Some avenues Beyond Standard Model Higgs

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1. The Hierarchy problem

2. The SUSY avenue to solve the Hierarchy problem

3. The Compositeness avenue to solve the Hierarchy problem

Motivation for Beyond Standard Model:

The Standard Model (SM) cannot be the ultimate theory

– The SM does not contain gravity

– The SM does not provide gauge coupling unification

– Hierarchy problem

– Cold Dark Matter exists, SM has no candidate

– Non-vanishing Neutrino masses and neutrino intergenerational mixings found in experiments, within SM they are zero

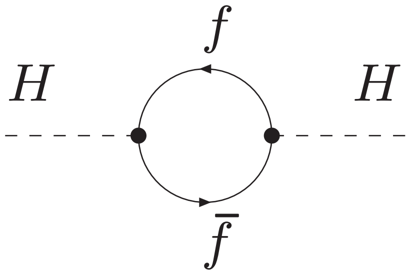
Motivation for Beyond Standard Model Higgs Boson:

– Hierarchy problem

The Hierarchy Problem

Free propagation: 

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections: 

inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

$$\frac{i}{\not{k} - m_f} = \frac{i(\not{k} + m_f)}{k^2 - m_f^2}$$

$$\Sigma_H^f \sim N_f\, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right) (-1)$$

$$\text{for } \Lambda \to \infty : \quad \Sigma_H^f \sim N_f\, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_f^2 \underbrace{\int \frac{d^4k}{k^4}}_{\sim \ln \Lambda} \right) (-1)$$

$$\delta M_H^2 = N_f \frac{\lambda_f^2}{16\pi^2} \left(-2\Lambda^2 + 6m_f^2 \log \frac{\Lambda}{m_f} + \ldots \right) \qquad \text{(E)}$$

$\Rightarrow$ quadratically divergent!

For $\Lambda = M_{\text{Pl}}$:

$$\delta M_H^2 \sim M_{\text{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

$\Rightarrow$ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\text{GUT}}^2$

Two main avenues for solving the hierarchy problem

Elementary Higgs

⋆ There should exist an extra symmetry and new particles with couplings dictated by this symmetry such that quadratic sensitivity to high scale cancels.

⋆ Typical example is Supersymmetry the sparticle cancels the quadratic divergence generated by the particle.

⋆ The soft SUSY breaking scale acts as a cutoff of divergences

⋆ Higgs boson is weakly interacting

⋆ Higgs self-coupling related to EW gauge coupling

⋆ Higgs boson mass is at EW scale

Composite Higgs

⋆ At some scale the Higgs dissolves and the theory of constituents is at work

⋆ Similar to QCD where the pions dissolve into quarks

⋆ The compositeness scale acts as a cutoff of quadratic divergences

⋆ Typical example is Technicolor Higgs boson is strongly interacting. Higgs mass is at TeV scale

⋆ Modern theories of compositeness involve an extra dimension through the AdS/CFT correspondence.
The Higgs mass and couplings are very model dependent

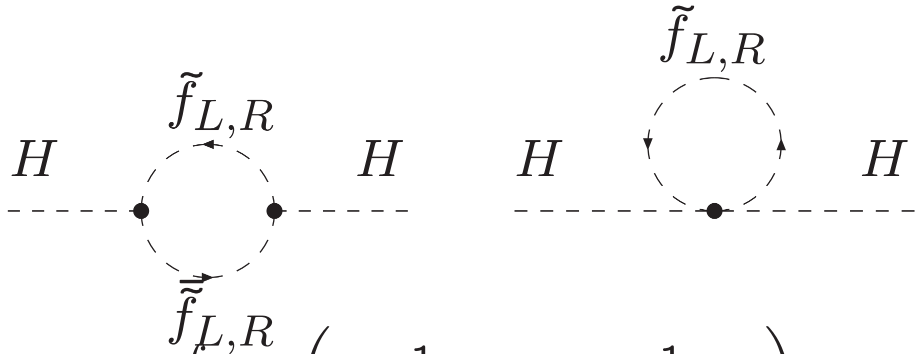
Supersymmetry:

Symmetry between fermions and bosons

$$Q|\text{boson}\rangle = |\text{fermion}\rangle$$
$$Q|\text{fermion}\rangle = |\text{boson}\rangle$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde{f}_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde{f}} \sim N_{\tilde{f}}\, \lambda_{\tilde{f}} \int d^4k \left(\frac{1}{k^2 - m^2_{\tilde{f}_L}} + \frac{1}{k^2 - m^2_{\tilde{f}_R}} \right) + \text{ first diagram } (\sim \log \Lambda)$$

for $\Lambda \to \infty$: $\delta M_H^2 = 2N_{\tilde{f}} \frac{\lambda_{\tilde{f}}}{16\pi^2} \left(\Lambda^2 - 2m^2_{\tilde{f}} \log \frac{\Lambda}{m_{\tilde{f}}} \right) + \ldots$ (E)

$(m_{\tilde{f}_L} = m_{\tilde{f}_R} = m_{\tilde{f}})$ $\Rightarrow$ also quadratically divergent!

⇒ quadratic divergences cancel for

$$N_{\tilde{f}_L} = N_{\tilde{f}_R} = N_{\tilde{f}} \;=\; N_f$$

$$\lambda_{\tilde{f}} \;=\; \lambda_f^2$$

complete correction vanishes if furthermore

$$m_{\tilde{f}} = m_f$$

SUSY breaking: $m_{\tilde{f}}^2 = m_f^2 + \Delta^2, \quad \lambda_{\tilde{f}} = \lambda_f^2$

$$\Rightarrow \; \Sigma_H^{f+\tilde{f}} \sim N_f \, \lambda_f^2 \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

$$M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

1. Soft SUSY-breaking

Exact SUSY: $m_f = m_{\tilde{f}}, \ldots$

$\Rightarrow$ in a realistic model: SUSY must be broken

Only satisfactory way for model of SUSY breaking:

spontaneous SUSY breaking

Specific SUSY-breaking schemes (see below) in general yield effective Lagrangian at low energies, which is supersymmetric except for explicit soft SUSY-breaking terms

Soft SUSY-breaking terms: do not alter dimensionless couplings

(i.e. dimension of coupling constants of soft SUSY-breaking terms > 0)
otherwise: re-introduction of the hierarchy problem

$\Rightarrow$ no quadratic divergences (in all orders of perturbation theory)

scale of SUSY-breaking terms: $M_{\text{SUSY}} \lesssim 1$ TeV

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved

no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

$\Rightarrow$ relations between dimensionless couplings unchanged
no quadratic divergences

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

Good phenomenological description for universal breaking terms

B. Constrained models (mSUGRA, . . .):

assumption on the scenario that achieves spontaneous SUSY breaking

$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

Experimental determination of SUSY parameters

$\Rightarrow$ Patterns of SUSY breaking

Constrained SUSY models

"Hidden sector":	$\longrightarrow$	Visible sector:
SUSY breaking		MSSM

"Gravity-mediated": CMSSM/mSUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
"Gaugino-mediated"
...

For instance:

CMSSM/mSUGRA: mediating interactions are gravitational

GMSB: mediating interactions are gauge interactions

All constrained models are special versions of the MSSM !!!

