

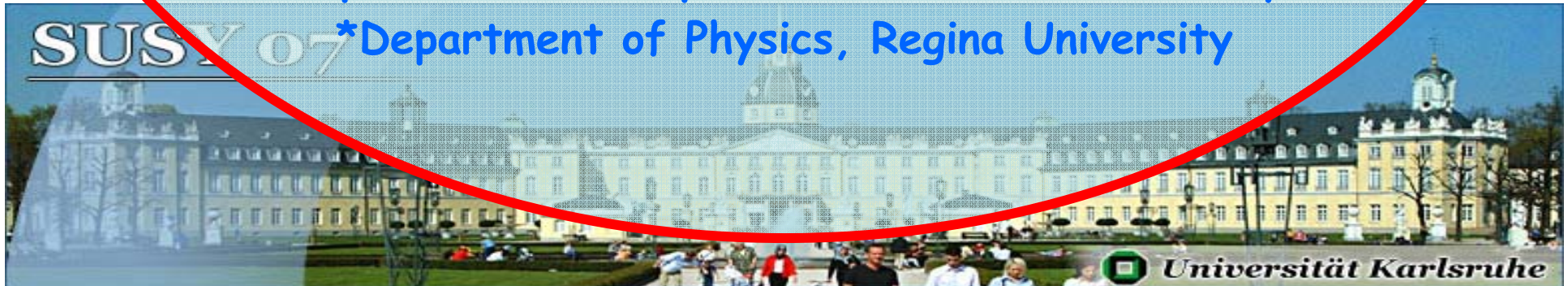
Dark Matter in SUGRA Models and the LHC

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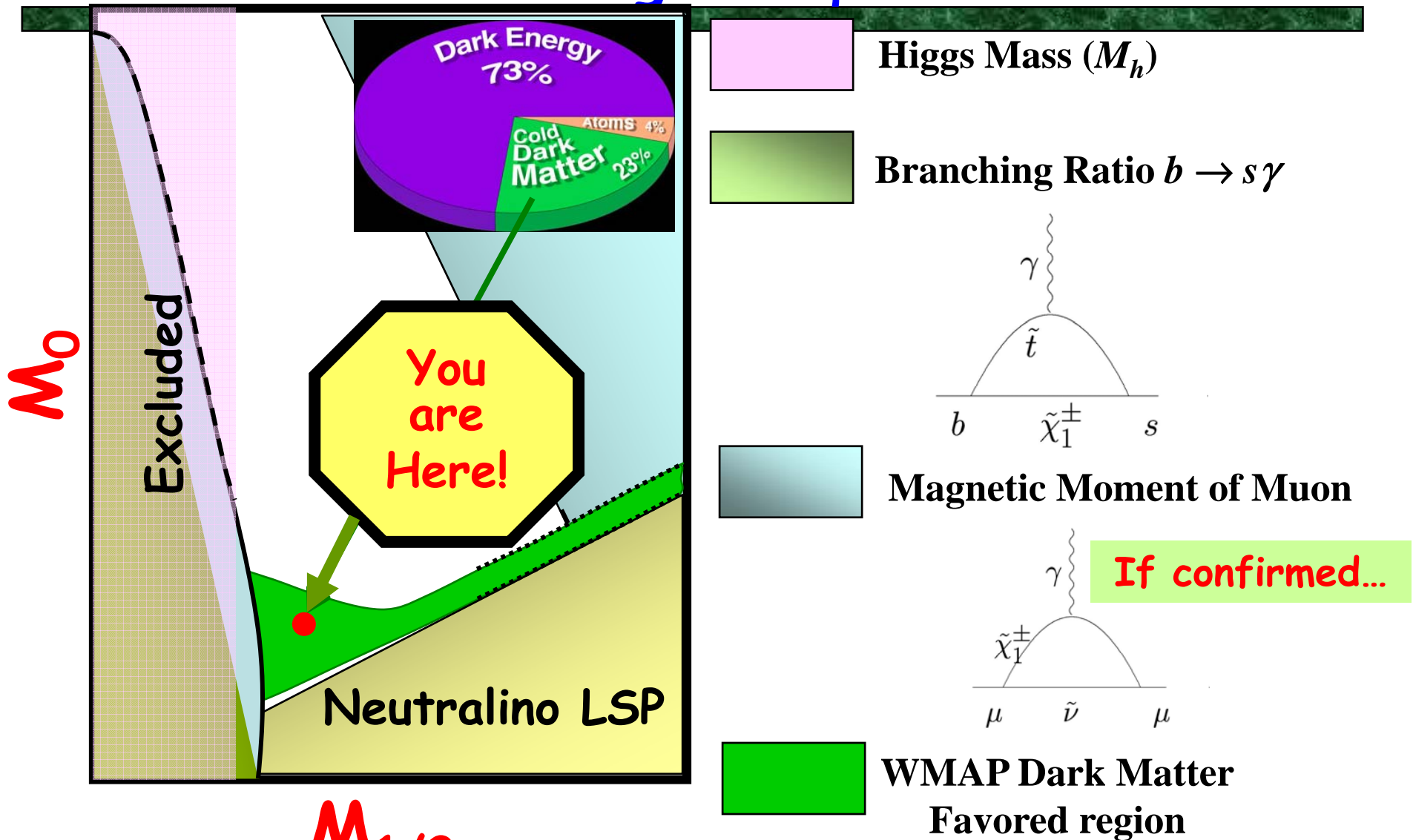
*Department of Physics, Regina University

