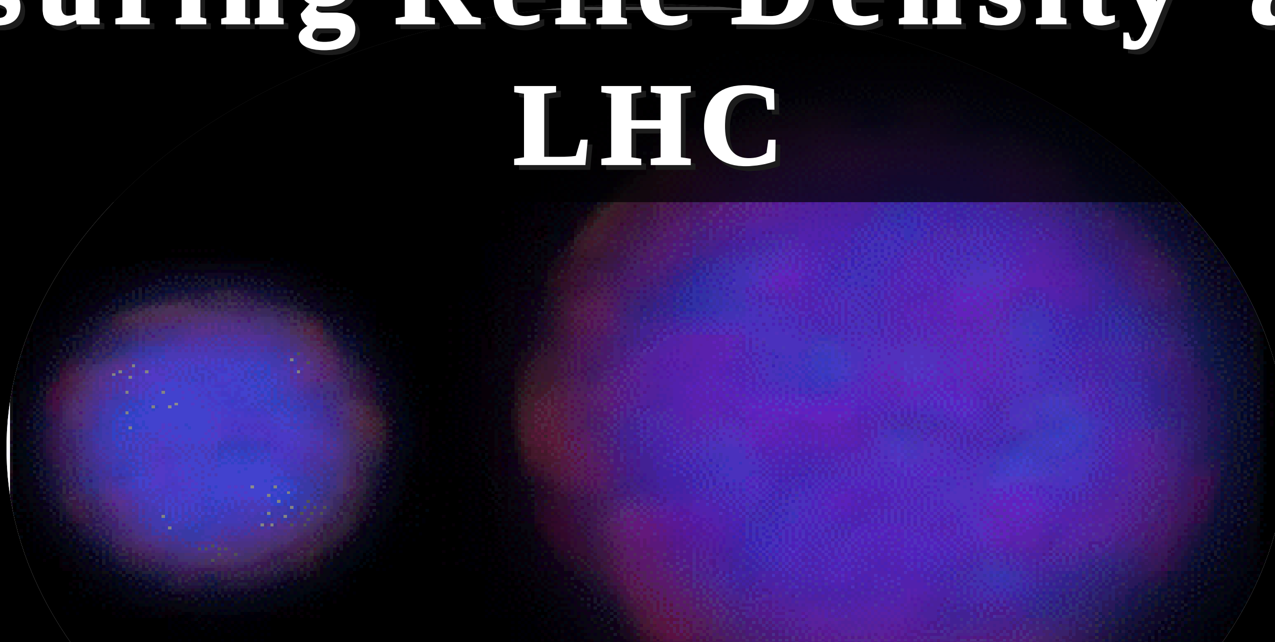
Measuring Relic Density at the LHC



Bhaskar Dutta

Collaborators R. Arnowitt, A. Gurrola, T. Kamon, A. Krislock, D. Toback

Texas A&M University

OUTLINE

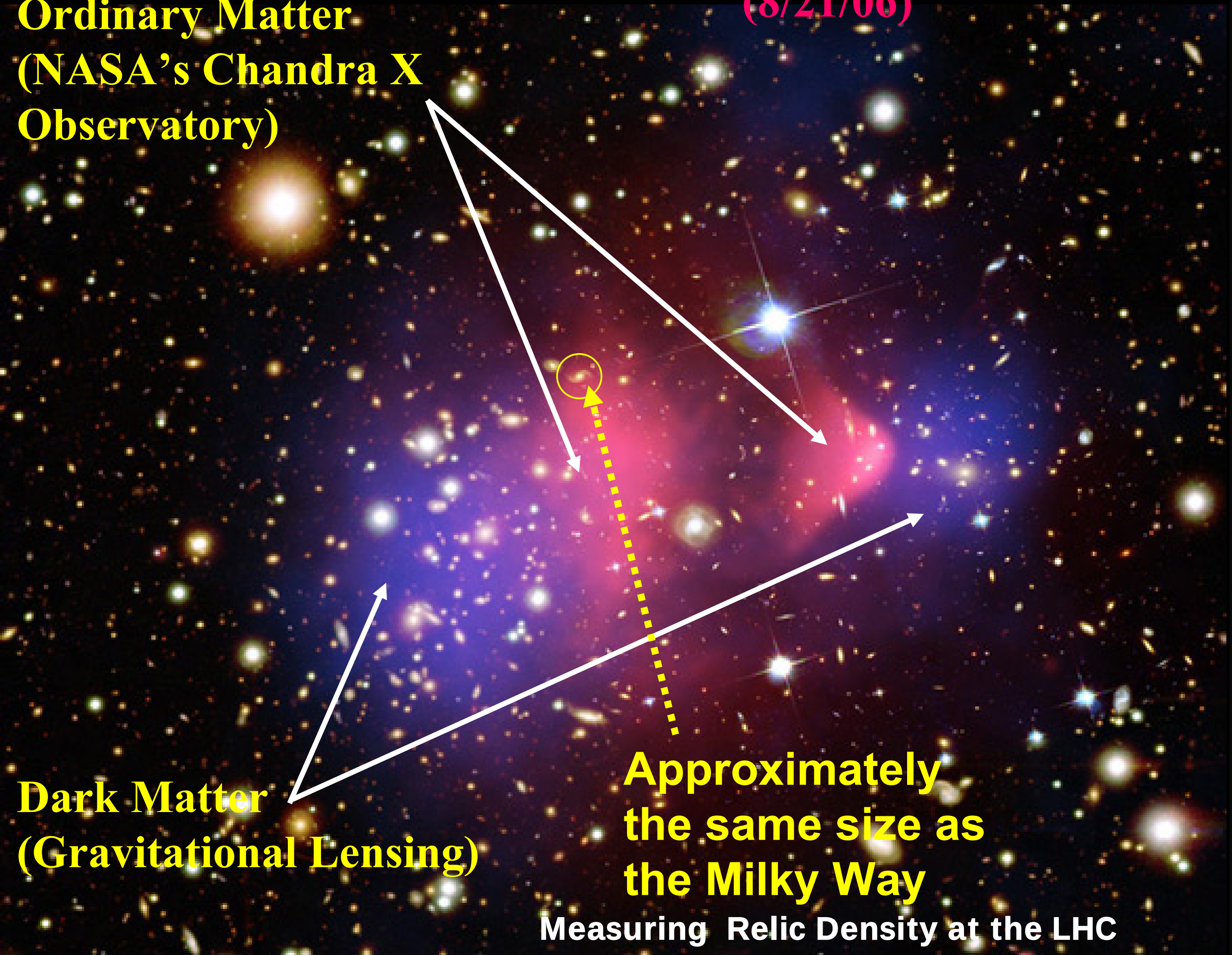
- Dark Matter (DM) in Universe
- DM Relic Density (Ωh^2) in SUSY
- mSUGRA Co-annihilation (CA) Region at the LHC
- Prediction of DM Relic Density (Ωh^2)
- Summary

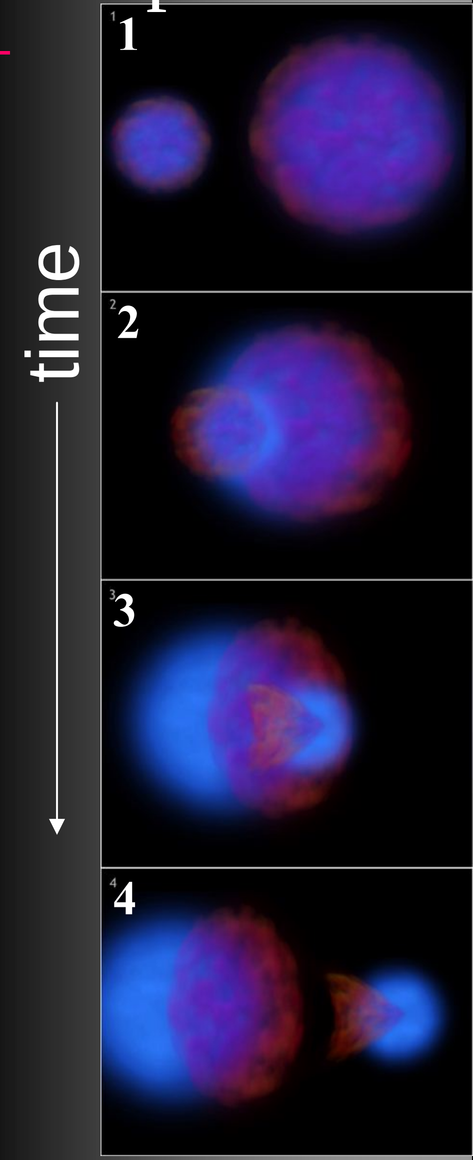
Arnowitt, Dutta, Kamon, Kolev, Toback, PLB 639 (2006) 46
Arnowitt, Arusano, Dutta, Kamon, Kolev, Simeon, Toback, Wagner, PLB 649 (2007) 73
Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, Phys. Rev. Lett. 100, (2008) 231802

Dark Matter (DM) in Universe

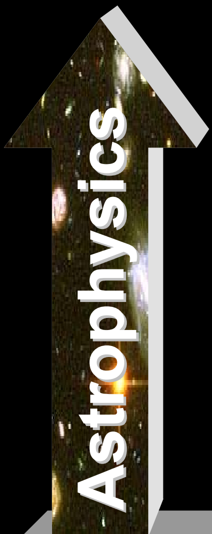
splitting normal matter and dark matter apart

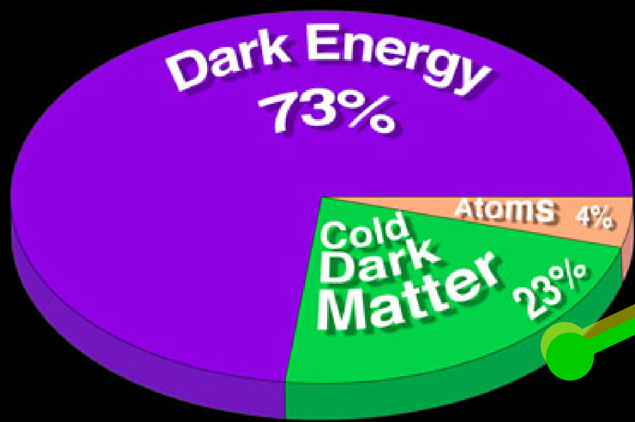
– Another Clear Evidence of Dark Matter – (8/21/06)





DM Particle in SUSY

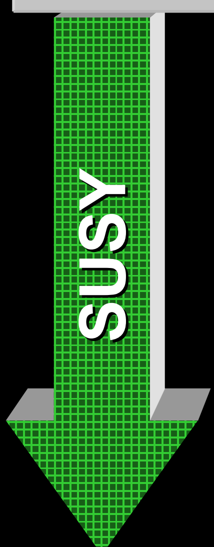




$$\underbrace{\Omega_{\tilde{\chi}_1^0} h^2}_{0.23} \sim \int_0^{x_f} \frac{1}{\langle \sigma_{ann} v \rangle} dx$$

$$\underbrace{\langle \sigma_{ann} v \rangle}_{0.9\,\mathrm{pb}} = \frac{\pi \alpha^2}{8M^2}$$

CDM = Neutralino ($\tilde{\chi}_1^0$)

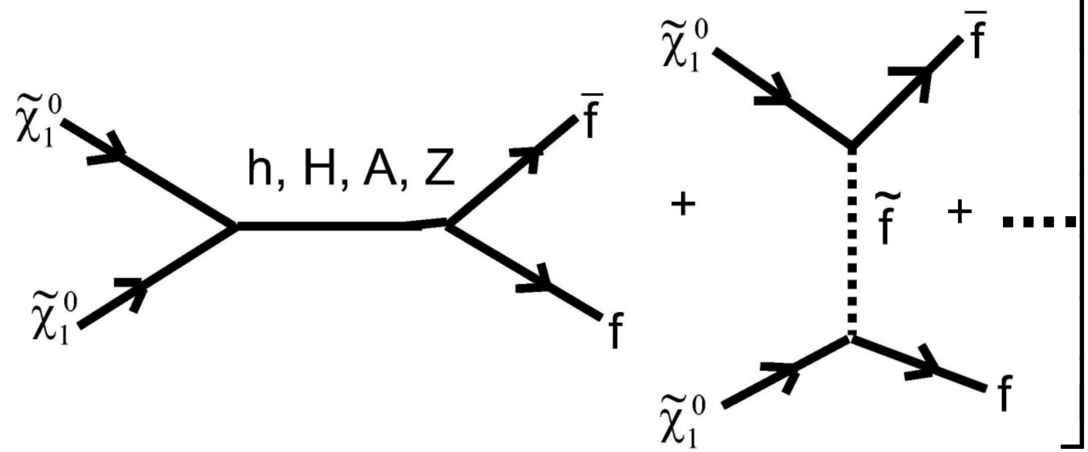


SUSY is an interesting class of models to provide a weakly interacting massive neutral particle ($M \sim 100$ GeV).

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

Anatomy of σ_{ann}

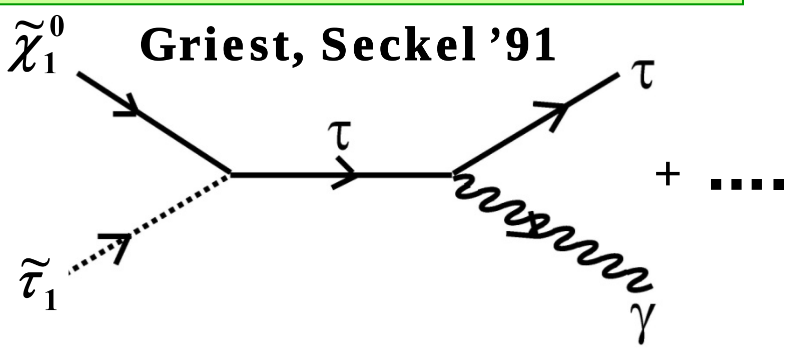
$$(\Omega_{\mathrm{CDM}})^{-1} \propto \Big[\cdots \Big]^2$$



$$+ \Big[\cdots \Big]^2$$

Co-annihilation (CA) Process

Griest, Seckel '91



$$e^{-\Delta M / 20}$$

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

A near degeneracy occurs naturally for light stau in mSUGRA.

Coannihilation, GUT Scale

In mSUGRA model the lightest stau seems to be naturally close to the lightest neutralino mass especially for large tanβ

For example, the lightest selectron mass is related to the lightest neutralino mass in terms of GUT scale parameters:

$$m^2_{\tilde{E}^c} = m_0^2 + 0.15 m_{1/2}^2 + (37\,\mathrm{GeV})^2 \qquad m^2_{\tilde{\chi}_1^0} = 0.16 m_{1/2}^2$$

Thus for $m_0 = 0$, $\tilde{E}_c^2$ becomes degenerate with $\tilde{\chi}_1^0$ at $m_{1/2} = 370$ GeV, i.e. the coannihilation region begins at

