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Orsay, 9-12 January '07

Beyond the Standard Model

Guido Altarelli

Univ. Roma Tre
CERN

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:

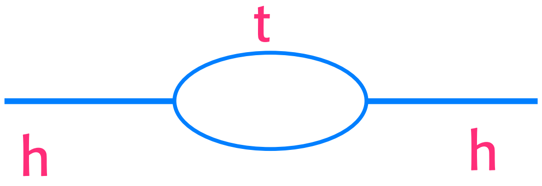
- Coupling unification
- Neutrino masses
- Baryogenesis
- Dark matter
- Vacuum energy
- •••••

Some of these problems point at new physics at the weak scale: eg
Hierarchy
Dark matter

For the low energy theory: the “little hierarchy” problem:

e.g. the top loop (the most pressing):

$m_h^2 = m^2_{bare} + \delta m_h^2$



$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

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 were not visible at LEP

And also are not visible in flavour physics

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

exact (unrealistic): cancellation of $\delta\mu^2$
approximate (possible): $\Lambda \sim m_{SUSY}\text{-}m_{ord}$ → top loop $\Lambda \sim m_{stop}$

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. Coming back in new forms

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

"Little Higgs" models. Some extra trick needed to solve problems with EW precision tests

- Extra spacetime dim's that bring M_{Pl} down to o(1TeV)

Exciting. Many facets. Rich potentiality. No baseline model emerged so far

- Ignore the problem: invoke the anthropic principle

Back to the “little” hierarchy problem:

$$\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$$

In broken SUSY Λ^2 is replaced by m_{stop}^2-m_t^2

m_H>114.4 GeV, $m_{\chi+}$ >100 GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) on minimal realizations (MSSM, CMSSM…).

Yet SUSY is a completely specified, consistent, computable model, perturbative up to M_{Pl} quantitatively in agreement with coupling unification
(unique among NP models)
and has a good DM candidate: the neutralino
(actually more than one).

Remains the reference model for NP

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
Good Dark Matter candidates

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

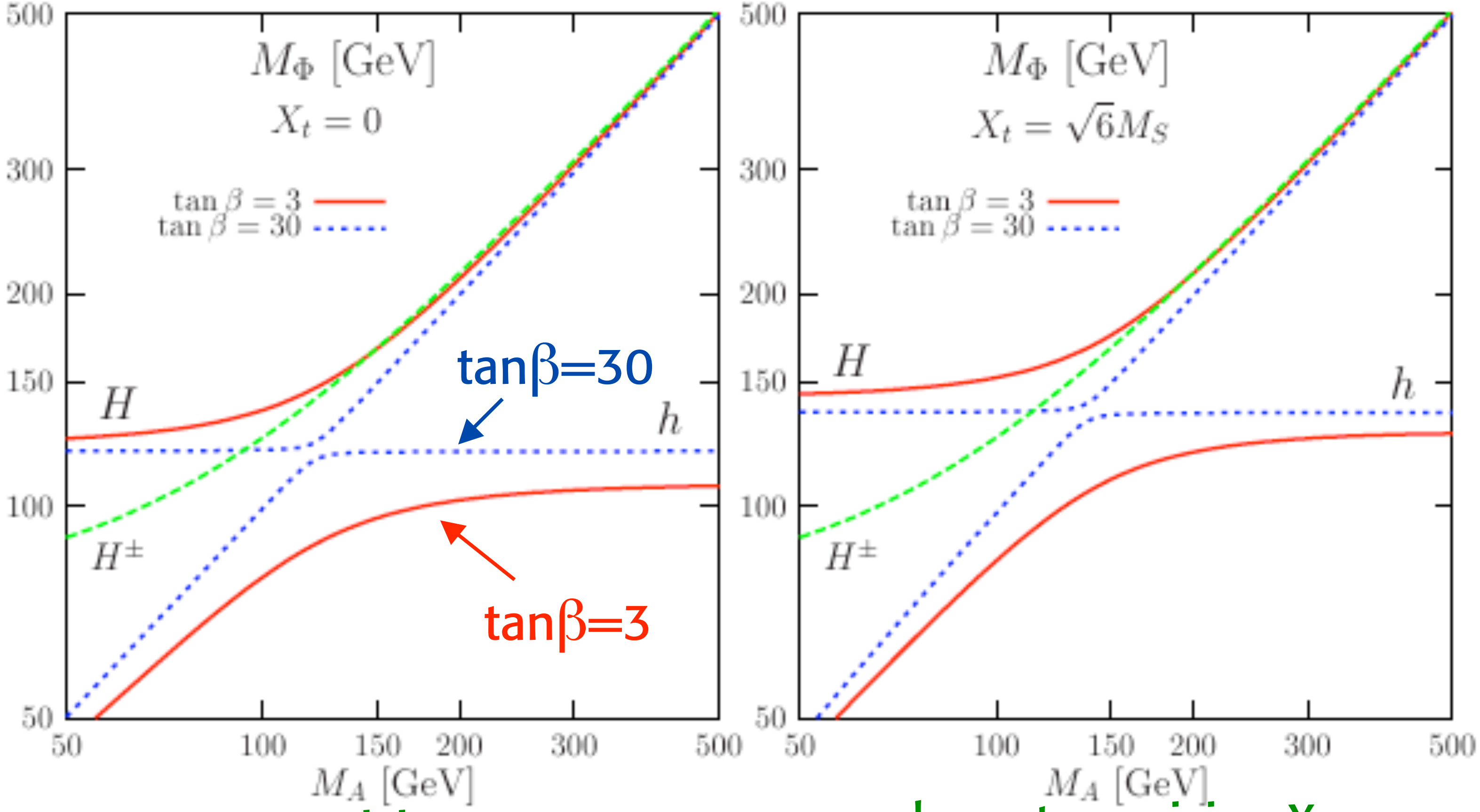
Dominant error:
thresholds near M_{GUT}

- Proton decay: Far too fast without SUSY
- M_{GUT} ~ 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 , extra dimensions,
little higgs etc., there is no ground for GUT's

In SUSY: 2 Higgs doublets, 5 in the phys. spectrum h, A, H, $H^{\pm}$

Djouadi



tanβ=30

tanβ=3

no top mixing: X_t=0

large top mixing X_t

m_t = 178 GeV (conservative: smaller m_t, smaller m_{hmax})

$m_h < \sim 135$ GeV

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

→ problems for minimal SUSY

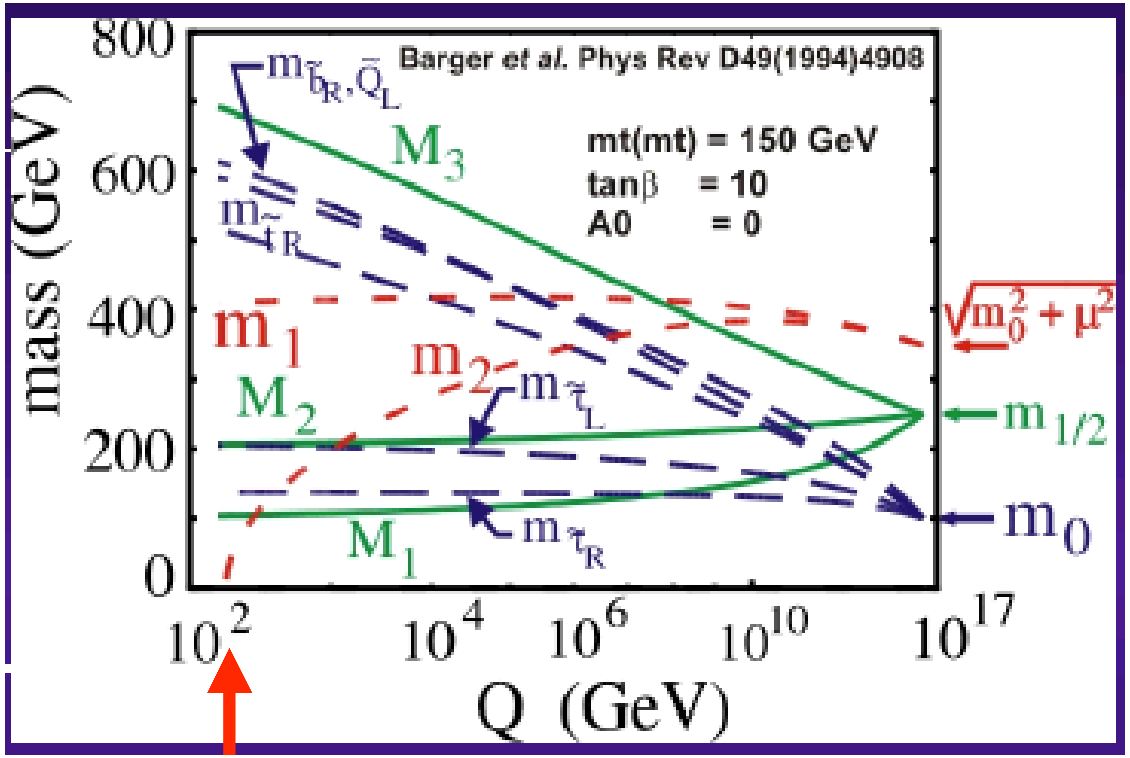
- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln \frac{\tilde{m}_t^4}{m_t^4} < \sim 130 \text{ GeV}$$

So $m_H > 114$ GeV considerably reduces available parameter space.

m_{stop} large tends to clash with $\delta m_h^2 \sim m_{stop}^2$

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

Exact location implies constraints



m_Z can be expressed in terms of SUSY parameters

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

$$m_Z^2 \approx c_{1/2} m_{1/2}^2 + c_0 m_0^2 + c_t A_t^2 + c_\mu \mu^2$$

$c_a = c_a(m_t, \alpha_i, \ldots)$

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

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

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

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

The fine tuning problem and the LEP paradox can be made less acute in SUSY models with enlarged Higgs sector

NMSSM: a singlet S is added

$W_\lambda = \lambda S H_1 H_2 + \ldots$

(extra bonus: solution of μ problem)

For the theory to remain perturbative up to M_{GUT}
λ must be small and the advantage is sizable but modest

Bastero-Gil et al '00

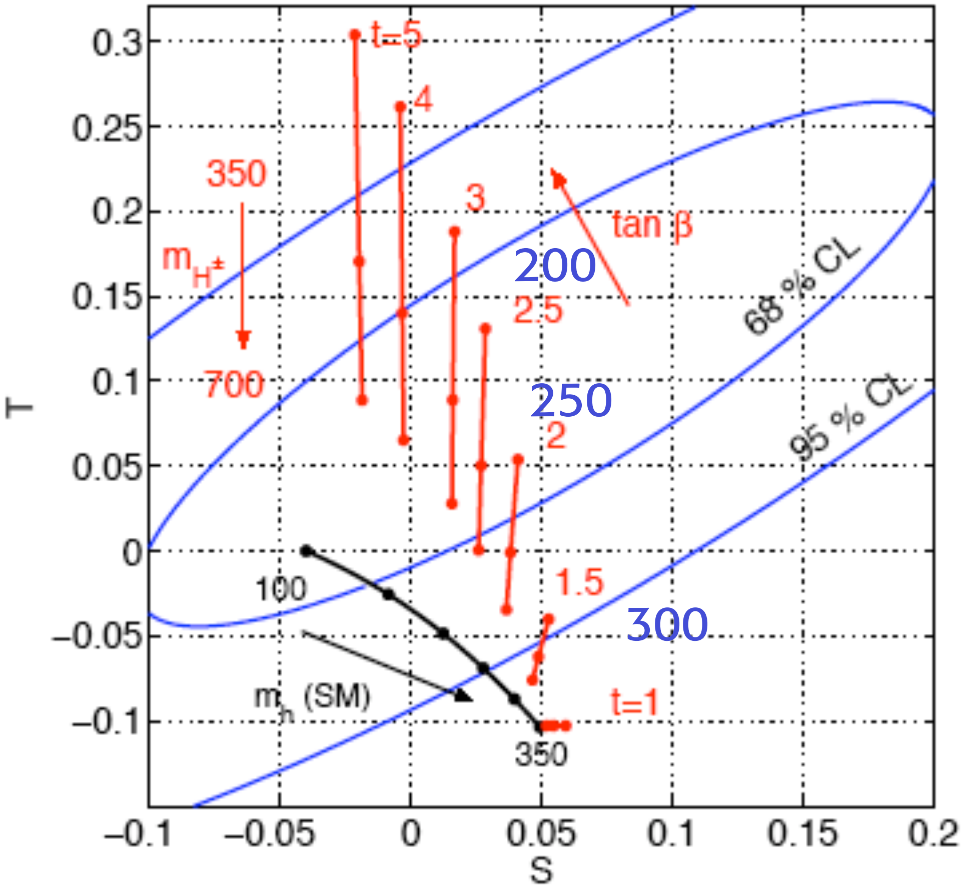
[Other similar extensions of the MSSM Higgs sector: e.g. adding an extra doublet with no vev and no coupling to fermions] Barbieri, Hall, Rychkov '06

But if one accepts loss of perturbativity at ~10 TeV then the Higgs mass can go up to ~ 250 GeV without conflicting with EW precision tests

Barbieri et al '06

λSUSY

m_h ~ 100 GeV Barbieri et al '06



In this model the light Higgs mass is increased without conflicting with precision tests but one needs an UV completion beyond 10 TeV and the connection with GUT's is lost.

