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The Standard Model confronts the LHC

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Lecture 1

- Status of the SM EW theory
- The Higgs problem

Lecture 2

- Status of QCD
- Top quark

Lecture 3

- Problems of the SM
- Motivation for new physics at the TeV scale
- Avenues for new physics

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
- The flavour problem

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and experimental clues:

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

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

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 "big" hierarchy problem

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

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

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

$$\mathcal{L} = \underbrace{o(\Lambda^2)\mathcal{L}_2 + o(\Lambda)\mathcal{L}_3 + o(1)\mathcal{L}_4}_{\text{Renorm.ble part}} \quad + \underbrace{o(1/\Lambda)\mathcal{L}_5 + o(1/\Lambda^2)\mathcal{L}_6 + \ldots}_{\text{Non renorm.ble part}}$$

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): $\Lambda \to m\log\Lambda$

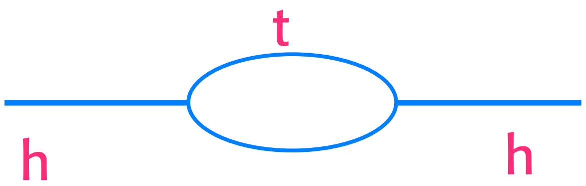
$\mathcal{L}_4$: Renorm.ble interactions, e.g. $\bar{\psi}\gamma^\mu\psi A_\mu$

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

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

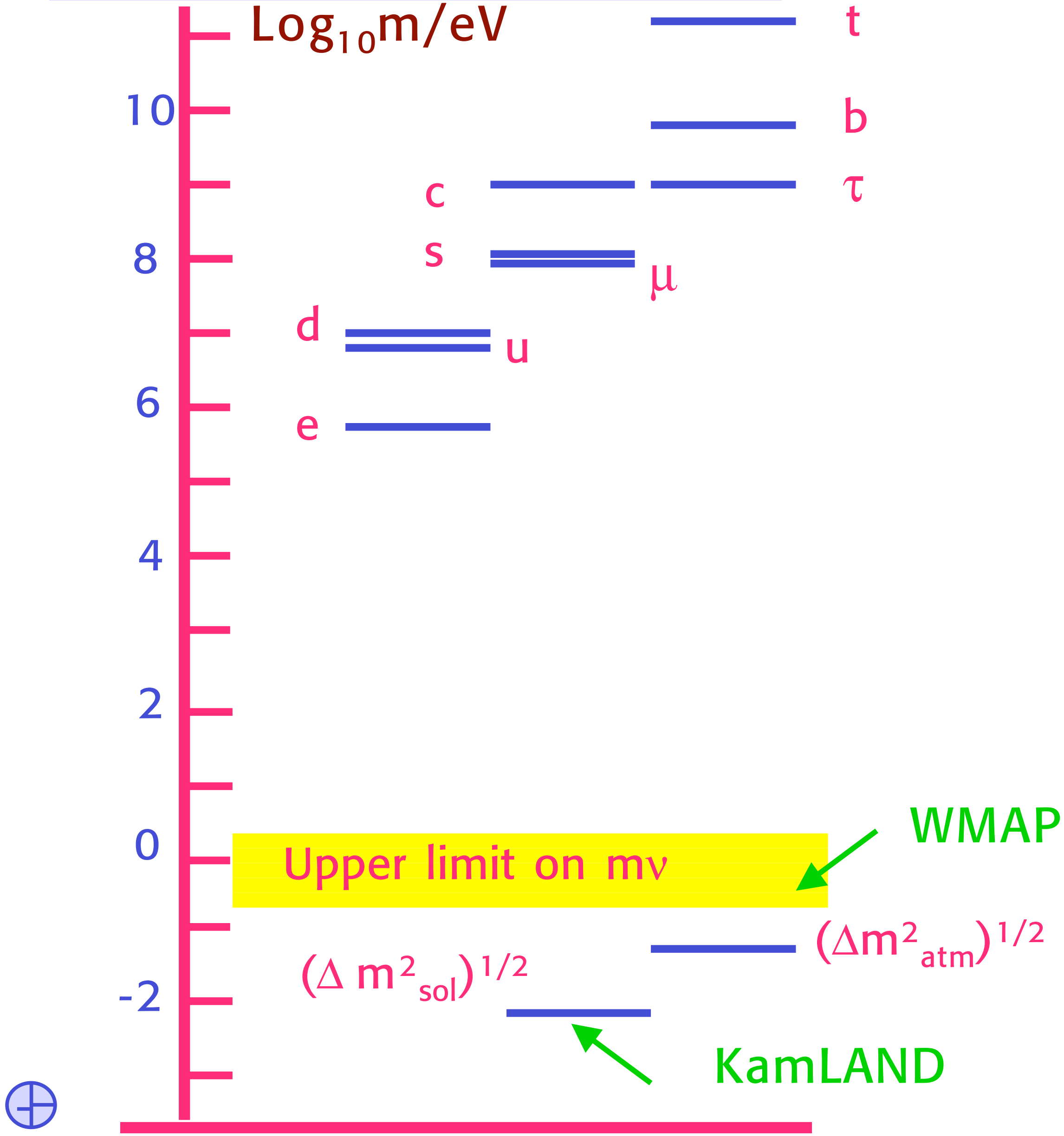
The LEP Paradox: m_h light, new physics must be so close but its effects were not visible at LEP2

The B-factory Paradox: and not visible in flavour physics

Before discussing possible forms of new physics we now consider some important evidence for it

- Neutrino masses
- Baryogenesis
- Dark matter

ν masses and mixings are new flavour physics!



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 $M \sim M_{GUT}$

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

$m: \leq m_t \sim v \sim 200$ GeV

M: scale of L non cons.

Note:

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

$m \sim v \sim 200$ GeV

$M \sim 10^{14} - 10^{15}$ GeV

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

A signal in $0\nu\beta\beta$ would be an essential confirmation

Baryogenesis

$n_B/n_\gamma \sim 10^{-10}$, $n_B >> n_{Bbar}$

Conditions for baryogenesis: (Sacharov '67)

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

Baryogenesis by decay of heavy Majorana ν's

BG via Leptogenesis near the GUT scale

$T \sim 10^{12\pm 3}$ GeV (after inflation)

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

Only survives if Δ(B-L) is not zero
(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 for hierarchy

$m_i < 10^{-1}$ eV

Buchmuller, Di Bari, Plumacher; Giudice et al; Pilaftsis et al; Hambye et al

Can be relaxed for degenerate neutrinos
So fully compatible with oscill'n data!!

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?