MSSM spectrum

	SUSY particles			
Extended Standard Model spectrum	$SU(3)_C \times SU(2)_L \times U(1)_Y$ interaction eigenstates		Mass eigenstates	
	Notation	Name	Notation	Name
$q = u, d, s, c, b, t$ $l = e, \mu, \tau$ $\nu = \nu_e, \nu_\mu, \nu_\tau$	$\tilde{q}_L, \tilde{q}_R$ $\tilde{l}_L, \tilde{l}_R$ $\tilde{\nu}$	squarks sleptons sneutrino	$\tilde{q}_1, \tilde{q}_2$ $\tilde{l}_1, \tilde{l}_2$ $\tilde{\nu}$	squarks sleptons sneutrino
g	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$ $H_1^+ \supset H^+$ $H_2^- \supset H^-$	$\tilde{W}^\pm$ $\tilde{H}_1^+$ $\tilde{H}_2^-$	wino higgsino higgsino	$\tilde{\chi}_i^\pm$ $(i=1,2)$	charginos
γ Z $H_1^o \supset h^0, H^0, A^0$ $H_2^o \supset h^0, H^0, A^0$ W^3 B	$\tilde{\gamma}$ $\tilde{Z}$ $\tilde{H}_1^o$ $\tilde{H}_2^o$ $\tilde{W}^3$ $\tilde{B}$	photino zino higgsino higgsino wino bino	$\tilde{\chi}_j^o$ $(j=1,\ldots,4)$	neutralinos

Enlarged Higgs sector of the MSSM versus SM

Two Higgs doublets needed in MSSM:

$\Rightarrow$ H_d (H_1) and H_u (H_2) give masses to down- and up-type fermions

In the SM, just one Higgs doblet H needed:

$$\mathcal{L}_{\text{SM}} = \underbrace{m_d \bar{Q}_L \Phi d_R}_{\text{d-quark mass}} + \underbrace{m_u \bar{Q}_L \tilde{\Phi} u_R}_{\text{u-quark mass}}$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \tilde{\Phi} = i\sigma_2 \Phi^*, \quad \Phi \to \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \tilde{\Phi} \to \begin{pmatrix} v \\ 0 \end{pmatrix}$$

In SUSY: term $\bar{Q}_L \Phi^*$ not allowed

Superpotential is holomorphic function of chiral superfields, i.e. depends only on φ_i, not on φ_i^*

Furthermore: two doublets also needed for cancellation of anomalies

Enlarged Higgs sector with two doublets $\Rightarrow$ 5 physical states: $h^0, H^0, A^0, H^\pm$

The most relevant prediction of SUSY models: h^0 is light: $m_{h^0} < 135$ GeV

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2(\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) + \underbrace{\frac{g'^2 + g^2}{8}}(H_1\bar{H}_1 - H_2\bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}|H_1\bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ ('oscillations' around asymetric vacuum state)

Goldstone bosons dissapear in unitary gauge and lead to gauge masses

$$M_W^2 = \frac{1}{2} g'^2 (v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, $\quad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$

Tree-level result for m_h, m_H:

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow m_h^2 \leq M_Z^2 \cos^2 2\beta$ (the equality holds for $M_A >> M_Z$)

$\Rightarrow$ Light Higgs boson h required in SUSY

In contrast to SM: $m_{H_{SM}}$ and self-coupling $\lambda = \frac{g^2 m^2_{H_{SM}}}{8M_W^2}$ are both unknown

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

Higgs couplings, tree level:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\text{SM}}, \qquad V = W^{\pm}, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\text{SM}} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W} \\
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}
\end{aligned}
$$

$\Rightarrow$ $g_{hVV} \leq g_{HVV}^{\text{SM}}$, g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

The decoupling limit: $M_A >> M_Z$

$m_h^{\text{tree}} \to M_Z |\cos 2\beta|$

The lightest MSSM Higgs is SM-like

$-\frac{\sin\ \alpha}{\cos\beta} \to 1,\ \frac{\cos\ \alpha}{\sin\beta} \to 1,\ \sin(\beta-\alpha) \to 1$
$\Rightarrow g_{hVV} \to g_{HVV}^{\text{SM}},\ g_{hf\bar{f}} \to g_{Hf\bar{f}}^{\text{SM}}$

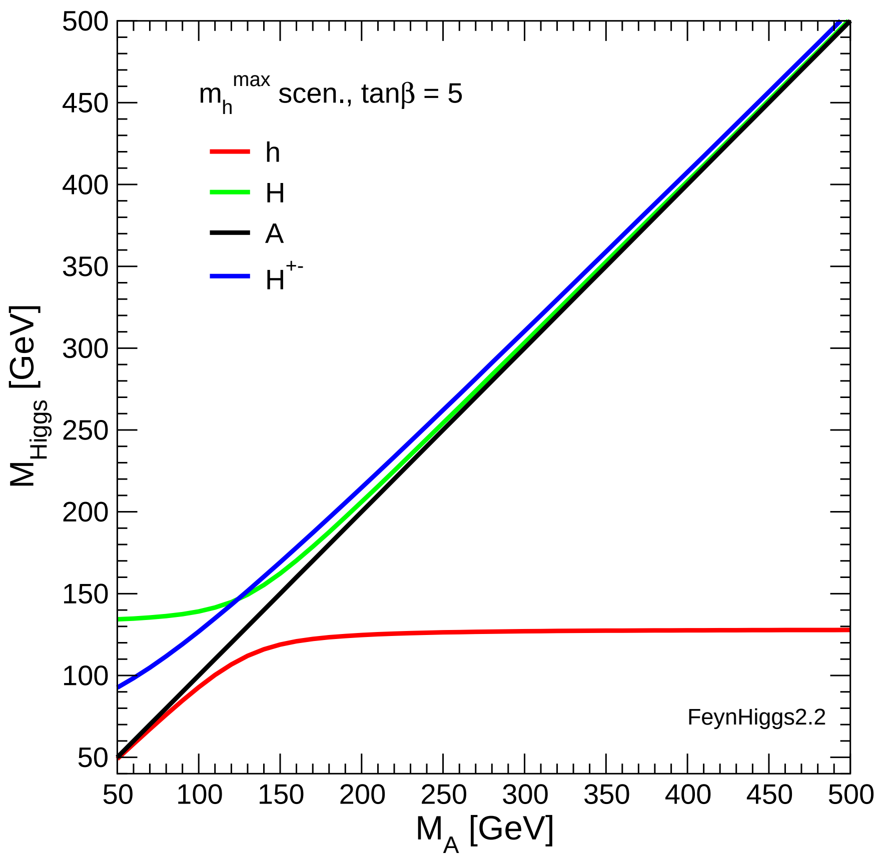
Effectively, $h \approx H_{SM}$

The heavy MSSM Higgses:
$M_A \approx M_H \approx M_{H^\pm}$

approximately degenerate and heavy

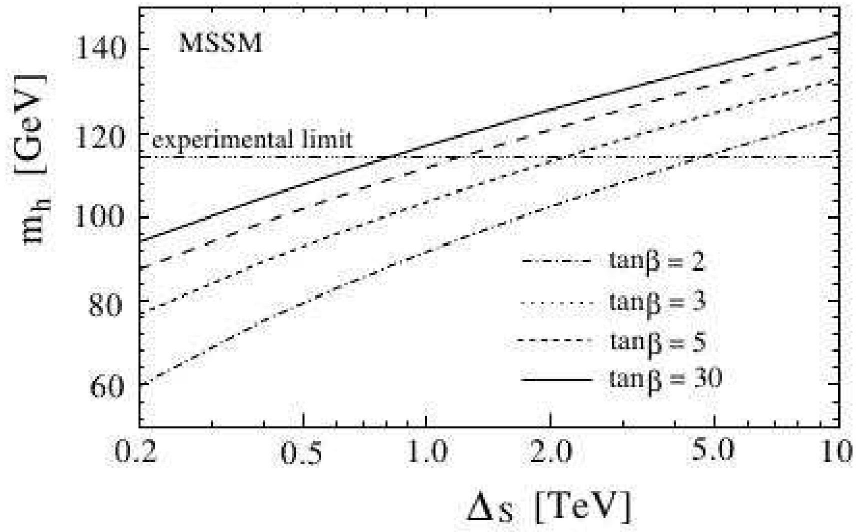
$A, H, H^\pm$ decouple from low energy physics: MSSM $\to$ SM (Higgs sector)

