Exotic Higgs (at the LHC)

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This talk will be a grab-bag of exotic Higgs topics.

I'll try to go into detail on the theory background in each case:
- why it's interesting
- where the characteristic features come from

Outline

CP-even, CP-odd, and mixtures

Higgs triplets (and higher)

Multi-doublet models

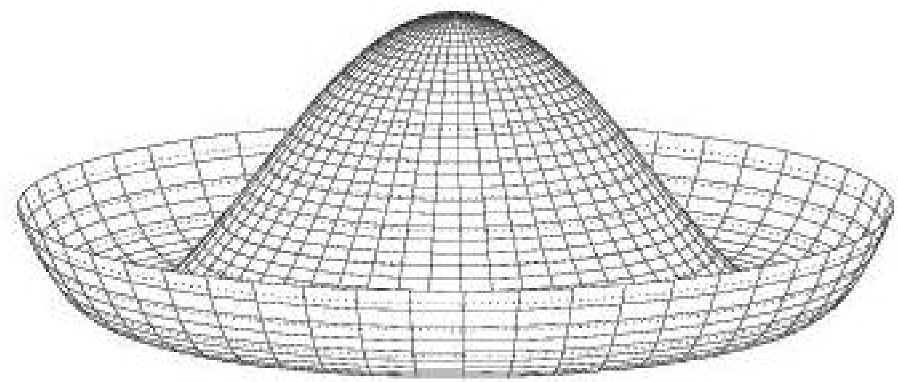
1. CP-even, CP-odd, and mixtures

Consider first the Higgs mechanism in the Standard Model: electroweak symmetry is broken by a single scalar Higgs doublet.

Electroweak symmetry breaking comes from the Higgs potential:

$$V = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

where $\lambda \sim \mathcal{O}(1)$
and $m^2 \sim \mathcal{O}(M_{\rm EW}^2)$



Expand in perturbations about the vacuum:

$$H = \begin{pmatrix} G^+ \\ (h+v)/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

- G^+ and G^0 are the Goldstone bosons that get "eaten" by the W^+ and Z bosons, giving them mass.
- v is the SM Higgs vacuum expectation value (vev), $v = 2m_W/g \simeq 246$ GeV.
- h is the SM Higgs field, a physical CP-even scalar particle.

The CP-odd state in H is G^0 – it got eaten by the Z boson.
To get a physical CP-odd state, need an extra Higgs multiplet.

Two Higgs Doublet Model (2HDM):
prototype model for CP-odd Higgs couplings.

- Two Higgs doublets, H_1 and H_2:

$$H_i = \left(\begin{array}{c} \phi_i^+ \\ (\phi_i^{0,r} + v_i)/\sqrt{2} + i\phi_i^{0,i}/\sqrt{2} \end{array} \right)$$

- To get the W boson mass right, need to have

$$v_1^2 + v_2^2 = v_{\mathrm{SM}}^2 = (2m_W/g)^2 \simeq (246 \text{ GeV})^2$$

- Ratio of vevs is a free parameter; usual notation is

$$v_2/v_1 = \tan\beta$$

Assume CP conservation for now.

Physical states defined in terms of H_1, H_2 by mixing angles α, β:

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^{0,i} \\ \phi_2^{0,i} \end{pmatrix}$$

$$\begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^{0,r} \\ \phi_2^{0,r} \end{pmatrix}$$

Can think of this as a rotation of basis for the doublets by the angle β, to the vev basis:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \to \begin{pmatrix} H_v \\ H_0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

where

$$H_v = \begin{pmatrix} G^+ \\ (\sin(\beta-\alpha)h^0 + \cos(\beta-\alpha)H^0 + v_{\rm SM})/\sqrt{2} + iG^0/\sqrt{2} \end{pmatrix}$$

- contains the total vev and the Goldstone bosons

$$H_0 = \begin{pmatrix} H^+ \\ (\cos(\beta-\alpha)h^0 - \sin(\beta-\alpha)H^0)/\sqrt{2} + iA^0/\sqrt{2} \end{pmatrix}$$

- contains H^+ and A^0, and zero vev

Higgs–gauge couplings:

These come from the covariant derivative term:

$$\mathcal{L} = (\mathcal{D}_\mu H)^\dagger (\mathcal{D}^\mu H) + \cdots$$

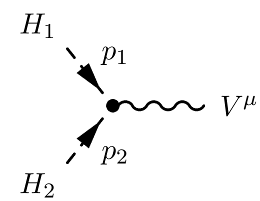
where
$$\begin{aligned} \mathcal{D}_\mu &= \partial_\mu - i g W_\mu^a T^a - i g' \frac{Y}{2} B_\mu \qquad\qquad (Q = T^3 + Y/2) \\ &= \partial_\mu - i \frac{g}{\sqrt{2}} \left(W_\mu^+ T^+ + W_\mu^- T^- \right) \\ &\quad - i \frac{g}{\cos\theta_W} Z_\mu \left(T^3 - \sin^2\theta_W Q \right) - i e Q A_\mu \end{aligned}$$

Generates Higgs-Vector couplings:

HHV from one ∂_μ and one V^μ

SM: not present (antisym. in $H_1 \leftrightarrow H_2$)

2HDM: hAZ, HAZ, hH^+W^-, HH^+W^-

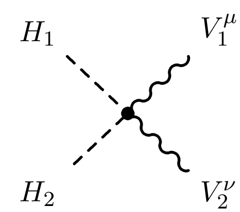


$= i g_{H_1 H_2 V} (p_1 - p_2)^\mu$

$HHVV$ from two V_μ

SM: $hhZZ$, hhW^+W^-

2HDM: $hhZZ$, $AAZZ$, $hH^+\gamma W^-$, etc

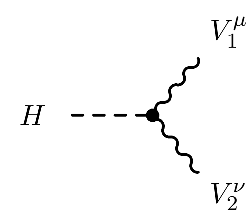


$= i g_{H_1 H_2 V_1 V_2} g^{\mu\nu}$

HVV from two V_μ and replacing one H with its vev.

SM: hZZ, hW^+W^-

2HDM: hZZ, hWW, HZZ, HWW



$= i g_{H V_1 V_2} g^{\mu\nu}$

A closer look at the HVV couplings:

- The tensor structure is $HV_\mu V^\mu$.
  - + Normally such a coupling would not be gauge invariant!
  - + It works because of Higgs mechanism: replace one field with its vev.

- Coupling is only nonzero for scalars with a vev.
  - + No such coupling for CP-odd state: it would violate CP.

How else can a scalar couple to two vector bosons?
Easy to construct a gauge invariant coupling from the field strength tensor:

$HV_{\mu\nu}V^{\mu\nu}$ for a CP-even scalar.
$AV_{\mu\nu}\widetilde{V}^{\mu\nu}$ for a CP-odd scalar.

These are dimension-5 operators – generated by a loop.

