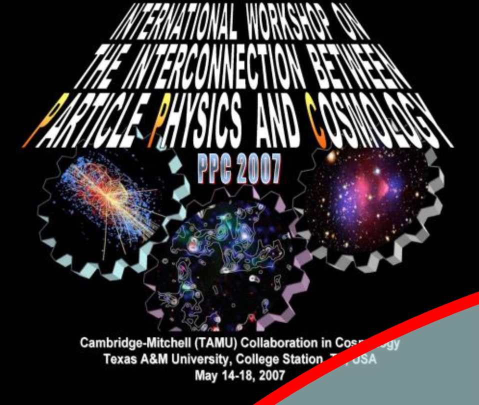
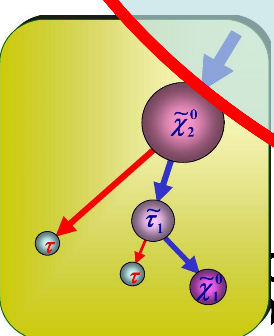
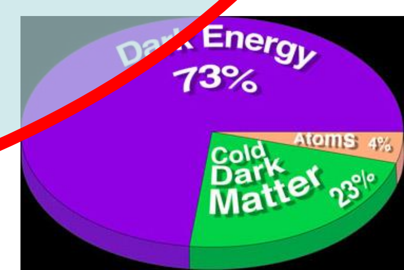



# Particle Physics and Cosmology in the Co-Annihilation Region

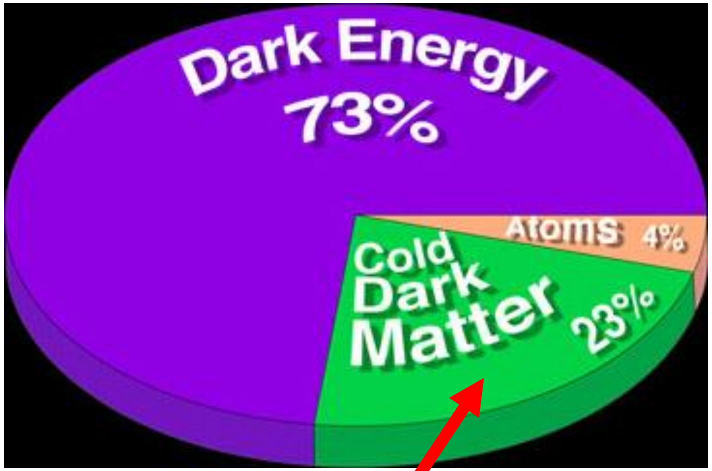
R. Arnowitt, A. Aurisano, B. Dutta,
Gurrola, T. Kamon, A. Krislock, N. Kolev*,
P. Simeon, D. Toback & P. Wagner
Department of Physics, Texas A&M University
*Department of Physics, Regina University



# Introduction

- What problems are we trying to solve?
  - Dark Matter
  - Hierarchy problem in the Standard Model
  - Other Particle Physics problems…
- Is there a single solution to both of these problems?
  - Minimal solution?




Particle Physics solution to this problem?

# The Players and their Roles


Cosmologists/ Astronomers

Particle Theorists

Particle Experimentalists

# The Players and Their Roles



Astronomy and Cosmology tell us about Dark Matter

Particle Physics Theory Predicts Supersymmetry
→Dark Matter Candidate

Experimentalists at FNAL/LHC do direct searches for SUSY particles

Learn more about the universe with two separate measurements of $\Omega h^2$

Convert the masses into SUSY model parameters and $\Omega h^2$

Do we live in a world with Universal Couplings?

Discover SUSY and measure the masses of the superparticles

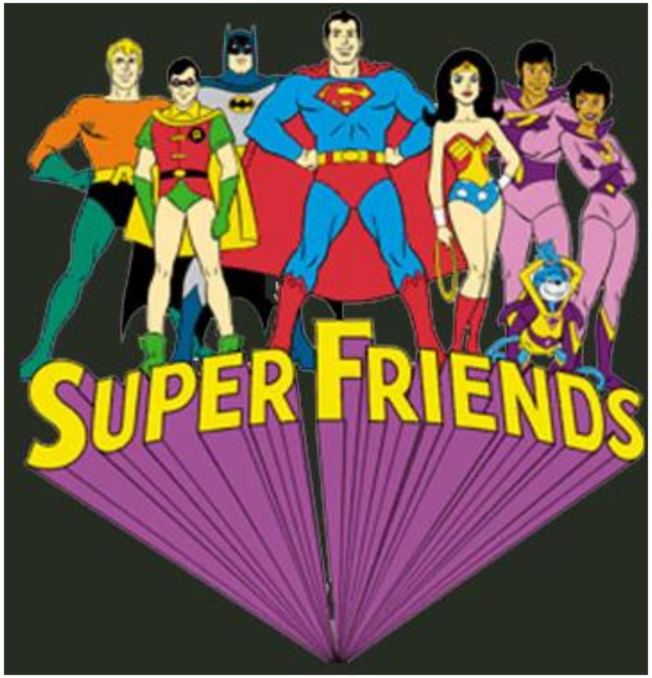
# Outline of the Talk

- Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$

- Identifying events at the LHC
  - Discovery and Experimental Observables
- Measurements of
  - Particle masses: $\Delta M$, $M_{Gluino}$ & $M_{\chi 2}$
  - Supersymmetry parameters: $M_0$ and $M_{1/2}$
  - Cosmological implications: $\Omega_{LSP} h^2$
- Conclusions

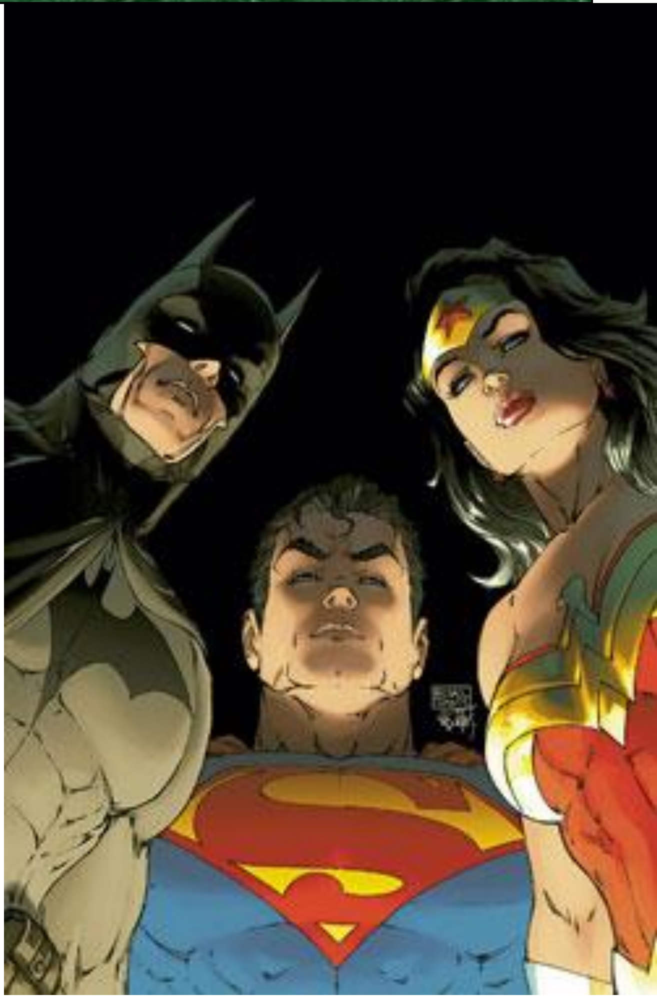
# Structure of the Analysis

1. Use the current constraints/understanding to motivate the co-annihilation region of Supersymmetry in mSUGRA
2. Assume this is a correct description of nature and see how well we could measure things at LHC
3. Convert these results into useful numbers for both particle physics and cosmology



# Hypothetical Timeline

- Pre-2005: Strong constraints on Dark Matter density, the Standard Model and Supersymmetry
- 2005: Phenomenologists use these results to constrain a SUSY model → Tell the experimentalists at LHC where to look
- 2008-10: Establish that we live in a Supersymmetric world at the LHC
- 2011: Precision measurements of the particle masses and SUSY parameters → compare Dark Matter relic density predictions to those from WMAP



# SUSY, mSUGRA and Cosmology

- Many models of Supersymmetry provide a Cold Dark Matter candidate
- Work in an Minimal Supergravity (mSUGRA) framework
  - Build models from $M_{Gut}$ to Electroweak scale
  - Models consistent with all known experiments
  - Universal Couplings ← More on this later
  - Straight-forward predictions


*Lighest SUSY Particle*

⇕

*Lightest Neutralino*

⇕

$\tilde{\chi}_1^0$

⇕

*Cold Dark Matter*

# mSUGRA in 1 Slide

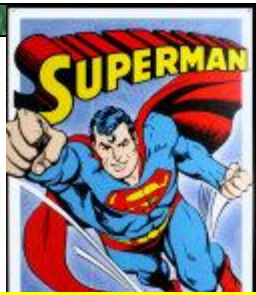

***4 parameters + 1 sign***

| | |
|---|---|
| $m_{1/2}$ | Gaugino mass at $M_{GUT}$ |
| $m_0$ | Scalar soft breaking mass at $M_{GUT}$ |
| $A_0$ | Cubic soft breaking mass at $M_{GUT}$ |
| $\tan\beta$ | $\langle H_2 \rangle / \langle H_1 \rangle$ at the electroweak scale |
| sign($\mu$) | Sign of Higgs mixing parameter ($W^{(2)} = \mu H_1 H_2$) |

## Translation for Experimentalists and Cosmologists:

*Each combination of these parameters uniquely determines the masses of all the superparticles and the Relic Density ( $\Omega_{\tilde{\chi}_1^0} h^2$ )*

# Example Translation






$$M_0 = 210\ GeV$$
$$M_{1/2} = 350\ GeV$$
$$\tan\beta = 40$$
$$A_0 = 0$$
$$Sgn(\mu) > 0$$

$\longleftrightarrow$

$$M_{\tilde{g}} = 830\ GeV$$
$$M_{\tilde{\chi}_2^0} = 260\ GeV$$
$$M_{\tilde{\tau}} = 151.2\ GeV$$
$$M_{\tilde{\chi}_1^0} = 140.6\ GeV$$

$\longleftrightarrow$

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

In general for mSUGRA models with University Constraints

$$M_{\tilde{g}} \sim 2.8 m_{1/2},\ M_{\tilde{\chi}_2^0} \sim 0.8 m_{1/2},\ M_{\tilde{\chi}_1^0} \sim 0.4 m_{1/2}$$