EW DATA and New Physics

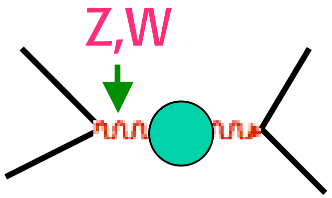
For an analysis of the LEP data beyond the SM we use the ε formalism GA, R.Barbieri, F.Caravaglios, S. Jadach

One introduces ε_1, ε_2, ε_3, ε_b such that:

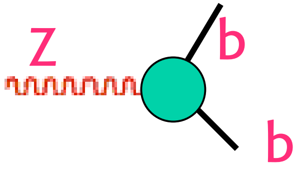
- Focus on pure weak rad. correct's, i.e. vanish in limit of tree level SM + pure QED and/or QCD correct's
[a good first approximation to the data]

- Are sensitive to vacuum pol. and Z->bb vertex corr.s (but also include non oblique terms)

ε_1, ε_2, ε_3 →

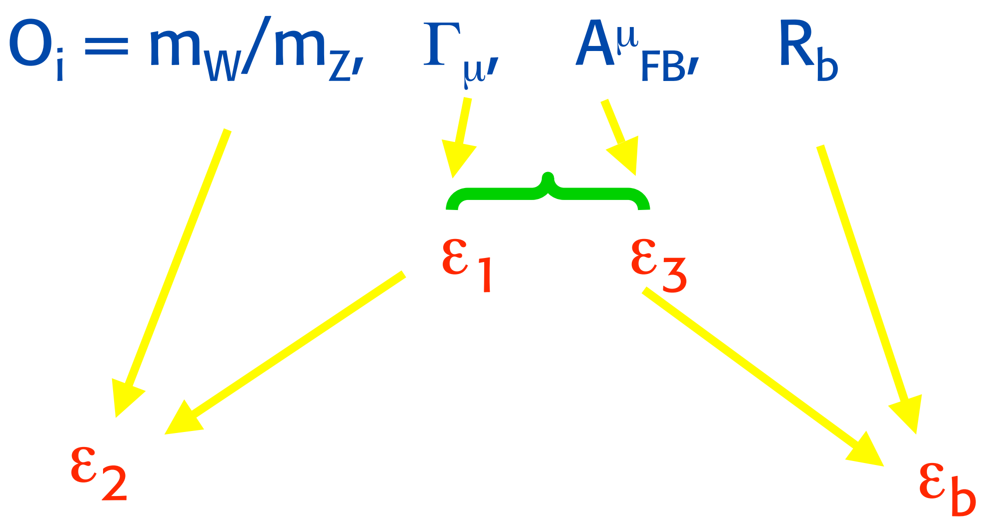


ε_b →



- Can be measured from the data with no reference to m_t and m_H (as opposed to S, T, U -> ε_3, ε_1, ε_2)

One starts from a set of defining observables:



$O_i = m_W/m_Z, \quad \Gamma_\mu, \quad A^\mu_{FB}, \quad R_b$

$\varepsilon_1 \quad \varepsilon_3$

$\varepsilon_2 \quad \varepsilon_b$

$$O_i[\varepsilon_k] = O_i^{\text{"Born"}}[1 + A_{ik}\, \varepsilon_k + \ldots]$$

$O_i^{\text{"Born"}}$ includes pure QED and/or QCD corr's.

A_{ik} is independent of m_t and m_H

Assuming lepton universality: Γ_μ, A^μ_{FB} --> Γ_l, A^l_{FB}

To test lepton-hadron universality one can add Γ_Z, σ_h, R_l to Γ_l etc.

The EWWG gives ('06):

$\varepsilon_1 = 5.4 \pm 1.0\ 10^{-3}$

$\varepsilon_2 = -\ 8.9 \pm 1.2\ 10^{-3}$

$\varepsilon_3 = 5.34 \pm 0.94\ 10^{-3}$

$\varepsilon_b = -\ 5.0 \pm 1.6\ 10^{-3}$

Non-degenerate
much larger shift of ε_1

For comparison:
a mass degenerate fermion multiplet gives

$$\Delta\varepsilon_3 = N_C \frac{G_F m_W^2}{8\pi^2\sqrt{2}} \cdot \frac{4}{3}[T_{3L} - T_{3R}]^2$$

For each member
of the multiplet

One chiral quark doublet (either L or R):

$$\Delta\varepsilon_3 = +\ 1.4\ 10^{-3}$$

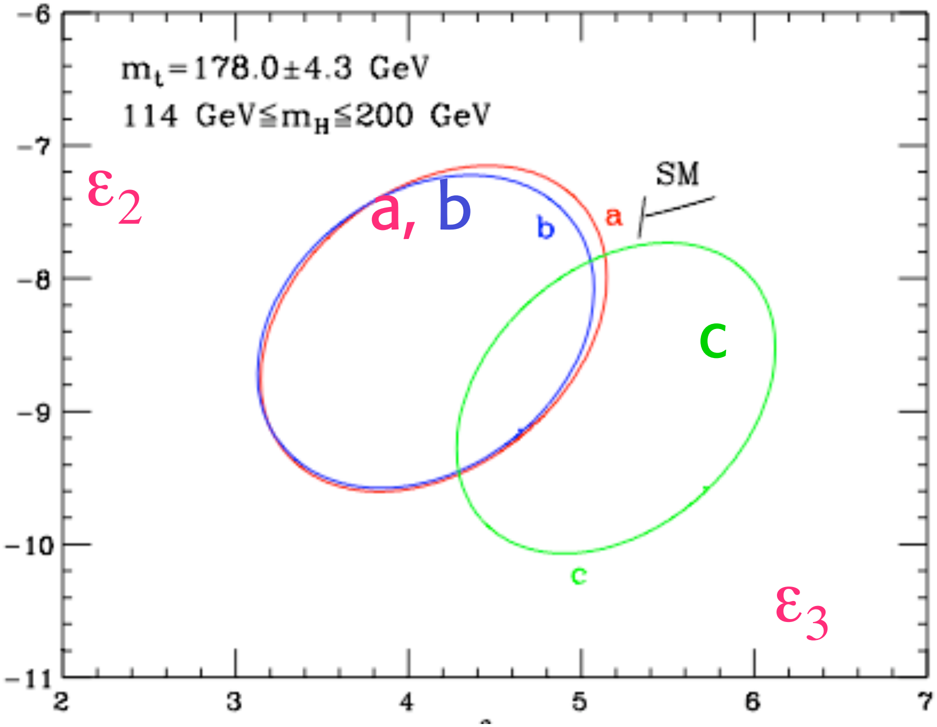
(Note that ε_3 if anything is low!)

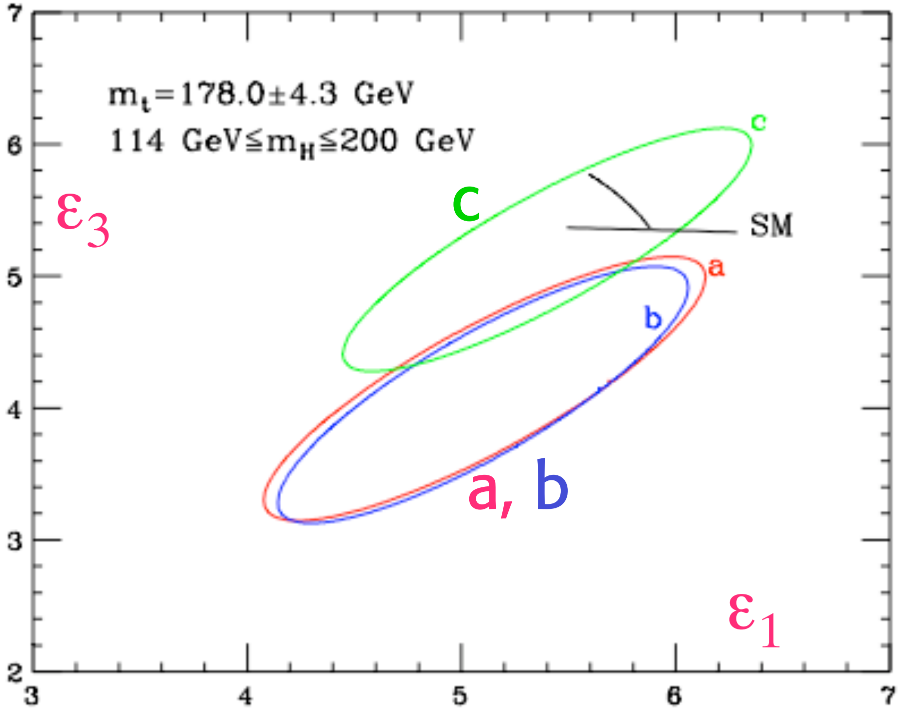
GA, F. Caravaglios, G. Giudice, P. Gambino, G. Ridolfi
(updated 2004)

a: m_W, Γ_l, R_b, $[\sin^2\theta]_l$
b: m_W, Γ_l, R_b, Γ_Z, σ_h, R_l, $[\sin^2\theta]_l$
c: m_W, Γ_l, R_b, Γ_Z, σ_h, R_l, $[\sin^2\theta]_l+[\sin^2\theta]_h$

Note:
1σ ellipses (39% cl)

Units: 10^{-3}

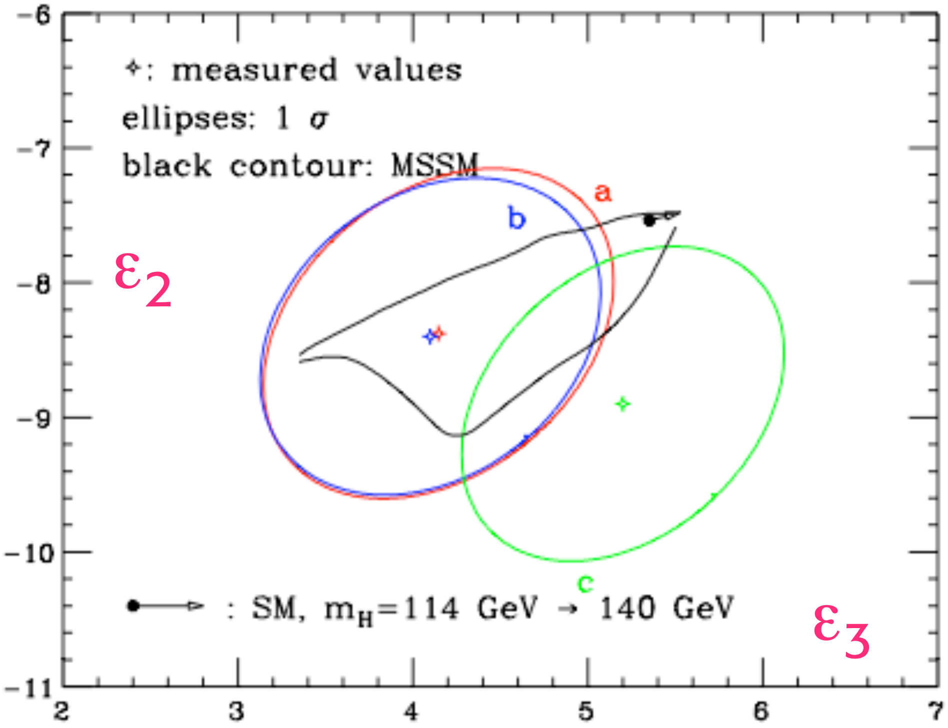


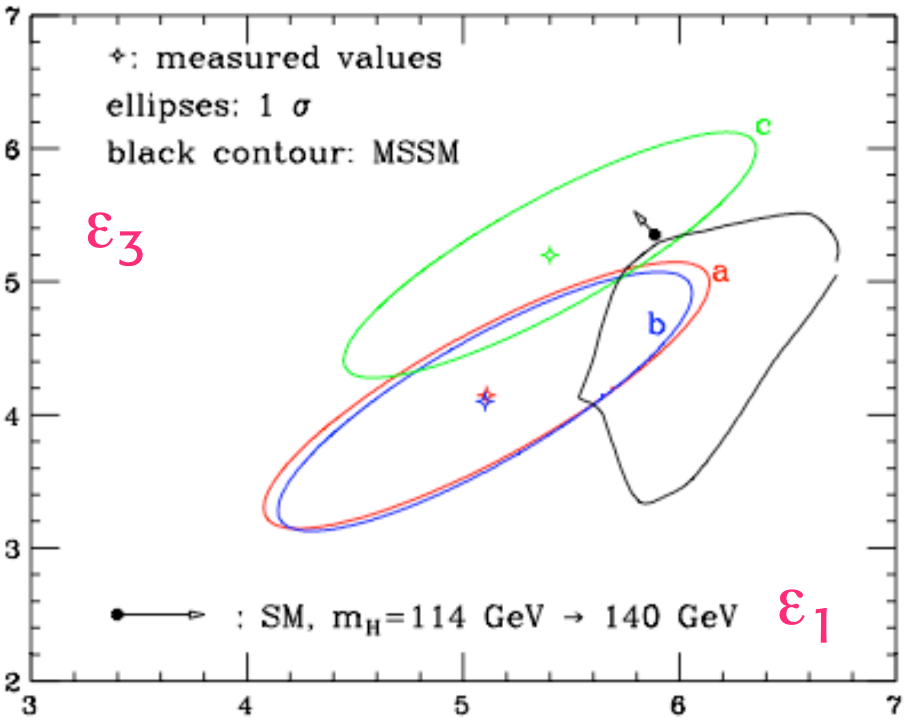


ε_1 is ~OK (on the low side), ε_2 is a bit low (m_W),
ε_3 depends on $\sin^2\theta$: low for $[\sin^2\theta]_l$ (m_H)

