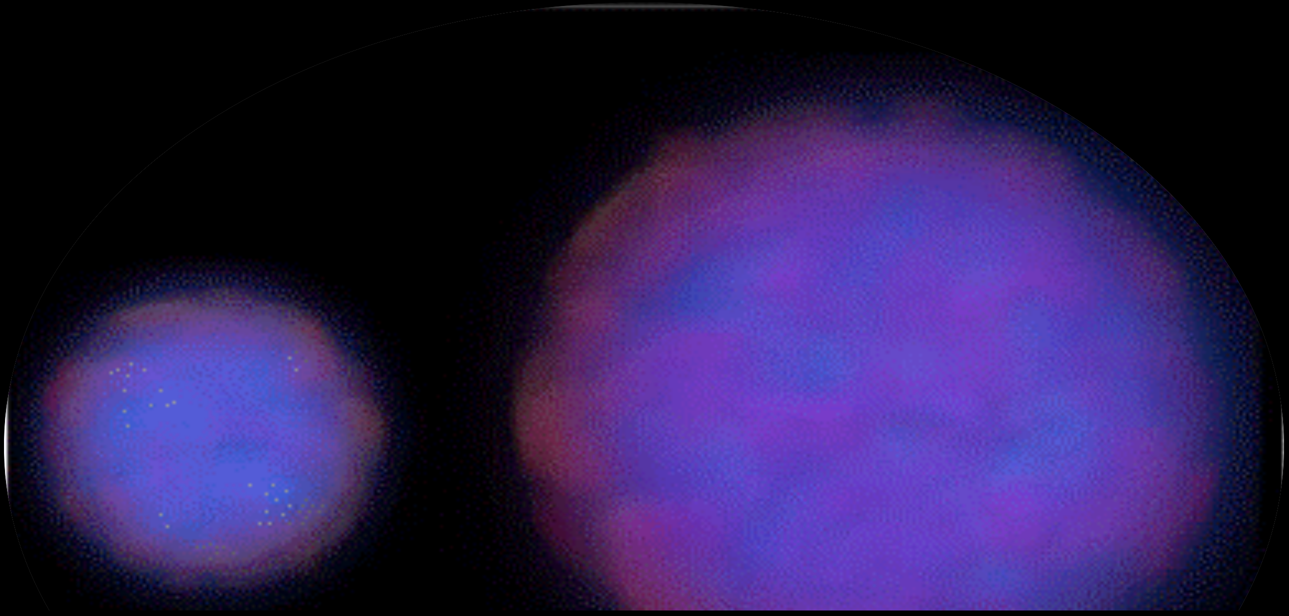
Dark Matter at the LHC

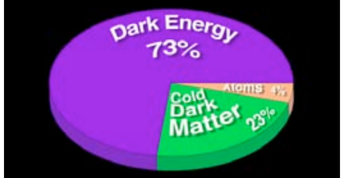


Bhaskar Dutta

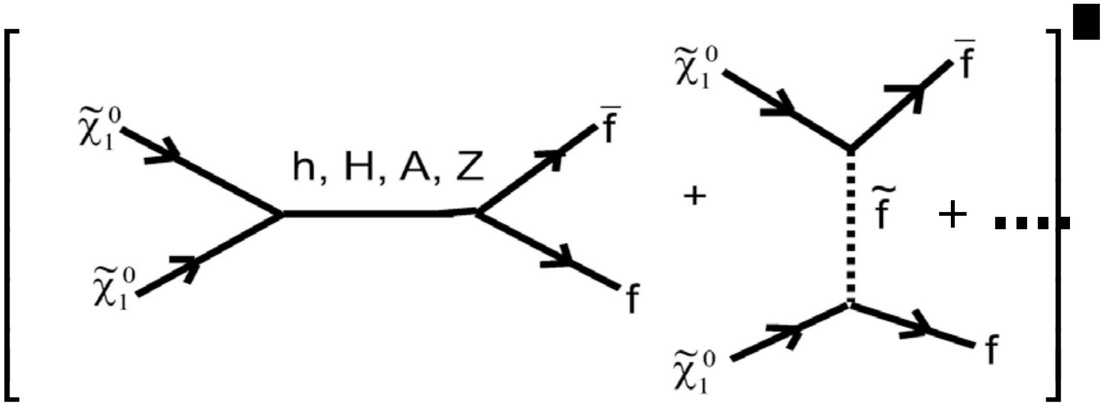
Texas A&M University

Texas Cosmology Network Meeting, UT, Austin

Dark Matter and SUSY



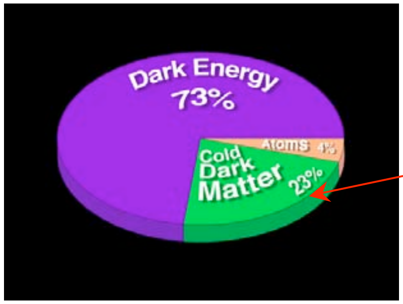
$(\Omega_{\blacksquare\blacksquare\blacksquare})^{-\blacksquare} \propto$



$$\underbrace{\Omega_{\tilde{\chi}_1^0}}_{0.23} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx \quad \Rightarrow \quad < \ _{ann} v > \sim \frac{!\ ^2}{M^2} \sim 1 pb$$