SUSY 07



Experimental Constraints on mSUGRA at Large $\tan\beta$

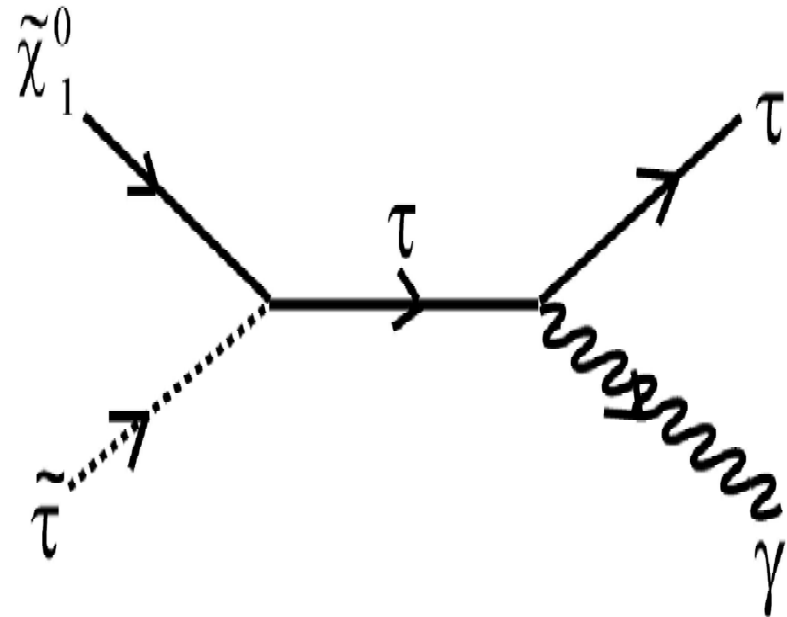
Wanted:



Co-Annihilation in the Early Universe

- 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 Dark Matter relic density to the value observed today
 - Co-annihilation effect (Griest, Seckel:92)
 - Common in many models

Particle Physics solution to a Cosmology problem?



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

Outline of the Talk

- *Co-annihilation Signals at the LHC*

A Smoking Gun: Small $\Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0}$

- *Experimental Observables and Discovery*

- *Measurements*

Masses: $\Delta M, M_{\text{Gluino}}, M_{\tilde{\chi}_2^0}, M_{\tilde{\chi}_1^0}$

mSUGRA Parameters: M_0 and $M_{1/2}$

- *Do we live in a mSUGRA world*

with Universal Couplings?