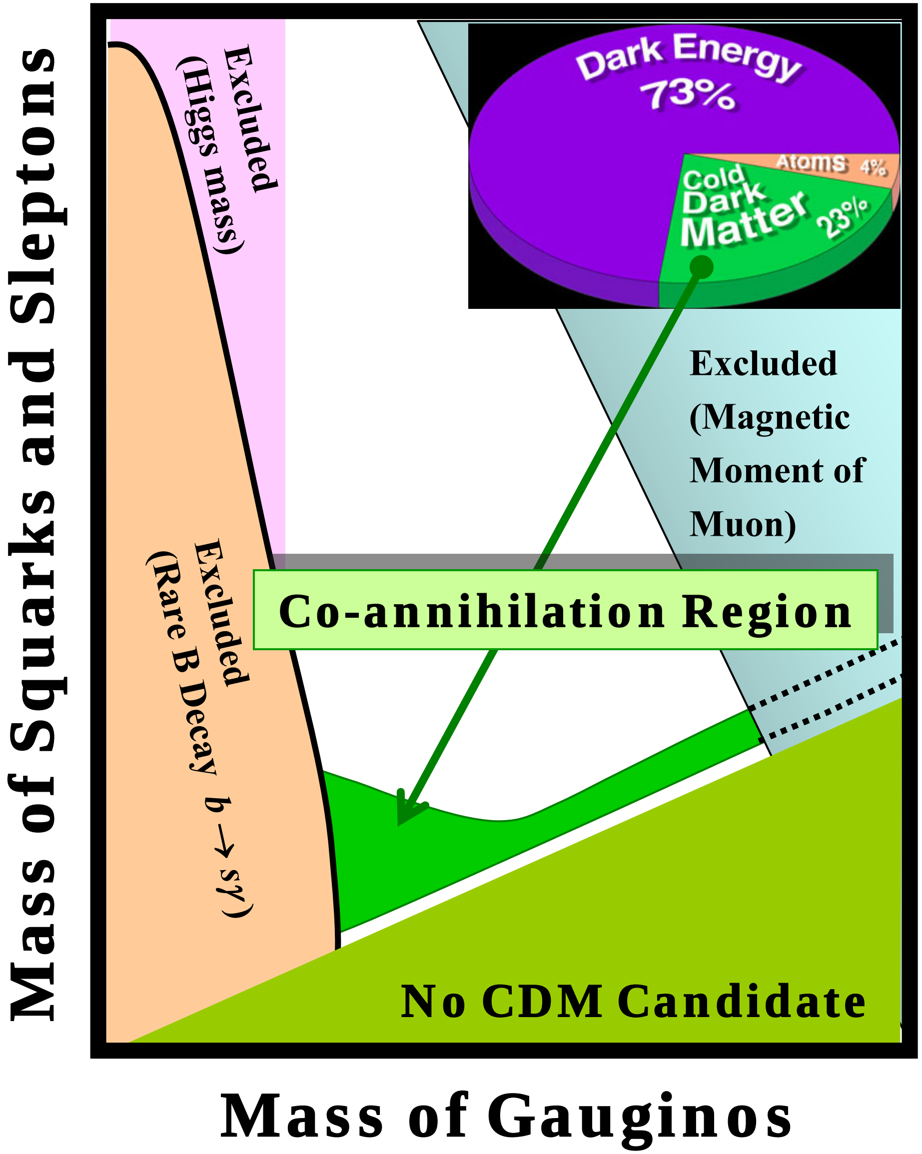
Arnowitt, Dutta, Santoso' 01

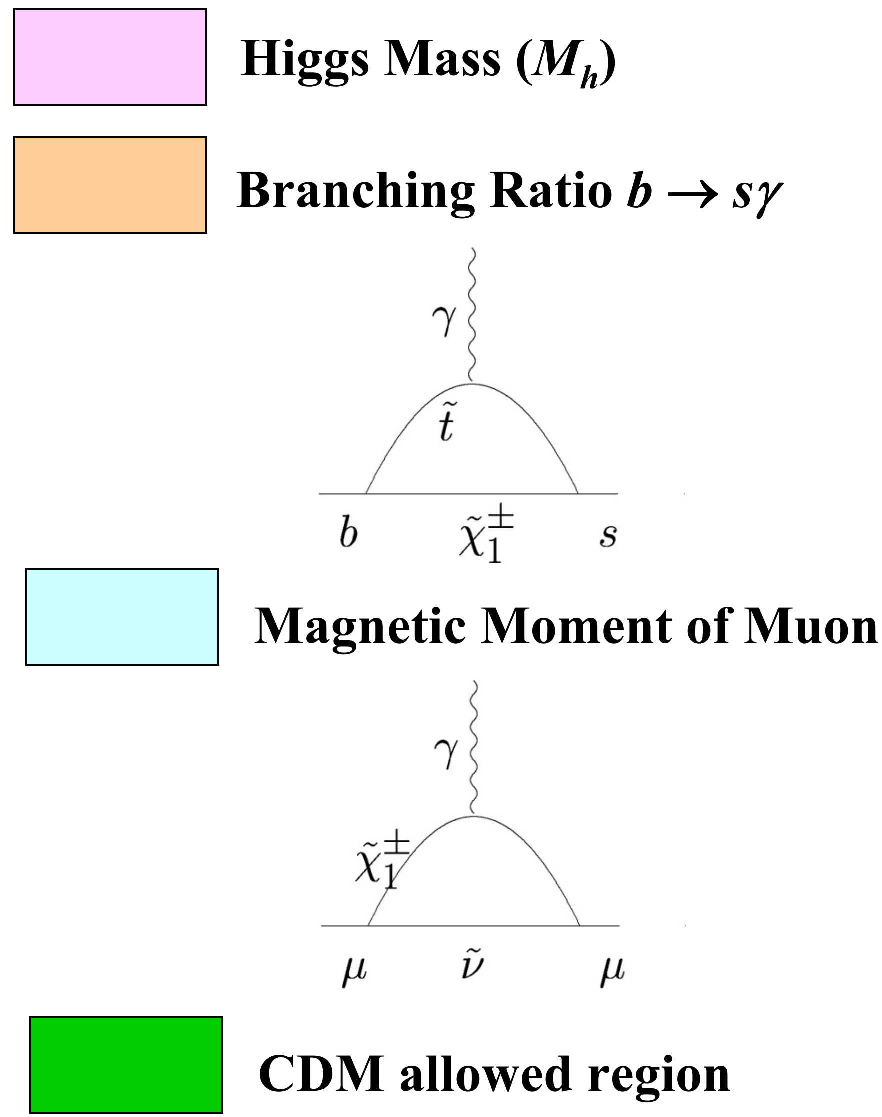
$$m_{1/2} = (370\text{-}400)\ \mathrm{GeV}$$

For larger $m_{1/2}$ the degeneracy is maintained by increasing m_0 and we get a corridor in the m_0 - $m_{1/2}$ plane.

The coannihilation channel occurs in most SUGRA models with non-universal soft breaking,

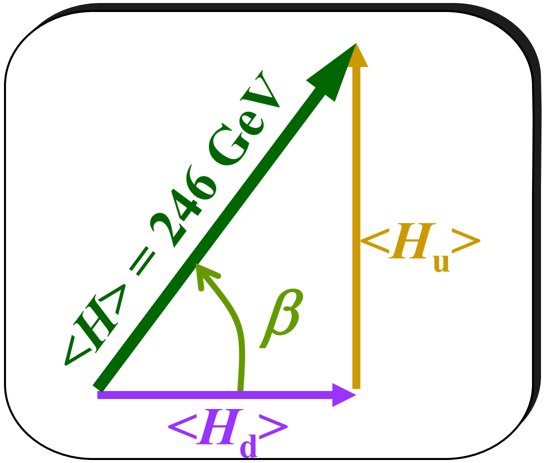
DM Allowed Regions - Illustration



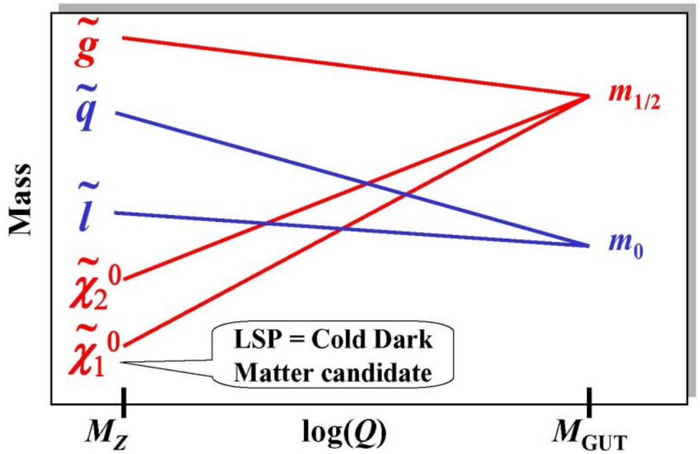


Minimal Supergravity (mSUGRA)

SUSY model in the framework of unification:



+



4 parameters + 1 sign

- $\tan\beta$ — $\langle H_u \rangle / \langle H_d \rangle$ at M_Z
- $m_{1/2}$ — Common gaugino mass at M_{GUT}
- m_0 — Common scalar mass at M_{GUT}
- A_0 — Trilinear couping at M_{GUT}
- sign(μ) — Sign of μ in $W^{(2)} = \mu H_u H_d$

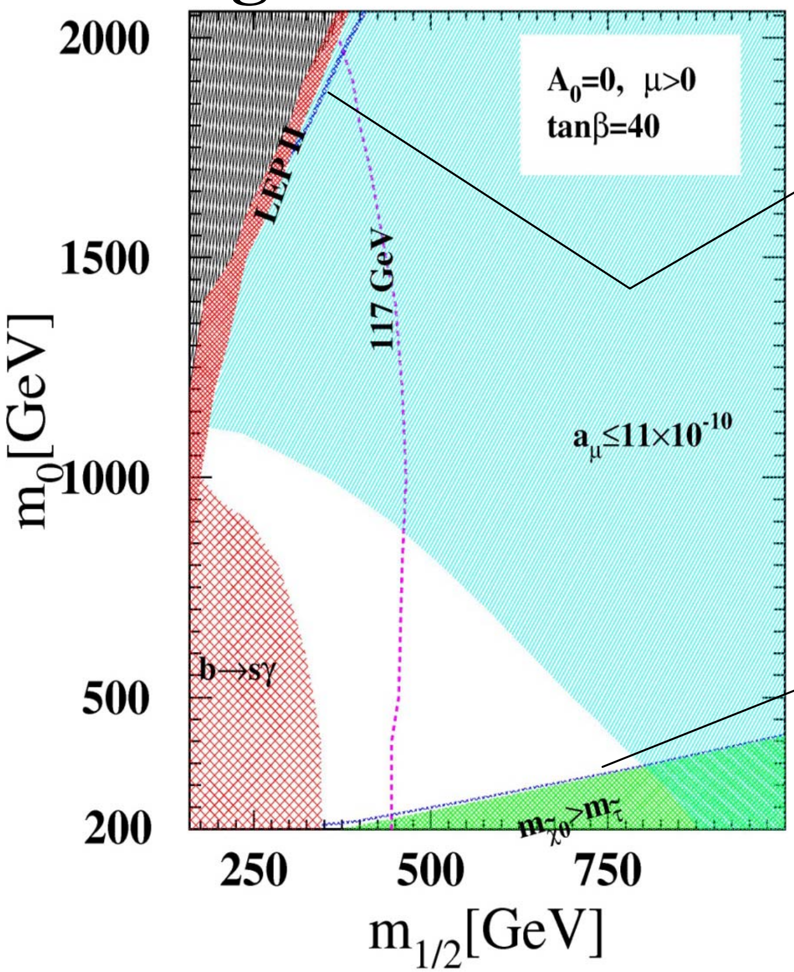
Arnowitt, Chamesdinne, Nath, PRL 49 (1982) 970; NPB 227 (1983) 121.
Barbieri, Ferrara, Savoy, PLB 119 (1982) 343.
Lykken, Hall, Weinberg, PRD 27 (1983) 2359.

Key Experimental Constraints

- ✓ $M_{Higgs} > 114$ GeV
- ✓ $M_{chargino} > 104$ GeV
- ✓ $2.2\times10^{-4} < \mathcal{B}(b \to s\,\gamma) < 4.5\times10^{-4}$
- ✓ $(g-2)_\mu$: 3 σ deviation from SM
- ✓ $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

DM Allowed Regions in mSUGRA

Below is the case of mSUGRA model. However, the results can be generalized.



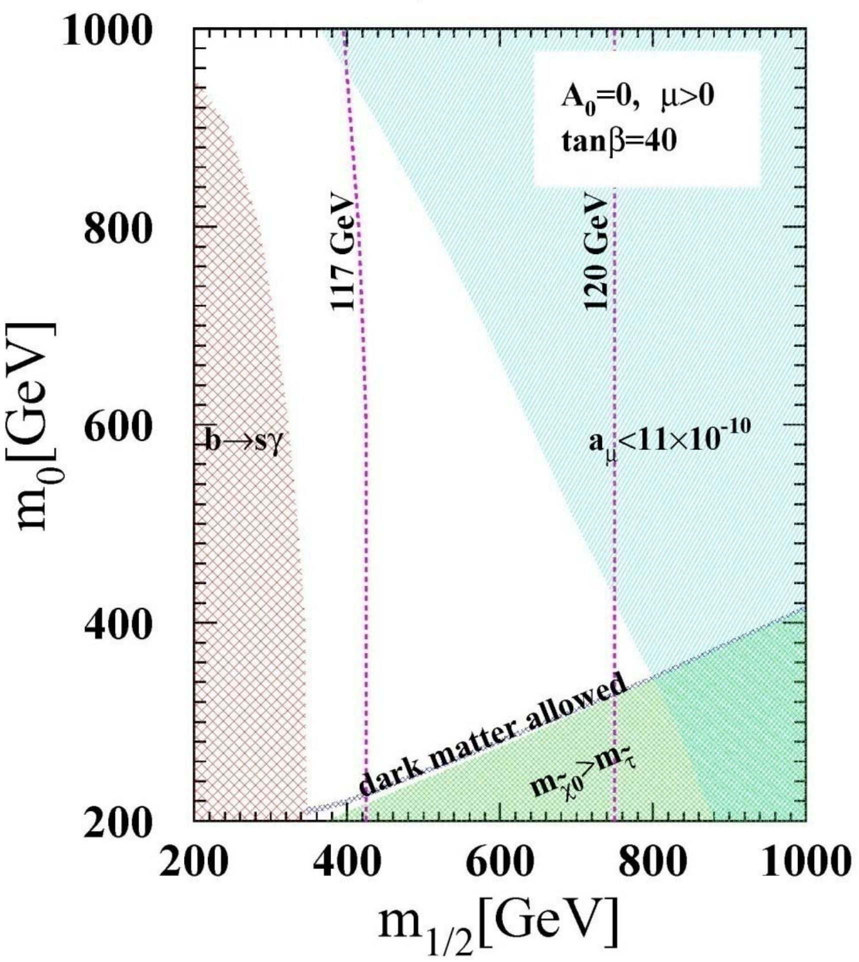
[Focus point region]
the lightest neutralino has a larger Higgsino component

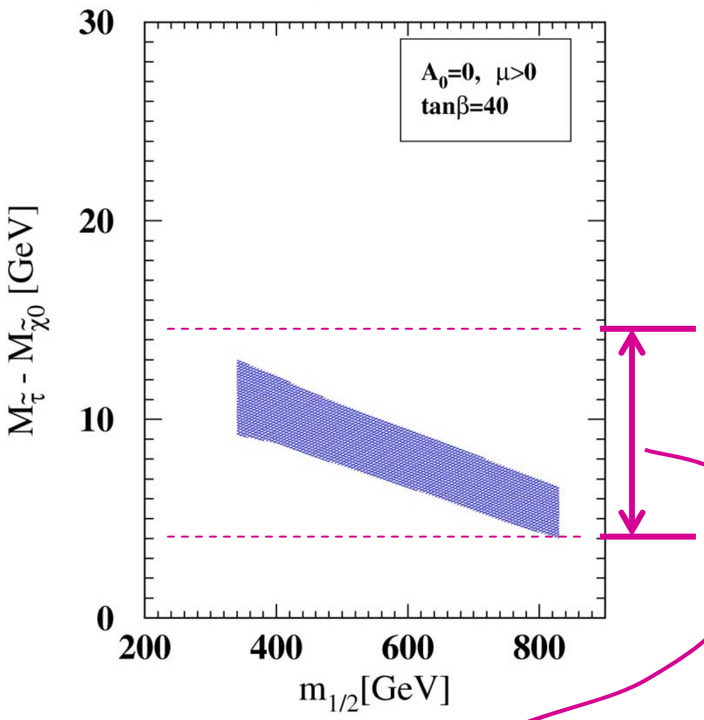
[*A*-annihilation funnel region]
This appears for large values of $m_{1/2}$

[Stau-Neutralino CA region]

[Bulk region] almost ruled out

CA Region at $\tan\beta = 40$

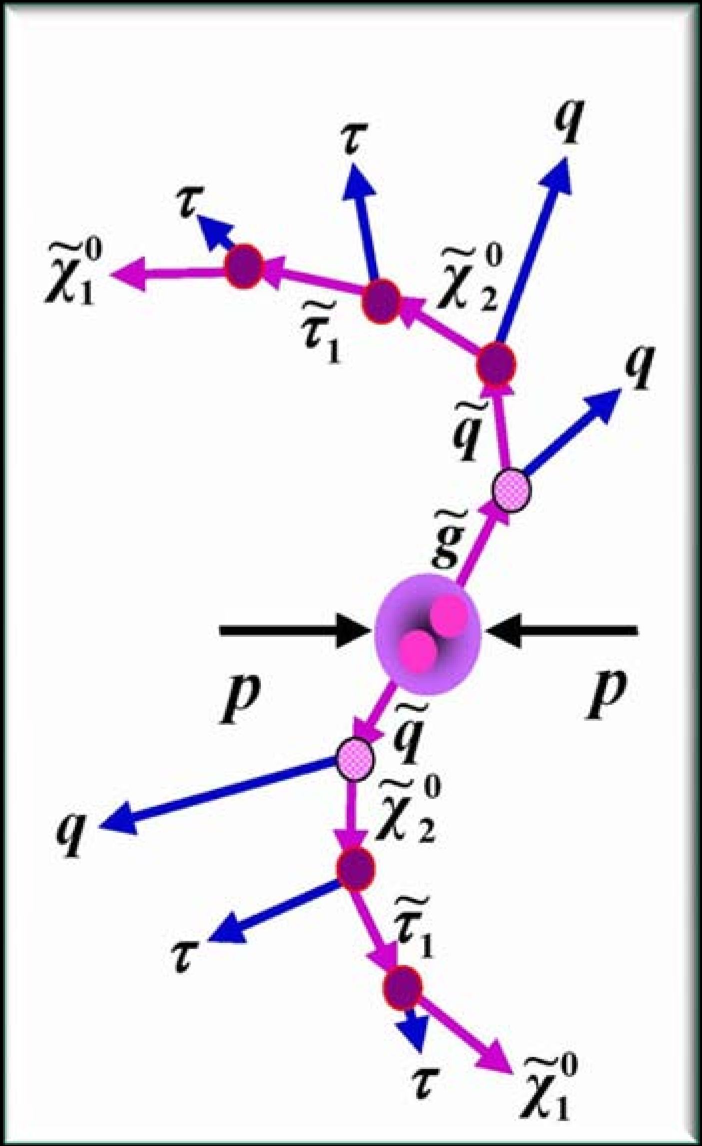




$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15\ \text{GeV}$$

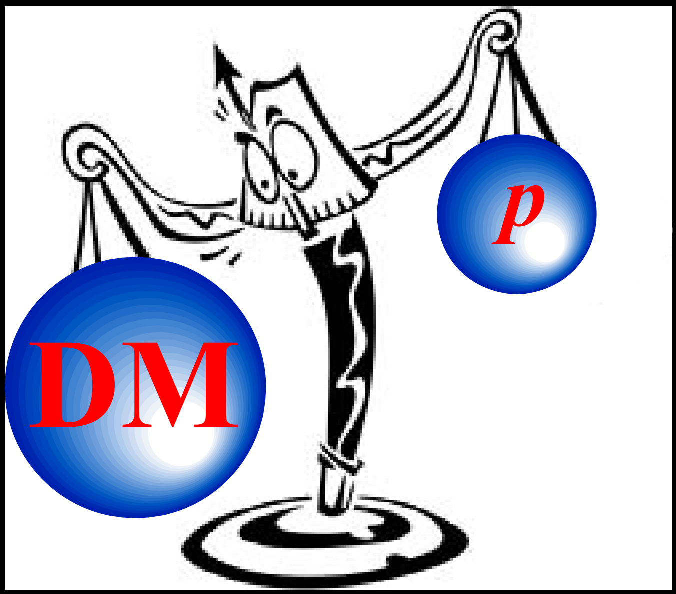
Can we measure ΔM at colliders?