We need to observe the new layer of matter in order to establish this explanation

SUSY at the LHC

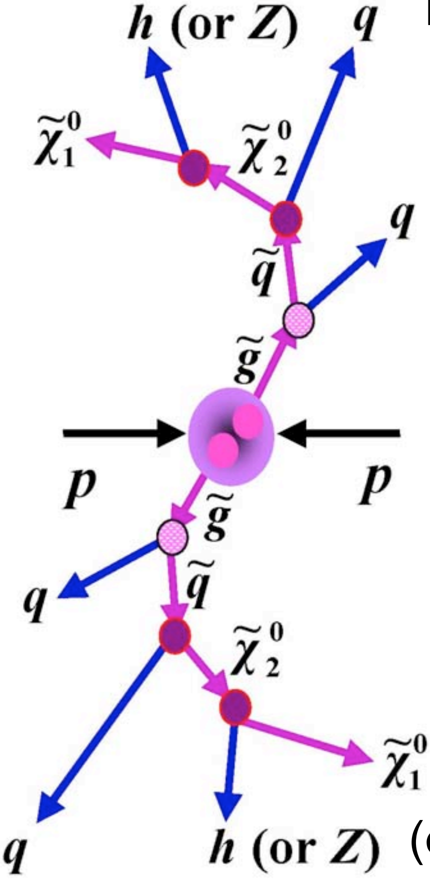


DM

(or l^+l^-, $\tau^+\tau^-$)

High P_T jet

[mass difference is large]



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

Colored particles get produced and decay into weakly interacting stable particles

DM

R-parity conserving

High P_T jet

(or l^+l^-, $\tau^+\tau^-$)

The signal : jets + leptons + missing E_T

SUSY Models

Minimal Supersymmetry Standard Model has more than 100 parameters

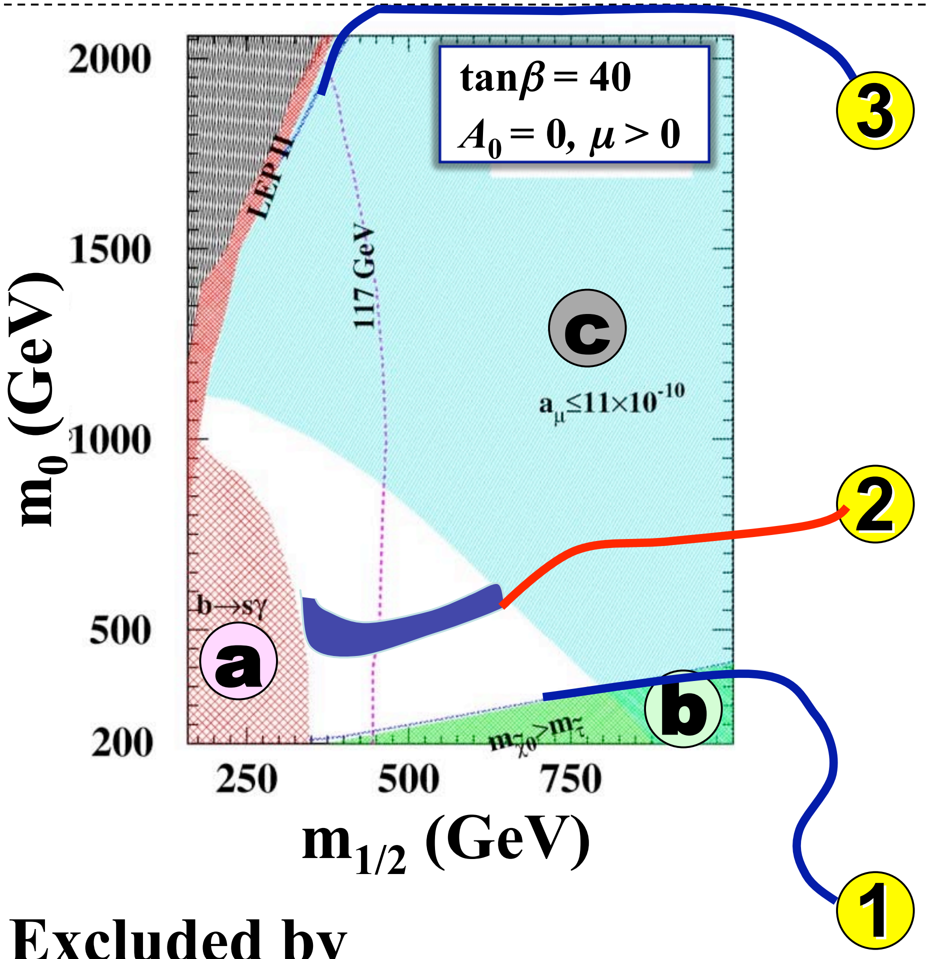
- **We may not have enough observables to establish them**
- **We start with a simple scenario and go to complicated cases**

