

# A not so elementary Higgs boson

Corfu Summer Institute  
Workshop on Fields and Strings  
Sept. 14-18 2011



*Christophe Grojean*  
CERN-TH & CEA-Saclay/IPhT  
( christophe.grojean@cern.ch )



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# The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

massive  $W^\pm, Z$ : 3 physical polarizations=eaten Goldstone bosons  $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

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At which scale should we expect to see something?

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Lee, Quigg & Thacker '77

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$$\Sigma = e^{i\sigma^a \pi^a / v}$$

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contact interaction growing with energy

$$\mathcal{A}(\pi^a \pi^b \rightarrow \pi^c \pi^d) = \mathcal{A}(s, t, u) \delta^{ab} \delta^{cd} + \mathcal{A}(t, s, u) \delta^{ac} \delta^{bd} + \mathcal{A}(u, t, s) \delta^{ad} \delta^{bc}$$

$$\mathcal{A}(s, t, u) = \frac{s}{v^2} \quad \text{Weinberg's LET}$$

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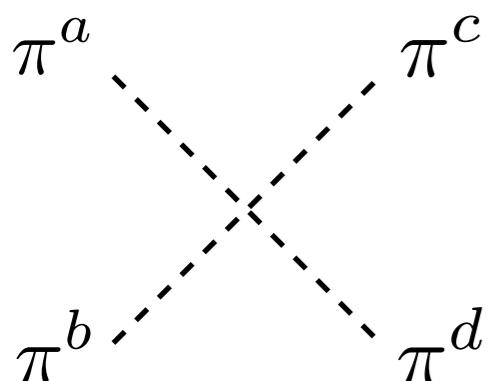
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$$\mathcal{A}(s, t, u) = \frac{s}{v^2} \quad \text{Weinberg's LET}$$

the behavior of this amplitude is not consistent above  $4\pi v$  ( $\approx 1 \div 3 \text{ TeV}$ )

Lee, Quigg & Thacker '77

# Higgs as a PGB: a natural extension of SM

One solution to the hierarchy pb:

Higgs transforms non-linearly under some global symmetry

Higgs=Pseudo-Goldstone boson (PGB)



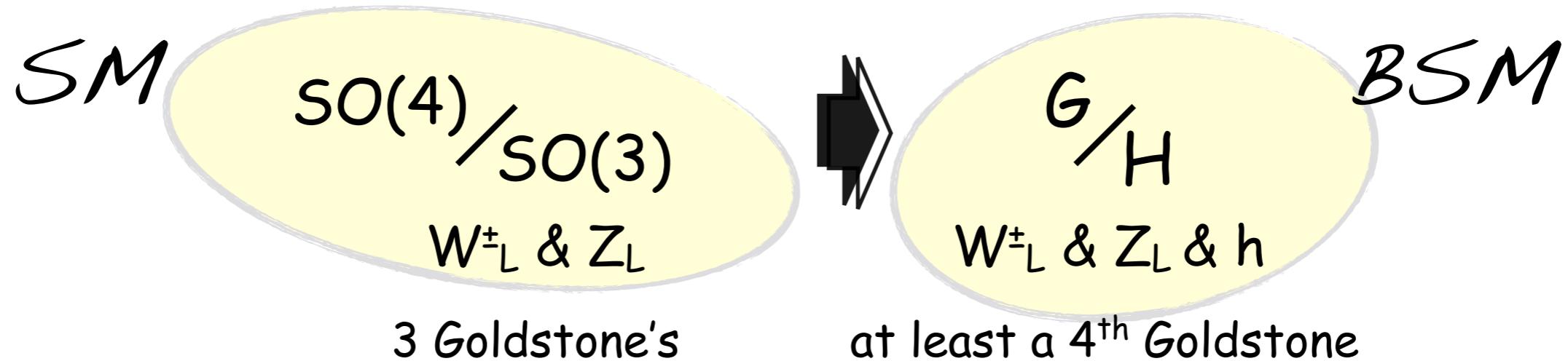
Chacko, Batra '08

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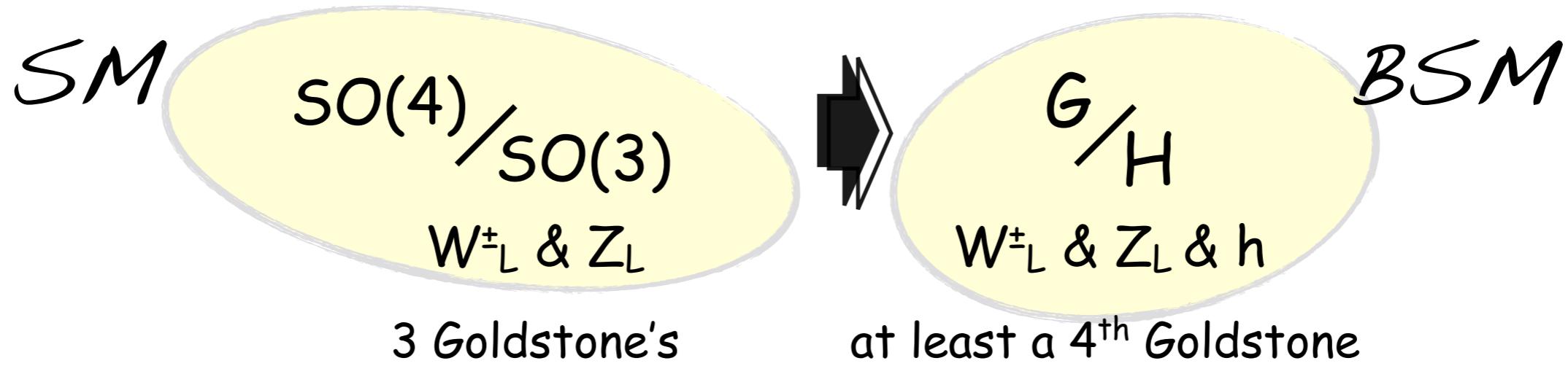
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Examples:  $SO(5)/SO(4)$ : 4 PGBs= $W_L^\pm, Z_L, h$

Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

$SO(6)/SO(5)$ : 5 PGBs= $H, a$

Next MCHM

$SU(4)/Sp(4, \mathbb{C})$ : 5 PGBs= $H, s$

Gripaios, Pomarol, Riva, Serra '09

Chacko, Batra '08

$SO(6)/SO(4) \times SO(2)$ : 8 PGBs= $H_1+H_2$

Minimal Composite  
Two Higgs Doublets

Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

# *How to probe the composite nature of the Higgs?*

## *I. Anomalous couplings*

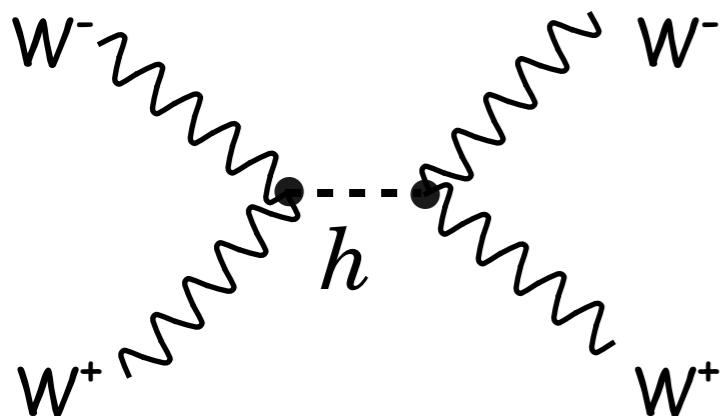


# What is the SM Higgs?

A single scalar degree of freedom neutral under  $SU(2)_L \times SU(2)_R / SU(2)_L$

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4} \text{Tr} \left( D_\mu \Sigma^\dagger D_\mu \Sigma \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - \lambda \bar{\psi}_L \Sigma \psi_R \left( 1 + c \frac{h}{v} \right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2} \left( s - \frac{a^2 s^2}{s - m_h^2} \right)$$

growth cancelled for  
 $a = 1$   
restoration of  
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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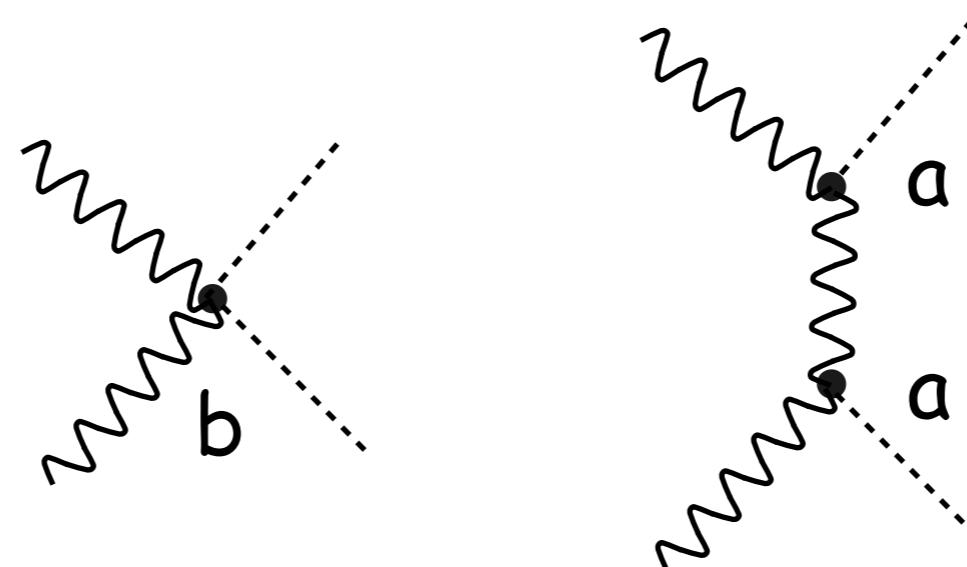
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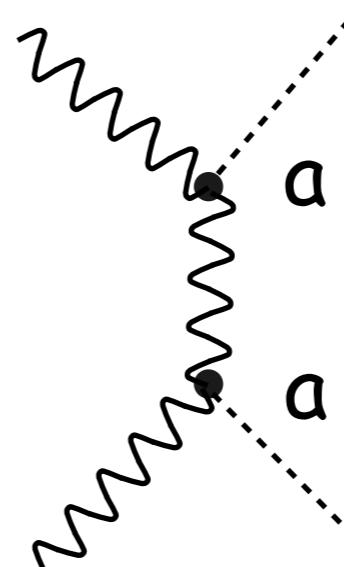
For  $a=1$ : perturbative unitarity in elastic channels  $WW \rightarrow WW$

