Relic-density-consistent SUSY models without soft term universality : consequences for collider and neutralino dark matter searches

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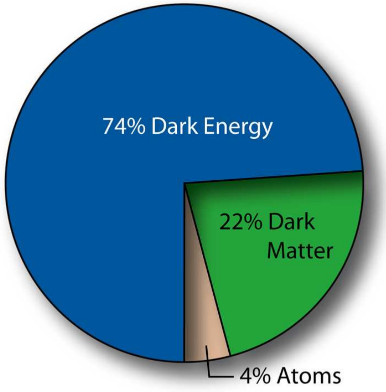
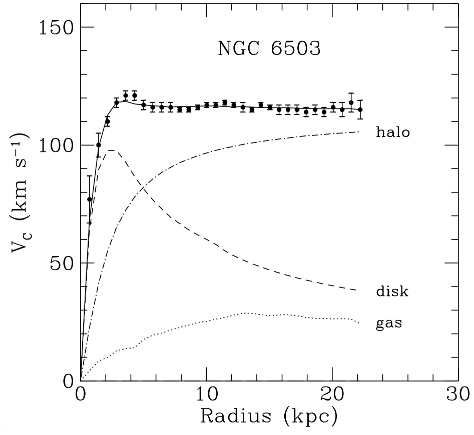
Dark Matter

- Dominant composition of matter in our universe is not detected visibly but inferred from gravitational effects (Galactic Clustering, Rotation Curves, Gravitational Lensing, Cosmic Microwave Background ...)
- Dark Matter should be non-baryonic (no candidate in the SM), non-relativistic (cold), stable(or long-lived), weakly (or super-weakly) interacting matter
- 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)



http://map.gsfc.nasa.gov



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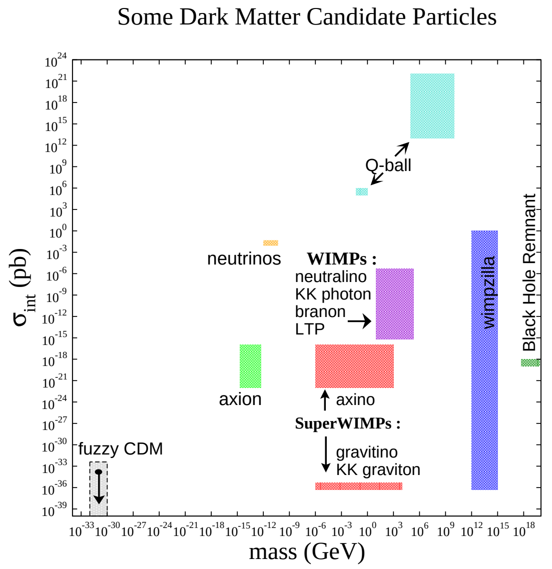
Neutralino

- In SUSY models with R-parity conservation
  $\Rightarrow$ the Lightest Supersymmetric Particle(LSP) is 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)
  $$\tilde{z}_1 = v_1^{(1)} \psi_{h_u^0} + v_2^{(1)} \psi_{h_d^0} + v_3^{(1)} \lambda_3 + v_4^{(1)} \lambda_0$$
  Here, $R_{\tilde{w}} = |v_3^{(1)}|$, $R_{\tilde{B}} = |v_4^{(1)}|$ and $R_{\tilde{H}} = \sqrt{|v_1^{(1)}|^2 + |v_2^{(1)}|^2}$
  : W-ino, B-ino and Higgsino



- We assume,
  - MSSM is an effective theory between the weak and GUT scale
  - R-parity is conserved
  - Neutralino LSP

- 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

Universal SUSY model : mSUGRA

- **Parameter space : universal Soft Susy Breaking terms at** $Q = M_{GUT}$
  m_0, $m_{1/2}$, A_0, tanβ, $sign(\mu)$

- **WMAP allowed Regions in** m_0**-**$m_{1/2}$ **space**
  1. $\tilde{\tau}$ co-annihilation region at low m_0, $m_{\tilde{\tau}_1} \sim m_{\tilde{Z}_1}$
  2. bulk region at low m_0 and $m_{1/2}$, light sleptons (LEP2 excluded)
  3. Higgs-funnel H, A resonance($2m_{\tilde{Z}_1} \simeq m_{A,H}$) at large tan$\beta \sim 50$ or h-resonance at low $m_{1/2}$ ($2m_{\tilde{Z}_1} \simeq m_h$)
  4. FP/HB region at large m_0, low μ → mixed higgsino dark matter (MHDM)
  ⋆ Region 1, 2, 3 → Bino-like LSP