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:

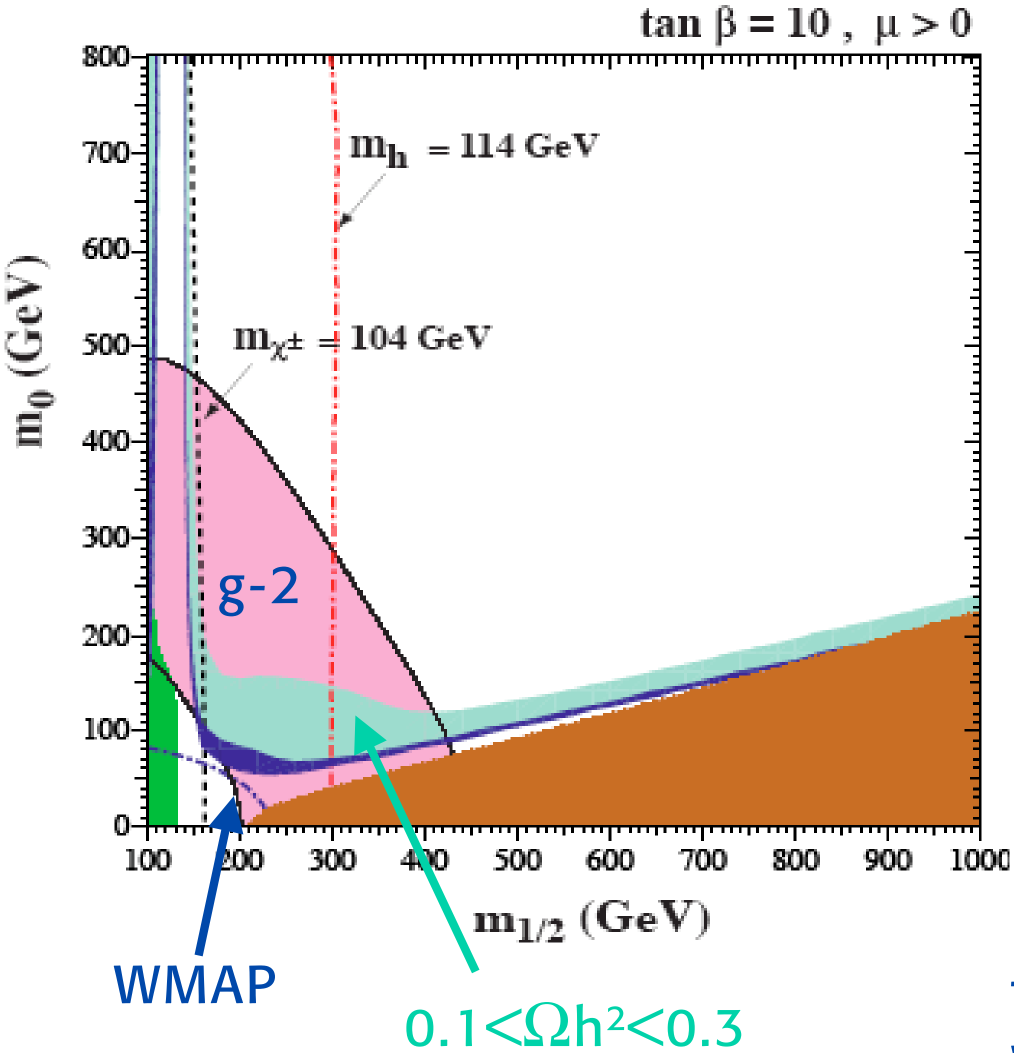
$$\boxed{\Omega_\chi h^2 \simeq const. \cdot \frac{T_0^3}{M_{\rm Pl}^3 \langle \sigma_A v \rangle} \simeq \frac{0.1\ \mathrm{pb} \cdot c}{\langle \sigma_A v \rangle}}$$

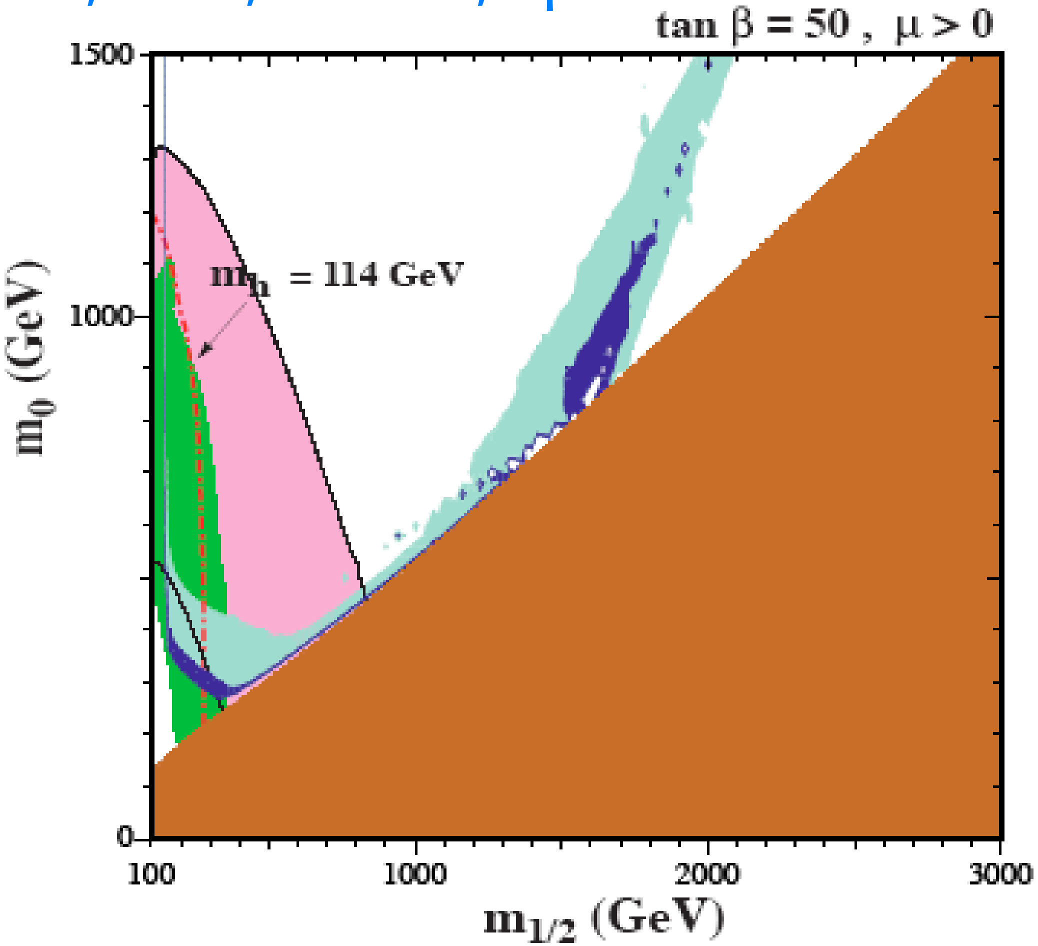
can work for typical weak cross-sections!!!

