Composite Higgs Physics at a Linear Collier

LCSW20111

Granada, Sept. 26-30 2011

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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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Lee, Quigg & Thacker '77

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⇛ UV behavior of these Goldstone's? ⇚

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

$$\mathcal{L}_{\text{mass}} = m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} \text{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

Goldstone of
$SU(2)_L \times SU(2)_R / SU(2)_V$

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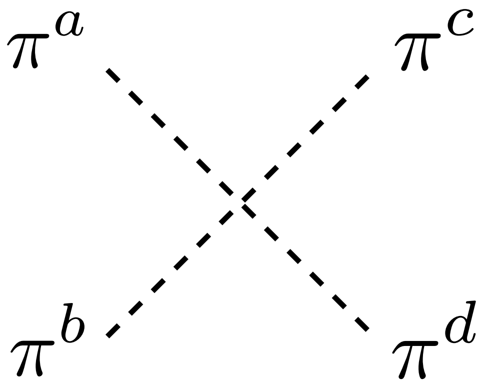
Goldstone of SU(2)$_L$xSU(2)$_R$/SU(2)$_V$

$$\boxed{\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2 \right) + \ldots}$$

contact interaction growing with energy



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

Lee, Quigg & Thacker '77

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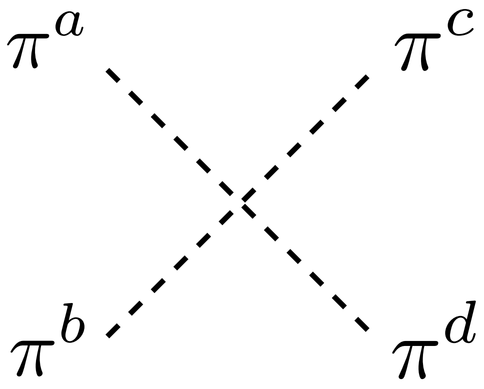

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the behavior of this amplitude is not consistent above 4πv (≈1÷3TeV)

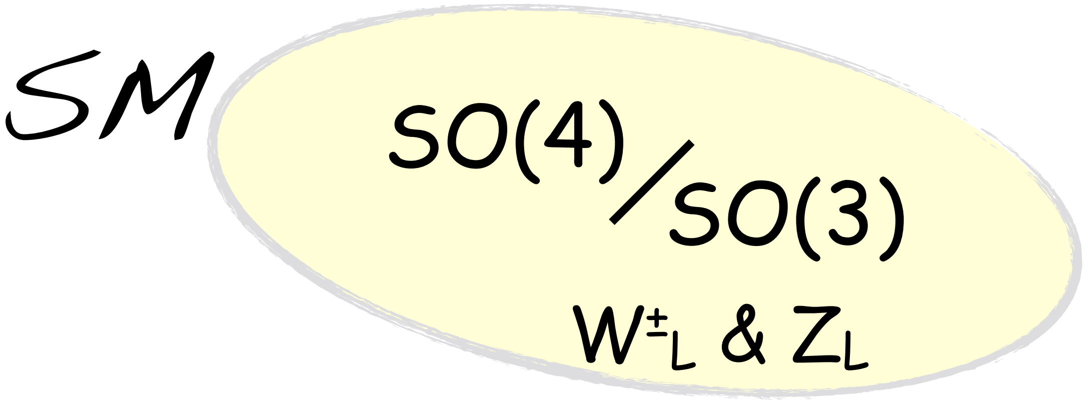
Lee, Quigg & Thacker '77

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)



SM

$SO(4)/SO(3)$

$W^{\pm}_L$ & Z_L

3 Goldstone's

Chacko, Batra '08

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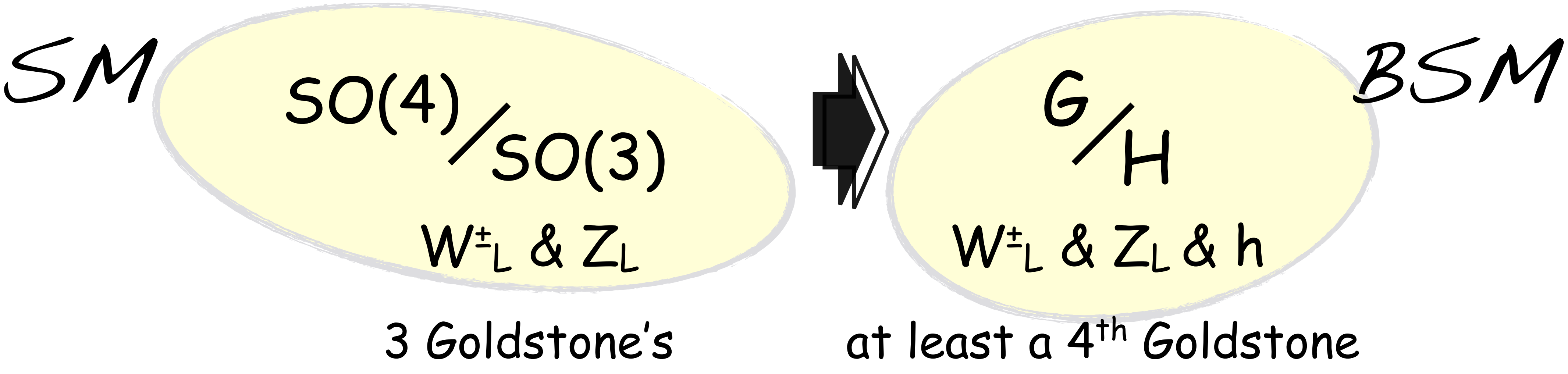

SM

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BSM

G/H

$W^{\pm}_L$ & Z_L & h

at least a 4th Goldstone

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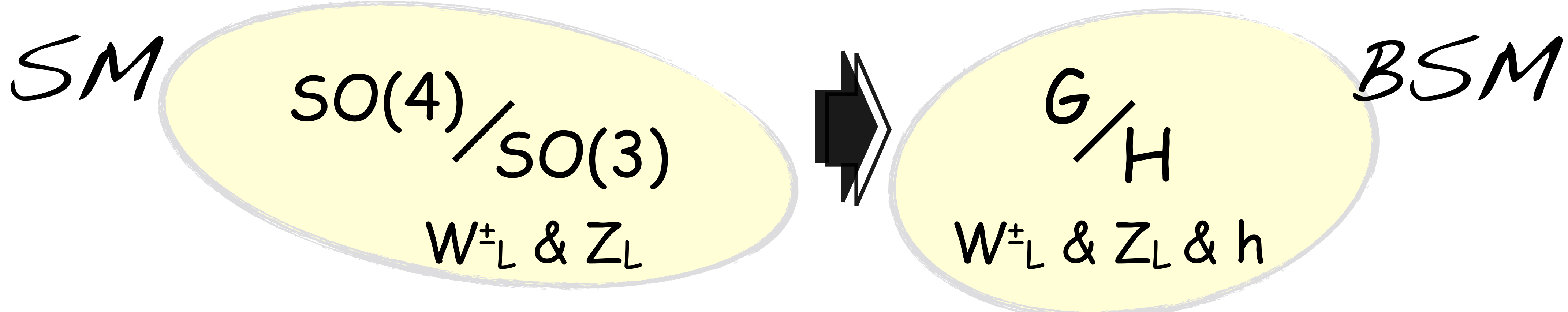


3 Goldstone's

at least a 4th Goldstone

Examples:

$SO(5)/SO(4)$: 4 PGBs=$W^\pm_L$, Z_L, h ← Minimal Composite Higgs Model

Agashe, Contino, Pomarol '04

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

Gripaios, Pomarol, Riva, Serra '09

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

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?

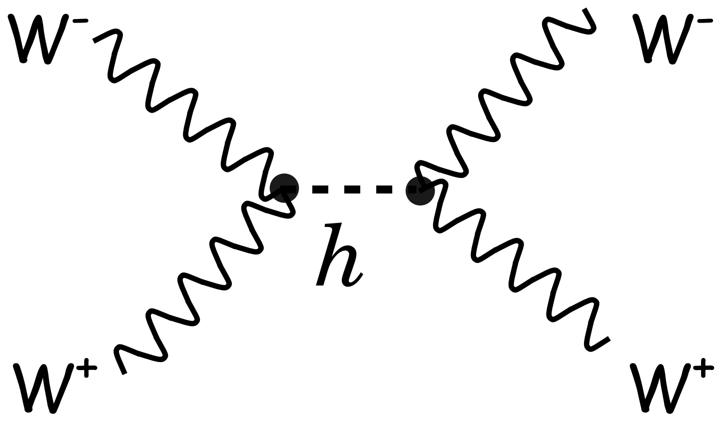
1. Anomalous couplings

What is the SM Higgs?