For  $b = a^2$ : perturbative unitarity in inelastic channels  $WW \rightarrow hh$

Cornwall, Levin, Tiktopoulos '73



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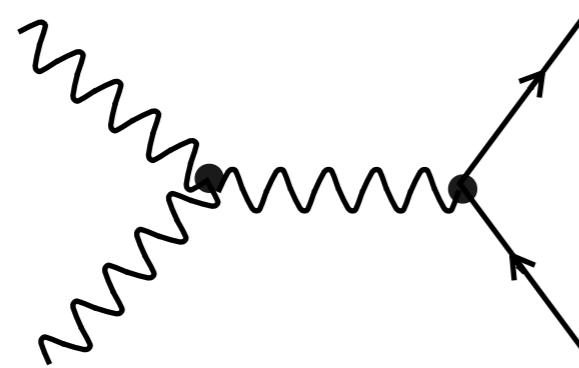
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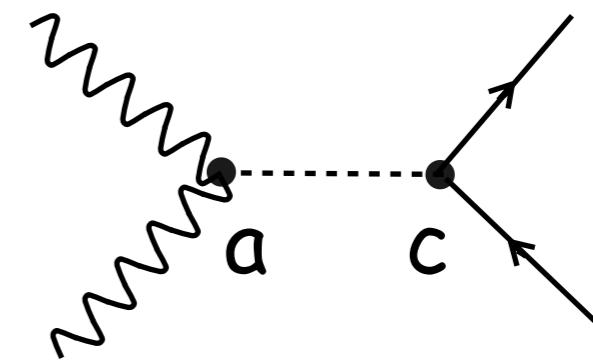
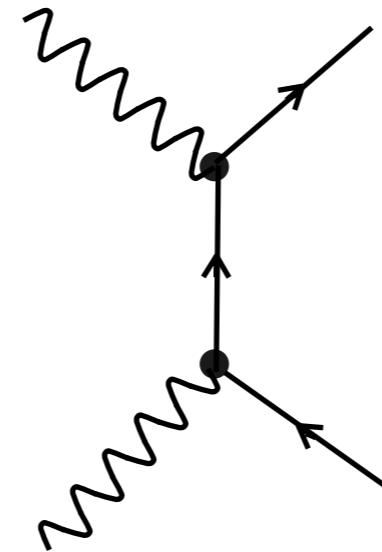
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'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties depend on a single unknown parameter ( $m_H$ )

$\mathcal{L}_{\text{EWSB}}$  can be rewritten as  $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a/v} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$h$  and  $\pi^a$  (ie  $W_L$  and  $Z_L$ ) combine to form a linear representation of  $SU(2)_L \times U(1)_Y$

# What is a composite Higgs?

A  $\sigma$  particle that combines with  $W_L$  and  $Z_L$  to form a  $SU(2)$  doublet  
that acquires a vev

$SU(2)_L \times U(1)_Y$  linearly realized  $\Leftrightarrow$  Standard Model  $\Leftrightarrow a=b=c=1$

renormalizable level = uniqueness

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non-renormalizable level

$SU(2)_L \times U(1)_Y$  linearly realized &  $a, b, c \neq 1 \Leftrightarrow$  Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

$$(\partial_\mu |H|^2)^2 \quad |H|^2 \bar{\psi} H \psi \quad |H|^2 B_{\mu\nu} B^{\mu\nu} \quad |H|^2 G_{\mu\nu} G^{\mu\nu}$$

# Anomalous composite-Higgs couplings

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L} \supset \frac{c_H}{2f^2} \partial^\mu (|H|^2) \partial_\mu (|H|^2) \quad c_H \sim \mathcal{O}(1)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix} \rightarrow \mathcal{L} = \frac{1}{2} \left( 1 + c_H \frac{v^2}{f^2} \right) (\partial^\mu h)^2 + \dots$$

Modified Higgs propagator  $\sim$  Higgs couplings rescaled by  $\frac{1}{\sqrt{1 + c_H \frac{v^2}{f^2}}} \sim 1 - c_H \frac{v^2}{2f^2} \equiv 1 - \xi/2$

$$\xi = v^2/f^2$$

$$a = 1 - \xi/2 \quad b = 1 - 2\xi \quad c = 1 - \xi/2$$

# PGB Higgs: Strong EWSB with 2 Scales

$$\xi = \frac{v^2}{f^2} = \frac{(\text{weak scale})^2}{(\text{strong coupling scale})^2}$$

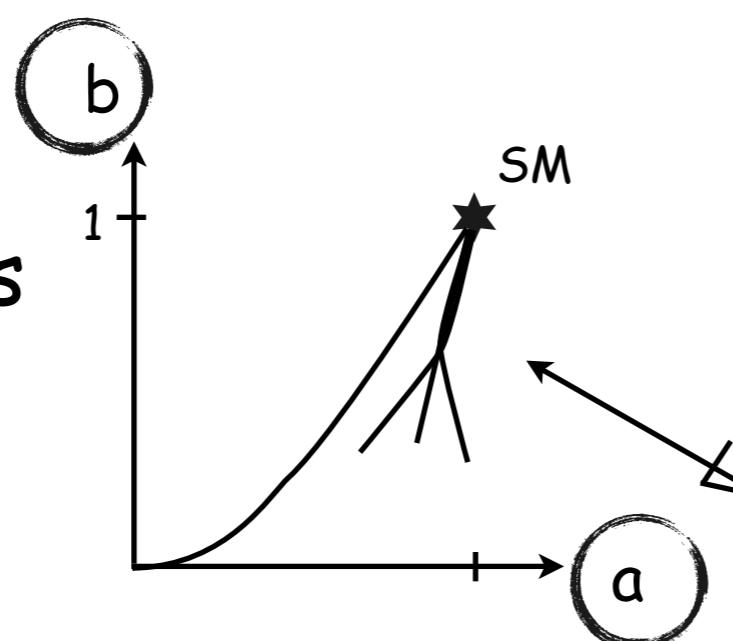
$\xi = 0$   
SM limit

all resonances of strong sector,  
except the Higgs, decouple

$\xi = 1$   
Technicolor limit

Higgs decouple from SM;  
vector resonances like in TC

Composite Higgs  
vs.  
SM Higgs



$$\mathcal{L}_{\text{EWSB}} = \left( a \frac{v}{2} h + b \frac{1}{4} h^2 \right) \text{Tr} (D_\mu \Sigma^\dagger D_\mu \Sigma)$$

Composite Higgs  
universal behavior for large f  
 $a=1-v^2/2f^2$     $b=1-2v^2/f^2$

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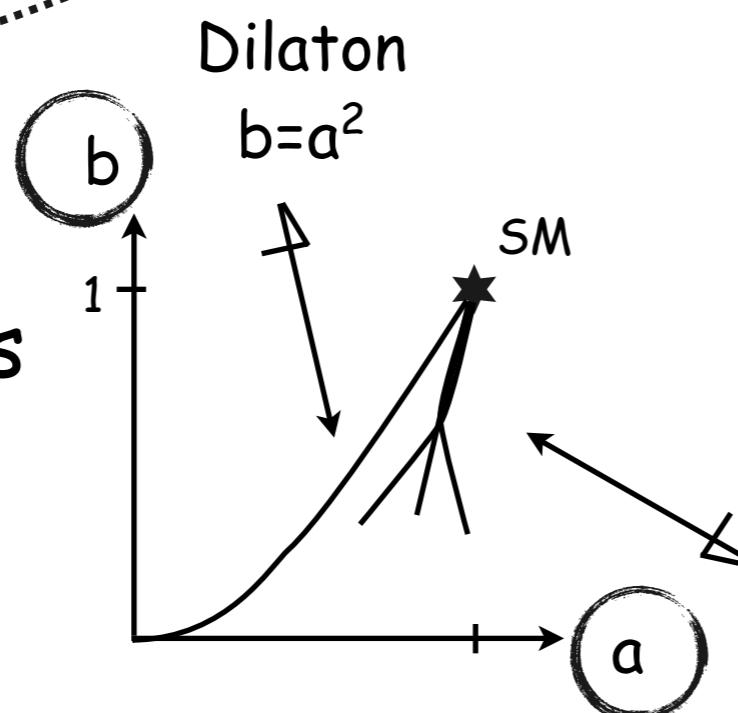
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# Composite Higgs vs generic anomalous couplings

generic anomalous couplings can be quite complicated, e.g.

$$\mathcal{L}_{h-Z} = m_Z h \left( c_1 Z_\mu Z^\mu + \frac{c_2}{m^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{c_3}{m^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

...many coefficients, various possible origins

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...many coefficients, various possible origins

if Higgs emerges as a bound state of strongly interacting theory

a few coefficients only and related to symmetries of the coset space

$$\frac{c_H}{2f^2} \left( \partial^\mu |H|^2 \right)^2$$

$$\frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2} |H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2} |H|^6$$

