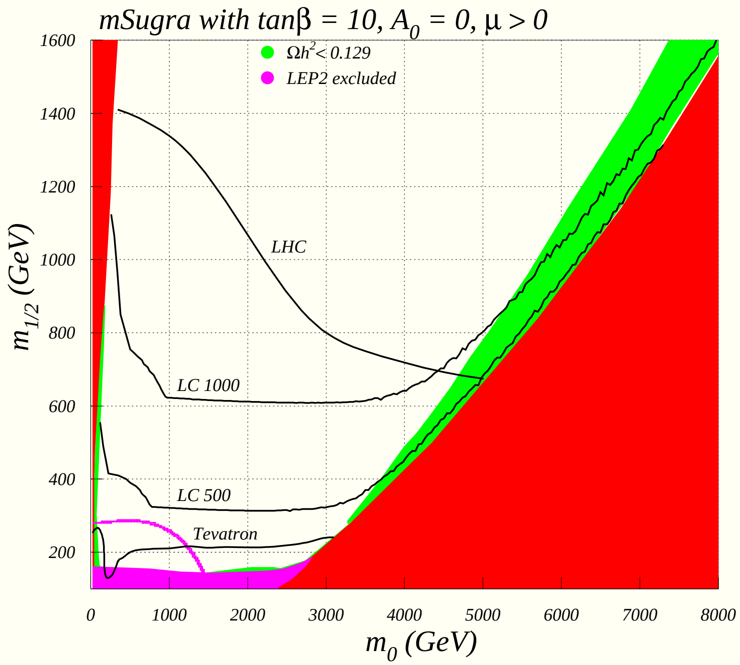
LHC/ILC synergy for SUSY

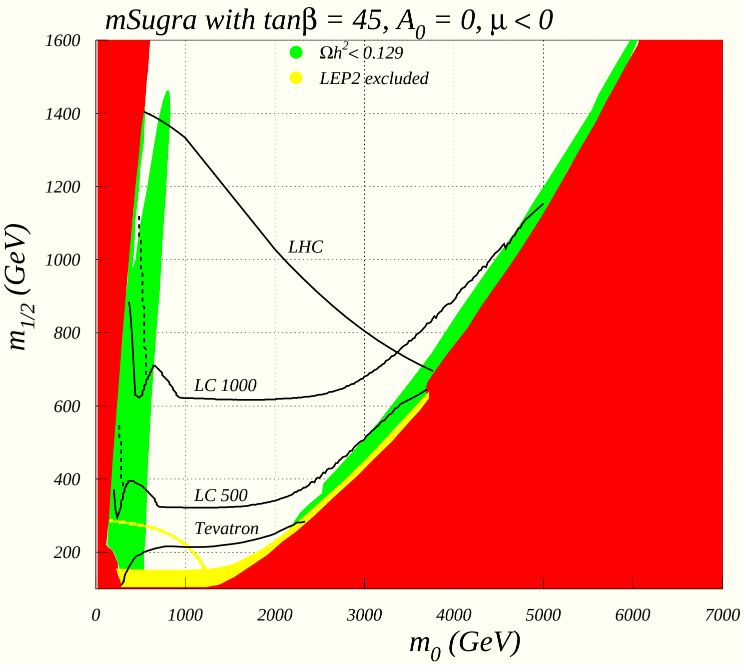
Howie Baer
Florida State University

Outline

- ⋆ LHC/ILC reach in mSUGRA model
- ⋆ New opportunities for LHC/ILC synergy
- NUHM1 model
- NUHM2 model
- Normal Scalar Mass Hierarchy (NMH) model

