NON-MSSM EXTENSIONS OF THE STANDARD MODEL

Beautiful prediction of the MSSM (with GUT normalization of the U(1) generator)

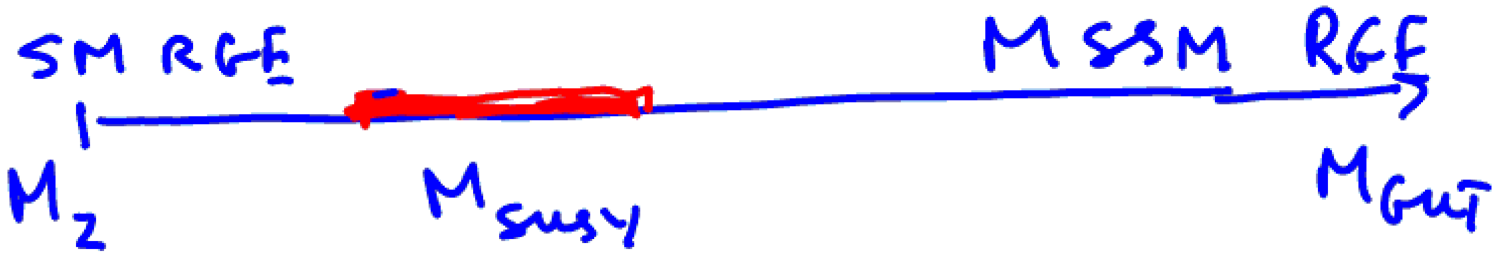
$$Q = T_3 + Y = L^{11} + \sqrt{\frac{5}{3}}\, L^{12}$$

L^{ij} - SU(5) generators

is the gauge coupling unification: the three measured gauge couplings evolved to higher energy scales with the MSSM renormalization group equations (almost) meet at one point

A closer look at the gauge coupling unification

$$\alpha_i(Q) = f\big(\alpha_i(M_Z),\, m_t,\, m_h,\, \mathrm{tg}\beta,\, \text{superparticle masses}\big)$$



Define Mgut by

$$\alpha_2(M_{GUT}) = \alpha_1(M_{GUT}) = \alpha_{GUT}$$

hence $M_{GUT} = 2 \cdot 10^{16}\,\mathrm{GeV}$

Evolve $\alpha_3(M_Z) = 0.12$ to M_{GUT}

and define

$$\Delta = \frac{\alpha_3(M_{GUT}) - \alpha_{GUT}}{\alpha_{GUT}}$$

Superpartner mass mass dependence can be described (in LL approx) by a single effective parameter Tsusy