mSUGRA: Minimal Scenario

4 parameters + 1 sign

$$\left\{\begin{array}{ll}
\tan\beta & : \langle H_u \rangle / \langle H_d \rangle \text{ at } M_Z \\
m_{1/2} & : \text{Common gaugino mass at } M_{\text{GUT}} \\
m_0 & : \text{Common scalar mass at } M_{\text{GUT}} \\
A_0 & : \text{Trilinear couping at } M_{\text{GUT}} \\
\text{sign}(\mu) & : \text{Sign of } \mu \text{ in } W^{(2)} = \mu H_u H_d
\end{array}\right.$$

Dark Matter Allowed Regions



③ **FP/HB Region**

$$\underbrace{\Omega_{\tilde{\chi}_1^0}}_{0.23} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx$$

② **Over-dense DM Region**

$$\underbrace{\Omega_{\tilde{\chi}_1^0}}_{0.23} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle f(x)} dx$$

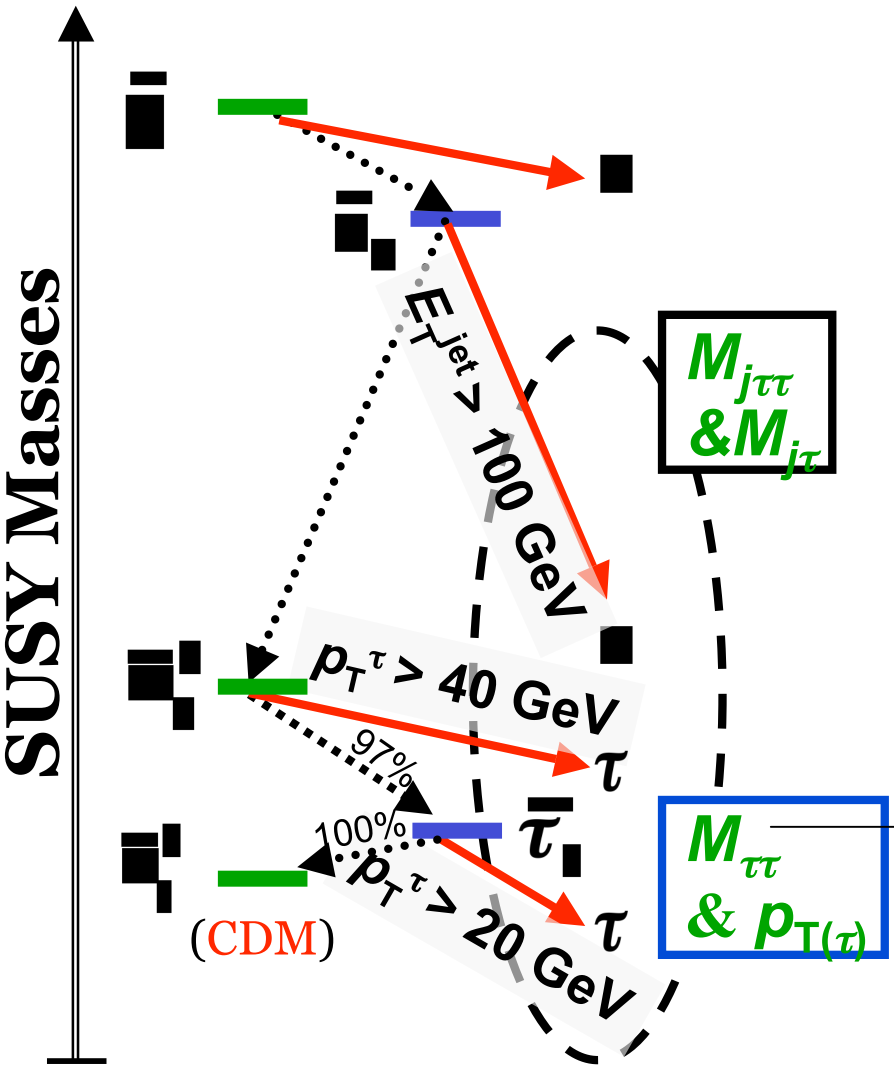
① **Coannihilation Region**

$$\underbrace{\Omega_{\tilde{\chi}_1^0}}_{0.23} h^2 \sim \int_0^{x_f} \frac{1}{\langle \sigma_{\text{ann}} v \rangle} dx$$

