Direct, Indirect and Collider Detection of Neutralino Dark Matter in SUSY models without Gaugino Mass Universality

Eun-Kyung Park
Physikalisches Institut, Universität Bonn

in collaboration with
H. Baer(FSU), A. Mustafayev (U. of Kansas), T. Krupovnickas (BNL),

S. Profumo (Caltech) and X. Tata (U.of Hawaii)

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Outline

- Introduction
  - ⋆ Neutralino Dark Matter
  - ⋆ Review of mSUGRA
- Non-universal Gaugino Mass Models
  - ⋆ Mixed Wino Dark Matter (MWDM): JHEP 0507 (2005) 065
  - ⋆ Bino-Wino Co-Annihilation Scenario (BWCA): JHEP 0512 (2005) 011
  - ⋆ Low M3 Dark Matter (LM3DM): JHEP 0604 (2006) 041
  - ⋆ High M2 Dark Matter (HM2DM):

    H. Baer, A. Mustafayev, H. Summy and X. Tata JHEP 0710 (2007) 088
- Direct/Indirect Detection of Dark Matter in NUGM Models: in progress
- Collider Searches for Dark Matter in NUGM Models
- Conclusions

Neutralino Dark Matter

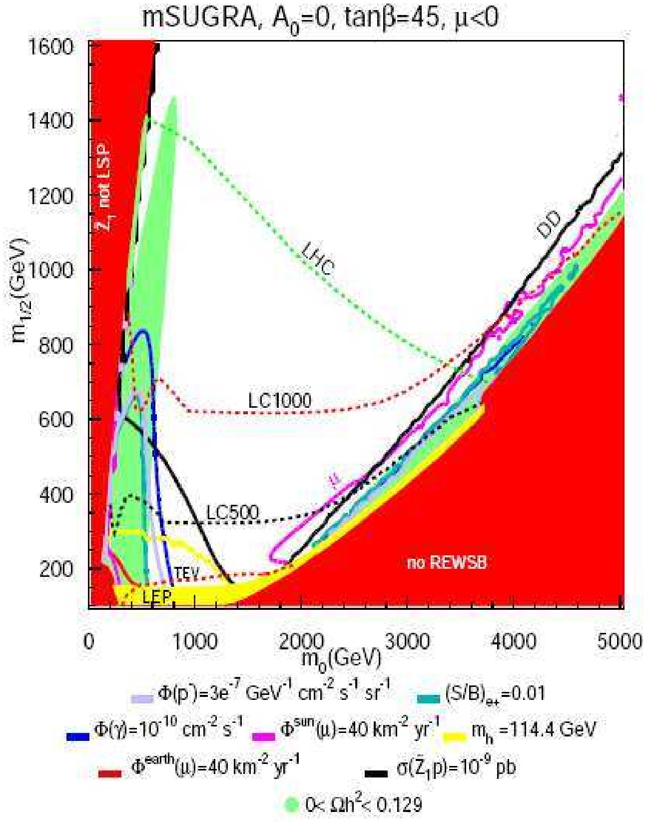
- Dark Matter should be non-baryonic (no candidate in the SM), non-relativistic (cold) stable matter
- Flat universes in the ΛCDM cosmological model are characterized by baryon density, matter density, vacuum density, expansion rate(h)
- From the WMAP results, the cold dark matter density of the universe is $\Omega_{CDM}h^2 = 0.111^{+0.011}_{-0.015}$ (upper bound is a tight constraint on SUSY models containing DM candidates)
- 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
- IsaReD program

WMAP allowed Regions in mSUGRA

- **Parameter Space :**
  m_0, $m_{1/2}$, A_0, $\tan\beta$, $sign(\mu)$
- **WMAP allowed Regions :**
  (Green colored 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)



H. Baer et al., JCAP 0408 (2004) 005

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

Non-Universal Gaugino Mass Models

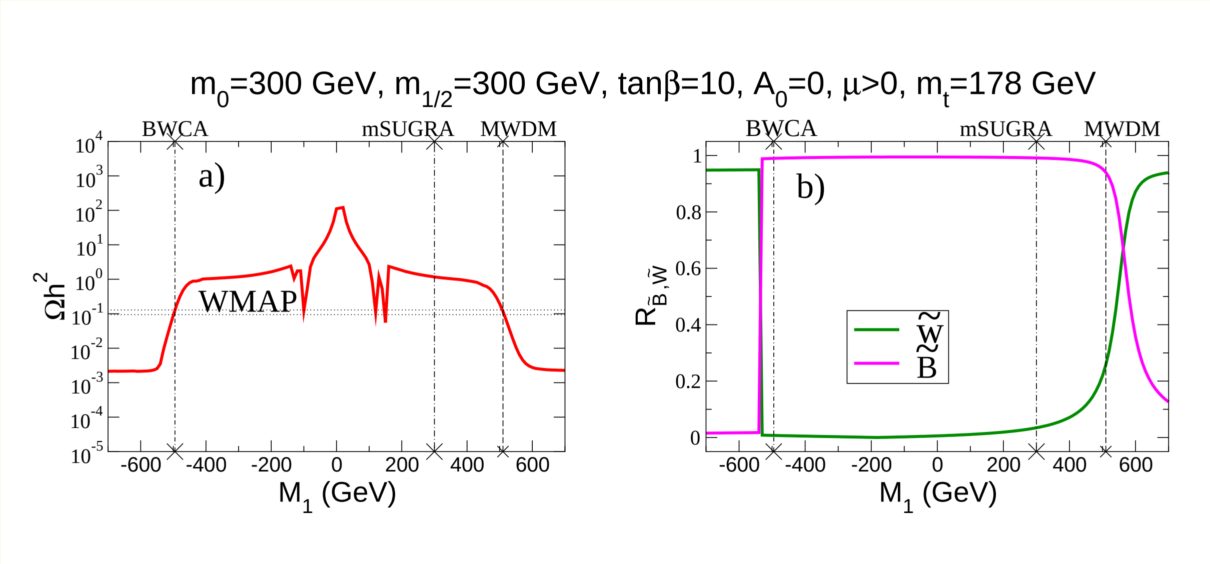
- M_1, M_2, M_3 are gauginos of $U(1)$, $SU(2)$ and $SU(3)$ respectively
- In mSUGRA : minimal gauge kinetic function f_{AB}
  $\rightarrow$ equal gaugino masses at GUT scale : $M_1 = M_2 = M_3 = m_{1/2}$
- Motivation for non-universal gaugino mass models :
  - non-minimal f_{AB} in SUGRA models,
    e.g. $f_{AB} \ni 1, 24, 75, 200$ in $SU(5)$ SUSY GUTs
  - various string models, e.g. KKLT model
  - extra-dim SUSY GUTs with gaugino mediated SUSY breaking,
    e.g. Dermisek-Mafi $SO(10)$ model
- Generally, the lightest neutralino mass eigenstate is determined by the content of the LSP $\tilde{z}_1 = v_1^{(1)} \psi_{h_u^0} + v_2^{(1)} \psi_{h_d^0} + v_3^{(1)} \lambda_3 + v_4^{(1)} \lambda_0$

