A not so elementary Higgs boson

Planck conference

Lisbon, June May 30th - June 3rd 2011

Christophe Grojean

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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 $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

$\Rightarrow$ UV behavior of Goldstone scattering? $\Leftarrow$

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

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

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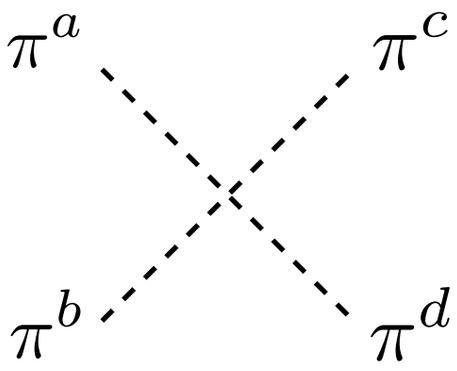
$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \dots$$

contact interaction growing with energy



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

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$

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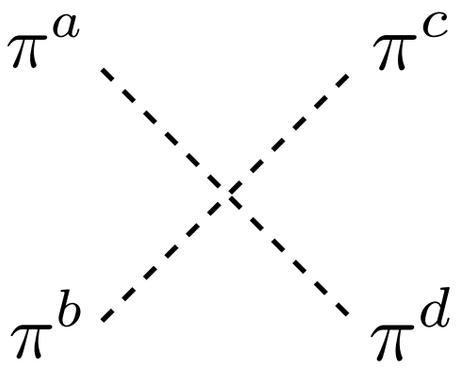

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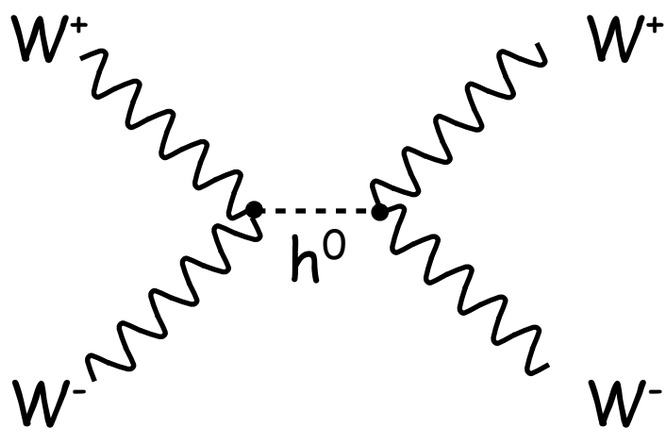
$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$

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

Weak vs. Strong EWSB

what is unitarizing the WW scattering amplitude?

Weakly coupled models



prototype: Susy

susy partners ~ 100 GeV

need new particles to stabilize the Higgs mass

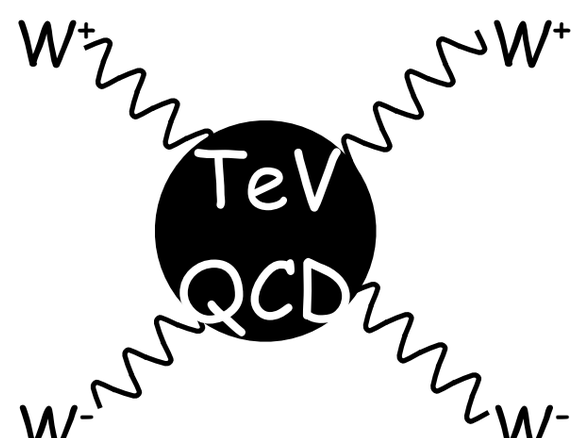
bounds on the masses of these particles

⇓

fine-tuning O(1%)

other ways?

Strongly coupled models



prototype: Technicolor

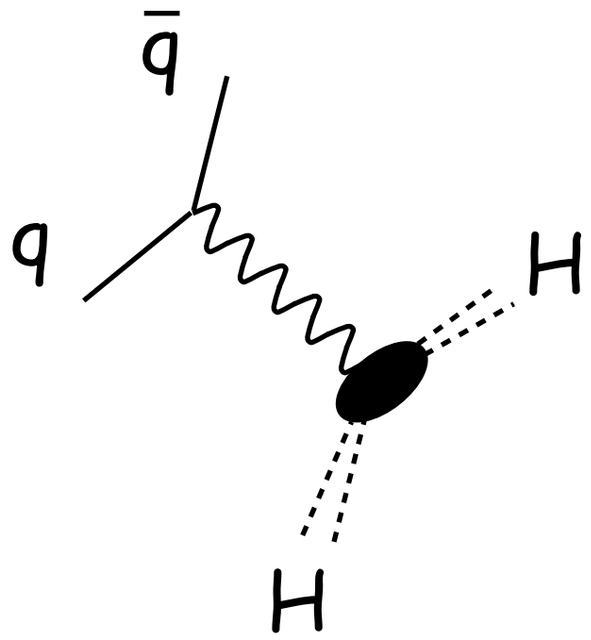
rho meson ~ 1 TeV

resonances needed for unitarization

generate EW oblique corrections

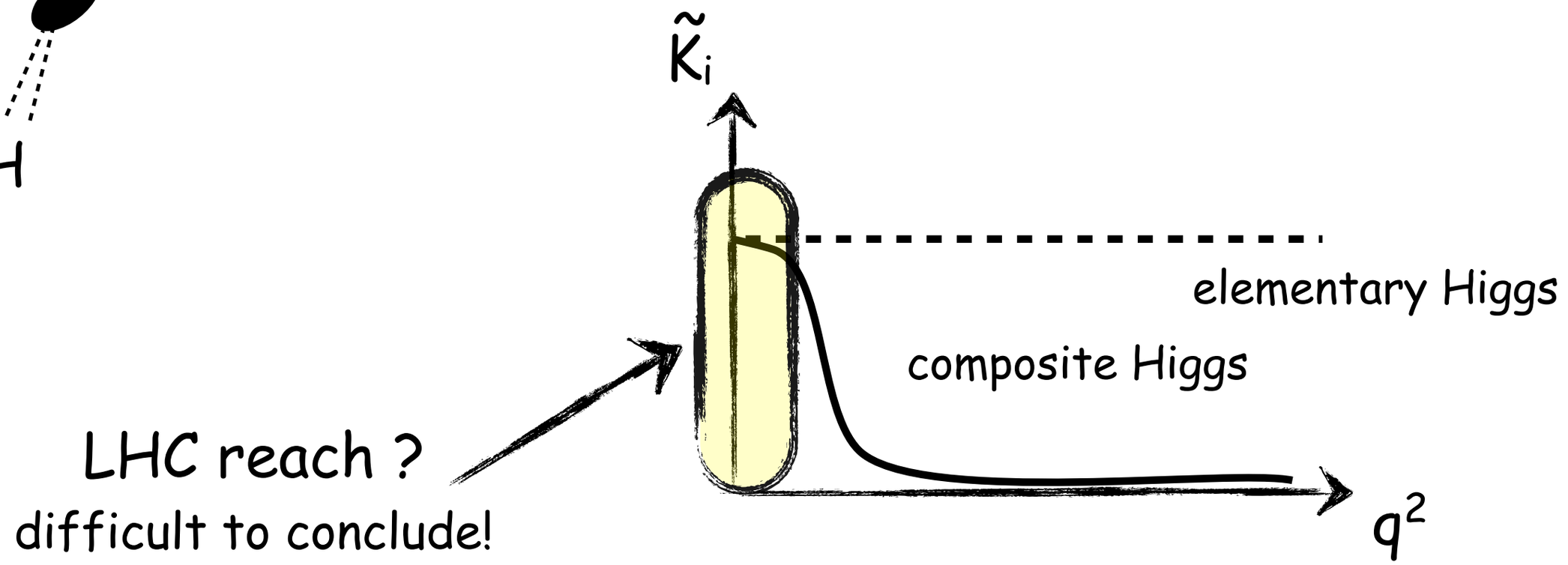
$$\hat{S} \sim \frac{m_W^2}{m_\rho^2} \xrightarrow[@95\%\ \mathrm{CL}]{|\hat{S}| < 10^{-3}} m_\rho > 2.5\ \mathrm{TeV}$$

Is the Higgs boson an elementary scalar?



