Implications of Compressed Supersymmetry for Collider and Dark Matter Searches

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Outline

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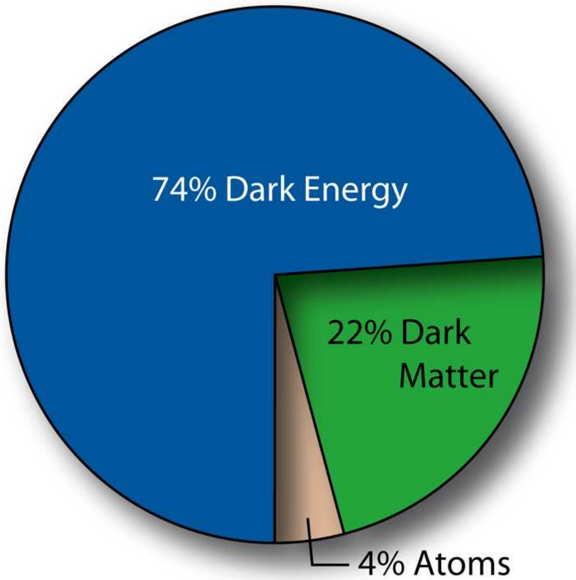
  - ⋆ Non-universal scalar mass model
  - ⋆ Non-universal gaugino mass model
- NUGM models at Colliders
- Compressed SUSY model
- Summary and Conclusion

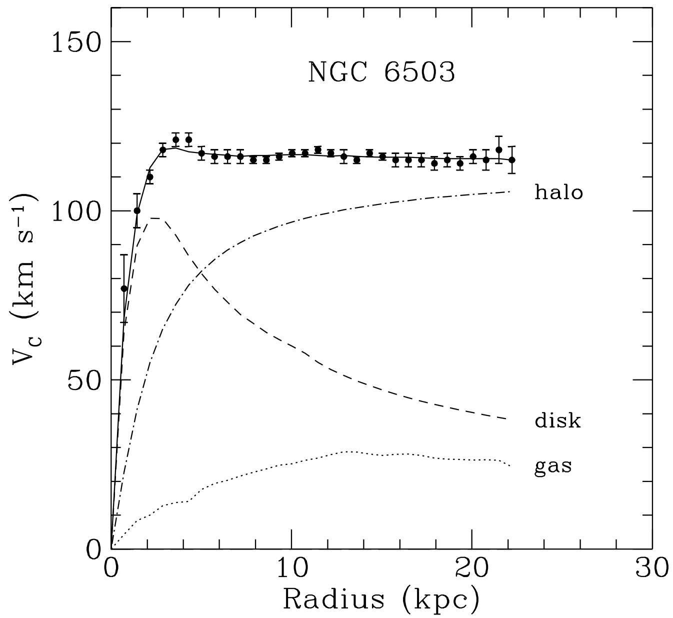
Dark Matter

- Properties of Dark Matter
  - not detected visibly
  - inferred from gravitational effects
  - dominant composition of matter in our universe
  - no DM candidate in the SM



http://map.gsfc.nasa.gov

- Evidence for Dark Matter
  - Galactic Clustering
  - Rotation Curves



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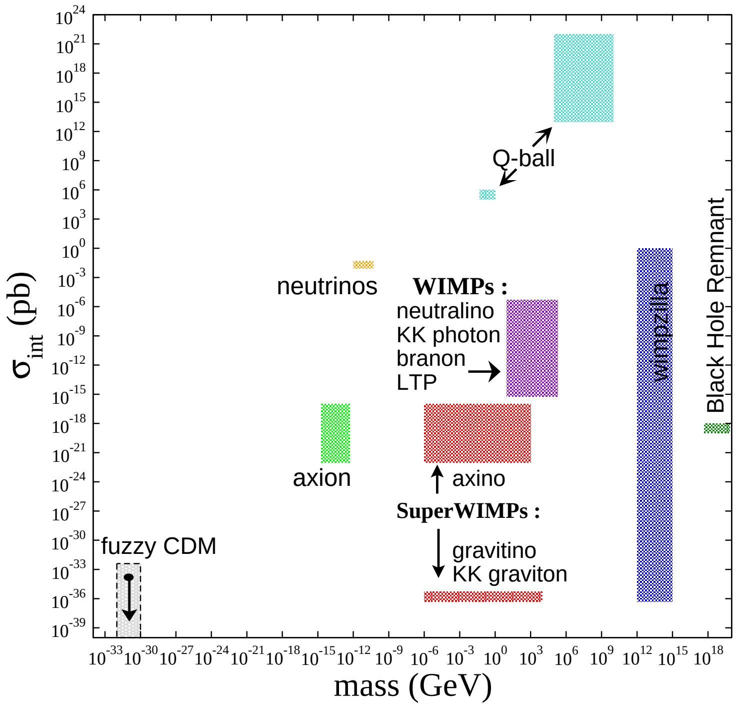
  - Gravitational Lensing
  - Cosmic Microwave Background
  - ...

Dark Matter Candidates

- Baryonic dark matter (MACHOs): small fraction of total DM
- Non-baryonic dark matter
  - Hot dark matter: ultra relativistic
  - Warm dark matter: relativistic
  - Cold dark matter: non-relativistic
    * Axion
    * WIMPs (Weakly Interacting Massive Particles): Neutralino (SUSY), KK-photon (extra dim. th.), branon (large extra dim. th.), ...
    * SuperWIMPs: gravitino
    * many other possibilities

Some Dark Matter Candidate Particles



Neutralino Dark Matter

- Dark Matter should be non-baryonic (no candidate in the SM), non-relativistic (cold), stable(or long-lived), weakly (or super-weakly) matter
- Flat universes in the ΛCDM cosmological model are characterized by baryon density, matter density, vacuum density, expansion rate(h)
- From the WMAP results, the cold dark matter density of the universe is $\Omega_{CDM}h^2 = 0.111^{+0.011}_{-0.015}$ (upper bound is a tight constraint on SUSY models containing DM candidates : DM may consist of several components)
- In SUSY models with R-parity conservation
  $\Rightarrow$ the Lightest Supersymmetric Particle(LSP) is absolutely stable
  $\Rightarrow$ lightest neutralino $\tilde{Z}_1$ is the LSP in most of MSSM parameter space
  $\Longrightarrow$ $\tilde{Z}_1$ is good candidate for Cold Dark Matter (CDM)
- number density is governed by Boltzmann equation,
  $dn/dt = -3Hn - \langle\sigma v_{rel}\rangle(n^2 - n_0^2)$
  $\Rightarrow$ requires evaluating many thousands Feynman diagrams
  $\Longrightarrow$ high (co-)annihilation cross section implies low relic abundance