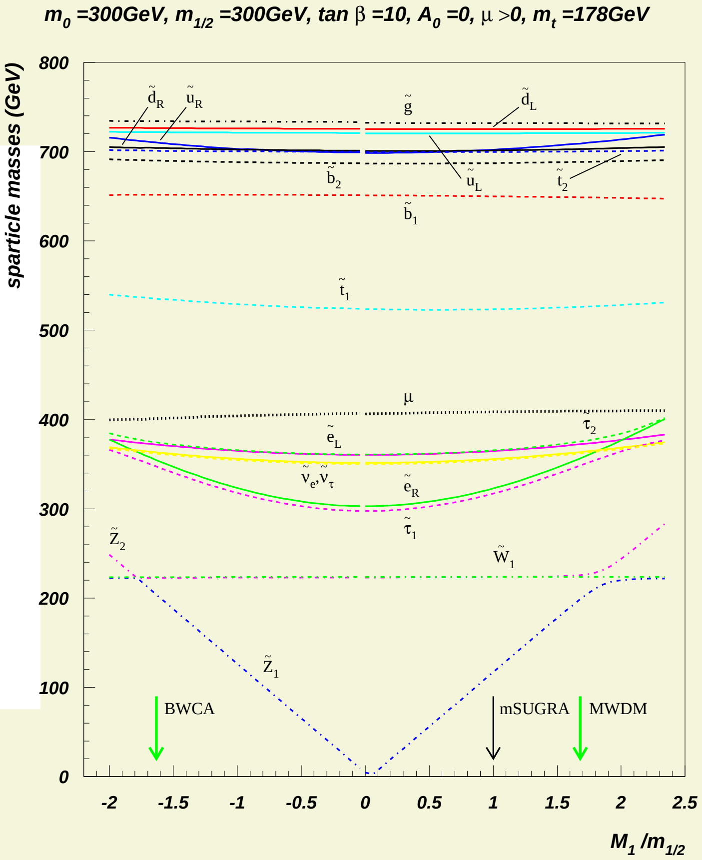
  Here, $R_{\tilde{w}} = |v_3^{(1)}|$, $R_{\tilde{B}} = |v_4^{(1)}|$ and $R_{\tilde{H}} = \sqrt{|v_1^{(1)}|^2 + |v_2^{(1)}|^2}$: W-ino, B-ino and Higgsino

Non-Universal Gaugino Mass Models

- Several ways which can increase the annihilation rate of a LSP without gaugino mass universality
  - by increasing the wino content of the LSP by reducing the ratio M_2/M_1 (MWDM) : – $M_1 \neq M_2 = M_3 = m_{1/2}$ or $M_2 \neq M_1 = M_3 = m_{1/2}$
    – parameter space : m_0, $m_{1/2}$, M_1(or M_2), A_0, tanβ, $sign(\mu)$
  - by allowing co-annihilation between high bino-like and wino-like states (BWCA scenario) : – M_1 and M_2 are of opposite sign
    – parameter space : m_0, $m_{1/2}$, M_1(or M_2), A_0, tanβ, $sign(\mu)$
  - by increasing the higgsino content of the LSP by decreasing the gluino mass (LM3DM) : – $M_3 \neq M_1 = M_2 = m_{1/2}$
    – parameter space : m_0, $m_{1/2}$, M_3, A_0, tanβ, $sign(\mu)$
  - by allowing large M_2 mass (HM2DM) : – $M_2 >> M_1 = M_3 = m_{1/2}$
    – parameter space : m_0, $m_{1/2}$, M_2, A_0, tanβ, $sign(\mu)$

NUGM Models - MWDM, BWCA





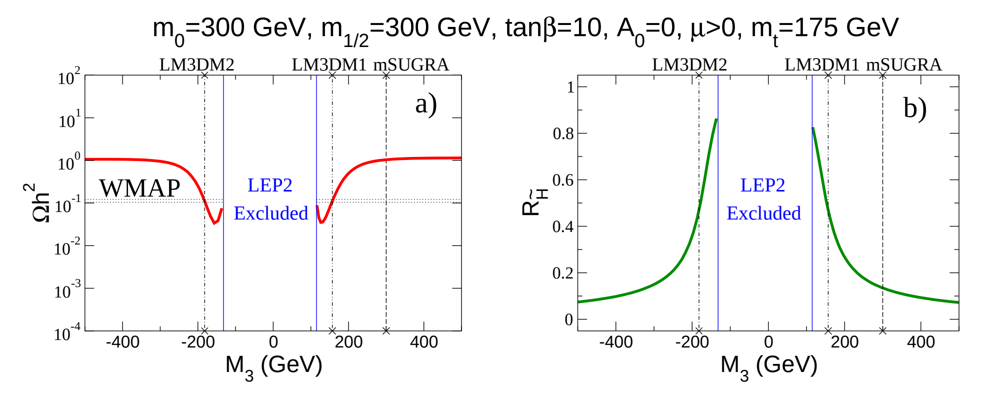
- ⋆ As $|M_1|(|M_2|)$ increases(decreases) past its mSUGRA value,

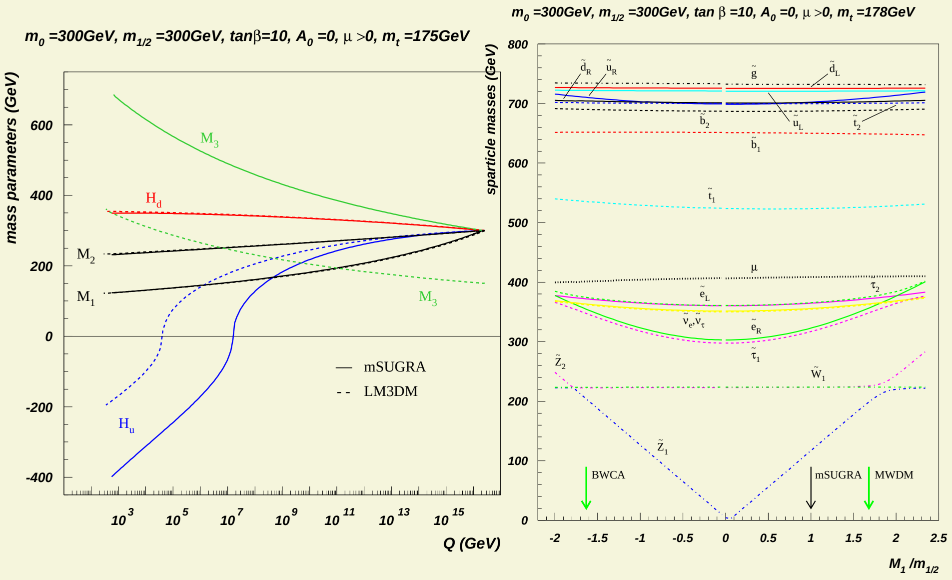
  $\longrightarrow$ $\tilde{Z}_1$ becomes wino-like(MWDM) or bino-like but $m_{\tilde{Z}_1} \sim m_{\tilde{W}_1}$ (BWCA)

