ELECTROWEAK VACUUM

LECTURE 4: BEYOND THE STANDARD MODEL

V FERRARA INTERNATIONAL SCHOOL
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OUTLINE

The outline of Lecture 4 is

Beyond the Standard Model

- UV sensitivity of EW vacuum
- Supersymmetry (MSSM)
- Little Higgs (LH)
- Gauge-Higgs Unification (GHU)
- Warped models
  - Randall-Sundrum model (RS)
  - Soft Wall models (SW)
  - Custodial models (dual to composite Higgs)
- Conclusion

UV SENSITIVITY OF EW VACUUM

Drawbacks of SM

- Big Hierarchy problem: The Higgs mass is sensitive to UV physics. Quantum corrections are UV sensitive

  $$\Delta m_H^2(F,B) = \mp \frac{n_{F,B} g_{F,B}^2}{16\pi^2} \Lambda^2$$

  They are not protected by any symmetry which is enhanced when $m_H = 0$
- On the contrary fermions masses

  $$\Delta m_F \propto \frac{m_F}{16\pi^2} \log \Lambda$$

  are protected by chiral symmetry for $m_F = 0$
- Electroweak symmetry breaking requires a tachyonic mass for the Higgs
- Dark Matter: there is no candidate
- There is no gauge coupling unification
- Strong CP-problem: axion required

The Little Hierarchy Problem and LEP paradox

- The leading quantum correction to the Higgs mass parameter is expected to come from the top sector as

$$\Delta m_H^2 = -\frac{3h_t^2}{8\pi^2}\Lambda^2$$

- In the absence of tuning this implies a lower bound on the cutoff scale as

$$\Lambda < 600\, GeV \left(\frac{m_H}{200\, GeV}\right) \simeq 400\ \ GeV$$

- Why did LEP2 not detect any deviation from the SM predictions? (Barbieri's LEP paradox)
- In particular one can parametrize the new effects as non-renormalizable operators ($d = 6$)

$$\mathcal{L}_{eff} = \frac{c_1}{\Lambda^2}\left(\bar{e}\gamma^\mu e\right)^2 + \dots$$

- If $c_i = \mathcal{O}(1) \Rightarrow \Lambda > 10$ TeV $\Rightarrow$ tension

Possible solutions to the Higgs hierarchy problems are motivating the presence of New Physics

Possible solutions ⇔ New Physics

- Supersymmetry: bosonic (fermionic) partners cancel the quadratic divergences produced by fermions (bosons)
- Higgs as pseudo Goldstone boson: little Higgs theories and gauge-Higgs unification in higher dimensions
- Higgs as a condensate that "dissolves" at high energies ⇒ strongly interacting gauge sector at TeV scales: technnicolor, holographic Higgs, warped extra dimensions

MSSM

Minimal Supersymmetric Extension of the Standard Model

Higgs sector

- An extended Higgs sector

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}_{-1/2} , \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}_{1/2}$$

- After the Higgs mechanism $\langle H_1^0 \rangle = v_1$, $\langle H_2^0 \rangle = v_2$, $\tan\beta = v_2/v_1$ there are five Higgses left: two scalar (h, H), one pseudoscalar (A) and two charged $(H^\pm)$
- Supersymmetry has to be broken, e.g. by embedding the MSSM into a local supersymmetry
- The Higgs spectrum is determined by two free parameters: m_A and $\tan\beta$
  $m_{H^\pm} = m_A^2 + M_W^2, \qquad m_{h,H}^2 =$
  $\frac{1}{2}\left[m_A^2 + M_Z^2 \mp \sqrt{(m_A^2 + M_Z^2)^2 - 4 m_A^2 M_Z^2 \cos^2 2\beta}\right]$

MSSM FEATURES

It solves the Big Hierarchy problem

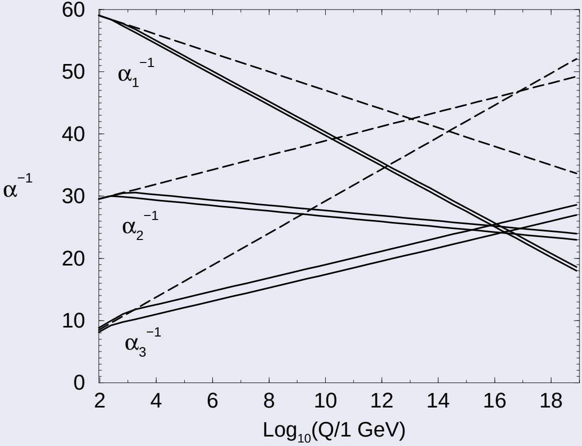
- Because quantum corrections to the Higgs mass from bosonic loops have *opposite* signs to fermionic loops there is a cancellation between supersymmetric partners. Supersymmetry protects the Higgs mass!
- When supersymmetry is broken by *soft* terms the supersymmetric cancellation holds up to supersymmetry breaking terms
- Quadratic divergences are still absent
- Hierarchy problem is *technically* solved by the *non-renormalization theorems* of supersymmetry

It provides candidate to Dark Matter

There is a natural candidate for Cold Dark Mater (WIMP) in the MSSM: the lightest neutralino (LSP), provided that R-parity is unbroken

