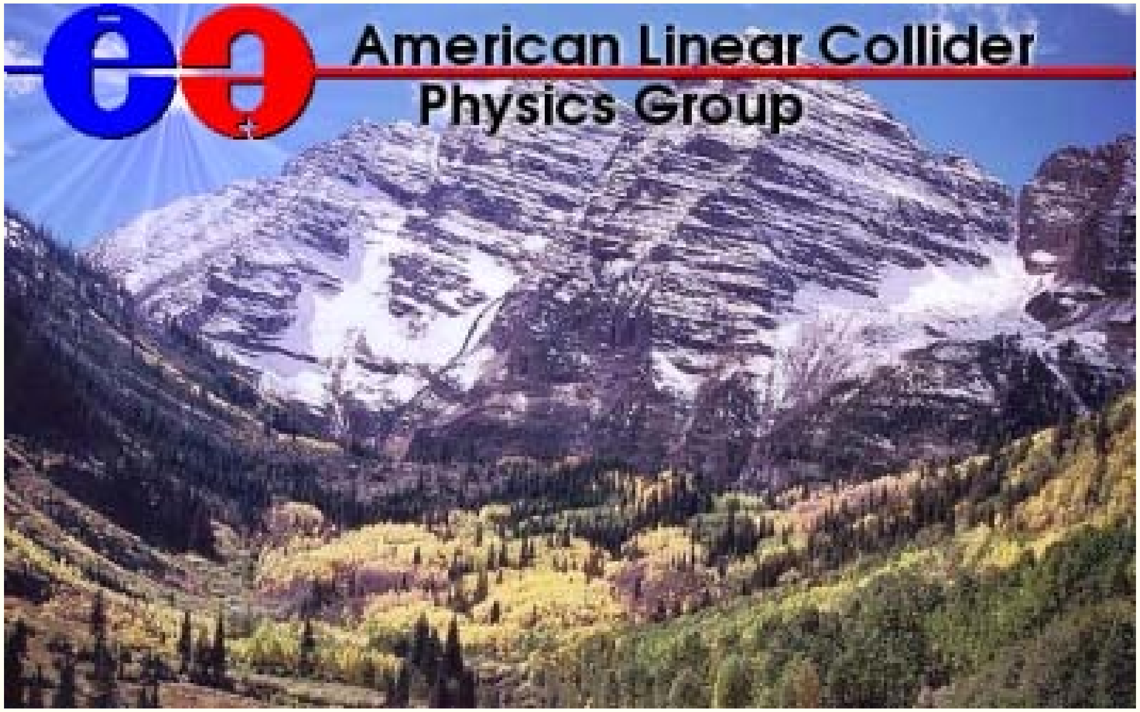
Implications of non-universal SUGRA models at ILC

Alexander Belyaev
Michigan State University

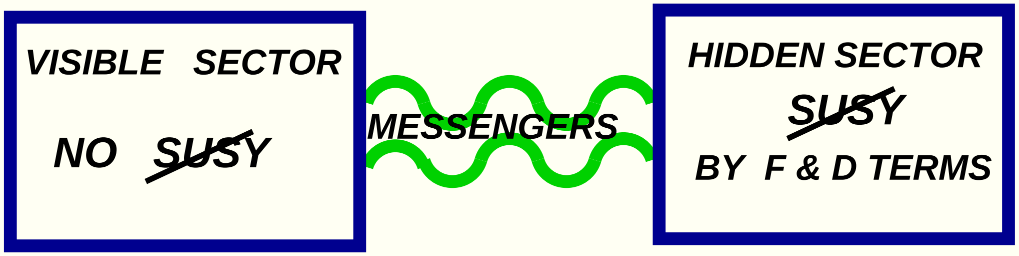


OUTLINE

- The present status of mSUGRA
- Motivations for non-universality in SUGRA
- One-parameter extensions of mSUGRA – minimal non-universal SUGRA models
  - parameter space
  - relic density, $b \to s\gamma$, $g-2$ constraints
  - dark matter search experiments
  - collider signatures
- Conclusions and outlook

SUSY breaking and mSUGRA scenario

- SUSY is not observed $\Rightarrow$ must be broken
- hidden-messenger-visible sectors scenarios:
  - SUGRA • GMSB • AMSB • inoMSB



- SUGRA: the hidden sector communicates with visible one via gravity
  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

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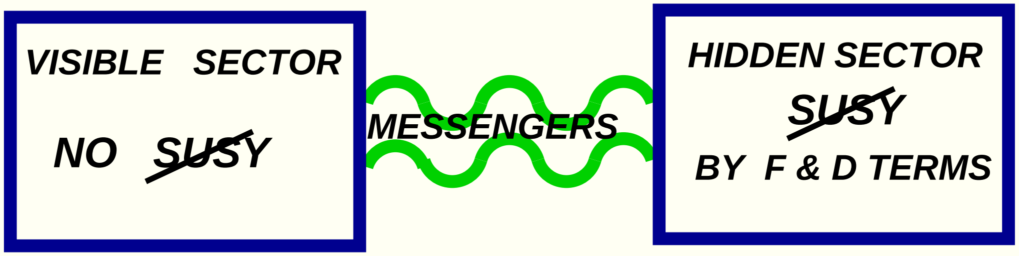

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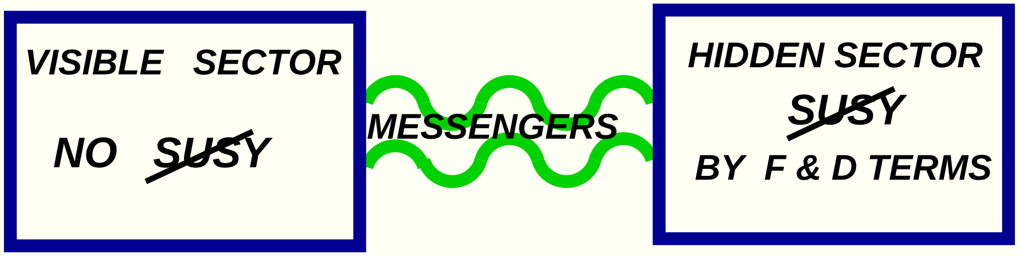

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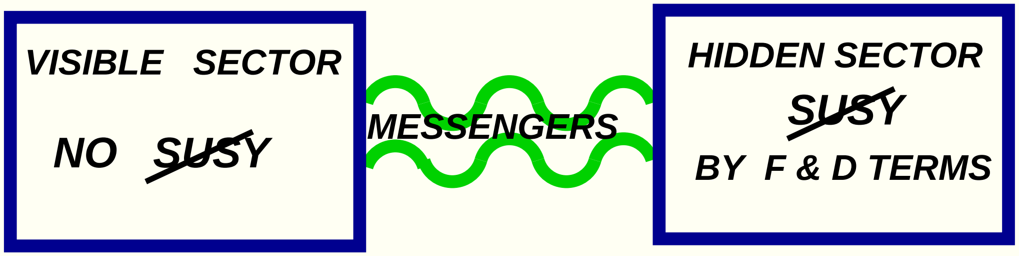

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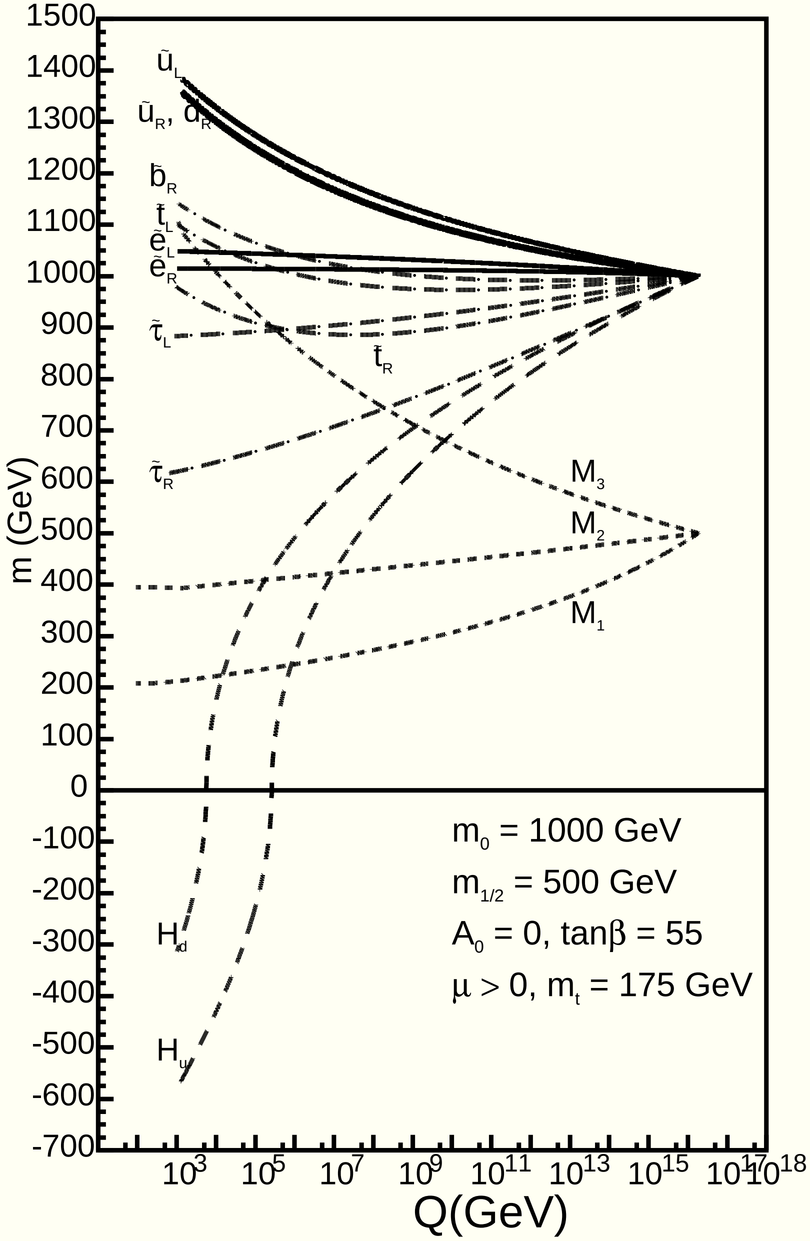
flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, μ^2 value is fixed by the minim condition for Higgs potential
- B - parameter – usually expressed via $\tan\beta$
- $\Rightarrow$ mSUGRA parameters: $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