(other resonances etc give subleading contributions)

very predictive models:

given the coset space, the Higgs couplings depend only on  $\xi$

# Effective Lagrangian

Giudice, Grojean, Pomarol, Rattazzi '07

◆ extra Higgs leg:  $H/f$

◆ extra derivative:  $\partial/m_\rho$

◆ Genuine strong operators (sensitive to the scale  $f$ )

$$\frac{c_H}{2f^2} \left( \partial^\mu |H|^2 \right)^2$$

$$\frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right)^2$$

custodial breaking

$$\frac{c_y y_f}{f^2} |H|^2 \bar{f}_L H f_R + \text{h.c.}$$

$$\frac{c_6 \lambda}{f^2} |H|^6$$

◆ Form factor operators (sensitive to the scale  $m_\rho$ )

$$\frac{i c_W}{2m_\rho^2} \left( H^\dagger \sigma^i \overleftrightarrow{D}^\mu H \right) (D^\nu W_{\mu\nu})^i$$

$$\frac{i c_B}{2m_\rho^2} \left( H^\dagger \overleftrightarrow{D}^\mu H \right) (\partial^\nu B_{\mu\nu})$$

$$\frac{i c_{HW}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i$$

$$\frac{i c_{HB}}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

minimal coupling:  $h \rightarrow \gamma Z$

loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}$$

$$\frac{c_g}{m_\rho^2} \frac{g_\rho^2}{16\pi^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}$$

Goldstone sym.

# Deformation of the SM Higgs: current constraints

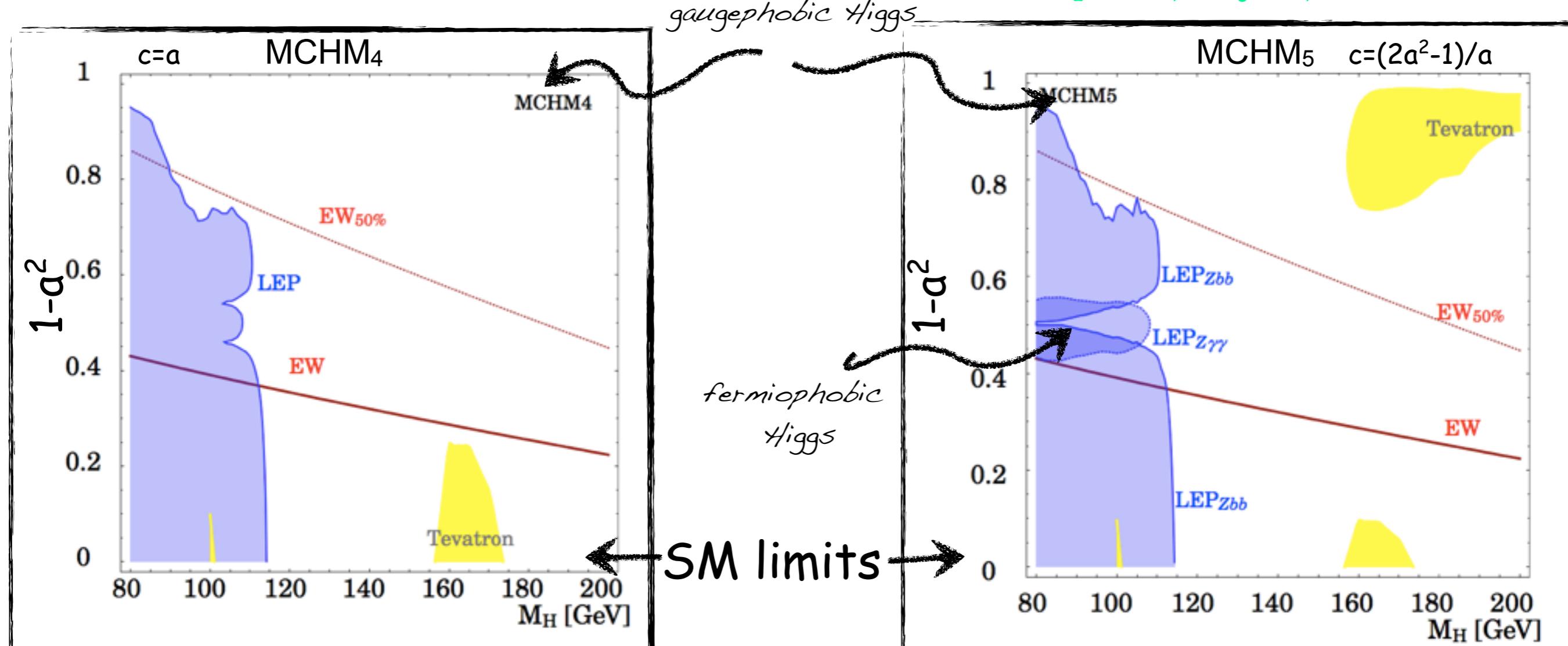
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$\Sigma = e^{i\sigma^a \pi^a/v}$       Goldstone of  $SU(2)_L \times SU(2)_R / SU(2)_V$        $D_\mu \Sigma \approx W_\mu$