Some standard results from mSUGRA/CMSSM model



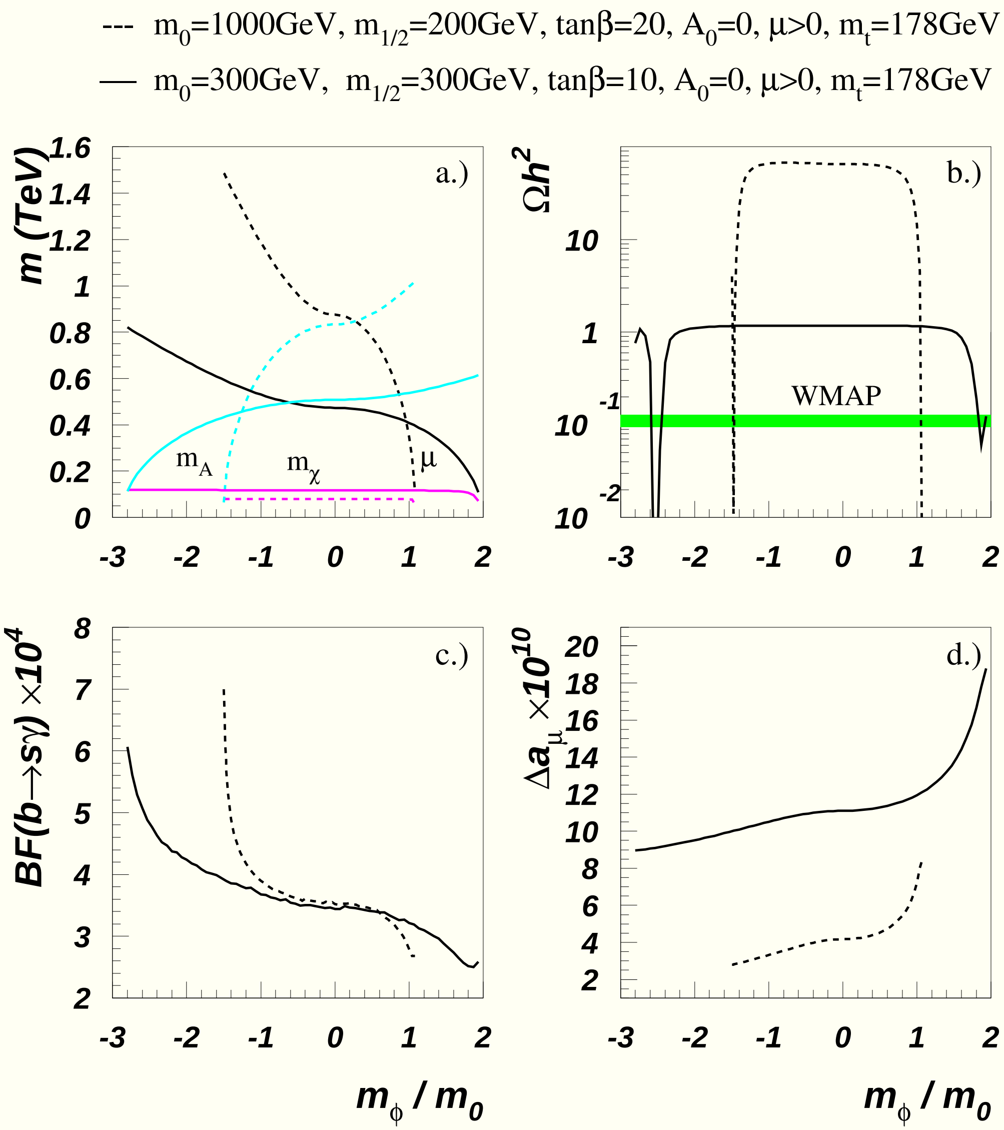


- Well known parameter space: $m_0,\ m_{1/2},\ A_0,\ \tan\beta, sign(\mu),\ (m_t)$

Simplest extension of parameter space: NUHM1 model

- Non-universal Higgs mass: 1 parameter extension
- $m_\phi = sign(m_{H_u}^2)\cdot\sqrt{|m_{H_u}^2|} = sign(m_{H_d}^2)\cdot\sqrt{|m_{H_d}^2|} \neq m_0$
- Motivated by $SO(10)$ SUSY GUTS since $\hat{H}_u, \hat{H}_d \in \hat{\phi}(10)$; matter superfields $\in \hat{\psi}(16)$
- m_ϕ can be > 0 or < 0: (recall $m_{H_u}^2$ driven "-" in RG running to yield REWSB
- GUT stability constraint: $m_{H_{u,d}}^2 + \mu^2 > 0$ at $Q = M_{GUT}$ (?)
- $m_0,\ m_\phi,\ m_{1/2},\ A_),\ \tan\beta,\ sign(\mu)$
- HB, Belyaev, Mustafayev, Profumo and Tata

NUHM1 model:



--- m0=1000GeV, m1/2=200GeV, tanβ=20, A0=0, μ>0, mt=178GeV
— m0=300GeV, m1/2=300GeV, tanβ=10, A0=0, μ>0, mt=178GeV
a.)
m (TeV)
mA
mχ
μ
b.)
Ωh2
WMAP
c.)
BF(b→sγ) ×10^4
d.)
Δaμ ×10^10
mφ / m0
mφ / m0

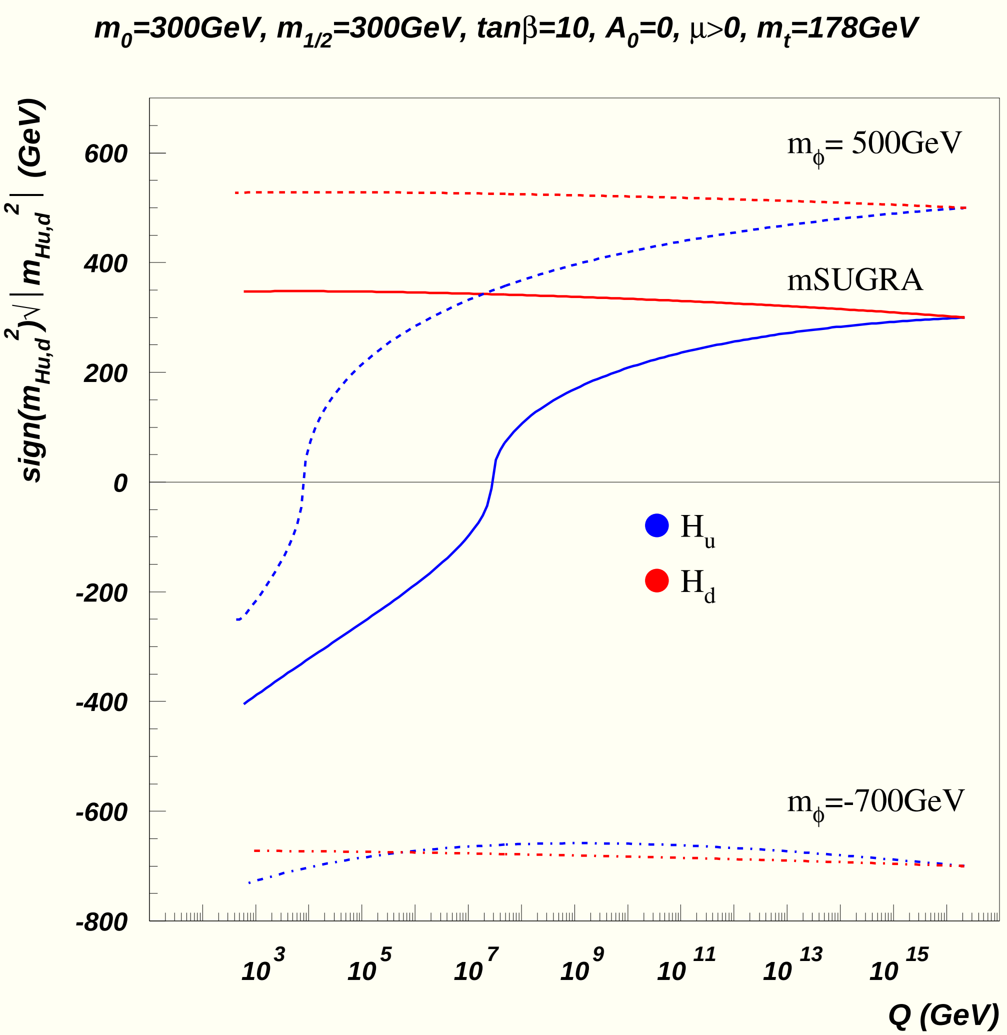
Higgs soft mass running in NUHM1 case:

- $\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t\right)$
- $\frac{dm_{H_d}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2 M_1^2 - 3g_2^2 M_2^2 - \frac{3}{10}g_1^2 S + 3f_b^2 X_b + f_\tau^2 X_\tau\right)$
- $X_t = m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2$

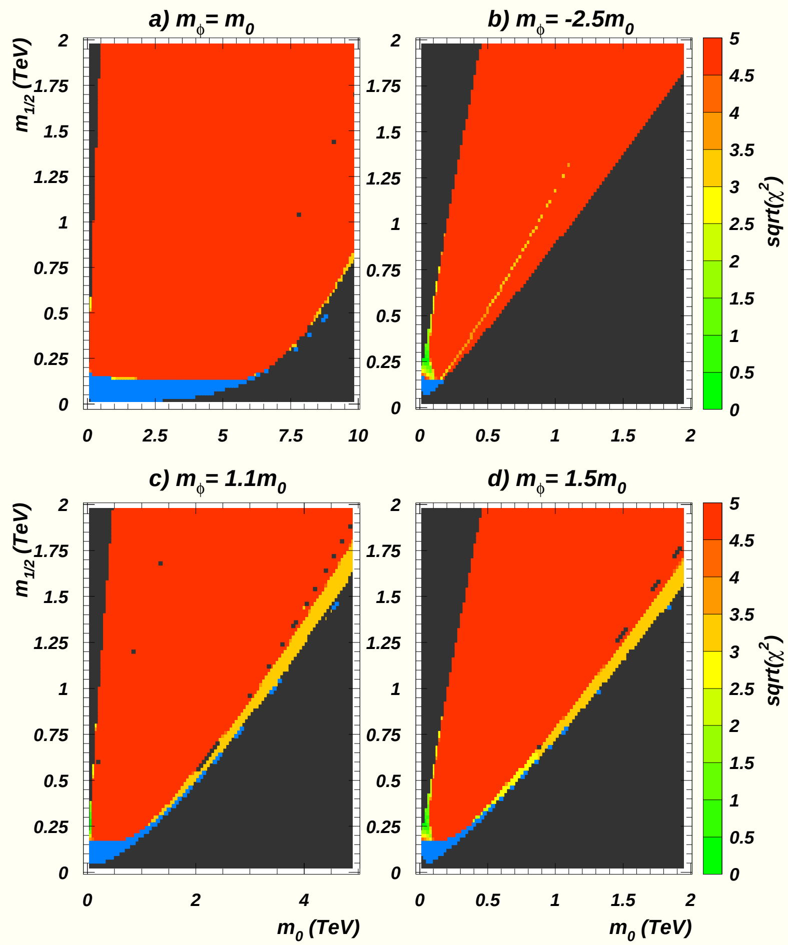
⋆ Tree-level minimization condition

- $\mu^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{(\tan^2\beta - 1} - \frac{M_Z^2}{2}$
- at moderate to large $\tan\beta$: $\mu^2 \sim -m_{H_u}^2$
- $m_A^2 = m_{H_u}^2 + m_{H_d}^2 + 2\mu^2 \simeq m_{H_d}^2 - m_{H_u}^2$