Excluded by

ⓐ Rare B decay $b \rightarrow s\gamma$
ⓑ No CDM candidate
ⓒ Muon magnetic moment

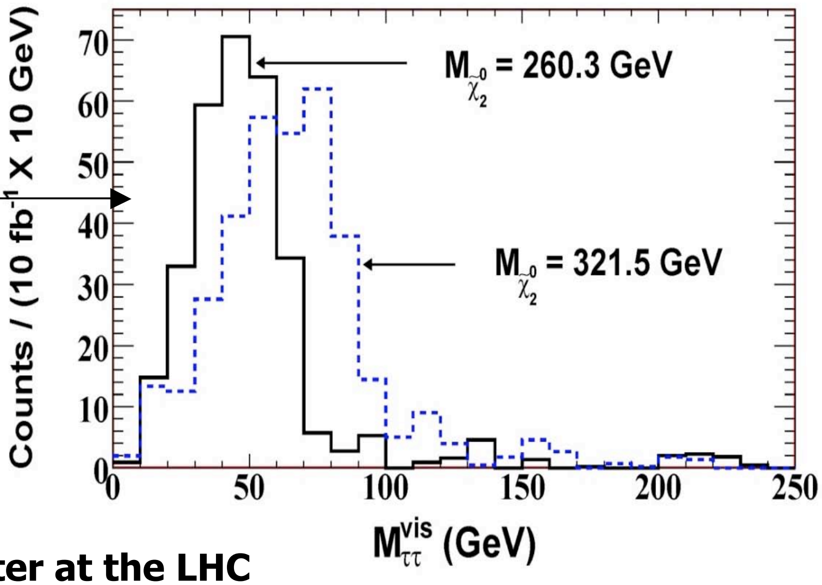
Observables at the LHC



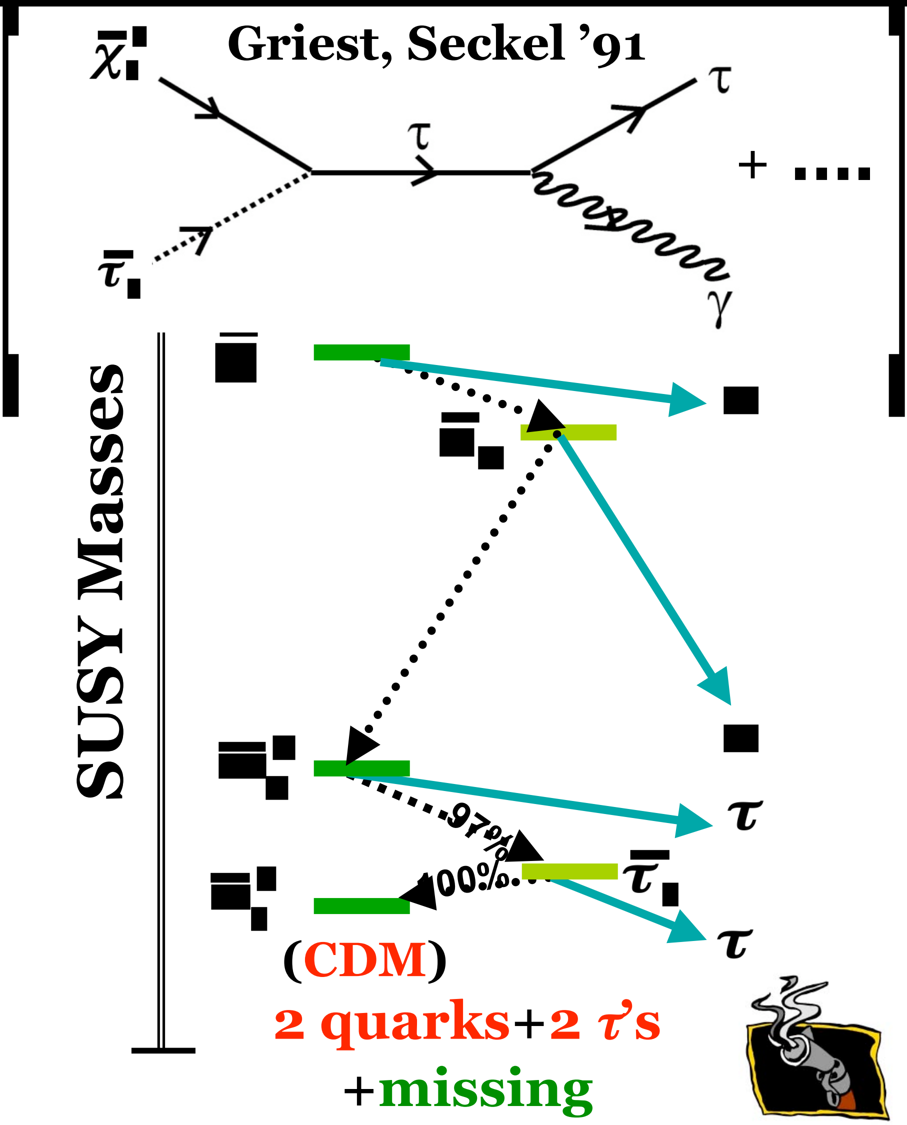
The observables include:

Z, h, W, τ, t, b, jet, *l* and missing energy

The observables are determined by the underlying physics of the model



Case 1. Coannihilation Region



(CDM)