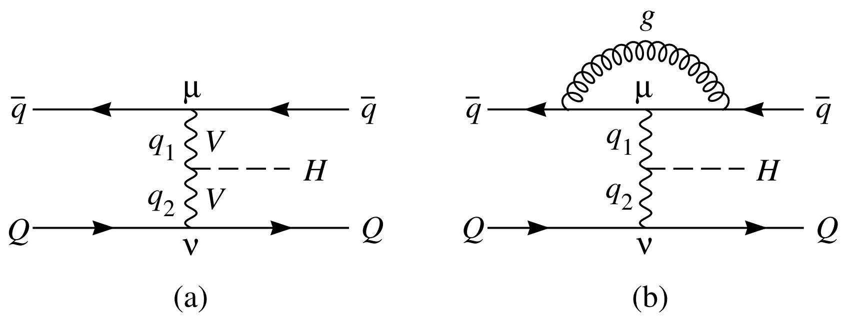
+ These are exactly the operators that generate $H \to \gamma\gamma$, $gg \to H$, $gg \to A^0$ in the MSSM, etc.

+ The scalar need not have a vev.

Measuring the tensor structure of the HVV coupling in VBF

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



$$
\begin{aligned}
T^{\mu\nu} \quad = \quad & a_1 \, g^{\mu\nu} \; + \\
& a_2 \, \left(q_1 \cdot q_2 \, g^{\mu\nu} - q_1^{\nu} q_2^{\mu} \right) + \\
& a_3 \, \varepsilon^{\mu\nu\rho\sigma} \, q_{1\rho} q_{2\sigma}
\end{aligned}
$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

Physical interpretation of terms:

SM Higgs $\quad \mathcal{L}_I \sim H V_\mu V^\mu \longrightarrow a_1$

loop induced couplings for neutral scalar

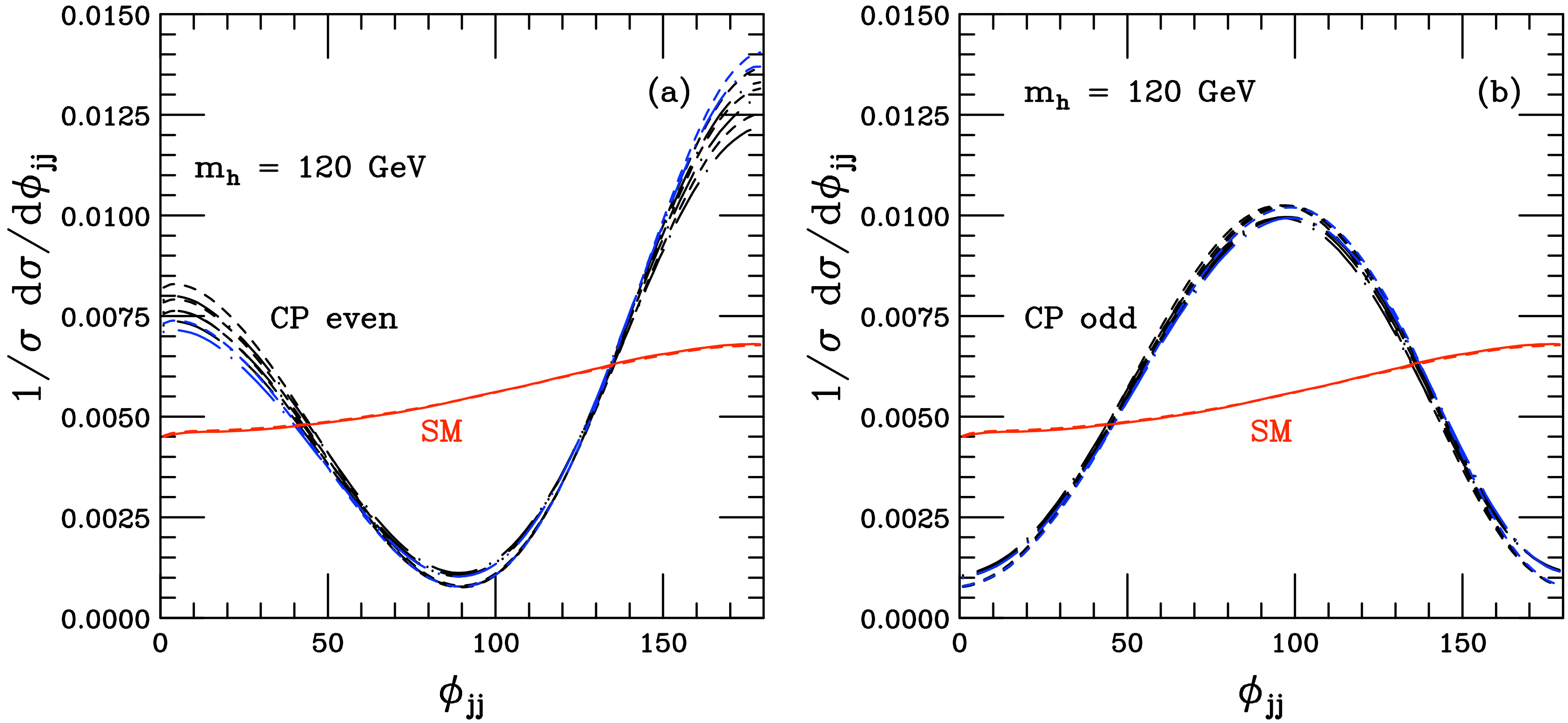
CP even $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} V^{\mu\nu} \longrightarrow a_2$

CP odd $\quad \mathcal{L}_{eff} \sim H V_{\mu\nu} \tilde{V}^{\mu\nu} \longrightarrow a_3$

Must distinguish a_1, a_2, a_3 experimentally

Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Tell-tale signal for non-SM coupling is azimuthal angle between tagging jets



Dip structure at 90° (CP even) or $0/180^\circ$ (CP odd) only depends on tensor structure of HVV vertex. Very little dependence on form factor, LO vs. NLO, Higgs mass etc.

Dashed lines include LO vs NLO and formfactor effects for LHC

[plots from Figy & Zeppenfeld, hep-ph/0403297]

[see also Plehn, Rainwater & Zeppenfeld, hep-ph/0105325]

A closer look at the WWϕ couplings

It doesn't help us much for a SM Higgs with a CP-odd admixture.

SM $HV_\mu V^\mu$ coupling is tree-level.

- Comes from covariant derivative term $|\mathcal{D}_\mu H|^2$ in the Lagrangian, with one Higgs field replaced by its vev.

CP-odd $\phi V_{\mu\nu}\widetilde{V}^{\mu\nu}$ coupling is dimension-5 (e.g., loop-induced): gives only a tiny contribution to VBF rate.

