SUSY in the light of present experimental data

and

Normal Scalar Mass Hierarchy

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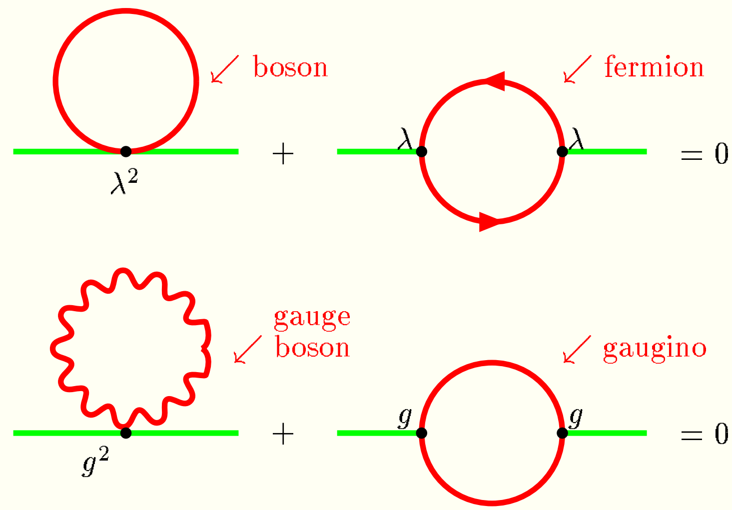
OUTLINE

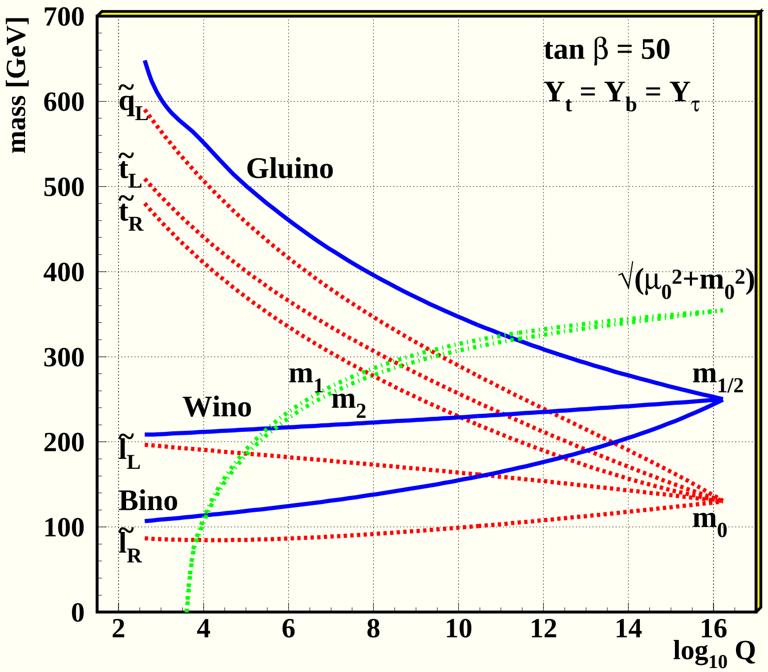
- *mSUGRA model: problem to reconcile relic density, $b \to s\gamma$, $(g-2)$ and LEP2 data*
- *Normal Scalar Mass Hierarchy scenario as a gracefull solution*
- *Oulook for Normal Scalar Mass Hierarchy for SUSY GUTS models*
- *Conclusions*

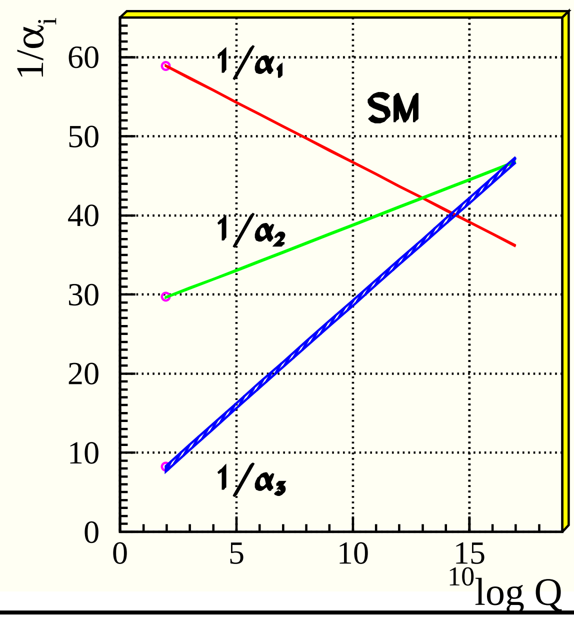
"SUSY Normal Scalar Mass Hierarchy Reconciles
$(g-2)_\mu$, $b \to s\gamma$ and Relic Density"
by H.Baer, AB, T.Krupovnickas, A.Mustafayev, hep-ph/0403214

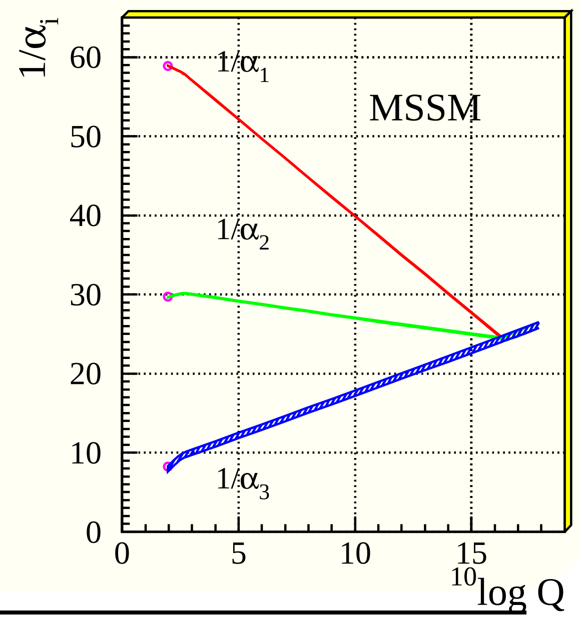
Supersymmetry: Beauty and Solution of Principle Problems

- *Extension of space-time symmetry, includes Einstein's general relativity, provides link to gravity, consistency of string theories*
- *Provides unification of gauge couplings, solves the hierarchy problem and fine tuning (cancellation of quadratic divergences)*
- *Electroweak symmetry breaking is derived result*
- *Provides nice dark matter candidate*









minimal SUGRA (cMSSM)

- *Visible-Hidden sectors interact with each other via gravity, fields in the hidden sector develop non-zero vevs*
- *Weak scale model constructed via RGE evolution, assuming:*
  - *Universality of the soft breaking parameters at GUT ($\sim 10^{16}$ GeV)*
  - *diagonal form of Yukawa matrices and trilinear parameters*
  - *gauge couplings unification*

$$-\mathcal{L}_{Breaking} = m_0^2 \sum_i |\varphi_i|^2 + (\tfrac{1}{2} m_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha + A[y^U_{ab}\tilde{Q}_a\tilde{U}^c_b H_2 + y^D_{ab}\tilde{Q}_a\tilde{D}^c_b H_1 + y^L_{ab}\tilde{L}_a\tilde{E}^c_b H_1] + B[\mu H_1 H_2] + h.c.)$$

- *Independent parameters left:*
  - m_0, $m_{1/2}$ *– universal scalar and gaugino masses*
  - $sign(\mu)$, μ^2 *value is fixed by the minimization condition for REWSB*
  - A *- the initial value of trilinear soft parameter*
  - B *- parameter – usually expressed via* $\tan\beta$

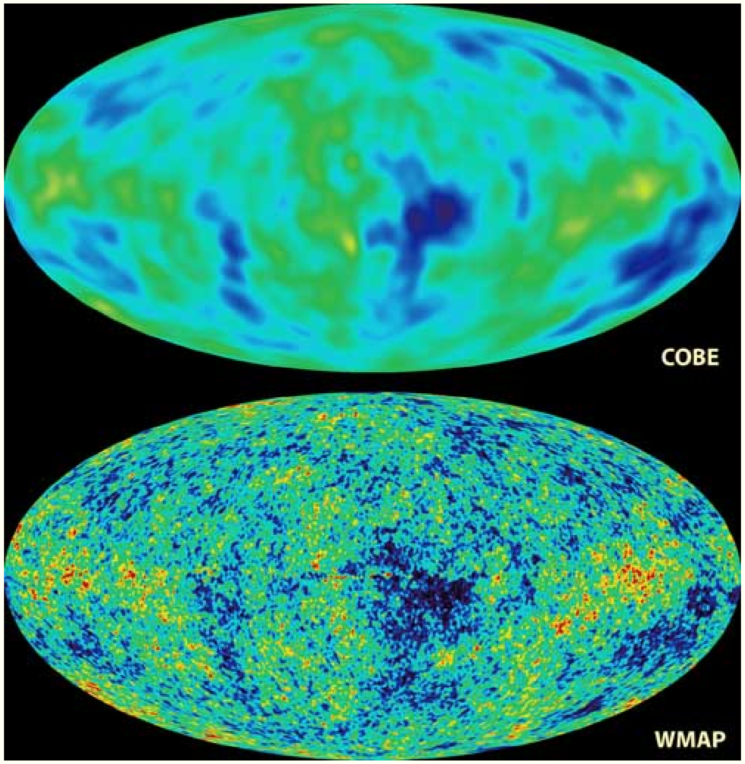
Present constraints : How viable is mSUGRA?

- *Relic density: Wilkinson Microwave Anisotropy Probe (WMAP) results: unprecendent resolution of millionths of a degree of temperature fluctuation!*

$$\Omega_b = 0.044 \pm 0.004$$
$$\Omega_m = 0.27 \pm 0.04$$
$$\Omega_\Lambda = 0.73 \pm 0.04$$
$$h = 0.71^{+0.04}_{-0.03}$$
$$0.094 < \quad \Omega_{CDM} h^2 < 0.129 (95\% CL)$$

