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KIT, 6-10 February '12

Beyond the Standard Model

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Solutions to the hierarchy problem

- Supersymmetry: boson-fermion symm.

  The most ambitious and widely accepted
  Simplest versions now marginal
  Plenty of viable alternatives

- Strong EWSB: Technicolor

  Strongly disfavoured by LEP. Coming back in new forms

  Composite Higgs

  Higgs as PG Boson, Little Higgs models……

- Extra spacetime dim's that somehow "bring" M_{Pl} down to o(1TeV) [large ED, warped ED, ……]. Holographic composite H

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

- Ignore the problem: invoke the anthropic principle

  Extreme, but not excluded by the data

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)

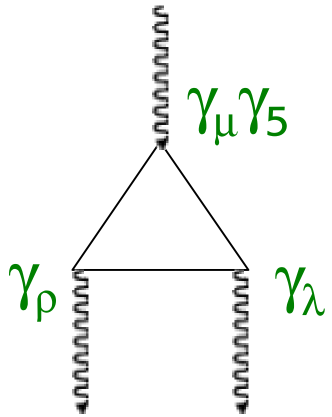
When SUSY is broken but SU(2)xU(1) is unbroken s-particles get a mass, particles remain massless

Particles of the minimal SUSY model (MSSM)

spin 0	spin 1/2	spin 1	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\tilde{u}_L, \tilde{d}_L$	u_L, d_L		$\mathbf{3}$	$\mathbf{2}$	$+\frac{1}{3}$
$\tilde{u}_R$	u_R		$\mathbf{3}$	$\mathbf{1}$	$+\frac{4}{3}$
$\tilde{d}_R$	d_R		$\mathbf{3}$	$\mathbf{1}$	$-\frac{2}{3}$
$\tilde{\nu}, \tilde{e}_L$	ν, e_L		$\mathbf{1}$	$\mathbf{2}$	-1
$\tilde{e}_R$	e_R		$\mathbf{1}$	$\mathbf{1}$	-2
H_u^+, H_u^0	$\tilde{h}_u^+, \tilde{h}_u^0$		$\mathbf{1}$	$\mathbf{2}$	$+1$
H_d^0, H_d^-	$\tilde{h}_d^0, \tilde{h}_d^-$		$\mathbf{1}$	$\mathbf{2}$	-1
	$\tilde{g}$	g	$\mathbf{8}$	$\mathbf{1}$	0
	$\tilde{w}^\pm, \tilde{w}^0$	$W^\pm, W^0$	$\mathbf{1}$	$\mathbf{3}$	0
	$\tilde{b}^0$	B^0	$\mathbf{1}$	$\mathbf{1}$	0

Two Higgs doublets are needed in the MSSM

- for cancellation of the chiral anomaly



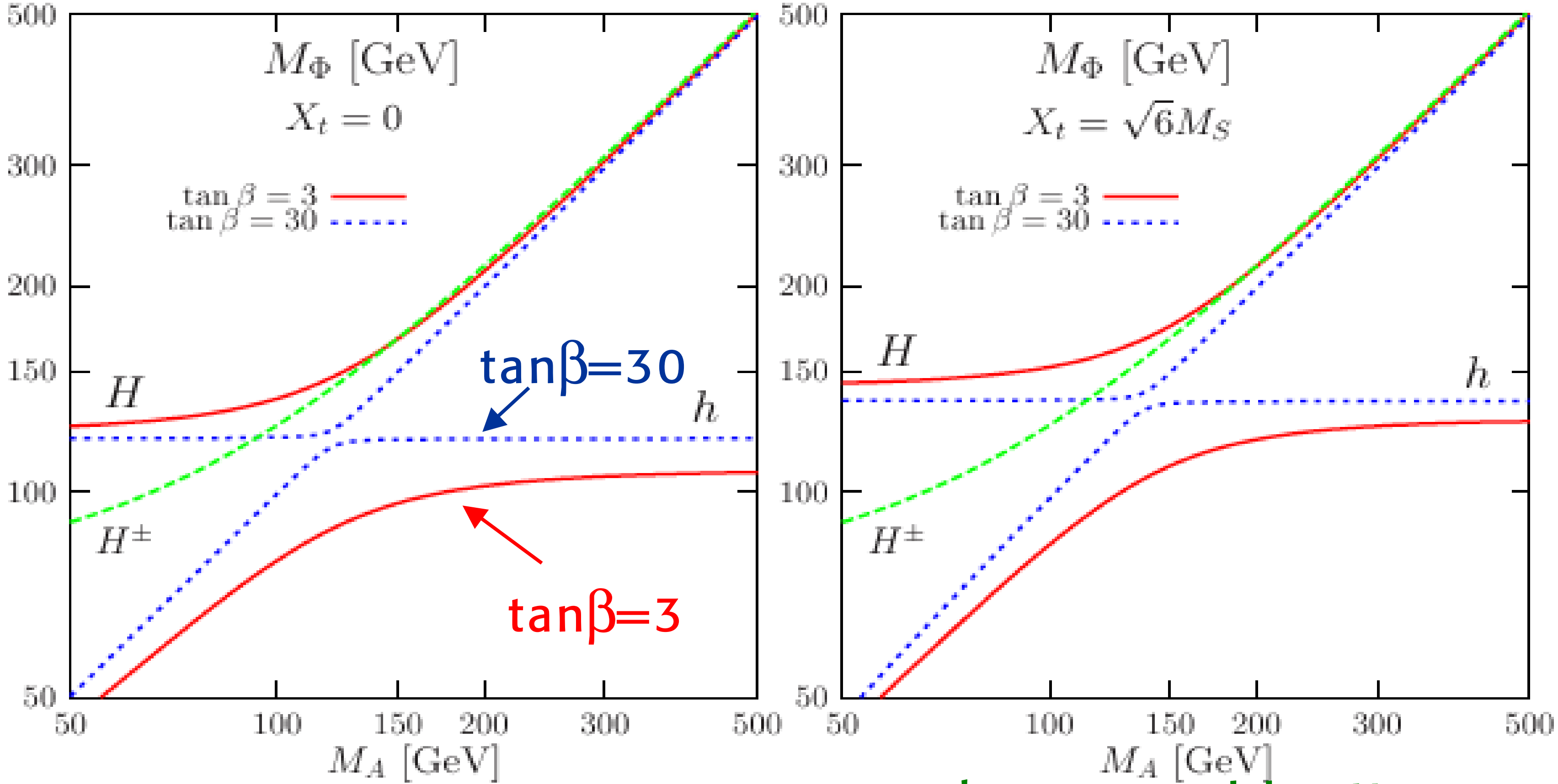
$Tr(Q^2 t_3) = Tr(Q t_3{}^2) = Tr(t_3{}^3) = ... = 0$
for fermions in the loop

- for the superpotential cannot contain both ϕ and ϕ^*

In the SM $H_u = H_d{}^*$

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

Djouadi



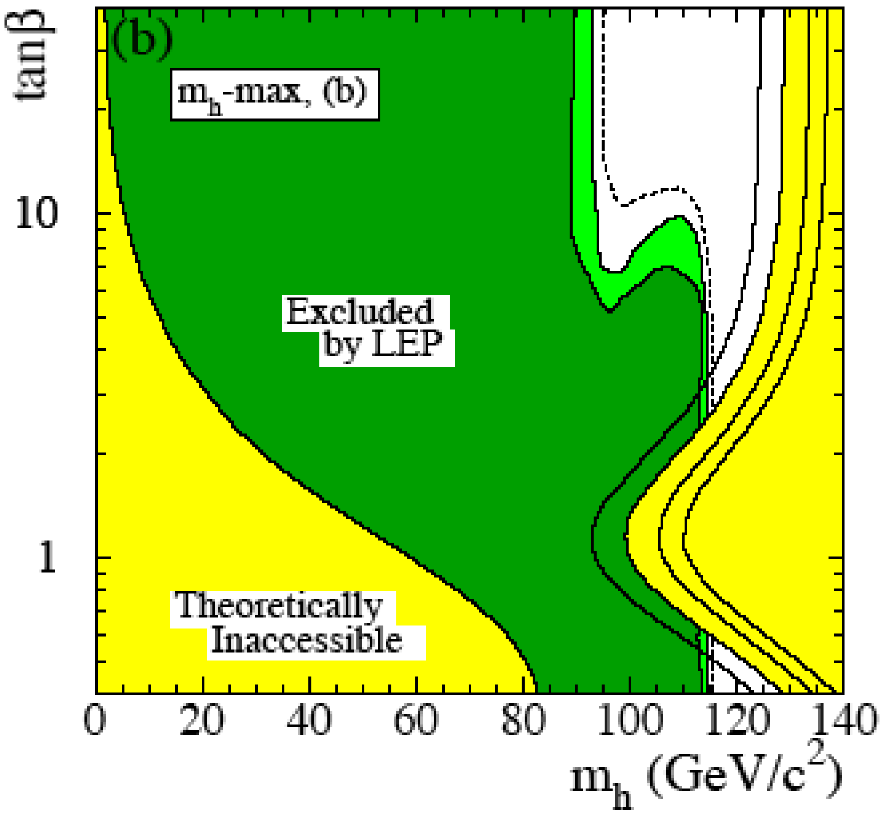
no top mixing: X_t=0

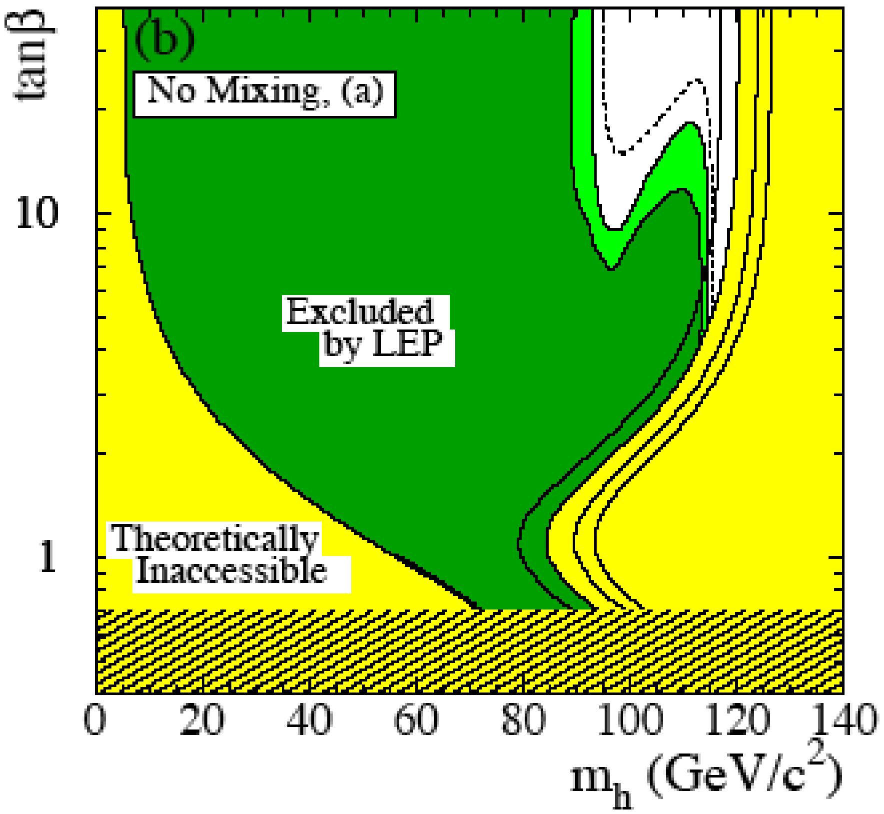
large top mixing X_t

m_t = 173.2 GeV (smaller m_t, smaller m_{hmax}) **m_h < ~135 GeV**

Exclusion plots

LEP Working group on Higgs hep-ex/0602042





SUSY: boson fermion symmetry

The 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 $(m_{stop}^2 - m_t^2)\log\Lambda$

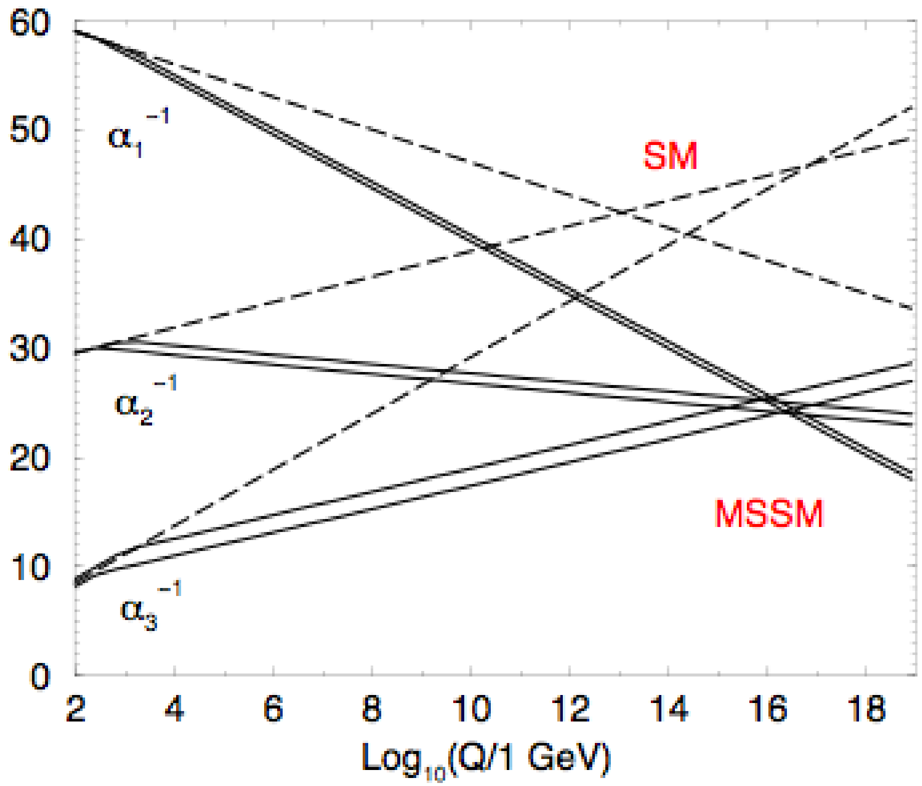
More precisely $\delta m^2_{H_u}|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{Q_3} + m^2_{u_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