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16 m_H^2 \sin^4\theta/2} \frac{E'}{E^3} \left(2\tilde{K}_1 q^2 \sin^2\theta/2 + \tilde{K}_2 \cos^2\theta/2 \right)$$

Rosenbluth-type cross-section



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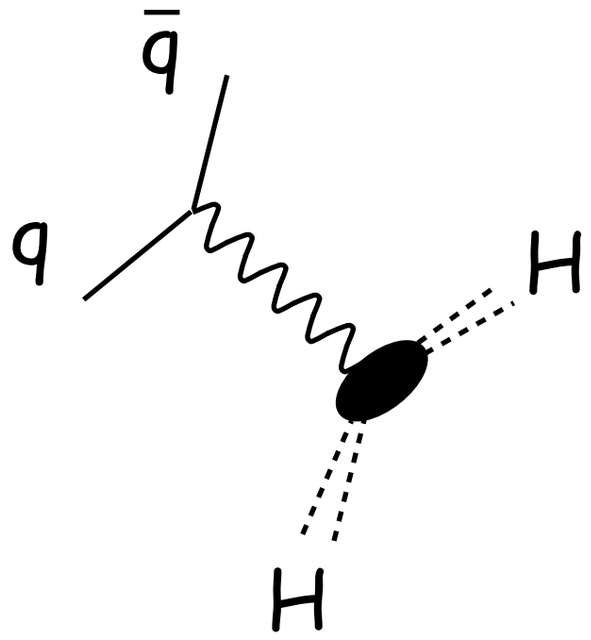

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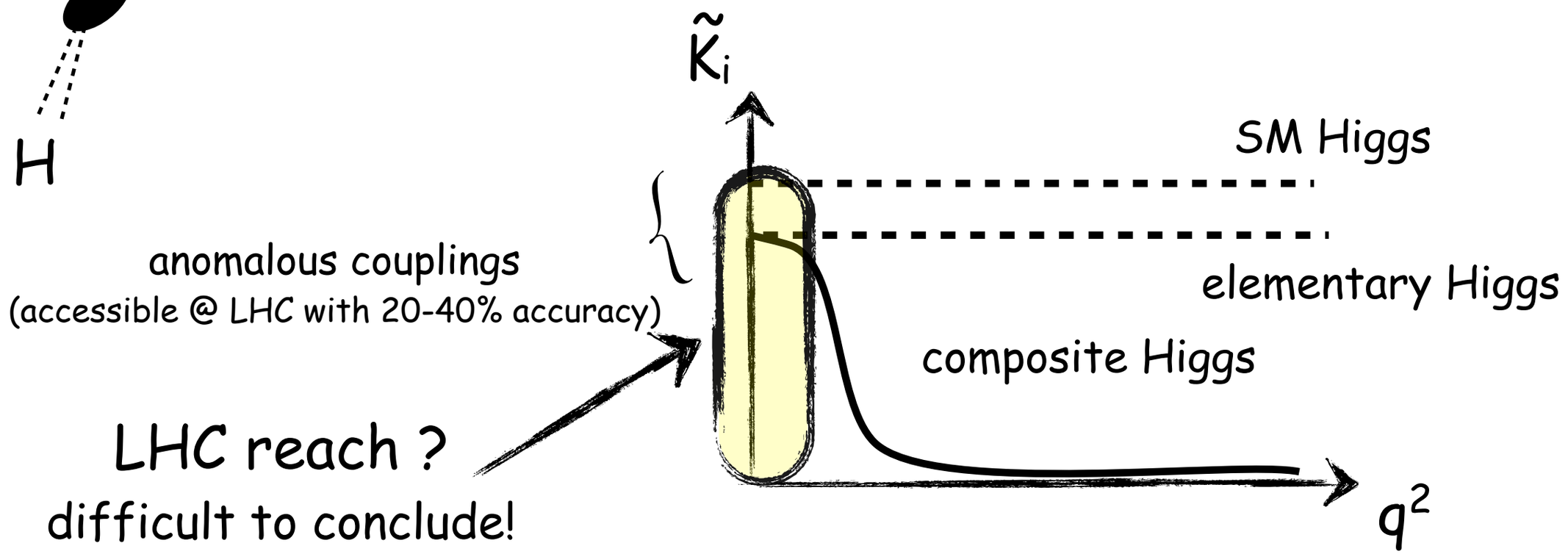

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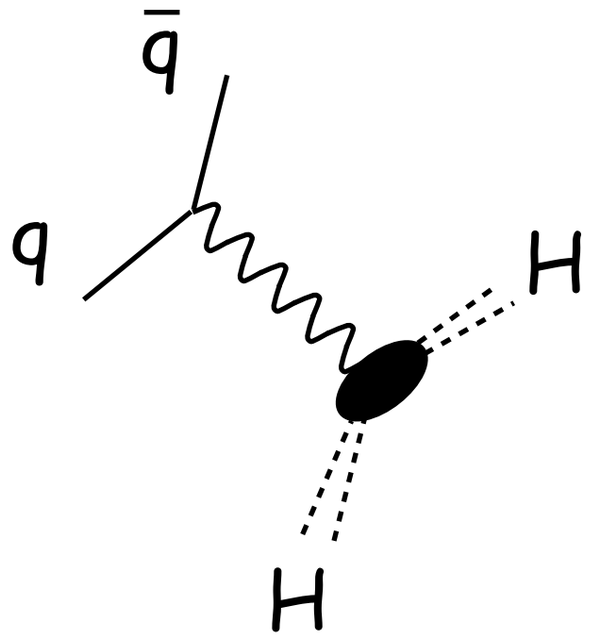

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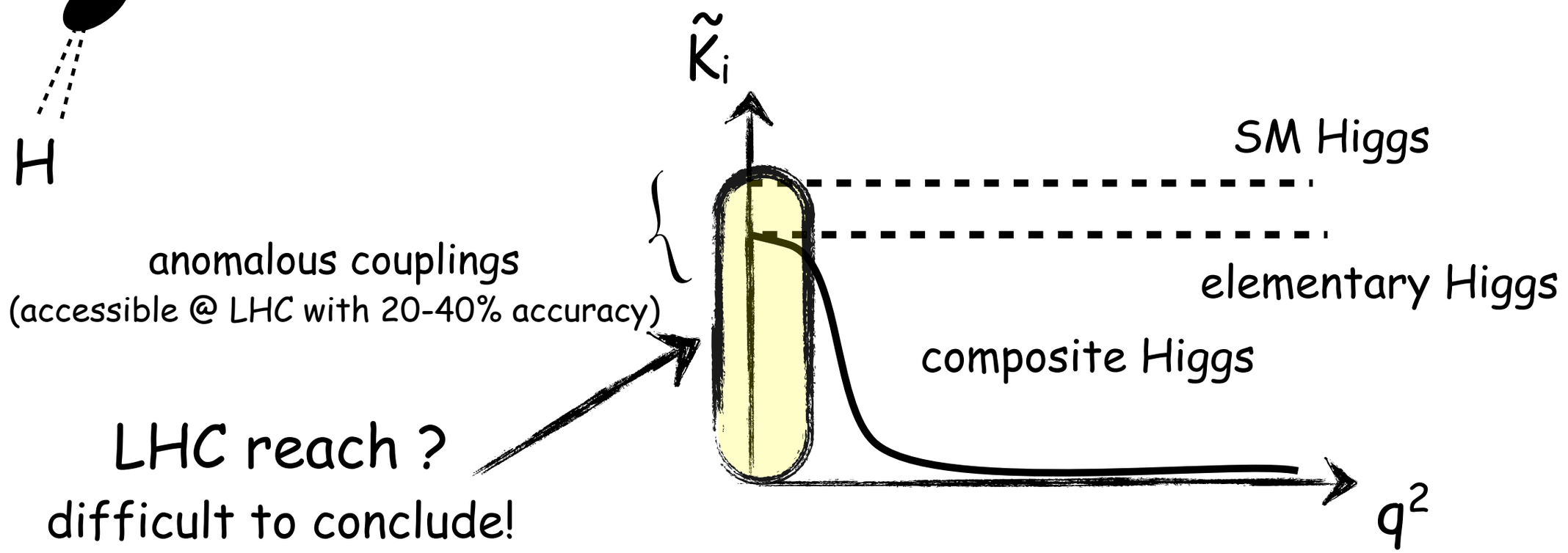


Need to develop tools to understand the physics of a composite Higgs

- use effective theory approach
- rely on symmetries of the problem

} identify interesting processes

How to probe the composite nature of the Higgs?

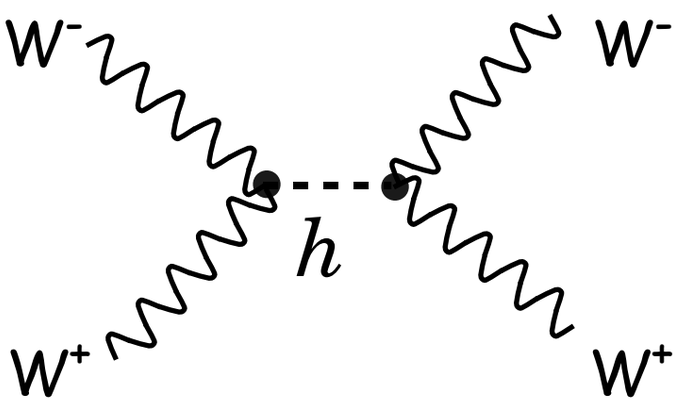
1. Anomalous couplings

What is the SM Higgs?