C. L. Bennett et al. ApJS.148:97,'03

D. N. Spergel et al. ApJS.148:175,'03

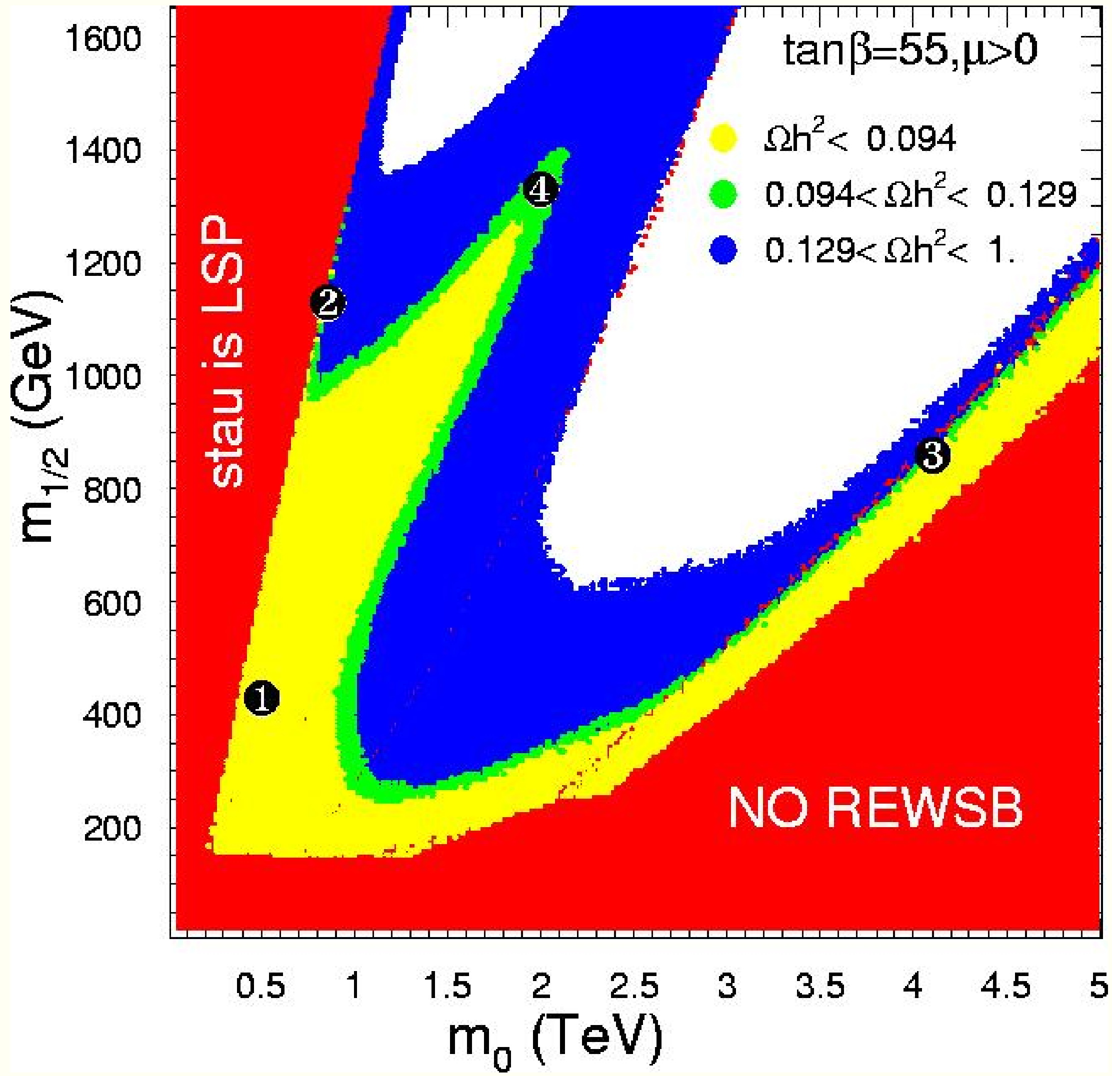


- *SUSY neutralino relic density calculation:*
  - *Complete set of co-annihilation processes[Baer-Balazs-AB code (ISARED)]* $\widetilde{Z}_1$, $\widetilde{Z}_2$, $\widetilde{W}_1$, $\tilde{e}_1$, $\tilde{\mu}_1$, $\tilde{\tau}_1$ $\tilde{t}_1$ *and* $\tilde{b}_1$*; exact calculation with CompHEP interfaced with ISAJET [similar to MicrOMEGAs* (Belanger,Boudjema,Pukhov,Semenov)*]*
  - *Evolution of the number density of supersymmetric relics (Griest and Seckel), relativistic thermal averaging of CS times velocity (Gondolo,Gelmini, Edsjö)*

SUGRA: DM favored regions of parameter space

1. *annihilation through t-channel slepton exchange (low m_0 and $m_{1/2}$)*
2. *the stau co-annihilation region (very low m_0 but large $m_{1/2}$)*
3. *the focus point region (large m_0 but low to intermediate $m_{1/2}$)*
4. *funnel region – s-channel annihilation corridor via A and H at large $\tan\beta$*

point	1	2	3	4
m_0	950	820	4000	1900
$m_{1/2}$	400	1100	830	1300
$\tan(\beta)$	55	55	55	55
$m_{\tilde{g}}$	986	2412	2034	2870
$m_{\tilde{b}_1}$	968	1949	3074	2574
$m_{\tilde{b}_2}$	1035	2017	3318	2639
$m_{\tilde{t}_1}$	864	1786	2715	2314
$m_{\tilde{t}_2}$	1015	2026	3098	2618
$m_{\tilde{e}_L}$	987	1109	4031	2083
$m_{\tilde{\tau}_1}$	578	471	2688	1148
$m_{\tilde{\tau}_2}$	832	924	3443	1767
$m_{\tilde{Z}_1}$	162	465	336	558
$m_{\tilde{Z}_2}$	313	895	402	1071
$m_{\tilde{W}_1}$	314	896	401	1072
m_h	117	123	122	123
m_A	410	889	1177	1120
μ	482	1213	390	1347
Ωh^2	0.10	0.11	0.10	0.10
$b \to s\gamma$	1.8	3.24	3.35	3.32
a_μ^{SUSY}	19.5	6.5	1.7	2.9



$b \to s\gamma$ **and** $(g-2)_\mu/2$ **data**

- $b \to s\gamma$: $BF(b \to s\gamma) = (3.25 \pm 0.37) \times 10^{-4}$ *[BELLE,CLEO and ALEPH]*

  $2.16 \times 10^{-4} < BF(b \to s\gamma) < 4.34 \times 10^{-4}$*(at 95%CL, incl 10% theory)*

  Baer,Brhlik,Castano,Tata code

  no signifi cant deviation from SM $\Longrightarrow m_{\tilde{t}_{1,2}}, m_{\tilde{W}_{1,2}}, m_{\tilde{H}^+}$ *should be heavy!*

- $(g-2)_\mu/2 =$*116591 208(6) [g-2 collaboration]* $\Leftarrow$ *Experiment*

  $\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$(Davier *et al.*) $\Leftarrow$ *Theory*

  $\Delta a_\mu = (31.7 \pm 9.5) \times 10^{-10}$(Hagiwara *et al.*) *(for $e^+e^- \to$ hadrons data)*

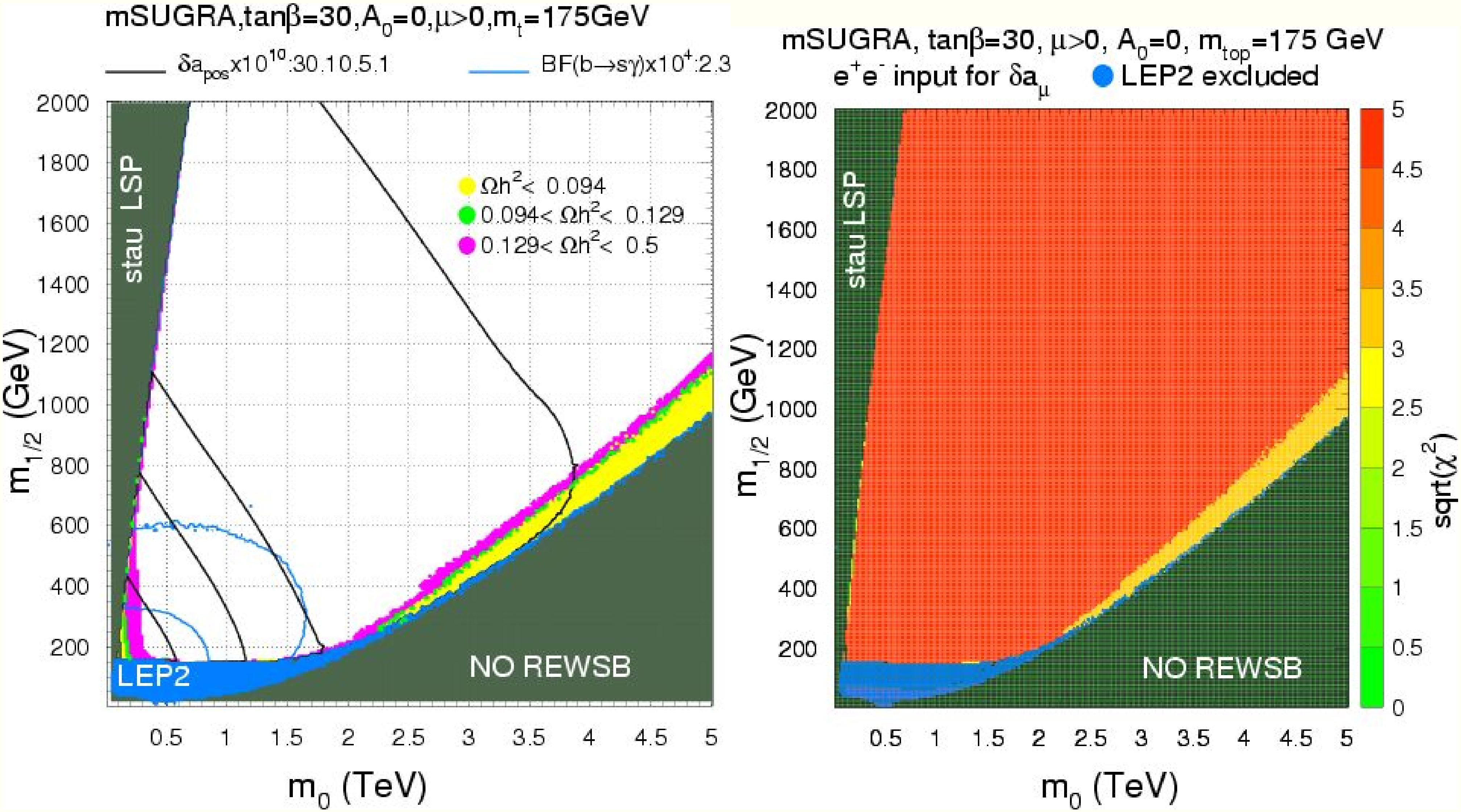
  (τ decay data $\Delta a_\mu = (12.4 \pm 8.3) \times 10^{-10}$ (Davier et al.))

