Dark Matter and Supersymmetry Models

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Outline

- **Understand dark matter in the context of particle physics models**
- **Consider models with grand unification motivated by string theory**
- **Check the cosmological connections of these well motivated models at direct, indirect detection and collider experiments**

Dark Matter: Thermal

Production of thermal non-relativistic DM:

To actually calculate $\Omega_{\tilde{\chi}_1^0} h^2$, one must solve the Boltzman equation:

$$\frac{dn_{\tilde{\chi}_1^0}}{dt} = -3H(t)\, n_{\tilde{\chi}_1^0}(t) - \langle \sigma_{ann} v \rangle [n^2_{\tilde{\chi}_1^0} - n_0^2]$$

$n_0 =$ equilib. distribution

$\langle\ \rangle =$ thermal average

One finds

$$\Omega_{\tilde{\chi}_1^0} h^2 = 2.48 \times 10^{-11} \left(\frac{T_{\tilde{\chi}_1^0}}{T_\gamma} \right)^3 \left(\frac{T_\gamma}{2.73} \right)^3 \frac{N_F^{1/2}}{\int_0^{x_F} dx \langle \sigma_{ann} v \rangle}$$

where

$\Omega_{\tilde{\chi}_1^0} = \rho_{\tilde{\chi}_1^0} / \rho_c$; $\rho_c = 3H_0^2 / 8\pi G_N$; $h = H_0/100$

and

$\sigma_{ann} =$ early universe annihilation cross section

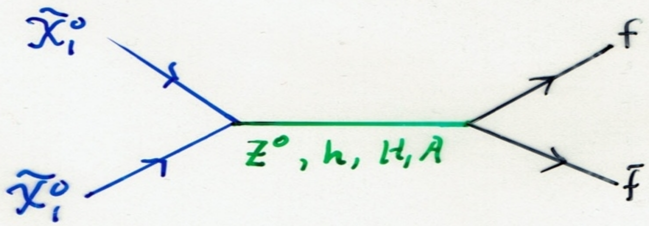
Assuming : $\langle \sigma v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$ **$\alpha_\chi \sim O(10^{-2})$ with $m_\chi \sim O(100)$ GeV leads to the correct relic abundance**

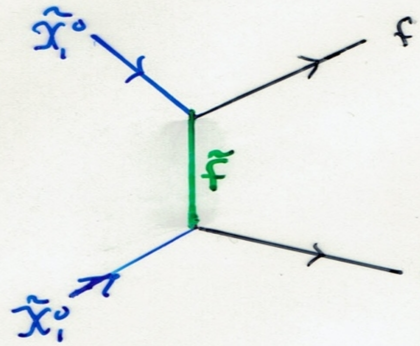
Anatomy of σ_{ann}

In the early universe, $\tilde{\chi}_1^0$ created by the Big Bang can annihilate in pairs into ordinary matter. The main Feynman diagrams for e.g.

$\tilde{\chi}_1^0 + \tilde{\chi}_1^0 \longrightarrow f + \bar{f}$; f = SM fermion

are

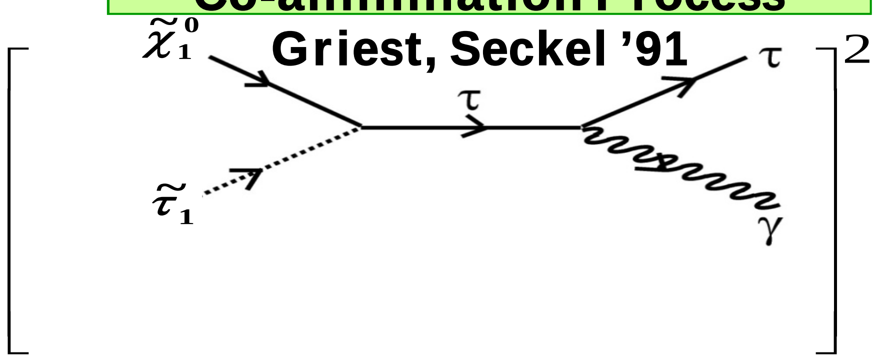




$\tilde{f}$ = squark / slepton

Co-annihilation Process

Griest, Seckel '91

+ 

$e^{-\Delta M / kT_f}$

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$$

Arnowitt, Dutta, Santoso, Nucl.Phys. B606 (2001) 59,

A near degeneracy occurs naturally for light stau in mSUGRA.

Models

There are a number of models based on grand unification of the gauge coupling constants at $M_G \cong 2\times10^{16}$ GeV:

Minimal Supergravity GUT (mSUGRA)
Universal soft breaking at M_G

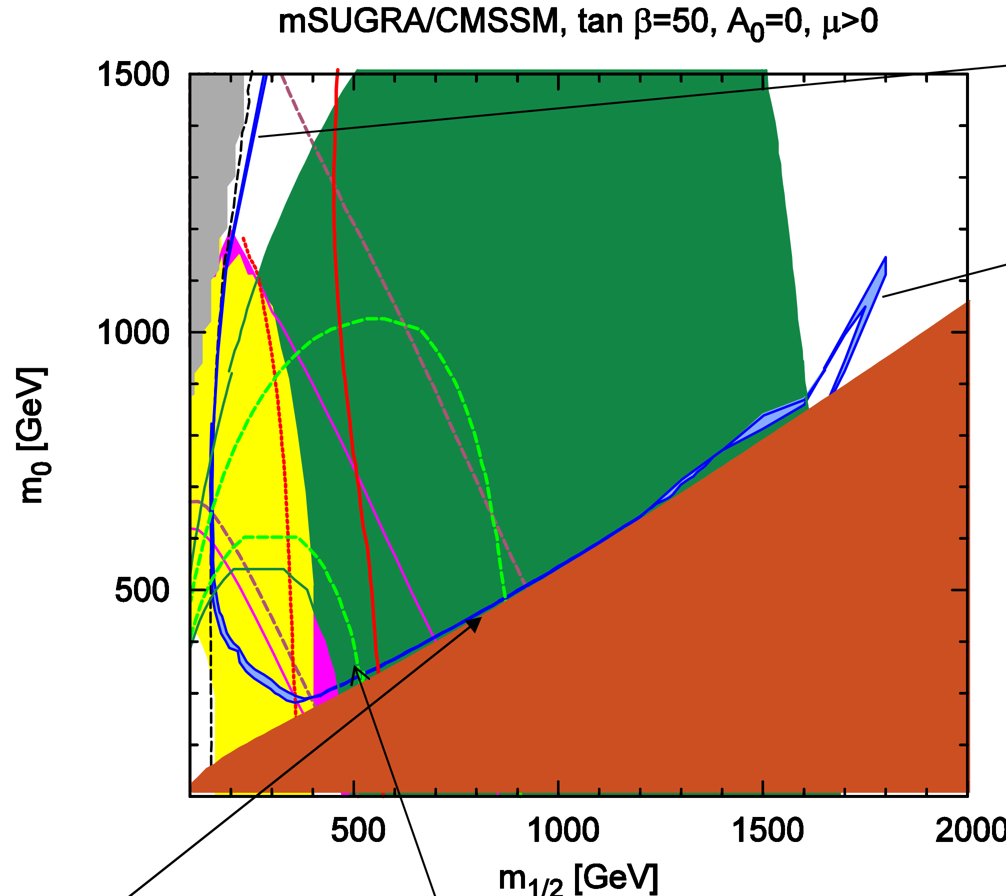
Nonuniversal Soft Breaking Models
Nonuniversal scalar masses in Higgs and third generation at M_G

There are "string inspired" models

D-brane Models (IIB Orientifolds)
Nonuniversal gaugino masses at M_G
$SU(2)_L$ doublet masses different from singlet scalar masses at M_G

Horava-Witten M-Theory (Calabi-Yau)
Universal gaugino masses at M_G
Generation nonuniversality of scalar masses at M_G

mSUGRA Parameter space



Focus point

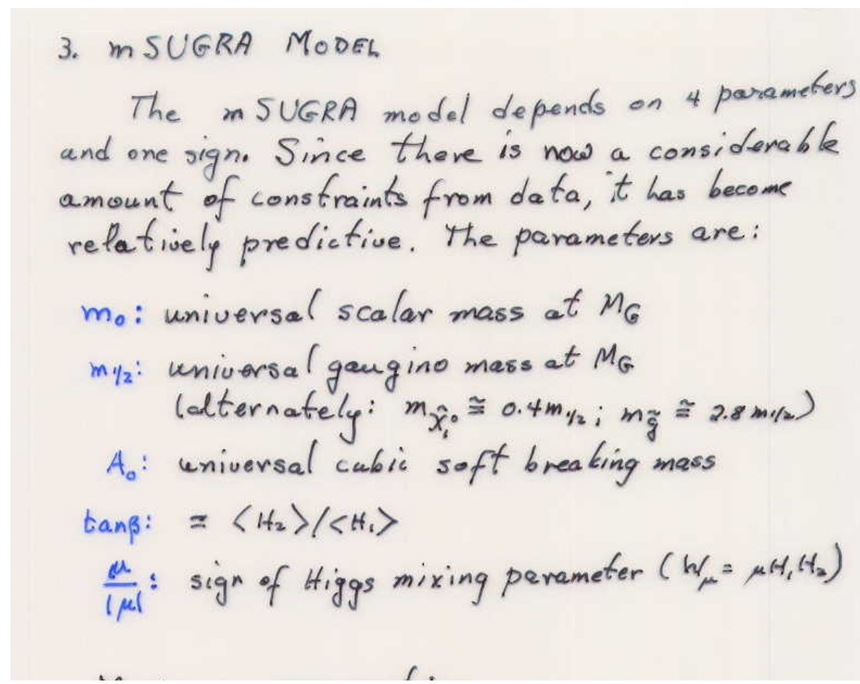
Resonance

Narrow blue line is the dark matter allowed region

Coannihilation Region

1.3 TeV squark bound from the LHC

Arnowitt, Dutta, Santoso, Phys.Rev. D64 (2001) 113010 , Arnowitt, Dutta, Hu, Santoso, Phys.Lett. B505 (2001) 177



3. mSUGRA MODEL

The mSUGRA model depends on 4 parameters and one sign. Since there is now a considerable amount of constraints from data, it has become relatively predictive. The parameters are:

m_0: universal scalar mass at M_G

$m_{1/2}$: universal gaugino mass at M_G (alternately: $m_{\tilde{\chi}_1^0} \cong 0.4 m_{1/2}$; $m_{\tilde{g}} \cong 2.8 m_{1/2}$)

A_0: universal cubic soft breaking mass

$\tan\beta$: $= \langle H_2 \rangle / \langle H_1 \rangle$

$\frac{\mu}{|\mu|}$: sign of Higgs mixing parameter ($W_\mu = \mu H_1 H_2$)

mSUGRA Parameter space

(2) Accidental near degeneracy between $\tilde{l}_R$ and $\tilde{\chi}^0_1$ in a small region of parameter space. Thus low $\tan\beta$:

$$m_{\tilde{e}_R}^2 = m_0^2 + \frac{6}{5}\frac{\alpha_G}{4\pi} f_1 m_{1/2}^2 - \sin^2\theta_W M_W^2 \cos 2\beta$$

$$f_1 = \frac{1}{\beta_1}\left[1 - \frac{1}{1+\beta_1 t}\right]$$

$$m_{\tilde{\chi}^0_1} \cong \frac{\alpha_1}{\alpha_G} m_{1/2}$$

or numerically:

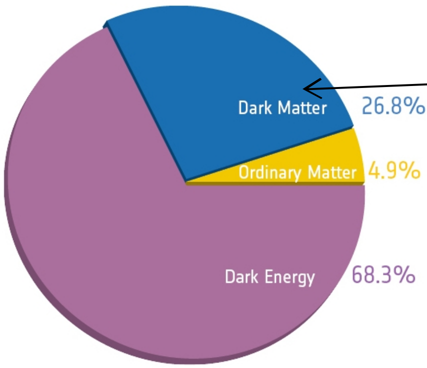
$$m_{\tilde{e}_R}^2 \cong m_0^2 + \underline{0.15}\, m_{1/2}^2 + (40\ \mathrm{GeV})^2$$

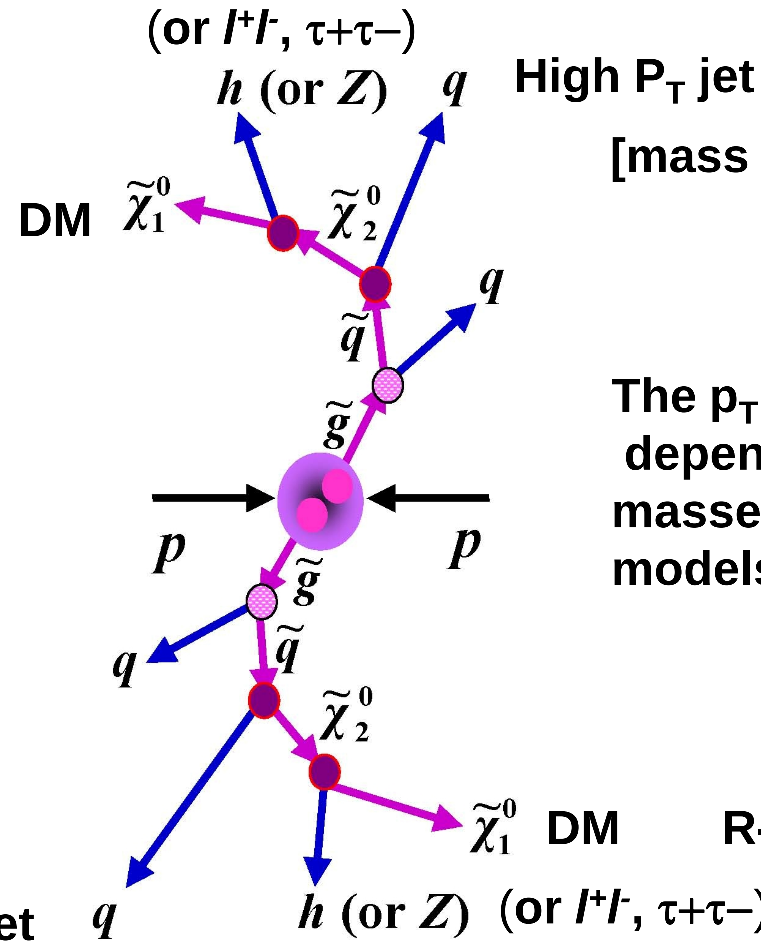
$$m_{\tilde{\chi}^0_1}^2 \cong \underline{0.16}\, m_{1/2}^2$$

Thus by chosing m_0 one can make $m_{\tilde{e}_R} > m_{\tilde{\chi}^0_1}$ but nearly degenerate in a narrow "chimney" in $m_0 - m_{1/2}$ space

Arnowitt, ICHEP'00, Arnowitt, Dutta, Santoso, Nucl.Phys. B606 (2001) 59,

Small ΔM at the LHC





[mass difference is large]

