Islamabad, March '04

Electroweak Interactions in the SM and Beyond

G. Altarelli
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A short course on the EW Theory

We start from the basic principles and formalism (a fast recall).
Then we go to present status and challenges

Content

- Formalism of gauge theories
- The SU(2)xU(1) symmetric lagrangian
- The symmetry breaking sector
- Beyond tree level
- Precision tests
- Problems of the SM
- Beyond the SM

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The Standard Model works very well

So, why not find the Higgs and declare particle physics solved?

First, you have to find it! ⇒ LHC

Because of both:

Conceptual problems

- Quantum gravity
- The hierarchy problem
- •••••

and experimental clues:

- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy
- •••••

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Conceptual problems of the SM

Most clearly:

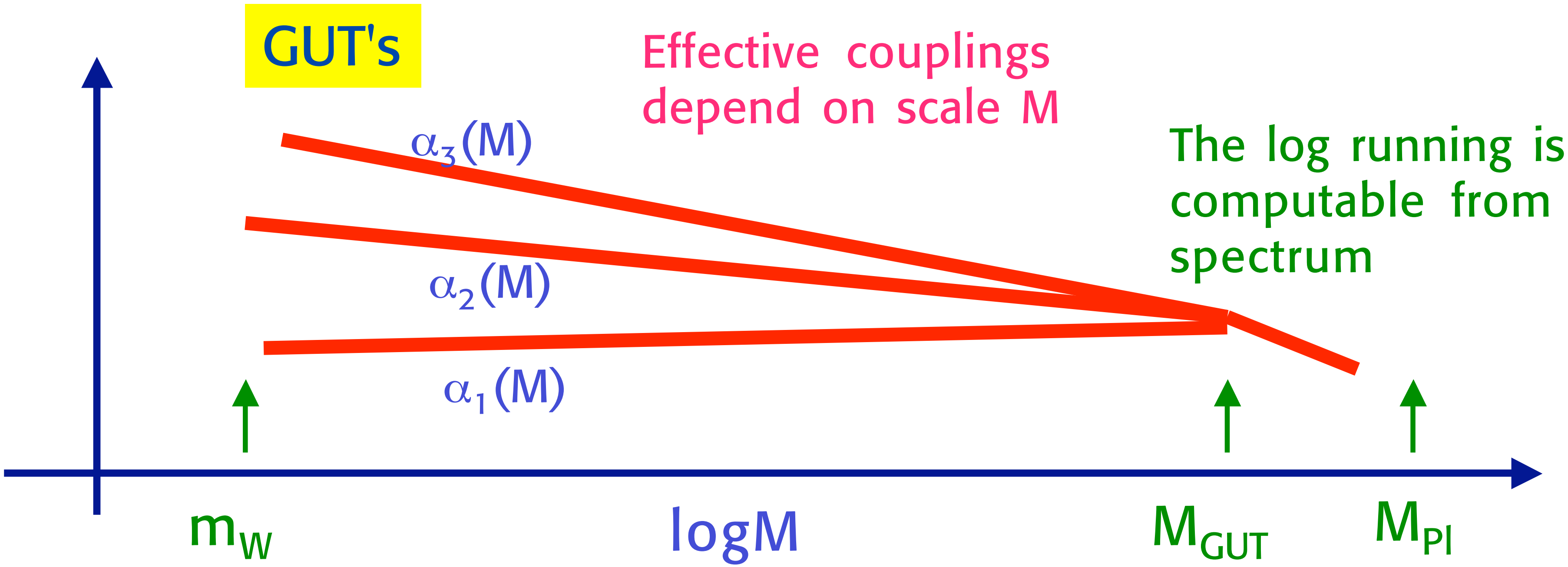
- No quantum gravity ($M_{Pl} \sim 10^{19}$ GeV)
- But a direct extrapolation of the SM leads directly to GUT's ($M_{GUT} \sim 10^{16}$ GeV)

M_{GUT} close to M_{Pl}

- suggests unification with gravity as in superstring theories
- poses the problem of the relation m_W vs M_{GUT} - M_{Pl}

Can the SM be valid up to M_{GUT} - M_{Pl}?? ← The hierarchy problem

Not only it looks very unlikely, but the new physics must be near the weak scale!



The large scale structure of particle physics:

- SU(3) ⊗ SU(2) ⊗ U(1) unify at M_{GUT}
- at M_{Pl}: quantum gravity

$$G_{Newton} = \frac{\hbar c}{M_{Pl}^2}$$

r ~ 10^{-33} cm

Superstring theory:
a 10-dimensional non-local, unified theory of all interact's

The really fundamental level

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By now GUT's are part of our culture in particle physics

- Unity of forces: $G \supset SU(3) \otimes SU(2) \otimes U(1)$

  unification of couplings
- Unity of quarks and leptons

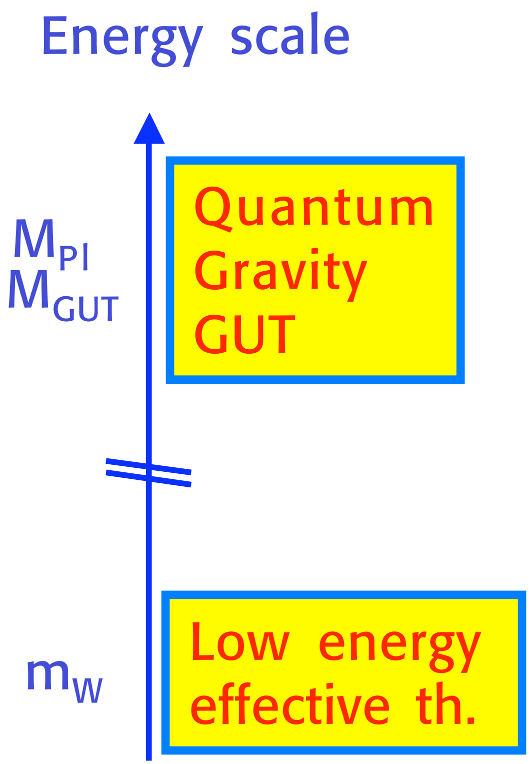
  different "directions" in G
- B and L non conservation