  $\longrightarrow$ relic density decreases

  $\longrightarrow$ WMAP $\Omega_{CDM}h^2$ value is reached

NUGM Models - LM3DM

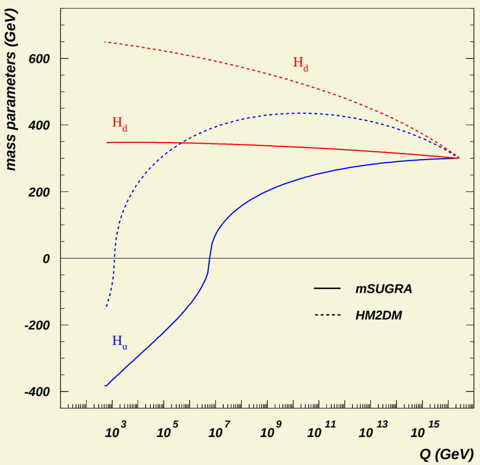




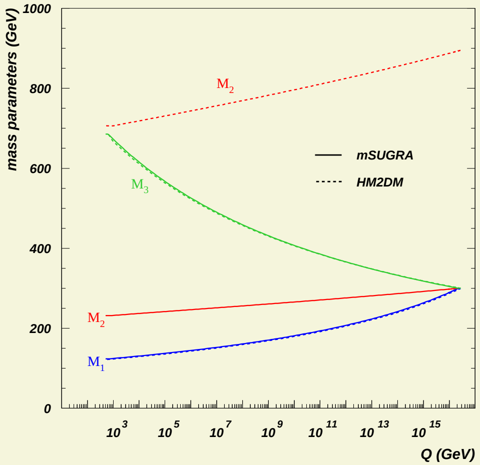
- Mild evolution of $m^2_{H_d}$ due to small Yukawa coupling $f_b,\ f_\tau$
- Lighter squarks and gluons → reduced effect of f_t on $m^2_{H_u}$ $\Rightarrow$ smaller μ
- $\frac{dm^2_{H_d}}{dt} \propto f^2_{b,\tau} X_{b,\tau}, \quad \frac{dm^2_{H_u}}{dt} \propto f^2_t X_t$
- $\mu^2 = \frac{m^2_{H_d} -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

NUGM Models - HM2DM

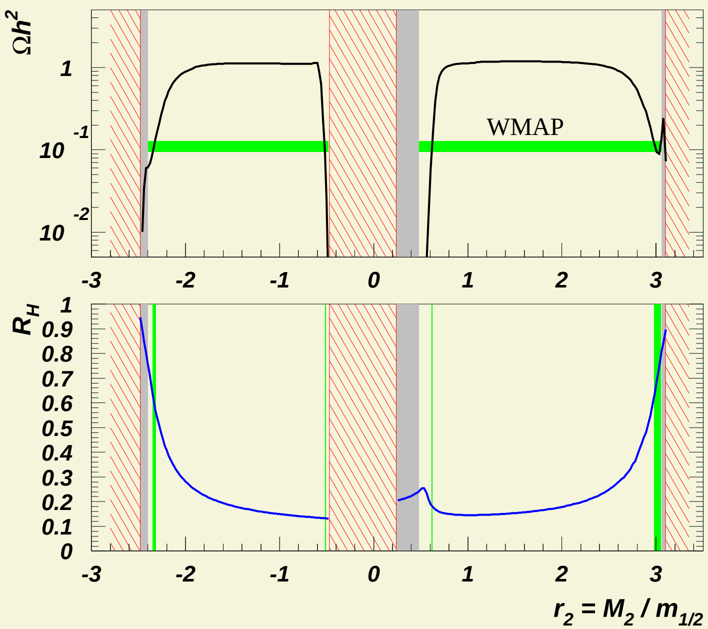
m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =171.4GeV



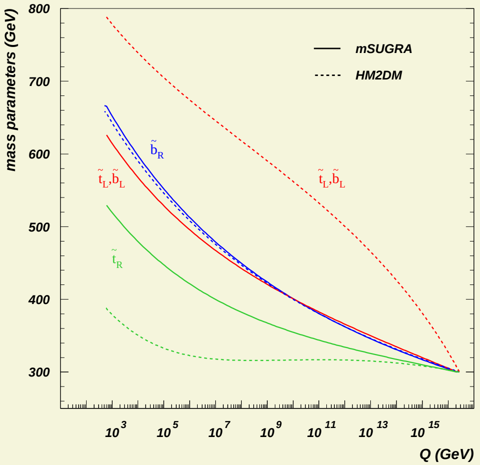
m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =171.4GeV



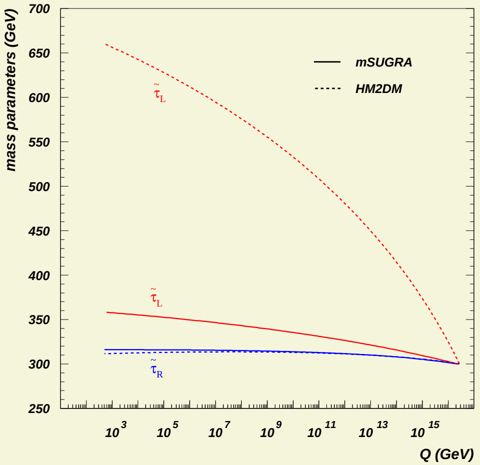
m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =171.4GeV



m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =171.4GeV



m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =171.4GeV



- large $M_2 \rightarrow$ reduced effect on $m^2_{H_u}$ at weak scale $\rightarrow$ smaller μ $\Rightarrow$ MHDM!
- large L-R splitting in squark and slepton sector