Hunting for SUSY

One calculate SUSY mass spectrum



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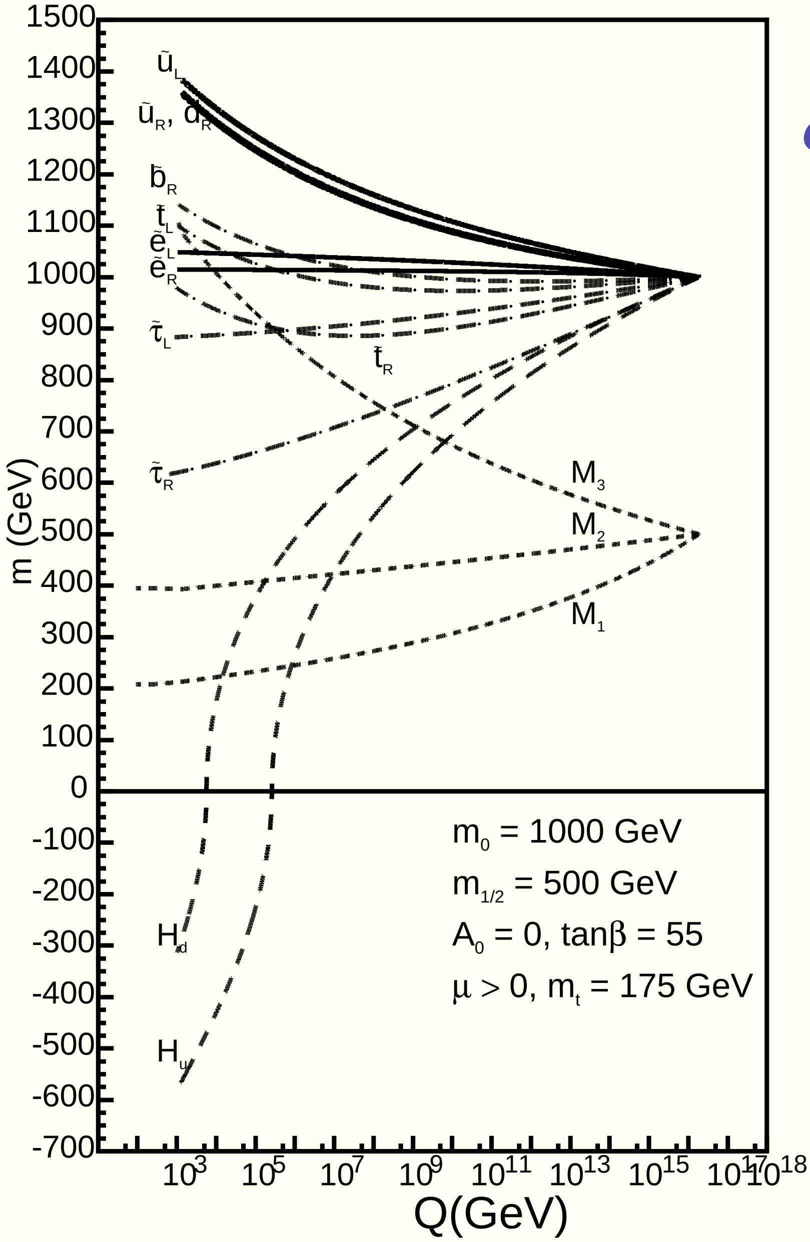

and test against experiments

- ***SUSY dark matter search (under $R-parity$):***
  neutralino relic density, Ωh^2 ***(WMAP result)***
  direct DM search, $\sigma_{\widetilde{Z}1p}$
  (CDMS/EDELWEIS/ZEPLIN/DAMA/CRESST/GENIUS...)
  indirect DM search,
  ν_μ ***(Antares/ICECUBE),*** γ***'s (EGRET/GLASS),***
  e^+***'s (PAMELA/Ams02/HEAT),*** $\bar{p}$***(BESS)***
- $b \to s\gamma$ ***(BELLE, CLEO, ALEPH),*** $B_s \to \mu^+\mu^-$***(CDF),*** δa_μ***(E821),***
- ***collider search at LEP2,Tevatron, LHC, ILC***

SUGRA: DM favored regions of parameter space

WMAP limit: $0.094 < \Omega_{\tilde{Z}_1} h^2 < 0.129$

1 bulk region:

t-channel sfermion exchange

low m_0 and $m_{1/2}$

constrained by LEP2

2 stau co-annihilation region:

(low m_0, large $m_{1/2}$)

3 the focus point (FP) region:

large m_0, low- medium $m_{1/2}$:

low μ value, $M_{\tilde{Z}_1} \sim M_{\tilde{Z}_2} \sim M_{\widetilde{W}_1}$

Matchev, Morroi; Feng,Matchev; Barger

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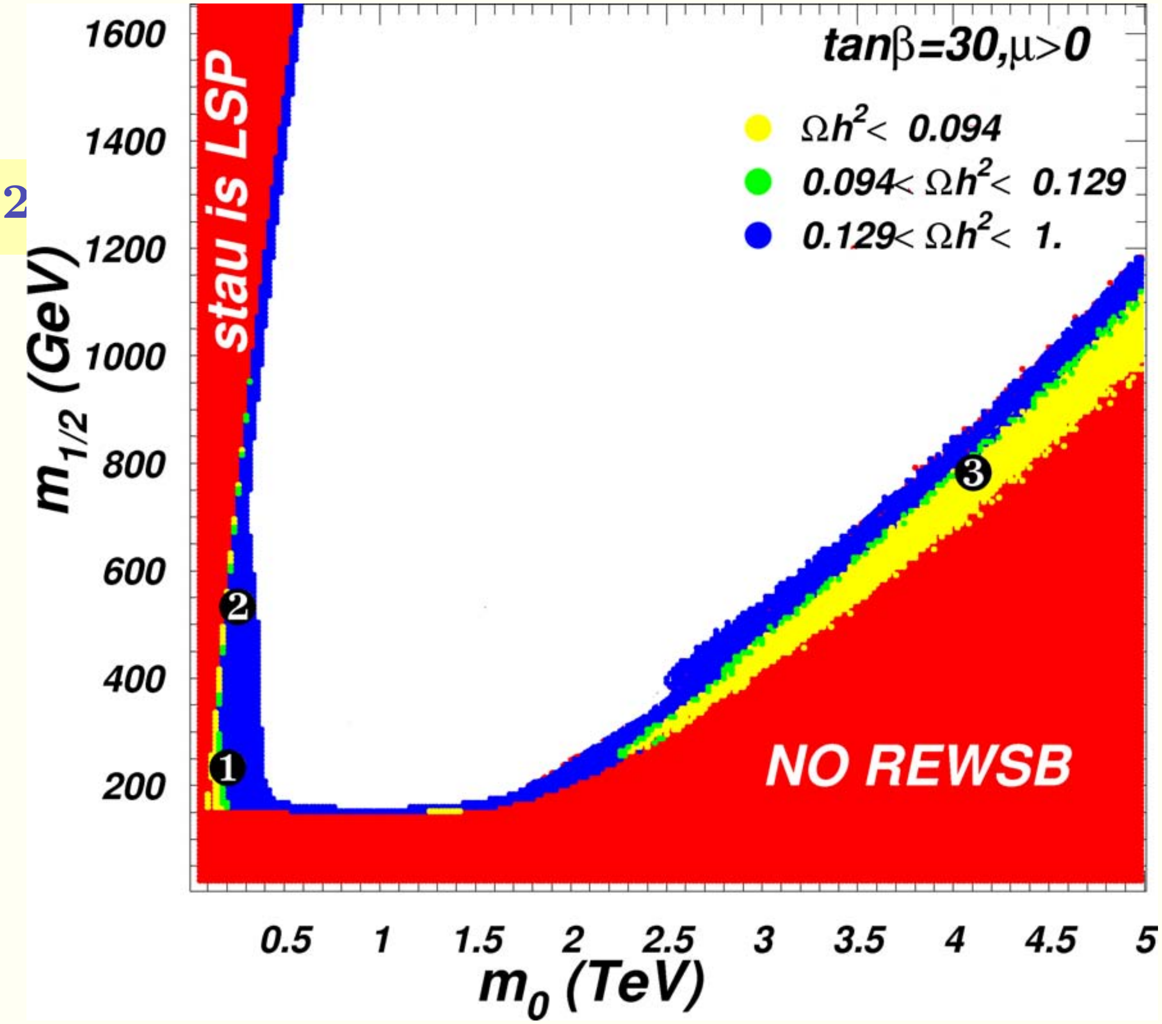

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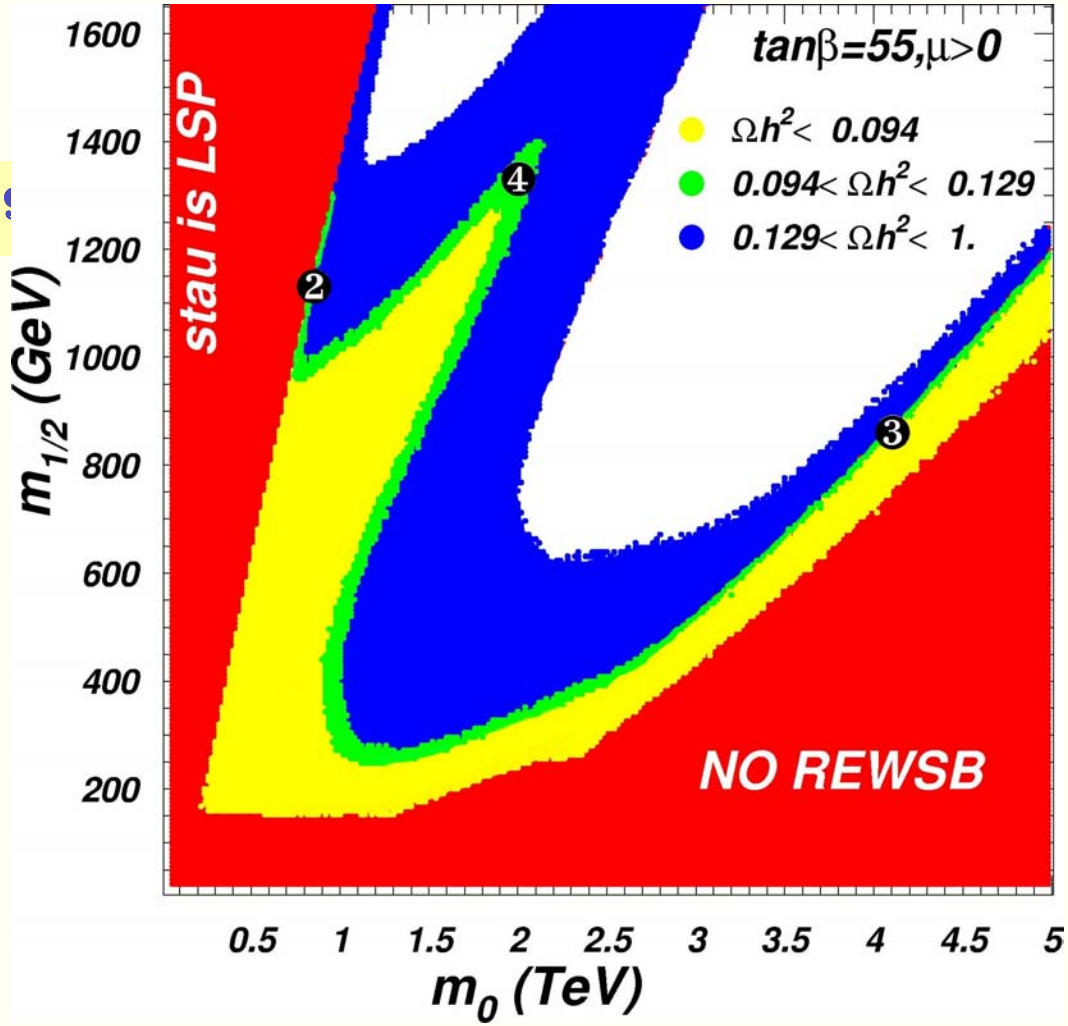