  ->p-decay, baryogenesis, ν masses
- Family Q-numbers

  e.g. in SO(10) a whole family in 16
- Charge quantisation: Q_d= -1/3-> -1/N_{colour}

• • • • •

Most of us believe that Grand Unification must be a feature of the final theory!



The hierarchy problem

Assume:

- A TOE at $\Lambda \sim M_{GUT} \sim M_{Pl}$
- A low en. th at o(TeV)
- A "desert" in between

The low en. th must be renormalisable as a necessary condition for insensitivity to physics at Λ.

[the cutoff can be seen as a parametrisation of our ignorance of physics at Λ]

But, as Λ is so large, in addition the dep. of ren. masses and couplings on Λ must be reasonable:

e.g. a mass of order m_W cannot be linear in Λ if $\Lambda \sim M_{GUT}, M_{Pl}$.

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With new physics at Λ the low en. th is only an effective theory. After integration of the heavy d.o.f.:

$\mathcal{L}_i$: operator of dim i

$$\mathcal{L} = o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4 + \; + o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \ldots$$

Renorm.ble part — Non renorm.ble part

In absence of special symmetries or selection rules, by dimensions $c_i\mathcal{L}_i \sim o(\Lambda^{4-i})\mathcal{L}_i$

$\mathcal{L}_2$: Boson masses ϕ^2. In the SM the mass in the Higgs potential is unprotected: $c_2 \sim o(\Lambda^2)$

$\mathcal{L}_3$: Fermion masses $\bar{\psi}\psi$. Protected by chiral symmetry and SU(2)xU(1): $\Lambda \to m\log\Lambda$

$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

$\mathcal{L}_{i>4}$: Non renorm.ble: suppressed by $1/\Lambda^{i-4}$ e.g. $1/\Lambda^2\bar{\psi}\gamma^\mu\psi\bar{\psi}\gamma^\mu\psi$

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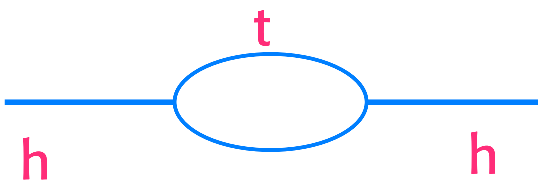
For the low energy theory: the "little hierarchy" problem:

e.g. the top loop (the most pressing): $m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim (0.3\Lambda)^2$$

This hierarchy problem demands new physics near the weak scale

$\Lambda \sim o(1\text{TeV})$

Λ: scale of new physics beyond the SM

- $\Lambda >> m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of m_h or m_W

Barbieri, Strumia

The LEP Paradox: m_h light, new physics must be so close but its effects are not directly visible

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Examples:

SUSY

- Supersymmetry: boson-fermion symm.
  exact (unrealistic): cancellation of $\delta\mu^2$
  approximate (possible): $\Lambda \sim m_{SUSY}-m_{ord}$

The most widely accepted

- The Higgs is a $\bar{\psi}\psi$ condensate. No fund. scalars. But needs new very strong binding force: $\Lambda_{new} \sim 10^3 \Lambda_{QCD}$ (technicolor).

Strongly disfavoured by LEP

- Large extra spacetime dimensions that bring M_{Pl} down to o(1TeV)

Elegant and exciting. Rich potentiality. Does it work?

- Models where extra symmetries allow m_h only at 2 loops and non pert. regime starts at $\Lambda \sim 10$ TeV

"Little Higgs" models. Does it work?

SUSY at the Fermi scale

- Many theorists consider SUSY as established at M_{Pl} (superstring theory).
- Why not try to use it also at low energy to fix some important SM problems.
- Possible viable models exists:
  - MSSM softly broken with gravity mediation
    - or with gauge messengers
    - or with anomaly mediation
    - •••
- Maximally rewarding for theorists
  - Degrees of freedom identified
  - Hamiltonian specified
  - Theory formulated, finite and computable up to M_{Pl}

Unique!

Fully compatible with, actually supported by GUT's

SUSY fits with GUT's

From $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ measured at LEP predict $\alpha_s(m_Z)$ for unification (assuming desert)

EXP: $\alpha_s(m_Z)=0.119\pm0.003$
Present world average

- Coupling unification: Precise matching of gauge couplings at M_{GUT} fails in SM and is well compatible in SUSY

Non SUSY GUT's
$\alpha_s(m_Z)=0.073\pm0.002$

SUSY GUT's
$\alpha_s(m_Z)=0.130\pm0.010$

Langacker, Polonski

Dominant error: thresholds near M_{GUT}

- Proton decay: Far too fast without SUSY
- $M_{GUT} \sim 10^{15}$GeV non SUSY ->10^{16}GeV SUSY
- Dominant decay: Higgsino exchange

While GUT's and SUSY very well match, (best phenomenological hint for SUSY!) in technicolor , large extra dimensions, little higgs etc., there is no ground for GUT's