Decoupling effective at $M_A \gtrsim 150$ GeV:



2. The lightest MSSM Higgs boson

MSSM predicts upper bound on m_h:
tree-level bound: $m_h < M_Z$,
excluded by LEP Higgs searches!
Large radiative corrections:
Mainly from large Yukawa couplings: top the largest, ...



Very relevant increase of m_h
with $\Delta_S = m_{\tilde{t}}$ and $\tan\beta$
Corrected m_h is OK with data

$\Rightarrow$ With dominant 1-loop corrections (and $M_A \gtrsim 150$ GeV):

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2}\frac{m_t^4}{M_W^2} \log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

The MSSM Higgs sector is connected to all other sectors via loop corrections
(especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete one-loop and 'almost complete' two-loop result available

Soft breaking terms in MSSM:

$$\begin{aligned}\mathcal{L}_{\text{soft}} \;=\; & -\frac{1}{2}\Big(M_1\widetilde{B}\widetilde{B}+M_2\widetilde{W}\widetilde{W}+M_3\tilde{g}\tilde{g}\Big)+\text{h.c.} \\ & -(m^2_{H_u}+|\mu|^2)H_u^+H_u-(m^2_{H_d}+|\mu|^2)H_d^+H_d-(bH_uH_d+\text{h.c.}) \\ & -\Big(\tilde{u}_R\mathbf{a_u}\widetilde{Q}H_u-\tilde{d}_R\mathbf{a_d}\widetilde{Q}H_d-\tilde{e}_R\mathbf{a_e}\widetilde{L}H_d\Big)+\text{h.c.} \\ & -\widetilde{Q}^+\mathbf{m^2_Q}\widetilde{Q}-\widetilde{L}^+\mathbf{m^2_L}\widetilde{L}-\tilde{u}_R\mathbf{m^2_u}\tilde{u}^*_R-\tilde{d}_R\mathbf{m^2_d}\tilde{d}^*_R-\tilde{e}_R\mathbf{m^2_e}\tilde{e}^*_R \end{aligned} \tag{1}$$

Most general parameterization of SUSY-breaking terms that keep relations between dimensionless couplings unchanged
$\Rightarrow$ no quadratic divergences

$\mathbf{m^2_i}, \mathbf{a_j}$: 3×3 matrices in family space

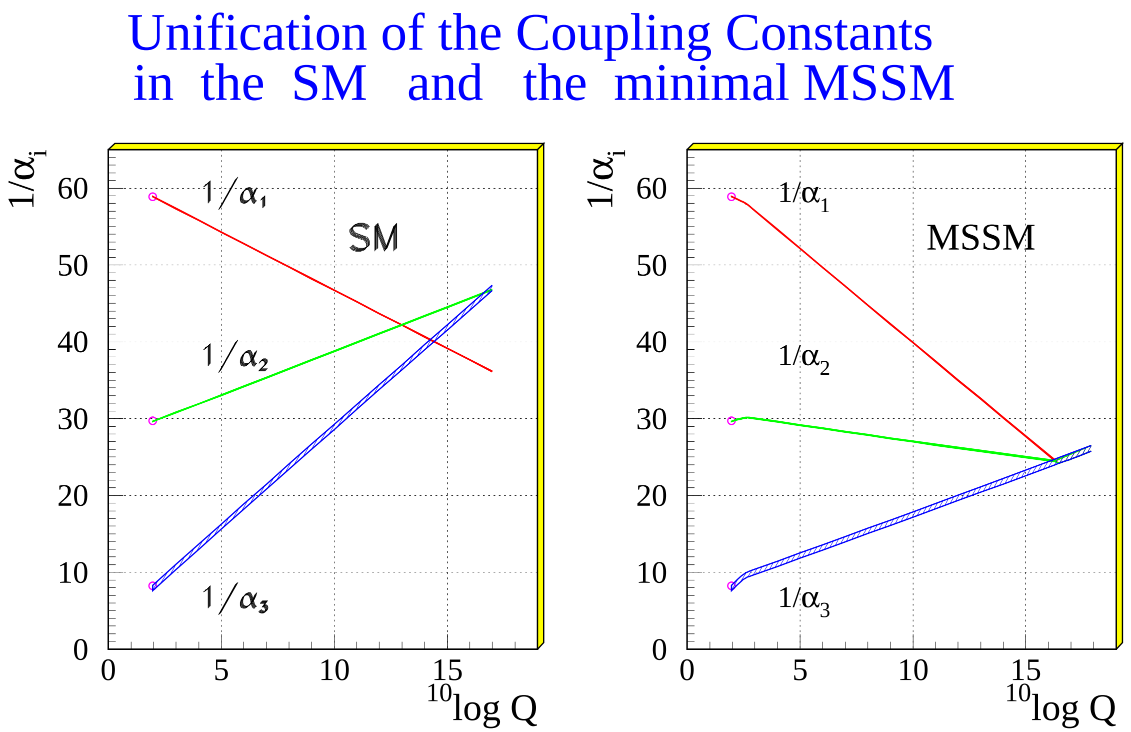
$\Rightarrow$ many new parameters

Coupling constant unification

[RGE: equations that connect parameters at different energy scales]

$\longrightarrow$ use RGE's to evolve gauge coupling constants from electroweak scale to the GUT scale

$$\alpha_i(Q_{\text{electroweak}}) \longrightarrow \alpha_i(Q_{\text{GUT}})$$



gauge couplings do not meet in the SM

they unify in the MSSM although it was not designed for it!