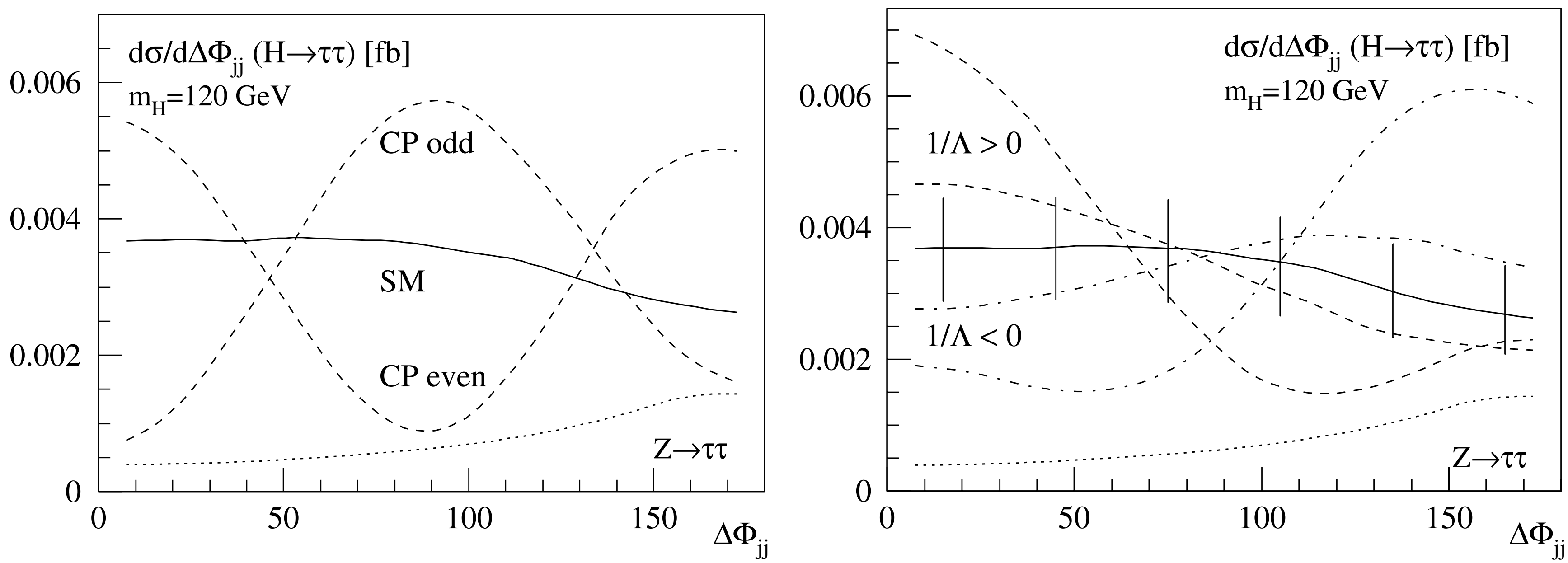
- Won't see enough "CP-odd" events in VBF if ϕ couples only through the loop.

CP-even $\phi V_{\mu\nu}V^{\mu\nu}$ coupling is also dimension-5 (e.g., loop-induced).

- Get interference term between $\phi V_\mu V^\mu$ and $\phi V_{\mu\nu}V^{\mu\nu}$ production:

"SM times dimension-5" gives better sensitivity to small dimension-5 contribution.

Interference term between $\phi V_\mu V^\mu$ and $\phi V_{\mu\nu} V^{\mu\nu}$:



[from Plehn, Rainwater & Zeppenfeld, hep-ph/0105325]

[Left] Curves are normalized to each give the SM cross section.

[Right] Shows interference effect for either sign of the $\phi V_{\mu\nu} V^{\mu\nu}$ operator coefficient, with $\sigma_{\mathrm{new}}/\sigma_{\mathrm{SM}} = 1.0$ and 0.04.

Error bars are statistical for 100 fb^{-1} times 2 experiments.

Mixed CP states: a closer look

- A^0 in the MSSM is a CP-odd scalar

    + Often nearly mass-degenerate with H^0

    + Production modes and couplings very similar to H^0

- Can get mixing among h^0, H^0, A^0 in MSSM if there are CP-violating phases [CPX scenario]

    + If A^0 and H^0 are close in mass, can have large mixing even if CP-violating phases are relatively small

    + Get two CP-mixed states nearby in mass [mixing increases level splitting]

- CP-odd component couples to vector bosons like $\phi V_{\mu\nu} \widetilde{V}^{\mu\nu}$

    + Coupling is loop-induced and therefore typically small

    + No interference term with a tree-level $\phi V_\mu V^\mu$ coupling: CP-odd component of VBF cross section is very tiny.

Ideally, want to look at a process where the SM-like and CP-odd parts would come in at the same level.

Couplings to fermions

- Again consider H^0 and A^0 in the MSSM.

$$H^0 b\bar{b} = -\frac{igm_b}{2m_W}\left[\tan\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$
$$A^0 b\bar{b} = -\frac{gm_b}{2m_W}\tan\beta\gamma_5$$
$$H^0 t\bar{t} = -\frac{igm_t}{2m_W}\left[-\cot\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$
$$A^0 t\bar{t} = -\frac{gm_t}{2m_W}\cot\beta\gamma_5$$

Couplings to gluons or photons

- Loop induced for both CP-even and CP-odd states.
  + CP-even: $\phi G_{\mu\nu}G^{\mu\nu}$
  + CP-odd: $\phi G_{\mu\nu}\widetilde{G}^{\mu\nu}$

- CP-even and CP-odd components of the coupling are a priori of the same order of magnitude!

Tensor structure of the Hgg coupling (!) at LHC

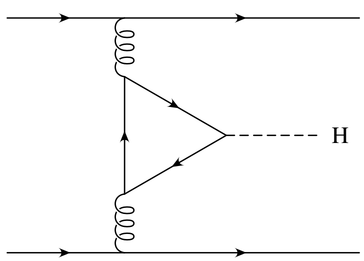
Slide from D. Zeppenfeld, plenary talk at SUSY'06 conference

Effective Hgg vertex is induced via top-quark loop

$$\text{CP}-\text{even}: \quad i\frac{m_t}{v} \quad \rightarrow \quad H\, G^a_{\mu\nu} G^{\mu\nu,a} \text{ coupling}$$

$$\text{CP}-\text{odd}: \quad \frac{m_t}{v}\,\gamma_5 \quad \rightarrow \quad H\, G^a_{\mu\nu} \tilde{G}^{\mu\nu,a} \text{ coupling}$$

Consider Hjj production via gluon fusion, e.g.