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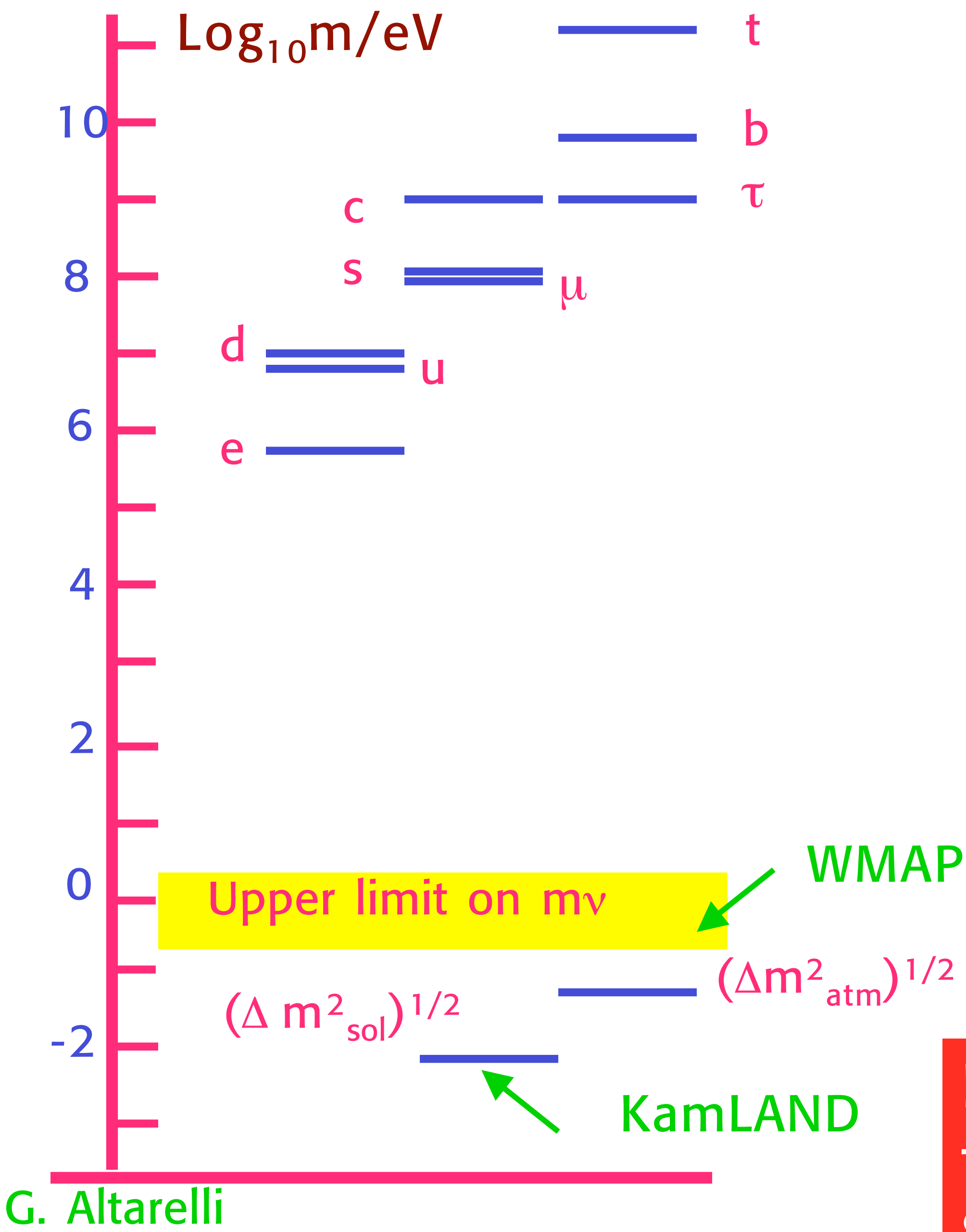
Neutrino masses point to M_{GUT}, well fit into the SUSY picture and in GUT's and have added considerable support to this idea.



Neutrino masses are really special!

$m_t/(\Delta m^2_{atm})^{1/2} \sim 10^{12}$

Massless ν's?

- no ν_R
- L conserved

Small ν masses?

- ν_R very heavy
- L not conserved

Neutrino masses point to M_{GUT}, well fit into the SUSY picture and in GUT's

A very natural and appealing explanation:

ν's are nearly massless because they are Majorana particles and get masses through L non conserving interactions suppressed by a large scale M ~ M_{GUT}

$$m_\nu \sim \frac{m^2}{M}$$

m m_t ~ v ~ 200 GeV

M: scale of L non cons.

Note:

$m_\nu \sim (\Delta m^2_{atm})^{1/2} \sim 0.05$ eV

m ~ v ~ 200 GeV

M ~ 10^{15} GeV

Neutrino masses are a probe of physics at M_{GUT} !

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Baryogenesis

$n_B/n_\gamma \sim 10^{-10}$, $n_B << n_{\bar{B}}$

Conditions for baryogenesis: (Sacharov '67)

- B non conservation (obvious) —
- C, CP non conserv'n (B-B odd under C, CP)
- No thermal equilib'm (n=exp[μ-E/kT]; $\mu_B = \mu_{\bar{B}}$, $m_B = m_{\bar{B}}$ by CPT

If several phases of BG exist at different scales the asymm. created by one out-of-equilib'm phase could be erased in later equilib'm phases: BG at lowest scale best

Possible epochs and mechanisms for BG:

- At the weak scale in the SM Excluded
- At the weak scale in the MSSM Disfavoured
- Near the GUT scale via Leptogenesis

Very attractive

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Possible epochs for baryogenesis

- BG at the weak scale: T_{EW} ~ 0.1- 10 TeV

Rubakov, Shaposhnikov; Cohen, Kaplan, Nelson; Quiros....