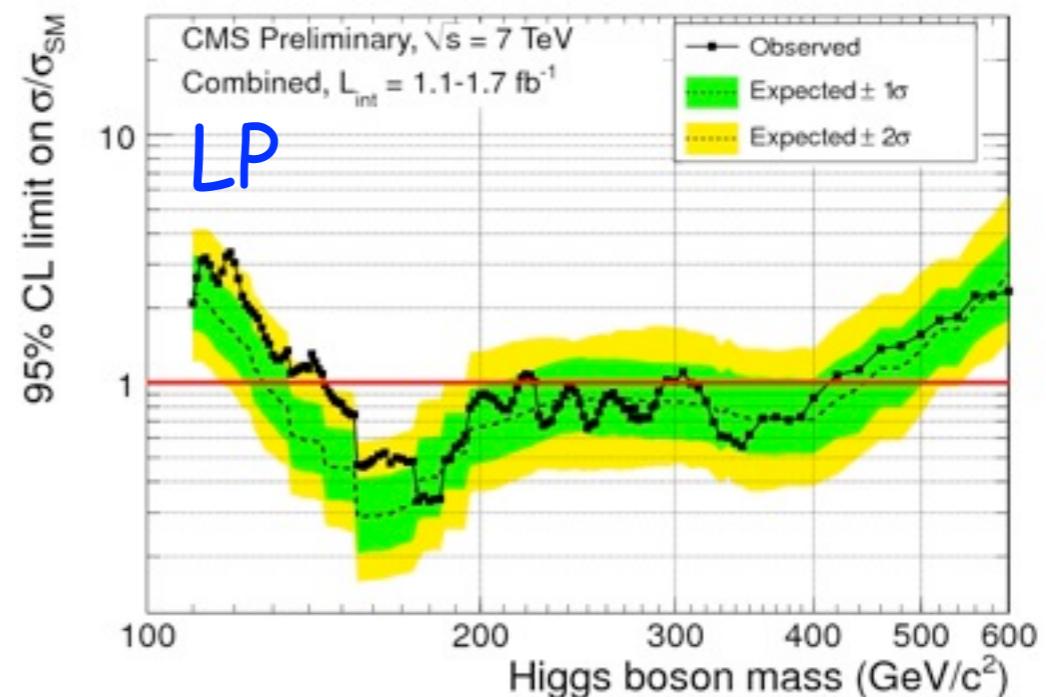
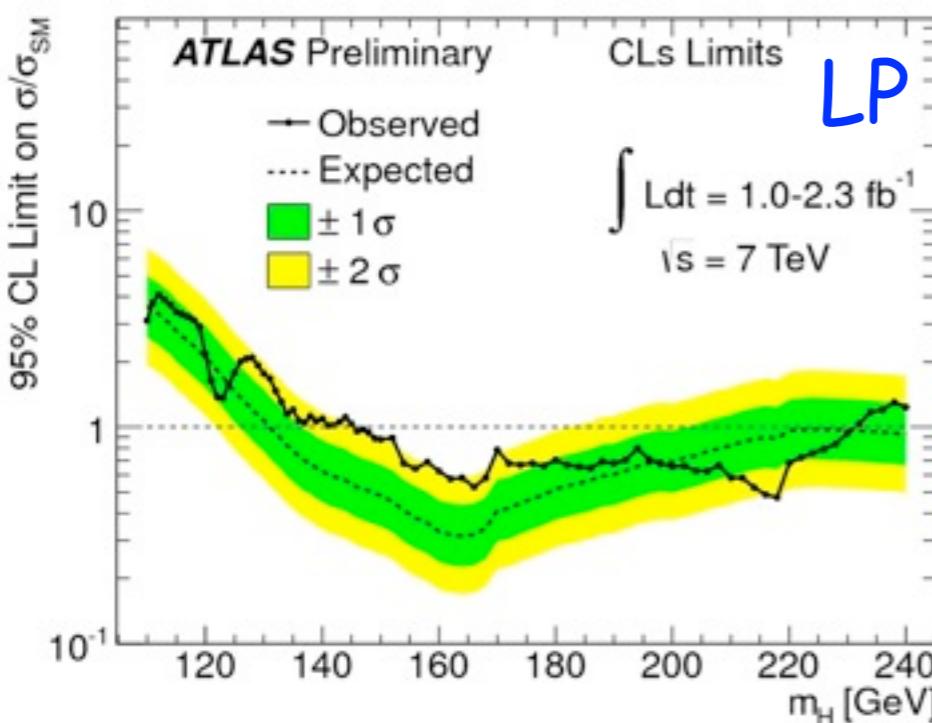
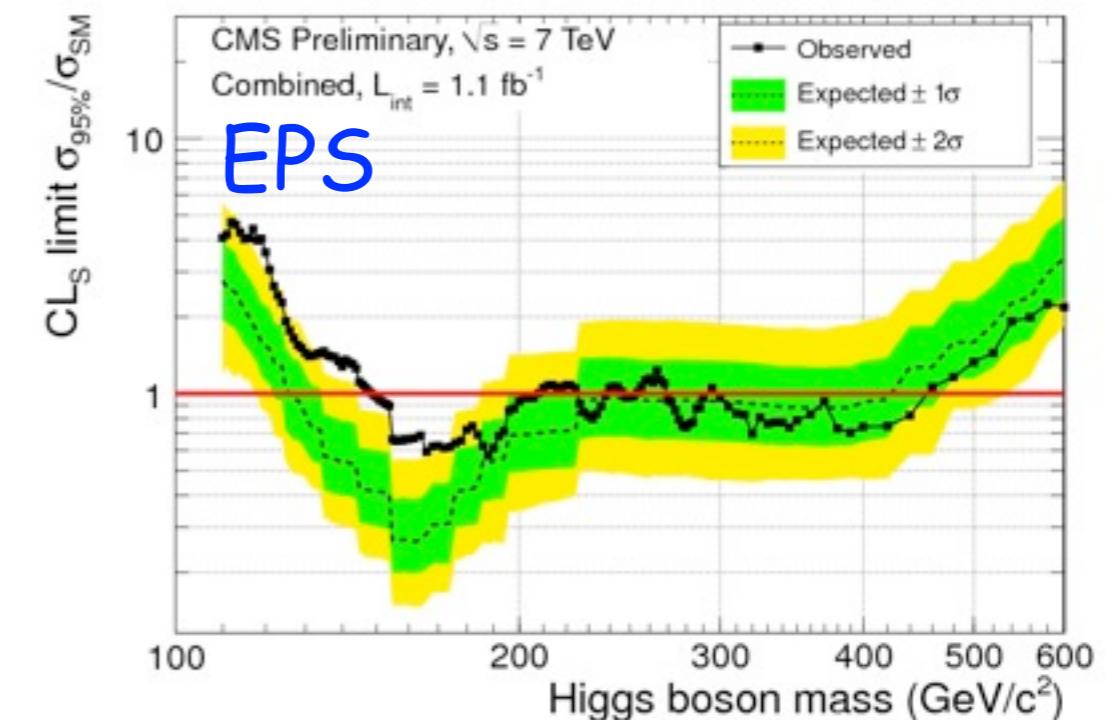
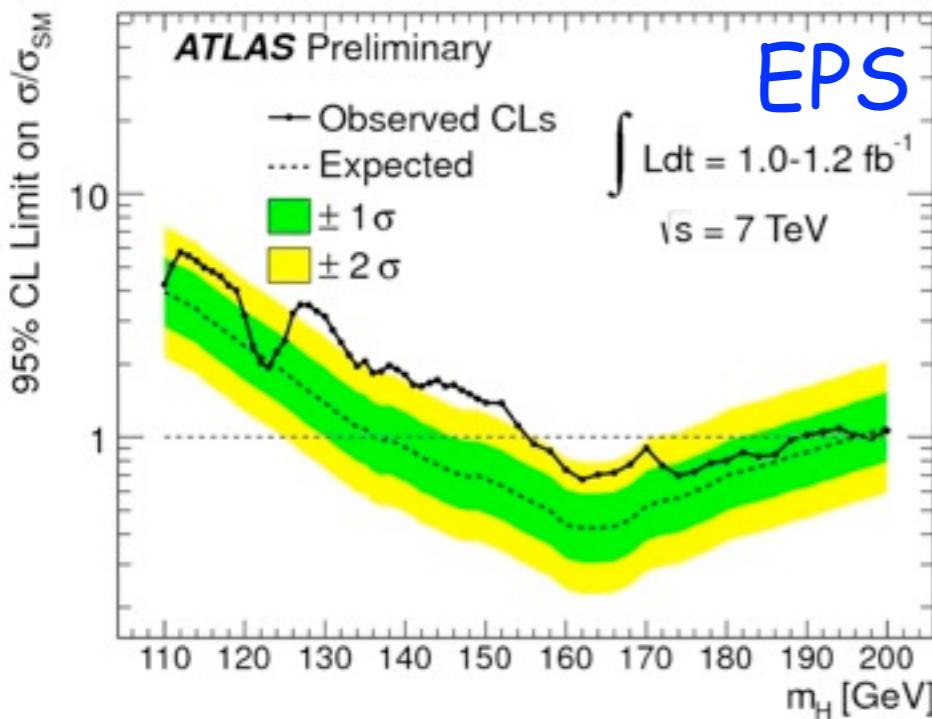
SM 'a=1', 'b=1' & 'c=1'

Current EW data constrain only 'a' (and marginally 'c')

Espinosa, Grojean, Muehlleitner '10

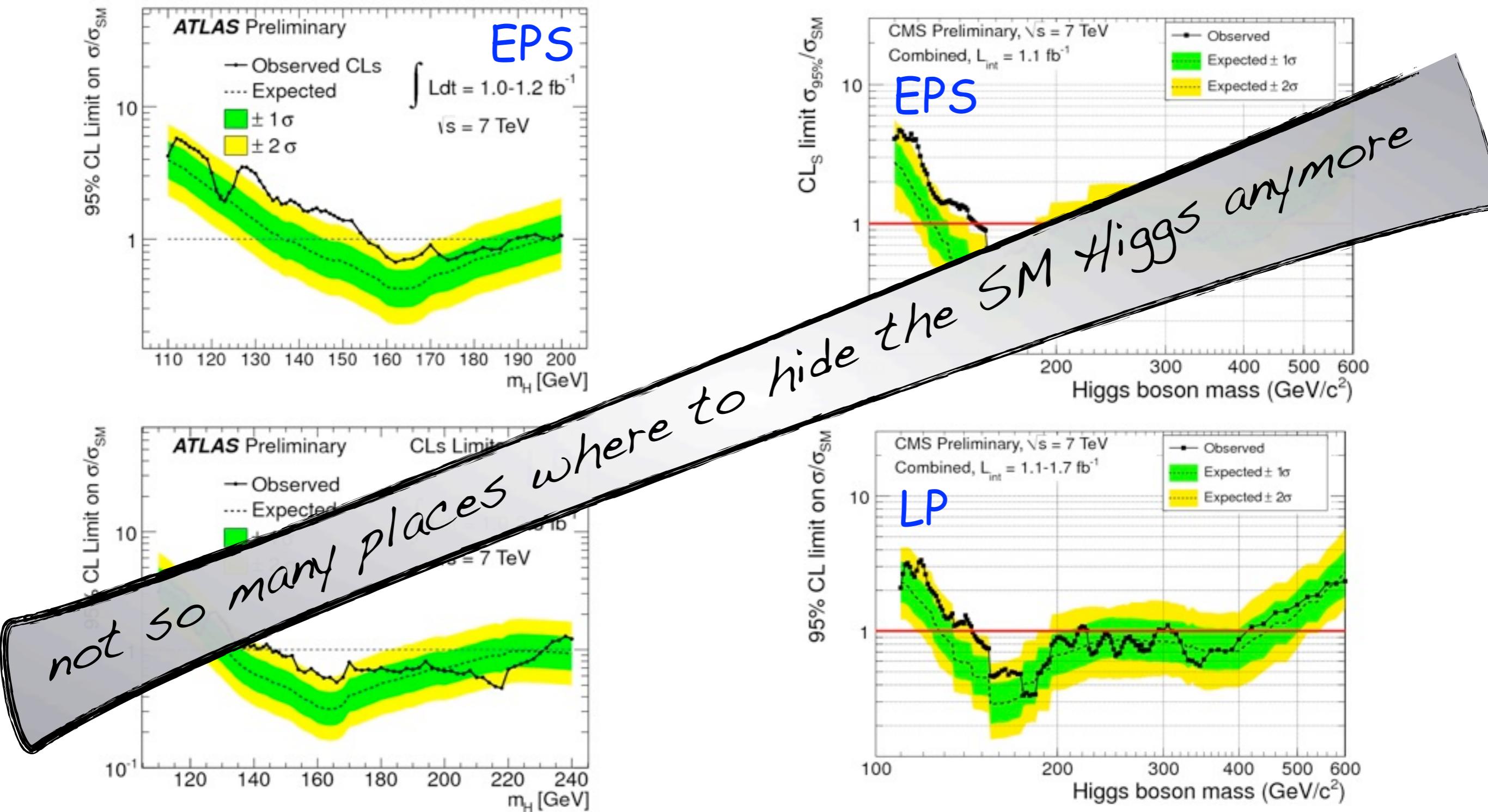


# Deformation of the SM Higgs: LHC constraints



LHC is now a Higgs exploring machine  
(and it has quickly surpassed Tevatron)