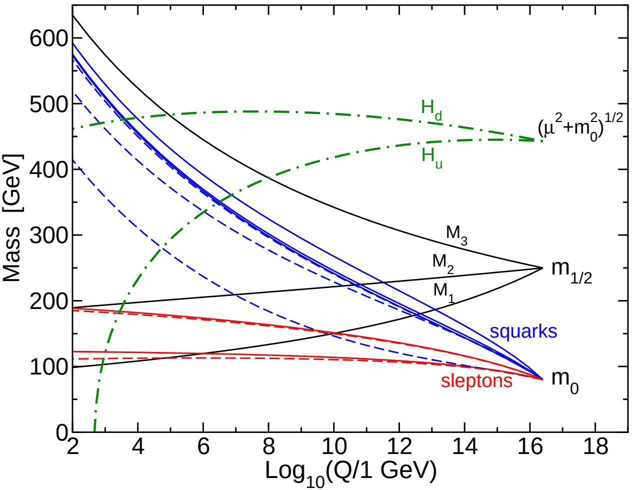
It predicts Gauge coupling unification

Consistently with LEP measurements and if superparticles are at ∼ TeV scale gauge couplings unify at a scale $M_{GUT} \sim 2 \times 10^{16}$ GeV



It triggers Electroweak breaking

If soft breaking parameters are generated at M_{GUT} a tachyonic mass can be triggered by RGE at the weak scale



It solves the Stability/Triviality problems

- The stability ($\lambda < 0$) and triviality/Landau pole ($\lambda \to \infty$) problems are solved because of the supersymmetric relation

$$\lambda = \frac{1}{8}(g^2 + g'^2)$$

- Because the gauge couplings remain perturbative (and positive) up to M_{GUT} there is no stability and/or triviality problem in the MSSM
- As a consequence: the Higgs mass (unlike in the SM) is NOT a free parameter. For the SM-like Higgs

$$m_h^2 \lesssim M_Z^2 \cos^2 2\beta \ + \ \textit{radiative corrections}$$

- The Higgs mass is a prediction in a supersymmetric theory ⇒ theoretical constraints

THE HIGGS MASS

- The Higgs mass is a prediction in the MSSM
    - At the tree level there is the absolute bound

$$m_h^2 \leq M_Z^2$$

- At one-loop there is an important contribution controlled by the top/stop sector

One-loop

$$\Delta m_h^2 = \frac{3 G_F m_t^4}{\sqrt{2}\pi^2}\left[\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$X_t = A_t - \mu/\tan\beta$$

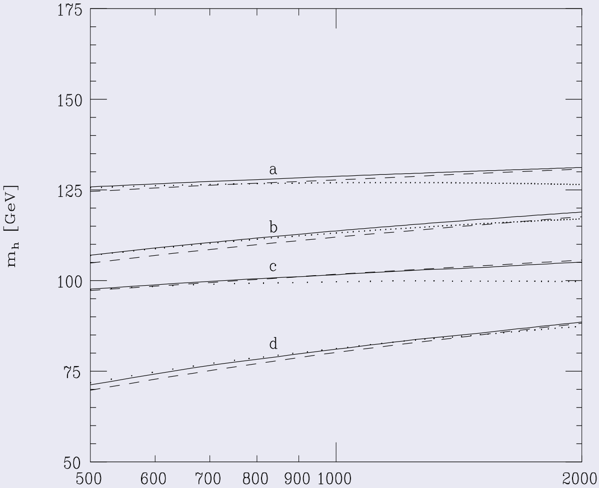
- Even if the one-loop contribution can be larger than the tree-level perturbation theory holds

Little fine-tuning problem

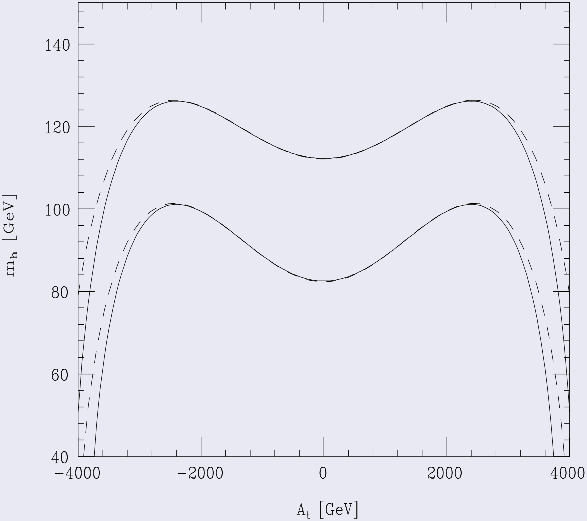
To satisfy the experimental bound on the Higgs mass a stop around the TeV scale is needed which produces a $\sim 1\%$ fine-tuning in the determination of the Z-mass

PRE-LHC PLOTS

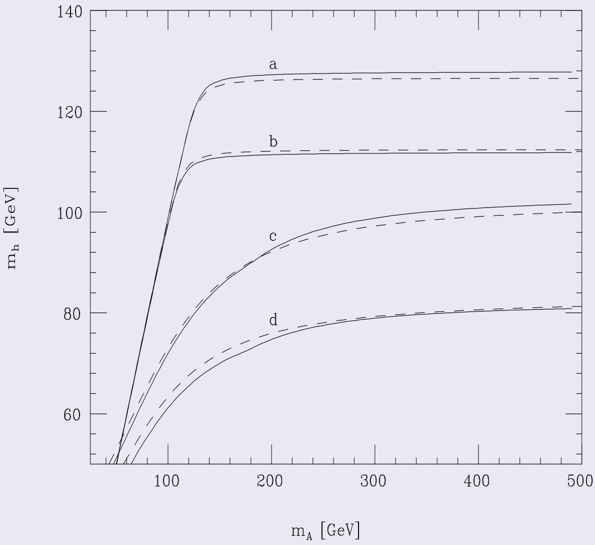
m_h Vs. M_{SUSY} [$m_A \sim 1$ TeV, (a,b) $\tan\beta = 15$ $A_t/M_{SUSY} = (\sqrt{6}, 0)$; (c,d) $\tan\beta = 2$]