Review of mSUGRA

- **Parameter Space :**

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

- **WMAP allowed Regions :**

  Region 1. $\tilde{\tau}$ co-annihilation region at low m_0

  Region 2. bulk region at low m_0 and $m_{1/2}$

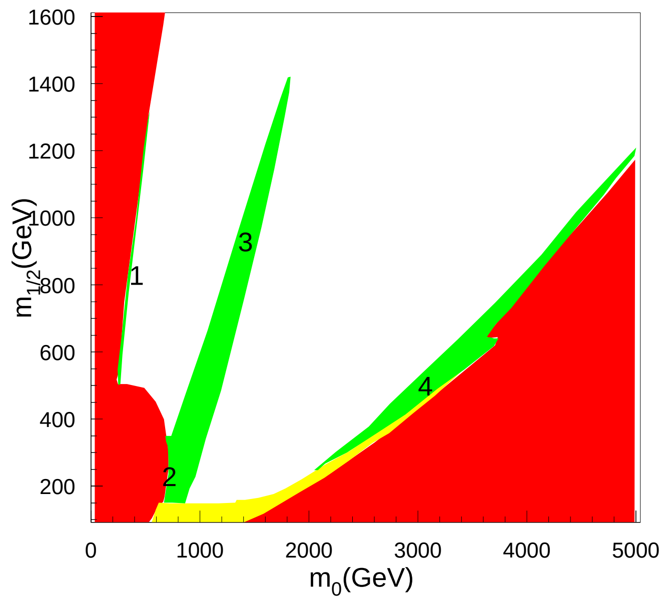
  – light sleptons (LEP2 excluded)

  Region 3. *A*-funnel

  – **H**, **A** resonance annihilation

  Region 4. FP/HB region at large m_0, small μ

  – mixed higgsino dark matter (MHDM)



- In most of the parameter space of the mSUGRA model, a value of neutralino relic density is beyond the WMAP bound $\Omega_{CDM}h^2 = 0.111^{+0.011}_{-0.015}$

SUSY models without universality

- Non-universal scalar mass models
  - Generation non-universality: Normal scalar mass hierarchy (NMH)
  - Non-universal Higgs mass: one extra parameter case ($\mathrm{NUHM1}_\mu$, $\mathrm{NUHM1}_A$)
  - non-universal Higgs mass: two extra parameter case (HS-Higgs Splitting)
- Non-universal gaugino mass models
  - Mixed Wino Dark Matter (MWDM)
  - Bino-Wino Co-Annihilation Scenario (BWCA)
  - Low $|M_3|$ Dark Matter: Compressed SUSY (LM3DM)
  - High $|M_2|$ Dark Matter: left-right split SUSY (HM2DM)
- Some benchmark cases with m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$ = 300 GeV, 300 GeV, 0, 10, +1 and m_t = 171.4 GeV

for more details, see Baer, Mustafayev,EKP and Tata, arXiv:0802.3384

Parameter space of SUSY models without universality

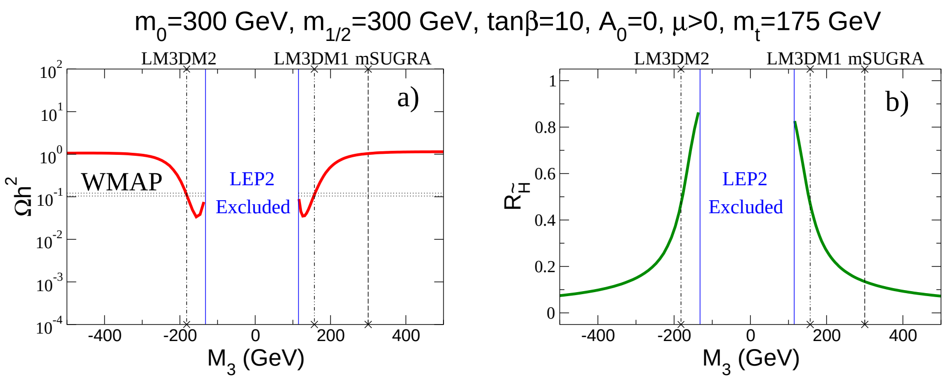
- Non-universal scalar mass models
  - NMH: $m_0(1,2)$, m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
    $m_0(1,2)$: first/second generation, $m_0(3) = m_{H_u} = m_{H_d} \equiv m_0$: remaining
    dial $m_0(1,2)$ to low enough to bulk (co-)annihilation via light sleptons
  - NUHM1$_\mu$, NUHM1$_A$: m_0, δ_ϕ, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
    $m_\phi = m_0(1+\delta_\phi)$, $m^2_{H_u} = m^2_{H_d} \equiv sign(m_\phi)|m_\phi|^2$
    $m_\phi >> m_0$: small μ and MHDM, $m_\phi < 0$: $m_A \sim 2m_{\tilde{Z}_1}$
  - HS: m_0, $m^2_{H_u}$(equivalently μ), $m^2_{H_d}$(equivalently m_A), $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
    $m^2_{H_{u,d}} = m^2_0\ (1 \mp \delta_H)$
    $\delta_H < 0$: low μ and low m_A, $\delta_H > 0$: WMAP region via $\tilde{l}_L/\tilde{\nu}$ or $\tilde{u}_R/\tilde{c}_R$
    co-annihilation

