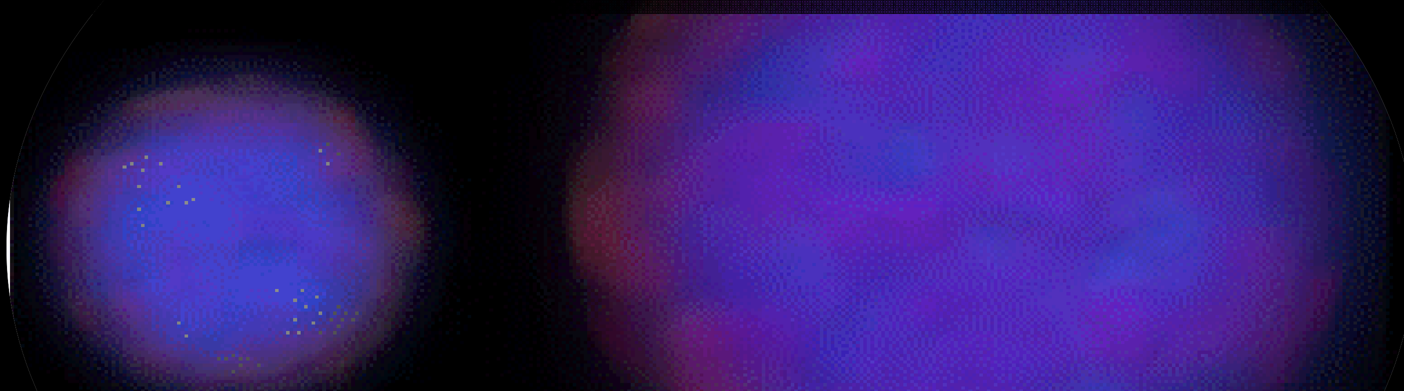
Cosmological Connection at the LHC
:
Stau Neutralino Co-annhilation Case



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"Facing the LHC Data"
Institute for Physics and Mathematics of the Universe
The University of Tokyo, Japan
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OUTLINE

- Dark Matter (DM) in Universe
  - DM Particle in SUSY
- Cosmological Connection (CC) at the LHC and Ωh^2 [Co-annihilation (CA) Case]
  - Summary

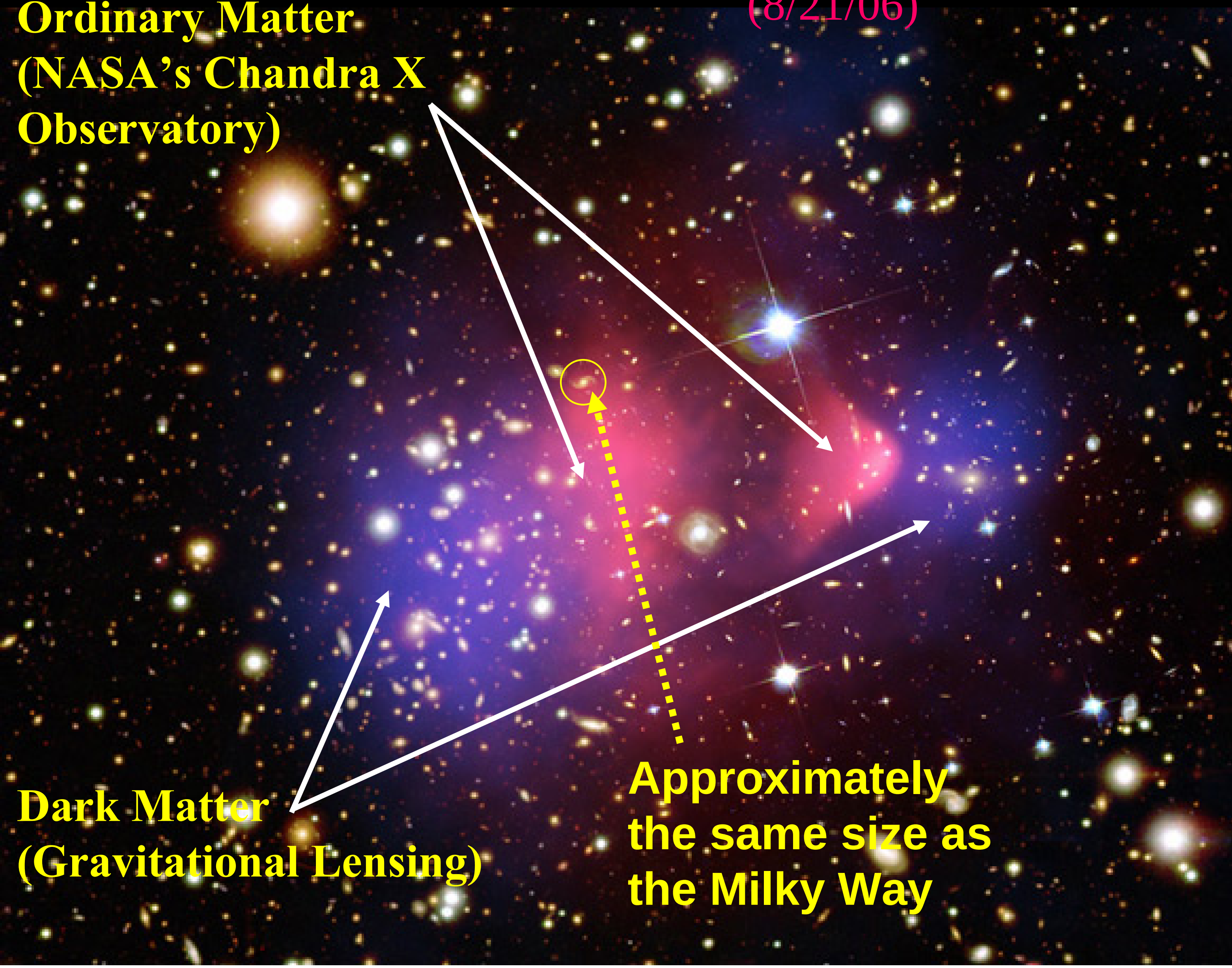
Arnowitt, Dutta, Kamon, Kolev, Toback, PLB 639 (2006) 46
Arnowitt, Arusano, Dutta, Kamon, Kolev, Simeon, Toback, Wagner, PLB 649 (2007) 73
Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, in preparation w

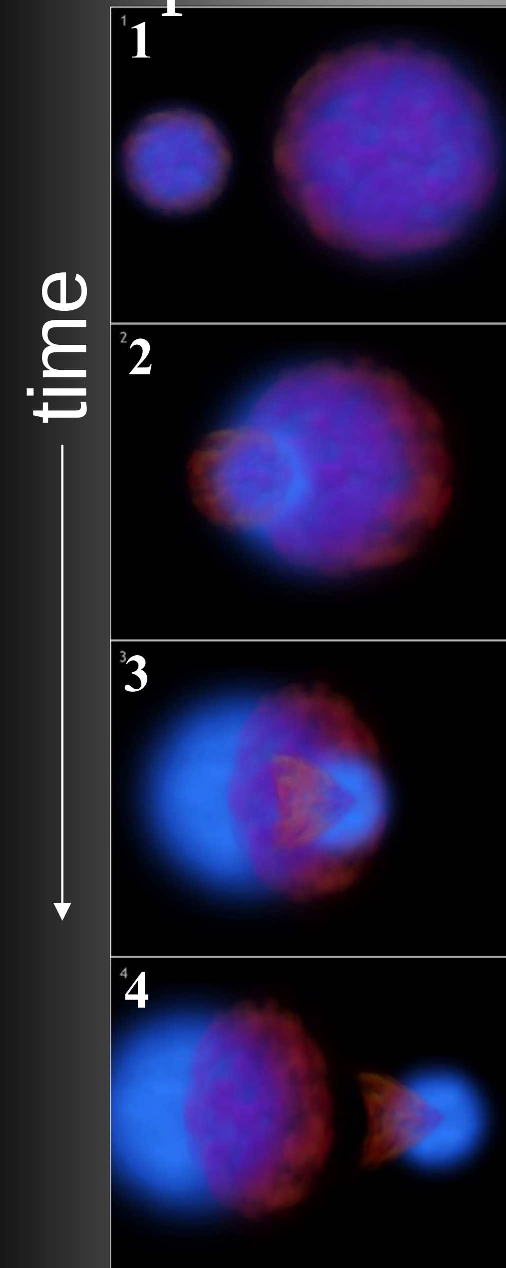
Dark Matter (DM) in Universe

splitting normal matter and dark matter apart

– Another Clear Evidence of Dark Matter –

(8/21/06)





DM Particle

I'm hungry. Can you make the DM sandwich with the elementary particles?

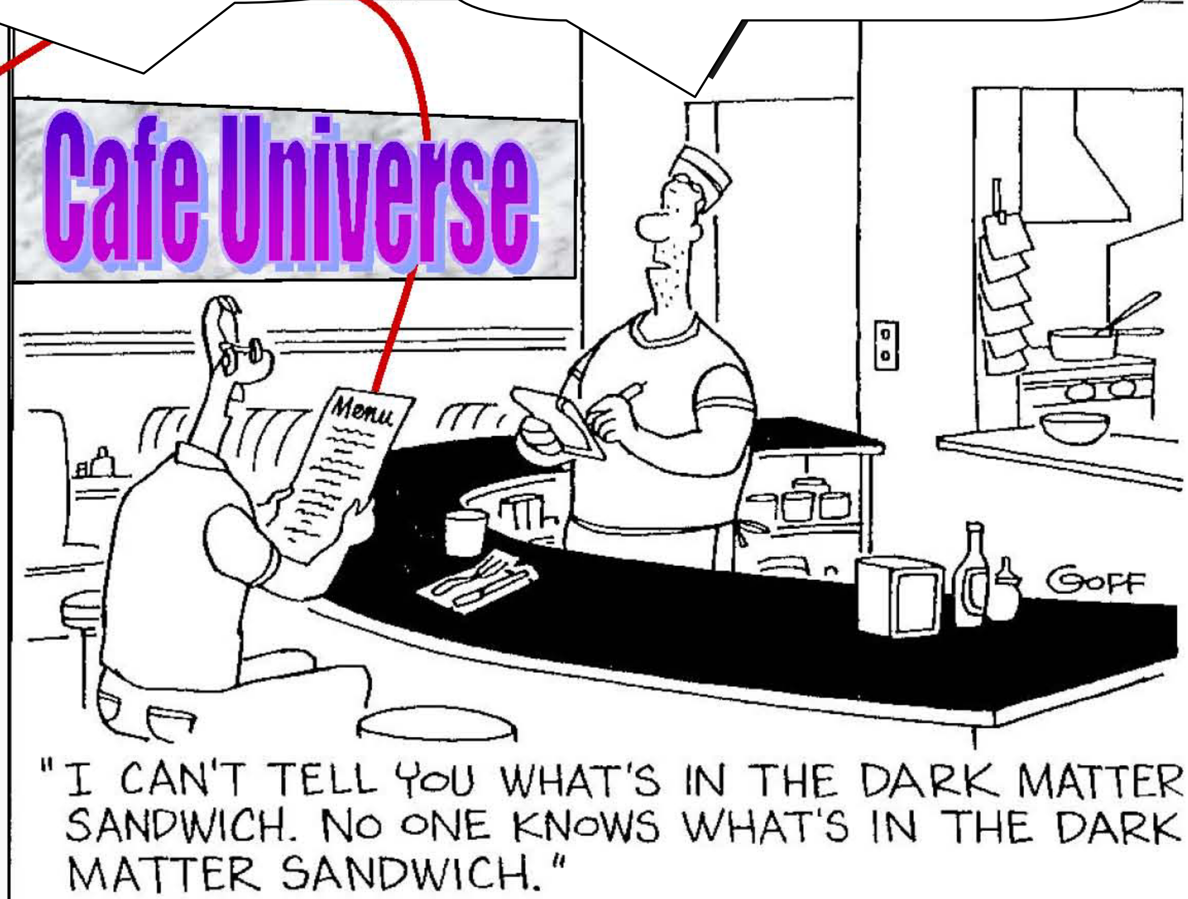
No, sir. But with Neutrino?

MENU
~SPECIALS~

*Dark Energy Power Drink .. $73
- Chef's choice

*Dark Matter Sandwich …… $23
- Neutral, long-lived
- $\tilde{\chi}_1^0$, $\tilde{G}$ or $\tilde{\nu}$ from SUSY
- γ_{KK} from UED
- Heavy γ from LHT

*Atomic Soup ………………. $4
- All elements in one



DM Particle

It sounds good.
Extra charge?

No, sir.
Free of charge.

MENU
~SPECIALS~

*Dark Energy Power Drink .. $73
- Chef's choice

*Dark Matter Sandwich …… $23
- Neutral, long-lived
- $\tilde{\chi}_1^0$, $\tilde{G}$ or $\tilde{\nu}$ from SUSY
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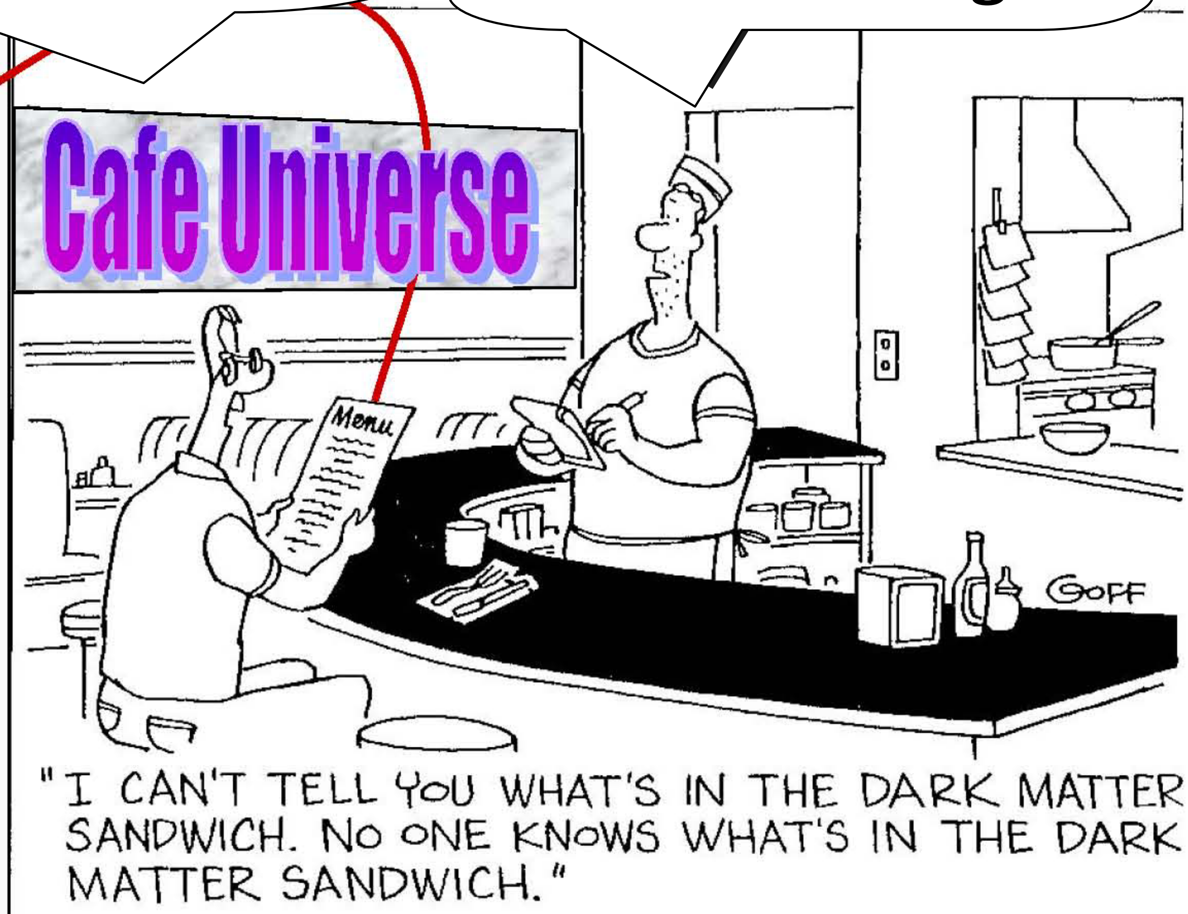
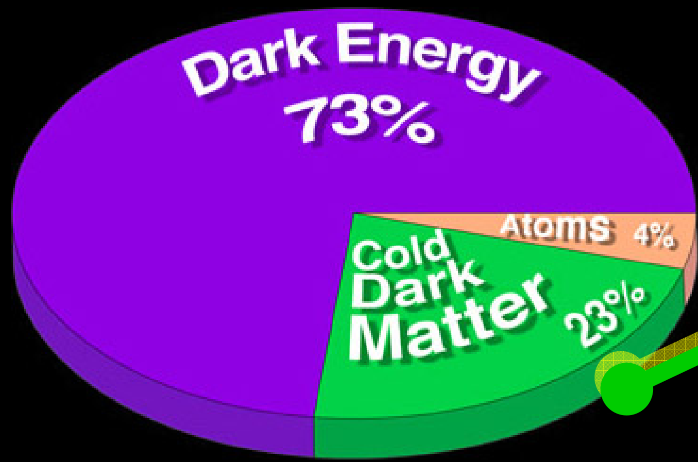