# Experimental Constraints


**Particle Physicists:**

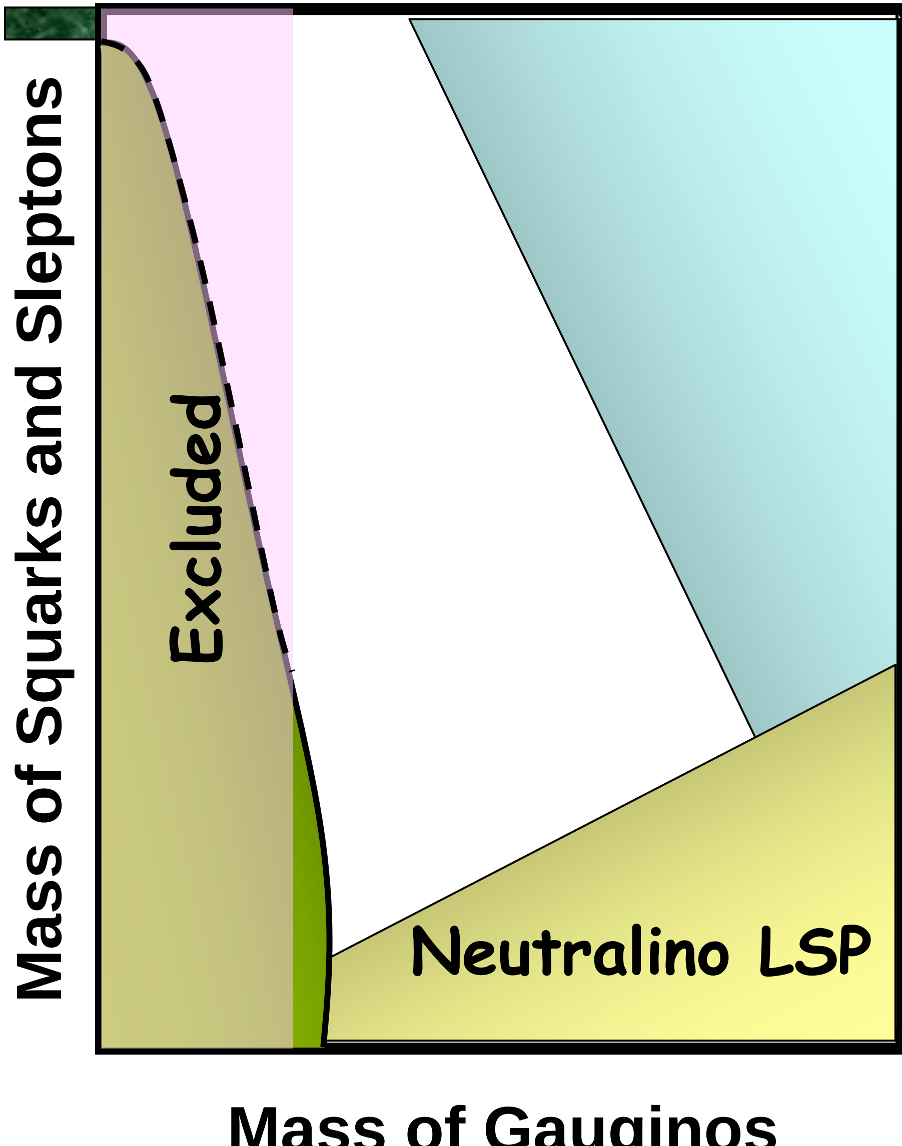
- Non-observation of the Higgs and the Gauginos and their mass limits
- Measurement of branching ratio of the *b-quark*$\rightarrow s\gamma$

**Astronomers and Cosmologists:**

- WMAP measurement of the Relic Density

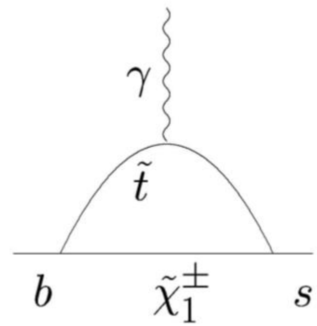

- $M_{Higgs} > 114$ GeV
- $M_{chargino} > 104$ GeV
- $2.2\times10^{-4} < Br\ (b \rightarrow s\gamma) < 4.5\times10^{-4}$
- $a_\mu \times 10^{-10} = 27 \pm 10\ (g-2)$
- $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$ (WMAP)

# Particle Physics Constrained Region




**Higgs Mass ($M_h$)**

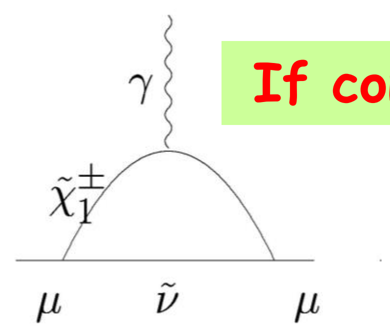
**Branching Ratio $b \to s\gamma$**





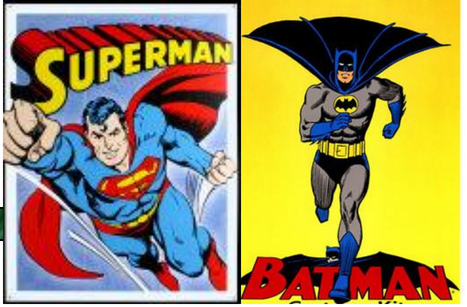
**Neutralino LSP**

**Magnetic Moment of Muon**




If confirmed…

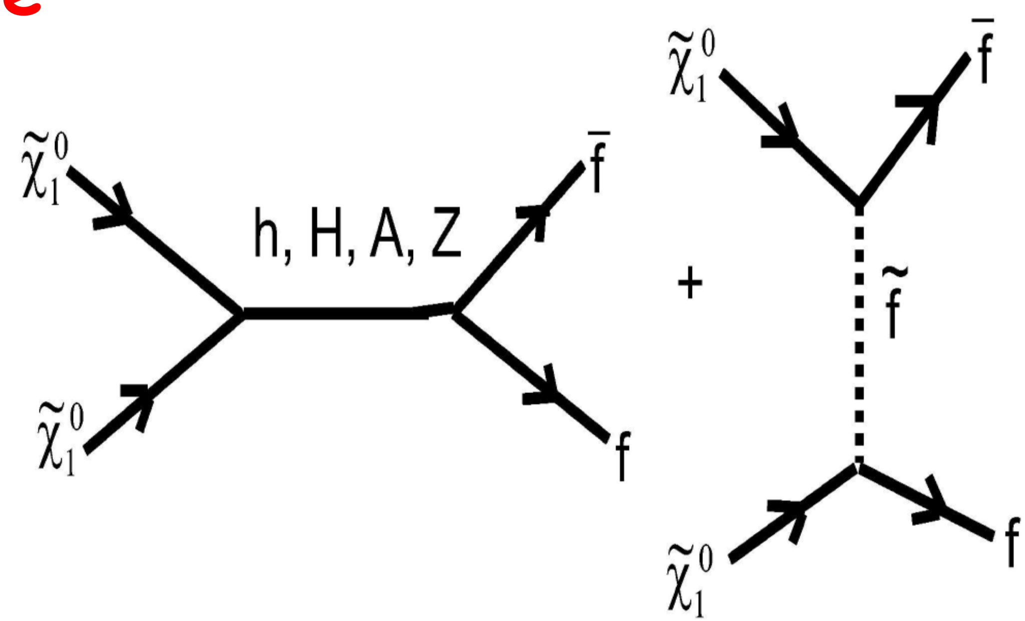
# "Vanilla" mSUGRA and Cosmology




mSUGRA parameters uniquely determine the

- LSP mass
- Interaction Cross Sections
- Sparticle abundances in the early universe
- Relic Density today

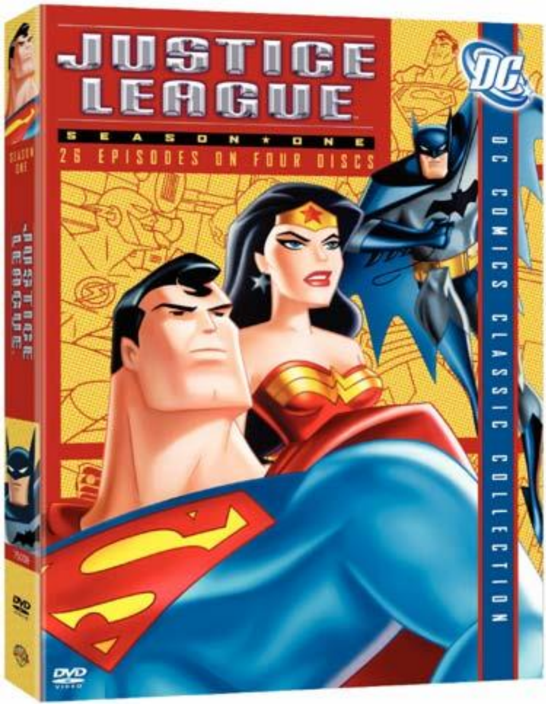
Use WMAP Relic Density measurements to further constrain SUSY parameter space



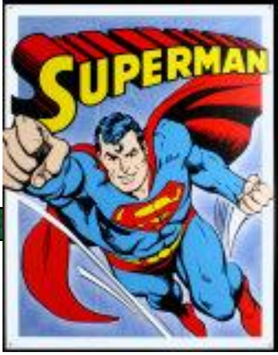

Typically the following annihilation diagrams are important…

# Problem

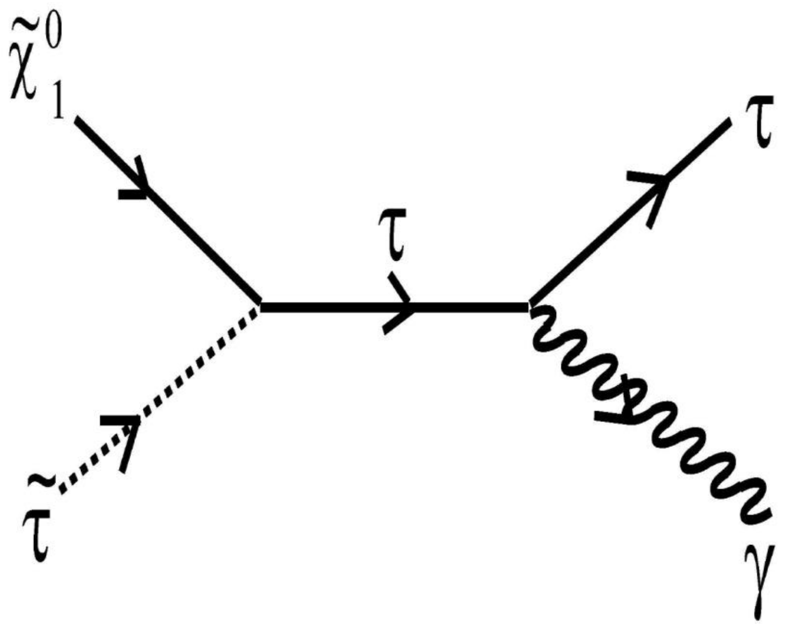
- Most of mSUGRA space predicts too much Dark Matter today
- Need another mechanism to reduce the predicted LSP relic density to be consistent with the amount of Dark Matter observed by WMAP