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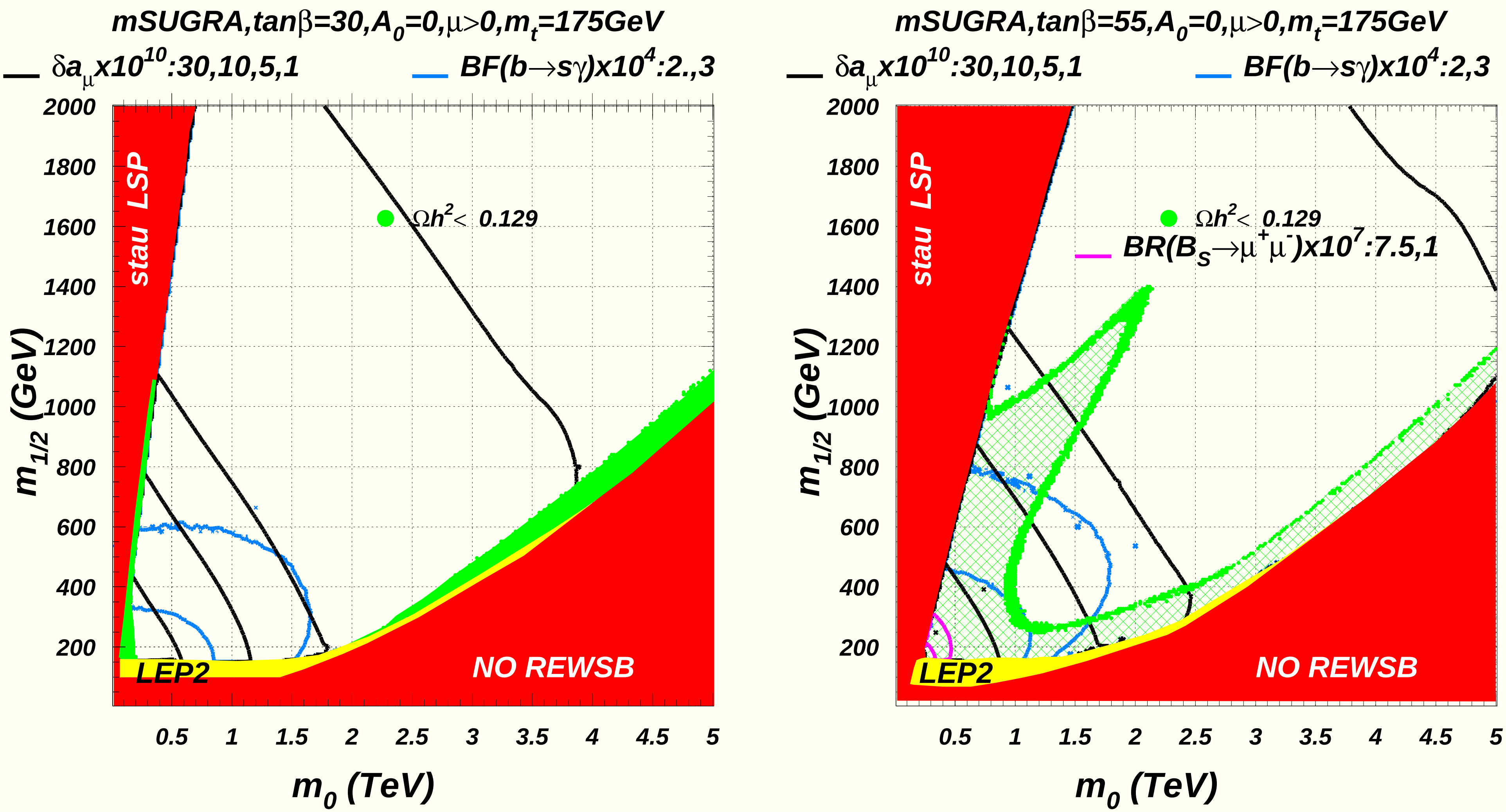
4 funnel region: s-channel annihilation corridor via A and H at large $\tan\beta$, takes place at high tan beta

Also: Z-/h- resonance regions, stop co-annihilation

mSUGRA constraints

Baer,Belyaev,Krupovnickas,Mustafayev, hep-ph/0403214



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

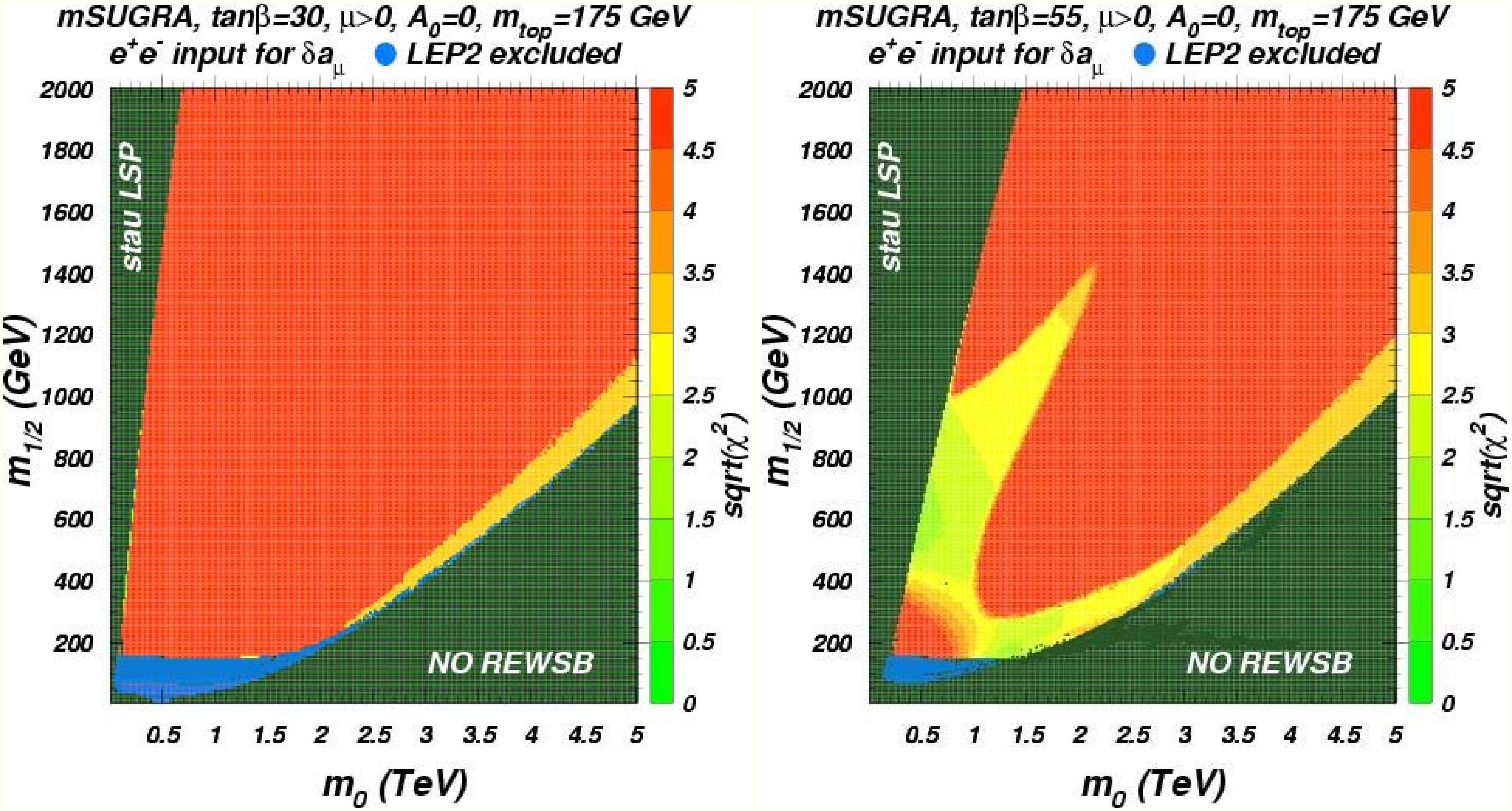
$(g-2)_\mu/2 =$ 116591 208(6) (g-2 collaboration) ⇐ Experiment

$\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ Davier,Eidelman,Höcker,Zhang ⇐ TH ($e^+e^- \to had$ data)

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

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

Baer,Belyaev,Krupovnickas,Mustafayev, hep-ph/0403214



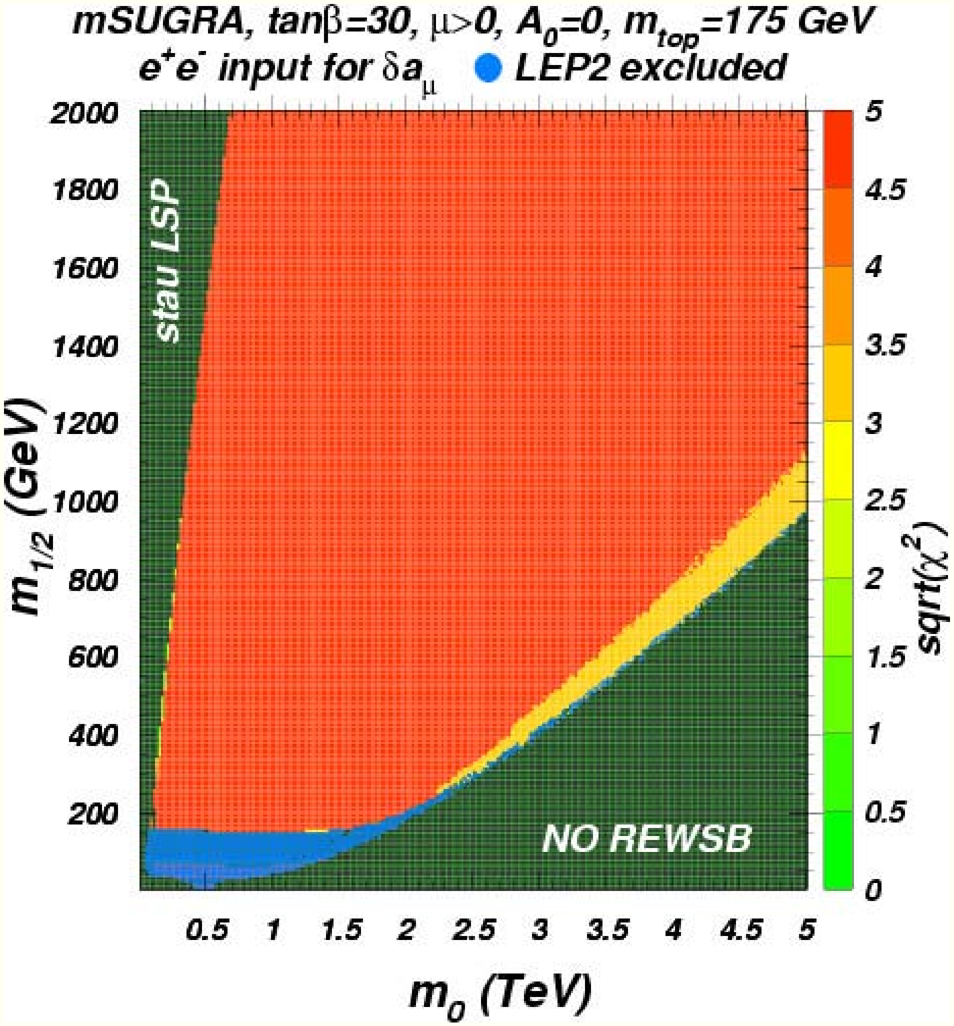
Δa_μ *favors light second generation sleptons, while* $BF(b \to s\gamma)$ *prefers heavy third generation: hard to realize in mSUGRA model.*