DM Particle in SUSY

Astrophysics



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

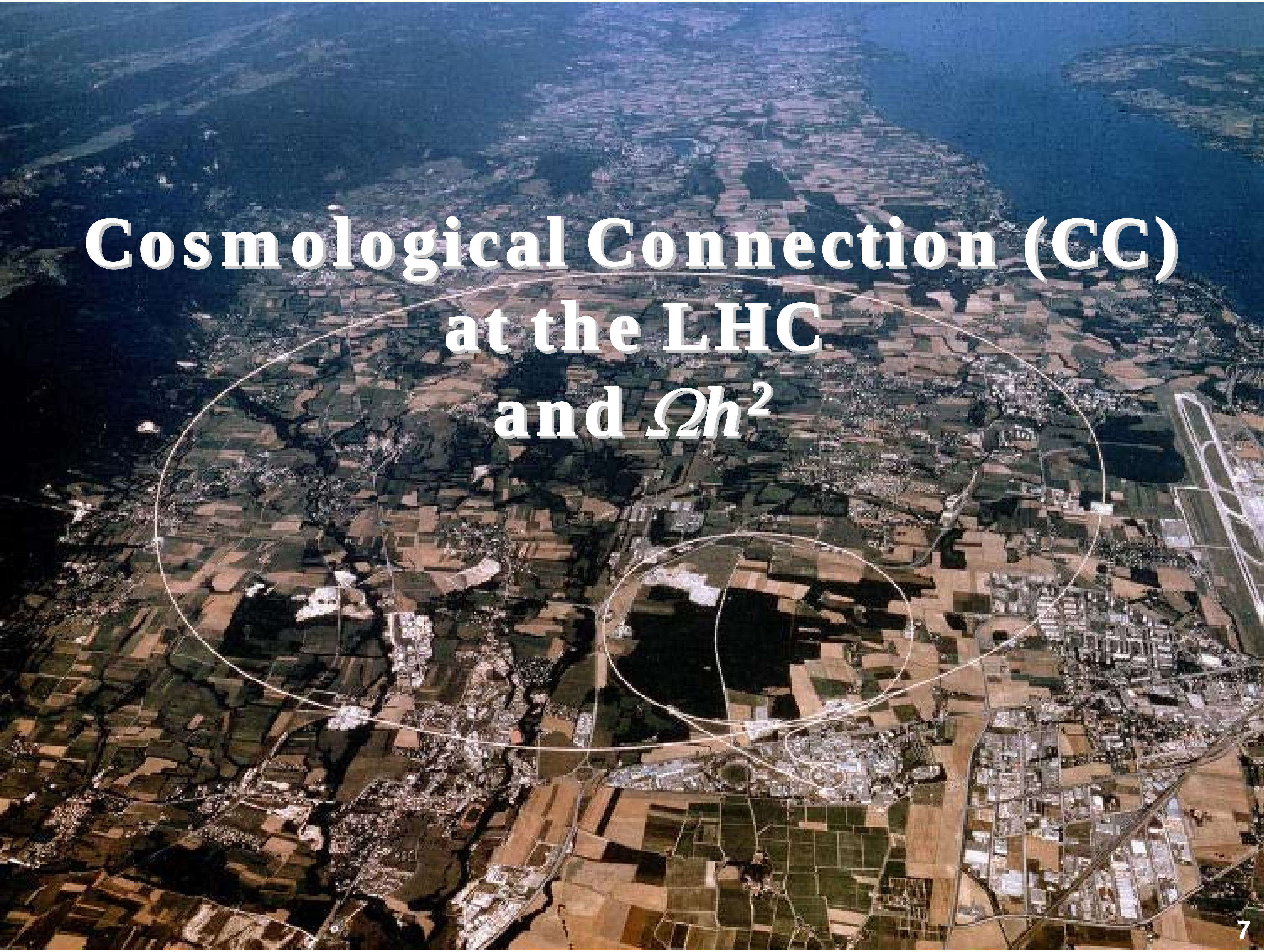
$$\underbrace{\langle \sigma_{ann} v \rangle}_{0.9\ \text{pb}} = \frac{\pi \alpha^2}{8M^2}$$

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

SUSY

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

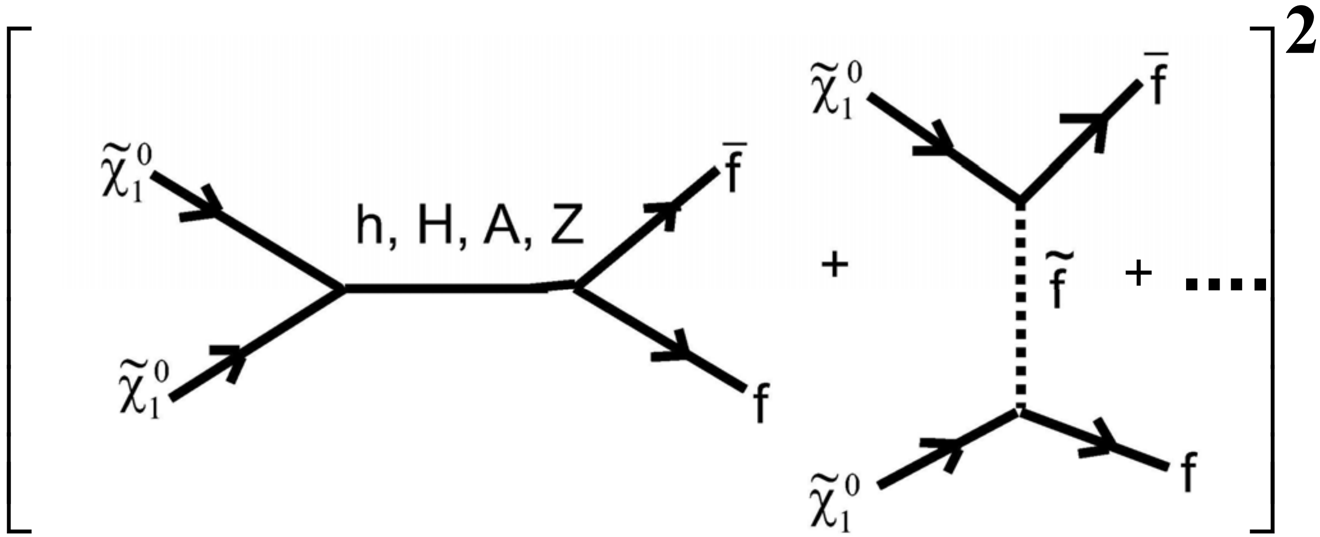
Cosmological Connection (CC) at the LHC and Ωh^2



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

Anatomy of σ_{ann}

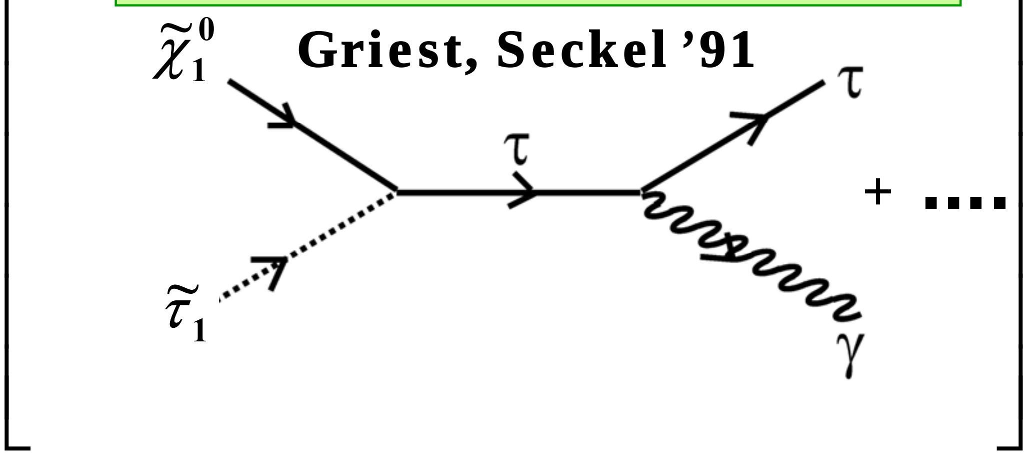
$(\Omega_{CDM})^{-1} \propto$



Co-annihilation (CA) Process

Griest, Seckel '91

+



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

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

An accidental near degeneracy occurs naturally for light stau in mSUGRA.

Minimal Supergravity (mSUGRA)

4 parameters + 1 sign

$m_{1/2}$	Common gaugino mass at M_G
m_0	Common scalar mass at M_G
A_0	Trilinear coupling at M_G
$\tan\beta$	$\langle H_u \rangle / \langle H_d \rangle$ at the electroweak scale
sign(μ)	Sign of Higgs mixing parameter ($W^{(2)} = \mu H_u H_d$)

Experimental Constraints

i. $M_{\text{Higgs}} > 114$ GeV $\quad M_{\text{chargino}} > 104$ GeV

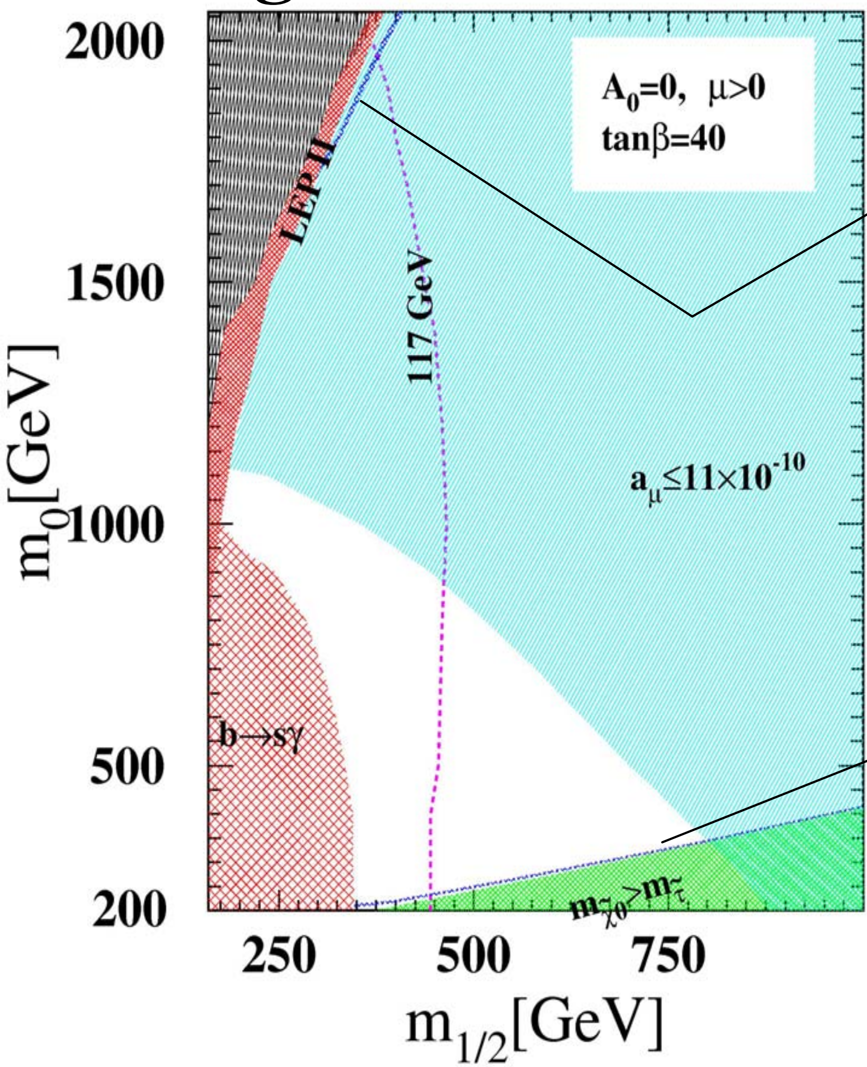
ii. $2.2\times10^{-4} < Br\,(b \to s\,\gamma) < 4.5\times10^{-4}$

iii. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$

iv. $(g-2)_\mu$ [~3σ deviation from the SM calculation]

DM Allowed Regions

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



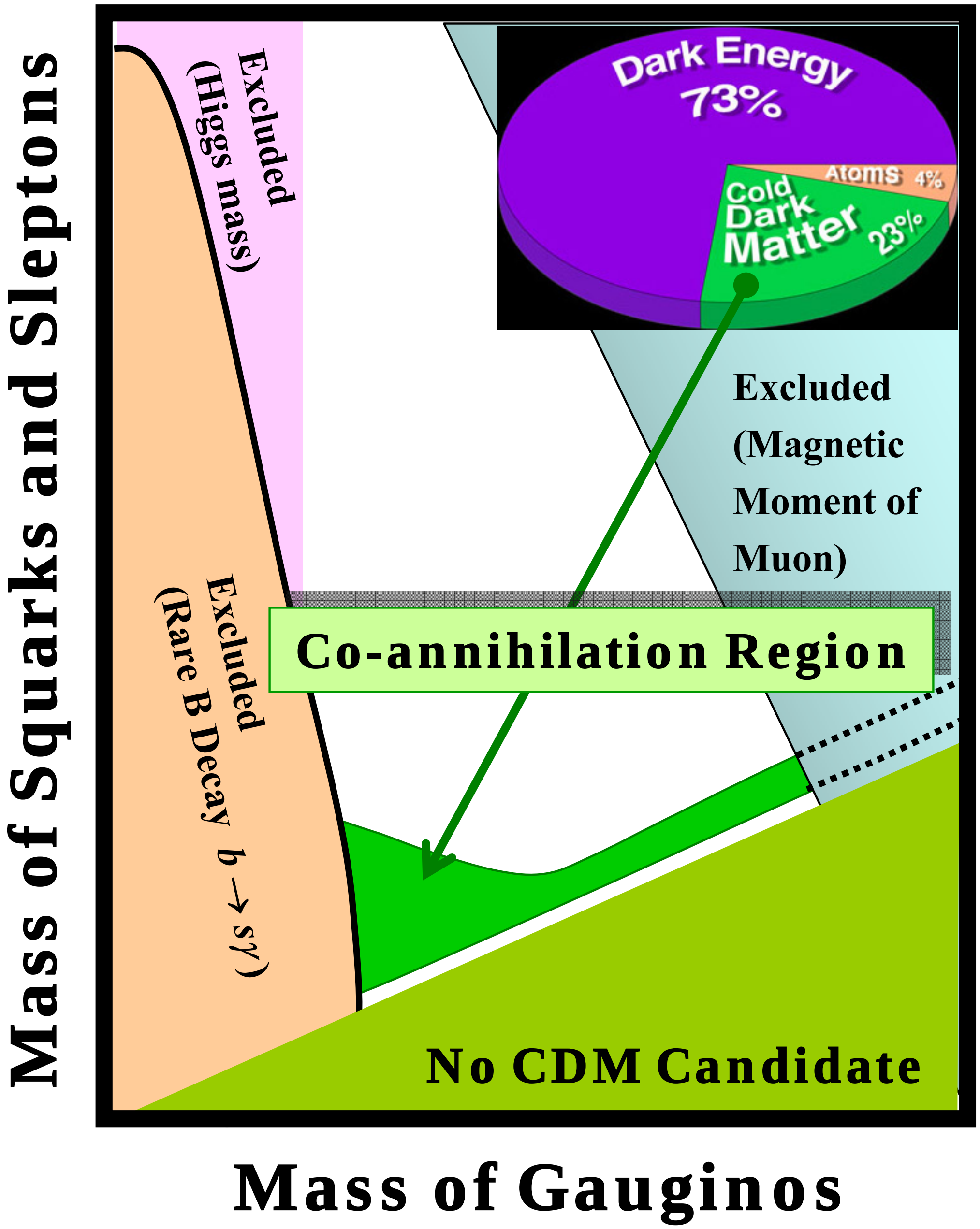
[Focus point region]
the lightest neutralino has a larger Higgsino component

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

[Neutralino-stau CA region]

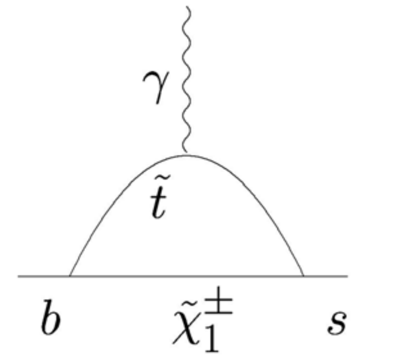
[Bulk region] almost ruled out

CA Regions - Illustration

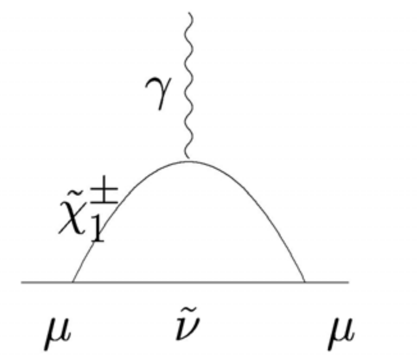


Higgs Mass (M_h)