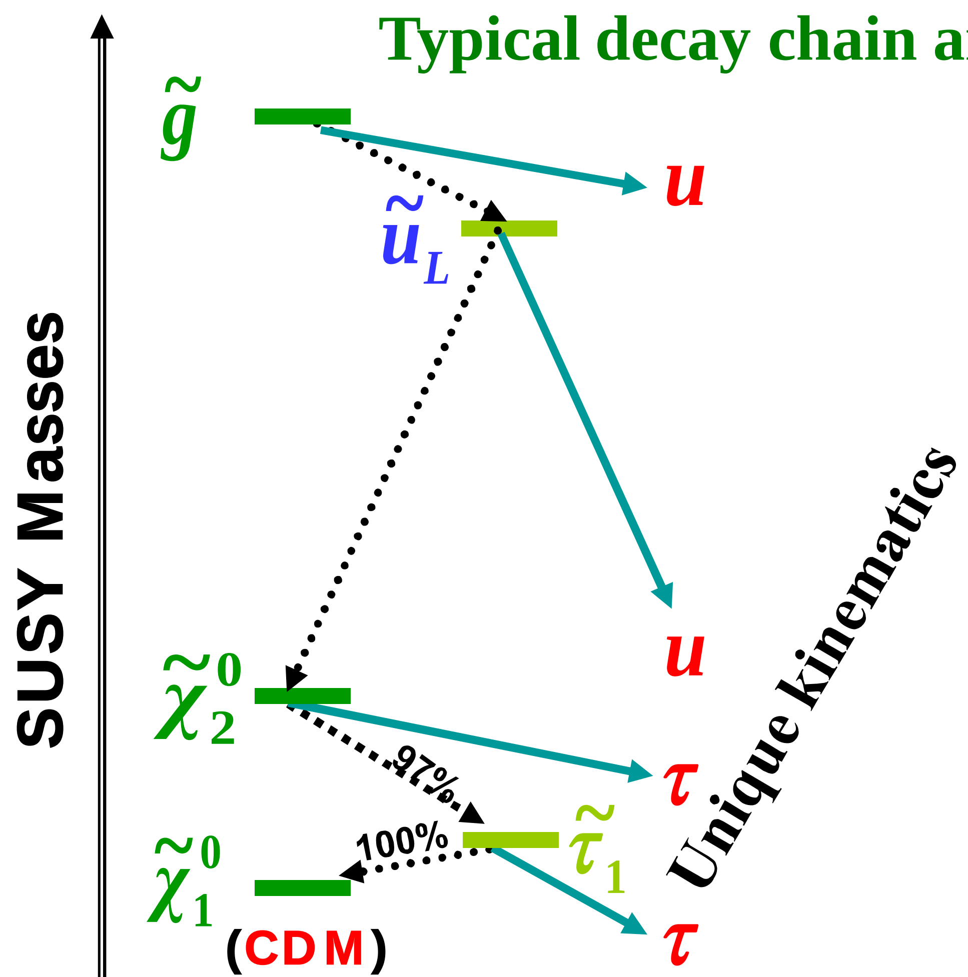
The p_T of jets and leptons depend on the sparticle masses which are given by models

Colored particles are produced and they decay finally to the weakly interacting stable particle

R-parity conserving

The signal :
jets + leptons+ t's +W's+Z's+H's + missing E_T

Small ΔM via cascade



2 jets+2 τ's +missing energy

$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}$$

Jets + τ's+ missing energy

Low energy taus characterize the small mass gap

However, one needs to measure the model parameters to predict the dark matter content in this scenario

Arnowitt, Dutta, Kamon, Kolev, Toback Phys.Lett. B639 (2006) 46-53

Arnowitt, Aurisano, Dutta, Kamon, Kolev, Simeon,Toback Phys.Lett. B649 (2007) 73-82

Small ΔM via cascade and DM

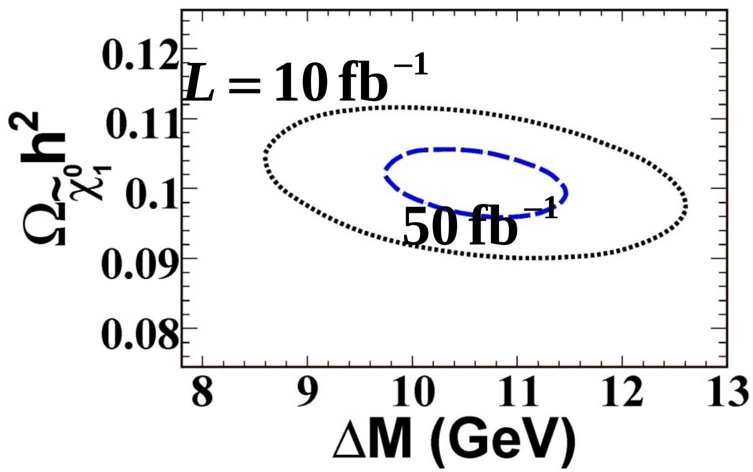
✓**Solved by inverting the following functions:**

$$M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)$$
$$M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan\beta, A_0)$$
$$M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)$$
$$M_{\text{eff}}^{(b)\,\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

$\xrightarrow{10\ \mathrm{fb}^{-1}}$

$$\left\{\begin{array}{lcl} m_0 & = & 210 \pm 5 \\ m_{1/2} & = & 350 \pm 4 \\ A_0 & = & 0 \pm 16 \\ \tan\beta & = & 40 \pm 1 \end{array}\right.$$

$$\boxed{\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2}\ \tan\beta, A_0)}$$



$$\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 = 6.2\%\ (30\ \mathrm{fb}^{-}$$
$$= 4.1\%\ (70\ \mathrm{fb}^{-}$$

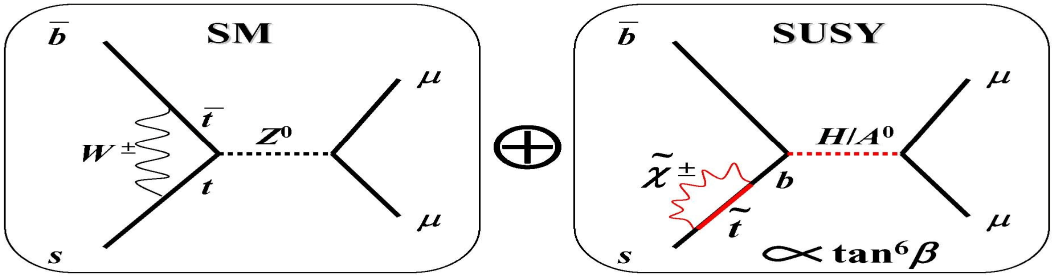
Arnowitt, Dutta, Gurrola, Kamon, Krislock and Toback Phys.Rev.Lett. 100 (2008) 231802

Rare Decay $B_s \to \mu^+\mu^-$

How to understand particle physics models at the Tevatron

Rare Decay mode:

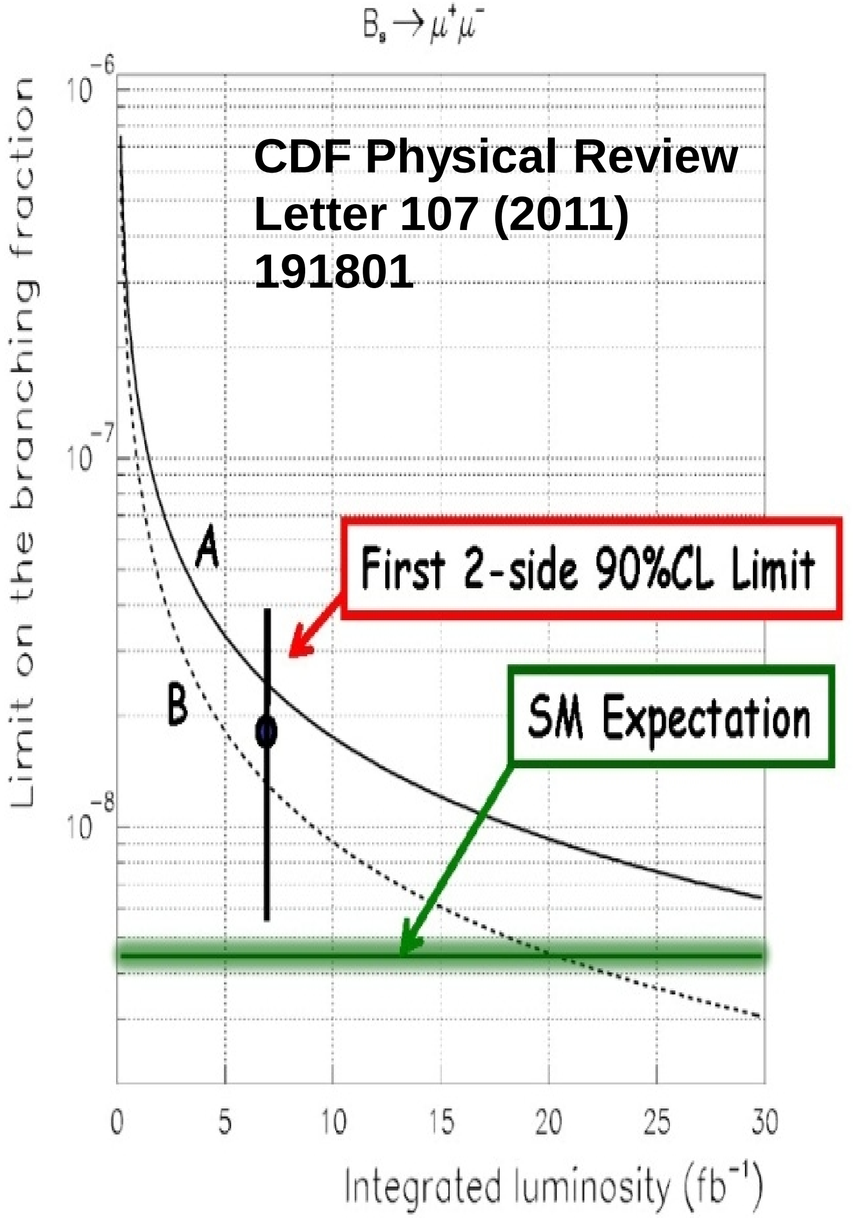
$$B_{SM} = 3.4 \times 10^{-9} \quad B_{SUSY} \propto (\tan\beta)^6$$



Babu, Kolda, Phys.Rev.Lett. 84 (2000) 228

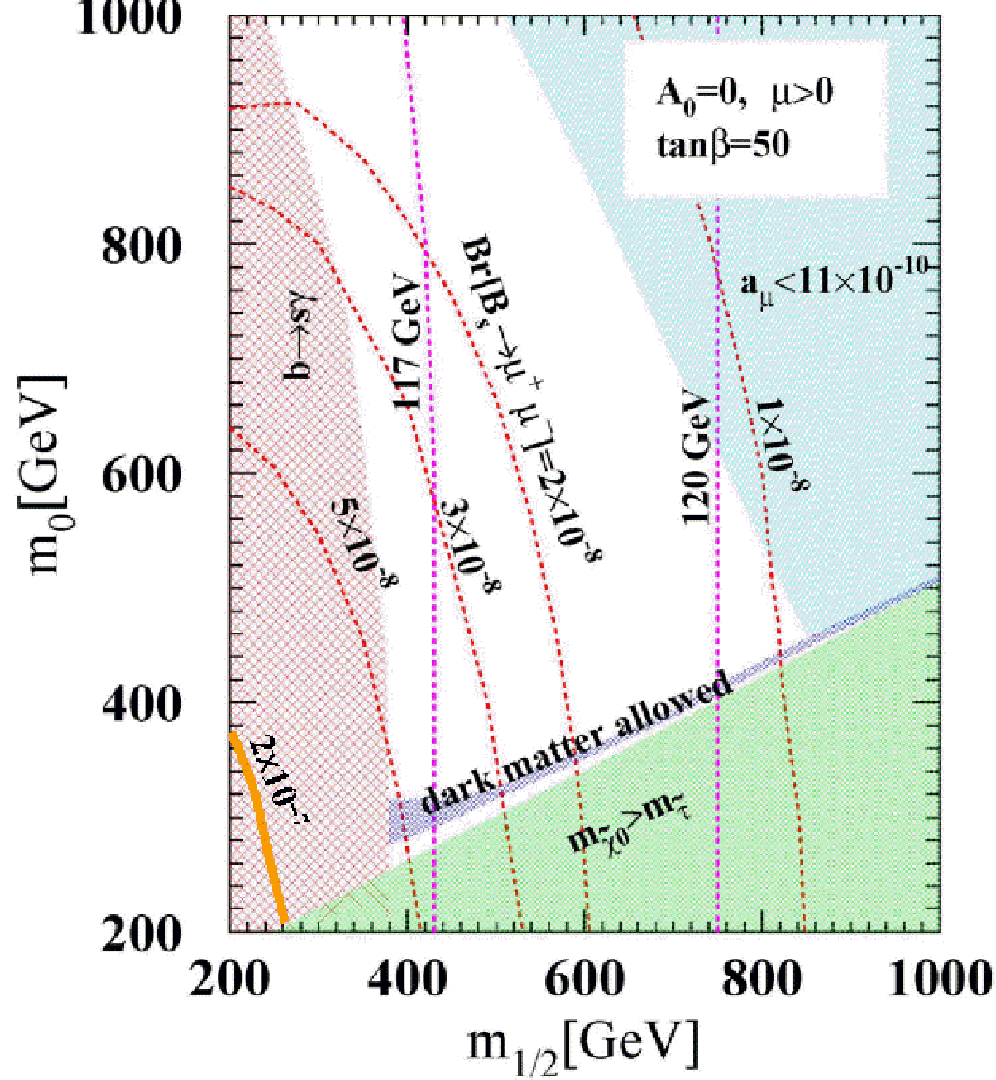
In the SUSY models (large tanβ), which are cosmologically consistent, the decay can be enhanced by up to 1,000.