# Co-Annihilation?




- If there is a second SUSY particle with small mass (similar to that of the LSP) it can have a large abundance in the early universe
- The presence of large amounts of this second particle would allow large amounts of the LSP to annihilate away and reduce the relic density observed today
  - Co-annihilation effect (Griest, Seckel:92)
  - Common in many models




*The lightest $\tilde{\tau}$ is a good candidate*

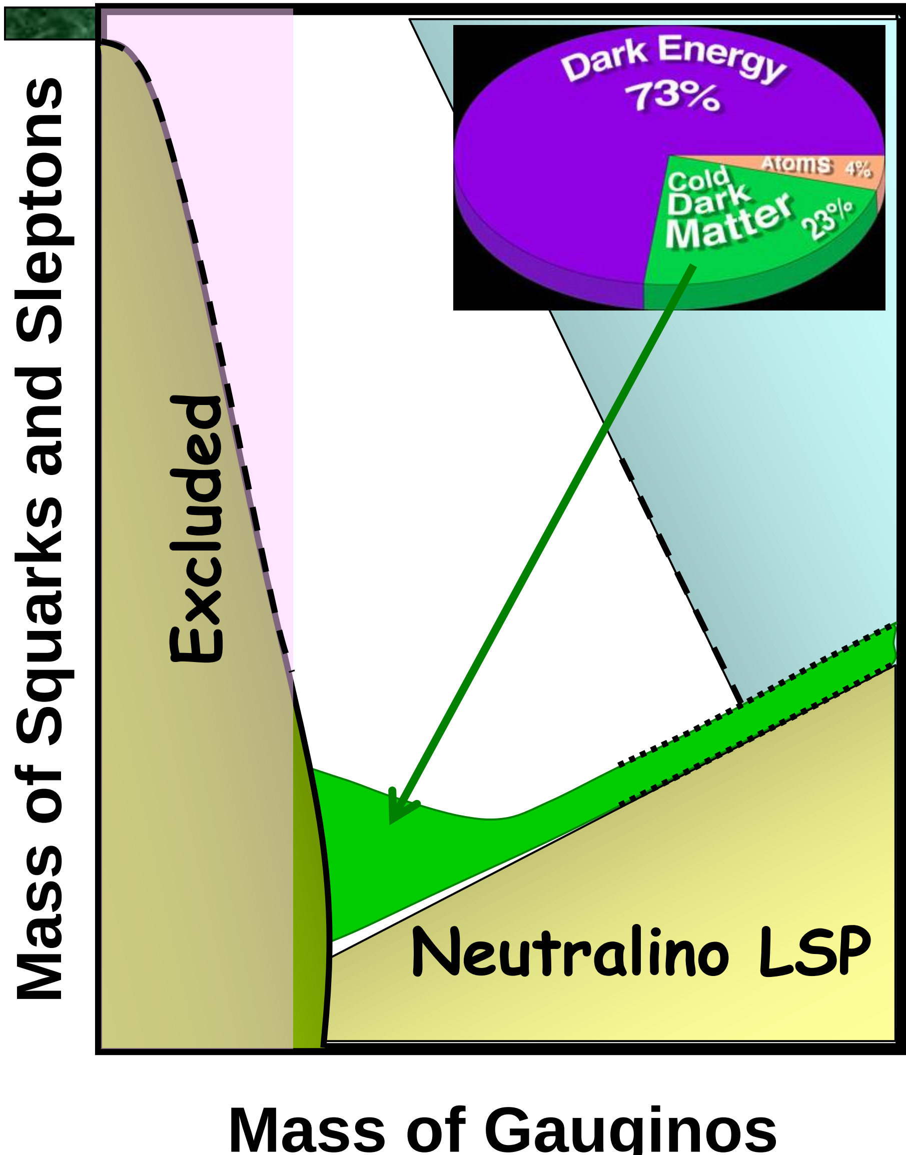
# Small $\tilde{\tau}$ Mass

In mSUGRA models the mass of the lightest $\tilde{\tau}$ can be close to the $\tilde{\chi}_1^0$ mass because of the Renormalization Group Equations (RGEs) for small $m_0$

For small mass difference we can get the right relic density

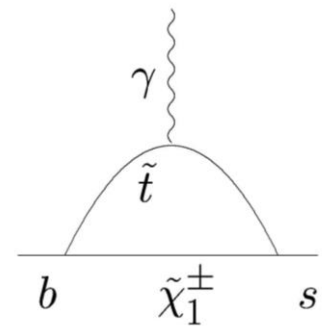
$$\Delta M \equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$$
$$= 5 \sim 15 \ \text{GeV}$$

# Add Dark Matter Constraints




Higgs Mass ($M_h$)

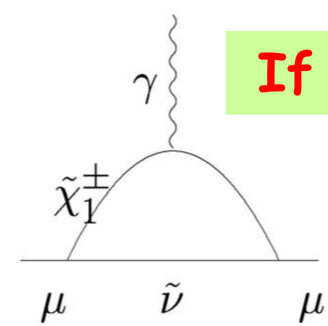
Branching Ratio $b \to s\gamma$





Magnetic Moment of Muon

If confirmed…




WMAP Favored region

# Aside on our Assumptions…

The WMAP constraints limits the parameter space to 3 regions that should all be studied:

1. The stau-neutralino co-annihilation region

If $(g-2)_\mu$ holds, mostly only this region is left

Concentrate on this region for the rest of this talk…

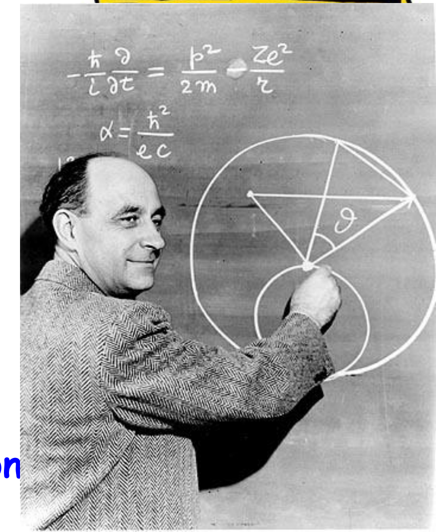
# What if the Co-Annihilation Region is realized in Nature?

1. Can such a small mass difference be measured at the LHC?

   The observation of such a striking small ΔM would be a smoking gun!

   → Strong indication that the neutralino is the Dark Matter

2. If we can observe such a signal, can we make important measurements?



# Outline

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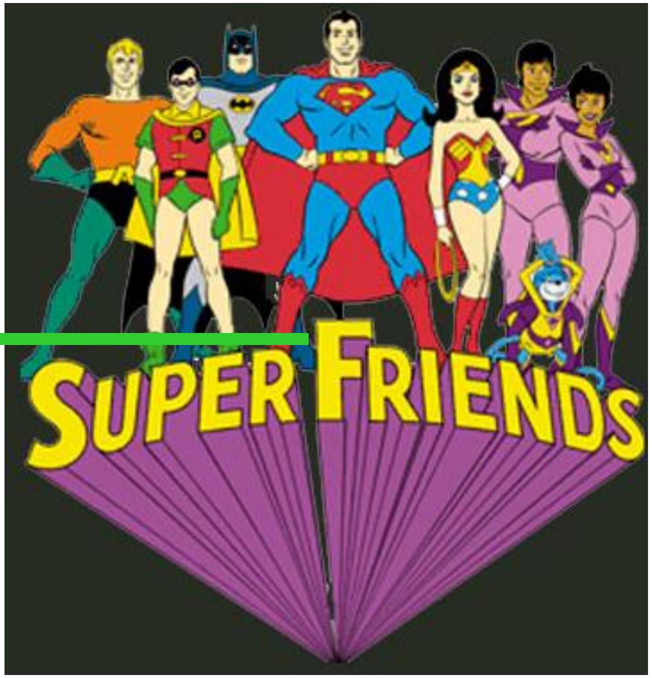
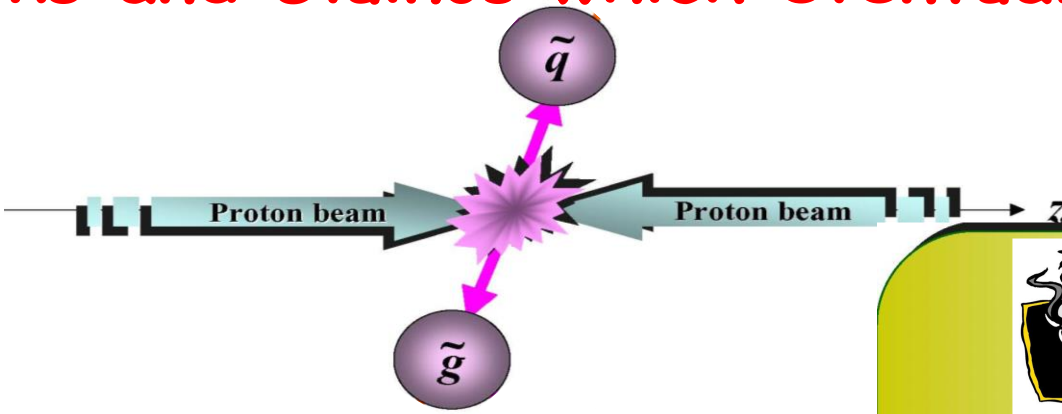
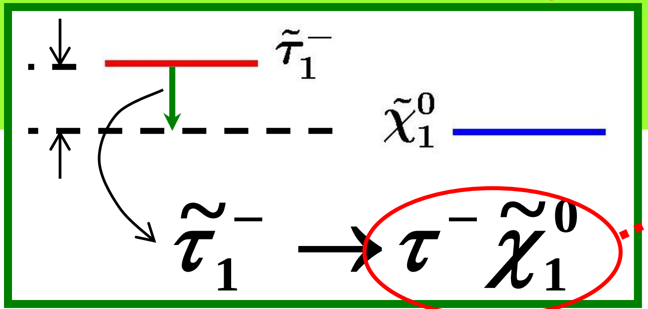