Branching Ratio $b \to s\gamma$

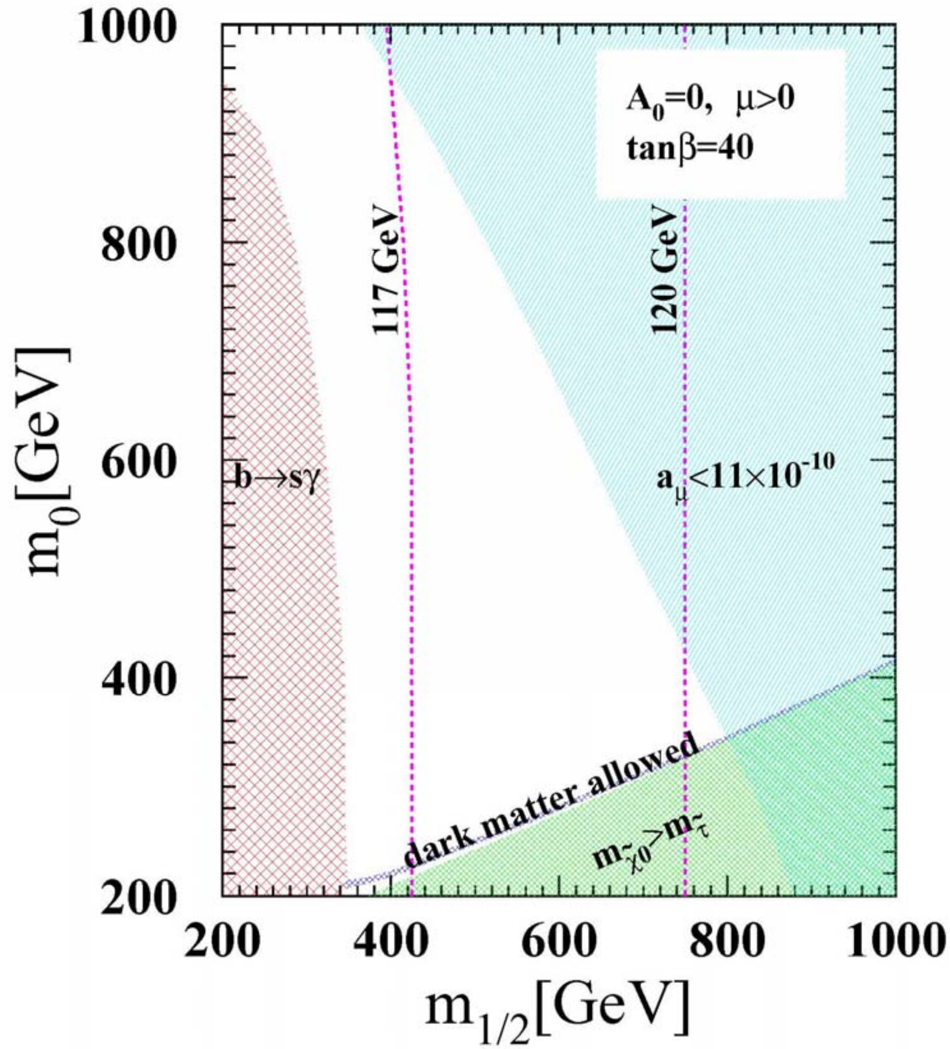


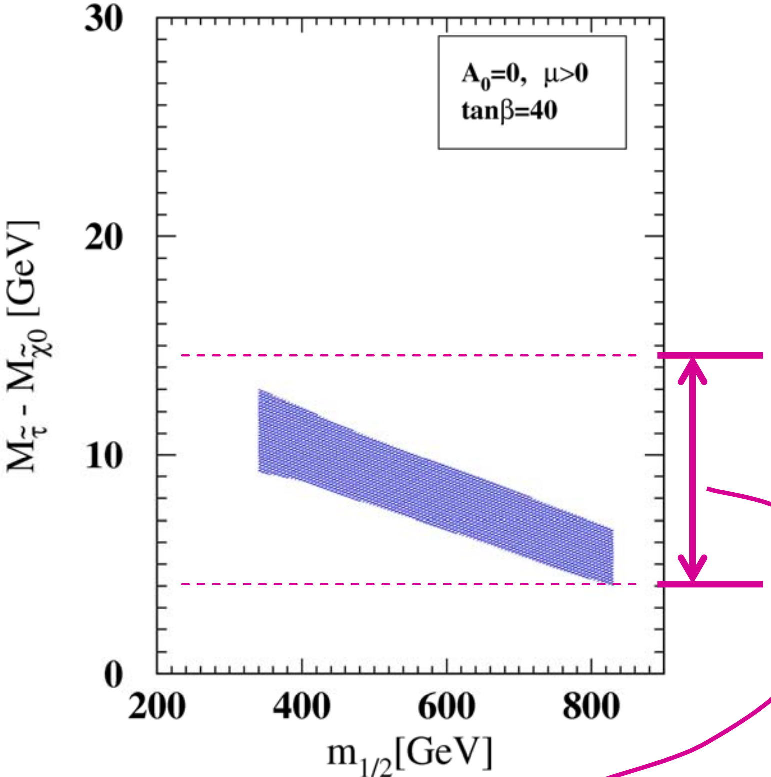
Magnetic Moment of Muon



CDM allowed region

CA Region at tanβ = 40

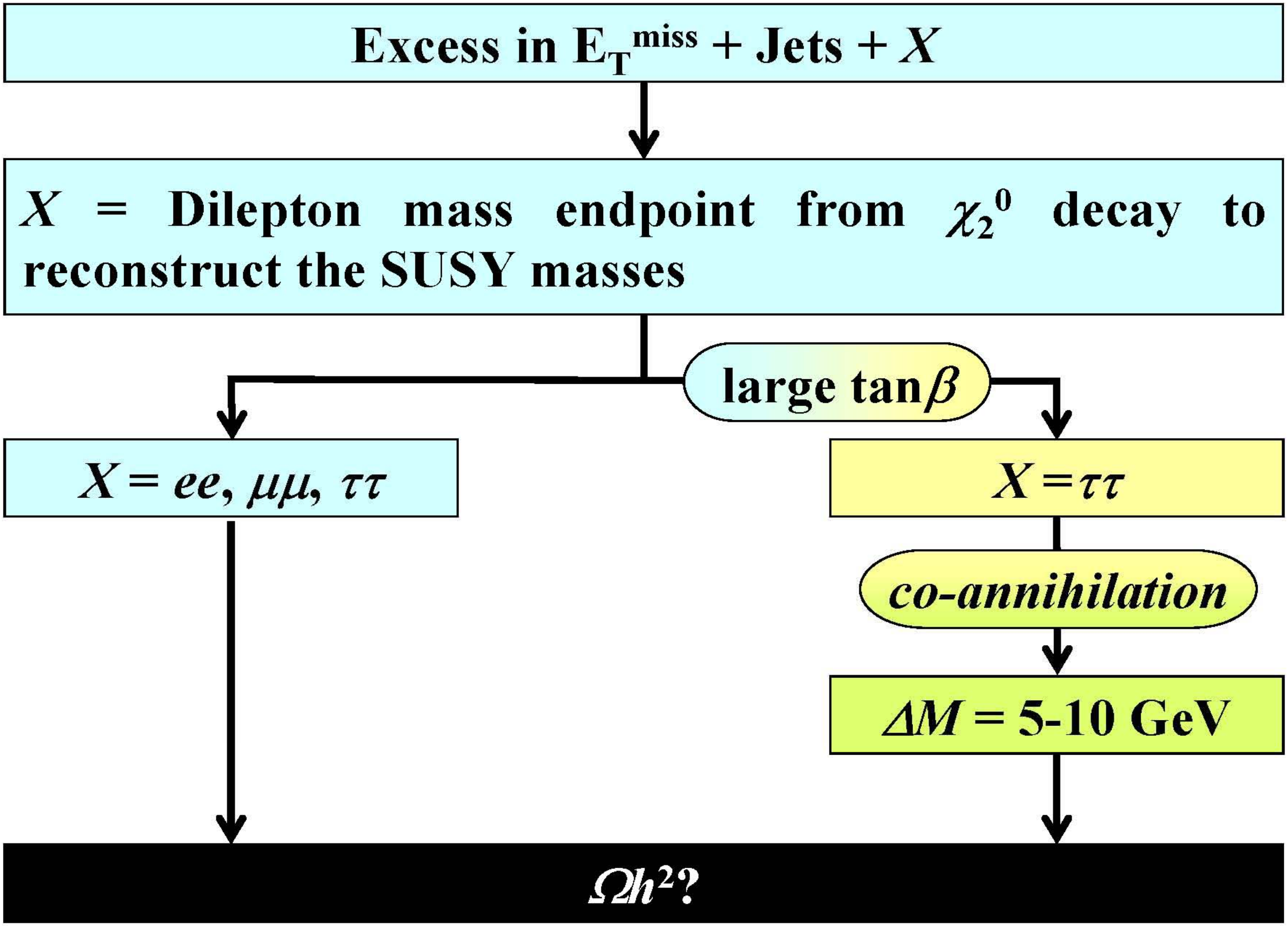




$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} = 5 \sim 15 \text{ GeV}$$

Can we measure ΔM at colliders?

CC at the LHC


Excess in E_T^{miss} + Jets + X
X = Dilepton mass endpoint from χ_2^0 decay to reconstruct the SUSY masses
large tanβ
$X = ee, \mu\mu, \tau\tau$
$X = \tau\tau$
co-annihilation
ΔM = 5-10 GeV
Ωh^2?

Excess in E_T^{miss} + Jets

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

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

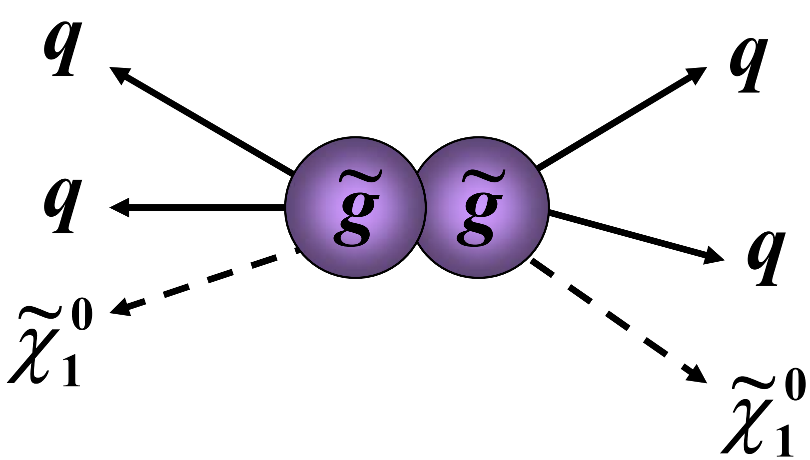
- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV
- $M_{eff} > 400$ GeV ($M_{eff} \equiv E_T^{j1}+E_T^{j2}+E_T^{j3}+E_T^{j4}+ E_T^{miss}$)
- $E_T^{miss} > \max[100, 0.2\, M_{eff}]$

HM1: High Mass Scenario 1

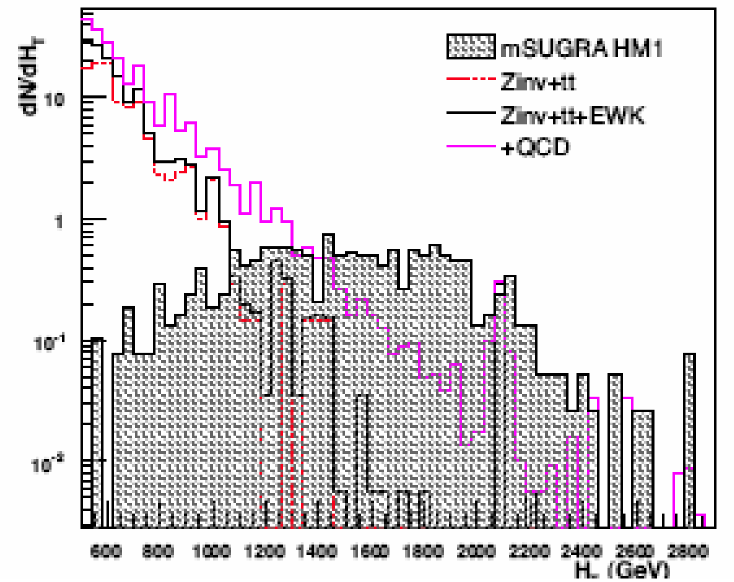
The heavy SUSY particle mass is measured by combining the final state particles

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

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



CMS



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

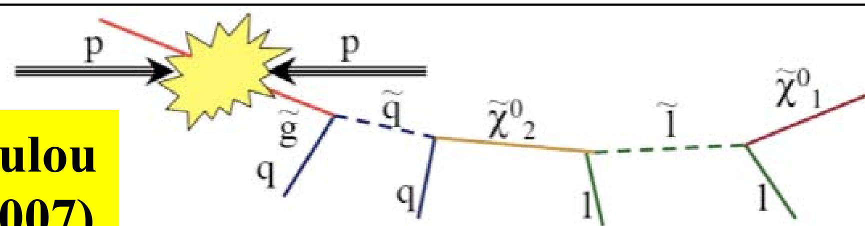
gluino → squark+quark

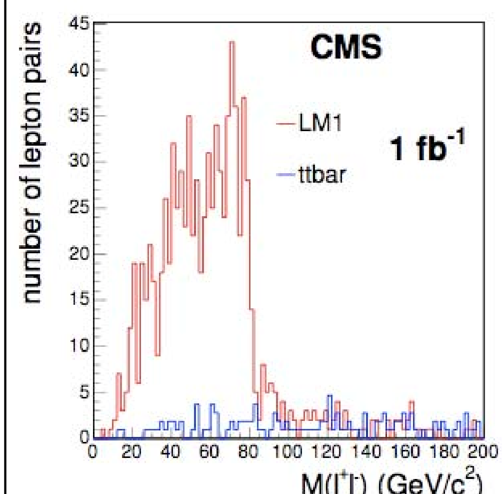
B(X02 → slep_R lept) = 11.2%

B(X02 → stau_1 tau) = 46%

B(X+1 → sneut_L lept) = 36%

Spiropoulou (SUSY2007)





- SFOS dilepton+jets+E_T^{miss}
- $t\bar{t}$:WW+j:Z+j:other~ 6:1:1:1
- flavor subtraction ($e^-\mu^+ + e^+\mu^-$) to supress chargino, W, $t\bar{t}$, WW, "other"
- L1+HLT trigger path required
- overall systematic on the background 20% (JES dominated)
- 5σ discovery with ~ 20 pb^{-1} (of data understood as expected with 1 fb^{-1}).

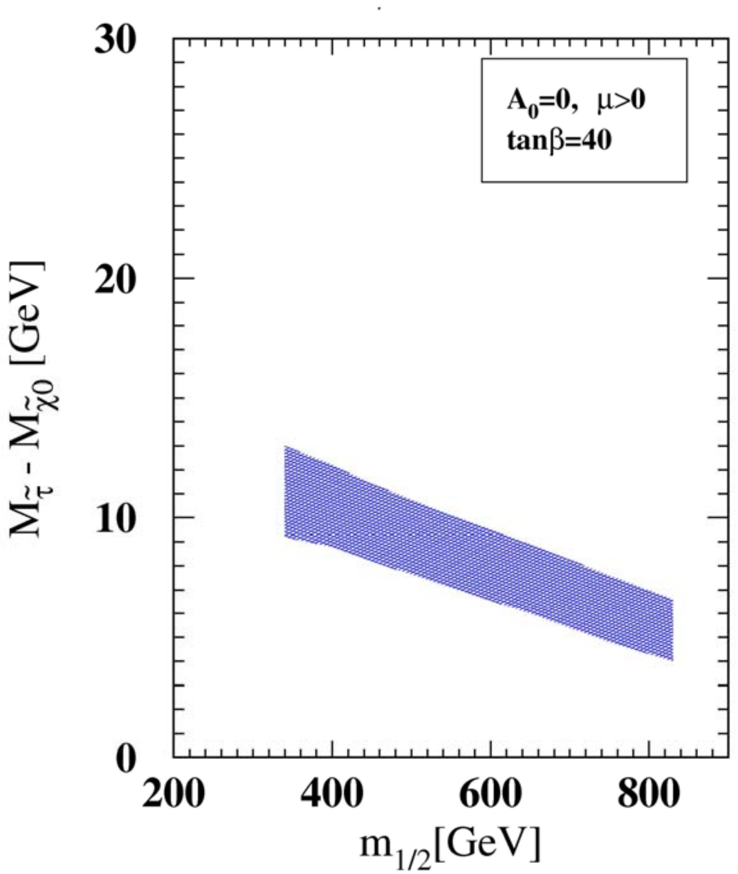
Dilepton Endpoint in CA Region

- In the CA region, however, the *ee* and $\mu\mu$ channels are almost absent. We are in a different game:

  $Br(\chi_2^0 \rightarrow ee, \mu\mu) \sim 0\%$

  $Br(\chi_2^0 \rightarrow \tau\tau) \sim 100\%$

  ΔM = 5-15 GeV



- Questions:

(1) How can we establish the dark matter allowed regions?

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

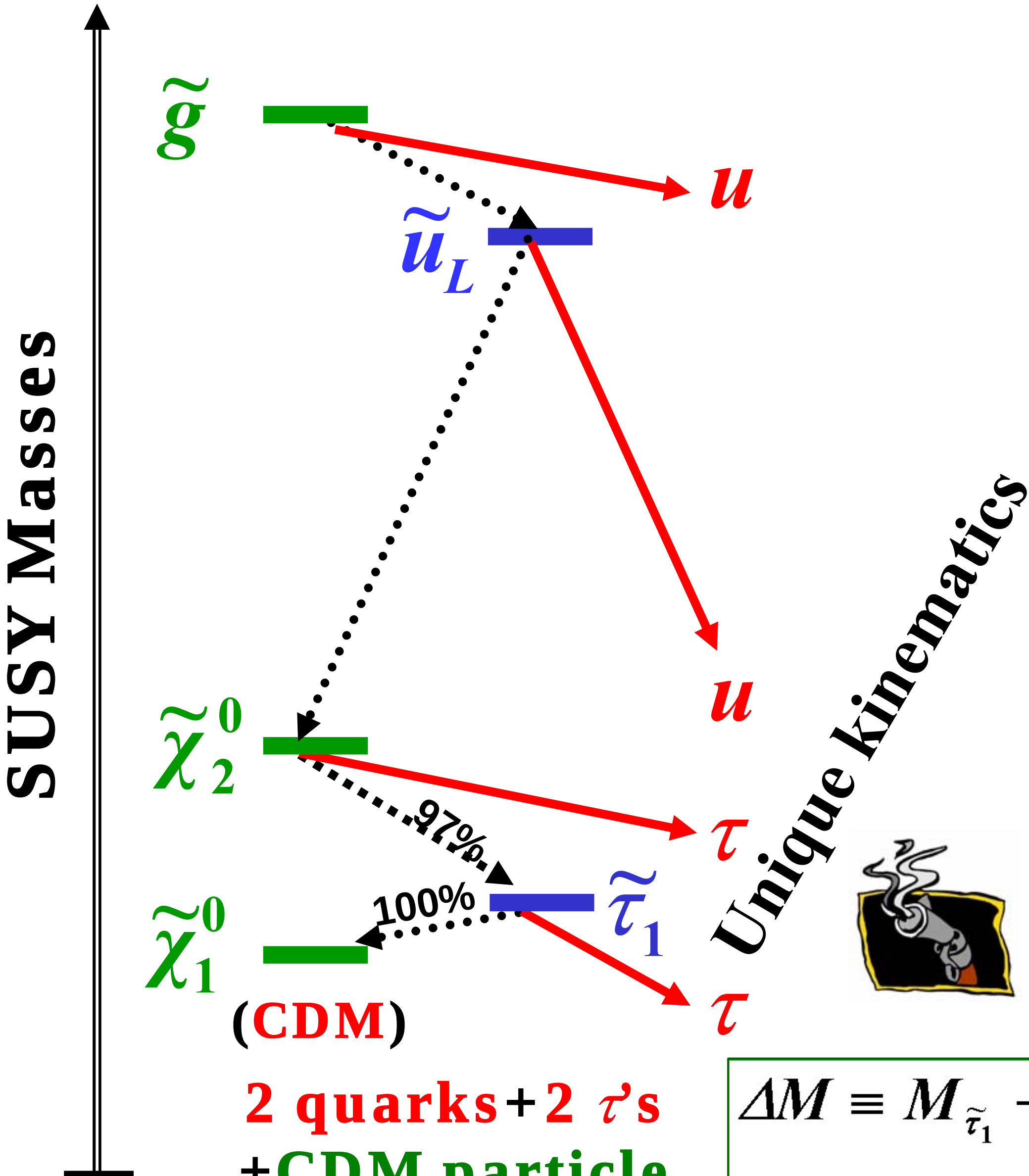
Our Reference Point

$m_{1/2}$ = 351, m_0 = 210, tanβ = 40, μ >0, A_0 = 0 [ISAJET version 7.69]

TABLE I: Masses (in GeV) of SUSY particles for our reference point $m_{1/2} = 351$ GeV, $m_0 = 210$ GeV, $\tan\beta = 40$, $\mu > 0$, and $A_0 = 0$. We use **ISAJET** v7.69 The $\tilde{q}_L$ and $\tilde{q}_R$ masses are represented by the $\tilde{u}_L$ and $\tilde{u}_R$ masses. $\Delta M = 10.6$ GeV.