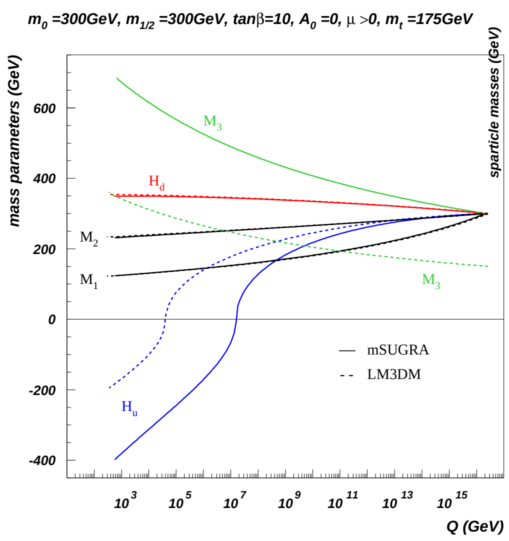
- Non-universal gaugino mass models
  - MWDM: m_0, M_1(or M_2), $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
  - BWCA: same as MWDM but M_1 and M_2 are in opposite sign
  - LM3DM: m_0, M_3, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
  - HM2DM: m_0, M_2, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$

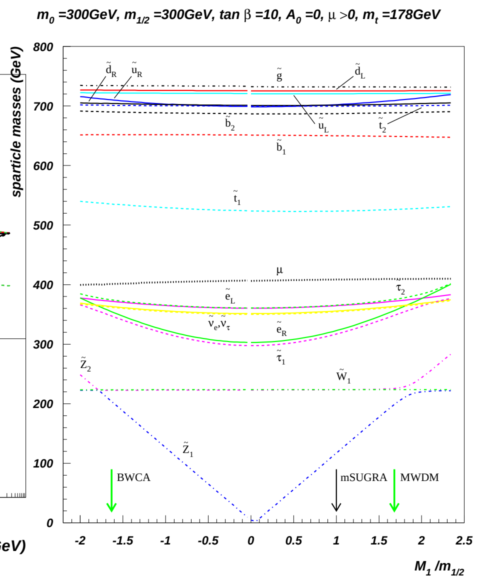
parameter	mSUGRA	NMH	$\mathrm{NUHM1}_{\mu}$	$\mathrm{NUHM1}_{A}$	HS
special	—	$m_0(1,2)$	m_ϕ	m_ϕ	δ_H
value	—	54	549	-728	-1.36
μ	385.1	386.5	105.8	748.5	269.3
$m_{\tilde{g}}$	729.7	722.1	731.4	733.4	728.9
$m_{\tilde{u}_L}$	720.8	658.4	724.3	720.5	720.1
$m_{\tilde{t}_1}$	523.4	526.5	484.1	624.5	505.8
$m_{\tilde{b}_1}$	656.8	659.8	642.2	689.5	645.4
$m_{\tilde{e}_L}$	364.5	216.2	364.8	365.8	373.4
$m_{\tilde{e}_R}$	322.3	128.9	322.5	321.9	301.8
$m_{\tilde{\tau}_1}$	317.1	317.6	317.8	316.4	299.3
$m_{\widetilde{W}_2}$	411.7	412.7	264.7	754.8	321.1
$m_{\widetilde{W}_1}$	220.7	219.5	91.1	234.9	196.6
$m_{\widetilde{Z}_2}$	220.6	219.4	117.4	234.5	198.1
$m_{\widetilde{Z}_1}$	119.2	118.4	69.0	121.5	115.4
m_A	520.3	521.9	584.5	268.5	279.0
m_{H^+}	529.8	531.4	593.8	281.6	292.0
m_h	110.1	110.1	109.8	110.5	109.8
$\Omega_{\widetilde{Z}_1} h^2$	1.1	0.10	0.11	0.11	0.10
$\sigma_{SI}(\widetilde{Z}_1 p)$	2.1×10^{-9} pb	2.1×10^{-9} pb	7.8×10^{-8} pb	1.2×10^{-9} pb	2.7×10^{-8} pb
$R_{\tilde{H}}$	0.15	0.14	0.84	0.06	0.26

parameter	mSUGRA	MWDM	BWCA	LM3DM	HM2DM
special	—	$M_1(M_{GUT})$	$M_1(M_{GUT})$	$M_3(M_{GUT})$	$M_2(M_{GUT})$
value	—	490	-480	160	900
μ	385.1	385.9	376.6	185.3	134.8
$m_{\tilde{g}}$	729.7	729.9	731.7	420.2	736.4
$m_{\tilde{u}_L}$	720.8	721.2	722.0	496.9	901.8
$m_{\tilde{u}_R}$	702.7	708.9	709.9	467.0	696.3
$m_{\tilde{t}_1}$	523.4	526.5	536.3	312.2	394.3
$m_{\tilde{b}_1}$	656.8	656.0	658.9	443.2	686.4
$m_{\tilde{e}_L}$	364.5	371.5	371.4	366.1	669.3
$m_{\tilde{e}_R}$	322.3	353.3	352.2	322.6	321.3
$m_{\widetilde{W}_2}$	411.7	412.4	404.5	282.9	719.7
$m_{\widetilde{W}_1}$	220.7	220.8	220.0	152.5	136.5
$m_{\widetilde{Z}_2}$	220.6	223.2	219.2	163.6	142.3
$m_{\widetilde{Z}_1}$	119.2	194.6	201.7	105.5	94.8
m_A	520.3	525.9	518.6	398.3	670.7
m_{H+}	529.8	535.3	528.1	408.7	679.8
m_h	110.1	110.2	109.8	106.0	111.9
$\Omega_{\widetilde{Z}_1} h^2$	1.1	0.10	0.10	0.10	0.10
$\sigma_{SI}(\widetilde{Z}_1 p)$	2.1×10^{-9} pb	1.5×10^{-8} pb	3.1×10^{-11} pb	7.2×10^{-8} pb	3.4×10^{-8} pb
$R_{\tilde{H}}$	0.15	0.25	0.16	0.50	0.67