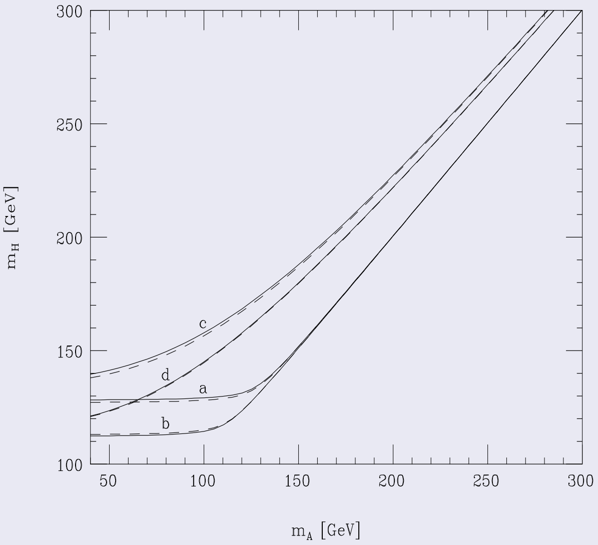
m_h Vs. A_t $[M_{SUSY}, m_A \sim 1$ TeV, $\tan\beta = 15, 2]$



m_h Vs. m_A $[M_{SUSY} \sim 1$ TeV$]$



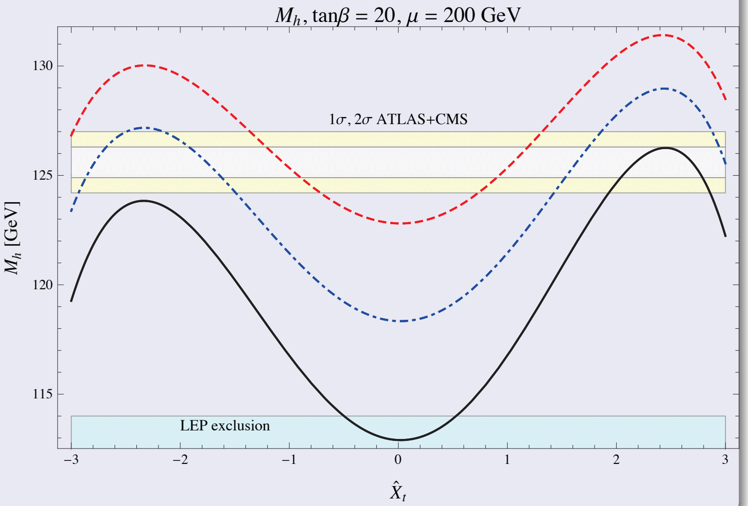
m_H Vs. m_A $[M_{SUSY} \sim 1$ TeV$]$



POST-LHC PLOTS

Some recent results [1]

$M_{SUSY} = 1, 2, 4$ TeV, $\hat{X}_t = X_t / M_{SUSY}$



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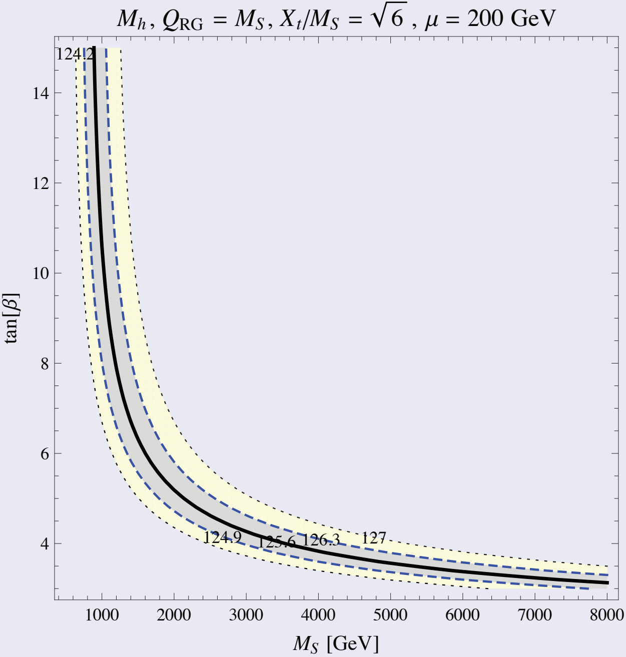
[1] P. Draper, G. Lee and C. E. M. Wagner, arXiv:1312.5743 [hep-ph]


M_h, $Q_{RG} = M_S$, $X_t/M_S = \sqrt{6}$, $\mu = 200$ GeV
tan[β]
M_S [GeV]
124.2
124.9
125.6
126.3
127
14
12
10
8
6
4
1000
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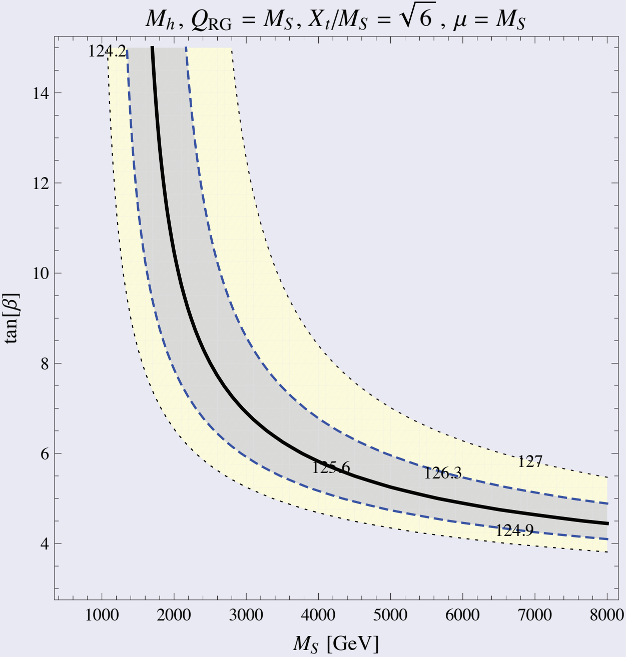
4000
5000
6000
7000
8000


