Conference in honor of
ROBERTO CASALBUONI
70th Birthday

From BESS to Composite Higgs

Stefania De Curtis & Michele Redi

INFN

Firenze, September 21, 2012

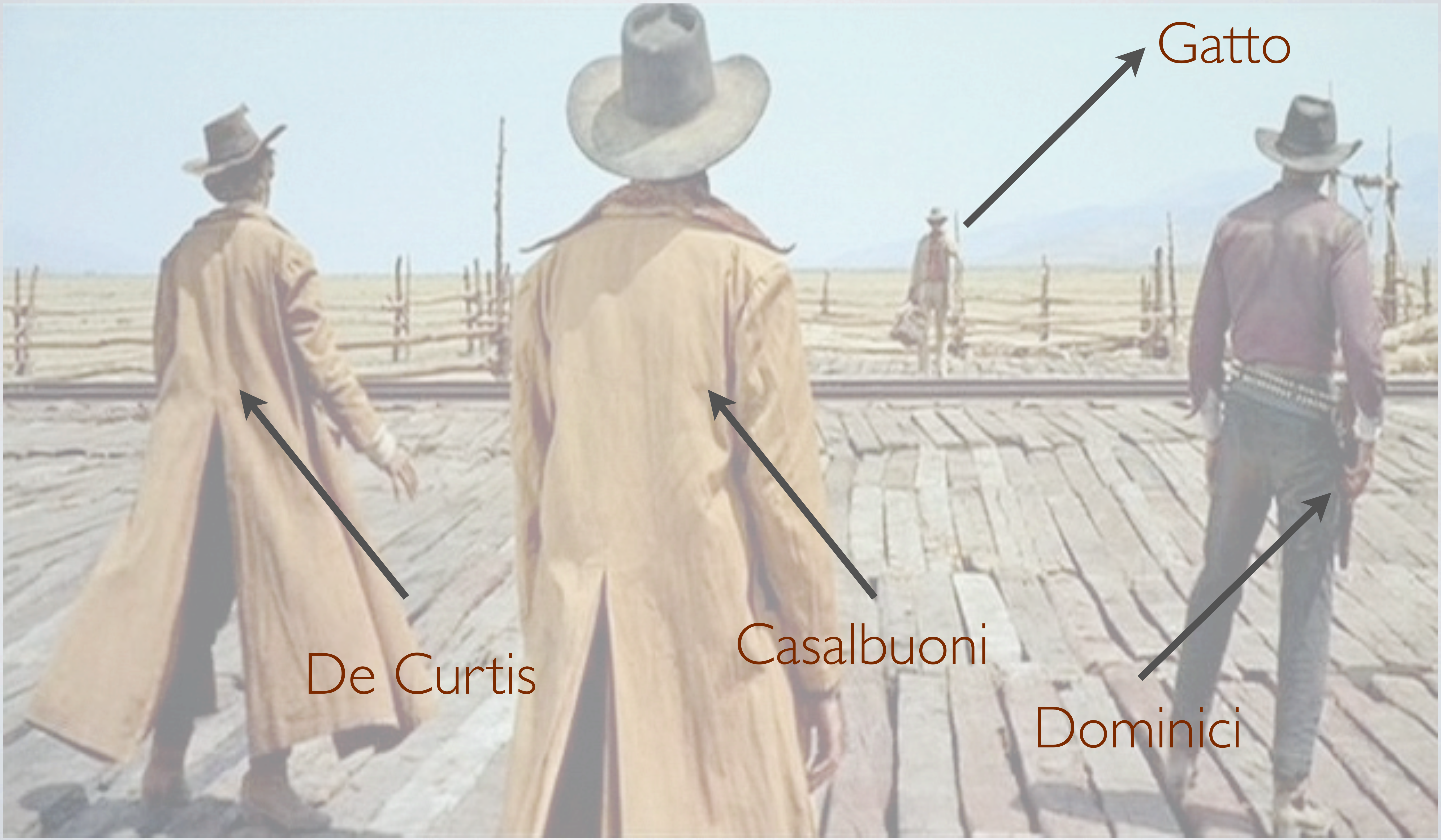
PART I:
BESS

Breaking Electroweak Symmetry Strongly

Acronymous by Ferruccio Feruglio inspired by the Gershwins' "PORGY and BESS"

~1985

Once upon a time...



We knew

$$m_W \approx 80\,\mathrm{GeV} \qquad\qquad m_Z \approx 90\,\mathrm{GeV}$$

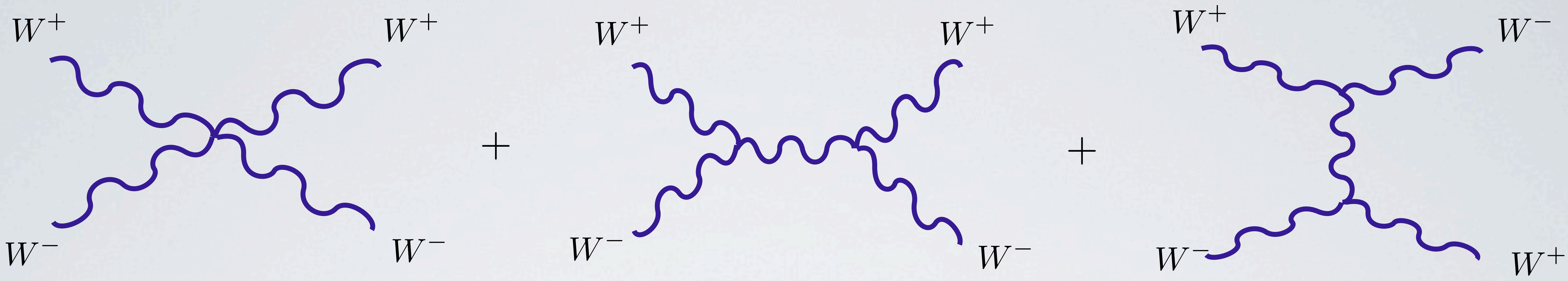
Mass for gauge bosons implies new degrees of freedom
These are the Goldstone bosons

$$SU(2)_L \otimes U(1)_Y \to U(1)_Q$$

Important hint:

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \approx 1 \longrightarrow \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}$$

This, in principle, did not require the Higgs at all:



$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{v^2}(s+t)$$

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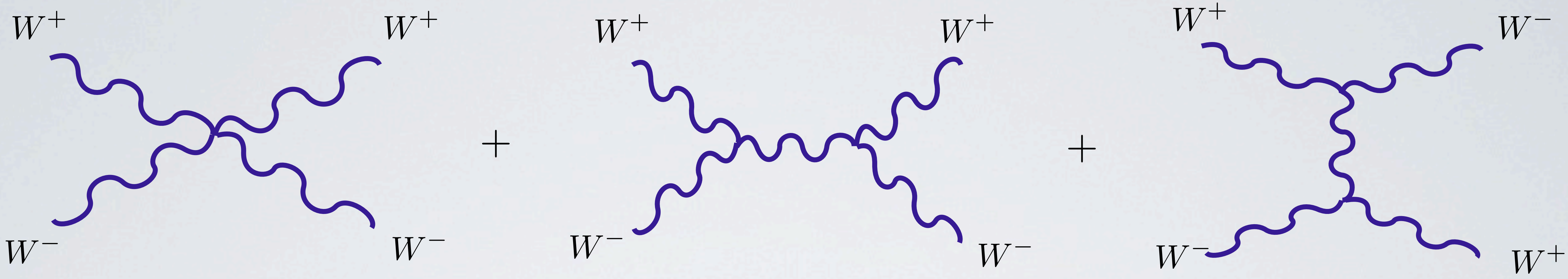


$$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{1}{v^2}(s+t)$$

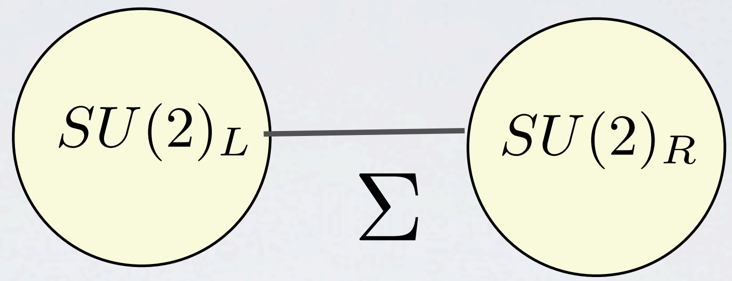
- Technicolor:

New strong dynamics breaks the electro-weak symmetry as QCD does:

$$< \bar{\Psi}_L^i \Psi_R^j >= \Lambda_{QCD}^3 \, \delta_{ij} \quad \longrightarrow \quad \frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}$$

The EWSB sector can be described at low energy by a σ-model

$$\Sigma \to g_L \Sigma g_R^\dagger, \quad g_L \in SU(2)_L,\ g_R \in SU(2)_R$$



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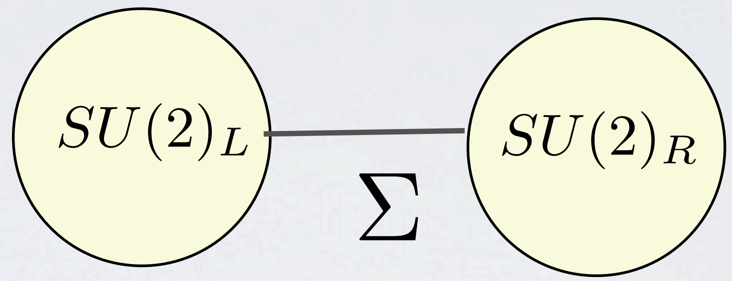

The breaking is produced by $\langle \Sigma \rangle = 1$

GBs

$$\boxed{L = \frac{v^2}{4} (\partial_\mu \Sigma \partial^\mu \Sigma^\dagger)} \qquad \Sigma = e^{i \vec{\pi} \cdot \vec{\tau} / v}$$

Introduce a covariant derivative $\quad D_\mu \Sigma = \partial_\mu \Sigma + i g W_\mu \Sigma - i g' \Sigma Y_\mu$

non linear σ-model can be obtained as a formal limit of the SM for $m_H \to \infty$

Enlarge the σ-model (following CCWZ 1969)

- Introduce vector resonances to improve unitarity properties (learn from QCD)

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- Introduce vector resonances to improve unitarity properties (learn from QCD)

- Use the tool of hidden gauge symmetries (Bando et al 1985): a theory formulated in G with a local symmetry H is equivalent to the non-linear model formulated over G/H

- Vector resonances as gauge fields of the new local interaction

- The new vectors are massive due to the breaking induced by the non-linear realization, the gauge symmetry is not explicitly broken

- BESS:
General parametrization of strongly coupled physics

Volume 155B, number 1,2 PHYSICS LETTERS 16 May 1985

EFFECTIVE WEAK INTERACTION THEORY WITH A POSSIBLE NEW VECTOR RESONANCE FROM A STRONG HIGGS SECTOR ☆

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Received 21 February 1985

We consider the effective lagrangian for electroweak interactions in the limit of a strong interacting Higgs sector ($m_H \to \infty$) We assume that the appearing $SU(2)_V$ hidden local symmetry is realized through a new dynamical vector boson resonance V We derive the physical admixtures and masses of W, Z and V bosons and calculate the couplings of the physical bosons to fermions No physical Higgs remains in the spectrum We find that the standard low energy phenomenology of weak interactions, as well as the W-, Z-masses and properties, may be rather closely reproduced in our effective theory, even for low values of the mass of the new vector resonance, within presently accessible energies.

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Simplest enlargement of the non-linear model with $H_{local} = SU(2)$

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Based on two cosets $SU(2)_L \times SU(2)_R / SU(2)$ described by Σ_1 , Σ_2

$$\Sigma_1(x) \to g_L \Sigma_1(x) h^\dagger(x), \;\Sigma_2(x) \to h(x)\Sigma_2(x) g_R^\dagger, \;h \in H$$

chiral field $U = \Sigma_1 \Sigma_2 \to g_L \Sigma_1 h^\dagger h \Sigma_2 g_R^\dagger = g_L \Sigma_1 \Sigma_2 g_R^\dagger$ blind to H_{local}

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The most general Lagrangian, symmetric under $G \otimes H \otimes P_{LR}$

$$\boxed{L = -v^2 [Tr(\omega_\mu^\perp)^2 + \alpha \, Tr(\omega_\mu^\parallel - V_\mu)^2]}$$

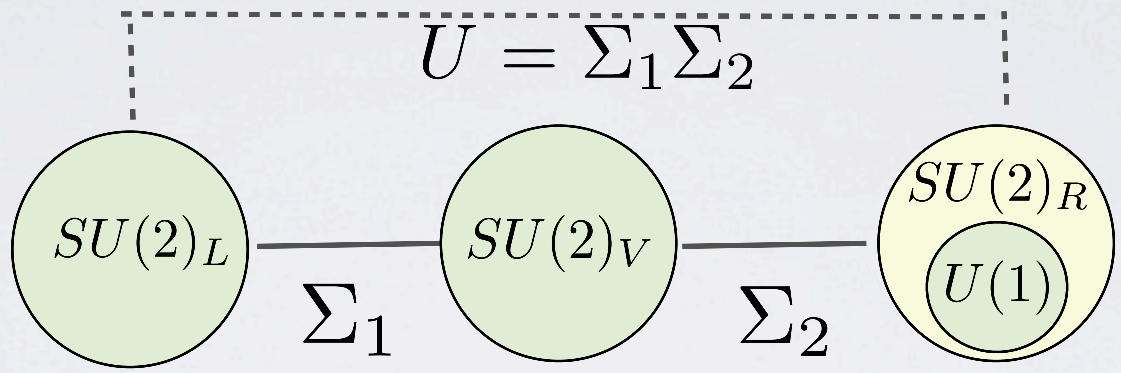
$$\omega_\mu^\parallel = \frac{1}{2}(\Sigma_1^\dagger D_\mu \Sigma_1 + \Sigma_2^\dagger D_\mu \Sigma_2)$$

$$\omega_\mu^\perp = \frac{1}{2}(\Sigma_1^\dagger D_\mu \Sigma_1 - \Sigma_2^\dagger D_\mu \Sigma_2)$$

gauge fields of H_{local}

$$D_\mu \Sigma_1 = \partial_\mu \Sigma_1 + \Sigma_1 V_\mu, \quad D_\mu \Sigma_2 = \partial_\mu \Sigma_2 - V_\mu \Sigma_2$$

To get the complete BESS Lagrangian we gauge the $SU(2)_L \times U(1)$ SM gauge group by the covariant derivatives and include kinetic term for the gauge fields $W_\mu,\ Y_\mu,\ V_\mu$



moose diagram for the BESS model

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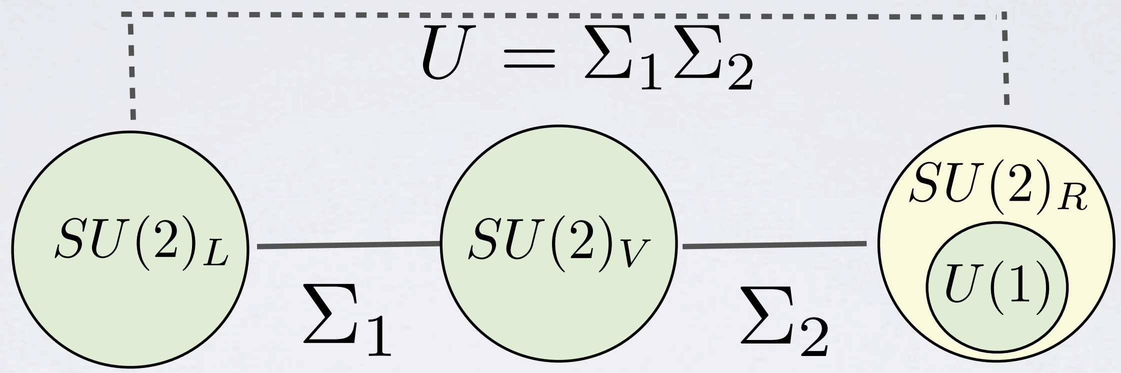

moose diagram for the BESS model

$\boxed{\text{new parameters: } g",\ \alpha}$

$$M_V^2 = \frac{v^2}{4}\alpha g"^2$$

3-site model corresponds to $\alpha = 1$

linear moose

Linear Moose Models
Breaking the EW symmetry without a Higgs

- Generalize the moose construction: many copies of the gauge group G intertwined by link variables Σ . Simplest example $G_i = SU(2)$.