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

SUSY Dark Matter: we hope it is the neutralino
[the gravitino is a non WIMP alternative]

Ellis, Olive, Santoso, Spanos





This is for the CMSSM

With less constraints, more space

Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  exact (unrealistic): cancellation of Λ^2 in δm_h^2

  approximate (possible): $\Lambda \sim m_{SUSY}-m_{ord}$ → 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

In many cases "naturalness" has been a good guide in particle physics

For example: $(m_K - m_{Kbar})/m_K \sim G_F^2 f_K^2 m_c^2$

Without charm and GIM the short distance contribution is $\sim G_F^2 f_K^2 m_W^2$ and an unnatural cancellation between long and short distance contributions is needed

Note that $\Lambda_{QCD} << M_{GUT}$ is natural (log running of α_s):

$$\alpha_s(M_{GUT})^{-1} = 2b \log \frac{M_{GUT}}{\Lambda_{QCD}}$$

$$\Lambda_{QCD} = M_{GUT} \exp[-\frac{1}{2b\alpha_s(M_{GUT})}]$$

"Dimensional transmutation" brings in exponential suppression

The anthropic route

The scale of the cosmological constant is a big mystery.

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

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

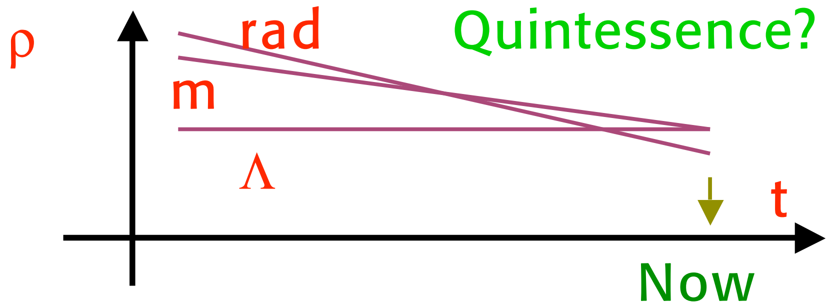
If $\Lambda_{cutoff} \sim M_{Pl}$ $\longrightarrow$ $\rho_\Lambda \sim 10^{123}\,\rho_{obs}$

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?

Is naturalness relevant?

Speculative physics reasons to doubt:

- The empirical value of the cosmological constant Λ poses a tremendous, unsolved naturalness problem

  yet the value of Λ is close to the Weinberg upper bound for galaxy formation
- Possibly our Universe is just one of infinitely many continuously created from the vacuum by quantum fluctuations
- Different physics in different Universes according to the multitude of string theory solutions ($\sim 10^{500}$)

Perhaps we live in a very unlikely Universe but one that allows our existence

I find applying the anthropic principle to the SM 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 residual fine tuning

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....)

SUSY: boson fermion symmetry

An equal number of bosonic and fermionic degrees of freedom

Examples:

Electron field (4 components) → 2 charged scalar s-electron fields

Gluon (massless: 2 dof) → gluino: Majorana fermion $g = g^c$

Why s-particles not yet seen? A clue:

Observed particles are those whose mass is forbidden by SU(2)xU(1)

When SUSY is broken but SU(2)xU(1) is unbroken s-particles get a mass, particles remain massless