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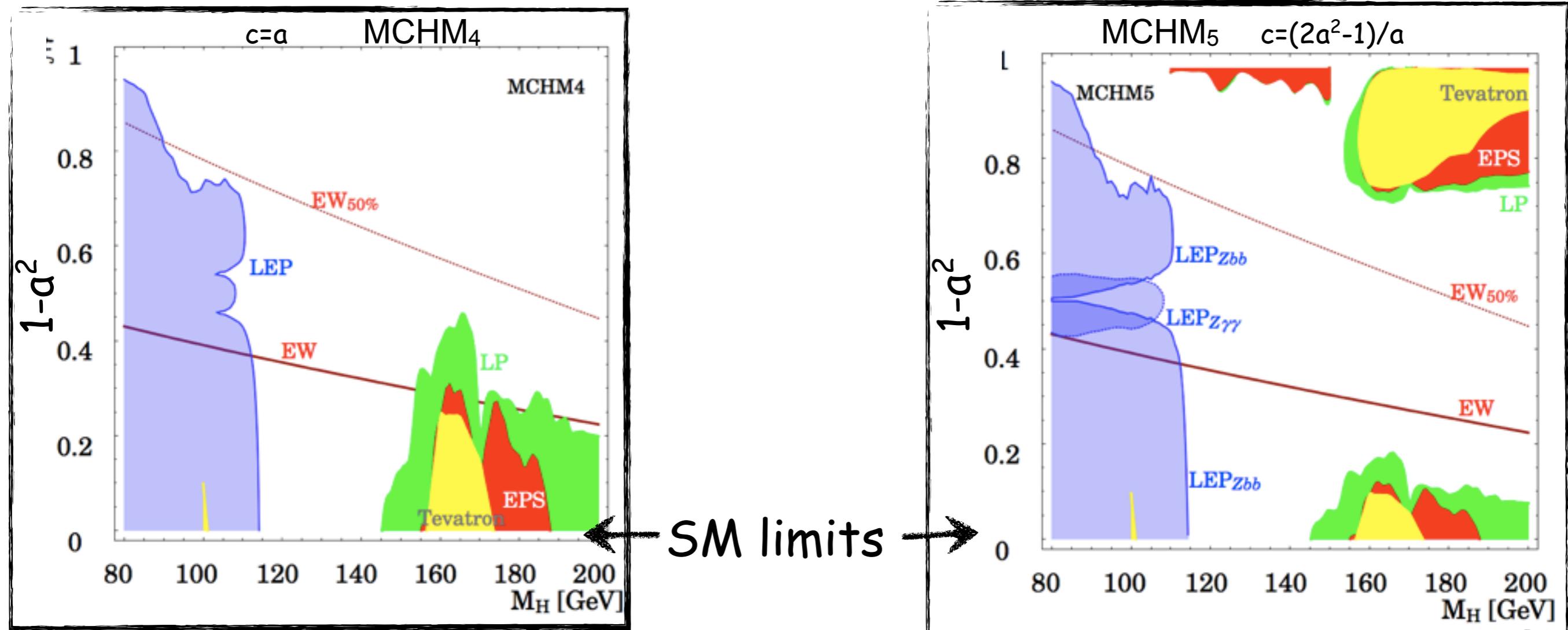


LHC is now a Higgs exploring machine  
(and it has quickly surpassed Tevatron)

# Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the  $(m_H, \alpha)$  plane

Espinosa, Grojean, Muehleitner '11

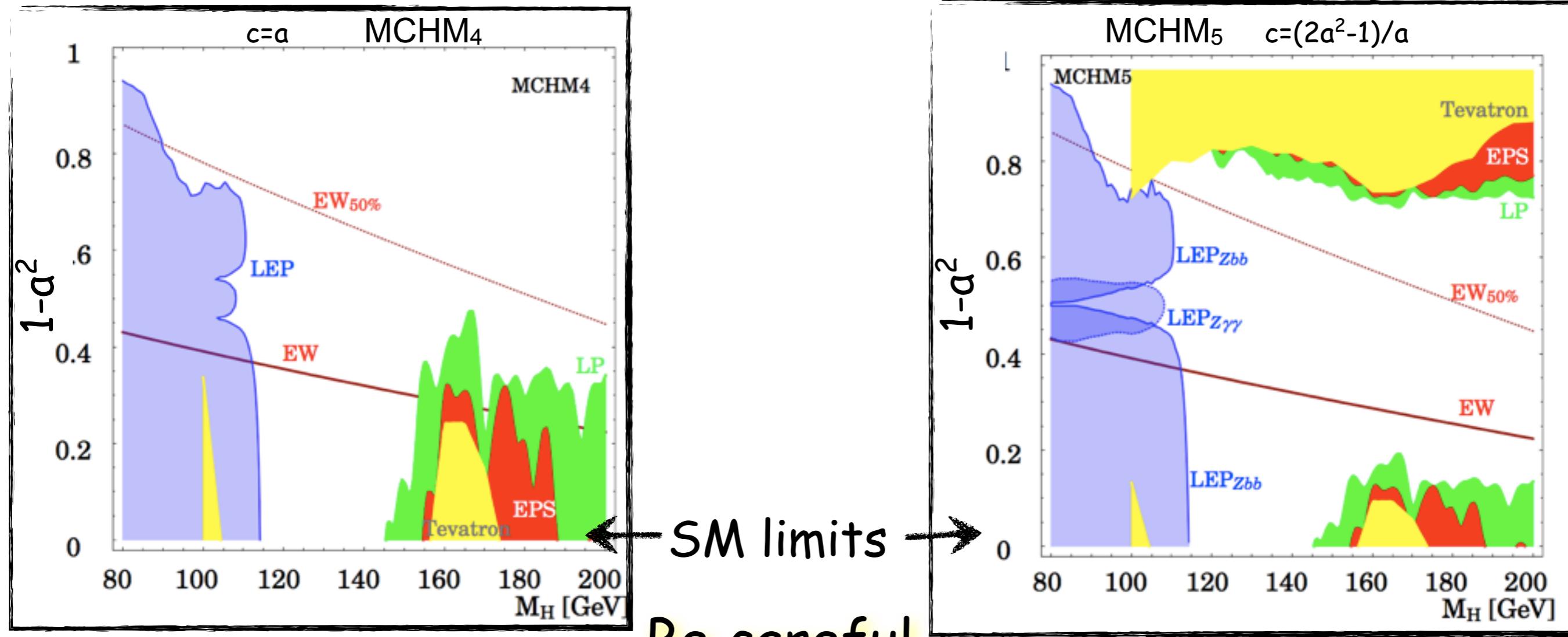


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Espinosa, Grojean, Muehleitner '11



- rescaling combination  $\neq$  combination of the rescaled channels  
(can be particularly important far away from SM)
- efficiency of the cuts may also depends on  $\xi$

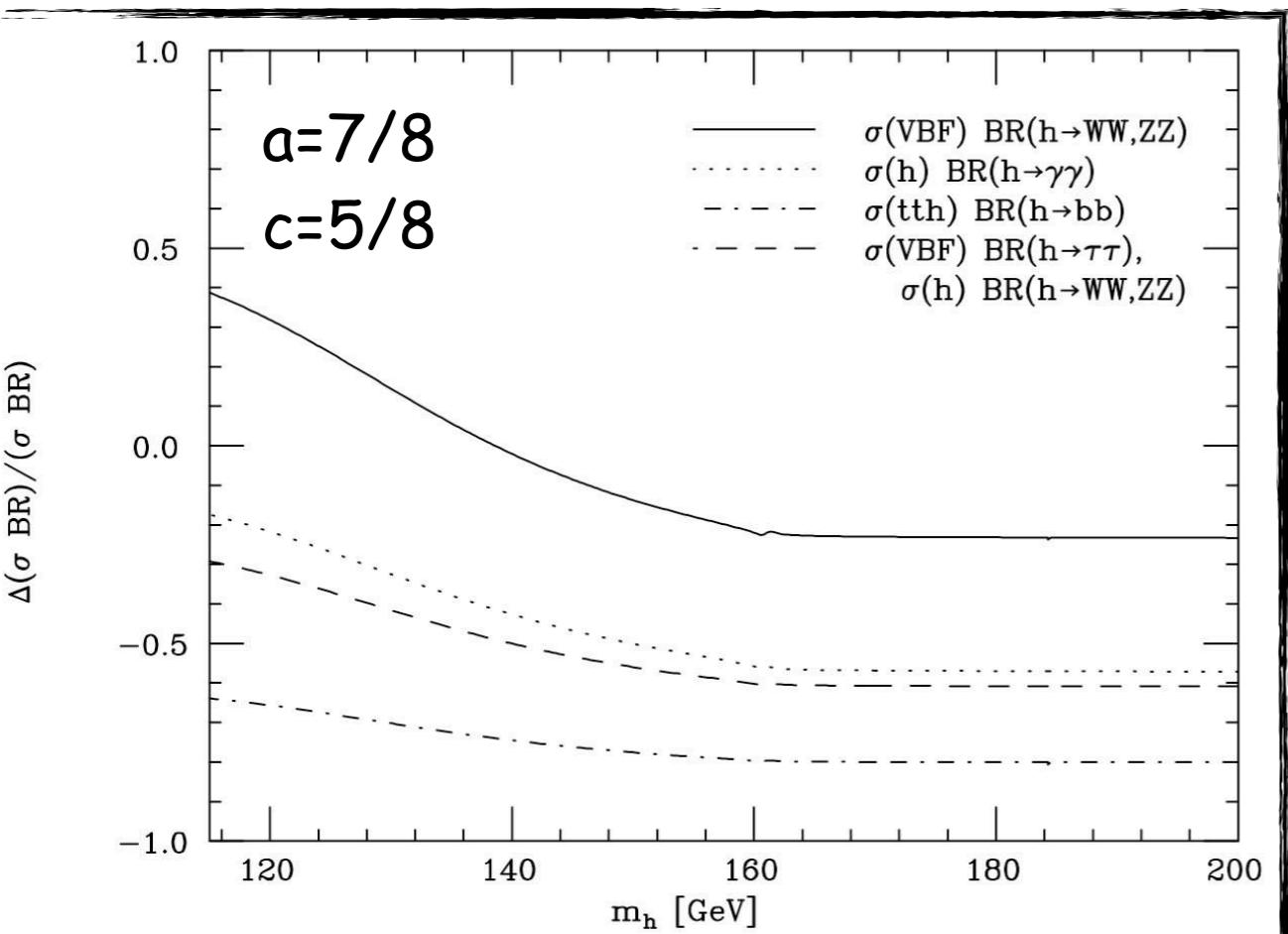
# Higgs anomalous couplings @ LHC

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4} \text{Tr} \left( D_\mu \Sigma^\dagger D_\mu \Sigma \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + b_3 \frac{h^3}{v^3} + \dots \right) - \lambda \bar{\psi}_L \Sigma \psi_R \left( 1 + c \frac{h}{v} + c_2 \frac{h^2}{v^2} + \dots \right)$$

$$a = \sqrt{1 - \xi} \quad b = 1 - 2\xi \quad b_3 = -\frac{4}{3}\xi\sqrt{1 - \xi} \quad c = \left( \sqrt{1 - \xi}, \frac{1 - 2\xi}{\sqrt{1 - \xi}} \right) \quad c_2 = -(\xi, 4\xi)$$