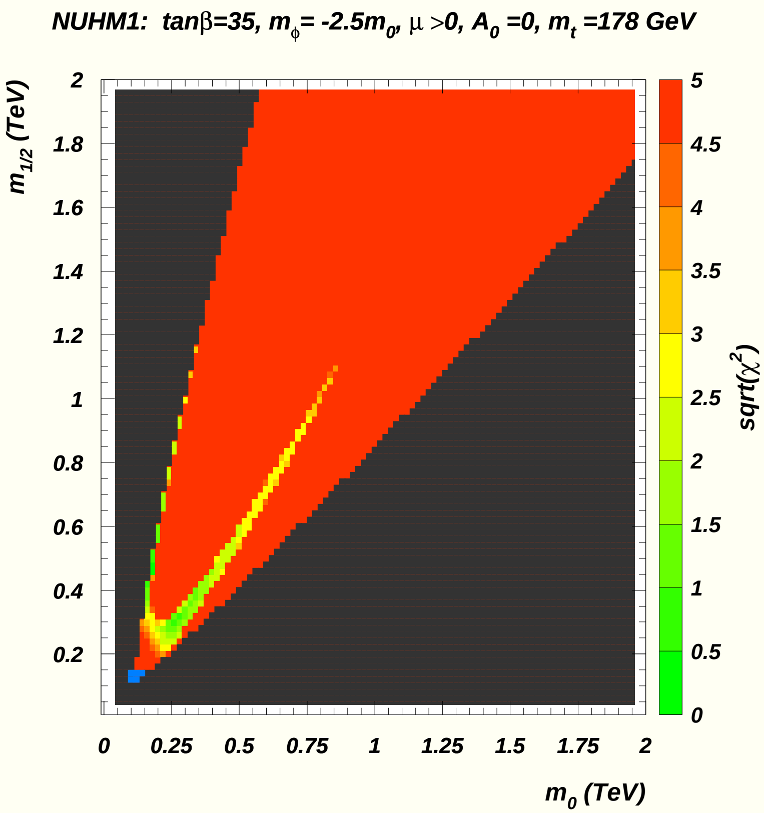
Running of $m^2_{H_u}$ and $m^2_{H_d}$



χ^2 evaluation of NUHM1 model for various m_ϕ



χ^2 evaluation of NUHM1 model for $\tan\beta = 35$, $m_\phi = -2.5m_0$



Collider reach for NUHM1 model

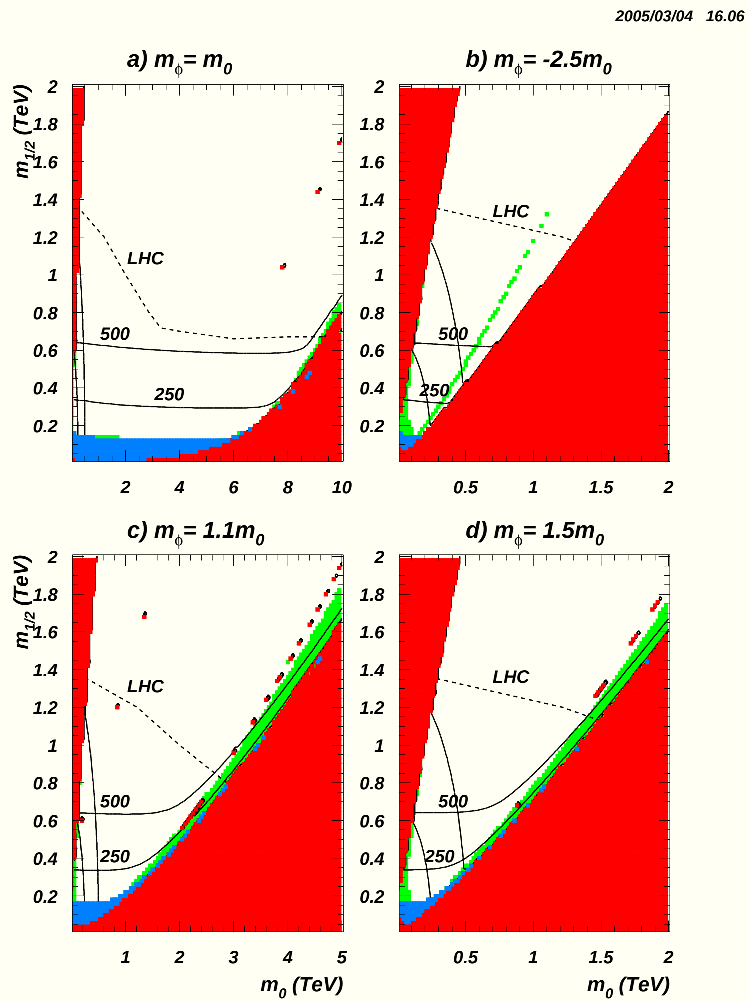


Table of masses for NUHM1 model

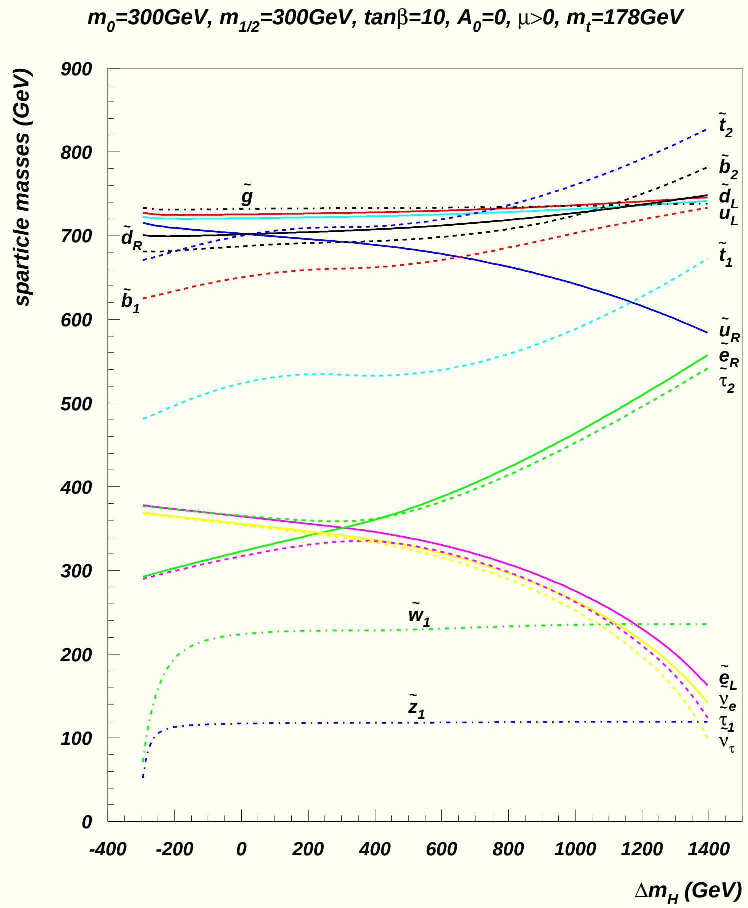
$m_0 = m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $m_t = 178$ GeV

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	11.9×10^{-10}	9.1×10^{-10}	17×10^{-10}