NUGM Models - LM3DM







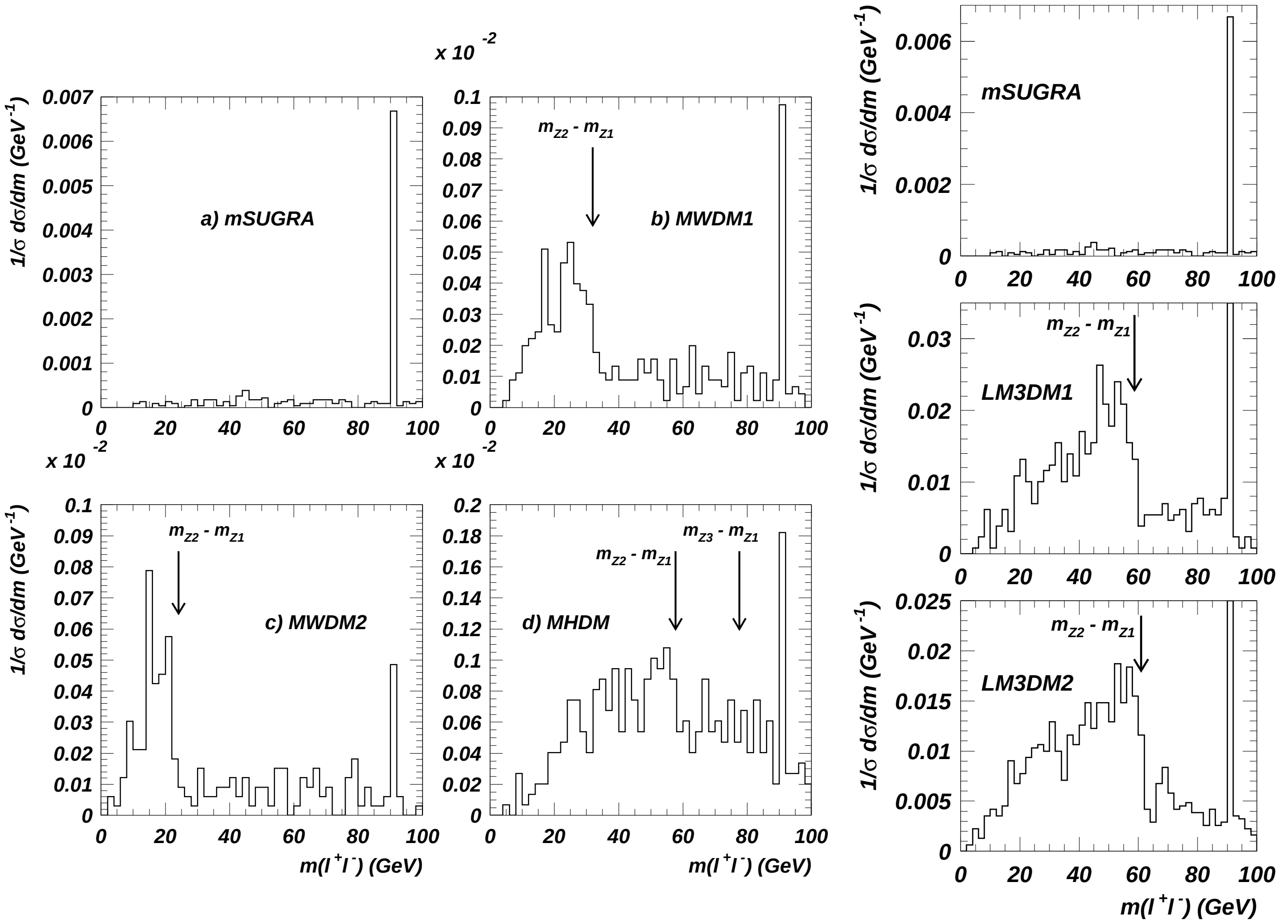
- Mild evolution of $m^2_{H_d}$ due to small Yukawa coupling f_b, f_τ
- Lighter squarks and gluinos $\rightarrow$ reduced effect of f_t on $m^2_{H_u}$ $\Rightarrow$ smaller μ
- $\frac{dm^2_{H_d}}{dt} \propto f^2_{b,\tau} X_{b,\tau}$, $\frac{dm^2_{H_u}}{dt} \propto f^2_t X_t$
- $\mu^2 = \frac{m^2_{H_d} - m^2_{H_u} tan\beta}{tan^2\beta - 1} - \frac{M^2_Z}{2} \simeq -m^2_{H_u}$

NUGM at Colliders

- CERN LHC and Fermilab Tevatron
  - If $\tilde{Z}_2 \longrightarrow \tilde{l}\bar{l}, \bar{\tilde{l}}l \longrightarrow \tilde{Z}_1 l\bar{l}$ or $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 l\bar{l}$ are open ($l = e$ or μ)
    $\Longrightarrow$ good prospects for measuring the $\tilde{Z}_2$ - $\tilde{Z}_1$ mass gap at the CERN LHC and possibly at the Fermilab Tevatron
  - In the mSUGRA case, most of the parameter space has $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} > 90$ GeV,
    $\Longrightarrow \tilde{Z}_2 \longrightarrow \tilde{Z}_1 Z^0$ or $\tilde{Z}_1 h$ "spoiler" decays dominant
  - When the mass gap is much smaller
    - ∗ spoiler decays are closed, 3-body decays are open
    - ∗ $l\bar{l}$ mass edge always visible at LHC