  There are growing consensus that e^+e^- data are more to be trusted since they offer a direct determination of the hadronic vauum polarization

  $\sim 3\sigma \Longrightarrow$ *second generation of slepton are relatively light!*

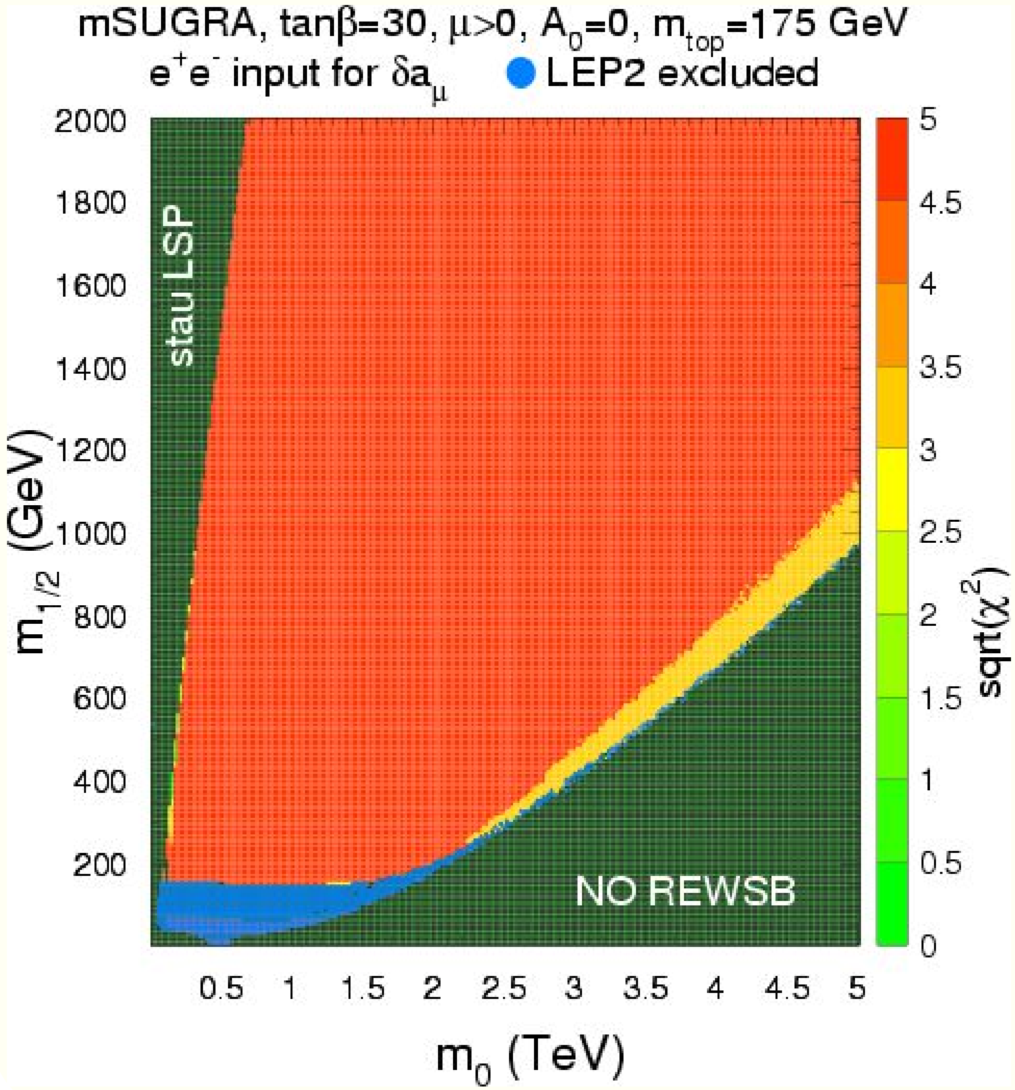
  We use code of Baer,Balazs,Ferrandis,Tata

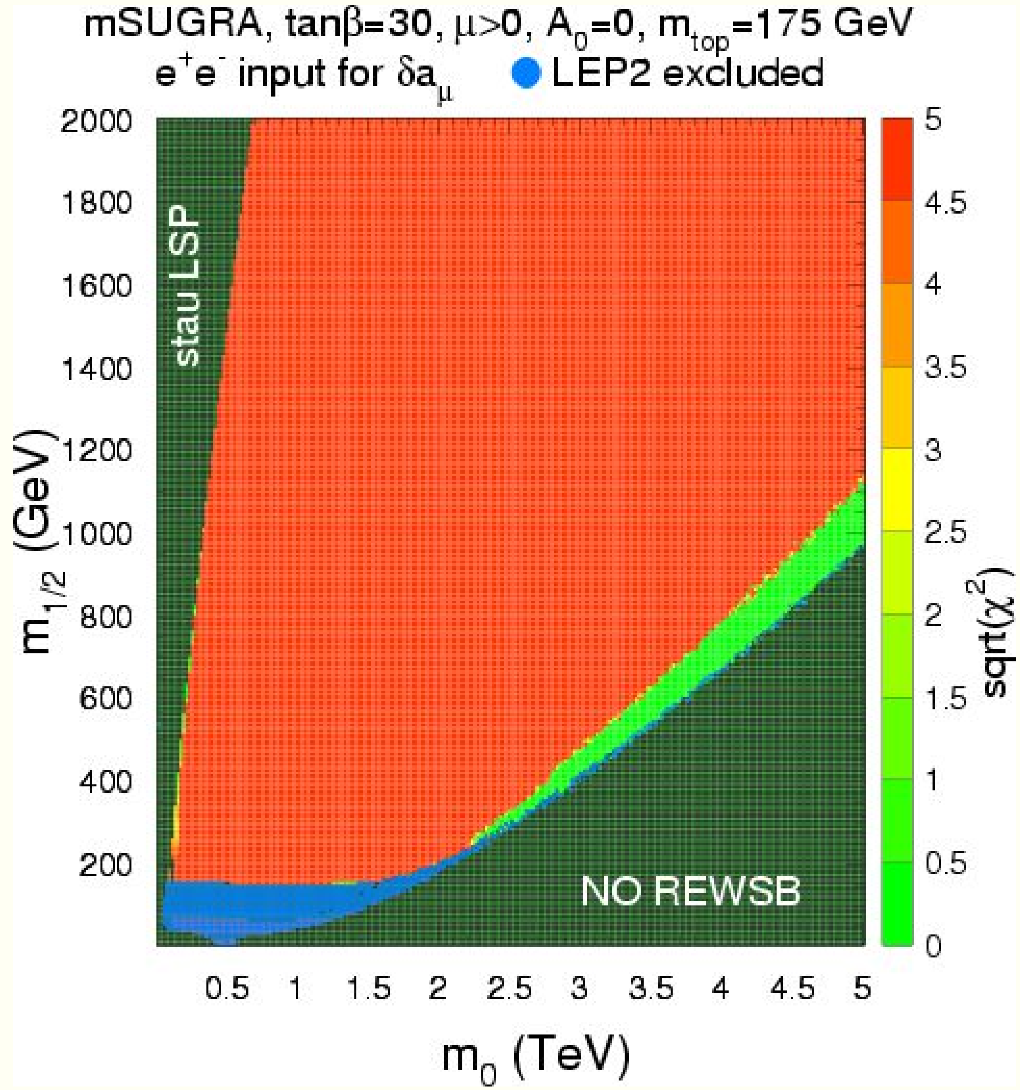
mSUGRA parameter space and $\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} + \chi^2_{b\to s\gamma}$



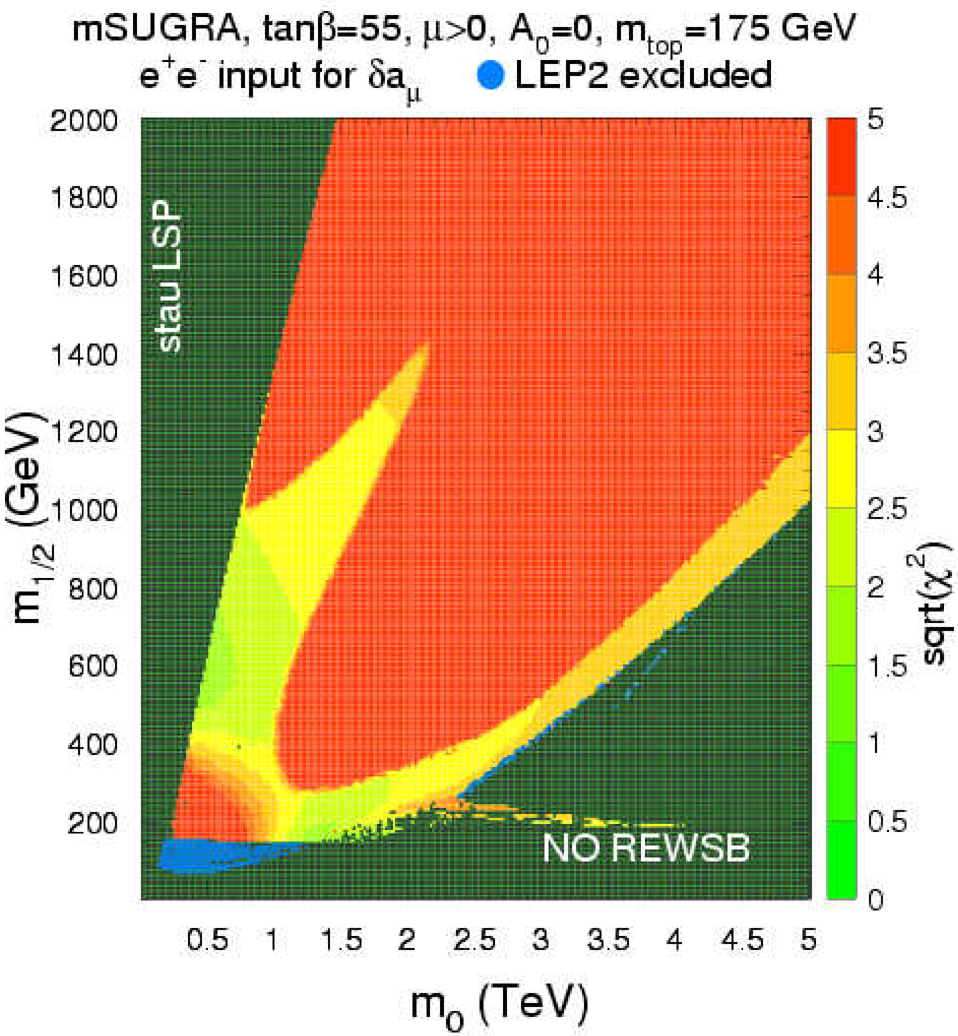
mSUGRA parameter space:

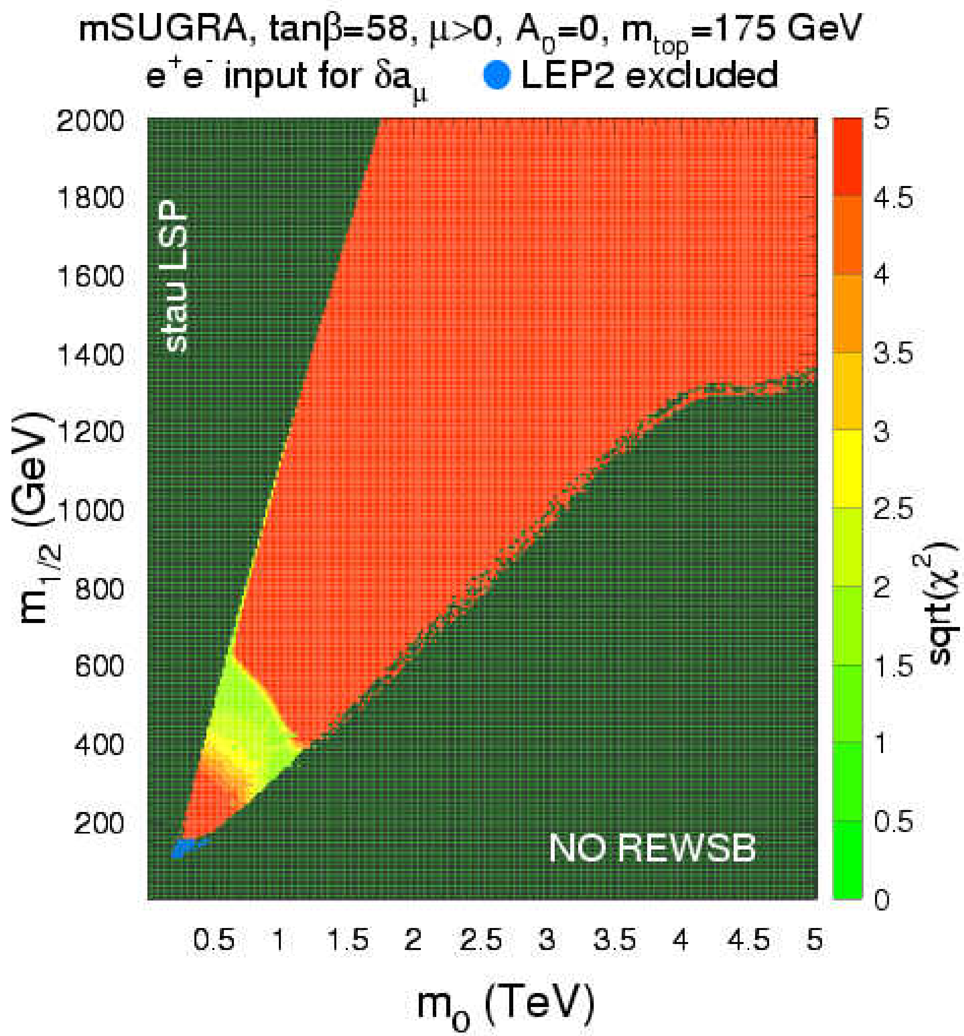
$$\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} \qquad \textbf{and} \qquad \chi^2 = \chi^2_{b\to s\gamma} + \chi^2_{\Omega h^2}$$