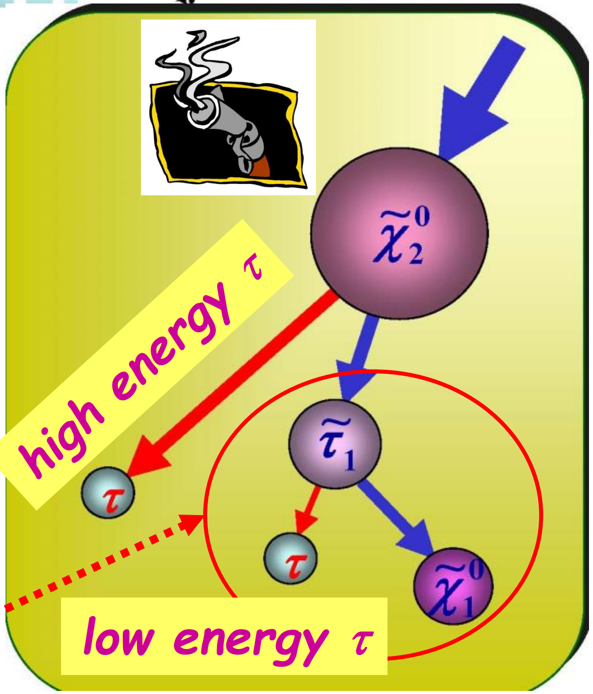
# A Smoking Gun at the LHC?


High Energy Proton-Proton collisions produce lots of Squarks and Gluinos which eventually decay

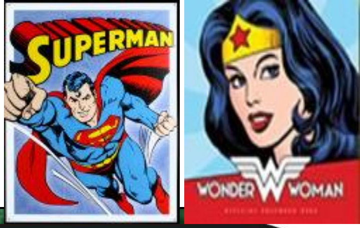



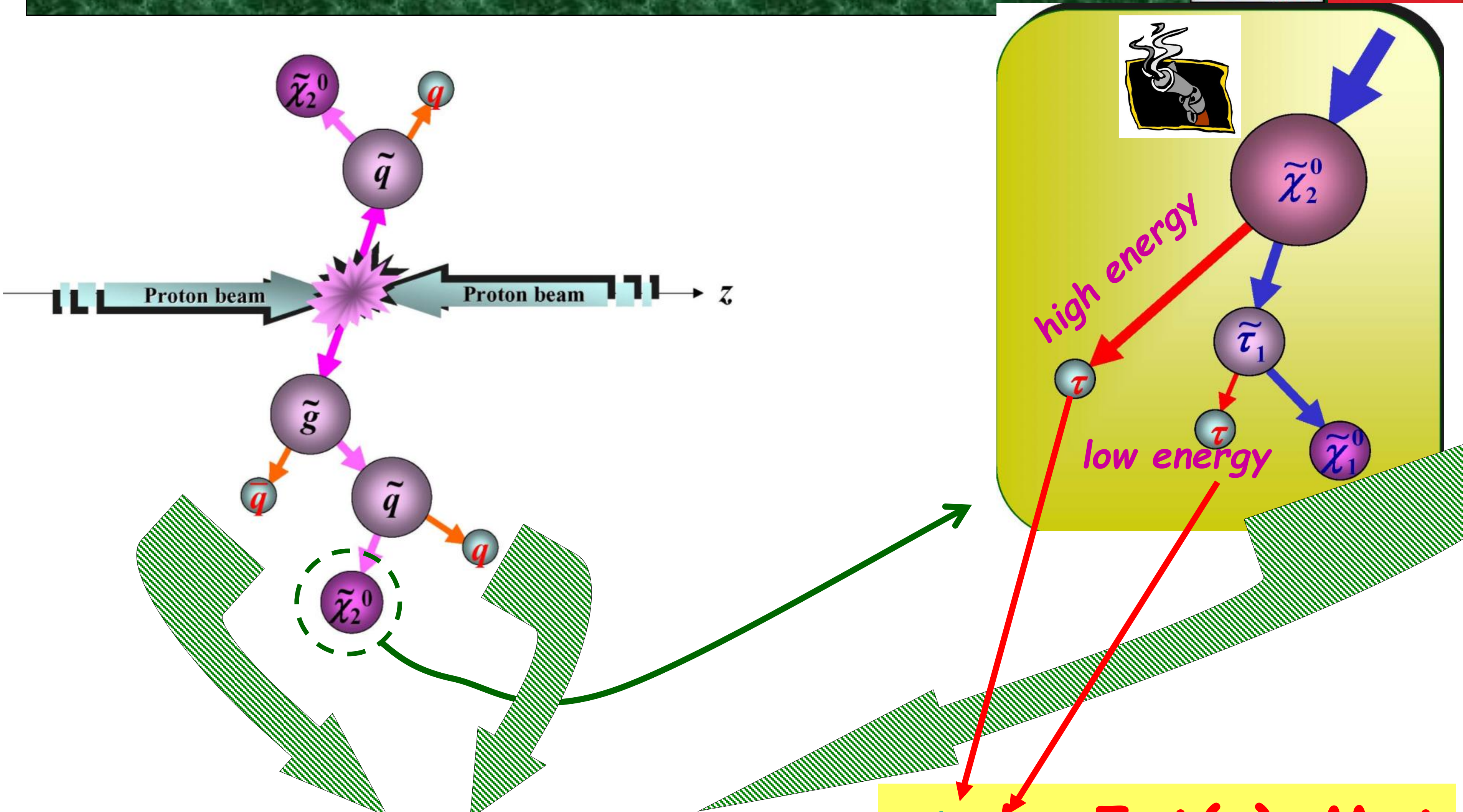

Identify a special decay chain that can reveal ΔM information



# SUSY Signature at the LHC





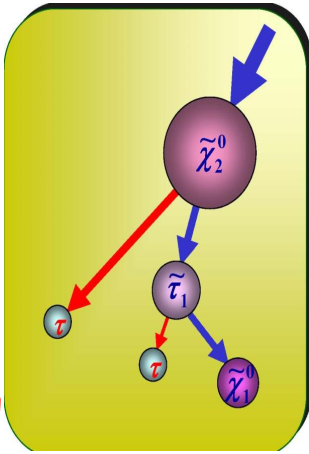

**Trigger on the jets and missing $E_T$**

**$\tau^+\tau^-$s+Jet(s)+Met**

# Not just any $\tau$ will do!


Our $\tau$'s are special!

1. $\chi_2$ decays produce a pair of opposite sign $\tau$'s
   - Many SM and SUSY backgrounds, jets faking $\tau$'s will have equal number like-sign as opposite sign
2. Each $\chi_2$ produces one *high energy $\tau$* and one *low energy $\tau$*
3. The invariant mass of the $\tau$-pair reflects the mass of the SUSY particles and their mass differences




$$M_{\tau\tau} \propto M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M^2_{\tilde{\tau}_1}}{M^2_{\tilde{\chi}_2^0}}}\sqrt{1-\frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{\tau}_1}}}$$

# Create a Sample of $\tilde{\chi}_2^0$ Events


- *Require at least two $\tau$' s to get our $\tilde{\chi}_2^0$*
- *Large Missing Transverse energy to get the $\tilde{\chi}_1^0$*
- *At least one very energetic jet to indicate the presence of a squark or gluino at the top of the chain*

The dominant background is typically ttbar, so we require an extra object and large kinematics to reject it

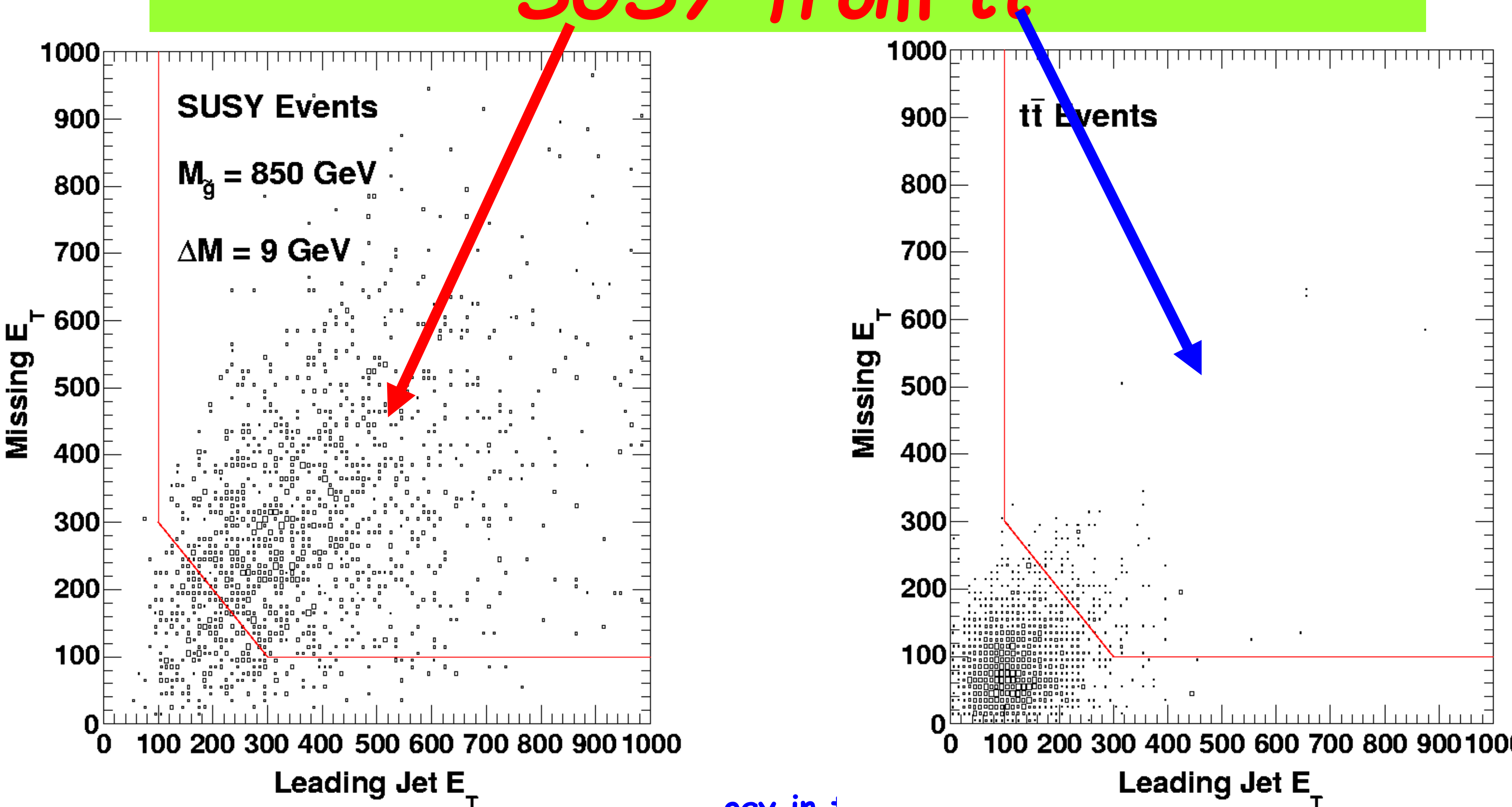
1. Require a third $\tau$ from one of the other gauginos (common) → $3\tau$+Jet+Met
2. Require a second large jet from the other squark/gluino and large $H_T$ → $2\tau$+2Jets+Met