- **Motivations for models with non-universality**
  - ⋆ all relic-density-consistent regions in mSUGRA are near the edges of theoretically (or LEP2 experiment) excluded regions
  - ⋆ need to examine how already drawn conclusions from the mSUGRA model are affected by relaxing the universality assumptions
  - ⋆ within R-parity conserved neutralino dark matter assumption, WMAP value provides a strong constraint reducing model parameter space by one unit

Models without universality in SSB terms

- **Relic-density-consistent models** obtained by adjusting
  - composition of neutralino (WTN: Well-Tempered Neutralino*)

    *:Arkani-Hamed et al. Nucl.Phys.B741, 108, 2006
  - masses of neutralino or other sparticles
- **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 mSUGRA parameter space

  m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu) = 300$ GeV, 300 GeV, 0, 10, +1 and $m_t = 171.4$ GeV

Non-universal scalar mass models

- generation non-universality: Normal scalar Mass Hierarchy (**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
- non-universal Higgs mass: one extra parameter case (**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
  - $m_\phi < 0$: $m_A \sim 2m_{\tilde{Z}_1}$ → at any $\tan\beta$
- non-universal Higgs mass: two extra parameter case (**HS**-Higgs Splitting)
  m_0, $m^2_{H_u}$(equivalently μ), $m^2_{H_d}$(equivalently m_A), $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
  - $m^2_{H_{u,d}} = m_0^2\ (1 \mp \delta_H)$
  - $\delta_H < 0$: 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

- Mixed Wino Dark Matter (**MWDM1**, **MWDM2**):
  m_0, M_1(or M_2), $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by increasing the wino content of the LSP by reducing the ratio M_2/M_1
  - $M_1 \neq M_2 = M_3 = m_{1/2}$ or $M_2 \neq M_1 = M_3 = m_{1/2}$
- Bino-Wino Co-Annihilation Scenario (BWCA1, BWCA2):
  same as MWDM but M_1 and M_2 are in opposite sign
  - by allowing co-annihilation between high bino-like and wino-like states
- Low $|M_3|$ Dark Matter: Compressed SUSY (**LM3DM**):
  m_0, M_3, $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by increasing the higgsino content of the LSP by decreasing the gluino mass
  - $M_3 \neq M_1 = M_2 = m_{1/2}$
- High $|M_2|$ Dark Matter: left-right split SUSY (**HM2DM**):
  m_0, M_2, $m_{1/2}$, A_0, tanβ, $sign(\mu)$
  - by allowing large M_2 mass
  - $M_2 >> M_1 = M_3 = m_{1/2}$

Some Benchmark Cases: non-universal scalar mass models

parameter	mSUGRA	NMH	NUHM1$_\mu$	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