mSUGRA: high $\tan\beta$ case





Normal Mass Hierarchy(NMH) model

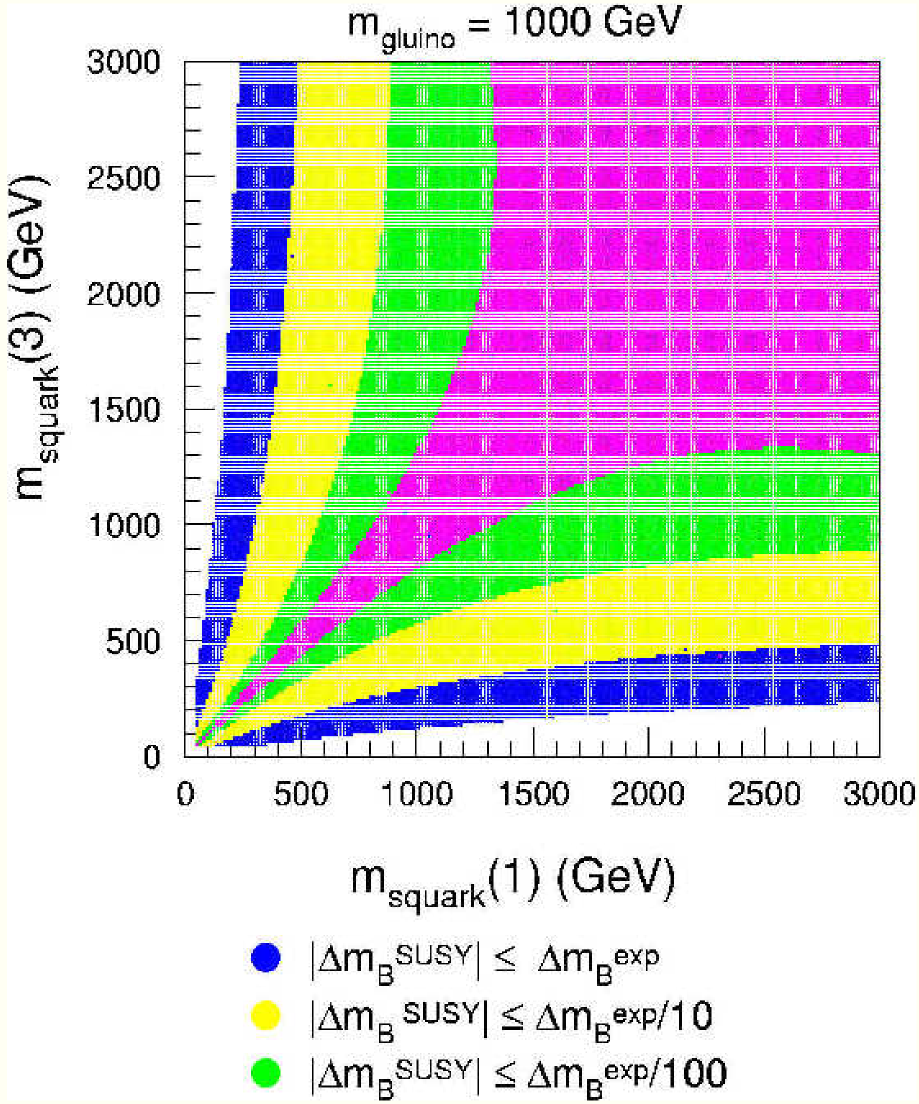
- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: hard to realize in mSUGRA model. Probably, this is an indication that one must move beyon the assumption of universality!

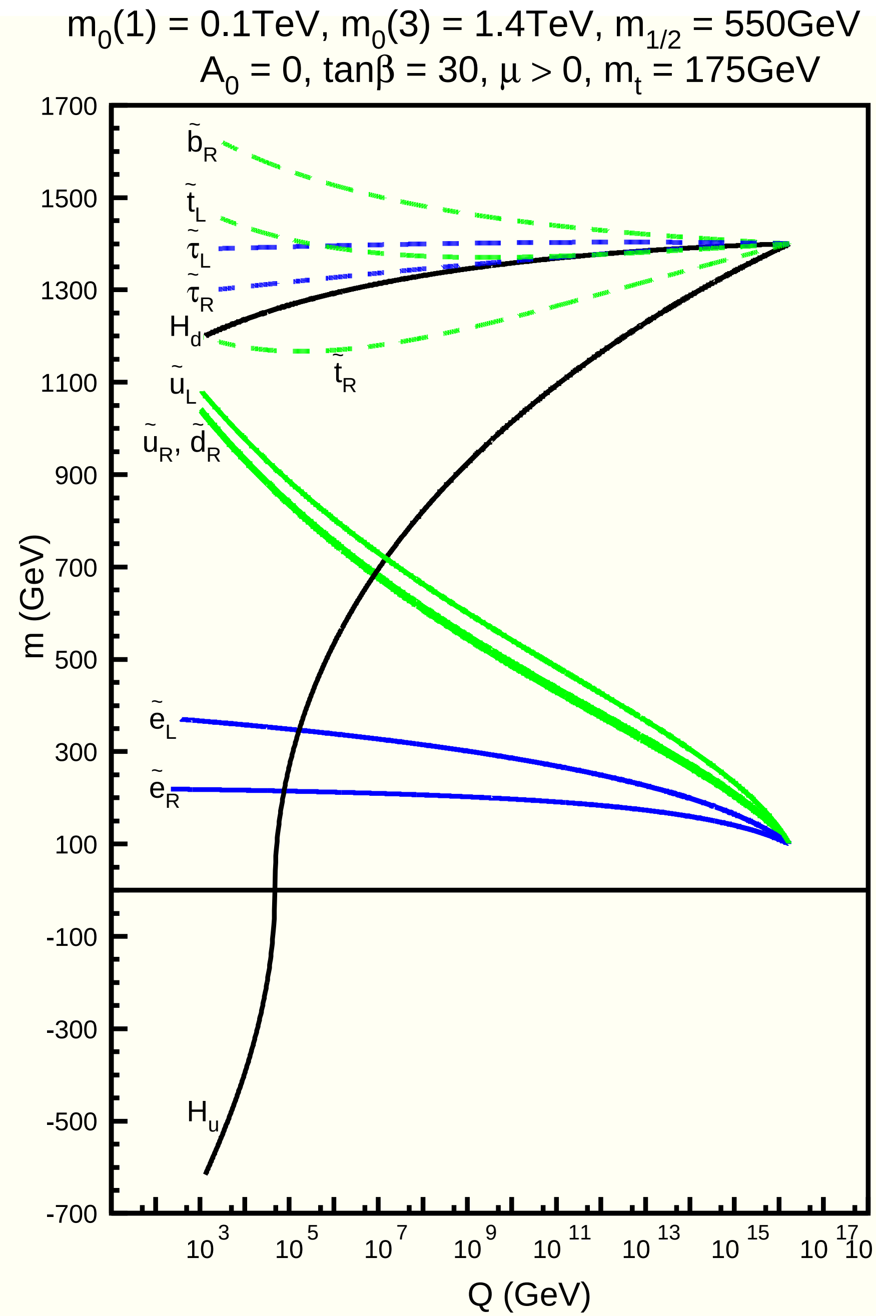
- $m_0(1),\ m_0(3),\ m_H,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
  Parameter space is well motivated by SO(10) SUSY GUTs

- Potential problem: $B^0_H - \bar{B}^0_L = \Delta m_B$ mass splitting bounds
  $|m_{\tilde{q}}(1) - m_{\tilde{q}}(3)| \lesssim \frac{m^2_{\tilde{q}}}{M_W}($ for $m_{\tilde{q}} \simeq m_{\tilde{g}})$
  Limits on Δm_B in the super-CKM basis translated to limits on mass split off-diagonal soft breaking mass terms [Misiak,Pokorski,Rosiek;Hagelin,Kelley,Tanaka]

- approximate relation of weak scale and GUT scale squark and slepton masses:
  $m^2_{\tilde{q}} \simeq m^2_0 + (5-6)m^2_{1/2}$, while $m^2_{\tilde{\ell}} \simeq m^2_0 + (0.15-0.5)m^2_{1/2}$

Constraints on (1,2-3) squark masses split from Δm_B? No!