More details in

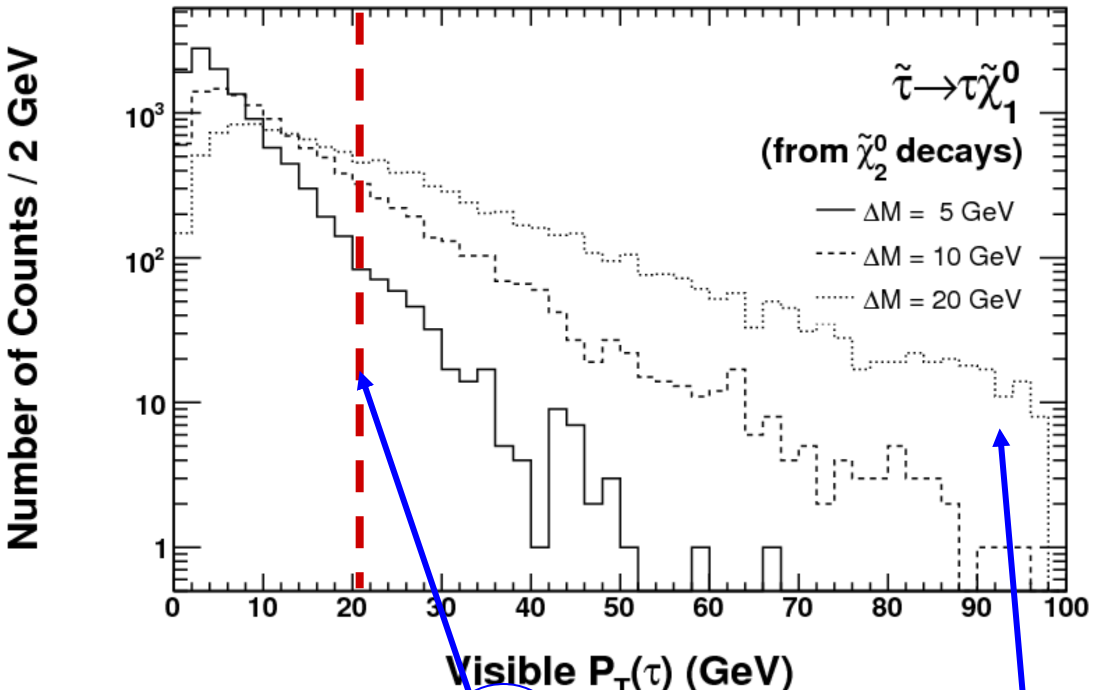
R. Arnowitt *et al.* Phys.Lett.B639:46,2006 and Phys. Lett.B649:72, 2007

# Some Technical Details

***Use event kinematics to separate SUSY from $t\bar{t}$***



# Look at the $P_T$ distribution of our softest $\tau$

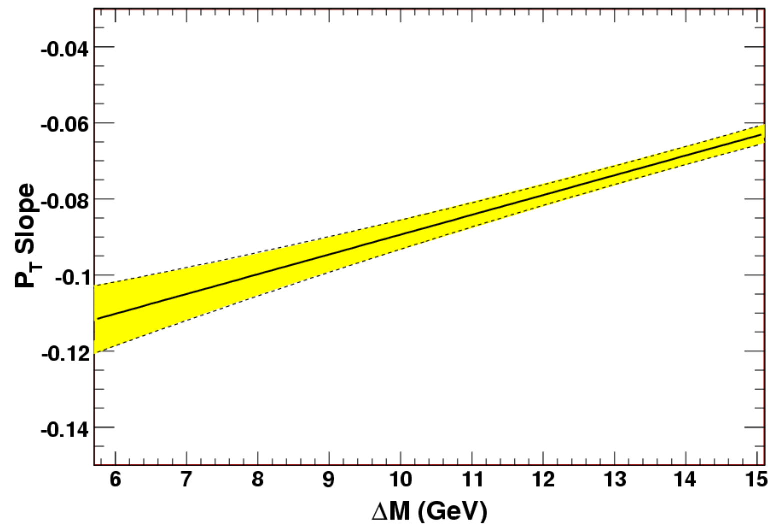



$$\tilde{\tau} \rightarrow \boxed{\tau}\ \tilde{\chi}_1^0$$

Slope of $P_T$ distribution contains ΔM Information

Low energy $\tau$'s are an enormous challenge for the detectors

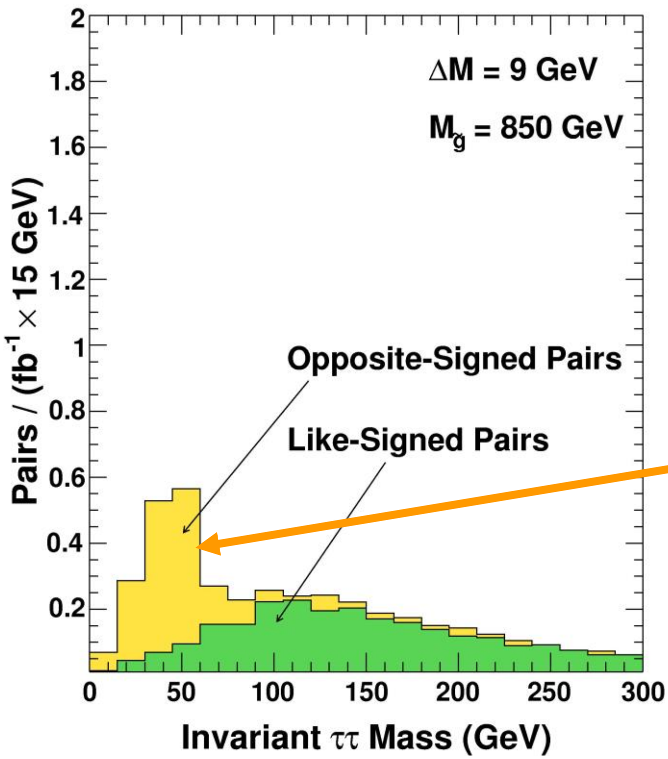
Also, get more events for large ΔM




Slope of $P_T$ distribution is largely unaffected by Gluino Mass

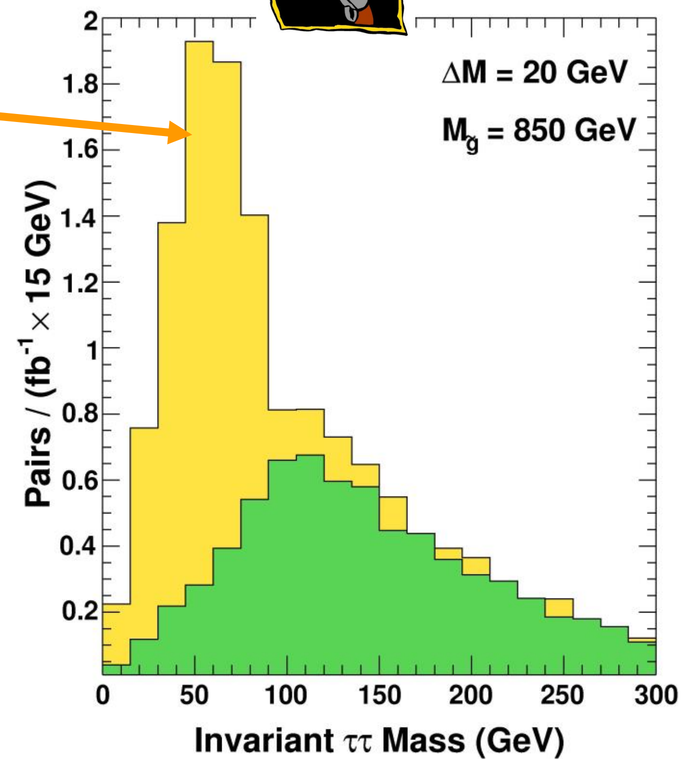
# More Observables…

- Look at the mass of the $\tau^+\tau^-$ in the events
- Can use the same sample to subtract off the non-$\chi_2$ backgrounds → Clean peak!