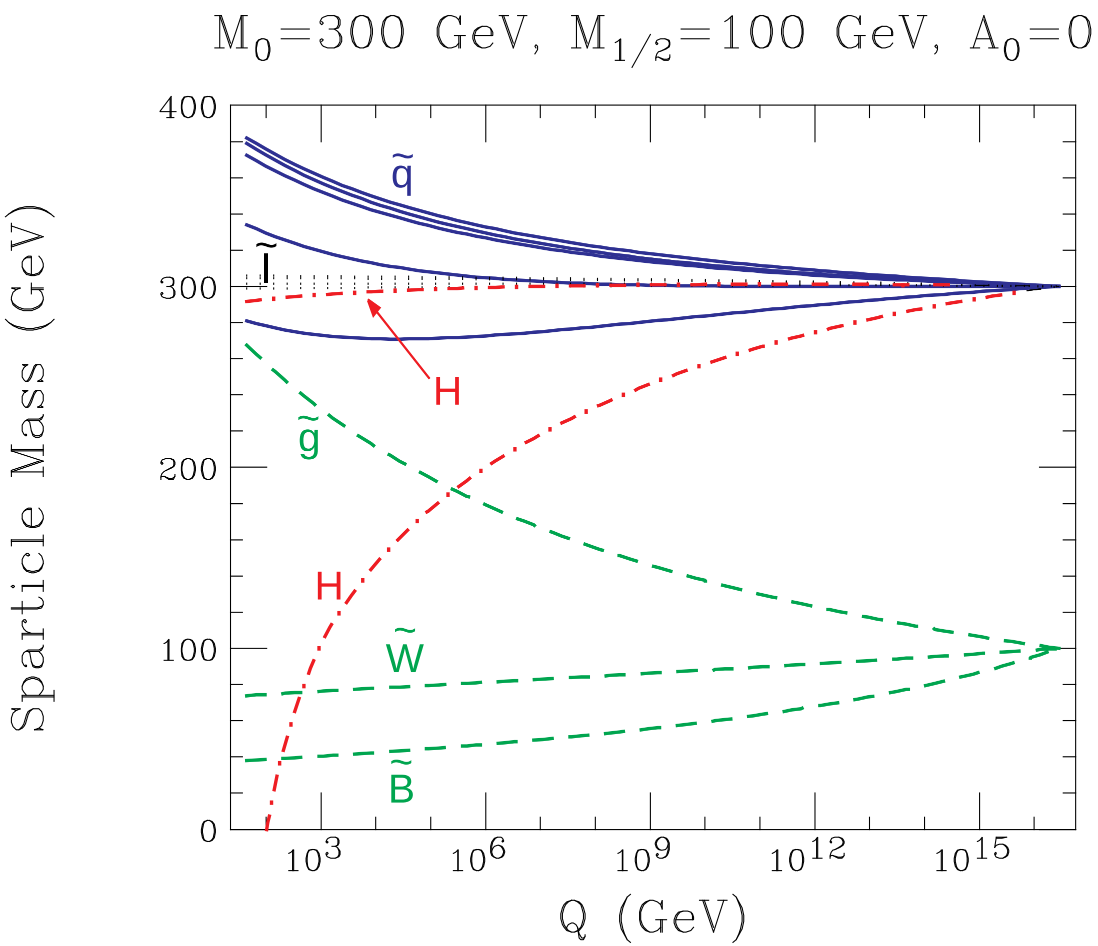
$\Rightarrow M_{\text{SUSY}} \approx 1$ TeV

Radiative EWSB in SUSY: negative μ^2 comes for free

– assume GUT scale (as motivated by coupling constant unification)

– take universal input parameters at the GUT scale (see mSUGRA below)

– run down to the electroweak scale with RGEs



Exactly one parameter turns negative: the "μ^2" in the Higgs potential

But this only works if

$m_t = 150 \ldots 200$ GeV

and $M_{\rm SUSY} \approx 1$ TeV

R-parity $\Rightarrow$ the LSP

MSSM has further symmetry: "R-parity"

all SM-particles and Higgs bosons: even R-parity, $P_R = +1$

all superpartners: odd R-parity, $P_R = -1$

$\Rightarrow$ SUSY particles appear only in pairs, e.g. $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$

$\Rightarrow$ lightest SUSY particle (LSP) is stable

(usually the lightest neutralino)

good candidate for Cold Dark Matter

$\Rightarrow M_{\text{SUSY}} \lesssim 1$ TeV

LSP neutral, uncolored $\Rightarrow$ leaves no traces in collider detectors

$\Rightarrow$ Typical SUSY signatures: "missing energy"

$\Rightarrow$ prediction for collider phenomenology!

What if the Higgs is composite: Look for simmilarities with QCD

Use the alternative way of writing the (ungauged) Lagrangian of SBS:

$$\mathcal{L}_{\text{SBS}} = \frac{1}{4}\text{Tr}\left[(\partial_\mu M)^\dagger(\partial^\mu M)\right] - V(M) \;;$$
$$V(M) = \frac{1}{4}\lambda\left[\frac{1}{2}\text{Tr}(M^\dagger M) + \frac{\mu^2}{\lambda}\right]^2$$

where M is a 2×2 matrix containing the four real scalar fields of Φ:

$$M \equiv \sqrt{2}(\widetilde{\Phi}\Phi) = \sqrt{2}\begin{pmatrix} \phi_0^* & \phi^\dagger \\ -\phi^- & \phi_0 \end{pmatrix} \;;$$
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi_0 \end{pmatrix} \;;$$
$$\widetilde{\Phi} = i\tau_2\Phi^* = \begin{pmatrix} \phi_0^* \\ -\phi^- \end{pmatrix}$$

$\mathcal{L}_{\text{SBS}}$ is invariant under the global transformations:

$$M \to g_L M g_R^+ \;;\;\; g_L \subset SU(2)_L \;;\;\; g_R \subset SU(2)_R$$

This global symmetry $SU(2)_L \times SU(2)_R$ is called chiral symmetry (for analogy with QCD) and it is spontaneously broken down to the diagonal subgroup $SU(2)_{L+R} \equiv SU(2)_{\text{custodial}}$. The pattern of global symmetry breaking is:

$$SU(2)_L \times SU(2)_R \to SU(2)_{\text{custodial}}$$

C ould it be that the Higgs is a scalar resonance emerging from some new strong interactions, as it happens in QCD where many resonances (like σ, ρ, etc) emerge from the strong interactions among quarks?

The way to Higgs composite models: QCD as an example (I)

In QCD to low energies: the dynamics of pions is well described by an effective lagrangian that is invariant under chiral symmetry: Chiral Lagrangian . This is writen in terms of a non-linear representation of the GBs :

$$U(x) = \exp\left(\frac{i}{f_\pi}\pi_a(x)\sigma^a\right) \text{ with } \sigma^a(a=1,2,3) = \text{Pauli matrices}$$

and f_π the pion decay constant, meassured, for instance, in $\pi^+ \to \mu^+\nu_\mu$:

$$< 0|J^{+\mu}|\pi^-(p) >= \frac{if_\pi}{\sqrt{2}}p^\mu \ , \ \ f_\pi = 94\,\text{MeV}$$

Under a chiral transformation the $U(x)$ transforms linearly (but π transform non-linearly):

$$U(x) \to g_L U(x) g_R^+ \text{ with } g_L \in SU(2)_L \ , \ \ g_R \in SU(2)_R$$