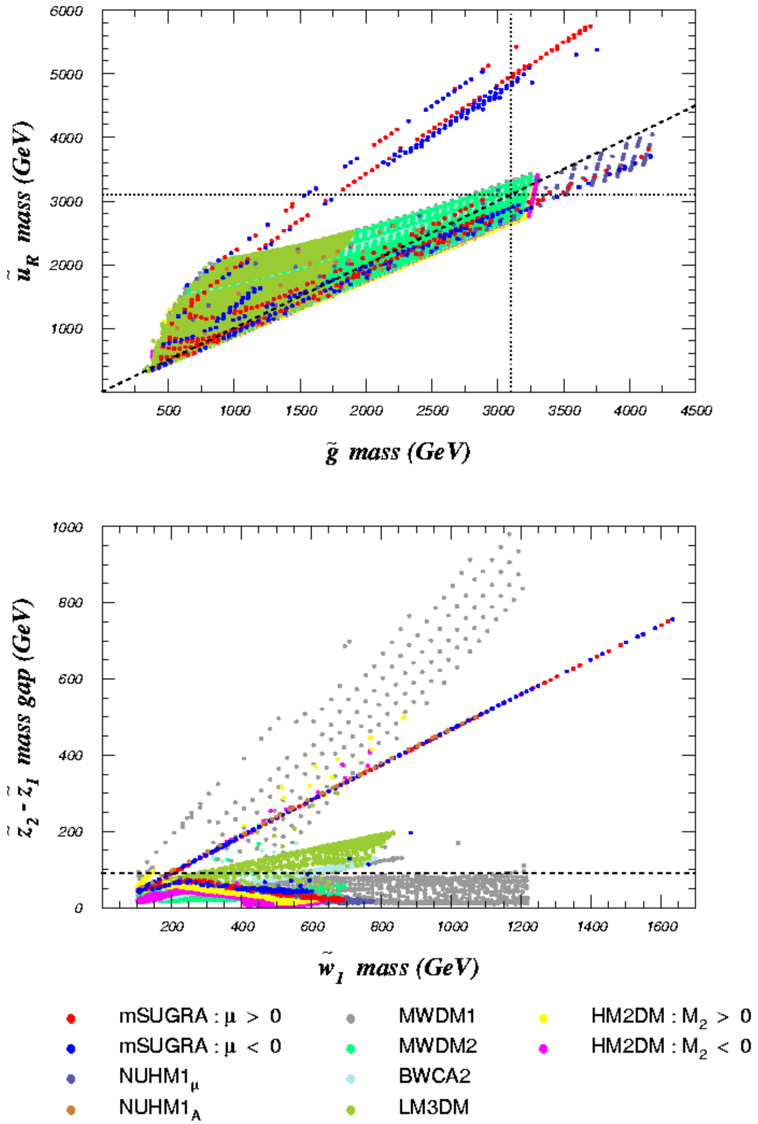
Some Benchmark Cases: non-universal gaugino mass models

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

Dark matter 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
- ISAJET program (H. Baer, F.E. Paige, S.D. Protopopescu, and X. Tata)