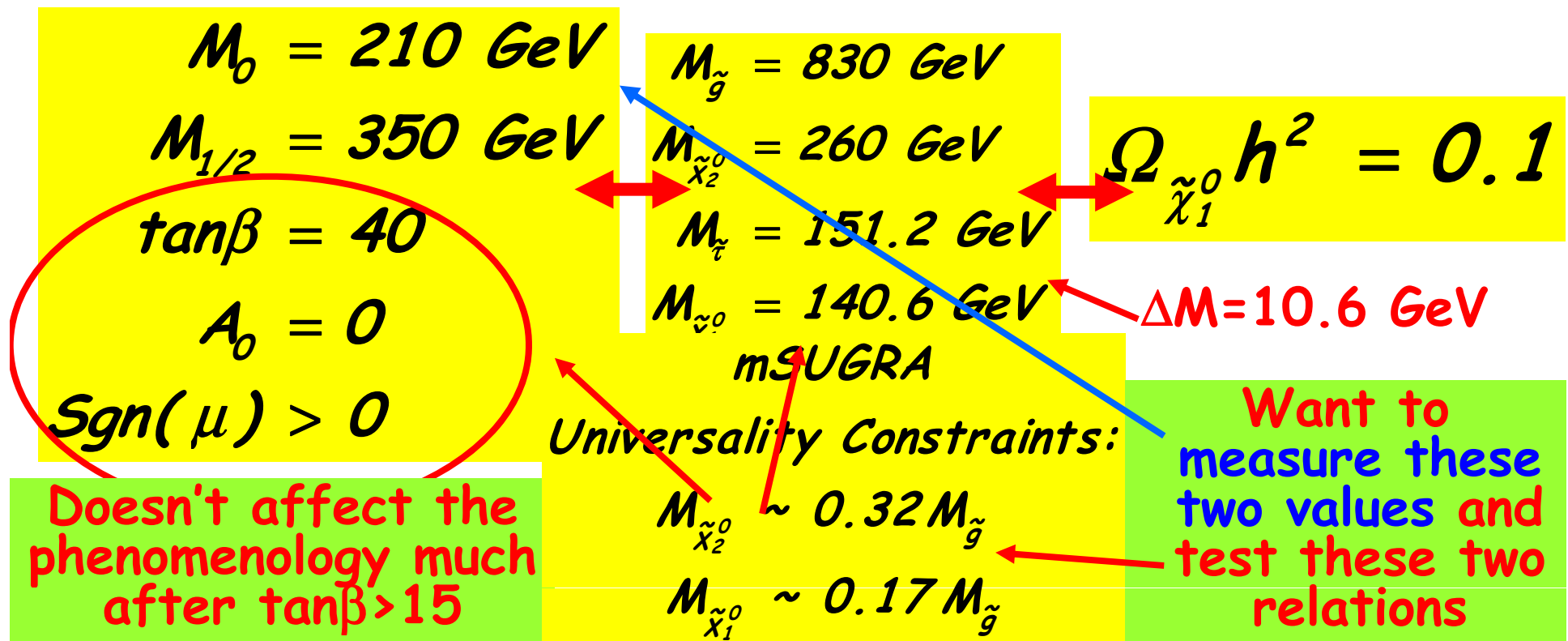
- *Cosmological Measurement: $\Omega_{\tilde{\chi}_1^0} h^2$*