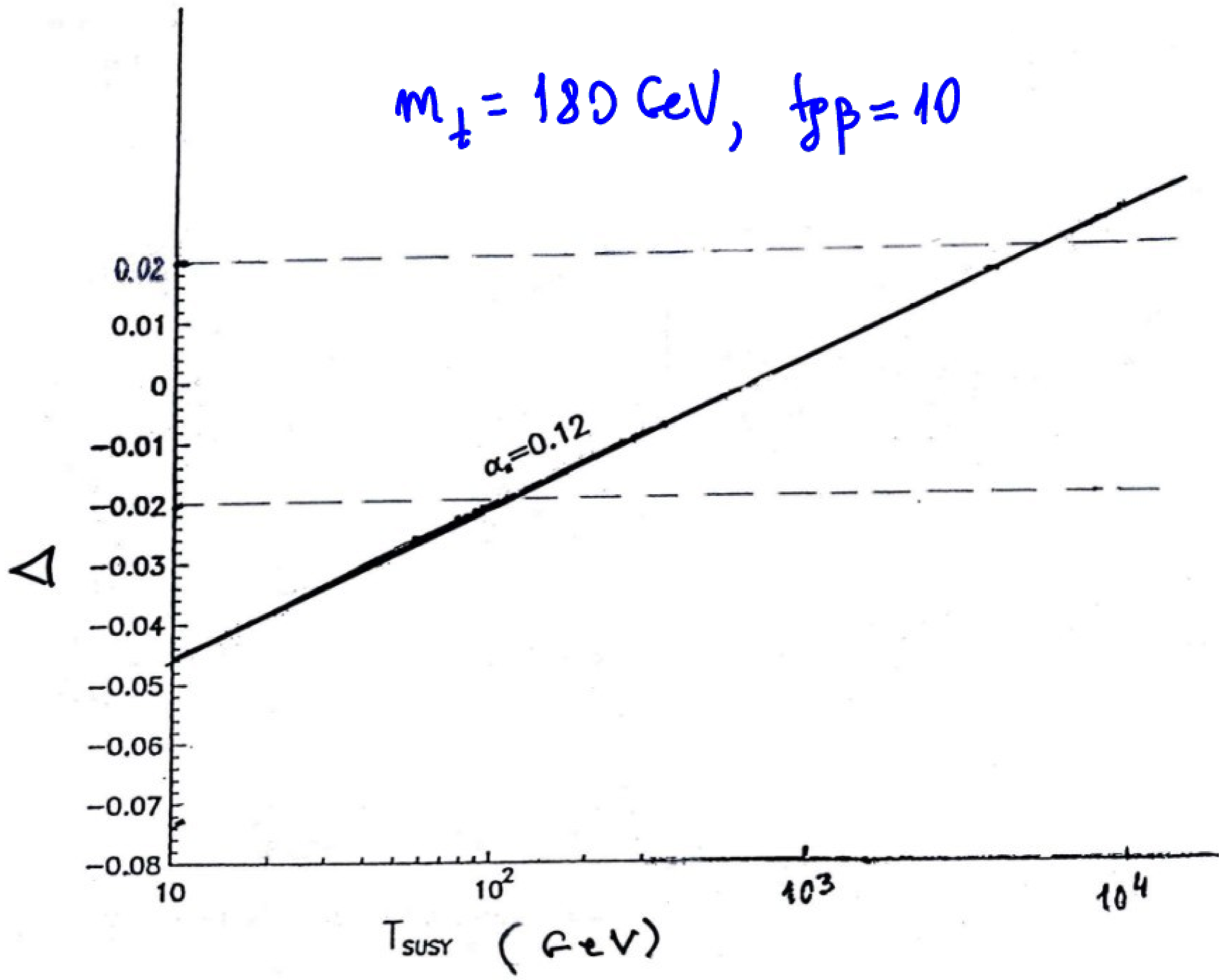
$$T_{susy} = |\mu| \left(\frac{m_{\tilde{w}}}{m_{\tilde{g}}}\right)^{3/2} \left(\frac{M_{\tilde{\ell}}}{M_{\tilde{q}}}\right)^{3/19} \left(\frac{M_{A^0}}{|\mu|}\right)^{3/19} \left(\frac{m_{\tilde{w}}}{|\mu|}\right)^{3/19}$$

$$\approx |\mu| \left[\frac{m_{\tilde{w}}}{m_{\tilde{g}}}\right]^{3/2}$$

For instance, for universal gaugino masses at the GUT scale

$$T_{SUSY} \simeq |\mu| \left[\frac{\alpha_2(M_Z)}{\alpha_3(M_Z)} \right]^{3/2} \sim \frac{1}{7} |\mu|$$

How precise is the gauge coupling unification in the MSSM?



$m_t = 180$ GeV, $tg\beta = 10$
Δ
0.02
0.01
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
−0.08
α_s=0.12
10
10^2
10^3
10^4
T_{SUSY} (GeV)

Generically, unification of the gauge couplings is lost in non-MSSM extensions of the SM

Secondly, MSSM is easily consistent with precision electroweak data; other extensions are strongly constrained by them.

In addition, good dark matter candidate

So, why there are discussed various supersymmetric and non-supersymmetric non-MSSM extensions of the Standard Model?