Implications for collider searches 1



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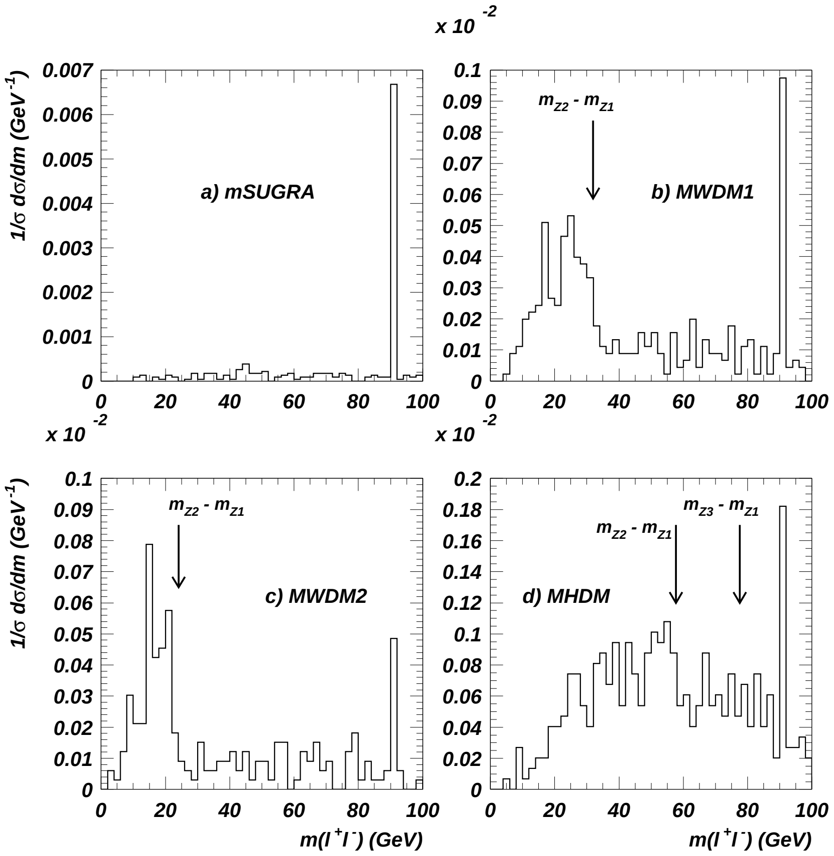
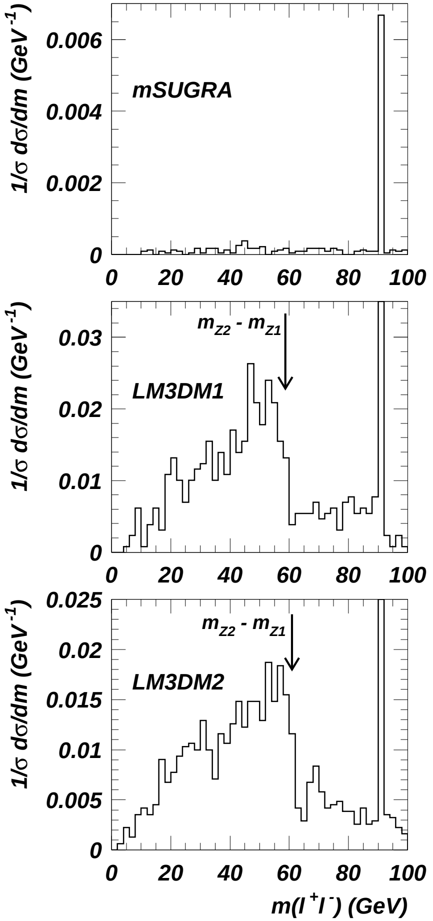
  - with $A_0 = 0$, $m_t = 171.4$ GeV, $\tan\beta = 10$ (except for the mSUGRA model: $\tan\beta = 10$, 30, 45, 50, 52 and 55)
  - non-universal mass dialed to yield $\Omega_{\tilde{Z}_1} h^2 \simeq 0.11$
- $m_{\tilde{g}}$ *vs.* $m_{\tilde{u}_R}$
  - dotted lines: 100 fb^{-1} reach of CERN LHC
  - dashed line: $m_{\tilde{u}_R} = m_{\tilde{g}}$
  - most of models within reach of LHC except HB/FP region of mSUGRA
- $m_{\widetilde{W}_1}$ *vs.* $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$
  - dashed line: $m_{\tilde{Z}_2} - m_{\tilde{Z}_1} = M_Z$
  - below the line, 3-body decay like $\tilde{Z}_2 \to \tilde{Z}_1 l\bar{l}$ open
  - in most models, $m(l\bar{l})$ mass edge visible at LHC