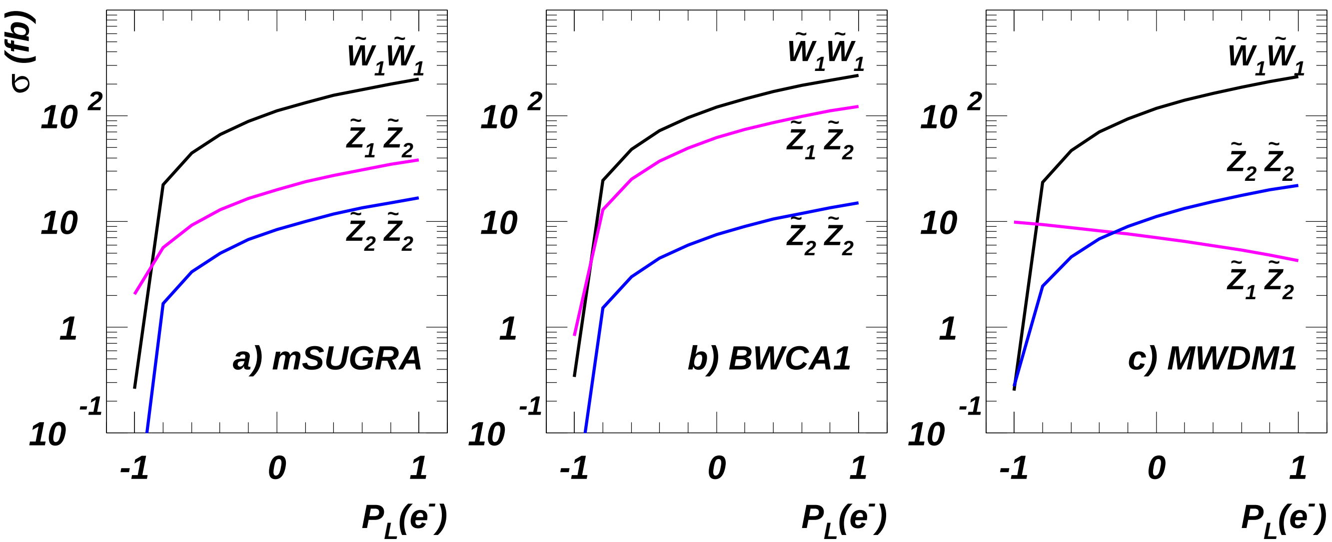
- Linear e^+e^- collider(ILC)
  - $m_{\tilde{Z}_2}$, $m_{\tilde{W}_1}$ and $m_{\tilde{Z}_1}$ can be inferred from $\tilde{W}_1^+\tilde{W}_1^- \longrightarrow \bar{l}\nu_l\tilde{Z}_1 + q\bar{q}\tilde{Z}_1$
    (dijet events)
  - $\tilde{W}_1^+\tilde{W}_1^-$, $\tilde{Z}_1\tilde{Z}_2$, $\tilde{Z}_2\tilde{Z}_2$ production cross sections can be measured as a function of beam polarization: $P_L(e^-) = f_L - f_R$
    ($f_{L,R}$: fraction of left(right) polarized electron in the beam)

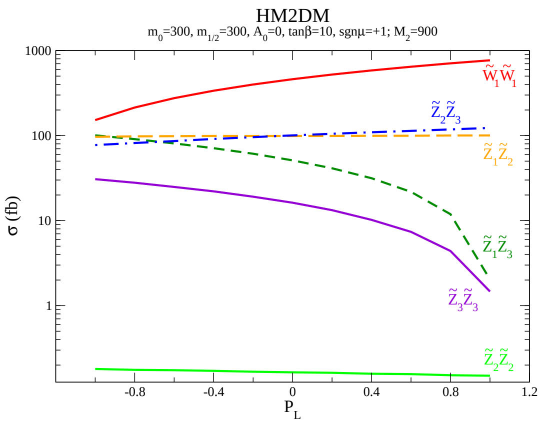
Dilepton Distribution at LHC



- mSUGRA : sharp peak at $m(l^+l^-) \sim M_Z$ from $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 Z^0$ decays
- NUGM : Z^0 peak from $\tilde{Z}_3$, $\tilde{Z}_4$, $\tilde{W}_2$ decays + continuum distribution $m(l^+l^-) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$

Cross Section for $\tilde{W}_1^+\tilde{W}_1^-$ and $\tilde{Z}_i\tilde{Z}_j$ Production at ILC

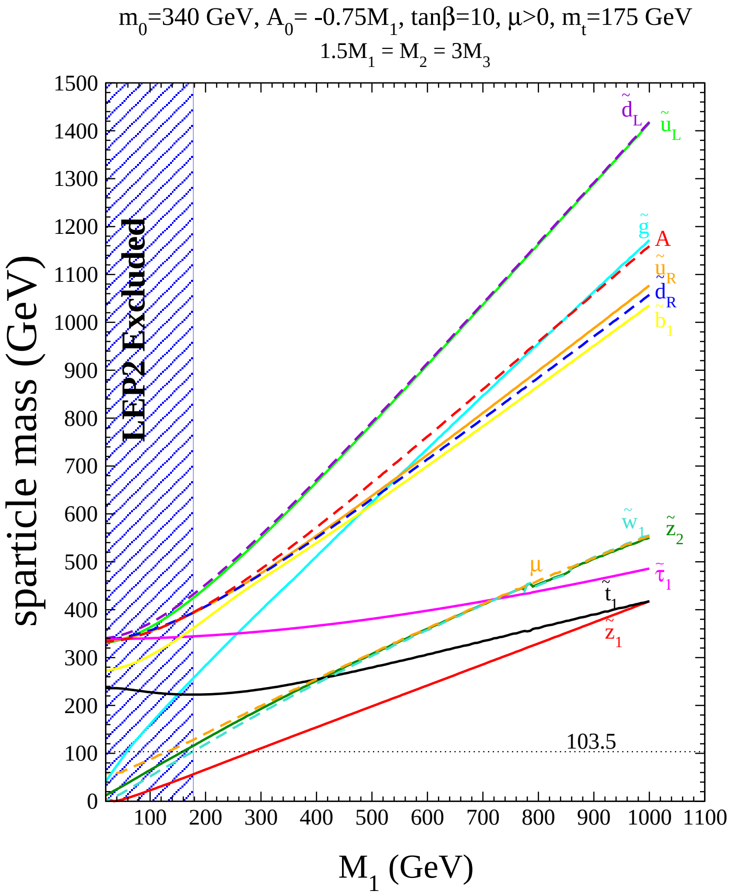




- $\tilde{W}_1$ and $\tilde{Z}_2$ are mainly wino-like
  $\longrightarrow \sigma(\tilde{W}_1\tilde{W}_1)$ and $\sigma(\tilde{Z}_2\tilde{Z}_2)$ are similar to one another
- $\tilde{Z}_1\tilde{Z}_2$ process are quite different