Minimal composite Higgs model (MCHM):  $SO(5)/SO(4)$

$$\Gamma(h \rightarrow f\bar{f}) = (2c - 1) \Gamma(h \rightarrow f\bar{f})_{\text{SM}} \quad \Gamma(h \rightarrow ZZ) = (2a - 1) \Gamma(h \rightarrow ZZ)_{\text{SM}}$$



Giudice, Grojean, Pomarol, Rattazzi '07

LHC can probe

$\Delta a$  &  $\Delta c$   
up to  $\sim 0.1 \div 0.2$   
i.e.  $4\pi f \sim 5 \div 7$  TeV

compositeness scale of the Higgs  
(ILC/CLIC could go to few %, ie, test composite Higgs up to  $4\pi f \sim 30/60$  TeV)

# How to probe the composite nature of the Higgs?

2. Strong scattering

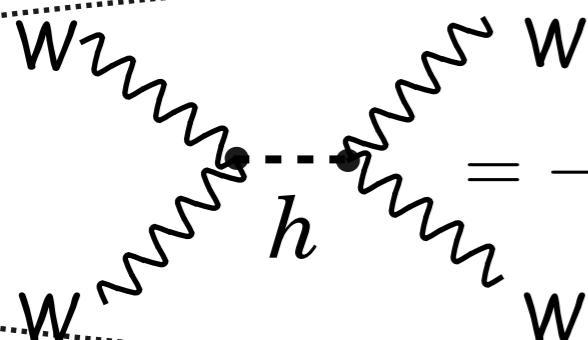


# How to probe the strong dynamics?

Look at pair production of strong states

Giudice, Grojean, Pomarol, Rattazzi '07

## strong WW scattering:



$$= -(1 - \xi) g^2 \frac{E^2}{M_W^2}$$

no exact cancellation  
of the growing amplitudes

$$\mathcal{A}(W_L^a W_L^b \rightarrow W_L^c W_L^d) = \mathcal{A}(s, t, u) \delta^{ab} \delta^{cd} + \mathcal{A}(t, s, u) \delta^{ac} \delta^{bd} + \mathcal{A}(u, t, s) \delta^{ad} \delta^{bc}$$

$\mathcal{A} = \underbrace{(1 - a^2)}_{\frac{s}{f^2}} \frac{s}{v^3}$

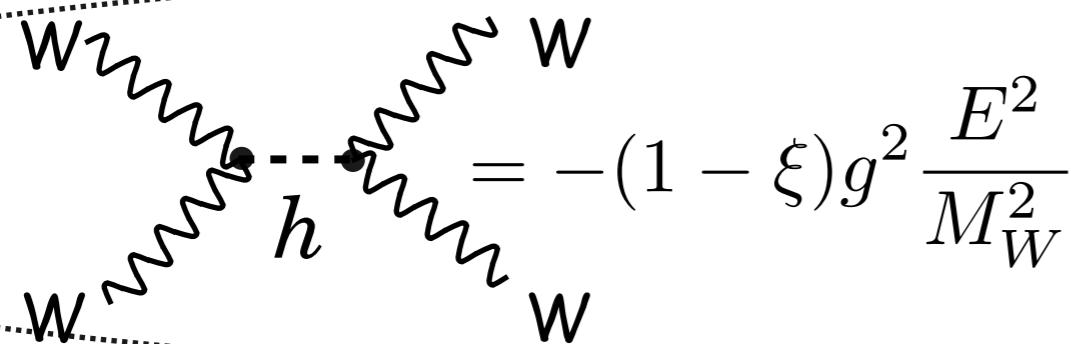
large  $L_{int}$  needed  
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## strong double Higgs production:

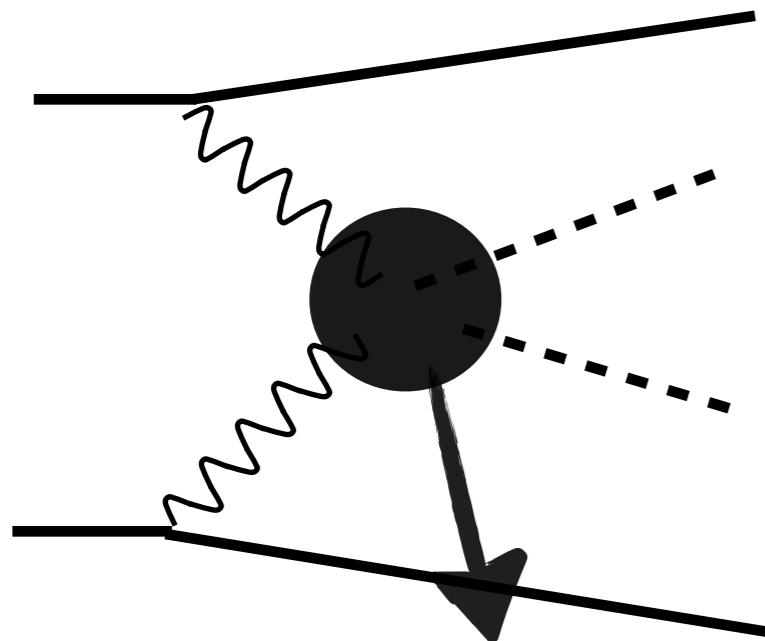
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow hh) = (W_L^+ W_L^- \rightarrow hh) = (b - a^2) \frac{s}{v^2}$$

access to a new interaction, 'b'

distinction between 'active' (higgs) and 'passive' (dilaton) scalar in EWSB dynamics

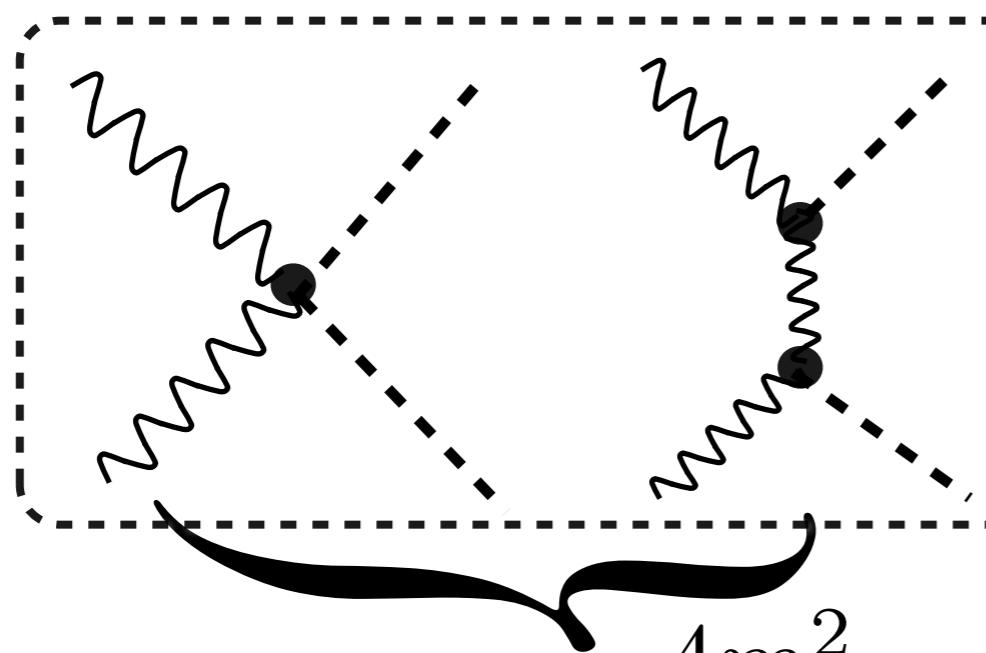
# Double Higgs production: 'b' and 'd<sub>3</sub>' couplings



$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4} \text{Tr} \left( D_\mu \Sigma^\dagger D_\mu \Sigma \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right)$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 + d_4 \frac{1}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \dots$$