also in hep-ph/0508169 by Ellis,Heinemeyer,Olive,Weiglein; see Georg's talk

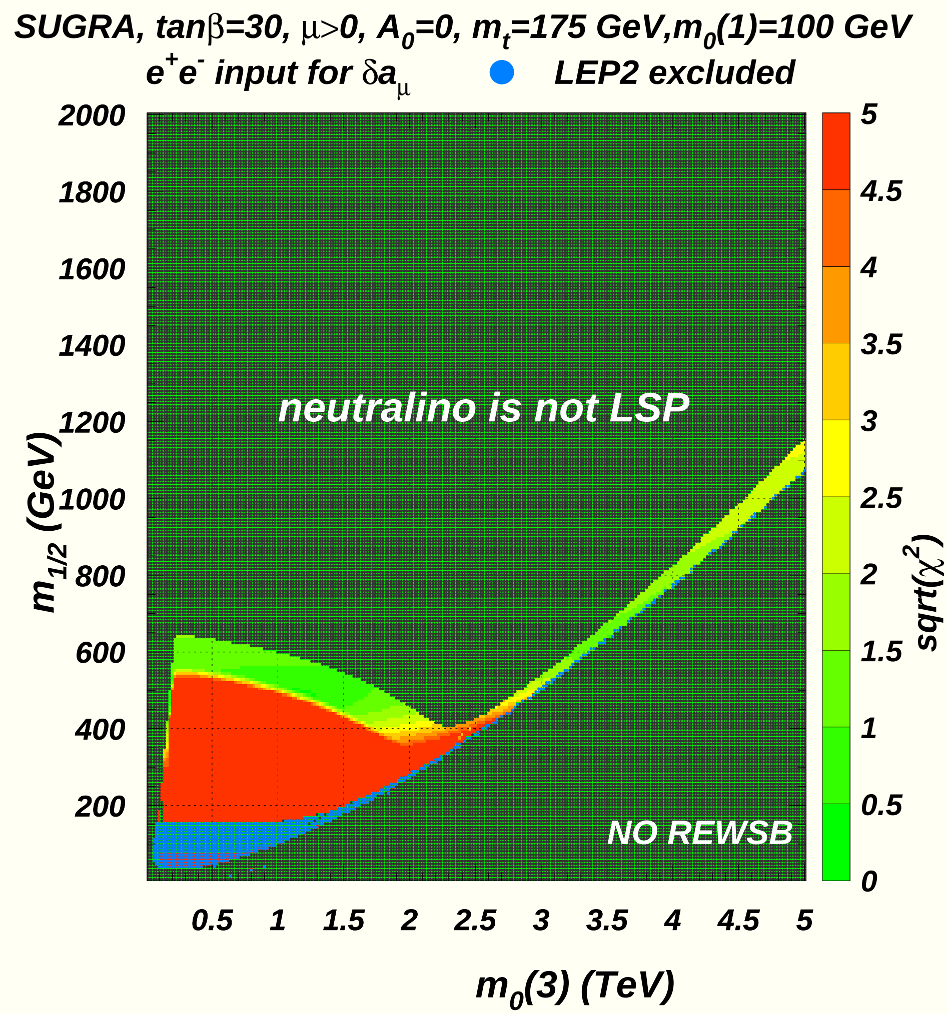
Normal Mass Hierarchy(NMH) in SUGRA

- one step beyond universality solves the problem!

$$m_0, m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu) \Longrightarrow m_0^{1,2}, m_0^3,\ m_H,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu$$

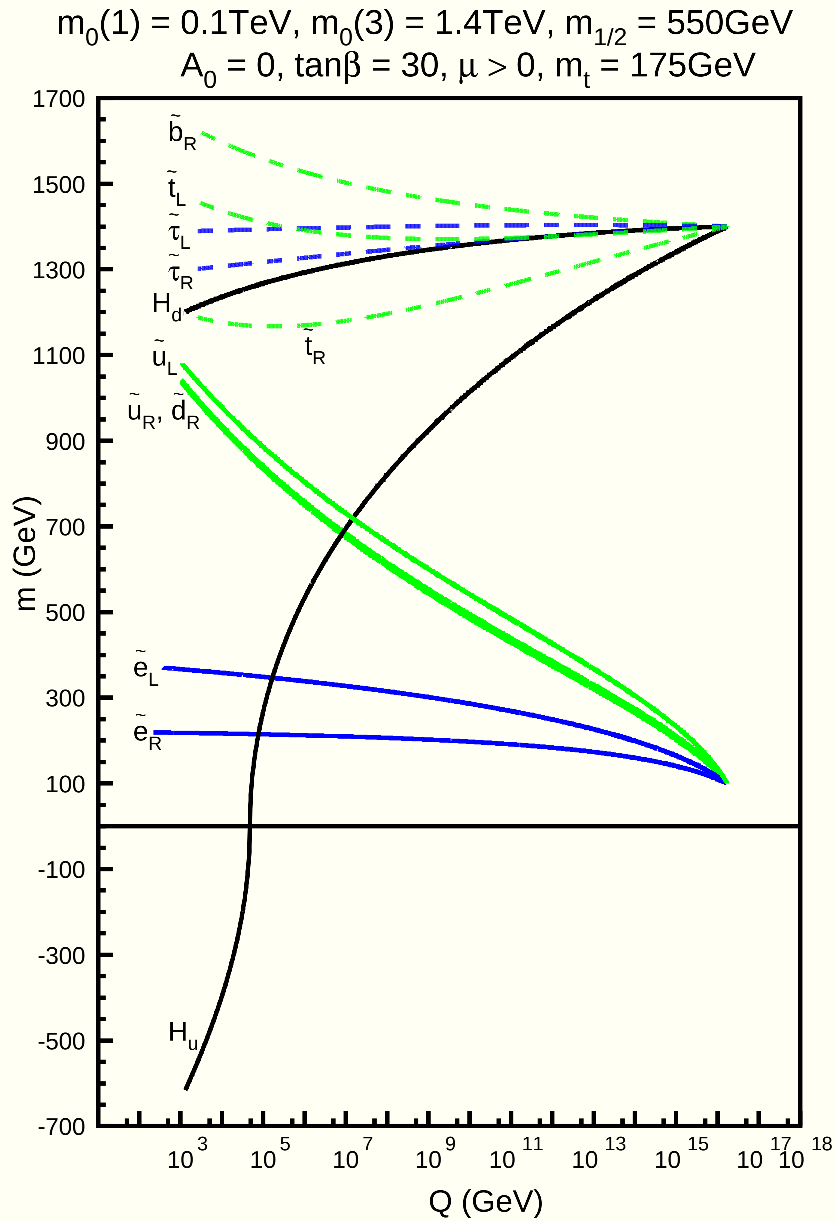


$\Rightarrow$



- $B_H^0 - B_L^0 = \Delta m_B$ mass splitting bound is safe

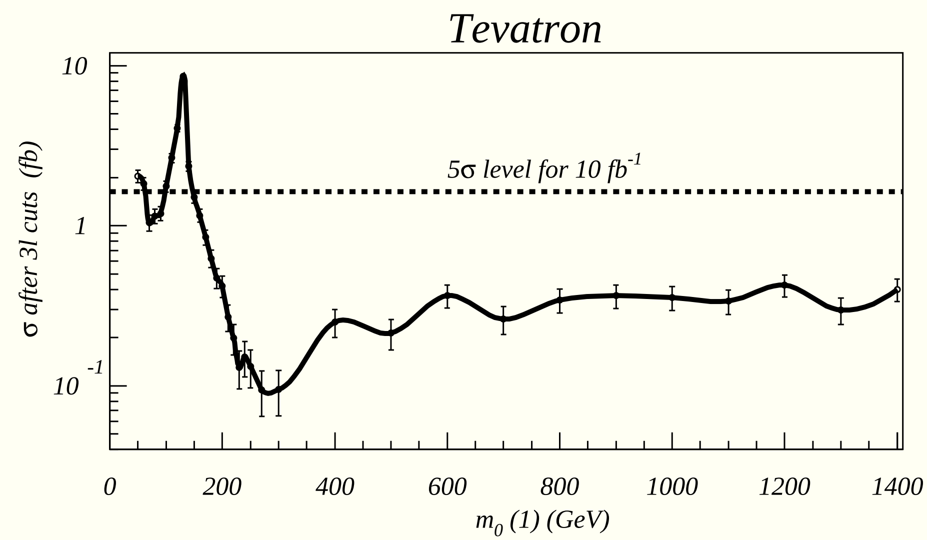
Collider implications of NHM model: the mass spectrum

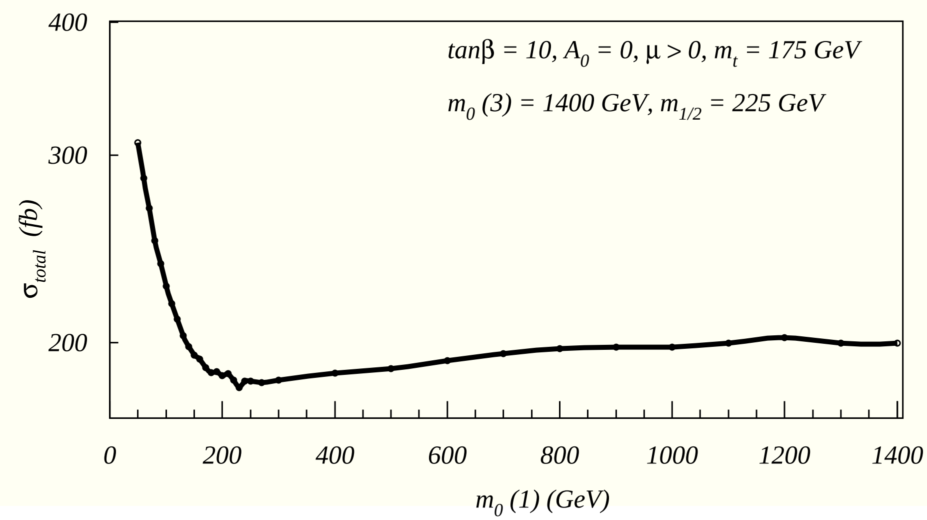


approximate formula relating weak scale to GUT scale squark and slepton masses is $m_{\tilde{q}}^2 \simeq m_0^2 + (5-6)m_{1/2}^2$, *while* $m_{\tilde{\ell}}^2 \simeq m_0^2 + (0.15-0.5)m_{1/2}^2$