2 quarks+2 τ's

+missing

energy

[illegible]

[illegible] $_{\tilde{\tau}_1}$ – [illegible] $_{\tilde{\chi}_1^0}$ [illegible]

Low energy taus characterize the CA region

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

Arnowitt, Dutta, Kamon,Toback'08

Determining mSUGRA Parameters

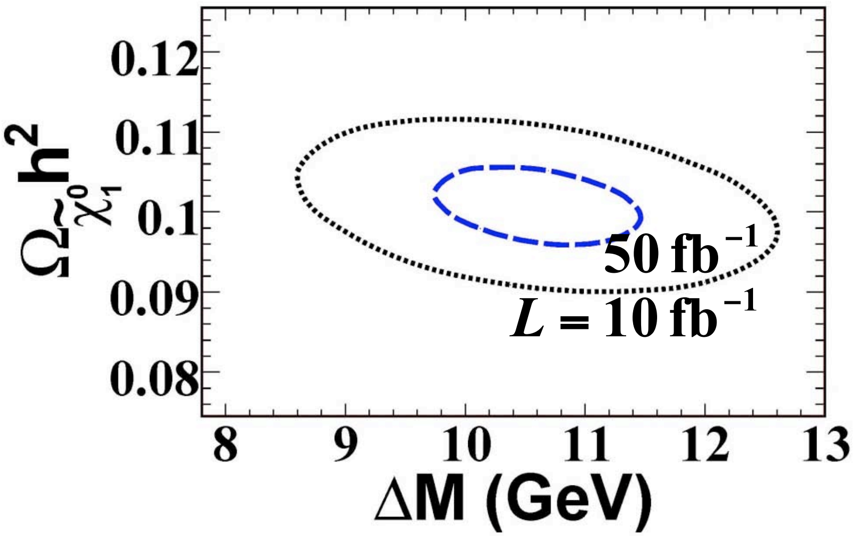
✓Solved by inverting the following functions:

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

10 fb^{-1}

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

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

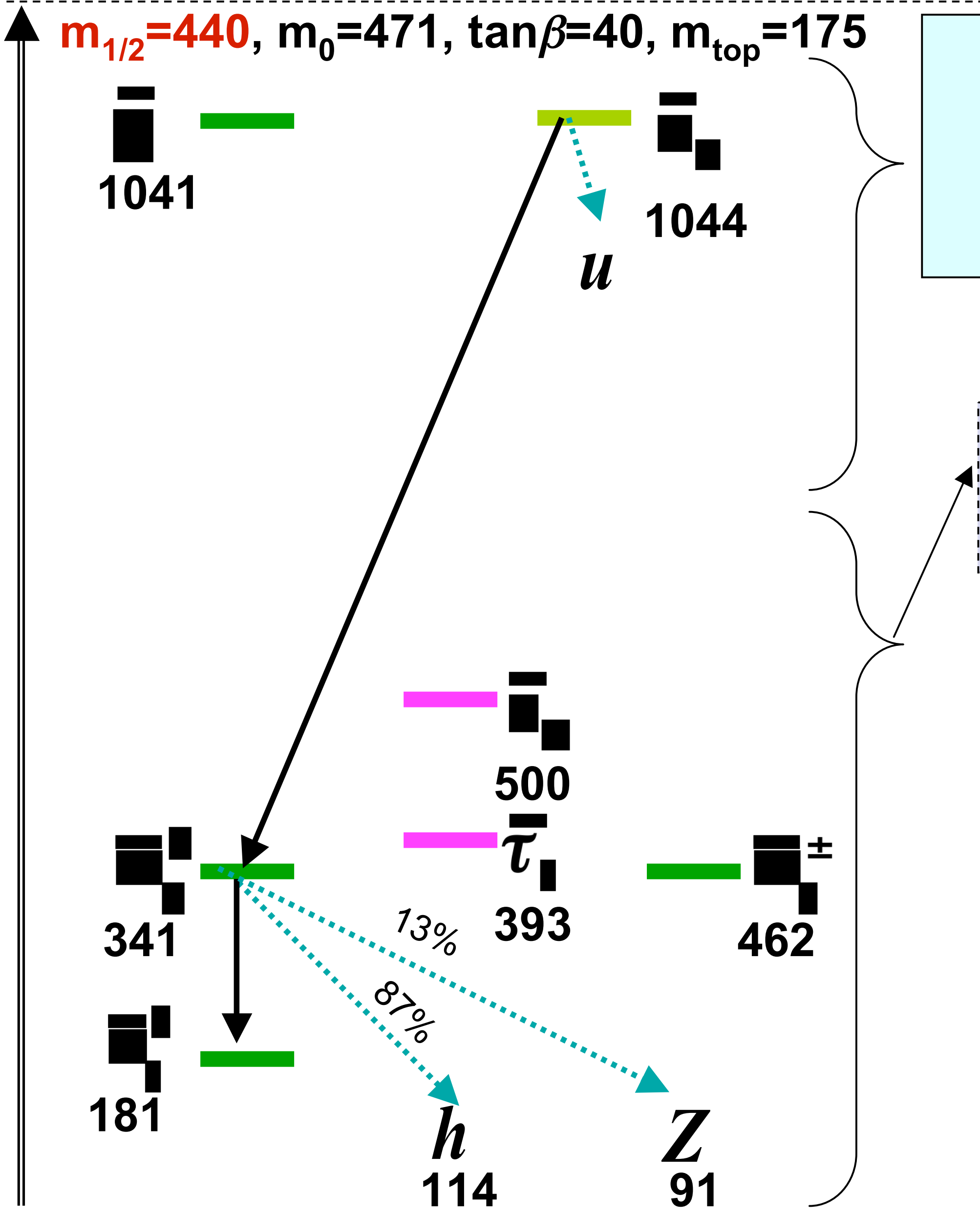


$$
\begin{aligned}
\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 &= 6.2\%\ (30\ \mathrm{fb}^{-1}) \\
&= 4.1\%\ (70\ \mathrm{fb}^{-1})
\end{aligned}
$$

Phys.Rev.Lett.100:231802,2008.

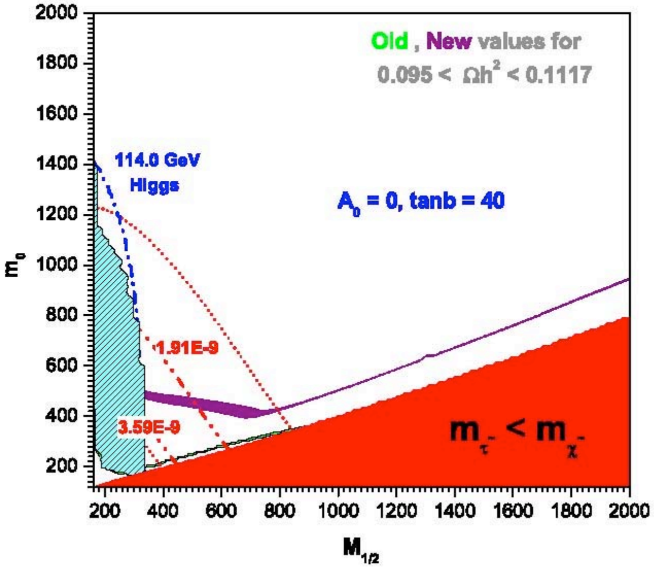
Case 2 : Over-dense region

$m_{1/2}=440$, $m_0=471$, $\tan\beta=40$, $m_{top}=175$



$E_T^{miss} > 180$ GeV;
N(jet) ≥ 2 with $E_T > 200$ GeV;
$E_T^{miss} + E_T^{j1} + E_T^{j2} > 600$ GeV

N(*b*) ≥ 2 with
$P_T > 100$ GeV; $0.4 < \Delta R_{bb} < 1$



Determining Ωh^2

✓Solved by inverting the following functions:

$$M_{jbb}^{\text{end point}} = X_1(m_{1/2}, m_0)$$

$$M_{\text{eff}}^{\text{peak}} = X_2(m_{1/2}, m_0)$$

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

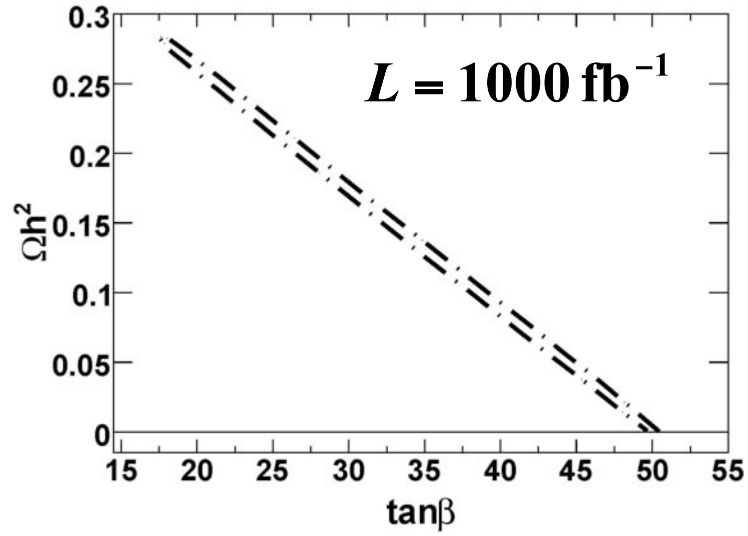
$$M_{\text{eff}}^{(bb)\,\text{peak}} = X_4(m_{1/2}, m_0, \tan\beta, A_0)$$

1000 fb^{-1}

$$\begin{cases} m_0 = 472 \pm 50 \\ m_{1/2} = 440 \pm 15 \\ A_0 = 0 \pm 95 \\ \tan\beta = 39 \pm 18 \end{cases}$$