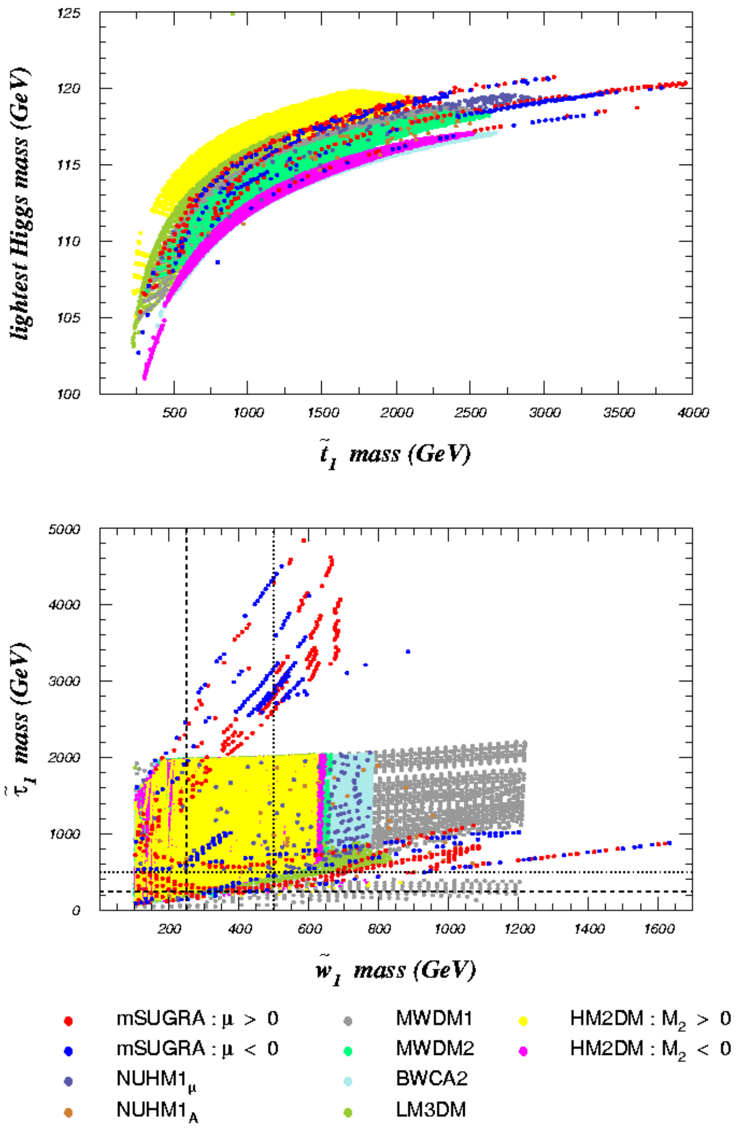
Dilepton Distribution at LHC





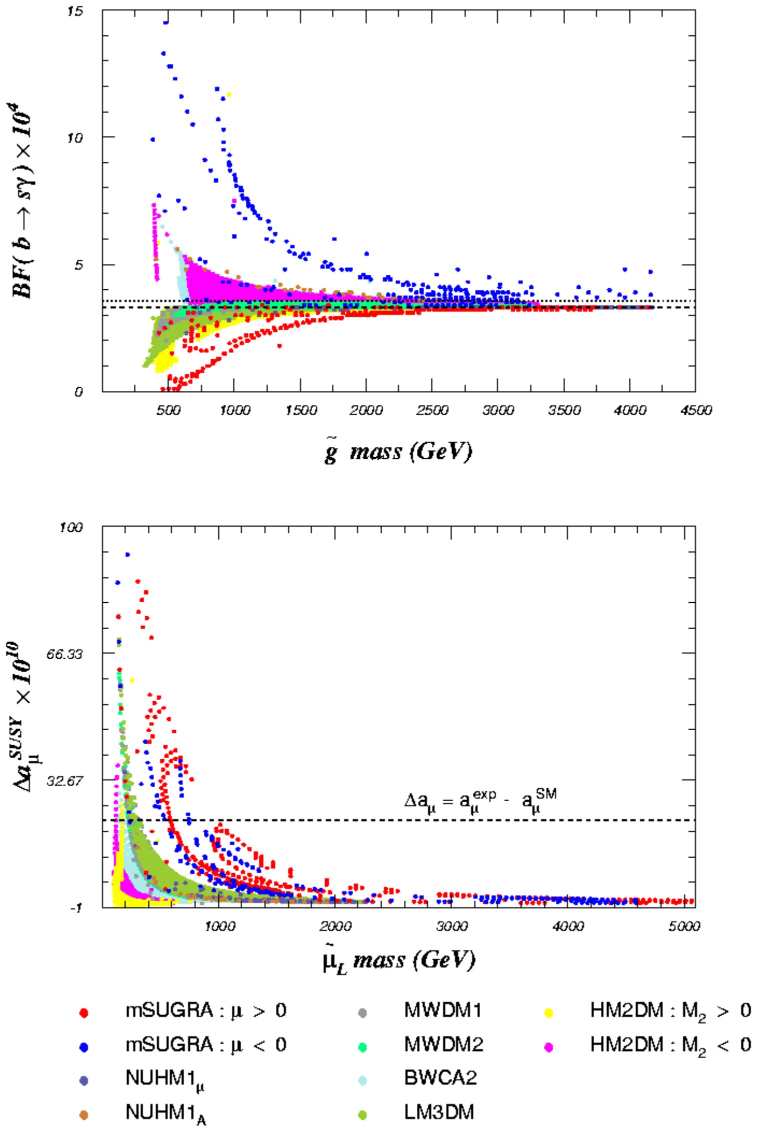
- mSUGRA : sharp peak at $m(l^+l^-) \sim M_Z$ from $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 Z^0$ decays
- NUGM : Z^0 peak from $\tilde{Z}_3$, $\tilde{Z}_4$, $\tilde{W}_2$ decays + continuum distribution $m(l^+l^-) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$