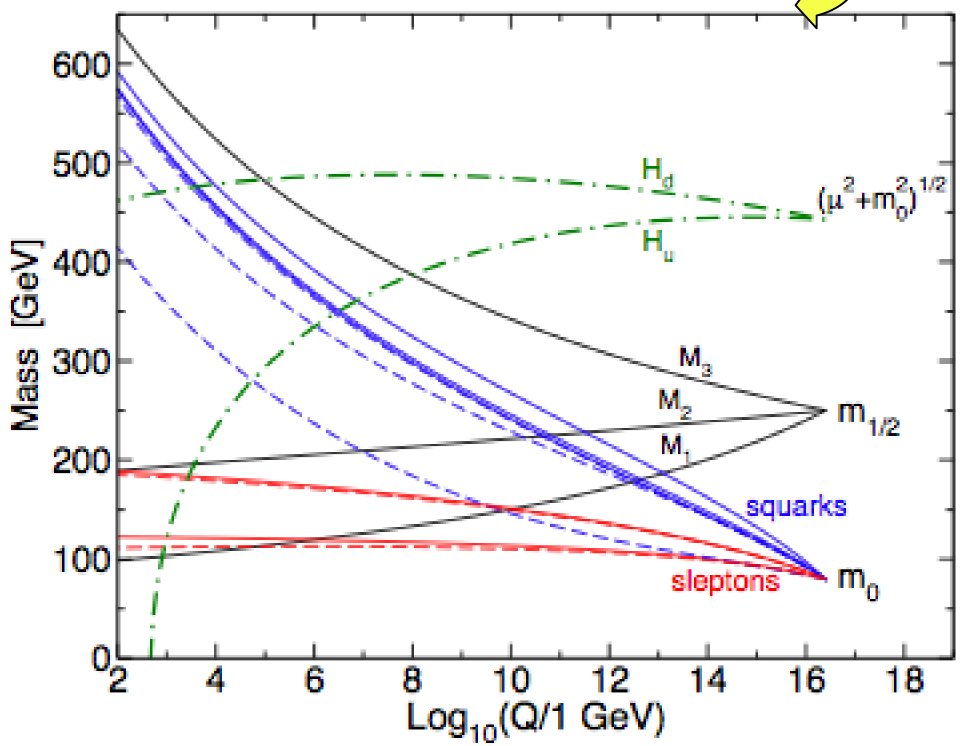
m_H>114.4 GeV, $m_{\chi+}$ >100 GeV, EW precision tests, success of CKM, absence of FCNC, all together, impose sizable Fine Tuning (FT) particularly on minimal realizations (MSSM, CMSSM…).

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

SUSY is unique in providing a weakly interacting theory up to the GUT/Planck scale. Better unification than in SM.

In a picture with simple GUT boundary conditions EW symmetry breaking is induced by running (large y_t)





Other BSM models (little Higgs, composite Higgs, Higgsless....) all become strongly interacting at a multi-TeV scale

SUSY breaking

Origin not clear:

- gravity mediated
- gauge mediated
- anomaly mediated
- ....

Phenomenologically described in terms of soft terms (operator dimension < 4)
Renormalizability and non renormalization theorems maintained

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} = & -\frac{1}{2}\left(M_3 \widetilde{g}\widetilde{g} + M_2 \widetilde{W}\widetilde{W} + M_1 \widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& - \left(\widetilde{\overline{u}}\, \mathbf{a_u}\, \widetilde{Q} H_u - \widetilde{\overline{d}}\, \mathbf{a_d}\, \widetilde{Q} H_d - \widetilde{\overline{e}}\, \mathbf{a_e}\, \widetilde{L} H_d + \text{c.c.}\right) \\
& - \widetilde{Q}^\dagger\, \mathbf{m_Q^2}\, \widetilde{Q} - \widetilde{L}^\dagger\, \mathbf{m_L^2}\, \widetilde{L} - \widetilde{\overline{u}}\, \mathbf{m_{\overline{u}}^2}\, \widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\, \mathbf{m_{\overline{d}}^2}\, \widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\, \mathbf{m_{\overline{e}}^2}\, \widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}) \,.
\end{aligned}
$$

s-particle masses

More than 100 parameters!

SUSY and flavour

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

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

The MSSM does provide an approximate 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 $\mu \to e\gamma$ (MEG), $\tau \to \mu\gamma$).
Made even more plausible by ν large mixings

All constraints met by assuming universality at the GUT scale

$$\mathbf{m^2_Q} = m^2_Q \mathbf{1}, \quad \mathbf{m^2_{\bar{u}}} = m^2_{\bar{u}} \mathbf{1}, \quad \mathbf{m^2_{\bar{d}}} = m^2_{\bar{d}} \mathbf{1}, \quad \mathbf{m^2_L} = m^2_L \mathbf{1}, \quad \mathbf{m^2_{\bar{e}}} = m^2_{\bar{e}} \mathbf{1}$$

plus proportionality of soft (scalar)^3 to Yukawa's

$$\mathbf{a_u} = A_{u0}\,\mathbf{y_u}, \qquad \mathbf{a_d} = A_{d0}\,\mathbf{y_d}, \qquad \mathbf{a_e} = A_{e0}\,\mathbf{y_e}$$

and reality of couplings

$$\arg(M_1),\ \arg(M_2),\ \arg(M_3),\ \arg(A_{u0}),\ \arg(A_{d0}),\ \arg(A_{e0}) \;=\; 0 \text{ or } \pi.$$

This provides a realization of MFV: no new flavour structure other than that in the SM Yukawa's at GUT's
(still broken by ren. group running)

Alignment: small or vanishing mixings for s-quarks and s-leptons but non vanishing mass splittings

But: Lack of SUSY signals + exp. limits on m_H

$\rightarrow$ problems for minimal SUSY

- In MSSM:

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

More precisely

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2} \right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2} \right) \right)$$

$$X_t = A_t - \mu \cot\beta$$

So $m_H > 115$ 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

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

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

Result:
gluino, stop, higgsino must be light to limit fine tuning.
Other s-particles less constrained.

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

Light charginos and sleptons would help g-2 and EW tests

B and L conservation in SM:

"Accidental" symmetries: in SM there is no dim.$\leq$4 gauge invariant operator that violates B and/or L

(if no ν_R, otherwise M $\nu^T_R \nu_R$ is dim-3 $|\Delta L|=2$)

The same is true in SUSY with R-parity cons.

e. g. for the $\Delta B=\Delta L= -1$ transition $u + u \to e^+ + \bar{d}$

all good quantum numbers are conserved:

e.g. colour $u\sim 3$, $\bar{d}\sim\bar{3}$ and $3\mathrm{x}3 = 6+\bar{3}$ but

$$\frac{\lambda}{M^2}\,\overline{d^c}\Gamma u\ \overline{e^c}\Gamma u$$

dim-6

SU(5): $p \to e^+\pi^0$

B and L conservation and R-parity

In SM B and L conservation is "accidental"

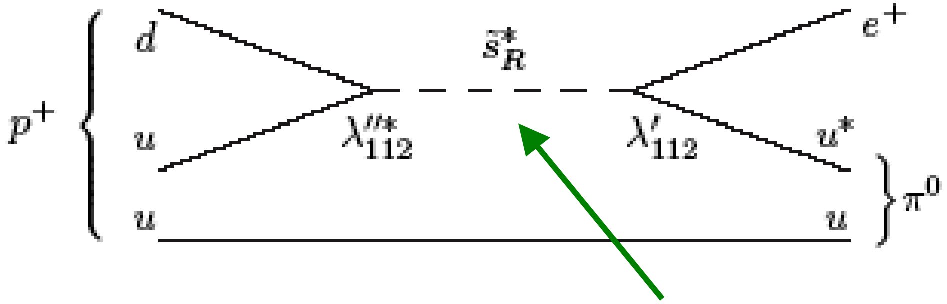
In the MSSM a list of B and L violating terms are allowed:

$$W_{\Delta L=1} = \frac{1}{2}\lambda_{abc}\tilde{L}_a\tilde{L}_b\tilde{\bar{e}}_c + \lambda'_{abc}\tilde{L}_a\tilde{Q}_b\tilde{\bar{d}}_c + \mu'_a\tilde{L}_aH_u$$

$$W_{\Delta B=1} = \frac{1}{2}\lambda''_{abc}\tilde{\bar{u}}_a\tilde{\bar{d}}_b\tilde{\bar{d}}_c$$

B=1/3 for Q, -1/3 for u^{bar}, d^{bar}
L=1 for L, -1 for e^{bar}

Strong constraints from p decay



λ''_{abc} antisymm in last 2 indices

$$\Gamma_{p\to e^+\pi^0} \sim m^5_{\rm proton}\sum_{i=2,3}|\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$$

To eliminate these unwanted terms an additional symmetry is invoked: matter parity or R-parity (multiplicative ±1 factors)

Not B and L conservation, because:

- good for baryogenesis, GUT's, proton decay
- broken by non perturbative effects (instantons)

Matter parity: $P_M=(-1)^{3(B-L)}$ Commutes with SUSY

q and l supermultiplets -> $P_M = -1$
gauge and Higgs supermultiplets -> $P_M = +1$

R-parity: $R=(-1)^{3(B-L)+2S}$ Does not commute with SUSY

It is equivalent to P_M because S, the spin, can only change by an integer in a vertex

SM particles -> R = +1
s-partners -> R = -1

The origin of R-parity is at a more fundamental level

Consequences of exact R-parity conservation

- The lightest s-particle with R=-1 is absolutely stable

It is called the LSP and is a good candidate for dark matter

- s-particles decay into a final state with an odd number of s-particles

(finally there will be the LSP in the decay chain)

- s-particles are produced in pairs at colliders

The result of the first LHC search for new physics has been negative

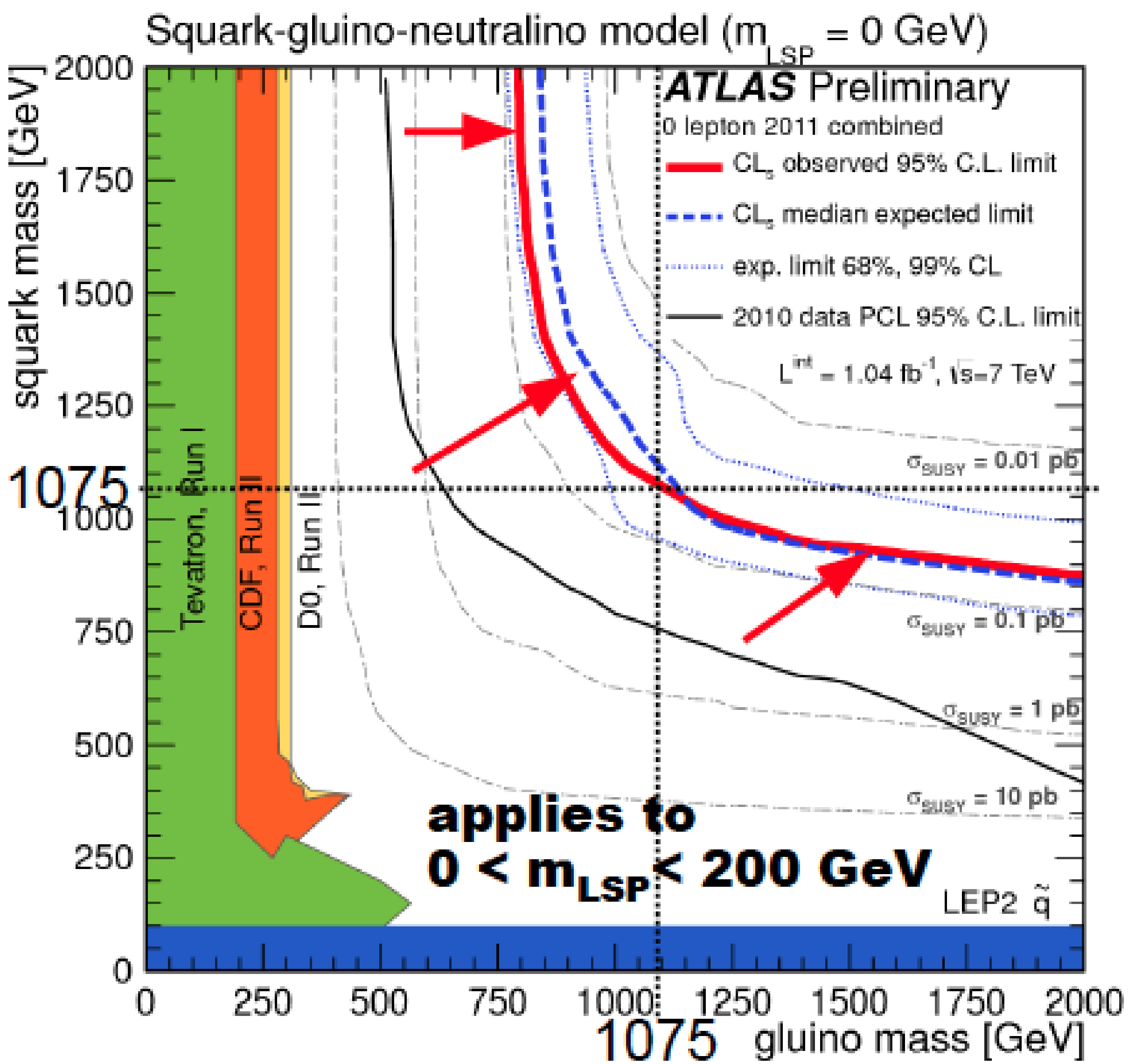
A big domain of new territory has been explored but no signal was found