MSSM RGEs

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

$$
\begin{aligned}
\frac{dm_{Q_3}^2}{dt} &= \frac{2}{16\pi^2}\left(-\frac{1}{15}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{10}g_1^2S + f_t^2X_t + f_b^2X_b\right) \\
\frac{dm_{\tilde{t}_R}^2}{dt} &= \frac{2}{16\pi^2}\left(-\frac{16}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 - \frac{2}{5}g_1^2S + 2f_t^2X_t\right) \\
\frac{dm_{\tilde{b}_R}^2}{dt} &= \frac{2}{16\pi^2}\left(-\frac{4}{15}g_1^2M_1^2 - \frac{16}{3}g_3^2M_3^2 + \frac{1}{5}g_1^2S + 2f_b^2X_b\right) \\
\frac{dm_{L_3}^2}{dt} &= \frac{2}{16\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 - \frac{3}{10}g_1^2S + f_\tau^2X_\tau\right) \\
\frac{dm_{\tilde{\tau}_R}^2}{dt} &= \frac{2}{16\pi^2}\left(-\frac{12}{5}g_1^2M_1^2 + \frac{3}{5}g_1^2S + 2f_\tau^2X_\tau\right)
\end{aligned}
$$

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

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

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

Direct and Indirect Dark Matter Detection

- Direct Detection

  Spin independent Neutralino-Proton scattering Cross section
  - Underground cryogenic or noble liquid detectors
  - current best limit by XENON-10
  - Projected reaches : SuperCDMS, LUX, XENON-1 ton
- Indirect Detection
  - Detection of μ : Neutrinos from the Sun - Antares, IceCube

    $\tilde{Z}_1\tilde{Z}_1 \to W^+W^-, q\bar{q}, \ldots \to \pi^-(\pi^+) \to \bar{\nu_\mu}(\nu_\mu) \to \mu^-(\mu^+)$
  - Detection of antiparticles : $\tilde{Z}_1\tilde{Z}_1 \to W^+W^-, q\bar{q}, ZZ, \ldots \to jets$

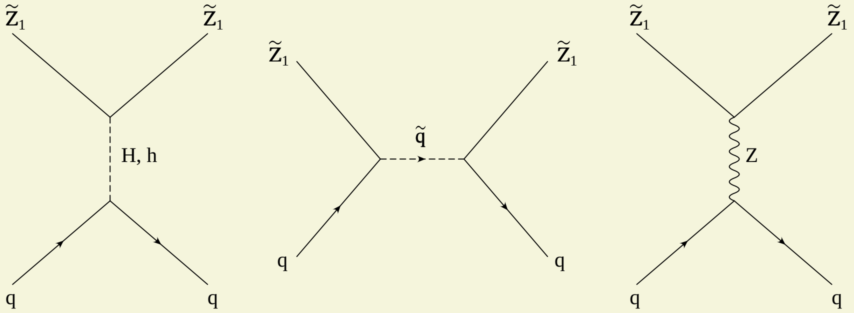
    –Antiprotons ($jets \ni \bar{p}$) : BESS, AMS-02, PAMELA

    –Positrons ($jets \ni e^+$) : HEAT, AMS-02, PAMELA

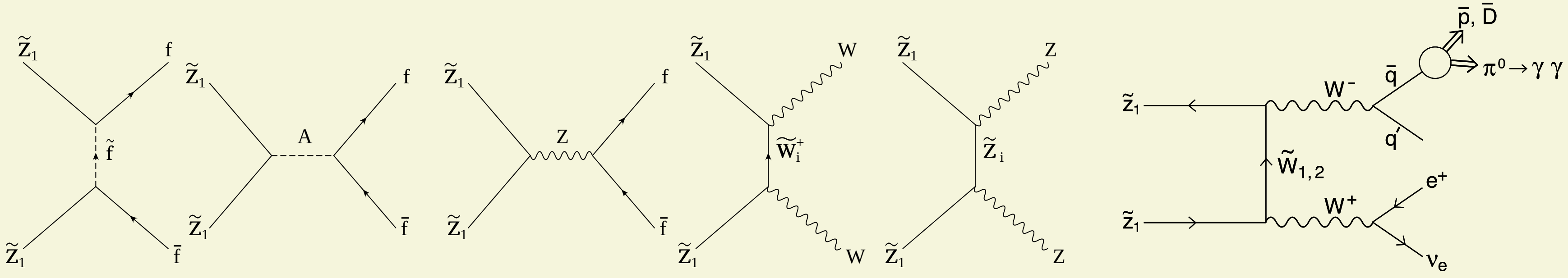
    –Antideuterons ($jets \ni \bar{D}$) : BESS, AMS-02, GAPS
  - Detection of Gamma Rays from the galactic center - EGRET, GLAST
- IsaRES code and DarkSUSY