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

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

'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

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

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

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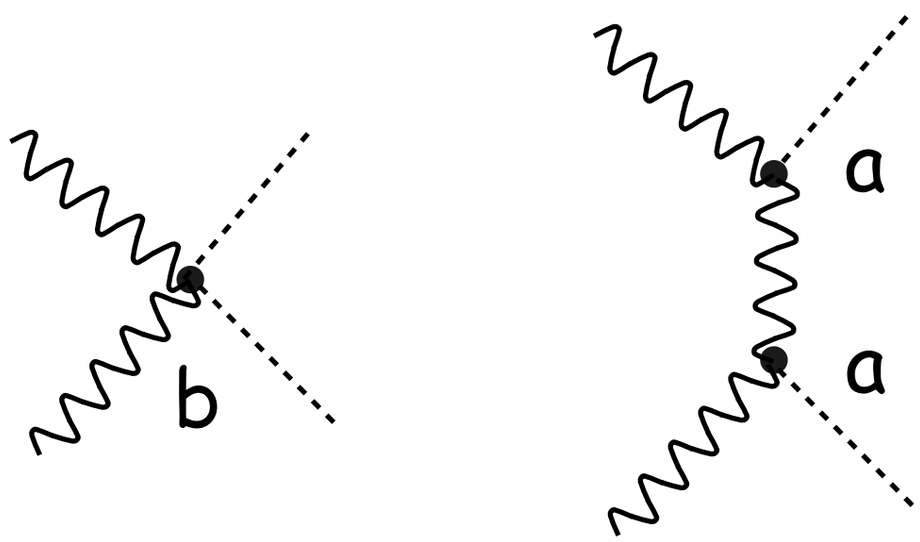

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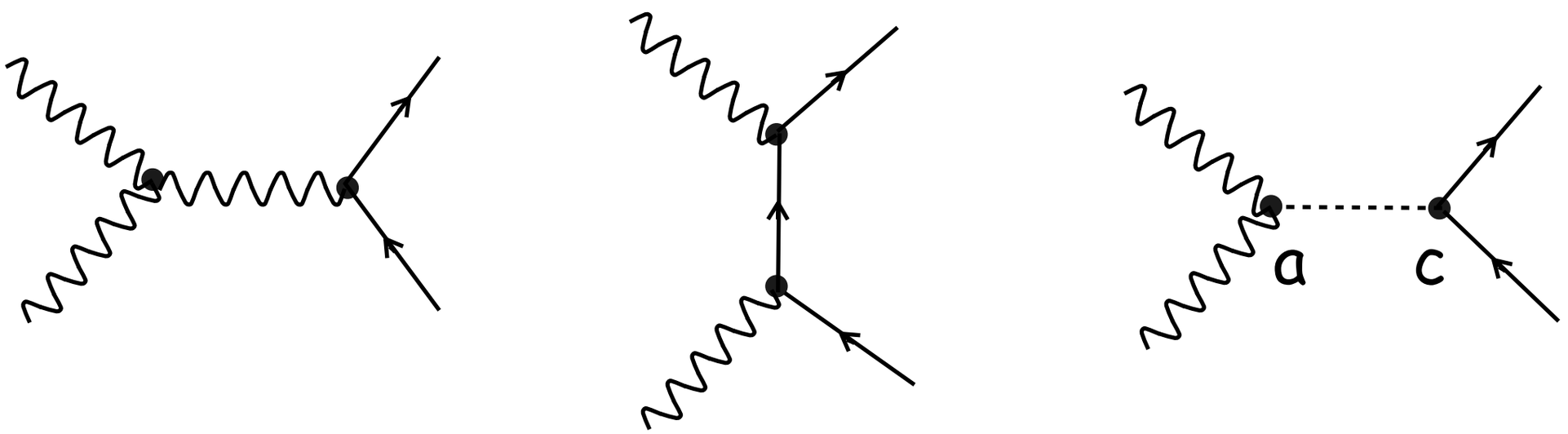

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'a=1', 'b=1' & 'c=1' define the SM Higgs

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 and Z_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

renormalizable level = uniqueness

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

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renormalizable level = uniqueness

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

non-renormalizable level

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

deviations of Higgs couplings originate from higher dimensional operators

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

Anomalous Higgs Couplings

Giudice, Grojean, Pomarol, Rattazzi '07

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

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

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

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

a = 1-ξ/2 b = 1-2ξ c = 1-ξ/2

Deformation of the SM Higgs: current constraints

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

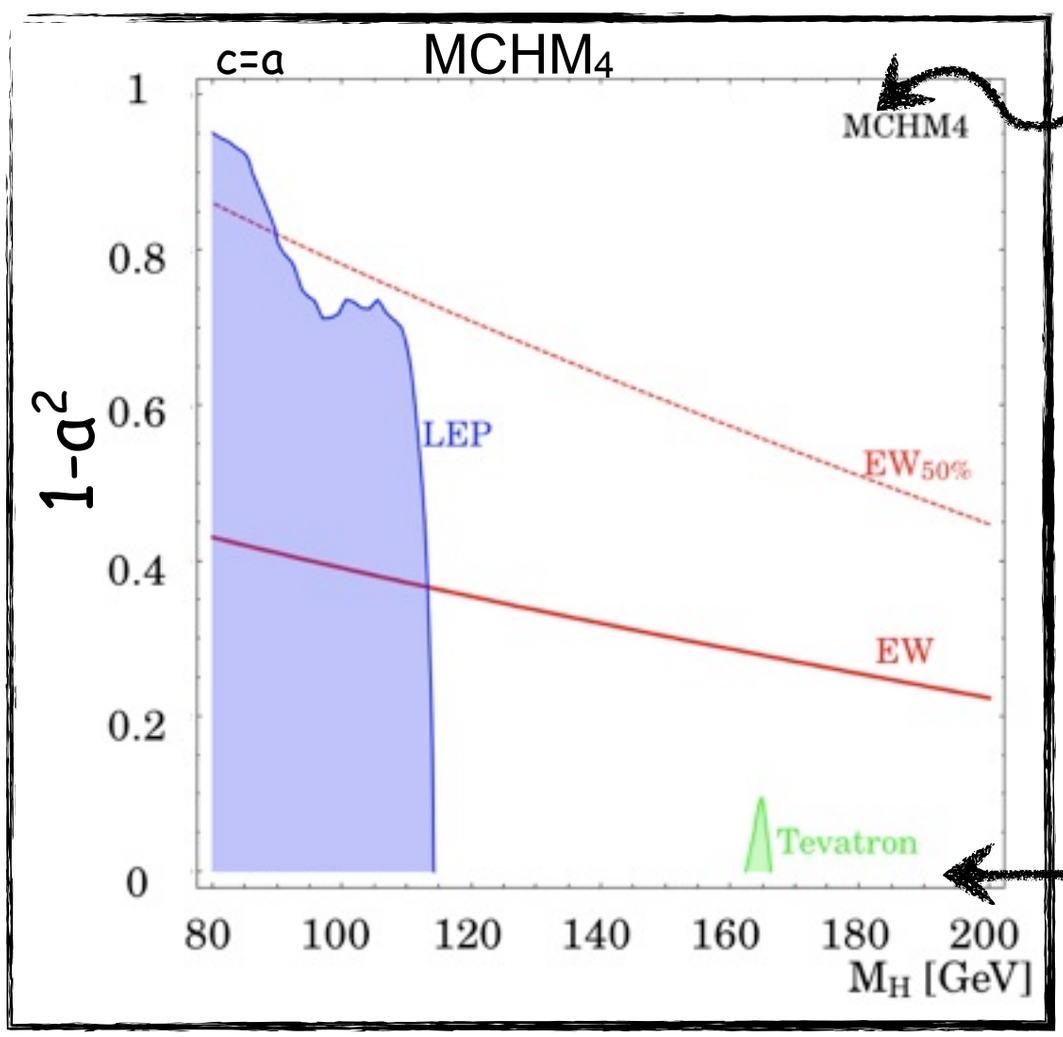
$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu \Sigma \approx W_\mu$