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- Particle content: $W^{\pm}, \ Z$, the massless photon and **3K** massive vectors

$$L = \sum_{i=1}^{K+1} f_i^2 Tr[D_\mu \Sigma_i^\dagger D^\mu \Sigma_i] - \frac{1}{2} \sum_{i=0}^{K+1} Tr[(F_{\mu\nu}^i)^2]$$

$A^0 = W, \ A^{K+1} = Y$
gauge fields of $SU(2)_W \times U(1)_Y$

$A^i \quad i = 1, \cdots, K$
gauge fields of $G_i = SU(2)$

The continuum limit

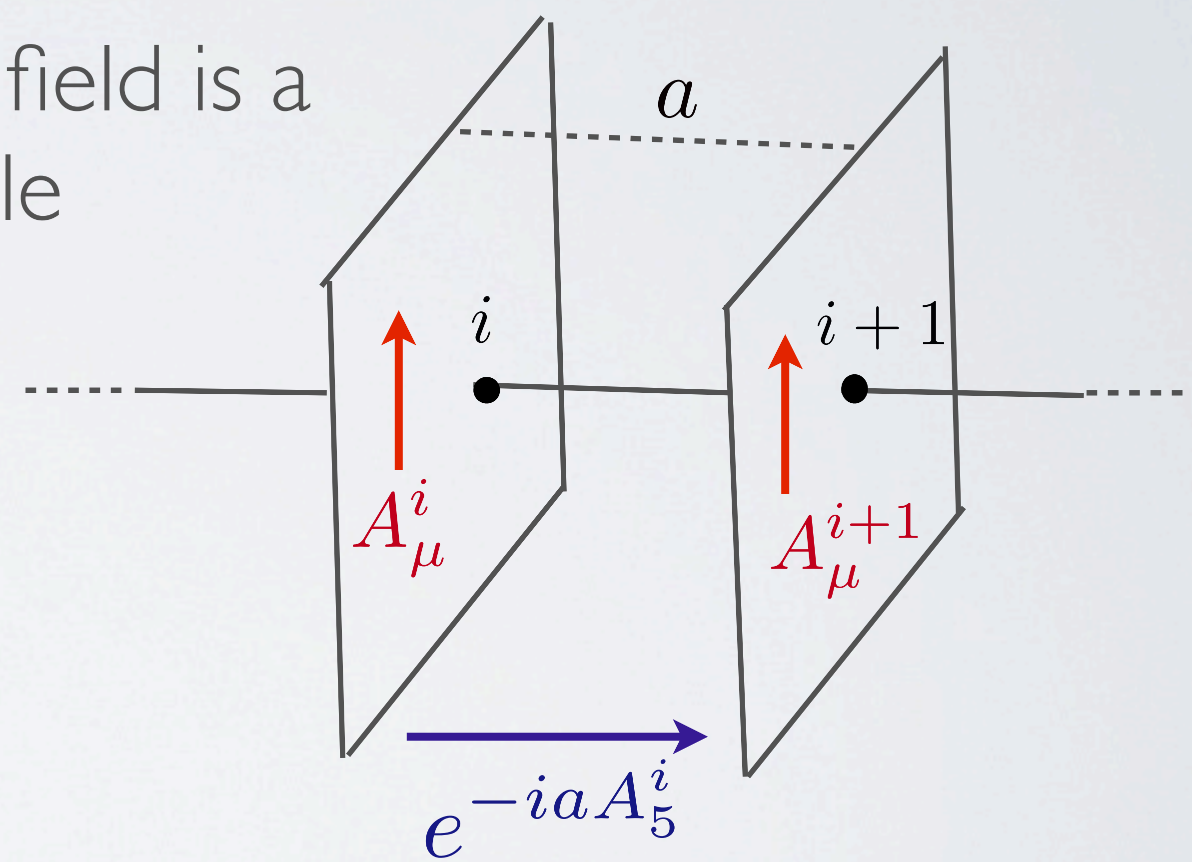
For large **K** the moose picture is interpreted as a discretization of a 5D gauge theory along the 5th dim.

$$K \to \infty, \quad a \to 0, \quad Ka \to \pi R$$
$$\lim_{a\to 0} a g_i^2 = g_5^2, \quad \lim_{a\to 0} a f_i^2 = f^2(z)$$

flat metric corresponds to equal f's and g's

geometrical Higgs mechanism: gauge field is a connection $\xrightarrow{\text{discretization}}$ link variable

$$\Sigma_i \approx 1 - iaA^i{}_5 \approx e^{-iaA^i{}_5}$$
$$\Sigma\Sigma^\dagger = 1$$
$$D_\mu \Sigma_i = -iaF^{i-1}_{\mu 5}$$
$$F^i_{\mu 5} = \partial_\mu A^i_5 - \partial_5 A^i_\mu - i[A^i_\mu, A^i_5]$$



$$S = \int d^4x \frac{a}{g_5^2}\left(-\frac{1}{2}\sum_i \mathrm{Tr}\left[F^i_{\mu\nu}F^{\mu\nu i}\right] + \frac{1}{a^2}\mathrm{Tr}\left[(D_\mu\Sigma_i)(D_\mu\Sigma_i)^\dagger\right]\right), \quad A^i_\mu = \text{KK modes}$$

Georgi '86, Hill, Pokorsky,Wang; Arkani-Hamed; Cohen,Georgi '01

July 31, 2012   Phys. Lett. B716

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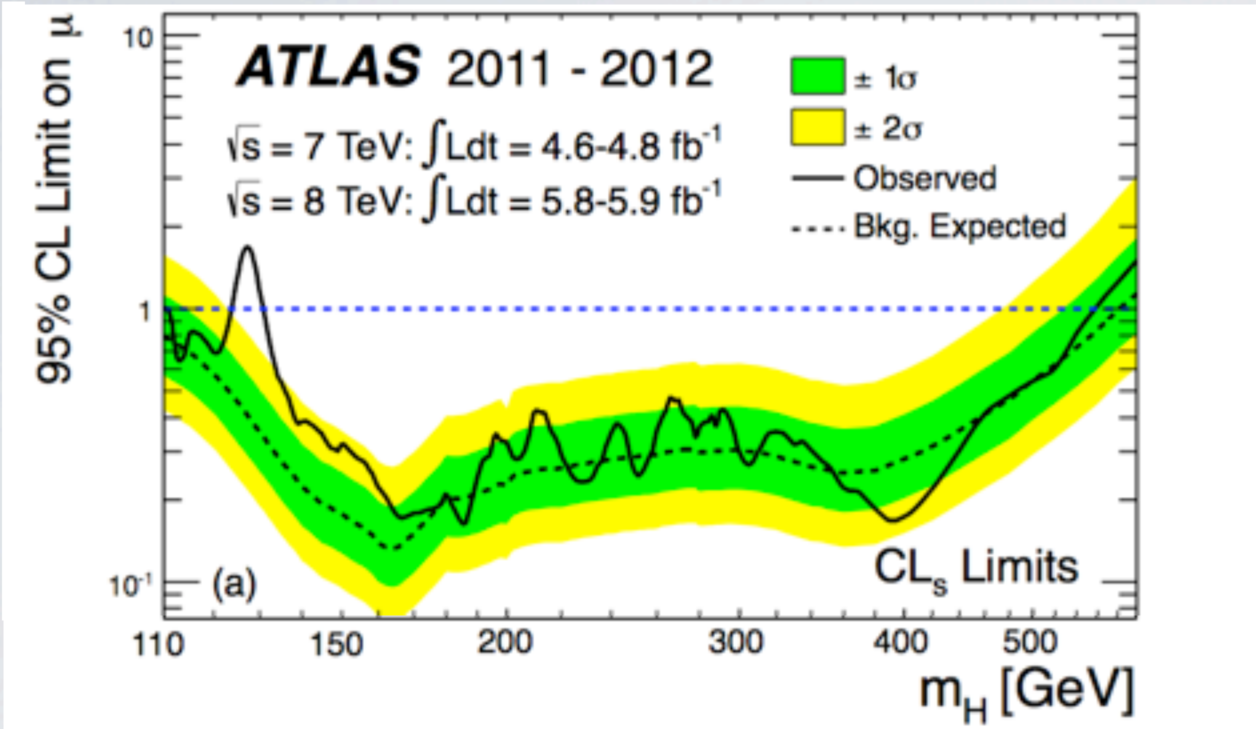

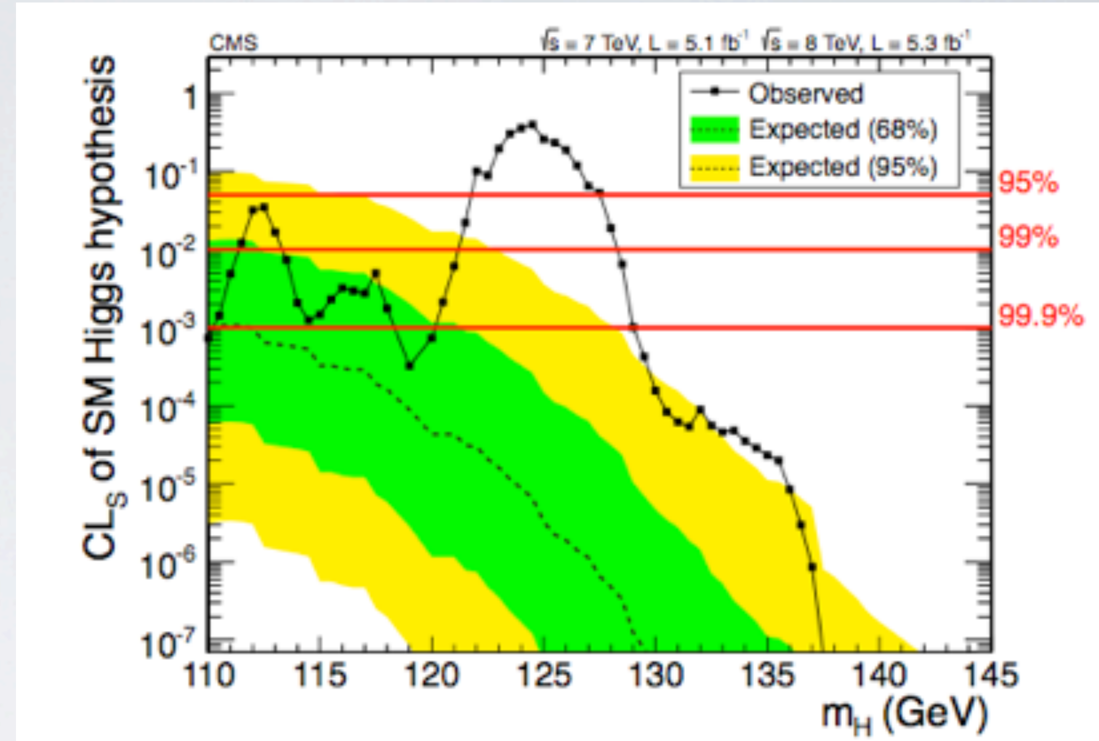

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS and the CMS Detector at the LHC

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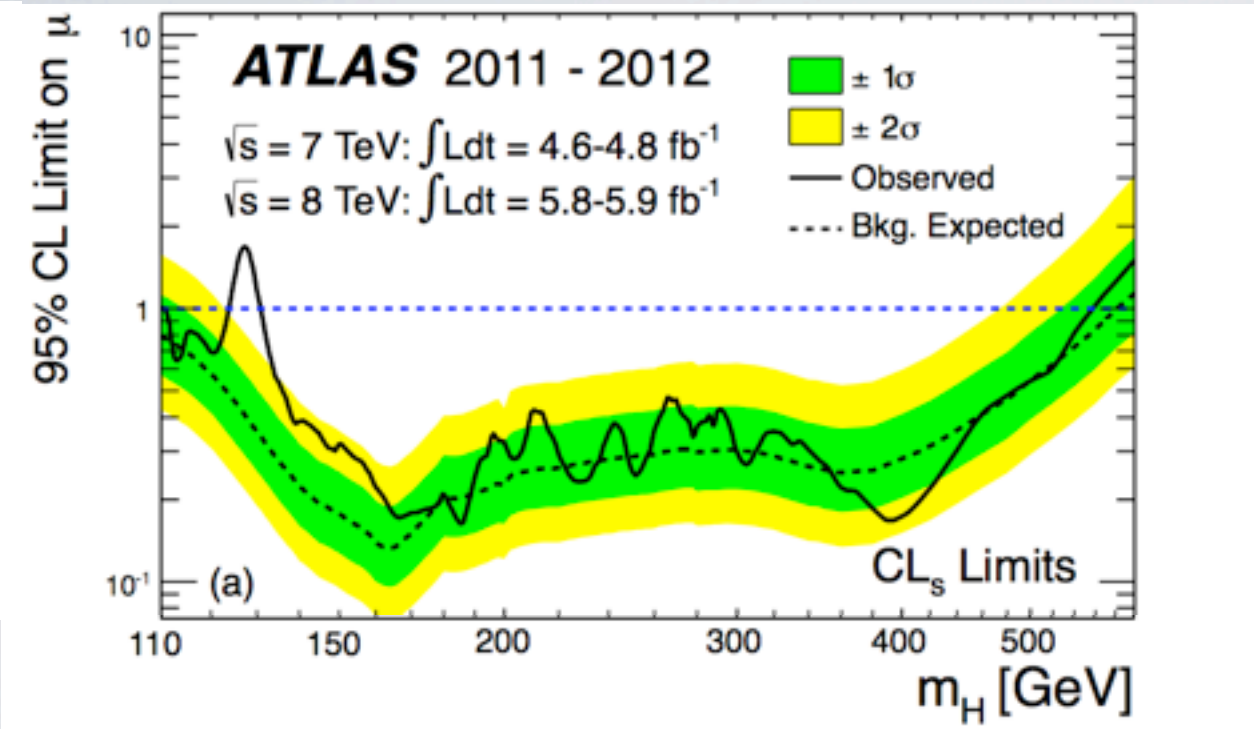