Original motivation: little hierarchy problem of the MSSM

Effective Higgs potential for EWSB in many extensions of the SM (including MSSM for moderate tan beta)

$$V = m_H^2 \, H H^\dagger + \frac{1}{2}\lambda (H H^\dagger)^2$$

$$v^2 = \frac{-2 m_H^2}{\lambda} \, , \quad m_h^2 = \lambda v^2$$

$$\left(H = \frac{1}{\sqrt{2}} v \right) \qquad v \to M_Z$$

For $m_h \sim O(100)\,\text{GeV} - O(1)\,\text{TeV}$

unitarity bound

$$\lambda \lesssim O(1)$$

$$|m_H^2| \sim 10^{-2}\,\text{TeV} - 3\times 10^{-2}\,\text{TeV}$$

$$m_H^2 = m_H^2\big|_{\text{tree}} + \delta m_H^2$$

loop corrections

$$\delta m_H^2\big|_{1\,\text{loop}} = c_2 M^2 + c_4 \ln M^2 + \ldots$$

M - cut-off to the effective theory

$$\boxed{\left(m_H^2\big|_{tree},\ \delta m_H^2\right) \text{ vs } M_Z^2\ ?}$$

MSSM

$$\frac{1}{2} M_Z^2 \approx -\left(m_{H_u}^2 + \mu^2\right)\Big|_{\text{tree}} + $$

$$+\ 0.1\, M_{susy}^2 \ln \frac{\Lambda_{MSSM}}{M_{susy}}$$

$$10^{-2}\ \text{TeV} \quad \text{vs} \quad O(1)\,\text{TeV}\Big|_{\text{tree}} + \underbrace{O(1)\,\text{TeV}}_{\text{for } \Lambda_{MSSM} \sim M_{GUT}}$$

constrained by

$m_h \gtrsim 114$ GeV

MSSM: cancellations 1:100 in the Higgs potential

Little hierarchy problem (if a problem!) can be solved if both the tree level and the higher order corrections to mH are comparable to the Z mass

Except for some more complicated supersymmetric models, the original motivation fails in non-supersymmetric extensions of the SM because of a new type of tension, namely with precision electroweak data

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The impact of physics beyond the Standard Model on precision electroweak data can be studied in a model independent way by adding to the SM lagrangian higher dimension operators

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^n} O_i^{(4+n)}$$

$$c_i \sim \begin{cases} O\left(\frac{1}{16\pi^2}\right) & \text{for Loop physics} \\ O(1) & \text{for new tree level} \\ & \text{or strongly interacting sector} \end{cases}$$

Results of the fits to precision data:

for new tree –level and/or strongly interacting sector

$$M \gtrsim O(5)\ \mathrm{TeV}$$

Generically, non-MSSM extensions of the SM give new tree level effects and/or contain new strongly interacting sector.

Typically

$$|\delta m_H^2| \sim \frac{3}{8\pi^2} M^2 \ln M + \ldots$$

requires at least 1:100 tuning

The precision electroweak data are a challenge for realistic extensions of the SM aiming to understand better the origin of the Fermi scale.

Although, non-supersymmetric extensions of the SM do not solve the little hierarchy problem of the MSSM, they can naturally protect the Higgs potential to the same extent as MSSM and are considered for their theoretical attractiveness.

MAIN LOSS: UNIFICATION

An attractive idea: extra dimensions.

Originally, gravity in extra dimensions (with a low fundamental Planck scale) have been used as new strong dynamics to cut-off the SM at 1 TeV. Gravity effects would then be seen at the LHC , with signatures depending on whether the extra dimensional space is flat or e.g. of the Randall-Sundrum type.

But in conflict with with precision data unless the strong gravity sets on at 5 TeV or higher.

Gauge – Higgs unification : gravity can be decoupled (no gravitational effects at low energies); Higgs doublet is identified as a component along the extra dimension of a gauge field; gauge invariance in extra dimensions protects the Higgs potential

Deconstructed version of this idea gives Little Higgs models; in 4 d the Higgs scalar is a pseudo- Nambu-Goldstone boson of some spontaneously broken global symmetry

A large set of recently proposed models , either in 4+n dim or in 4d, have the same underlying idea, linked by deconstruction.