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

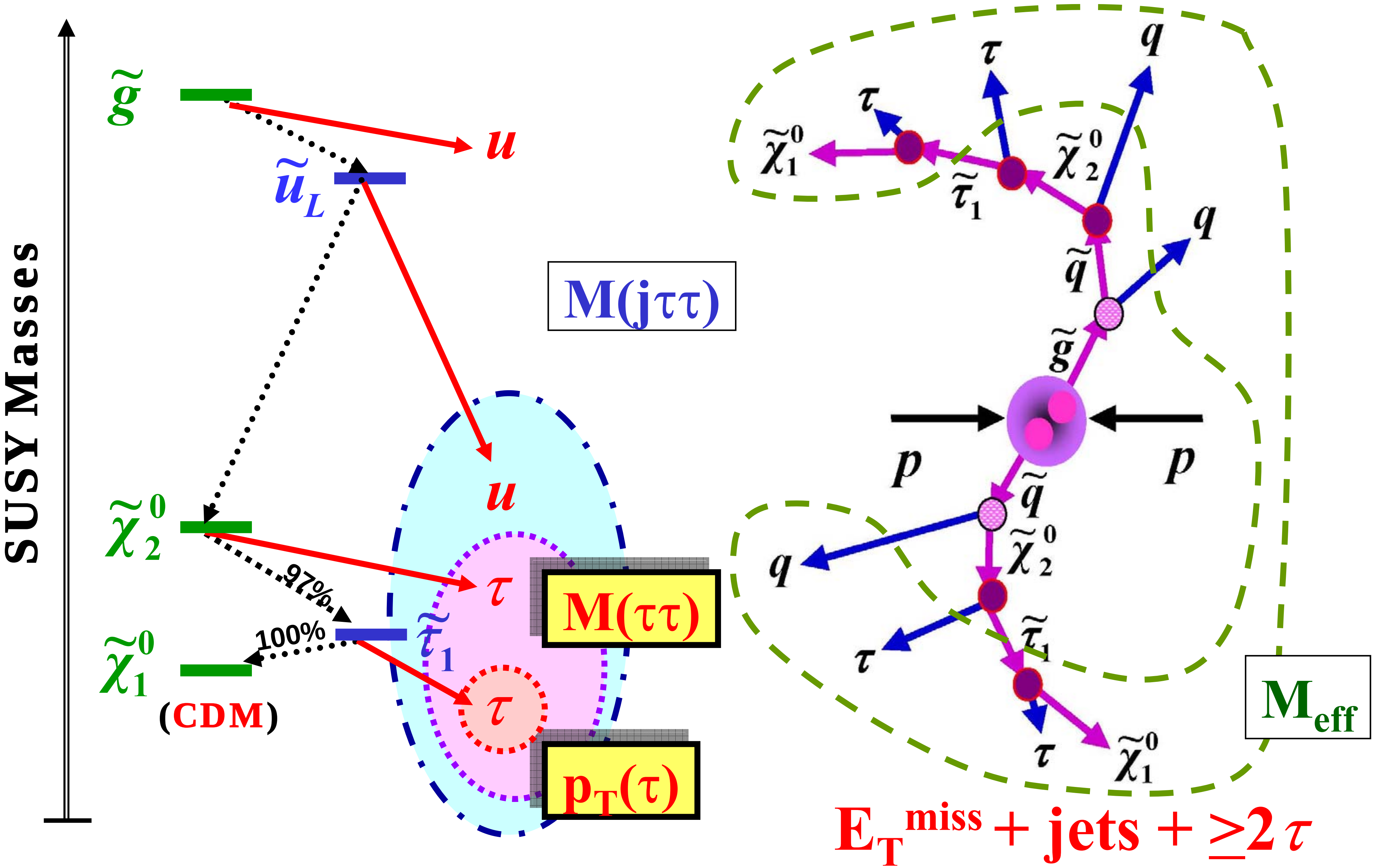
Smoking Gun of CA Region



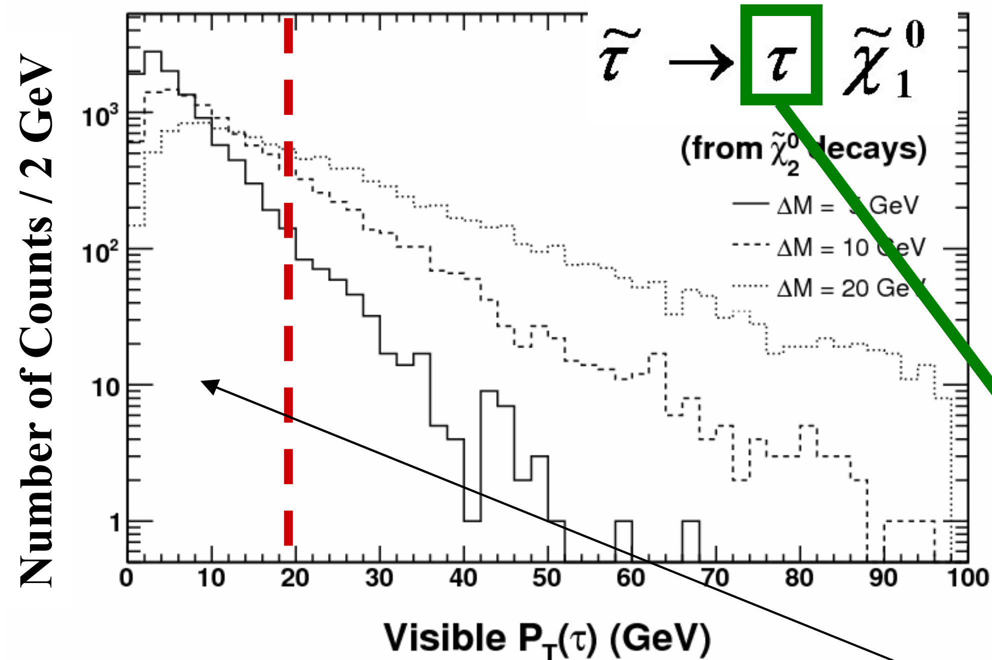
2 quarks + 2 τ's
+ CDM particle

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

SUSY Anatomy



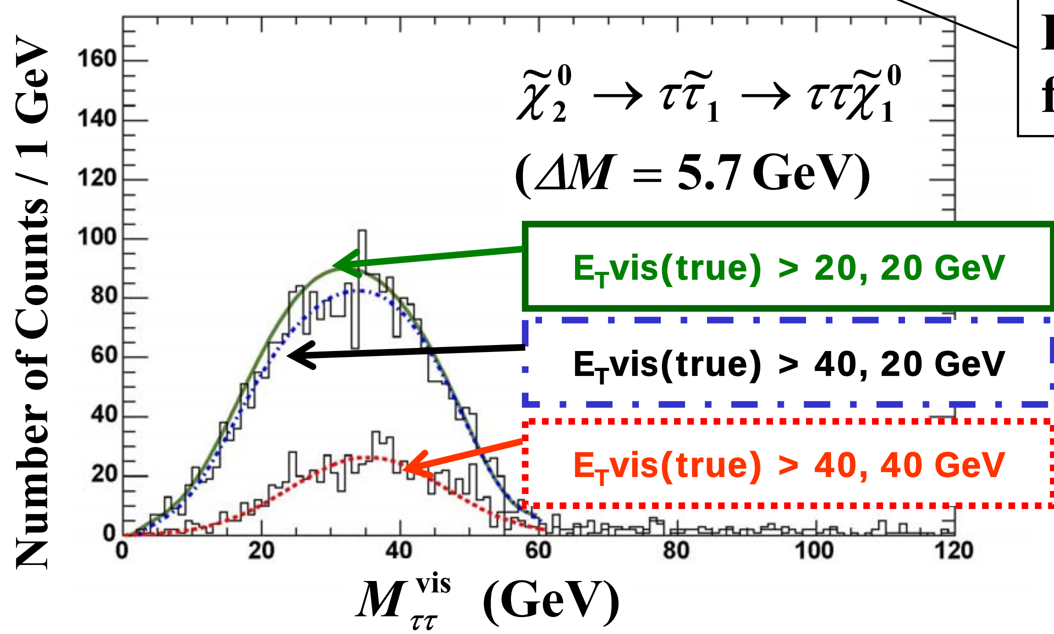
P_T^{soft} Slope and $M_{\tau\tau}$



P_T and $M_{\tau\tau}$ distributions in true di-τ pairs from neutralino decay with $|\eta| < 2.5$

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, because e or μ does not tell us the evidence of tau leptons

II. How low in p_T?

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

III. Worries about triggers?

- E_T^{miss} + jet trigger for SUSY
- Lepton+tau trigger for Z's (calibration)

[Assumption] $\varepsilon_\tau = 50\%$, fake rate 1%

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$\tau\tau$

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

LS $\tau\tau$

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

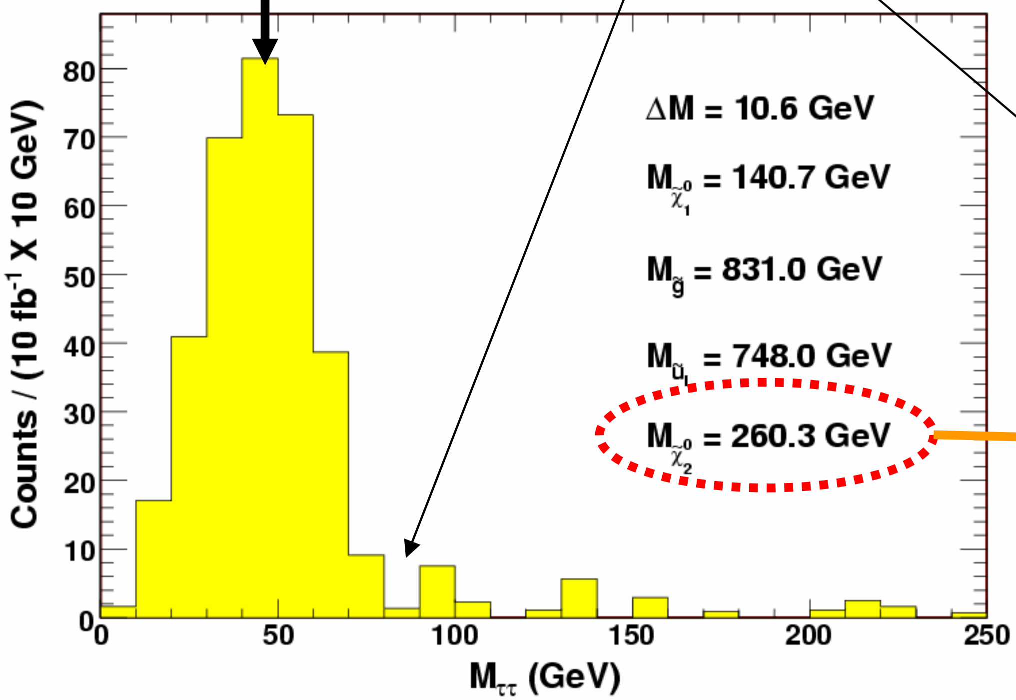
OS mass → **OS–LS mass** ← **LS mass**

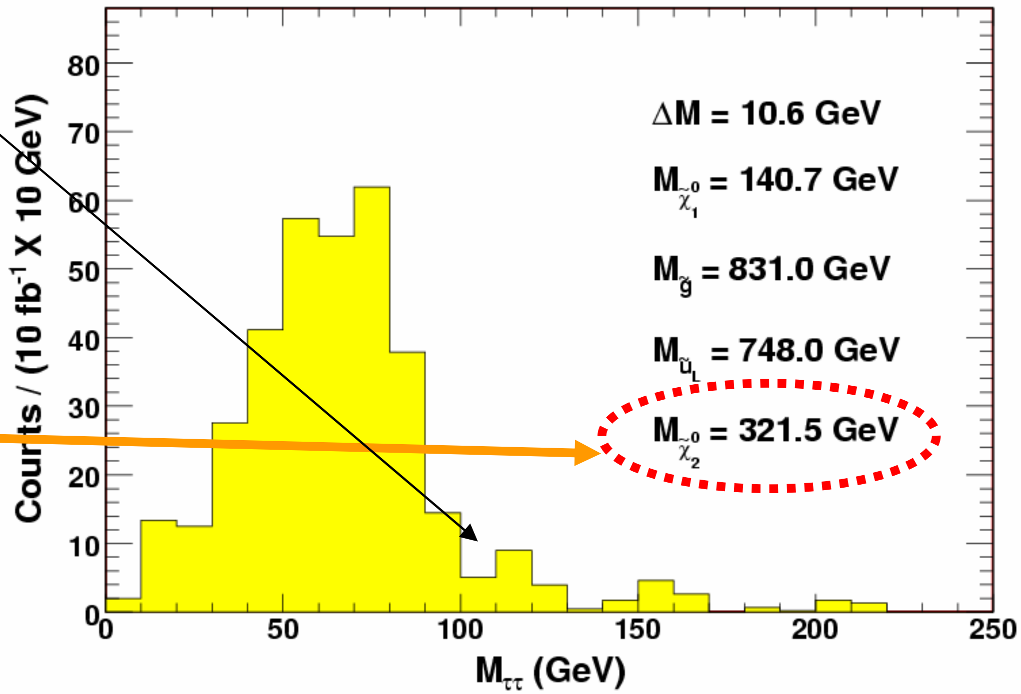
$M_{\tau\tau}$ Distribution

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

Clean peak even for low ΔM

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





We choose the peak position as an observable.