Implications for collider searches 2



- m_h *vs.* $m_{\tilde{t}_1}$
  - heavier $\tilde{t}_1$ squarks are correlated with larger values of m_h (due to top-Yukawa radiative corrections to m_h)
  - in many models with $m_A \gg M_Z$, then $h \simeq H_{\rm SM}$: the LEP2 lower bound of 114.1 GeV applicable
- $m_{\widetilde{W}_1}$ *vs.* $m_{\tilde{\tau}_1}$
  - dashed lines: reach of ILC500 ($\sqrt{s} = 500$ GeV)
  - dotted lines: reach of ILC1000 ($\sqrt{s} = 1000$ GeV)

Implications for $BF(b \to s\gamma)$ and $(g-2)_\mu$



- $BF(b \to s\gamma)$
  - dotted line: combined experimental measurement (CLEO, Belle, BABAR) $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$
  - dashed line: SM prediction $BF(b \to s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$
- $(g-2)_\mu$
  - *positive* deviation in $a_\mu \equiv \frac{(g-2)_\mu}{2}$ $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 22(10) \times 10^{-10}$
  - $\Delta a_\mu^{\mathrm{SUSY}} \propto \tan\beta$

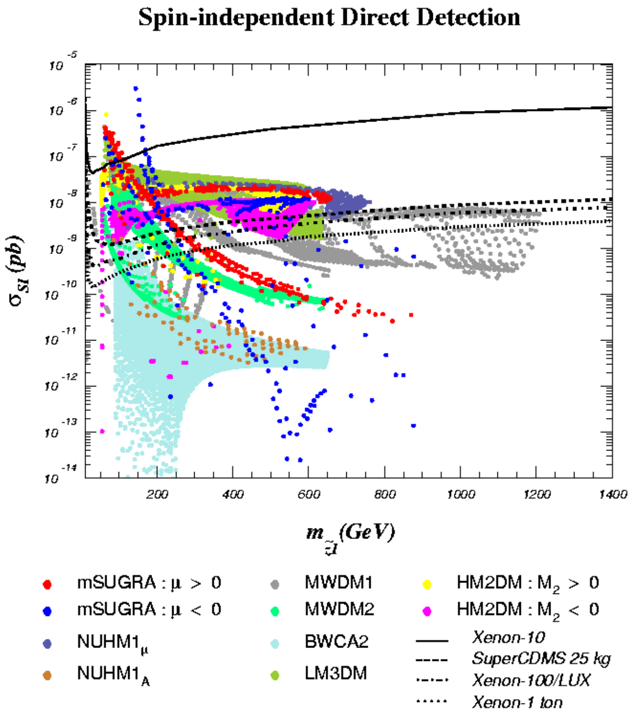
⋆ We assume,

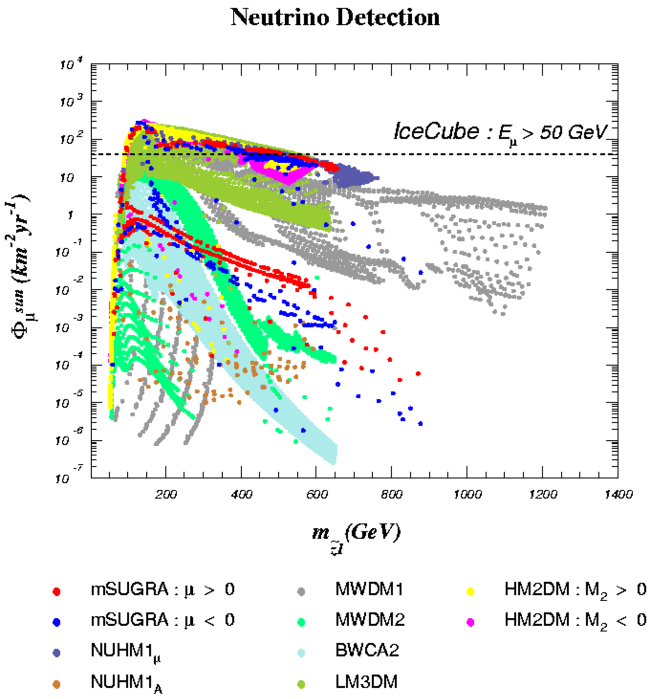
  - (near)degeneracy of first and second generation of SSB sfermions → FCNC suppressed
  - CP-violating phases in SSB suppressed → CP contribution of SUSY is small