In SM:

- B non cons. by instantons ('t Hooft)
(non pert.; negligible at T=0 but large at $T=T_{EW}$
B-L conserved!

- CP violation by CKM phase. Enough??
By general consensus far too small.

- Out of equilibrium during the EW phase trans.
Needs strong 1st order phase trans. (bubbles)
Only possible for m_H<~80 GeV
Now excluded by LEP

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Is BG at the weak scale possible in MSSM?

- Additional sources of CP violation

Sofar no signal at beauty factories

- Constraint on m_H modified by presence of extra scalars with strong couplings to Higgs sector (e.g. s-top)

- Requires:
m_h<80-100 GeV; $m_{s\text{-}topl}$<m_t; tgβ~1.2-5 preferred

Espinosa, Quiros, Zwirner; Giudice; Myint; Carena, Quiros, Wagner; Laine; Cline, Kainulainen; Farrar, Losada…..

Disfavoured by LEP

Baryogenesis A most attractive possibility:

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm3}$ GeV (after inflation)

Buchmuller,Yanagida, Plumacher, Ellis, Lola, Giudice et al, Fujii et al …..

Only survives if Δ(B-L) 0
(otherwise is washed out at T_{ew} by instantons)

Main candidate: decay of lightest ν_R ($M \sim 10^{12}$ GeV)

L non conserv. in ν_R out-of-equilibrium decay:
B-L excess survives at T_{ew} and gives the obs. B asymmetry.

Quantitative studies confirm that the range of m_i from ν oscill's is compatible with BG via (thermal) LG

In particular the bound was derived

$m_i < 10^{-1}$ eV

Close to WMAP

Buchmuller, Di Bari, Plumacher

Dark Matter

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.04$, $\Omega_m \sim 0.3$

Most is non baryonic dark matter and dark energy

Cold

Non relativistic at freeze out

Good clustering at small distances (galaxies, …)

SUSY:

Neutralino: Good candidate

Axions not excluded

Hot

Relativistic at freeze out → Could be ν's

But: $\Omega_\nu < 0.015$ (WMAP)

Relevant for large scale mass distrib'ns

Conclusion:

Most Dark Matter is Cold (Neutralinos, Axions…)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant.

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65$ → $\rho_\Lambda \sim (2\ 10^{-3}\ \text{eV})^4 \sim (0.1\text{mm})^{-4}$ → Similar to m_ν!?

In Quantum Field Theory: $\rho_\Lambda \sim (\Lambda_{cutoff})^4$

If $\Lambda_{cutoff} \sim M_{Pl}$ → $\rho_\Lambda \sim 10^{123}\ \rho_{obs}$

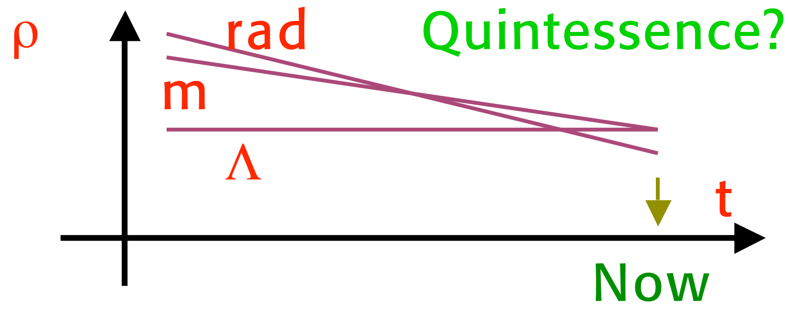
Exact SUSY would solve the problem: $\rho_\Lambda = 0$

But SUSY is broken: $\rho_\Lambda \sim (\Lambda_{SUSY})^4 < 10^{59}\ \rho_{obs}$

It is interesting that the correct order is $(\rho_\Lambda)^{1/4} \sim (\Lambda_{EW})^2/M_{Pl}$

So far no solution:
- A modification of gravity at 0.1mm?(large extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- ...

Other problem:
Why now?