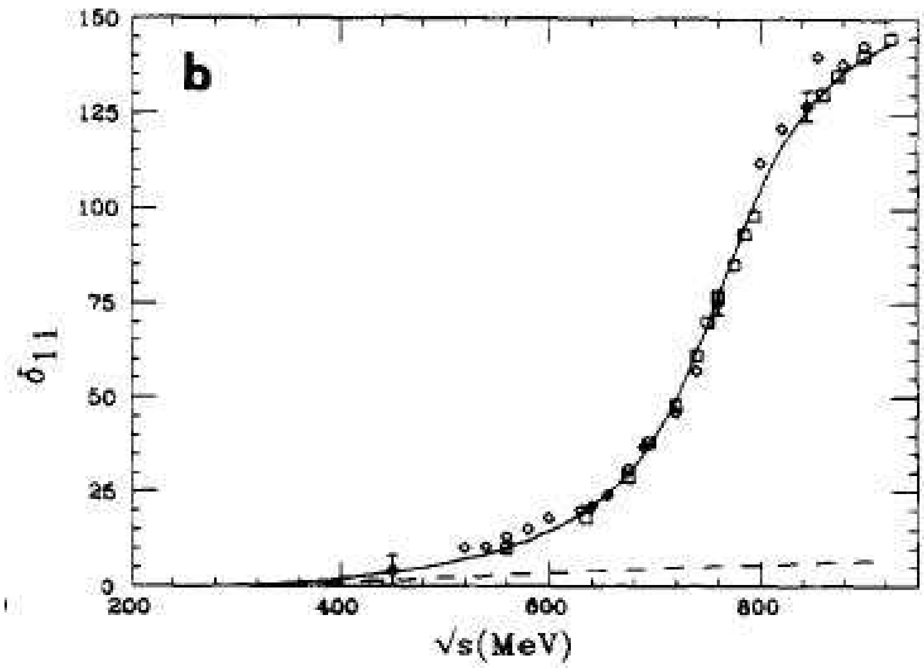
The most general chiral invariant Lagrangian is a sum of an infinite number of terms with increasing number of derivatives in the $U(x)$ and the $U^+(x)$ fields and with an infinite number of arbitrary parameters. Chiral Perturbation Theory (ChPT) is the associated Effective Quantum Field Theory. To lowest order:

$$\mathcal{L}_0 = \frac{f_\pi^2}{4}Tr(\partial_\mu U \partial^\mu U^+) \Rightarrow T(\pi^+\pi^- \to \pi^+\pi^-) = -\frac{u}{f_\pi^2} \ , \ \ T(\pi^+\pi^- \to \pi^0\pi^0) = \frac{s}{f_\pi^2} \ \text{(LETs)}$$

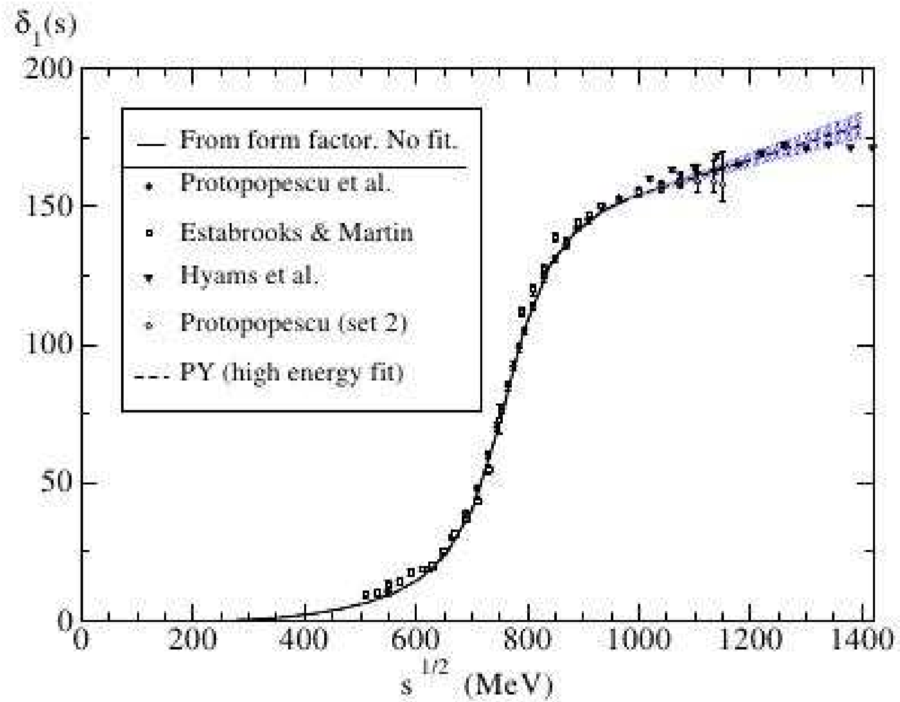
The way to Higgs composite models: QCD as an example (II)

Going to higher orders in ChPT, i.e $\mathcal{O}(p^4)$ and above, and using either unitarization methods or dispersion relations, resonances can be implemented.
They are seen as resonant peaks in $\pi\pi \to \pi\pi$ scattering .

For instance, the ρ vector meson appears clearly in the phase shift plot $\delta_{11}(\sqrt{s})$ for $I = J = 1$. See figs: $\delta_{11} \simeq 90^o$ when $\sqrt{s} = m_\rho = 775$ MeV.



(Dobado,Herrero,Truong,PLB235(1990)134)



(Pelaez,Yndurain,PRD71(2005)074016)

From QCD to Techicolor Theories (I)

Assume $SU(N_{TC})$ gauge theory of new strong interactions in analogy to usual $SU(3)_C$

New constituents : Techniquarks q_{TC}

New gauge bosons : Technigluons g_{TC}

Number of Technicolors = N_{TC}.

Assume global chiral symmetry of the Electroweak Theory broken by the techniquark condensate:

$$< 0|\bar{q}_{TC} q_{TC}|0 > \neq 0 \Rightarrow SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$$

The 3 Goldstone bosons are identified with the 3 Technipions: $\pi^{\pm}_{TC}$ and π^0_{TC}

When the subgroup $SU(2)_L \times U(1)_Y$ is gauged: the three GB $\pi^{\pm}_{TC}$ and π^0_{TC} dissapear and they are replaced by the longitudinal gauge bosons, $W^{\pm}_L$, Z_L.

The EW bosons get the proper mass (Higgs mechanism without an elementary Higgs)

The coupling of the technipions to the weak current (in analogy to f_π):

$$< 0|J_L^{+\mu}|\pi^-_{TC}(p) >= \frac{iF_\pi^{TC}}{\sqrt{2}} p^\mu \text{ with } F_\pi^{TC} = v = 246\ GeV \quad (2)$$

From QCD to Technicolor Theories (II)

The spectrum of $SU(N_{TC})$ is a replica of QCD spectrum:

Technipions $(\pi^{\pm}_{TC}, \pi^{0}_{TC})$, Technirhos $(\rho^{\pm}_{TC}, \rho^{0}_{TC})$, etc..

By using large N techniques one can re-scale QCD quantities to the Technicolor ones:

$$\frac{m_{\text{Tmeson}}}{m_{\text{meson}}} \sim \frac{F_\pi^{TC}}{f_\pi} \cdot \sqrt{\frac{N_C}{N_{TC}}} \text{ with } \frac{F_\pi^{TC}}{f_\pi} = \frac{246\ GeV}{0.094\ GeV} \sim 2700$$

The first expected resonance is the technirho:

$$m_{\rho_{TC}} = \frac{F_\pi^{TC}}{f_\pi} \cdot \sqrt{\frac{N_C}{N_{TC}}} m_\rho$$

$$\Gamma_{\rho_{TC}} = \frac{N_C}{N_{TC}} \frac{m_{\rho_{TC}}}{m_\rho} \Gamma_\rho$$

For $N_C = 3$, $N_{TC} = 4$, $m_\rho = 760\ MeV$, $\Gamma_\rho = 151\ MeV \Rightarrow m_{\rho_{TC}} = 1.8\ TeV$, $\Gamma_{\rho_{TC}} = 260\ GeV$.