$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection



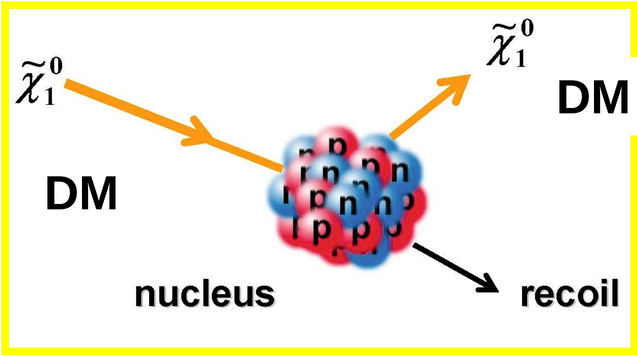
mSUGRA at tanβ = 50

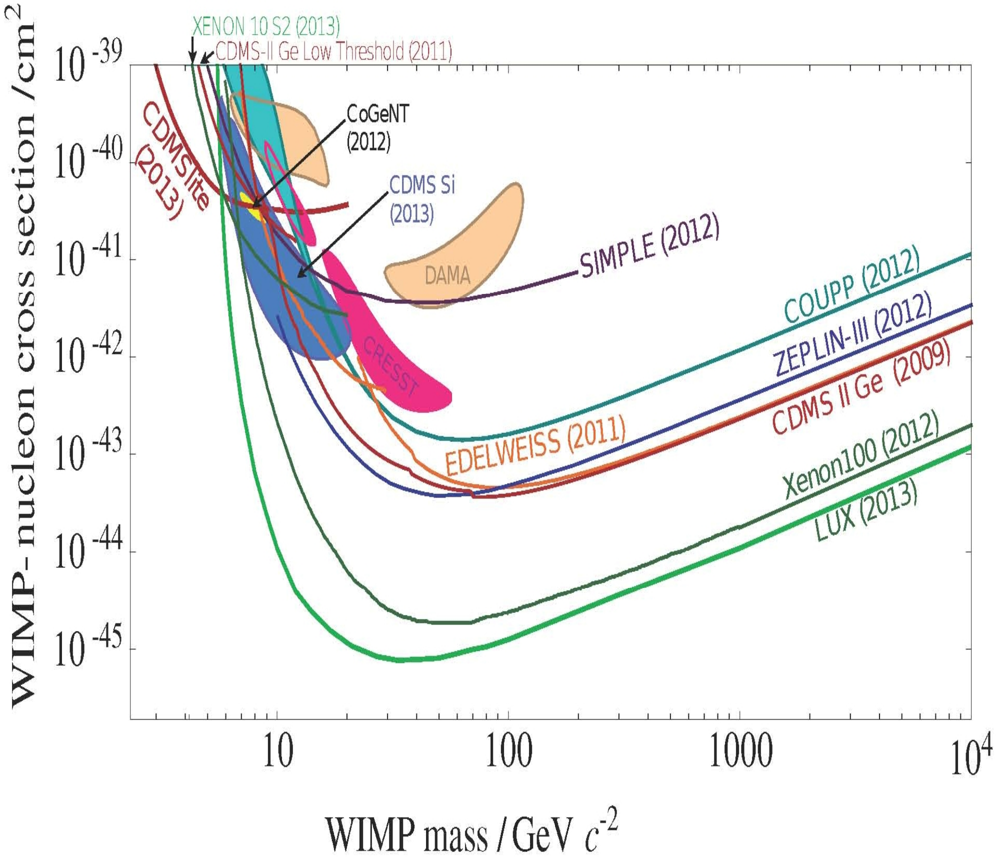
Arnowitt, Dutta, Kamon, Tanaka, 02



Direct Detection of DM

New physics/SUSY in the direct detection experiments:





DAMA, CoGeNT:
Signal for Low mass DM

LUX: No signal for Low or High DM mass

Direct Detection of DM

Properties of proton

Theory gives naturally the $\tilde{\chi}_i^0$ - quark cross section and one must convert this to $\tilde{\chi}_i^0$ - proton scattering to compare with experiment. One need the quantities [Ellis, Flores; Drees, Nojiri]:

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d) \langle p | \bar{u}u + \bar{d}d | p \rangle$$

$$\sigma_0 = \frac{1}{2}(m_u + m_d) \langle p | \bar{u}u + \bar{d}d - 2\bar{s}s | p \rangle$$

$$r = \frac{m_s}{\frac{1}{2}(m_u + m_d)}$$

We use in the following

$\sigma_{\pi N} = 65$ MeV [Ollson; Paven et al.]