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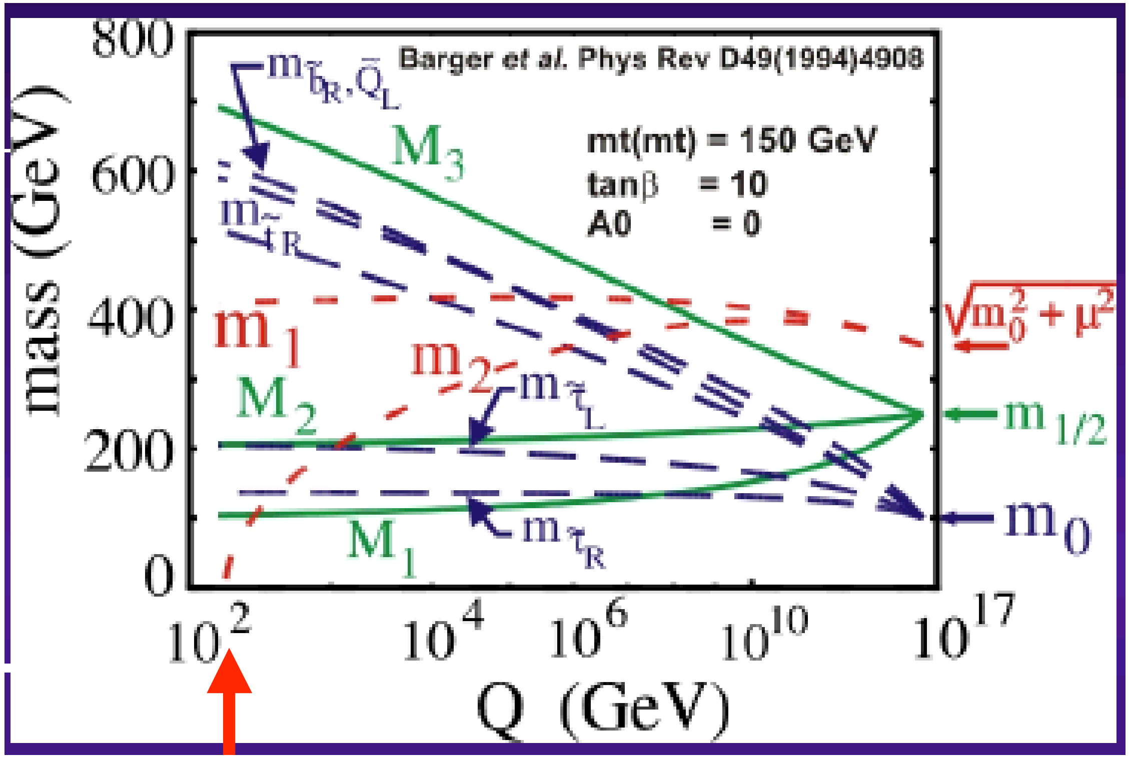
But: Lack of SUSY signals at LEP + lower limit on m_H

→ problems for minimal SUSY

- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln \frac{\tilde{m}_t^4}{m_t^4} < \sim 130 \text{ GeV}$$

So m_H > 114 GeV considerably reduces available parameter space.

- In SUSY EW symm. breaking is induced by H_u running



Exact location implies constraints

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m_Z can be expressed in terms of SUSY parameters

For example, assuming universal masses at M_{GUT} for scalars and for gauginos

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2 \qquad c_a = c_a(m_t, \alpha_i, \ldots)$$

Clearly if $m_{1/2}$, m_0,... >> m_Z: Fine tuning!

LEP results (e.g. $m_{\chi+}$ >~100 GeV) exclude gaugino universality if no FT by > ~20 times is allowed

Without gaugino univ. the constraint only remains on m_{gluino} and is not incompatible

$$m_Z^2 \approx 0.7 m_{gluino}^2 + \ldots$$

[Exp. : m_{gluino} >~200GeV]

Barbieri, Giudice; de Carlos, Casas; Barbieri, Strumia; Kane, King; Kane, Lykken, Nelson, Wang......

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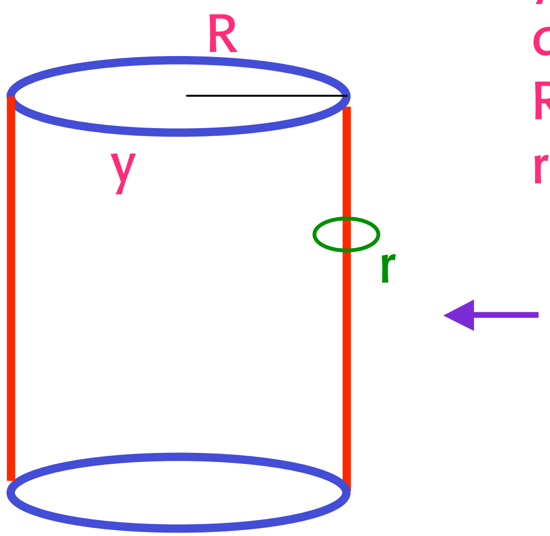
Large Extra Dimensions

Solve the hierachy problem by bringing gravity down from M_{Pl} to o(1TeV)

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis/ Randall,Sundrun…..

Inspired by string theory, one assumes:

- Large compactified extra dimensions
- SM fields are on a brane
- Gravity propagates in the whole bulk



y: extra dimension
R: compact'n radius

y=0 "our" brane (possibly with thickness r)

$G_N \sim 1/M^2_{Pl}$: Newton const.
M_{Pl} large as G_N weak

The idea is that gravity appears weak as a lot of lines of force escape in extra dimensions

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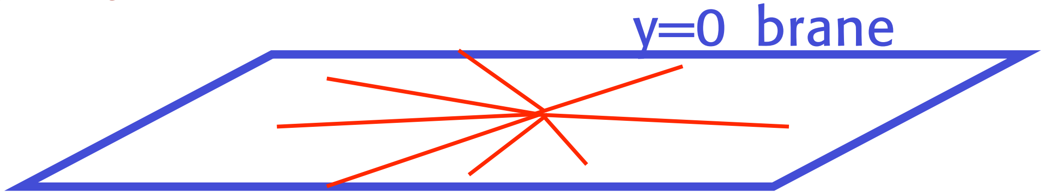
r >> R: ordinary Newton law

$$F \sim \frac{G_N}{r^2} \sim \frac{1}{M_{Pl}^2 r^2}$$

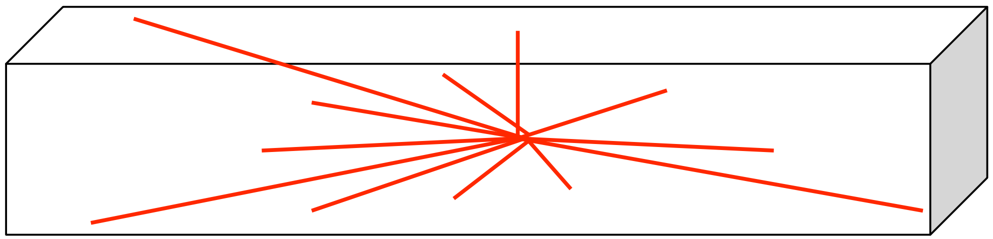


r << R: lines in all dimensions

Gauss in d dim:

$r^{d-2}\,\rho \sim m$

$$F \sim \frac{1}{m^2 (mr)^{d-4} \cdot r^2}$$



By matching at r=R

$$\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4}$$

For m ~ 1 TeV, (d-4 = n)

n = 1 R~ 10^{15} cm (excluded)
n = 2 R~ 1mm (close to limits)
n = 4 R~ 10^{-9} cm
…

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Limits on deviations from Newton law

$$V(r) = -G\frac{m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

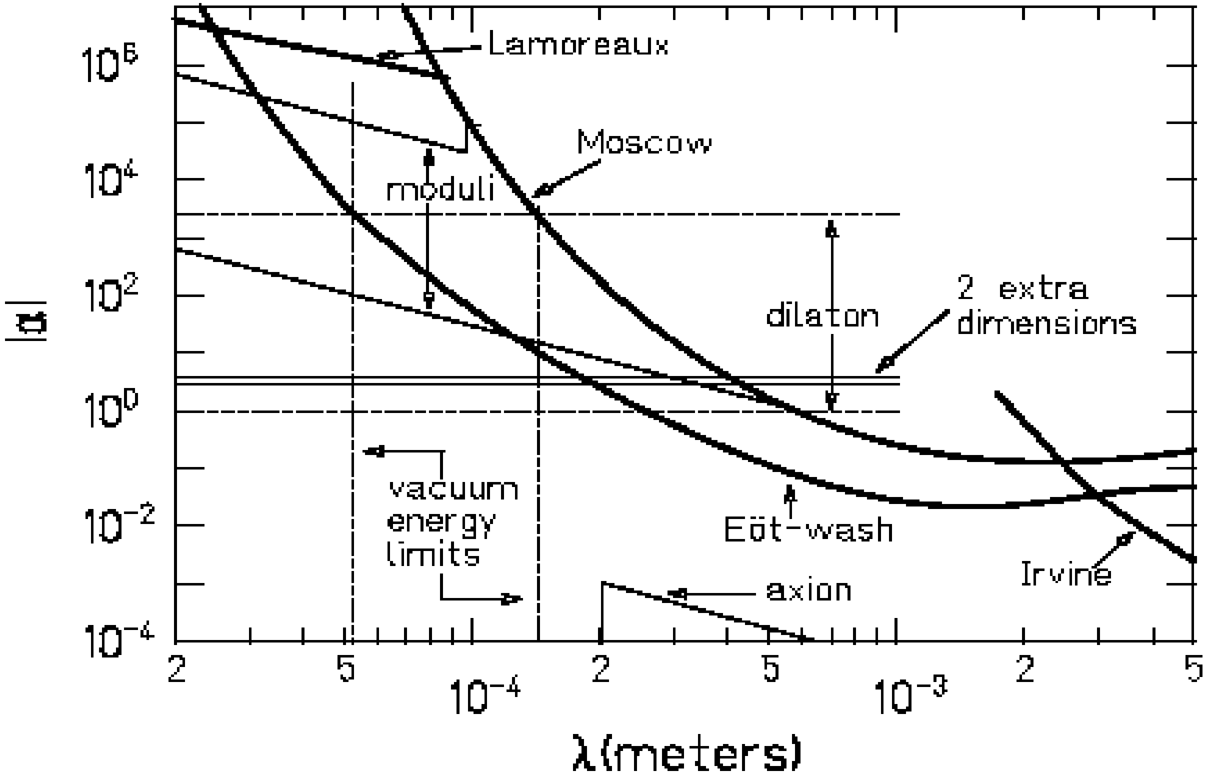


FIG. 4. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by Eq. (2). The region excluded by previous work [2,3,20] lies above the heavy lines labeled Irvine, Moscow and Lamoreaux, respectively. The data in Fig. 3 imply the constraint shown by the heavy line labeled Eöt-wash. Constraints from previous experiments and the theoretical predictions are adapted from Ref. [8], except for the dilaton prediction which is from Ref. [14].

Hoyle et al,

PRL 86,1418,2001

Generic feature:
compact dim. → Kaluza-Klein (KK) modes

$p=n/R$ $m^2=n^2/R^2$ (quantization in a box)

Many possibilities:

- SM fields on a brane

The brane can itself have a thickness r:
$1/r >\sim 1$ TeV → $r <\sim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr: • Gravity on bulk
$1/R >\sim 10^{-3}$ eV → $R <\sim 0.1$ mm

- Factorized metric:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}(y) dy^i dy^j$$

- Warped metric: Randall-Sundrum (R-S)

perhaps the most promising

$$ds^2 = e^{-2mR|\varphi|} \eta_{\mu\nu} dx^\mu dx^\nu - R^2 \varphi^2$$

$m = M_{Pl} \exp(-2mR\pi)$ → $Rm \sim 10$

- Large Extra Dimensions is a very exciting scenario.

- However, by itself it is difficult to see how it can solve the main problems (hierarchy, the LEP Paradox)

  * Why (Rm) not 0(1)?