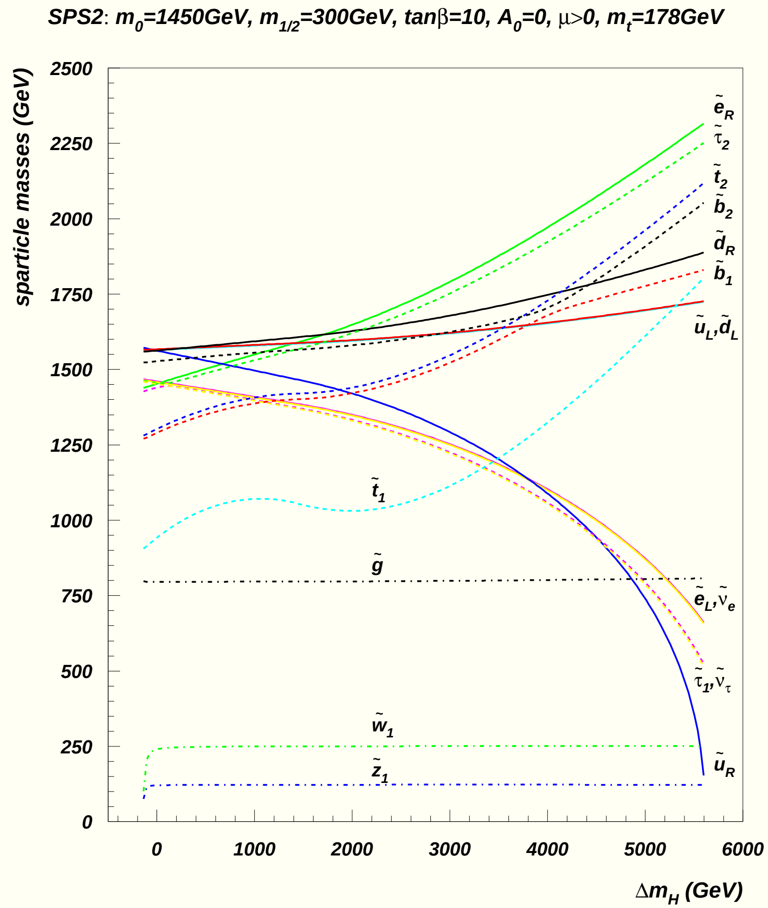
NUHM2 model:

- $m_0,\ m^2_{H_u},\ m^2_{H_d},\ m_{1/2},\ A_0,\ \tan\beta, sign(\mu)$
- REWSB: $m^2_{H_u},\ m^2_{H_d} \leftrightarrow \mu,\ m_A$
- Can always dial parameters so that in A-funnel or higgsino region
- See also Berezinsky et al.; Arnowitt and Nath; Ellis, Olive, Falk, Santoso
- $S = m^2_{H_u} - m^2_{H_d} + Tr[\mathbf{m}^2_Q - \mathbf{m}^2_L - 2\mathbf{m}^2_U + \mathbf{m}^2_D + \mathbf{m}^2_E] = 0$ in mSUGRA and NUHM1 case; $\neq 0$ for NUHM2 model
- For large scalar masses, S can dominate RG running

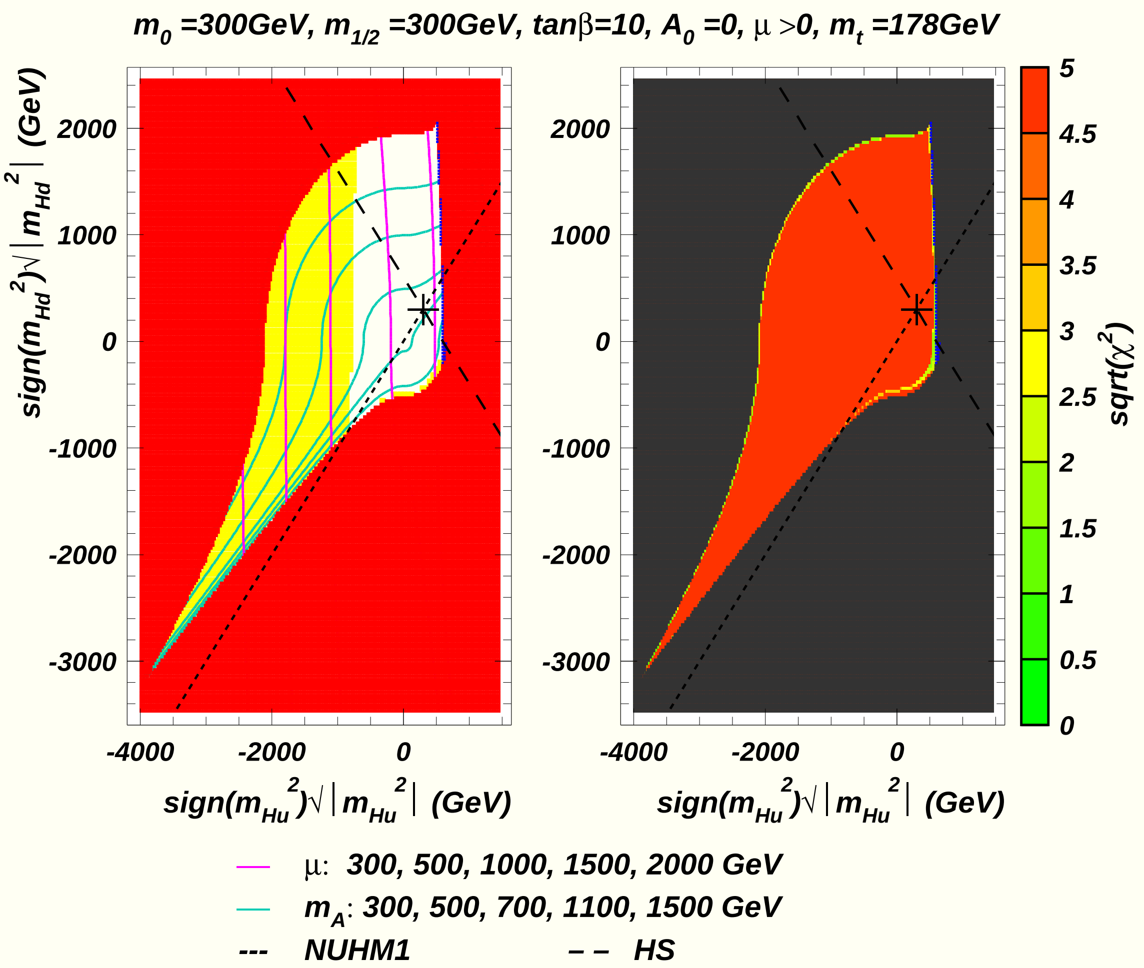
NUHM2 model with HS: $m_0 = m_{1/2} = 300$ GeV