MOST WANTED!



This is one of the key reactions to discover the neutralinos at the LHC.

We will have to extract this reaction out of many trillion pp collisions and measure SUSY masses.



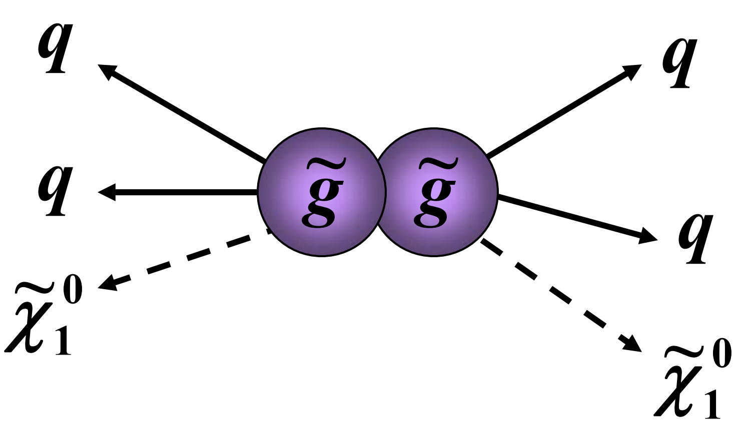
1^{st} analysis: Excess in E_T^{miss} + Jets

- ❑ Excess in E_T^{miss} + Jets → R-parity conserving SUSY
- ❑ M_{eff} → Measurement of the SUSY scale at 10-20%.

Hinchliffe and Paige, Phys. Rev. D 55 (1997) 5520

- ➢ $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV
- ➢ $M_{eff} > 400$ GeV ($M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$)
- ➢ $E_T^{miss} > \max[100, 0.2\, M_{eff}]$

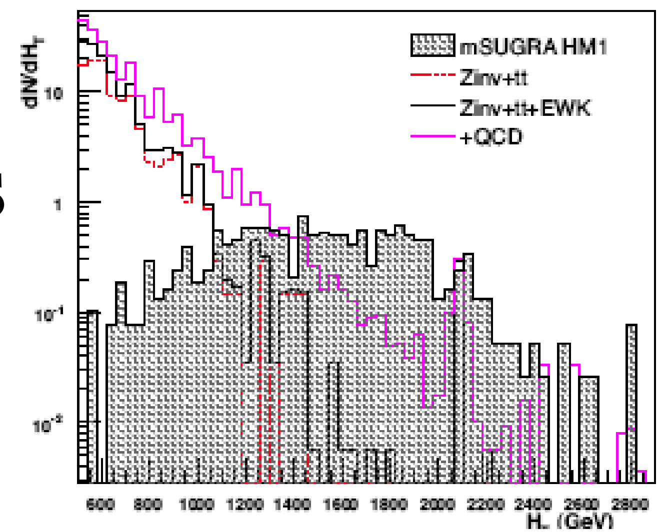
The heavy SUSY particle mass is measured by combining the final state particles



$m_{1/2} = 250$, $m_0 = 60$; $\sigma = 45$ fb

M(gluino) = 1886; M(squark) = 1721

CMS



Relic Density and M_{eff}

SUSY scale is measured with an accuracy of 10-20%

- This measurement does not tell us whether the model can generate the right amount of dark matter

- The dark matter content is measured to be 23% with an accuracy of around 4% at WMAP

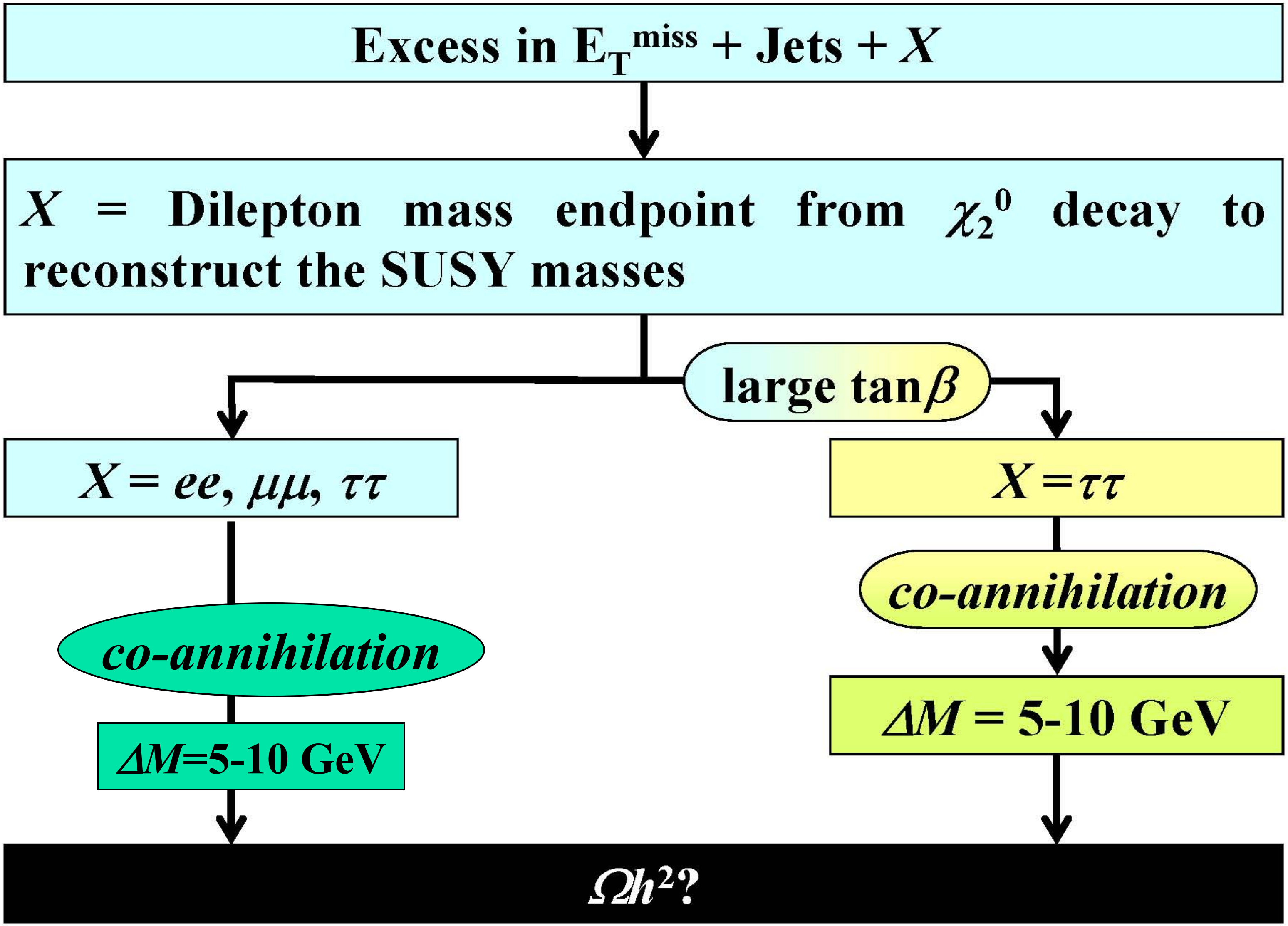
- Question:

To what accuracy can we calculate the relic density based on the measurements at the LHC?

Goal

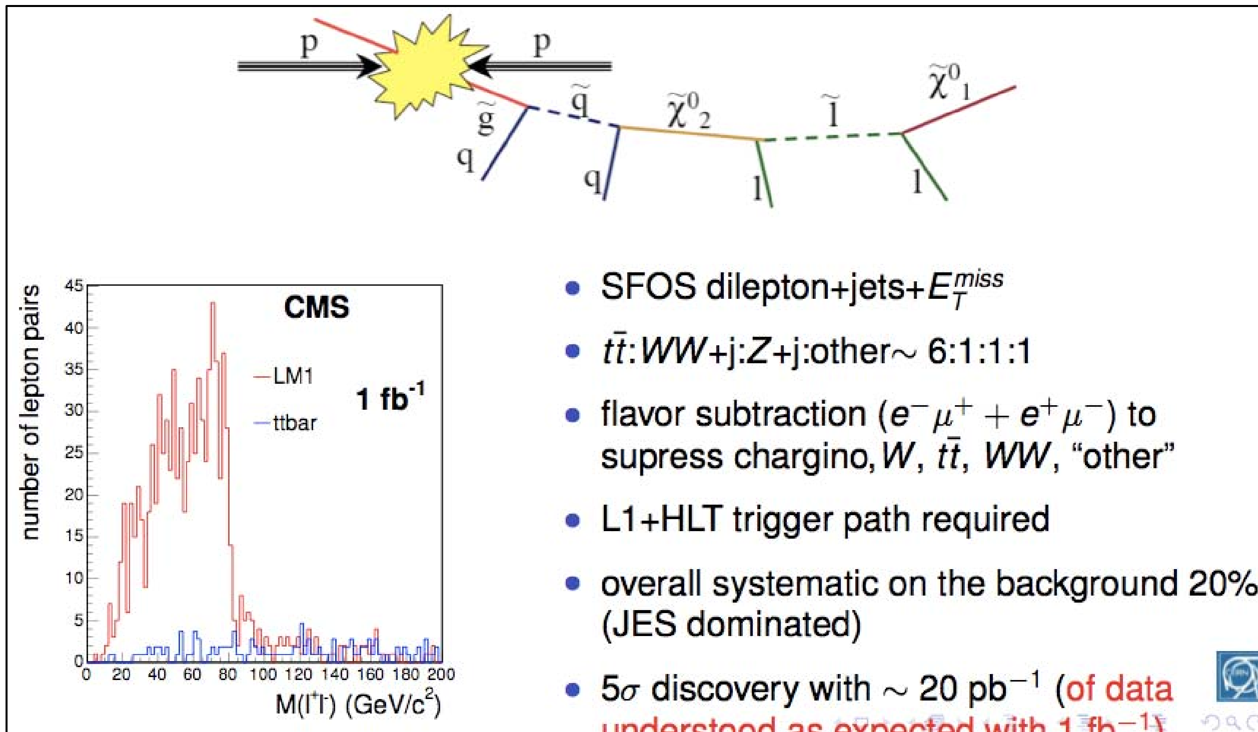
- ✓ Establish the "CA region" signal
- ✓ Measure SUSY masses
- ✓ Determine mSUGRA parameters
- ✓ Predict $\Omega_\chi h^2$ and compare with $\Omega_{CDM}h^2$

Analysis Strategy



Dilepton Endpoint

- **DM content → Measurements of the SUSY masses [e.g., M.M. Nojiri, G. Polesselo, D.R. Tovey, JHEP 0603 (2006) 063]**
- **Dilepton "edge" in the χ_2^0 decay in dilepton (ee, $\mu\mu$, $\tau\tau$) channels for reconstruction of decay chain.**



LM1:

(Low Mass Case 1)

$m_{1/2}$= 180, m_0= 850;

σ = 55 pb

[post-WMAP benchmark point B']

M(gluino) = 611

M(squark) = 559

gluino → squark+quark

B(χ_2^0→ slep_R lep) = 11.2%

B(χ_2^0 → stau_1 tau) = 46%

B(χ_1^+ → sneu_L lep) = 36%

Dilepton Endpoint in CA Region

- In the CA region (after the experimental constraints), the *ee* and $\mu\mu$ channels are almost absent

  $\mathrm{Br}(\chi_2^0 \rightarrow ee\chi_2^0, \mu\mu\chi_1^0) \sim 0\%$

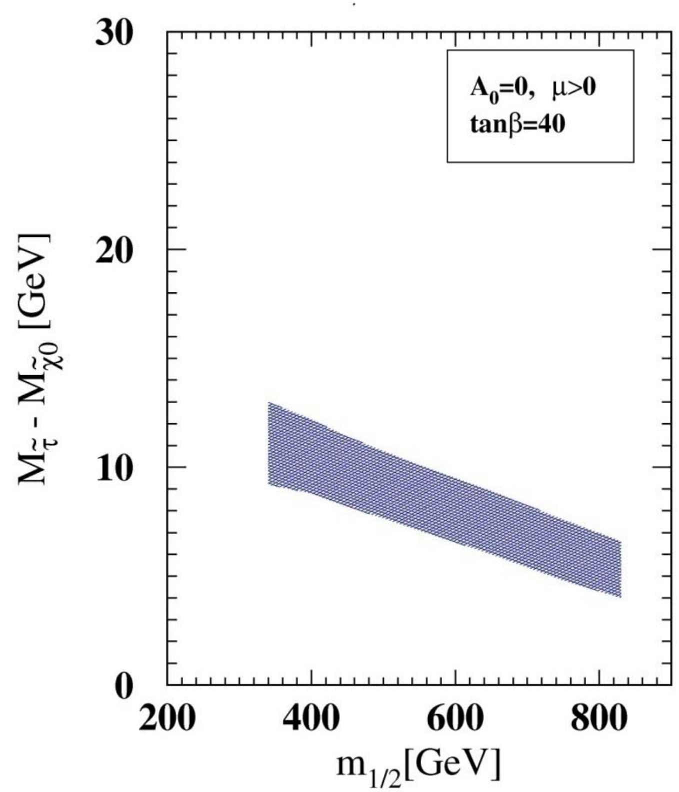
  $\mathrm{Br}(\chi_2^0 \rightarrow \tau\tau\chi_1^0) \sim 100\%$

  ΔM = 5-15 GeV

- Questions:

(1) How can we establish the DM allowed regions?

(2) To what accuracy can we calculate the relic density based on the measurements at the LHC?



Our Reference Point

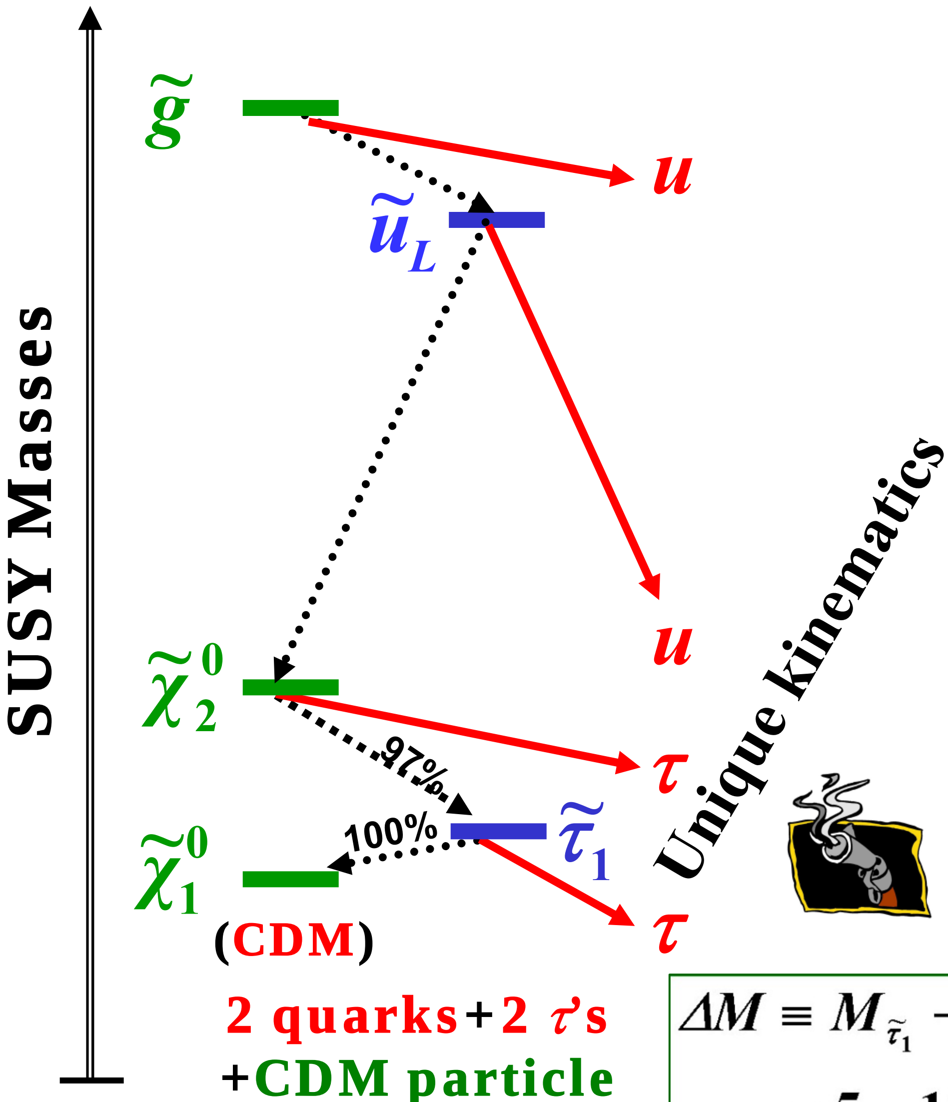
$m_{1/2}$ = 350, m_0 = 210, tanβ = 40, μ >0, A_0 = 0 [ISAJET version 7.64]

PLB 639 (2006) 46

TABLE I: SUSY masses (in GeV) for our reference point $m_{1/2}$ = 350 GeV, $m_0 = 210$ GeV, $\tan\beta = 40$, $A_0 = 0$, and $\mu > 0$.