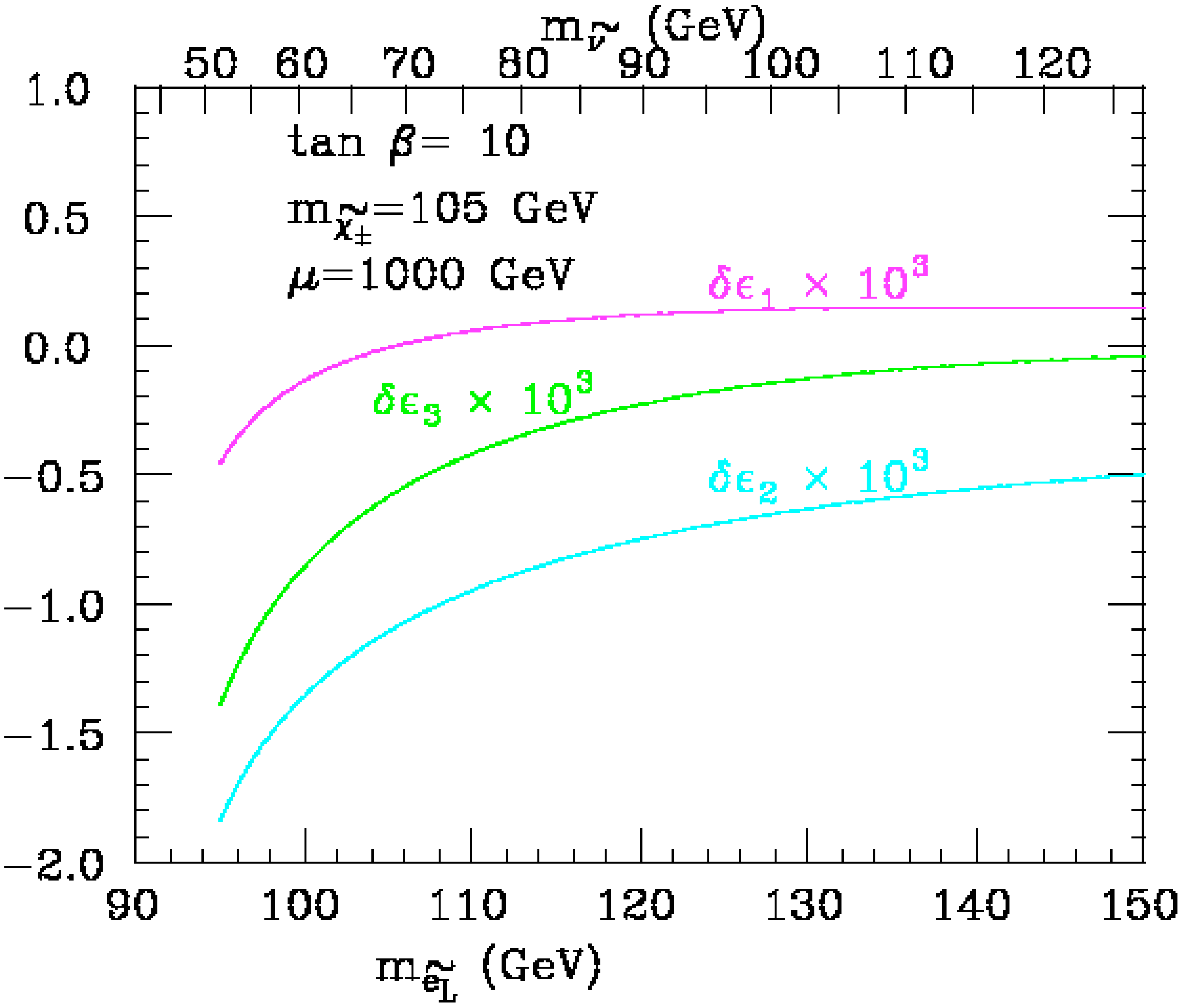
MSSM: $m_{\tilde{e}L} = 96\text{-}300$ GeV, $m_{\chi^-} = 105\text{-}300$ GeV,
$\mu = (-1)\text{-}(+1)$ TeV, $tg\beta = 10$, $m_h = 114$ GeV,
$m_A = m_{\tilde{e}R} = m_{\tilde{q}} = 1$ TeV

Units: 10^{-3}





to get
large
(ie ~1σ)
effects
s-leptons
and s-ν's
plus
gauginos
must be
as light as
possible
given the
present exp.
bounds!



In general in MSSM: $m^2_{\tilde{e}^-}=m^2_{\tilde{\nu}}+m^2_W|\cos2\beta|$

Light SUSY is compatible with $(g\text{-}2)_\mu$

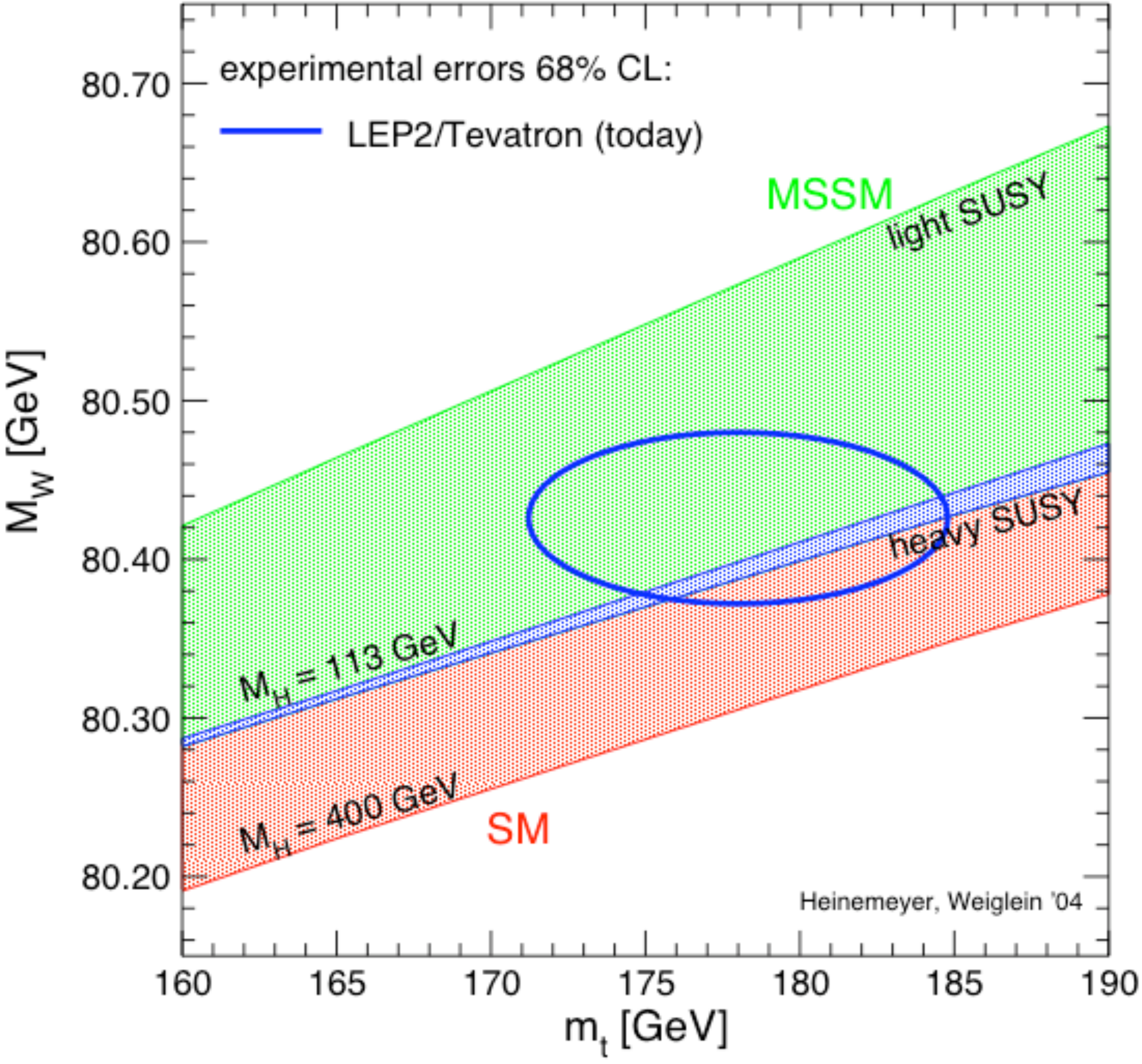
Typically at large tgβ:

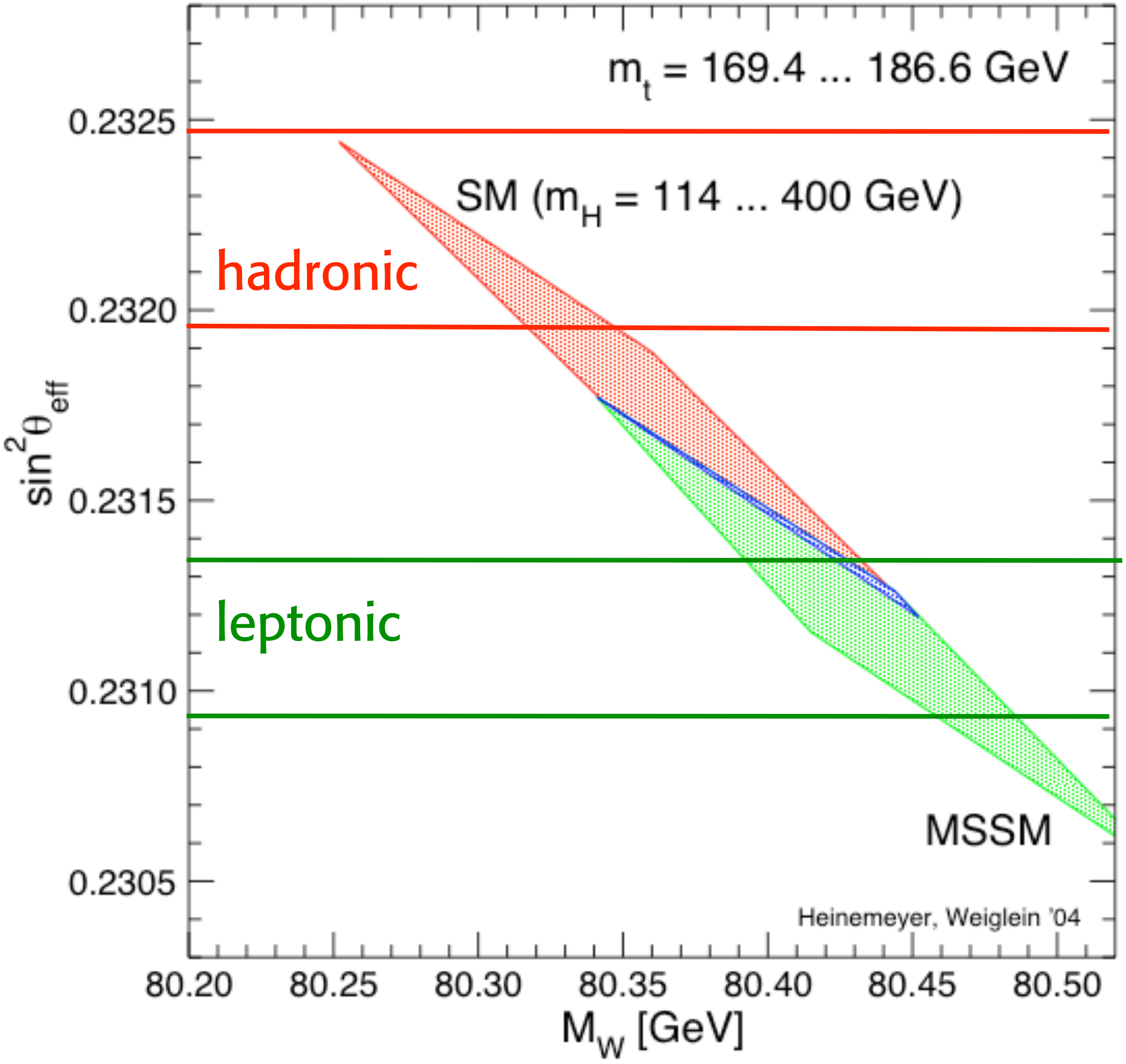
Exp. ~275

$$\delta a_\mu \sim 130\ 10^{-11}(100\ \mathrm{GeV}/m)^2\ tg\beta$$

OK for e.g. tanβ~4, m_{χ^+}~ m ~140 GeV

Light s-leptons and gauginos predict a deviation!


experimental errors 68% CL:
LEP2/Tevatron (today)
MSSM
light SUSY
heavy SUSY
M_H = 113 GeV
M_H = 400 GeV
SM
Heinemeyer, Weiglein '04
M_W [GeV]
80.20
80.30
80.40
80.50
80.60
80.70
m_t [GeV]
160
165
170
175
180
185
190