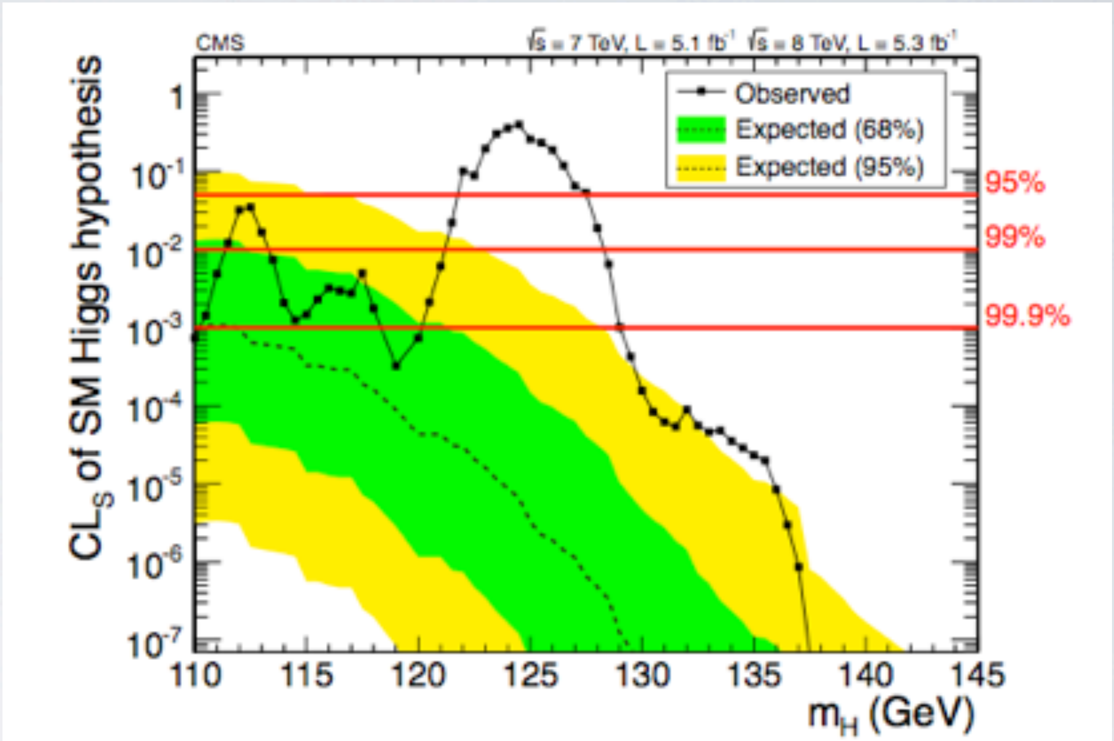

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Technicolor:
Higgsless models:

Is this New Particle the Standard Model Higgs Boson ?

Only precise measurements of its physical properties (mainly its Branching Ratios) will answer the question ....

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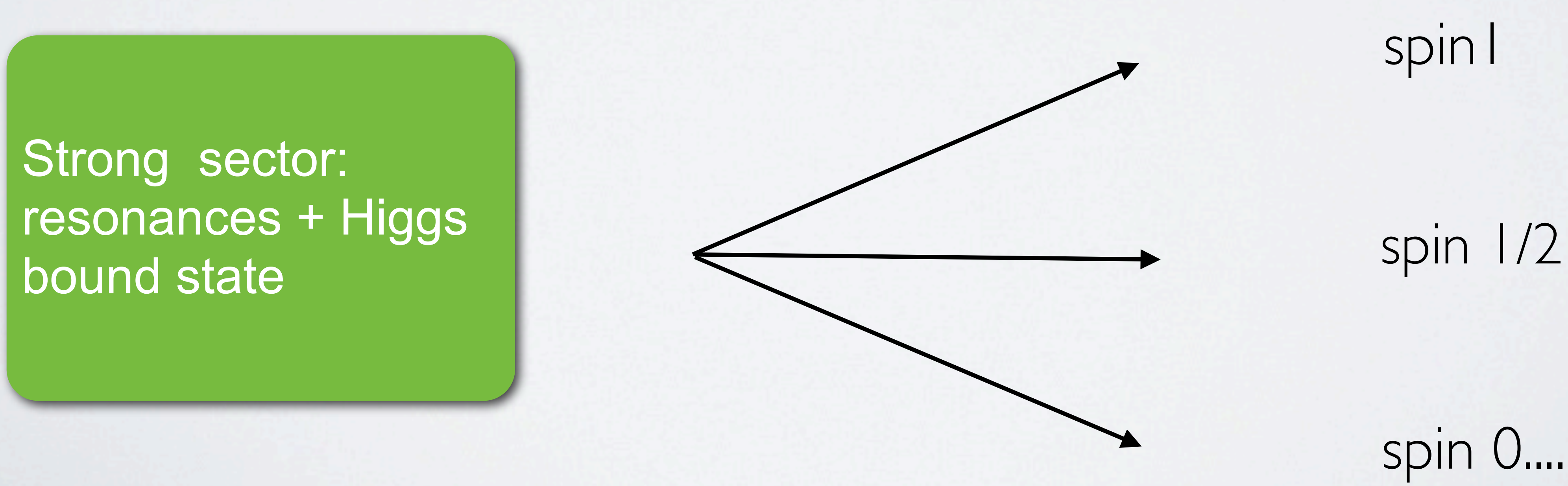
Possibility:

Higgs doublet is a light remnant of strong dynamics



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ELSEVIER

Physics Letters B 403 (1997) 86–92

PHYSICS LETTERS B

Indirect effects of new resonances at future linear colliders

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Received 26 February 1997
Editor: R. Gatto

Abstract

In this paper we consider a general $SU(2)_L \otimes SU(2)_R$ invariant Lagrangian describing scalar, vector and axial-vector resonances. By expanding the *WW* and the *ZZ* scattering amplitude up to the fourth order in the external momenta we can compare the parameters of our Lagrangian with the ones used in the effective chiral Lagrangian formalism. In the last approach there has been a recent study of the fusion processes at future e^+e^- colliders at energies above 1 TeV. We use these results to put bounds on the parameter space of our model and to show that for the case of vector resonances the bounds obtained from the annihilation channel in fermion pairs are by far more restrictive, already at energies of the order of 500 GeV.

Enlarge the BESS model to include vector and axial-vector resonances

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$$G = [SU(2)_L \otimes SU(2)_R]_{\text{global}}$$
$$H = [SU(2)_L \otimes SU(2)_R]_{\text{local}}$$

$$\mathcal{L}_G = -\frac{v^2}{4} f(\mathbf{L}_\mu, \mathbf{R}_\mu)$$

with

$$f(\mathbf{L}_\mu, \mathbf{R}_\mu) = aI_1 + bI_2 + cI_3 + dI_4$$

$$I_1 = \mathrm{tr}[(V_0 - V_1 - V_2)^2]$$
$$I_2 = \mathrm{tr}[(V_0 + V_2)^2]$$
$$I_3 = \mathrm{tr}[(V_0 - V_2)^2]$$
$$I_4 = \mathrm{tr}[V_1^2]$$

gauge fields associated to H

4 independent invariants

when decoupling the new resonances the SM is recovered for

$$a + \frac{cd}{c+d} = 1$$

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Include also a **scalar particle S** as bound state of the strong dynamics

$$\mathcal{L} = \tfrac{1}{2}\partial_\mu S \partial^\mu S - \tfrac{1}{2}m^2 S^2 - \frac{v\kappa}{2} S f(\mathbf{L}_\mu, \mathbf{R}_\mu) + \mathcal{L}_R + \cdots$$

this is not the most general interaction allowed by the symmetry

k=1 corresponds to the SM Higgs

The Higgs as a composite scalar is still a very topical subject

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Strong dynamics

(Bellazzini, C.C., Hubisz, Serra, Terning '12)

•Produces light higgs

•Additional resonances at cutoff Λ

•Higgs couplings could be different from SM values

Csaki talk at Blois '12

•If higgs couplings very different from SM: unitarity may break down BEFORE cutoff scale

•Need additional light states to maintain unitarity to Λ

•Assume additional spin-1 triplet $\rho^{\pm,0}$

•Simplified model: assume custodial symmetry

•Pion Lagrangian for longi modes of W,Z from CCWZ

•Assume $\rho^{\pm,0}$ triplet of $SU(2)_C$

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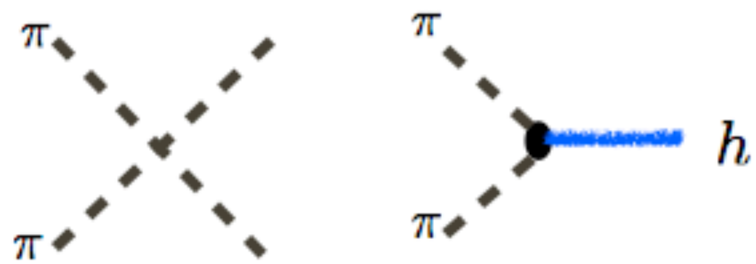
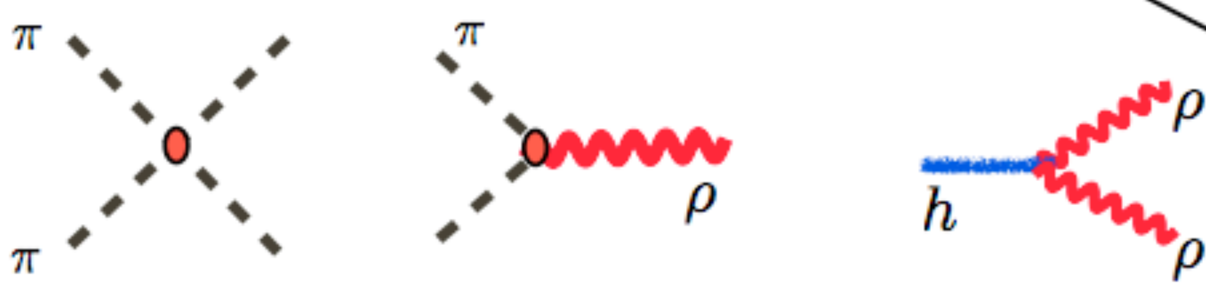
Higgs+Vector

Bellazzini talk Planck '12

Higgs: $$|D_\mu \Sigma|^2 \left(1 + 2a\frac{h}{v} + \ldots\right) + c_t h\bar{t}t + \ldots$$



spin-1: $$-\frac{1}{4g_\rho^2}\rho_{\mu\nu}^2 + \frac{a_\rho^2 v^2}{2}\left(\rho_\mu^a + \ldots\right)^2 \left[1 + 2c_\rho \frac{h}{v} + \ldots\right]$$



$$\vec{\pi} \times \partial_\mu \vec{\pi} + \ldots$$

$\pi \sim W_L, Z_L$

Modification of the Higgs BRs will be measured at the LHC

Natural questions:

- If the Higgs is a bound state from an unknown strong dynamics, why is it so light ?

- Is there any symmetry protecting its mass to become large ?

PART II:
Higgs as a Goldstone

~2011

De Curtis

Redi

Tesi

$$\frac{SU(2)_L \otimes SU(2)_R}{SU(2)_{L+R}}$$

Only delivers the longitudinal polarization of W & Z

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Only delivers the longitudinal polarization of W & Z

A logical possibility is that the Higgs itself is a GB

Georgi, Kaplan '80s

Ex: $\dfrac{SO(5)}{SU(2)_L \otimes SU(2)_R} \longrightarrow GB = (2,2)$

Agashe , Contino,Pomarol '04

Contino, da Rold, Pomarol, '06

Low energy lagrangian:

$$\mathcal{L} = f^2\, D_\mu \Sigma^i D^\mu \Sigma^i + \ldots \xrightarrow{SU(2)_L \otimes SU(2)_R} \rho = \frac{m_W^2}{m_Z^2 \cos\theta_W} \approx 1$$

Particularly compelling because the Higgs is massless at leading order.