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(τ) $\geq$ 2 with $P_T > 40, 20$ GeV

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

OS$\tau\tau$

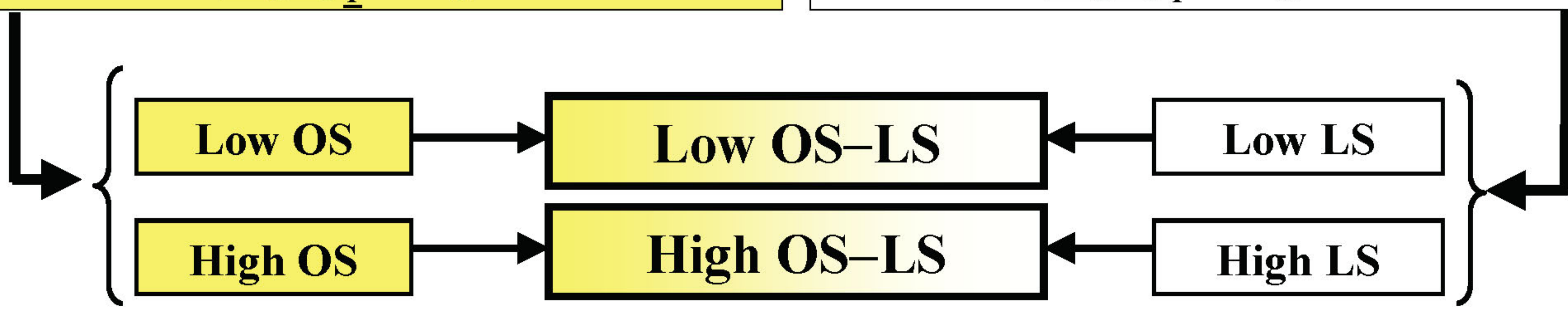
Low p_T *histogram*

High p_T *histogram*

LS $\tau\tau$

Low p_T *histogram*

High p_T *histogram*

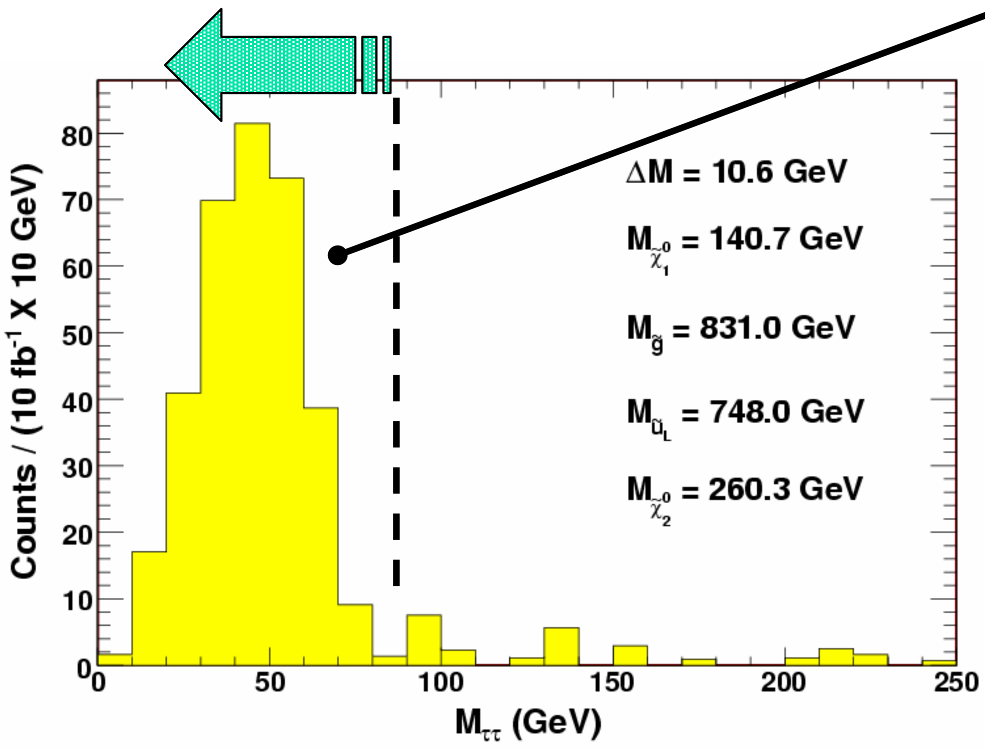


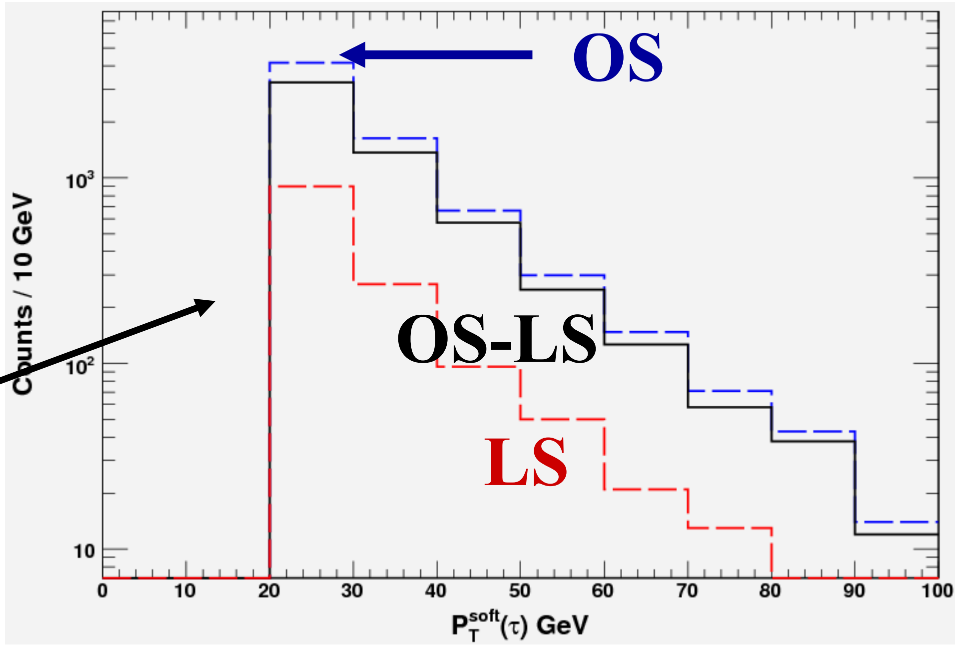
OS–LS Slope(P_T^{soft})

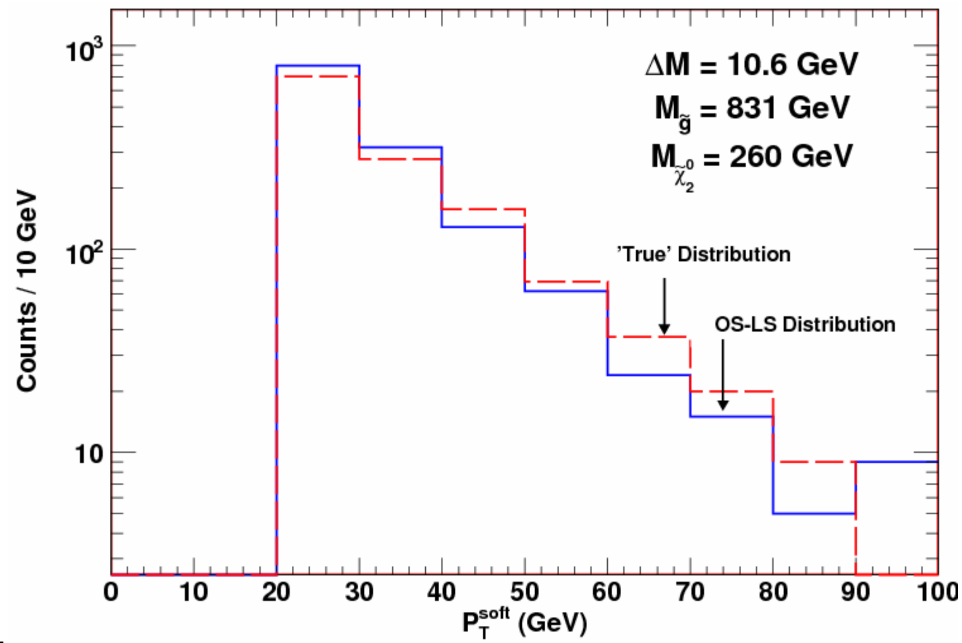
$\Delta M = 10.6$ GeV

$M_{\tilde{g}} = 831$ GeV

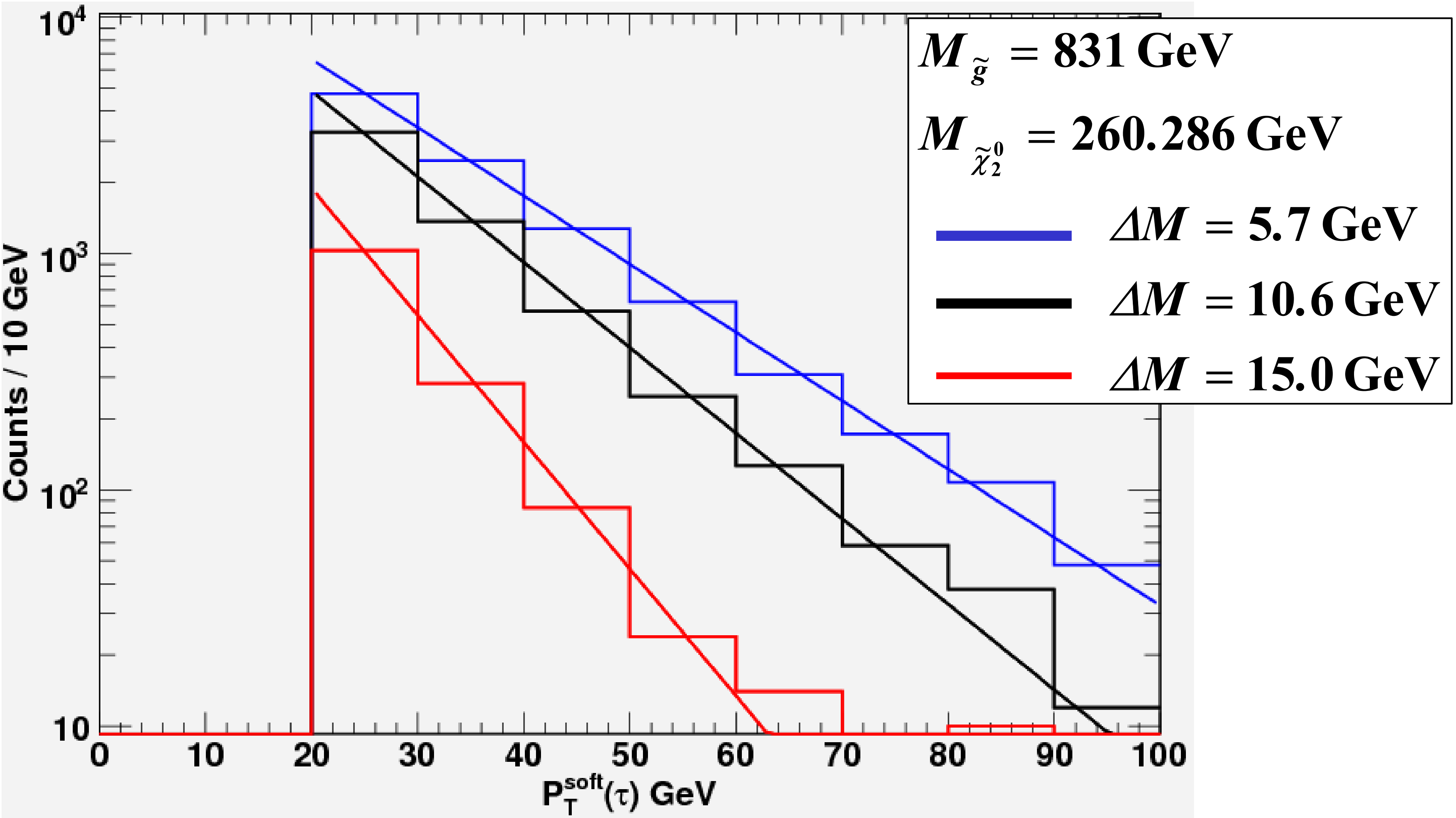
M(ττ) < M(ττ)^{endpoint}





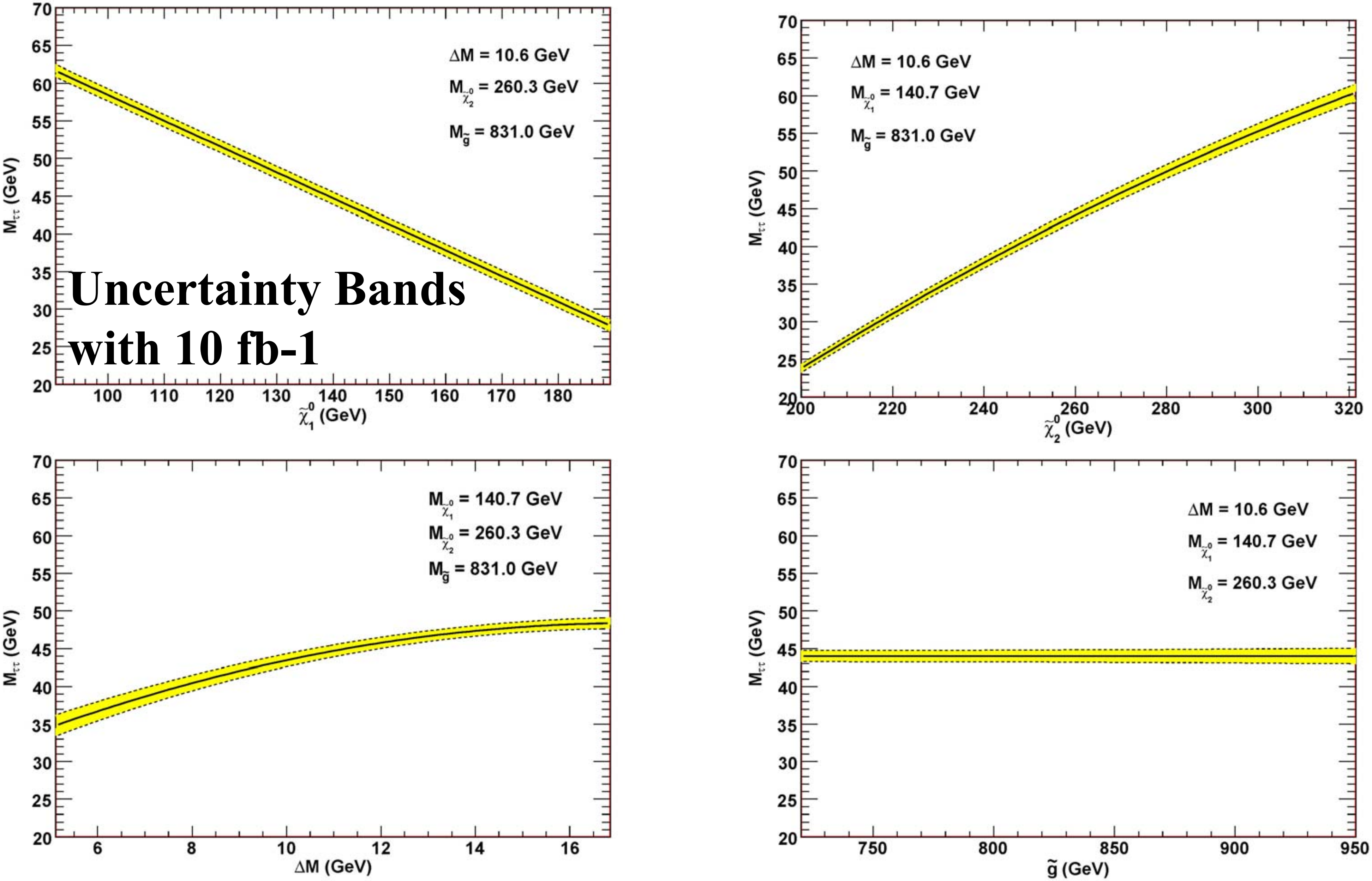


ΔM Dependence of Slope(P_T^{soft})

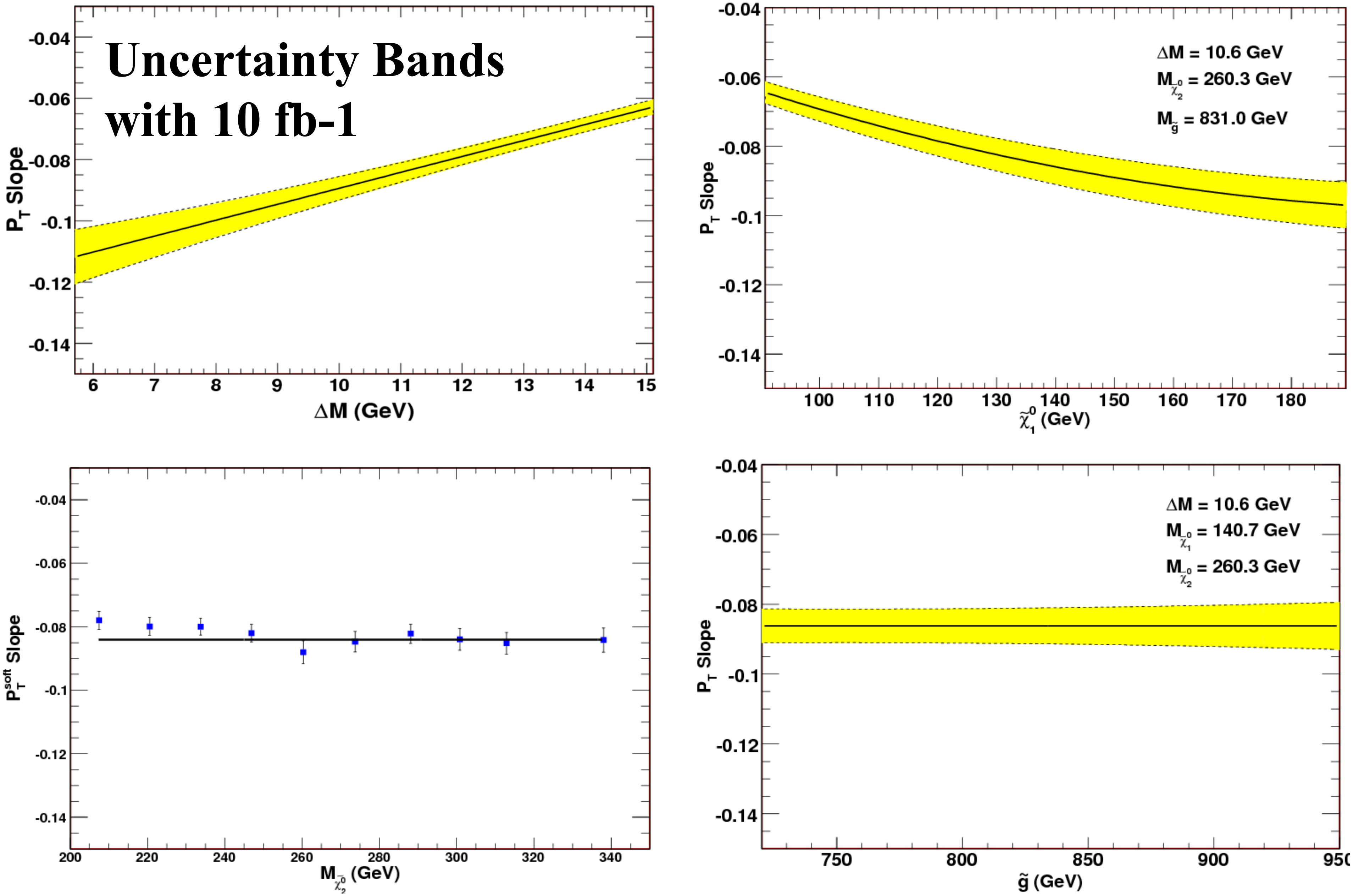


We can still see the dependence of the P_T slope on ΔM using OS–LS method.