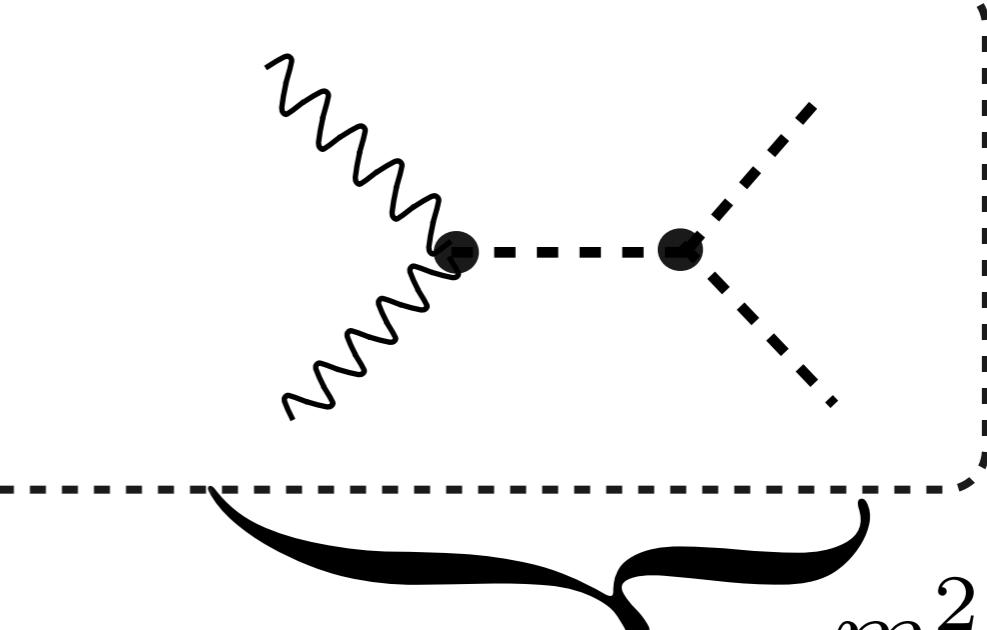
SM:  $a=b=d_3=d_4=1$



$$\mathcal{A} \sim (b - a^2) \frac{4m_{hh}^2}{v^2}$$

$m_{hh}^2 \gg m_W^2$

asymptotic behavior  
sensitive to strong interaction



$$\mathcal{A} \sim \text{cst.} + 3ad_3 \frac{m_h^2}{v^2}$$

$m_{hh}^2 \sim 4m_h^2$

threshold effect  
anomalous coupling'

# Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

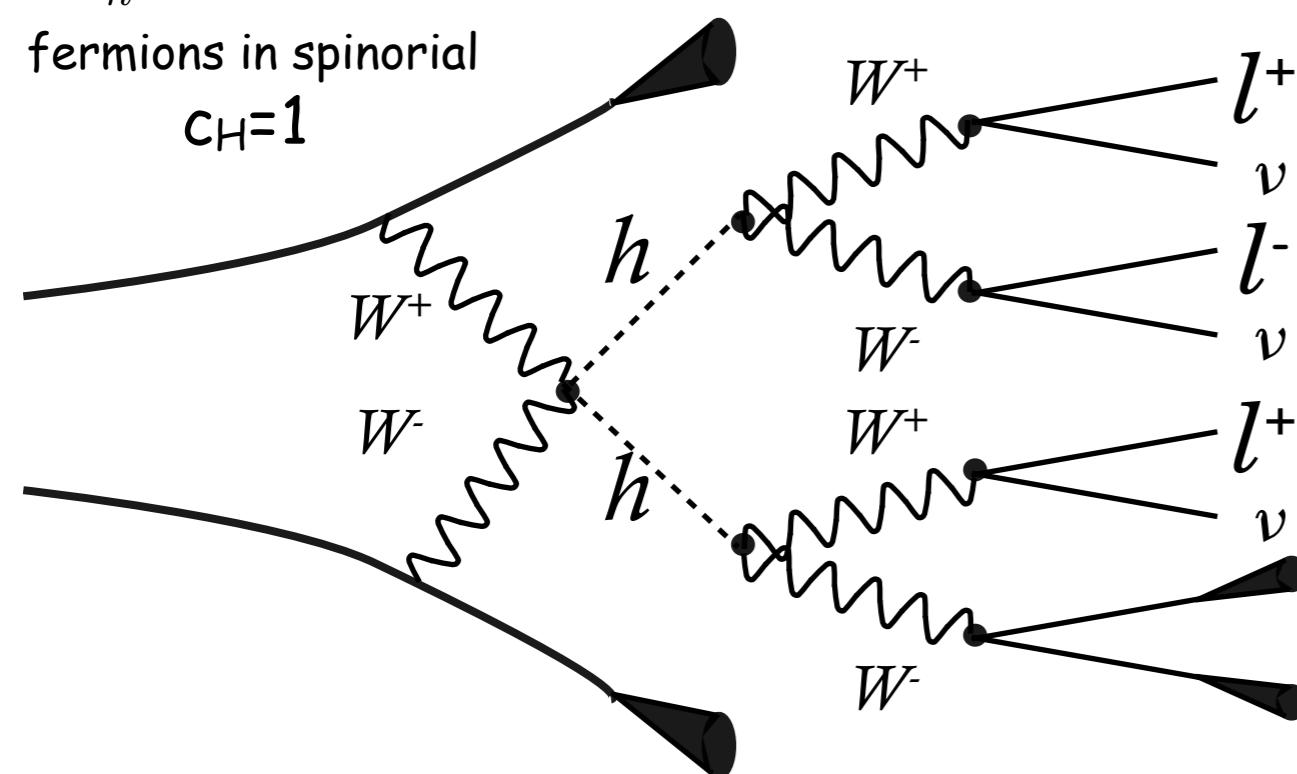
strong boson scattering  $\Leftrightarrow$  strong Higgs production

$$\mathcal{A}(Z_L^0 Z_L^0 \rightarrow hh) = \mathcal{A}(W_L^+ W_L^- \rightarrow hh) = \frac{c_{HS}}{f^2}$$

$m_h = 180$  GeV

fermions in spinorial

$c_H=1$



acceptance cuts:	
jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(l\bar{l})} > 0.4(0.2)$
$ \eta_j  \leq 5$	$ \eta_j  \leq 2.4$

Dominant backgrounds:  $Wll4j$ ,  $t\bar{t}W2j$ ,  $t\bar{t}2W(j)$ ,  $3W4j\dots$

forward jet-tag, back-to-back lepton, central jet-veto

$v/f$	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb $^{-1}$	4.0	2.9	1.3
luminosity for $5\sigma$ (fb $^{-1}$ )	450	850	3500

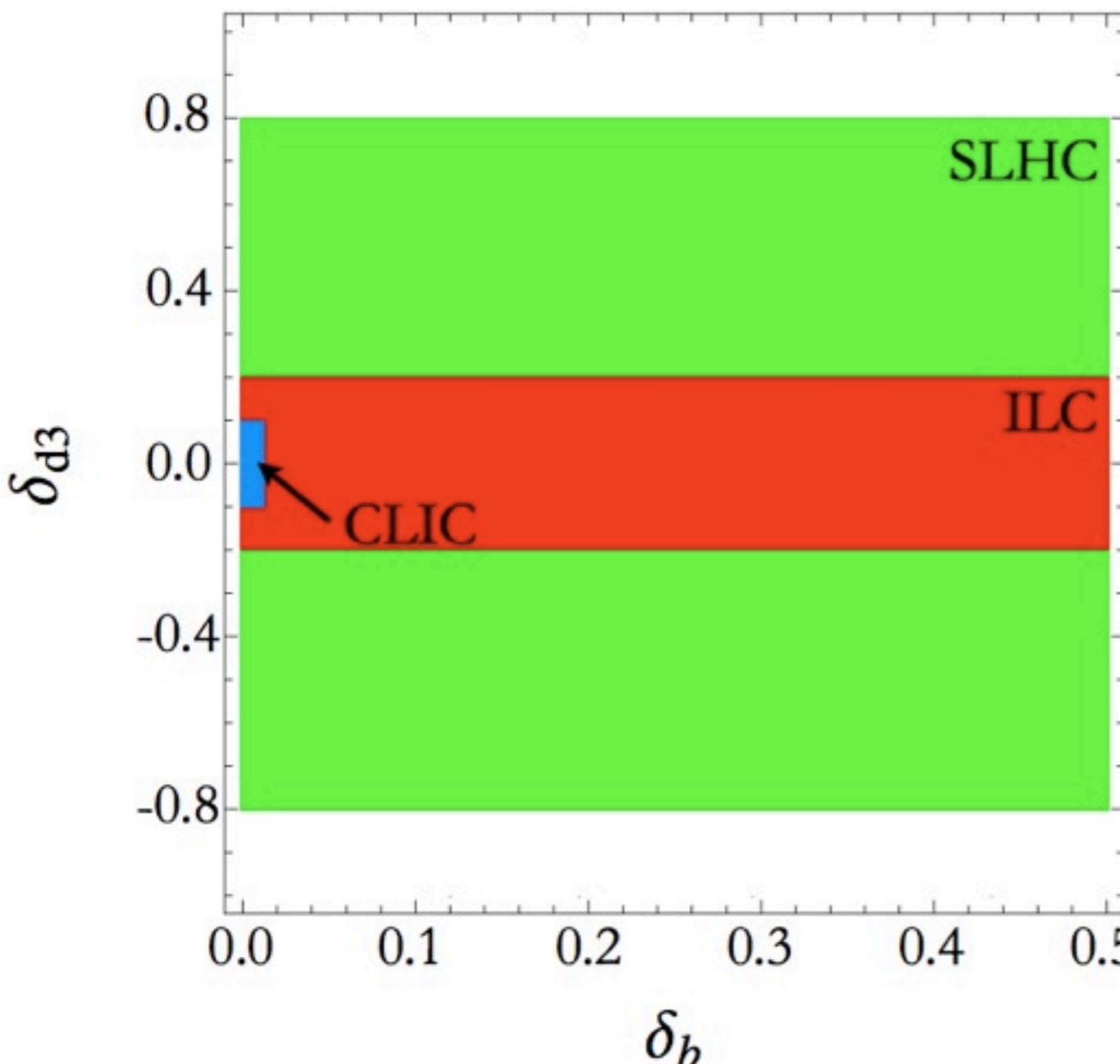
◀ good motivation to SLHC

# Measuring the non-linearities of the Higgs

Contino, Grojean, Pappadopulo, Rattazzi, Thamm ‘in progress’

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4} \text{Tr} \left( D_\mu \Sigma^\dagger D_\mu \Sigma \right) \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right)$$

$$V(h) = \frac{1}{2} m_h^2 h^2 + d_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3$$



- (S)LHC is barely sensitive to  $d_3$  and  $b$
- ILC has a sensitivity on  $d_3$  but not on  $b$
- CLIC can probe both  $d_3$  and  $b$

How to probe the composite nature of the Higgs?