Feynman Diagrams Contributing to Neutralino DM Detection

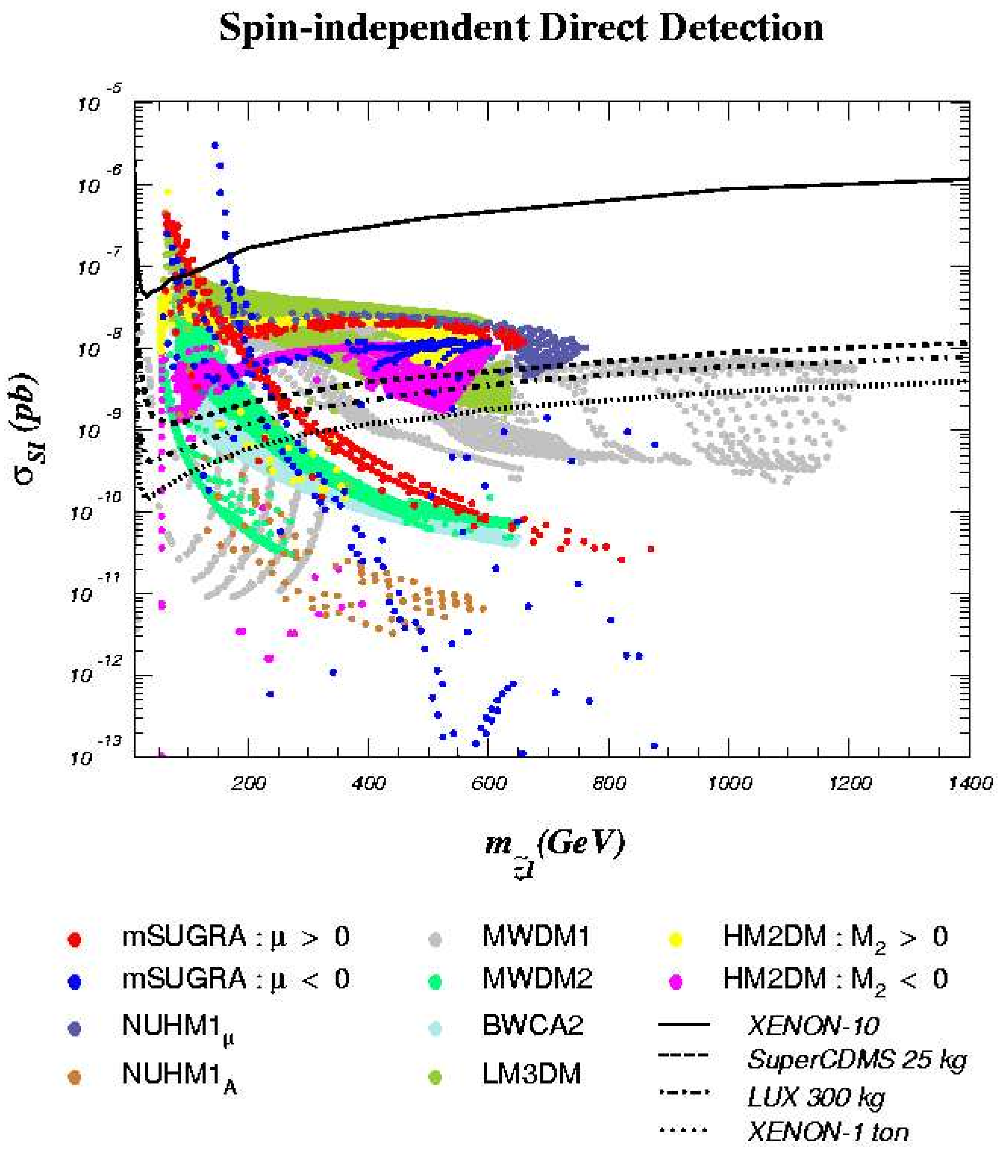
- Direct Detection



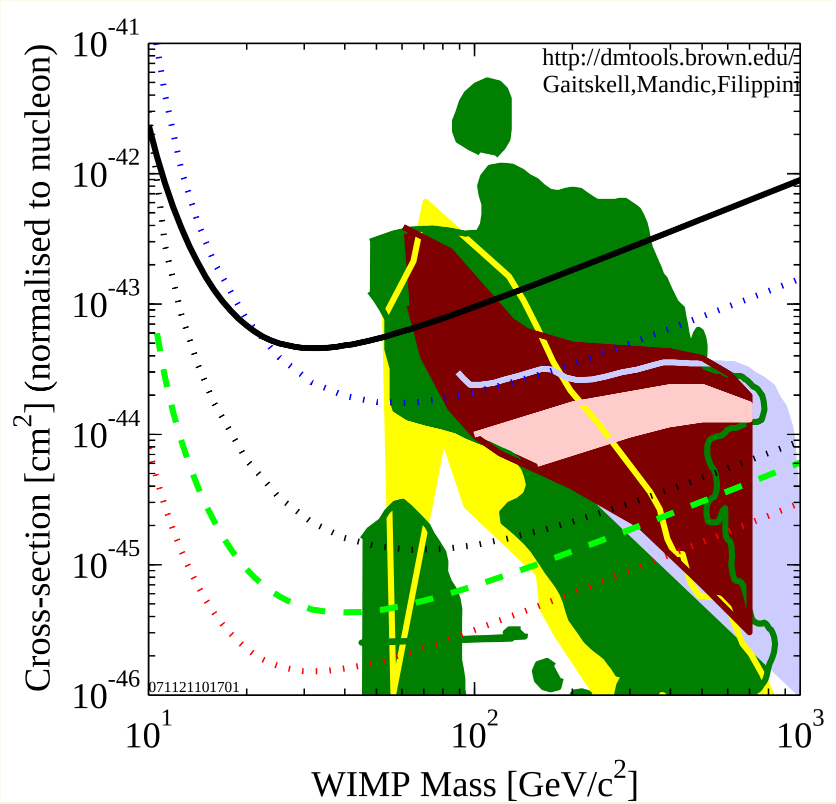
- Indirect Detection

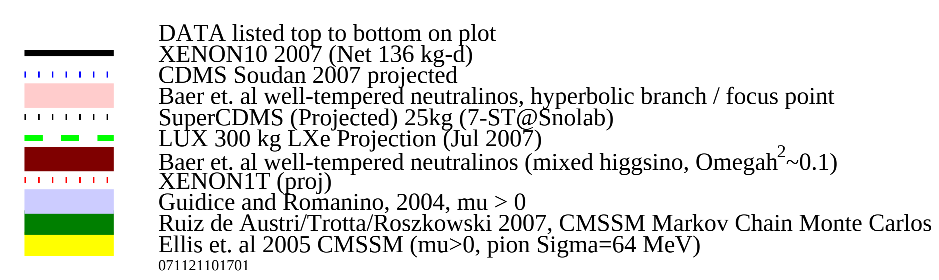


Direct Detection Rates for NUGM Models



WTN Models with Projected Direct Detection Reaches





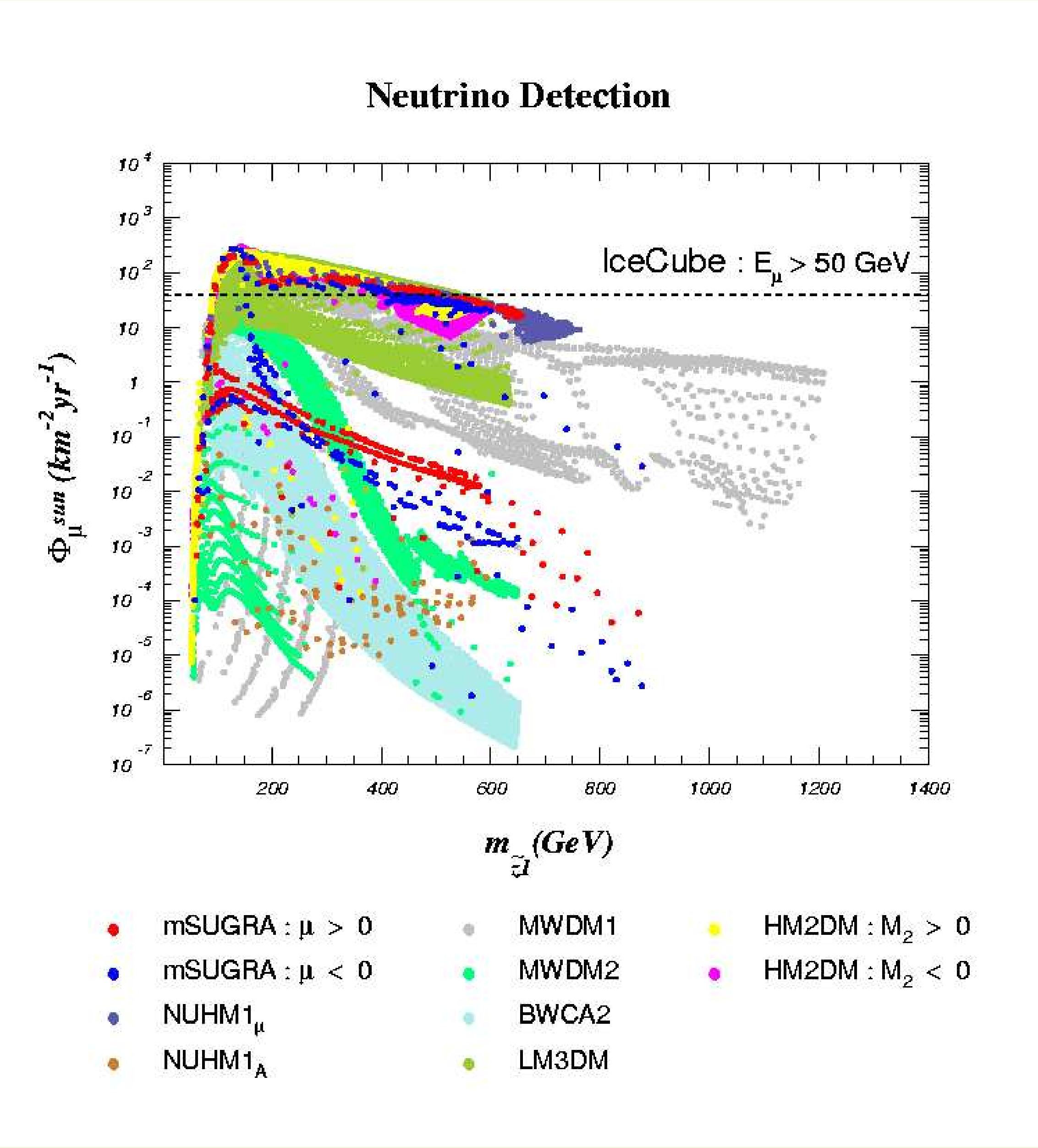
*well-tempered neutralino(WTN) models : components of a neutralino adjusted to give WMAP allowed relic density.