The effective cut-off of Technicolor Theory where the new physics sets in is:

$$\Lambda^{\text{eff}}_{TC} \sim O(1\ TeV)$$

and therefore there is not hierarchy problem.
Resonances would appear in $V_L V_L$ scattering $(V = W, Z)$ (as the ρ appears in $\pi\pi$ scattering)

The Higgs is another resonance at $O(1\ TeV)$, may be a copy of the σ particle of QCD.

Strongly Interacting Electroweak Symmetry Breaking Sector

Technicolor and other Strongly Interacting theories of EWSB can be described generically with effective Chiral Lagrangians.

$SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$ with 3 GBs of EWSB: w^+, w^-, w^0.

The Electroweak Chiral Lagrangian (EChL) is similar to the Chiral Lagrangian for QCD, but with the proper gauging for $SU(2)_L \times U(1)_Y$:

$$\mathcal{L}_{\text{EChL}} = \mathcal{L}_{\text{GCL}} + \sum_{i=0}^{13} \mathcal{L}_i.$$

$\mathcal{L}_{\text{GCL}}$ Gauged Chiral Lag., $\mathcal{L}_{\text{YM}}$ Yang Mills Lag. EW fields.

$$\mathcal{L}_{\text{GCL}} = \frac{v^2}{4}\, Tr\left[D_\mu U^\dagger D^\mu U\right] + \mathcal{L}_{\text{YM}}$$

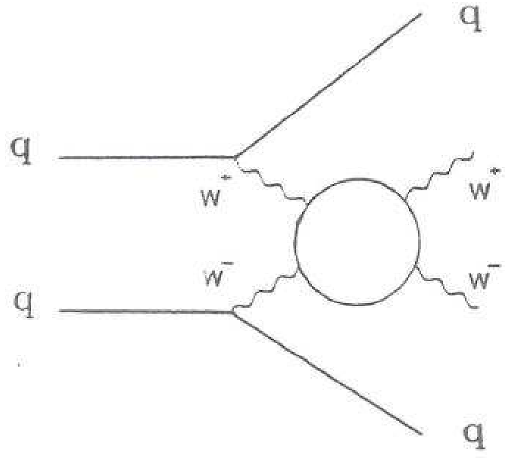
$$U \equiv \exp\left(i\,\frac{\vec{\tau}\cdot\vec{w}}{v}\right), \quad v = 246 \text{ GeV}, \quad \vec{w} = (w^1, w^2, w^3)$$

$$D_\mu U \equiv \partial_\mu U + i\frac{g}{2}\vec{W}_\mu \cdot \vec{\tau} U - i\frac{g'}{2} U B_\mu\, \tau^3$$

$$\mathcal{L}_4 = a_4 \left[Tr\left((D_\mu U)U^\dagger (D_\nu U)U^\dagger\right)\right]^2 \;,\; \mathcal{L}_5 = a_5 \left[Tr\left((D_\mu U)U^\dagger (D^\nu U)U^\dagger\right)\right]^2 \ldots$$

Resonances of SIEWSB at LHC

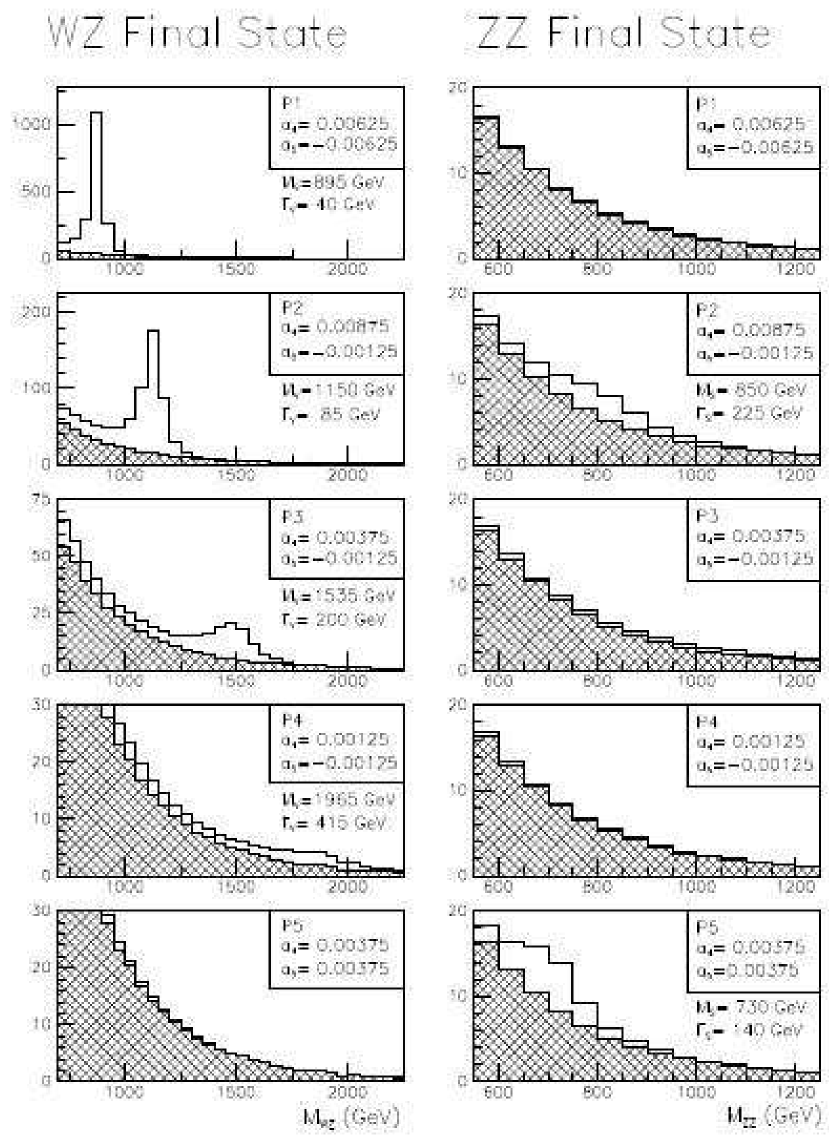
Some examples:



The resonances should show clearly in WW scattering

Looking at peaks in invariant mass of WW, WZ, ZZ, pairs

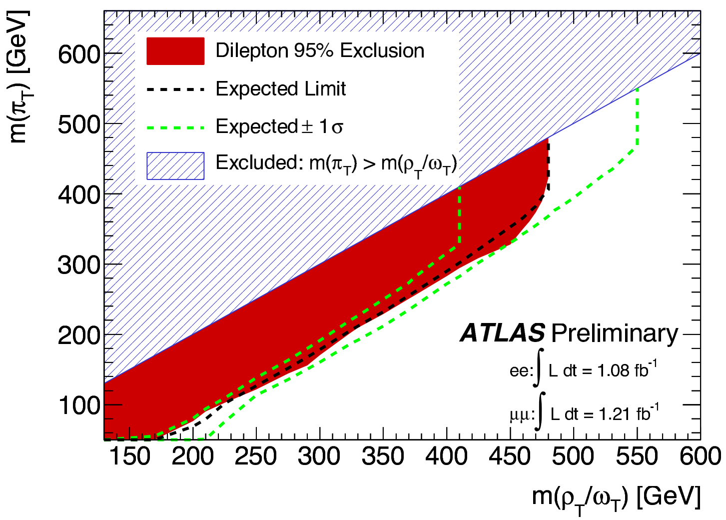
Depending on the particular model (i.e. values of a_i) There could be: scalar, vector,...both. So far.......not seen any