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

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

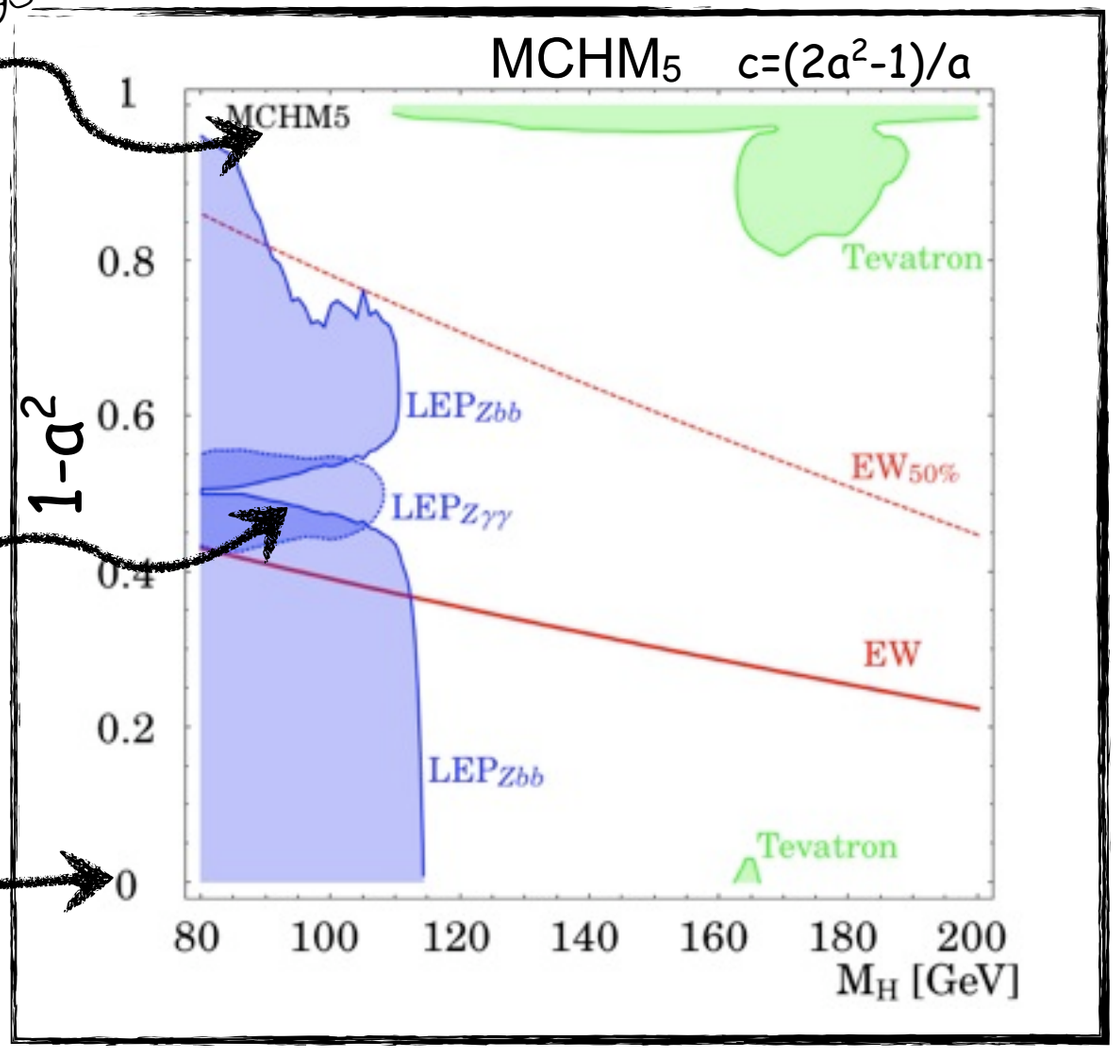
Espinosa, Grojean, Muehlleitner '10

gaugephobic Higgs



fermiophobic Higgs

SM limit



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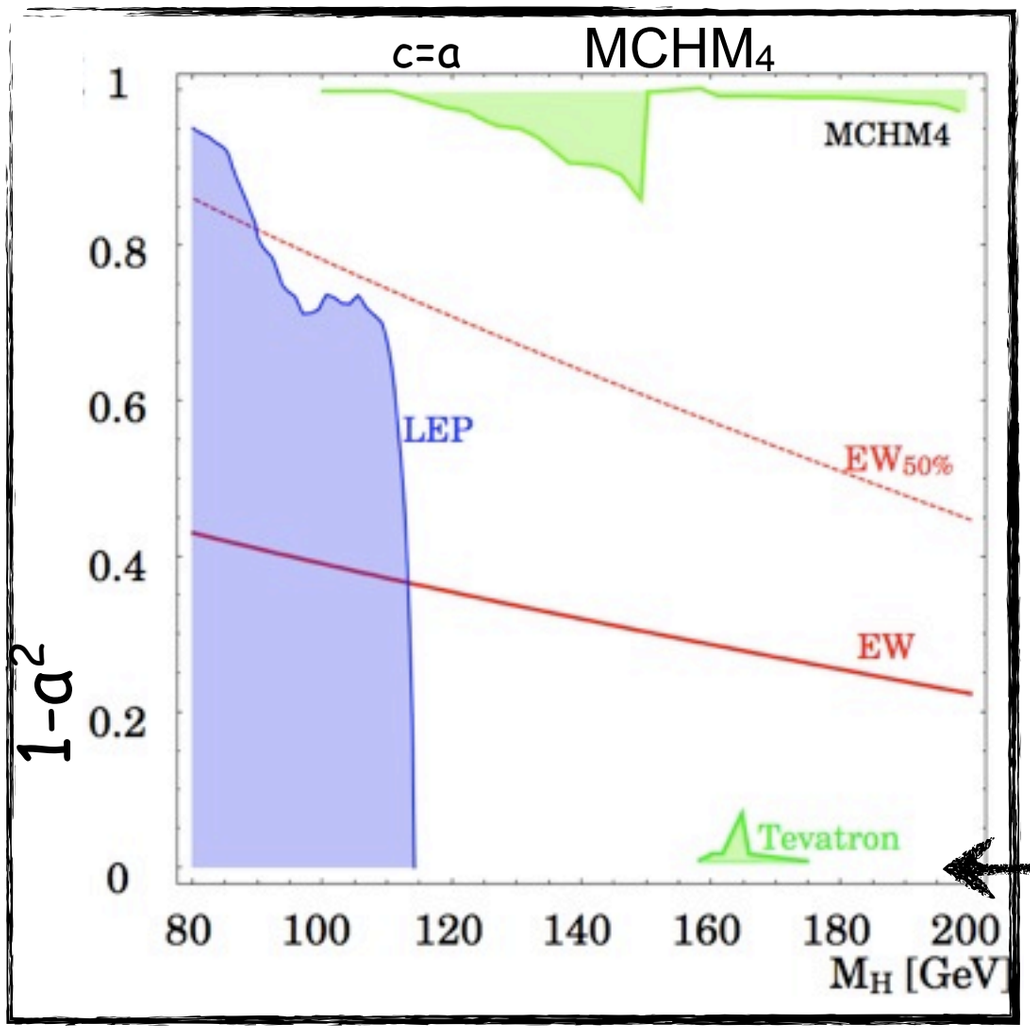
Current EW data constrain only 'a' (and marginally 'c')

New Tevatron constraints

Espinosa '11



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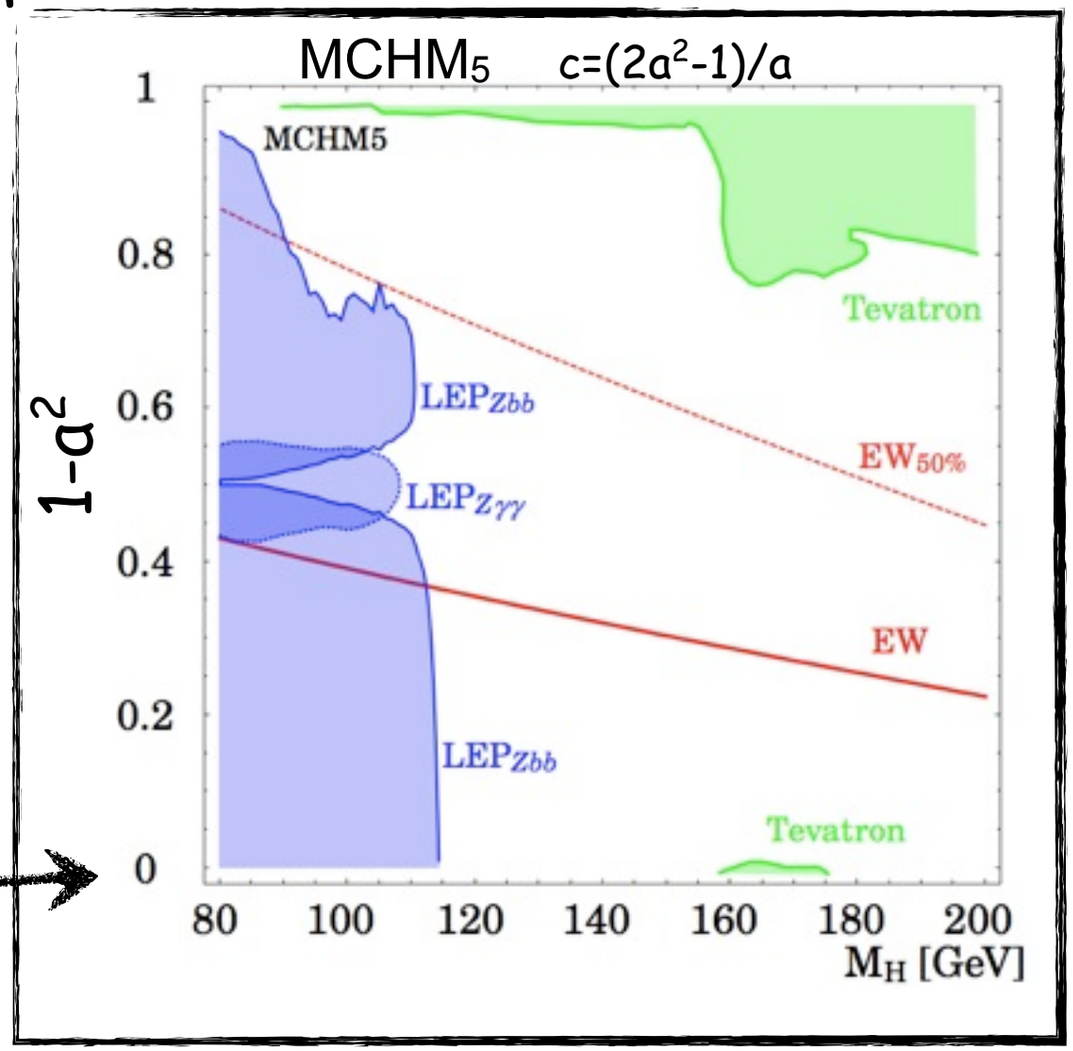