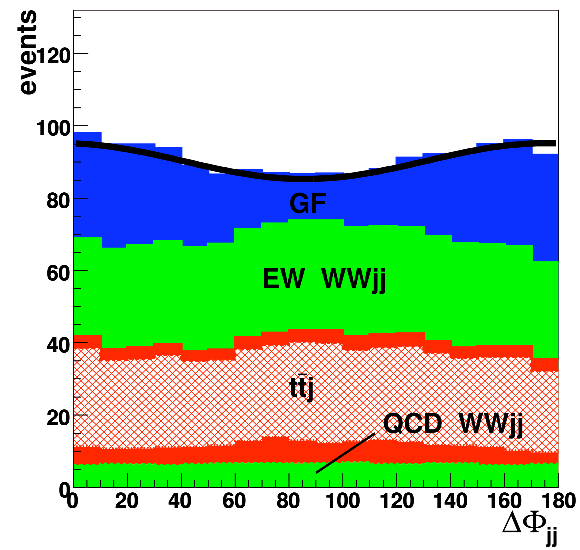
(a)

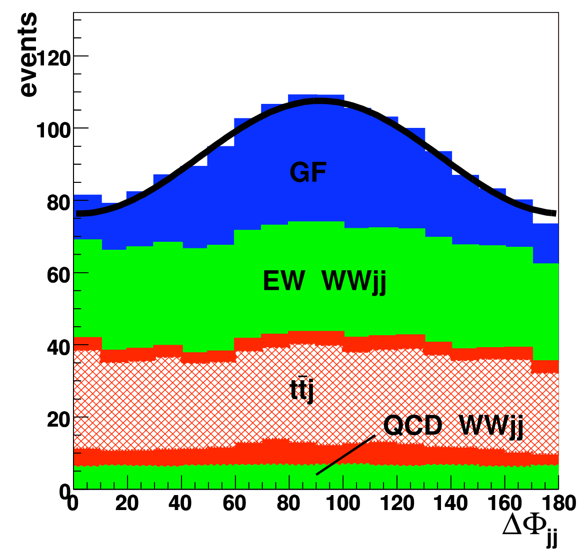
Parton level analysis with relevant backgrounds

(Hankele, Klämke, DZ, hep-ph/0605117)

$\Longrightarrow$ Difference visible in Hjj, $H \rightarrow WW \rightarrow l^+ l^- \not{p}_T$ events at $m_H \approx 160$ GeV with 30 fb^{-1} at 6σ level

Method can be generalized for any Higgs mass. Problem is lower signal rate for $h \rightarrow \tau\tau$ or $h \rightarrow \gamma\gamma$



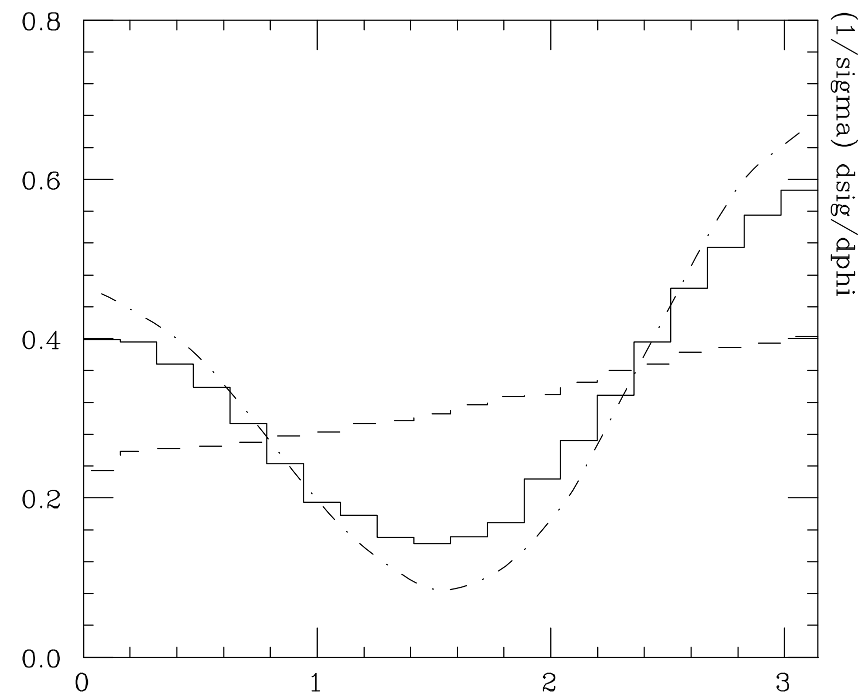


Monte Carlo simulations begun in Del Duca et al, hep-ph/0608158

Angular correlations survive the parton shower.

Shown is SM gluon fusion Hjj with and without parton shower, and SM VBF with parton shower.

[from Del Duca et al, hep-ph/0608158]



Can separate gluon fusion and VBF events using rapidity gap between two “tagging jets”.

Expectation in CP-mixed case:
- See sum of CP-even and CP-odd shapes in gluon fusion
- See SM-like shape in VBF Higgs production (CP-odd part much smaller; no interference term)

Where does the CP-violation come from?

- Can have a "CP-mixed" mass eigenstate
  + e.g., mixture of A^0 and H^0 in MSSM.

- Can have CP-violation in the coupling
  + e.g., new physics in radiative corrections to $Ht\bar{t}$ coupling with new CP-violating phases will induce a CP-odd coupling proportional to γ_5.

Measuring the CP-even and CP-odd components of a single cross section does not tell you where the CP violation comes from.

+ Not a direct measurement of CP admixture. Really measuring BR(even) and BR(odd).

Combining enough measurements within a model context allows to overconstrain/test the model.

+ Kind of reminiscent of B physics.

2. Higgs triplets (and higher)

The SM Higgs multiplet is a doublet of SU(2).

- Let's consider larger SU(2) multiplets.

The next-larger multiplet is the SU(2) triplet:

$$\Phi = \begin{pmatrix} \phi \\ \phi \\ \phi \end{pmatrix}$$

What about the electric charges?

- Need to assign Φ a hypercharge: $Q = T^3 + Y/2$
- We'll want to give Φ a vev: need a neutral component so as not to break electromagnetism.

Two options: $Y = 0$ (real triplet) and $Y = 2$ (complex triplet).

$$Y = 0: \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix} \qquad\qquad Y = 2: \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}$$

$$Y = 0 \text{ real triplet : } \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$$

- Real triplet: three degrees of freedom.

  + ξ^0 is a real scalar: one degree of freedom.

  + ξ^0 can have a vev: $\xi^0 \to \xi^0 + v_0$.

  + $\xi^- = -\xi^{+*}$ is a complex scalar: two degrees of freedom.

  + The minus sign in $\xi^- = -\xi^{+*}$ is just a phase convention.

$$Y = 2 \text{ complex triplet : } \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}$$

- Complex multiplet: six degrees of freedom.

  + Any multiplet with nonzero hypercharge must be complex: its complex conjugate has opposite hypercharge.

  + χ^{++} and χ^+ are both complex scalars: two degrees of freedom each.

  + $\chi^0 = (\chi^{0.r} + i\chi^{0,i})/\sqrt{2}$ is a complex scalar: two more degrees of freedom.

