Spin and Parity Determination of the New Boson

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Introduction

Model-independent description

Complementary processes

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

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

Summary

SYC, Miller, Muhlleitner, Zerwas, 2002
SYC, Muhlleitner, Zerwas, 2012

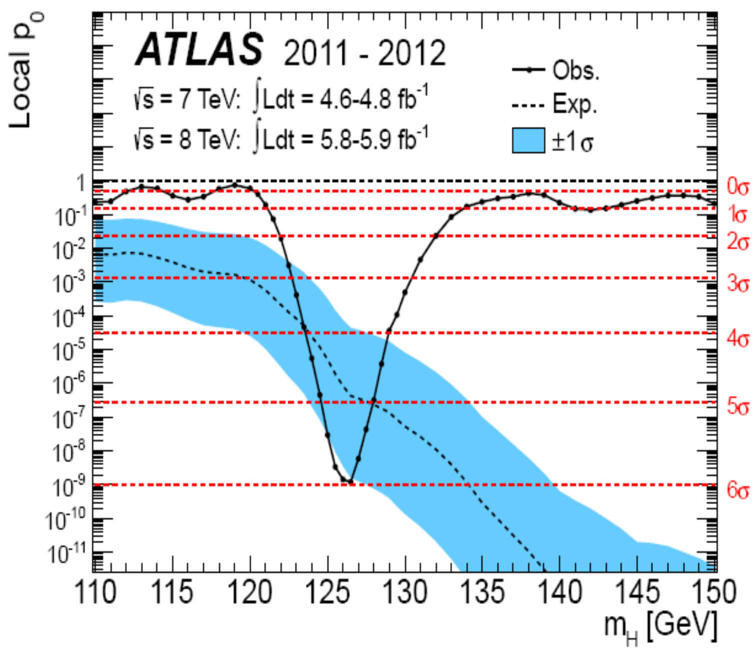
Hagiwara, Li, Mawatari, 2009
Gao, Gritsan, Guo, Melnikov, Schulze, Tran, 2010
De Rujula, Lykken, Pierini, Rogan, Spiropulu, 2010
Ellis, DS Hwang, 2012
...

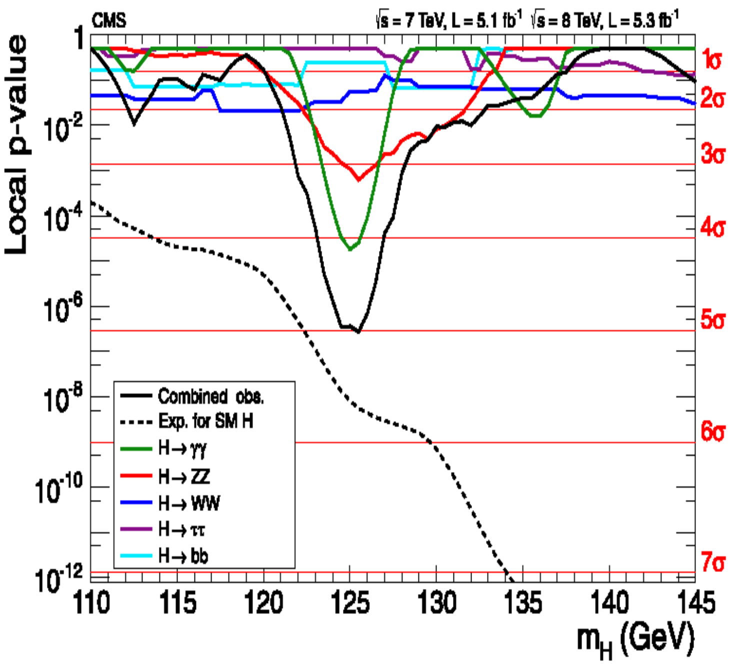
Introduction

Model-independent description
Complementary processes

Discovery of a new boson

ATLAS – PLB716(2012) 1, arXiv:1207.7214v1 [hep-ex]
CMS – PLB716 (2012) 30, arXiv:1207.7235v1 [hep-ex]





5.9 σ

5.0 σ

Mass : reasonably precise

125 GeV ~ 126 GeV

SM Higgs boson or not?

$J^P = 0^+$?

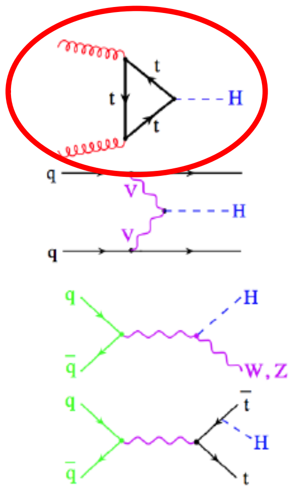
Model independent
Clean and transparent
Complementary