For a recent analysis, see also Bonnet, Gavela, Ota, Winter '11

See also F. Bonnet's talk

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

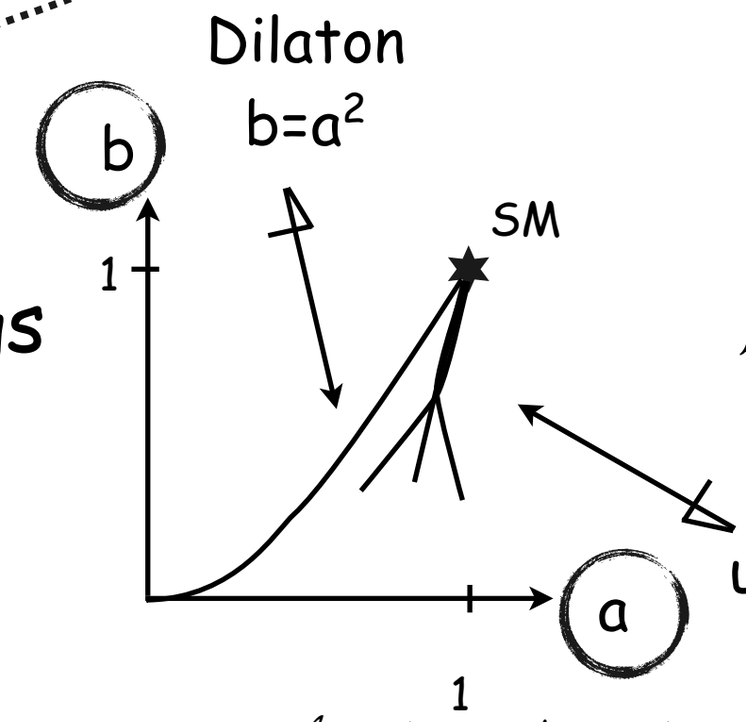
all resonances of strong sector, except the Higgs, decouple

$\xi = 1$

Technicolor limit

Higgs decouple from SM; vector resonances like in TC

Composite Higgs vs. SM Higgs



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

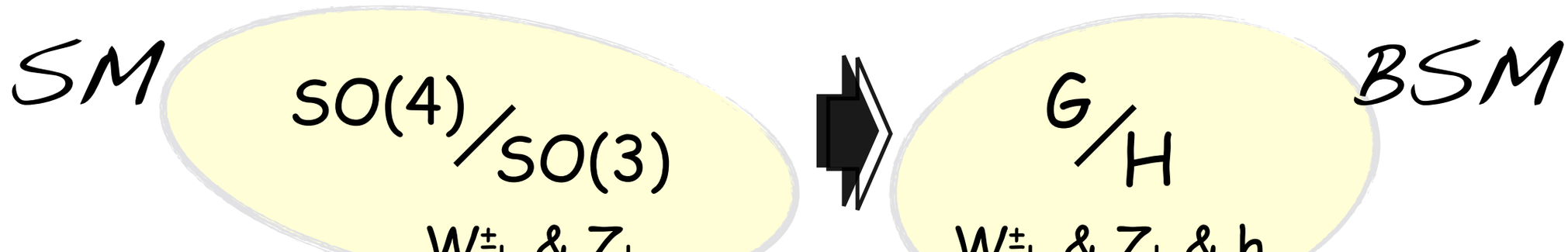
Composite Higgs
universal behavior for large f
$a=1-v^2/2f^2$ $b=1-2v^2/f^2$

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)



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

SO(6)/SO(4)xSO(2): 8 PGBs=H_1+H_2 ↔ Minimal Composite Two Higgs Doublets

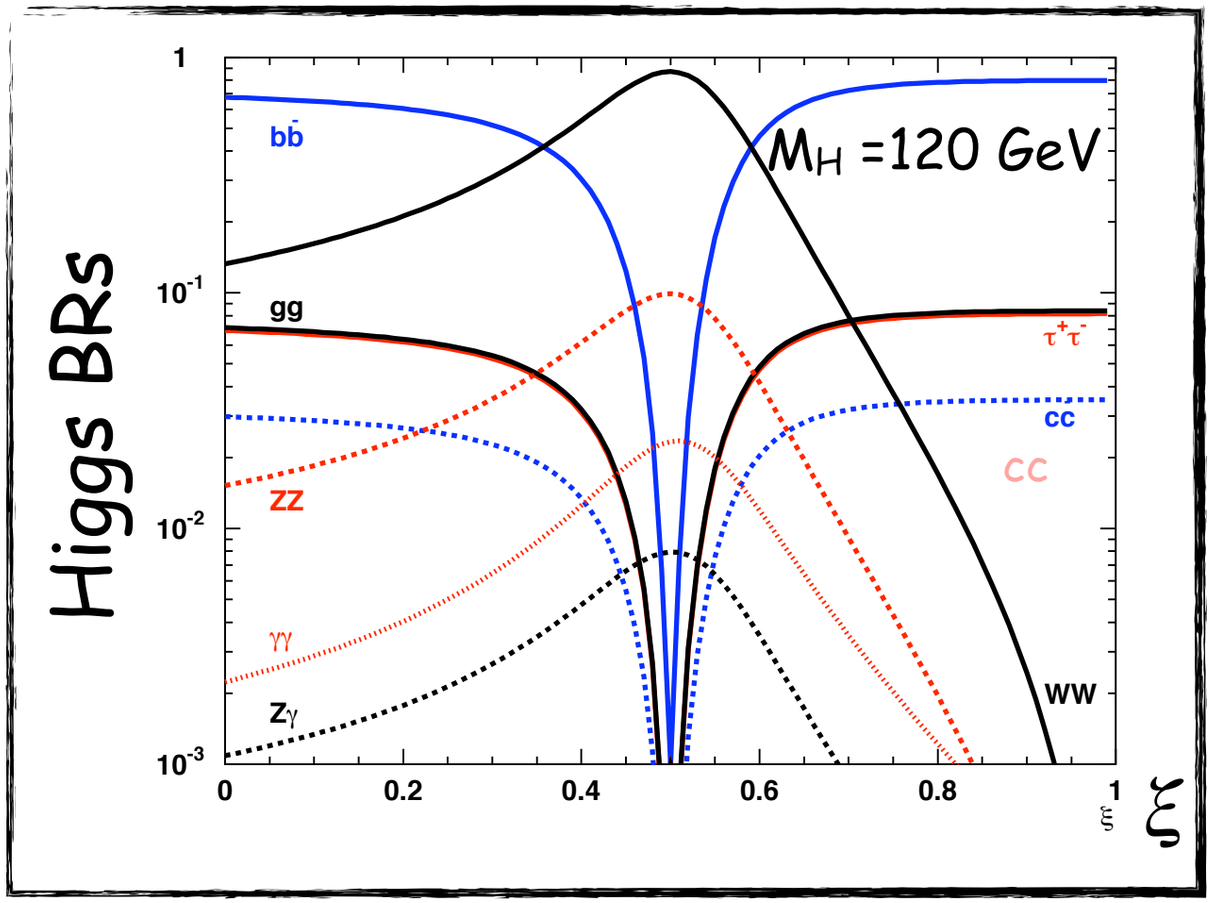
Mrazek, Pomarol, Rattazzi, Serra, Wulzer '11

Anomalous Higgs BRs

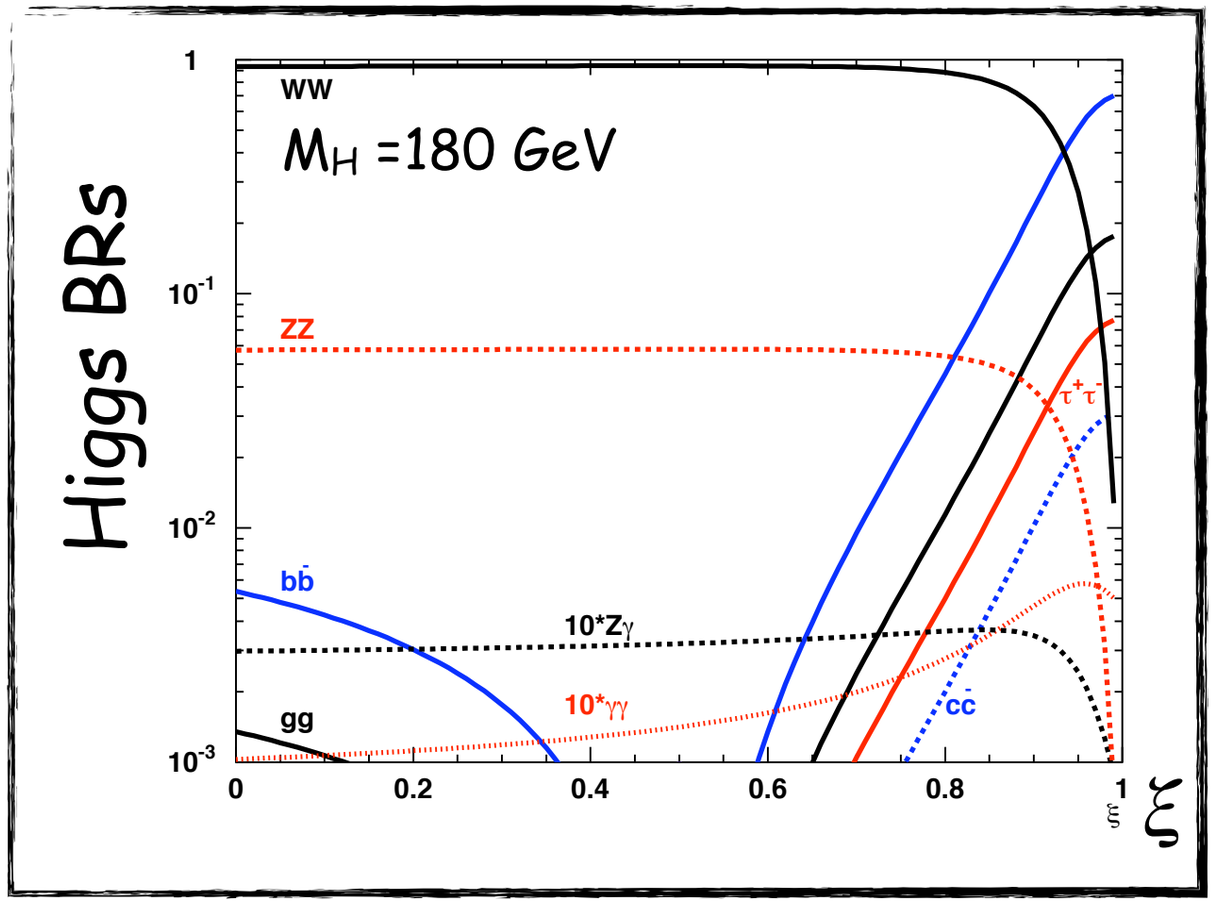
Fermions embedded in 5+10 of SO(5)