    R-S better in this respect

$$\left(\frac{M_{Pl}}{m}\right)^2 = (Rm)^{d-4}$$

$$m = M_{Pl} exp(-2mR\pi)$$

  * Λ ~ 1/R must be small (m_H light)

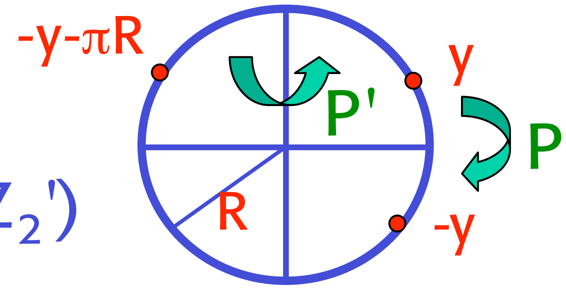
  * But precision tests put very strong lower limits on Λ (several TeV)

In fact in typical models of this class there is no mechanism to sufficiently quench the corrections

- But could be part of the truth!

- Interesting directions explored →

Symmetry breaking by orbifolding



$S/(Z_2xZ_2')$

For $1/R \sim M_{GUT}$
GUT's in ED: very appealing
SU(5), SO(10) in 5 or 6 dimensions

Z_2-> P: y ⟺ -y

Kawamura/GA, Feruglio/ Hall, Nomura;
Hebecker, March-Russell;
Hall, March-Russell, Okui, Smith
Asaka, Buchmuller, Covi
....

Z_2'-> P': y' ⟺ -y'
$y' = y + \pi R/2$
or y ⟺ $-y- \pi R$

- No baroque Higgs system
- Natural doublet-triplet splitting
- Coupling unification can be maintained
- ● ● ●

$$\phi_{++}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{++}^{(2n)}(x_\mu) \cos\frac{2ny}{R}$$

$$\phi_{+-}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{+-}^{(2n+1)}(x_\mu) \cos\frac{2n+1}{R}y$$

$$\phi_{-+}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{-+}^{(2n+1)}(x_\mu) \sin\frac{2n+1}{R}y$$

$$\phi_{--}(x_\mu, y) = \sqrt{\frac{2}{\pi R}} \cdot \sum_n \phi_{--}^{(2n+2)}(x_\mu) \sin\frac{2n+2}{R}y$$

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Symmetry breaking at the weak scale

- SUSY Breaking   Barbieri, Hall, Nomura...

5D SUSY-SM compactified on $S/(Z_2\text{-}Z_2')$

•Different SUSY breaking at each boundary (Scherk-Schwarz)

→effective theory non-SUSY

(SUSY recovered at d<R)

- Higgs boson mass constrained (rather insensitive to UV)

- **Gauge Symmetry Breaking (Higgsless theories)**

Csaki et al/Nomura/Davoudiasl et al/Barbieri, Rattazzi, Pomarol....

$U(1)_Y$ | $SU(2)_L x SU(2)_R x U(1)$ | $SU(2)_D$

M_{Pl} TeV

Symmetries broken by Boundary Conditions (BC) on the branes

Altogether only $U(1)_Q$ unbroken

Warped R-S background

Unitarity breaking (no Higgs) delayed by KK recurrences
Still problems with EW precision tests

A new way to look at walking technicolor by AdS/CDF correspondence

Little Higgs Models

Georgi (moose)/Arkani-Hamed et al/Low, Skiba, Smith/Kaplan, Schmaltz/Chang,Wacker/Gregoire et al

$$G \supset [SU(2) \otimes U(1)]^2 \supset SU(2) \otimes U(1)$$

global (G), gauged ($[SU(2) \otimes U(1)]^2$), SM ($SU(2) \otimes U(1)$)

H is (pseudo)-Goldstone boson of G: takes mass only at 2-loops (needs breaking of 2 subgroups or 2 couplings)

cut off Λ ~10 TeV

Λ^2 divergences canceled by:

$\delta m^2_{H\|top}$	new coloured fermion χ	~1 TeV
$\delta m^2_{H\|gauge}$	W', Z', γ'	~1 TeV
$\delta m^2_{H\|Higgs}$	new scalars	~1 TeV

2 Higgs doublets ~0.2 TeV

E-W Precision Tests? Problems

GUT's? But signatures at LHC clear

e.g.: enlarge $SU(2)_{weak}$ → global SU(3)

quark doublet → triplet $\begin{bmatrix} t_L \\ b_L \\ \chi_L \end{bmatrix}$

SU(3) broken spont.ly

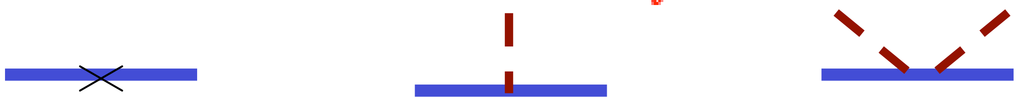
$$\varphi = \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$$

Yukawa coupling:

expl. SU(3) breaking

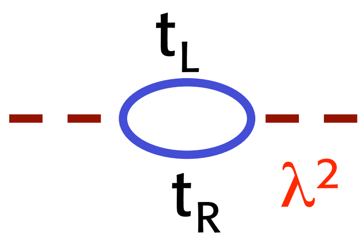
$$\lambda \begin{bmatrix} t^\dagger{}_L & b^\dagger{}_L & \chi^\dagger{}_L \end{bmatrix} \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} t_R + M \chi^\dagger{}_L \chi_R$$