  + χ^0 can have a vev: $\chi^0 \to (\chi^{0,r} + v_2 + i\chi^{0,i})/\sqrt{2}$

Where do we find Higgs triplets?

- Little Higgs models:
  + Littlest Higgs: 1 complex triplet
  + Littlest Higgs with custodial sym. [Chang]: 1 complex + 1 real triplet
  + Minimal Moose: 1 light complex triplet
  + Minimal Moose with custodial sym. [Chang & Wacker]: 1 real triplet
  + Moose with T-parity [Cheng & Low]: 3 real triplets

- Models for neutrino mass generation from scalar triplets
  + Typically contain 1 complex triplet

- Models of a composite Higgs
  + Can contain scalar triplets of SU(2) analogous to isospin-triplet mesons

- Ad-hoc models
  + Designed to study in a model-independent way whatever Nature might throw at us

How can the triplet states be produced?

- Single-production from couplings to gauge bosons:
  + $\mathcal{L} = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + \cdots$ gives ΦVV couplings proportional to Φ vev.

- Single-production from couplings to fermions:
  + Forbidden because the relevant Lagrangian terms aren't gauge invariant.
  + But see below for lepton-number violating couplings...

- Pair production from couplings to gauge bosons:
  + $\mathcal{L} = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + \cdots$ gives $\Phi\Phi VV$ gauge couplings.
  + Pair production signatures are kinematically suppressed for heavy Φ

Single-production from couplings to gauge bosons

Real triplet:

$\xi^0 W^+ W^- = 2ig^2 v_0 g^{\mu\nu}$ compare $H_{\rm SM} W^+ W^- = i\frac{g^2 v}{2} g^{\mu\nu}$

$\xi^0 ZZ = 0$ compare $H_{\rm SM} ZZ = i\frac{g^2 v}{2c_W^2} g^{\mu\nu}$

+ ξ^0 production in WW boson fusion

$\xi^+ W^- Z = ig^2 c_W v_0 g^{\mu\nu}$ compare $H^+_{\rm 2HDM} W^- Z = 0$

$\xi^+ W^- \gamma = igev_0 g^{\mu\nu}$ compare $H^+_{\rm 2HDM} W^- \gamma = 0$

+ ξ^+ production in WZ, $W\gamma$ fusion; characteristic coupling to identify non-doublet state

Complex triplet:

$\chi^{0,r} W^+ W^- = ig^2 v_2 g^{\mu\nu}$ compare $H_{\rm SM} W^+ W^- = i\frac{g^2 v}{2} g^{\mu\nu}$

$\chi^{0,r} ZZ = 2i\frac{g^2 v_2}{c_W^2} g^{\mu\nu}$ compare $H_{\rm SM} ZZ = i\frac{g^2 v}{2c_W^2} g^{\mu\nu}$

+ $\chi^{0,r}$ production in WW and ZZ boson fusion ($\chi^{0,i}WW = \chi^{0,i}ZZ = 0$)

$\chi^+ W^- Z = i\frac{g^2 v_2}{\sqrt{2} c_W}(-1 - s_W^2) g^{\mu\nu}$ compare $H^+_{\rm 2HDM} W^- Z = 0$

$\chi^+ W^- \gamma = i\frac{egv_2}{\sqrt{2}} g^{\mu\nu}$ compare $H^+_{\rm 2HDM} W^- \gamma = 0$

+ χ^+ production in WZ, $W\gamma$ fusion; characteristic non-doublet coupling

$\chi^{++} W^- W^- = \sqrt{2} ig^2 v_2 g^{\mu\nu}$

+ Production in like-sign WW fusion; characteristic like-sign W signature in decay of "doubly-charged Higgs"

All these single-production signatures are proportional to the triplet vev (v_0 or v_2).

But the triplet vev is tightly constrained by the measurement of the ρ parameter: $\rho \equiv \frac{m_W^2}{m_Z^2 c_W^2} = 1$ in the Standard Model.

Real triplet plus doublet(s):

$$m_W^2 = \frac{g^2}{4}(v_d^2 + 4v_0^2), \; m_Z^2 = \frac{g^2}{4c_W^2} v_d^2 \quad \longrightarrow \quad \rho = \frac{v_d^2 + 4v_0^2}{v_d^2} = 1 + \frac{4v_0^2}{v_d^2}$$

Complex triplet plus doublet(s):

$$m_W^2 = \frac{g^2}{4}(v_d^2 + 2v_2^2), \; m_Z^2 = \frac{g^2}{4c_W^2}(v_d^2 + 4v_2^2) \longrightarrow \rho = \frac{v_d^2 + 2v_2^2}{v_d^2 + 4v_2^2} \simeq 1 - \frac{2v_2^2}{v_d^2}$$

Rho parameter constraint forces $v_{0,2} \ll v_{\rm SM}$.
Single-production cross section suppressed by tiny triplet vev.

Have to pair-produce the triplet states
(via gauge coupling, unsuppressed):

$$\begin{array}{lll} \gamma^* & \rightarrow & \xi^+\xi^-; \;\; \chi^+\chi^-, \chi^{++}\chi^{--} \\ Z^* & \rightarrow & \chi^{0,r}\chi^{0,i}, \chi^+\chi^-, \chi^{++}\chi^{--} \\ W^{+*} & \rightarrow & \xi^+\xi^0; \;\; \chi^+\chi^{0,r}, \chi^+\chi^{0,i}, \chi^{++}\chi^- \end{array}$$

Another way around the ρ parameter constraint:
Engineer a cancellation between a real triplet and a complex triplet!

$$\rho = \frac{v_d^2 + 2v_2^2 + 4v_0^2}{v_d^2 + 4v_2^2} \rightarrow \text{Need } v_2 = \sqrt{2} v_0.$$

Removes the constraint on the triplet vevs from the ρ parameter.

Georgi-Machacek model

Combine one complex triplet and one real triplet into a multiplet of $SU(2)_L \times SU(2)_R$ [along with the usual SM Higgs doublet]:

$$\chi = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & \xi^- & \chi^0 \end{pmatrix}, \qquad \langle \chi \rangle = \begin{pmatrix} v_\chi & 0 & 0 \\ 0 & v_\chi & 0 \\ 0 & 0 & v_\chi \end{pmatrix}$$

so that $v_0 = v_\chi$, $v_2 = \sqrt{2} v_\chi = \sqrt{2} v_0$.

The unbroken diagonal subgroup of $SU(2)_L \times SU(2)_R$ is the (global) "custodial symmetry": ensures $\rho = 1$ at tree level.

- Preserved by the Higgs vevs and potential.
- Violated by hypercharge – ρ gets a counterterm beyond tree level.
- Get χVV couplings $\propto v_\chi$: single production of triplet states.

Used in Littlest Higgs with custodial symmetry [Chang].