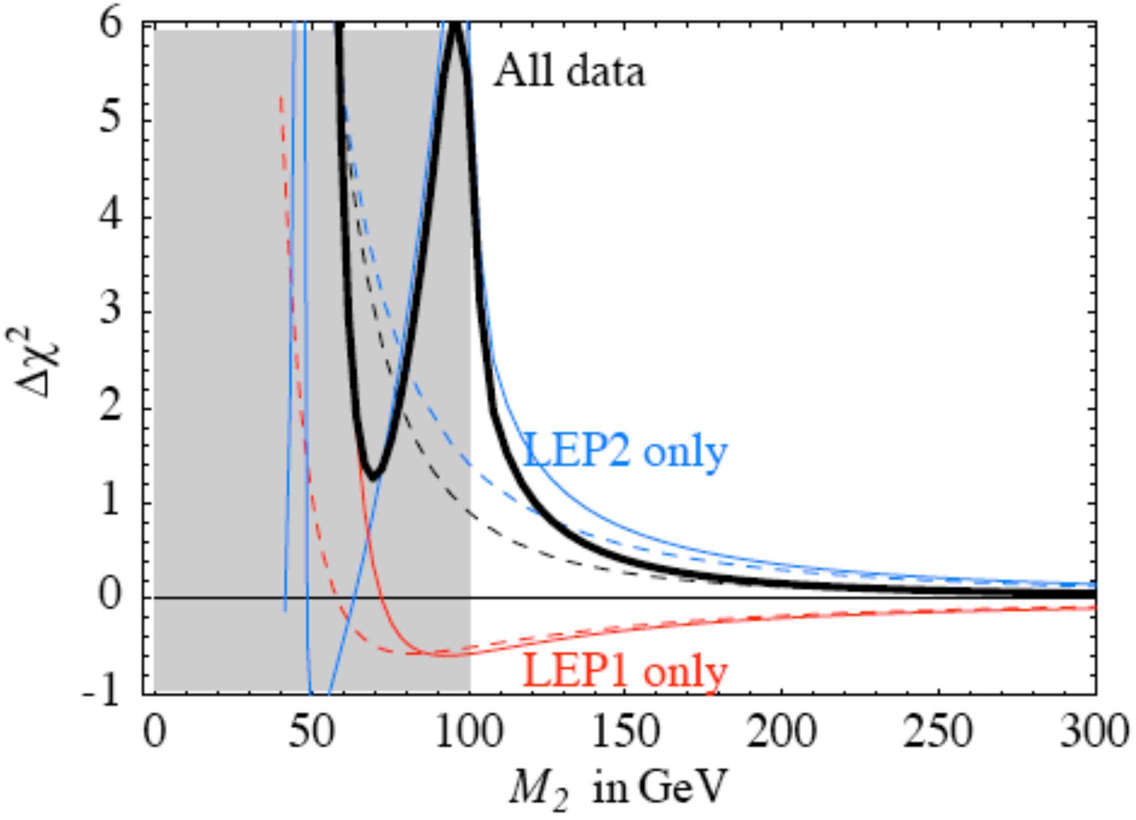

m_t = 169.4 ... 186.6 GeV
SM (m_H = 114 ... 400 GeV)
hadronic
leptonic
MSSM
Heinemeyer, Weiglein '04
sin²θ_eff
0.2325
0.2320
0.2315
0.2310
0.2305
80.20
80.25
80.30
80.35
80.40
80.45
80.50
M_W [GeV]

Recent:

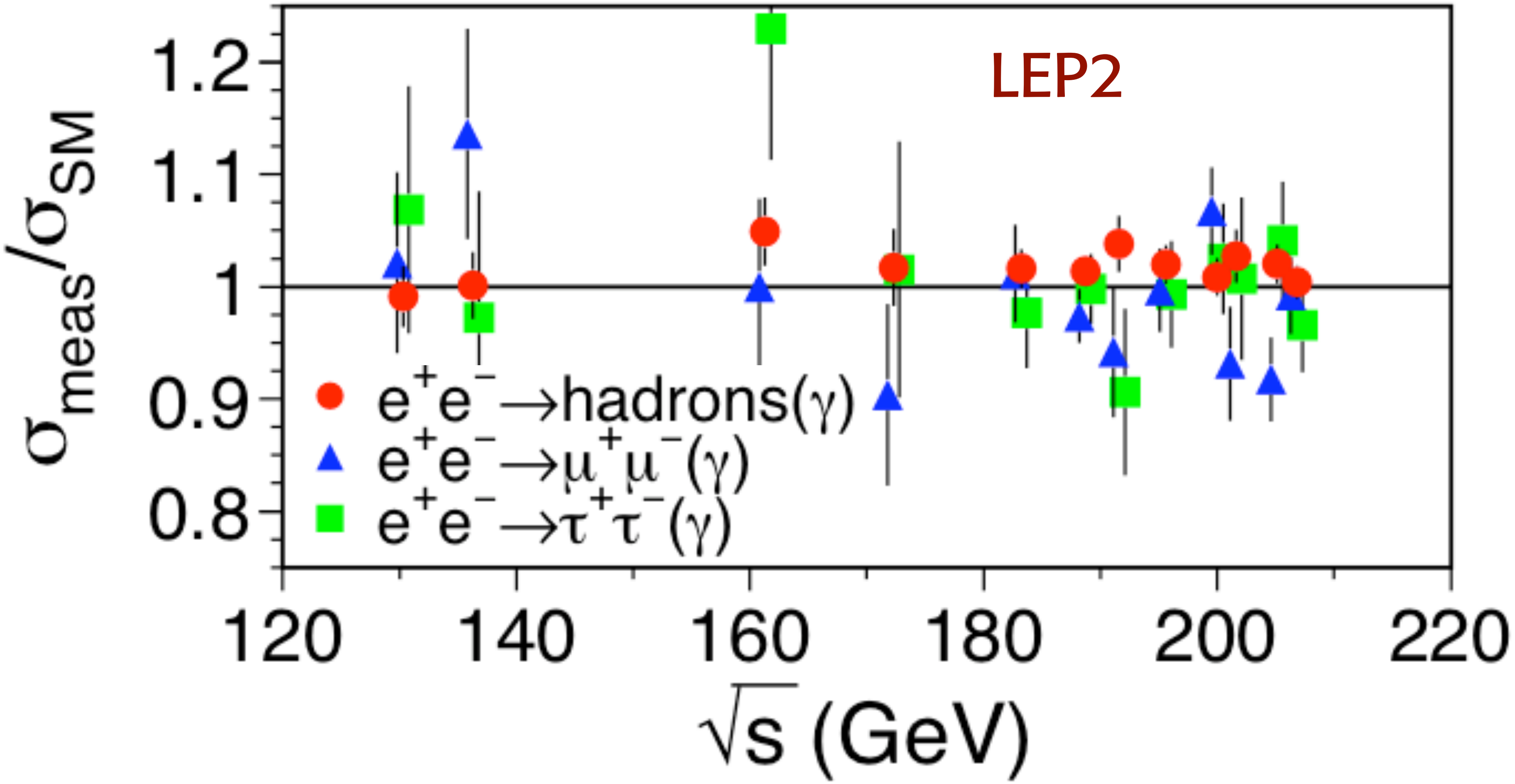
However, LEP2 data do not support the virtual effects of light SUSY Marandella, Schappacher, Strumia '05

When including LEP2: ε1, ε2, ε3 --> $\hat{S}, \hat{T}, W, Y$

Barbieri, Pomarol, Rattazzi, Strumia '04



A 1.7σ excess in the hadronic cross-section at LEP2



Virtual light SUSY effects would go in the opposite direction.
But this effect looks too large to be a virtual SUSY effect
(a 2% effect is like increasing α_s by a factor 1.5)

SUSY and flavour

In general new sources of FCNC and CP violation are introduced e.g. from s-quark mass matrices

Universality and alignment should be assumed at a large scale, but ren. group running can still produce large effects

The MSSM does provide a realization of MFV in the assumption of R parity conservation, universality of soft masses and proportionality of trilinear terms to the SM Yukawas (still broken by ren. group running)

Large effects in the lepton sector well possible
(eg μ->eγ (MEG), τ->μγ).
Made even more plausible by ν large mixings

Dark Matter

At the end of the XIX century J. J. Thomson showed the necessity of new physics (beyond em and gravity) proving that the energy from the sun and the stars cannot be obtained from chemistry

Today the clearest evidence for new physics comes from dark matter and dark energy

[More and more unity of particle physics and cosmology]

Dark matter could be accessible to present particle physics: a most important mission (LHC)

Dark Matter

WMAP, SDSS,
2dFGRS….

Most of the Universe is not made up of atoms: $\Omega_{tot} \sim 1$, $\Omega_b \sim 0.044$, $\Omega_m \sim 0.27$
Most is Dark Matter and Dark Energy

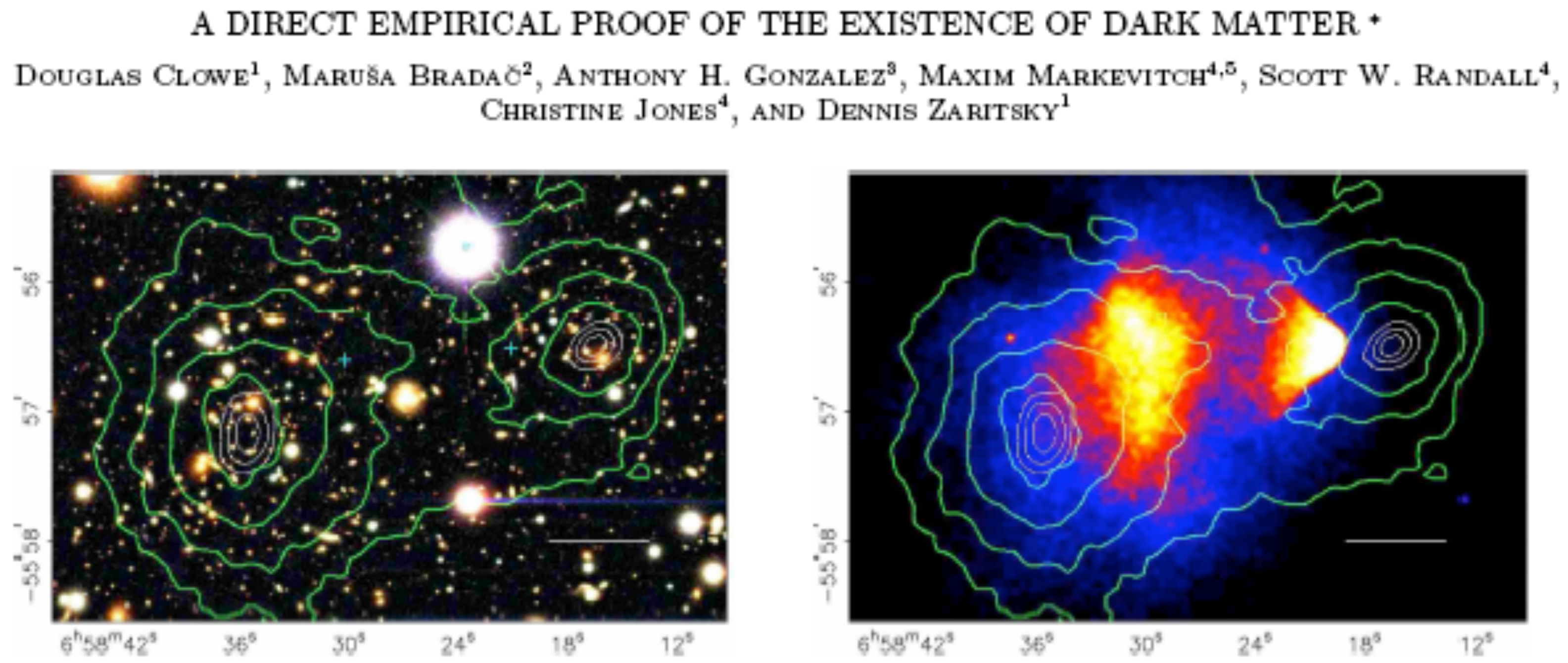
Most Dark Matter is Cold (non relativistic at freeze out)
Significant Hot Dark matter is disfavoured
Neutrinos are not much cosmo-relevant: $\Omega_\nu < 0.015$

SUSY has excellent DM candidates: eg Neutralinos (--> LHC)
Also Axions are still viable
(in a mass window around m $\sim 10^{-4}$ eV and $f_a \sim 10^{11}$ GeV
but these values are simply a-posteriori)

Identification of Dark Matter is a task of enormous importance for particle physics and cosmology

LHC?

A new confirmation of dark matter (astro-ph/0608407)



A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER *

Douglas Clowe[1], Maruša Bradač[2], Anthony H. Gonzalez[3], Maxim Markevitch[4,5], Scott W. Randall[4], Christine Jones[4], and Dennis Zaritsky[1]

Two galaxy clusters collide.
Most baryonic matter is in the gas.
The gas is stopped in the collision, the stars continue.
Grav. lensing shows that the potential follows the stars.
Hence most of the matter is hidden around the stars.
No alternative theory of gravitation can explain this.

LHC has good chances because it can reach any kind of WIMP:

WIMP: weakly interacting particle with m ~ 10^1-10^3 GeV

For WIMP’s in thermal equilibrium after inflation the density is:

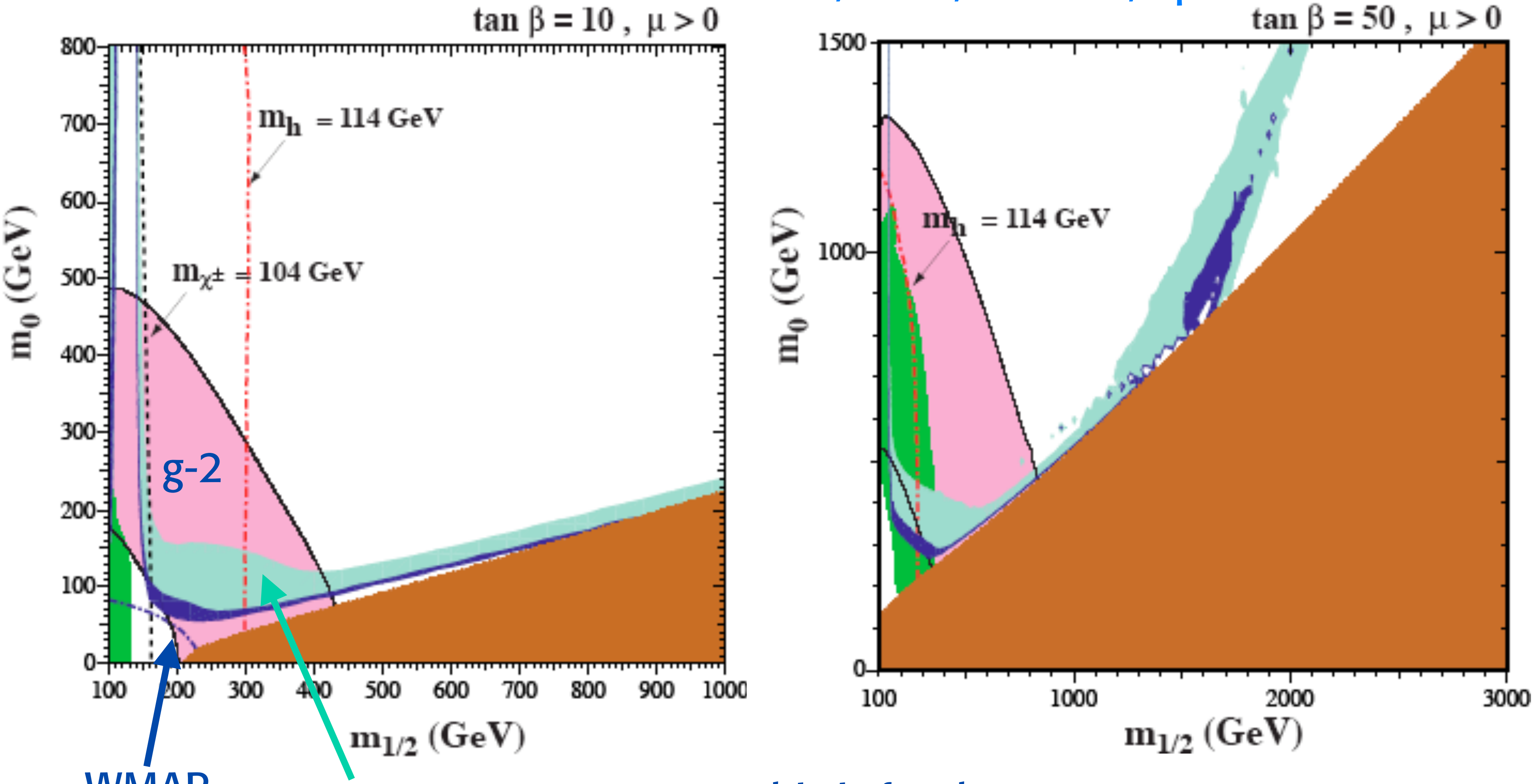
$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\mathrm{Pl}}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1 \ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

can work for typical weak cross-sections!!!