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

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

'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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For a=1: perturbative unitarity in elastic channels WW → WW

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

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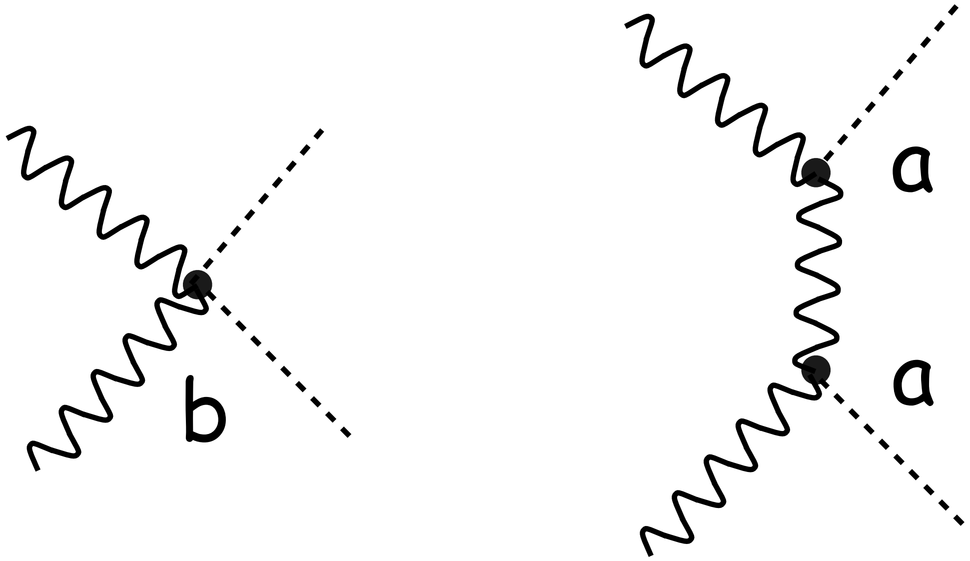

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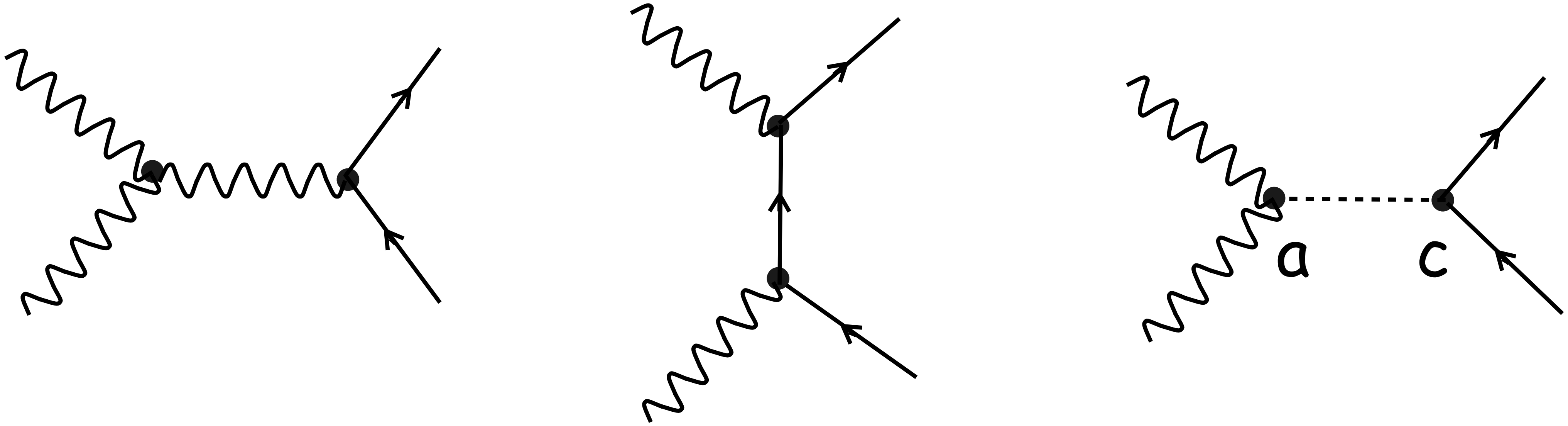

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'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties depend on a single unknown parameter (m_H)

$\mathcal{L}_{\rm EWSB}$ 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 π^a (ie W_L andZ_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

What is a composite Higgs?

A σ 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 ⇔ Standard Model ⇔ 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 ≠ 1 ⇔ Composite Higgs

deviations of Higgs couplings originate from higher dimensional operators

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

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Anomalous composite-Higgs couplings

Giudice, Grojean, Pomarol, Rattazzi ‘07

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

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

Modified Higgs propagator ~ 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 = $1-\xi/2$ b = $1-2\xi$ 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

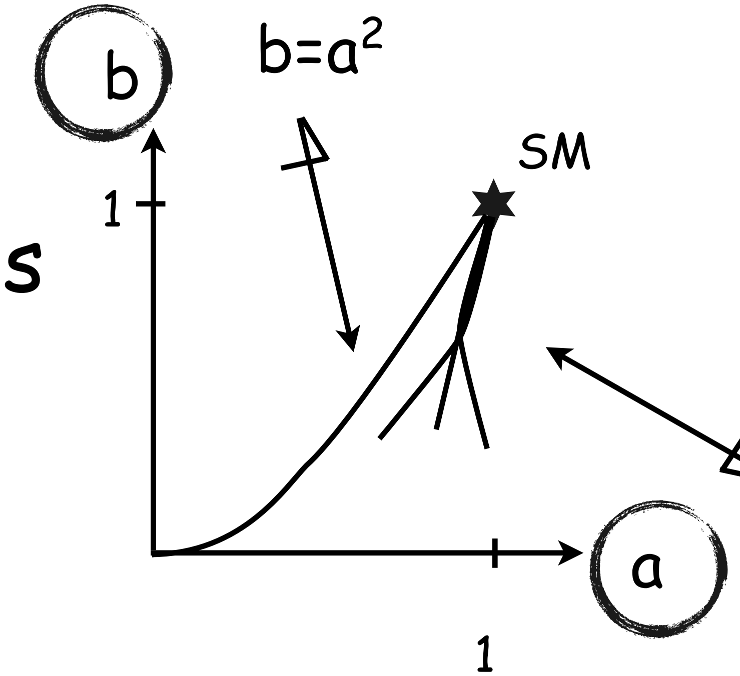
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. Dilaton Higgs



Dilaton
$b=a^2$

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

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

Effective Lagrangian

Giudice, Grojean, Pomarol, Rattazzi ‘07

- extra Higgs leg: H/f
- extra derivative: ∂/m_ρ

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$_\rho$)

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

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

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

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

minimal coupling: $h \to \gamma Z$

loop-suppressed strong dynamics

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

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

Goldstone sym.

Deformation of the SM Higgs: current constraints

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

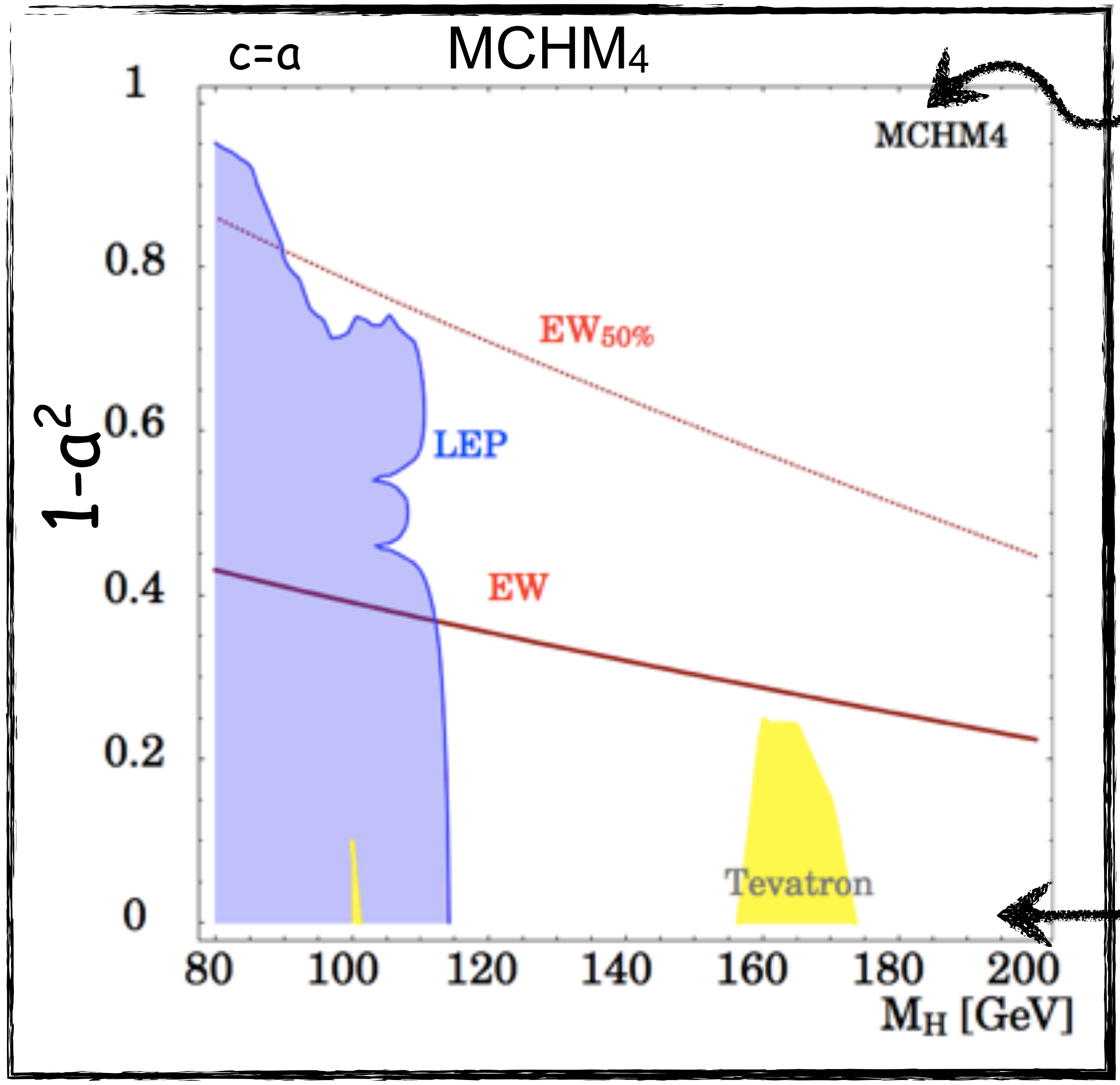
$\Sigma = e^{i\sigma^a\pi^a/v}$ Goldstone of $SU(2)_L\times SU(2)_R/SU(2)_V$ $D_\mu\Sigma \approx W_\mu$