- *Conclusions*

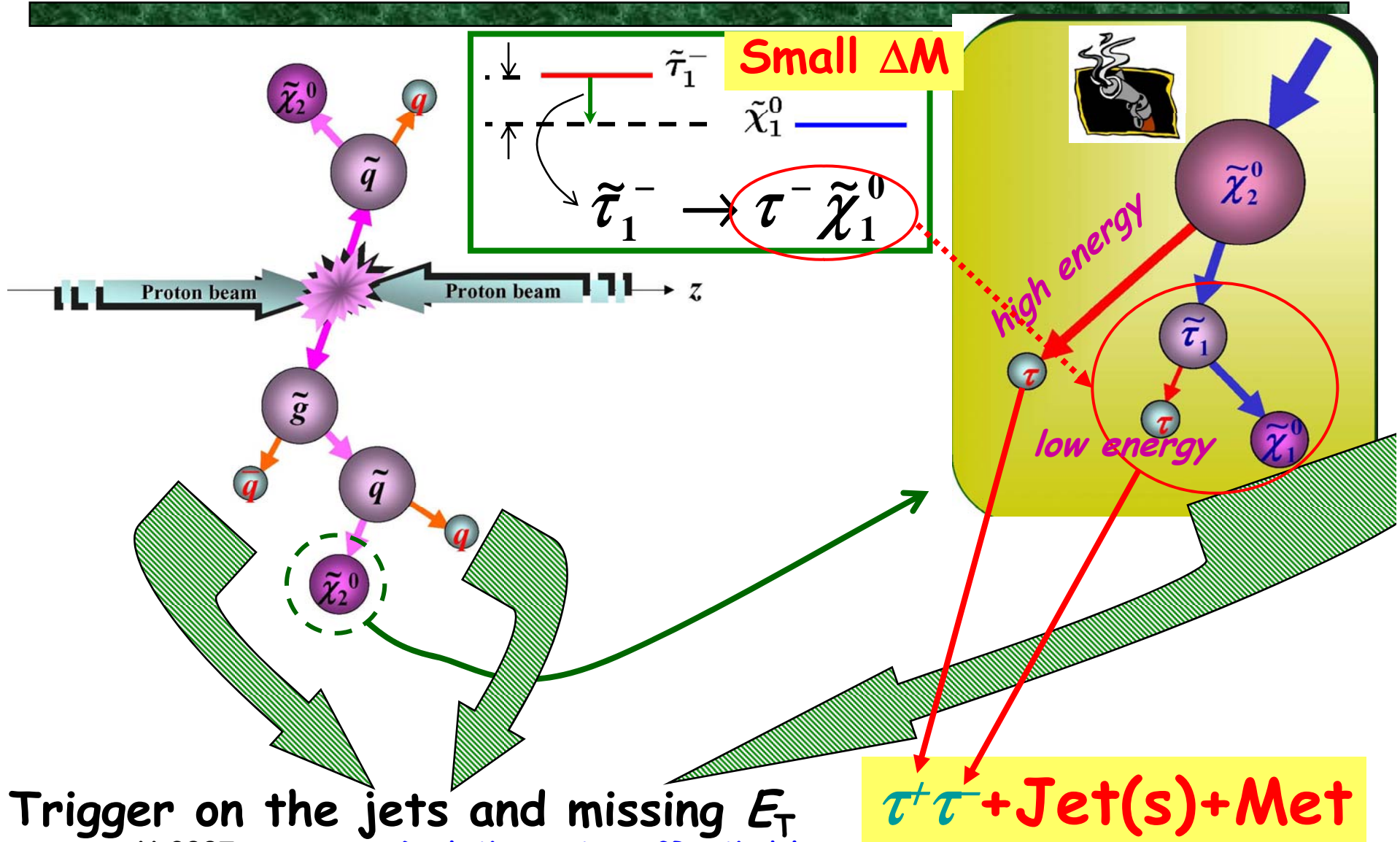


What do we want to know?