$\sigma_0 = 30$ MeV [Bottino et al.]

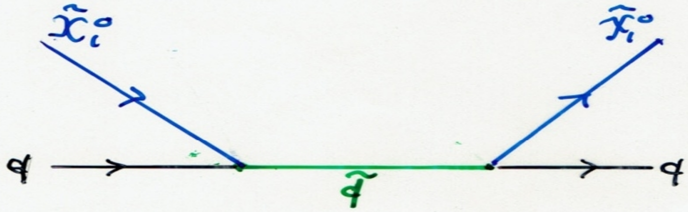
$r = 24.4 \pm 1.5$ [Leutwyler]

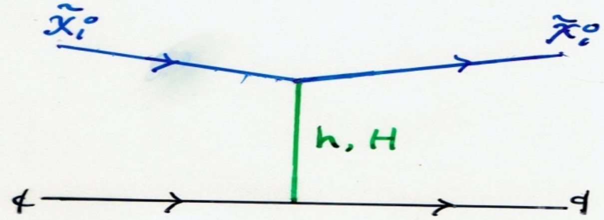
Other choices can change $\sigma_{\tilde{\chi}_i^0 - p}$ by about a factor ≈ 3.

Direct Detection of DM

(19)

What does the mSUGRA theory predict? The basic scattering is the $\tilde{\chi}_i^0$ off quarks in a nucleon in the nucleus:





One can use these to calculate the scattering by quarks and convert this into $\sigma_{\tilde{\chi}_i^0-p}$ (there are certain uncertainties here: the s-quark content of the proton; the π-N $\sigma_{\pi N}$ term; leading perhaps to a factor ≈ 2 uncertainty in $\sigma_{\tilde{\chi}_i^0-p}$.)

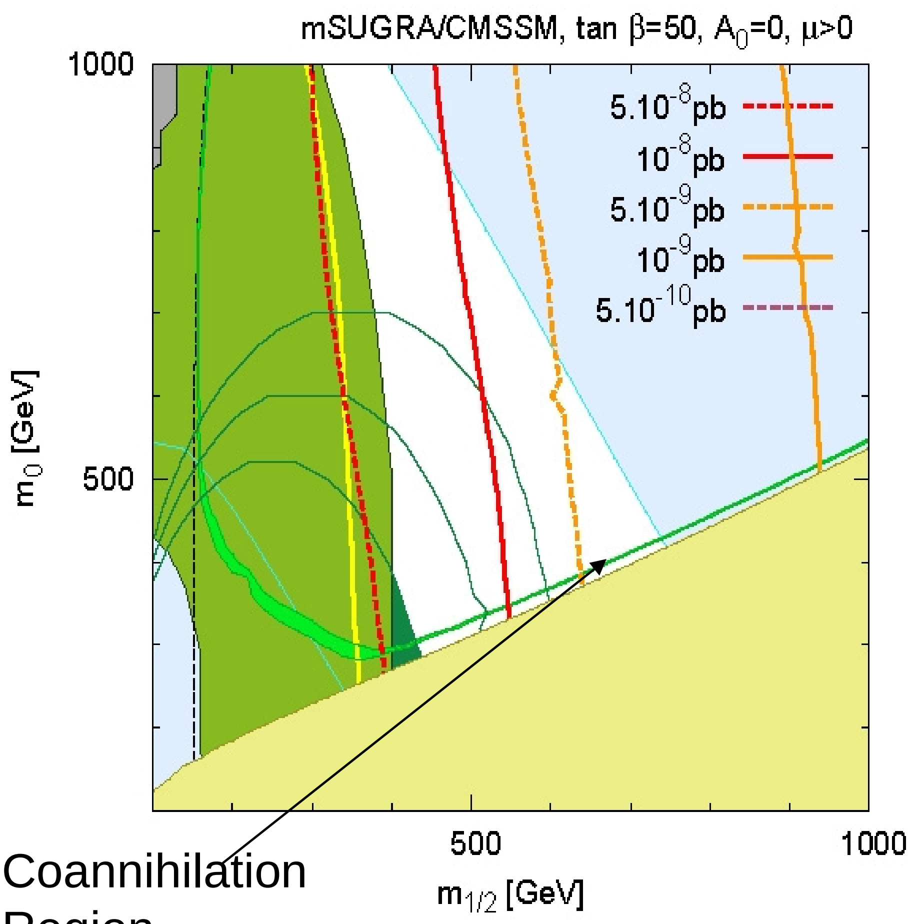
In general $\sigma_{\tilde{\chi}_i^0-p}$ is a function of the SUSY parameters of mSUGRA:

$$\sigma_{\chi_i^0-p}\left(m_{1/2}, m_0, A_0, \tan\beta; \frac{\mu}{|\mu|}\right)$$

However, mSUGRA is a full theory. It can be applied to many other phenomena and current experiment limits the parameters.

mSUGRA Parameter space

The minimal model: mSUGRA → 4 parameters: m_0, $m_{1/2}$, A_0, tanβ and Sign(μ)