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

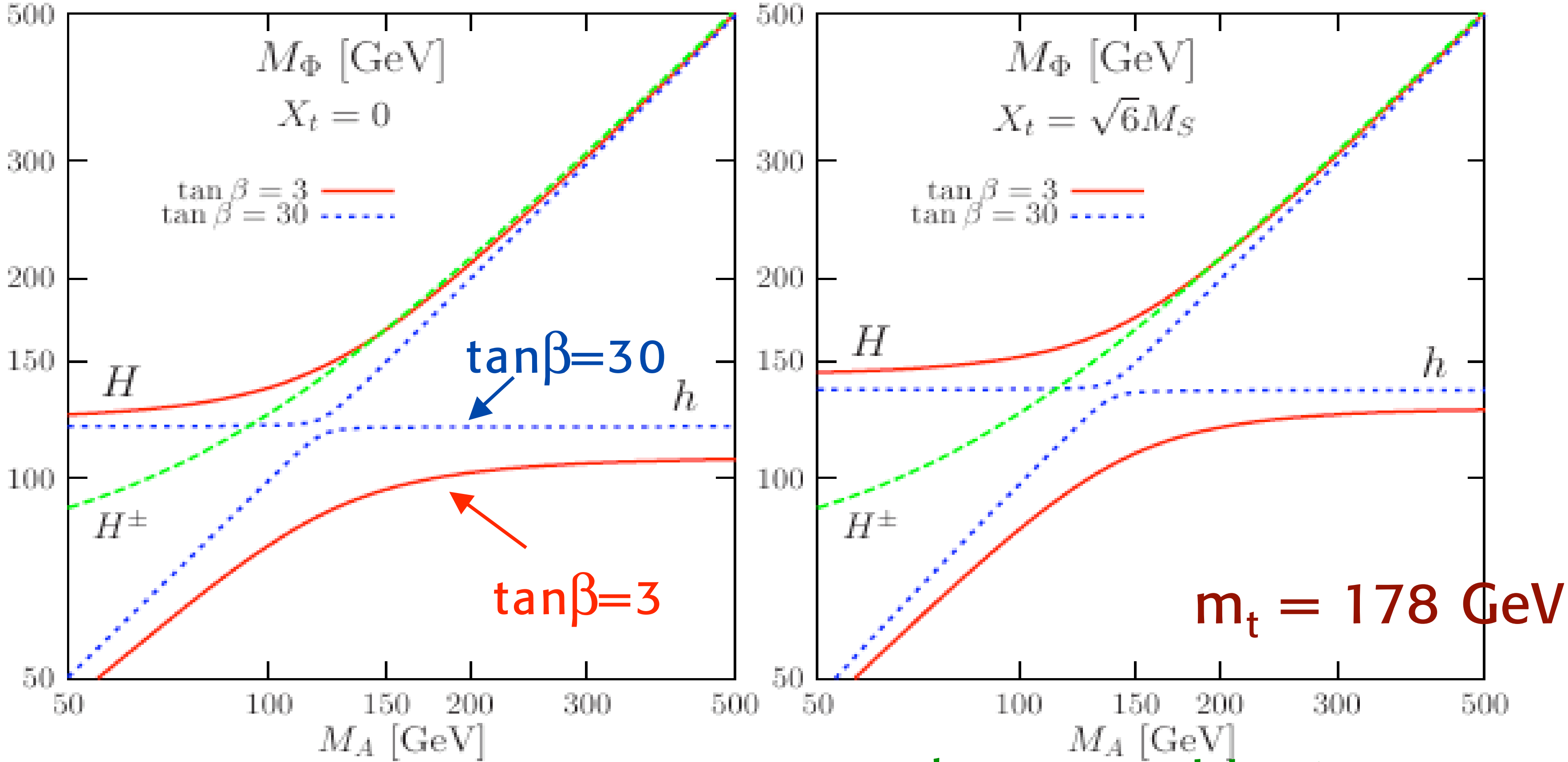
Dominant error: thresholds near M_{GUT}

- 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



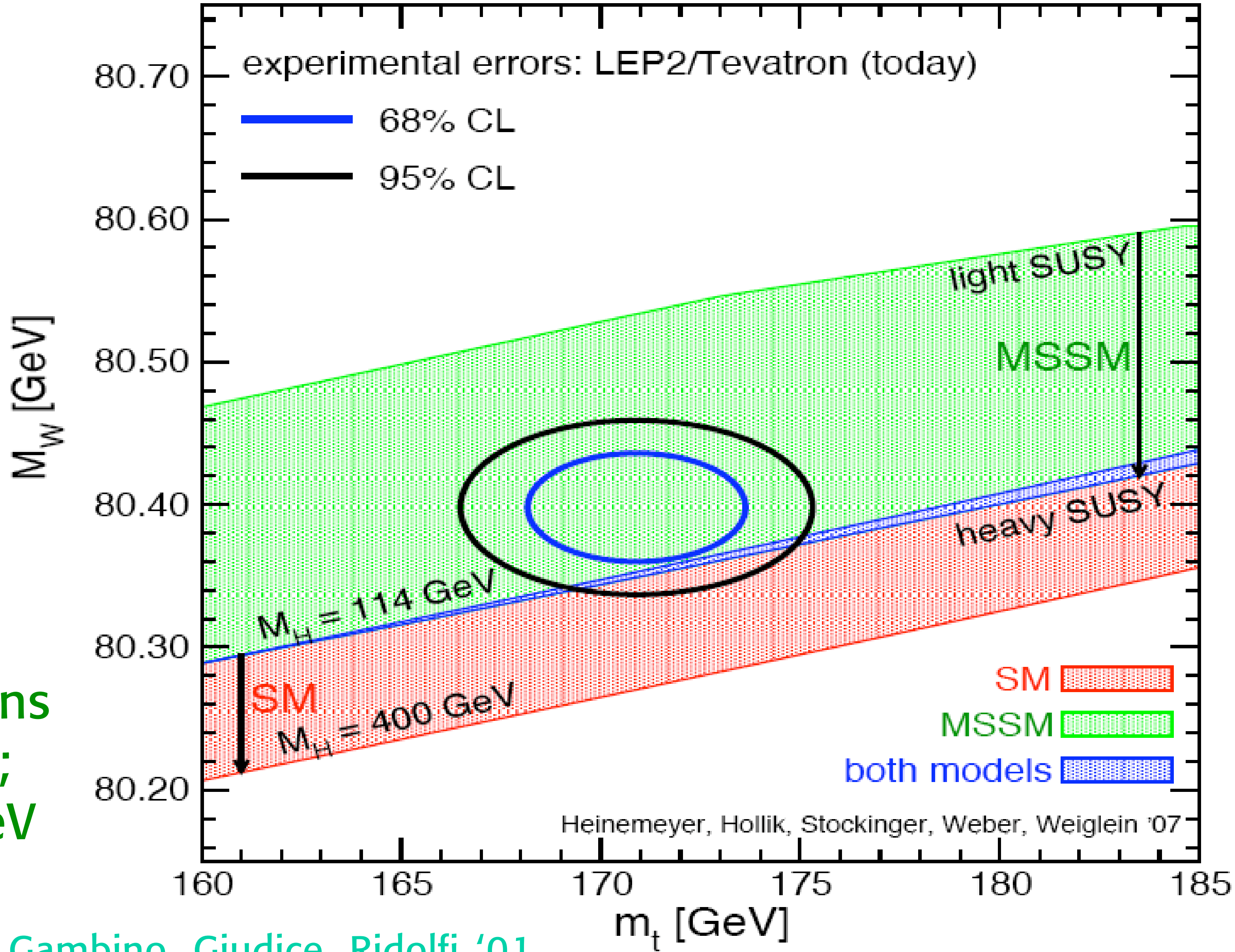
no top mixing: X_t=0

large top mixing X_t

Now with m_t ~171 GeV:

$m_h <$ ~125 GeV

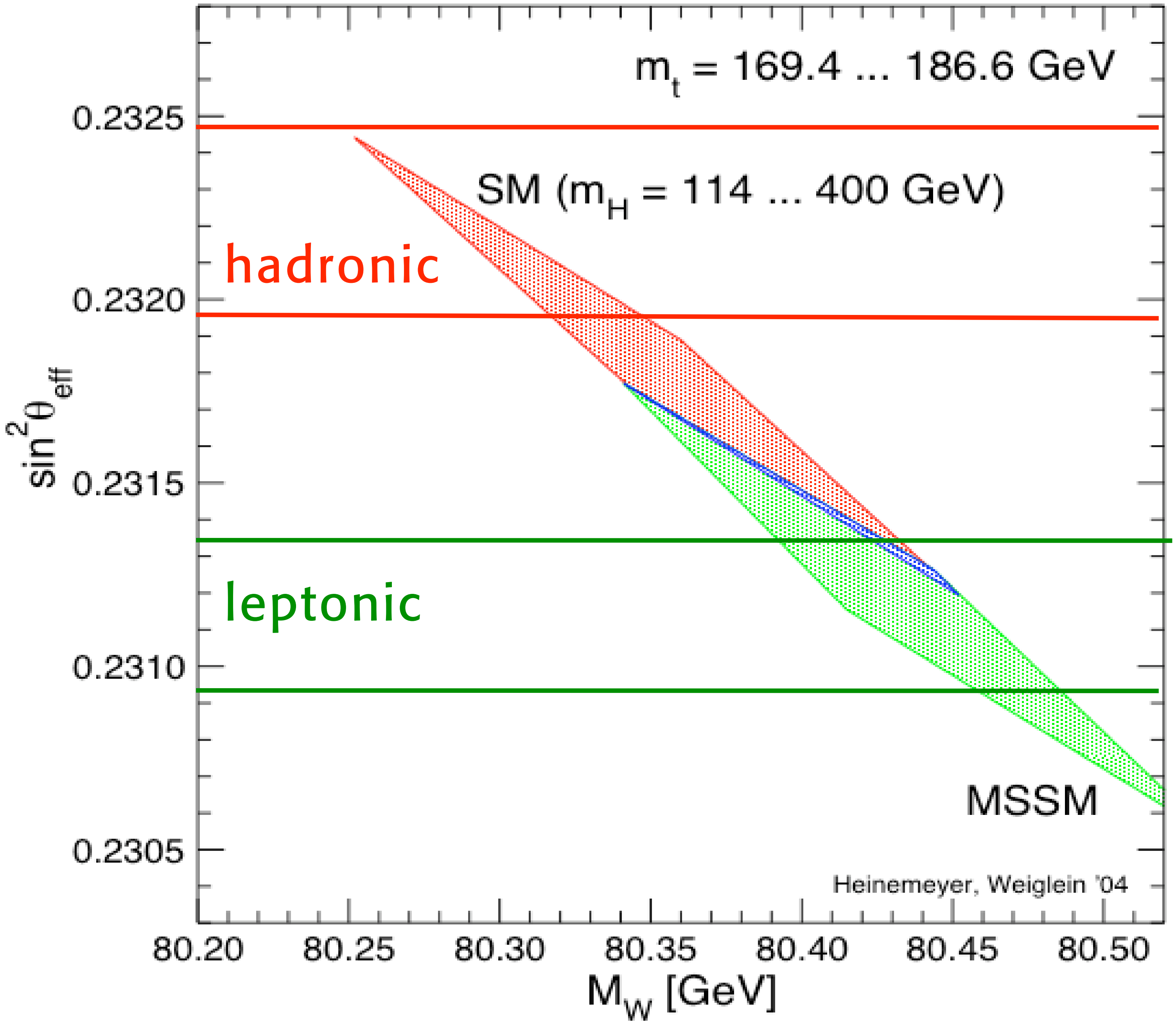
SUSY effects could modify the SM fit



"light SUSY"=
= light s-leptons
and charginos;
s-quarks ~1 TeV

G.A, Caravaglios, Gambino, Giudice, Ridolfi '01

$\sin^2\theta$ is unfortunately ambiguous



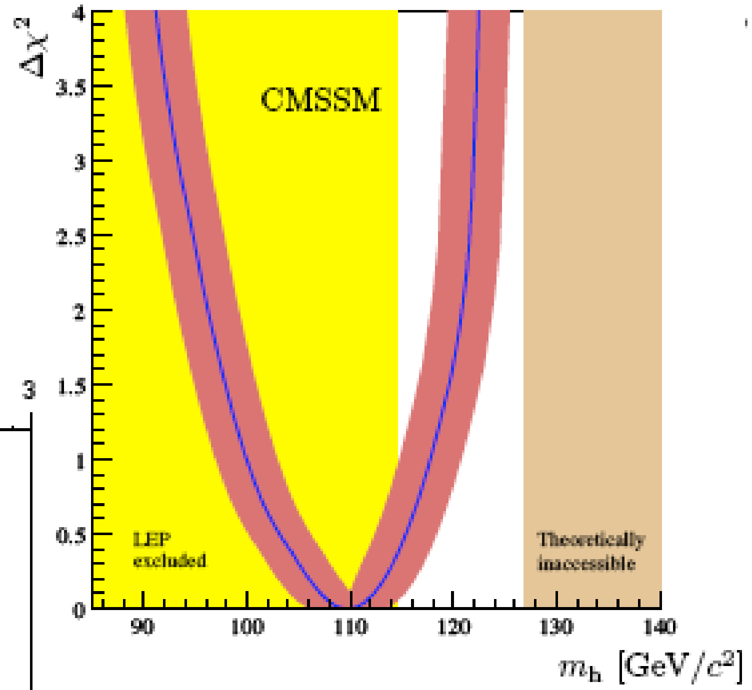
A recent study indicates that m_h goes up in CMSSM when b->sγ, a_μ, Ω_{DM} are added