Measure the SUSY masses/parameters
4 Independent Variables



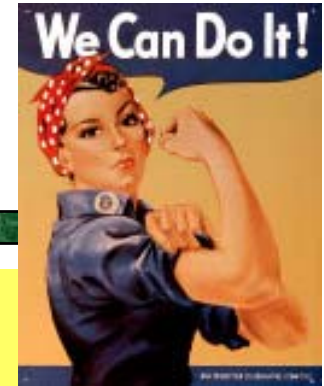
Identifying Events at the LHC



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



- Require at least two τ '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

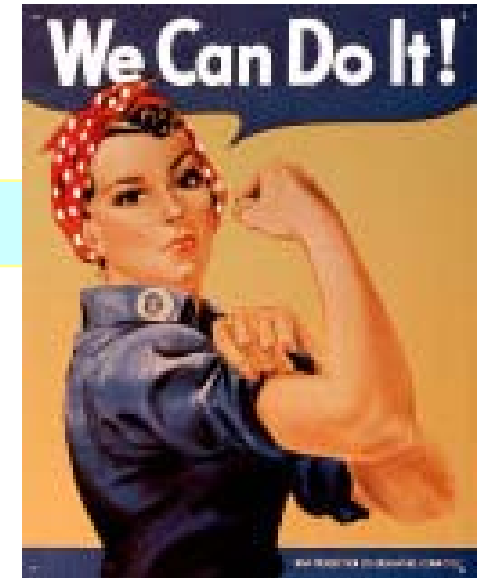
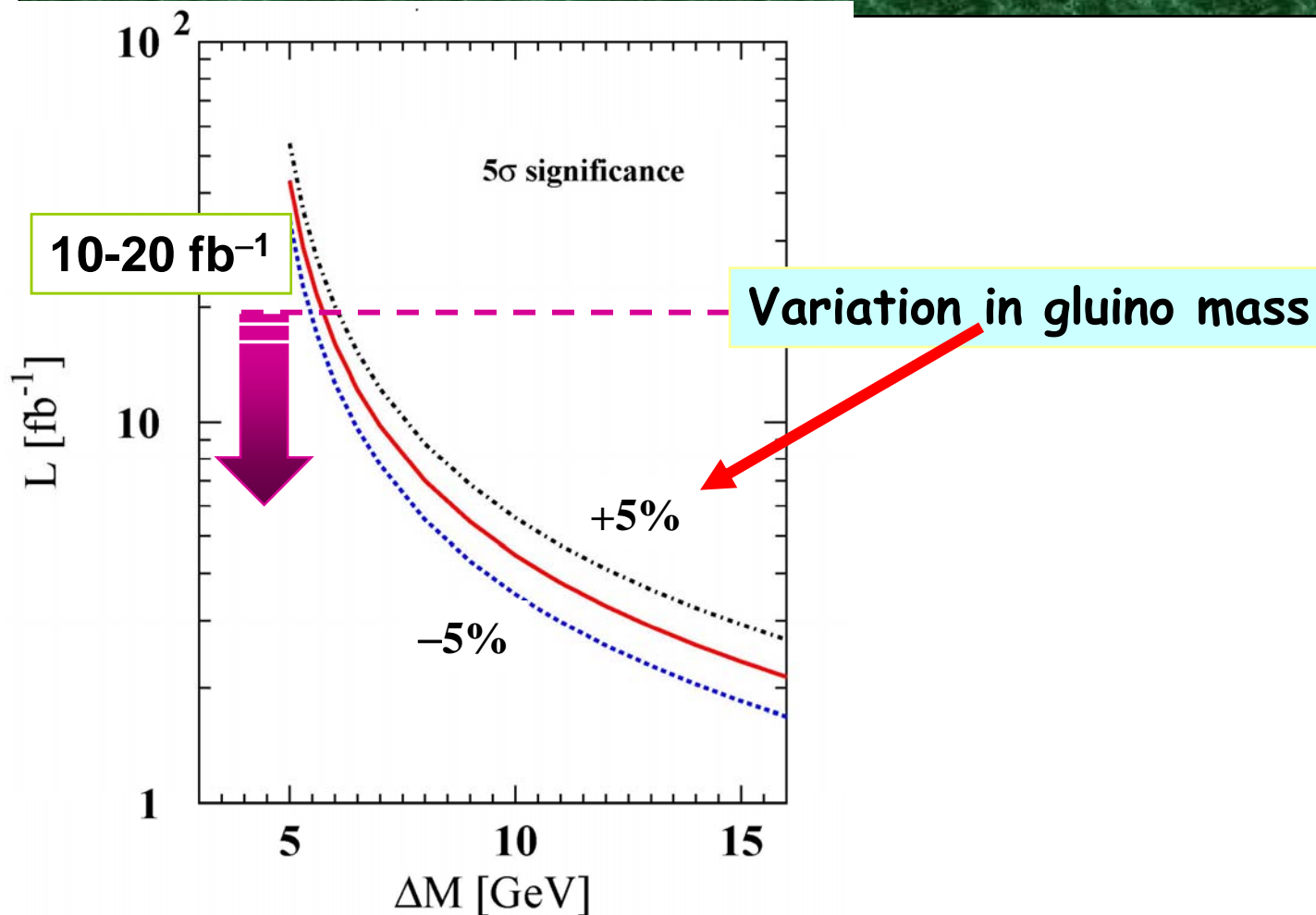
The dominant background is typically $t\bar{t}$, so we require an extra object and large kinematics to reject it