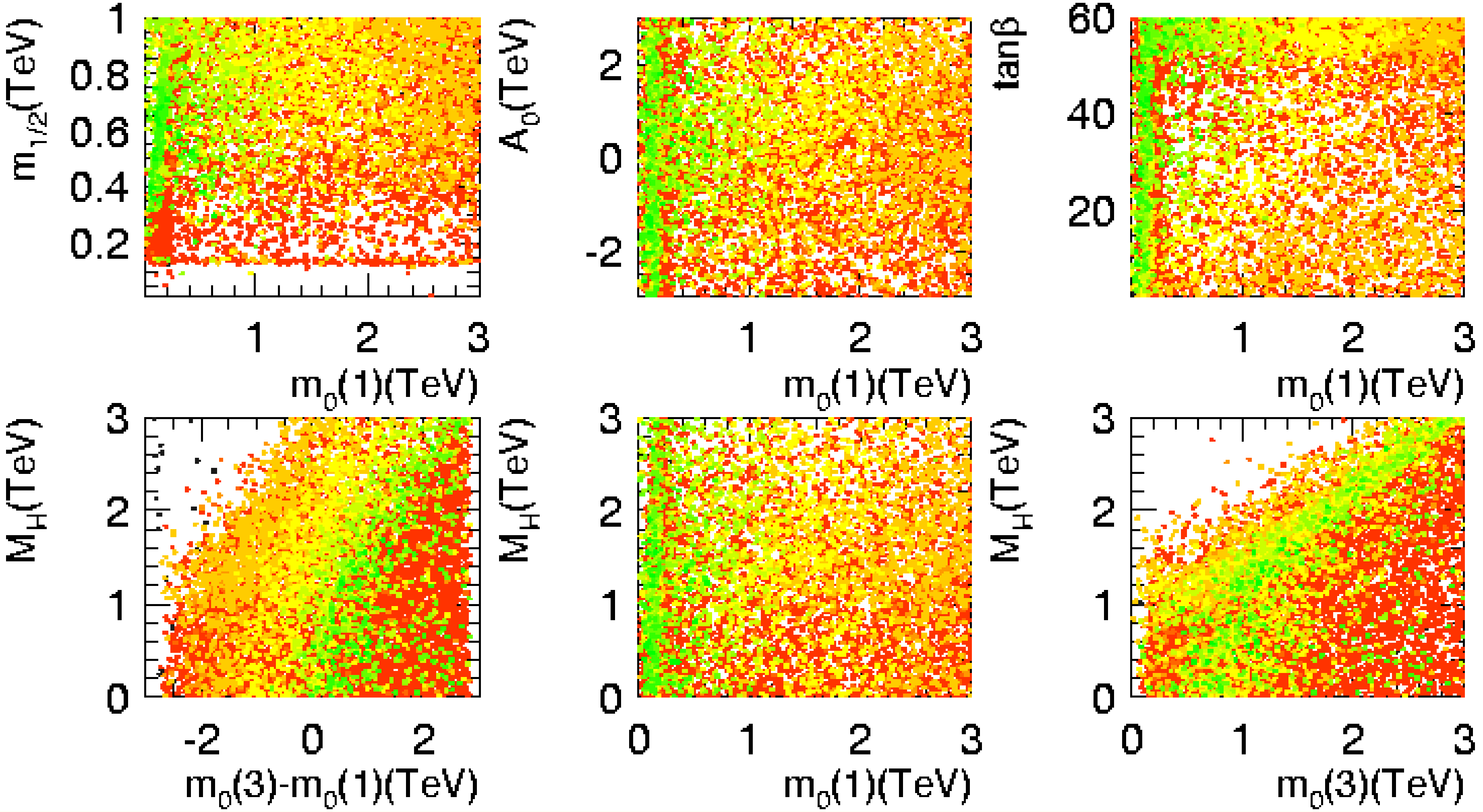




Scan in $m_0(1)$, $m_0(3)$, m_H, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$ **space**

$m_0(1): 0 - 3$ *TeV* $m_0(3): 0 - 3$ *TeV* $m_H: 0 - 3$ *TeV*

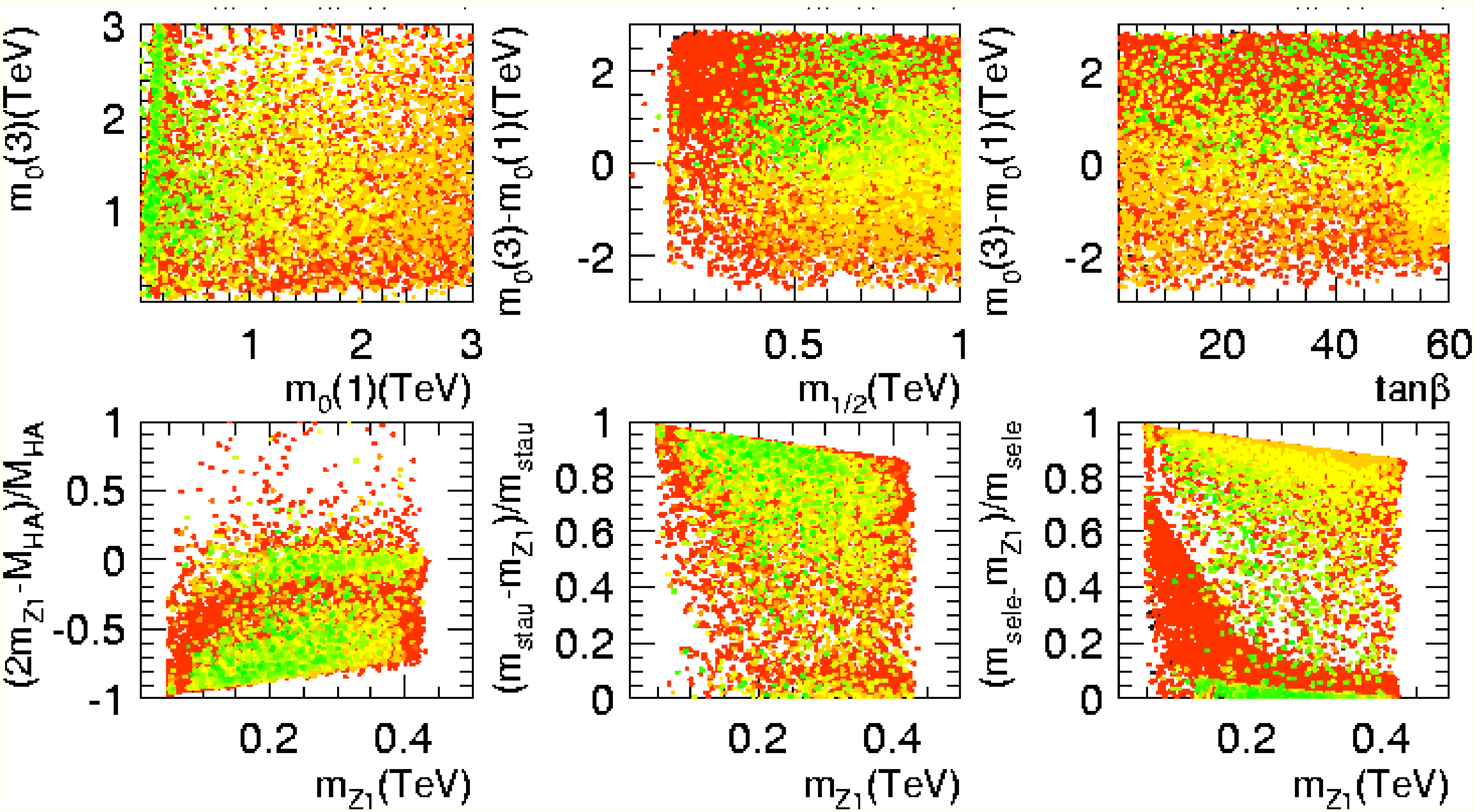
$m_{1/2}: 0 - 1$ *TeV* $A_0: -3 - 3$ *TeV* $\tan\beta: 2 - 60$



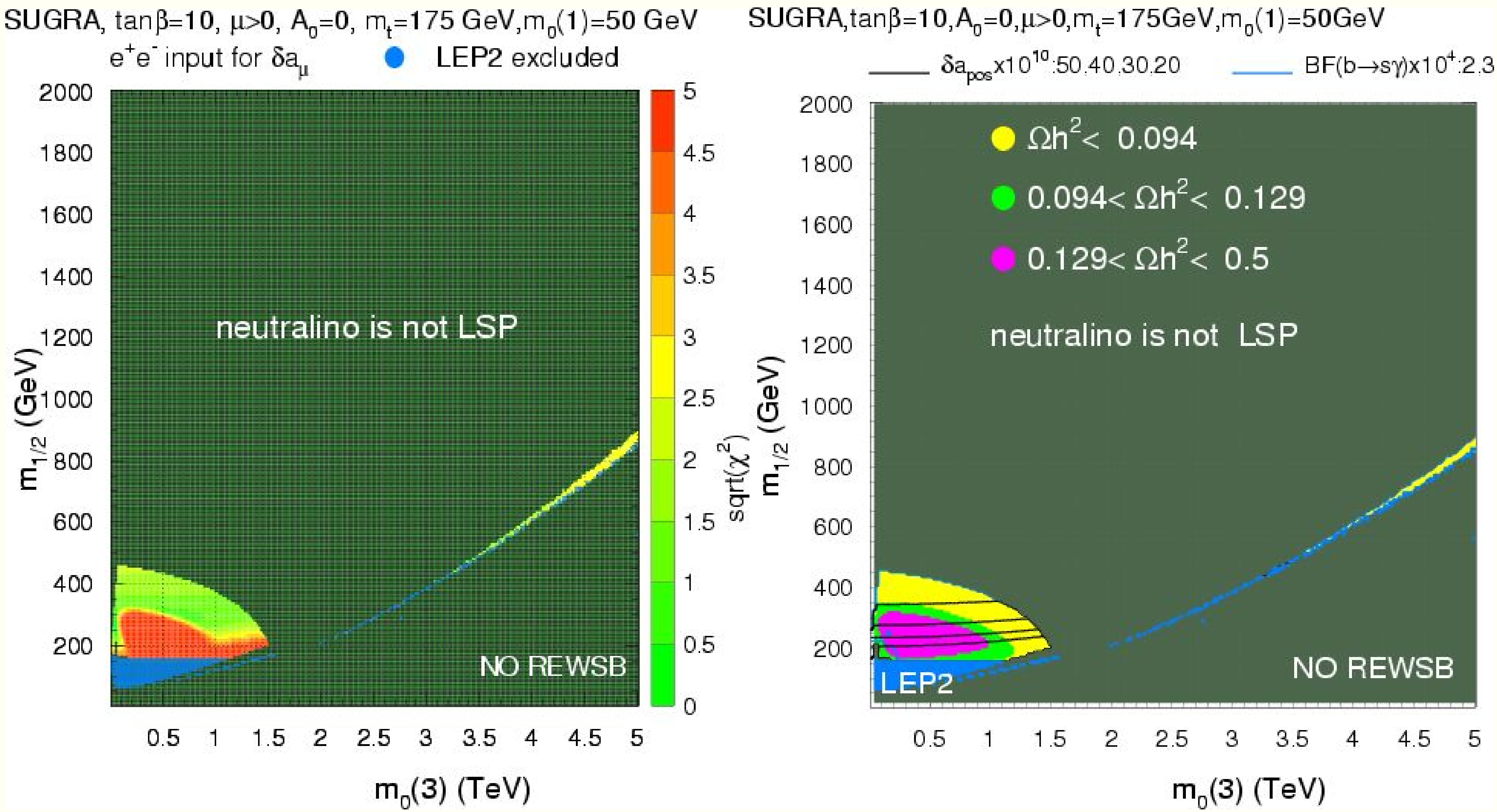
Scan in $m_0(1)$, $m_0(3)$, m_H, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$ **space**