Collider implications of NHM model: Tevatron

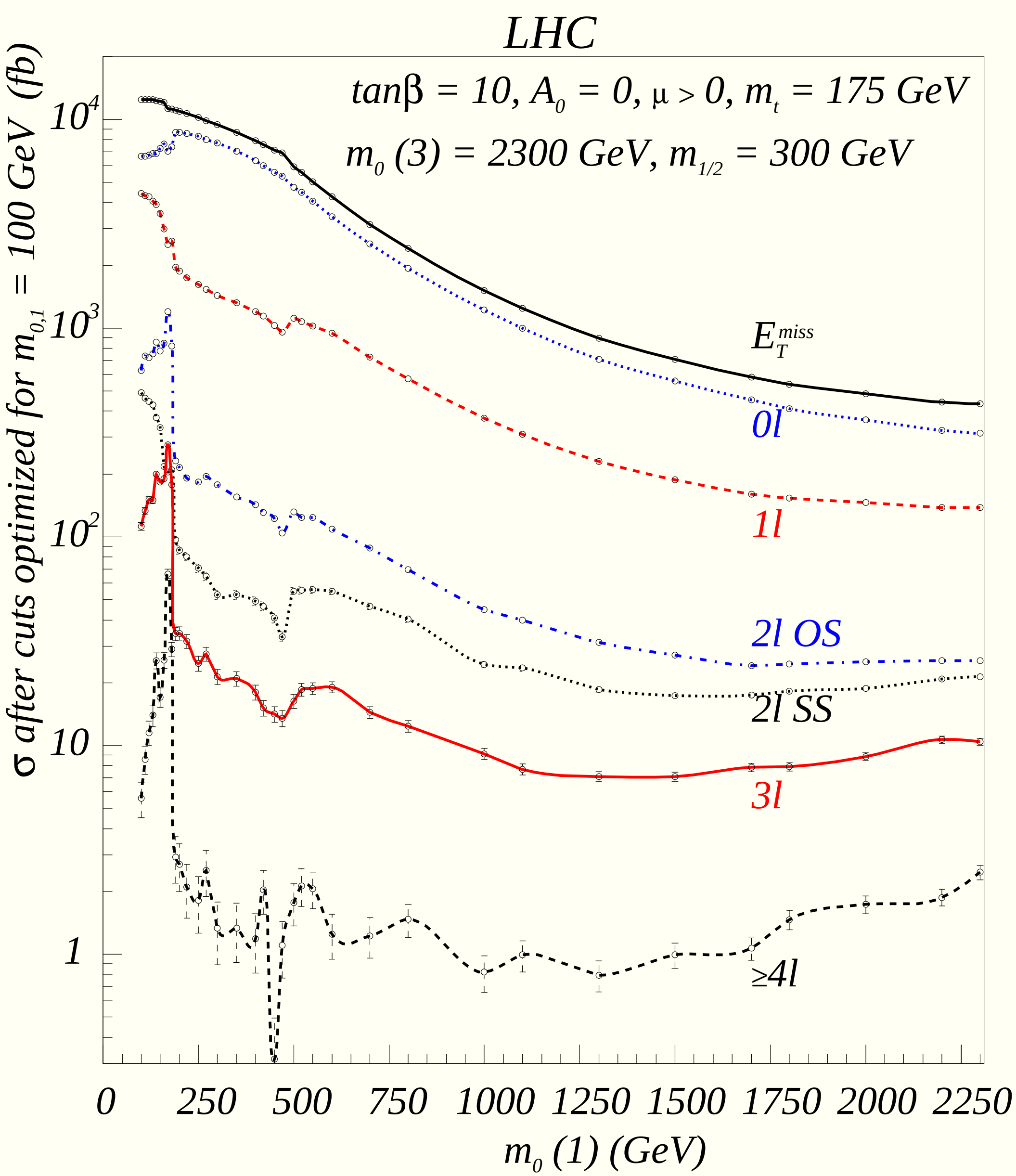
- $p\bar{p} \to \widetilde{W}_1^+ \widetilde{W}_1^- X$, $\widetilde{W}_1 \widetilde{Z}_2 X$ have $\simeq$ 1pb(!) cs for $m_{\widetilde{W}_1}, m_{\widetilde{Z}_2} \simeq 150$ GeV
- Even if two-body decays are not kinematically open, $\simeq 100-300$ GeV $\tilde{e}, \tilde{\mu}$ yield enhancement in $\widetilde{W}_1, \widetilde{Z}_2$ 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(!)





cut	SC2
$p_T(\ell_1)$	>11 GeV
$p_T(\ell_2)$	>7 GeV
$p_T(\ell_3)$	>5 GeV
$\|\eta(\ell_{1,2/3})\|$	<1.0,2.0
$\not{E}_T$	>25 GeV
Z^{veto}	<81 GeV
$m(\ell\bar{\ell})$	> 20 GeV
$m^{veto}_{T(\ell\not{E}_T)}$	60-85 GeV

Collider implications of NHM model: LHC



enhanced chargino and neutralino (s)leptonic branching fractions

As $m_0(1)$ drops below 200 GeV, multilepton rates rise steeply.

SUSY as manifested in the NMH SUGRA model would be easily discovered.

Signal events would be unusually rich in multilepton events – especially useful for reconstructing sparticle masses in gluino and squark cascade decay events

Collider implications of NHM model: ILC

$m_0(3)$	$m_{1/2}$	A_0	$\tan\beta$	$sign(\mu)$
1500	450	0	30	+1

$m_0(1) = 100$

Depending on sparticle masses and the collider energy, charginos and neutralinos may or may not be accessible.

However, in the NMH SUGRA model, light first and second generation sleptons are needed both to explain the $(g-2)_\mu$ anomaly, but also to enhance neutralino annihilation in the early universe.

This means slepton masses are typically in the 100-300 GeV range, and likely within reach of a linear e^+e^- collider

par	value (GeV)
M_2	351.1
M_1	184.2
μ	516.9
$m_{\tilde{g}}$	1067.7
$m_{\tilde{u}_L}$	939.8
$m_{\tilde{u}_R}$	910.0
$m_{\tilde{t}_1}$	1175.1
$m_{\tilde{t}_2}$	1477.5
$m_{\tilde{e}_L}$	319.3
$m_{\tilde{e}_R}$	188.2
$m_{\tilde{\tau}_1}$	1386.1
$m_{\tilde{\tau}_2}$	1475.4
$m_{\widetilde{W}_1}$	348.2
$m_{\widetilde{W}_2}$	542.4
$m_{\widetilde{Z}_1}$	179.4
$m_{\widetilde{Z}_2}$	347.2
m_A	1379.3
m_h	118.4
$\Omega_{\widetilde{Z}_1} h^2$	0.115
$BF(b \to s\gamma)$	3.52×10^{-4}
Δa_μ	35.1×10^{-10}

Next option: SUGRA with non-universal Higgs Masses

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the minimal non-universal Higgs extension of mSUGRA $\Rightarrow$ NUHM1:

$m_0,\ m_\phi,\ m_{1/2},\ A_0,\ \tan\beta$ and $sign(\mu)$

$m_\phi = sign(m^2_{H_{u,d}}) \cdot \sqrt{|m^2_{H_{u,d}}|}$

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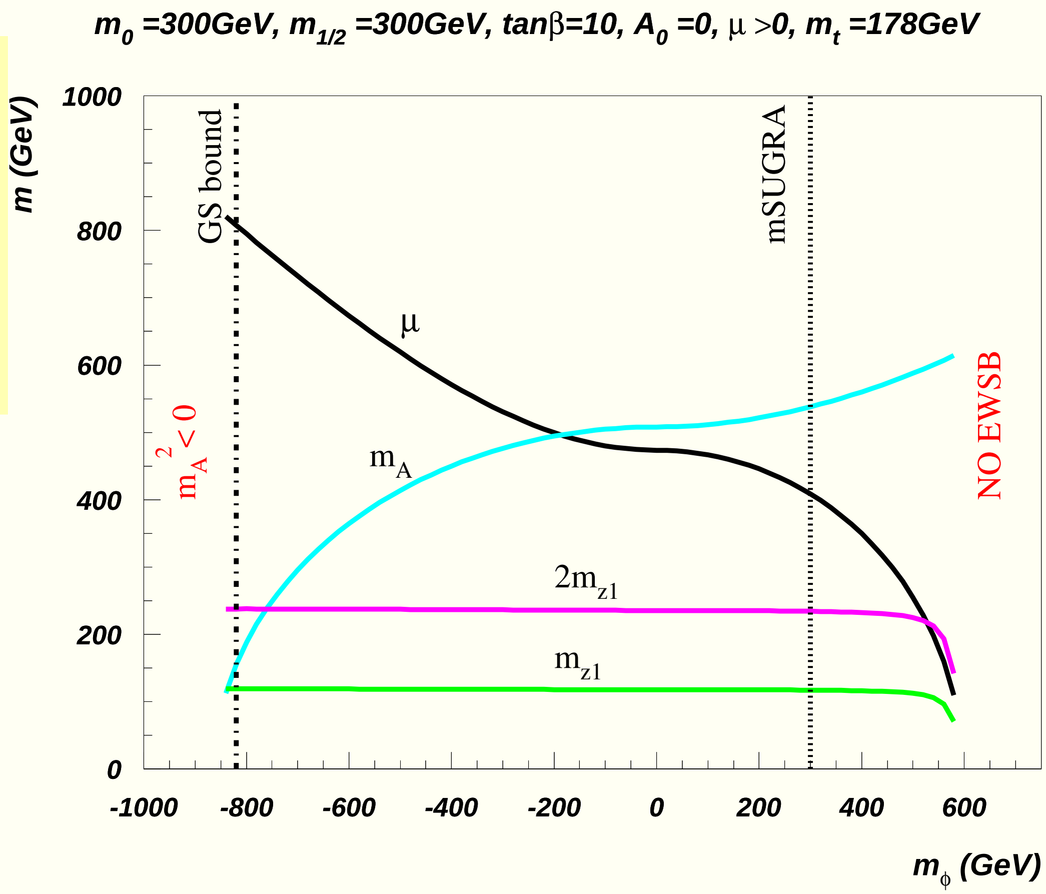