Extra dimensions/deconstruction and Higgless models:

Unitarity protected by contributions from
Kaluza-Klein modes
of vector bosons

Instructive example: 5 dim SU(n) gauge theory

$$S = -\frac{1}{4}\int d^4x\, dy\; F^{\alpha}_{MN} F^{MN}_{\alpha}$$

$$0 \le y \le 2\pi R$$

vector potential $(A_\mu, \underbrace{A_5}_{\text{a scalar in 4d!}})$

$m^2_{A_5}\big|_{\text{tree}} = 0$ (gauge inv in 5d)

However, there exists a <u>non-local</u> operator (Wilson line)

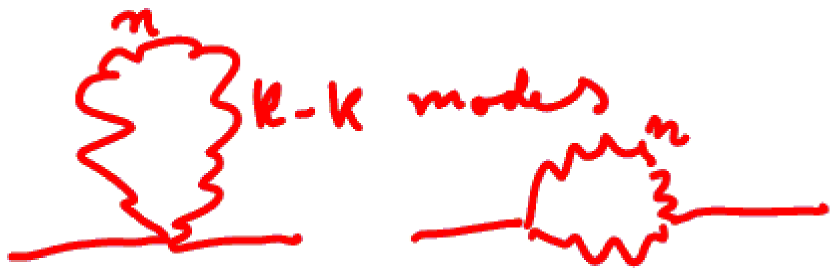
$$W = e^{i\int_0^{2\pi R} dy\, A_5(y)}$$

which is gauge invariant

$$|\mathrm{tr}\, W|^2 \sim (A_5^0)^2 \quad (\text{mass term for the zero mode of } A_5)$$

Since this is a non-local operator, its coefficient calculated in perturbation theory must be finite

$$\delta m^2_{A_5} \sim \frac{1}{R^2}$$



Non-supersymmetric theory, even perturbative at the scale $1/R$, and yet the 4d scalar A_5^0 gets finite mass!

To identify A5 with Higgs doublet:

- A5 must be in a fundamental, not adjoint representation of SU(2)
- the loop scalar potential must have a minimum for non-vanishing VeV
- the generated quartic coupling for A5 must be large enough to get mh>114 GeV

We need model building

More realistic model

$SU(3)_W$ on S_1/Z_2 orbifold;

- the adjoint of $SU(3)_W$ decomposes into $(3,0) + \underline{(2,1/2)} + \underline{(2,-1/2)} + (1,0)$ of $SU(2)_L \times U(1)_Y$

- Z_2: symmetry of the Lagrangian under $y \to -y$

The orbifold breaks

$$SU(3)_W \to SU(2)_L \times U(1)_Y$$

via the projection matrix

$$P = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where the gauge fields transform

as $A_\mu(-y) = P A_\mu(y) P^+$, $A_5(-y) = -P A_5(y) P^+$

$$A_M(x,y) = A_M^a(x,y)\,\lambda^a$$

K - K decomposition

$$A_M = \frac{1}{\sqrt{\pi}R}\left(\frac{1}{\sqrt{2}}A_\mu^{(0)} + \right.$$

$$\left. + \sum_{n=1}^{\infty} \sin\left(\frac{ny}{R}\right) A_M^{(n)} + \cos\left(\frac{ny}{R}\right) A_M^{(-n)}\right)$$

Projection operator cuts-off some components

With this choice, only SM fields A_μ have a zero mode.
In the scalar (A_5) sector, the zero mode is a single complex SU(2) doublet (can play a role of Higgs)

$$A_5^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} - & H_5 \\ H_5^+ & - \end{pmatrix}$$

(For a zero mode we need $A_M^a(y) = A_M^a(-y)$))

Note that all the massive modes of A5 are eaten by the massive KK modes of the gauge bosons;

The only physical scalar left in the spectrum is the zero mode of A5

A tree level potential for A5 is forbidden by 5d gauge symmetry, also on the fixed points, and only loop contributions will generate a potential for the Higgs, that will be non-local from the 5d point of view, and therefore FINITE

To generate an effective potential with a negative effective mass squared parameter one needs new fermions in the bulk

Experimental signatures

New fermions

Heavy replica of W, Z and γ

(but not for Higgsless because they are fermio-phobic; for Higgless one should measure gauge bosons self-couplings to see KK contribution