$\tilde{g}$	$\tilde{u}_L$ / $\tilde{u}_R$	$\tilde{t}_2$ / $\tilde{t}_1$	$\tilde{b}_2$ / $\tilde{b}_1$	$\tilde{e}_L$ / $\tilde{e}_R$	$\tilde{\tau}_2$ / $\tilde{\tau}_1$	$\tilde{\chi}_2^0$ / $\tilde{\chi}_1^0$	ΔM
831	748 / 725	728 / 561	705 / 645	319 / 251	329 / 151.3	260.3 / 140.7	10.6

Smoking Gun of CA Region

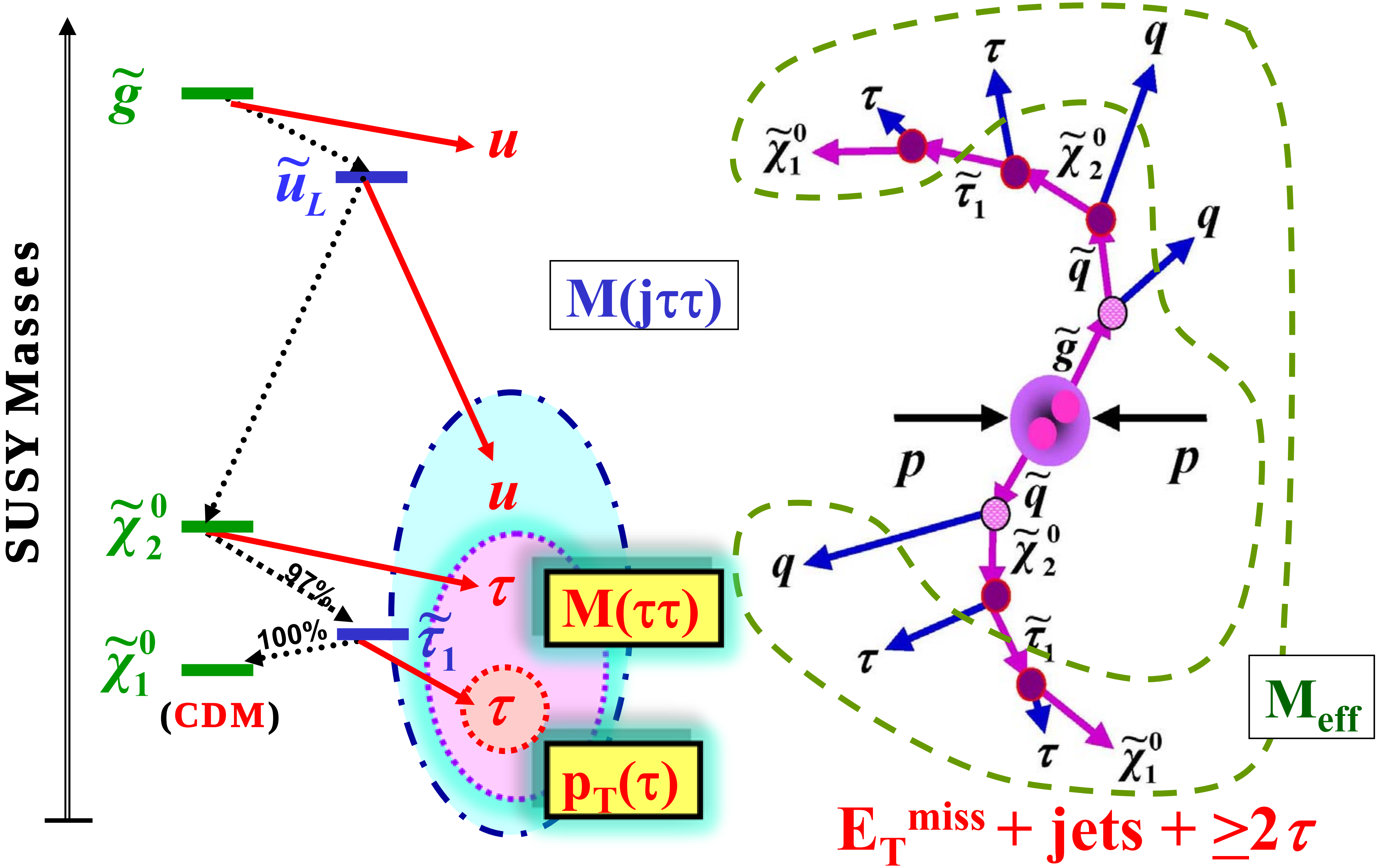


$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}$$

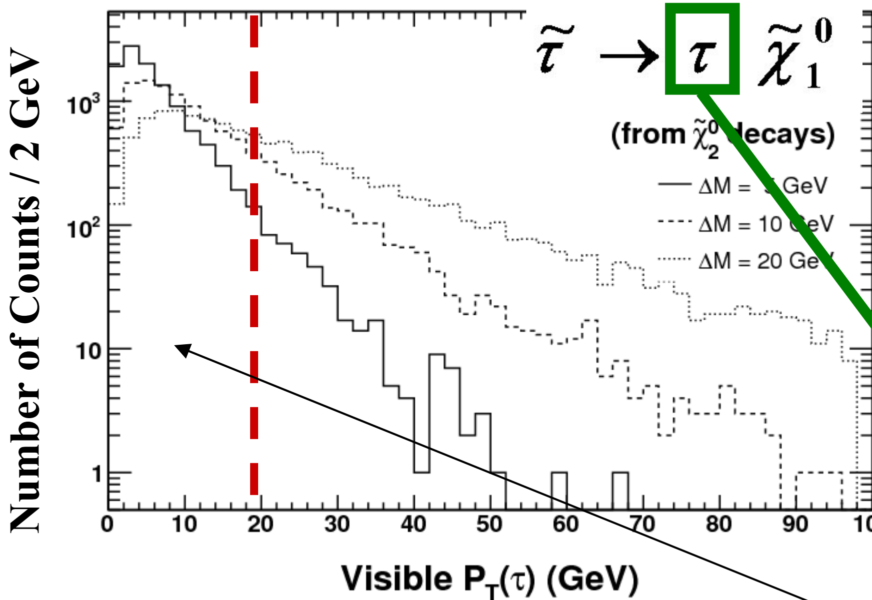
Low energy taus exist in the CA region

However, one needs to measure the model Parameters to predict the Dark matter content in this scenario

SUSY Anatomy I



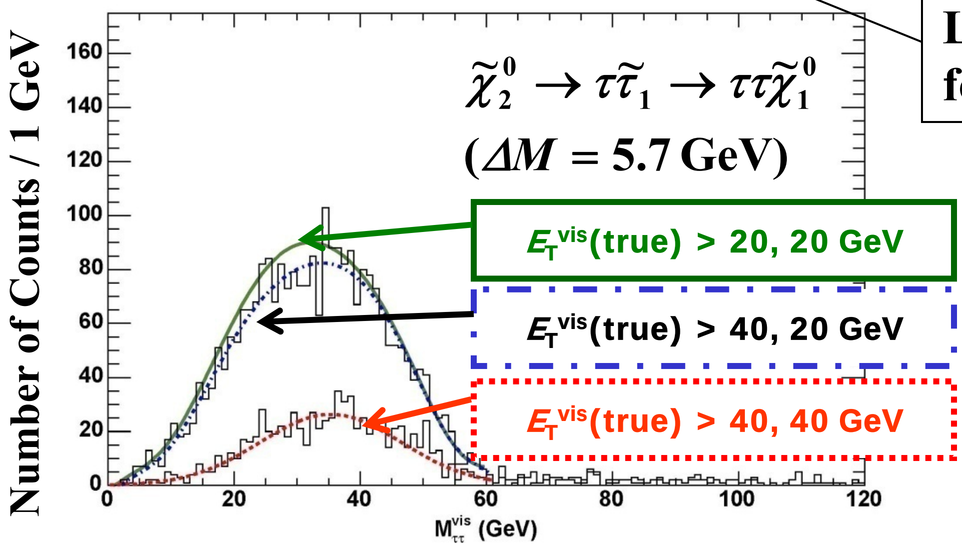
p_T^{soft} Slope and $M_{\tau\tau}$



p_T and $M_{\tau\tau}$ distributions in true di-τ pairs from neutralino decay

Slope of p_T distribution of "soft τ" contains ΔM information

Low energy τ's are an enormous challenge for the detectors



$\tilde{g}$ = 831 GeV
$\tilde{\chi}_2^0$ = 264 GeV
$\tilde{\chi}_1^0$ = 137.4 GeV
$\tilde{\tau}_1$ = 143.1 GeV
End pont = 62.0 GeV

Warming-up Quizzes

I. Hadronic or leptonic?

- Hadronic

II. How low in p_T?

- CDF : p_T^{vis} >15-20 GeV

[Assumption]

$\varepsilon_\tau = 50\%$, fake rate 1% for $p_T^{vis} > 20$ GeV

E_T^{miss} + 2j + 2τ Analysis Path

Cuts to reduce the SM backgrounds (*W*+jets, …)

$E_T^{miss} > 180$ GeV, $N(jet) \geq 2$ with $E_T > 100$ GeV

$E_T^{miss} + E_T^{j1} + E_T^{j2} > 600$ GeV; $N(\tau) \geq 2$ with $P_T > 40, 20$ GeV

CATEGORIZE opposite sign (OS) and like sign (LS) ditau events

OS$\tau\tau$	LS $\tau\tau$
$M_{\tau\tau}$ *histogram*	$M_{\tau\tau}$ *histogram*

OS mass → **OS–LS mass** ← **LS mass**

We use ISAJET + PGS4

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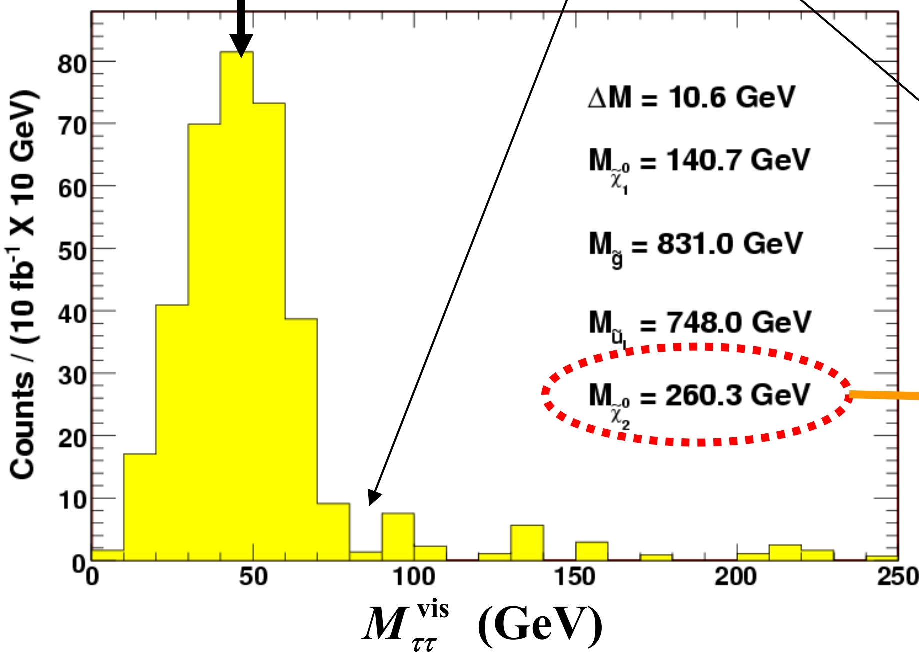
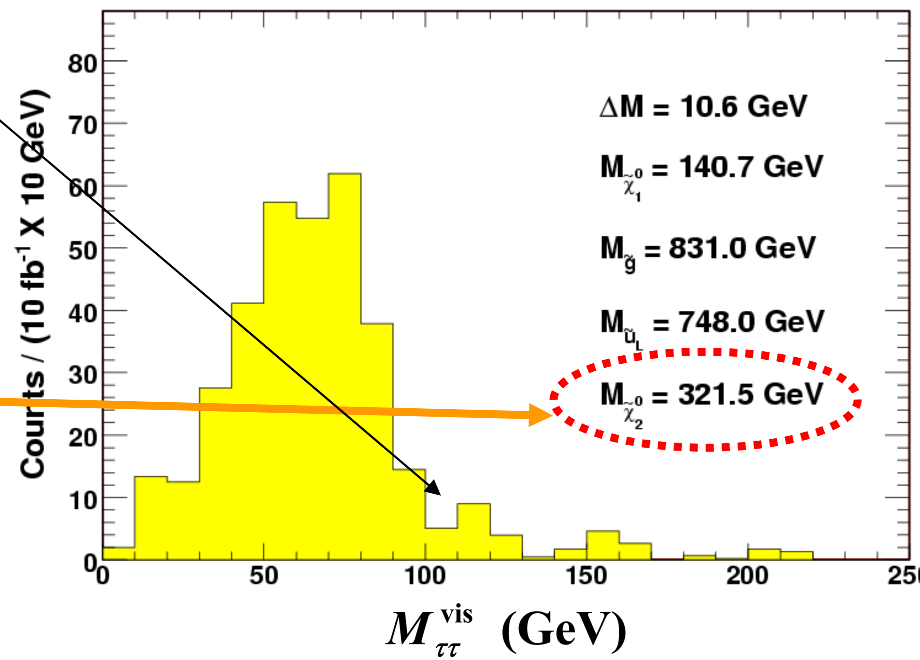
$M_{\tau\tau}$ Distribution

$$M_{\tau\tau}^{max} = M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}}$$

Clean peak even for low ΔM

Larger $\tilde{\chi}_2^0$ Mass $\rightarrow$ Larger $M_{\tau\tau}$





We choose the peak position as an observable.

E_T^{miss} + 2j + 2τ Background

[1] Sample of E_T^{miss}, 2 jets, and at least 2 taus with p_T^{vis} > 40, 20 GeV and ε_τ = 50%, fake ($f_{j\rightarrow\tau}$) = 1%.

Optimized cuts :

E_T^{jet1} > 100 GeV; E_T^{jet2} > 100 GeV; E_T^{miss} > 180 GeV; E_T^{jet1} + E_T^{jet2} + E_T^{miss} > 600 GeV

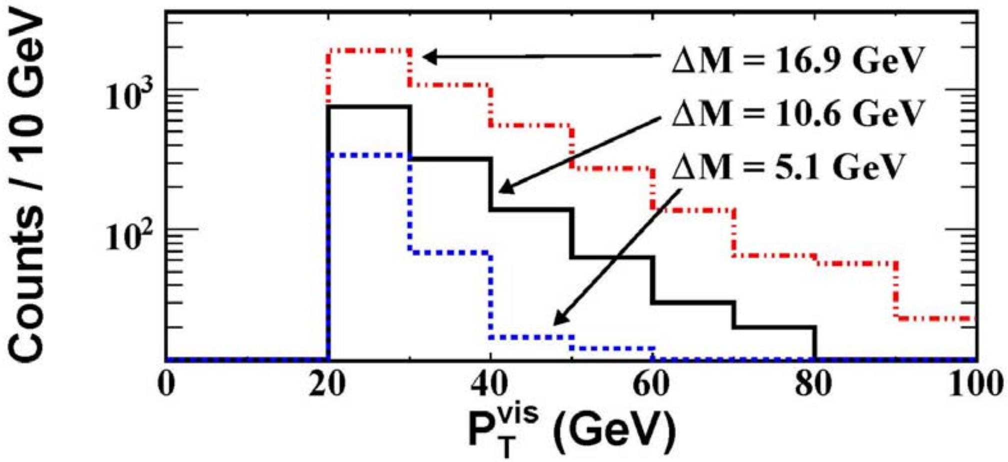
[2] Number of SUSY and SM events (10 fb^{-1}):