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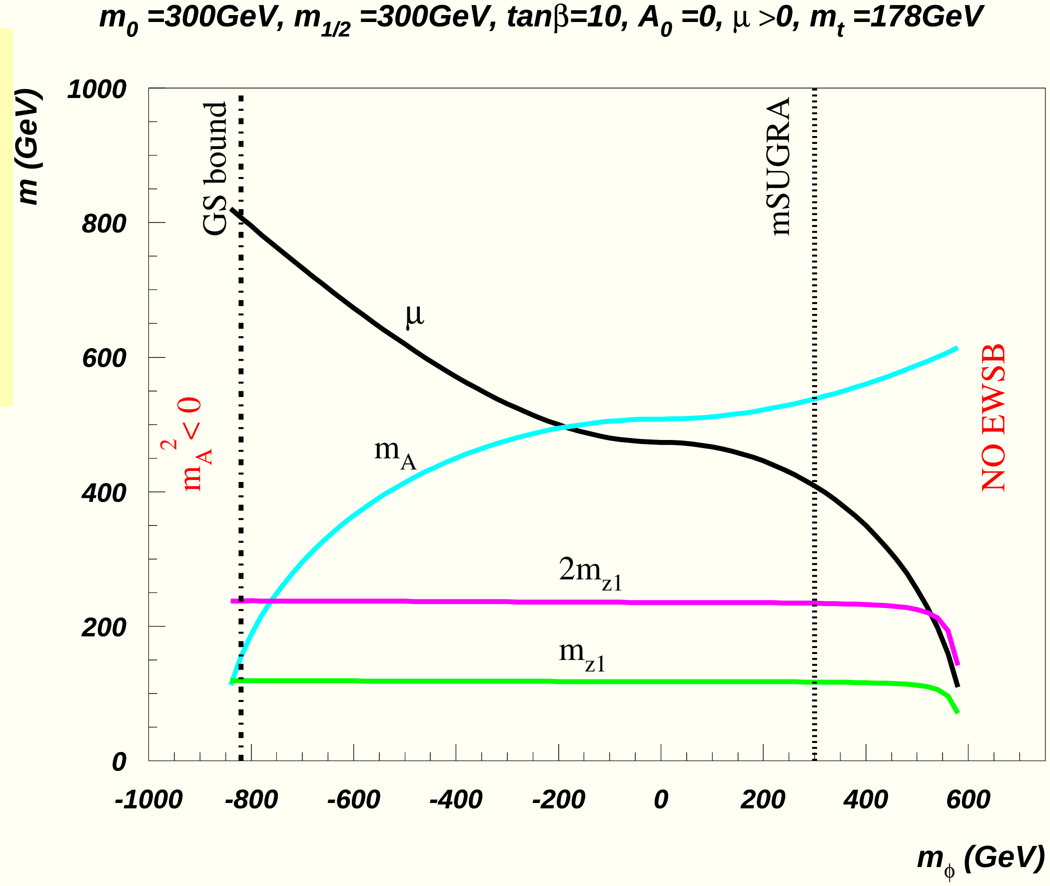
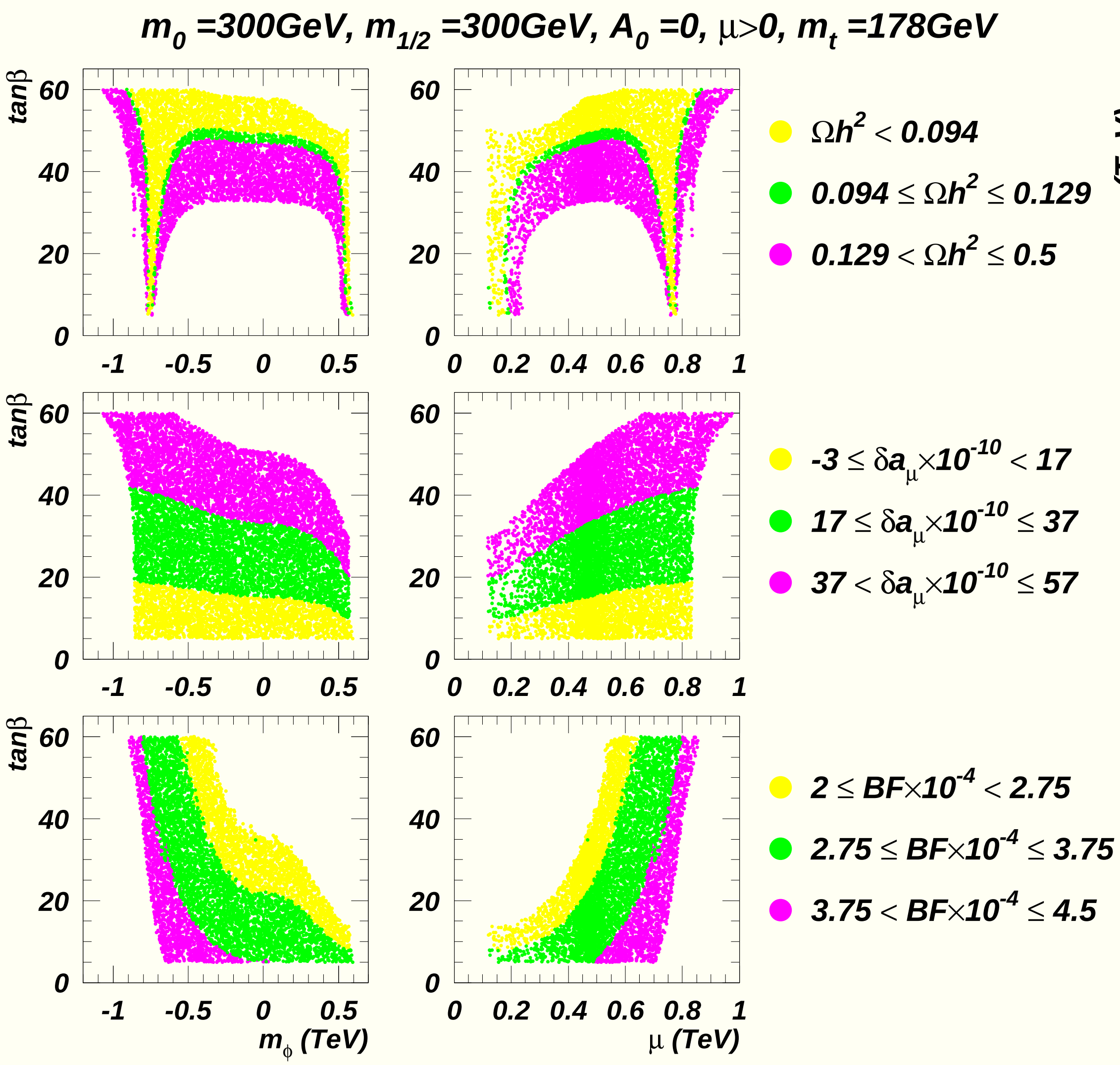
$m_\phi = sign(m^2_{H_{u,d}}) \cdot \sqrt{|m^2_{H_{u,d}}|}$
$m^2_{H_{u,d}}$ *are allowed to be negative*

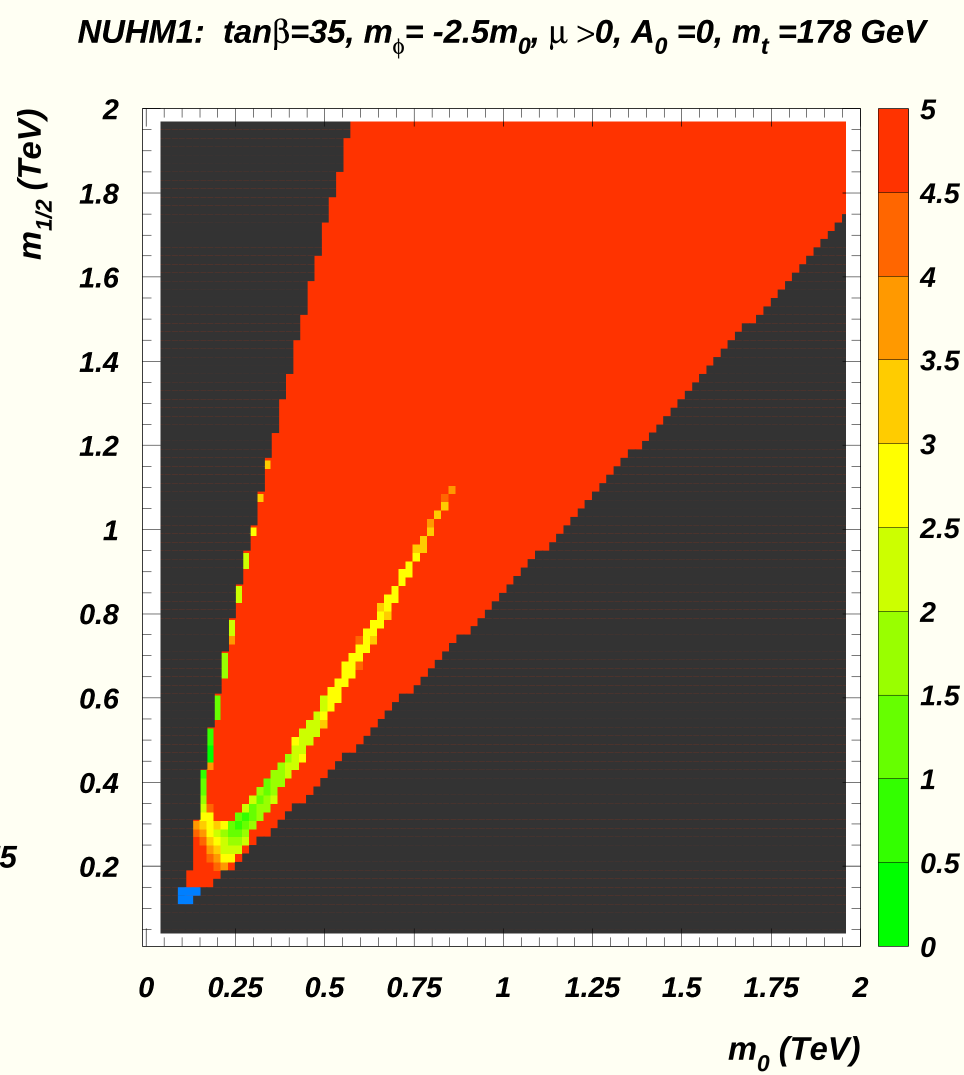
- *μ becomes small for $m_\phi > m_0$ $\Rightarrow$ FP! can be reached even for low m_0 and $m_{1/2}$!*
- *M_A decrease down to $2m_{\widetilde{Z}_1}$ for m_ϕ going down $\Rightarrow$ Funnel! Even for low $\tan\beta$! Requires $m^2_\phi < 0$.*