Named by N. Arkani-Hamed et al., Nucl. Phys. B741 (2006) 108

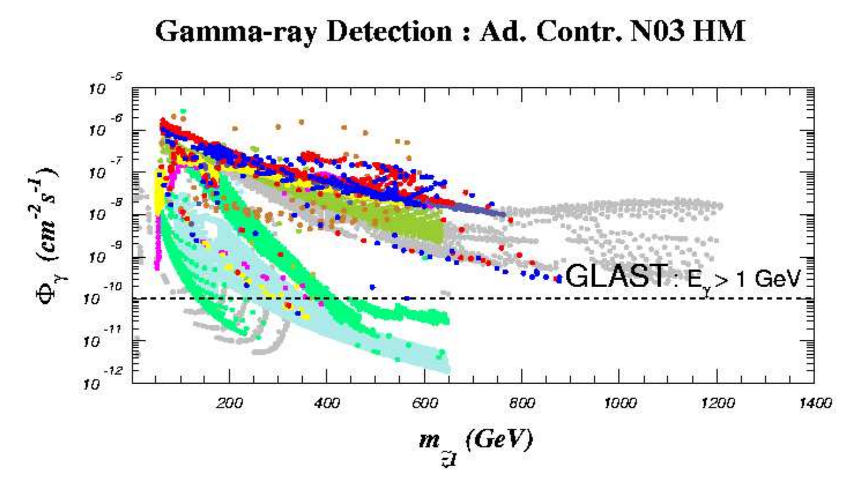
SUSY Dark Matter/Interactive Direct Detection Limit Plotter

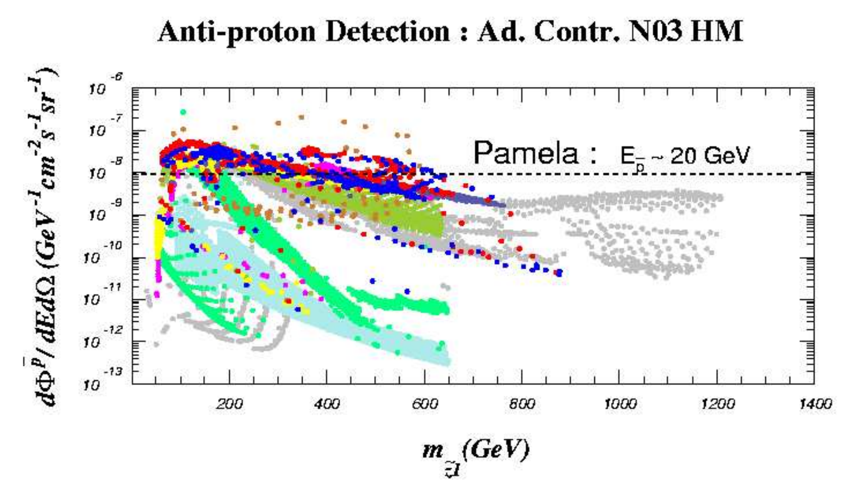
http://dmtools.berkeley.edu/limitplots/

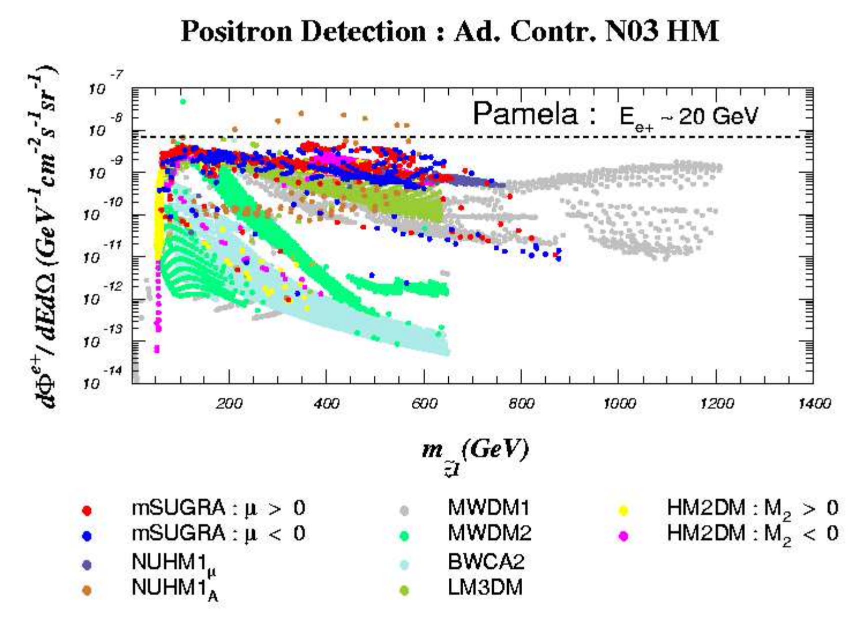
Indirect Detection Rates from neutrino telescopes