$M_h, Q_{\rm RG} = M_S, X_t/M_S = \sqrt{6}, \mu = M_S$
124.2
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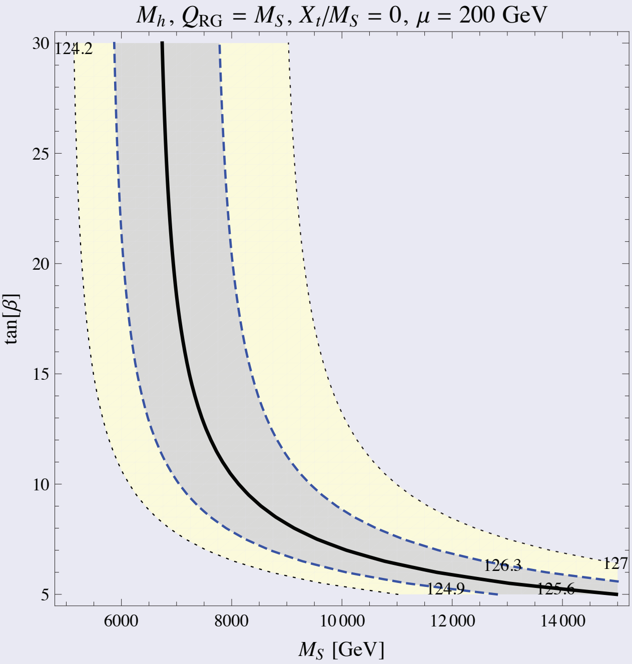
M_S [GeV]


M_h, $Q_{\rm RG} = M_S$, $X_t/M_S = 0$, $\mu = 200$ GeV
tan[β]
M_S [GeV]
30
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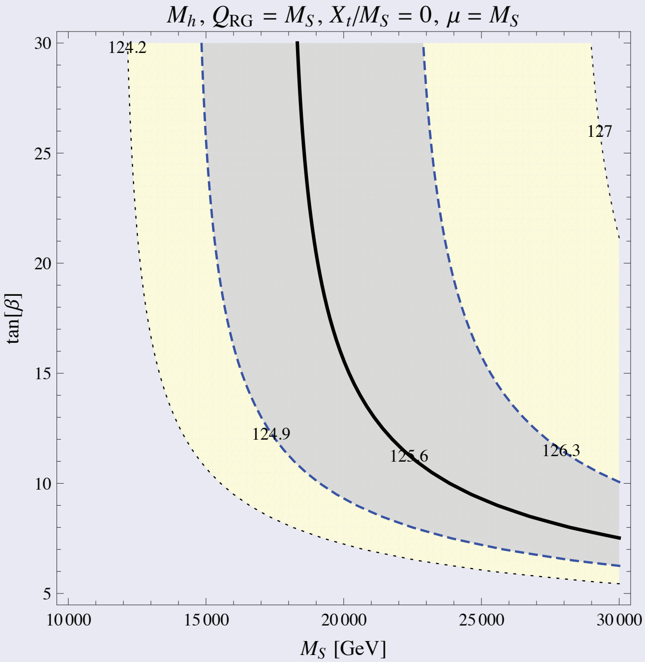


M_h, $Q_{\rm RG} = M_S$, $X_t/M_S = 0$, $\mu = M_S$

Drawbacks of the MSSM

- Little fine tuning: $\sim 1\%$ fine-tuning
- Large number ($\sim 10^2$) of free parameters
- Uncertainty in the mechanism of supersymmetry breaking:
  - Gravity mediation:
    - Universal mechanism solving the $\mu/B\mu$ problem
    - Its minimal version reduces the number of free parameters to a few
    - So-called Supergravity models
  - Gauge mediation
    - It is flavor blind
    - It has a $\mu/B\mu$ problem
    - Gravitino is the LSP
  - Anomaly mediation
    - Tachyonic sleptons
- Supersymmetric flavor problem: supersymmetric partners can create FCNC and CP violating operators
- Gravity mediation has to be subdominant ($\sim 0.1\%$ of gauge mediation)

LITTLE HIGGS

- Little Higgs models aim to solve the Little Hierarchy problem (say between EW scale and 10 TeV)
- The symmetry that protects the (little) hierarchy is a global symmetry of which the Higgs is an approximate (pseudo) Goldstone boson
- It is inspired from low energy hadronic physics: there $\pi^{\pm 0}$ are Goldstone bosons associated to the spontaneous breaking $SU(2)_L \times SU(2)_R \to SU(2)_I$
- Similarly the Higgs is the Goldstone boson of a global symmetry $G_0 \to H_0$. It is in the coset space $H \in G_0/H_0$
- The symmetry $H \to H + c$ is broken (in particular) by Yukawa interactions

$$\Rightarrow m_H^2 \sim \frac{\alpha_t}{4\pi}\Lambda^2 \Leftrightarrow LEP\ paradox$$

- LH is a clever construction to avoid the appearance of the lowest order contribution to m_H^2

Collective breaking

- The mass of a Higgs pseudo-Goldstone boson from the different couplings α_i that break the Goldstone symmetry is

$$m_H^2 = \left(c_i \frac{\alpha_i}{4\pi} + c_{ij} \frac{\alpha_i \alpha_j}{(4\pi)^2} \right) \Lambda^2$$

where the coefficients are controlled by selection rules

- If the Goldstone symmetry is restored when any single coupling $\alpha_i = 0$
$\Rightarrow$ To totally destroy the Goldstone symmetry one requires the combined effect [collective breaking] of at least two non-zero couplings

$$\Rightarrow m_H^2 \sim \left(\frac{\alpha}{4\pi} \right)^2 \Lambda^2 \Rightarrow \Lambda \sim 10 \; TeV$$