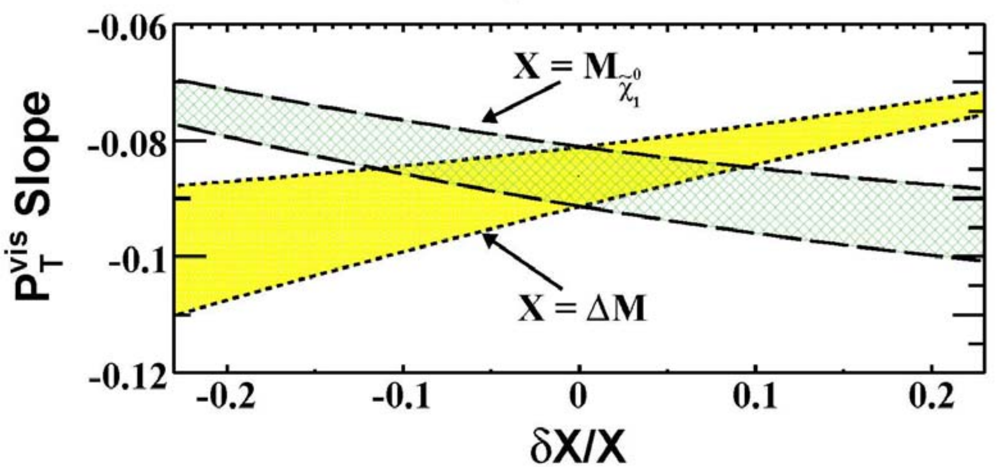
Top : 115 events

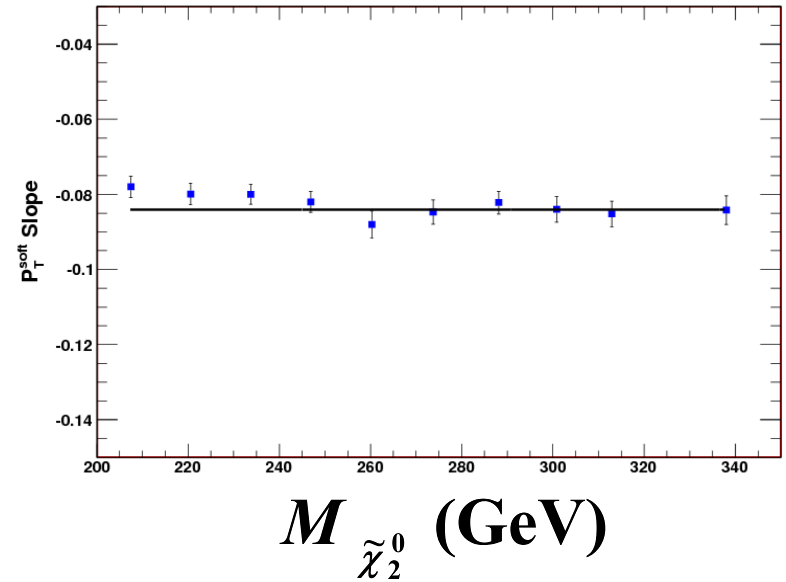
W+jets : 44 events

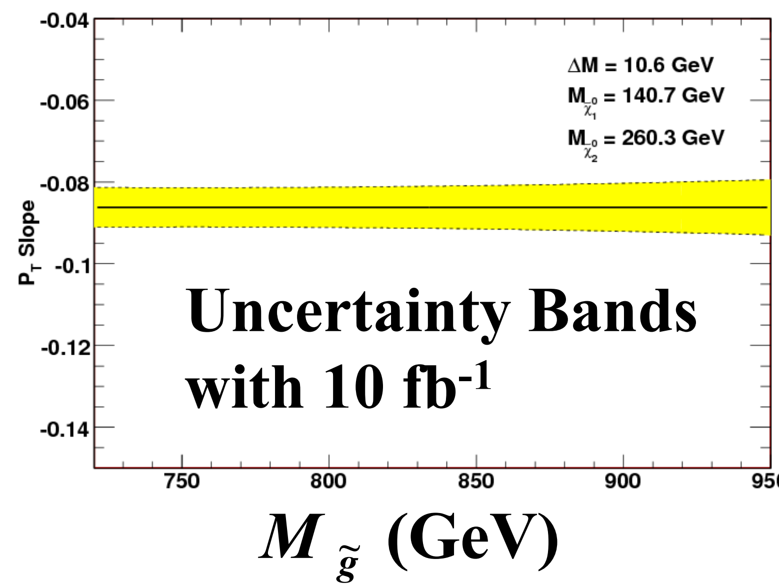
SUSY : 590 events

Slope(p_T^{soft}) vs. X

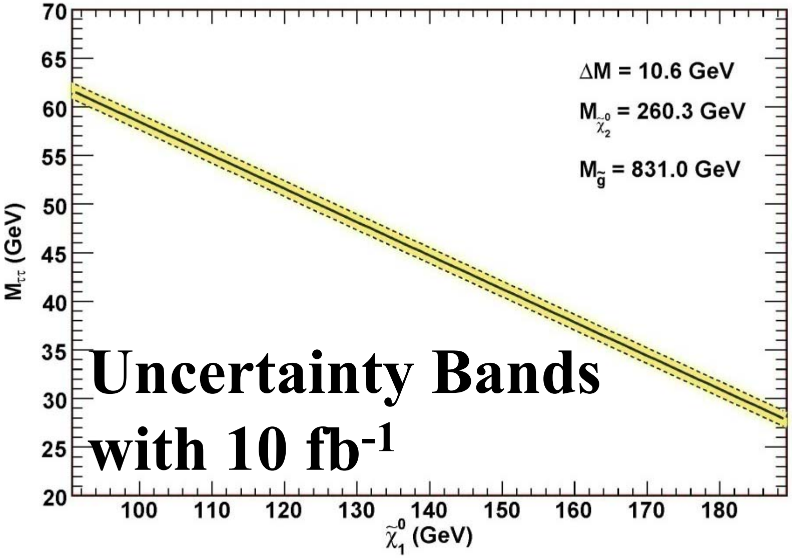


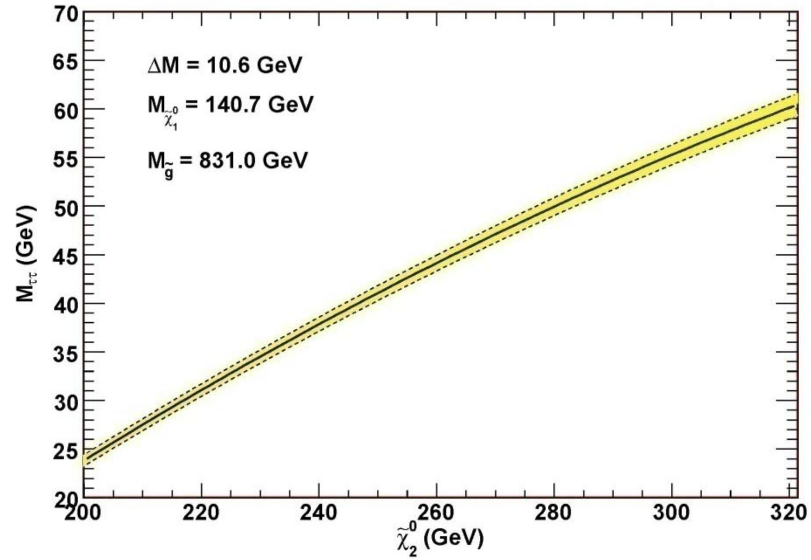


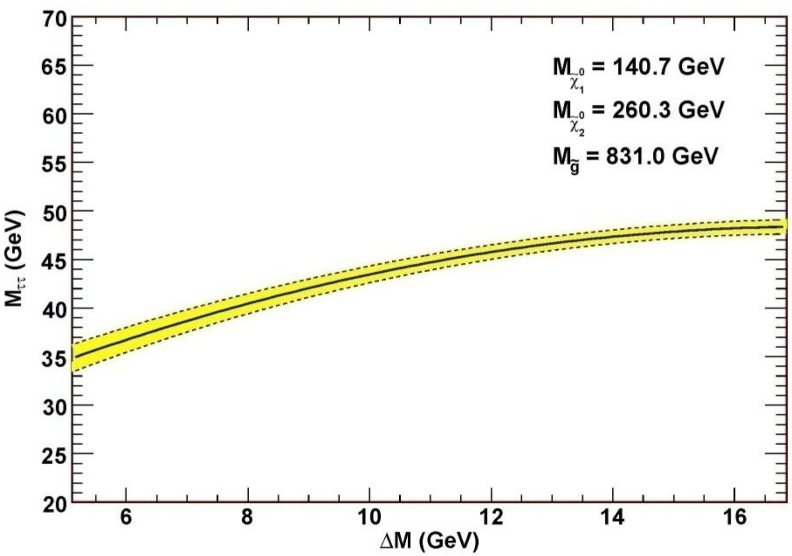


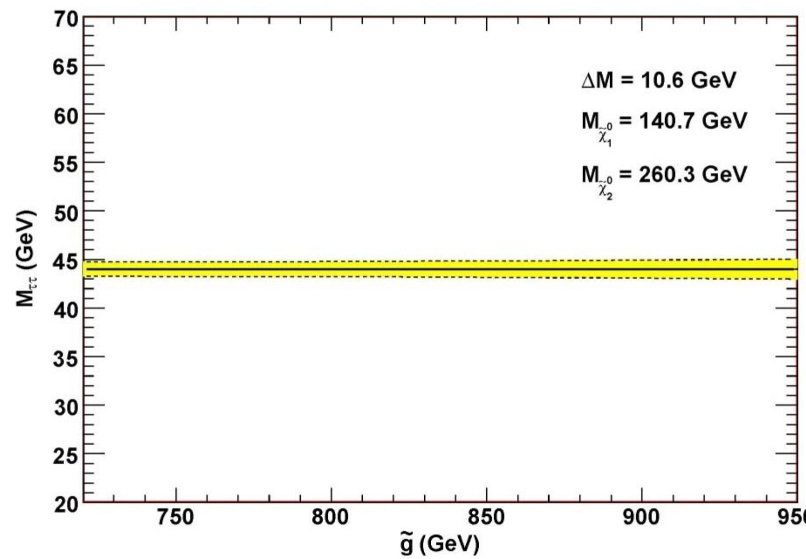


$M_{\tau\tau}^{\text{peak}}$ vs. X

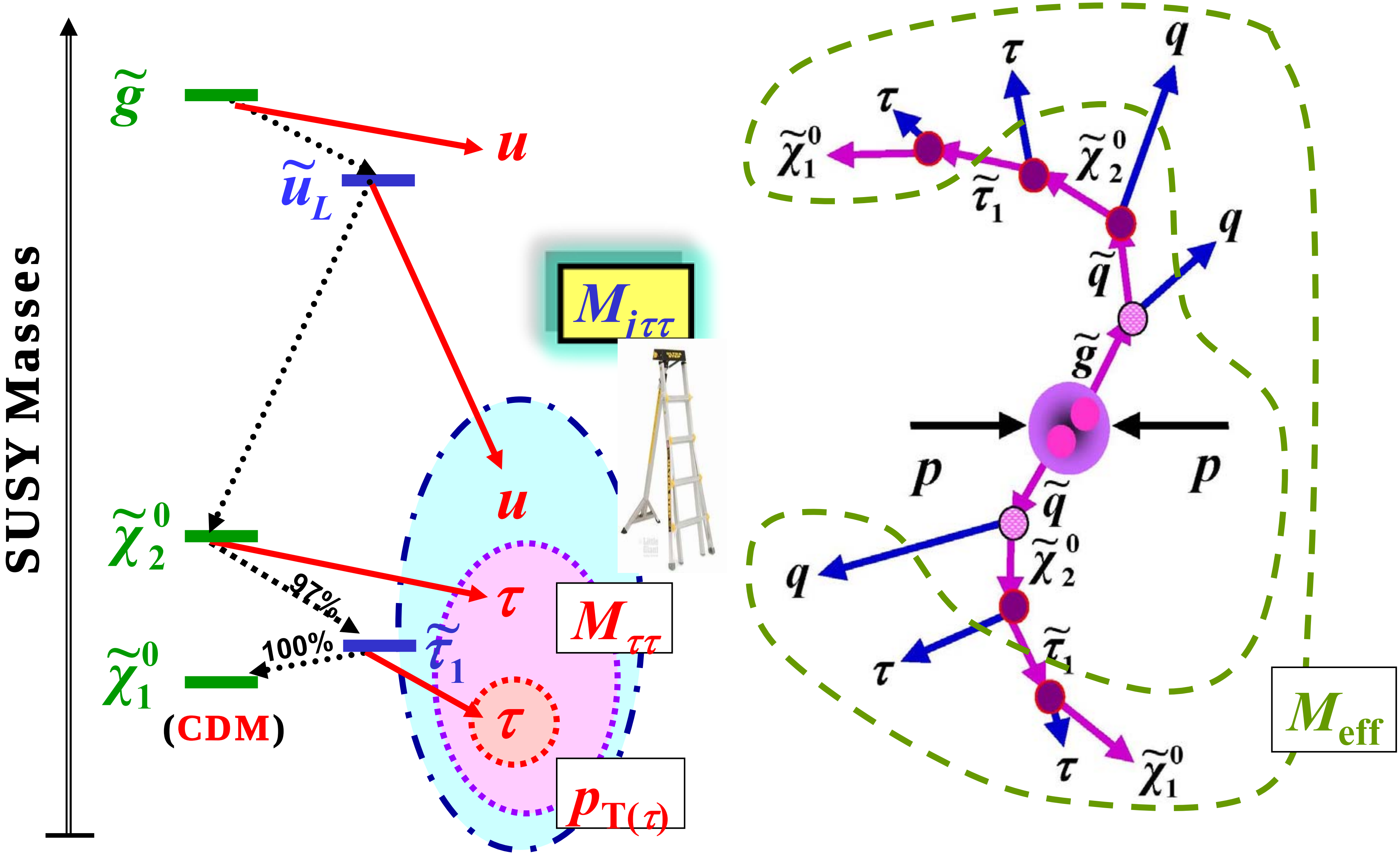




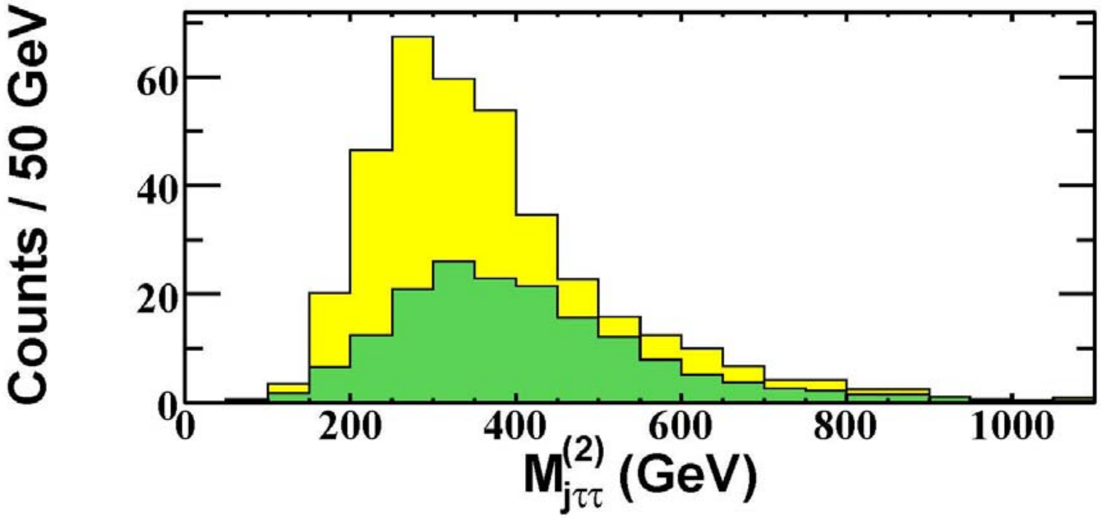




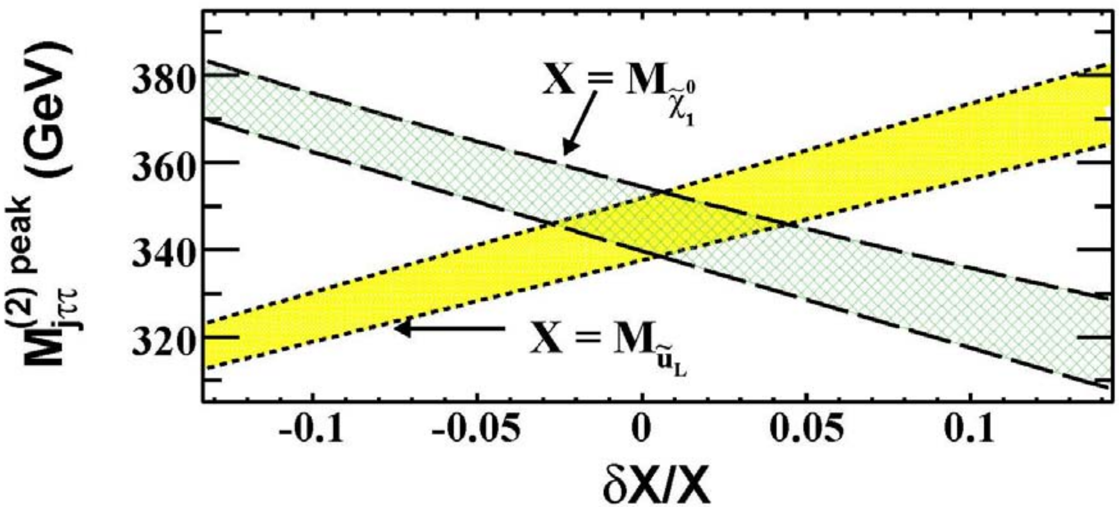
SUSY Anatomy II



Mjττ vs. *X*



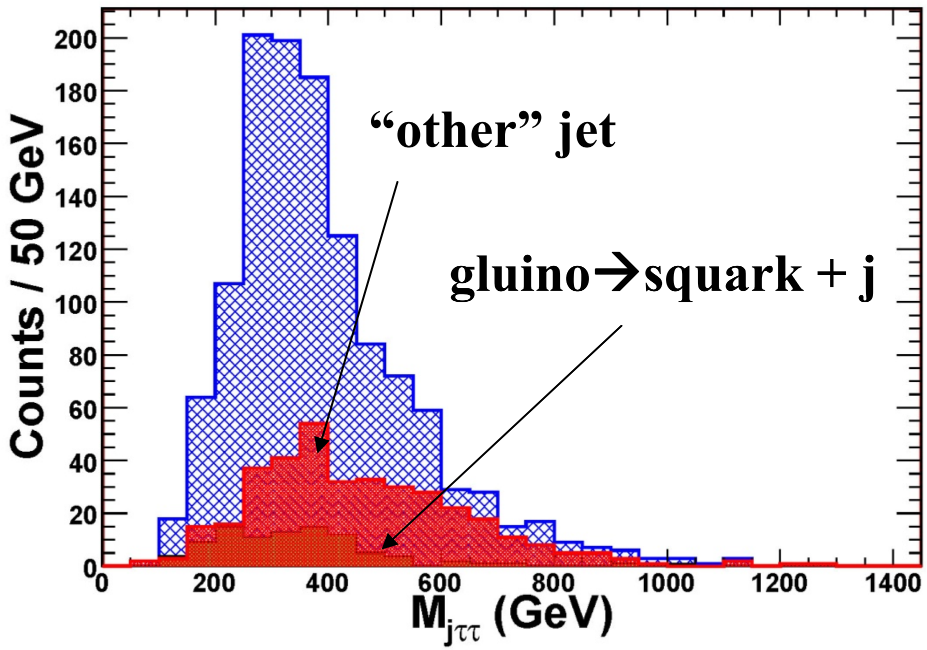
Counts / 50 GeV
60
40
20
0
0
200
400
600
800
1000
$M^{(2)}_{j\tau\tau}$ (GeV)