This “coincidence” is a good indication in favour of a WIMP explanation of Dark Matter

SUSY Dark Matter: we hope it is the neutralino

Ellis, Olive, Santoso, Spanos

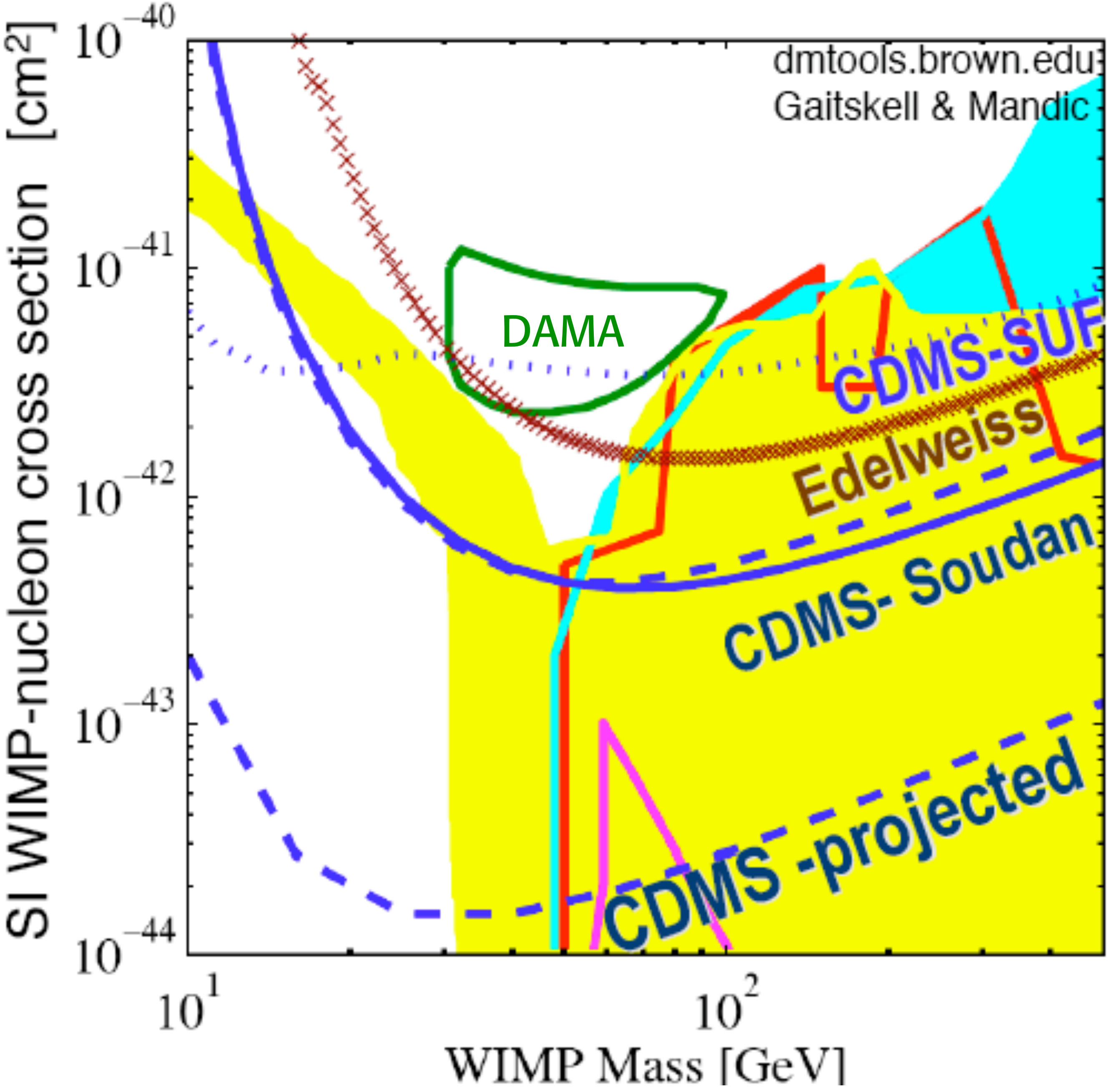


WMAP

$0.1<\Omega h^2<0.3$

This is for the CMSSM
With less constraints, more space

Search for neutralinos



No signals of SUSY sofar (not in EW tests, not in flavour)-->
--> fine tuning is needed at the level of a few percent

Possibly some tricks could help:

- Only 3rd generation spartners light
- A more complicated Higgs sector (NMSSM, λSUSY)
- ....

But a new wave of model building was started

Sofar no model has emerged which needs much less fine tuning than SUSY.
The need of fine tuning appears to be imposed on us by the data!

Pessimist views:
If you must tolerate % fine tuning, why not $^0/_{00}$ and we see no new physics at the LHC? Even worse:
perhaps naturalness not a good criterium --> anthropic

Principles tried to ensure a light Higgs:

H is a (pseudo) Goldstone; no mass, derivative couplings

Little Higgs

H is the 5th comp of a gauge boson in 5 dimensions

H is replaced to some extent by boundary conditions or orbifolding in extra-dim. models

Extra dimensions

Little Higgs Models

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

$$\underset{\substack{\uparrow\\ \text{global}}}{G} \supset [SU(2) \underset{\substack{\uparrow\\ \text{gauged}}}{\otimes} U(1)]^2 \supset SU(2) \underset{\substack{\uparrow\\ \text{SM}}}{\otimes} U(1)$$

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:

$$\left.\begin{array}{ll} \delta m^2_{H|top} & \text{new coloured fermion } \chi \text{ with } Q=2/3 \\ \delta m^2_{H|gauge} & W', Z', \gamma' \\ \delta m^2_{H|Higgs} & \text{new scalars} \end{array}\right\} \sim 1 \text{ TeV}$$

2 Higgs doublets ~0.2 TeV

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

quark doublet $\longrightarrow$ triplet

$$\begin{bmatrix} t_L \\ b_L \\ \chi_L \end{bmatrix}$$

SU(3) broken spont.ly

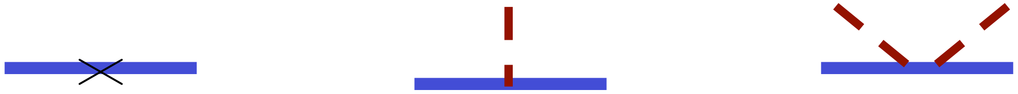
$$\varphi = \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix}$$

Yukawa coupling:

expl. SU(3) breaking

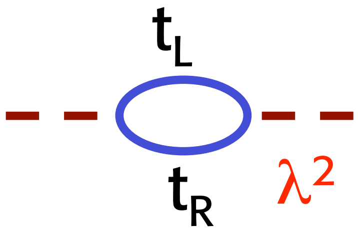
$$\lambda \begin{bmatrix} t^\dagger{}_L & b^\dagger{}_L & \chi^\dagger{}_L \end{bmatrix} \exp i \frac{\begin{bmatrix} - & h \\ h^\dagger & - \end{bmatrix}}{f} \begin{bmatrix} 0 \\ 0 \\ f \end{bmatrix} t_R + M\chi^\dagger{}_L \chi_R$$

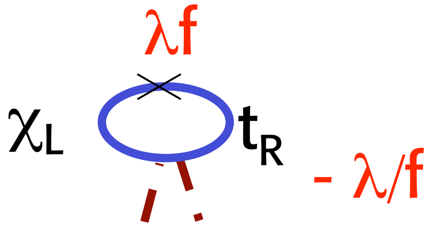
$$\lambda f \chi^\dagger{}_L t_R + i\lambda t^\dagger h t_R - \frac{\lambda}{2f} \chi^\dagger{}_L t_R h^\dagger h + \ldots$$



top loop:

coeff. Λ^2





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 $m_h \sim 200$ GeV
better if m_H heavier

Can be fixed by complicating the model: T-parity, mirror fermions….

Cheng, Low

Little Higgs with T parity

T parity interchanges the two SU(2)xU(1) groups

Standard gauge bosons are T even while heavy ones are T odd

As a consequence no tree level contributions from heavy W & Z in processes with external SM particles

More in general, all corrections to EW observables at loop level only

Like for R-parity in MSSM, the lightest T-odd particle is stable (usually a B') and can be a candidate for Dark Matter.
T-odd particles are produced in pairs (missing energy).

In conclusion, for little Higgs:

E-W Precision Tests? Problems. Needs epicycles: T-parity, mirror fermions….

Cheng, Low

But the worse is:
Little Higgs provides just a postponement:
UV completion? GUT's?

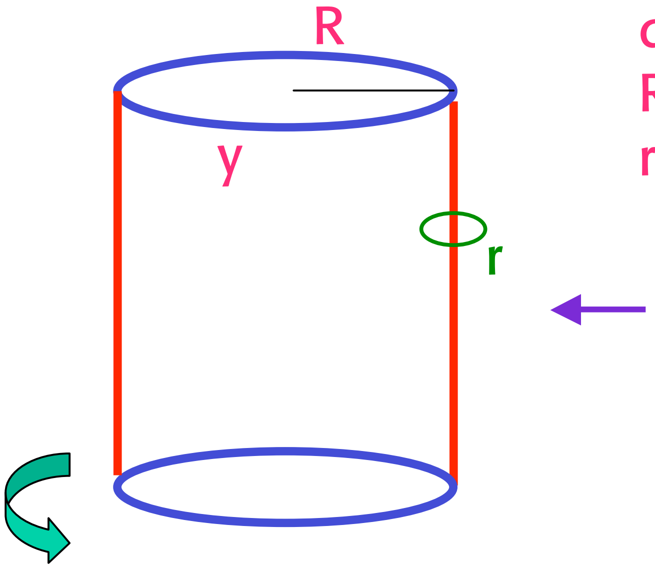
Extra Dimensions

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

Arkani-Hamed, Dimopoulos/ Dvali+Antoniadis

Early formulation: inspired by string theory, one assumes:

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



the compactified version

y: extra dimension
R: compact'n radius

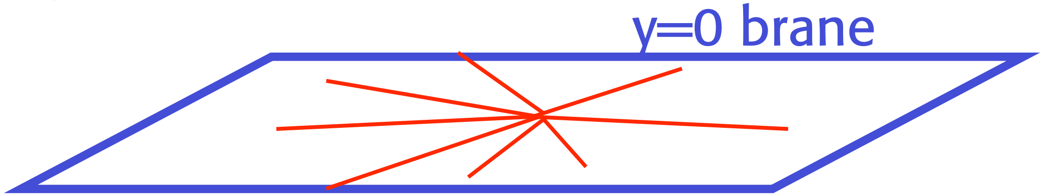
y=0 "our" brane (possibly with thickness r)

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

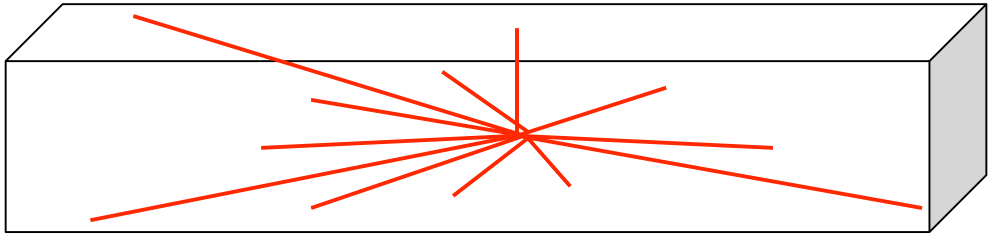
M_{Pl} large as G_N weak

The idea is that gravity appears weak as a lot of lines of force escape in extra dimensions 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~ 1 mm (close to limits)
n = 4 R~ 10^{-9} cm
•••