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

$$\delta Ù_{\tilde{\chi}_1^0} h^2 / Ù_{\tilde{\chi}_1^0} h^2 \sim 150\%$$



Dutta, Kamon,Nanopoulos etal ’09

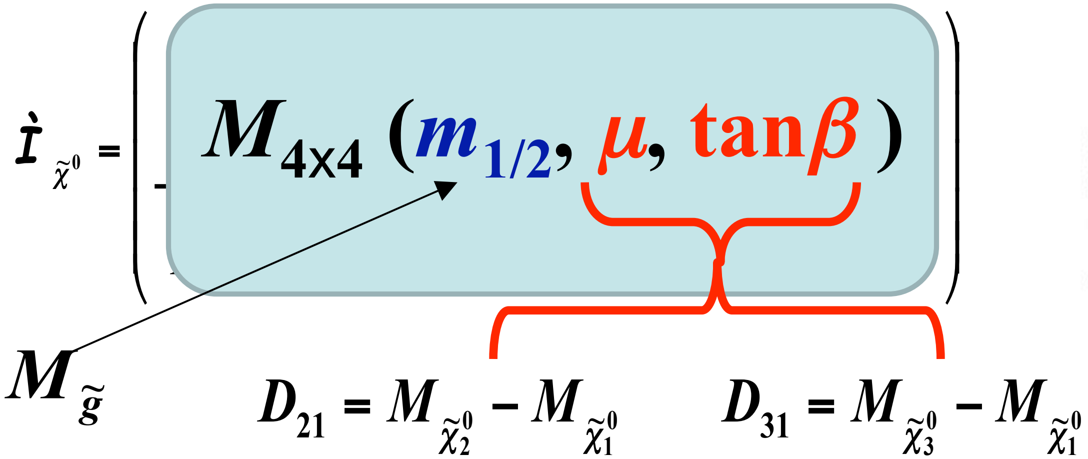
Phys.Rev.D79:055002,2009

Case 3 : Focus Point /HB

Prospects at the LHC:

A few mass measurements are available: 2nd and 3rd neutralinos, and gluino

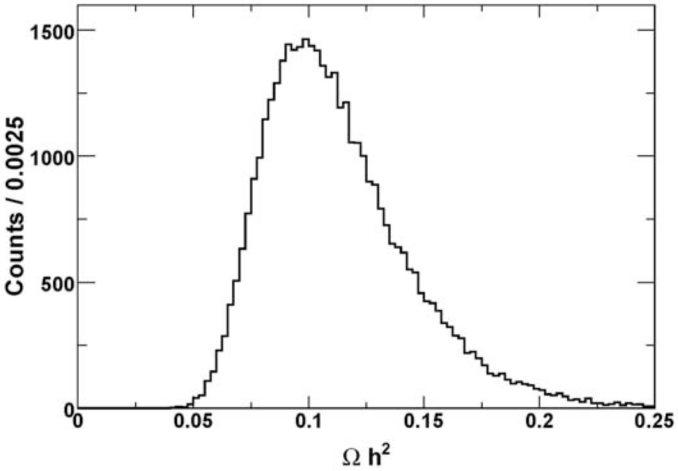
$$\boxed{\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_{1/2}, \mu, \tan\beta)}$$



$$\dot{\imath}_{\tilde{\chi}^0} = \left(M_{4x4}\,(m_{1/2}, \underbrace{\mu, \tan\beta}) \right)$$

$$M_{\tilde{g}}$$

$$D_{21} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \qquad D_{31} = M_{\tilde{\chi}_3^0} - M_{\tilde{\chi}_1^0}$$



Case 4 : Non-U SUGRA

Nature may not be so kind … Our studies have been done based on a minimal scenario (= mSUGRA).

…

Let's consider a non-universal scenario: Higgs non-universality: m_{Hu}, $m_{Hd} \neq m_0$

Steps:

1) Reduce Higgs coupling parameter, μ, by increasing

2) m_{Hu}, … → More annihilation (less abundance)

→ correct values of Ωh^2

3) Find smoking gun signals → Technique to calculate Ωh^2

Extraction of Model Parameters

Utilizing the characteristic decays, we can create some observables to determine our model parameters:

$$\left.\begin{array}{c} M_{\mathrm{eff}}(m_0, m_{1/2}) \\ M_{j\tau\tau}(m_0, m_{1/2}) \end{array}\right. \Rightarrow m_0, m_{1/2}$$

$$\left.\begin{array}{c} M_{W\tau\tau}(m_{1/2}, \mu(m_{H_u}), \tan\beta) \\ M_{jW}(m_0, m_{1/2}, \mu(m_{H_u}), \tan\beta) \end{array}\right. \Rightarrow \mu(m_{H_u}), \tan\beta$$

$$M_{\mathrm{eff}}^{(b)}(m_0, m_{1/2}, \mu(m_{H_u}), \tan\beta, A_0) \Rightarrow A_0$$