Baer,Belyaev,Mustafayev,Profumo,Tata

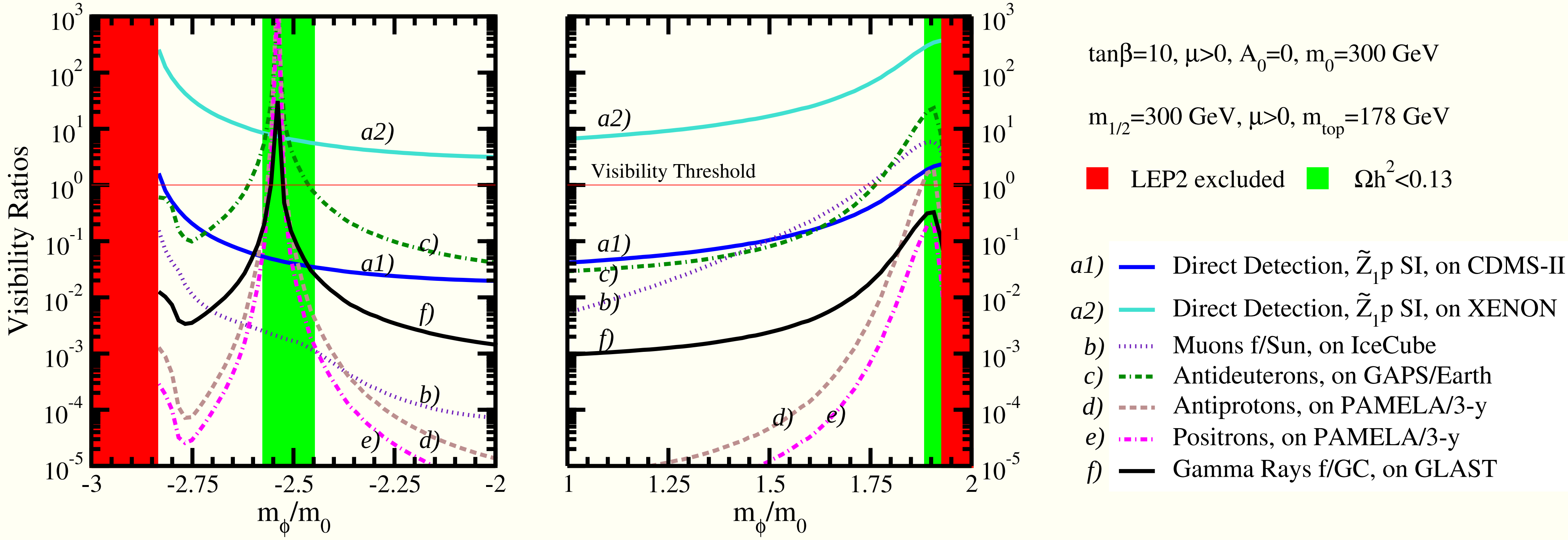
Scan of NUMH1 parameter space





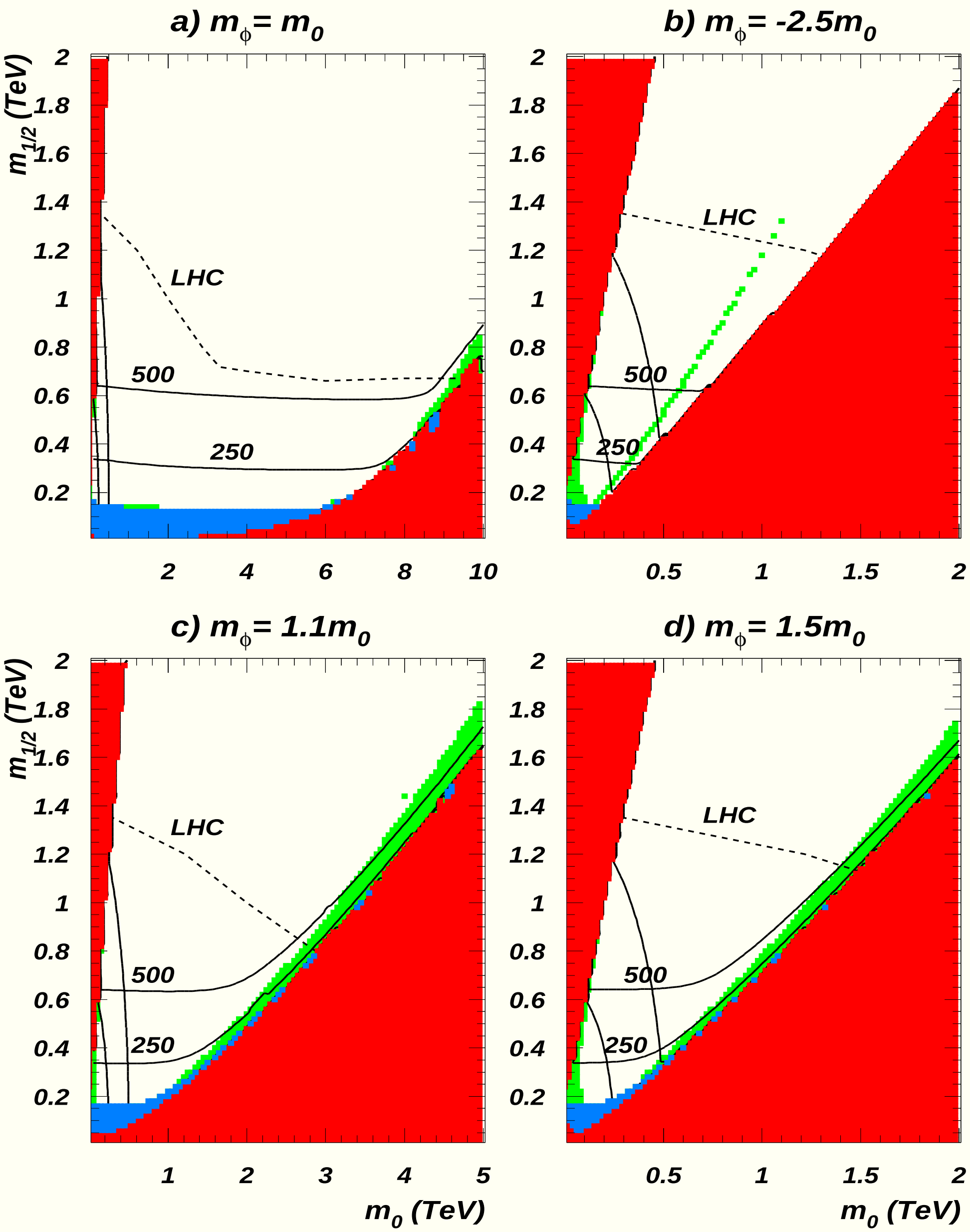
there are always two viable solutions corresponding to FP and Funnel regions

Dark matter detection rates



- *all m_ϕ $\Rightarrow$ the signal is accessible to stage-3 DD facilities (XENON 1-ton)*
- *stage-2 detectors (CDMS-II) $\Rightarrow$ probe only the HB/FP at large m_ϕ*
- *large negative m_ϕ $\Rightarrow$ enhancement of the t-channel H exchange*
- *large positive m_ϕ $\Rightarrow$ higgsino fraction is up $\Rightarrow$ $\sigma^{SI}_{\tilde{Z}_1 p}$, neutrino telescopes*
- *muon flux from the sun $\Rightarrow$ the resonant annihilation region rates **below** the sensitivity of IceCube (the sun capture rate is not large enough)*
- *funnel region gives very large rates in all channels!*

Collider signatures



- **Tevatron:** 3ℓ from $p\bar{p} \to \widetilde{W}_1 \widetilde{Z}_2 X$ followed by $\widetilde{W}_1 \to \ell\nu_\ell \widetilde{Z}_1$ and $\widetilde{Z}_2 \to \ell\bar{\ell}\widetilde{Z}_1$. When $m_\phi > m_0$ and $|\mu|$ is small
$\Rightarrow$ improved prospects for clean 3ℓ
(no dominant events with tau leptons)

- **LHC:** similar reach (in terms of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ parameters) in the mSUGRA and NUHM1 models, but detailed gluino and squark cascade decays will change! H and A Higgs could be much lighter $\Rightarrow$ direct production followed by $H, A \to \tau\bar{\tau}$.

- **NLC:** In addition to "standard" mSUGRA FP signatures, $H^0 Z^0$, $A^0 h$ (possibly a good determ of $\tan\beta$), $H^+ H^-$ become accessible to study; $\widetilde{Z}_1\widetilde{Z}_3$, $\widetilde{Z}_1\widetilde{Z}_4$, $\widetilde{Z}_2\widetilde{Z}_2$, $\widetilde{Z}_2\widetilde{Z}_3$, $\widetilde{Z}_2\widetilde{Z}_4$ and even $\widetilde{Z}_3\widetilde{Z}_4$ as well as $\widetilde{W}_1^\pm \widetilde{W}_2^\mp$ are kinematically accessible.

SUSY spectroscopy would become a reality!

Two-parameter extension of mSUGRA: NUMH2 model

- **NUHM2 model parameter space:**

  $m_0,\ m^2_{Hu},\ m^2_{Hd},\ m_{1/2},\ A_0,\ tan\beta,\ sign(\mu)$

  or alternatively

  $m_0,\ \mu,\ m_A,\ m_{1/2},\ A_0,\ tan\beta$

- Motivated by GUTs where $\hat{H}_u$ and $\hat{H}_d$ belong to different multiplets (e.g.$SU(5)$ GUTs)

- See also **Berezinsky et al; Arnowitt and Nath; Ellis, Olive, Falk and Santoso; De Roeck,Ellis,Gianotti,Moortgat,Olive,Pape**

- $$\frac{dm^2_{\tilde{t}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2f_t^2X_t\right)$$

  $$\frac{dm^2_{\tilde{\tau}_R}}{dt} = \frac{2}{16\pi^2}\left(-\frac{12}{5}g_1^2M_1^2 + \frac{3}{5}g_1^2S + 2f_\tau^2X_\tau\right)$$

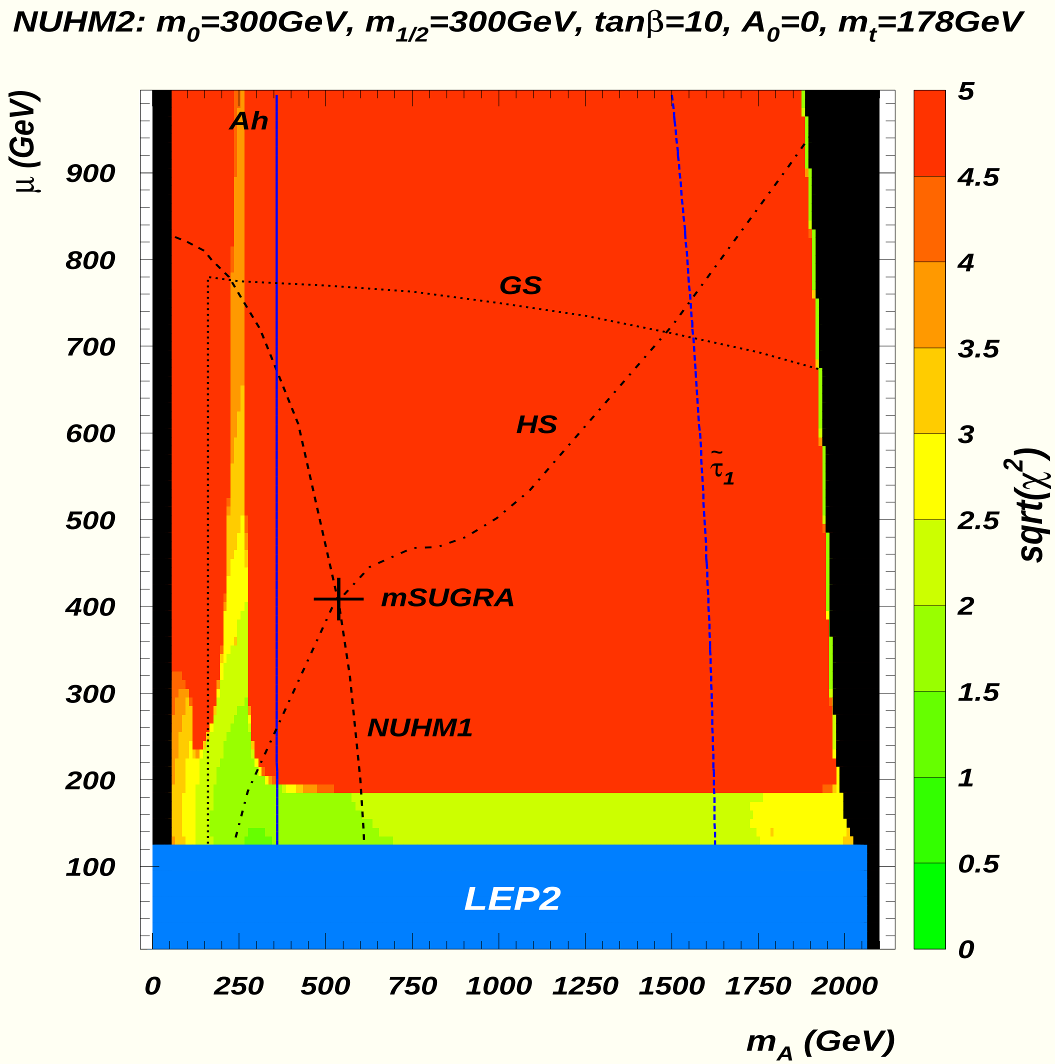
  $$S = m^2_{H_u} - m^2_{H_d} + Tr\left[\mathrm{m}^2_Q - \mathrm{m}^2_L - 2\mathrm{m}^2_U + \mathrm{m}^2_D + \mathrm{m}^2_E\right]$$

  $S \gg 0$: $\tilde{\tau}_R,\ \tilde{e}_R,\ \tilde{\mu}_R$ are suppresed, $\tilde{u}_R,\ \tilde{c}_R,\ \tilde{t}_R$ are enhanced

  $S \ll 0$:$\tilde{\tau}_R,\ \tilde{e}_R,\ \tilde{\mu}_R$ are enhanced, $\tilde{u}_R,\ \tilde{c}_R,\ \tilde{t}_R$ are suppressed