- This is a solution to the LEP paradox/Little Hierarchy problem

General structure

- There is a global group G_g which spontaneously breaks to a subgroup H_g at a scale $f \sim 1$ TeV and the theory becomes strong at the scale $\Lambda \sim 4\pi f \sim 10$ TeV [Scales are similar to Λ_{QCD} and f_π in QCD]
- The subgroup $G_l \subset G_g$ is gauged: $G_l \supset SU(2) \times U(1)$
- The combination of spontaneous and collective breaking makes: $G_l \to SU(2) \times U(1)$ leaving heavy vector bosons and fermions with masses

$$M_{Heavy} \sim g\, f \sim 1\ TeV$$

- Higgs is part of the Goldstone multiplet which parametrizes the coset space G_g/H_g

Model	G_g	H_g
Littlest	$SU(5)$	$SO(5)$
Simplest	$SU(3)^2$	$SU(2)^2$

General structure

- The generators of G_l do not commute with the generators of the Higgs and thus gauge and Yukawa couplings collectively break the Goldstone symmetry and induce a Higgs mass
- The global invariance of the SM must be extended according to the different models (Littlest, Simplest,...)
- There are *same spin partners* for every SM field.
- When computing corrections to the Higgs mass these partners enforce the selection rule $c_i = 0$ by cancelling the one-loop quadratic divergent contributions of the Higgs field
- For instance if $SU(3) \subset G_g$
  - The quarks appear in triplets or singlets

$$\begin{pmatrix} t \\ b \\ T \end{pmatrix}_L, t_R, b_R, T_R$$

  - The Higgs boson arises as a pseudo-Goldstone boson from the spontaneous breaking $SU(3) \to SU(2) \times U(1)$

General structure

- The gauge structure is also enlarged

Model	G_g	H_g	G_l
Littlest	$SU(5)$	$SO(5)$	$[SU(2)\times U(1)]^2$
Simplest	$SU(3)^2$	$SU(2)^2$	$SU(3)\times U(1)$

- Littlest:
  - $SU(5)\to SO(5)$: 24-10=14 Goldstone bosons
  - 4 absorbed by the broken gauge group
  - 10 Goldstone bosons= 4 (Higgs doublet)+6 (Higgs triplet)
- The one-loop quadratic divergence from the top quark

$$\Delta M_H^2 \sim -\frac{\alpha_t}{4\pi}\Lambda^2$$

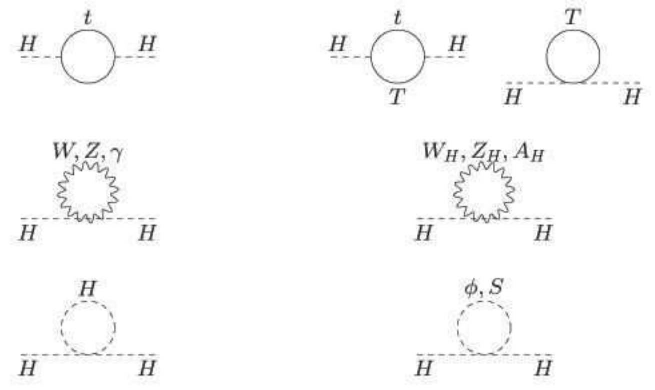
is cancelled by that from the T quark

- The one-loop quadratic divergence from the W gauge boson

$$\Delta M_H^2 \sim \frac{\alpha_W}{4\pi}\Lambda^2$$

is cancelled by that from the W_H gauge boson

Cancellation of quadratic divergences



Electroweak breaking

It is triggered by the $t - T$ sector analogously to the MSSM

$$\Delta m_H^2 = -\frac{3}{8\pi^2} h_t^2 m_T^2 \log \frac{\Lambda}{m_T}$$

Since $\Delta m_H^2 \sim m_T^2$ electroweak breaking requires some tuning of at least 5% as in the MSSM

Dark Matter

In the Littlest LH models one can introduce a T-parity such that SM particles (extra particles) are T-even (T-odd). In this case the lightest T-odd gauge bososon is a candidate to DM

Electroweak precision tests

T-parity forbids the mixing between T-odd and T-even gauge bosons leading naturally to $S = 0$

GAUGE HIGGS UNIFICATION

- We have explored two symmetries protecting the Higgs from quadratic divergences: supersymmetry and a global symmetry
- In higher dimensional theories there is another symmetry which could do the job: a gauge symmetry
- The gauge bosons of a higher dimensional gauge symmetry decompose as

Lorentz Decomposition

$$A_M^A = A_\mu^A,\ A_i^A\ [\mu = 0, \ldots, 3, i = 1, \ldots, d]$$

- A_μ^A are gauge bosons in four dimensions
- A_i^A are scalar in the adjoint representation

Orbifold constructions

We need to compactify extra dimensions in an orbifold:
e.g. for $d = 1$ (A_μ, A_5)

$$S^1/\mathbb{Z}_2$$

- The orbifold group has to act non trivially on the group generators such that:

Orbifold Decomposition

$$A_\mu^A = A_\mu^a(even),\ \ A_\mu^{\hat{a}}(odd)$$
$$A_5^A = A_5^a(odd),\ \ A_5^{\hat{a}}(even)$$

- Only even fields have zero modes $\phi_{even}^{(n)}, n = 0, 1, 2, \dots$ while odd field have only non zero modes $\phi_{odd}^{(n)}, n = 1, 2, \dots$
- The Higgs mechanism acts for all modes as