$M^{(2)\,peak}_{j\tau\tau}$ (GeV)
380
360
340
320
$X = M_{\tilde{\chi}^0_1}$
$X = M_{\tilde{u}_L}$
-0.1
-0.05
0
0.05
0.1
δX/X

$M_{j\tau\tau}$ Distribution

$$M_{j\tau\tau}^{end} = M_{\tilde{q}}\sqrt{1-\frac{M_{\tilde{\chi}_2^0}^2}{M_{\tilde{q}}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\chi}_2^0}^2}}$$



$M_{\tau\tau} < M_{\tau\tau}^{\text{endpoint}}$

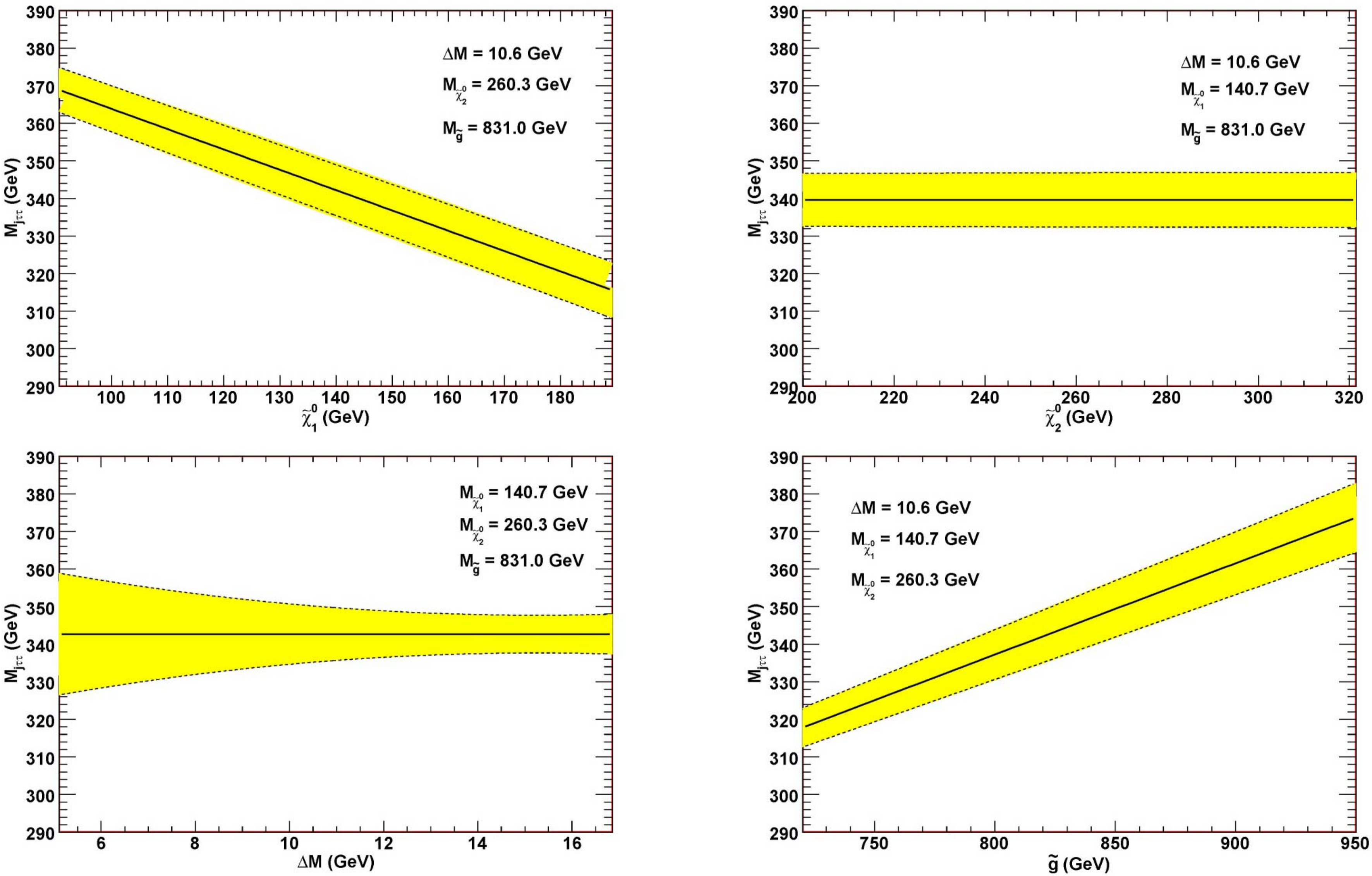
Jets with E_T > 100 GeV

$M_{j\tau\tau}$ masses for each jet

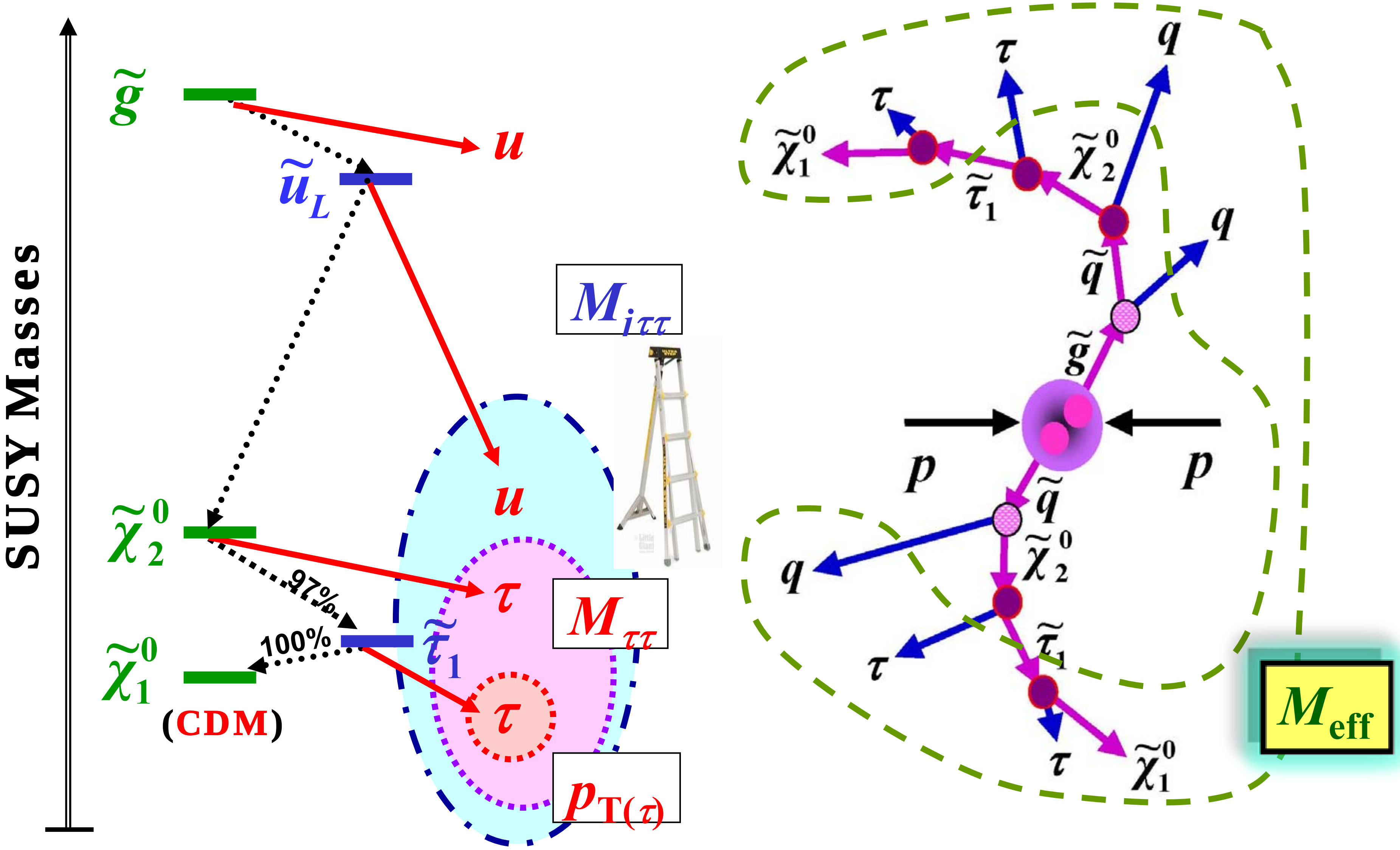
Choose the 2nd large value
→ $M_{j\tau\tau}^{(2)}$

We choose the peak position as an observable.

$M_{j\tau\tau}^{peak}$ vs. X



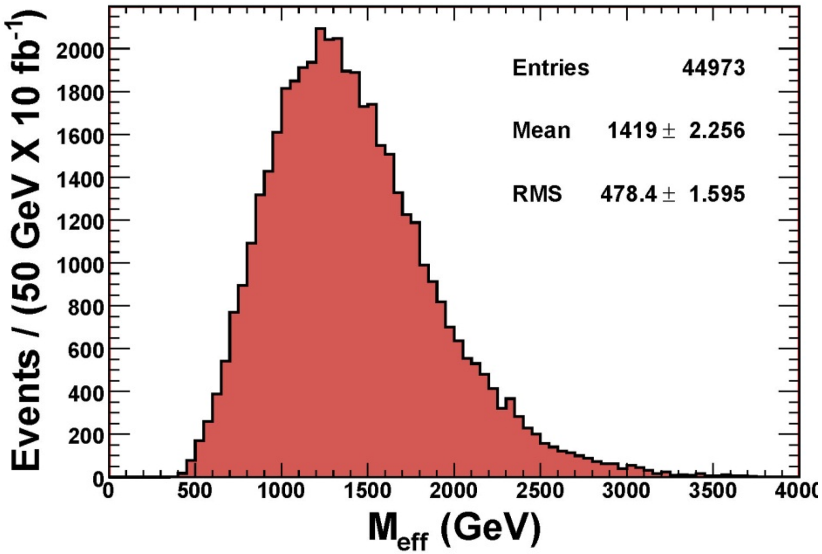
SUSY Anatomy III



M_{eff} Distribution

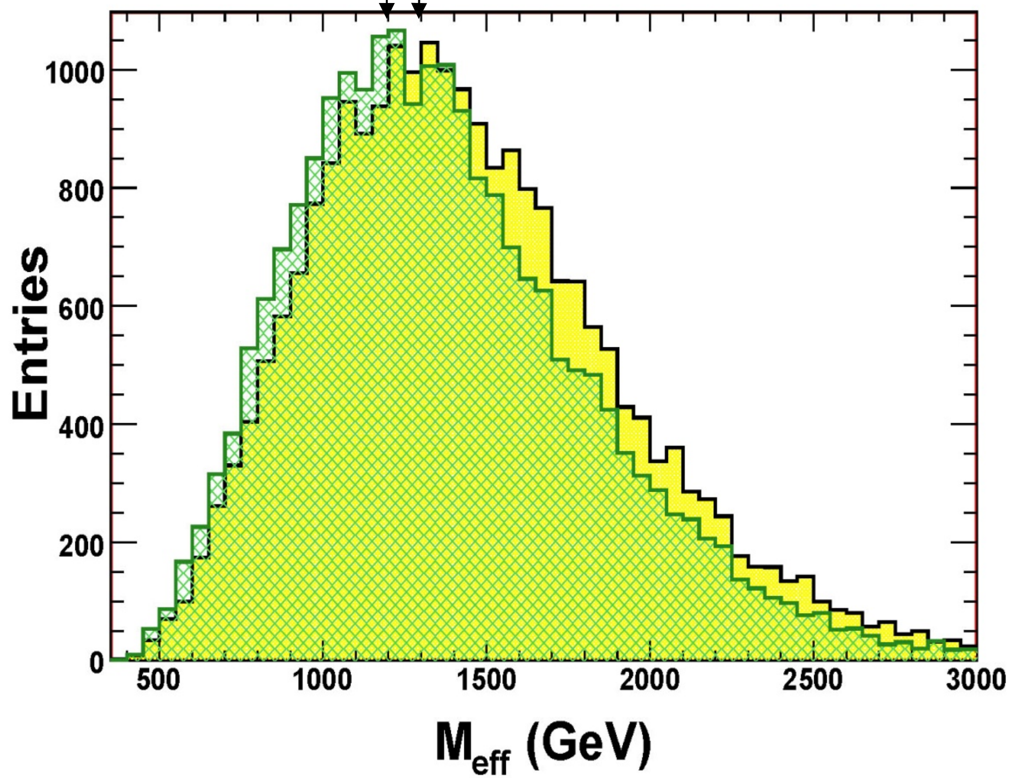
- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No e's, μ's with $p_T > 20$ GeV]
- $M_{eff} > 400$ GeV ($M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+E_T^{miss}$ [No b jets; $\varepsilon_b \sim 50\%$])
- $E_T^{miss} > \max[100, 0.2\, M_{eff}]$

At Reference Point
$M_{eff}^{peak} = 1274$ GeV



$M_{eff}^{peak} = 1220$ GeV ($m_{1/2} = 335$ GeV)

$M_{eff}^{peak} = 1331$ GeV ($m_{1/2} = 365$ GeV)



Five Observables

1. Sort τ's by E_T ($E_T^1 > E_T^2 > \ldots$)

- Use OS–LS method to extract τ pairs from the decays

$$N_{\tau^\pm\tau^\mp} - N_{\tau^\pm\tau^\pm}$$

SM+SUSY Background gets reduced

- Ditau invariant mass: $M_{\tau\tau}$
- Jet-τ-τ invariant mass: $M_{j\tau\tau}$
- Jet-τ invariant mass: $M_{j\tau}$
- P_T of the low energy τ
- M_{eff} : 4 jets +missing energy

All these variables depend on masses => model parameters

Since we are using 5 variables, we can measure the model parameters and the grand unified scale symmetry (a major ingredient of this model)

Determining SUSY Masses (10 fb^{-1})

6 Eqs (as functions of 5 SUSY masses)

$$M_{\tau\tau}^{\text{peak}} = f_1(\Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$Slope = f_2(\Delta M, \tilde{\chi}_1^0)$$

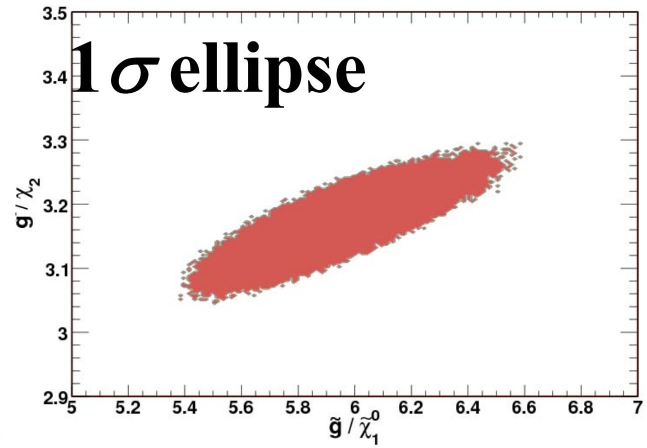
$$M_{j\tau\tau}^{(2)\text{peak}} = f_3(\tilde{q}_L, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$M_{j\tau 1}^{(2)\text{peak}} = f_4(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$M_{j\tau 2}^{(2)\text{peak}} = f_5(\tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$M_{\text{eff}}^{\text{peak}} = f_6(\tilde{g}, \tilde{q}_L)$$

Invert the equations to determine the masses



10 fb^{-1}

$$M_{\tilde{q}_L} = 748 \pm 25; \quad M_{\tilde{g}} = 831 \pm 21;$$

$$M_{\tilde{\chi}_2^0} = 260 \pm 15; \quad M_{\tilde{\chi}_1^0} = 141 \pm 19;$$

$$\Delta M = 10.6 \pm 2.0$$

$$M_{\tilde{g}} / M_{\tilde{\chi}_2^0} = 3.1 \pm 0.2 \, (theory = 3.19)$$

$$M_{\tilde{g}} / M_{\tilde{\chi}_1^0} = 5.9 \pm 0.8 \, (theory = 5.91)$$

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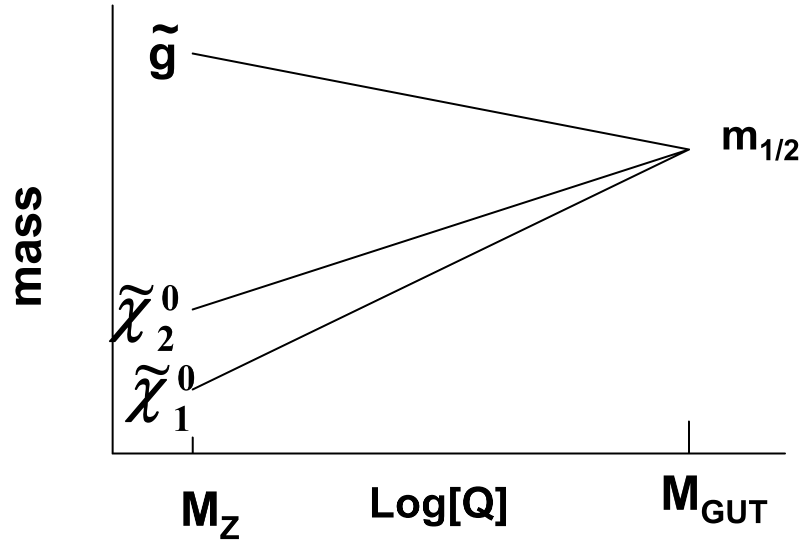
GUT Scale Symmetry

We can probe the physics at the Grand unified theory (GUT) scale



Use the masses measured at the LHC and evolve them to the GUT scale using mSUGRA

The masses $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{g}$ unify at the grand unified scale in SUGRA models

Gaugino universality test at ~15% (10 fb-1)

Another evidence of a symmetry at the grand unifying scale!