Direct and Indirect Dark Matter Detection

- Direct Detection: Spin independent Neutralino-Proton scattering Cross section (with current experimental sensitivities:Xenon-10(100, 1000), SuperCDMS, LUX)
- Indirect Detection
  - Detection of μ : Neutrinos from the Sun - IceCube
    $\tilde{Z}_1\tilde{Z}_1 \rightarrow W^+W^-, q\bar{q}, \ldots \rightarrow \pi^-(\pi^+) \rightarrow \bar{\nu_\mu}(\nu_\mu) \rightarrow \mu^-(\mu^+)$
  - Detection of antiparticles : $\tilde{Z}_1\tilde{Z}_1 \rightarrow W^+W^-, q\bar{q}, ZZ, \ldots \rightarrow jets$
    Antiprotons ($jets \ni \bar{p}$) : PAMELA, Positrons ($jets \ni e^+$) : PAMELA,
    Antideuterons ($jets \ni \bar{D}$) : GAPS
  - Detection of Gamma Rays from the galactic center - GLAST
- IsaRES code (Baer-Belyaev-O'Farrill) and DarkSUSY

Implications for direct/indirect(neutrino) DM detection

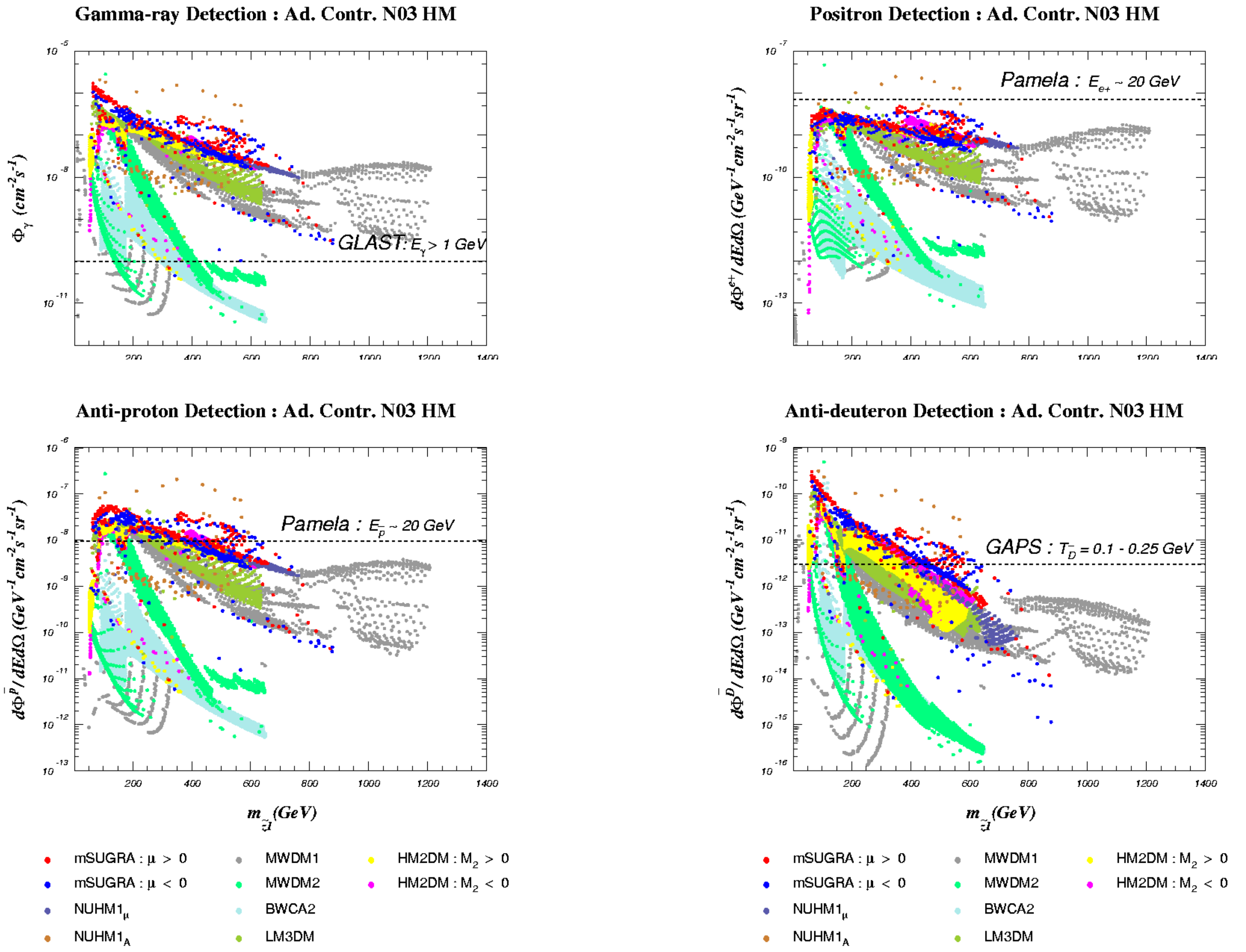




- models with WTN within reach of next generation of detectors
- models adjusted masses to get WMAP value below sensitivities of detectors

- muon fluxes from neutralino annihilation in the solar core to ν_μ states
- main contribution comes from Z-exchange ← enhanced if neutralino has high higgsino content

Implications for indirect(γ-ray, antiparticle) DM detection



Conclusions

1. ⋆ WTN occurs *only* in FP/HB region in mSUGRA (MHDM: $m_{\tilde{q}} >> m_{\tilde{Z}_1,\tilde{W}_1,\tilde{g}}$).
   But, in relic-density-consistent models, easily get WTN with $m_{\tilde{q}} \sim m_{\tilde{g}}$
   ⋆ Higgs funnel enhancement is *only* for very large tanβ values in mSUGRA.
   But, in non-universal Higgs mass models, we have Higgs funnel for any tanβ value