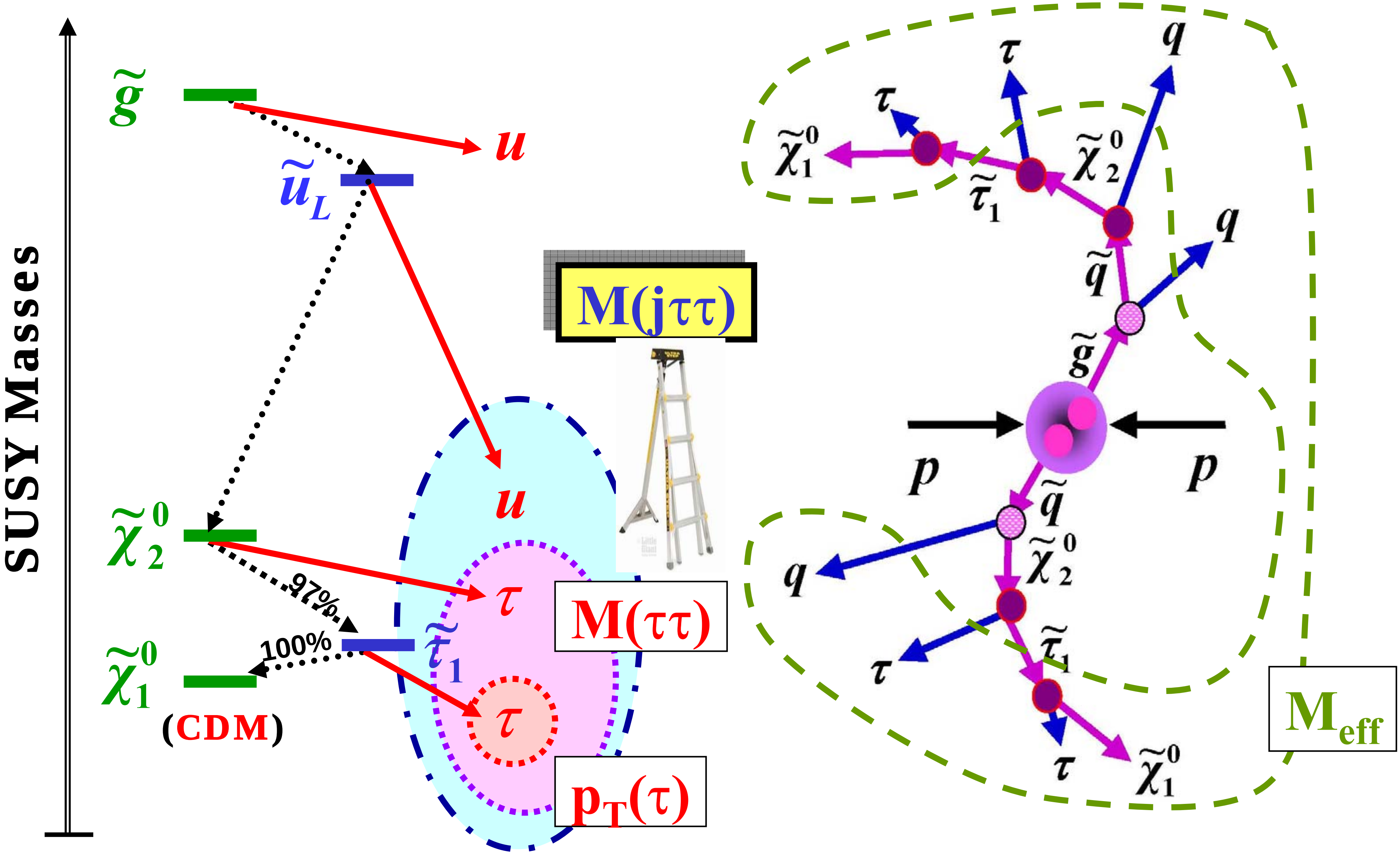
$M_{\tau\tau}^{peak}$ vs. *X*



Slope(P_T^{soft}) vs. X

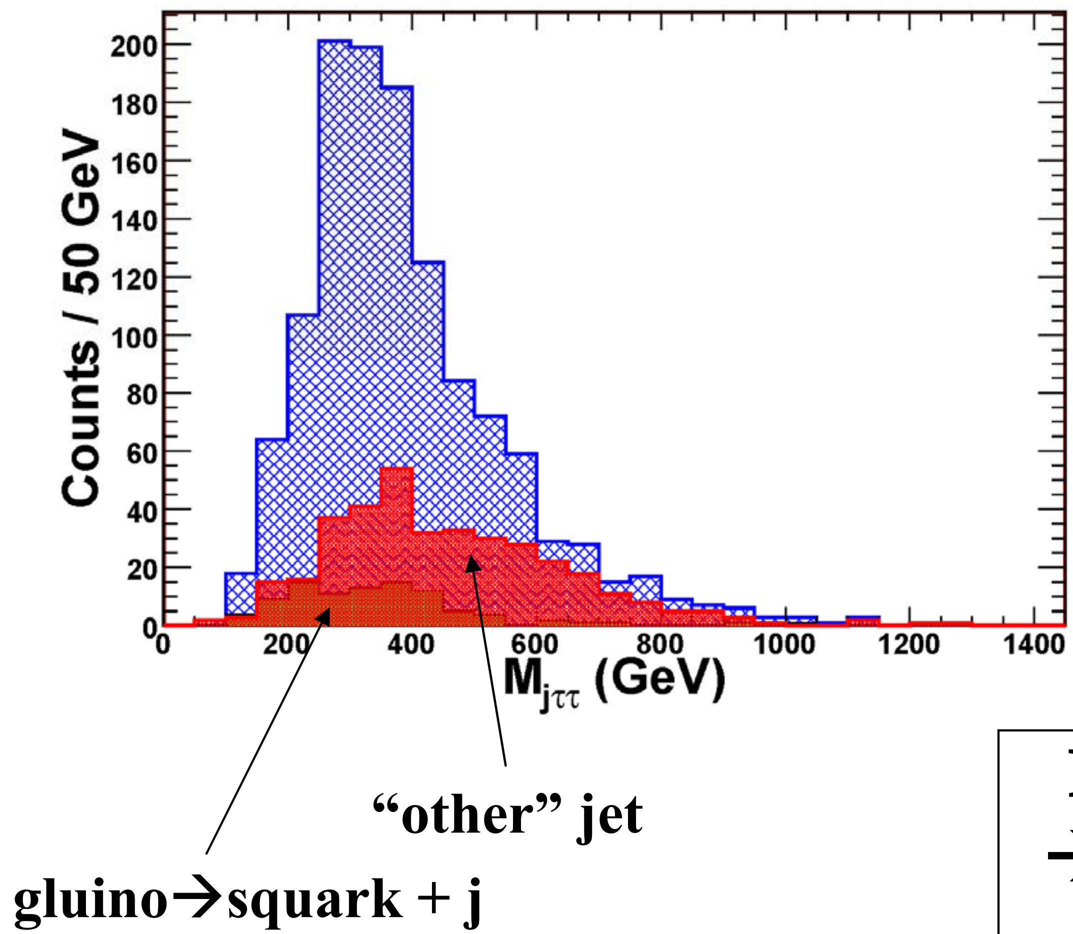


SUSY Anatomy



$M_{j\tau\tau}$ Distribution

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



$M(\tau\tau) < M(\tau\tau)^{endpoint}$

Jets with $E_T > 100$ GeV

$J\tau\tau$ masses for each jet

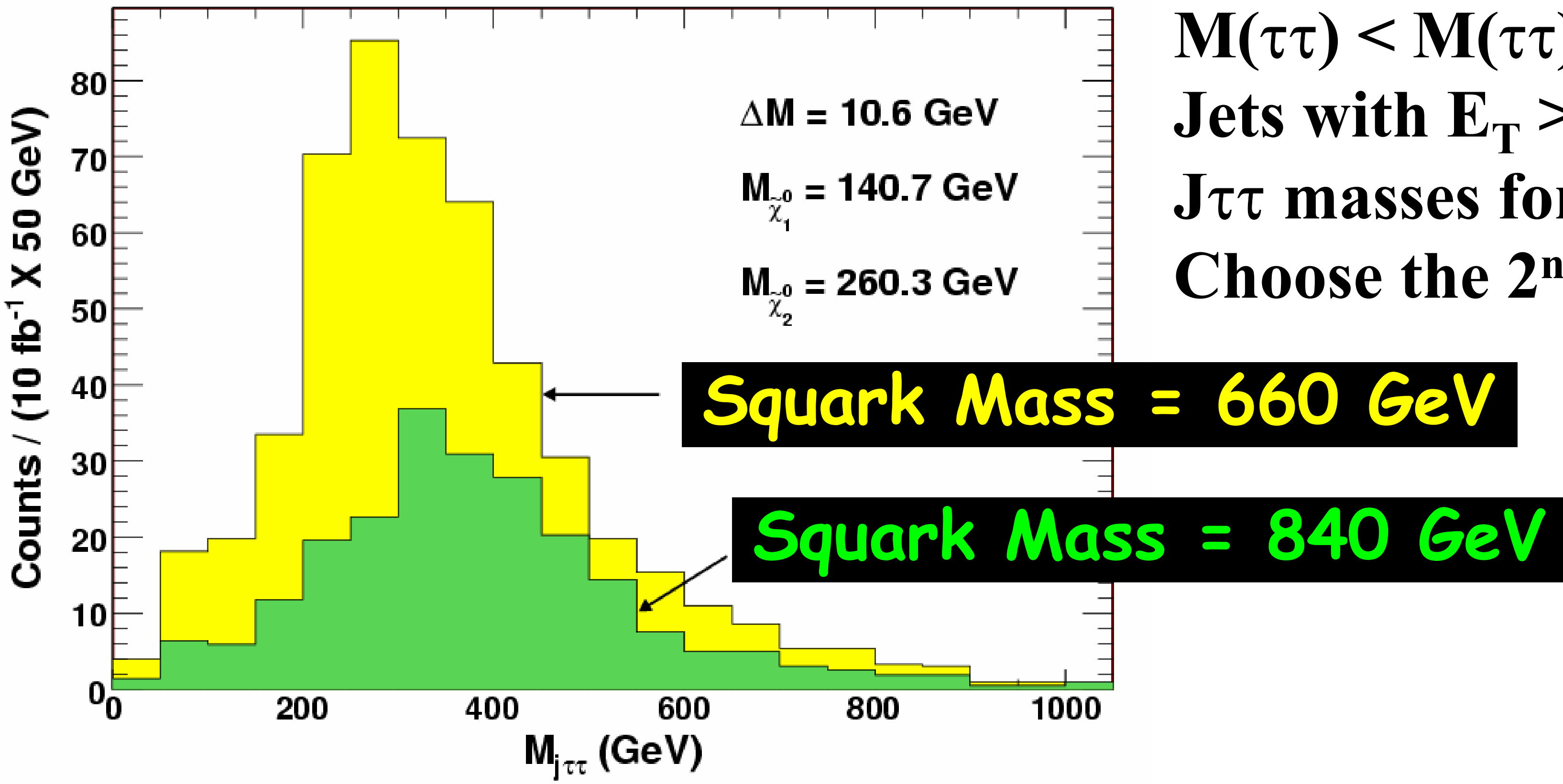
Choose the 2nd large value

Peak value ~ True Value
→ We take the peak value as an observable.

$M_{j\tau\tau}$ Distribution

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

$$M_{j\tau\tau}^{peak} \propto M_{j\tau\tau}^{end}$$

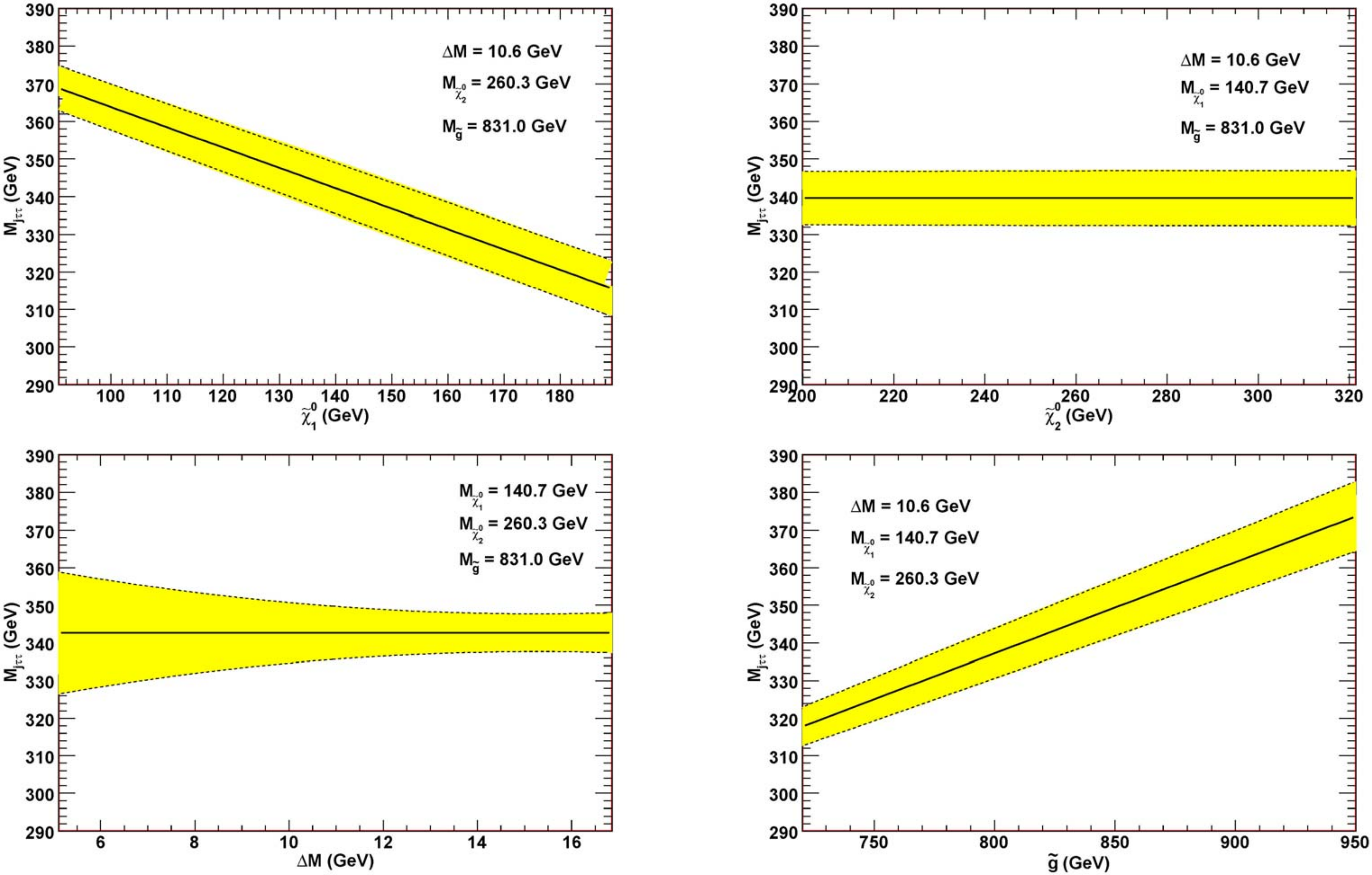


- $M(\tau\tau) < M(\tau\tau)^{endpoint}$
- Jets with $E_T > 100$ GeV
- $J\tau\tau$ masses for each jet
- Choose the 2nd large value

Peak value depends on squark mass

We choose the peak position as an observable.

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



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

4 observables defined as functions of 5 masses

$$N_{OS-LS} = f(\tilde{g}, \tilde{q}_L, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

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

$$Slope = w(\tilde{g}, \Delta M, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

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

Invert the equations to determine the masses as functions of the observables

$$\tilde{g} = f'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

$$\tilde{q}_L = 0.9 \cdot \tilde{g}$$

$$\Delta M = h'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

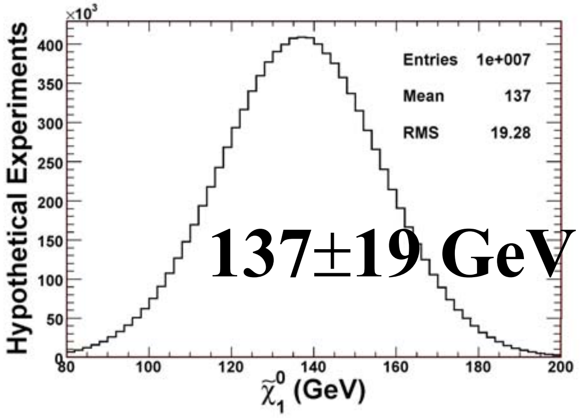
$$\tilde{\chi}_2^0 = w'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

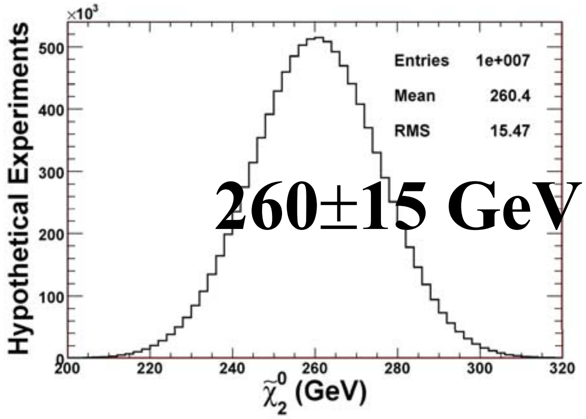
$$\tilde{\chi}_1^0 = y'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