DM Relic Density in mSUGRA

$$M_{\tilde{g}} = 831\ \text{GeV}$$
$$M_{\tilde{\chi}_2^0} = 260\ \text{GeV}$$
$$M_{\tilde{\tau}} = 151.3\ \text{GeV}$$
$$M_{\tilde{\chi}_1^0} = 140.7\ \text{GeV}$$

$$m_0 =$$
$$m_{1/2} =$$
$$\tan\beta =$$
$$A_0 =$$
$$sgn(\mu) > 0$$

$$\Omega_{\tilde{\chi}_1^0} h^2 =$$

[1] Established the CA region by detecting low energy τ's ($p_T^{vis} > 20$ GeV)

[2] Determined SUSY masses using:

$M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_{j\tau}$, M_{eff}

e.g., Peak($M_{\tau\tau}$) = f (M_{gluino}, M_{stau}, $M_{\tilde{\chi}_2^0}$, $M_{\tilde{\chi}_1^0}$)

[3] Measure the dark matter relic density by determining m_0, $m_{1/2}$, $\tan\beta$, and A_0

Determining mSUGRA Parameters

$$
\begin{aligned}
M_{j\tau\tau} &= X_1(m_{1/2}, m_0) \\
M_{\tau\tau} &= X_2(m_{1/2}, m_0, \tan\beta, A_0) \\
M_{\text{eff}} &= X_3(m_{1/2}, m_0) \\
? &= X_4(m_{1/2}, m_0, \tan\beta, A_0)
\end{aligned}
\Rightarrow
\left\{
\begin{aligned}
m_0 &= ? \\
m_{1/2} &= ? \\
A_0 &= ? \\
\tan\beta &= ?
\end{aligned}
\right.
$$

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

$$\boxed{\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx ???\ (???\ \text{fb}^{-1})}$$

Determination of tanβ

- ✓Determination of tanβ is a real problem
- ✓One way is to determine stop and sbottom masses and then solve for A_0 and tanβ

E.g., stop mass matrix:

$$\begin{pmatrix} m_{Q_L}^2 + \ldots & m_t(A_t + \mu\cot\beta) \\ m_t(A_t + \mu\cot\beta) & m_{t_R}^2 + \ldots \end{pmatrix}$$

Problem: Stop creates a background for sbottom and …

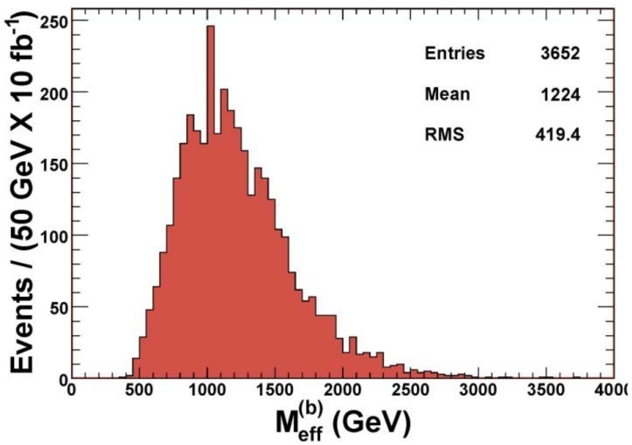
- ✓Instead, we use observables involving third generation sparticles: $M_{eff}(b)$ [the leading jet is a b-jet]
- ✓We can determine tanβ and A_0 with good accuracy
- ✓This procedure can be applied to different SUGRA models

$M_{\text{eff}}^{(b)}$ Distribution

- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No e's, μ's with $p_T > 20$ GeV]
- $M_{\text{eff}}^{(b)} > 400$ GeV ($M_{\text{eff}}^{(b)} \equiv E_T^{j1=b} + E_T^{j2} + E_T^{j3} + E_T^{j4} + E_T^{\text{miss}}$ [j1 = *b* jet])
- $E_T^{\text{miss}} > \max\,[100, 0.2\,M_{\text{eff}}]$

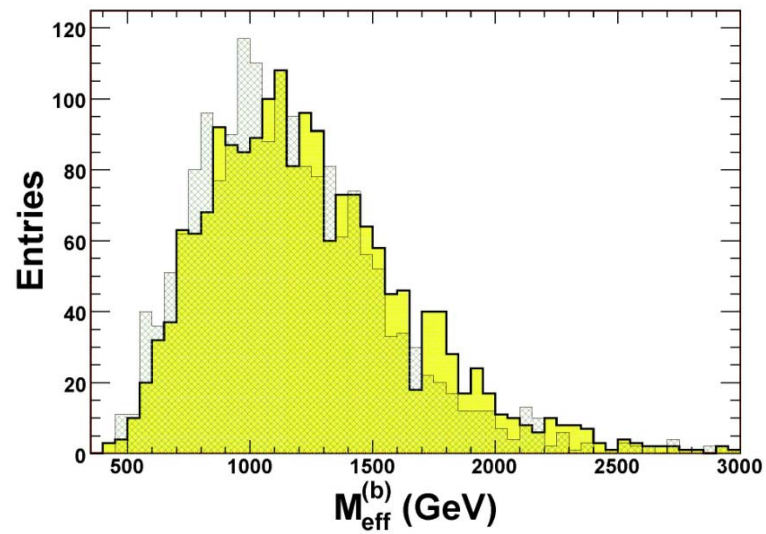
At Reference Point

$M_{\text{eff}}^{(b)\text{peak}} = 1026$ GeV



$M_{\text{eff}}^{(b)\text{peak}} = 933$ GeV ($m_{1/2} = 335$ GeV)

$M_{\text{eff}}^{(b)\text{peak}} = 1122$ GeV ($m_{1/2} = 365$ GeV)



$M_{\text{eff}}^{(b)}$ can be used to determine A_0 and $\tan\beta$ even without measuring stop and sbottom masses

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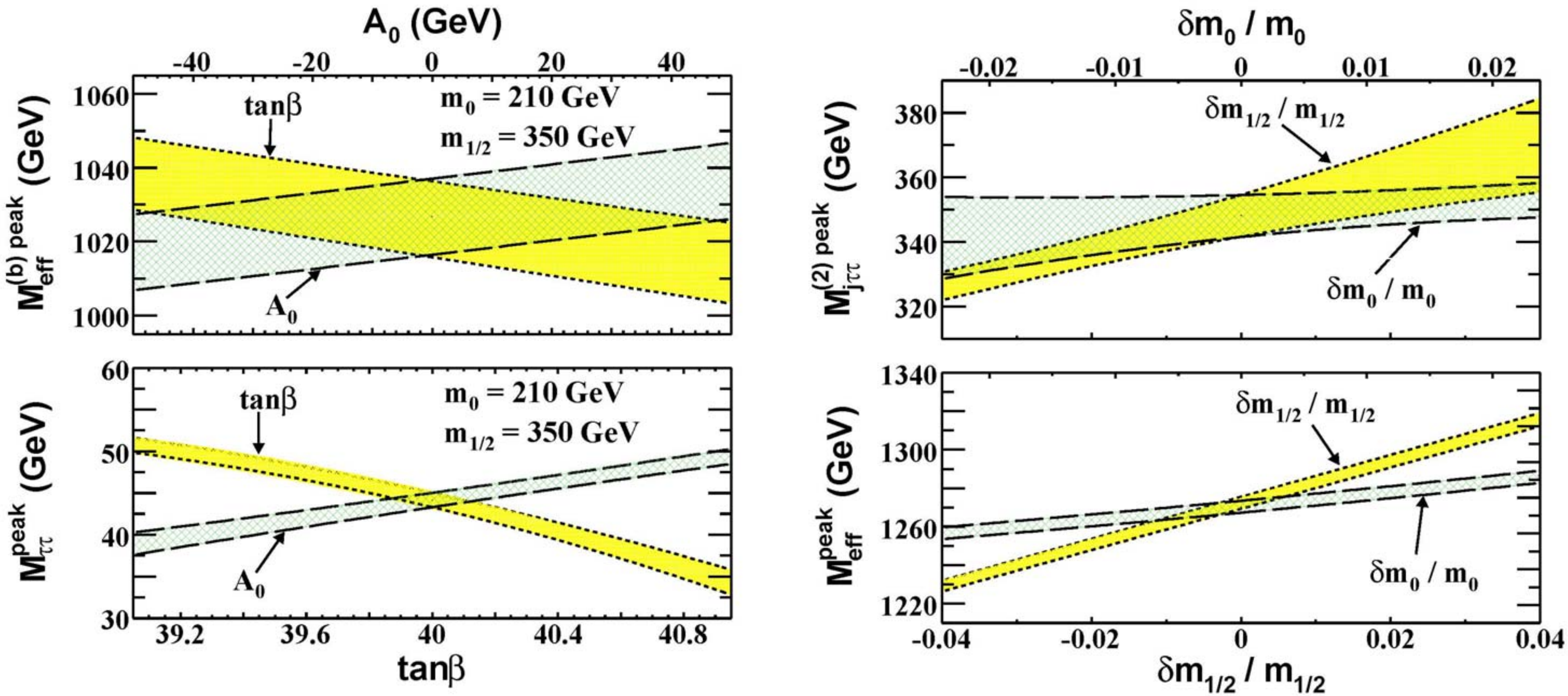
Mass Measurements → mSUGRA



$M_{\mathrm{eff}}^{(b)\mathrm{peak}}$ …. Sensitive to A_0 and tanβ

$M_{\mathrm{eff}}^{\mathrm{peak}}$ …. Very insensitive to A_0 and tanβ

Determining mSUGRA Parameters

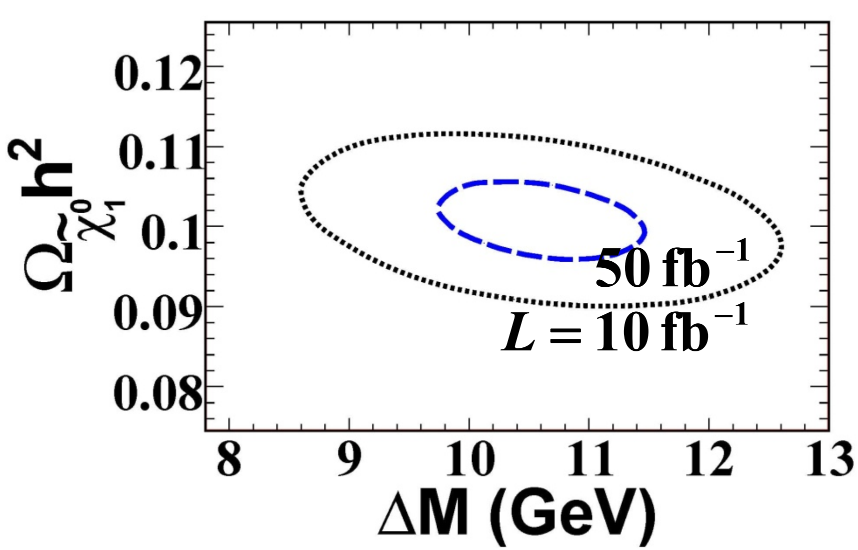
✓Solved by inverting the following functions:

$$\begin{aligned} M_{j\tau\tau} &= f_1(m_{1/2}, m_0) \\ M_{\tau\tau} &= f_2(m_{1/2}, m_0, \tan\beta, A_0) \\ M_{\text{eff}} &= f_3(m_{1/2}, m_0) \\ M_{\text{eff}}^{(b)} &= f_4(m_{1/2}, m_0, \tan\beta, A_0) \end{aligned}$$

10 fb^{-1}

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

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



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$$\boxed{\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx 6\% \ (30 \text{ fb}^{-1})}$$

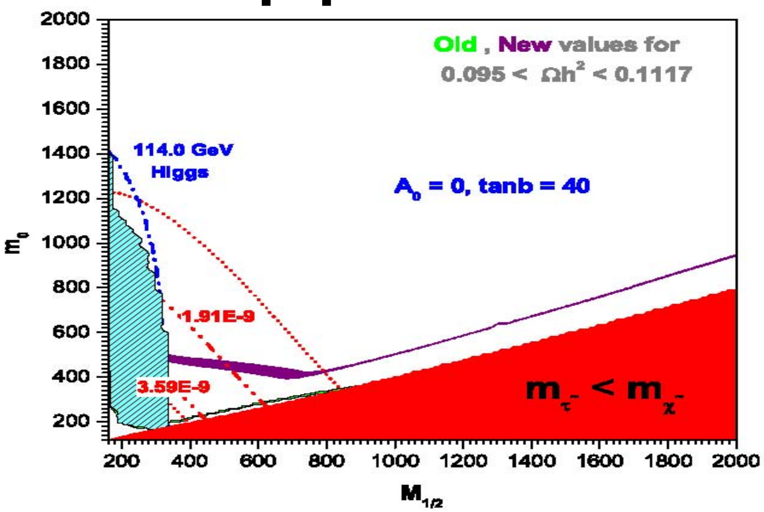
Accuracy of tanβ

The accuracy of determining tanβ is not so good if we do not have staus in the final states.