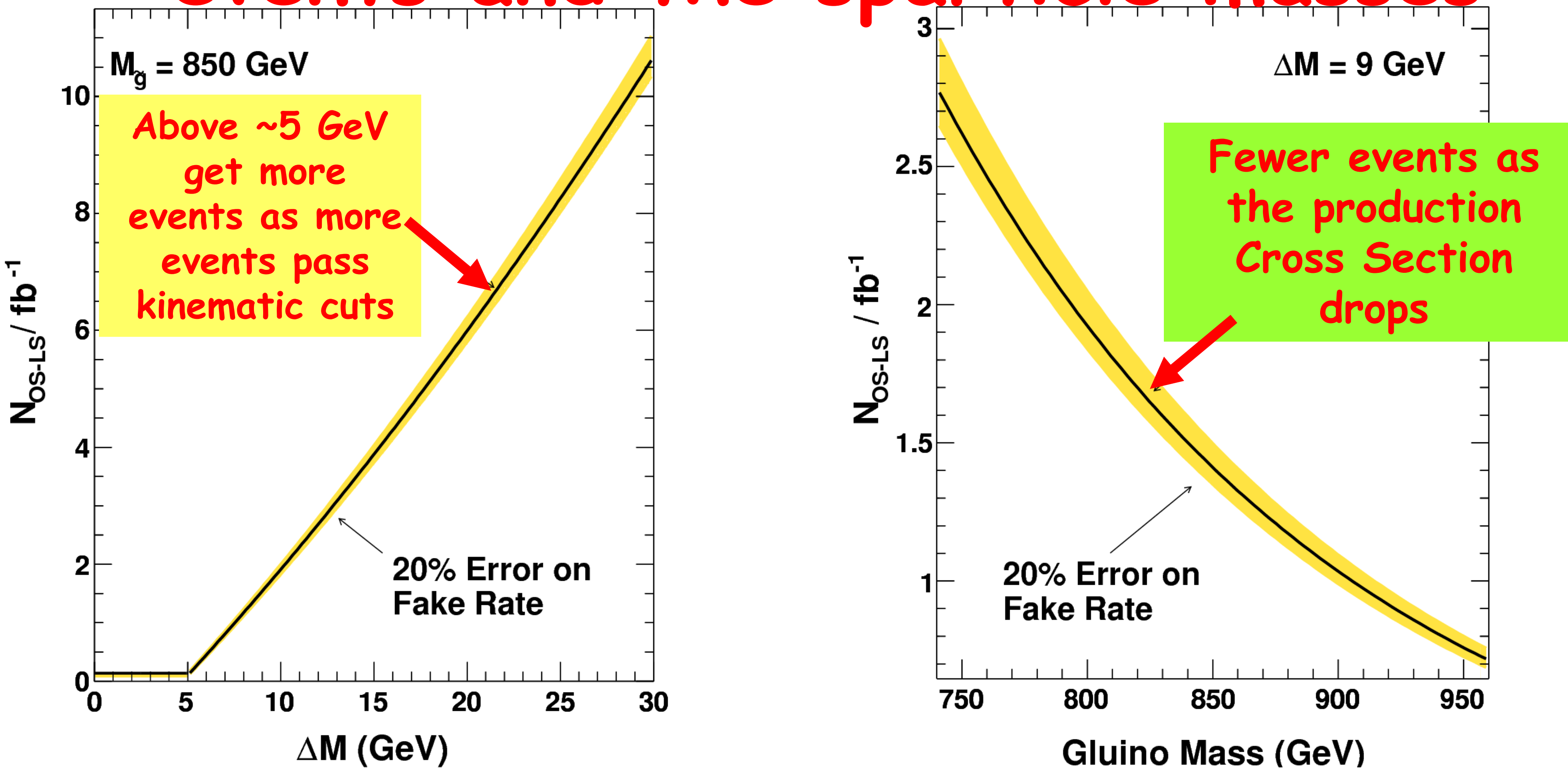

Larger ΔM:
- More events
- Larger mass peak

Clean peak Even for low ΔM

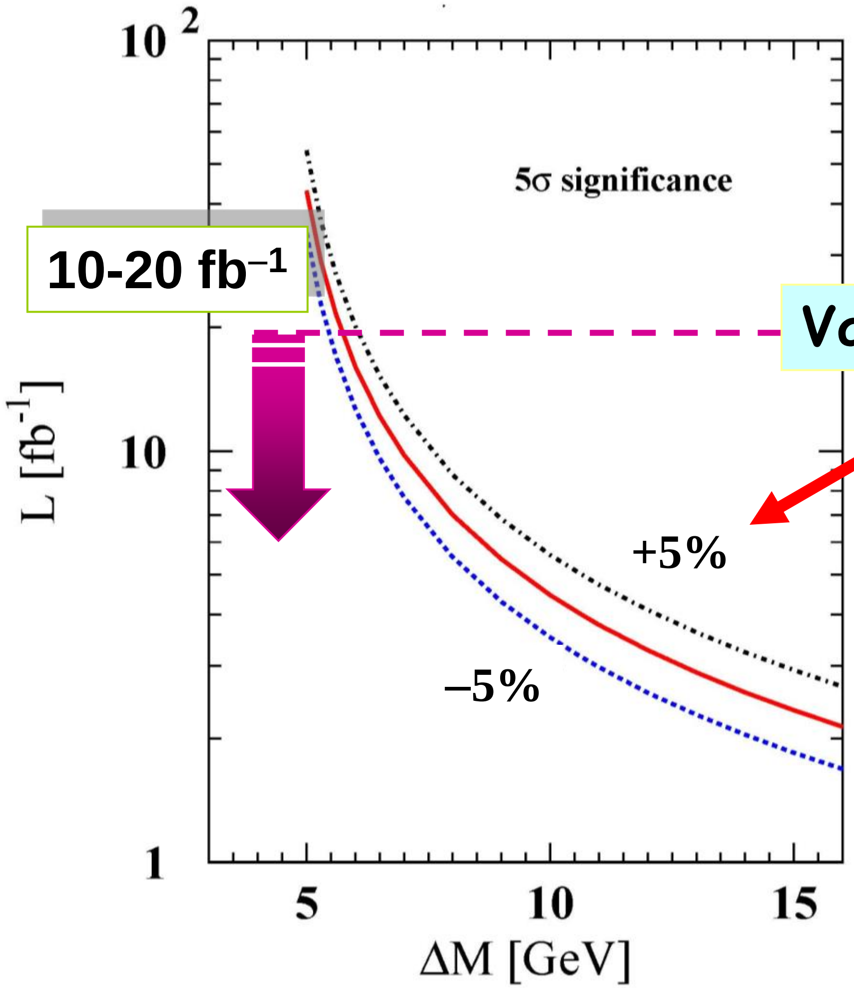


# Discovery Luminosity

## Depends on the number of observable events and the sparticle masses



# Discovery Luminosity




10-20 fb$^{-1}$

Variation in gluino mass


**A small ΔM can be detected in first few years of LHC ~100 Events**

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# What are we trying to measure?


*Our mSUGRA model (described by $m_0$ and $m_{1/2}$) can be written, equivalently, by*

$$M_{\tilde{g}} \text{ and } \Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0}$$

Measure these!

*The Universality relations "determine" the other mass values*

$$M_{\tilde{\chi}_2^0} \sim 0.32\, M_{\tilde{g}} \text{ and } M_{\tilde{\chi}_1^0} \sim 0.17\, M_{\tilde{g}}$$

Check these!

# Measuring the SUSY Masses



For our sample of events we can make three measurements

1. Number of events
2. Slope of the $P_T$ distribution of the softest $\tau$
3. The peak of the $M_{\tau\tau}$ distribution

Since we are using 3 variables, we can measure three things

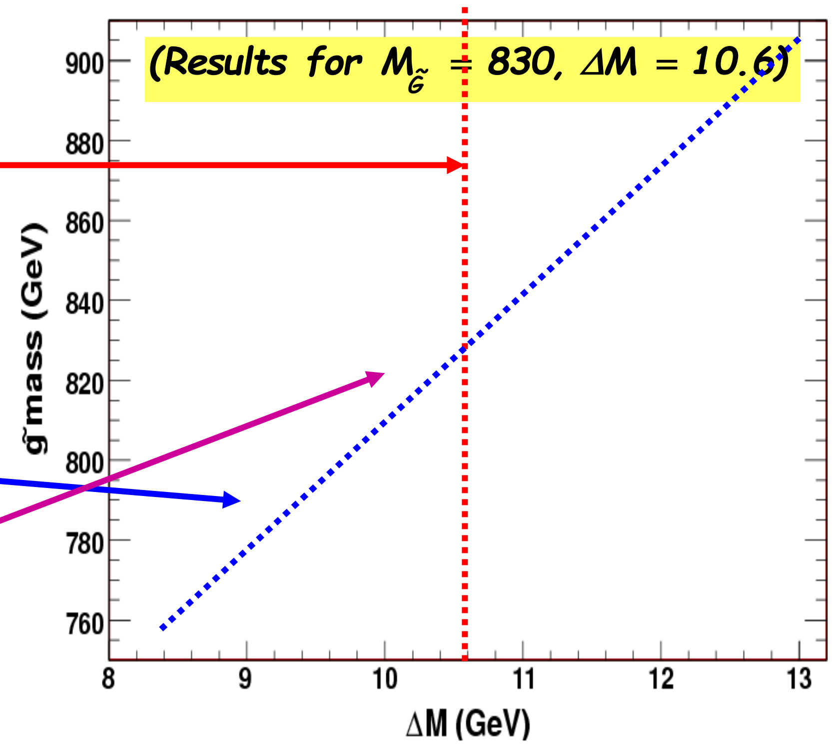
Since $A$, $\tan\beta$ and sign($\mu$) don't change the phenomenology much (for large $\tan\beta$) we choose to use our three variables to determine $\Delta M$, $M_{gluino}$ and the $\chi_2$ Mass

Model parameters

Universality Test

# Measure ΔM and the Gluino Mass

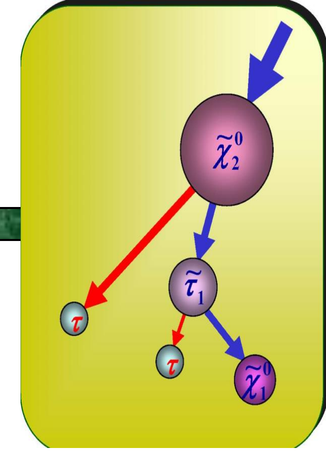

- The slope of the $P_T$ distribution of the τ's only depends on the ΔM
- The event rate depends on both the Gluino mass and ΔM
- Can make a simultaneous measurement




An important measurement without Universality assumptions!