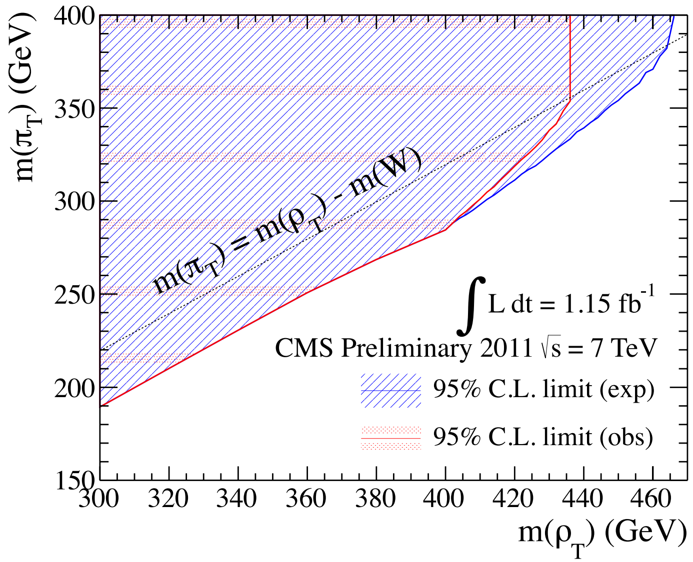


(Dobado,Herrero,Pelaez,Ruiz,PRD62(2000)055011)

Present bounds on Technicolor

⇒ From FCNC: Technicolor models when connecting quarks with techni-quarks tend to produce too much FCNC. Bounds very model dependent.
⇒ From EWPT: Present bounds on S, T exclude many Technicolor modes. Particularly those based on simple scaling from QCD, $S_{TC} \propto N_{TC} N_D$
$S_{TC} \sim 0.45$ for $N_{TC} = 4$ and $N_D = 1$
Compare with (1σ, 39.35%): $S_{\rm exp} = 0.04 \pm 0.09$. TC is many sigmas away!!!.
⇒ From colliders: LHC (from couplings to standard fermions) excludes light ρ_{TC} form direct searches and couplings to standard fermions





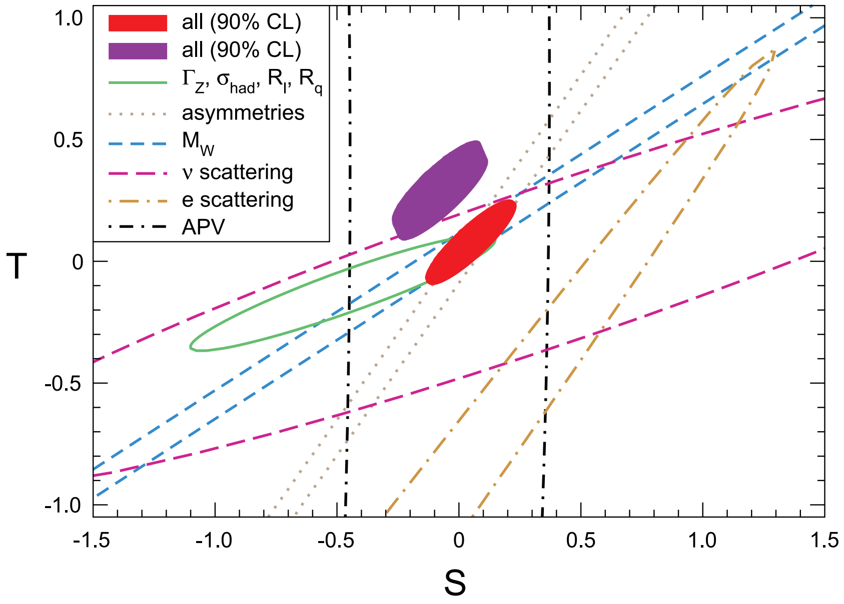
Excluded (PDG July 2012): $m_{\rho_{TC}} < 260 - 480 GeV$ (depending on channels)

Constraints to new physics with S and T parameters

Deviations in self-energies Π_{XY} of EW gauge bosons respect to SM are parameterized in terms of so-called oblique parameters (Peskin, Takeuchi,1990):

$$\hat{\alpha}(M_Z)T \equiv \frac{\Pi^{\text{new}}_{WW}(0)}{M_W^2} - \frac{\Pi^{\text{new}}_{ZZ}(0)}{M_Z^2}$$

$$\frac{\hat{\alpha}(M_Z)}{4\hat{s}_Z^2\hat{c}_Z^2}S \equiv \frac{\Pi^{\text{new}}_{ZZ}(M_Z^2) - \Pi^{\text{new}}_{ZZ}(0)}{M_Z^2}$$



PDG July 2012

1 σ (39.35%) constraints

$S_{\text{exp}} = 0.04 \pm 0.09$

$T_{\text{exp}} = 0.07 \pm 0.08$

violet 600 GeV $< M_H <$ 1000 GeV

red 115.5 GeV $< M_H <$ 127 GeV

Composite Higgs in Extra Dimensions

To get a ligth Higgs boson $\mathcal{O}(100\text{ GeV})$ in theories with extra dimensions, one interesting possibility is:

⇒ The Higgs is the scalar component of a gauge field in 5D

The mass of the Higgs is protected by gauge symmetry (Gauge-Higgs Unification Models):it is zero at tree level and a non-zero value is generated radiatively at one-loop, as in Coleman-Weinberg

By using the $\text{Ads}_5/\text{CFT}_4$ correspondence: the breaking of the bulk gauge group by boundary conditions on the IR brane is described in the CFT as the SSB $G \to H_1$ by strong dynamics at TeV scale. The Higgs in 4D is identified with one of the associated GBs of this breaking (simmilar to Little Higgs Models)

The main problem of all these wed models is the strong constraints from EWPT .

The KK modes contribute dangerously to S and/or T parameters $\Rightarrow m_{KK} > \mathcal{O}(10TeV)$

Usually wed models must include an additional symmetry in 5D leading to custodial symmetry protection in 4D .

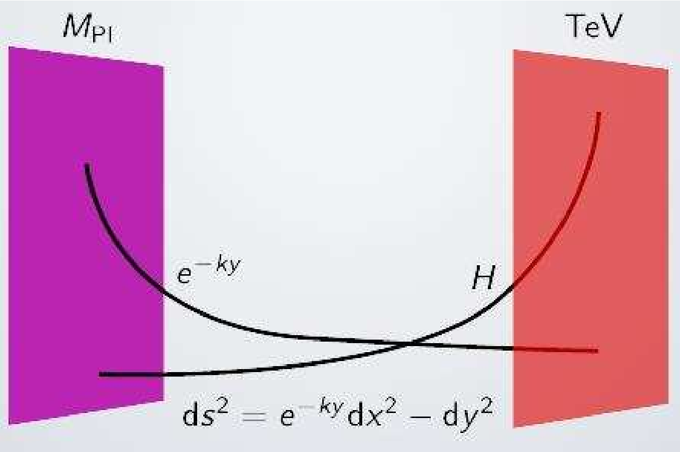
Back-up

Composite Higgs in Extra Dimensions (I)

Modern theories of compositeness involve one extra dimension through the AdS_5/CFT_4 correspondence :