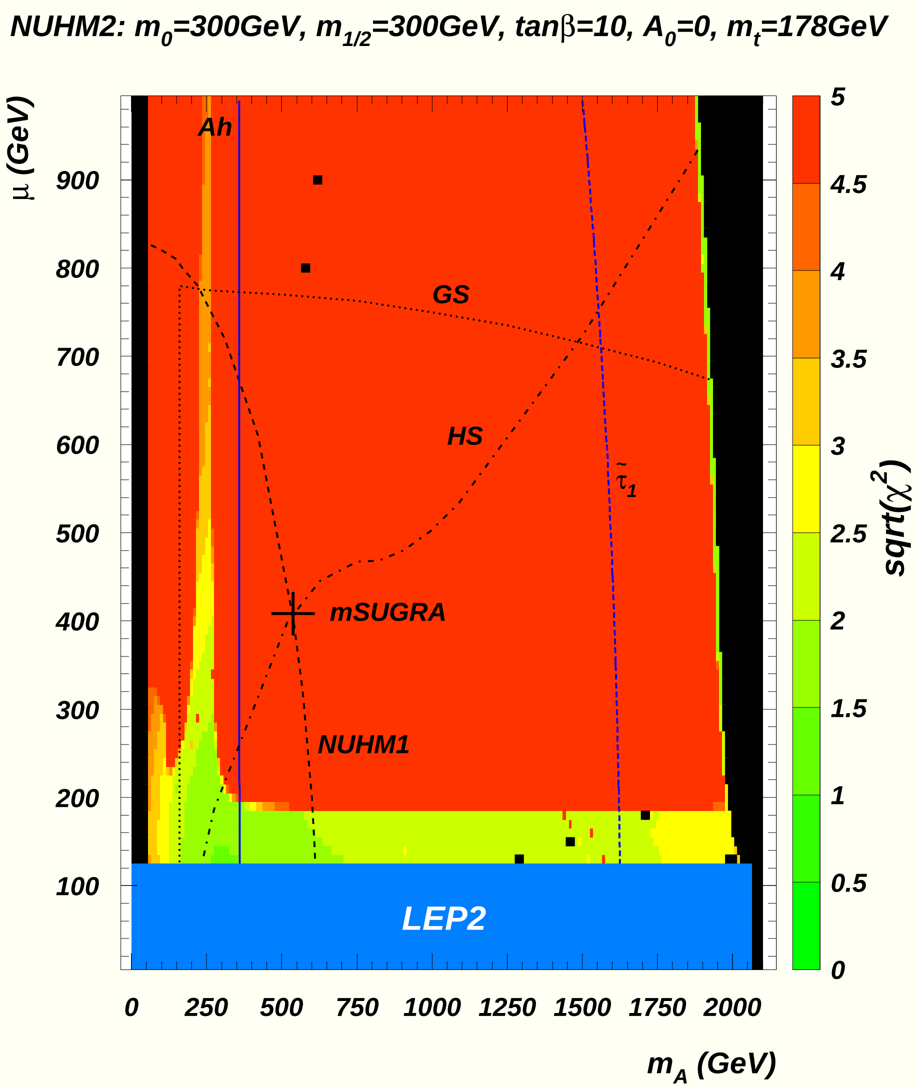
NUHM2 model with HS: $m_0 = 1450$ GeV, $m_{1/2} = 300$ GeV



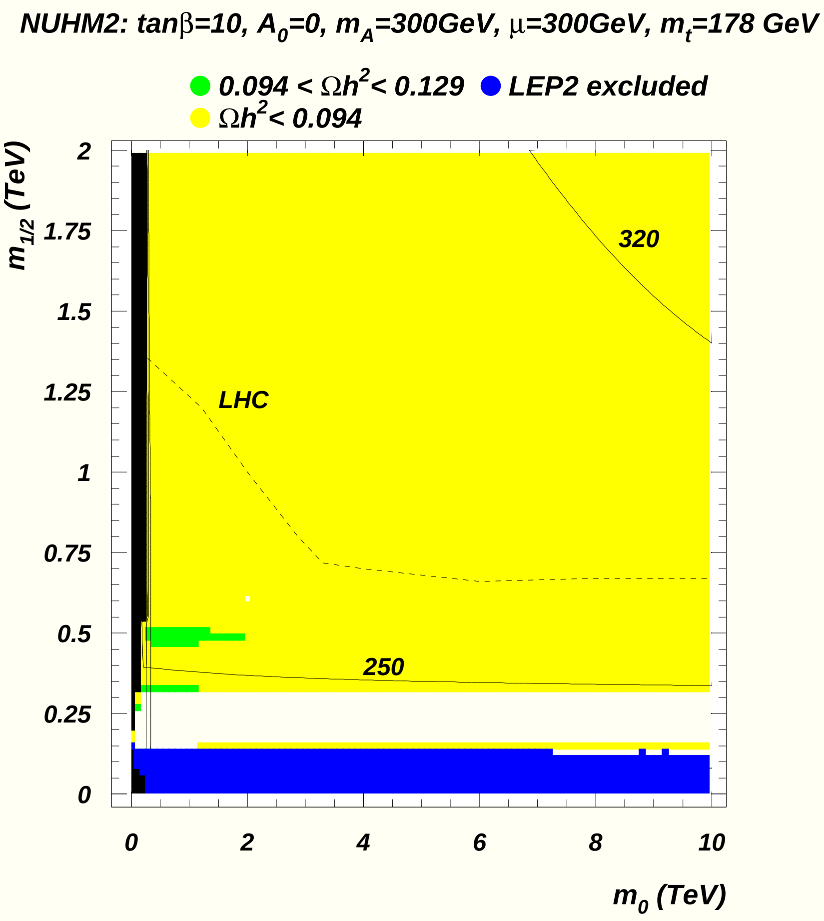
NUHM2 parameter space for $m_0 = m_{1/2} = 300$ GeV