Lepton-number-violating couplings and neutrino mass

There is only one gauge-invariant dimension-four coupling of a complex triplet to fermions:

$$\begin{aligned} \mathcal{L} &= Y_{ij} L_i^T \chi C^{-1} L_j + \text{h.c.} \\ &= Y_{ij} \left(\ell_L^T, \nu_L^T \right)_i \left(\begin{array}{cc} \chi^{++} & \chi^+/\sqrt{2} \\ \chi^+/\sqrt{2} & \chi^0 \end{array} \right) \left(\begin{array}{c} C^{-1}\ell_L \\ C^{-1}\nu_L \end{array} \right)_j + \text{h.c.} \end{aligned}$$

This coupling violates lepton number!

- Majorana neutrino masses $\mathcal{M}_{ij} = Y_{ij} v_2/\sqrt{2} \sim \mathcal{O}(0.1 \text{ eV})$
- Decays to like-sign dileptons: $\chi^{++} \to \ell_i^+ \ell_j^+$
- Decays of other triplet Higgs states: $\chi^+ \to \ell_i^+ \bar\nu_j$; $\chi^{0,r}, \chi^{0,i} \to \nu_i \nu_j, \bar\nu_i \bar\nu_j$
- Flavour structure of decays related to Majorana neutrino mass matrix.

Higgs multiplets larger than triplets

Any scalar multiplet Φ with a vev can contribute to the W and Z boson masses through the covariant derivative term:

$$\mathcal{L} = (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + \cdots,$$

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}\left(W_\mu^+ T^+ + W_\mu^- T^-\right) - i\frac{g}{c_W} Z_\mu \left(T^3 - s_W^2 Q\right) - ieQA_\mu$$

To keep the photon massless, the vev can only be in the neutral component of Φ: plug in $Q = T^3 + Y/2 = 0$.

$$m_Z^2 = \frac{g^2}{4c_W^2} \sum_k Y_k^2 v_k^2$$

$$m_W^2 = \frac{g^2}{4} \left\{ \sum_k 2 \left[T_k(T_k+1) - \frac{Y_k^2}{4} \right] v_k^2 + \sum_i 2T_i(T_i+1) v_i^2 \right\}$$

where k sums over complex multiplets and i sums over real ($Y = 0$) multiplets.

Problem: $\rho \equiv m_W^2 / m_Z^2 c_W^2 \neq 1$ at tree level!

Solutions:

- Engineer a cancellation between positive and negative contrib'ns to ρ.
- Use only multiplets for which $\rho = 1$ automatically (like doublets).

Consider multiplets for which $\rho = 1$ automatically.

Need to satisfy the relation $(2T+1)^2 - 3Y^2 = 1$.

This is satisfied by:

- Singlet $(T, Y) = (0, 0)$
- Familiar doublet $(T, Y) = (1/2, 1)$

and a series of larger multiplets:

- Seven-plet $(T, Y) = (3, 4)$
- Twenty-six-plet $(T, Y) = (25/2, 15)$
- etc.

An important issue: extra accidental U(1) symmetries.

- Each scalar field transforms under a U(1) rotation: this is just its hypercharge.

- Adding a new scalar field to the SM can introduce a new global U(1) symmetry if the new field can be rotated without rotating all the rest of the hypercharged fields.

- Giving the new scalar field a vev breaks this global U(1), resulting in a massless Goldstone boson: $\phi^{0,i}$ is massless.

Singlet with a vev:

- Must be neutral: can write a complex state as a sum of two real states.
- Can always write $m_S^2 SS$ term to eliminate extra U(1) rotating S.

Any real multiplet R with a vev:

- Can always write $m_R^2 RR$ term to eliminate extra U(1) rotating R.

Doublet with a vev:

- Can always write $m_{12}^2 H_1^\dagger H_2$ term to eliminate extra U(1) rotating H_2.

Complex triplet with a vev:

- Can always write $m H^\dagger \chi H^*$ term to eliminate extra U(1) rotating χ.

Multiplet larger than a triplet:

- Need to conserve SU(2): In order to eliminate the extra U(1), must construct an N-plet out of H's to couple to one N-plet.
- This is impossible for anything larger than a four-plet.
- Any model with a doublet (to give masses to fermions) plus a larger multiplet for which $\rho = 1$ automatically (seven-plet, twenty-six-plet, etc) fails this condition.
- If the larger multiplet gets a vev, its $\chi^{0,i}$ will be massless.

A (contrived) way around this: Ladder multiplets

Start with doublet(s) (to give mass to fermions).

Add a triplet; couple to the doublet to get rid of triplet's U(1).

- Can use Georgi-Machacek mechanism to avoid ρ param. constraint.

With triplets, can build up a seven-plet.

- The ($\rho = 1$)-preserving seven-plet X has $Y = 4$:
- Need a $Y = 2$ triplet χ and a $Y = 0$ triplet ξ
- Can then write $X\chi^\dagger\chi^\dagger\xi$ to eliminate the extra U(1) rotating X

Had to introduce multiplets that don't preserve $\rho = 1$:
lost the nice feature of the ($\rho = 1$)-preserving-multiplets idea.

This looks rather unconvincing.

Scalars without vevs [can we really call this a Higgs?]

Without a vev, extra global U(1)'s don't cause any problems.

- Extra global U(1) leads to a stable particle that could be dark matter!

Vevless singlet:

- Couple to gauge bosons only in pairs.
- Neutral singlet can mix with SM doublet Higgs – SM decay modes.
  - [Unless prevented by an imposed symmetry.]

Vevless doublet:

- Can couple singly to fermions – decay mode.
- Can mix with SM doublet – SM decay modes.
  - [Unless prevented by an imposed symmetry.]

Vevless triplet:

- Can couple singly to two SM Higgs doublets – decay mode.
- Can couple to lepton doublets (LNV) – decay mode.
  - [Unless prevented by an imposed symmetry.]

All other vevless multiplets:

- If we can't get rid of accidental global U(1), scalar will be stable!

- Any gauge invariant Lagrangian term you can write will have an even number of factors of the field.

3. Multi-Higgs-doublet models

Consider again the covariant derivative terms: $\mathcal{L} = \sum_i (\mathcal{D}_\mu H_i)^\dagger (\mathcal{D}^\mu H_i)$

- W and Z masses come from replacing both H_i's with their vevs.
- ϕWW and ϕZZ couplings come from replacing one H_i with its vev.

Doublets: $m_W^2 = \frac{g^2}{4} \sum_i v_i^2$ $\quad \rightarrow \quad$ Sum rule for vevs: $\sum_i v_i^2 = v_{\rm SM}^2$

Couplings: $\phi_i^{0,r} W^+ W^- = i \frac{g^2}{2} v_i g^{\mu\nu}$ and $\phi_i^{0,r} ZZ = i \frac{g^2}{2c_W^2} v_i g^{\mu\nu}$

Result is a sum rule for the Higgs couplings: $\sum_i g^2_{\phi_i^{0,r} VV} = g^2_{H_{\rm SM} VV}$

with $V = W$ or Z

Obvious consequence of sum rule: $g^2_{\phi_i^{0,r} VV} \leq g^2_{H_{\rm SM} VV}$ for any individual $\phi_i^{0,r}$.