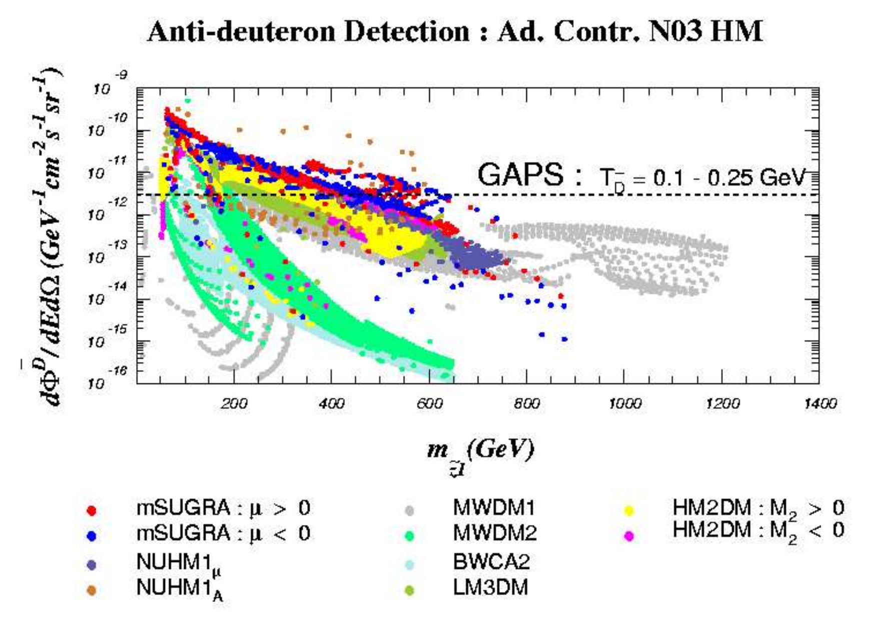


Indirect Detection Rates from Halo Annihilations

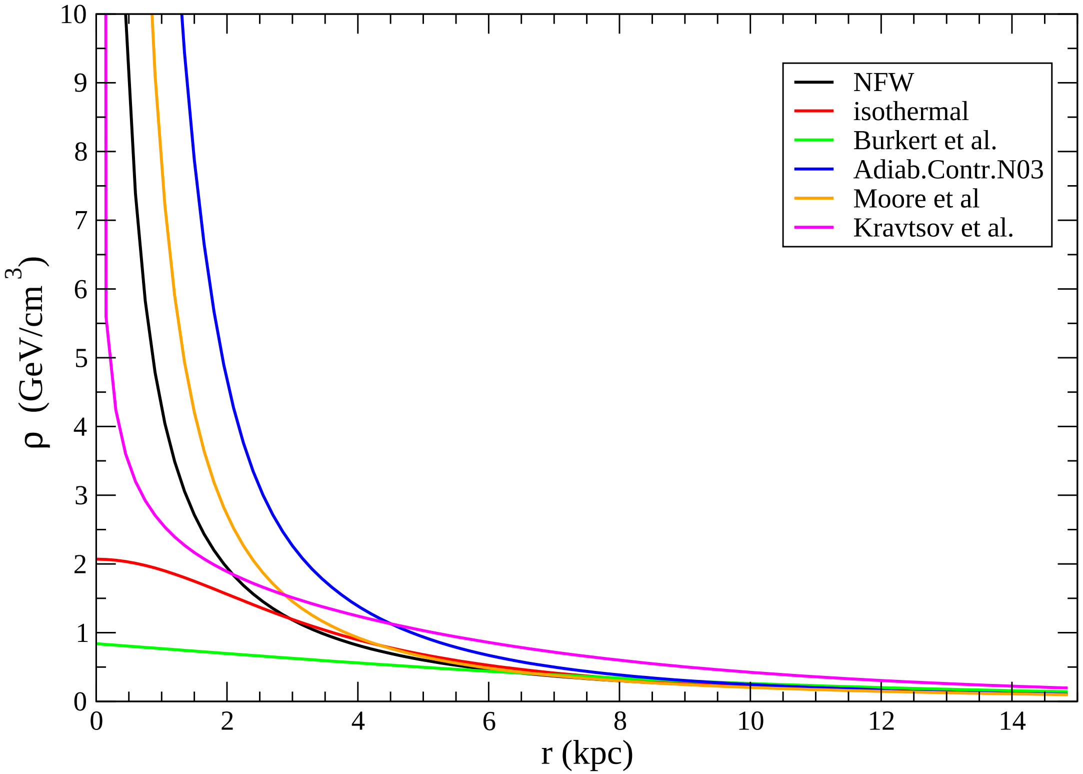








Some Halo Density Profiles

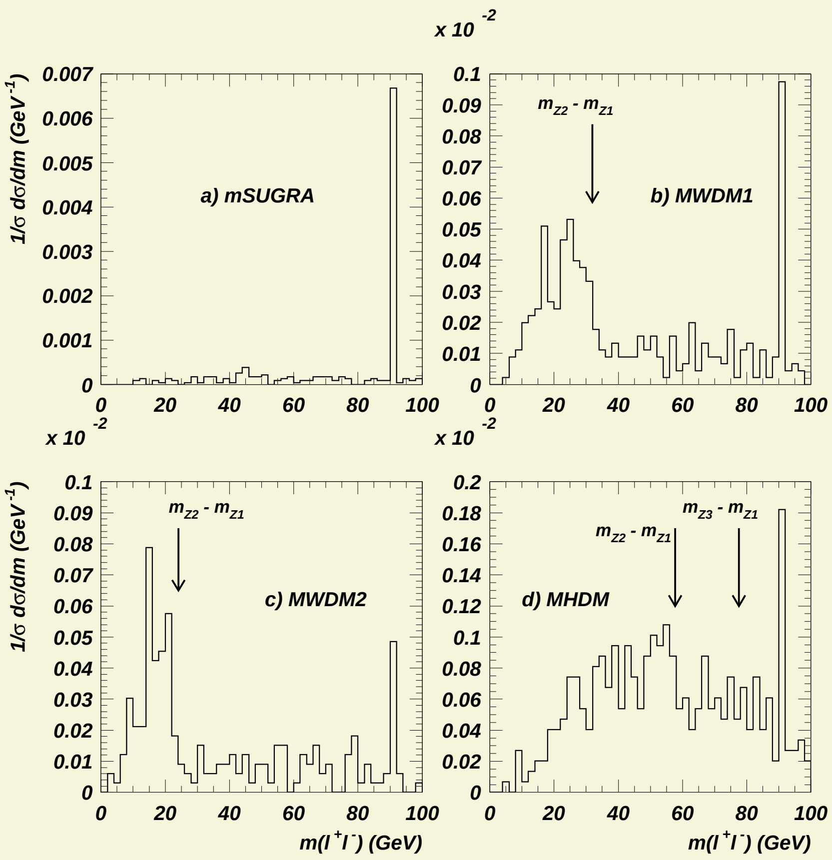


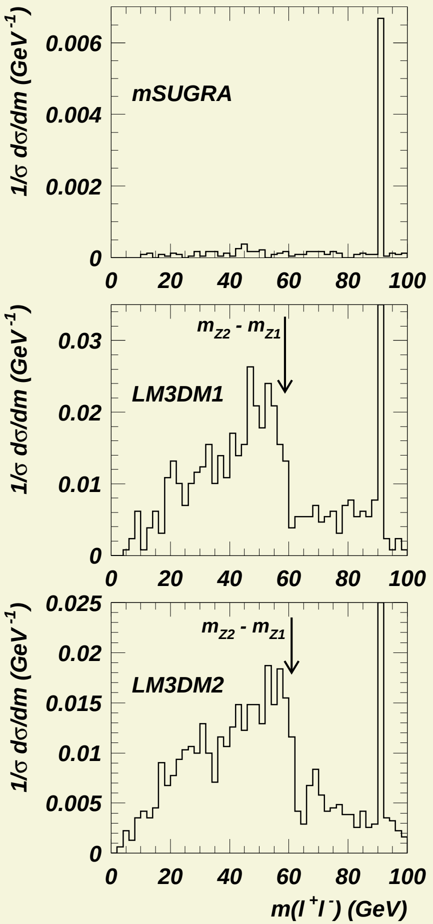
in DarkSUSY code

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: $P_L(e^-) = f_L - f_R$
    ($f_{L,R}$: fraction of left(right) polarized electron in the beam)
- ISAJET program

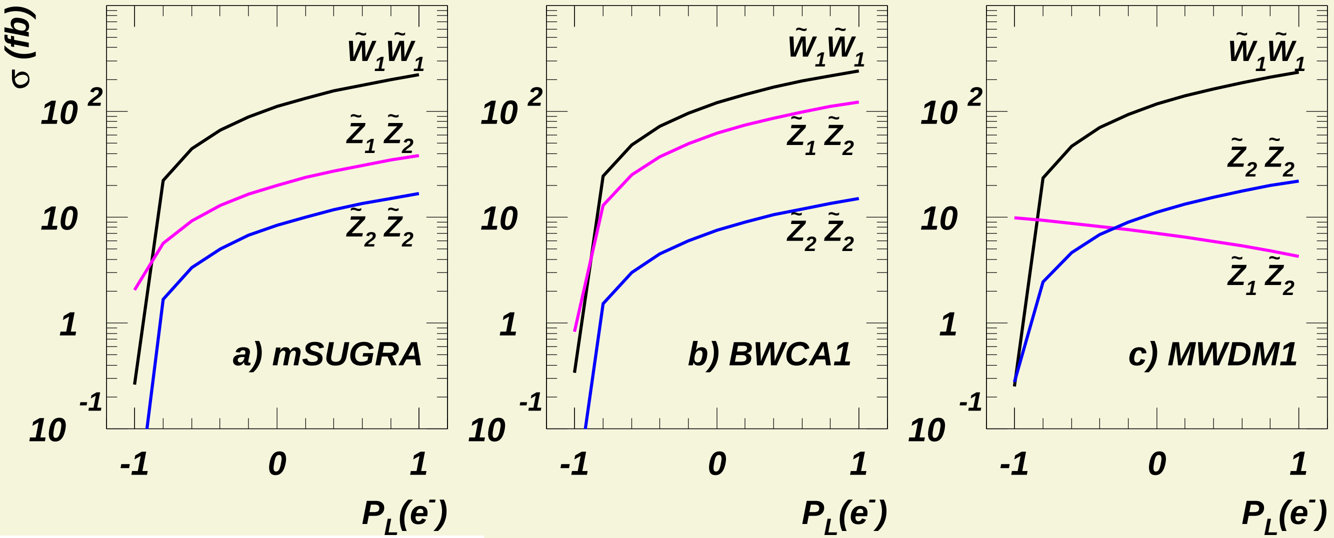
Dilepton Distribution at LHC

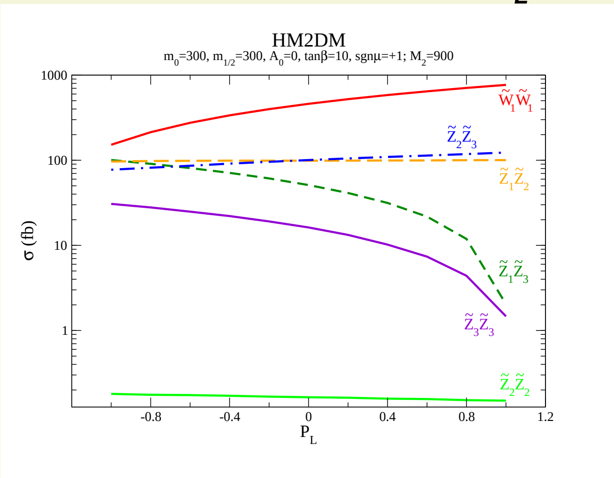




- mSUGRA : sharp peak at $m(l^+l^-) \sim M_Z$ from $\tilde{Z}_2 \longrightarrow \tilde{Z}_1 Z^0$ decays
- NUGM : Z^0 peak from $\tilde{Z}_3$, $\tilde{Z}_4$, $\tilde{W}_2$ decays + continuum distribution $m(l^+l^-) < m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$

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

Conclusions

- Most of mSUGRA parameter space is excluded by WMAP bound
- New perspectives open with gaugino mass non-universalities in SUGRA