Coannihilation Region

Accomando, Arnowitt, Dutta, Santoso, Nucl.Phys. B585 (2000) 124-142
Accomando, Arnowitt, Dutta, Phys.Rev. D61 (2000) 075010

SUGRA Parameter space

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W} + N_{13}\tilde{H}_1 + N_{14}\tilde{H}_2 \tag{19}$$

where N_{1i} are the amplitudes. In much of the parameter space, the t-channel Higgs exchanges $(h,\,H)$ dominate $\sigma_{\tilde{\chi}_1^0-p}$. The d and u quark Higgs amplitudes are [37]

$$A^d = \frac{g_2^2 m_d}{2M_W}\left(-\frac{\sin\alpha}{\cos\beta}\frac{F_h}{m_h^2} + \frac{\cos\alpha}{\cos\beta}\frac{F_H}{m_H^2}\right) \tag{20}$$

$$A^u = \frac{g_2^2 m_u}{2M_W}\left(\frac{\cos\alpha}{\sin\beta}\frac{F_h}{m_h^2} + \frac{\sin\alpha}{\sin\beta}\frac{F_H}{m_H^2}\right) \tag{21}$$

where α is the Higgs mixing angle and

$$F_h = (N_{12} - N_{11}\tan\theta_W)(N_{14}\cos\alpha + N_{13}\sin\alpha) \tag{22}$$

$$F_H = (N_{12} - N_{11}\tan\theta_W)(N_{14}\sin\alpha - N_{13}\cos\alpha) \tag{23}$$

Since the s-quark contribution to the scattering is quite large, the d-quark amplitude A^d will generally be quite large. However A^d will be suppressed if the amplitudes N_{13}, N_{14} obey the equation

$$N_{14} \simeq -N_{13}\frac{\tan\alpha + \frac{m_h^2}{m_H^2}\cot\alpha}{1 + \frac{m_h^2}{m_H^2}} \tag{24}$$

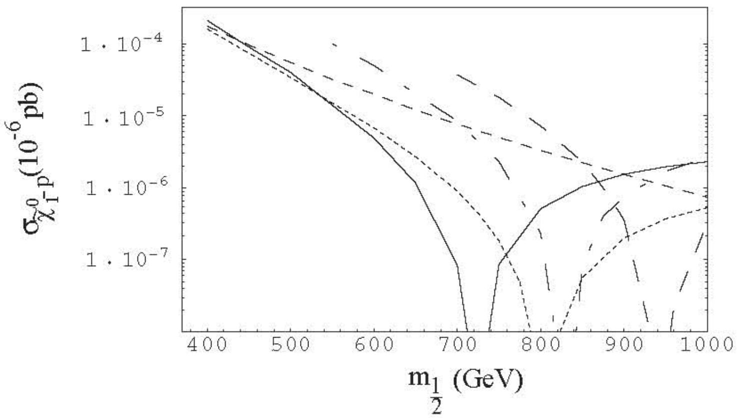


FIG. 5. $\sigma_{\tilde{\chi}_1^0-p}$ for mSUGRA for $\mu < 0$, $A_0 = 1500$ GeV, for $\tan\beta = 6$ (short dash), $\tan\beta = 8$ (dotted), $\tan\beta = 10$ (solid), $\tan\beta = 20$ (dot-dash), $\tan\beta = 25$ (dashed). Note that the $\tan\beta = 6$ curve terminates at low $m_{1/2}$ due to the Higgs mass constraint, and the other curves terminate at low $m_{1/2}$ due to the $b \to s\gamma$ constraint.

Models from String Theory

$$M_4 \times X \times S^1/Z_2$$

where

M_4 = Minkowski space

X = 6D Calabi-Yau space

$-\pi\rho \leq x^{11} \leq \pi\rho$

The space has thus 2 orbifold 10D manifolds $M_4 \times X$:

$x^{11} = 0$; visable sector

$x^{11} = \pi\rho$; hidden sector

each with a priori E_8 gauge symmetry.

Models from String Theory

Horava-Witten M-Theory has now progressed to the point where it offers a fundamental framework for building phenomenological models:

- Allows conventional GUT groups, SU(5), SO(10)
- Accomodates grand unification at $M_G \cong 3\times10^{16}$ GeV
- With torus fibered Calabi-Yau there are 3 generation models with a Wilson line to break the GUT group to $SU(3)\times SU(2)\times U(1)$

- **Construction of Yukawa couplings with hierarchy (as observed) in the fermion masses in such attractive framework is possible**
  Arnowitt, Dutta, Nucl.Phys. B592 (2001) 143-163

- **Construction of neutrino masses and mixings(as observed in the experiments) in possible**

  Arnowitt, Dutta, Hu, Nucl.Phys. B682 (2004) 347-366 , Arnowitt, Dent, Dutta, Phys.Rev. D70 (2004) 126001

Highlights

It's remarkable that it's possible to build models consistent with current data that discuss the energy range from low energies up to the GUT scale $M_G \approx 2\times10^{16}$ GeV and apply all the way back in time to the very early universe. The success of the Big Bang Nucleosynthesis analysis shows the validity of applying particle physics to the cosmology of the early universe, and if dark matter experiments do show that dark matter is made of neutralinos ($\tilde{\chi}_1^0$) it will be a major advance for both cosmology and particle physics.

There remains, however, one of the biggest puzzles, i.e. the nature of the cosmological constant.

Highlights

Future planned experiments could cover almost the entire SUSY parameter space, the same region that the LHC will examine in accelerator searches for supersymmetry. Thus dark matter experiments are complementary to particle physics experiments and test the link between cosmology and particle physics.