Sum rule holds when the model contains only Higgs doublets.

- Can add any number of singlets for free: no coupling to WW, ZZ, so they don't contribute to the sum.

The sum rule can be violated if larger multiplets are present.

Consider Georgi-Machacek model: triplet vevs not constrained by ρ parameter.

Sum rule for vevs: m_W, m_Z formulae $\quad \rightarrow \quad v_d^2 + 8 v_\chi^2 = v_{\rm SM}^2$

$$\sum_i g^2_{\phi^{0,r} WW} = g^2_{H_{\rm SM} WW} \frac{v_d^2 + 24 v_\chi^2}{v_{\rm SM}^2} = g^2_{H_{\rm SM} WW} [1 + 16 v_\chi^2 / v_{\rm SM}^2]$$

$$\sum_i g^2_{\phi^{0,r} ZZ} = g^2_{H_{\rm SM} ZZ} \frac{v_d^2 + 16 v_\chi^2}{v_{\rm SM}^2} = g^2_{H_{\rm SM} ZZ} [1 + 8 v_\chi^2 / v_{\rm SM}^2]$$

Violation of coupling sum rules proportional to triplet vev $v_\chi^2 / v_{\rm SM}^2$.

ϕWW and ϕZZ coupling sum rules violated by different amounts.

This is due to the different hypercharges and SU(2) Clebsch-Gordan coefficients for doublets vs. triplets.

$$m_Z^2 \sim Y_i^2 v_i^2; \qquad \sum g^2_{\phi ZZ} \sim (Y_i^2 v_i)^2$$

Testing the doublets/singlets sum rule:

A Higgs coupling $g^2_{\phi_i^{0,r}VV} > g^2_{H_{\rm SM}VV}$ is a smoking gun for Higgs multiplets larger than doublets, with a sizeable vev.

Look at Higgs production via the $\phi_i^{0,r}VV$ coupling

- Consider VBF, $W + H$, $Z + H$
- Production cross section is proportional to $g^2_{\phi_i^{0,r}VV}$.

All Higgs decay branching fractions must add up to 1.

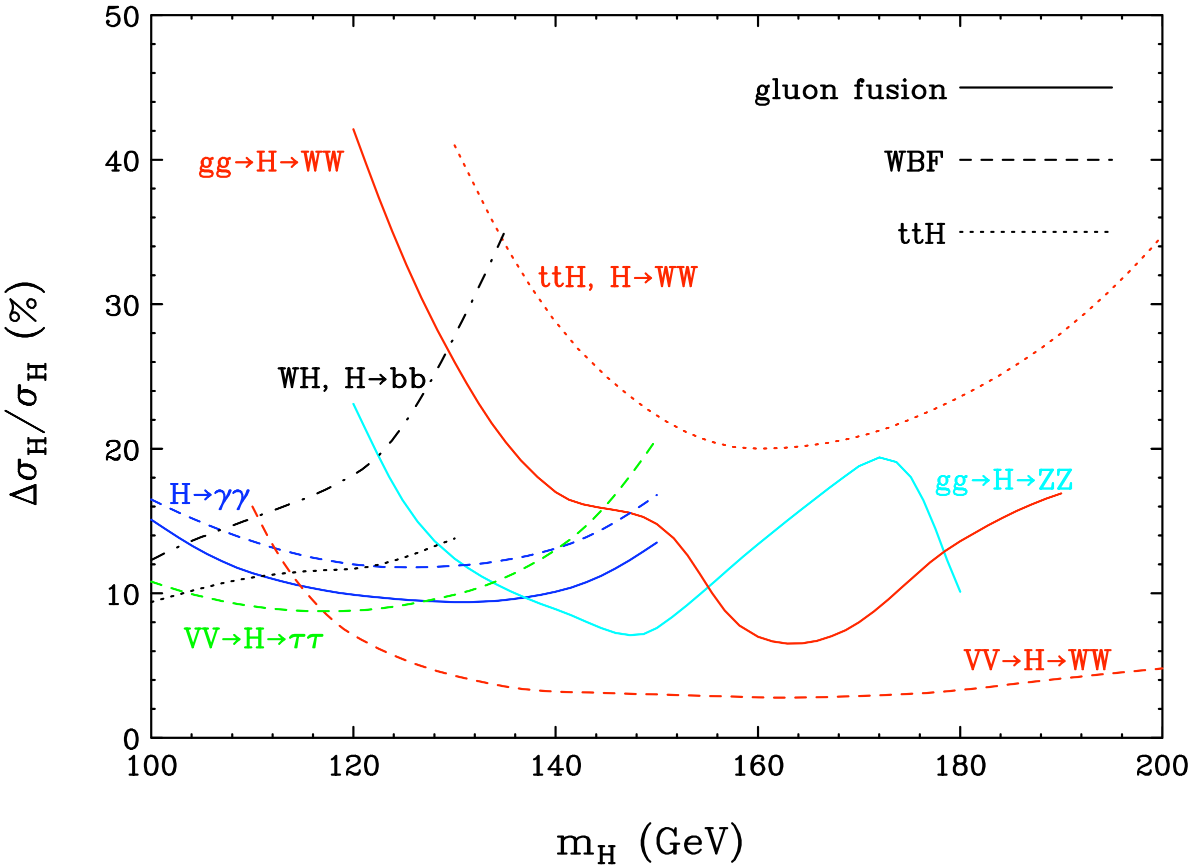
- Add up rates for all visible Higgs decay modes. A rate greater than the SM expectation indicates sum rule violation.

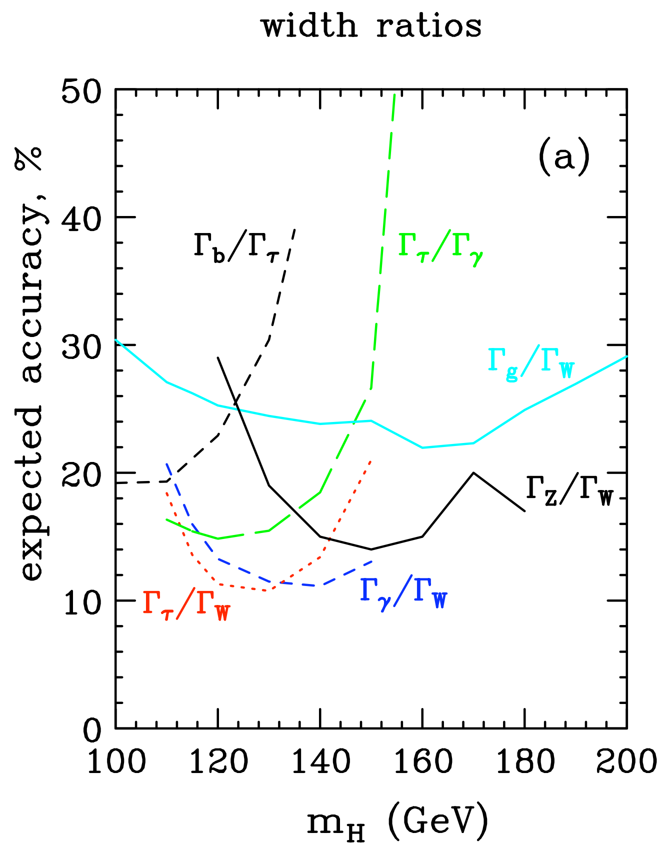
A ratio of ϕWW and ϕZZ couplings different from the SM expectation is also a smoking gun for Higgs multiplets larger than doublets, with a sizeable vev.