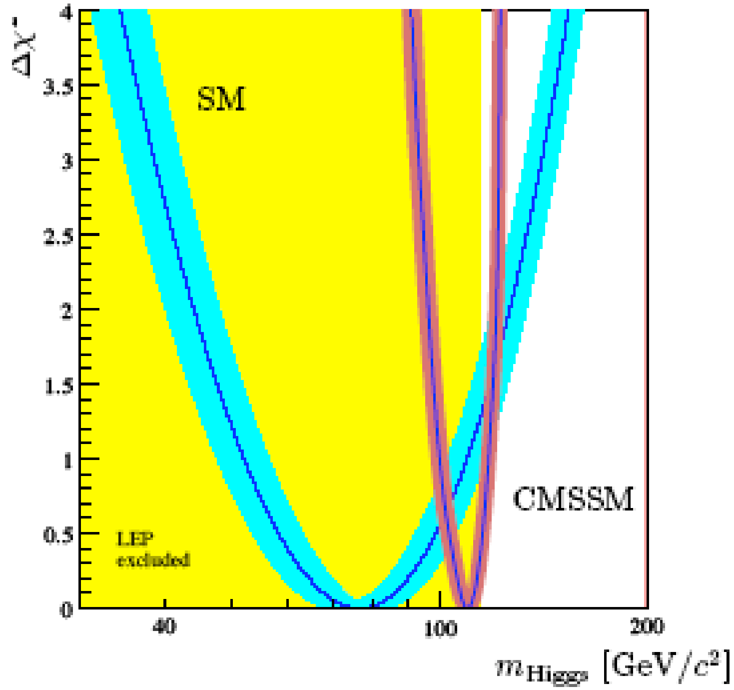
O. Buchmuller et al '07

also:
J. Ellis et al '07

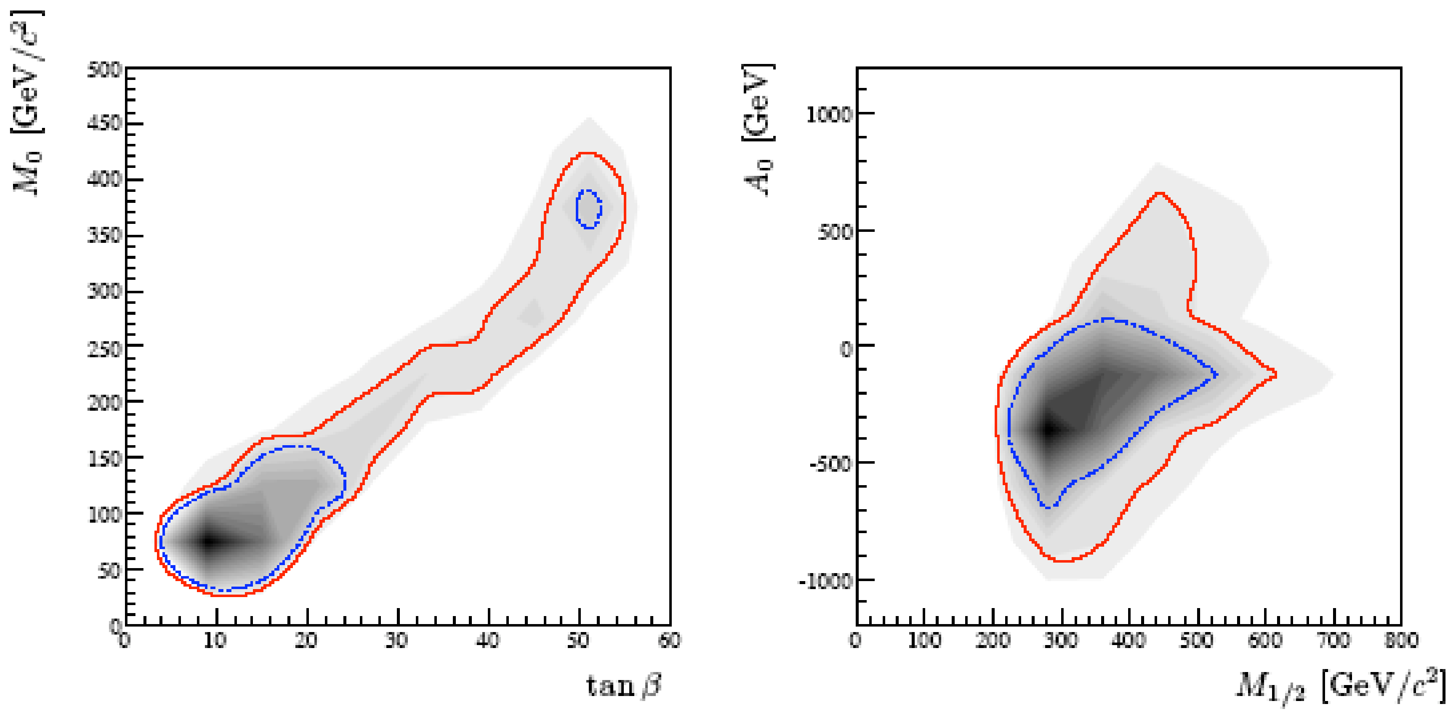
CMSSM

Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758± 0.00035	0.02774	
m_Z [GeV]	91.1875± 0.0021	91.1873	
Γ_Z [GeV]	2.4952± 0.0023	2.4952	
σ^0_{had} [nb]	41.540± 0.037	41.486	
R_l	20.767± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465± 0.0032	0.1479	
R_b	0.21629± 0.00066	0.21613	
R_c	0.1721± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992± 0.0016	0.1037	
$A^{0,c}_{fb}$	0.0707± 0.0035	0.0741	
A_b	0.923± 0.020	0.935	
A_c	0.670± 0.027	0.668	
A_l(SLD)	0.1513± 0.0021	0.1479	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324± 0.0012	0.2314	
m_W [GeV]	80.398± 0.025	80.382	
m_t [GeV]	170.9± 1.8	170.8	
$R(b\to s\gamma)$	1.13± 0.12	1.12	
$B_s\to\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times10^{-9}$]	2.95± 0.87	2.95	
Ωh^2	0.113± 0.009	0.113	





O. Buchmuller et al '07



Large neutrino mixings can induce observable $\tau \to \mu\gamma$ and $\mu \to e\gamma$ transitions

In fact, in SUSY models large lepton mixings induce large s-lepton mixings via RG effects
(boosted by the large Yukawas of the 3rd family)

Detailed predictions depend on the model structure and the SUSY parameters.

MEG exp under way->10^{-12}-10^{-13}

Typical values: $B(\mu \to e\gamma) \sim 10^{-11} - 10^{-14}$ (now: $\sim 10^{-11}$)

$B(\tau \to \mu\gamma) < \sim 10^{-7}$ (now: $\sim 10^{-7}$)

See, e.g., a review by Masiero, Vempati, Vives '07

But: Lack of SUSY signals at LEP2 + lower limit on m_H
→ problems for minimal SUSY

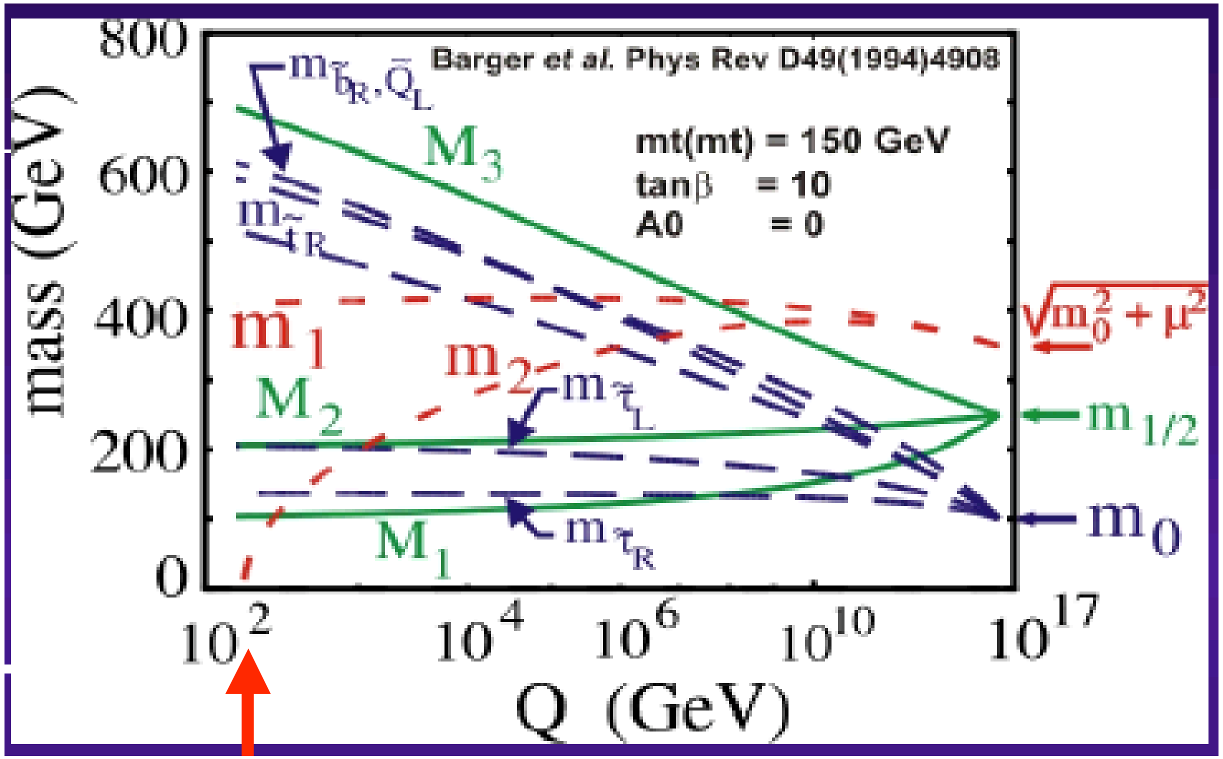
- In MSSM: $$m_h^2 \approx m_Z^2 \cos^2 2\beta + \frac{3\alpha_w m_t^4}{4\pi m_W^2 \sin^2\beta} \ln\frac{\tilde{m}_t^4}{m_t^4} < \sim 125 \text{ GeV}$$

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......