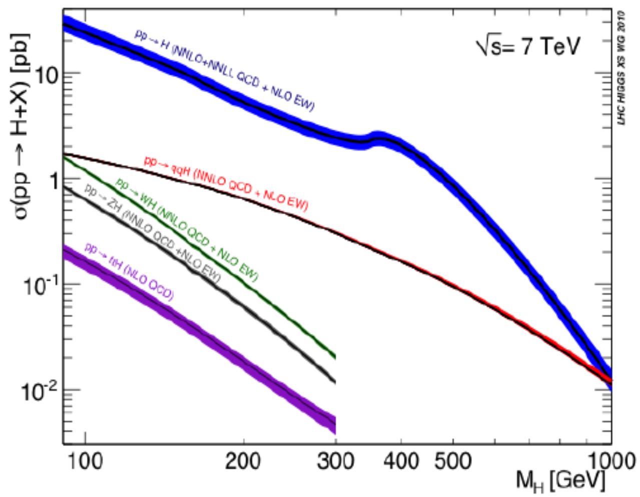
<u>Assumption</u>

SM-like production and decay

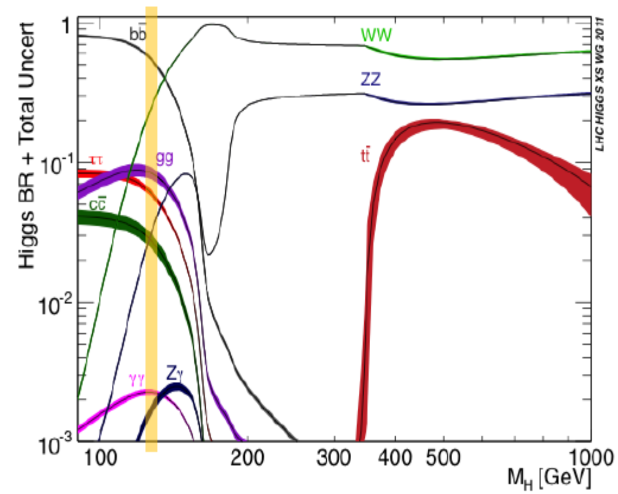
SM Higgs

Production





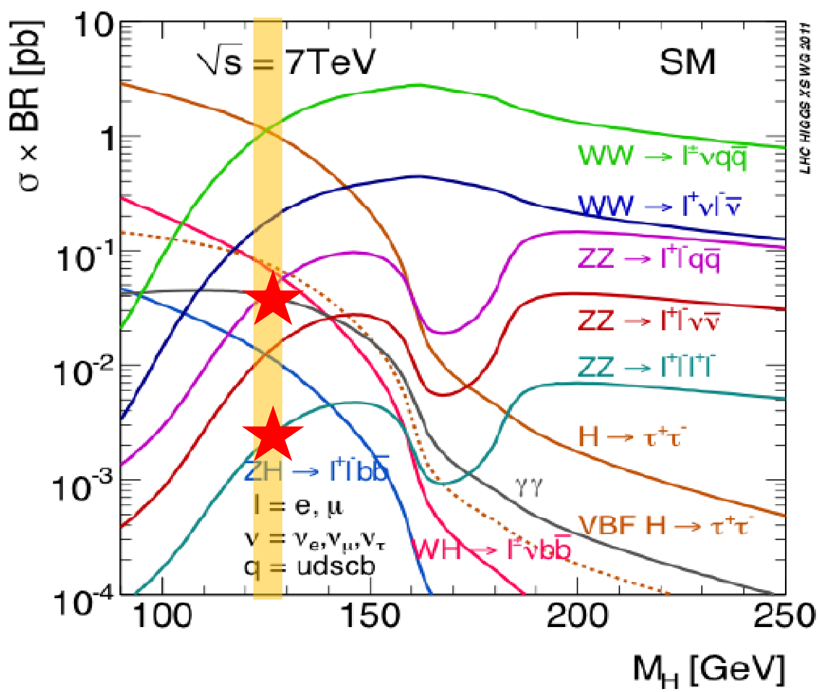
Decay



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

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

Combined

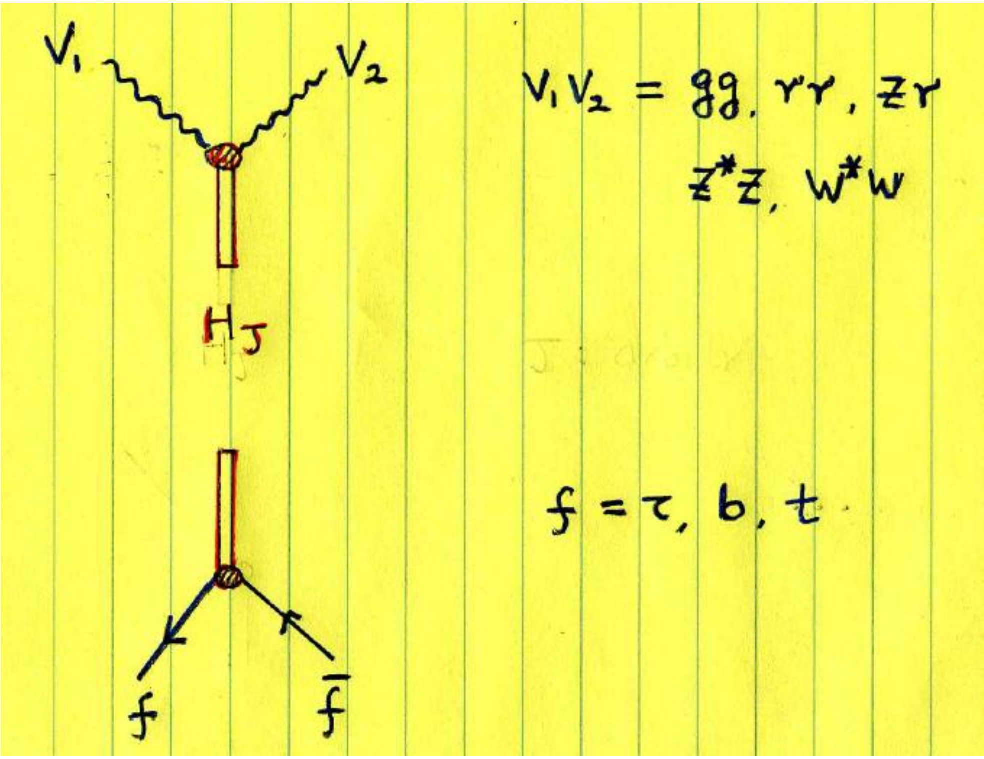


Clean signature

$[\gamma\gamma] \oplus [Z^*Z \to 4\ell]$

Model-independent analysis

General vertex structure

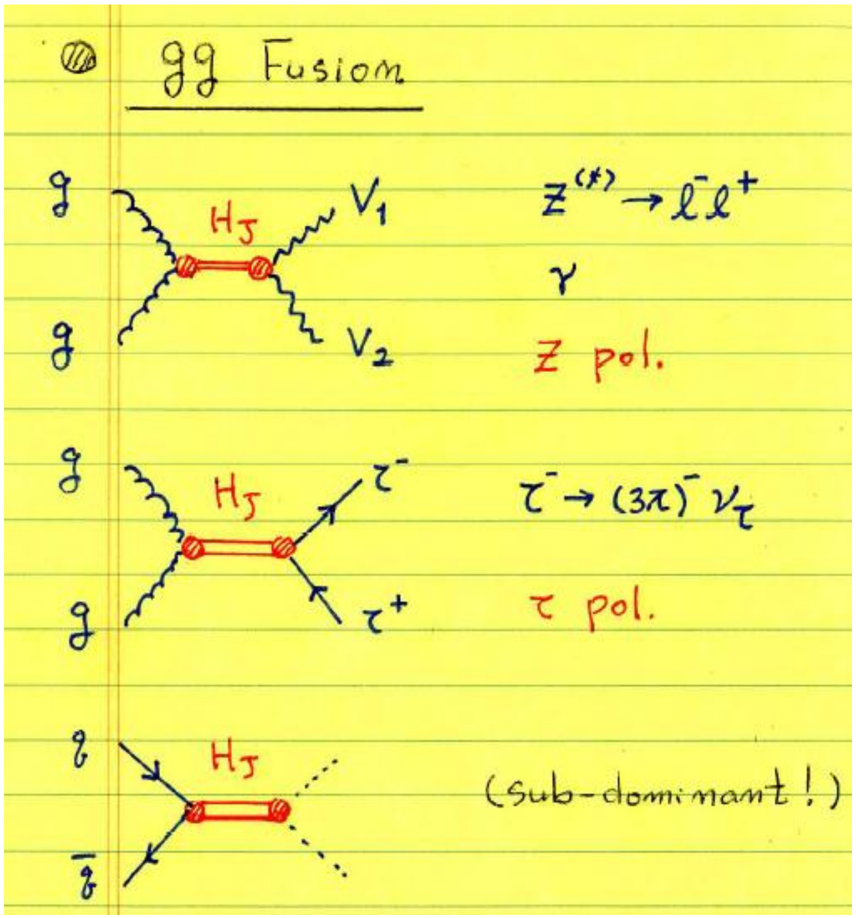


Arbitrary integer spin J
Even(+) vs. odd(-) parity

Angular correlations
Invariant mass distribution
Polarization

Complementary processes

LHC = Large Hadron Collider (pp)
LC = Linear Collider (e^+e^-)
PLC = Photon Linear Collider ($\gamma\gamma$)