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

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

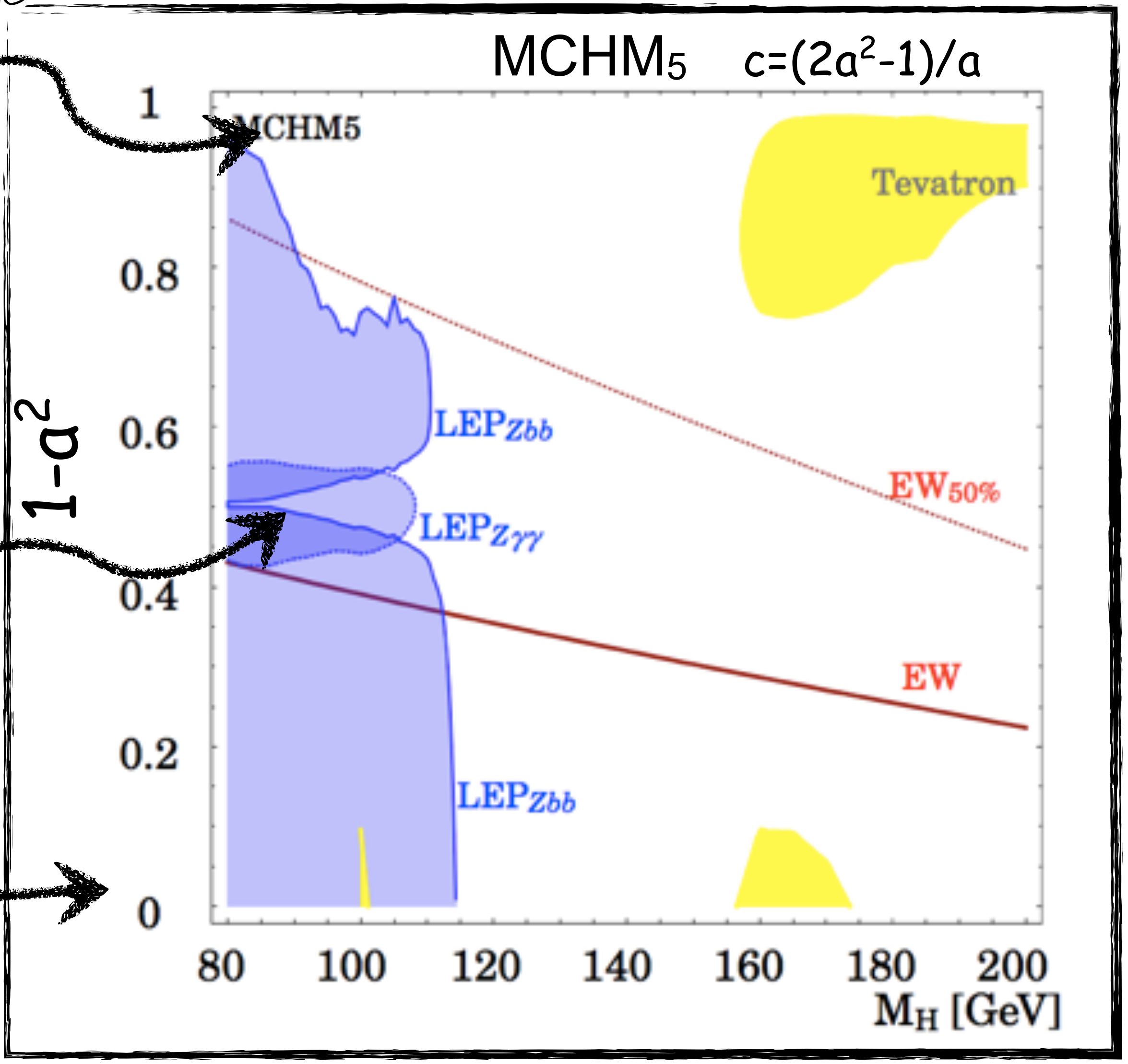
Espinosa, Grojean, Muehlleitner '10

gaugephobic Higgs



fermiophobic Higgs

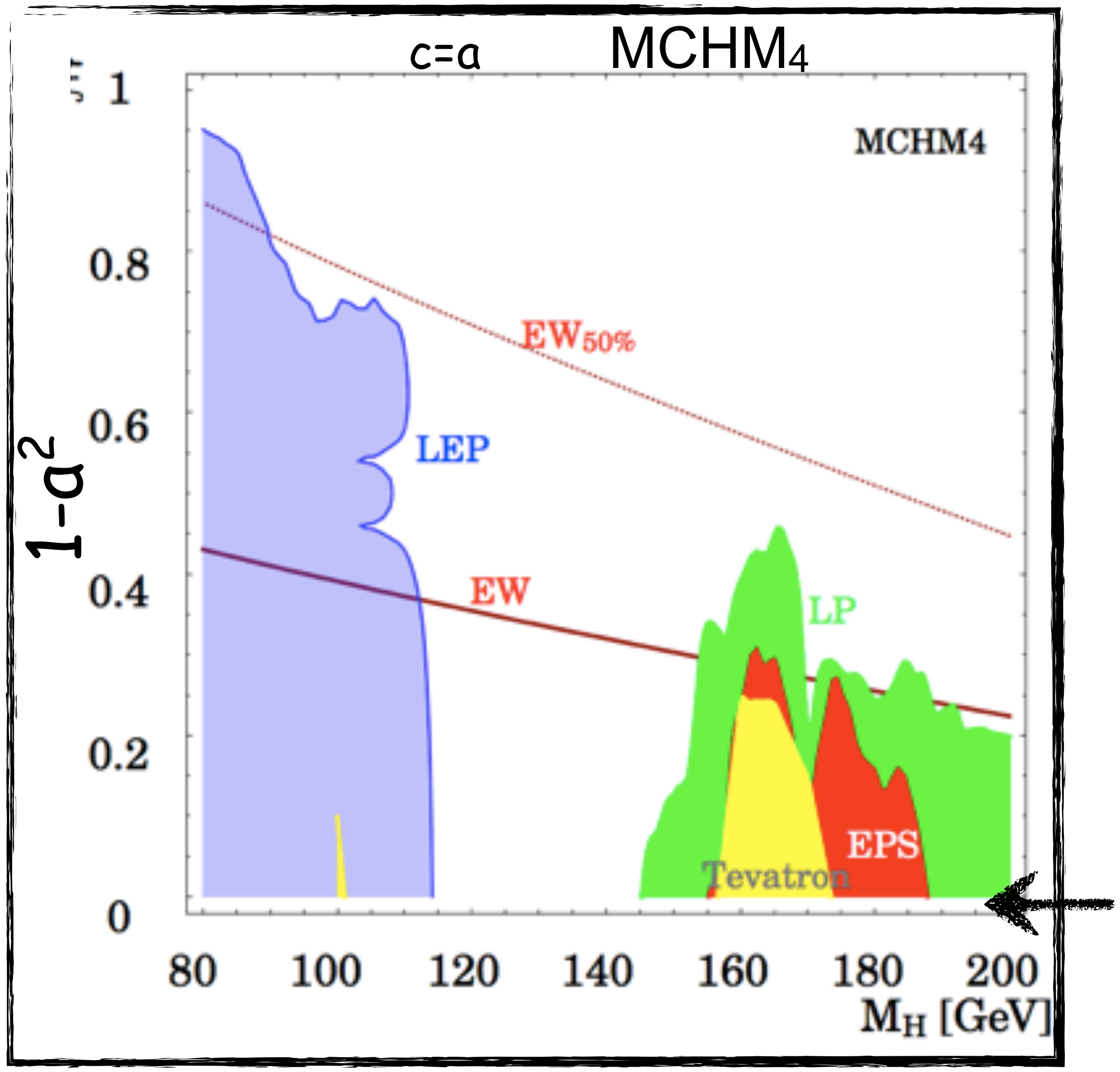
SM limits



Deformation of the SM Higgs: LHC constraints