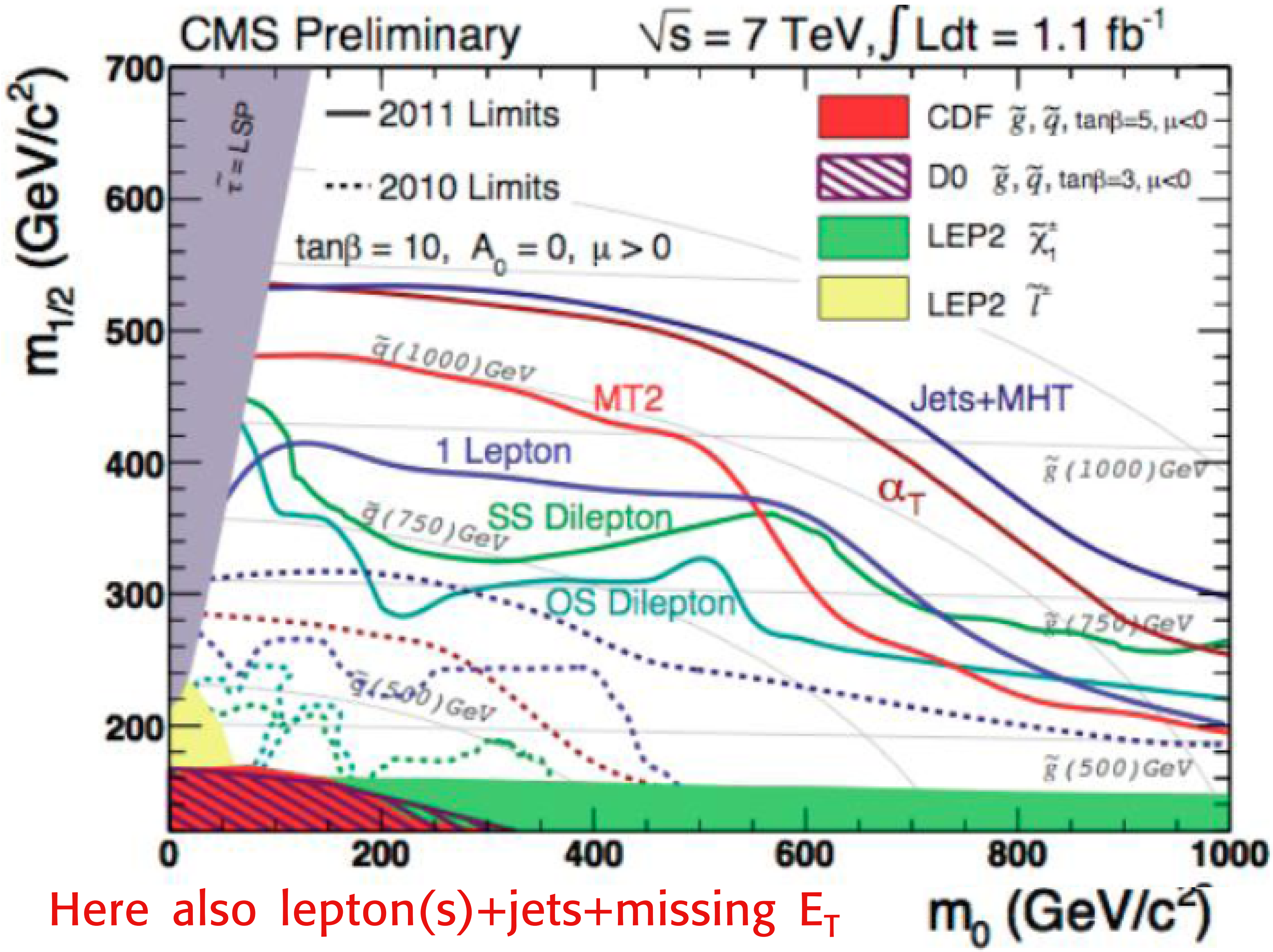
But, while for H search all 5 fb^{-1} have been analysed, for new physics only results for 1- 1.2 fb^{-1} have been released

The LHC search is still at the beginning!

Jets + missing E_T

CMSSM (degenerate s-quarks)

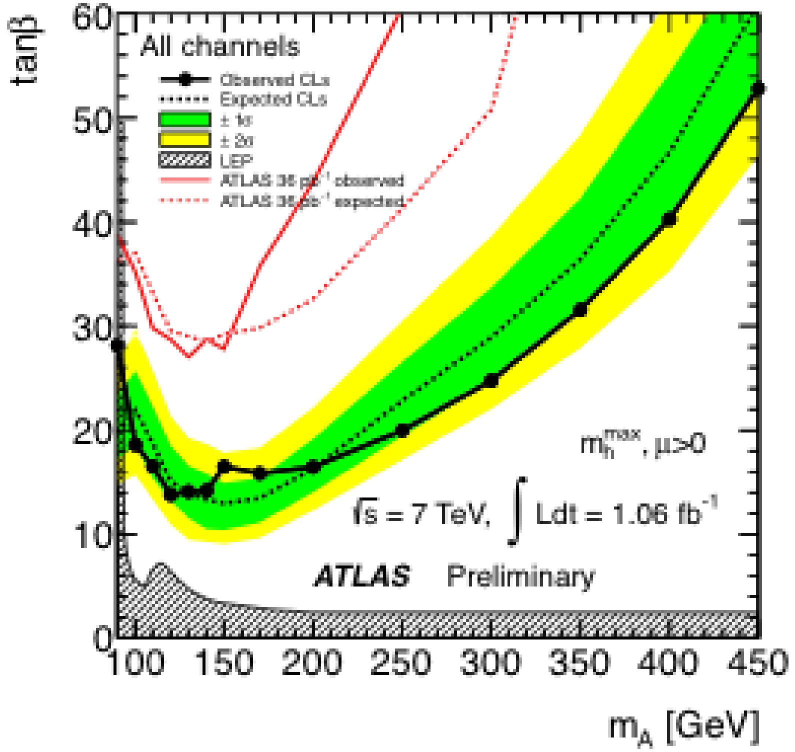




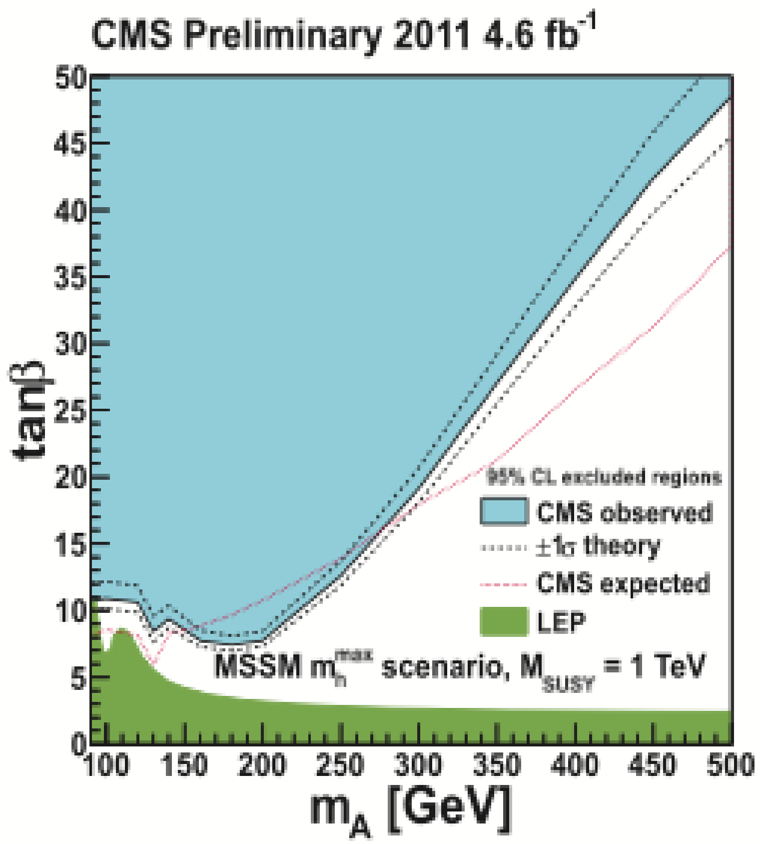
Here also lepton(s)+jets+missing E_T

Recent LHC result: light M_A is incompatible with large $\tan\beta$

[*ATLAS Collaboration '11*]



[*CMS Collaboration '11*]



The general MSSM has > 100 parameters

Simplified versions with a drastic reduction of parameters are used for practical reasons, e.g.

CMSSM, mSUGRA : universal gaugino and scalar soft terms at GUT scale $m_{1/2}$, m_0, A_0, $tg\beta$, $sign(\mu)$

NUHM1,2: different than m_0 masses for H_u, H_d (1 or 2 masses)

It is only these oversimplified models that are now cornered

Impact of m_H ~ 125 GeV on SUSY models

Simplest models with gauge mediation are disfavoured (predict m_H too light)

Djouadi et al; Draper et al, '11

some versions, eg gauge mediation with extra vector like matter, do work

Endo et al '11

Anomaly mediation is also generically in trouble

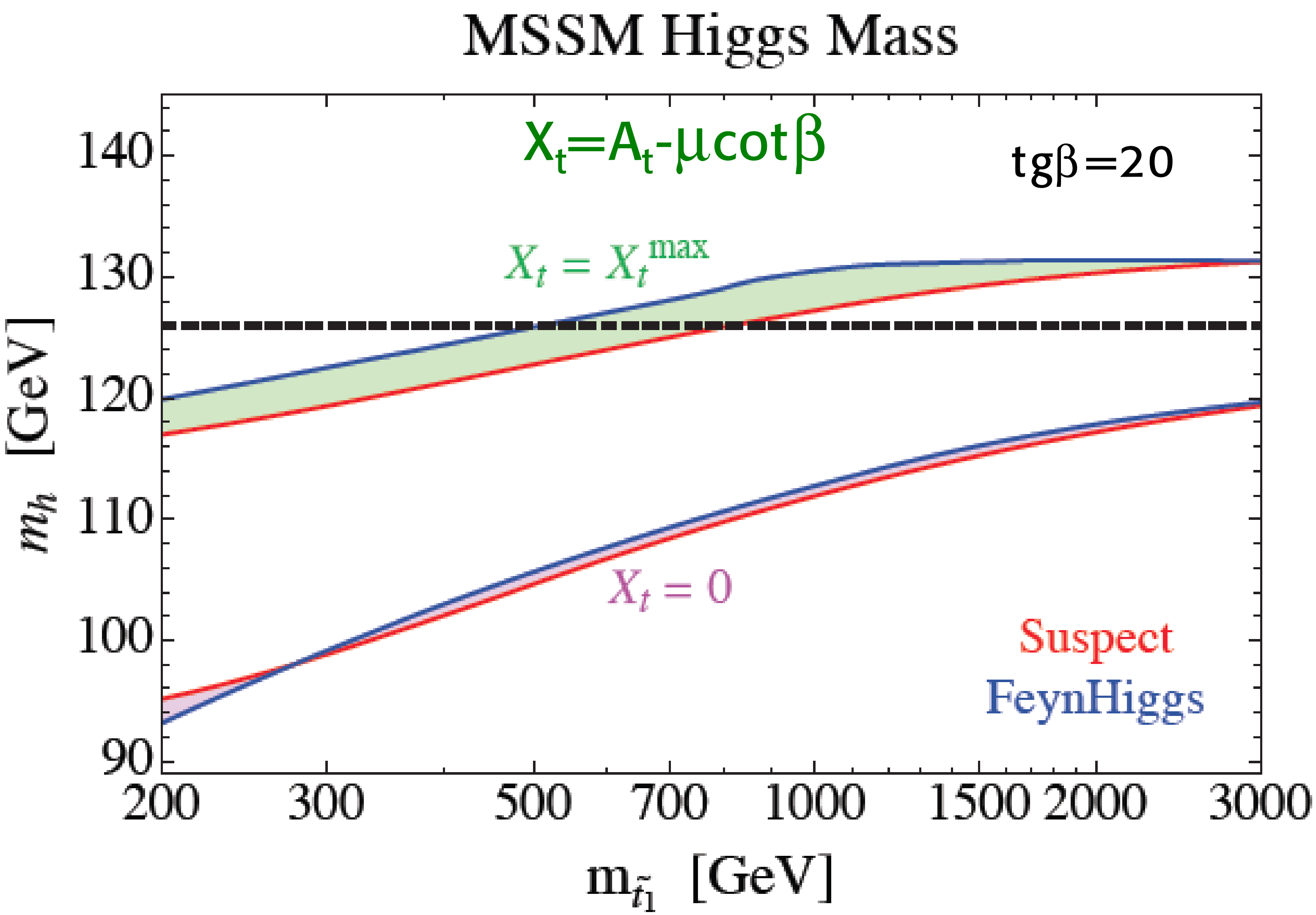
Gravity mediation is better but CMSSM, mSUGRA, NUHM1,2 need squarks heavy, A_t large and lead to tension with g-2 (that wants light SUSY) and $b \to s\gamma$