NUHM2 parameter space for $m_0 = m_{1/2} = 300$ GeV



Reach of colliders in NUHM2 model



Sparticle masses in NUHM2 model

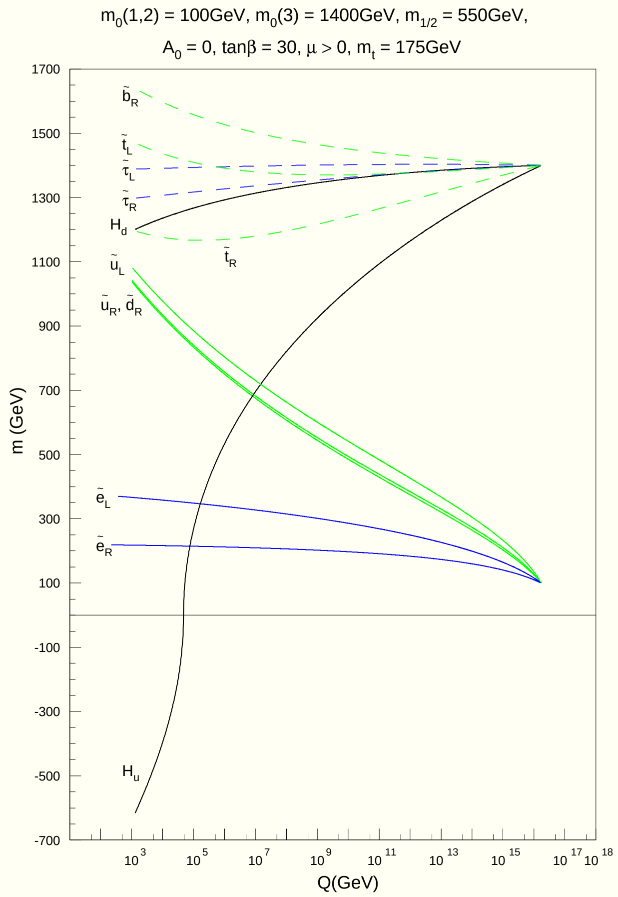
$m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$ and $m_t = 178$ GeV.

parameter	NUHM2a	NUHM2b	NUHM2c
m_0	300	300	1450
μ	220	933.2	3443.7
m_A	140	1884.6	7765.1
$m_{H_d}^2$	–	$(1651.7)^2$	$(7047.3)^2$
$m_{H_u}^2$	–	$-(1051.7)^2$	$-(4147.3)^2$
$m_{\tilde{g}}$	726.4	739.4	807.8
$m_{\tilde{u}_L}$	720.6	740.4	1724.8
$m_{\tilde{u}_R}$	713.3	591.9	151.6
$m_{\tilde{t}_1}$	491.0	661.9	1802.9
$m_{\tilde{b}_1}$	629.0	730.6	1830.5
$m_{\tilde{e}_L}$	377.6	180.9	660.7
$m_{\tilde{e}_R}$	292.4	546.3	2316.1
$m_{\tilde{\tau}_1}$	290.1	149.3	522.9
$m_{\tilde{\nu}_\tau}$	368.3	129.9	513.1
$m_{\widetilde{W}_2}$	293.8	937.1	3428.8
$m_{\widetilde{W}_1}$	174.4	236.0	250.4
$m_{\widetilde{Z}_4}$	296.4	935.7	3427.1
$m_{\widetilde{Z}_3}$	228.5	931.1	3426.5
$m_{\widetilde{Z}_2}$	178.7	236.1	251.5
$m_{\widetilde{Z}_1}$	108.9	119.2	122.0
m_{H^+}	162.1	1898.6	7816.6
m_h	113.3	116.5	120.3
$\Omega_{\widetilde{Z}_1} h^2$	0.10	0.11	0.12
$BF(b \to s\gamma)$	4.9×10^{-4}	3.4×10^{-4}	5.6×10^{-4}
Δa_μ	15.3×10^{-10}	13.0×10^{-10}	12.0×10^{-10}