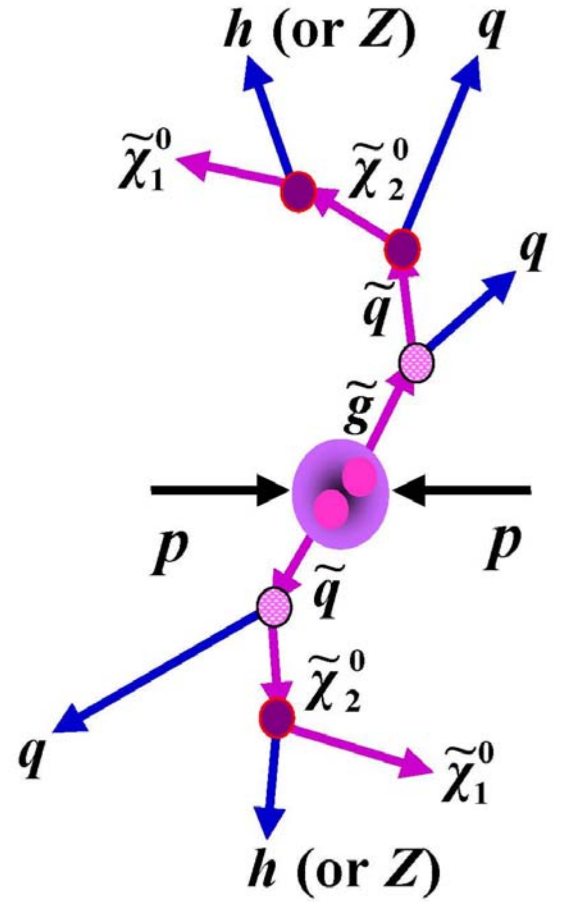
E.g., raise m_0

The final states can contain Z, Higgs

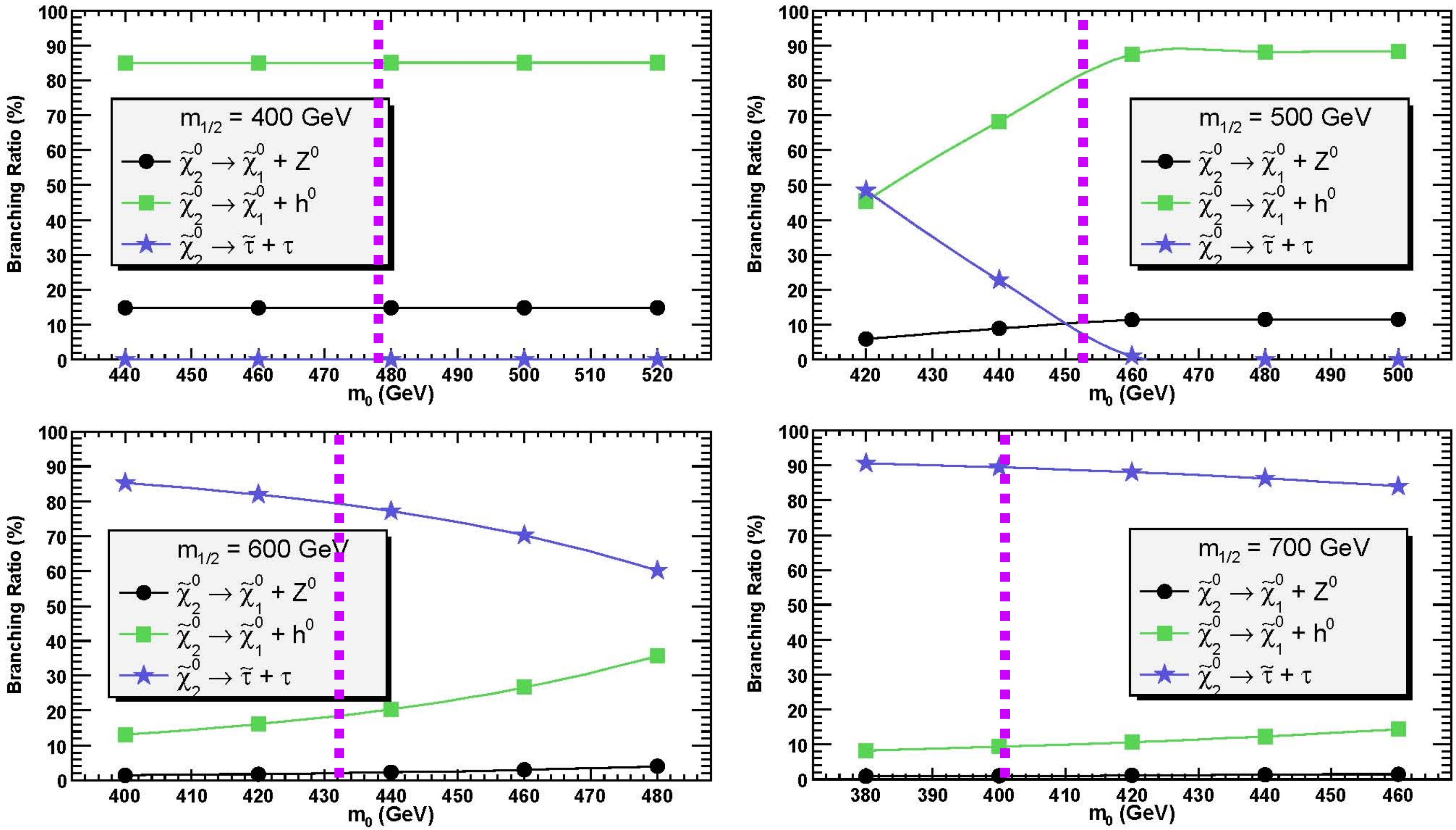
hep-ph/0612152



Lahanas, Mavromatos, Nanopoulos

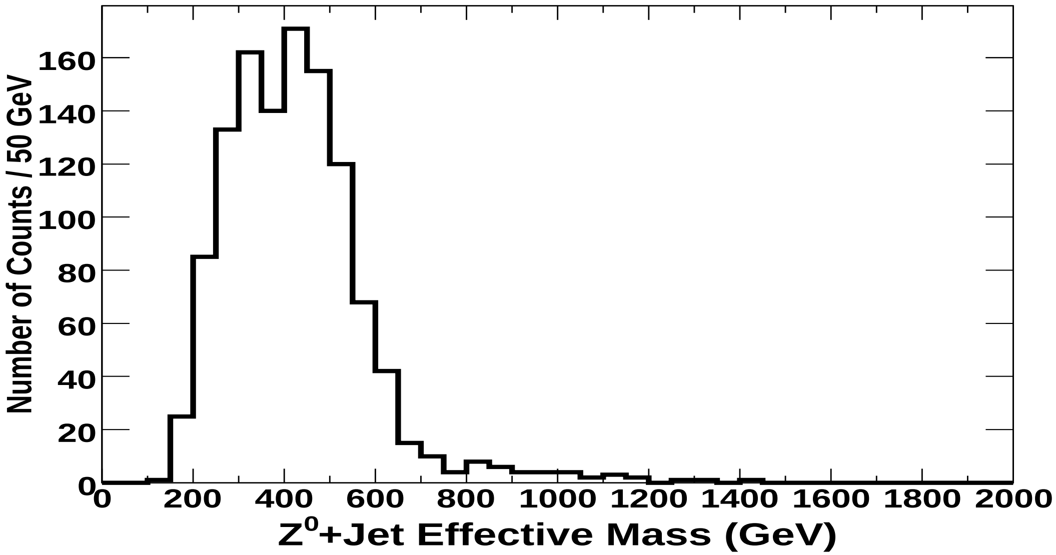


χ_2^0 Decay *Branching Ratios*



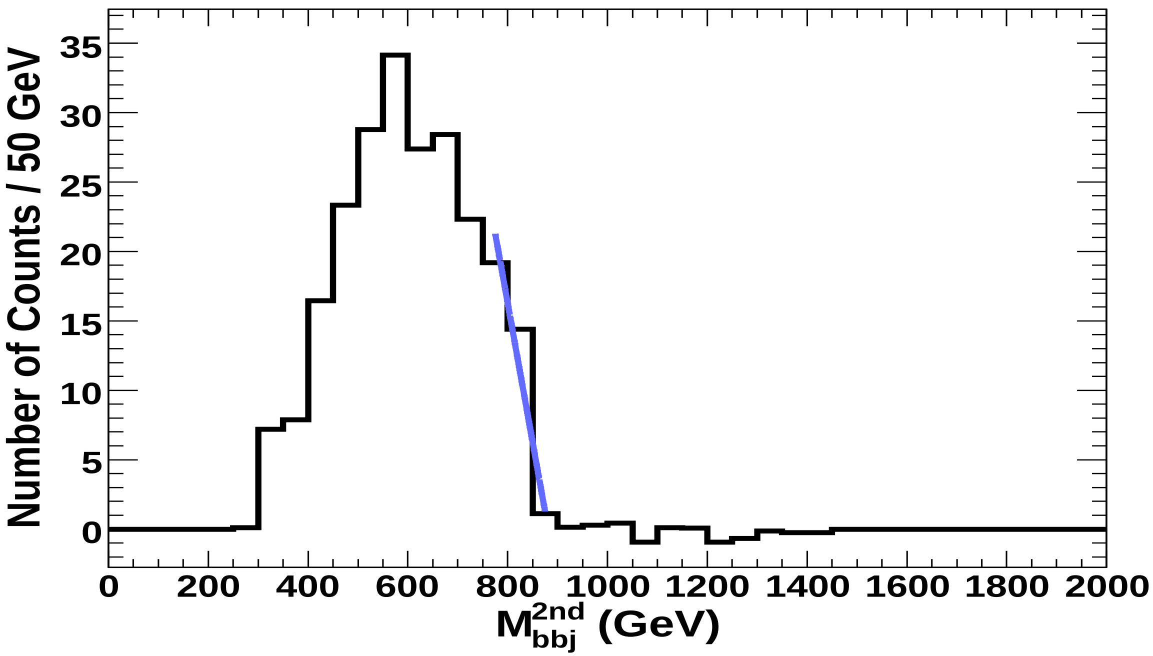
Identify and classify χ_2^0 decays

Observables involving Z and Higgs



$$M_{\tau\tau}^{\mathrm{end}} = M_{\tilde{\chi}_2^0}\sqrt{\left(1-\frac{M^2_{\tilde{\tau}_1}}{M^2_{\tilde{\chi}_2^0}}\right)\left(1-\frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\tau}_1}}\right)}$$

$$M_{\mathrm{jet}\tau\tau}^{\mathrm{end}} = M_{\tilde{q}_L}\sqrt{\left(1-\frac{M^2_{\tilde{\chi}_2^0}}{M^2_{\tilde{q}_L}}\right)\left(1-\frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\chi}_2^0}}\right)}$$



We can solve for masses by using the end-points

Observables

Higgs + plus jet + missing energy dominated region:

✓**Effective mass: M_{eff} (peak): $f_1(m_0,m_{1/2})$**

✓**Effective mass with 1 b jet: M_{eff} (b) (peak): $f_2(m_0,m_{1/2}, A_0, \tan\beta)$**

✓**Effective mass with 2 b jets: M_{eff} (2b) (peak): $f_3(m_0,m_{1/2}, A_0, \tan\beta)$**

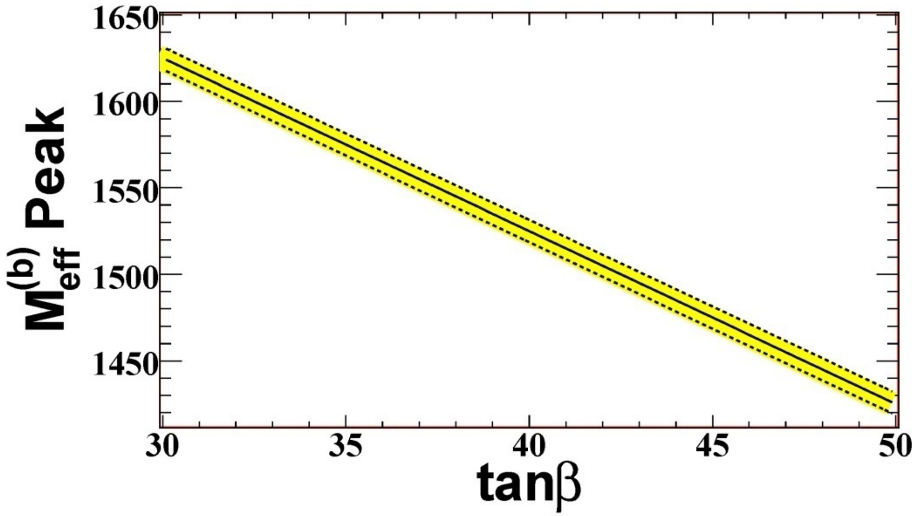
✓**Higgs plus jet invariant mass: M_{bbj}(end-point): $f_4(m_0,m_{1/2})$**

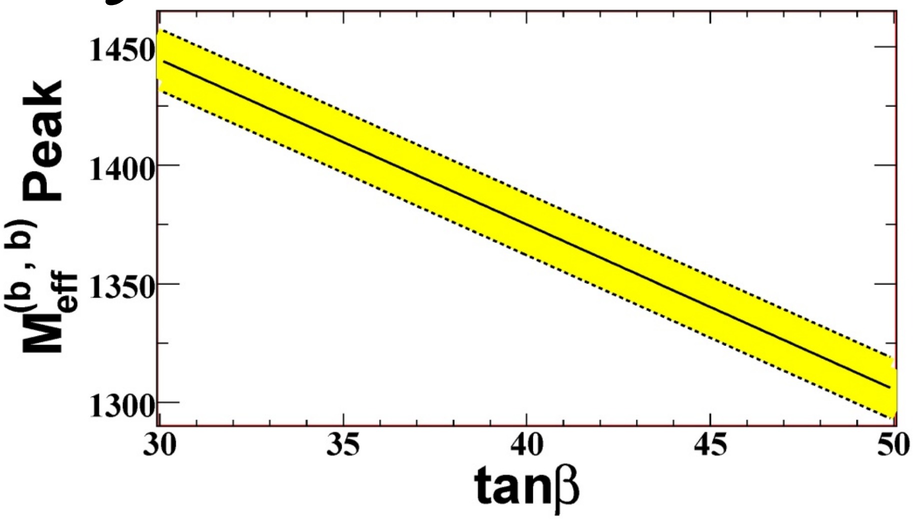
4 observables=> 4 mSUGRA parameters

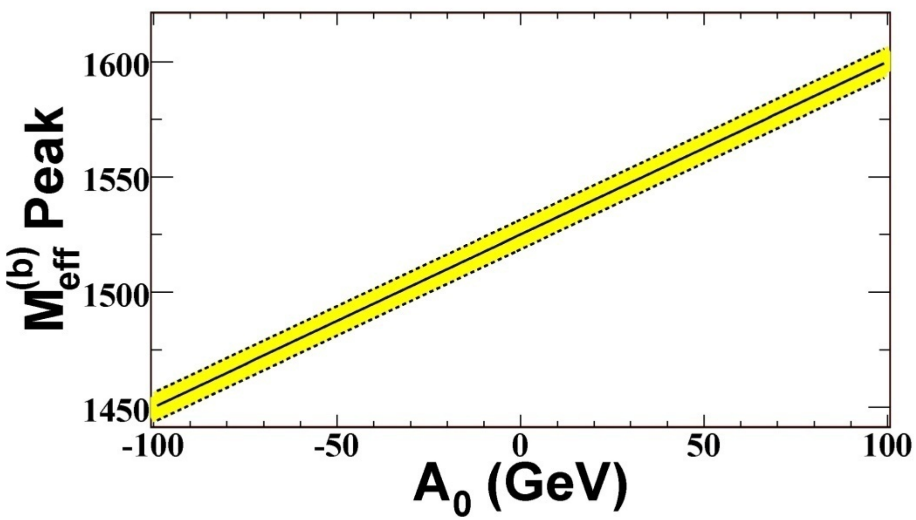
However there is no stau in the final states:
accuracy for determining tanβ will be less

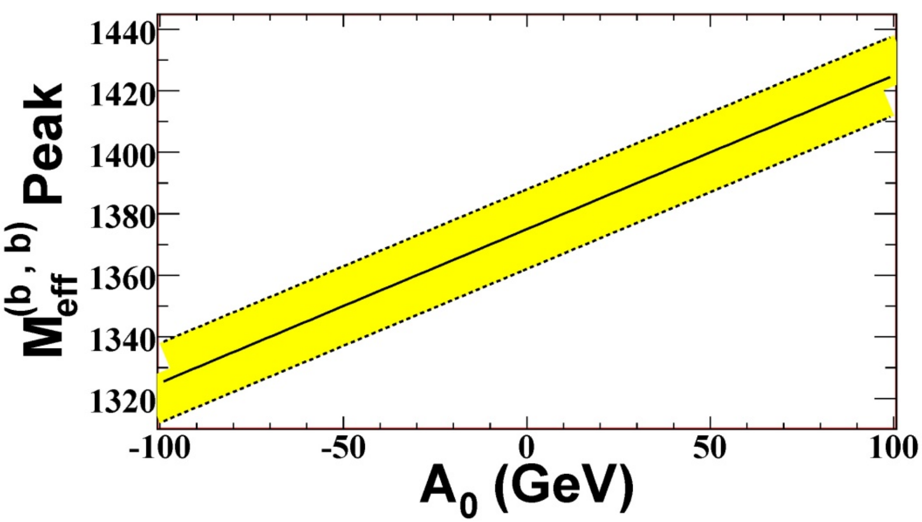
Observables...

Error with 1000 fb-1









Determining mSUGRA Parameters

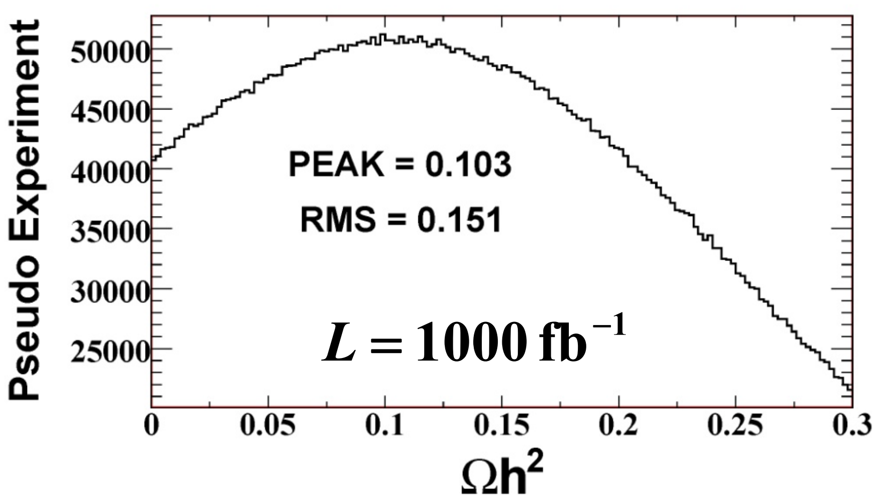
✓ *Solved by inverting the following functions:*

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

1000 fb^{-1}

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

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



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

2 tau + missing energy dominated regions:

✓ *Solved by inverting the following functions:*

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

500 fb^{-1}

$$\left\{\begin{array}{lcl} m_0 & = & 440 \pm 23 \\ m_{1/2} & = & 600 \pm 6 \\ A_0 & = & 0 \pm 45 \\ \tan\beta & = & 40 \pm 3 \end{array}\right.$$

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

$$\boxed{\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \sim 19\%}$$

For 500 fb^{-1} of data

Summary

$$
\begin{aligned}
M_{\tilde{g}} &= 831\,\mathrm{GeV} \\
M_{\tilde{\chi}_2^0} &= 260\,\mathrm{GeV} \\
M_{\tilde{\tau}} &= 151.3\,\mathrm{GeV} \\
M_{\tilde{\chi}_1^0} &= 140.7\,\mathrm{GeV}
\end{aligned}
$$

$$
\begin{aligned}
m_0 &= 210\,\mathrm{GeV} \\
m_{1/2} &= 351\,\mathrm{GeV} \\
\tan\beta &= 40 \\
A_0 &= 0 \\
sgn(\mu) &> 0
\end{aligned}
$$

$$\Omega_{\tilde{\chi}_1^0} h^2 = 0.1$$

[1] Established the CA region by detecting low energy τ's ($p_T^{vis} > 20$ GeV)

[2] Determined SUSY masses using:

$M_{\tau\tau}$, Slope, $M_{j\tau\tau}$, $M_{j\tau}$, M_{eff}

e.g., Peak($M_{\tau\tau}$) = f (M_{gluino}, M_{stau}, $M_{\tilde{\chi}_2^0}$, $M_{\tilde{\chi}_1^0}$)

Gaugino universality test at ~15% (10 fb^{-1})

[3] Measured the dark matter relic density by determining m_0, $m_{1/2}$, $\tan\beta$, and A_0 using $M_{j\tau\tau}$, M_{eff}, $M_{\tau\tau}$ and $M_{eff}^{(b)}$

$$\boxed{\delta\Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 \approx 6\%\ (30\ \mathrm{fb}^{-1})}$$

Summary...

[4] For large m_0, when staus are not present, the mSUGRA parameters can still be extracted, but with less accuracy

[5] It will be interesting to determine nonuniversal model Parameters, e.g., μ (Higgs sector nonuniversality)

work is in progress