LHC

$$gg \to H_J \to \gamma\gamma,\ Z\gamma,\ Z^*Z$$
$$gg \to H_J \to \tau^-\tau^+$$

Production angle
Z momentum
Z polarization
Z* invariant mass

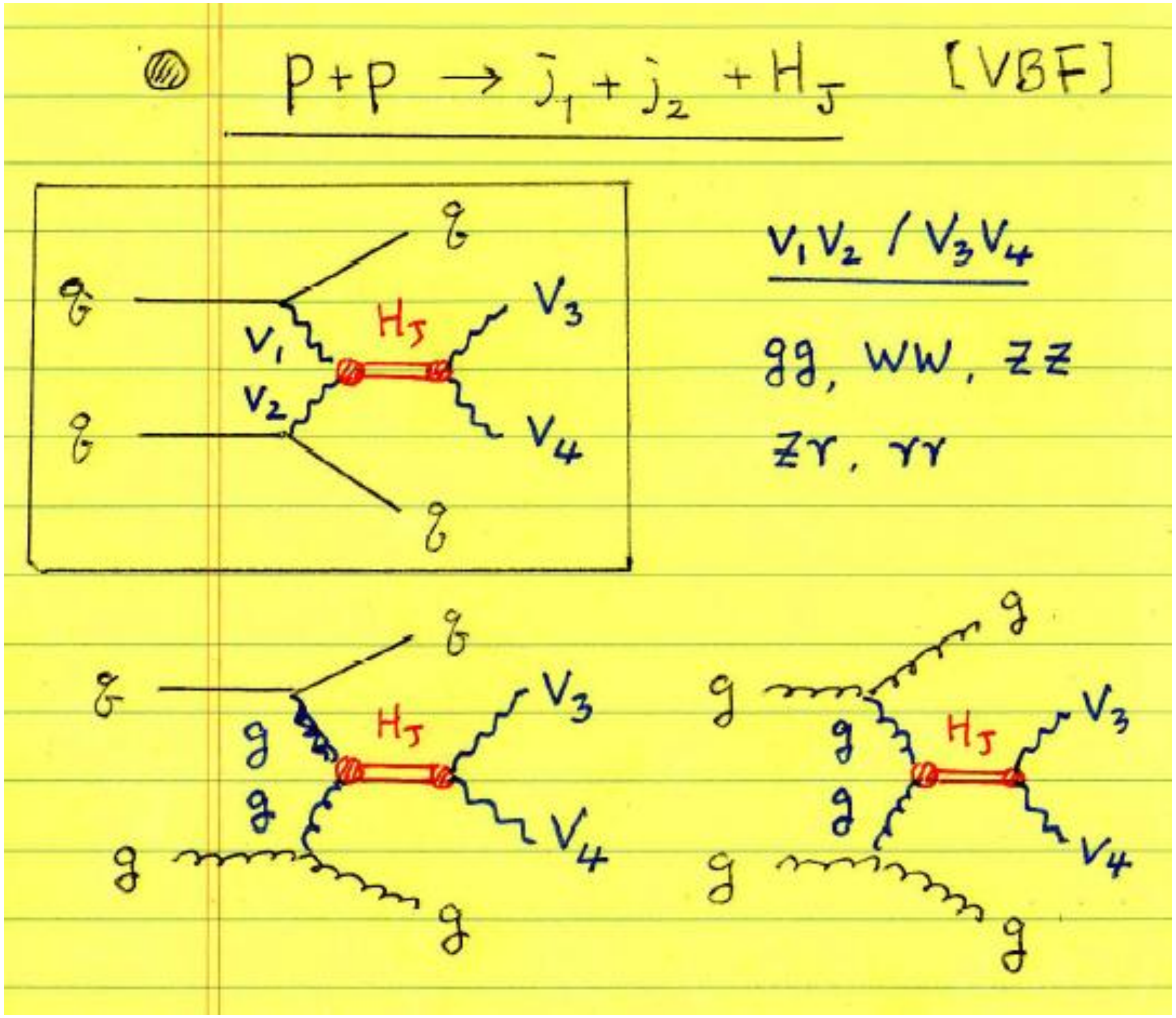
Gao ea, + De Rujula ea 2010

Partial spin (0, 1, 2) + parity

τ direction
τ polarization

Parity only

Berge, Bernreuther, Ziethe, 2008

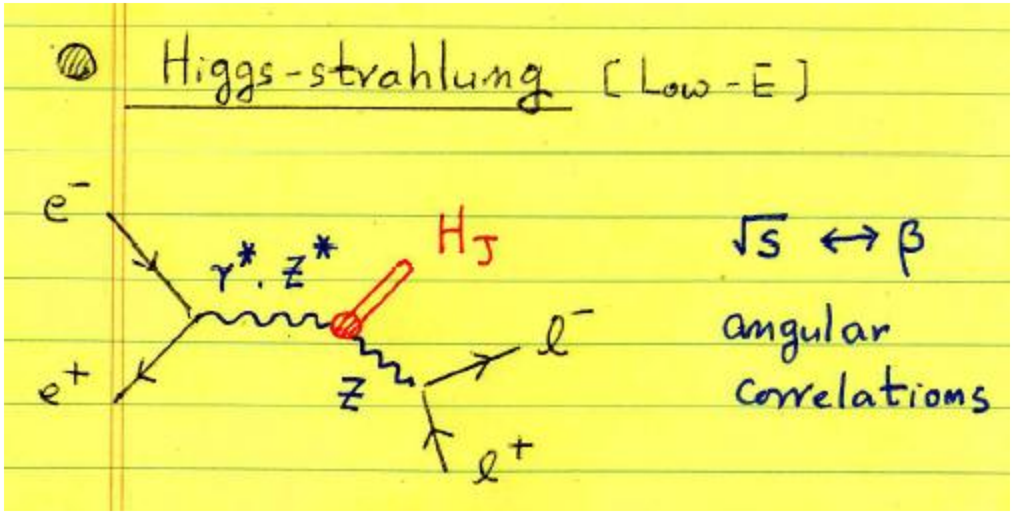


LHC

Various angular correlations

Partial spin (0 and 2) + parity analysis

Hagiwara, Li, Mawatari, 2009



Miller, SYC, Eberle, Muhlleitner, Zerwas, 2001

Full spin + parity

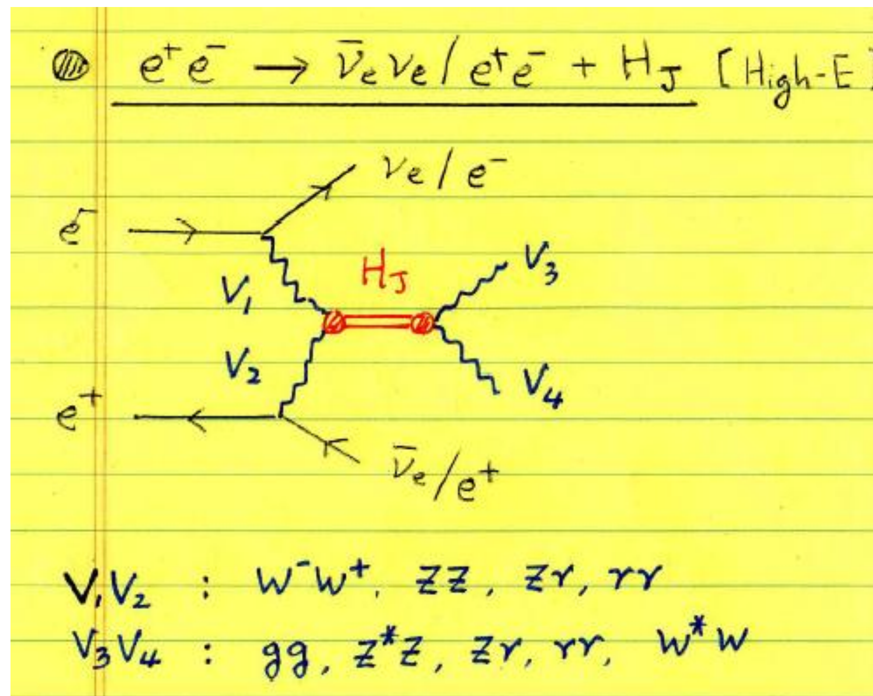
LC