Higgs mechanism

$$(A_\mu^{\hat{a}}\ massless + A_5^{\hat{a}})^{(n\neq 0)} = A_\mu^{\hat{a}\,(n\neq 0)} massive$$
$$(A_\mu^{a}\ massless + A_5^{a})^{(n\neq 0)} = A_\mu^{a\,(n\neq 0)} massive$$

- The massless states are the zero modes

Massless states

$$A_\mu^{a\,(n=0)},\ \ A_5^{\hat{a}\,(n=0)}$$

HOW TO GET A DOUBLET FROM AN ADJOINT

- To get a doublet out of an adjoint one has to make a careful orbifold breaking
- One has to enlarge the gauge group since the

SM Higgs is NOT in the adjoint representation of $SU(2) \times U(1)$

- For instance

$SU(3) \rightarrow SU(2) \times U(1)$

Achieved by the orbifold action
$A_\mu(-y) = UA_\mu(y)U^\dagger, \; A_5(-y) = -UA_5(y)U^\dagger$ with

$$diag(-1, -1, +1)$$

which breaks $SU(3)$ into $SU(2) \times U(1)$

- The Higgs mass is protected from quadratic divergences in the bulk by the 5D gauge symmetry

- The orbifold has two fixed points at $y = 0, \pi R$ which are singular and four-dimensional
- The Higgs mass is protected from quadratic divergences at the fixed points by the shift symmetry (inherited from the five-dimensional gauge invariance) $\delta A_5 = \partial_y A_5$

How to get the gauge bosons

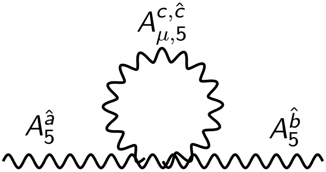
$$\begin{pmatrix} A^3_\mu + A^8_\mu/\sqrt{3} & A^2_\mu - iA^2_\mu & A^4_\mu - iA^5_\mu \\ A^1_\mu + iA^2_\mu & -A^3_\mu + A^8_\mu/\sqrt{3} & A^6_\mu - iA^6_\mu \\ A^4_\mu + iA^5_\mu & A^6_\mu + iA^7_\mu & -2A^8_\mu/\sqrt{3} \end{pmatrix}$$

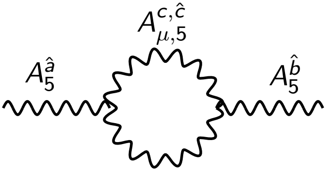
How to get the Higgs bosons

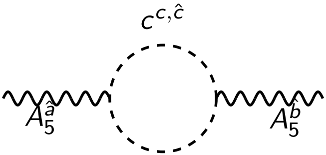
$$\begin{pmatrix} A^3_5 + A^8_5/\sqrt{3} & A^2_5 - iA^2_5 & A^4_5 - iA^5_5 \\ A^1_5 + iA^2_5 & -A^3_5 + A^8_5/\sqrt{3} & A^6_5 - iA^6_5 \\ A^4_5 + iA^5_5 & A^6_5 + iA^7_5 & -2A^8_5/\sqrt{3} \end{pmatrix}$$

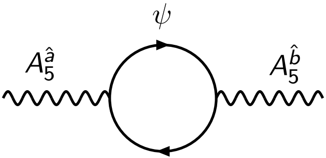
- Since the space is compactified there can be finite contributions to the $A_5^{\hat{a}}$ mass proportional to $1/R$

The diagrams contributing to the mass of $A_5^{\hat{a}}$ are









$$m_{\hat{a}}^2 = \frac{3g^2}{32\pi^4 R^2}\zeta(3)\left[3C_2(\mathcal{G}) - 4T(R)N_f\right]$$

There is a number of difficulties with this (otherwise very nice) scenario

Drawbacks

- In more than five dimensions a (quadratically divergent) tadpole localized at the fixed points F_{ij} is generated by radiative corrections while the quartic Higgs coupling is sizeable and generated by the term F_{ij}^2 in the bulk
- In five dimensions there is no localized tadpole but there is neither a tree-level quartic coupling which means difficulties with *too small a Higgs mass*
- It is difficult to have a theory with the correct prediction for the weak angle [extra $U(1)'s$ are usually required]
- Fermion masses are difficult to accomodate since they come from gauge couplings: in particular the top quark use to be too light
- The compactification scale is usually too small in conflict with EWPT
- The theory has a very low cutoff after which it becomes non-perturbative

WARPED MODELS

Some of these difficulties can be alleviated by embedding GHU in a warped (Randall-Sundrum) 5D space time

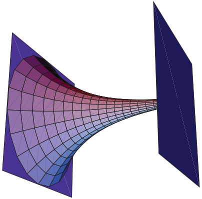
Ways out

- Warped models are valid up to scales of order M_{GUT} or M_{Planck} and they can unify
- The Higgs is holographic, i.e. it is localized towards the IR brane [at higher scales it is composite]
- Fermion masses can be implemented by means of their localization, i.e. five-dimensional masses
- The top quark (to get a big mass) is localized as the Higgs. So it is also holographic
- EWPT as well as corrections to the $Zb\bar{b}$ vertex lead to KK-masses in the $2.5-4$ TeV, which imply $\sim 1\%$ fine-tuning for the Higgs mass (similar to the MSSM)
- These models are the modern version of technicolor theories: they make use of the AdS/CFT correspondence for calculability

RANDALL-SUNDRUM MODEL: ADS_5

- The original AdS/CFT correspondence relates 5D theories of gravity in AdS to 4D strongly-coupled conformal field theories
- In the case of a slice of AdS a similar correspondence can also be formulated

- Boundary at $y = 0$ corresponds to UV cutoff in the 4D CFT
- $y = y_1$ corresponds to IR cutoff
- Matter at UV is elementary: e.g. light fermions
- Matter at IR is composite: e.g. KK modes, heavy fermions,...