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Extended Higgs sectors:

Ex: $$\frac{SO(6)}{SO(5)} \qquad \frac{SO(6)}{SO(4)\otimes U(1)} \qquad \frac{SU(5)}{SU(4)\otimes U(1)} \qquad + \ldots$$

Gripaios, Pomarol, Riva, Serra '09

Mrazek, Pomarol, Rattazzi, MR, Serra, Wulzer '11

Now also axions:

Ex: $$\frac{SU(6)_L \times SU(6)_R}{SU(6)_{L+R}}$$

Redi, Strumia '12

Increasing f CH approximates SM.

$$\text{DEVIATIONS} \sim \frac{v^2}{f^2}$$

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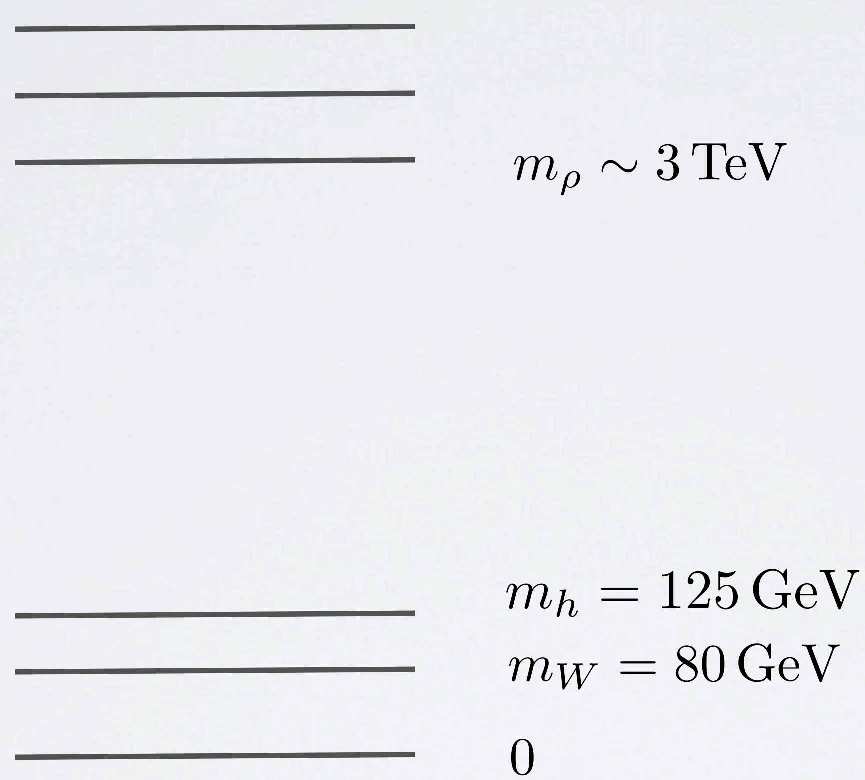
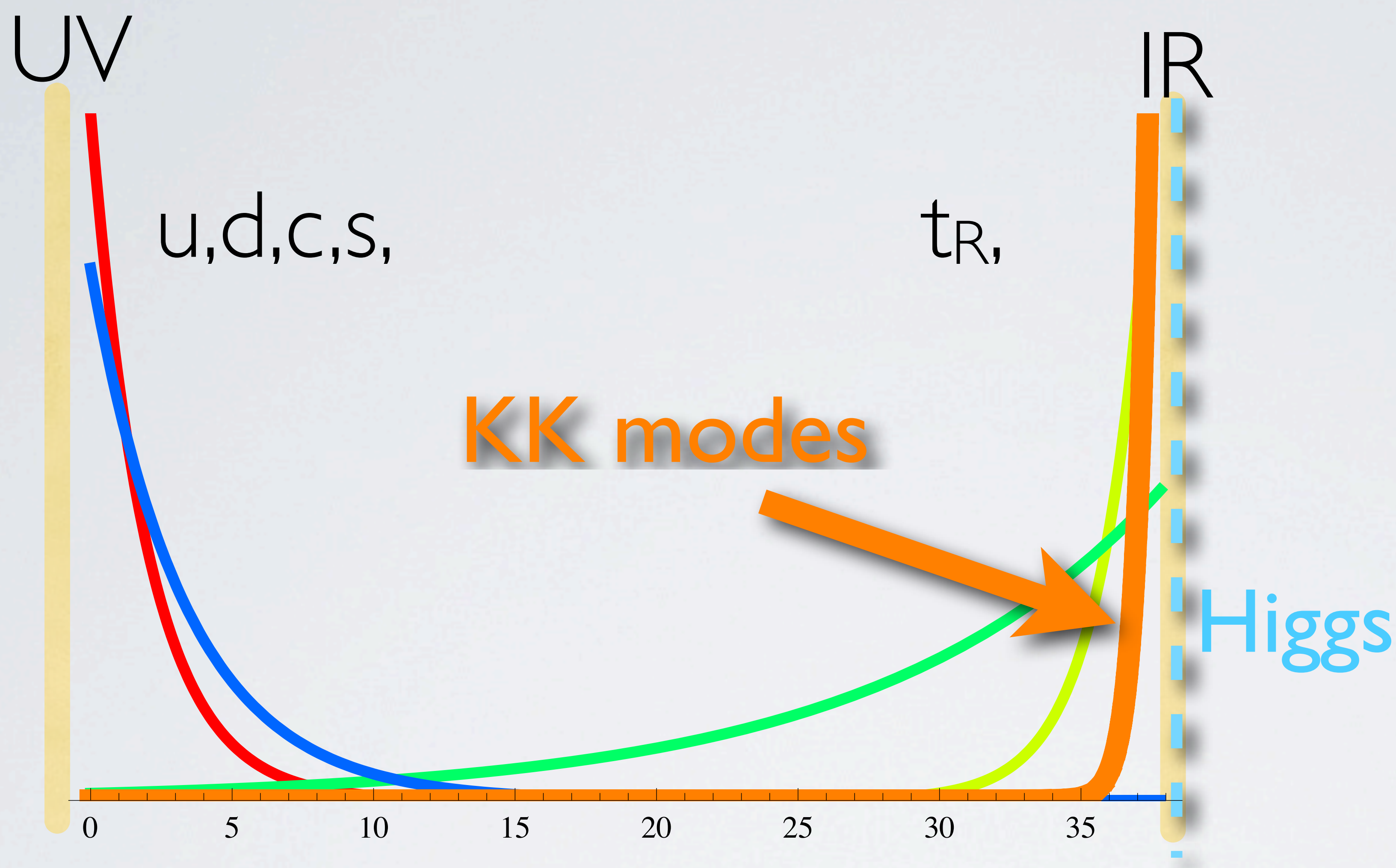
Spectrum:



Reasonable phenomenology can be obtained for $m_\rho \sim 3\,\mathrm{TeV}$

Possible to realize it in Randall-Sundrum scenarios.



(Randall-Sundrum '99)

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

Through AdS/CFT correspondence dual to 4D CFTs.
Relevant physics dominated by the lowest modes.

Necessary a useful 4D description:

- theoretical:
  - only very few resonances (1?) weakly coupled
  - relevant physics largely independent of 5D or AdS
  - what are the most general models?

- practical:
  - LHC will at best produce the lightest resonances
  - Simplified model useful for LHC

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VERY SIMILAR TO BESS!!

Introducing resonances works as in BESS

We start from G/H

$$\frac{G}{H}$$

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$$\frac{G_L \otimes G_R}{G_{L+R}} \qquad \Omega \to g_L \Omega g_R^\dagger \qquad + \qquad \frac{G}{H}$$

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and gauge $G_R + G$

$$\mathcal{L}_{2-site} = \frac{f_1^2}{4} \mathrm{Tr}\, |D_\mu \Omega|^2 + \frac{f_2^2}{2} \mathcal{D}_\mu^{\widehat{a}} \mathcal{D}^{\mu \widehat{a}} - \frac{1}{4 g_\rho^2} \rho_{\mu\nu}^A \rho^{A\mu\nu}$$

$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu \Omega + i \Omega \rho_\mu$$

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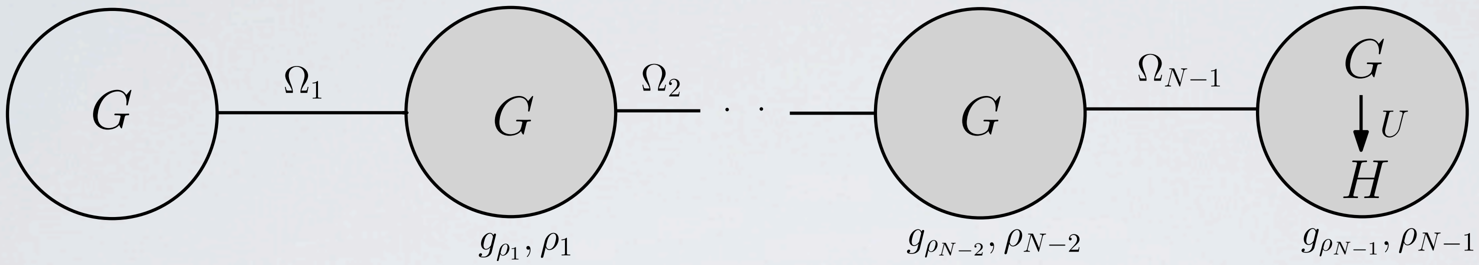
$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu \Omega + i \Omega \rho_\mu$$

Fermions introduced in a similar way.

In general:



$$\mathcal{L}_{N-sites} = \sum_{n=1}^{N-1} \frac{f_n^2}{4} \mathrm{Tr}\,|D_\mu \Omega_n|^2 + \frac{f_N^2}{2} \mathcal{D}_\mu^{\widehat{a}} \mathcal{D}^{\mu \widehat{a}} - \sum_{n=1}^{N-1} \frac{1}{4\, g_{\rho_n}^2}\, \rho_{n,\mu\nu}^A \rho_n^{A\mu\nu}$$

$$D^\mu \Omega_n = \partial^\mu \Omega_n - i \rho_{n-1}^\mu \Omega_n + i \Omega_n \rho_n^\mu, \qquad n = 1, .., N-1$$

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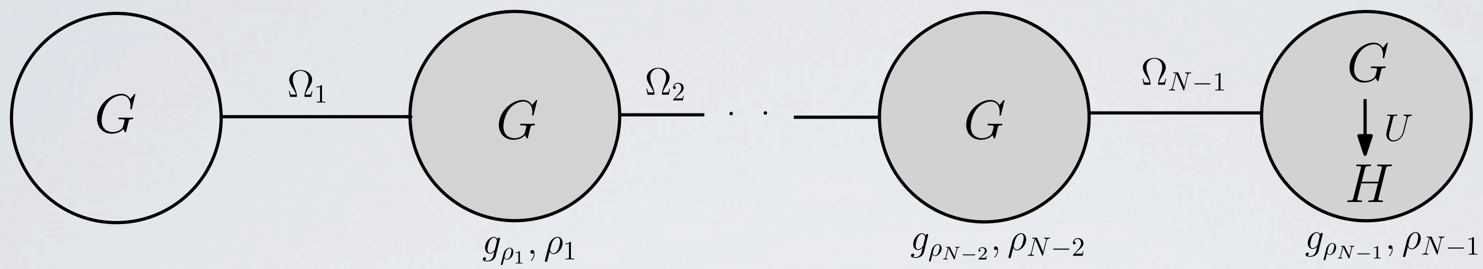


$$\mathcal{L}_{N-sites} = \sum_{n=1}^{N-1} \frac{f_n^2}{4} \mathrm{Tr}\, |D_\mu \Omega_n|^2 + \frac{f_N^2}{2} \mathcal{D}_\mu^{\widehat{a}} \mathcal{D}^{\mu \widehat{a}} - \sum_{n=1}^{N-1} \frac{1}{4\, g_{\rho_n}^2} \rho_{n,\mu\nu}^A \rho_n^{A\mu\nu}$$

$$D^\mu \Omega_n = \partial^\mu \Omega_n - i\rho_{n-1}^\mu \Omega_n + i\Omega_n \rho_n^\mu, \qquad n = 1, .., N-1$$

GBs are

$$\Omega_n = \exp i \frac{f}{f_n^2} \Pi, \quad n = 1, ..., N \qquad\qquad \sum_{n=1}^{N} \frac{1}{f_n^2} = \frac{1}{f^2}$$

$$\boldsymbol{U'} \equiv \left(\Pi_{n=1}^{N-1} \Omega_n \right) U$$

For N large we recover the 5D theory.

MINIMAL 4D COMPOSITE HIGGS

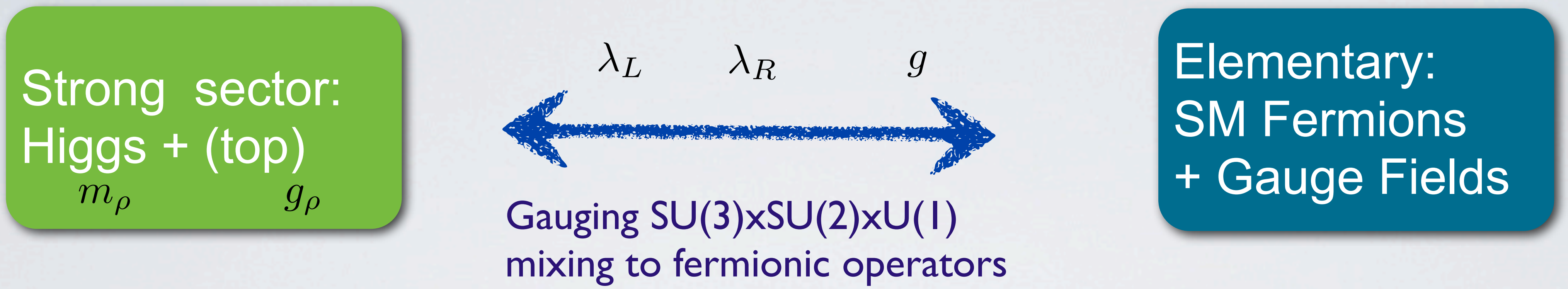
- One resonance for each SM field

General picture:

Strong sector:
Higgs + (top)
m_ρ g_ρ

Elementary:
SM Fermions
+ Gauge Fields

General picture:



They talk through linear couplings:

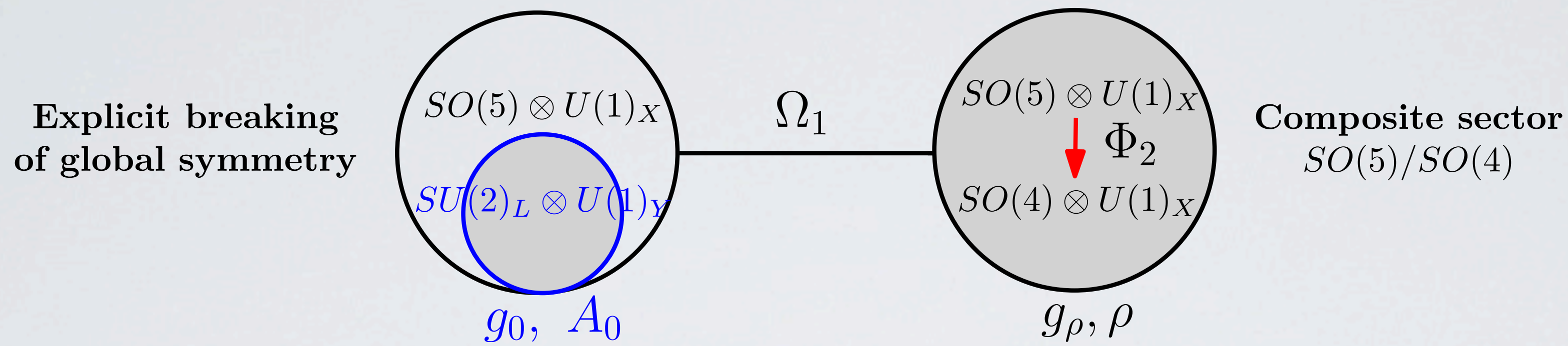
$$\mathcal{L}_{gauge} = g\, A_\mu J^\mu$$

$$\mathcal{L}_{mixing} = \lambda_L \bar{f}_L O_R + \lambda_R \bar{f}_R O_R \xrightarrow{\epsilon \sim \frac{\lambda}{Y}} y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R$$