MCHM5

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



h→WW can dominate even for low Higgs mass



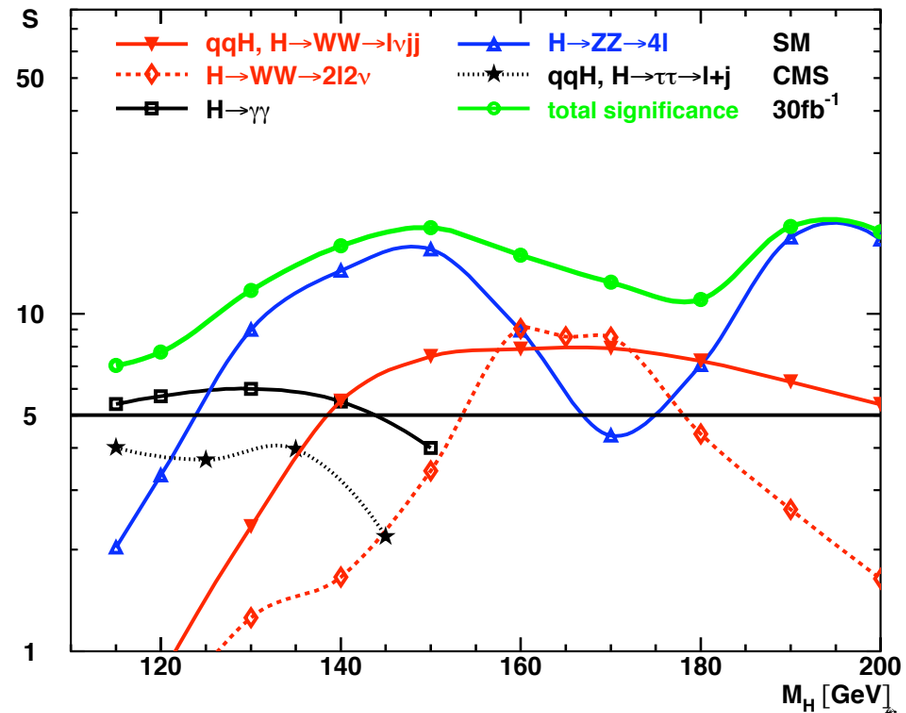
BRs remain SM like except for very large values of v/f