- Check for $g^2_{\phi_i^{0,r}WW}/g^2_{\phi_i^{0,r}ZZ} \neq g^2_{H_{\rm SM}WW}/g^2_{H_{\rm SM}ZZ} = c_W^4$

If no violation of the doublets/singlets sum rule is seen, it can be used as an assumption to extract Higgs couplings from LHC data.

LHC will measure Higgs production times decay rates
$\longrightarrow$ take ratios to get ratios of partial widths.



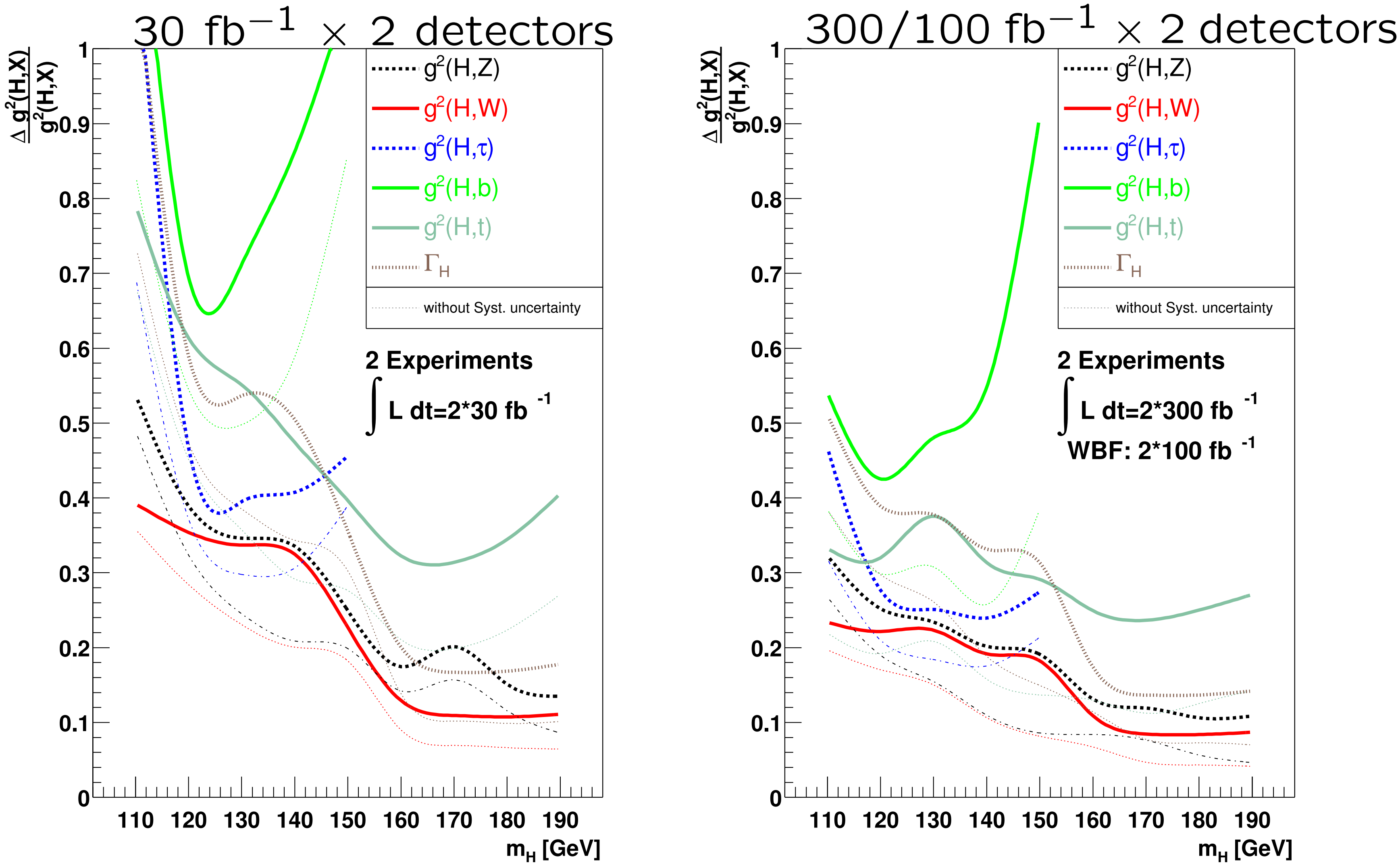


LHC, 200 fb^{-1} (except 300 fb^{-1} for $ttH, H \to bb$, $WH, H \to bb$)

from Zeppenfeld, hep-ph/0203123

No upper limit on total Higgs width: [lineshape too narrow for light Higgs]
need a theory assumption to fit Higgs couplings-squared.

$\rightarrow$ Assume only Higgs doublet(s) and singlet(s): $g^2_{\phi VV} \leq g^2_{H_{SM}VV}$



Dührssen, Heinemeyer, H.L., Rainwater, Weiglein & Zeppenfeld, hep-ph/0406323

4. Summary

CP-even, CP-odd, and mixtures

- Tensor structure of ϕVV coupling illuminates its source:
    + $\phi V_\mu V^\mu$ due to Higgs mechanism.
    + CP-even $\phi V_{\mu\nu} V^{\mu\nu}$ and CP-odd $\phi V_{\mu\nu} \widetilde{V}^{\mu\nu}$ are loop generated.
- Probe WW, gg tensor structures with Hjj signal, azimuthal angle ϕ_{jj}.

Higgs triplets (and higher)

- Triplets show up in many New Physics models.
- Tight constraint from ρ parameter: χVV coups $\propto v_\chi$ suppressed.
    + Pair production?
- Lepton number violation a possibility: $\chi^{++} \to \ell^+ \ell^+$.
- Larger SU(2) reps a possibility, but looks contrived.

Multi-Higgs-doublet models

- Sum rule for ϕVV couplings; violated by larger multiplets.
- Check for sum rule violations in production cross sections.
- If none observed, can use "doublets + singlets" assumption for model-dependent fit of Higgs couplings.