Scan of NUHM2 space: (μ, m_A) plane

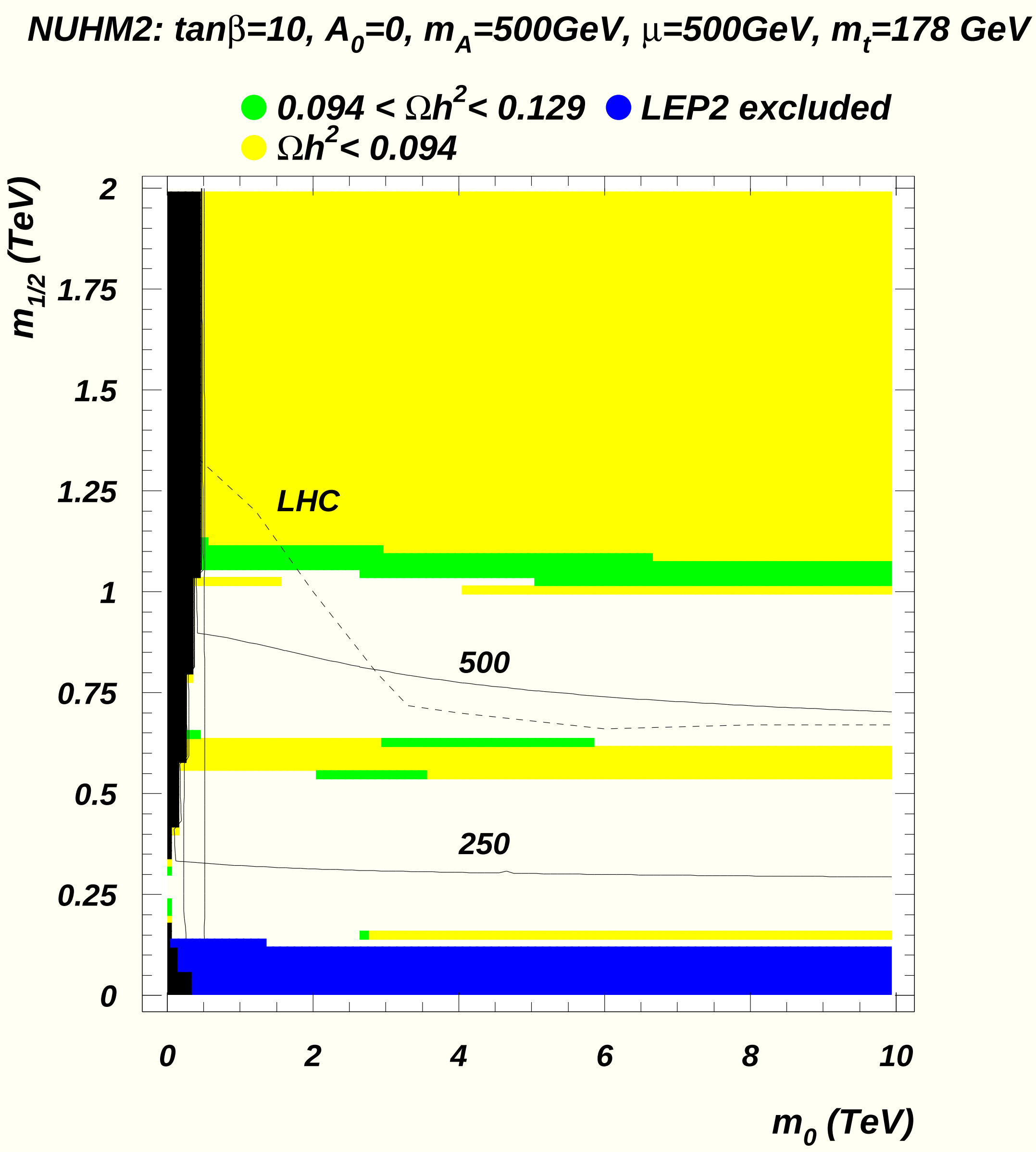
- $m_A \sim 250GeV$ - funnel region
- Large m_A - $\tilde{\nu}_\tau, \tilde{\tau}$ co-annihilation
- Small μ - HB/FP region
- Best fit area: $m_A \sim 300GeV,\ \mu \sim 130GeV$



Collider implications for NUMH2 model

In addition to NUHM1 signatures

- **Tevatron:** light $\tilde{u}_R, \tilde{c}_R$ for large $m_0, \Delta m_H$
- **LHC:** Higgs production followed by $H, A \to \tau^+\tau^-(\mu^+\mu^-)$; Wh or $t\bar{t}h$ production with W and t decaying leptonically
- **ILC:** $\tilde{\tau}_1, \tilde{e}_L$ or $\tilde{u}_R\bar{\tilde{u}}_R$ and $\tilde{c}_R\bar{\tilde{c}}_R$ production using beam polarization; for small μ reach can be greater than LHC



Conclusions and outlook

- Most of the parameter mSUGRA space is excluded! Too simple to be true?
- +1 extensions open a new perspectives for the exploring of SUGRA
- NMH model eliminates the pull between Ωh^2 and $(g-2)$ constraints!
- NUMH1 models provides two generic regions with low relic density for almost any mSUGRA non-viable point:
  $m_\phi < 0 \Rightarrow$ funnel region even for low $\tan\beta$, can not be realized in mSUGRA!
  $m_\phi \gg 0 \Rightarrow$ FP/HB region
- NMH and NUMH1 models has a distinctive mass spectrum, visible signals in dark matter detection experiments and specific intriguing collider signatures
- The case of non-universal Higgs mass with two parameters beyond mSUGRA one has even more degree of freedom, intriguing viable regions of parameter space and even more exciting experimental signatures
- Yet more one-parameter extension is possible –
  non-universal gaugino mass scenario – to push up higgsino(wino) component of neutralino (see talk by Howie Baer).

Understanding NUMH1 results

$$\frac{dm^2_{H_u}}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + 3f_t^2X_t\right), \quad X_t = m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A_t^2$$

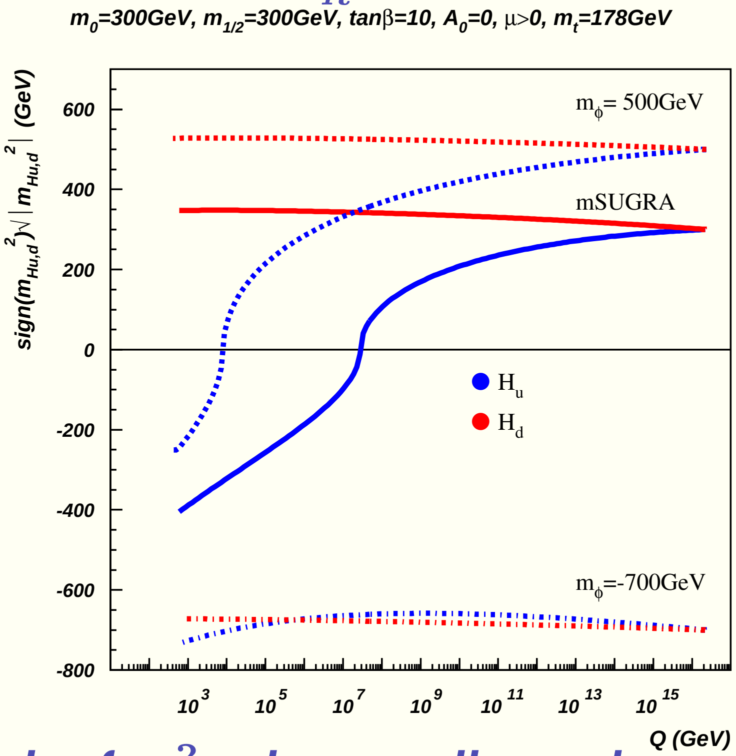
$$\frac{dm^2_{H_d}}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + 3f_b^2X_b + f_\tau^2X_\tau\right)$$

$$\Delta m^2_{H_{u,d}} \equiv m^2_{H_{u,d}}(\mathrm{NUHM1}) - m^2_{H_{u,d}}(\mathrm{mSUGRA})$$

$$\Delta m^2_{H_u}(\mathrm{weak}) \simeq \Delta m^2_{H_u}(\mathrm{GUT}) \times e^{-J_t}$$

$J_t = \frac{3}{8\pi^2}\int dt f_t^2 > 0 \Rightarrow \Delta m^2_{H_{u,d}}$ **maintains the sign**

$$\mu^2 = \frac{m^2_{H_d} - m^2_{H_u}\tan^2\beta}{(\tan^2\beta - 1)} - \frac{M_Z^2}{2}$$



- $X_t \ni m^2_{H_u}$ (low $\tan\beta$), $m_\phi > m_0 \Rightarrow$ a stronger push of $m^2_{H_u}$ to negative values
- if $m_\phi \ll 0$, there exist cancellations within the X_t term $\Rightarrow$ milder running of $m^2_{H_u}$
- $|m_{H_u}| \gg M_Z \Rightarrow \mu^2 \sim -m^2_{H_u} \Rightarrow$ for $m^2_\phi \gg 0$, $|\mu|$ is small
- $m^2_A = m^2_{H_u} + m^2_{H_d} + 2\mu^2 \simeq m^2_{H_d} - m^2_{H_u}$ for $m_\phi \ll 0$: $m^2_{H_u}$, $m^2_{H_d} < 0$ and can cancel against the $2\mu^2 \Rightarrow$ small M_A

NUMH1a and NUMH1b mass spectrum

parameter	mSUGRA	NUHM1a	NUHM1b
m_ϕ	300	-735	550
μ	409.2	754.0	180.6
$m_{\tilde{g}}$	732.9	736.2	732.0
$m_{\tilde{u}_L}$	720.9	720.5	722.4
$m_{\tilde{t}_1}$	523.4	632.4	481.0
$m_{\tilde{b}_1}$	650.0	691.6	631.0
$m_{\tilde{e}_L}$	364.7	366.4	364.5
$m_{\tilde{e}_R}$	322.8	322.1	323.0
$m_{\widetilde{W}_2}$	432.9	759.6	280.3
$m_{\widetilde{W}_1}$	223.9	236.2	150.2
$m_{\widetilde{Z}_4}$	433.7	759.5	283.4
$m_{\widetilde{Z}_3}$	414.8	752.0	190.3
$m_{\widetilde{Z}_2}$	223.7	235.8	160.7
$m_{\widetilde{Z}_1}$	117.0	118.7	102.7
m_A	538.6	265.0	603.8
m_{H^+}	548.0	278.2	613.0
m_h	115.7	116.1	115.3
$\Omega_{\widetilde{Z}_1} h^2$	1.2	0.12	0.11
$BF(b \to s\gamma)$	3.2×10^{-4}	4.7×10^{-4}	2.5×10^{-4}
Δa_μ	12.1×10^{-10}	9.4×10^{-10}	17.4×10^{-10}

Masses and parameters in GeV units for mSUGRA and two NUHM1 models, $m_0 = m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $m_t = 178$ GeV.

Beauty and self-motivation of SUSY

- *Boson-fermion symmetry – aimed to unify all forces in nature*

  $Q|\text{BOSON}\rangle = |\text{FERMION}\rangle$ **AND** $Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$

- *Potentially provides the link of gravity with other interactions*

- *crucial ingredient of superstring models – allows to include fermions*

- *Solves naturalness and gauge hierarchy problem of SM,* $\Lambda_{UV} \sim 10^{19}$

  $M_H^2 = M_{H^0}^2 + \Delta M_H$, ΔM_H **in SM (SUSY):** $\sim \Lambda_{UV}^2 (\sim m_{soft}^2 \log \frac{\Lambda_{UV}}{m_{soft}})$

- *Provides unification of gauge couplings*

- *Explains REWSB EW symmetry is broken radiatively via RGE of* H_u *and* H_d

- *Provides perfect dark matter candidate – stable neutral particle – the flat rotation curves of spiral galaxies provide the most direct evidence for large amount of the dark matter – spherical halo*

- *Solves baryogenesis problem – has an extra source of CP violation (baryon asymmetry from SM is* 10 *orders lower than the observed one)*

Halo profiles

- *the central cusp in the dark matter halo, as seen in numerical simulations, is smoothed out by a significant heating of the cold particles, leading to a cored density distribution, which has been modeled by the so called* **Burkert profile**

$$\rho_B(r) = \frac{\rho_B^0}{(1 + r/a)\,(1 + (r/a)^2)}. \tag{1}$$

length scale parameter $a = 11.7$ *kpc, the normalization* ρ_B^0 *is adjusted to reproduce the local halo density at the Earth position to* $\rho_B(r_0) = 0.34\ \mathrm{GeV\ cm}^{-3}$

- *spherical profile, which has no closed analytical form, roughly follows, in the inner galactic regions, the behavior of the profile proposed by Moore* et al.*, approximately scaling as* $r^{-1.5}$ *in the innermost regions, and features a local dark matter density* $\rho_{N03}(r_0) = 0.38\ \mathrm{GeV\ cm}^{-3}$ ***(Adiabatically Contracted N03 Halo Model).***