Details depend on the model

SUMMARY

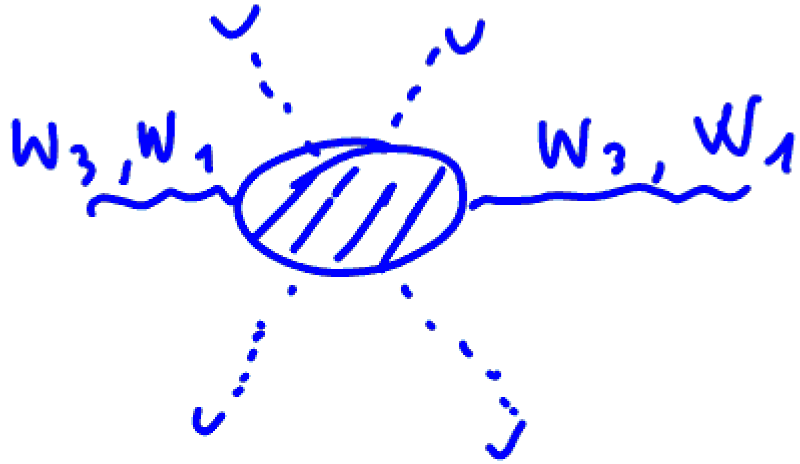
MSSM has important virtues (gauge coupling unification)

However, there are attractive non-MSSM extensions of the SM that naturally solve the big hierarchy problem and merit experimental verification;
The present models are fairly complicated and no specific model emerges and the leading competitor to MSSM

dim 6 operators (suppressed by M^2)

<u>e.g.</u>

$$|H^\dagger D_\mu H|^2$$



contributes to $\Pi_{W_3W_3}(0) - \Pi_{W_1W_2}(0) \equiv M_W^2 T$

$$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$$

contributes to $(g_2/g_1)\,\Pi'_{W_3Y}(0) \equiv S$

Deconstructed version of this mechanism ($\longrightarrow$ Little Higgs models)

4 d model which originates from a latticized version of the 5 d model

$$SU_1(n) \times SU_2(n) \times \ldots\ldots \times SU_{N-1}(n) \times SU_N(n)$$

$$\phi(N,\bar{1}) \qquad \phi(\bar{n}_1, n_2) \qquad \phi(\bar{n}_2, n_3) \ldots \qquad \phi(\overline{N-1}, N)$$

$$SU(n)^N \quad , \quad \phi_i(\bar{n}_i, n_{i+1}) \quad i = 1, N$$

$$\phi_i(x^\mu) = \exp\left[i \int_{ia}^{(i+1)a} dy\, A_5(x^\mu, y) \right]$$

$$\to \exp\left[i\, a\, A_5(x^\mu, i + \tfrac{1}{2})a) \right]$$

Take

$$\phi_i = v\, e^{i\varphi_i^a T^a / v}$$

and assume a potential $V(\phi_i)$ which has chiral $SU^N(n) \times SU^N(n)$ symmetry

VEVs of ϕ_i break global $SU^N(n) \times SU^N(n) \to SU^N(n)$

gauge $SU^N(n) \to SU(n)$

diagonal subgroup

N-1 Goldstone bosons are eaten up by gauge bosons, which correspond to KK modes of 5d theory

One Goldstone boson $\pi^a = \varphi_1^a + \varphi_2^a + \dots \varphi_N^a$ remains in the physical spectrum and corresponds to $A_5^{(0)}$ of 5d theory

No tree level potential for Goldstone boson!

Shift symmetry $\phi_i \to \phi_i + 1$

Gauge invariant operator which contributes to the Goldstone boson mass

$$[\mathrm{Tr}\, \phi_1 \phi_2 \cdots \phi_N]^2$$

Non-local; for $N > 2$ its $\dim > 4$ and finite

$N = 2 \rightarrow$ Little Higgs models

Model building has to solve the same problems as in 5d:

build effective potential for GB, with non-vanishing VEV (for electroweak symmetry breaking

The linearized gauge transformation in the bulk are

$$A_\mu \to A_\mu + \partial_\mu \lambda(x,y) + i[\lambda, A_\mu]$$

$$A_5 \to A_5 + \partial_y \lambda(x,y) + i[\lambda, A_5]$$

On the branes, $\lambda = 0$ for broken generators, however the $\partial_5 \lambda$ is non-zero and gives a shift symmetry on A_5