Anomalous Higgs Production

Espinosa, Grojean, Muehlleitner '10

the modification of Higgs couplings and BRs affects the Higgs search

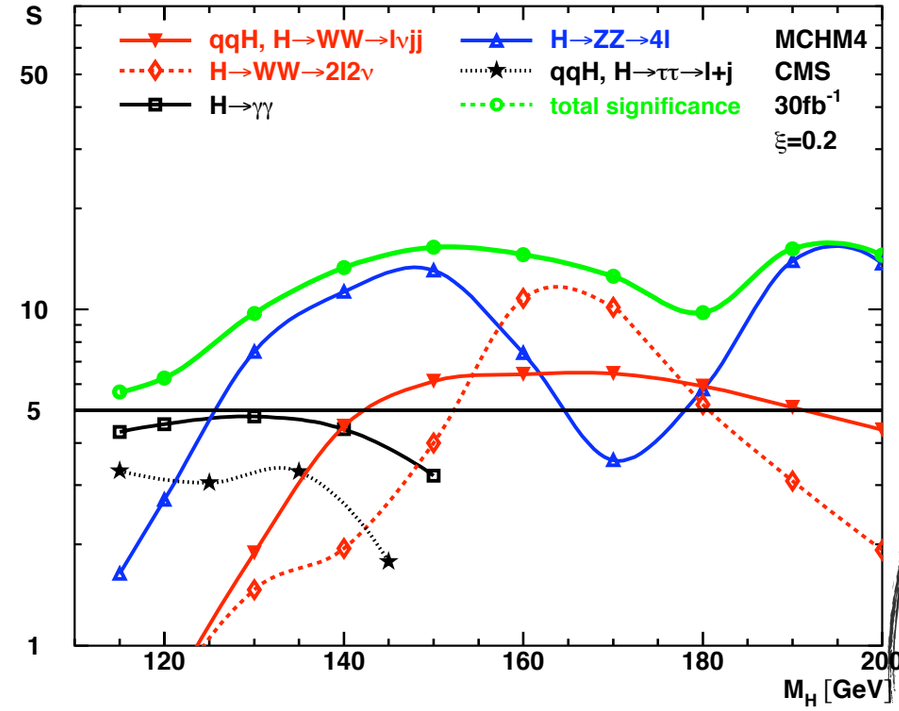
SM



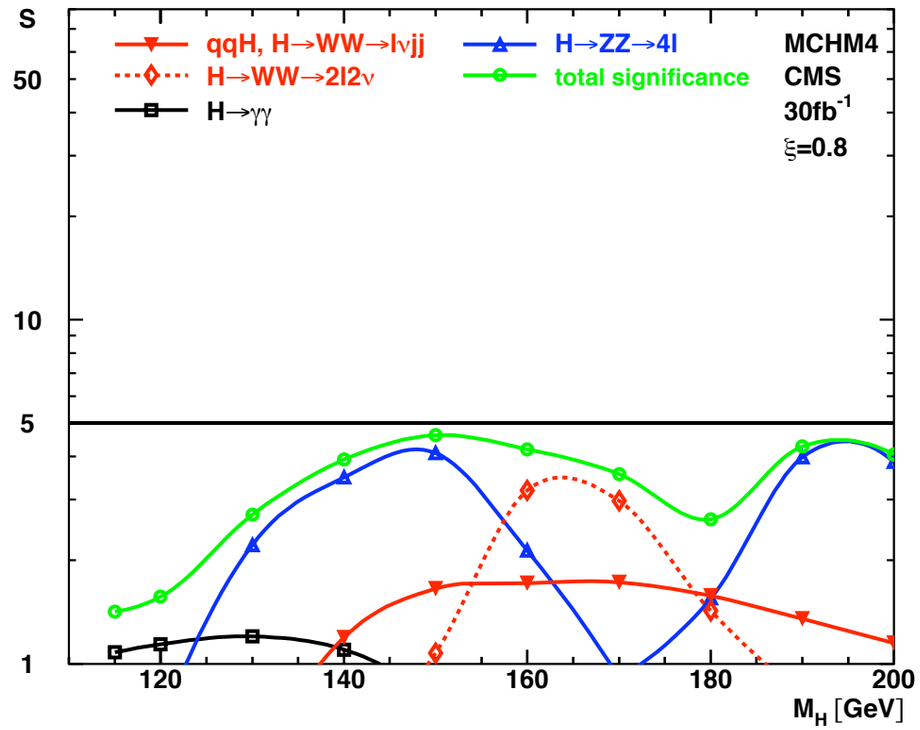
large compositeness scale

signal significance for L=30/fb

small compositeness scale



MCHM4



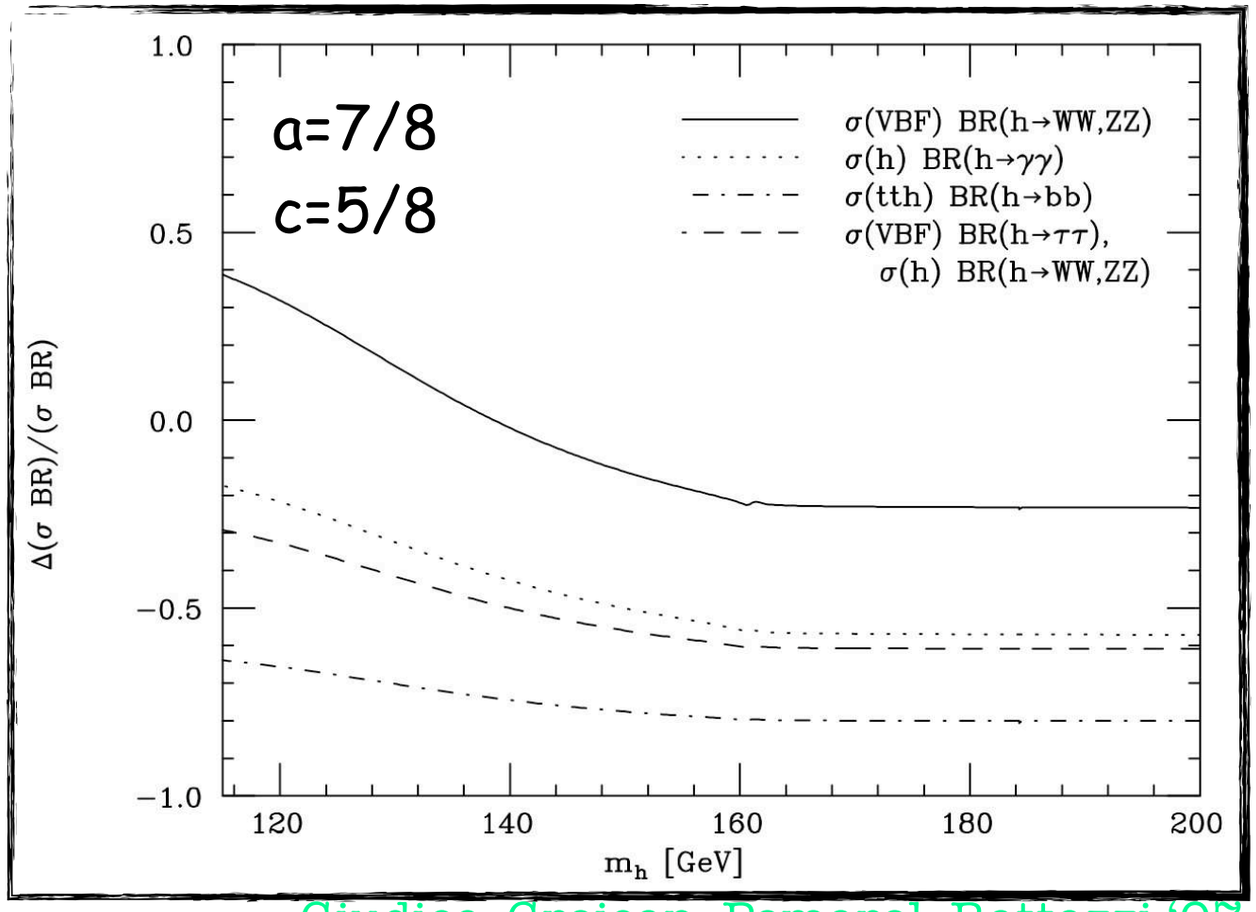
Higgs anomalous couplings @ LHC

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

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

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

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



Giudice, Grojean, Pomarol, Rattazzi '07

LHC can probe

Δa & Δc
up to ~ 0.1÷0.2
i.e. $4\pi f$ ~ 5÷7 TeV

compositeness scale of the Higgs

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

How to probe the composite nature of the Higgs?

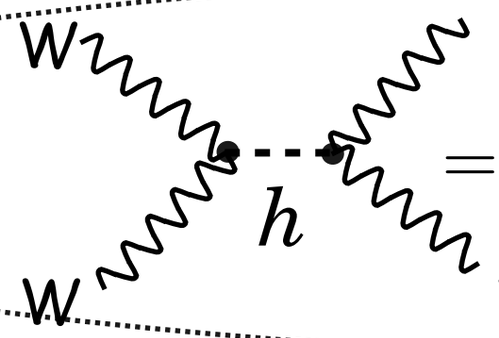
2. Strong scattering

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

$$\mathcal{A}\left(W_L^a W_L^b \to W_L^c W_L^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc} \qquad \mathcal{A} = \left(1-a^2\right)\frac{s}{v^2}$$

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

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

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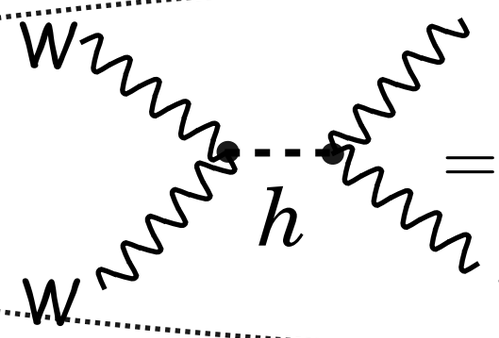

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strong double Higgs production

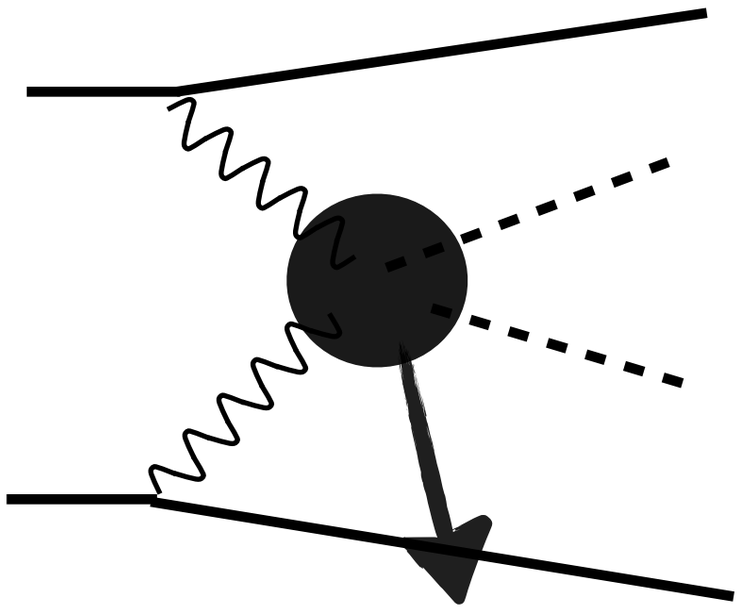
Contino, Grojean, Moretti, Piccinini, Rattazzi '10

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

access to a new interaction, 'b'

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

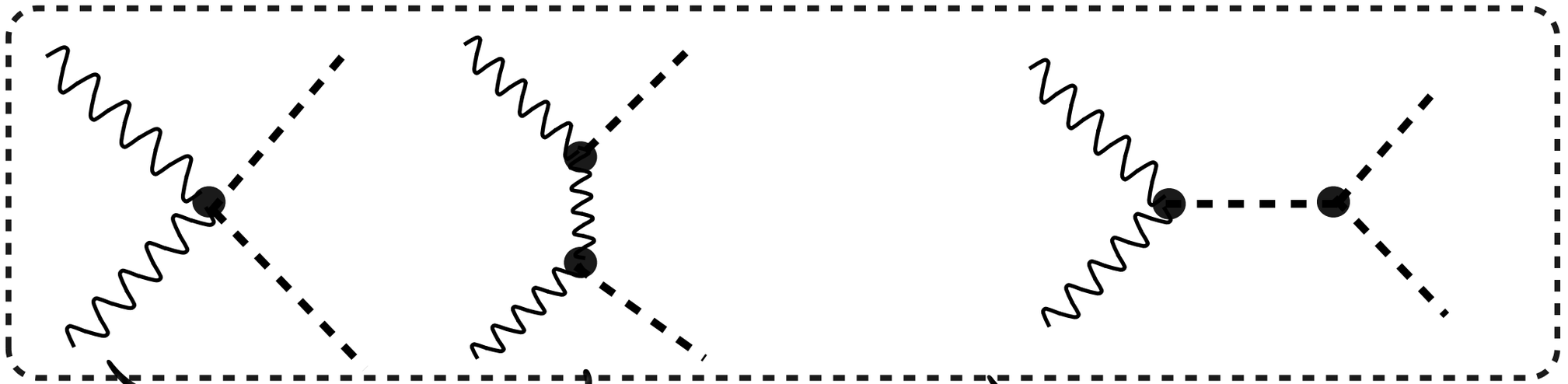
Double Higgs production: 'b' and 'd_3' couplings



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

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

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

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

threshold effect
anomalous coupling'