the SM exclusion bounds are easily rescaled in the (m_H,a) plane

Espinosa, Grojean, Muehlleitner '11



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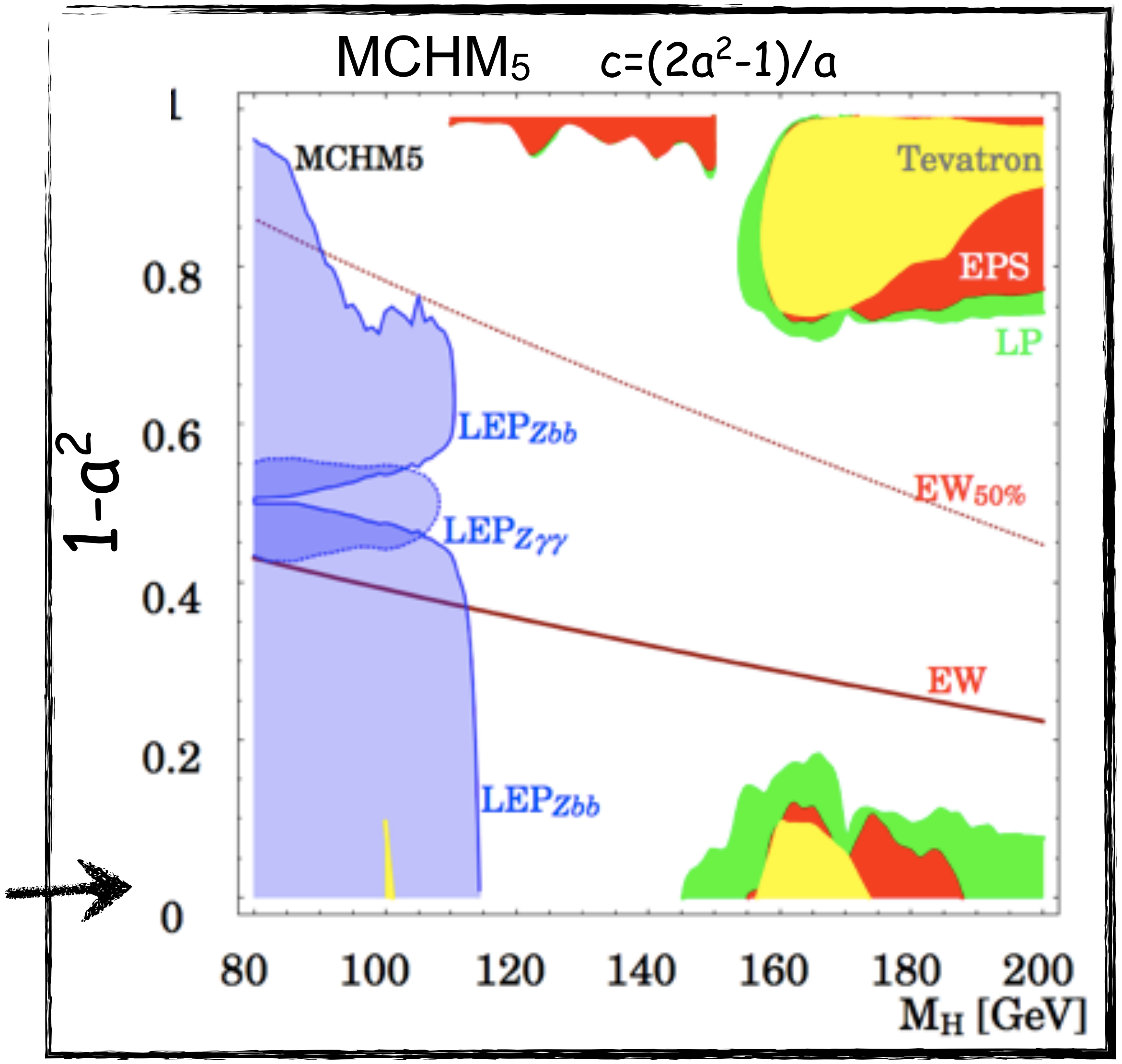

LHC is now a Higgs exploring machine
(and it has quickly surpassed Tevatron)

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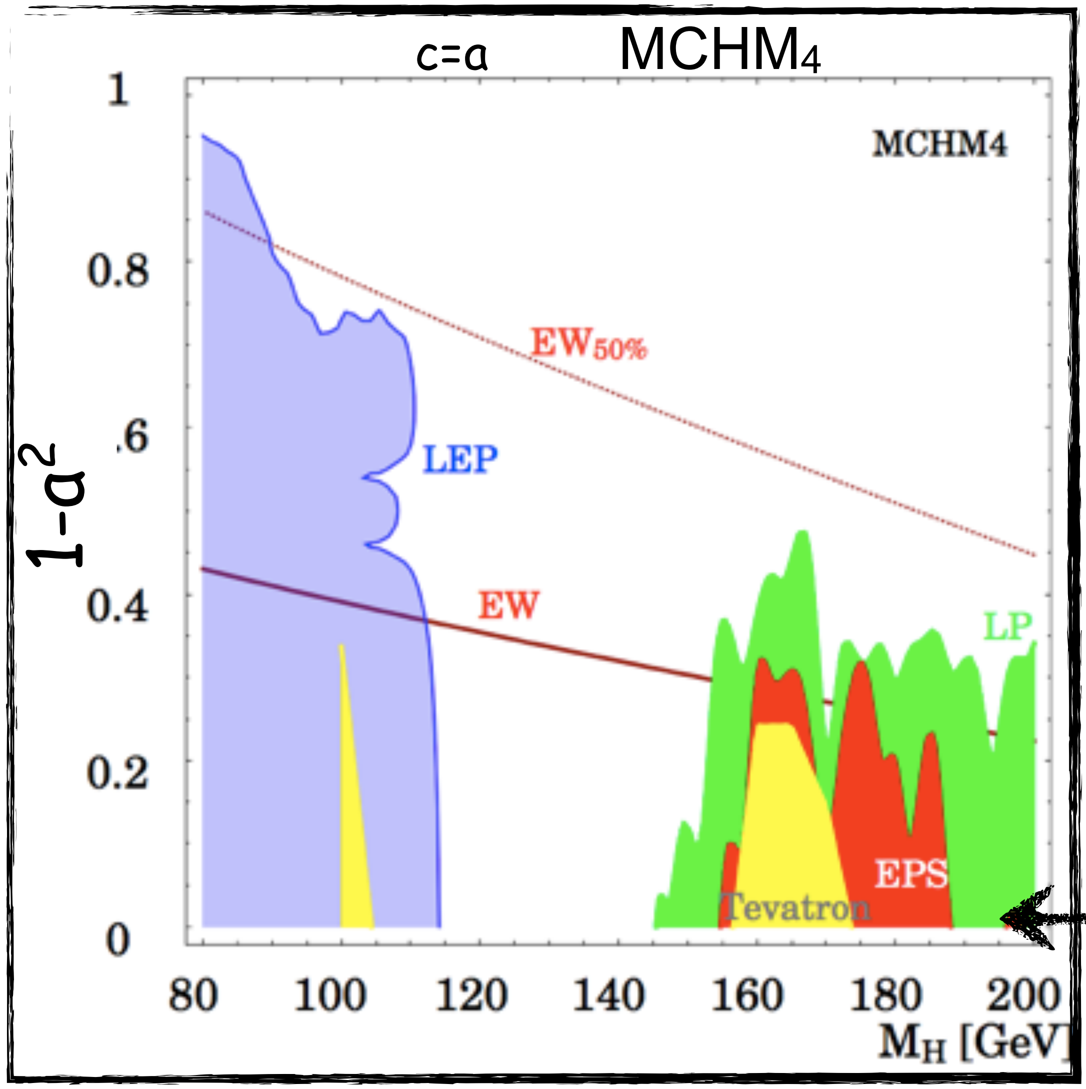