$y = 0$ $y = y_1$

Although the CFT picture is useful for understanding some qualitative aspects of the theory it is useless for obtaining quantitative predictions since the theory is strongly coupled

- An AdS 5D theory with two branes was proposed [2]

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad A(y) = ky$$

- To solve the hierarchy problem the Higgs should be
    - Localized on the IR brane (composite): theory is EWPT disfavored, or
    - Propagating in the bulk but with a profile along the extra dimensions leaning towards the IR brane (a degree of compositeness)

$$h(y) = h(0)e^{aky}, a > 2 \text{ (to solve hierarchy problem)}$$

- The hierarchy problem is solved because the Planckian Higgs mass is warped down to the weak scale by the geometry or in the dual picture because the conformal operator breaking EW has dimension > 2
- To "solve" the flavour problem fermions should propagate in the bulk and with different localizations
- Fermion localization is controlled by Dirac mass $c_f A'(y)$

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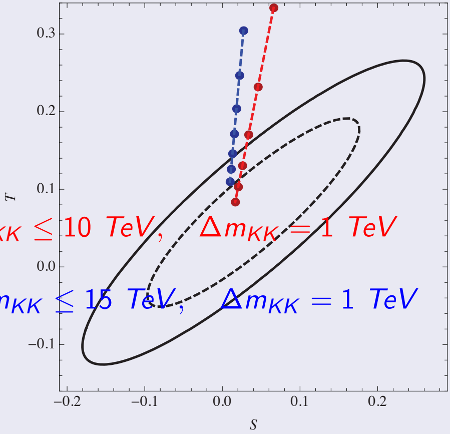
[2] L. Randall and R. Sundrum, hep-ph/9905221

Electroweak data impose very strong constraints

$m_{KK} \gtrsim 10$ TeV



$a = 2, \quad m_{KK} \leq 10 \;\; TeV, \quad \Delta m_{KK} = 1 \;\; TeV$

$a \to \infty, \quad m_{KK} \leq 15 \;\; TeV, \quad \Delta m_{KK} = 1 \;\; TeV$

SOFT-WALLS METRICS: AADS$_5$

- The RS model has to be modified to avoid the large corrections to EW observables.
- It can be done by deforming the AdS metric in the IR [3]
- A particularly simple model for the metric has been used as

IR deformed model

$$A(y) = ky - \frac{1}{\nu^2}\log\left(1-\frac{y}{y_s}\right)$$

$$\phi(y) = -\frac{\sqrt{6}}{\nu}\log[\nu^2 k(y_s - y)]$$

- A UV brane at $y = 0$ and a IR brane at $y_1 = y_s - \Delta$ with $k\Delta \ll ky_s$

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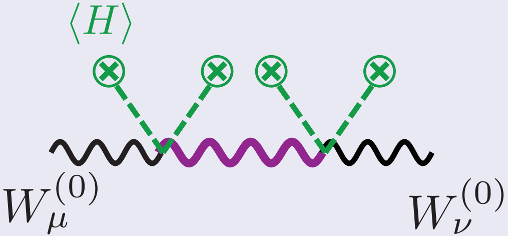
[3] J. A. Cabrer, G. von Gersdorff, MQ, arXiv:1011.2205 [hep-ph], arXiv:1103.1388 [hep-ph]

OBLIQUE PARAMETERS

- The main problem with RS is a large tree-level contribution to the T-parameter from KK modes

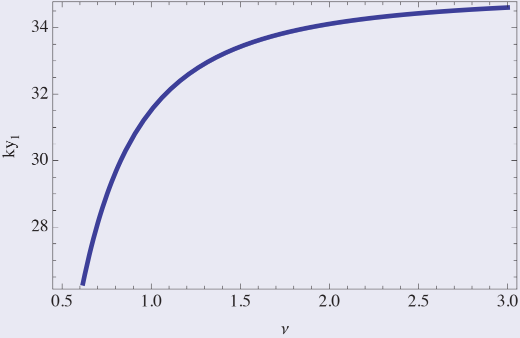
Diagram contributing to T



- There are two main facts by which the proximity of the singularity improves the behaviour of the T parameter

- One is the lowering of the compactification volume ky_1

$k\Delta = 1$ and $A(y_1) = 35$

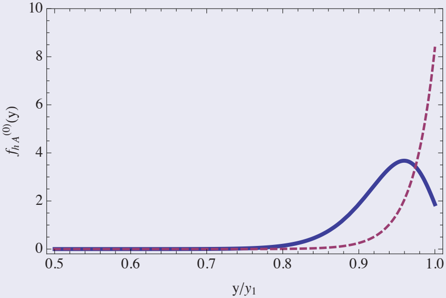


- As the T parameter is enhanced by ky_1

- Another reason is that the physical Higgs profile

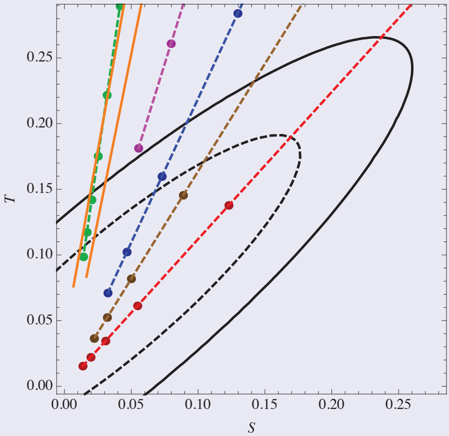
$$f_{hA}^{(0)} = N_0 e^{-A(y)} h(y) \to 0 \text{ when } y \to y_s, \quad h(y) \propto e^{kay}$$

Higgs profiles in RS a=2 (dashed) and SW a=3.1 (solid)