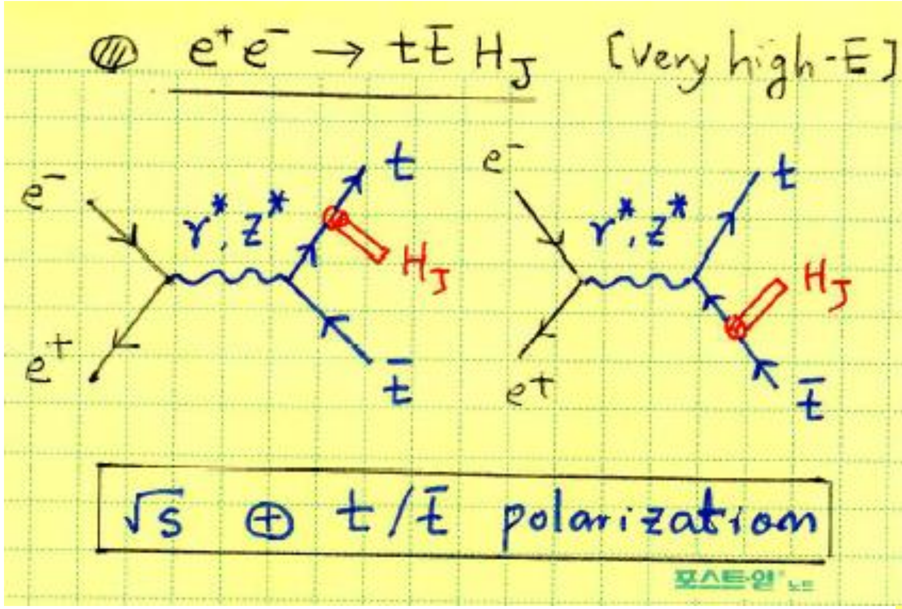
Higgs-strahlung at LHC

Ellis, DS Hwang, Sanz, T You, 2012

Topological similarity!

Not yet?

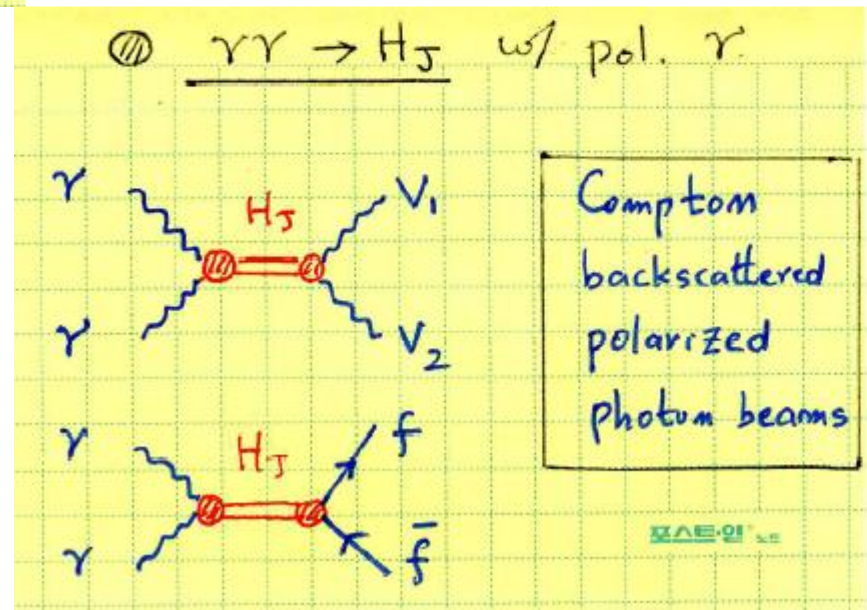




LC

Parity only

Bhupal Dev ea, 2008



PLC

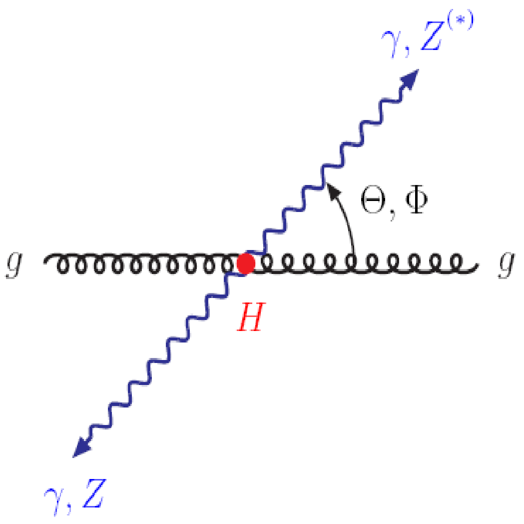
Parity only

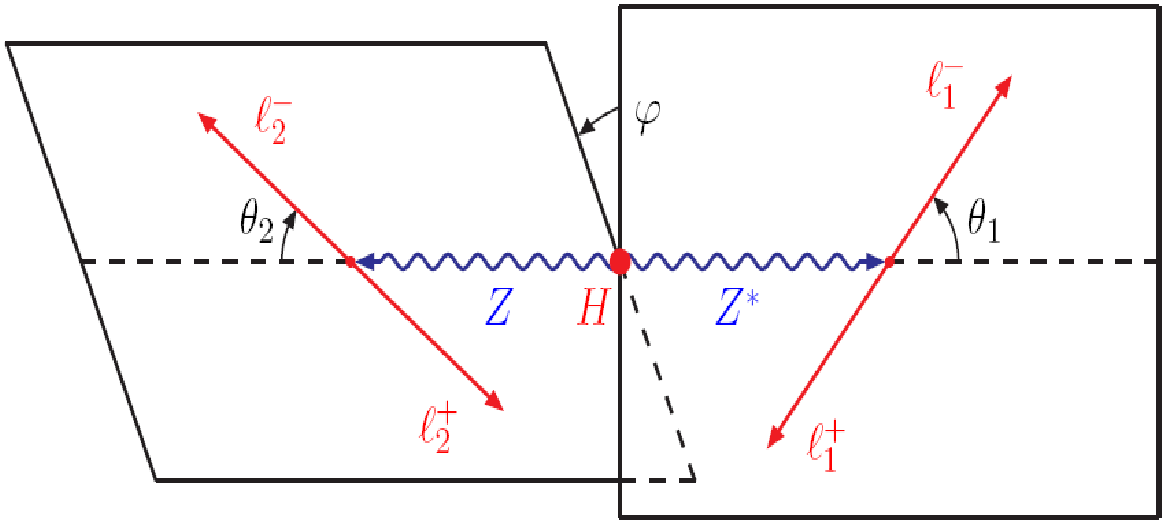
E.g., SYC, BC Chung, P Ko, J.S. Lee, 2002

Most powerful channels for spin/parity determination

$$gg \to H \to \gamma\gamma \oplus Z^*Z$$

Clean & precise
Fully reconstructed





$\ell = e, \mu$

Model-independent description for arbitrary H spin J

[Helicity Formalism]