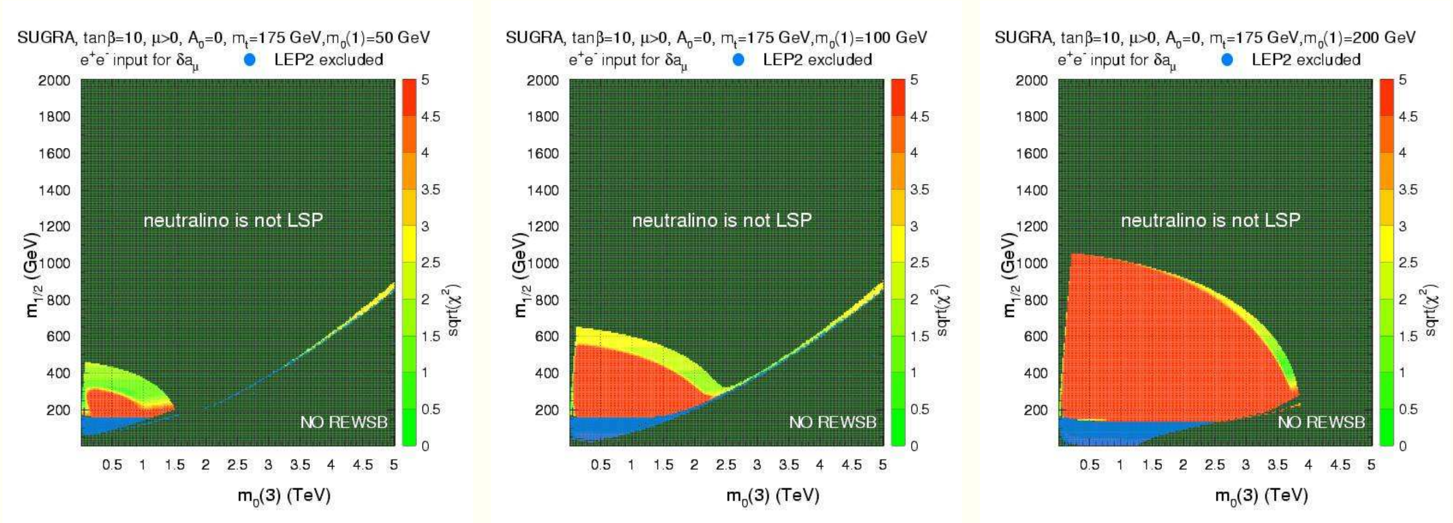
Normal Scalar Mass Hierarchy Case

- In mSUGRA model, WMAP relic density selects preferred regions of parameter space
- Measured $BF(b \to s\gamma)$ close to SM value:
- Measured value of $(g-2)_\mu \to\sim 3\sigma$ deviation: prefer light 2nd gen scalars e.g. $\widetilde{W}_{1,2}\tilde{\nu}_\mu$ loops
- All three can be matched in Normal Scalar Mass Hierarchy model (NMH)
- $m_0(1) \simeq m_0(2) \ll m_0(3) \simeq m_{H_{u,d}},\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$
- FCNC bounds mainly apply to 1+2 gen; more freedom on splitting 3rd gen.
- HB, Belyaev, Mustafayev, Krupovnickas

NMH model mass evolution



χ^2 fit to NMH model

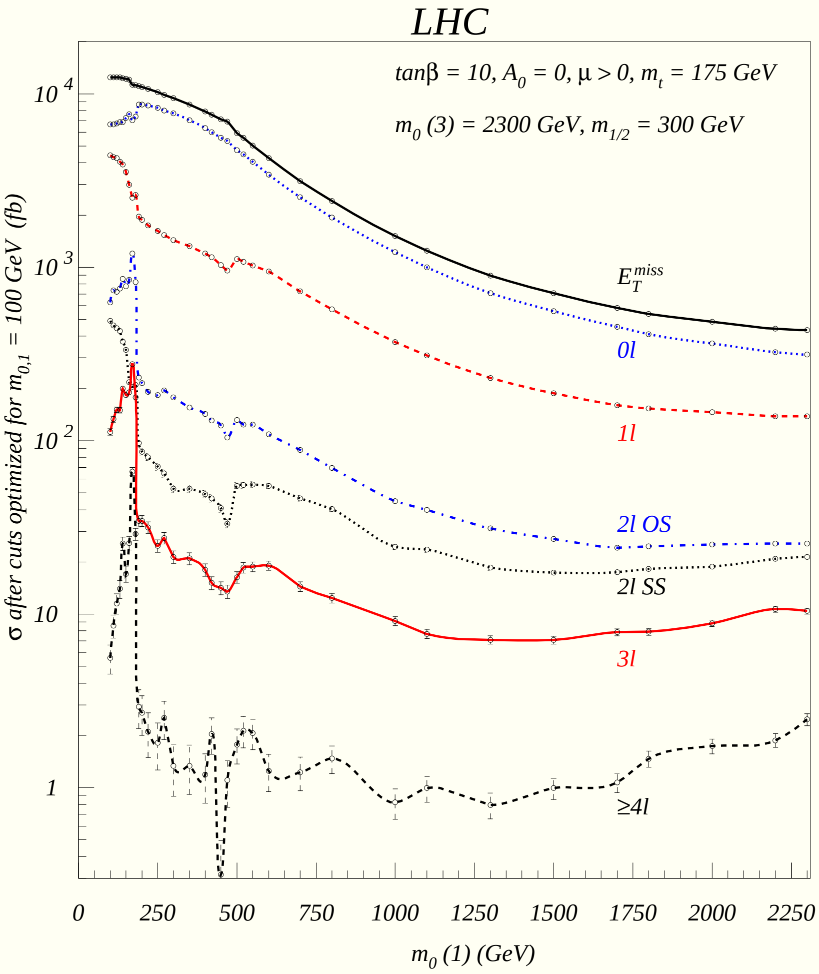


Sparticle masses in NMH model

$m_0(3) = m_H = 1500\ GeV,\ m_0(1) = 100\ GeV,\ m_{1/2} = 450\ GeV$

parameter	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
$m_{\tilde{d}_L}$	943.5
$m_{\tilde{d}_R}$	907.1
$m_{\tilde{t}_1}$	1175.1
$m_{\tilde{t}_2}$	1477.5
$m_{\tilde{b}_1}$	1460.0
$m_{\tilde{b}_2}$	1637.1
$m_{\tilde{e}_L}$	319.3
$m_{\tilde{e}_R}$	188.2
$m_{\tilde{\nu}_e}$	295.1
$m_{\tilde{\tau}_1}$	1386.1
$m_{\tilde{\tau}_2}$	1475.4
$m_{\tilde{\nu}_\tau}$	1468.5
$m_{\widetilde{W}_1}$	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}

χ^2 fit to NMH model



Conclusions

⋆ NUHM1 model:

- for any $m_0,\ m_{1/2},\ \tan\beta$ value, two solutions of m_ϕ give correct $\Omega_{CDM}h^2$
- A-funnel: light $A,\ H, H^\pm$
- higgsino region: light charginos/neutralino

⋆ NUHM2 model

- can dial to low μ, $2m_{\widetilde{Z}_1} \sim m_A$ regions
- light $A,\ H,\ H^\pm$ *and* light inos
- new $\tilde{e}_L$ and $\tilde{u}_R$ co-annihilation regions

⋆ NMH model

- light 1st/2nd gen. sleptons while other sparticles heavy
- enhanced multilepton cascade decays for LHC
- light $m_{\tilde{e}_{L,R}}$, $m_{\tilde{\mu}_{L,R}}$ masses for ILC