Akura et al; Baer et al; Battaglia et al; Buchmuller et al, Kadastik et al; Strege et al; '11

maximal top mixing is required

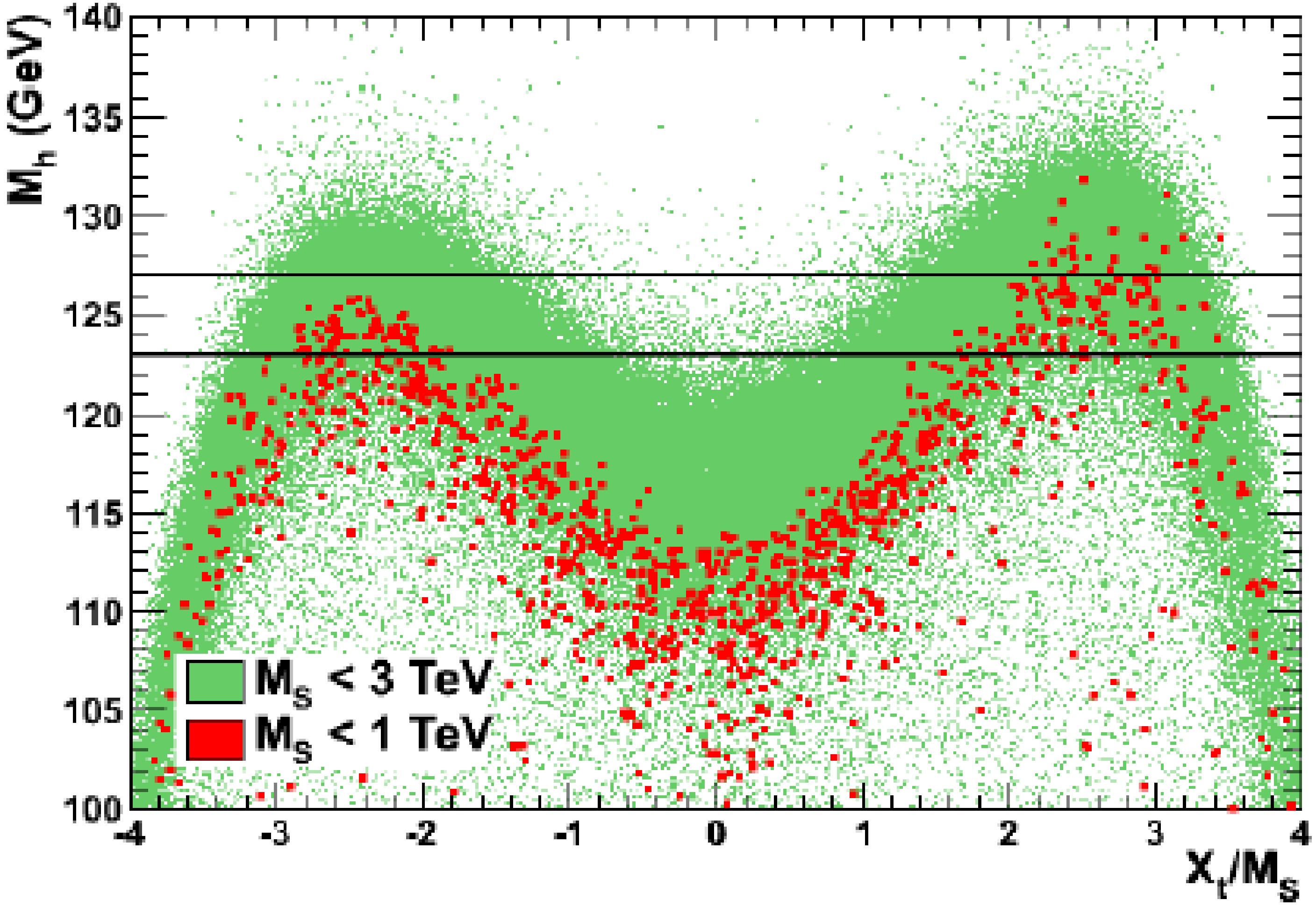
Hall et al '11

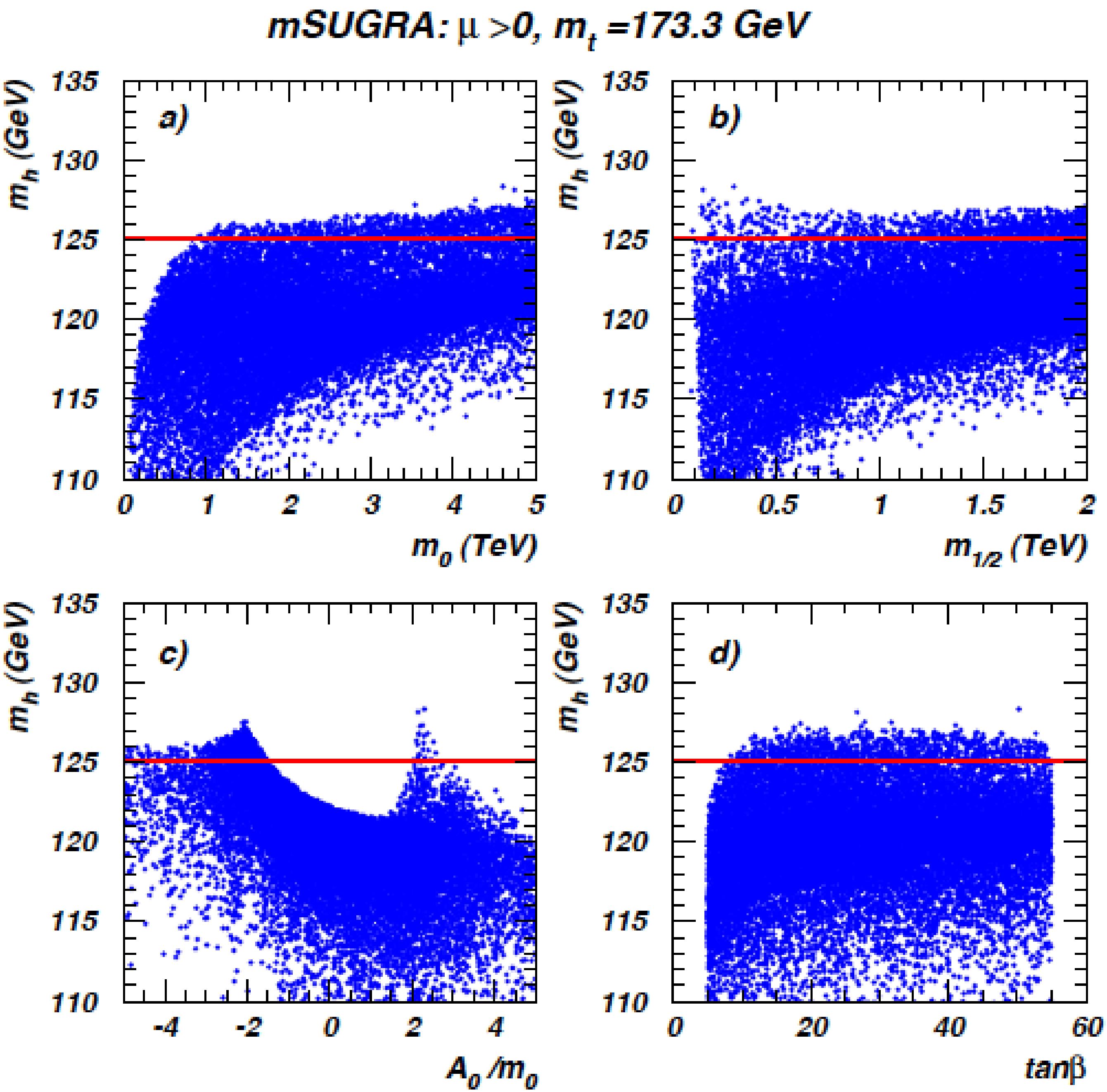
$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log\left(\frac{\overline{m}_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{\overline{m}_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12\overline{m}_{\tilde{t}}^2}\right)\right)$$



Arbey et al '11

CMSSM




mSUGRA: μ >0, m_t =173.3 GeV
a)
b)
c)
d)
m_h (GeV)
135
130
125
120
115
110
0
1
2
3
4
5
m_0 (TeV)
0.5
1.5
m_1/2 (TeV)
-4
-2
A_0 /m_0
20
40
60
tanβ

Baer et al ‘11

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

Typically at large tgβ:

Exp. ~287

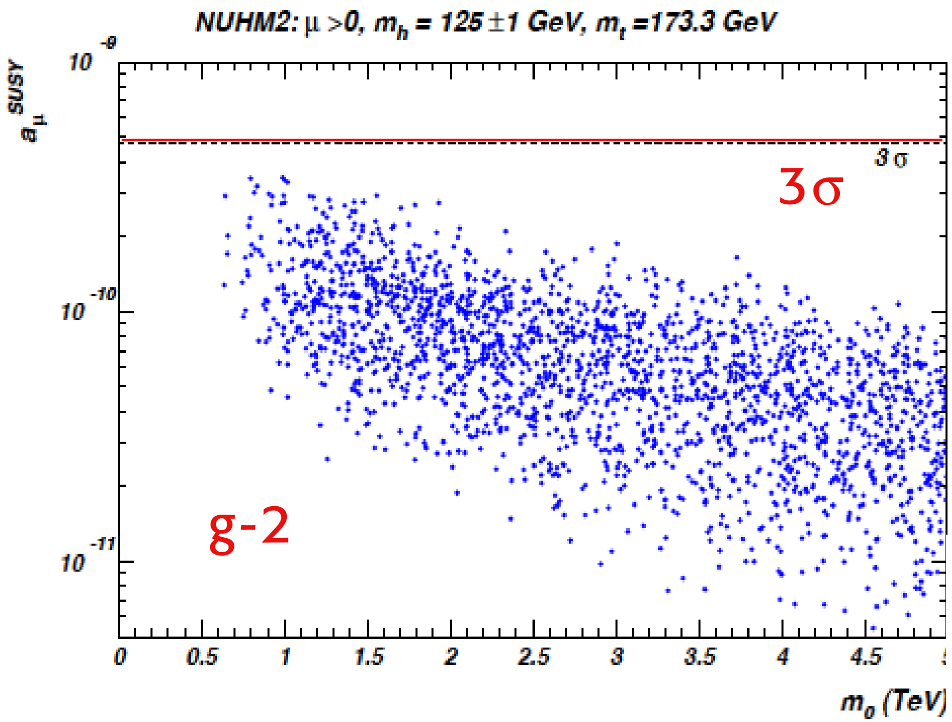
$$\delta a_\mu \sim 130\ 10^{-11} (100\ \mathrm{GeV}/m)^2\ \mathrm{tg}\beta$$

OK for e.g. $\tan\beta \sim 4$, $m\chi+ \sim m \sim 140$ GeV

Light s-leptons and gauginos predict a deviation!

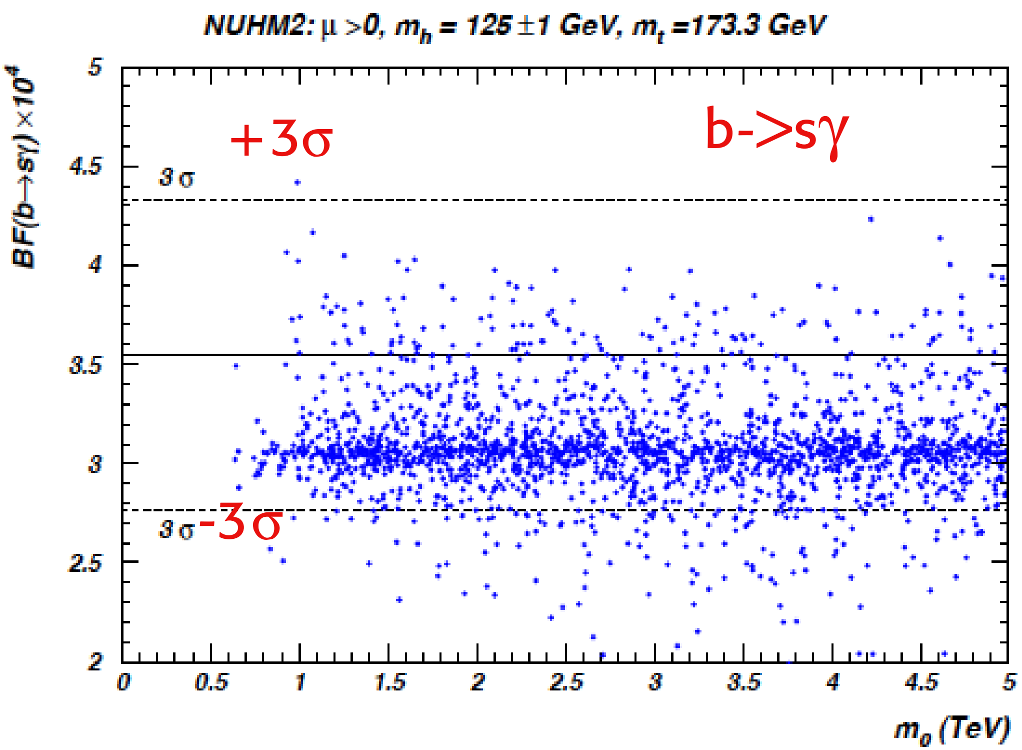
But now LHC appears to disfavour light SUSY
at least in simplest versions!