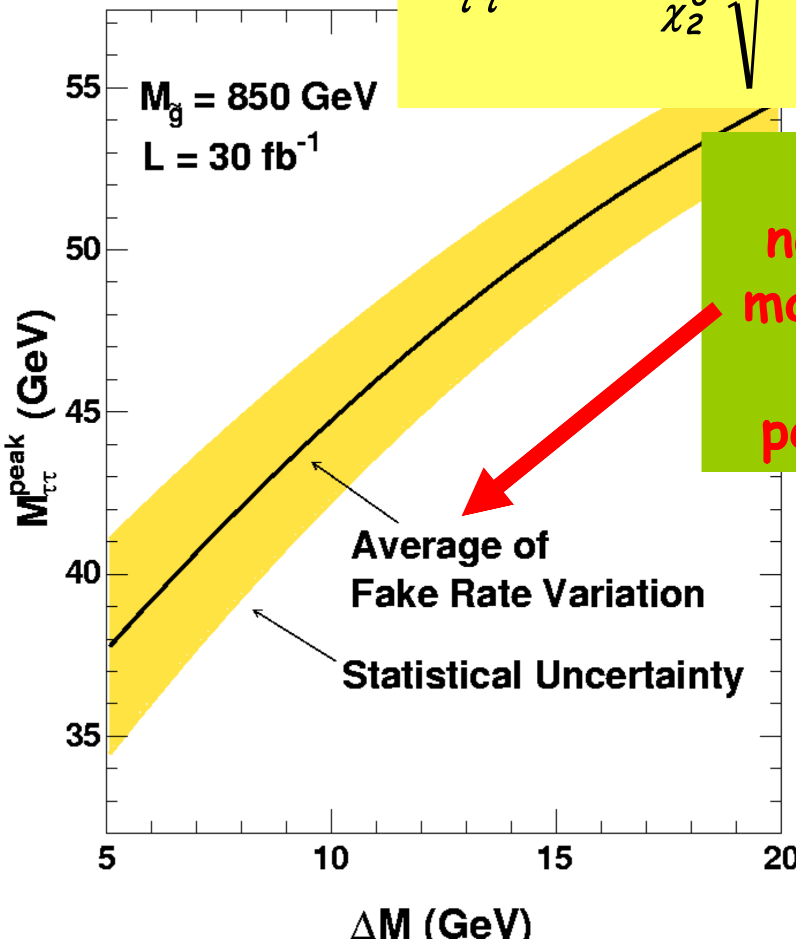
Results for ~300 events
(10 $fb^{-1}$ depending on the Analysis)

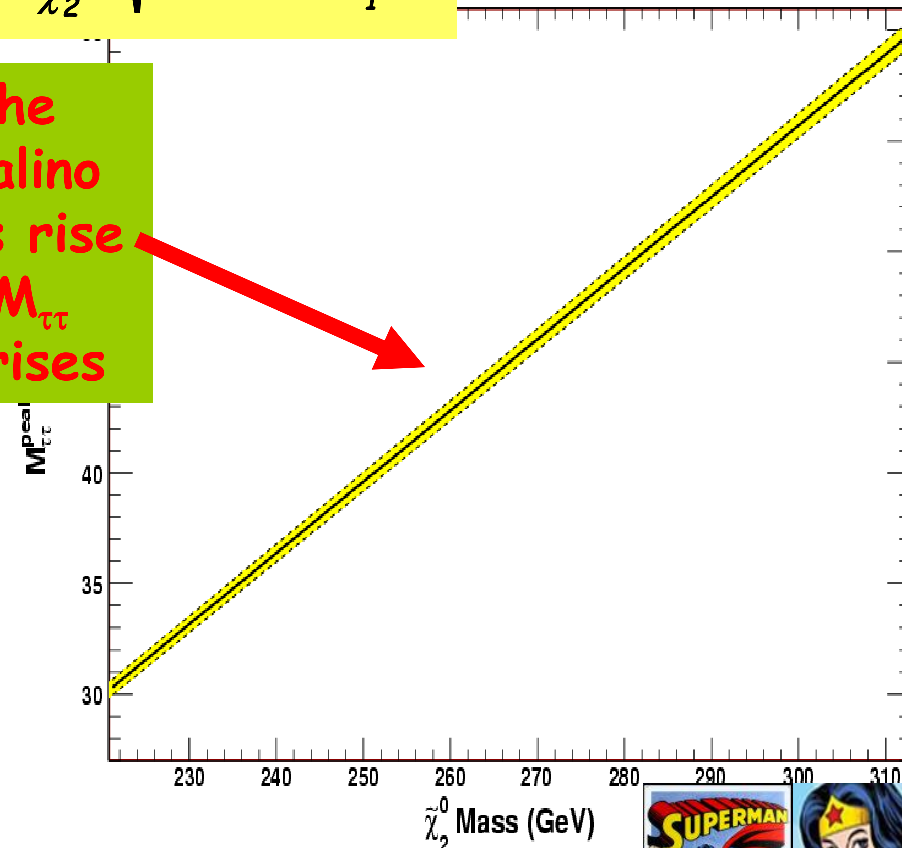
# Add in the Peak of $M_{\tau\tau}$




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

As the neutralino masses rise the $M_{\tau\tau}$ peak rises

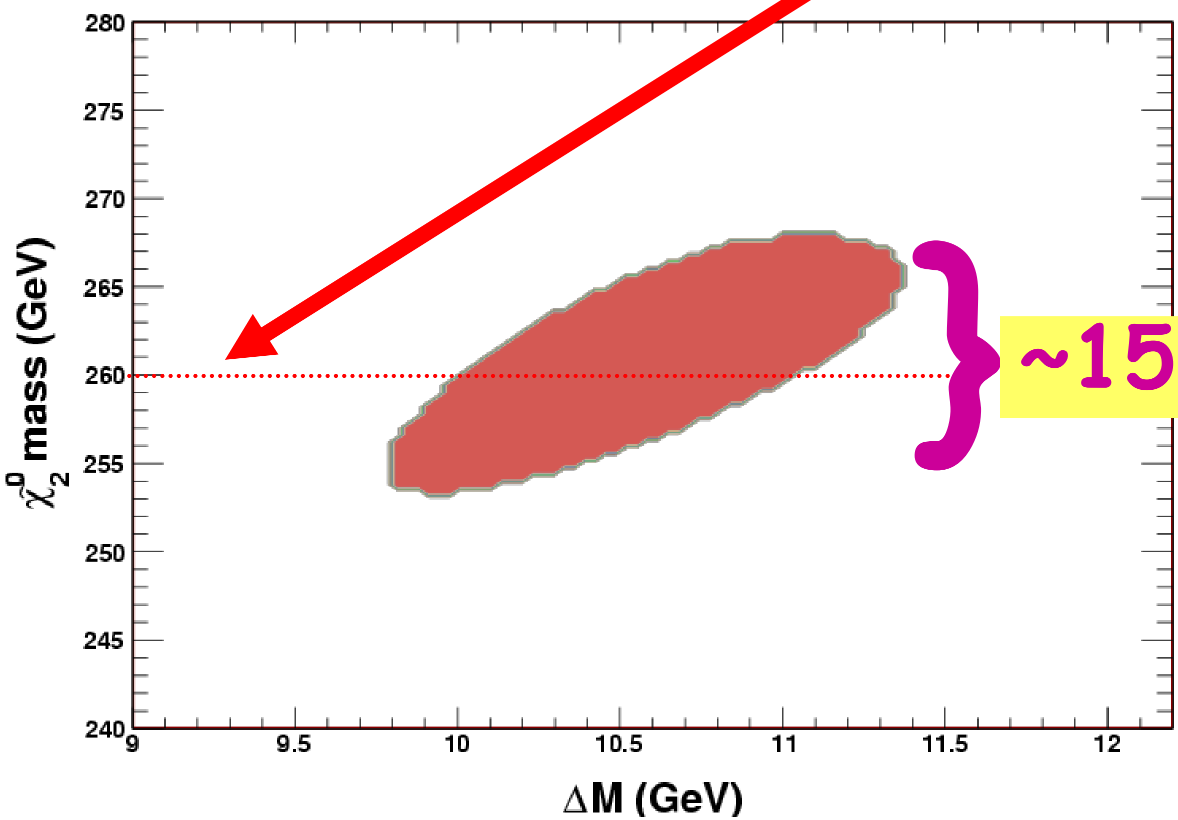



# Are we in a Universality World?

*Use all 3 observables to make simultaneous measurements*

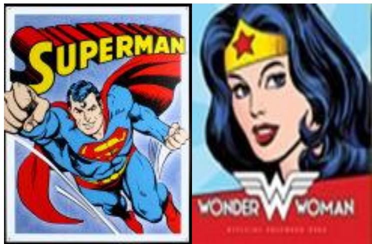
*Compare measured $M_{\tilde{\chi}_2^0}$ to $M_{\tilde{\chi}_2^0}^{Universality}$ from $\Delta M$, $M_{\tilde{g}}$*




~15 GeV or ~3%

*Only Assume*

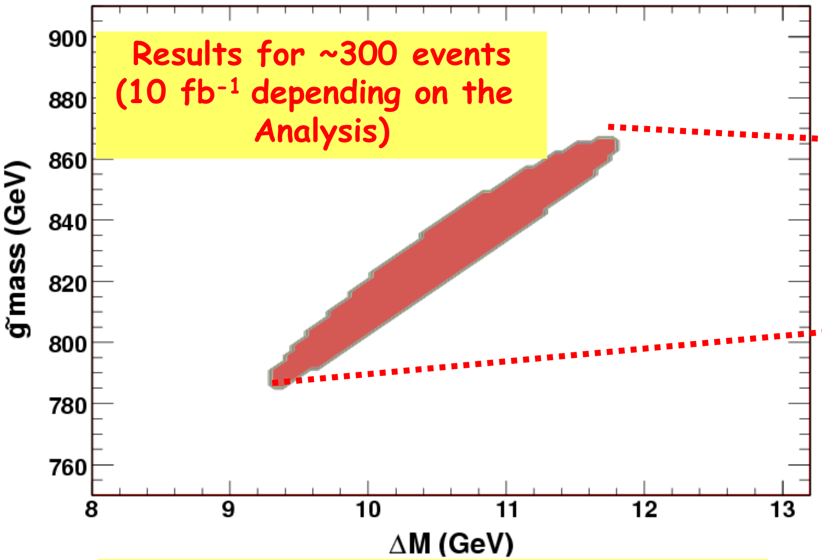
*$M_{\tilde{\chi}_1^0} \sim 0.17\, M_{\tilde{g}}$*

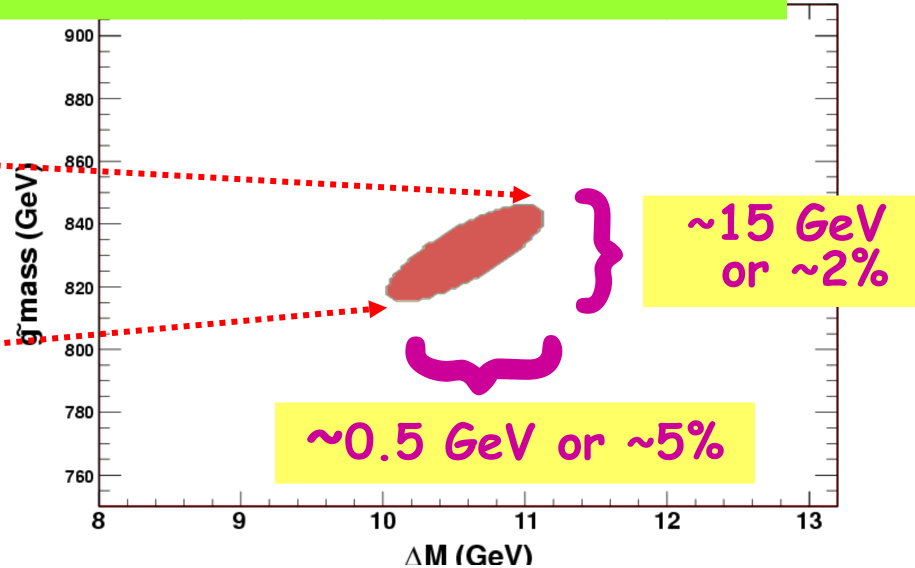


# What if we Assume the Universality Relations?

*Use Events, $M_{\tau\tau}$ and Slope to measure $\Delta M$, $M_{\tilde{g}}$ and $M_{\tilde{\chi}_2^0}$ simultaneously*