- If DM in nature is indeed composed of SUSY models with non-universal gaugino masses (MWDM($M_1 \sim M_2$), BWCA DM($M_1 \sim -M_2$), LM3DM($|M_3| \ll M_1 \simeq M_2$) or HM2DM ($|M_2| \gg M_1 \simeq M_3$))
  - $\tilde{Z}_2 - \tilde{Z}_1$ and $\tilde{W}_1 - \tilde{Z}_1$ mass gaps are reduced compared to the case with gaugino mass universality
  - Direct and Indirect detection experiments may discriminate these scenarios
  - CERN LHC should be able to measure $m_{\tilde{g}}$ and $m_{\tilde{Z}_2} - m_{\tilde{Z}_1}$ mass gap from dilepton distribution from $\tilde{Z}_2 \longrightarrow l\bar{l}\tilde{Z}_1$ decay (spoiler 2-body decay closed)
  - At ILC, $\tilde{W}_1^+\tilde{W}_1^-$, $\tilde{Z}_1\tilde{Z}_2$, $\tilde{Z}_2\tilde{Z}_2$ production cross sections as a function of beam polarization should be able to measurable.
- Where the neutralino composition is adjusted to give the WMAP value,
  - neutralino is typically of the mixed bino-wino or mixed bino-higgsino states
  - enhanced neutralino annihilation rates → direct and indirect detection rates enhanced