Baer et al '11

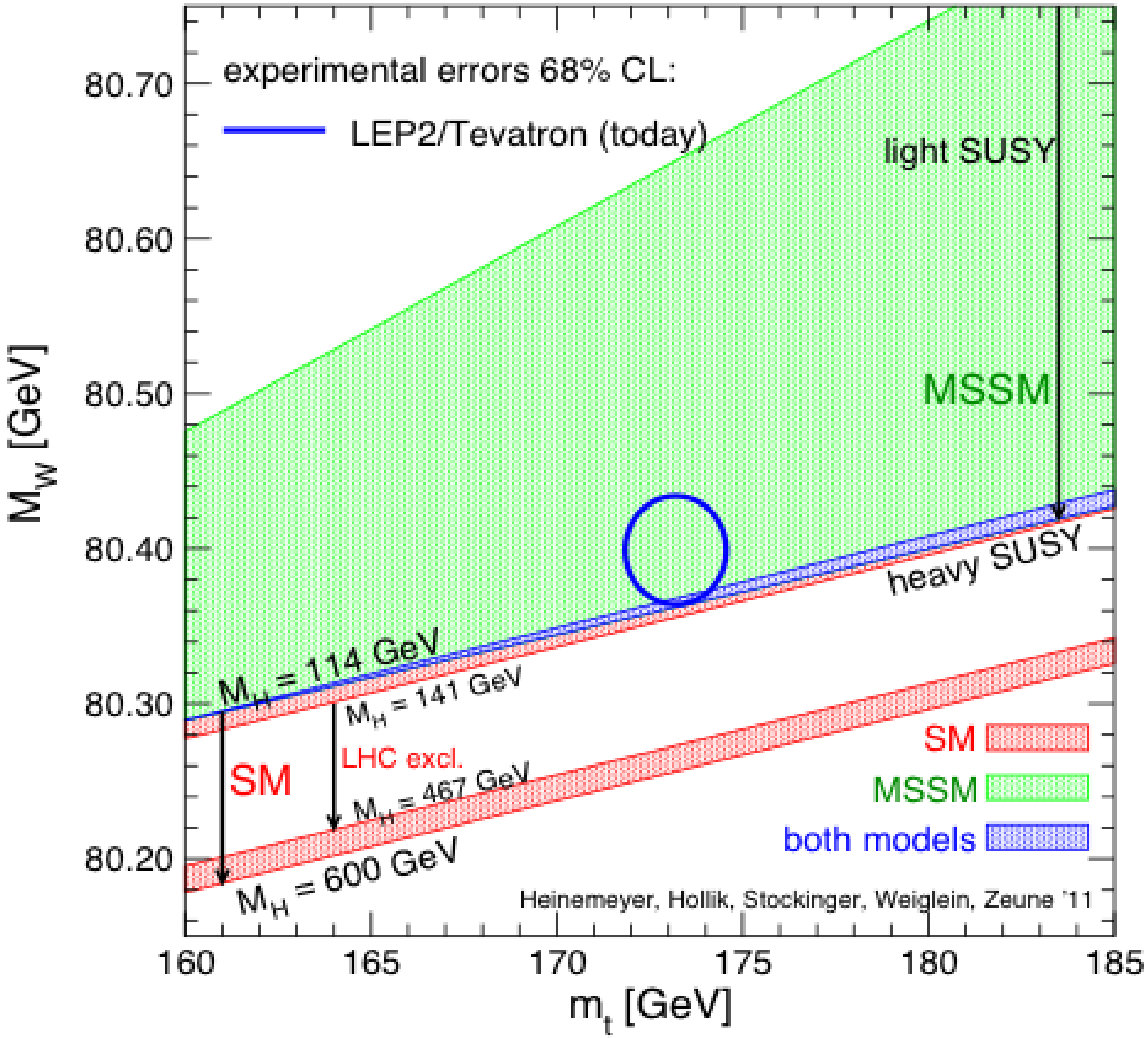


NUHM1,2

add 1 or 2 separate mass parameters for Hu, Hd



SUSY effects could improve the EW fit



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

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

Recent studies indicate that m_h goes up in CMSSM when b->sγ, a_μ, Ω_{DM} are added

O. Buchmuller et al '07, '08 [0808.4128]

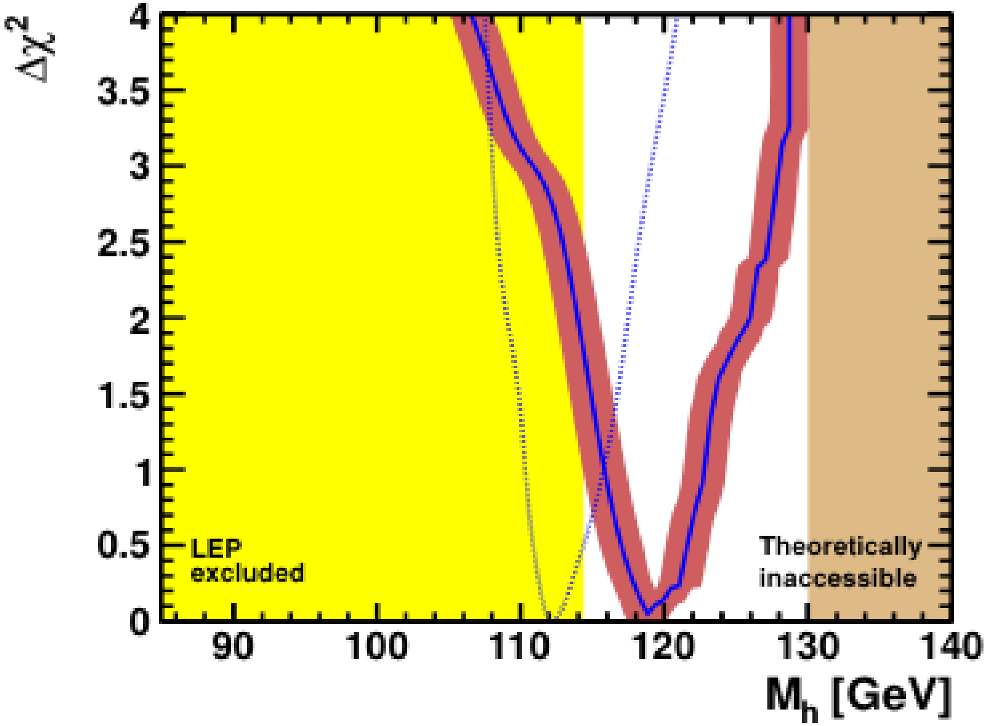
CMSSM

Variable	Measurement	Fit	$\lvert O^{meas} - O^{fit} \rvert / \sigma^{meas}$ (0 1 2 3)
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^0 [nb]	41.540± 0.037	41.486	
R_l	20.767± 0.025	20.744	
$A_{fb}^{0,l}$	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	
$A_{fb}^{0,b}$	0.0992± 0.0016	0.1037	
$A_{fb}^{0,c}$	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	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	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	
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95± 0.87	2.95	
Ωh^2	0.113± 0.009	0.113	

Input data for fits of CMSSM, NUHM1...... include

- The EW precision tests
- Muon g-2
- Flavour precision observables
- Dark Matter
- Higgs mass constraints and LHC

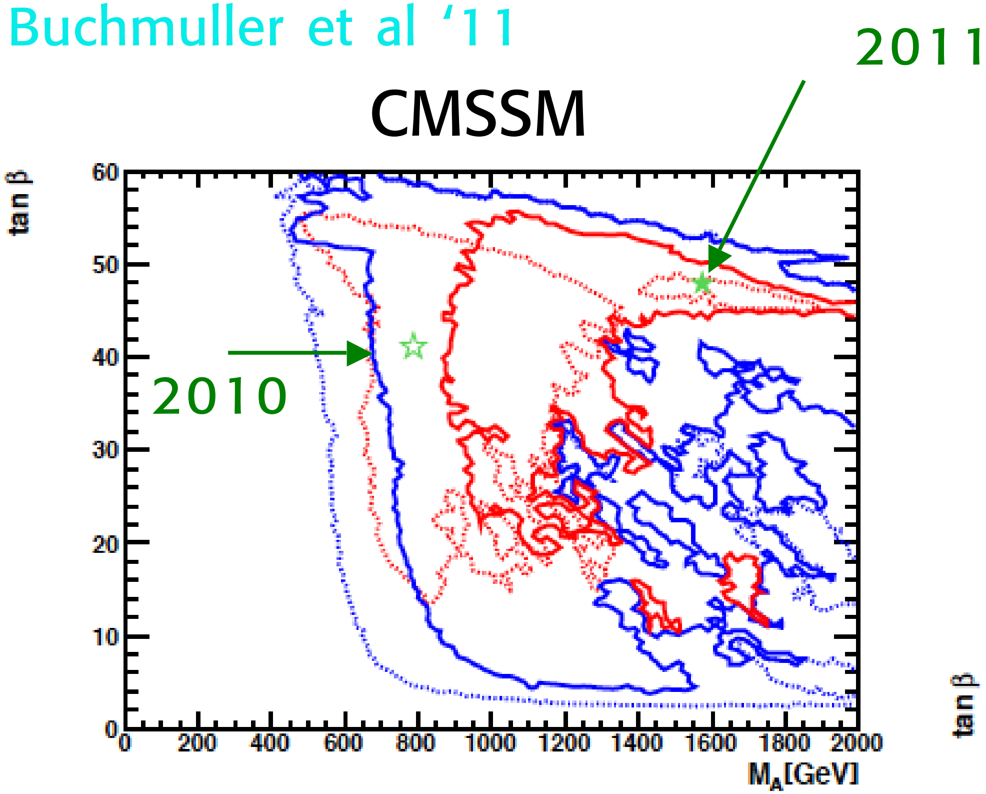
CMSSM:



$\Delta\chi^2$
4
3.5
3
2.5
2
1.5
1
0.5
0
90
100
110
120
130
140
M_h [GeV]
LEP
excluded
Theoretically
inaccessible