$m_0(1): 0 - 3$ *TeV* $m_0(3): 0 - 3$ *TeV* $m_H: 0 - 3$ *TeV*

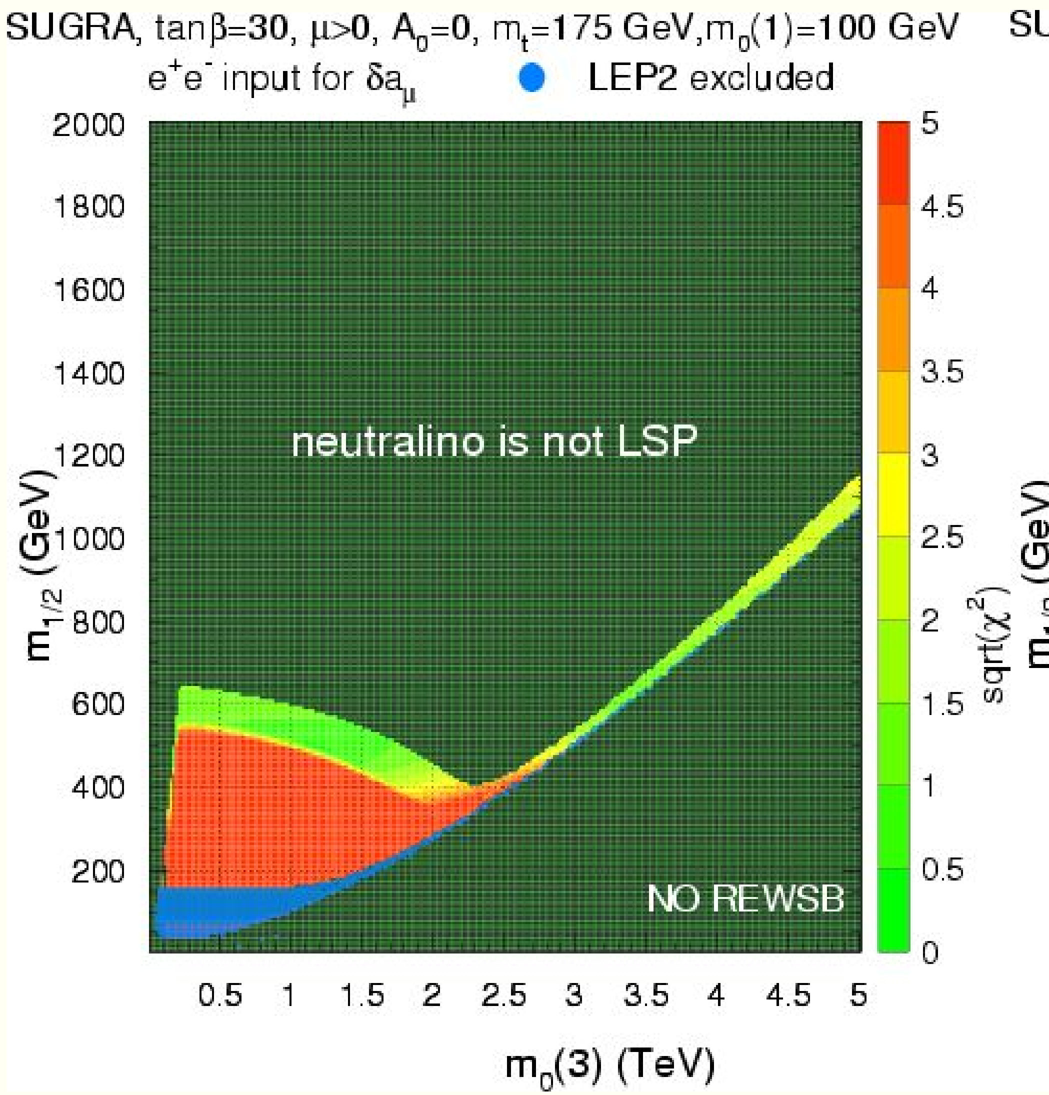
$m_{1/2}: 0 - 1$ *TeV* $A_0: -3 - 3$ *TeV* $\tan\beta: 2 - 60$

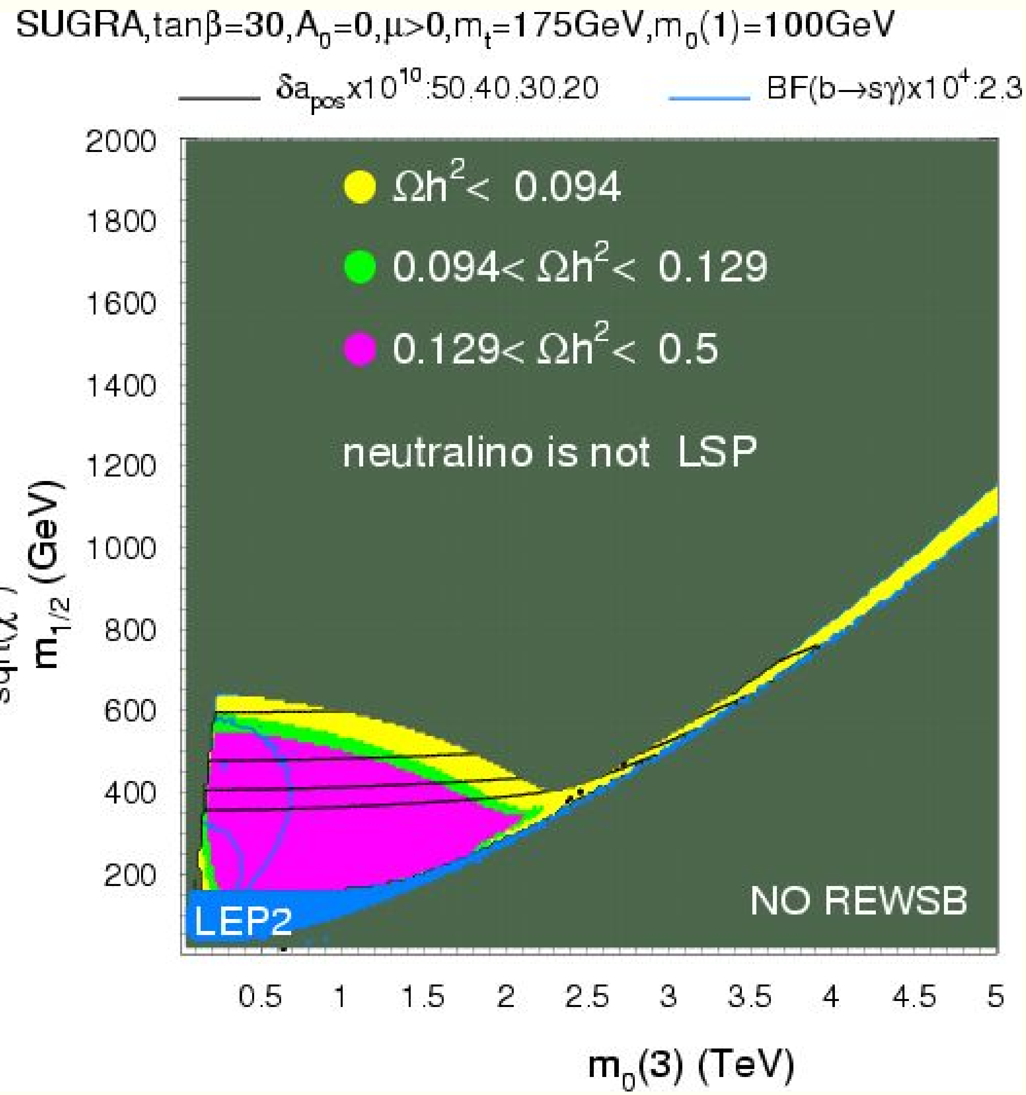


χ^2 *study of NMH SUSY scenario,* $\tan\beta = 10$



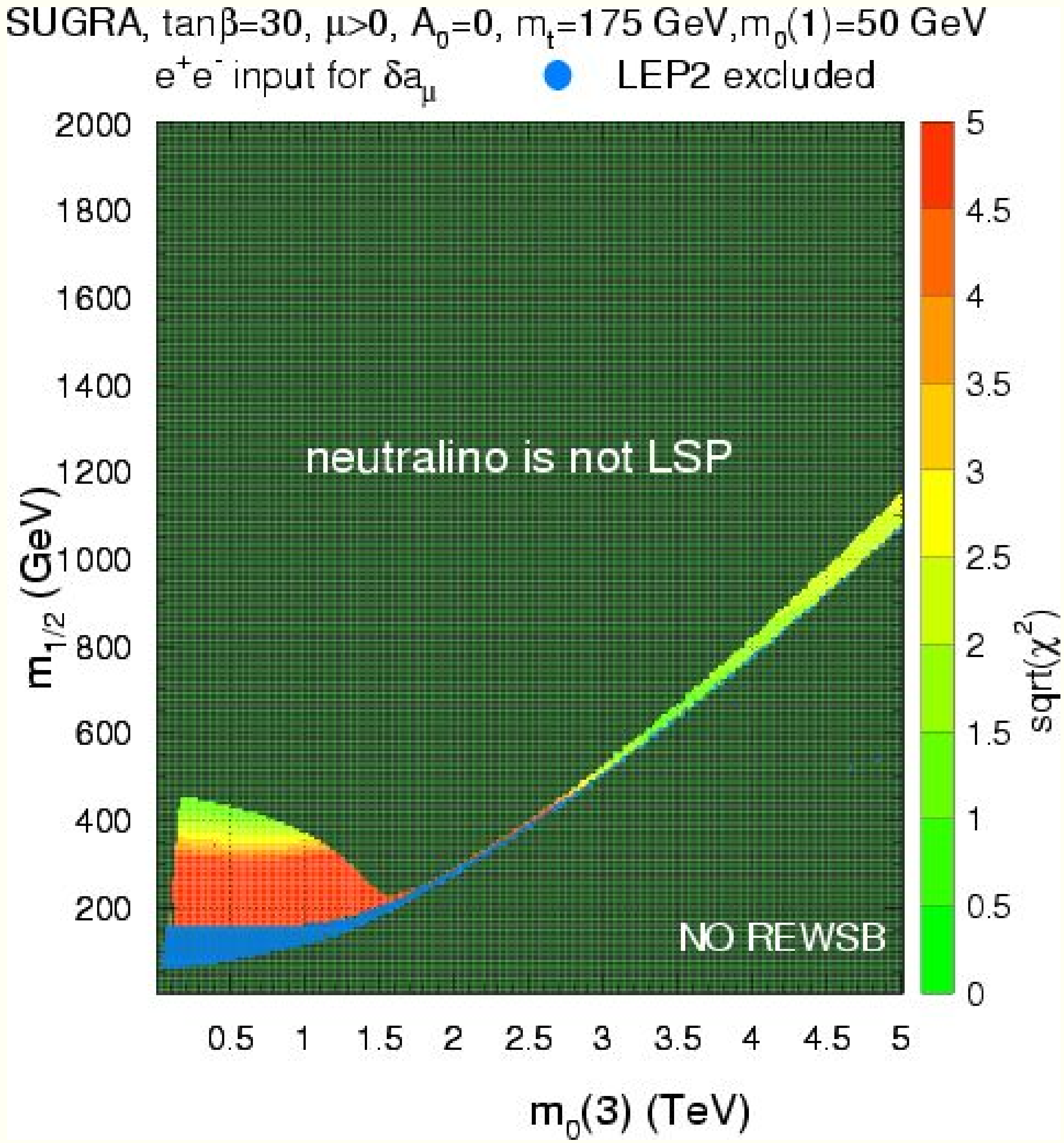
χ^2 ***study of NMH SUSY scenario,*** $\tan\beta = 30$