End-points-nonuniversal

M(jW) [$\chi_1^\pm \rightarrow \chi_1^0$] = 714.6 GeV

M(jW) [$\chi_2^\pm \rightarrow \chi_2^0$] = 727.3 GeV

[use 2 τ's since $\chi_2^0 \rightarrow \tau^\pm\tau^\mp\chi_0^1$]

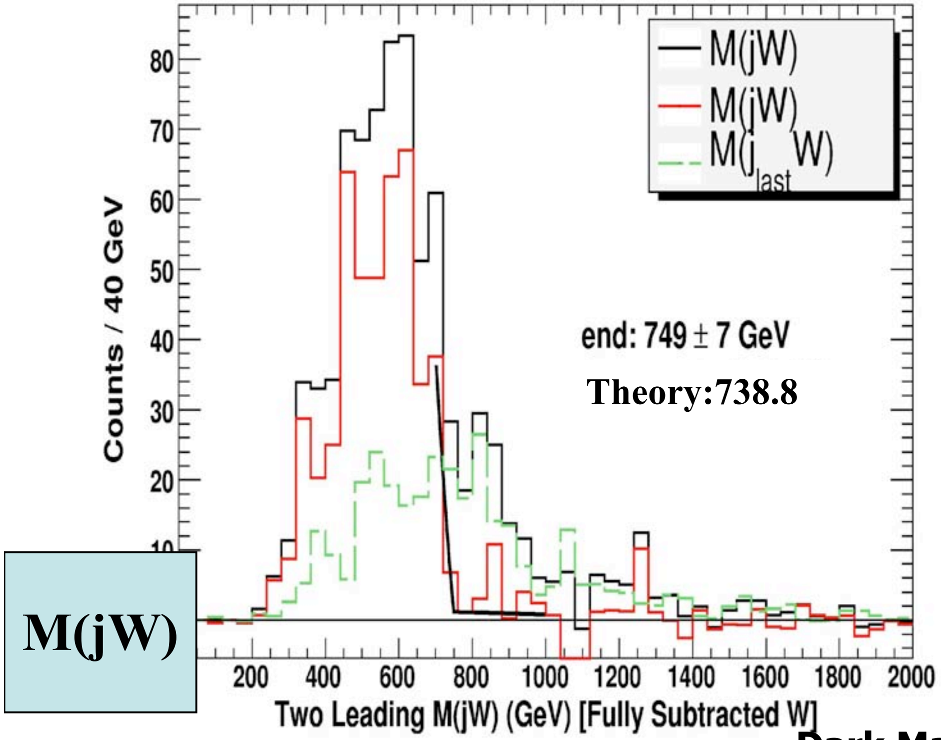
M(jW)[$\chi_2^\pm \rightarrow \chi_3^0$] = 652.4 GeV

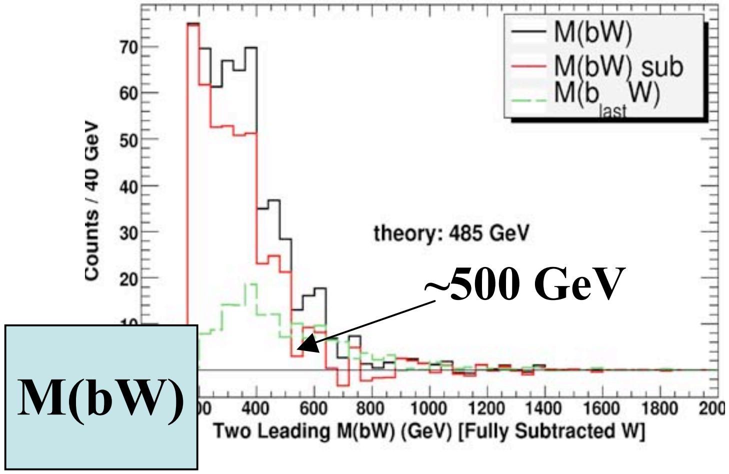
[use Z since $\chi_2^0 \rightarrow Z\chi_1^0$]

M(jW) [$\chi_4^0 \rightarrow \chi_1^\pm$] = 738.6 GeV

We have 3 (4) parameters in the chargino-neutralino system: $m_{1/2}$, μ, tanβ (m_1,m_2, μ, tanβ)

We can use stop decay chain
In this case we use a b/t





Similarly, M(tZ) $\chi_3^0 \rightarrow \chi_1^0$ =338 GeV

Mττ, Mjττ etc can also be constructed

Conclusion

Signature contains missing energy (R parity conserving) many jets and leptons : Discovering SUSY should not be a problem!

Once SUSY is discovered, attempts will be made to measure the sparticle masses (highly non trivial!), establish the model and make connection between particle physics and cosmology

Different cosmologically motivated regions of the minimal model have distinct signatures.
It is possible to determine model parameters and the relic density based on the LHC measurements

Work is in progress to determine non-universal model Parameters----looks promising