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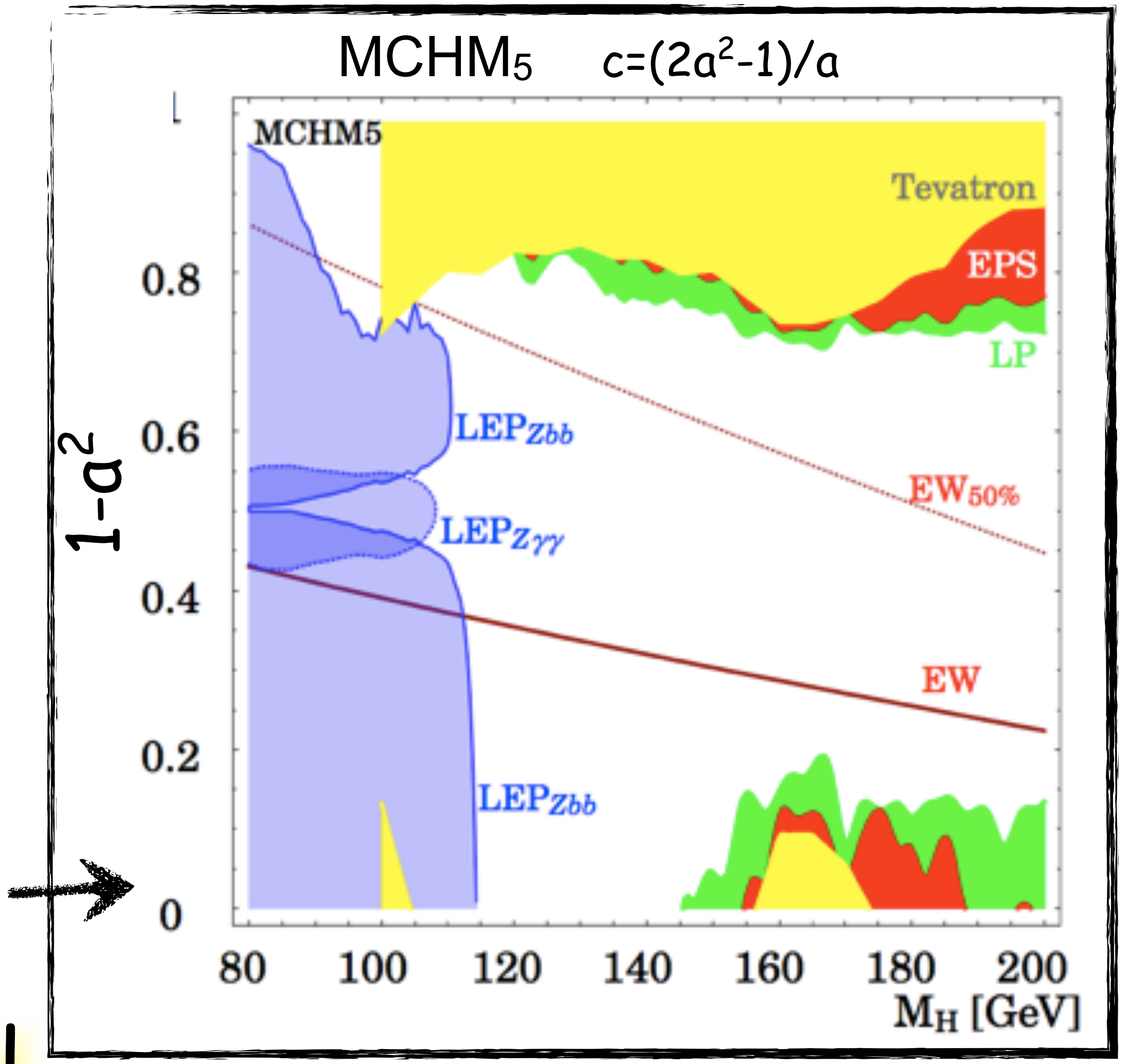


Be careful

- ○ rescaling combination ≠ combination of the rescaled channels

  (can be particularly important far away from SM)

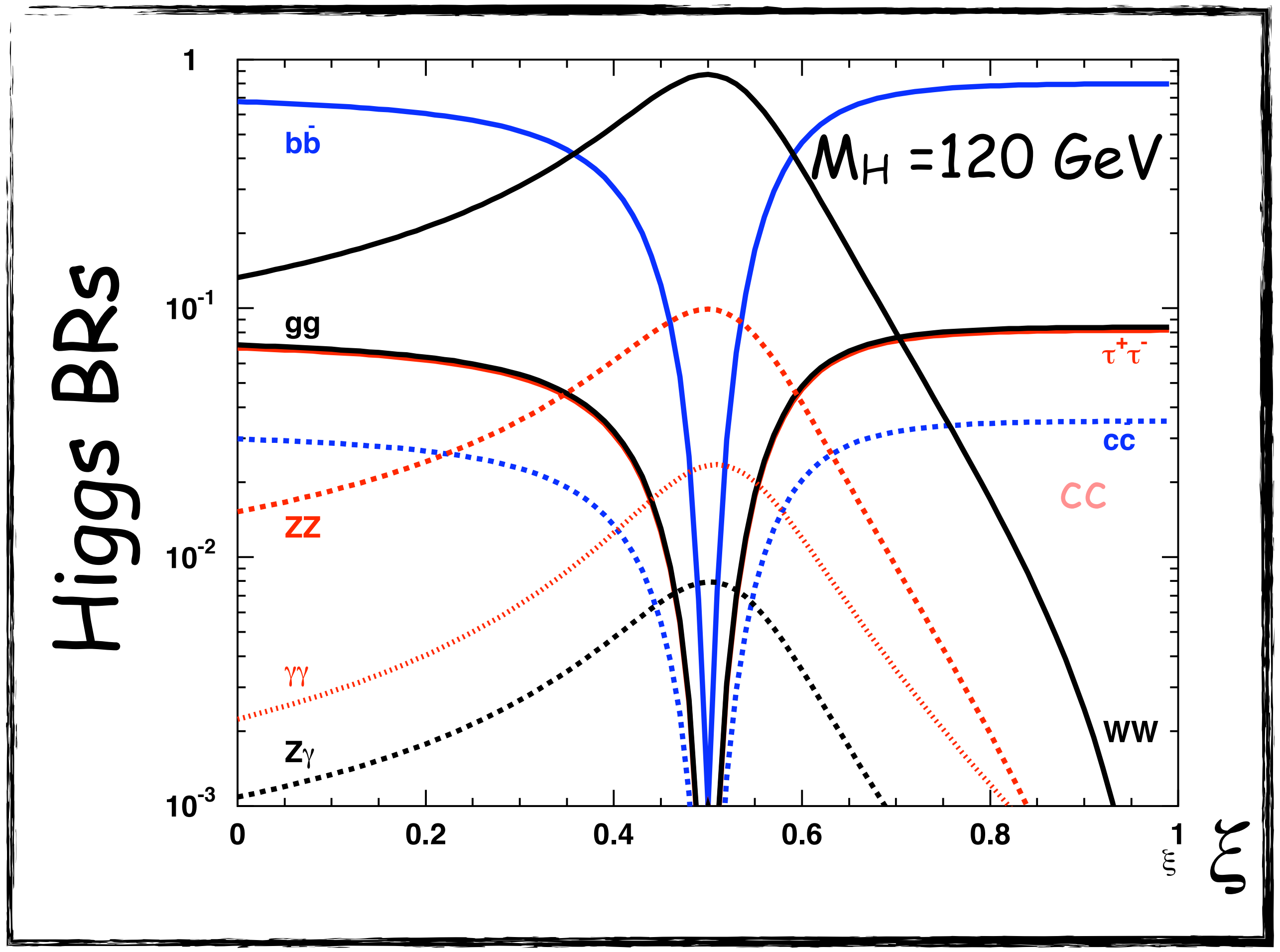
- ○ effeciency of the cuts may also depends on ξ