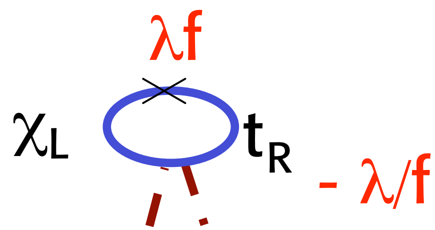
$$\lambda f \chi^\dagger{}_L t_R + i\lambda \begin{bmatrix} t^\dagger{}_L & b^\dagger{}_L \end{bmatrix} h t_R - \frac{\lambda}{2f} \chi^\dagger{}_L t_R h^\dagger h + \ldots$$



top loop:

coeff. Λ^2





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Little Higgs: Big Problems with Precision Tests

Hewett, Petriello, Rizzo/ Csaki et al/Casalbuoni, De Andrea, Oertel/ Kilian, Reuter/

Even with vectorlike new fermions large corrections arise mainly from W_i', Z' exchange.
[lack of custodial SU(2) symmetry]

A combination of LEP and Tevatron limits gives:

$$f > 4 \text{ TeV at } 95\% \ (\Lambda = 4\pi f)$$

Fine tuning > 100 needed to get m_h ~ 200 GeV

better if m_H heavier ⟹

Presumably can be fixed by complicating the model

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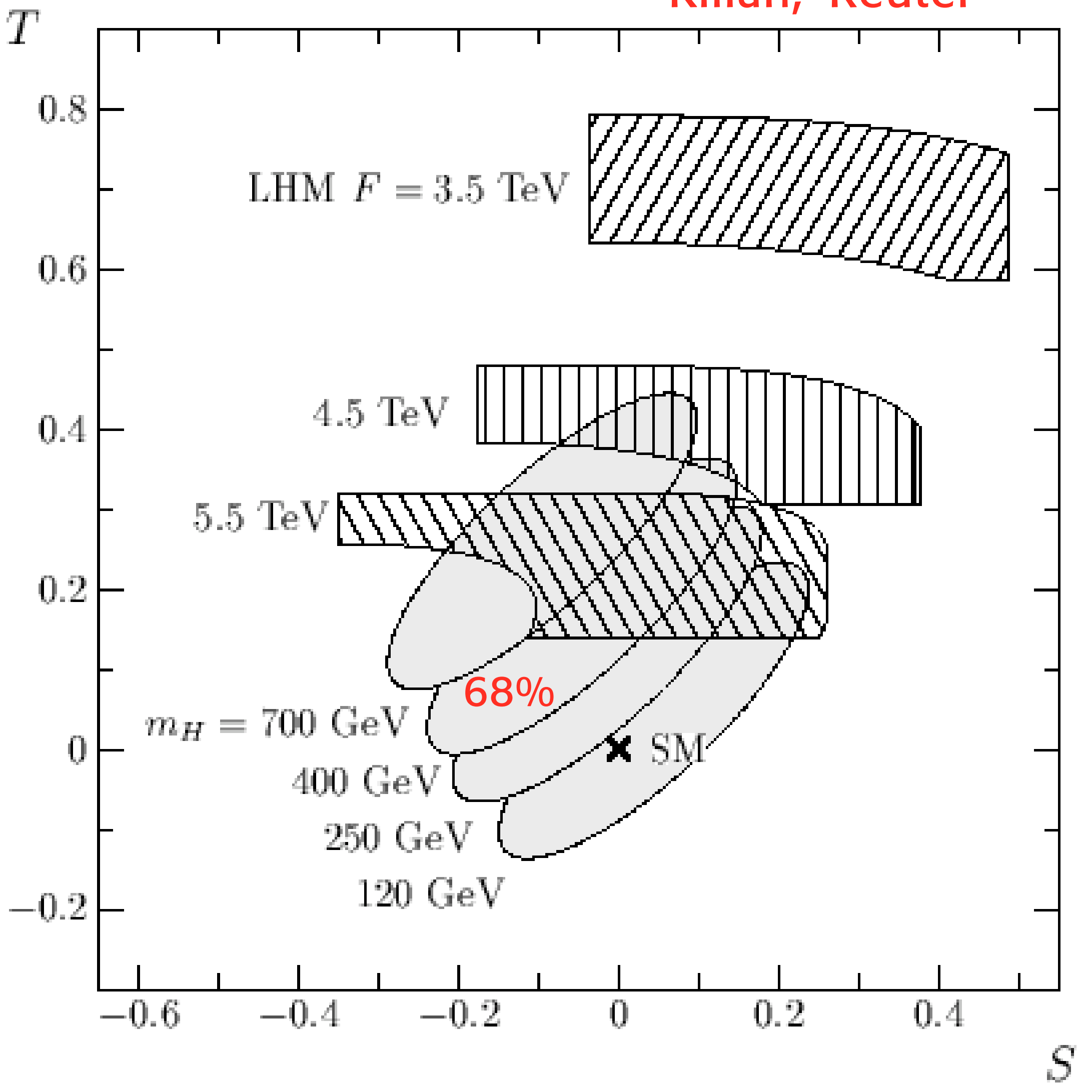
For a light Higgs F (=f) must be large.
Better if m_H increases

Kilian, Reuter



G. Altarelli

Summarizing

- SUSY remains the Standard Way beyond the SM
- What is unique of SUSY is that it works up to GUT's .

  GUT's are part of our culture!
  Coupling unification, neutrino masses, dark matter, ...
  give important support to SUSY
- It is true that the train of SUSY is already a bit late

(this is why there is a revival of alternative model building)

- No complete, realistic alternative so far developed

(not an argument! But…)

- Extra dim.s is a complex, rich, attractive, exciting

possibility.

- Little Higgs models look as just a postponement

(both interesting to pursue)