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

More details in

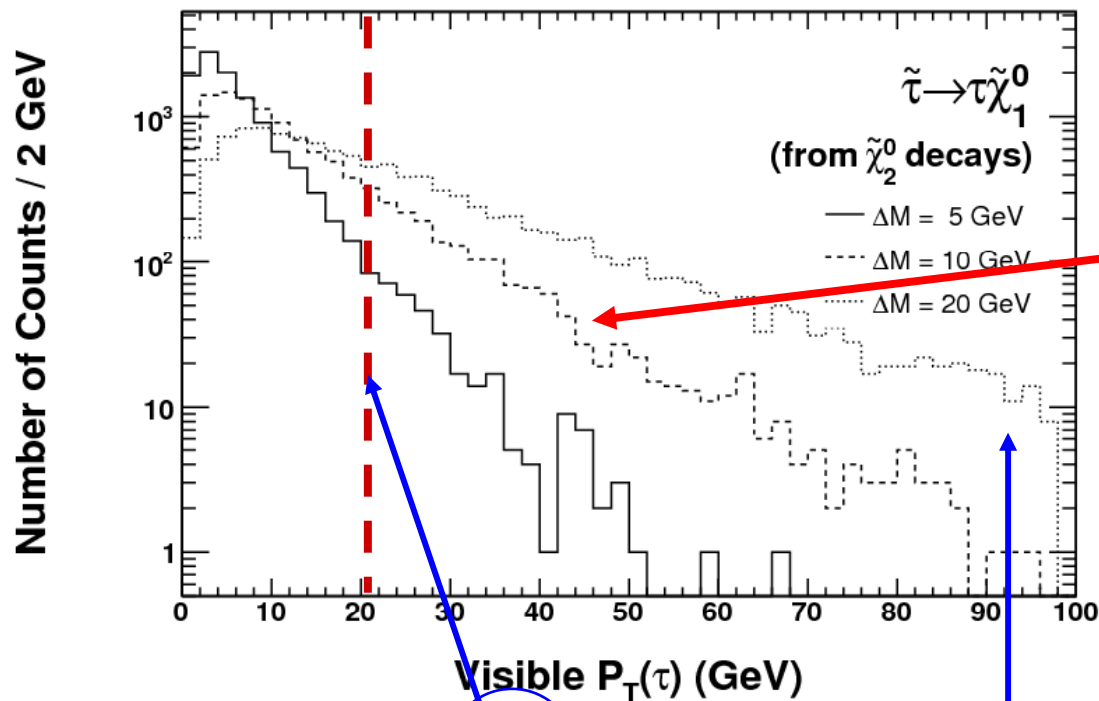
R. Arnowitt *et al.* Phys.Lett.B639:46,2006 and
Phys. Lett.B649:72, 2007

Discovery Luminosity



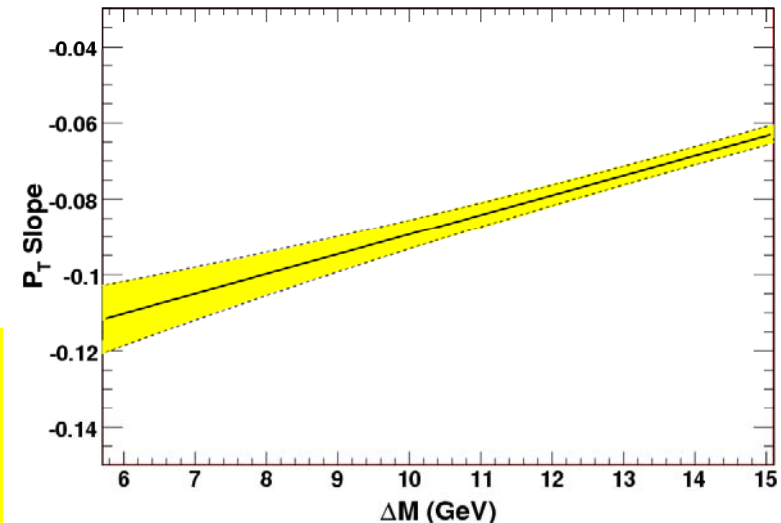
**A small ΔM can be detected in first few years of LHC
~100 Events**