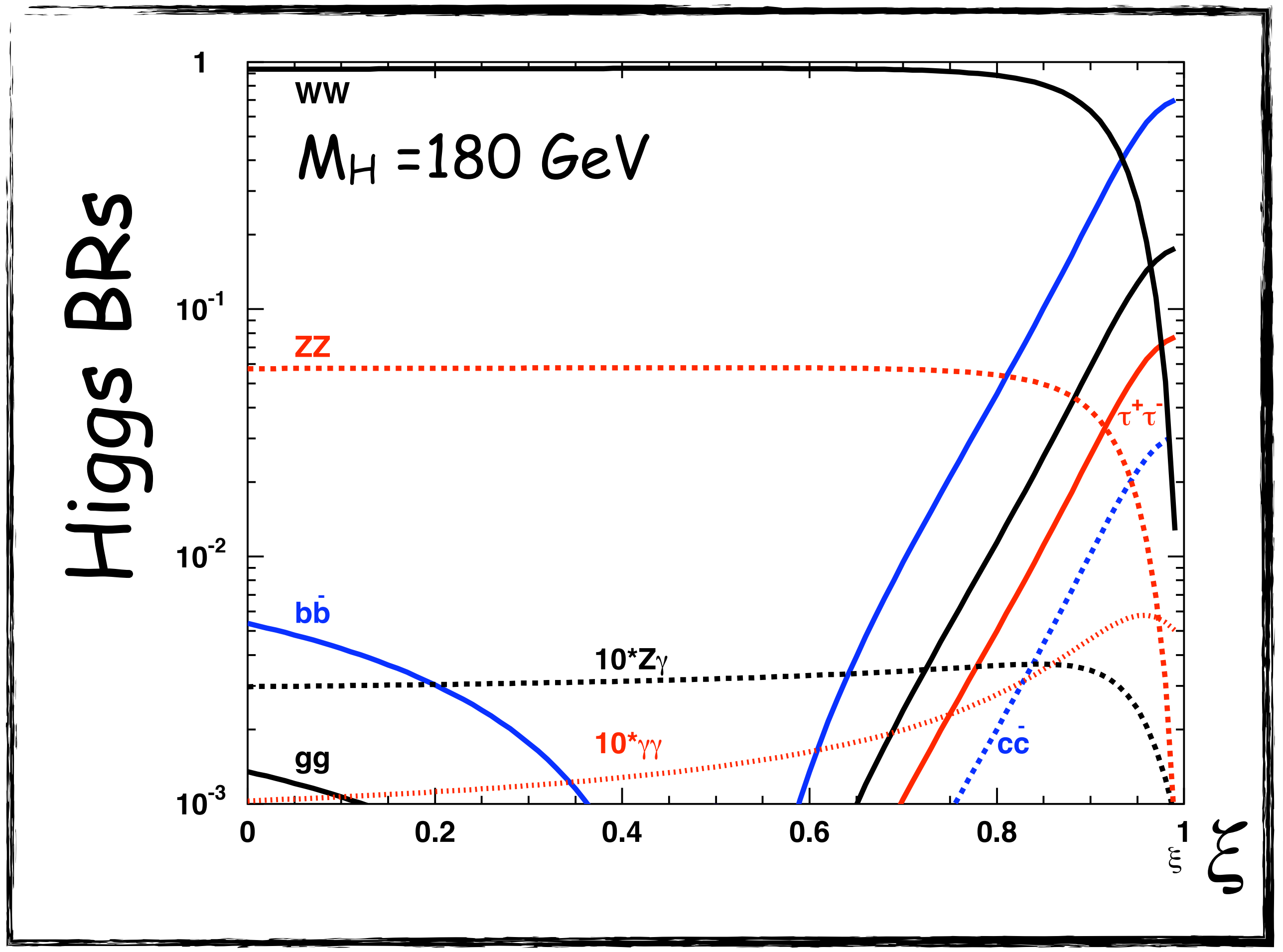
Anomalous Higgs BRs

MCHM5

Fermions embedded in 5+10 of SO(5)

$$a=\sqrt{1-\xi}\qquad b=1-2\xi\qquad c=\frac{1-2\xi}{\sqrt{1-\xi}}$$





h→WW can dominate
even for low Higgs mass

BRs remain SM like except
for very large values of v/f

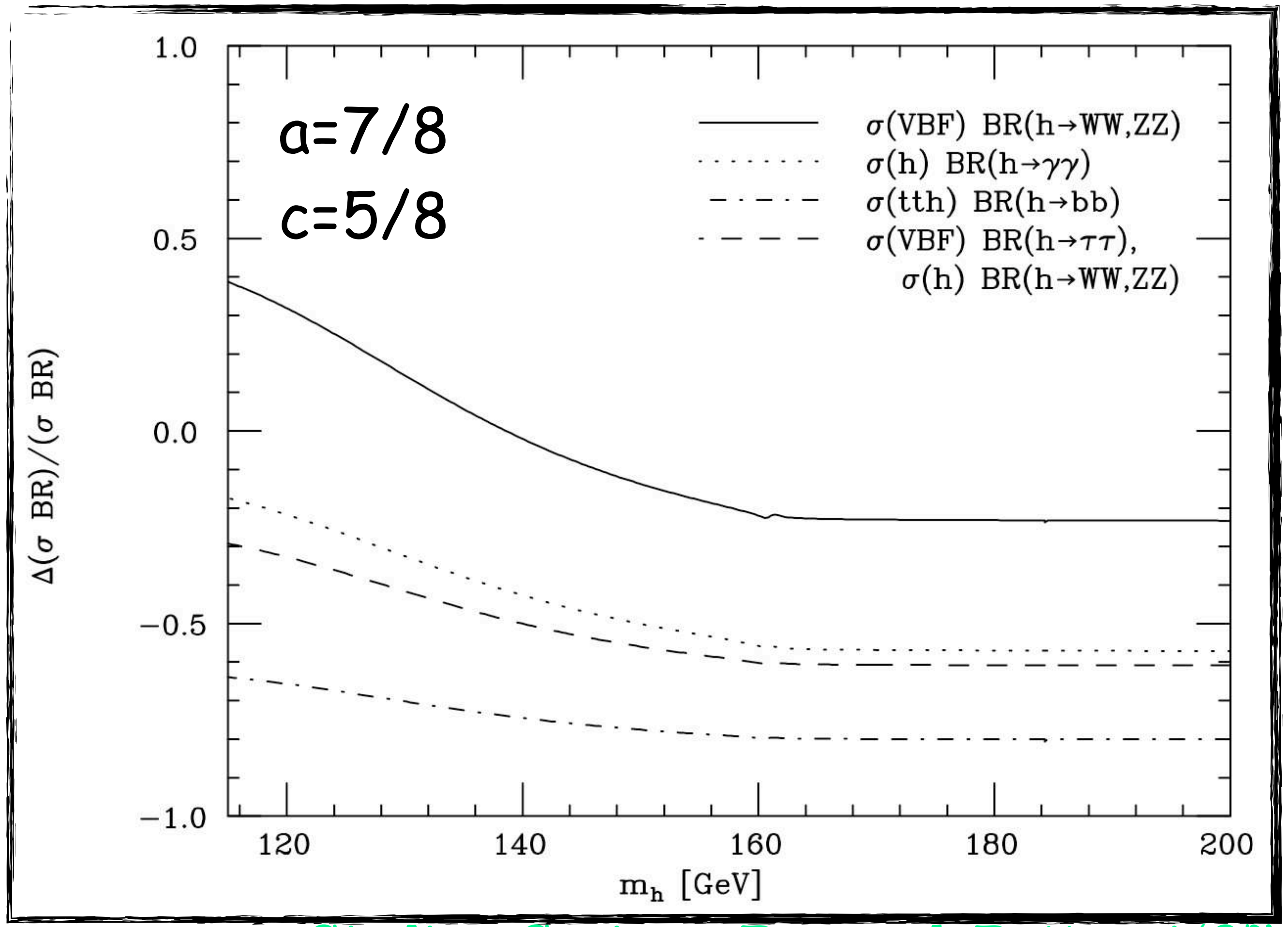
Higgs anomalous couplings @ LHC

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

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

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

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



Giudice, Grojean, Pomarol, Rattazzi '07

LHC can probe

Δa & Δc

up to ~ 0.1÷0.2

i.e. 4πf ~ 5÷7 TeV

compositeness scale of the Higgs

ILC/CLIC

could go to few %, ie, test

composite Higgs up to 4πf ~ 30/60 TeV

How to probe the composite nature of the Higgs?

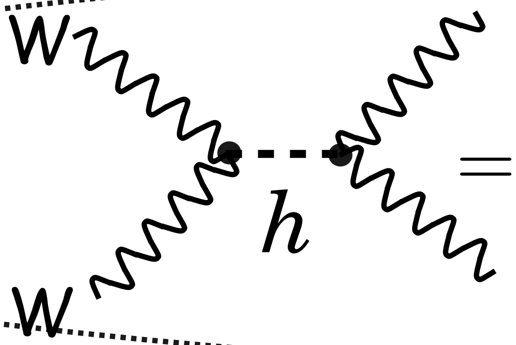
2. Strong scattering

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

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

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large $\mathcal{L}_{int}$ needed

not competitive with the measurement of 'a' via anomalous couplings

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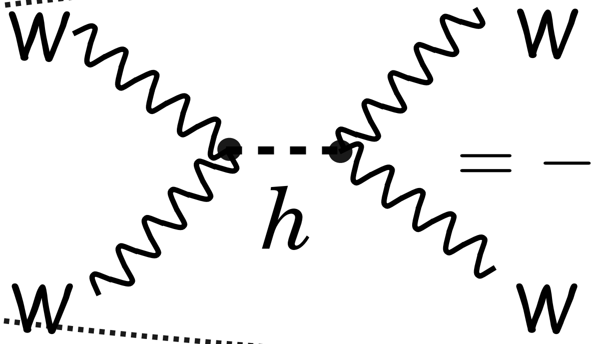

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- strong double Higgs production

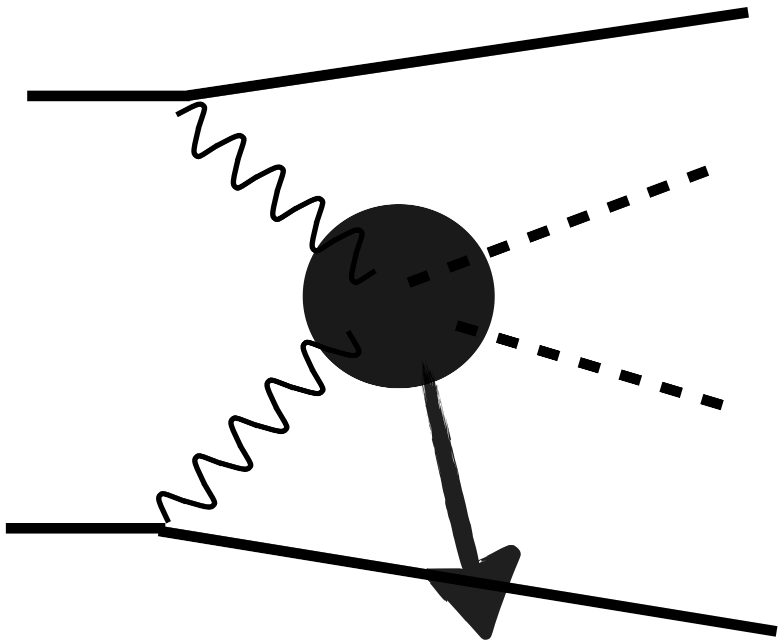
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