Buchmuller et al ‘11

CMSSM

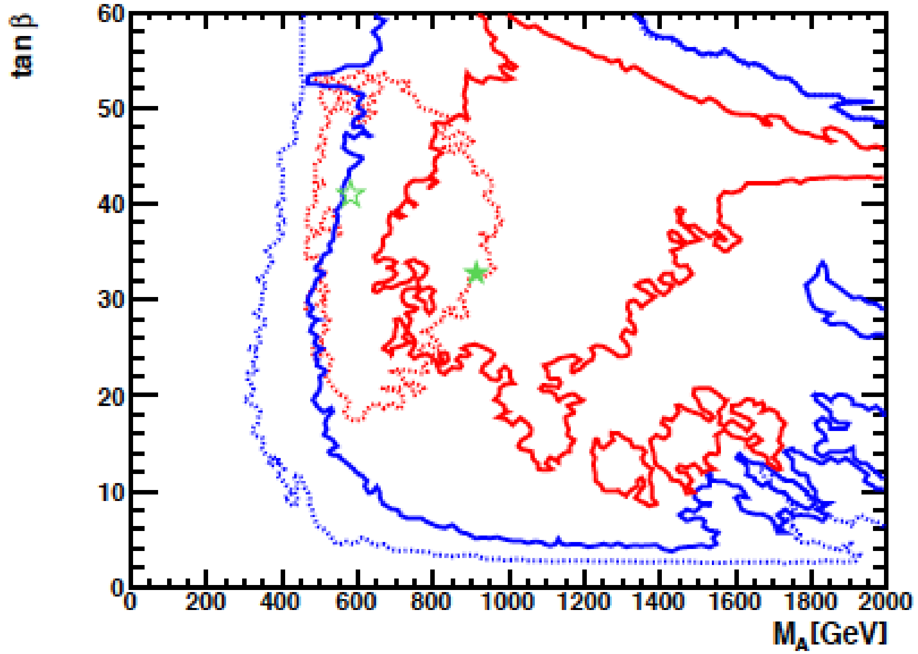


heavier scalars with new data

g-2 in trouble

with g-2 m_H ~ 119 GeV
without g-2 m_H ~ 125 GeV

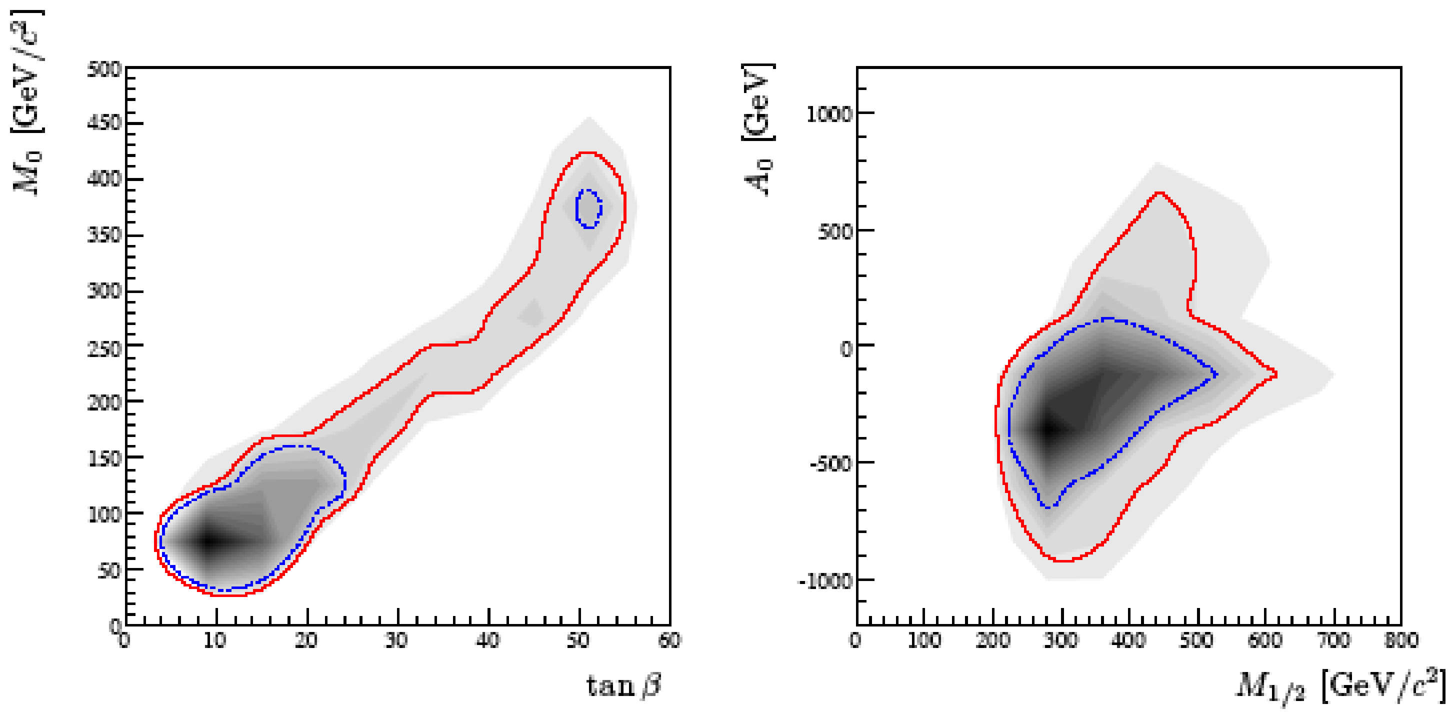
NUHM1



J. Ellis

Compare with the best fit in 2007!!

O. Buchmuller et al '07



SUSY

With new data ever increasing fine tuning

One must go to SUSY beyond the CMSSM, mSUGRA, NUHM1,2

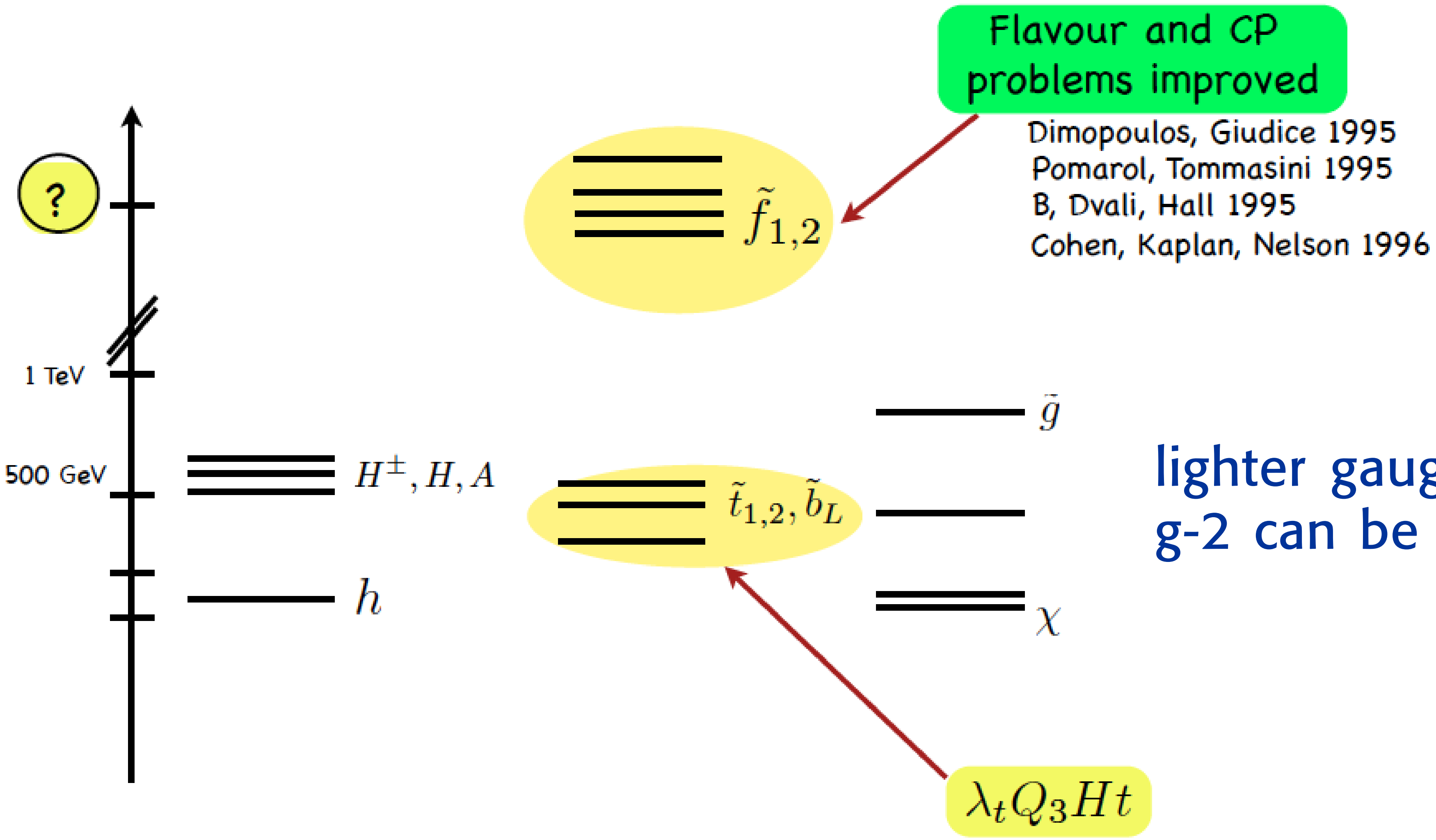
There is still room for more sophisticated versions

- Heavy first 2 generations
- NMSSM
- λ SUSY
- Split SUSY
- Large scale SUSY
- . . .

Beyond the CMSSM, mSugra, NUHM1,2

Heavy 1st, 2nd generations

Barbieri

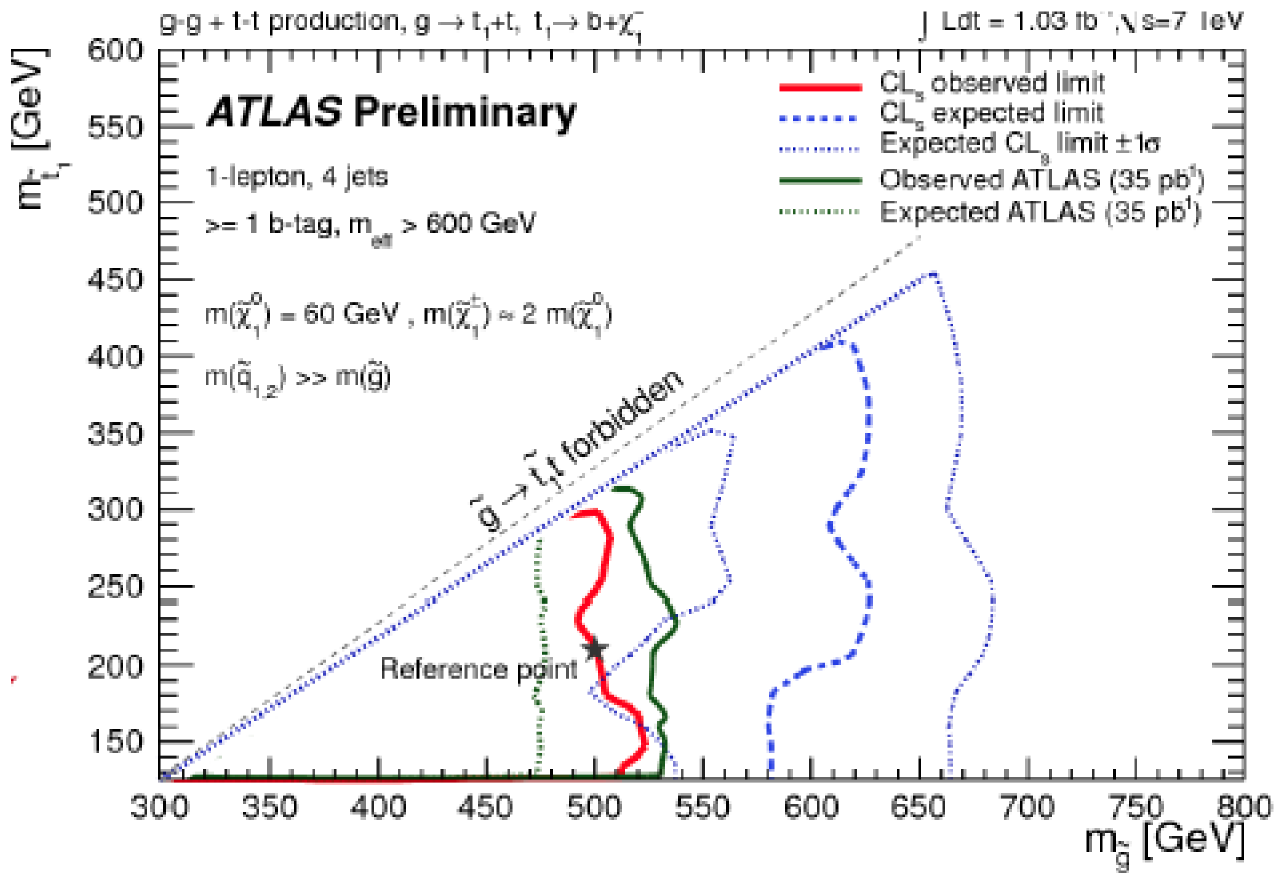


lighter gauginos,
g-2 can be rescued

For example, may be gluinos decay into 3-gen squarks

e.g. $\tilde{g} \rightarrow \tilde{t}_1 t \quad ; \quad \tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

and $\tilde{\chi}_1^{\pm} \rightarrow W^* \tilde{\chi}_1^0$



m(gluino) > 500 GeV at 95% C.L. $\quad\quad m_{s\text{-}top} >\sim 250$ GeV

An extra singlet Higgs

In a promising class of models a singlet Higgs S is added and the μ term arises from the S VEV (the μ problem is soved)