Compressed SUSY*: mass spectrum

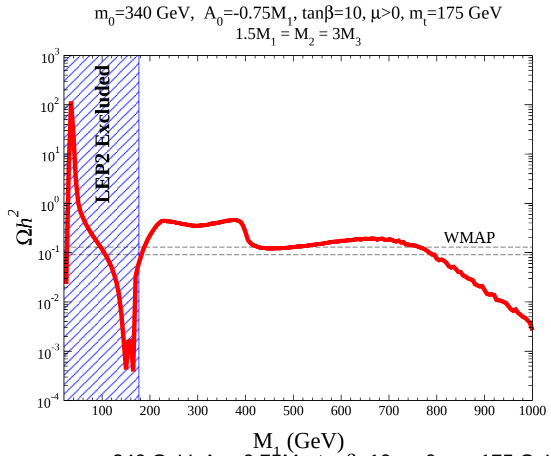
- $M_3 < M_1$or $M_2 \rightarrow$ gluino and squark masses reduced $\rightarrow$ compressed sparticle mass spectrum
- **Parameter Space at** $Q = M_{GUT}$
  Case A: m_0, $m_{1/2}$, M_3, A_0, $\tan\beta$, $sign(\mu)$
  ($M_1 = M_2 = m_{1/2}$, $A_0 = -1.5 m_{1/2}$)
  Case B: m_0, M_1, A_0, $\tan\beta$, $sign(\mu)$
  ($1.5M_1 = M_2 = 3M_3$, m_t=175 GeV,
  A_0=-0.75M_1, $\mu > 0$, $\tan\beta$=10, m_0=340 GeV)
- Case B
  - cut after 1000 GeV: $\tilde{t}_1$ LSP $\rightarrow$ imply upper bound on gluino and squark masses
  - LEP2 bound on chargino mass below $\sim$ 160 GeV
  - 440 GeV $< M_1 <$ 1000 GeV: light $\tilde{t}$ (NLSP), $m_{\tilde{Z}_1} > m_t \Rightarrow \tilde{Z}_1\tilde{Z}_1 \rightarrow t\bar{t}$ accessible in the early Universe

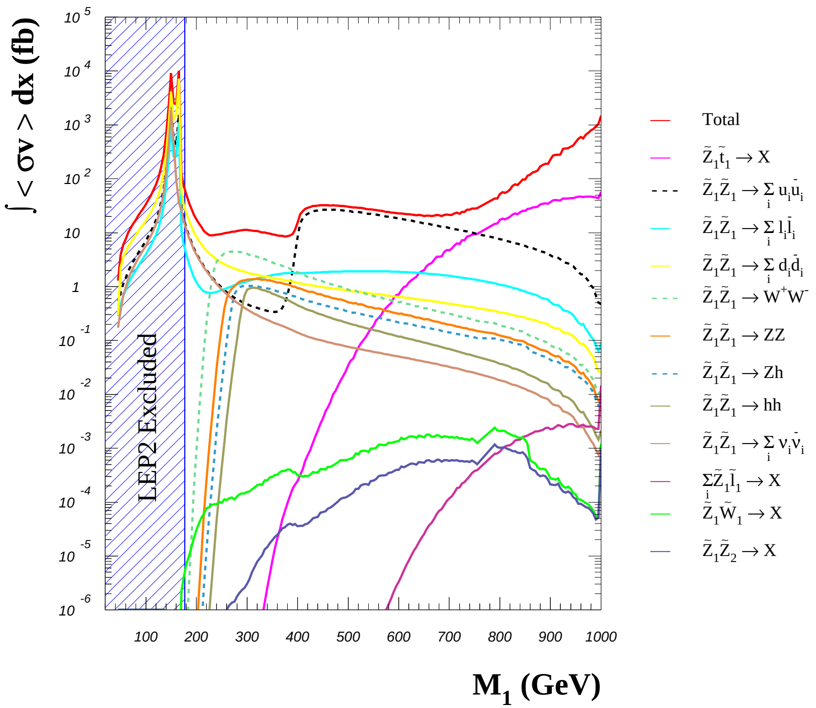


*: named by S. P. Martin Phys.Rev.D75 (2007) 115005

Compressed SUSY: neutralino relic density

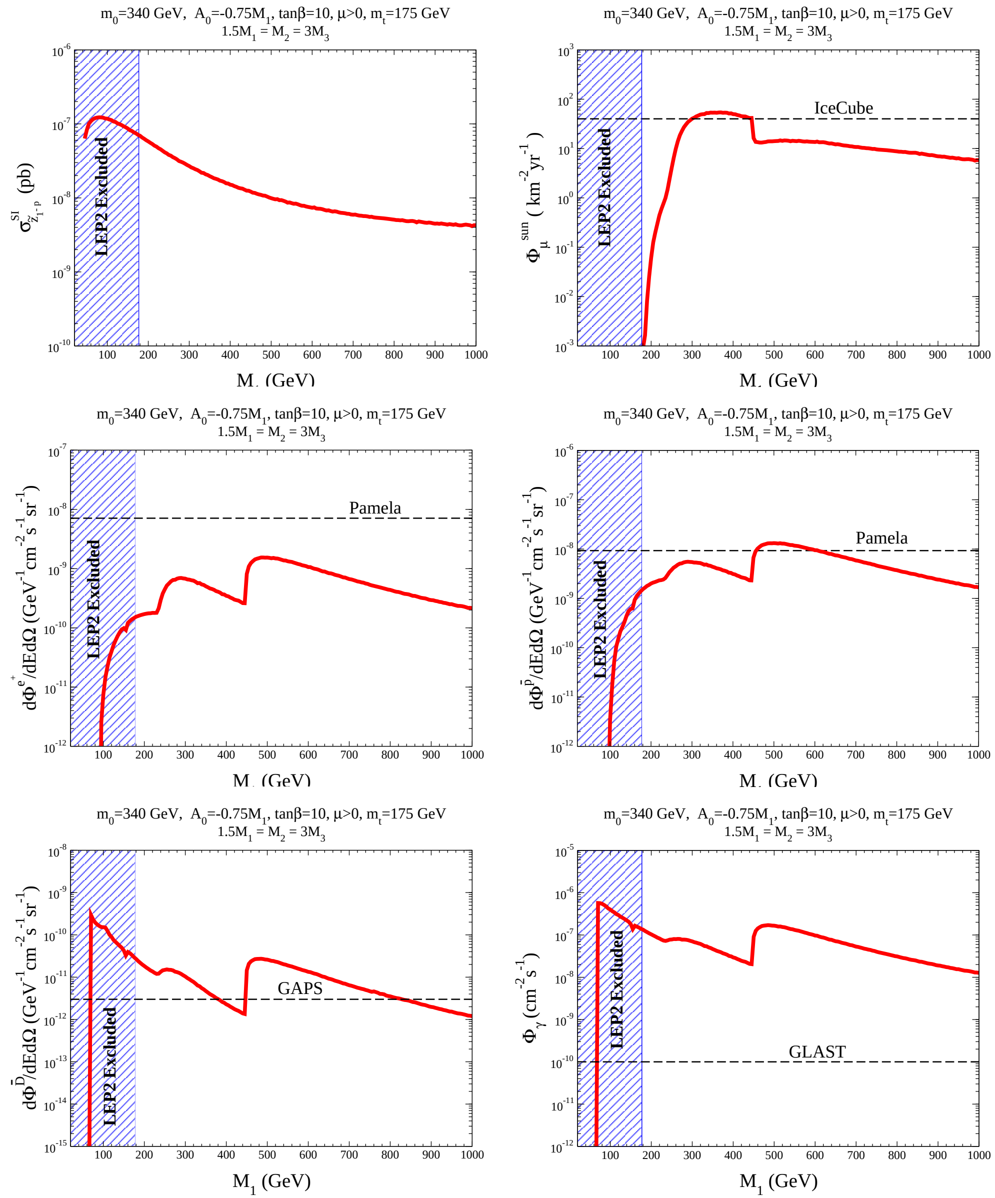
- M_1 400 - 800 GeV: $\tilde{Z}_1\tilde{Z}_1 \to t\bar{t}$ dominant $\Rightarrow$ neutralino relic density is in close accord with WMAP value
- larger M_1: $\tilde{t}_1 - \tilde{Z}_1$ mass gap low $\Rightarrow$ $\tilde{t}_1\tilde{Z}_1$ co-annihilation rate large $\Rightarrow$ below WMAP value
- $M_1 < 400$ GeV: annihilation into $t\bar{t}$ not allowed, $\tilde{Z}_1$ dominantly into WW and quarks and leptons $\Rightarrow$ h and Z poles