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

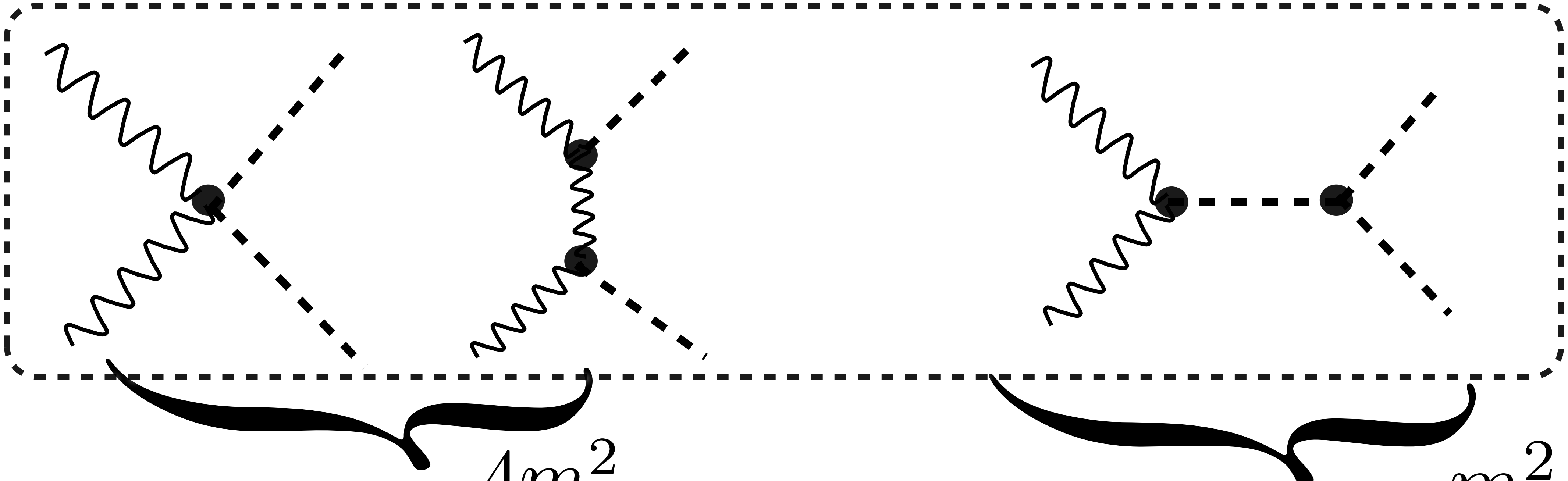
Double Higgs production: 'b' and 'd_3' couplings



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

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

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



$$\mathcal{A} \underset{m_{hh}^2 \gg m_W^2}{\sim} \left(b - a^2\right)\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2 \sim 4m_h^2}{\sim} \mathrm{cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling’

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

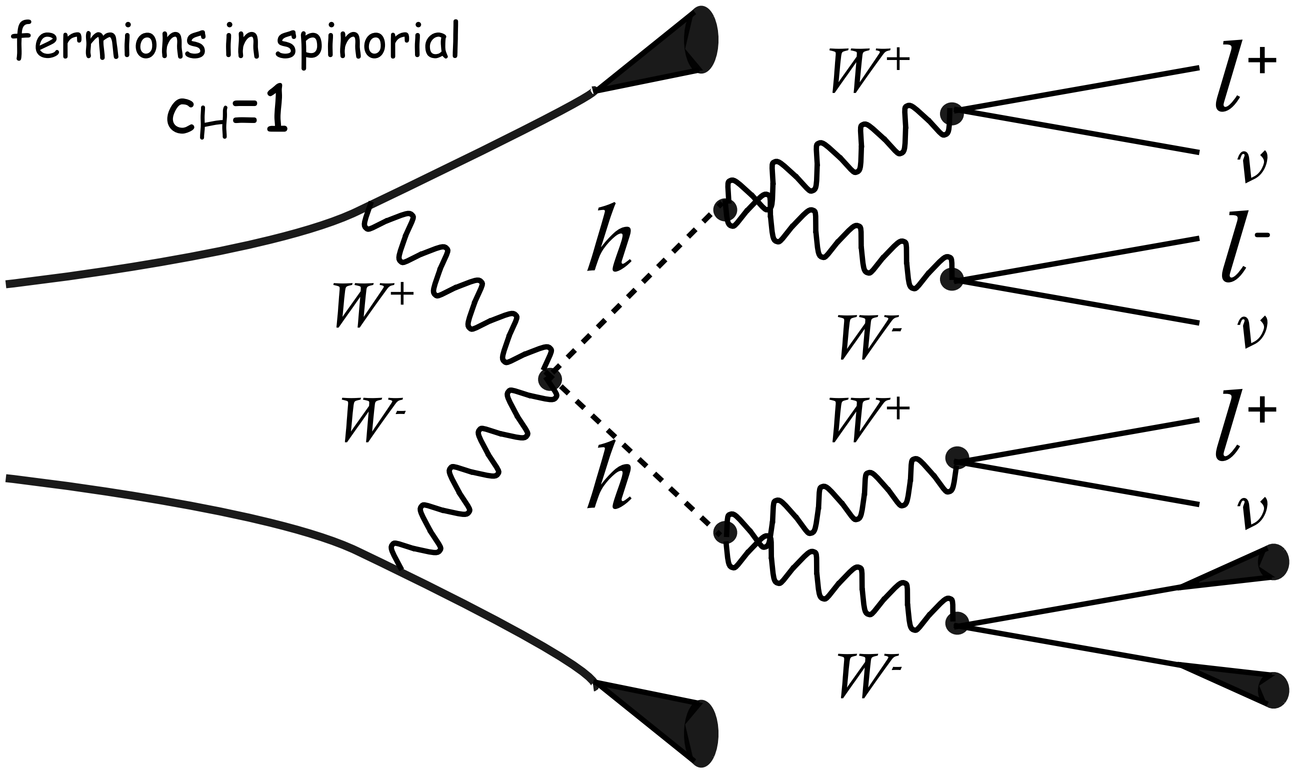
strong boson scattering ⇔ strong Higgs production

$$\mathcal{A}\left(Z_L^0 Z_L^0 \to hh\right) = \mathcal{A}\left(W_L^+ W_L^- \to hh\right) = \frac{c_H s}{f^2}$$

$m_h = 180$ GeV

fermions in spinorial

c_H=1



acceptance cuts

jets	leptons
$p_T \geq 30$ GeV	$p_T \geq 20$ GeV
$\delta R_{jj} > 0.7$	$\delta R_{lj(ll)} > 0.4(0.2)$
$\lvert\eta_j\rvert \leq 5$	$\lvert\eta_j\rvert \leq 2.4$