Limits on deviations from Newton law

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

Hoyle et al,

PRL 86,1418,2001

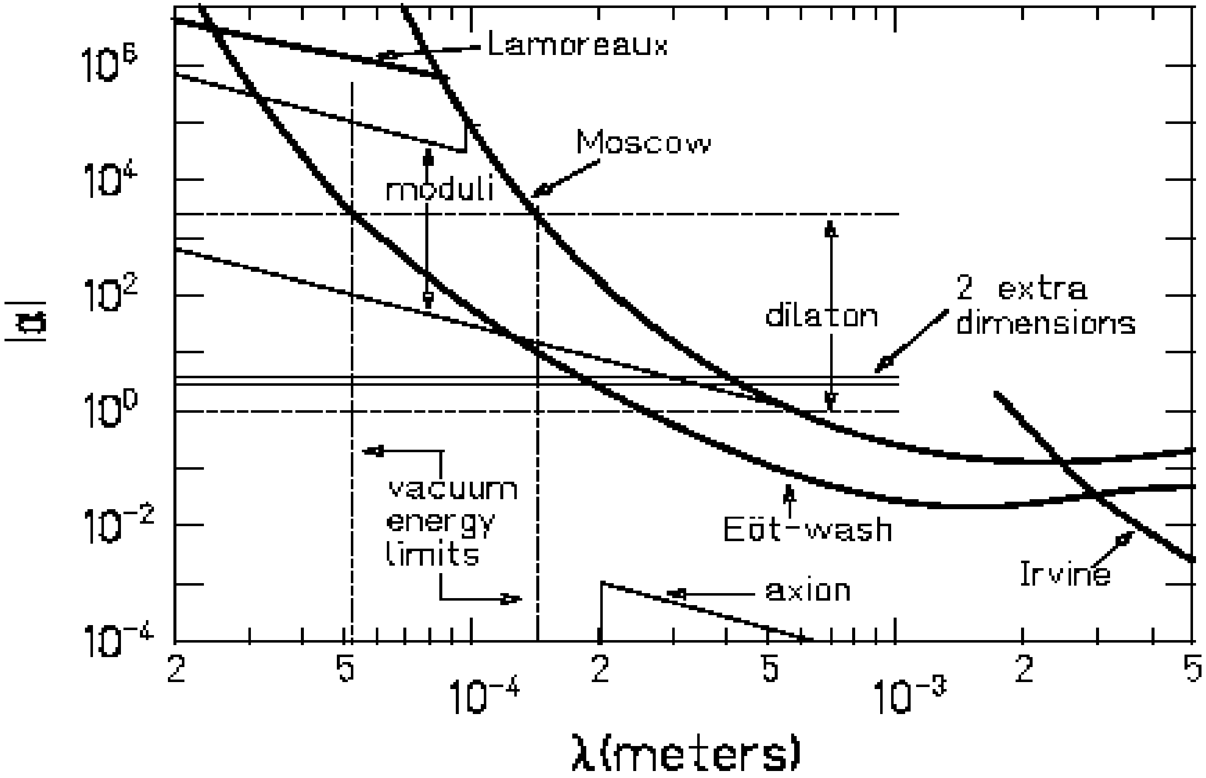


FIG. 4. 95% confidence upper limits on $1/r^2$-law violating interactions of the form given by Eq. (2). The region excluded by previous work [2,3,20] lies above the heavy lines labeled Irvine, Moscow and Lamoreaux, respectively. The data in Fig. 3 imply the constraint shown by the heavy line labeled 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].

- Large Extra Dimensions is an 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)?

    needs d-4 large

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

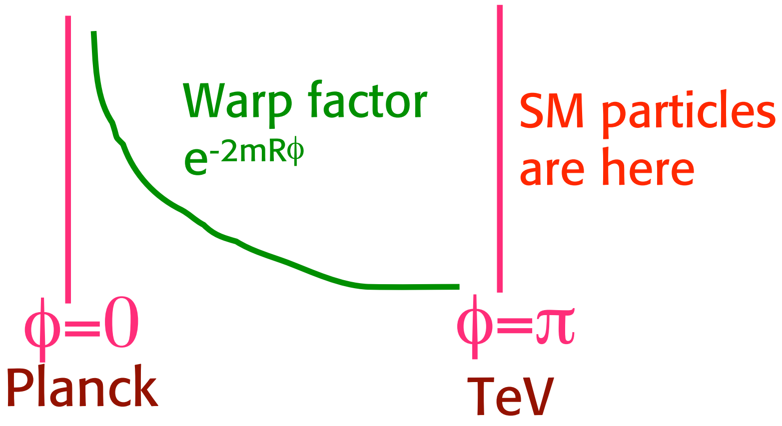
  - $\Lambda \sim 1/R$ must be small (m_H light)

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

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

- Randall-Sundrum: warped versions with non factorizable metric emerged as more promising

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



Warp factor $e^{-2mR\phi}$

SM particles are here

$\phi=0$ Planck

$\phi=\pi$ TeV

This non-fact.ble metric is solution of Einstein eq.s with 2 branes at $\phi=0,\pi$ and specified 5-dim cosmological term

$m \sim M_{Pl}$ for all mR: $m^2 \sim M_{Pl}^2(1-e^{-2mR\phi})$

All 4-dim masses m_4 are scaled down with respect to 5-dim masses $m_5 \sim M_{Pl}$ by the warp factor: $m_4=M_{Pl}e^{-mR\pi}$

The hierarchy problem demands that mR ~ 12: not too big!!

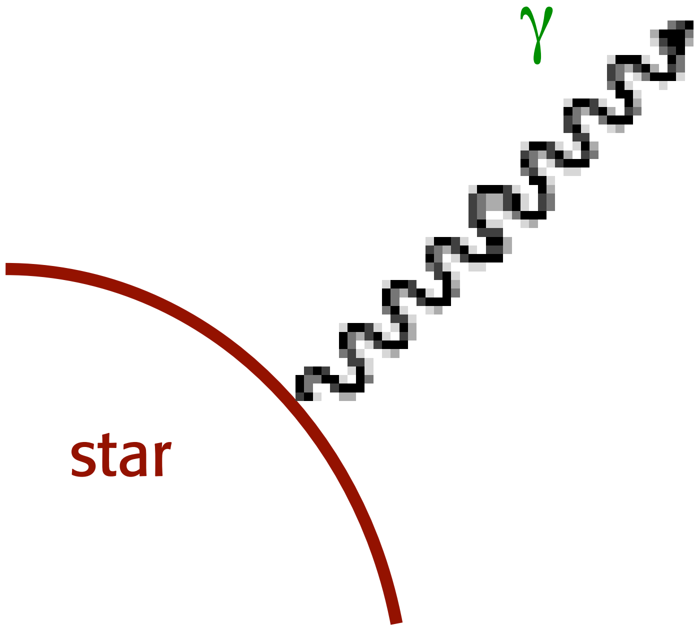
R not large in this case!

Stabilization of mR at a compatible value can be assured by a scalar field in the bulk with a suitable potential

↘ "radion"

Goldberger, Wise

$h\nu$ here is smaller:
kinetic energy lost
by climbing out of
grav. field



Similarly mc^2 is smaller
by the same factor
$g_{00}^{1/2}$--> $m_4=M_{Pl}e^{-mR\pi}$

Generic feature:

compact dim. → Kaluza-Klein (KK) modes

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

Many possibilities:

- SM fields on a brane or in bulk

The brane can itself have a thickness r:

$1/r >\sim 1\,\text{TeV}$ → $r <\sim 10^{-17}$ cm

→ KK recurrences of SM fields: W_n, Z_n etc

cfr:
- Gravity always 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)

emerges as the most promising

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

$m_{weak} = M_{Pl} \exp(-mR\pi)$ → $Rm \sim 12$

In RS models there is a tower of spin-2 KK graviton resonances.

At the LHC (ie on the TeV brane) their masses are

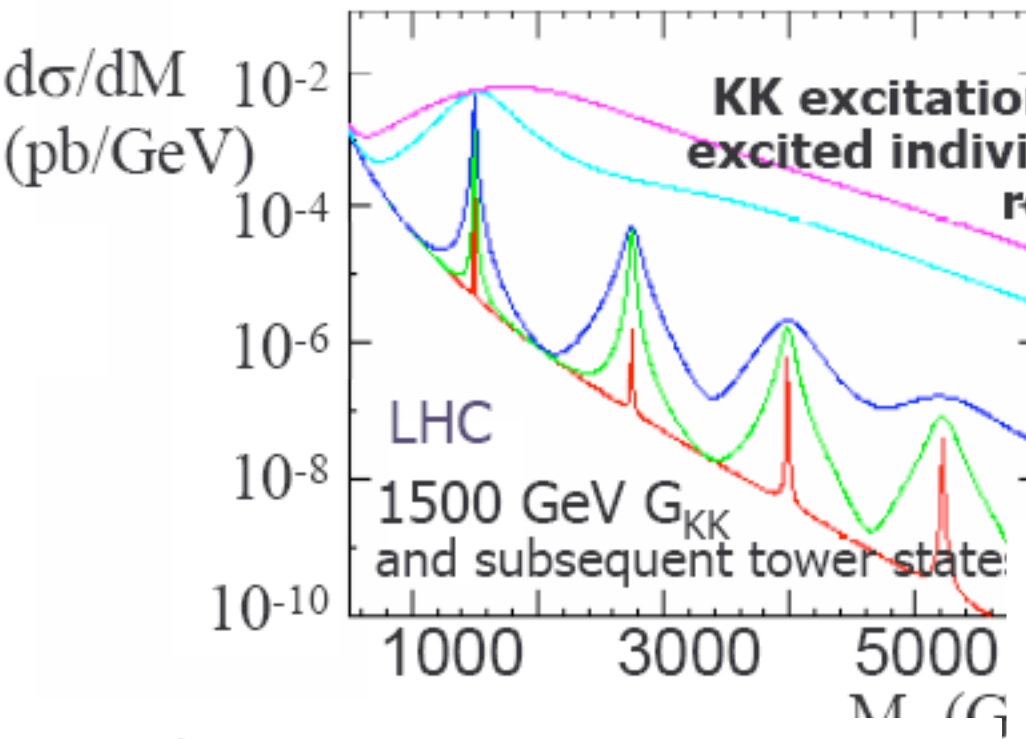
$M_n = m\, x_n \exp(-mR\pi)$

$J_1(x_n)=0$
$x_n = 3.8,\ 7.0\ ,\ 10.2\ldots.$

Their couplings are of EW order and universal for all particles

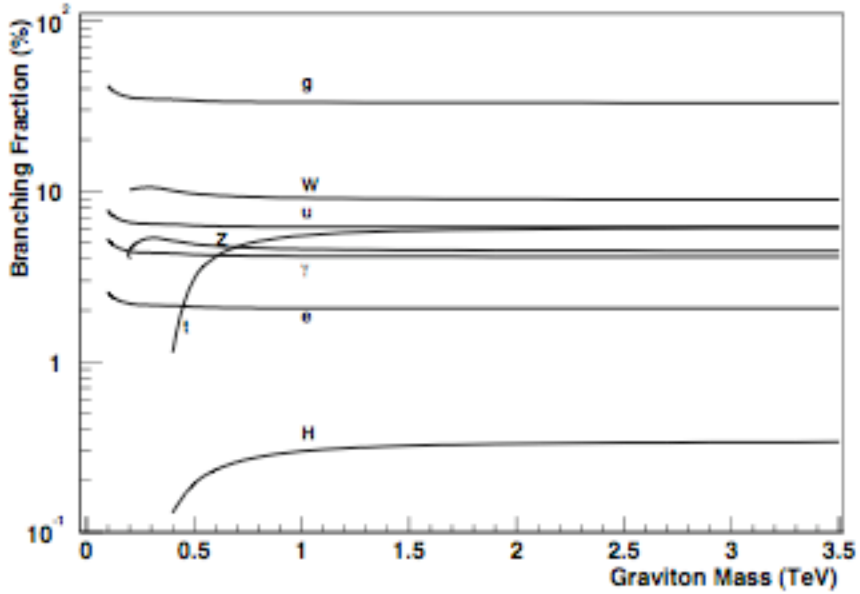
$\mathcal{L} = 1/\Lambda_\pi\, h_{\mu\nu}\, T^{\mu\nu}$

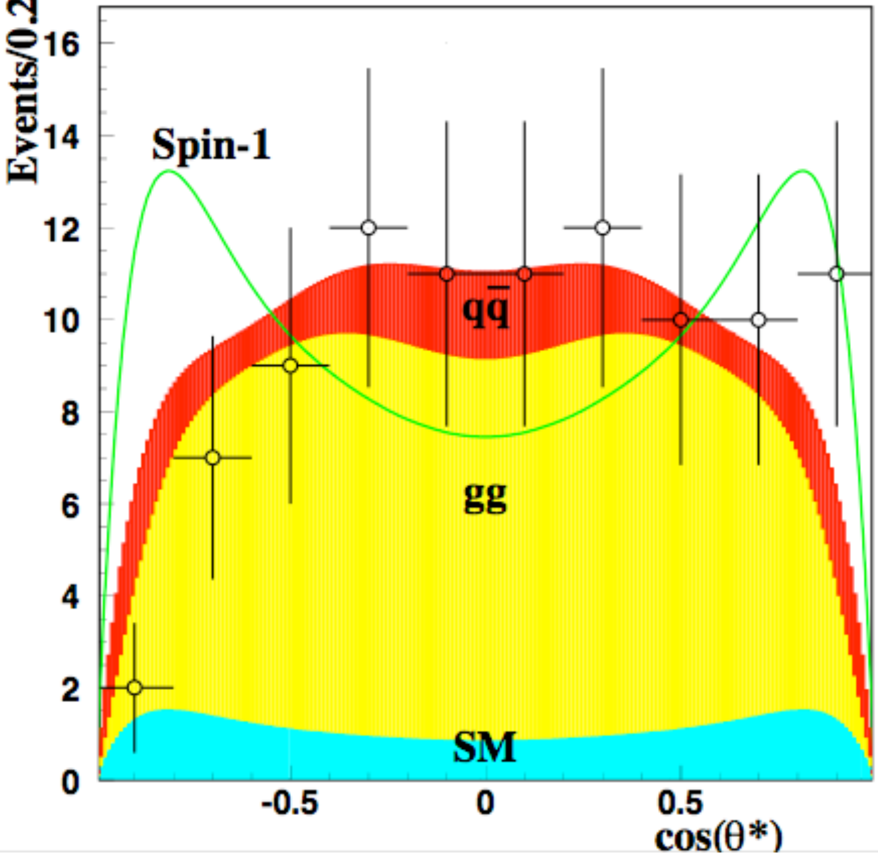
$\Lambda_\pi \sim M_{Pl} \exp(-mR\pi)$



KK excitations can be excited individually on resonance

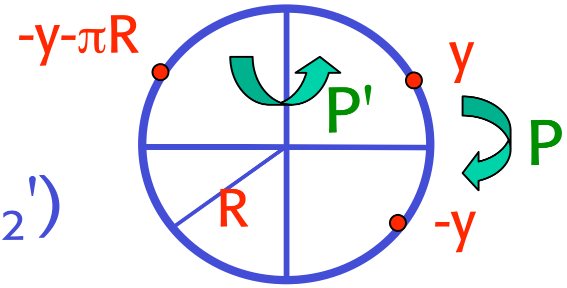
Davoudiasl, Hewett, Rizzo'00
Allanach et al, '00, '02





Symmetry breaking by orbifolding

P and P' break the symmetries of 5-dim theory



$S/(Z_2 x Z_2')$

Z_2-> P: y ⟺ -y

On the branes at the fixed points y=0 and y= -πR/2 symmetry is reduced

Z_2'-> P': y' ⟺ -y'

y'=y + πR/2

or y ⟺ -y- πR

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

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

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

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

Symmetry breaking at the weak scale

1/R ~ o(TeV)

- **SUSY Breaking**

Barbieri, Hall, Nomura.....Papucci, Marandella.