⇒ 5D theories of gravity in Anti-de Sitter are related to 4D strongly-coupled conformal field theories

⇒ If the 5th dimension y is compactified and the geometry is warped (Randall Sundrum '99) the small ratio $1\text{TeV}/M_{\text{Pl}}$ is explained in terms of the exponential supression produced by the 'warp' factor e^{-ky} ($k =$ AdS_5 curvature $\sim \mathcal{O}(M_{\text{Pl}})$)



fermions and gauge bosons can propagate in the bulk

Higgs originally localized in the IR

Recent works H also in the bulk

$$ds^2 = e^{-ky}dx^2 - dy^2$$

Mass generated by boundary conditions in y

IR brane (boundary) at $\mathcal{O}(1\,\text{TeV})$

UV brane (boundary) at $\mathcal{O}(M_{Pl})$

Matter at UV is elementary: e.g. light fermions

Matter at IR is composite: e.g. heavy fermions

KK modes $\phi(x,y) = \frac{1}{\sqrt{2\pi R M_5}} \sum_n e^{iny/R} \phi^{(n)}(x)$ The 'natural' value for compossiteness: TeV

H maybe composite or even do not exist

Composite Higgs in Extra Dimensions (II)

To get a ligther Higgs boson $\mathcal{O}$(100 GeV) in theories with extra dimensions, usually two main avenues:

⇒ The Higgs is placed in the bulk, but close to the IR brane . The AdS metric is deformed in the IR (→ partially composite Higgs). Overlaping of wave functions in the extra dimension gives size of couplings. For instance, (composite) H close to (composite) t_R give large top Yukawa coupling (while t_L is elementary)

⇒ The Higgs is the scalar component of a gauge field in 5D
The mass of the Higgs is protected by gauge symmetry (Gauge-Higgs Unification Models):it is zero at tree level and a non-zero value is generated radiatively at one-loop, as in Coleman-Weinberg
By using the $\text{Ads}_5/\text{CFT}_4$ correspondence: the breaking of the bulk gauge group by boundary conditions on the IR brane is described in the CFT as the SSB $G \to H_1$ by strong dynamics at TeV scale. The Higgs in 4D is identified with one of the associated GBs of this breaking (simmilar to Little Higgs Models)

The main problem of all these wed models is the strong constraints from EWPT .
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Usually wed models must include an additional symmetry in 5D leading to custodial symmetry protection in 4D .

Composite Higgs in Extra Dimensions (III)

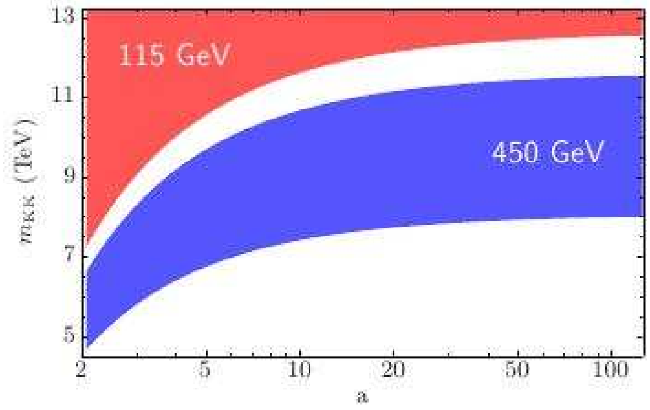

FIG. 2. *95% CL regions in the (a, m_{KK}) plane for RS and different values of the Higgs mass.*

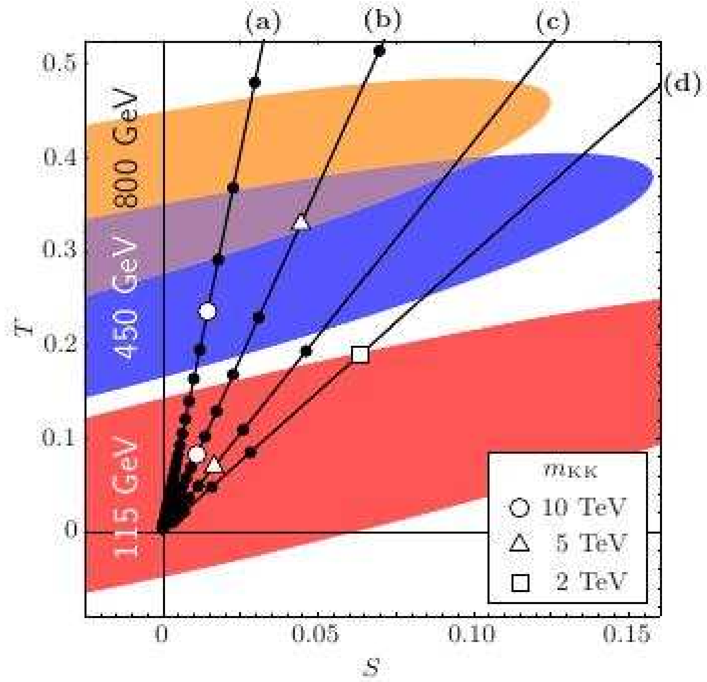

FIG. 1. *95% CL regions in the (S, T) plane for different values of the Higgs mass. Ray (a) [(b)] is RS with a localized [bulk with a=2.1] Higgs boson. Ray (c) [(d)] is model [12] with $k\Delta = 1$ and $\nu = 0.7$ [$\nu = 0.6$]. Dot spacing is 1 TeV. Increasing values of m_{KK} correspond to incoming fluxes.*

(Figs. from J.Cabrer, G.Gersdorff, M.Quiros PRD84(2011)035024)

Comparing RS metric, (a) and (b), with models with RS-deformed metric, (c) and (d), these latter allow for light Higgs, not too heavy KK modes, and still compatible with S,T

Squark mixing:

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

off-diagonal element prop. to mass of partner quark ($\tan\beta \equiv v_u/v_d$)

$\Rightarrow$ mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

gauge invariance $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

$\Rightarrow$ prediction for collider phenomenology!

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

Diagonalization of the mass matrix:

$$\mathbf{X} = \begin{pmatrix} M_2 & \sqrt{2}\sin\beta\, M_W \\ \sqrt{2}\cos\beta\, M_W & \mu \end{pmatrix} ,$$

$$\mathbf{M}_{\tilde{\chi}^-} = \mathbf{V}^* \, \mathbf{X}^\top \, \mathbf{U}^\dagger = \begin{pmatrix} m_{\tilde{\chi}_1^\pm} & 0 \\ 0 & m_{\tilde{\chi}_2^\pm} \end{pmatrix}$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

Diagonalization of mass matrix:

$$\mathbf{Y} = \begin{pmatrix} M_1 & 0 & -M_Z\, s_W \cos\beta & M_Z\, s_W \sin\beta \\ 0 & M_2 & M_Z\, c_W \cos\beta & -M_Z\, c_W \sin\beta \\ -M_Z\, s_W \cos\beta & M_Z\, c_W \cos\beta & 0 & -\mu \\ M_Z\, s_W \sin\beta & -M_Z\, c_W \sin\beta & -\mu & 0 \end{pmatrix},$$

$$\mathbf{M}_{\tilde{\chi}^0} = \mathbf{N}^* \, \mathbf{Y} \, \mathbf{N}^\dagger = \mathbf{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})$$

$\Rightarrow$ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos
$\Rightarrow$ prediction for collider phenomenology!