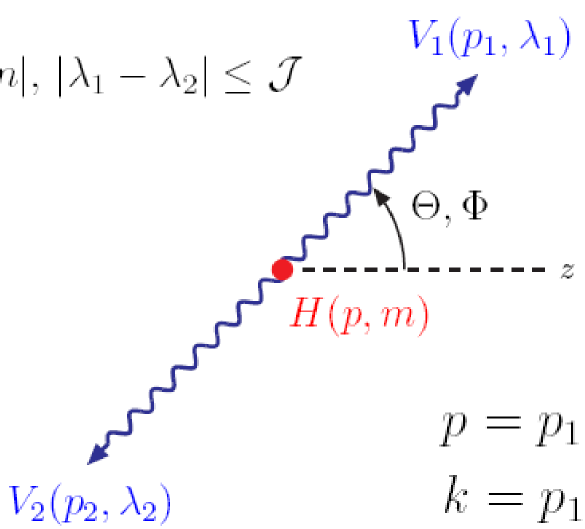
Traceless and symmetric

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

Wigner-Eckart theorem
(independent of m)

At most "9" independent terms

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



$$p = p_1 + p_2$$
$$k = p_1 - p_2$$

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

$$\mathcal{CP} \Rightarrow\ \mathcal{T}_{\lambda_1\lambda_2} = n_H\,\mathcal{T}_{-\lambda_1,-\lambda_2}$$
$$\mathcal{BS} \Rightarrow \mathcal{T}_{\lambda_1\lambda_2} = (-1)^{\mathcal{J}}\,\mathcal{T}_{\lambda_2\lambda_1}$$

$$\mathcal{CP}\ :\ n_H = -1\ \Rightarrow\ \mathcal{T}_{00} = 0$$
$$\mathcal{BS}\ :\ J = \text{odd}\ \Rightarrow\ \mathcal{T}_{\lambda\lambda} = 0$$

General HV_1V_2 couplings

Massive V1, V2

$\mathcal{J}^{\mathcal{P}}$	HV_1V_2 Coupling	Helicity Amplitudes	Threshold
		Even Normality $n_H = +$	
0^+	$a_1\, g^{\mu\nu} + a_2\, p^\mu p^\nu$	$\mathcal{T}_{00}=(2a_1(M_H^2-M_1^2-M_2^2)+a_2 M_H^4\beta^2)/(4M_1M_2)$ $\mathcal{T}_{11}=-a_1$	1 1
1^-	$b_1 g^{\mu\nu} k^\beta + b_2 g^{\mu\beta} p^\nu$ $+b_3 g^{\nu\beta} p^\mu + b_4 p^\mu p^\nu k^\beta$	$\mathcal{T}_{00}=\beta\,[-2b_1(M_H^2-M_1^2-M_2^2)-b_2(M_H^2-M_2^2+M_1^2)$ $+b_3(M_H^2-M_1^2+M_2^2)-b_4 M_H^4\beta^2]M_H/(4\,M_1M_2)$ $\mathcal{T}_{01}=\beta\, b_3 M_H^2/(2M_1)$ $\mathcal{T}_{10}=-\beta\, b_2 M_H^2/(2M_2)$ $\mathcal{T}_{11}=\beta\, b_1 M_H$	β β β β
2^+	$c_1\,(g^{\mu\beta_1} g^{\nu\beta_2} + g^{\mu\beta_2} g^{\nu\beta_1})$ $+c_2\, g^{\mu\nu}\, k^{\beta_1} k^{\beta_2}$ $+c_3\,(g^{\mu\beta_1} k^{\beta_2} + g^{\mu\beta_2} k^{\beta_1})\, p^\nu$ $+c_4\,(g^{\nu\beta_1} k^{\beta_2} + g^{\nu\beta_2} k^{\beta_1})\, p^\mu$ $+c_5\, p^\mu p^\nu k^{\beta_1} k^{\beta_2}$	$\mathcal{T}_{00}=\{-c_1\,(M_H^4-(M_2^2-M_1^2)^2)/M_H^2$ $+M_H^2\beta^2[c_2\,(M_H^2-M_2^2-M_1^2)+c_3\,(M_H^2-M_2^2+M_1^2)$ $-c_4\,(M_H^2-M_1^2+M_2^2)\,]+\frac{1}{2}c_5\, M_H^6\beta^4\}/(\sqrt{6}M_1M_2)$ $\mathcal{T}_{01}=(-c_1(M_H^2-M_2^2+M_1^2)-c_4\, M_H^4\beta^2)/(\sqrt{2}M_1M_H)$ $\mathcal{T}_{10}=(-c_1(M_H^2-M_1^2+M_2^2)+c_3\, M_H^4\beta^2)/(\sqrt{2}M_2M_H)$ $\mathcal{T}_{11}=-\sqrt{2/3}\,(c_1+c_2 M_H^2\beta^2)$ $\mathcal{T}_{1,-1}=-2\,c_1$	1 1 1 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^+	$b_1\, \epsilon^{\mu\nu\beta\rho} p_\rho$ $+b_2\, \epsilon^{\mu\nu\beta\rho} k_\rho$ $+b_3\,(\epsilon^{\mu\beta\rho\sigma} p^\nu$ $+\epsilon^{\nu\beta\rho\sigma} p^\mu)\, p_\rho k_\sigma$	$\mathcal{T}_{00}=0$ $\mathcal{T}_{01}=i\,(b_1\,(M_2^2-M_H^2-M_1^2)+b_2\,(M_H^2-M_2^2-3M_1^2)$ $+b_3\, M_H^4\beta^2)/(2M_1)$ $\mathcal{T}_{10}=i\,(b_1\,(M_1^2-M_H^2-M_2^2)-b_2\,(M_H^2-M_1^2-3M_2^2)$ $+b_3\, M_H^4\beta^2)/(2M_2)$ $\mathcal{T}_{11}=i\,(-b_1\, M_H^2+b_2\,(M_2^2-M_1^2))/M_H$	 1 1 1
2^-	$c_1\, \epsilon^{\mu\nu\beta_1\rho} p_\rho k^{\beta_2}$ $+c_2\, \epsilon^{\mu\nu\beta_1\rho} k_\rho k^{\beta_2}$ $+c_3\,(\epsilon^{\mu\beta_1\rho\sigma} p^\nu$ $+\epsilon^{\nu\beta_1\rho\sigma} p^\mu)\, k^{\beta_2} p_\rho k_\sigma$ $+c_4\, \epsilon^{\mu\nu\rho\sigma} p_\rho k_\sigma k^{\beta_1} k^{\beta_2}$ $+\beta_1 \leftrightarrow \beta_2$	$\mathcal{T}_{00}=0$ $\mathcal{T}_{01}=i\,\beta\,(c_1\,(M_H^2+M_1^2-M_2^2)-c_2\,(M_H^2-M_2^2-3M_1^2)$ $-c_3 M_H^4\beta^2)M_H/(\sqrt{2}M_1)$ $\mathcal{T}_{10}=i\,\beta\,(c_1\,(M_H^2+M_2^2-M_1^2)+c_2\,(M_H^2-M_1^2-3M_2^2)$ $-c_3 M_H^4\beta^2)M_H/(\sqrt{2}M_2)$ $\mathcal{T}_{11}=i\,\beta\, 2\sqrt{2/3}\,(c_1\, M_H^2+c_2\,(M_1^2-M_2^2)+c_4\, M_H^4\beta^2)$ $\mathcal{T}_{1,-1}=0$	 β β β