5D SUSY-SM compactified on S/(Z_2xZ_2')

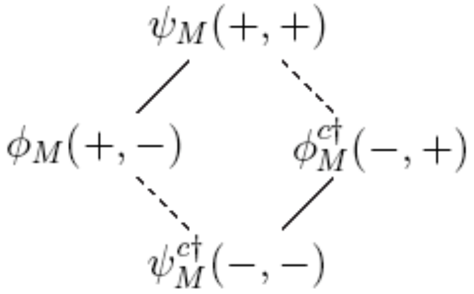
P breaks N=2 SUSY, P' N=1 SUSY (Scherk-Schwarz)

effective theory non-SUSY (SUSY recovered at $d < R$)

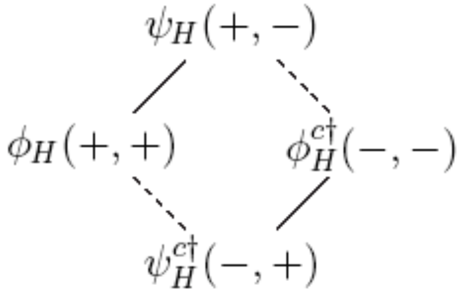
- Higgs boson mass in principle computable

no invariant Higgs mass operator in 5-dim

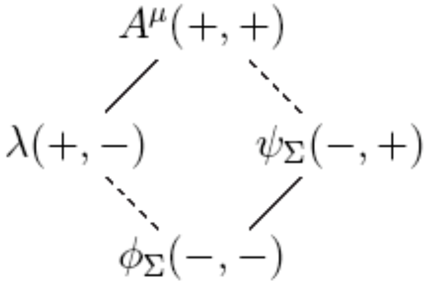
rather insensitive to UV m_H ~ 110 - 125 GeV



matter



Higgs (only 1!)



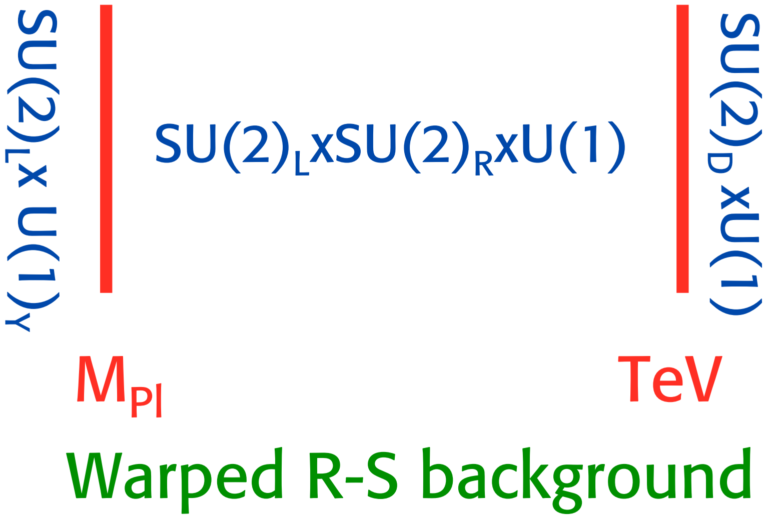
gauge

all are in the bulk

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

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

The only models were no Higgs would be found at LHC.
But signals of new physics would be observed



$SU(2)_L x U(1)_Y$

$SU(2)_L xSU(2)_R xU(1)$

$SU(2)_D xU(1)$

M_{Pl}

TeV

Warped R-S background

Symmetries broken by
Boundary Conditions (BC)
on the branes

Altogether only $U(1)_Q$
unbroken

- Unitarity breaking (no Higgs) delayed by KK recurrences

- Dirac fermions on the bulk (L and R doublets). Only one chirality has a zero mode on the interval

y-Boundary Conditions

A scalar example

Action: $$S = \int dx \int dy \left[\frac{1}{2}(\partial_M \phi)^2 - V(\phi)\right] + \int_{y=0,\pi R} dx \left[\frac{1}{2} M^2 \phi^2\right]$$

Varying the action: $$\delta S = \int dx \int dy \left[\Box \phi + \frac{\partial V}{\partial \phi}\right]\delta\phi + \int dx [(\partial_y \phi - M^2 \phi)\delta\phi]_0^{\pi R}$$

Thus, at $y=0,\pi R$ $\phi_{0,\pi R} = cte \Rightarrow 0$ or $[\partial_y \phi - M^2 \phi]_{0,\pi R} = 0$

Note: $M^2 \to 0$ $[\partial_y \phi]_{0,\pi R} = 0$ Neumann $\phi \sim \cos\frac{ny}{R}$

$M^2 \to$ infinity $\phi_{0,\pi R} = 0$ Dirichlet $\phi \sim \sin\frac{ny}{R}$

Gauge theory: $(A_\mu^a)_{0,\pi R} = 0$ or $[\partial_y A_\mu^a - V^{ab} A_\mu^b]_{0,\pi R} = 0$

$V^{ab} = v t^a t^b v$ can arise from a Higgs H localised on the brane: $D_M H D^M H$, $D_M = \ldots + t^a A_M^a$, $\langle H \rangle = v$

Suppose we want, at y=πR: $\partial_y A = VA$

We set: $A = A_0 \cos My$

Note. At y=0: $\partial_y A = 0$

We find M (mass of boson A):

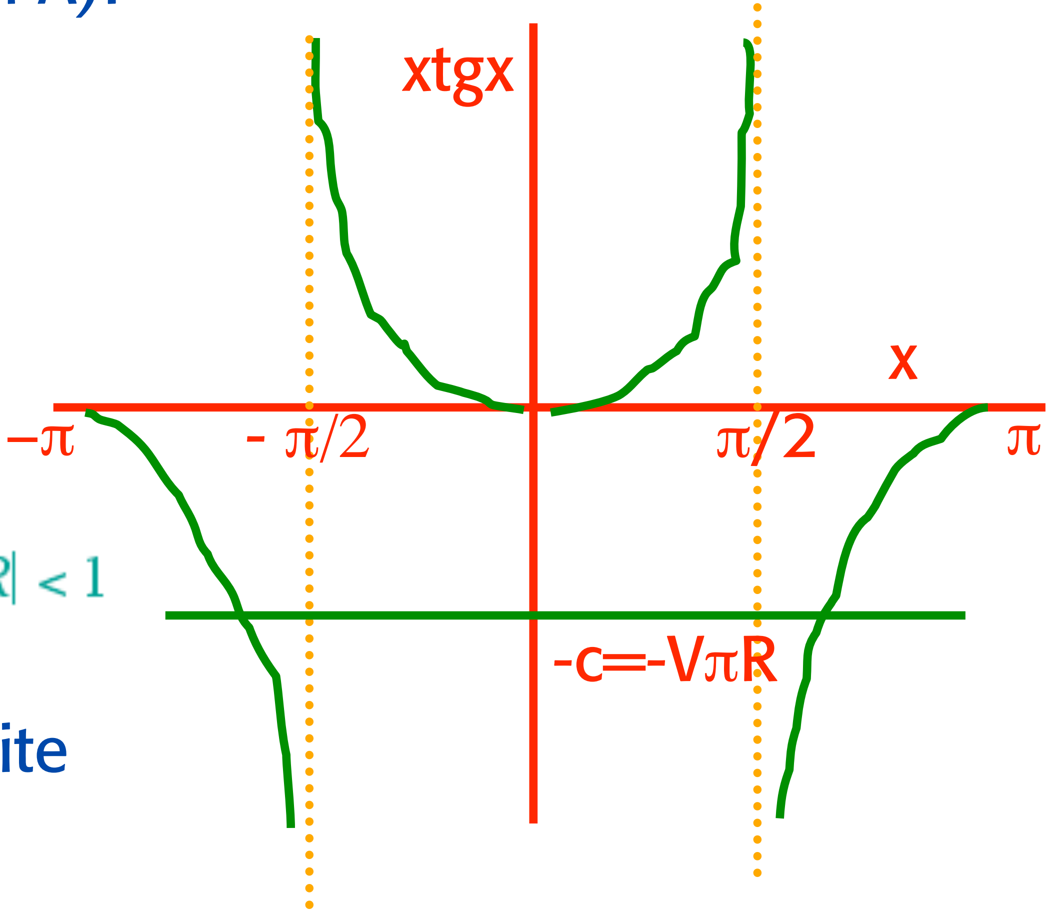
$$-M\sin M\pi R = V\cos M\pi R$$

$$-M\pi R\sin M\pi R = V\pi R\cos M\pi R$$

$$x\,tgx = -c$$

$$\frac{\pi}{2} < |x| < \pi \longrightarrow \frac{1}{2} < |MR| < 1$$

Note that MR remains finite for V-> infinity



With no Higgs unitarity violations, eg:

$$A\left(W_L^+ W_L^- \to Z_L Z_L\right) = \frac{G_F E^2}{8\sqrt{2}\pi}$$

At E ~ 1.2 TeV unitarity is violated

In Higgsless models unitarity is restaured by exchange of infinite KK recurrences, or the breaking is delayed by a finite number

$Z_k = k_{th}$ KK

Cancellation guaranteed
by sum rules implied
by 5-dim symmetry

$$g^2_{WWWW} - e^2 - \sum_k g^2_{WWZ_k} = 0 \; ;$$

$$4M_W^2 \, g^2_{WWWW} - 3\sum_k g^2_{WWZ_k} M_{Z_k^2} = 0 \; .$$

Boundary conditions allow a general breaking pattern
(for example, can lower the rank of the group)

equivalent to have generic Higgses on the brane
(with vev -> infinity)

Breaking by orbifolding is more rigid
(the rank remains fixed)

corresponds to Higgs in the adjoint (A_5 the 5th A_M)

No convincing, realistic Higgsless model for EW symmetry breaking emerged so far:

Serious problems with EW precision tests

e.g. Barbieri, Pomarol, Rattazzi '03 ; Chivukula et al

also with Z->bb

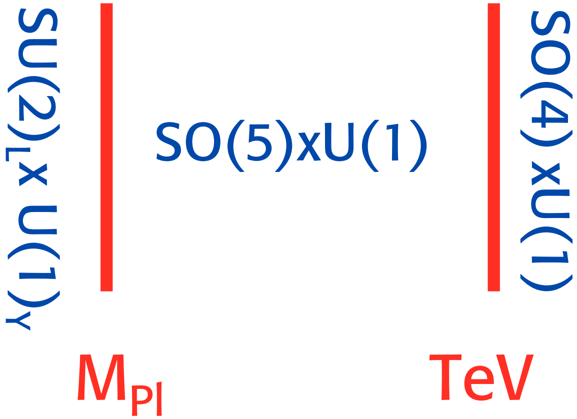
Substantial fine tuning required

Best try: Cacciapaglia et al '06

However be alerted of possible signals at the LHC: no Higgs but KK recurrences of W, Z and additional gauge bosons

- Composite Higgs in a 5-dim AdS theory

Agashe, Contino, Pomarol



A new way to look at walking technicolor using AdS/CFT corresp.