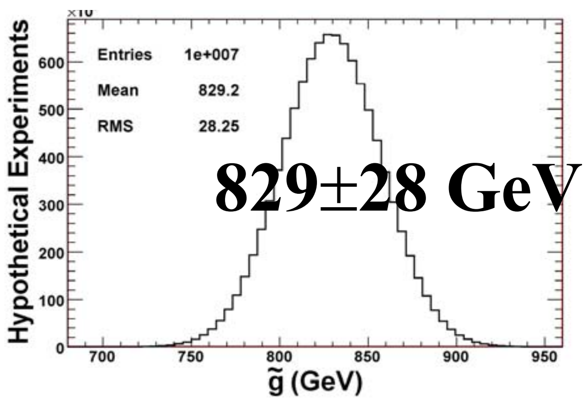
5th observable ($M_{j\tau}$) is not ready for this talk. We assume:

$$\tilde{q}_L = 0.9 \cdot \tilde{g}$$

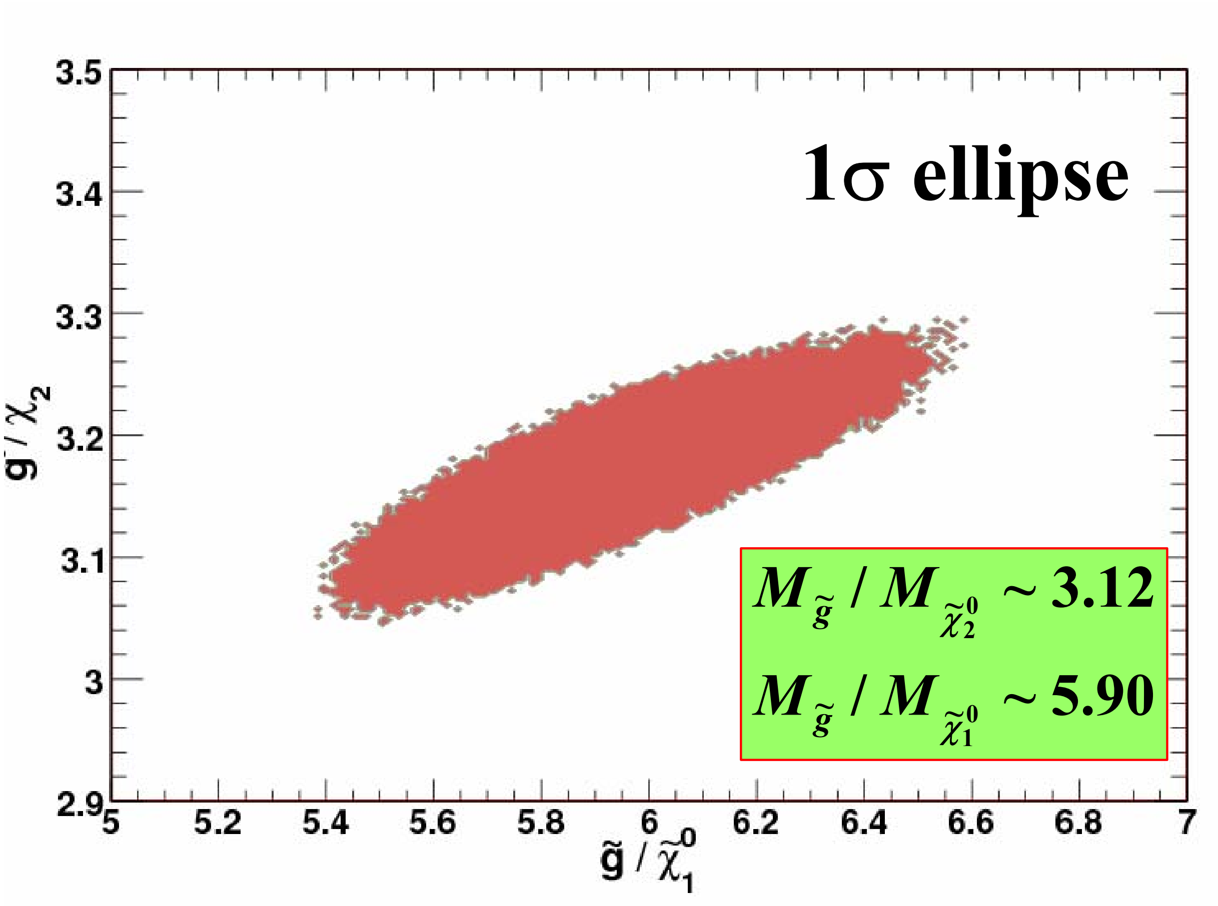
[This assumption will be removed once the $M_{j\tau}$ study is ready.]





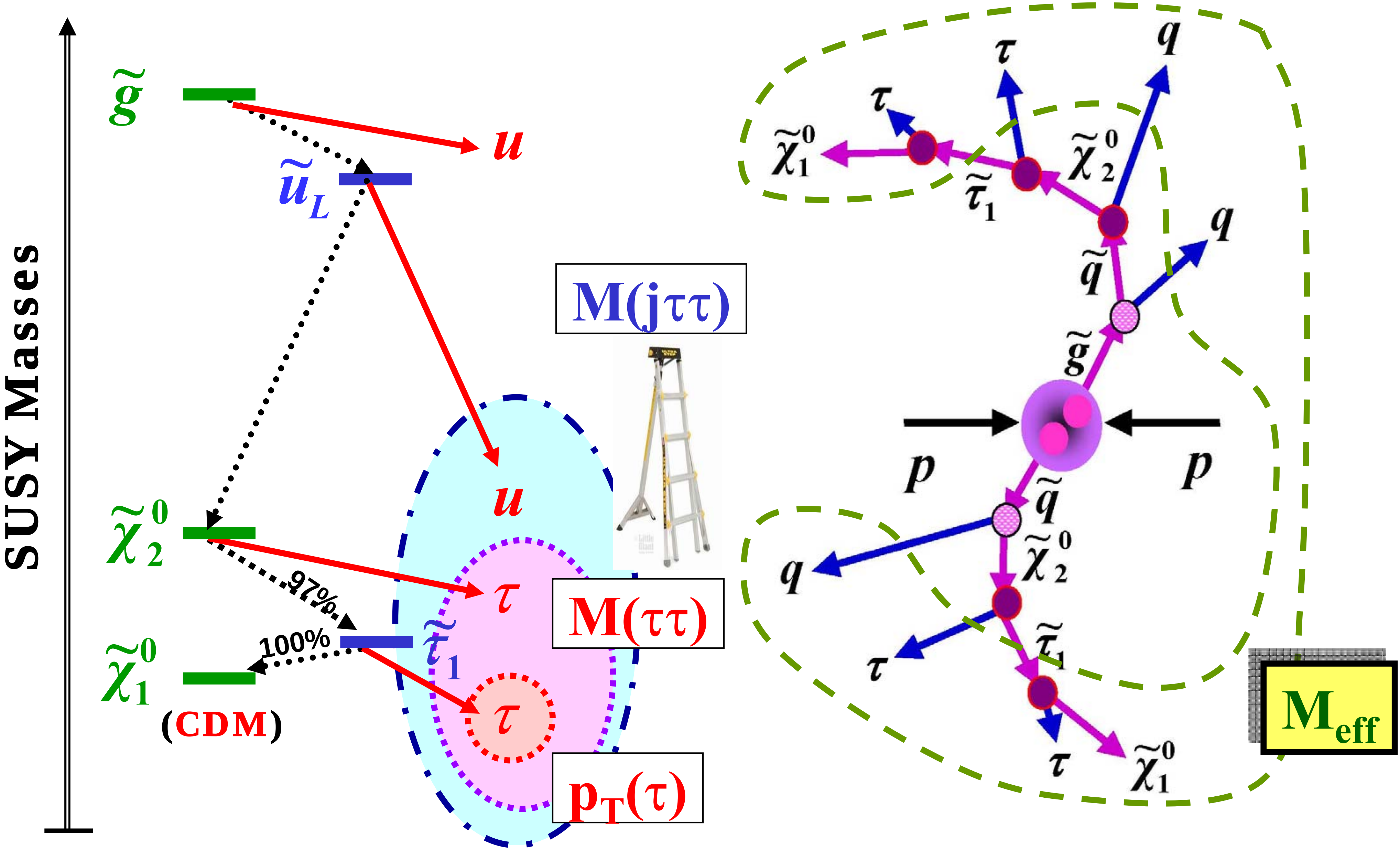


Gaugino Universality (10 fb^{-1})



We test a gaugino univesality.

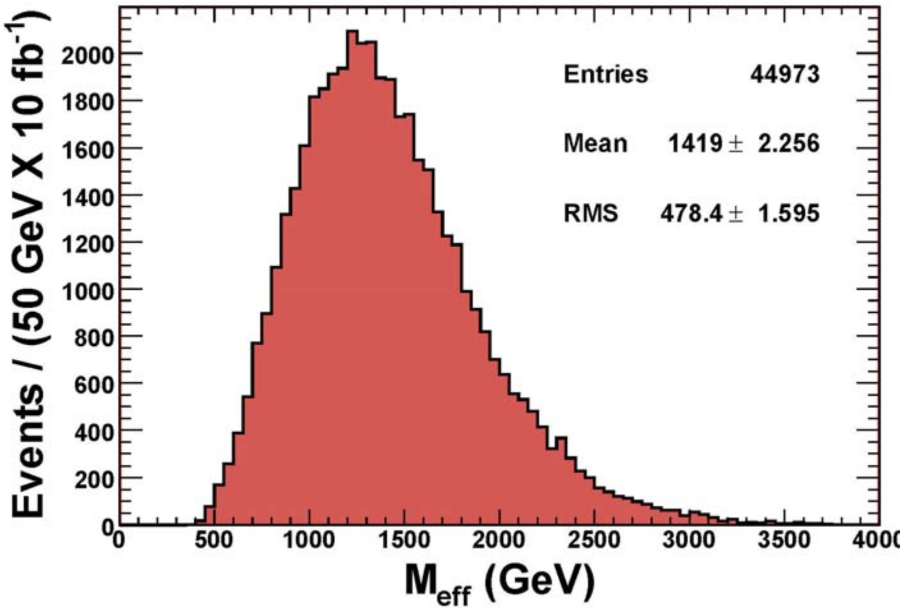
SUSY Anatomy



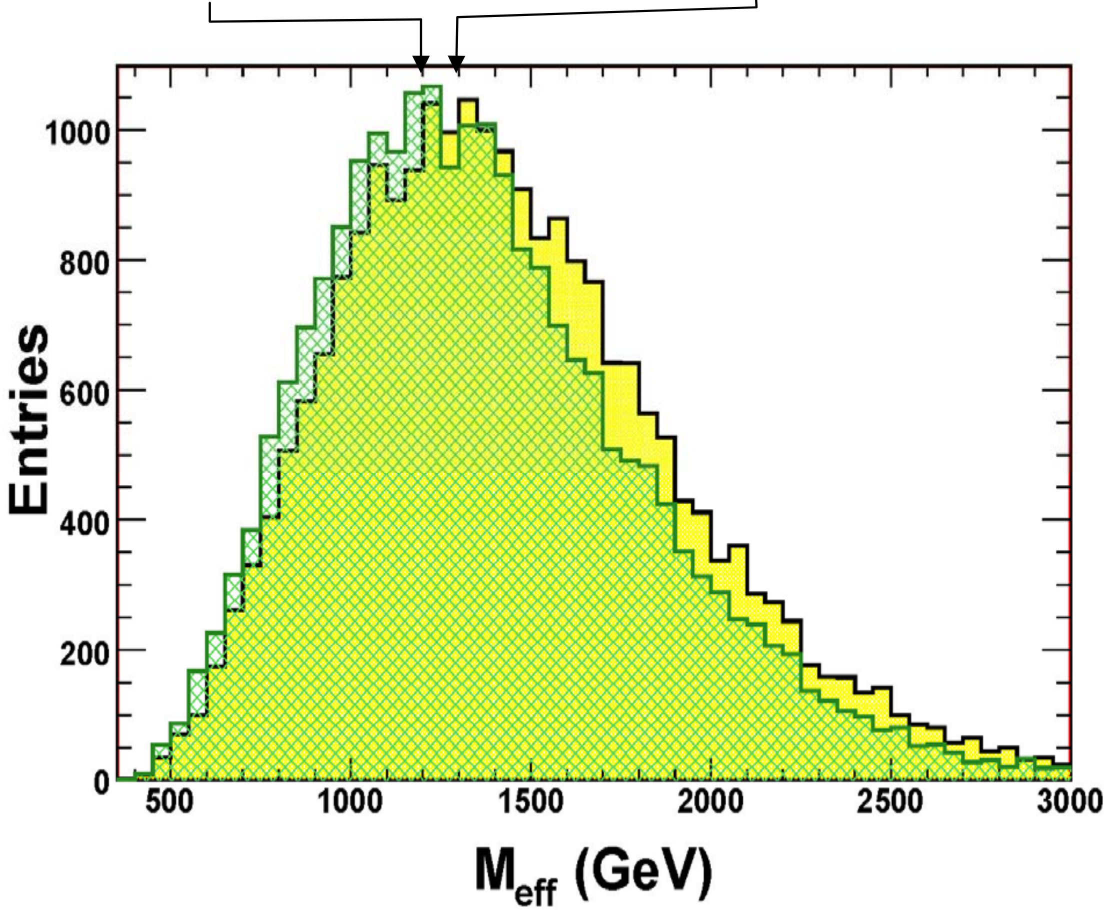
M_{eff} Distribution

- $E_T^{j1} > 100$ GeV, $E_T^{j2,3,4} > 50$ GeV [No ε'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; $\varepsilon_b \sim 50\%$])
- $E_T^{miss} > \max[100, 0.2\, M_{eff}]$

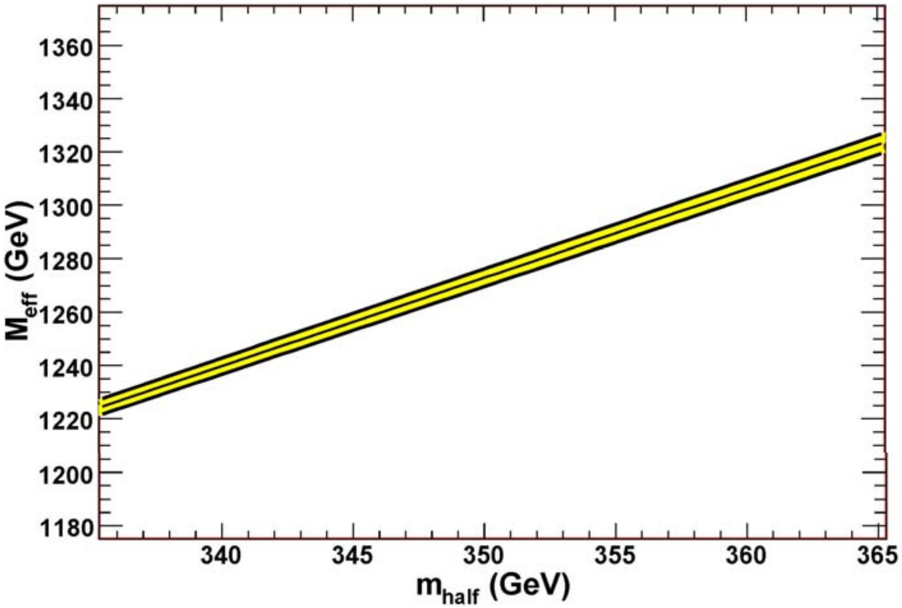
At Reference Point
$M_{eff}^{peak} = 1274$ GeV

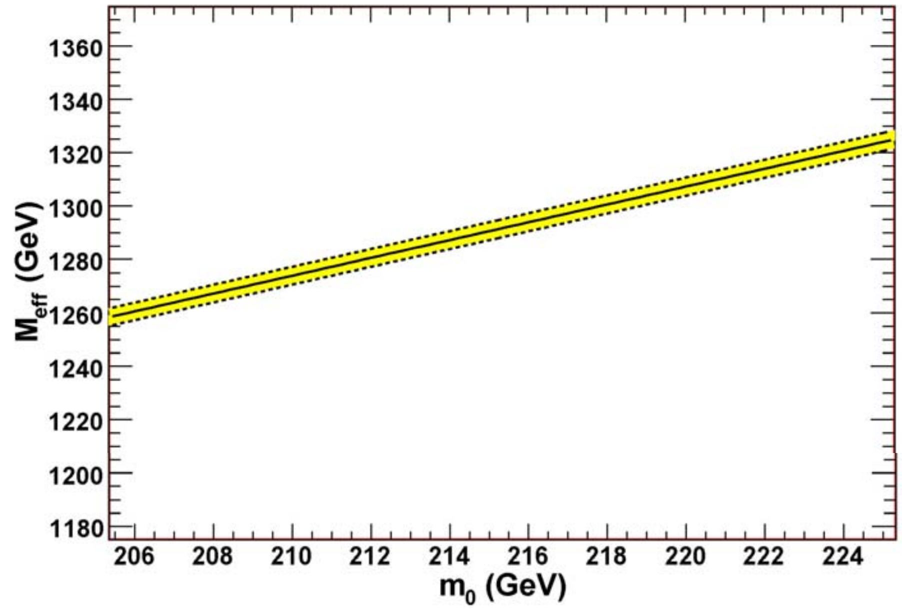


$M_{eff}^{peak} = 1220$ GeV ($m_{1/2} = 335$ GeV)
$M_{eff}^{peak} = 1331$ GeV ($m_{1/2} = 365$ GeV)



M_{eff}^{peak} vs X





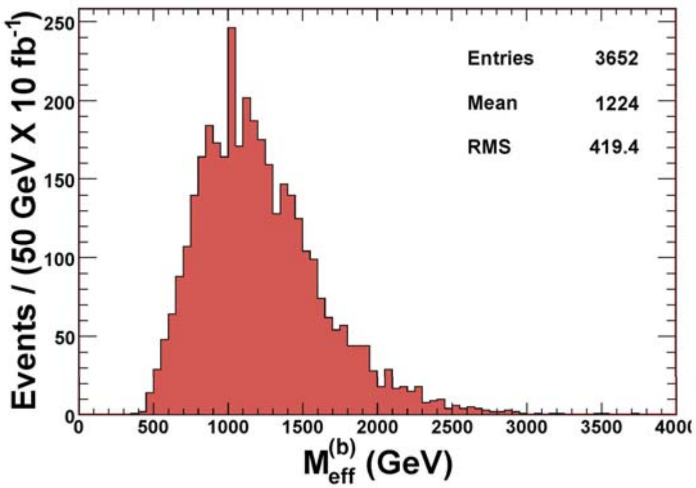
M_{eff}^{peak} …. Very insensitive to A_0 and tanβ.