Compressed SUSY: direct and indirect DM searches

- a)Direct detection: as M_1 decreases, the rate increases due to decreasing $m_{\tilde{q}}$ and μ
  $t\bar{t}$ dominant region $\Rightarrow$ detectable by SuperCDMS or 100-1000 kg noble liquid DM detectors
- b)Detection of μ: neutrinos in the solar core: as M_1 decreases, the rate slightly increase due to increasing sipn-dependent $\tilde{Z}_1 - N$ cross section
  $M_1 < 400$ GeV: rate jumps b/c $\nu\bar{\nu}$ jumps once $t\bar{t}$ turns off

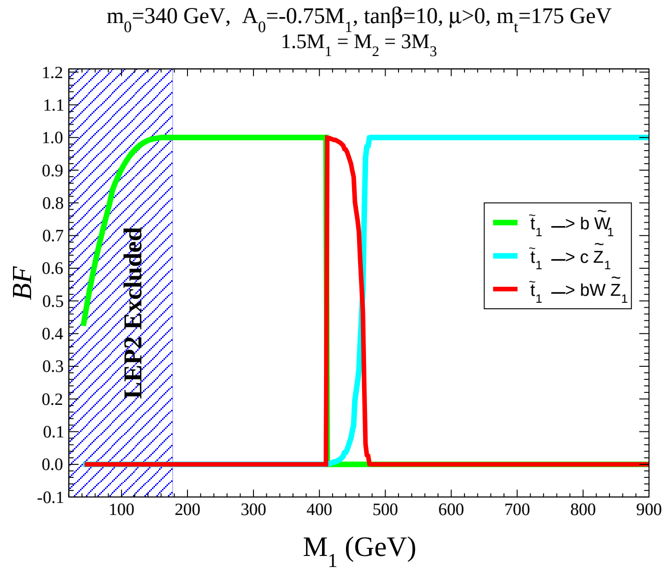


Compressed SUSY: direct and indirect DM searches (cont'd)

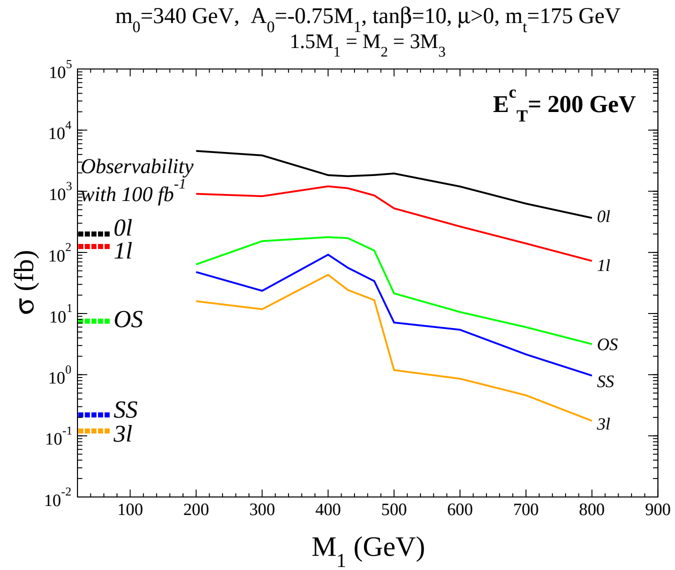
- c)d)e) Detection of anti-particle (e^+, $\bar{p}$, $\bar{D}$): annihilation in the galactic halo
  In the region where $m_{\tilde{Z}_1} > m_t$ so that $\tilde{Z}_1\tilde{Z}_1 \to t\bar{t}$ occurs, signals increase
  For the less clumpy Burkert halo profile, $\bar{D}$ rate lowered by a factor of 10-15
- Detection of γ - ray: from the galactic center
  For the Burkert halo model, scale downwards by over 4 orders