Warped R-S background

As in Little Higgs models

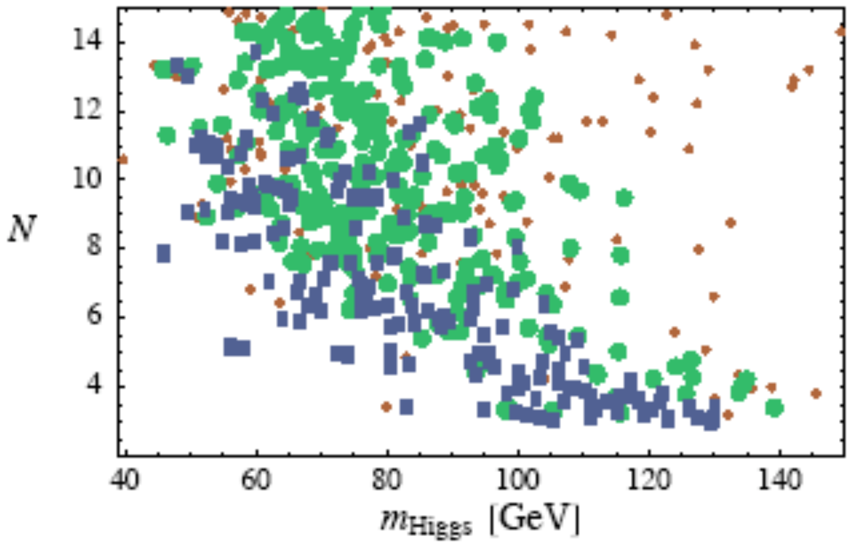
The Higgs is a PGB and EW symmetry breaking is triggered by top-loop effects. In 4-dim the bulk appears as a strong sector

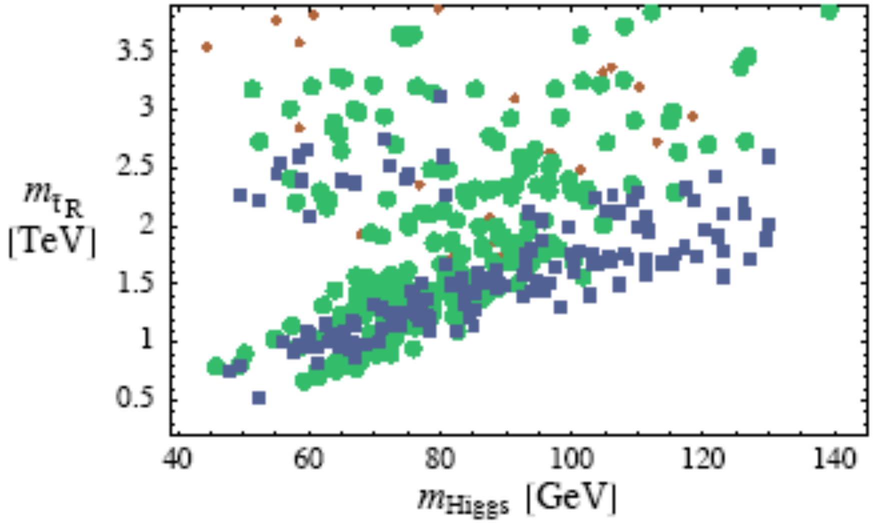
The 5-dim theory is weakly coupled so that the Higgs potential and EW observables can be computed

The Higgs is light: $m_H < 140$ GeV

The Higgs is (too?) light
in this model

Problems with EW precision
tests and Zbb (can be fixed)





Signals at the LHC:
a light Higgs and
new resonances at ~ 2 TeV

Apart from Higgsless models (if any?) all theories discussed
here have a Higgs in LHC range (most of them light)

The anthropic route: is naturalness relevant?

The scale of the cosmological constant is a big mystery.

$\Omega_\Lambda \sim 0.65 \longrightarrow \rho_\Lambda \sim (2\ 10^{-3}\ \text{eV})^4 \sim (0.1\text{mm})^{-4}$

Similar to m_ν!?

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

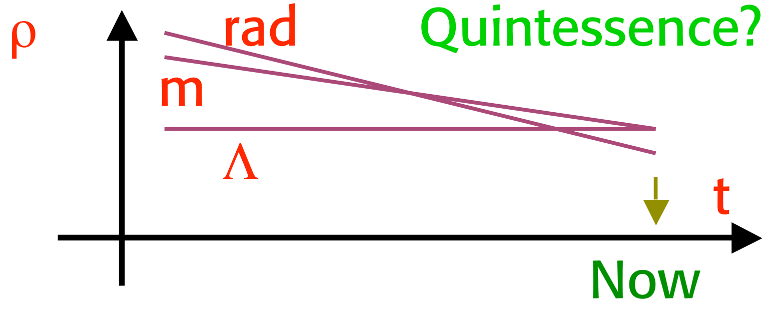
If $\Lambda_{cutoff} \sim M_{Pl} \longrightarrow \rho_\Lambda \sim 10^{123}\ \rho_{obs}$

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

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

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

Other problem:
"Why now"?



"Quintessence"
Λ as a vev of a field ϕ?

Coupled to gauge singlet matter, eg ν_R, to solve magnitude and why now?

The scale of vacuum energy poses a large naturalness problem!

So far no clear way out:

- A modification of gravity? (extra dim.)
- Leak of vac. energy to other universes (wormholes)?
- • • • •

Perhaps naturality irrelevant

- Anthropic principle: just right for galaxy formation

(Weinberg)

Perhaps naturality irrelevant also for Higgs: Arkani-Hamed, Dimopoulos; Giudice, Romanino '04, String Th. Landascapes '05

Split SUSY: a fine tuned light Higgs + light gauginos
and higgsinos. All other s-partners heavy (a new scale)
Preserves coupling unification and dark matter

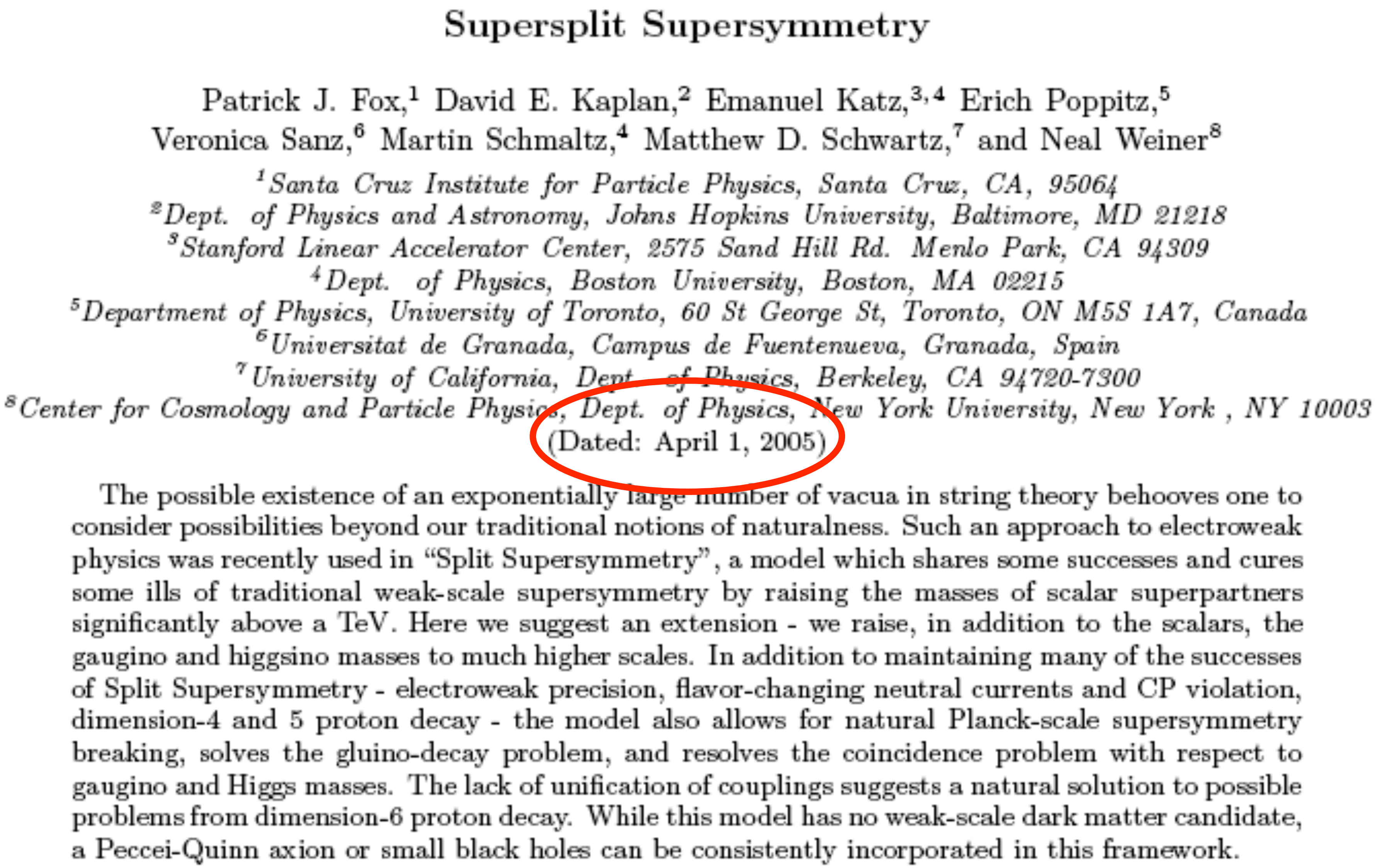
But then also a 2-scale non-SUSY GUT with axions as DM

Normal SUSY, no SUSY, split SUSY? LHC will tell

An April 1st joke?

hep-th/0503249

The SM

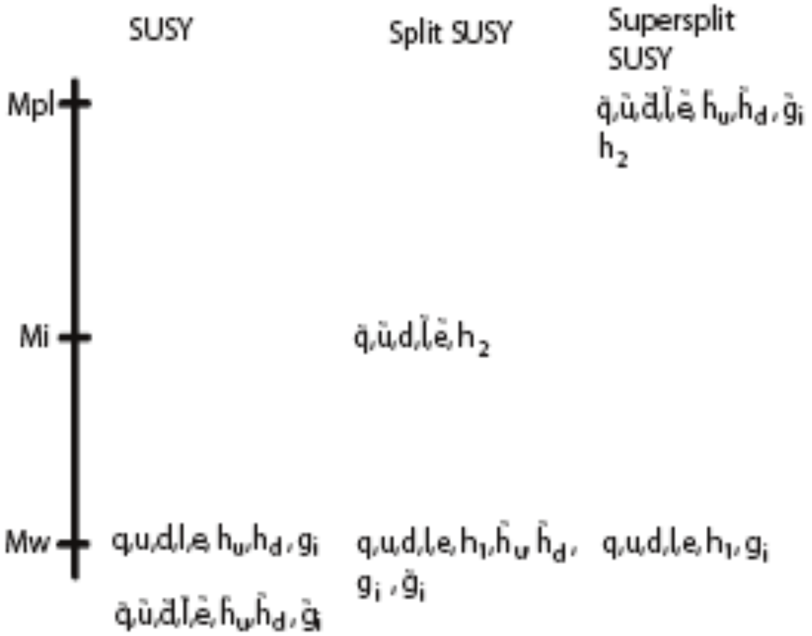


Supersplit Supersymmetry

Patrick J. Fox,[1] David E. Kaplan,[2] Emanuel Katz,[3,4] Erich Poppitz,[5]
Veronica Sanz,[6] Martin Schmaltz,[4] Matthew D. Schwartz,[7] and Neal Weiner[8]
[1] *Santa Cruz Institute for Particle Physics, Santa Cruz, CA, 95064*
[2] *Dept. of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218*
[3] *Stanford Linear Accelerator Center, 2575 Sand Hill Rd. Menlo Park, CA 94309*
[4] *Dept. of Physics, Boston University, Boston, MA 02215*
[5] *Department of Physics, University of Toronto, 60 St George St, Toronto, ON M5S 1A7, Canada*
[6] *Universitat de Granada, Campus de Fuentenueva, Granada, Spain*
[7] *University of California, Dept. of Physics, Berkeley, CA 94720-7300*
[8] *Center for Cosmology and Particle Physics, Dept. of Physics, New York University, New York , NY 10003*

(Dated: April 1, 2005)

The possible existence of an exponentially large number of vacua in string theory behooves one to consider possibilities beyond our traditional notions of naturalness. Such an approach to electroweak physics was recently used in "Split Supersymmetry", a model which shares some successes and cures some ills of traditional weak-scale supersymmetry by raising the masses of scalar superpartners significantly above a TeV. Here we suggest an extension - we raise, in addition to the scalars, the gaugino and higgsino masses to much higher scales. In addition to maintaining many of the successes of Split Supersymmetry - electroweak precision, flavor-changing neutral currents and CP violation, dimension-4 and 5 proton decay - the model also allows for natural Planck-scale supersymmetry breaking, solves the gluino-decay problem, and resolves the coincidence problem with respect to gaugino and Higgs masses. The lack of unification of couplings suggests a natural solution to possible problems from dimension-6 proton decay. While this model has no weak-scale dark matter candidate, a Peccei-Quinn axion or small black holes can be consistently incorporated in this framework.



Note added: While this work was being completed, we became aware of [18, 19, 20], a series of conference talks where a similar model was considered. While there are some similarities (specifically, field content and interactions), the philosophy is completely unrelated.

[18] S. Glashow, "Towards a Unified Theory - Threads in a Tapestry," Nobel Lecture, Dec 8, 1979.

[19] A. Salam, "Gauge Unification of Fundamental Forces," Nobel Lecture, Dec 8, 1979.

[20] S. Weinberg, "Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions," Nobel Lecture, Dec 8, 1979.

I find applying the anthropic principle to the “big” hierarchy problem excessive

After all we can find plenty of models that reduce the fine tuning from 10^{-14} to 10^{-2}: why make our Universe so terribly unlikely?

Perhaps it is relevant for the “little” hierarchy

The case of the cosmological constant is a lot different:
the context is not as fully specified as the for the SM
(quantum gravity, string cosmology, branes in extra dims., wormholes thru different Universes....)

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 one expected SUSY discovery at LEP

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

- No compelling, realistic alternative so far developed

(not an argument! Interesting models explored)

- Extra dim.s is a complex, rich, attractive, exciting possibility.
- Little Higgs models look as just a postponement

(both interesting to pursue)

Get the LHC ready fast; we badly need exp input!!!