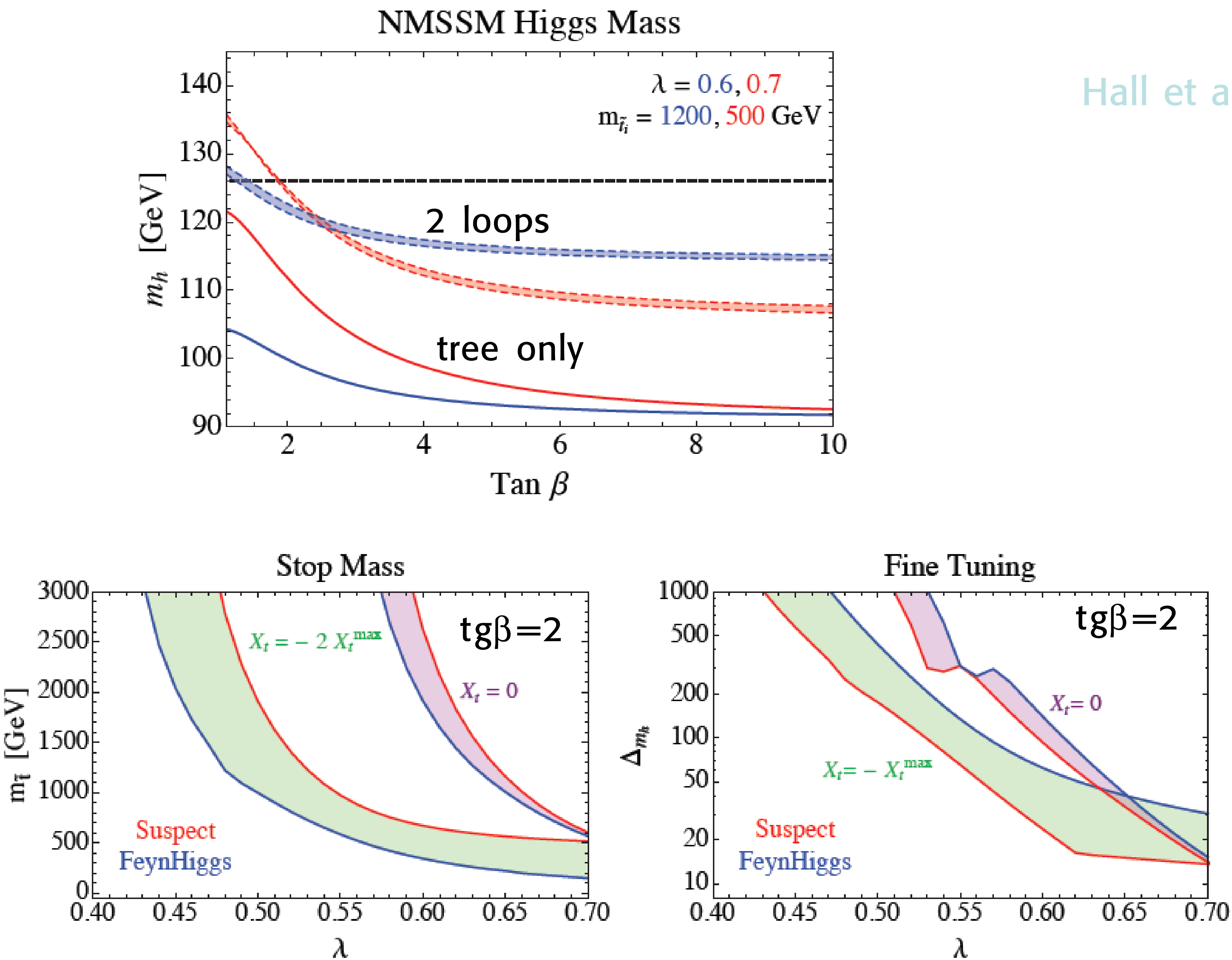
$$\lambda S H_u H_d$$

Mixing with S can bring the light Higgs mass down at tree level

(no need of large loop corrections)

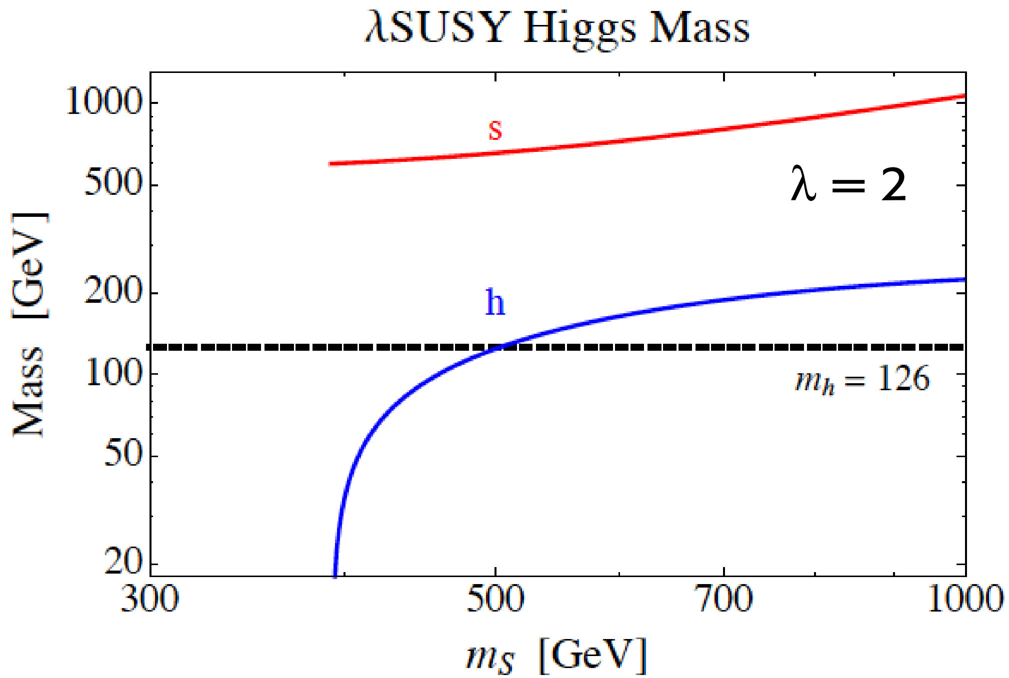
NMSSM: $\lambda <\sim 0.7$ the theory remains perturbative up to M_{GUT}
(no need of large stop mixing, less fine tuning)

λ SUSY: $\lambda \sim 1 - 2$ for $\lambda > 2$ theory non pert. at ~10 TeV


NMSSM Higgs Mass
λ = 0.6, 0.7
m_t̃i = 1200, 500 GeV
2 loops
tree only
m_h [GeV]
Tan β
Stop Mass
tgβ=2
X_t = − 2 X_t^max
X_t = 0
Suspect
FeynHiggs
m_t̃ [GeV]
λ
Fine Tuning
tgβ=2
X_t = 0
X_t = − X_t^max
Suspect
FeynHiggs
Δ_mh
λ

Hall et al '11

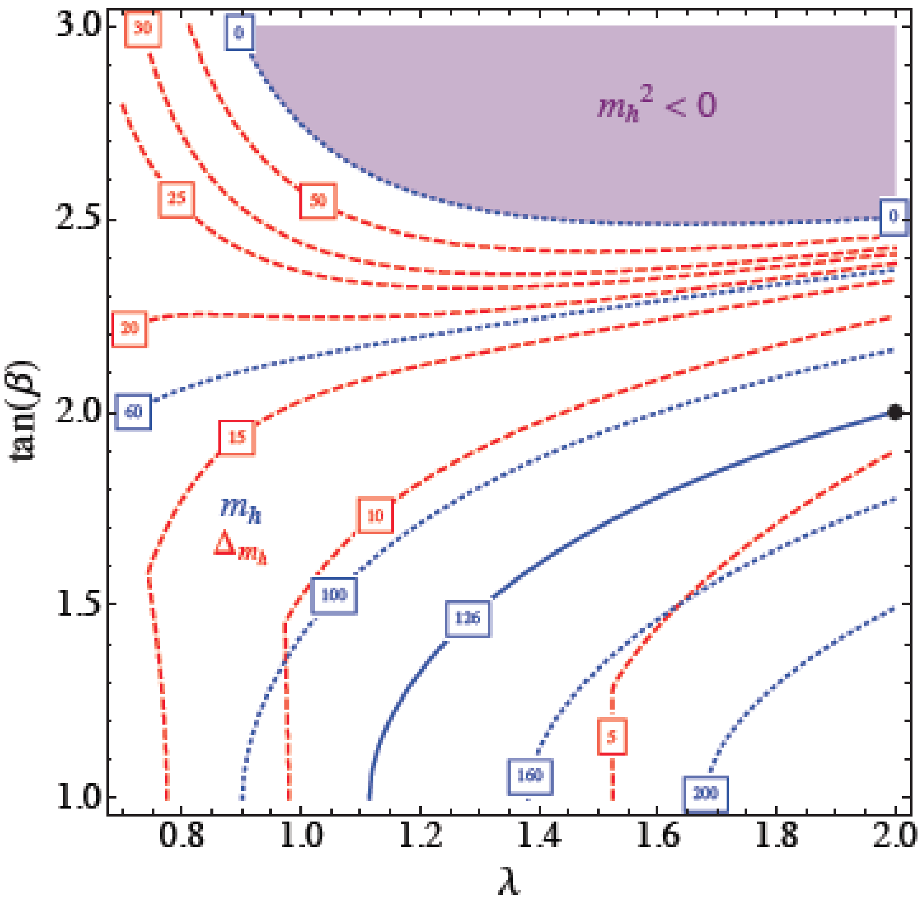
Hall et al '11



Mixing with S makes h heavy already at tree level

No need of loops

Fine tuning can be very small

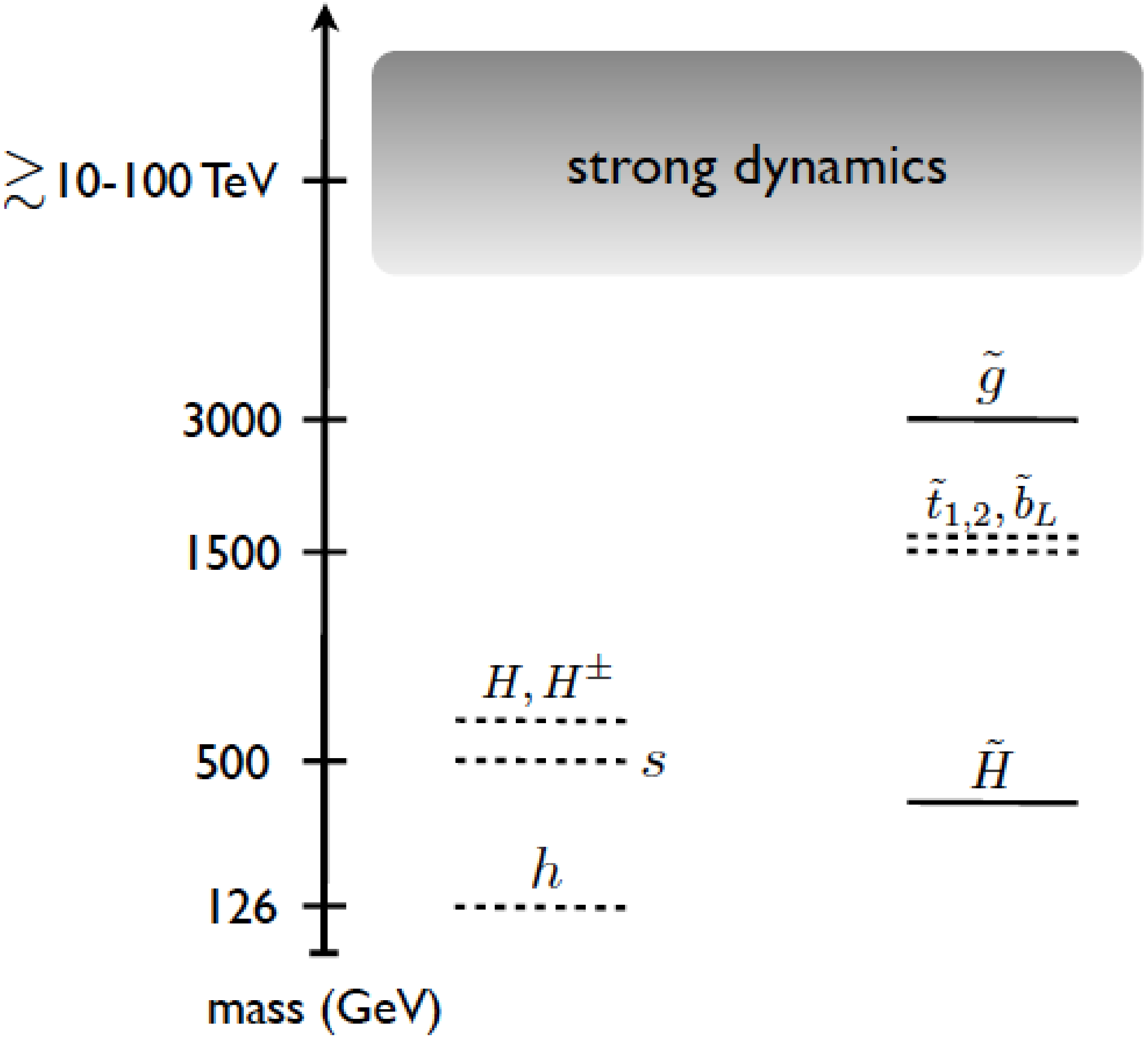


It is not excluded that
at 125 GeV
you see the heaviest of the two
and the lightest escaped detection
at LEP

Ellwanger '11

λSUSY spectrum ($\lambda = 2$)

Hall et al '11



Drawbacks:
relation with GUT's & coupling unification is generically lost

g-2?