General Hγγ and Hgg vertices

Bose symmetry & gauge invariance for massless photons and gluons

Landau, 1948; CN Yang, 1950

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

$\mathcal{J}^{\mathcal{P}}$	$H\gamma\gamma$ 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

$\Rightarrow\ c_2 = -c_1/M_H^2$

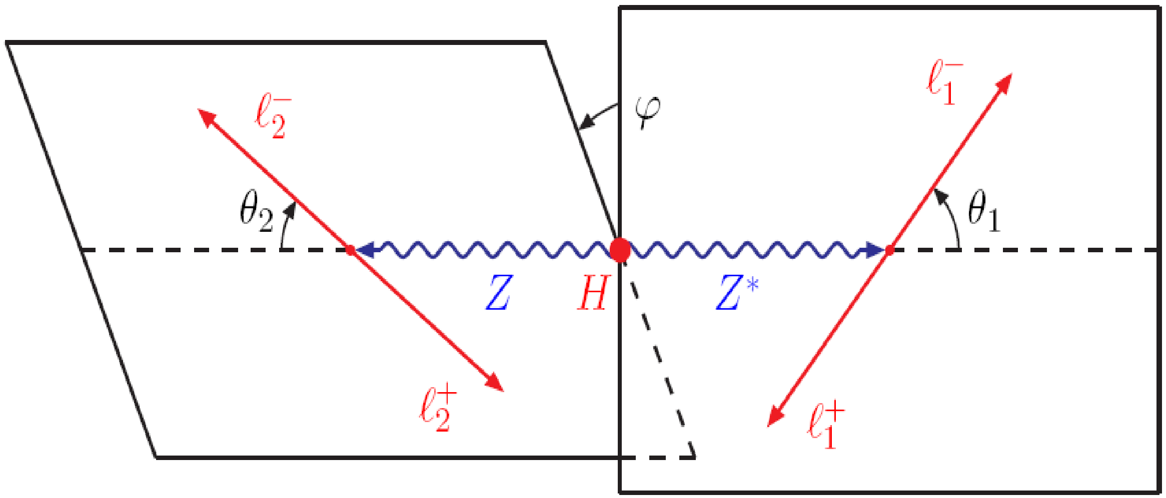
General Tensors for J ≥ 3

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

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

SYC, Miller, Muhlleitner, Zerwas, 2002

Reconstructible kinematic configuration



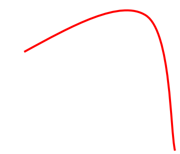
Kinematic observables

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

Invariant mass and polar & azimuthal angle distributions

$$\frac{d\Gamma}{dM_* dc_1 dc_2 d\varphi} \sim \frac{M_*}{(M_*^2 - M_Z^2)^2 + M_*^2\Gamma_Z^2} \times \beta \times \frac{d\Gamma}{dc_1 dc_2 d\varphi}$$

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



sharp decrease

Angular correlations

$$\frac{d\Gamma}{dc_1 dc_2 d\varphi} \sim s_1^2 s_2^2 \,|\mathcal{T}_{00}|^2 + \frac{1}{2}(1+c_1^2)(1+c_2^2)\left[|\mathcal{T}_{11}|^2 + |\mathcal{T}_{1,-1}|^2\right]$$

$$+ (1+c_1^2)\, s_2^2\, |\mathcal{T}_{10}|^2 + s_1^2\,(1+c_2^2)\,|\mathcal{T}_{01}|^2$$

$$+ 2 s_1 s_2 c_1 c_2 \Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{00}^* - \mathcal{T}_{10}\mathcal{T}_{0,-1}^*)\,\cos\varphi$$

$$+ \frac{1}{2} s_1^2 s_2^2\, \Re\mathrm{e}(\mathcal{T}_{11}\mathcal{T}_{-1,-1}^*)\cos 2\varphi + \cdots$$

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

$$\mathcal{CP}\ :\ \mathcal{T}_{00} = 0 \quad \Rightarrow\ \nexists\, s_1^2 s_2^2 \ \ \text{correlations}$$

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 $(1+c_i^2)s_j^2$

$J \geq 3$

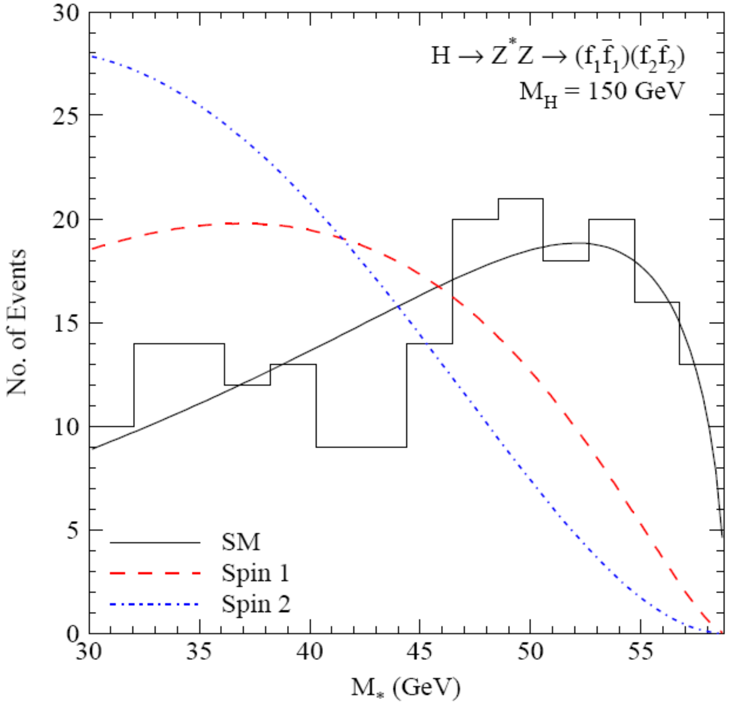
At least $(J-2)$ momentum factors $\Rightarrow d\Gamma/dM_* \sim \beta^{2J-3}$ with $2J-3 \geq 3$

Selection rules for SM Higgs boson

$$\text{Invariant mass spectrum linear in } \beta$$

$$\text{Observation of } \sin^2\theta_1 \sin^2\theta_2$$

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



$$\int \mathcal{L}\, dt = 300\,\text{fb}^{-1}$$

$$\sqrt{s} = 14 \text{ TeV}$$

What significance?

for $M_H = 125$ GeV

with $\int \mathcal{L}\, dt \sim 25\,\text{fb}^{-1}$

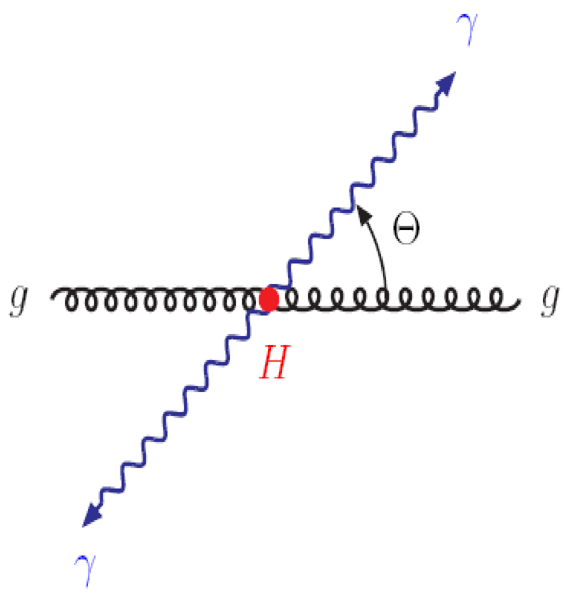
at $\sqrt{s} = 8$ TeV

Bolognesi ea, 2012

$$gg \longrightarrow H \longrightarrow \gamma\gamma$$

Ellis, D.S. Hwang, 2012
SYC, Muehlleitner, Zerwas, 2012
Alves, 2012
...