2. In many relic-density-consistent models, $\tilde{Z}_2 - \tilde{Z}_1$ mass gap $< M_Z$
   → 2-body decay modes kinematically closed
   → 3-body decay modes open ⇒ at least one dilepton mass edge detectable at LHC
   → location of dilepton mass edge is clean signature of SUSY models

3. ⋆ $m_{\tilde{q}} = m_{\tilde{g}}$, $m_{\tilde{q},\tilde{g}}$ <3100 GeV for most relic-density-consistent models
   → implies SUSY signals at LHC
   ⋆ $m_{\tilde{\tau}}$ <500 GeV for LM3DM
   → accessible at ILC with $\sqrt{s}$=1 TeV

4. In WTN models,
   ⋆enhanced annihilation rates enhance direct DM detection rates
   ⋆in many cases, muon neutrino signals accessible at IceCube
   ⋆indirect DM searches in galactic halo into gamma rays and anti-matter elevated; large uncertainties associated with unknown galactic DM density profile

MSSM RGEs

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

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

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

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

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

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

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

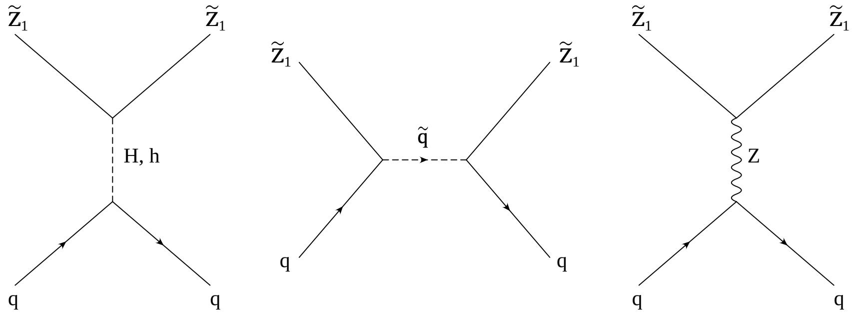
$$S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$$

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

$$\begin{aligned} X_t &= m^2_{Q_3} + m^2_{\tilde{t}_R} + m^2_{H_u} + A^2_t \\ X_b &= m^2_{Q_3} + m^2_{\tilde{b}_R} + m^2_{H_d} + A^2_b \\ X_\tau &= m^2_{L_3} + m^2_{\tilde{\tau}_R} + m^2_{H_d} + A^2_\tau \end{aligned}$$

Feynman Diagrams Contributing to Neutralino DM Detection

- Direct Detection



- Indirect Detection