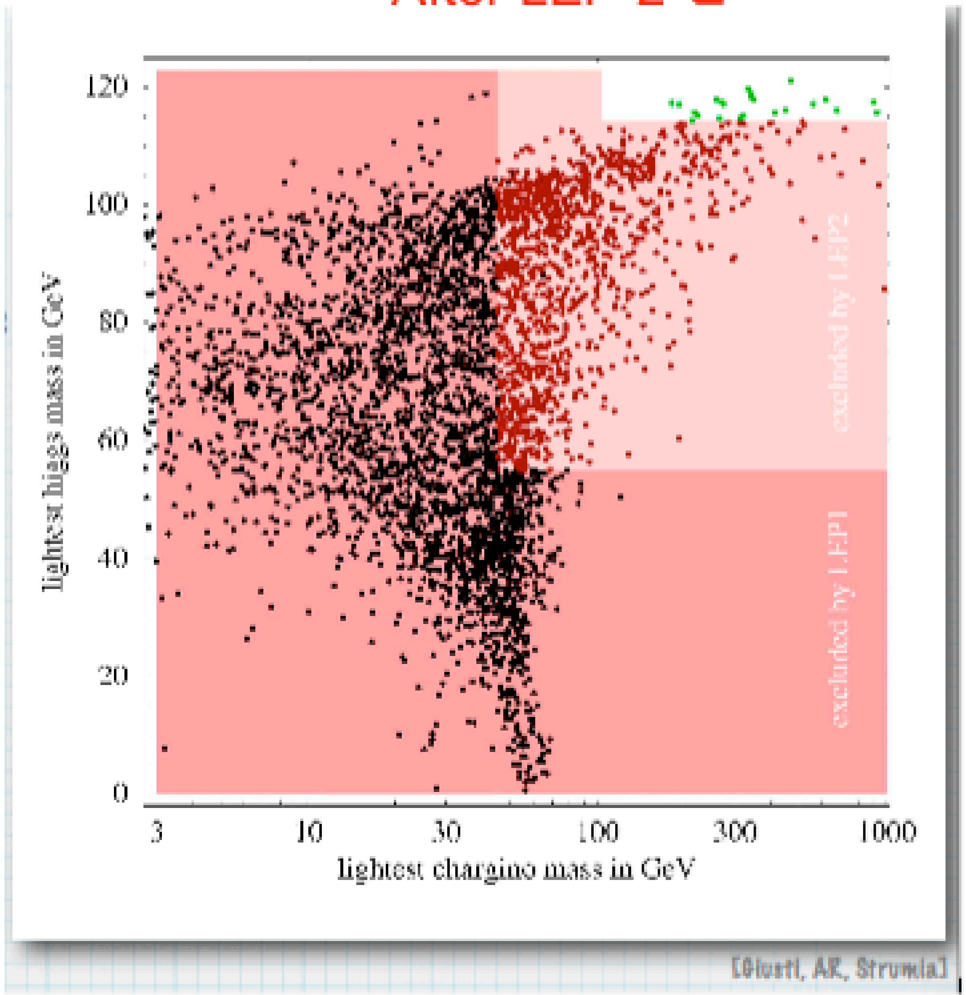
[Exp. : m_{gluino} >~200GeV]

Evolution of SUSY fine tuning

A typical supergravity model is in trouble by now

After LEP-2 ↘

lightest
Higgs
mass
(GeV)



← After LEP-1

Less fine tuning in non minimal models!

[Giusti-Romanino-Strumia, hep-ph/9811386]

lightest chargino mass (GeV)

Summarising

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

The hierarchy problem:

In broken SUSY Λ^2 is replaced by $(m_{stop}{}^2 - m_t{}^2)\log\Lambda$

$m_H > 114.4$ GeV, $m_{\chi+} > 100$ GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly 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

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 gauged SM

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

recall: $\delta m^2_{h|top} = -\frac{3G_F}{2\sqrt{2}\pi^2} m_t^2 \Lambda^2 \sim -(0.2\Lambda)^2$ $G_F \sim g^2 \to g^4$

cutoff Λ ~10 TeV

Λ^2 divergences canceled by:

$\delta m^2_{H|top}$ new coloured fermion χ with Q=2/3

$\delta m^2_{H|gauge}$ W', Z', γ'

$\delta m^2_{H|Higgs}$ new scalars

~1 TeV

2 Higgs doublets ~0.2 TeV

Little Higgs: Big Problems with Precision Tests

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

In early versions even with vectorlike new fermions large corrections arise mainly from W_i', Z' exchange.
[in particular if lack of custodial SU(2) symmetry]

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

Cheng, Low

Little Higgs with T parity and mirror fermions

Cheng, Low

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.
All corrections to EW observables at loop level only
(still dangerous -> mirror fermions)

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 (ME)].

T symmetry broken by anomalies? No stable B', no ME

Hill&Hill'07

In conclusion, for little Higgs:

One can make up a viable model.

Technically sophisticated

But the main drawback is:
Little Higgs provides just a postponement:
UV completion beyond ~10 TeV? GUT's?

Still important as it offers well specified signals and signatures for searching at the LHC:
a light Higgs, a new top-like fermion χ to damp the top loop, new W′, Z′ for the W, Z loops,.....