P-invariant polar-angle distribution for arbitrary spin



$m\ (\lambda) = g\ (\gamma)$ helicity difference

$$\mathcal{D}^J_{m\lambda} = \frac{1}{4}\left\{[d^J_{m,\lambda}]^2 + [d^J_{m,-\lambda}]^2 + [d^J_{-m,\lambda}]^2 + [d^J_{-m,-\lambda}]^2\right\}$$

$$\mathcal{X}^J_0 + \mathcal{X}^J_2 = 1 \quad \text{and} \quad \mathcal{Y}^J_0 + \mathcal{Y}^J_2 = 1$$

Scalar-type ⟺ Tensor-type

$$\frac{1}{\sigma}\frac{d\sigma[gg \to H \to \gamma\gamma]}{d\cos\Theta} = (2J+1)\left[\mathcal{X}^J_0\mathcal{Y}^J_0\,\mathcal{D}^J_{00} + \mathcal{X}^J_0\mathcal{Y}^J_2\mathcal{D}^J_{02} + \mathcal{X}^J_2\mathcal{Y}^J_0\mathcal{D}^J_{20} + \mathcal{X}^J_2\mathcal{Y}^J_2\,\mathcal{D}^J_{22}\right]$$

J extracted!

Non-negative $\mathcal{X}$'s and $\mathcal{Y}$'s $\Rightarrow$ $^\exists\cos^{2J}\Theta$ terms

Selection rules

Landau-Yang Theorem on angular distributions

$\mathcal{P} \setminus J$	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

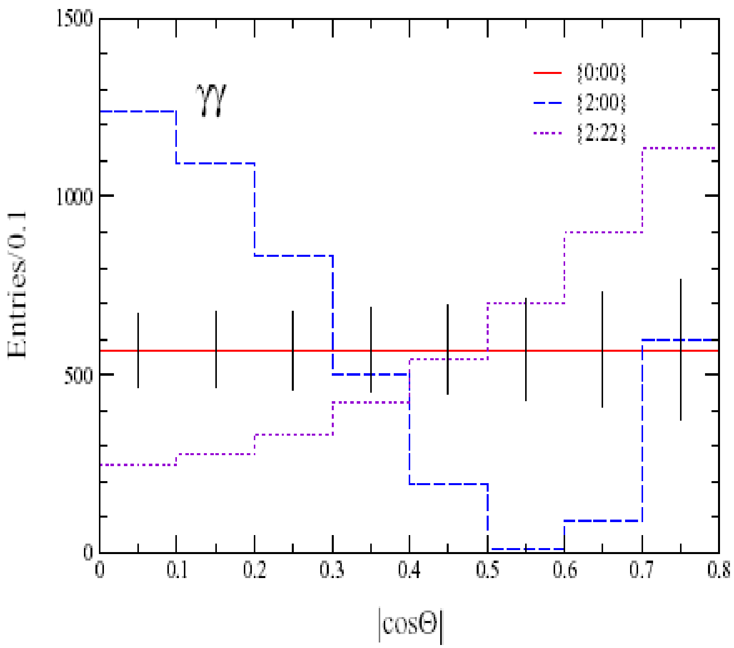
Isotropic

No {J;00} ⇒ no odd parity
{J;02}, {J;20} or {J;22} ⇒ even parity
Odd spin ⇒ only even parity

Numerical analysis

$$\int \mathcal{L}dt = 100\,\mathrm{fb}^{-1}, \quad \sqrt{s} = 14\,\mathrm{TeV}$$

4.6k [146k]
w/ angle cuts



⇔

$$\int \mathcal{L}\,dt = 35\,\mathrm{fb}^{-1}, \quad \sqrt{s} = 8\,\mathrm{TeV}$$

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs background	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	2.2	2.5	2.5	4.2

Bolognesi ea, [arXiv:1208.4018]

Background

$$\frac{d\sigma}{d\cos\Theta}[q\bar{q} \to \gamma\gamma] = \frac{2\pi\alpha^2}{3s} Q_q^4 \frac{1}{\sin^2\Theta}\left[1+\cos^2\Theta\right]$$

Clear 0 ⇔ 2 distinction!

Summary

Expect the unexpected $\Rightarrow$ model-independent analysis

Measure the mass, spin/parity etc of the new boson

$H \to Z^*Z \to 4\ell \oplus gg \to H \to \gamma\gamma$: powerful for spin/parity measurements

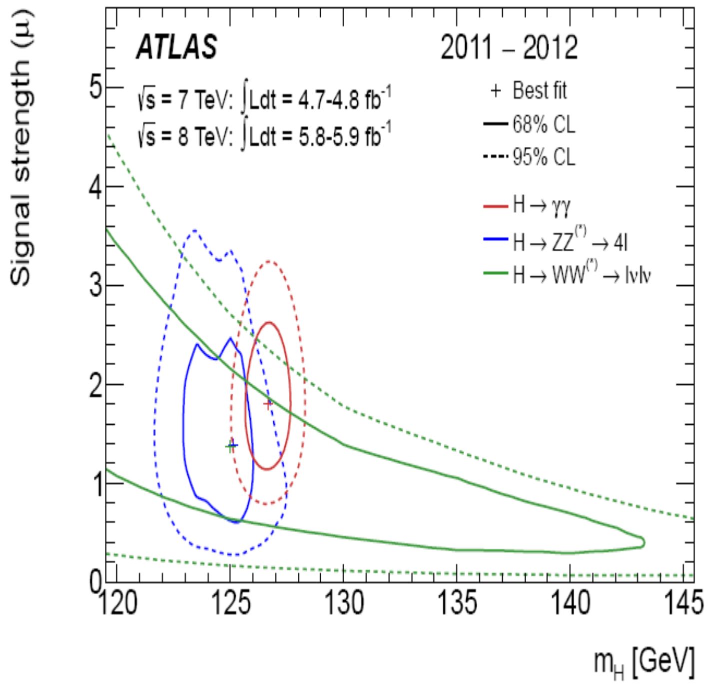
Various complementary processes and methods $\Rightarrow$ New approaches?!

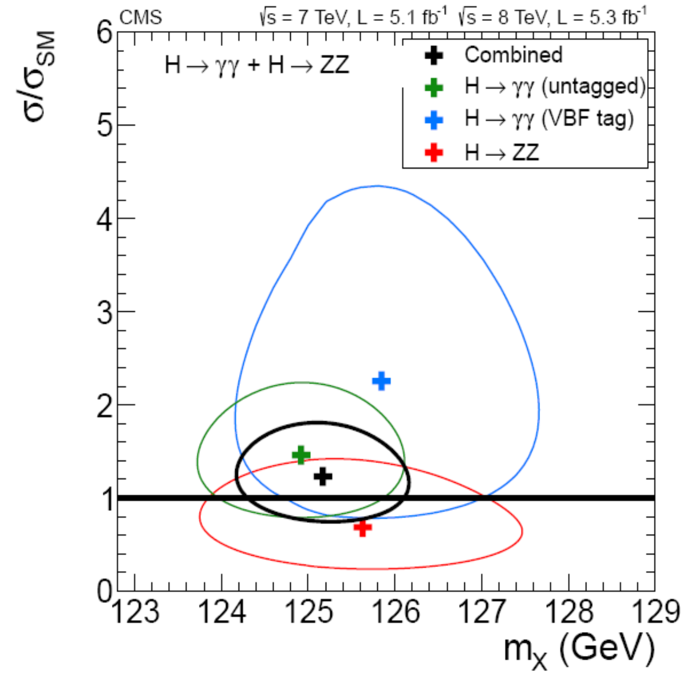
↓

Detailed/realistic theoretical/experimental analyses required urgently!