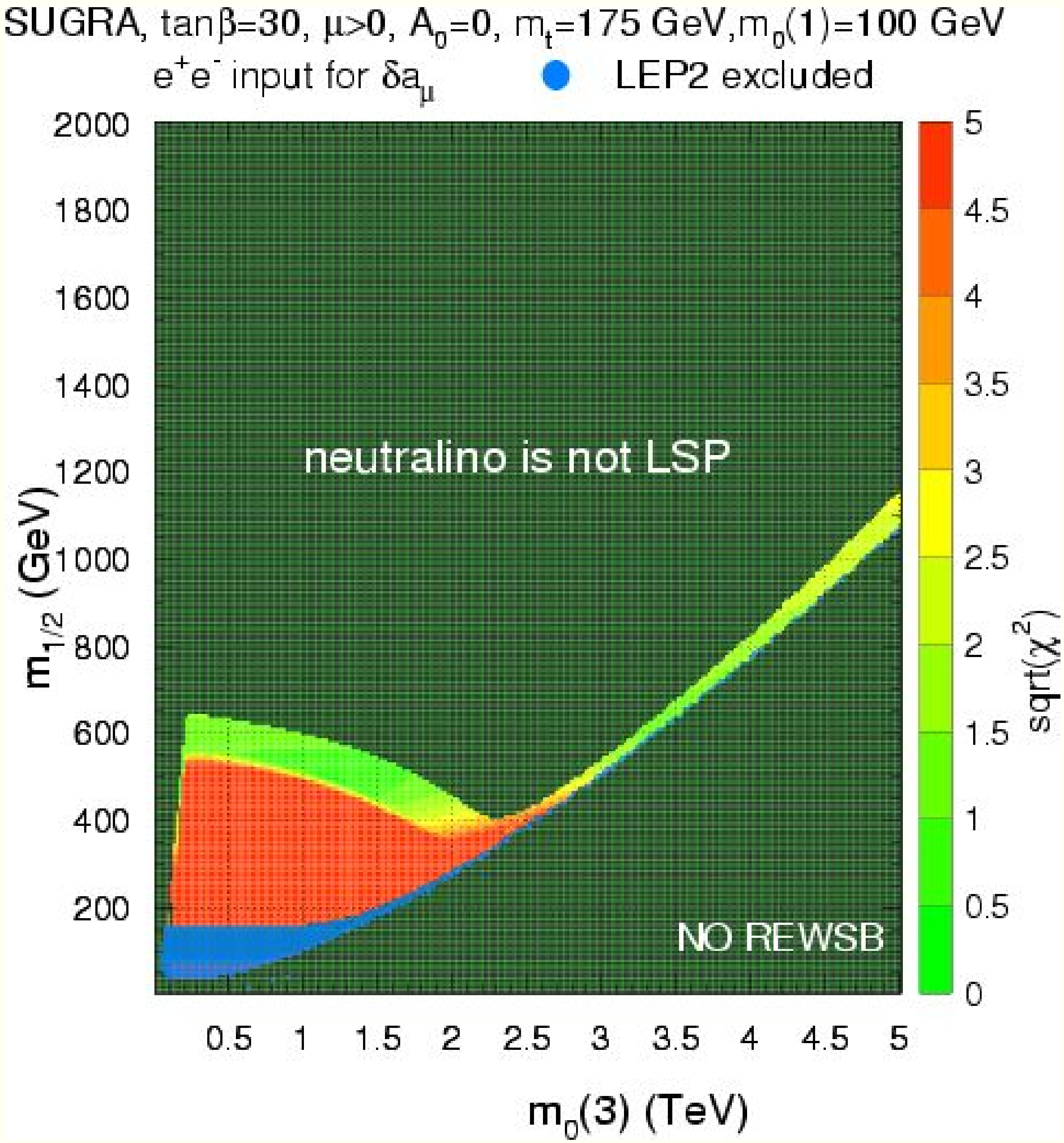


NMH SUGRA, $\tan\beta = 30$, $m0(1) = (50, 100, 200)$GeV

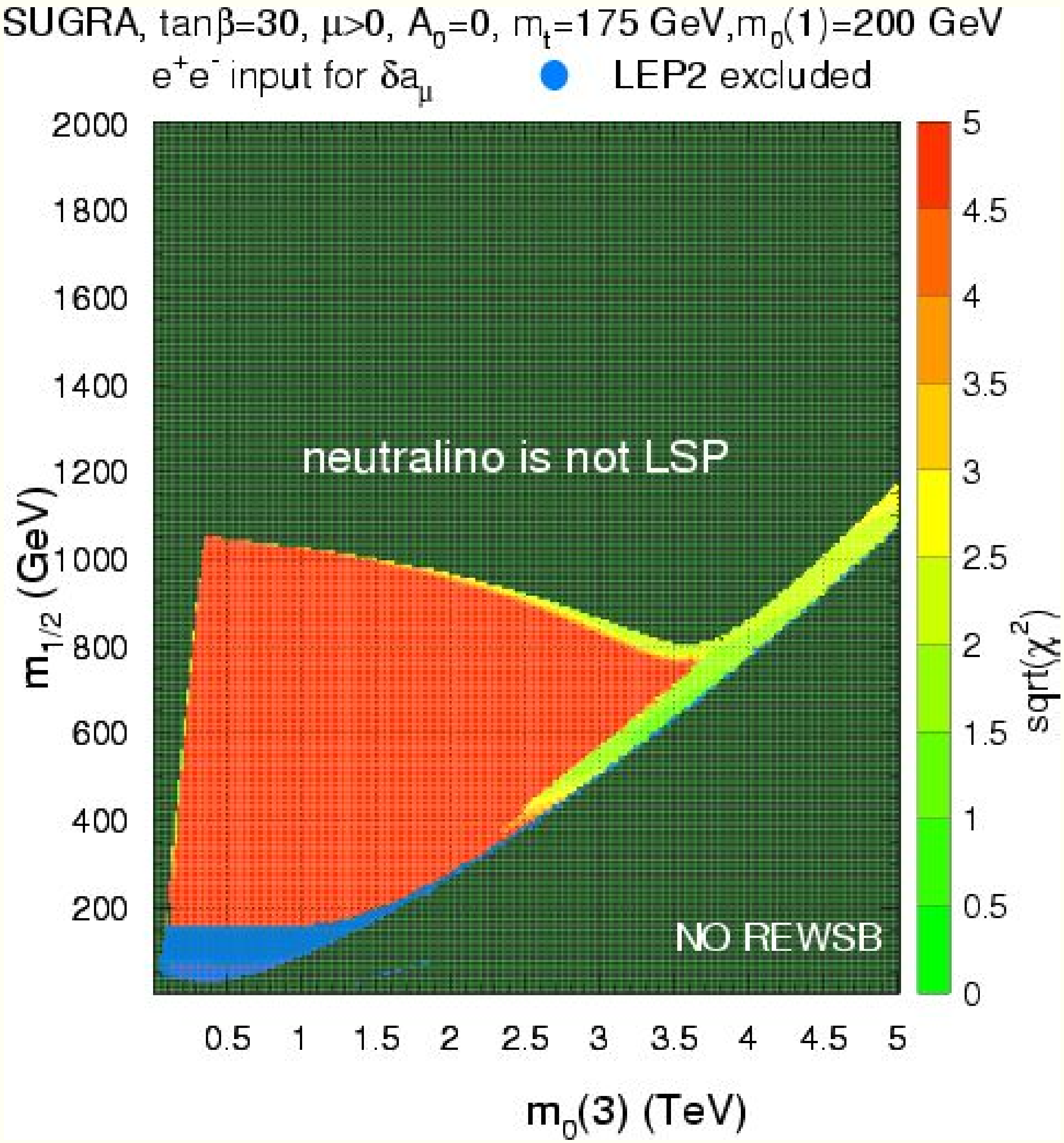
NMH SUGRA, $\tan\beta = 30$*,* $m0(1) = (50, 100, 200)$ *GeV*



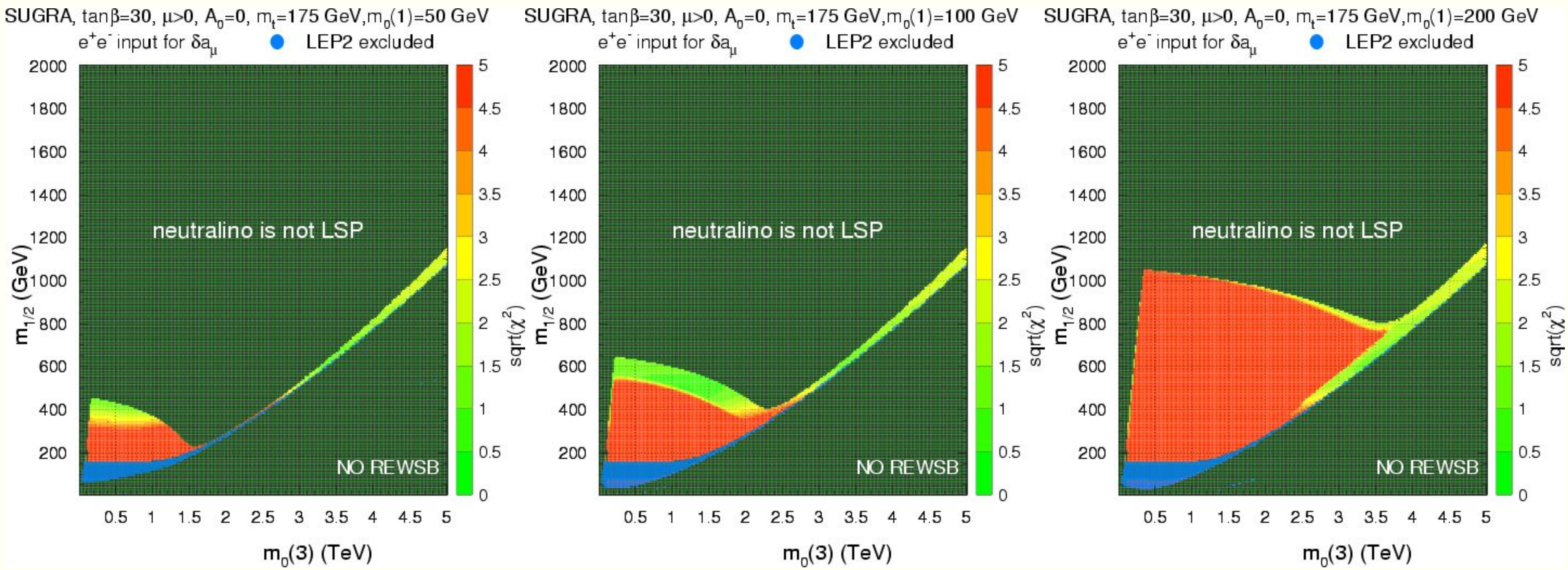
NMH SUGRA, $\tan\beta = 30$*,* $m0(1) = (50,100,200)$*GeV*



NMH SUGRA, $\tan\beta = 30$***,*** $m0(1) = (50, 100, 200)$***GeV***



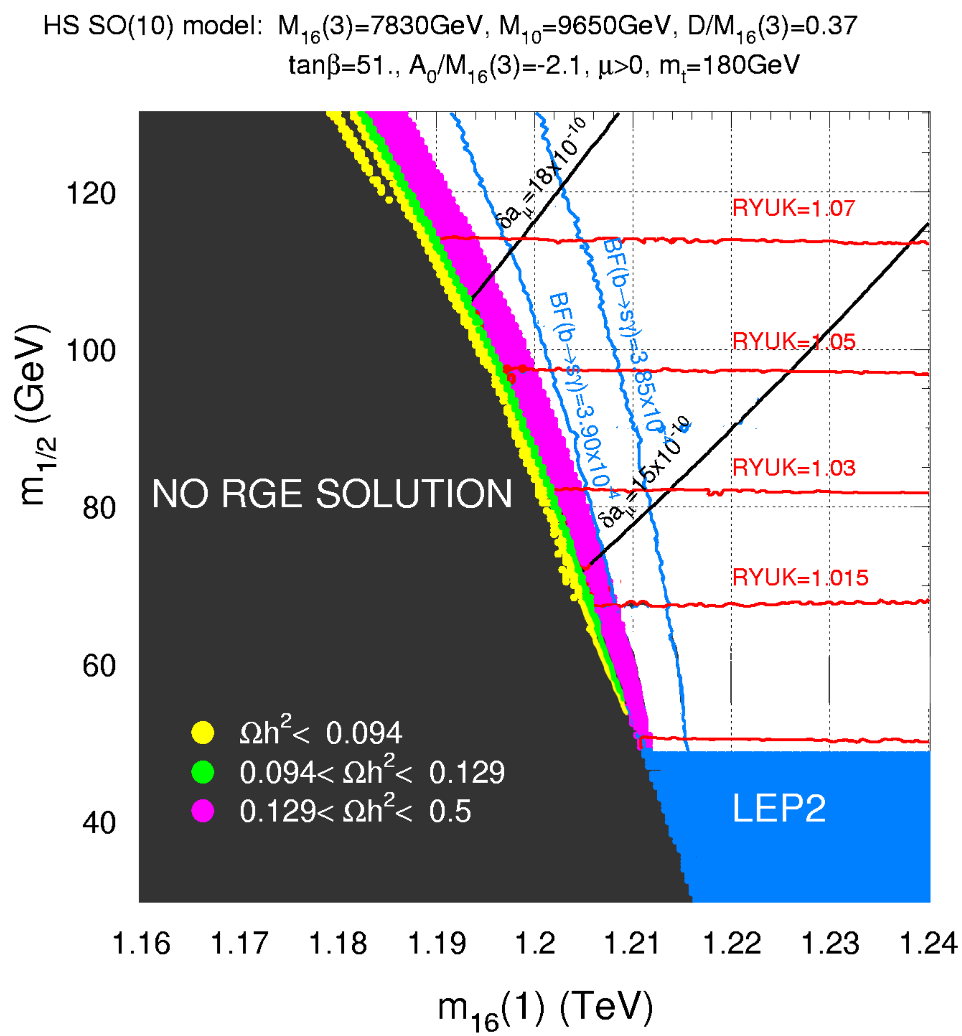
NMH SUGRA, $\tan\beta = 30$, $m0(1) = (50, 100, 200)$***GeV***