Compressed SUSY: LHC searches

- $\tilde{t}_1$ decay branching fraction
  - at large M_1, $m_{\tilde{t}_1} > m_b + M_W + m_{\tilde{Z}_1}$: $\tilde{t}_1 \to c\tilde{Z}_1$
  - for lower M_1: $\tilde{t}_1 \to bW\tilde{Z}_1$ opens up
  - for $M_1 < 400$ GeV, $m_{\tilde{t}_1} > m_b + m_{\tilde{W}_1}$: $\tilde{t}_1 \to b\tilde{W}_1$



- muti-isolated-lepton + jet + E_T^{miss}
  - signals in all channels obsevable with $E_T^c = 200$ GeV
  - jet multiplicity $n_{\rm jet} \geq 2$, transverse sphericity $S_T > 0.2$, $E_T(j_1)$, $E_T(j_2) > E_T^c$ and $E_T^{\rm miss} > E_T^c$
  - isolated leptons classified: $p_T > 10$ GeV, $|\eta(\ell)| < 2.5$, visible activity within a cone of $R = 0.3 < E_T({\rm cone}) = 5$ GeV.

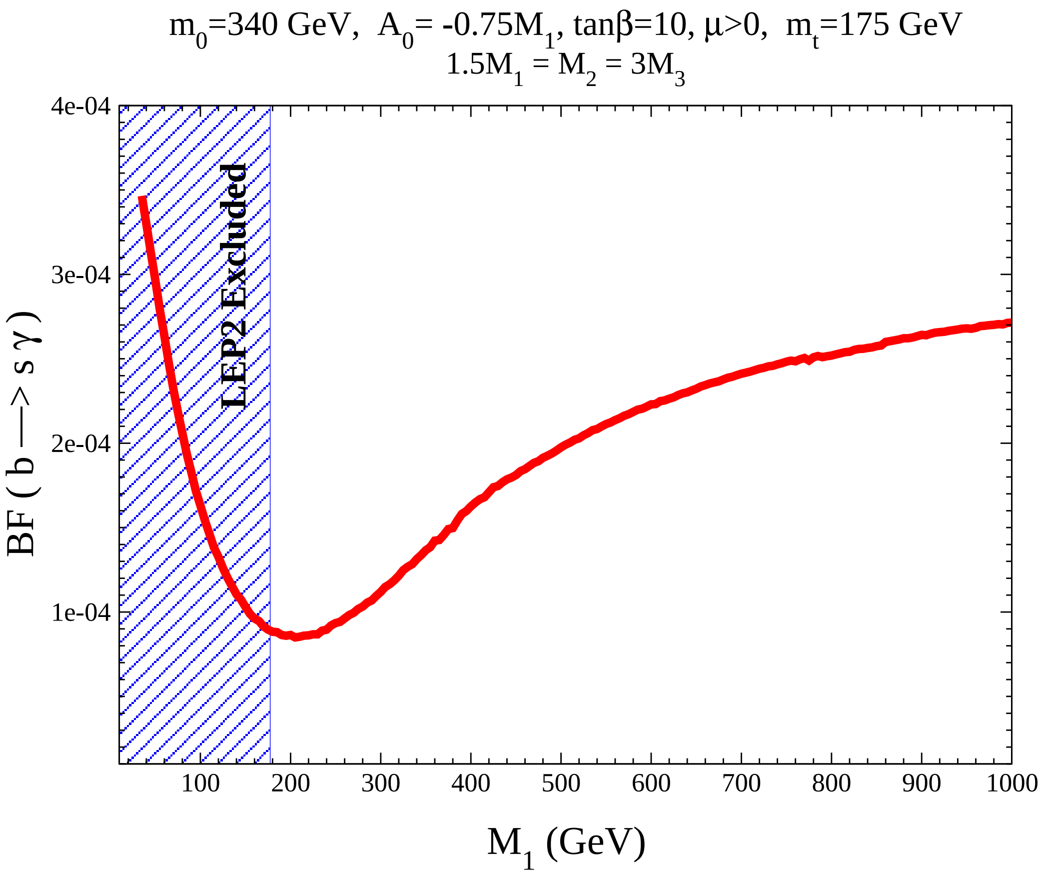


(for all applied cuts and background levels, see Phys.Rev.D52 (1995) 2746 and Phys.Rev.D53 (1996) 6241)

Summary and Conclusion

- In most region of mSUGRA parameter space, neutralino relic abundance is too high compared to the WMAP measured result
- Allowing non-universality of gaugino or scalar masses provides the relic density in agreement with WMAP
- Many relic-density-consistent models should lead to observable signals at LHC. For instance, in the models $\tilde{Z}_2 - \tilde{Z}_1$ mass gap is less than M_Z, so that at least one dilepton mass edge is likely to be detectable at LHC
- In non-universal models with mixed higgsino or higgsino-wino dark matter, we have enhanced rates for direct and indirect DM searches.
- In models with bino-like dark matter, if we have a mechanism to elevate neutralino annihilation rates such as into top-antitop quark pairs via top squark, we should be able to get enhanced direct and indirect detection rates due to reduced gluino, squark masses and μ parameter

$BF(b \to s\gamma)$



MSSM RGEs

$$\frac{dm_{H_u}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2S + 3f_t^2X_t\right)$$

$$\frac{dm_{H_d}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + 3f_b^2X_b + f_\tau^2X_\tau\right)$$

$$\frac{dm_{Q_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{1}{15}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{10}g_1^2S + f_t^2X_t + f_b^2X_b\right)$$

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

$$\frac{dm_{\tilde{b}_R}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{4}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{5}g_1^2S + 2f_b^2X_b\right)$$

$$\frac{dm_{L_3}^2}{dt} = \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + f_\tau^2X_\tau\right)$$

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

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

where $t = \log(Q)$, $f_{t,b,\tau}$ are the t, b and τ Yukawa couplings, and

$$\begin{aligned} X_t &= m_{Q_3}^2 + m_{\tilde{t}_R}^2 + m_{H_u}^2 + A_t^2 \\ X_b &= m_{Q_3}^2 + m_{\tilde{b}_R}^2 + m_{H_d}^2 + A_b^2 \\ X_\tau &= m_{L_3}^2 + m_{\tilde{\tau}_R}^2 + m_{H_d}^2 + A_\tau^2 \end{aligned}$$