Back-up Slides

Mass



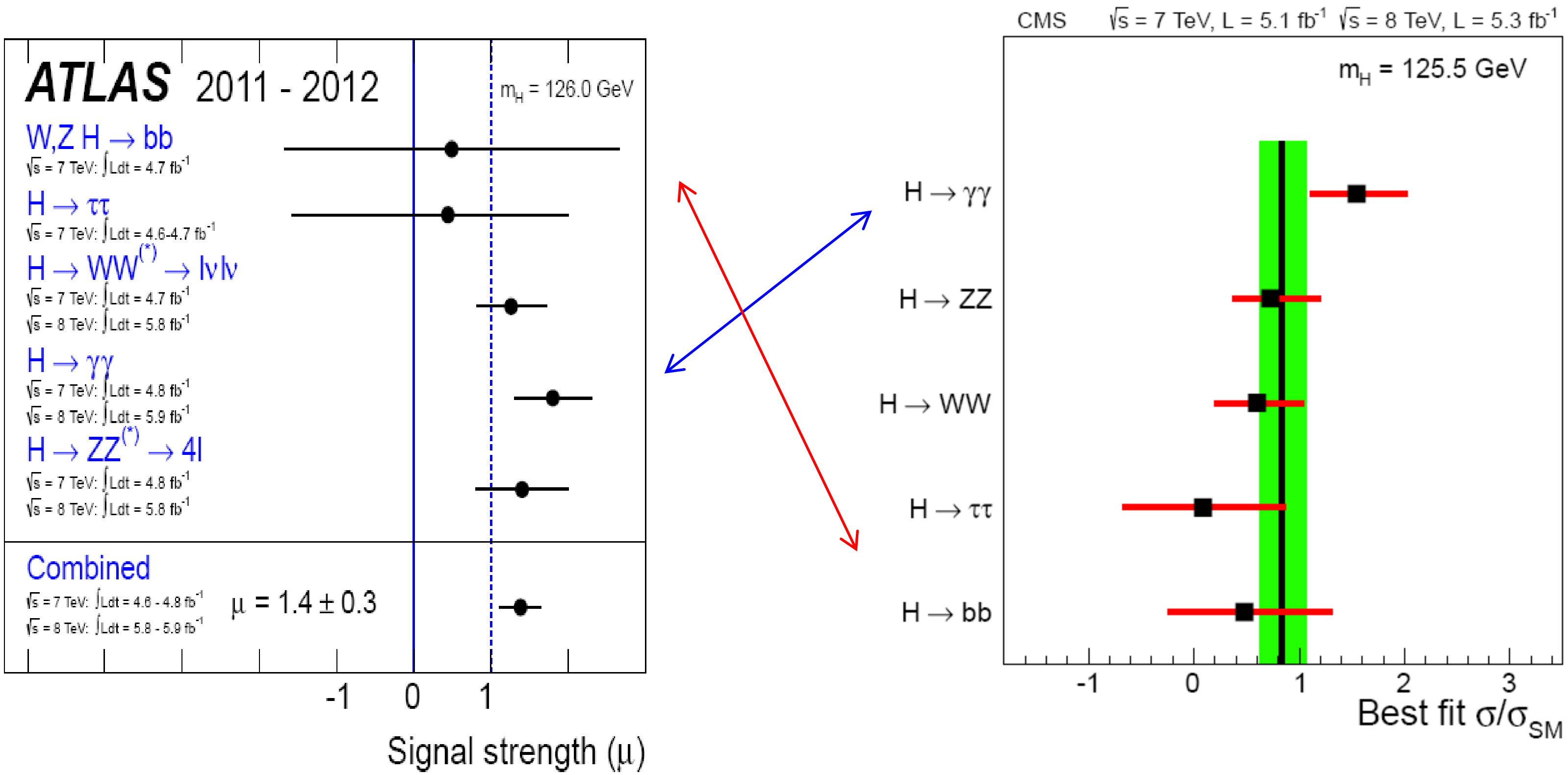


126.0 ± 0.4 (stat.) ± 0.4 (sys.) GeV

125.3 ± 0.4 (stat.) ± 0.5 (sys.) GeV

Mutually consistent and reasonably precise

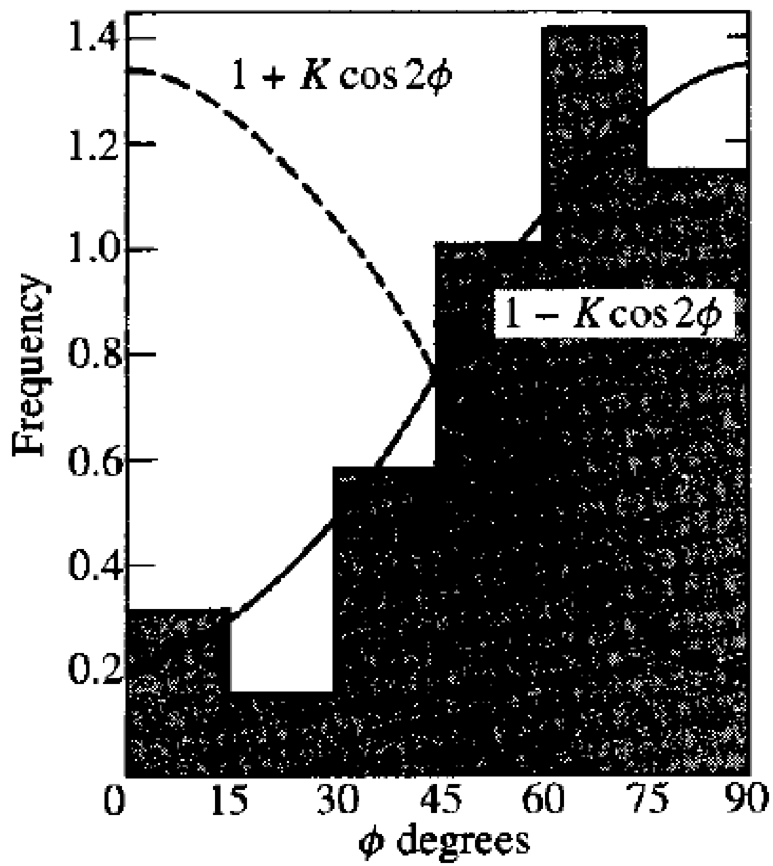
Couplings



Consistent with SM predictions?

Plehn, Rauch , arXiv:1207.6108v1 [hep-ph]
HM Lee's talk at this workshop

$$\pi^0 \to \gamma^*\gamma^* \to (e^-e^+)(e^-e^+)$$



Parity : Odd!

Plano, Prodell, Samios, Schwartz, Steinberger, 1959
Abouzaid ea, 2008 with much more improvement