Higgs potential generated at 1-loop:

$$V(h) \sim \frac{N_c}{16\pi^2} \epsilon^2_{L,R} m^4_\rho \hat{V}\left(\frac{h}{f}\right) + \dots$$

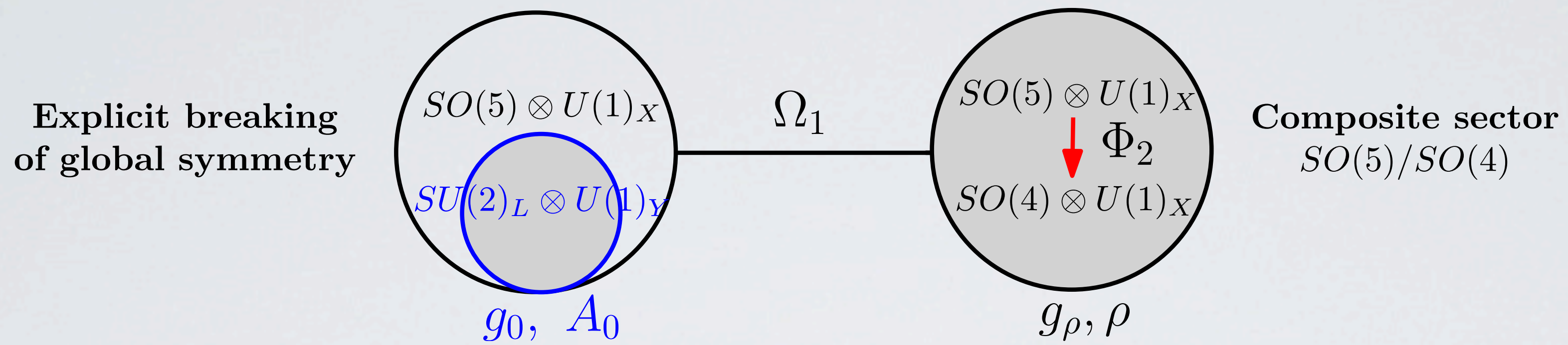
- SO(5)/SO(4)



Composite spin-1 lagrangian:

$$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad \Phi = \frac{SO(5)}{SO(4)}$$

- SO(5)/SO(4)



Composite spin-1 lagrangian:

$$\Omega = \frac{SO(5)_L \times SO(5)_R}{SO(5)_{L+R}} \qquad\qquad \Phi = \frac{SO(5)}{SO(4)}$$

$$\frac{f_1^2}{4}\mathrm{Tr}\left|D_\mu\Omega\right|^2 + \frac{f_2^2}{2}\left(D_\mu\Phi\right)^T\left(D^\mu\Phi\right) - \frac{1}{4g_\rho^2}\rho^a_{\mu\nu}\rho^{a\mu\nu}$$

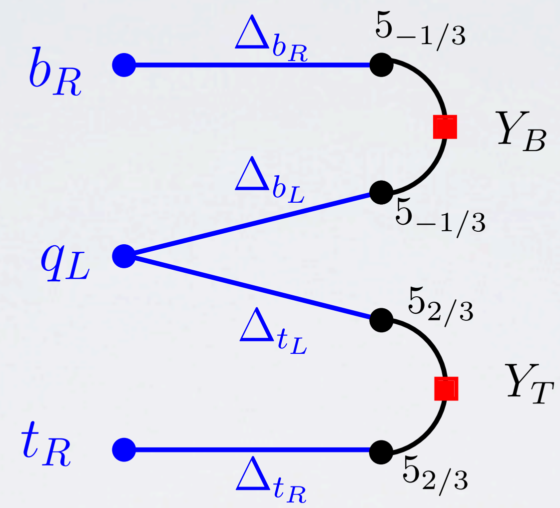
$$D_\mu\Omega = \partial_\mu\Omega - iA_\mu\Omega + i\Omega\rho_\mu \qquad\qquad D_\mu\Phi = \partial_\mu\Phi - i\rho_\mu\Phi$$

SO(4) and SO(5)/SO(4) spin-1 resonances.

Each SM fermion couples to Dirac fermion in a rep of SO(5).

Each SM fermion couples to Dirac fermion in a rep of SO(5).

CHM5:



Third generation:

$$
\begin{aligned}
\mathcal{L}^{\mathrm{CHM}_5} &= \mathcal{L}^{el}_{fermions} \\
&+ \Delta_{t_L}\, \bar{q}^{el}_L \Omega_1 \Psi_T + \Delta_{t_R}\, \bar{t}^{el}_R \Omega_1 \Psi_{\widetilde{T}} + h.c. \\
&+ \bar{\Psi}_T (i \not{D}^\rho - m_T) \Psi_T + \bar{\Psi}_{\widetilde{T}} (i \not{D}^\rho - m_{\widetilde{T}}) \Psi_{\widetilde{T}} \\
&- Y_T \bar{\Psi}_{T,L} \Phi_2^T \Phi_2 \Psi_{\widetilde{T},R} - m_{Y_T} \bar{\Psi}_{T,L} \Psi_{\widetilde{T},R} + h.c. \\
&+ (T \to B)
\end{aligned}
$$

$\longrightarrow$ Explicit SO(5) breaking

$\longrightarrow$ Composite physics SO(5)/SO(4)

Coleman-Weinberg effective potential:

$$V(h)_{fermions} = -2N_c \int \frac{d^4p}{(2\pi)^4} \left[\ln \Pi_{b_L} + \ln\left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi^2_{t_L t_R}\right)\right]$$

Contino, da Rold, Pomarol, '06

Form factors are simple functions:

$$\widehat{\Pi}[m_1, m_2, m_3] = \frac{\left(m_2^2 + m_3^2 - p^2\right)}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

$$\widehat{M}[m_1, m_2, m_3] = -\frac{m_1 m_2 m_3}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

Coleman-Weinberg effective potential:

$$V(h)_{fermions} = -2N_c \int \frac{d^4p}{(2\pi)^4} \left[\ln \Pi_{b_L} + \ln \left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi^2_{t_L t_R}\right)\right]$$

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$$\widehat{M}[m_1, m_2, m_3] = -\frac{m_1 m_2 m_3}{p^4 - p^2(m_1^2 + m_2^2 + m_3^2) + m_1^2 m_2^2}$$

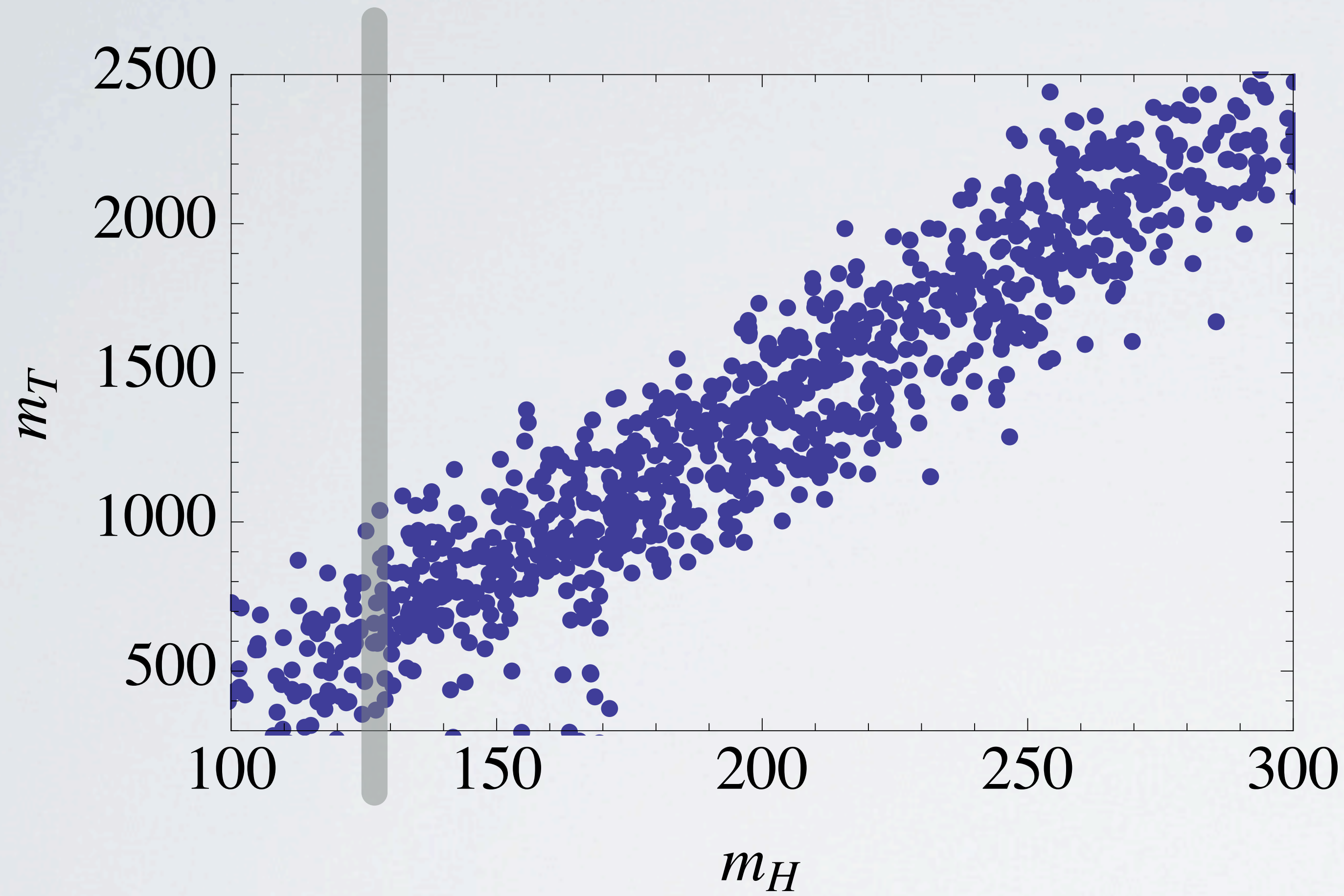
Potential is finite with a single SO(5) multiplet per SM field!

What is the Higgs mass?

- CHM5

General scan:

$$f = 500\,\mathrm{GeV}$$



- CHM5

General scan:

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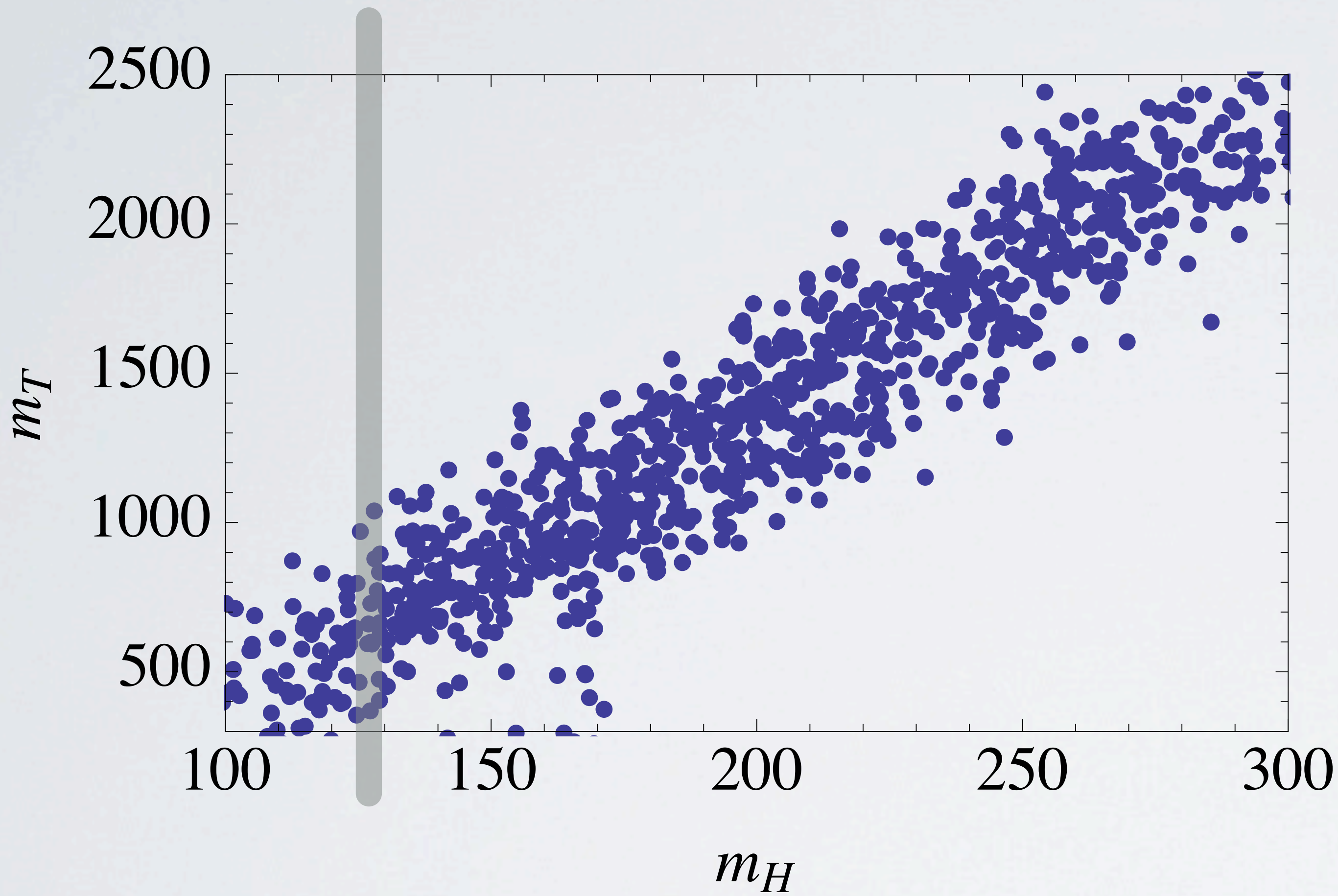
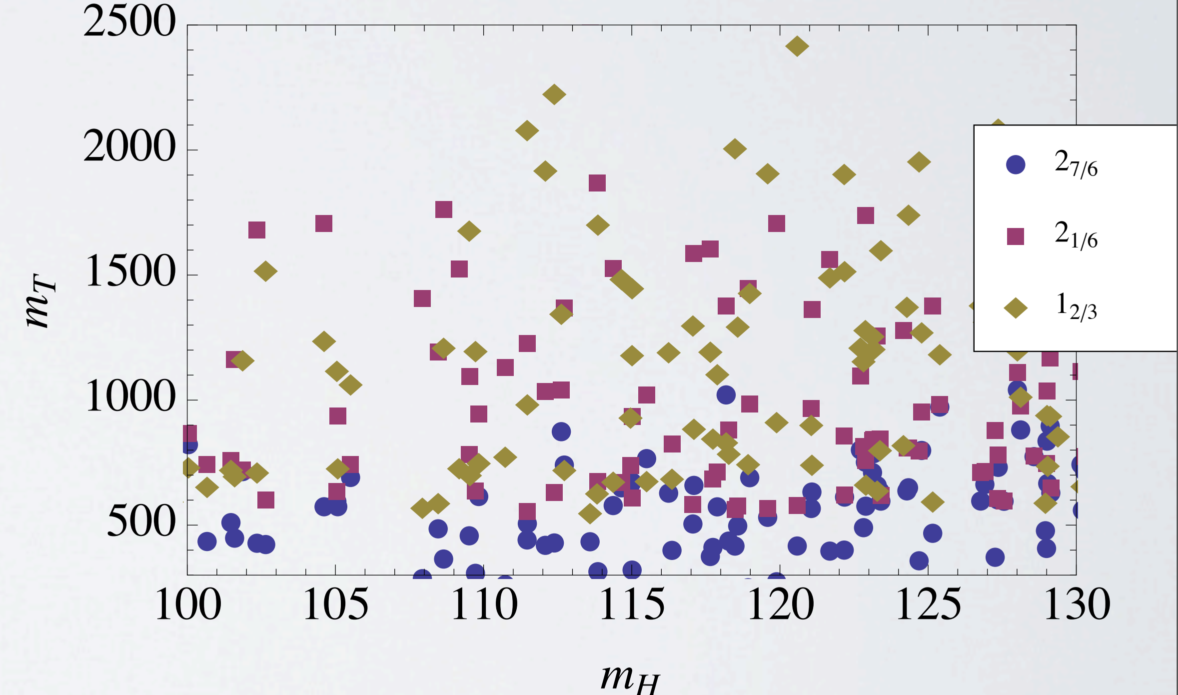
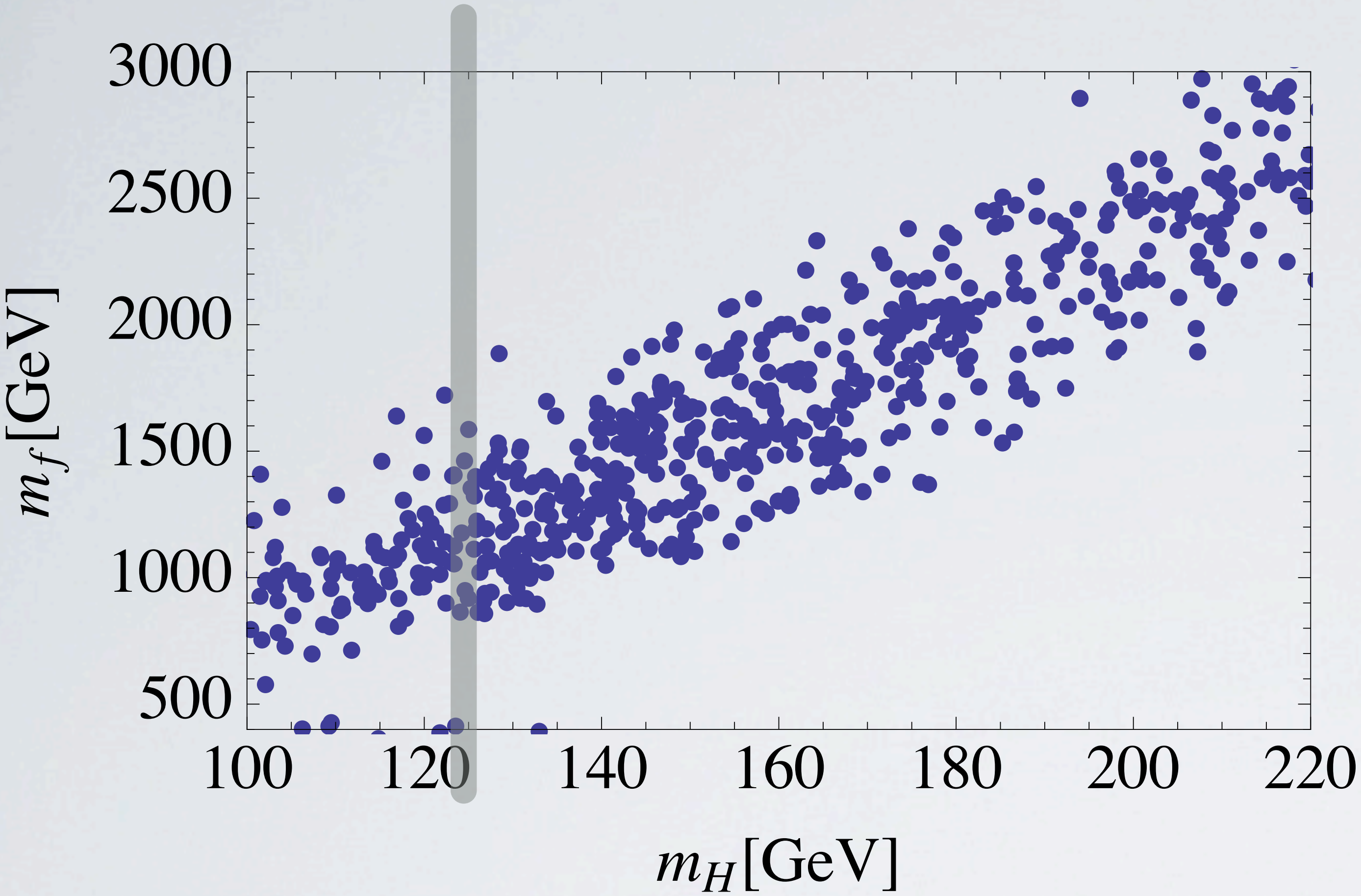


Low mass:



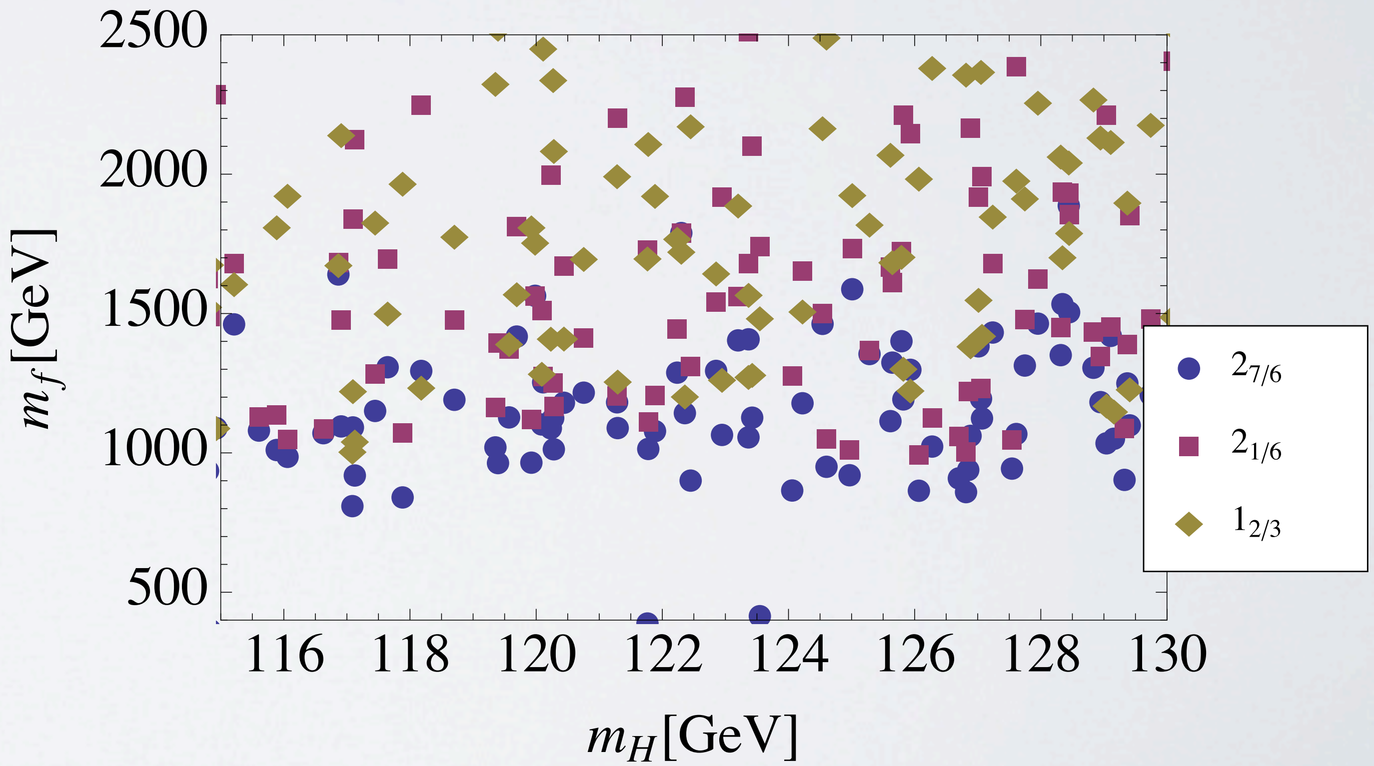
For mH=125 GeV, fermionic partners VERY close.

Should be visible at LHC7!



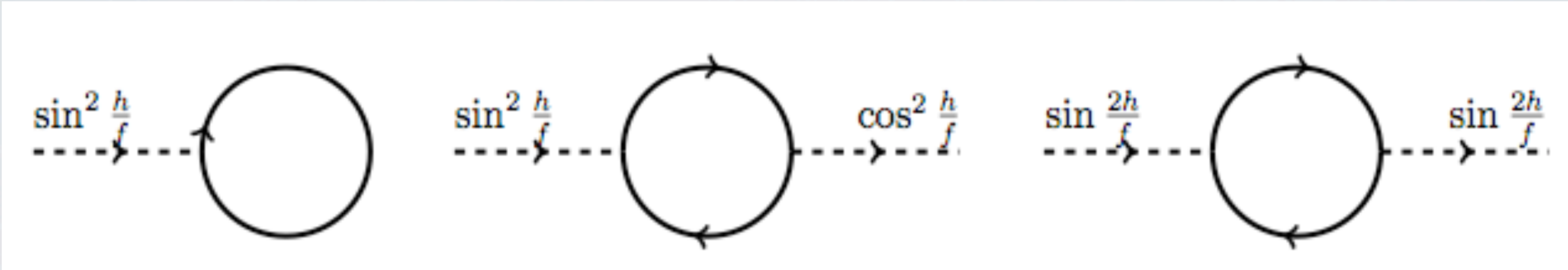
$$f = 800\,\mathrm{GeV}$$

Low mass:



Partners above experimental bound ~ TeV

MASS ESTIMATE



$$\mathcal{L}_{Yuk} = y_t f \, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \longrightarrow V(h)_{Yuk} \sim N_c \frac{y_t^2}{16\pi^2} m_f^2 f^2 s_h^2 c_h^2$$

$$s_h \equiv \sin \frac{h}{f} = \frac{v}{f}$$

Quartic is determined by top Yukawa,

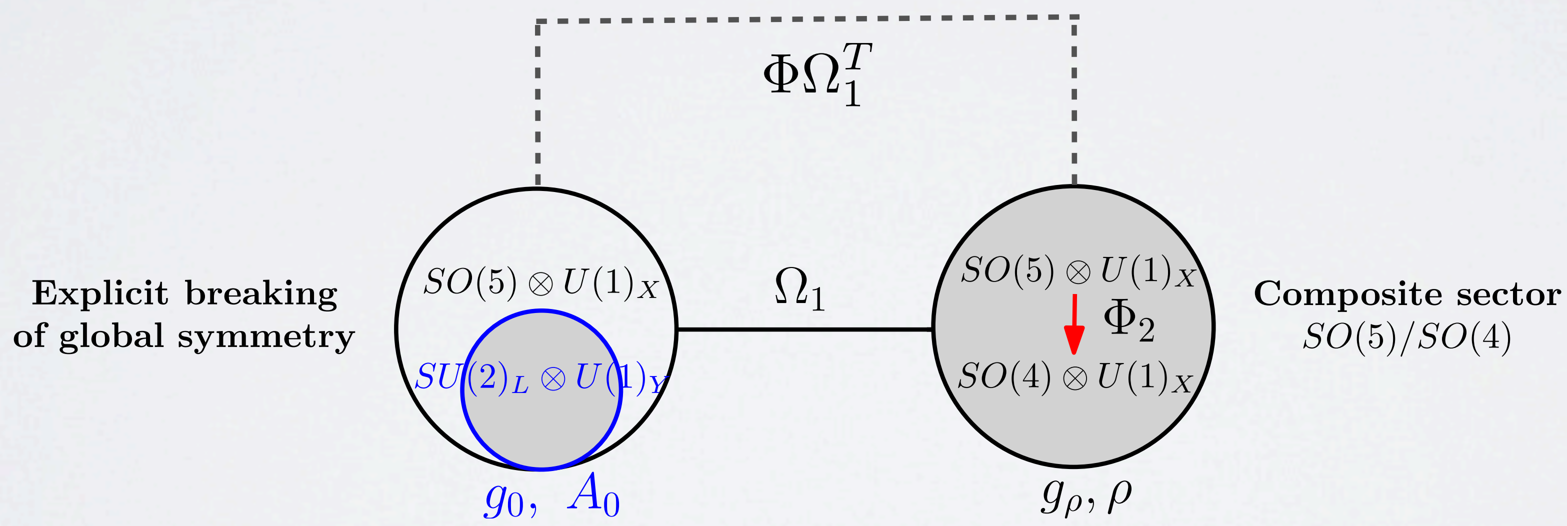
$$m_h \sim \sqrt{\frac{N_c}{2} \frac{y_t}{\pi}} \frac{m_f}{f} v$$