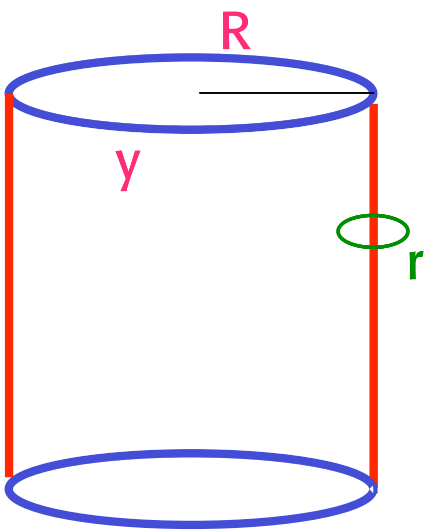
Extra Dimensions

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 assumed:

- 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

- 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

Generic feature of extra dim. models:

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 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:

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

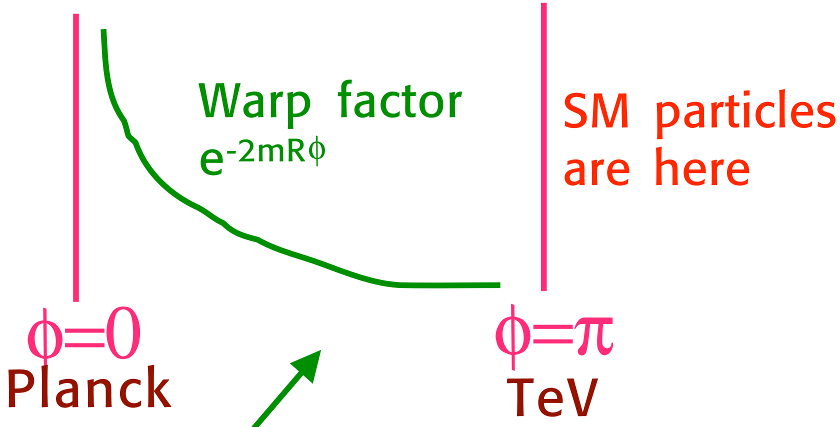
emerges as the most promising

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

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

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

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



original version

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 $mR \sim 12$: not too large!!

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

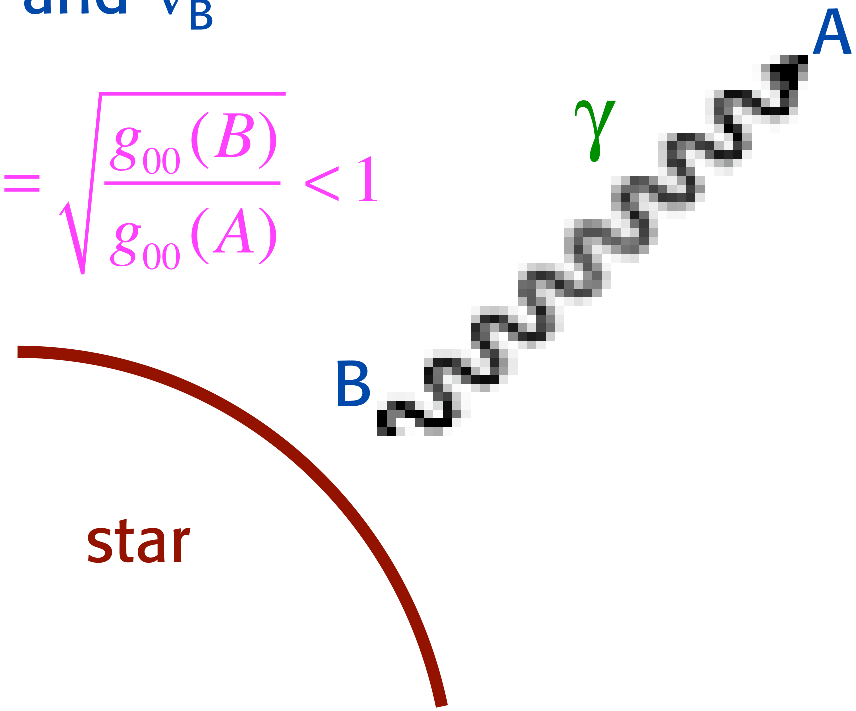
"radion"

Goldberger, Wise

2 identical atoms in A and B emit light with frequencies ν_A and ν_B

$$\frac{\nu_B}{\nu_A} = \sqrt{\frac{g_{00}(B)}{g_{00}(A)}} < 1$$

seen from A the B frequency is smaller: as if the photon kinetic energy lost by climbing out of grav. field



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

Good tutorials:
R. Sundrum '04
TASI lectures
R. Rattazzi '05
Cargese Lectures

The RS original formulation is very elegant but when going to a realistic formulation it has problems

- Electroweak precision tests

too large corrections (e.g. at tree level)

- In a description of physics from m_W to M_{Pl} there should be place for GUT's.

But, If all SM particles are on the TeV brane the effective theory cut-off is low and no way to M_{GUT} is open

Pomarol; Agashe, Delgado, Sundrum

Inspired by RS different realizations of warped geometry tried:

- gauge fields in the bulk
- all SM fields (except the Higgs) on the bulk
- • • • • • • •

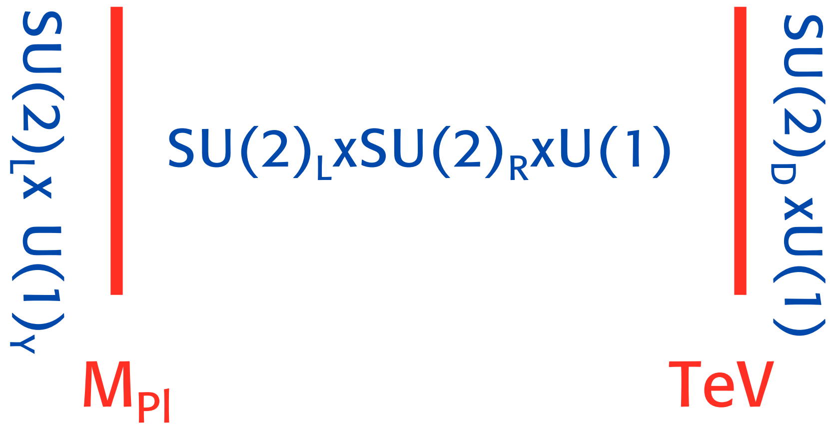
Model building based on RS explored in many directions

We consider now some ideas on electroweak symmetry breaking in extra dimensional models

- **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



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 brane

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 restored 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)

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

corresponds to Higgs in the adjoint ($H=A_5$ 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

m_W fixes the KK gap and it is not sufficiently large

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

$SU(2)_L \times U(1)_Y$ | $SO(5)\times U(1)$ | $SO(4)\times U(1)$

M_{Pl} TeV

Warped R-S background

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

All SM fields in the bulk (but the Higgs is localised near the TeV brane)

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 rather light: $m_H < 185$ GeV

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

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 LEP2

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

- No compelling, realistic alternative with less fine tuning so far developed (not an argument! Int. models explored)
- Extra dim.s is a complex, rich, attractive, exciting possibility.
- Little Higgs or composite models are just a postponement

  (both interesting to pursue)

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

Is it possible that the LHC does not find the Higgs particle?

Yes, it is possible, but then must find something else

Is it possible that the LHC finds the Higgs particle but no other new physics (pure and simple SM)?

Yes, it is technically possible but it is not natural

Is it possible that the LHC finds neither the Higgs nor new physics?

No, it is essentially impossible