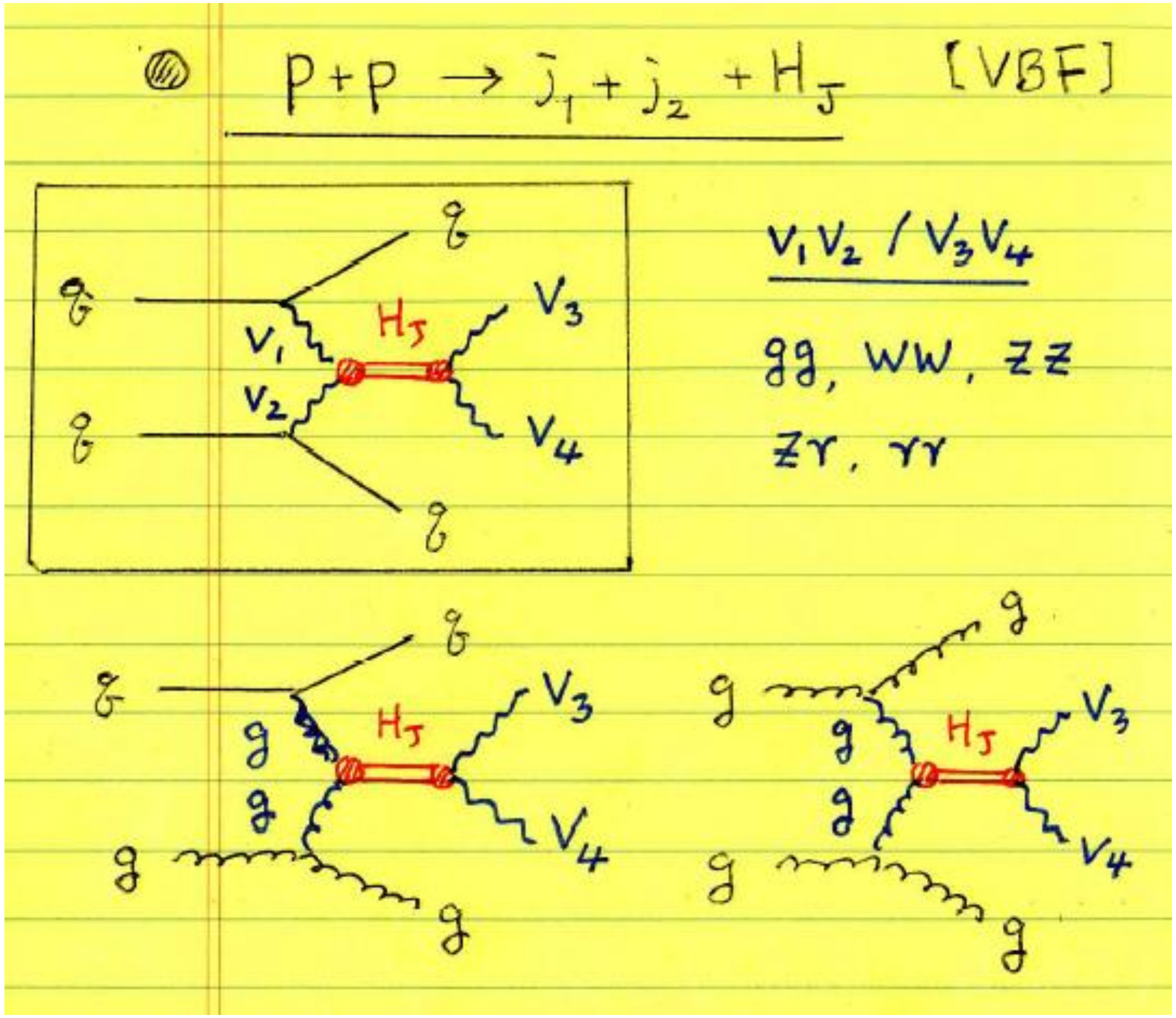
CMMZ, 2002
Gao ea, + De Rujula ea 2010

Partial spin (0, 1, 2) + parity

τ direction
τ polarization

Parity only

Berge, Bernreuther, Ziethe, 2008



Various angular correlations

Partial spin (0 and 2) + parity analysis

Hagiwara, Li, Mawatari, 2009

Summary

To veto any non-SM scenarios $\Rightarrow$ general analysis mandatory

Measure the mass, spin/parity, couplings and so on of the new boson

$$H \to Z^*Z \to 4\ell \quad \oplus \quad gg \to H \to \gamma\gamma$$

$$\Downarrow$$

Powerful and complementary for spin/parity measurements

[$J^P = 0^+$ already strongly favored!]

New approaches for spin/parity measurements?!

More detailed/realistic theoretical/experimental analyses highly recommended!

LHC Higgs CXN WG, YR3