NON LOCAL TERMS

Most general 2-site lagrangian contains

$$\frac{f_0^2}{2}(D_\mu \Phi)(D^\mu \Phi)^T \qquad \Phi = \Phi_2 \Omega_1^T$$

$$f^2 = f_0^2 + \frac{f_1^2 f_2^2}{f_1^2 + f_2^2}$$



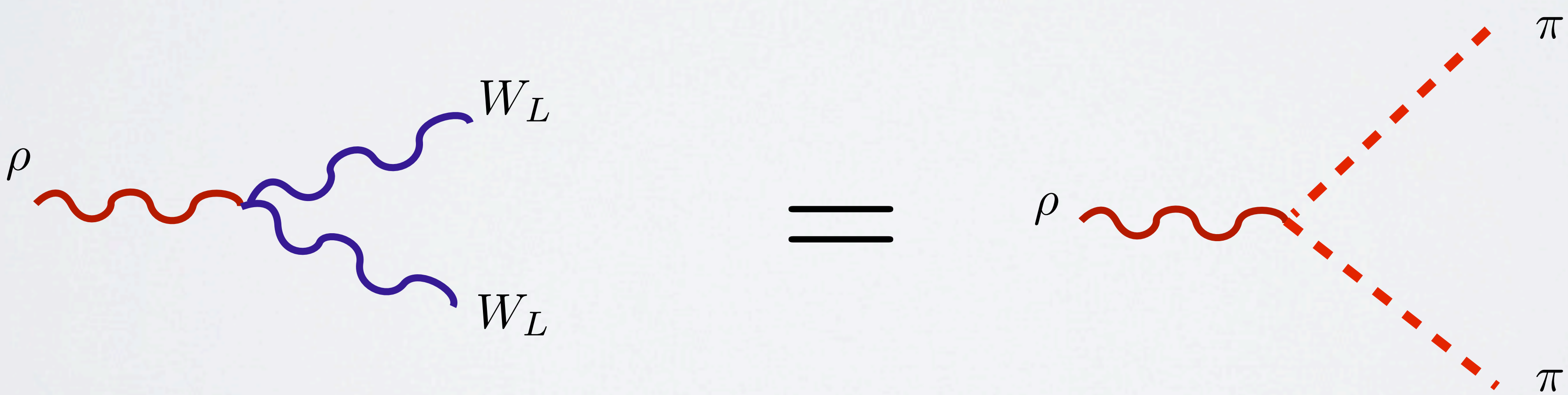
Analog of α in BESS.

New term modifies interactions

$$m_\rho^2 = 2\frac{f^2}{f^2 - f_0^2}\, g_{\rho\pi\pi}^2\, f^2 \qquad\qquad (m_{a_1} \to \infty)$$

Coset resonance could give further modifications.

Phenomenology modified



$$\Gamma(\rho^3 \to Zh) = \Gamma(\rho^3 \to W^+W^-) = \frac{g_{\rho\pi\pi}^2}{192\pi} m_\rho$$

New term modifies S-parameter:

$$S = 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2} \right) \frac{f^2 - f_0^2}{f^2}$$

S can vanish

$$f_0 = f$$

H and G/H resonances degenerate and do not participate to unitarization.

New term modifies S-parameter:

$$S = 4\pi v^2 \left(\frac{1}{m_\rho^2} + \frac{1}{m_{a_1}^2} \right) \frac{f^2 - f_0^2}{f^2}$$

S can vanish

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H and G/H resonances degenerate and do not participate to unitarization.

In QCD:

$$f_0^2 \sim -f^2$$

General?

Eur. Phys. J. C 18, 65–71 (2000)
Digital Object Identifier (DOI) 10.1007/s100520000532

THE EUROPEAN PHYSICAL JOURNAL C

Signals of the degenerate BESS model at the LHC

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Received: 11 July 2000 / Published online: 13 November 2000 – © Springer-Verlag 2000

Abstract. We discuss the possible signals of the degenerate BESS model at the LHC. This model describes a strongly interacting scenario responsible of the spontaneous breaking of the electroweak symmetry. It predicts two triplets of extra gauge bosons which are almost degenerate in mass. Due to this feature, the model has the property of decoupling and therefore, at low energies (below or of the order of 100 GeV) it is nearly indistinguishable from the Standard Model. However the new resonances, both neutral and charged, should give quite spectacular signals at the LHC, where the c.o.m. energy will allow to produce these gauge bosons directly.

BACK TO THE BEGINNING...

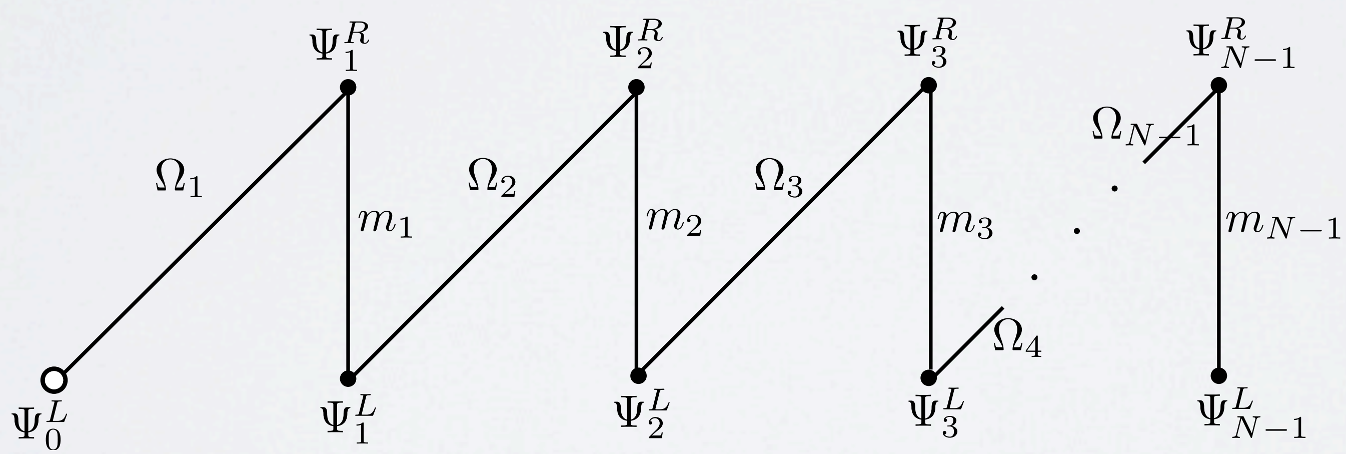
Fermions:

$$\mathcal{L}_{fermions} = \sum_{n=1}^{N-1} \bar{\Psi}_n^{(r)} \left[i \not{D}^{\rho_n} - m_n^{(r)} \right] \Psi_n^{(r)} + \sum_{n=1}^{N-1} \Delta_n^{(r)} \left(\bar{\Psi}^{n-1}_{r,L} \Omega_n \Psi^n_{r,R} + h.c. \right)$$

$$D^\mu \Psi_n^{(r)} = \partial^\mu \Psi_n^{(r)} - i \rho_n^\mu \Psi_n^{(r)}$$

$$\mathcal{L}_{\frac{G}{H}} = m_\Psi \sum \bar{\Psi}_L^{(r),N-1} U(\Pi) P_A^{rs} U(\Pi)^\dagger \Psi_R^{(s),N-1} + h.c$$

LR structure



Inspired by 5D.

SO(6)/SO(5):

Gripaios, Pomarol, Riva, Serra '09
Redi, Tesi '12

5 GBs:

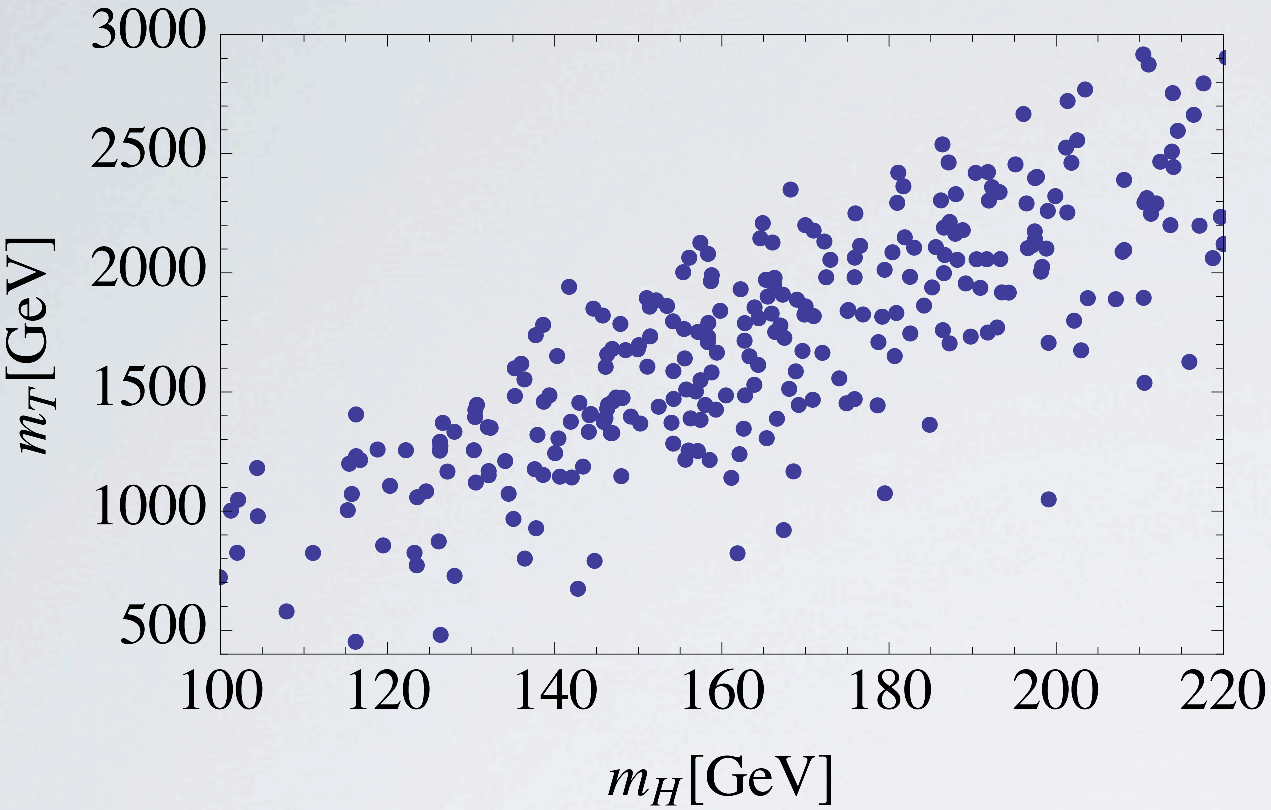
$$5 = (2,2) + 1$$

Fermions can be coupled to the 6=(2,2)+2 × 1

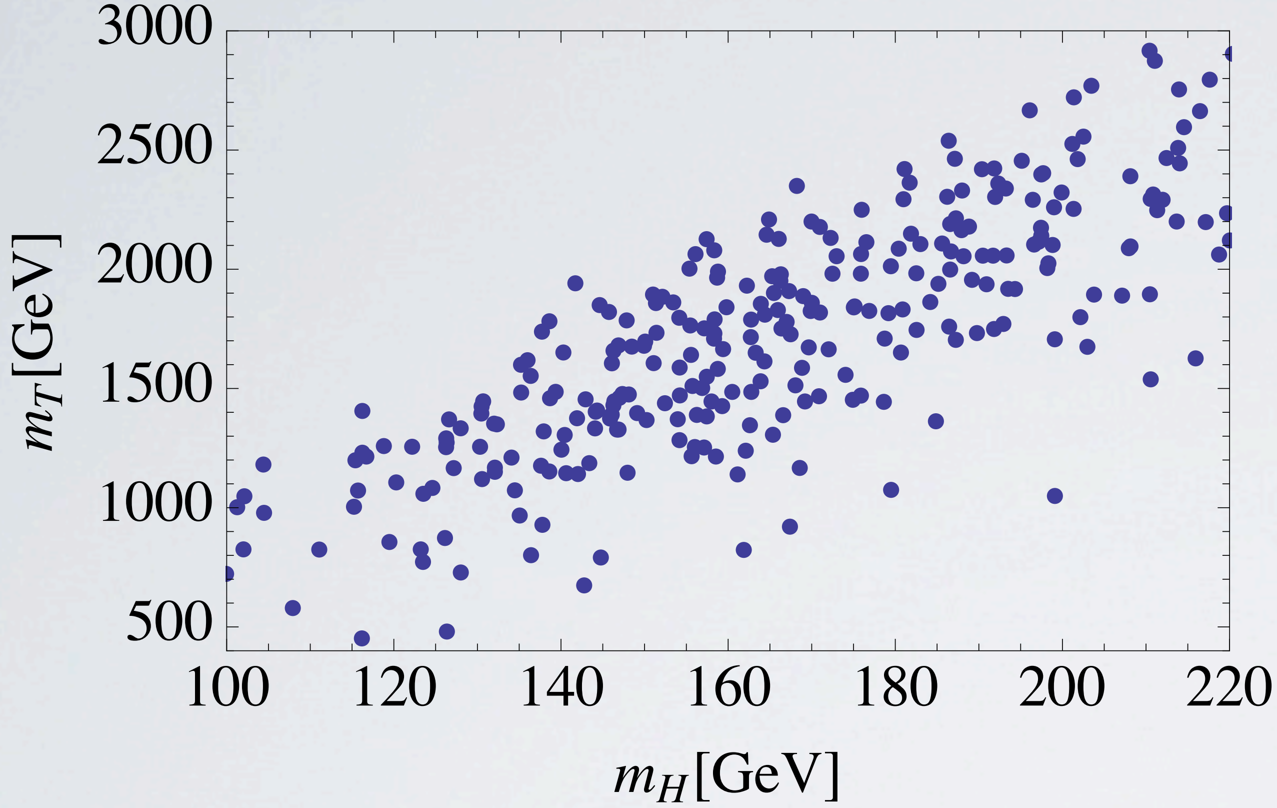
$$q_L \to \frac{1}{\sqrt{2}} \begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix} \qquad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ i\cos\theta\, t_R \\ \sin\theta\, t_R \end{pmatrix}$$