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

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

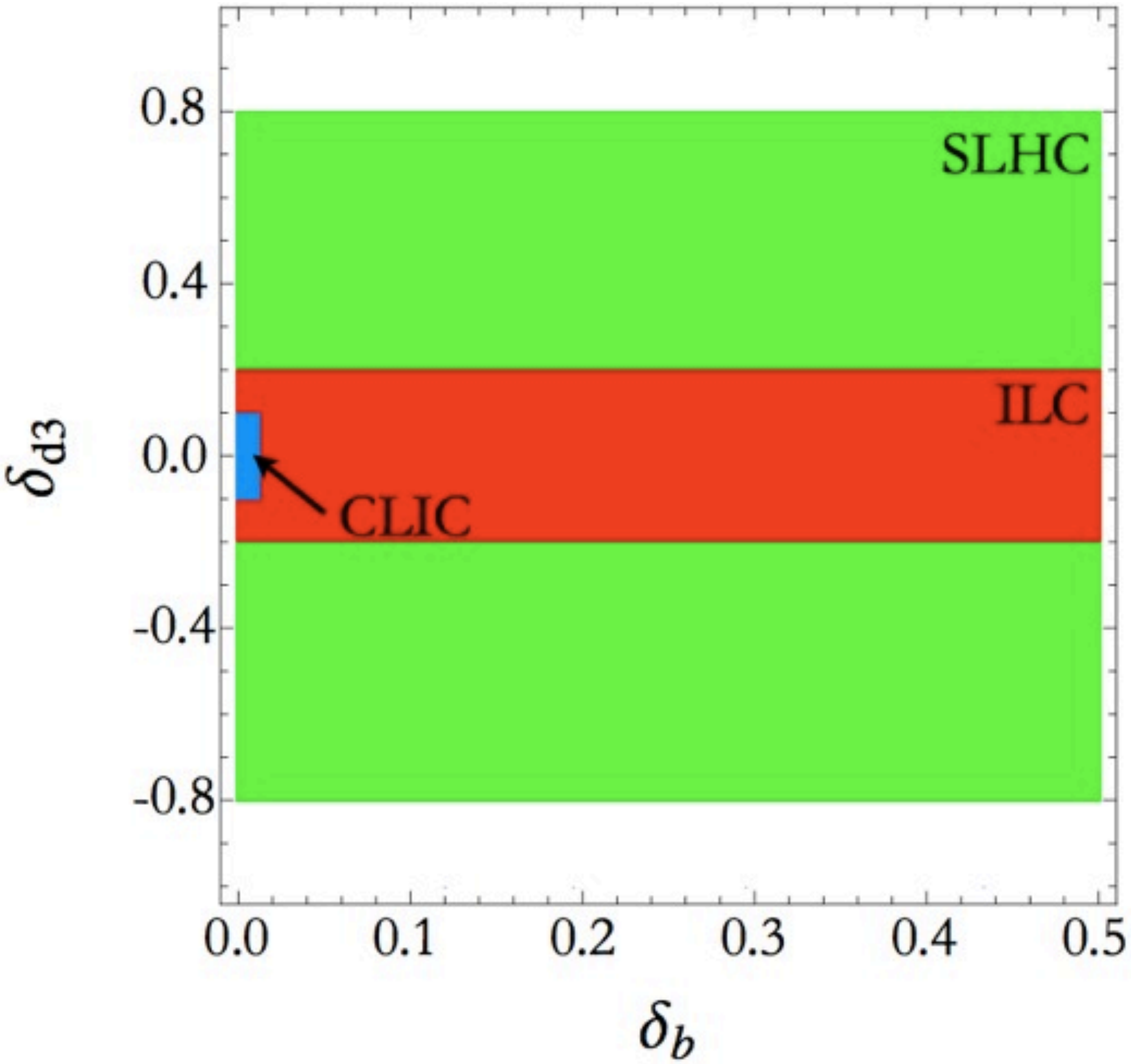
v/f	1	$\sqrt{0.8}$	$\sqrt{0.5}$
significance @ 300 fb^{-1}	4.0	2.9	1.3
luminisity for 5σ (fb^{-1})	450	850	3500

⇚ good motivation to SLHC

Measuring the non-linearities of the Higgs

Contino, Grojean, Pappadopoulo, Rattazzi, Thamm ‘in progress

$$\mathcal{L}_{\text{EWSB}} = \frac{v^2}{4}\text{Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right) \qquad V(h) = \frac{1}{2}m_h^2h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3$$



- (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

CLIC seems a unique machine to testing strong EWSB

How to probe the composite nature of the Higgs?

3. Identifying discrete symmetries of strong sector

Geometry of Coset from W⁺W⁻ → 3h

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

Strong EWSB

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

$$E/f \leftrightarrow g$$

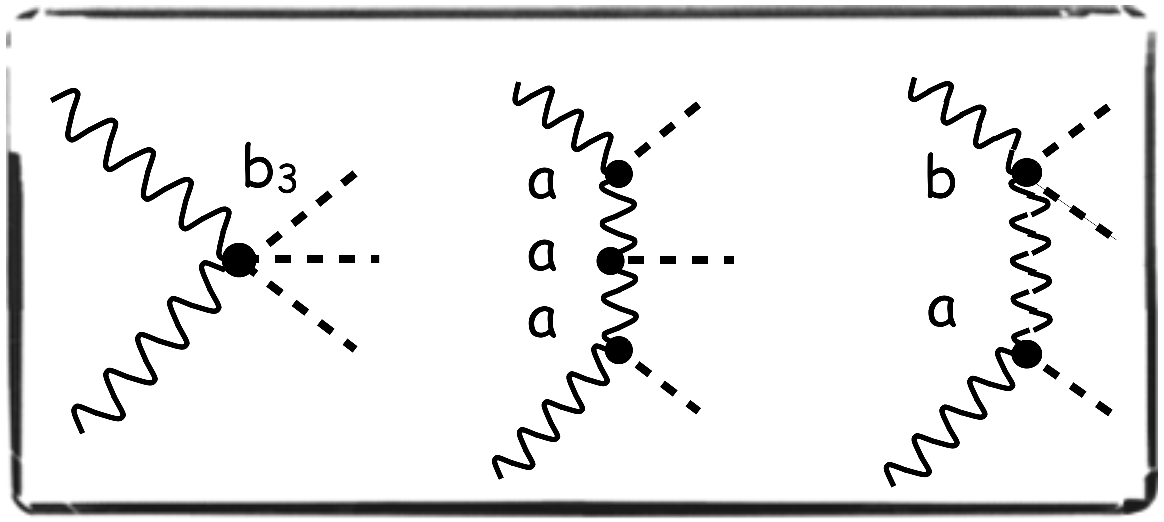
SM

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

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under π → -π

a process with an odd # of PGBs
requires a coupling breaking the coset structure
ie cannot be mediated by strong interactions alone

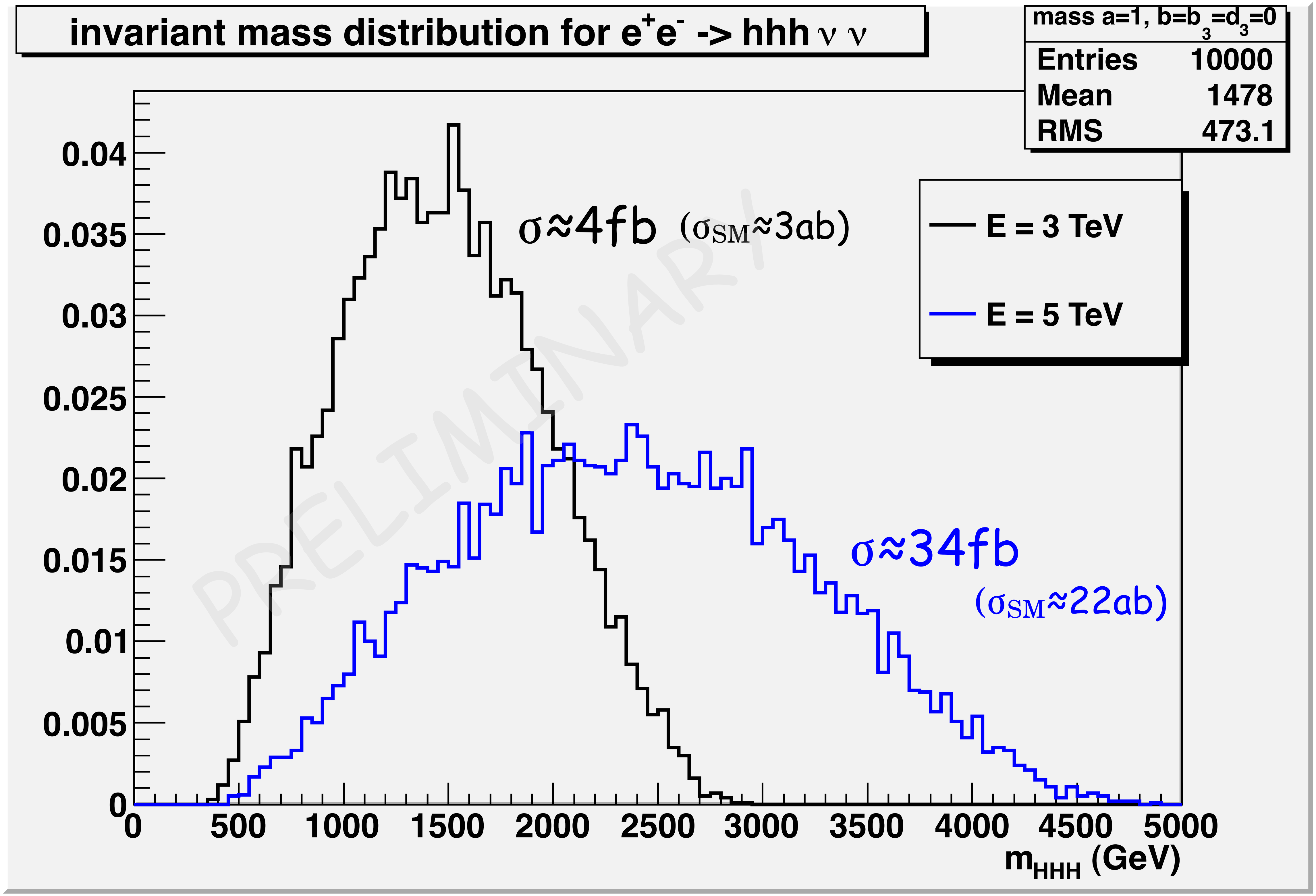


$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\underbrace{\left(a(b-a^2)-\frac{3}{4}b_3\right)}_{\text{=0 for symmetric coset}} + \underbrace{\sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

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

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

non-symmetric coset



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 ⇔ gauge principle
Higgs NC ⇔ ?

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!