- So the overlapping with KK modes is smaller than in RS models

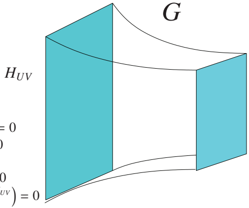
SW: $a = 3.1$, $m_{KK} \leq 3$ TeV, $\Delta m_{KK} = 0.5$ TeV



$\nu = 0.5, 0.525, 0.55, 0.6$;
$\nu = 5, m_{KK} \leq 12\,\mathrm{TeV}, \Delta m_{KK} = 1$ TeV

CUSTODIAL MODELS

- Another solution to the large T problem in RS is introducing a gauge custodial symmetry in the bulk to protect the T parameter
- The gauge symmetry G can protect the mass of extra dimensional components of gauge bosons
- A_μ^A (A_5^A) are gauge bosons (scalars) in four dimensions
- G is broken by boundary conditions to H_{UV} (H_{IR}) on the UV (IR) brane



$$H_{UV}:\begin{cases}A_\mu\,(+)\ \text{ i.e. }\ \partial_5 A_\mu^{H_{UV}}=0\\ A_5\,(-)\ \text{ i.e. }\ A_5^{H_{UV}}=0\end{cases}$$

$$G/H_{UV}:\begin{cases}A_\mu\,(-)\ \text{ i.e. }\ A_\mu^{G/H_{UV}}=0\\ A_5\,(+)\ \text{ i.e. }\ \partial_5\left(\frac{R}{z}A_5^{G/H_{UV}}\right)=0\end{cases}$$

$$H_{IR}:\begin{cases}A_\mu\,(+)\ \text{ i.e. }\ \partial_5 A_\mu^{H_{IR}}=0\\ A_5\,(-)\ \text{ i.e. }\ A_5^{H_{IR}}=0\end{cases}$$

$$G/H_{IR}:\begin{cases}A_\mu\,(-)\ \text{ i.e. }\ A_\mu^{G/H_{IR}}=0\\ A_5\,(+)\ \text{ i.e. }\ \partial_5\left(\frac{R}{z}A_5^{G/H_{IR}}\right)=0\end{cases}$$

- For $\mathcal{H}_{UV} = SU(2)_L \otimes U(1)_Y$ the number of PGB is $dim(G/\mathcal{H}_{IR})$
- Different models differ so by G and $\mathcal{H}_{IR}$ [4]

Model	# Goldstones ($A_5^{\hat{a}}$)
SO(4)/SO(3)	6-3=3 (Higgsless SM)
SU(3)/SU(2)×U(1)	8-4=4(H_{SM})
SO(5)/SO(4)	10-6=4 (H_{SM})
SO(6)/SO(5)	15-10=5 (H_{SM} + singlet)
SO(6)/SO(4)×SO(2)	15-6-1=8 (H_u, H_d)

- Some of the models contain the custodial group $SO(4)$ on the IR brane and so contribution to T parameter protected
- In the dual theory $G/\mathcal{H}_{IR}$ is characterized by the scale f

The expansion parameter in the theory

$$\xi = \left(\frac{v}{f}\right)^2$$

$$h^2_{WWH} = h^2_{WWH,SM}\left[1 - \xi\right]$$

- $\xi \to 0 \Rightarrow$ SM limit
- $\xi \to 1 \Rightarrow$ Technicolor limit

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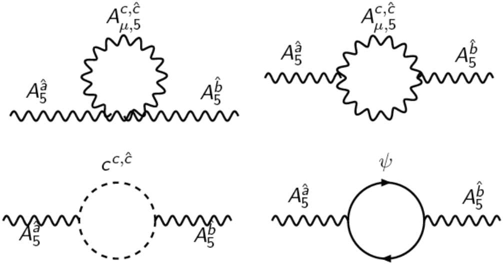
[4] R. Contino et al., hep-ph/0306259 and hep-ph/0612048; K. Agashe et al.,

$SU(2)_L \otimes U(1)$ breaking is radiative



One can consider an effective theory [a] parametrized by ξ which measures the degree of compositeness of the Higgs

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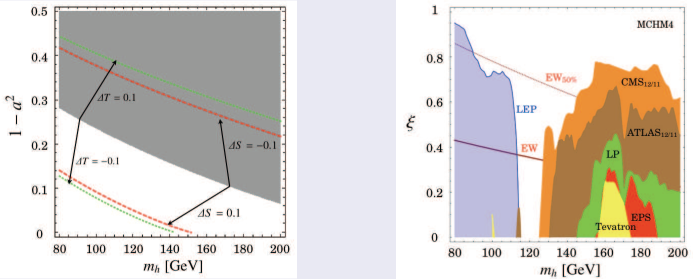
[a] J. R. Espinosa et al., arXiv:1003.3251 [hep-ph]

- All Higgs couplings depart from the SM values by quantities proportional to ξ
- Unitarity must be restored by new (TeV) resonances at scales which depend on ξ
- Models have been confronted to EWPT and direct searches [5]



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[5] J. R. Espinosa et al., arXiv:1202.1286 [hep-ph]

CONCLUSIONS

- The last word will be from LHC
- One possibility is that the theory below M_{Planck} is just the Standard Model: in that case we should try to find other solutions to the hierarchy problem, as e.g. an anthropic solution/landscape
- If New Physics is found at LHC it should possibly provide a (partial) solution to the "experimental" SM problems (DM, strong CP problem, baryogenesis,...) and/or the "theoretical" problems (hierarchy problem, vacuum instability/metastability/stability, flavour structure, neutrino patterns,...)
- Hopefully New Physics will interfere with the mechanism of electroweak breaking and should leave an "imprint" in Higgs observables.
- As for Higgs precision physics we will (probably) need a high-energy linear or circular collider