3. Identifying discrete symmetries of strong sector



# Geometry of Coset from $W^+W^- \rightarrow 3h$

Contino, Grojean, Pappadopulo, Rattazzi, Thamm 'in progress'

Strong

$EWSB$

$$\sigma_{2\pi \rightarrow 3\pi} \sim \frac{1}{8\pi} \frac{E^2}{f^4} \frac{E^2}{(4\pi f)^2}$$

$$E/f \leftrightarrow g$$

SM

$$\sigma_{2\pi \rightarrow 3\pi} \sim \frac{1}{8\pi} \frac{g^2}{v^2} \frac{g^2}{16\pi^2}$$

Probe of possible discrete symmetries in the strong dynamics

$G/H$  symmetric space

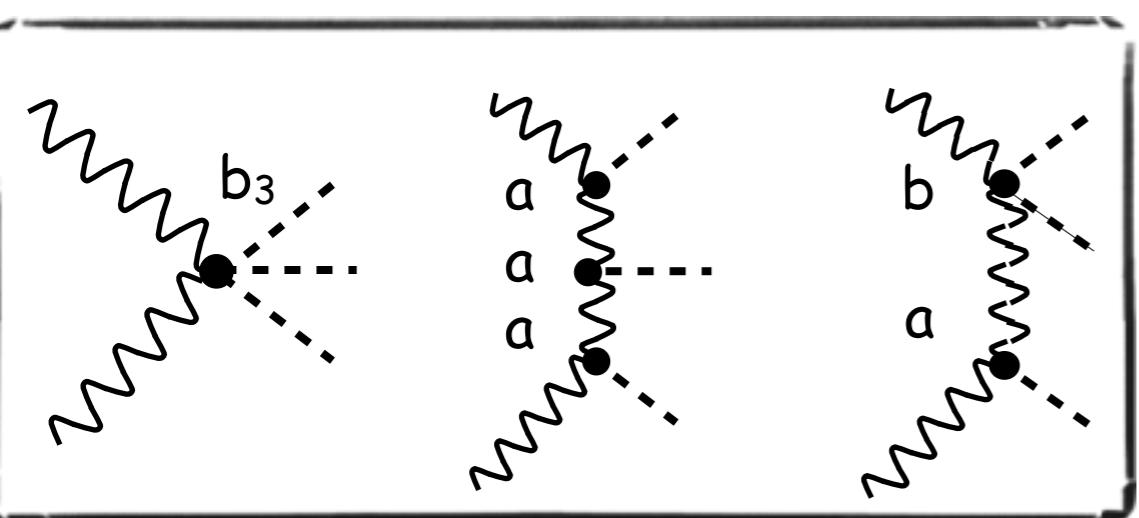


invariance under

$$\pi \rightarrow -\pi$$

a process with an odd # of PGBs

requires a coupling breaking the coset structure  
ie cannot be mediated by strong interactions alone



A not so elementary Higgs boson

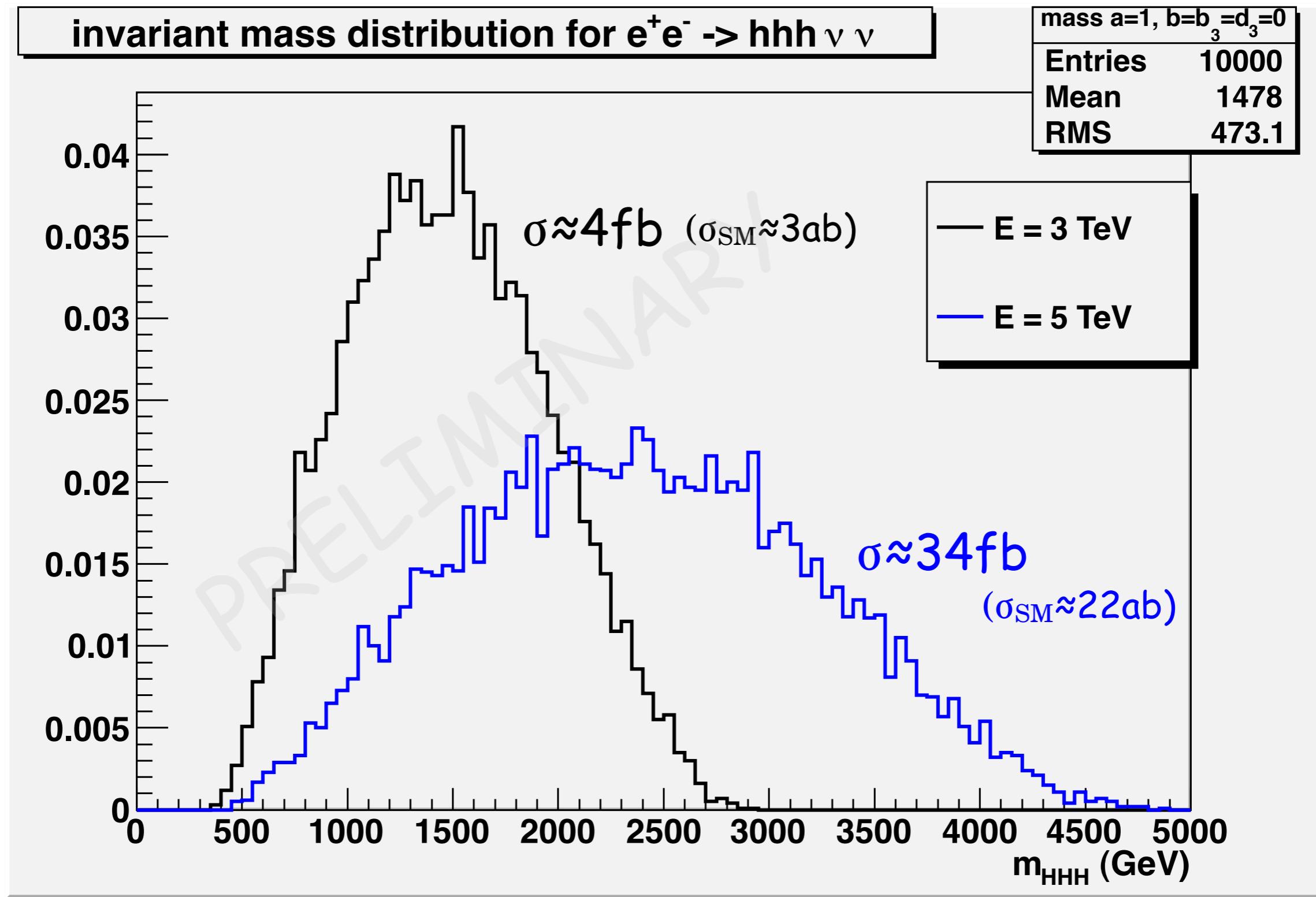
$$\mathcal{A}_{WW \rightarrow 3h} \sim 4i \frac{s}{v^3} \left( a(b - a^2) - \frac{3}{4} b_3 \right) + \text{# } s \times \left( \frac{m_W}{\sqrt{s}} \right)^2$$

=0 for  
symmetric coset

mediated by SM gauge  
interactions (breaking of  
coset structure)

# $W^+W^- \rightarrow 3h$ @ CLIC

Contino, Grojean, Pappadopulo, Rattazzi, Thamm ‘in progress’  
 non-symmetric coset



How to probe the composite nature of the Higgs?

#### 4. Detecting heavy resonances



# A heavy composite $W'$

Grojean, Salvioni, Torre '11

Observing a tower of resonances would be a direct evidence of the strong interactions  
However, in the best configuration, LHC will have access to a few ones only

*How can we tell the difference between a massive gauge field  
and a resonance from a strong sector?*

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elementary spin<sup>-1</sup>

$$g=2 \Leftrightarrow \Lambda \gg M/e \Leftrightarrow W' \rightarrow W\gamma \text{ highly suppressed}$$

gyromagnetic ratio of any elementary particle of mass  $M$   
coupled to photon must be  $g=2$  at tree-level to maintain  
perturbative unitarity up to energy  $\Lambda \gg M/e$

Ferrara, Porrati, Telegdi '92

$$(g-1)B^{\mu\nu}W_\mu'^+W_\nu'^- \quad \text{dimension-4 operator mediating } W' \rightarrow W\gamma \text{ after } W-W' \text{ mixing}$$

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Ferrara, Porrati, Telegdi '92

Composite spin-1

$$g \neq 2 \quad \& \quad \Lambda > 5 \div 10 \text{ M} \Leftrightarrow W' \rightarrow W\gamma \text{ allowed and potentially large}$$

$$(g - 1)B^{\mu\nu}W_\mu'^+W_\nu'^- \quad \text{dimension-4 operator mediating } W' \rightarrow W\gamma \text{ after } W-W' \text{ mixing}$$

# Conclusions

EW interactions need Goldstone bosons to provide mass to W, Z



EW interactions also need a UV moderator/new physics  
to unitarize WW scattering amplitude

We'll need another Gargamelle experiment

to discover the still missing neutral current of the SM: the Higgs

weak NC  $\Leftrightarrow$  gauge principle

Higgs NC  $\Leftrightarrow ?$

Strong EWSB w/o an elementary Higgs can be very similar to SM  
it might take some time to decipher the true dynamics of EWSB!

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

# An Emergency Tire Even Beyond the SM

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10



[picture courtesy to Andreas Weiler]