- *the band of very low χ^2 points in the $m_0(1) = 50$ and 100 GeV plots, where essentially a perfect fit to $(g-2)_\mu$, $BF(b \to s\gamma)$ and $\Omega_{\tilde{Z}_1} h^2$ can be obtained*
- *the low $m_{1/2}$ portion of the $m_0(3)$ vs. $m_{1/2}$ plane are largely excluded – too large a relic density and too large Δa_μ.*
- *HB/FP strip has moved to a somewhat lower χ^2 value compared to the $\tan\beta = 10$ plots due to a larger SUSY contribution to Δa_μ*

Outlook for NMH in SO(10) SUSY GUTS

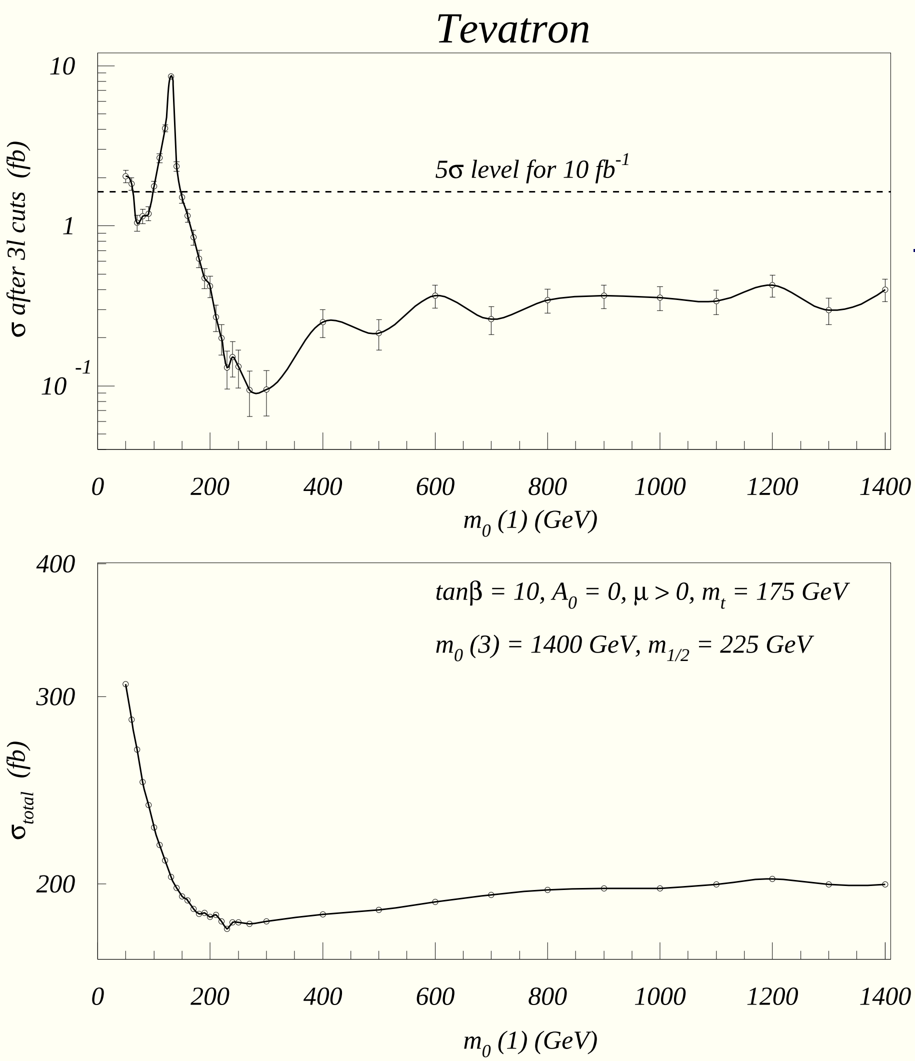
- *SO(10) SUSY GUT:*
  matter in 16d spinorial multiplet;
  contains gauge sinlet ν_R;
  cancellation of triangle anomalies;
  baryogenesis ...
- *min SO(10) – both Higgs doublets are in 10d*
  $Y_t = Y_b = Y_\tau$, $f\hat{\psi}(\mathbf{16})^T\hat{\psi}(\mathbf{16})\hat{\phi}(\mathbf{10}) + \cdots$.
- *HS Model for $\mu>0$:* $m^2_{H_{u,d}} = m^2_{10} \mp 2M^2_D$
  $m^2_Q = m^2_E = m^2_U = m^2_D = m^2_L = m^2_{16}$
- *Previous results* (Auto,Baer,Balazs,AB,Tata,Ferrandis)
  for $m_{16}, m_{10}, M^2_D, m_{1/2}, A_0, \tan\beta$:
  $m_{16} \simeq$ *10 TeV,* $m_{1/2} \lesssim$ *100 GeV*
  $m_{10} \simeq \sqrt{2} m_{16}$, $A_0 \simeq -2m_{16}$
  perfect $Y_{t,b,\tau}$ unifi cation but very high Ωh^2!
- *Split of m_{16} into $m_{16}(1,2)$ and $m_{16}(3)$*
  solves the 2 problems(!)(Auto,Baer,AB, to appea
  1)fast $\tilde{Z}_1$ annihilation (t-ch light $\tilde{u}$)$\Rightarrow$ low Ωh^2
  2) provides high enough Δa_μ



A testable consequence of the NMH scenario at the TEVATRON

- *NMH scenario: all squarks are heavy($\sim$ 1 TeV), while there is large large weak scale splitting, $100-300$ GeV range for $\tilde{e},\tilde{\mu}$(staus are in the TeV range)*
- *CS for slepton pair production is rather low (~ 10 fb for $m_{\tilde{\ell}} \sim 100$ GeV): direct detection is hard(Baer,Harris,Reno)*
- $p\bar{p} \to \widetilde{W}_1^+\widetilde{W}_1^- X,\ \widetilde{W}_1\widetilde{Z}_2 X$ *have $\simeq$ 1pb(!) cs for $m_{\widetilde{W}_1}, m_{\widetilde{Z}_2} \simeq 150$ GeV*
- *if sleptons are light enough: $\widetilde{W}_1 \to \nu_\ell \tilde{\ell}_L,\ \tilde{\nu}_\ell \ell$ and $\widetilde{Z}_2 \to \tilde{\ell}_R \ell,\ \tilde{\nu}_\ell \nu_\ell$ and $\tilde{\ell}_L \ell$*
- *Even if two-body decays are not kinematically open, $\simeq 100-300$ GeV $\tilde{e},\tilde{\mu}$ yeild enhancement in $\widetilde{W}_1, \widetilde{Z}_2$ 3-body decay: $\widetilde{W}_1 \to \ell\nu_\ell \widetilde{Z}_1$ and $\widetilde{Z}_2 \to \ell\bar{\ell}\widetilde{Z}_1$*
- *clean 3-lepton signal can be observable(!)*
  (Baer,Hagiwara,Tata; Nath,Arnowitt;Barbieri et al;Baer Kao Tata)

NMH SUSY 3-ℓ Signals at the Tevatron



cut	SC2
$p_T(\ell_1)$	>11 GeV
$p_T(\ell_2)$	>7 GeV
$p_T(\ell_3)$	>5 GeV
$\lvert\eta(\ell_{1,2/3})\rvert$	<1.0,2.0
$ISO_{\Delta R=0.4}$	<2 GeV
$\not{E}_T$	>25 GeV
Z	<81 GeV
$-veto$	
$m(\ell\bar{\ell})$	> 20 GeV
$m_T(\ell,\not{E}_T)$	60-85 GeV
$-veto$	

$m_0(1)$	65
$m_{\tilde{g}}$	566
$m_{\tilde{u}_L}$	472
$m_{\tilde{u}_R}$	464
$m_{\tilde{t}_1}$	922
$m_{\tilde{t}_2}$	1248
$m_{\tilde{e}_L}$	154
$m_{\tilde{e}_R}$	96
$m_{\tilde{\nu}_e}$	117
$m_{\tilde{\tau}_1}$	1391
$m_{\tilde{\tau}_2}$	1405
$m_{\tilde{\nu}_\tau}$	1399
$m_{\widetilde{W}_1}$	160
$m_{\widetilde{W}_2}$	341
$m_{\widetilde{Z}_1}$	84
$m_{\widetilde{Z}_2}$	159
m_A	1425
m_h	115
$\Omega_{\widetilde{Z}_1} h^2$	0.121
$b \to s\gamma$	4.6×10^{-4}
Δa_μ	$50. \times 10^{-10}$

Conclusions

- relaxing the universality between third and (first,second) generation of was advocated: Simultaneous fulfilling $(g-2)_\mu$, WMAP $\Omega_{\tilde{Z}_1}h^2$ and $BF(b\to s\gamma)$ constraints favors low values of $m_0(1)\simeq m_0(2)\sim 50-200$ GeV and TeV scale $m_0(3)$
- FCNC constraints from $B_d-\overline{B}_d$ and $BF(b\to s\gamma)$ are very weak and hardly affect the NMH SUGRA parameter space.
- Sleptons: large large weak scale splitting, $100-300$ GeV range for $\tilde{e},\tilde{\mu}$, while staus are in the TeV range. Neutralinos in the early universe annihilate via a combination of t-channel slepton exchange and slepton co-annihilation
- A testable consequence of the NMH scenario:
  1) TEVATRON – trilepton events for the light sleptons
  2) CERN LHC – multilepton production in SUSY cascade decay events
  3) High rates for direct($\sigma_{\tilde{Z}_1 p}$) and indirect($\bar{p},e^+,\gamma,\nu_\mu$) DM search experimets!
- NMH solves the main problem of high Ωh^2 of Yukawa Unified SUSY SO(10)
- NMH SUSY could naturally stand beyond the present experimental data!