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

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

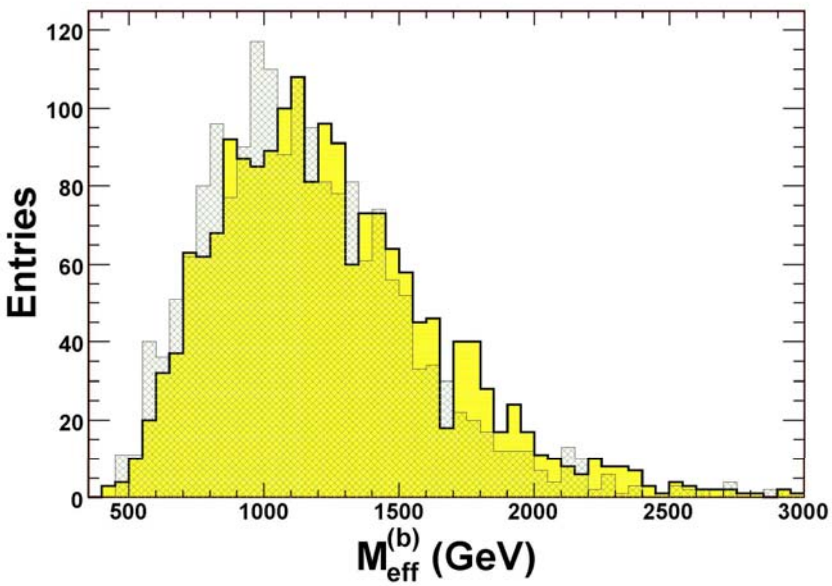
At Reference Point

$M_{eff}^{peak} = 1026$ GeV

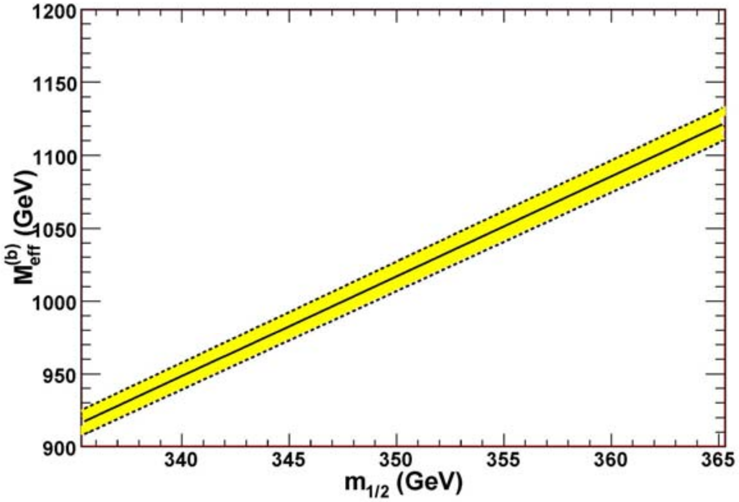


$M_{eff}^{peak} = 933$ GeV ($m_{1/2} = 335$ GeV)

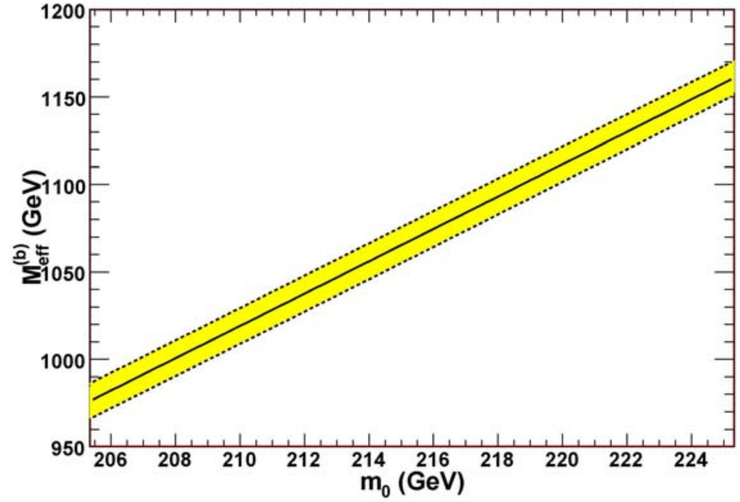
$M_{eff}^{peak} = 1122$ GeV ($m_{1/2} = 365$ GeV)



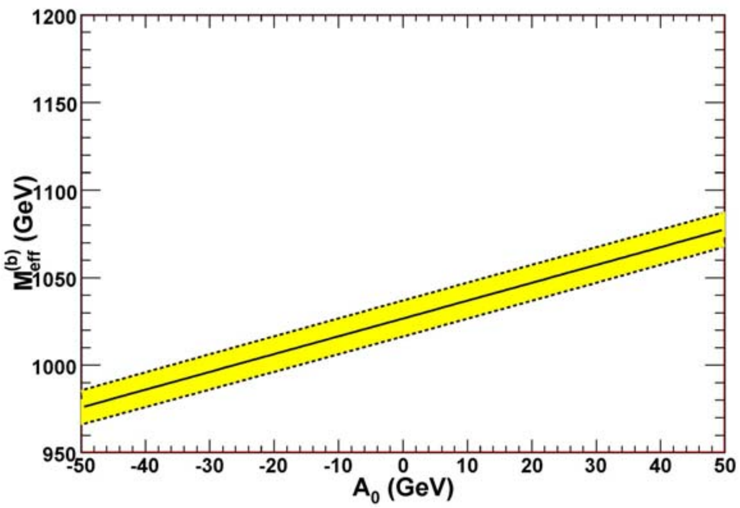
$M_{eff}^{(b)peak}$ vs X



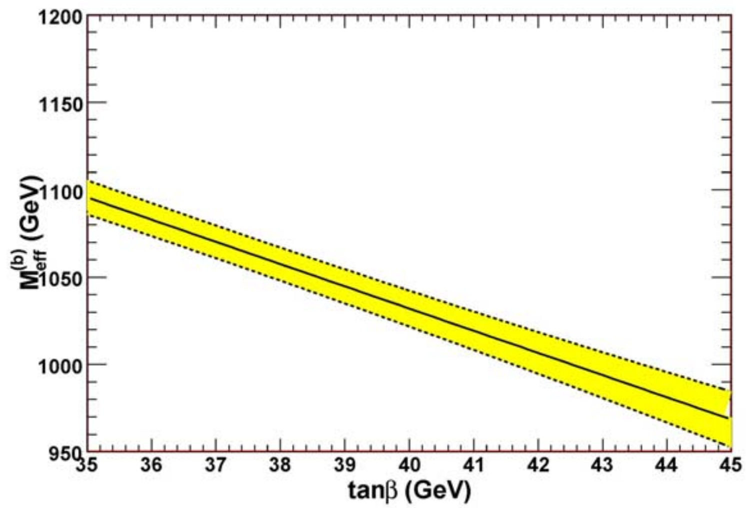
$m_{1/2}$



m_0



A0



tanβ

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

DM Connection

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

↕

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

↕

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

[1] Detection of low energy τ's (P_T > 20 GeV) in the stau-neutralino CA region.

[2] Construction of observables: $N_{OS\text{-}LS}$, $M_{j\tau\tau}$, $M_{\tau\tau}$, Slope, M_{eff}, $M_{eff}^{(b)}$

[3] Reconstruction of SUSY masses using:
e.g., Peak($M_{\tau\tau}$) = f (M_{gluino}, M_{stau}, $M_{\tilde{\chi}_2^0}$, $M_{\tilde{\chi}_1^0}$)

[4] $N_{OS\text{-}LS}$, $M_{j\tau\tau}$, Slope, M_{eff}, to solve for m_0 and $m_{1/2}$
e.g., Gaugino universality test

[5] $M_{\tau\tau}$, $M_{eff}^{(b)}$ to solve $\tan\beta$ and A_0

[6] Dark matter content in mSUGRA

mSUGRA Parameters (10 fb^{-1})

We have made a determination of the masses

$$\tilde{g} = f'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

$$\Delta M = h'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

$$\tilde{\chi}_2^0 = w'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

$$\tilde{\chi}_1^0 = y'(N_{OS-LS}, M_{\tau\tau}^{peak}, Slope, M_{j\tau\tau}^{peak})$$

The gaugino masses determine $m_{1/2}$

$$\tilde{g} = f_1(m_{1/2}), \tilde{\chi}_2^0 = f_2(m_{1/2}), \tilde{\chi}_2^0 = f_3(m_{1/2})$$

Incorporating the M_{eff} and $M_{eff}^{(b)}$ observables

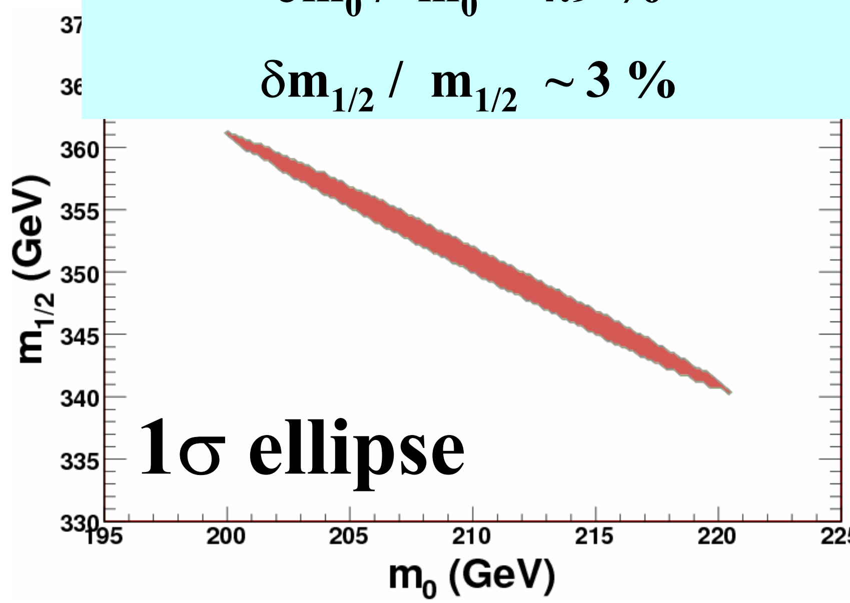
$$M_{eff} = f_4(m_{1/2}, m_0), M_{eff}^{(b)} = f_5(m_{1/2}, m_0, \tan\beta, A_0)$$

Writing ΔM as a function of the model parameters:

$$\Delta M = f_6(m_0, m_{1/2} \tan\beta, A_0)$$

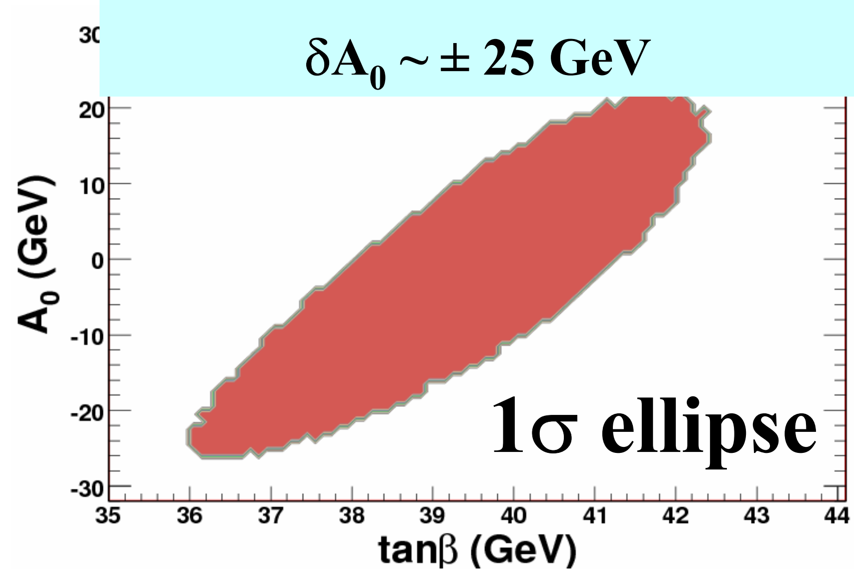
$\delta m_0 / m_0 \sim 4.9$ %

$\delta m_{1/2} / m_{1/2} \sim 3$ %



$\delta \tan\beta / \tan\beta \sim 7.75$ %

$\delta A_0 \sim \pm 25$ GeV



DM Relic Density (10 fb^{-1})

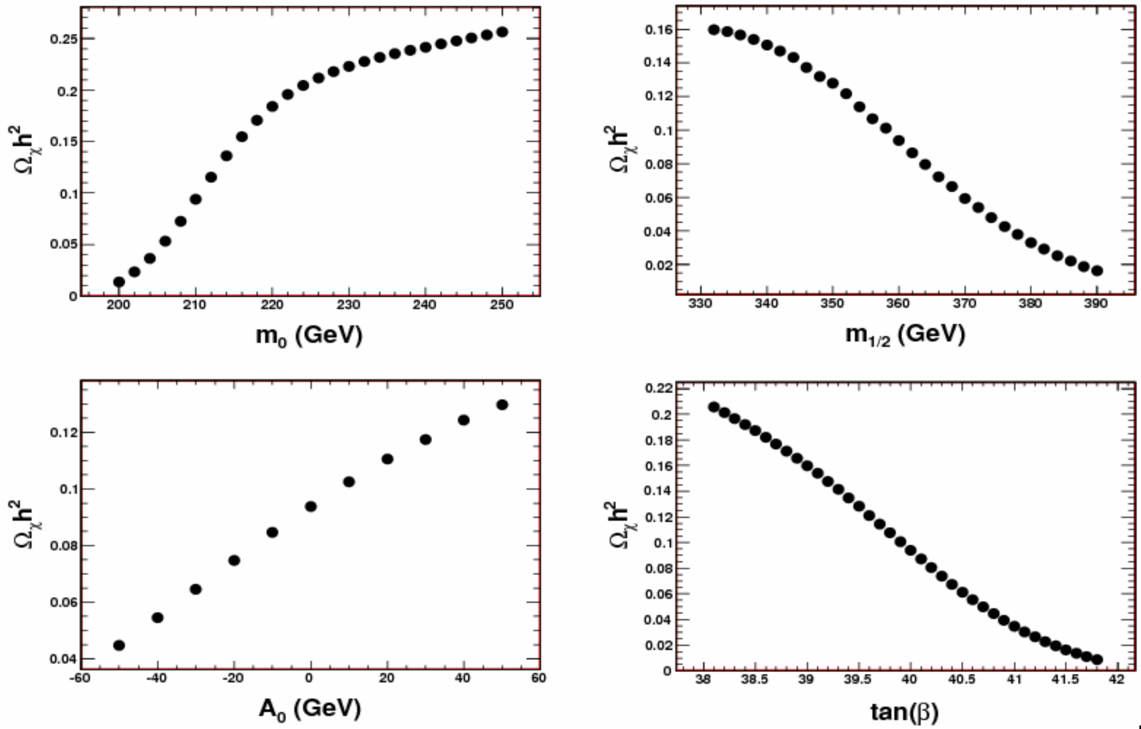
We have made a determination of the mSUGRA model parameters

$$m_{1/2} = f''(\tilde{g}, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

$$m_0 = h''(M_{eff}, \tilde{g}, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$$

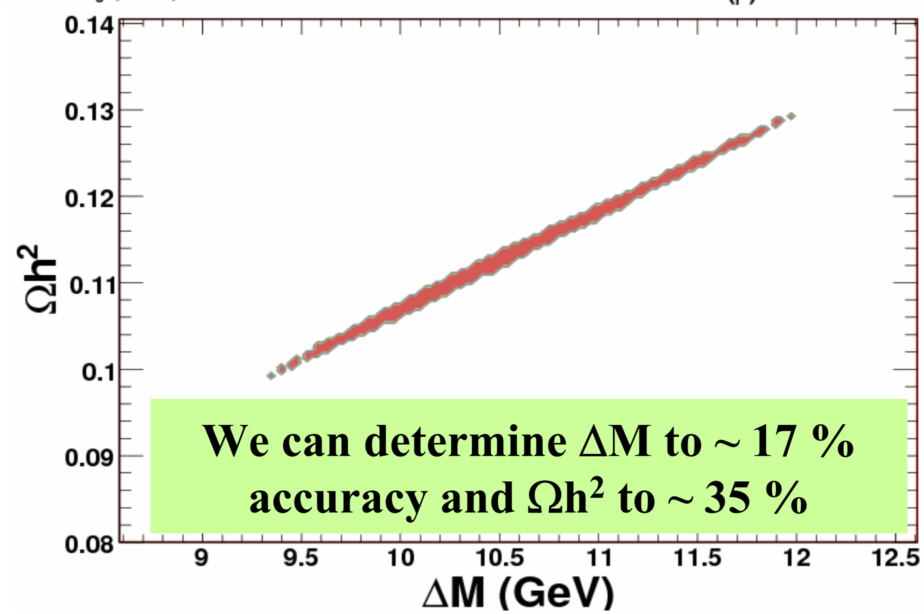
$$\tan\beta = w''(\Delta M, \tilde{g}, \tilde{\chi}_2^0, \tilde{\chi}_1^0, M_{eff}, M_{eff}^{(b)})$$

$$A_0 = y''(\Delta M, \tilde{g}, \tilde{\chi}_2^0, \tilde{\chi}_1^0, M_{eff}, M_{eff}^{(b)})$$



The Dark Matter relic density depends on the model parameters:

$$\Omega h^2 = f'''(m_0, m_{1/2} \tan\beta, A_0)$$



We can determine ΔM to ~ 17 % accuracy and Ωh^2 to ~ 35 %

Summary

- This talk is about a cosmological connection at the LHC in the case of co-annihilation (CA).
- The LHC should be able to uncover the striking small ΔM signature (smoking gun in the CA region) with ~10 fb^{-1} of data in multi-τ final states and make high quality measurements with the first few years of running.
- With the mSUGRA model in the CA region, the dark matter content can be measured with an accuracy of ~40%.

PPC 2007 → PPC 2008

The University of New Mexico
Albuquerque, USA
May 2008