*(Results for $M_{\tilde{G}}$ = 830 GeV, $\Delta M$ = 10.6 GeV)*




*Analysis only assumes*

$M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

*Analysis assumes*

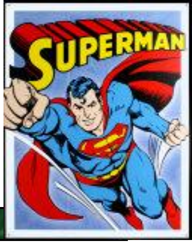
$M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}}$

*and* $M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

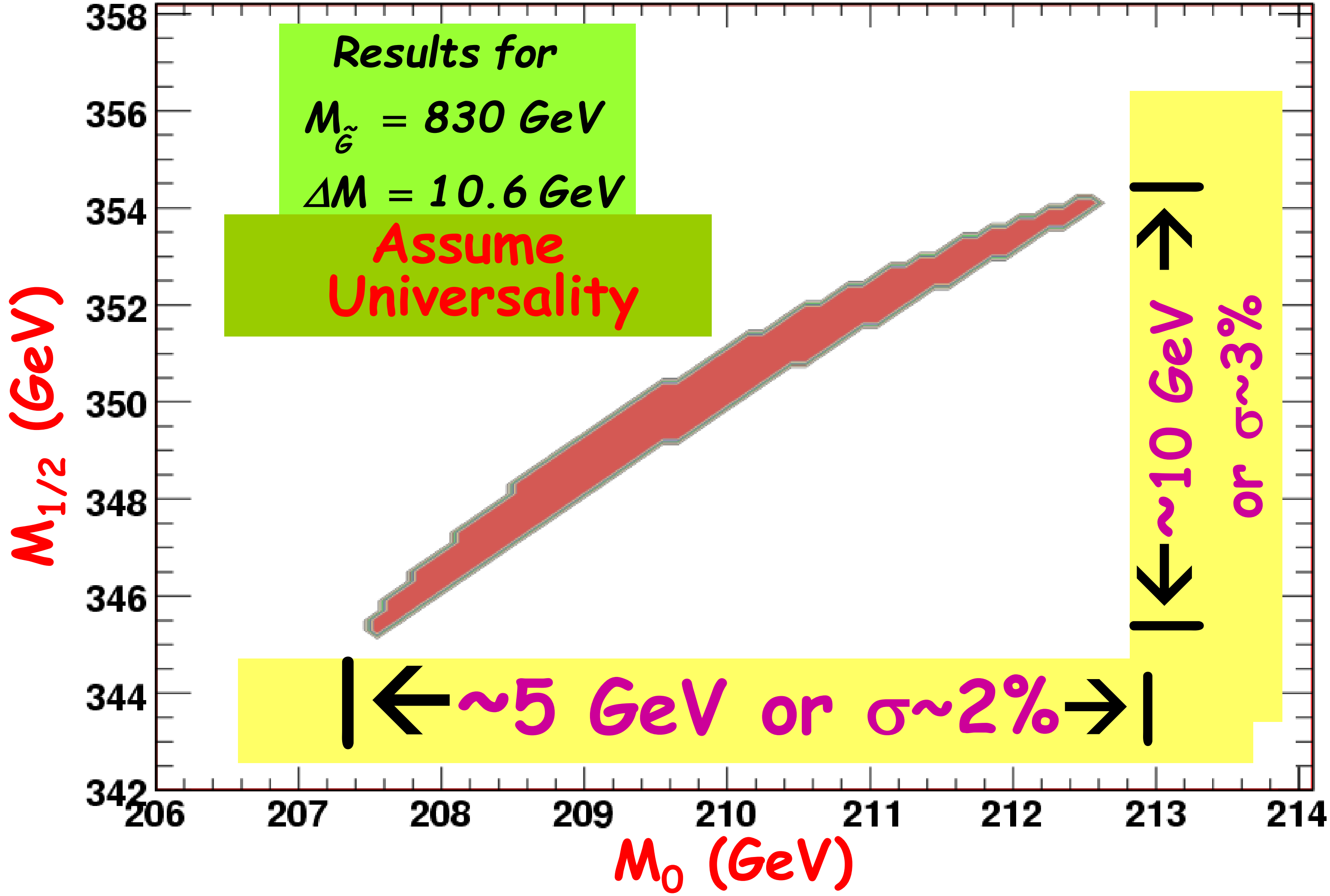
# Outline

- Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$
- Identifying events at the LHC
  - Discovery and Experimental Observables
- Measurements of
  - Particle masses: $\Delta M$, $M_{Gluino}$ & $M_{\chi 2}$
  - Supersymmetry parameters: $M_0$ and $M_{1/2}$
  - Cosmological implications: $\Omega_{LSP} h^2$
- Conclusions

# Infer $m_0$ and $m_{1/2}$



## Use $\Delta M$ and $M_{gluino}$ to measure $m_0$ and $m_{1/2}$

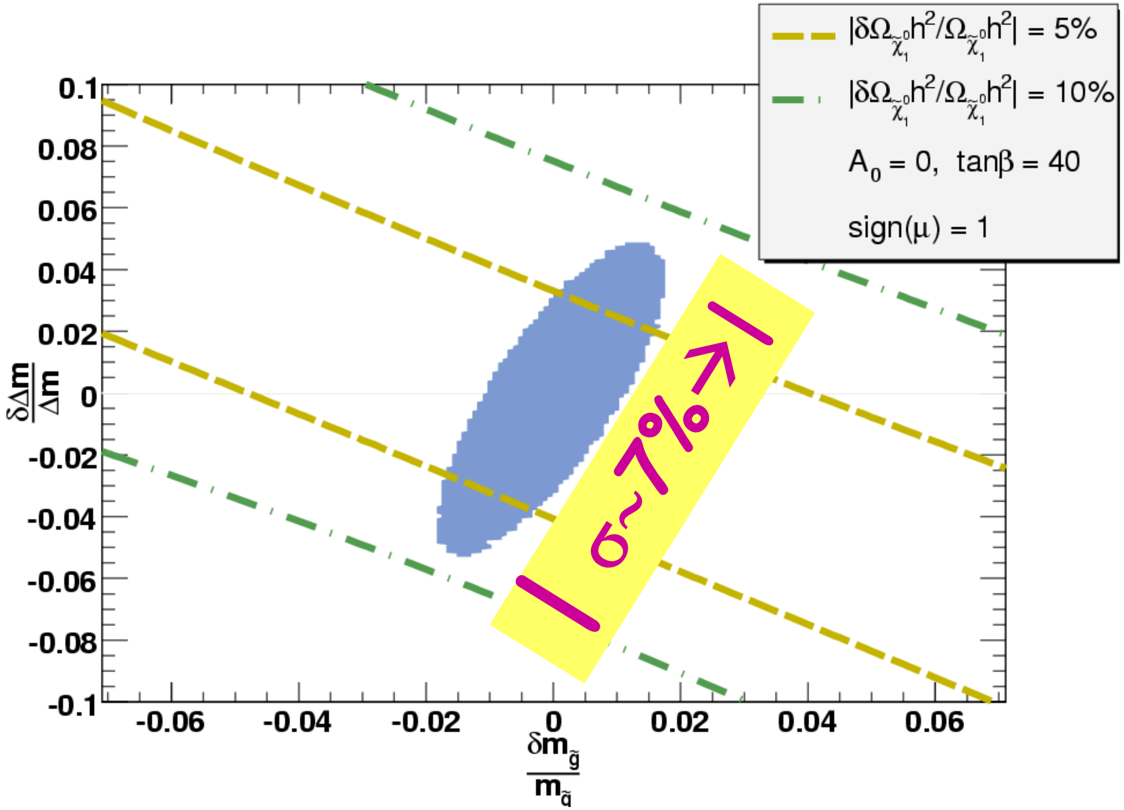


# Cosmology Measurements

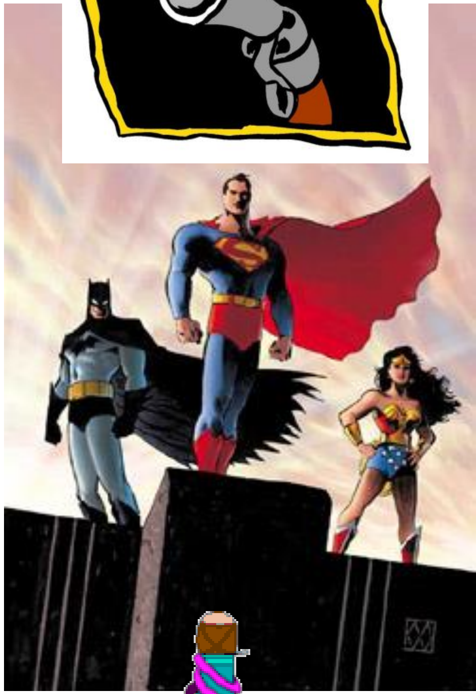
***With the same assumptions we can use***

***$\Delta M$, $M_{\tilde{g}}$ to measure $\Omega_{\tilde{\chi}_1^0} h^2$ to 7%***

***(Compare to WMAP which is 5%)***




# Conclusions



- If the co-annihilation region is realized in nature it provides a natural Smoking Gun
- The LHC should be able to uncover the striking small-$\Delta M$ signature with ~10 $fb^{-1}$ of data in multi-$\tau$ final states and make high quality measurements with the first few years of running
- The future is bright for Particle Physics and Cosmology as these precision measurements should allow us to measure the $\Delta M$ without Universality assumptions and make comparisons to the precision WMAP data with only minor assumptions

# Backup Slides

# Some caveats

# Aside...

We note that while the analysis here was done with mSUGRA, a similar analysis is possible for any SUGRA models (most of which possess a co-annihilation region) provided the production of neutralinos is not suppressed