Strong Higgs production: (3L+jets) analysis

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

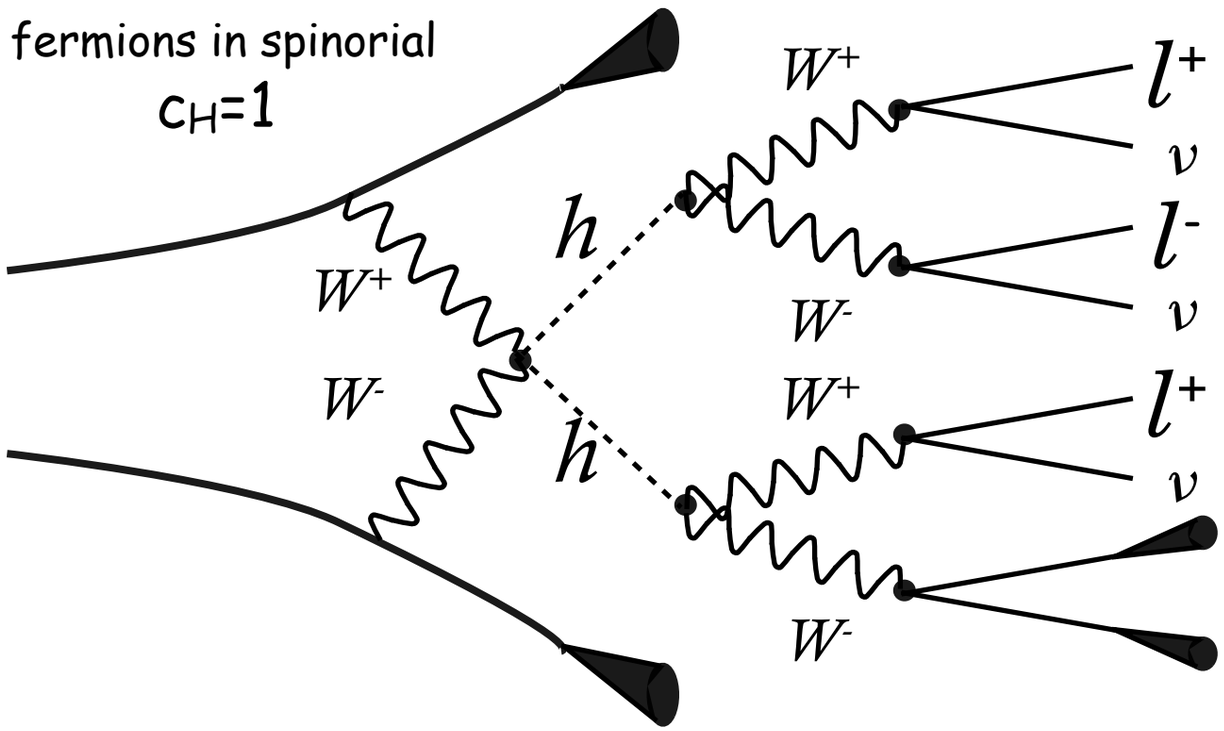
strong boson scattering ⇔ strong Higgs production

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

$m_h = 180$ 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

How to probe the composite nature of the Higgs?

3. Identifying discrete symmetries of strong sector

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

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

Strong EWSB

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

$E/f \leftrightarrow g$

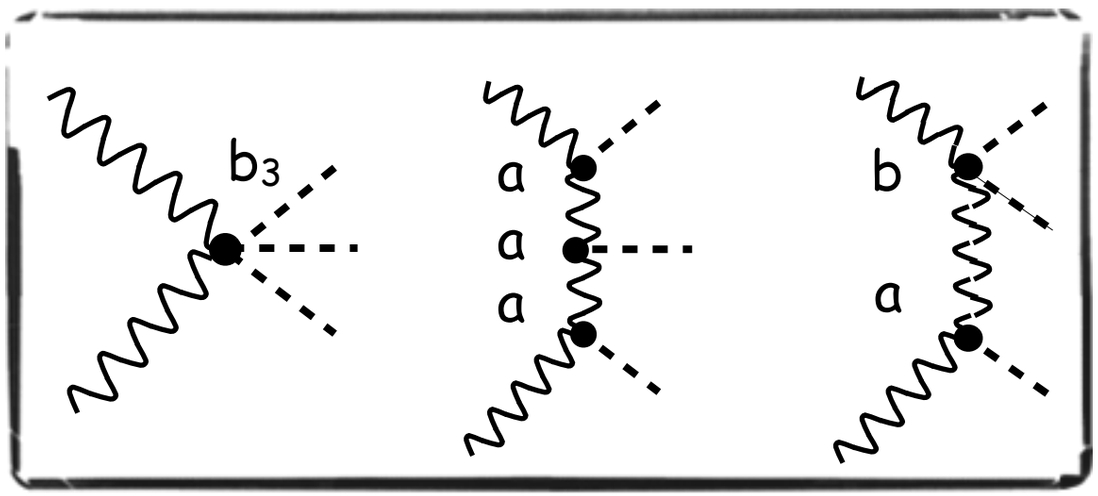
SM

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

Probe of possible discrete symmetries in the strong dynamics

G/H symmetric space ⇒ invariance under $\pi \to -\pi$

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

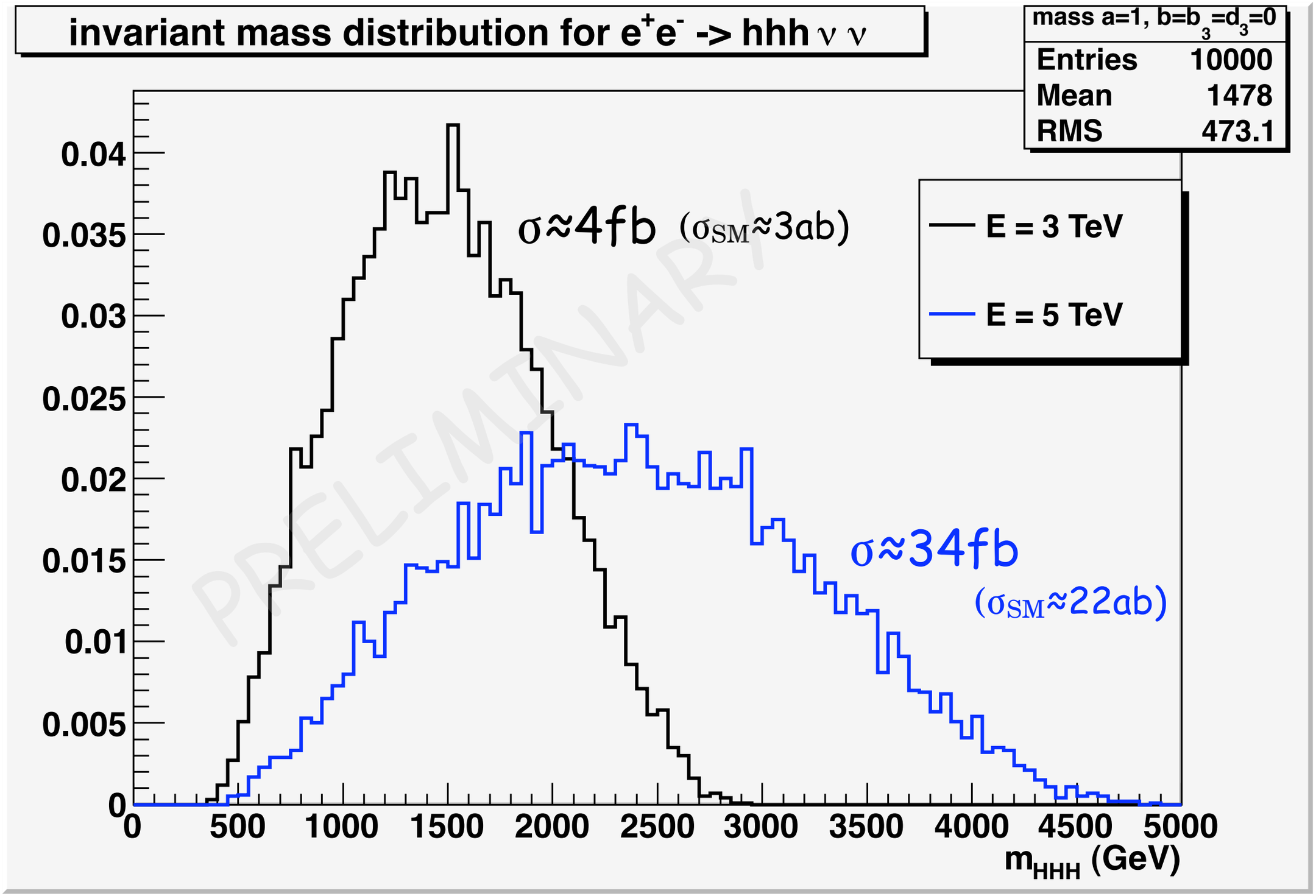


$$\mathcal{A}_{WW\to 3h} \sim 4i\frac{s}{v^3}\left(\underbrace{a(b-a^2)-\frac{3}{4}b_3}_{=0 \text{ for symmetric coset}}\right) + \underbrace{\sharp\, s \times \left(\frac{m_W}{\sqrt{s}}\right)^2}_{\text{mediated by SM gauge interactions (breaking of coset structure)}}$$

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

Contino, Grojean, Pappadopoulo, 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 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?

See E. Salvioni's talk

A heavy composite W'

Grojean, Salvioni, Torre '11

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elementary spin-1

$g=2 \Leftrightarrow \Lambda \gg M/e \Leftrightarrow W' \to W\gamma$ highly suppressed

See E. Salvioni's talk

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

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Ferrara, Porrati, Telegdi '92

composite spin-1

g≠2 & Λ > 5÷10 M $\Leftrightarrow$ W'→Wγ allowed and potentially large

$(g-1)B^{\mu\nu}W'^{+}_{\mu}W'^{-}_{\nu}$ dimension-4 operator mediating W' →Wγ after W-W' 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 ⇔ 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!

"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]

SILH Effective Lagrangian

(strongly-interacting light Higgs)

Giudice, Grojean, Pomarol, Rattazzi '07

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

EXTRA MATERIAL

- **Genuine strong operators** (sensitive to the scale f)

$$\frac{c_H}{2f^2}\left(\partial^\mu |H|^2\right)^2 \qquad \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)^2 \qquad \frac{c_y y_f}{f^2}|H|^2 \bar{f}_L H f_R + \text{h.c.} \qquad \frac{c_6 \lambda}{f^2}|H|^6$$

custodial breaking

- **Form factor operators** (sensitive to the scale m_ρ)

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

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

minimal coupling: $h \to \gamma Z$ — loop-suppressed strong dynamics

$$\frac{c_\gamma}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} \qquad \frac{c_g}{m_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}$$

Goldstone sym.