If the Fine Tuning problem is ignored (anthropic philosophy) than SUSY particles can drift at large scales

Split SUSY: maintains coupling unification and viable DM candidate but otherwiseallows heavy SUSY particles

Giudice et al '11

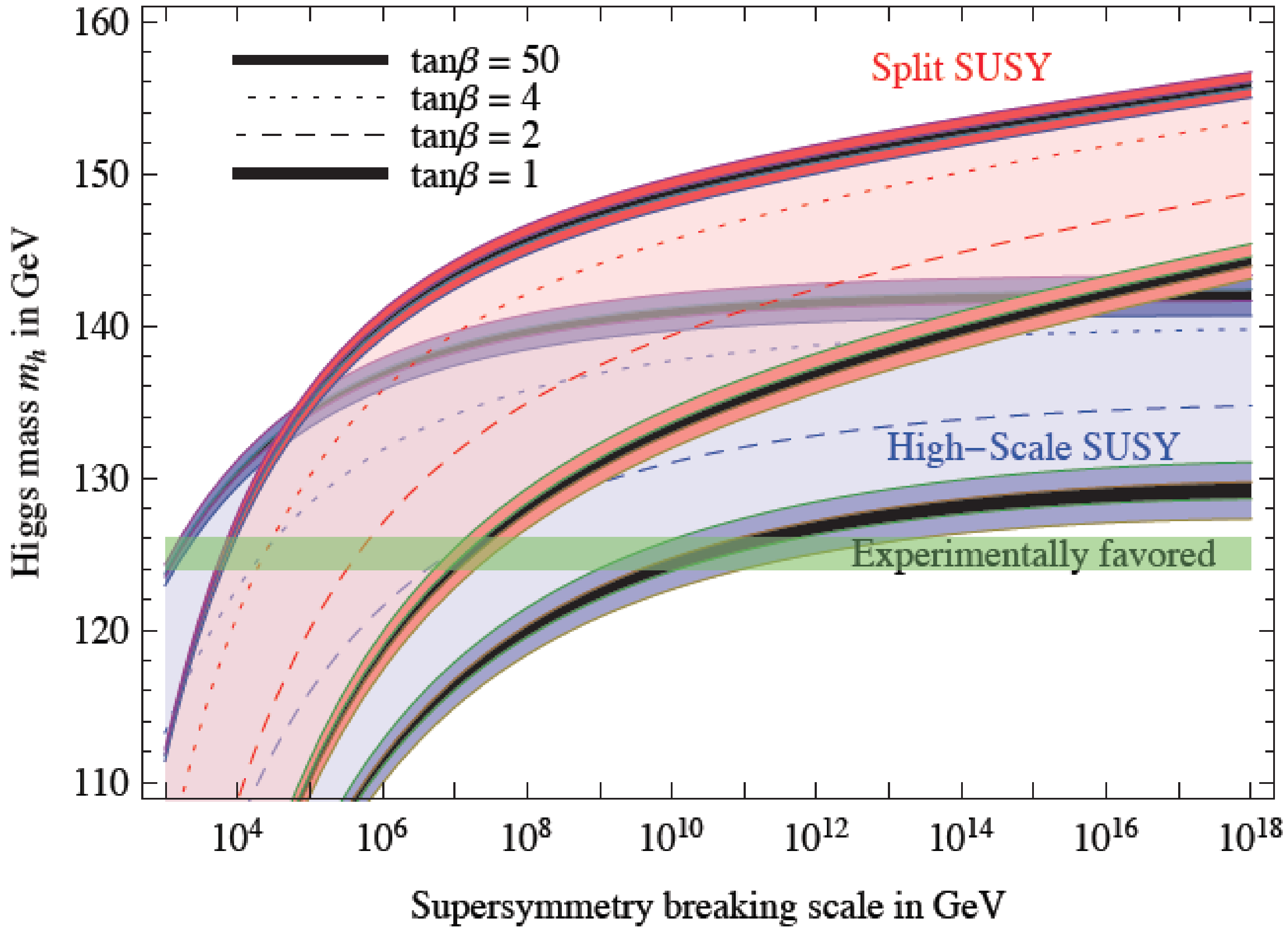
Large scale SUSY: all sparticles heavy. The quartic Higgs coupling is fixed by the gauge coupling at the large scale and fixes m_H at the EW scale

Hall et al '11

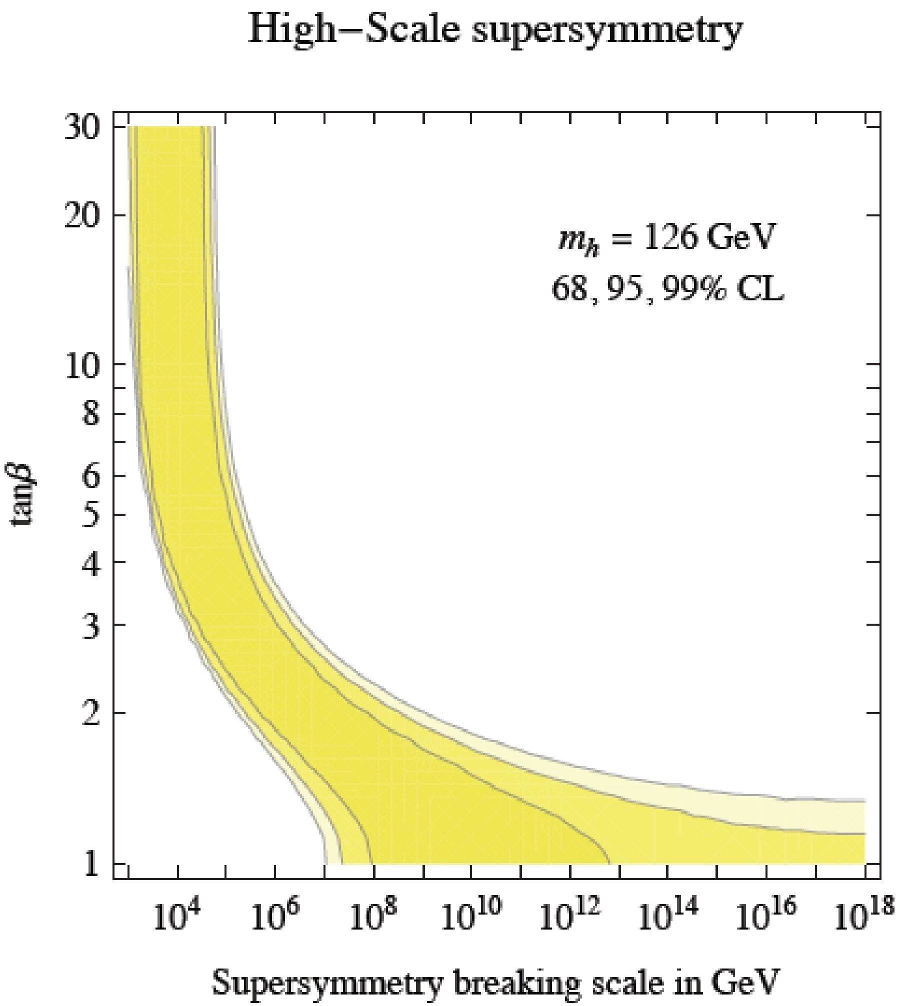
These models are strongly constrained by $m_H \sim 125$ GeV Remain valid with the large scale brought down, (more so if $tg\beta$ is large)

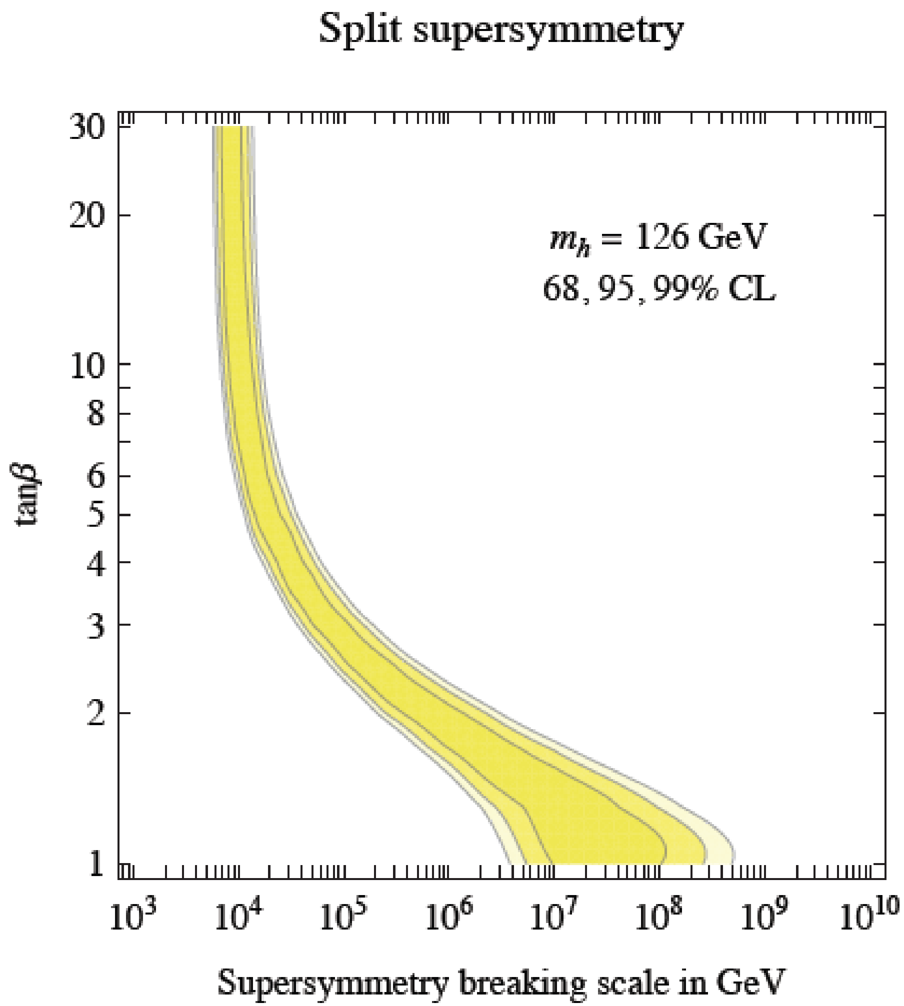
Predicted range for the Higgs mass

Giudice, Strumia'11



Giudice, Strumia'11





Summarising

- What is unique of SUSY is that it is consistent and computable up to GUT's .

  Coupling unification, dark matter, ... give important support to SUSY

- It is true that one hoped to discover SUSY in the first LHC runs

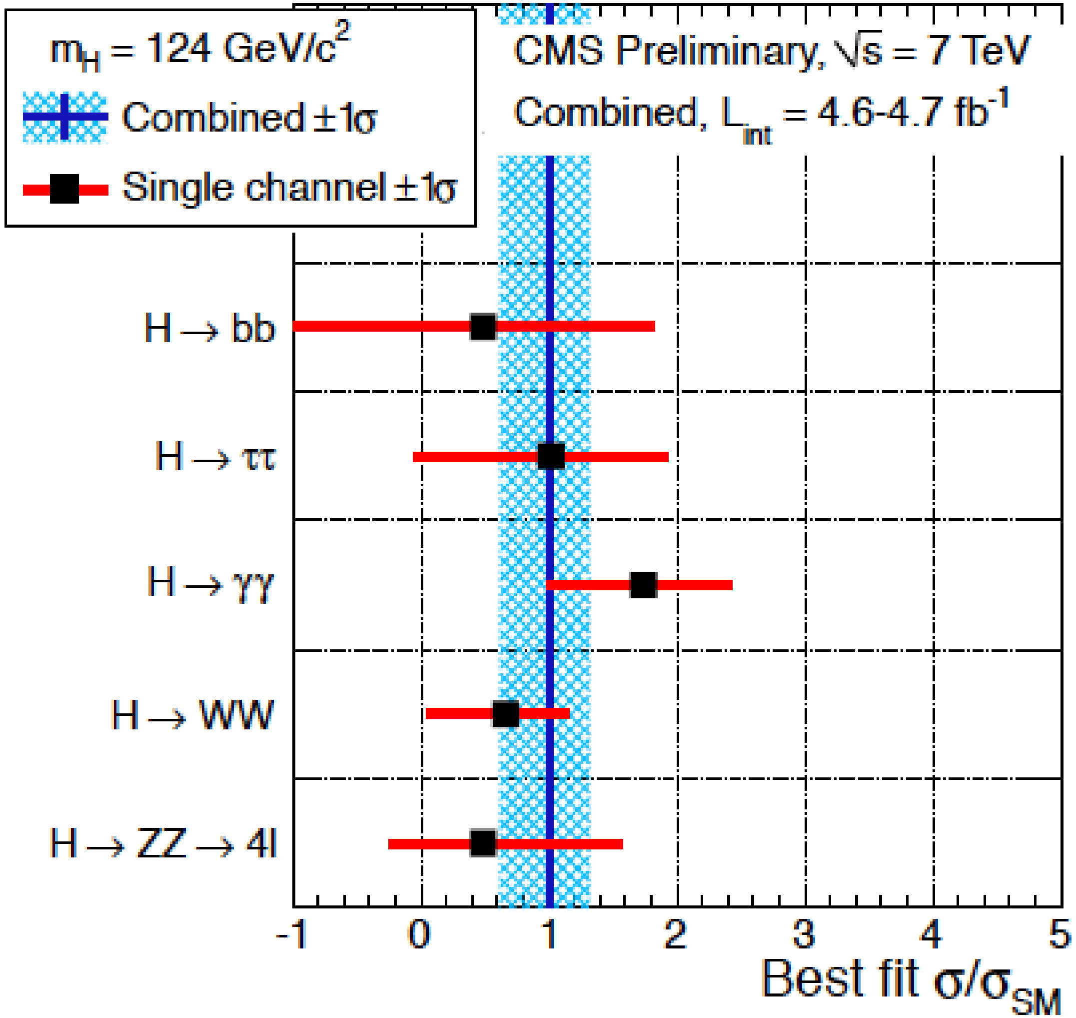
- At present only the simplest versions are in trouble

- There is still plenty of room for SUSY

- SUSY remains the Standard Way beyond the SM

BACKUP

A moderate enhancement of the $\gamma\gamma$ rate may be indicated



Summarising

- 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 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)

Soon the LHC will tell us; we badly need exp input!!!