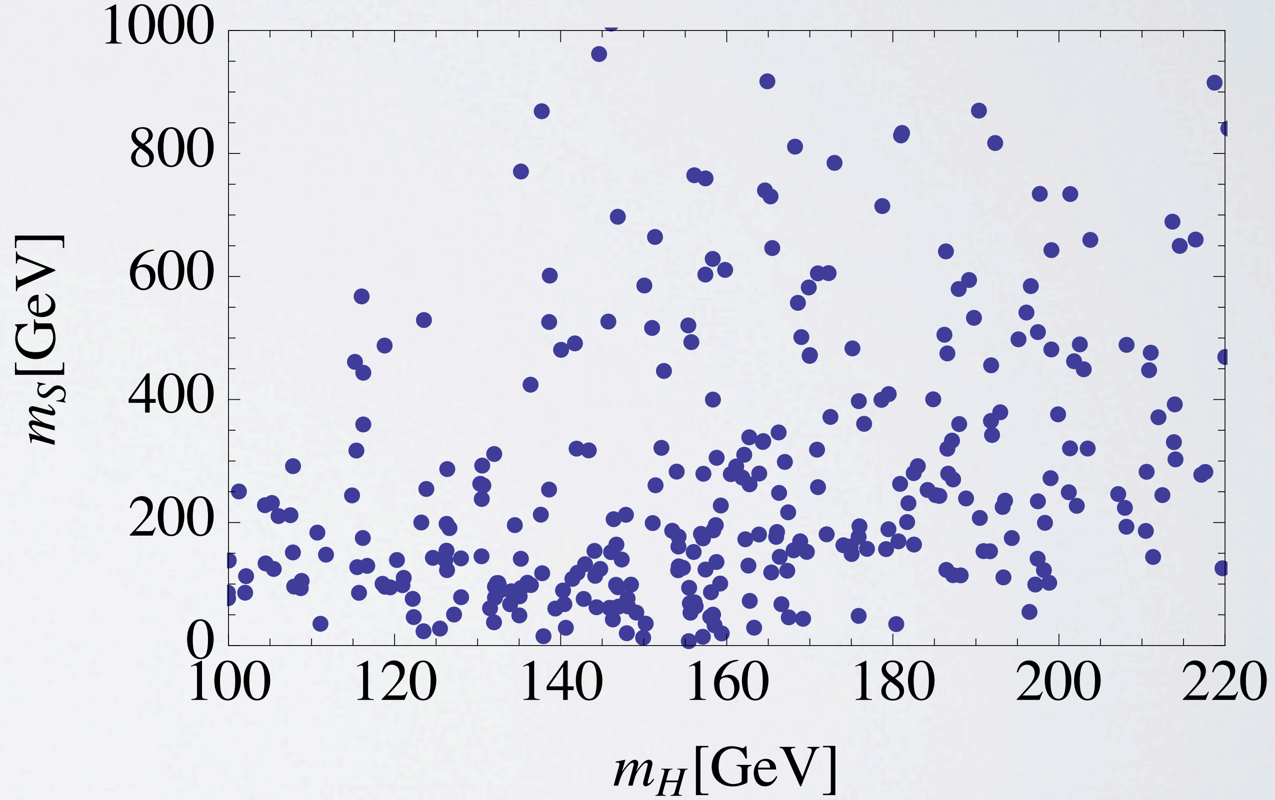
For $\theta = \frac{\pi}{4}$ singlet becomes exact GB.

$f = 800\,\mathrm{GeV}$



$$f = 800\,\mathrm{GeV}$$





Same correlation Higgs-fermions.

Singlet typically heavier than Higgs unless $\theta \approx \frac{\pi}{4}$

Particularly compelling because the Higgs is massless at leading order.

$$V(H) \sim \frac{g_{SM}^2}{16\pi^2}\, m_\rho^2 f^2\, \hat{V}\left(\frac{H}{f}\right)$$

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Extended Higgs sectors:

Ex: $\dfrac{SO(6)}{SO(5)}$ $\qquad \dfrac{SO(6)}{SO(4)\otimes U(1)}$ $\qquad \dfrac{SU(5)}{SU(4)\otimes U(1)}$ $\qquad + \dots$

Gripaios, Pomarol, Riva, Serra '09

Mrazek, Pomarol, Rattazzi, MR, Serra, Wulzer '11

BACKUP SLIDES

Fermionic Sector

Left- and right- handed fermions are SM like and coupled to the ends of the moose, but they can couple to any site by using a Wilson line

$$\chi_L^i = \Sigma_i^\dagger \Sigma_{i-1}^\dagger \cdots \Sigma_1^\dagger \psi_L, \quad \chi_L^i \to U_i \chi_L^i$$

$$\Downarrow$$

$$b_i \bar{\chi}_L^i \gamma^\mu \left(\partial_\mu + i g_i V_\mu^i + \frac{i}{2} g'(B-L) Y_\mu \right) \chi_L^i$$

extra new parameters

Fermion delocalization in 5D language

$$\mathcal{L}_{fermions}^{tot} = \bar{\psi}_R i \gamma^\mu \left[\partial_\mu + i \tilde{g}' \frac{\tau^3}{2} \tilde{\mathcal{Y}}_\mu + \frac{i}{2} \tilde{g}'(B-L) \tilde{\mathcal{Y}}_\mu \right] \psi_R$$

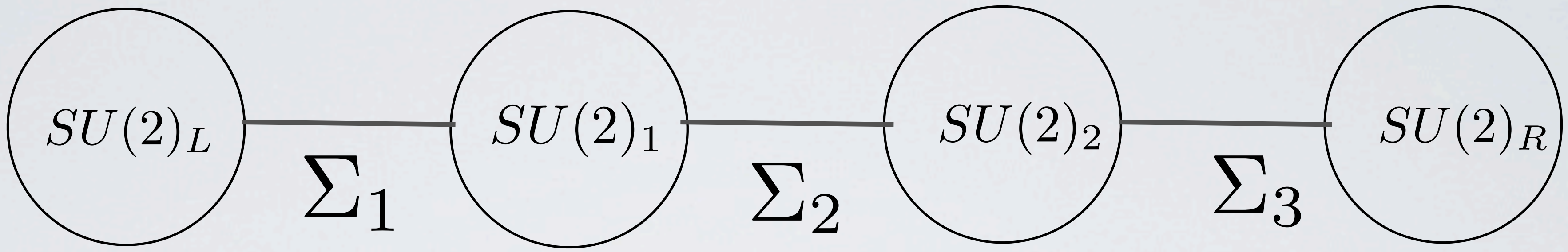
$$+ \bar{\psi}_L i \gamma^\mu \left[\partial_\mu + \frac{1}{1 + \sum_{i=1}^K b_i} \left(i \tilde{g} \tilde{W}_\mu + i \sum_{i=1}^K b_i g_i A_\mu^i \right) + \frac{i}{2} \tilde{g}'(B-L) \tilde{\mathcal{Y}}_\mu \right] \psi_L$$

correction to SM couplings

new couplings of the extra gauge bosons

EX. 4-site model + scalar

E. Accomando et al. (2012)



$$a = 0, b = c = \frac{2f_1^2}{v^2}, d = \frac{4f_2^2}{v^2}, g" = \frac{g_1}{\sqrt{2}}$$

$$\mathcal{L}_{hG} = (2a_h \frac{h}{v} + b_h \frac{h^2}{v^2}) f_1^2 [D_\mu \Sigma_1)^\dagger D^\mu \Sigma_1 + (D_\mu \Sigma_3)^\dagger D^\mu \Sigma_3] + (2c_h \frac{h}{v} + d_h \frac{h^2}{v^2}) f_2^2 (D_\mu \Sigma_2)^\dagger D^\mu \Sigma_2.$$

$$\Sigma_i = \exp(i \frac{f}{2f_i^2} \vec{\pi} \cdot \vec{\tau}), \quad i = 1, 2, 3,$$

in the unitary gauge
$\pi \sim W_L, Z_L$

$$2a \frac{h}{v} \frac{1}{2} (\partial_\mu \vec{\pi})^2$$

deviation in hWW coupling

$$a = a_h(1 - z^2) + c_h z^2.$$

$$z = \frac{f_1}{\sqrt{f_1^2 + 2f_2^2}} = \frac{M_1}{M_2}$$

$$a_h = c_h = k$$

7 November 1996

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 388 (1996) 112-120

An extension of the electroweak model with decoupling at low energy

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Received 11 July 1996

Editor: R. Gatto

Abstract

We present a renormalizable model of electroweak interactions containing an extra $SU(2)'_L \otimes SU(2)'_R$ symmetry. The masses of the corresponding gauge bosons and of the associated Higgs particles can be made heavy by tuning a convenient vacuum expectation value. According to the way in which the heavy mass limit is taken we obtain a previously considered non-linear model (degenerate BESS) which, in this limit, decouples giving rise to the Higgsless Standard Model (SM). Otherwise we can get a model which decouples giving the full SM. In this paper we argue that in the second limit the decoupling holds true also at the level of radiative corrections. Therefore the model discussed here is not distinguishable from the SM at low energy. Of course the two models differ deeply at higher energies.

two scale breaking

$$
\begin{gathered}
SU(2)_L \otimes U(1) \otimes SU(2)'_L \otimes SU(2)'_R \\
\downarrow u \\
SU(2)_{\mathrm{weak}} \otimes U(1)_Y \\
\downarrow v \\
U(1)_{\mathrm{em}}
\end{gathered}
$$

one light scalar and two heavy

$$
\begin{aligned}
m_1^2 &\sim 8hv^2 \\
m_2^2 &\sim 8u^2(\lambda - f_3) \\
m_3^2 &\sim 8u^2(\lambda + f_3)
\end{aligned}
$$

light and heavy sector

$$M_Z^2 = \frac{v^2}{4}\frac{g^2}{c_\theta^2}\left(1 - r s_\varphi^2 \frac{1 - 2c_\theta^2 + 2c_\theta^4}{c_\theta^4} + \cdots\right)$$

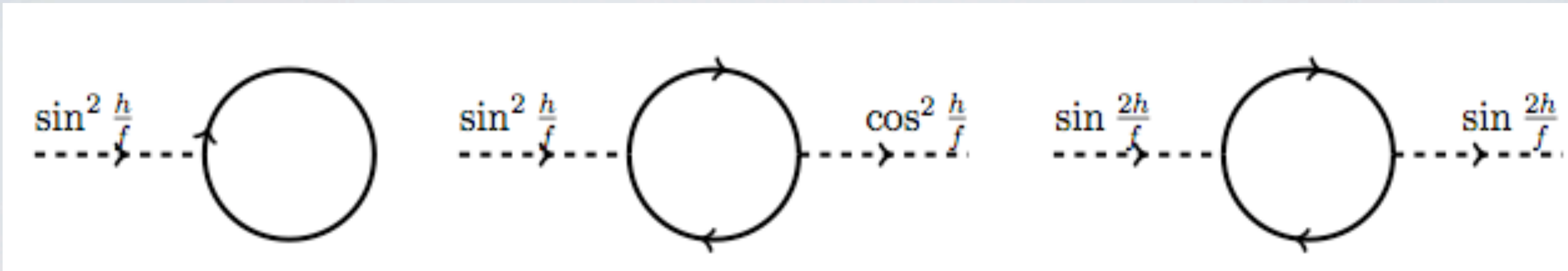
$$M_{V_{3L}}^2 = \frac{v^2}{4} g^2 \left(\frac{1}{r c_\varphi^2} + \frac{s_\varphi^2}{c_\varphi^2} - r s_\varphi^2 \frac{c_\theta^2}{1 - 2c_\theta^2} + \cdots\right)$$

$$M_{V_{3R}}^2 = \frac{v^2}{4}\frac{g^2}{c_\theta^2}\left(\frac{1}{r}\frac{c_\theta^4}{P} + \frac{s_\varphi^2 s_\theta^4}{P} + r\frac{s_\varphi^2 s_\theta^8}{c_\theta^4(1 - 2c_\theta^2)} + \cdots\right)$$

$$r = \frac{1}{4}\frac{g^2 v^2}{M^2} = \frac{v^2}{u^2}\frac{g^2}{g_2^2}$$

decoupling

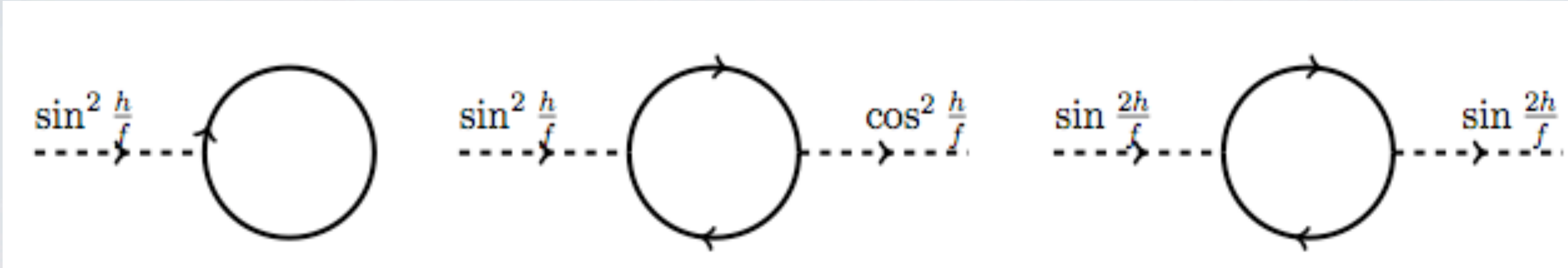
CHM5 ESTIMATES



$$\mathcal{L}_{Yuk} = y_t f \, \frac{s_h c_h}{h} (\bar{q}_L H^c t_R + h.c.) \longrightarrow V(h)_{Yuk} \sim N_c \frac{y_t^2}{16\pi^2} m_f^2 f^2 s_h^2 c_h^2$$

$$\mathcal{L}_{kin} = \epsilon_L^2 \, s_h^2 \, \bar{t}_L \, \not{D} t_L + 2\, \epsilon_R^2 \, s_h^2 \, \bar{t}_R \, \not{D} t_R \longrightarrow V(h)_{kin} \sim N_c \frac{2\epsilon_R^2 - \epsilon_L^2}{32\pi^2} \, m_f^4 \, s_h^2$$

CHM5 ESTIMATES



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$$\mathcal{L}_{kin} = \epsilon_L^2 \, s_h^2 \, \bar{t}_L \, \not{D} t_L + 2 \, \epsilon_R^2 \, s_h^2 \, \bar{t}_R \, \not{D} t_R \longrightarrow V(h)_{kin} \sim N_c \frac{2\epsilon_R^2 - \epsilon_L^2}{32\pi^2} \, m_f^4 \, s_h^2$$

Potential:

$$V(h) \approx \alpha \, s_h^2 - \beta \, s_h^2 c_h^2 \qquad s_h \equiv \sin \frac{h}{f} = \frac{v}{f}$$

Quartic is determined by top Yukawa,

$$m_h \sim \sqrt{\frac{N_c}{2} \frac{y_t}{\pi} \frac{m_f}{f}} v$$