Lots of handles in the cascade decays to provide good Observables



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

Slope of P_T distribution of "soft τ " contains ΔM Information



Slope of P_T distribution is largely unaffected by Gluino Mass

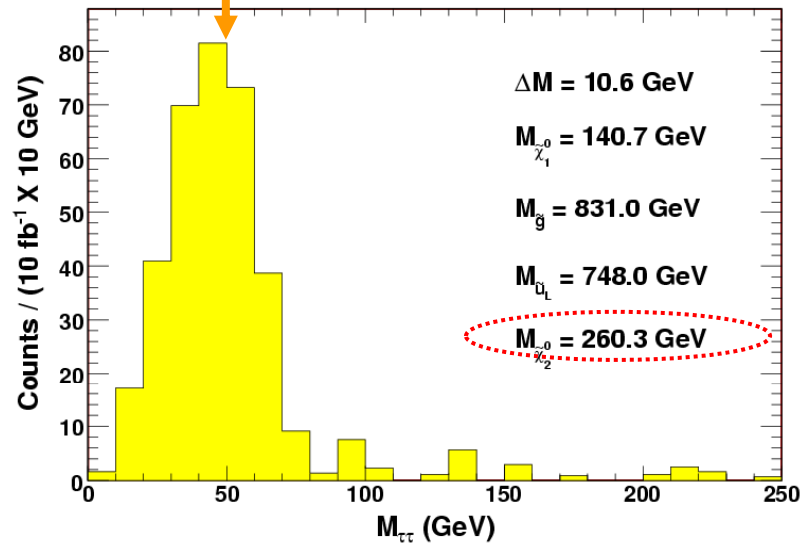
Low energy τ 's are an enormous challenge for the detectors

Independent variable: Get more events for large ΔM

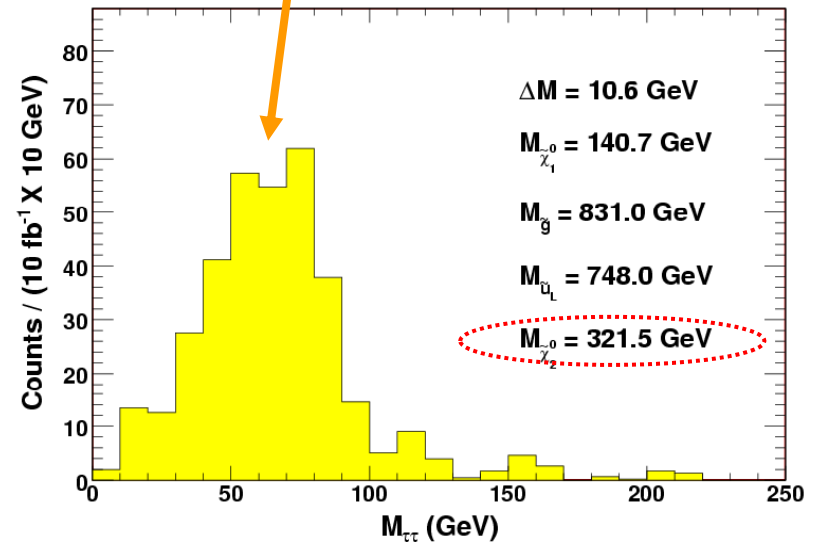
More Observables

$\tilde{\chi}_2^0 \rightarrow \tau\tau\tilde{\chi}_2^0$ gives a peak in $M_{\tau\tau}$

Clean peak
Even for low
 ΔM

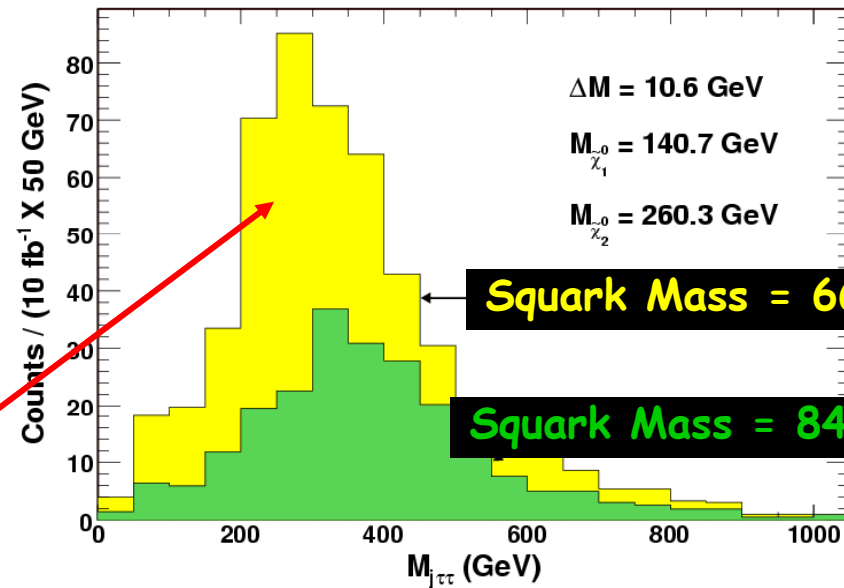
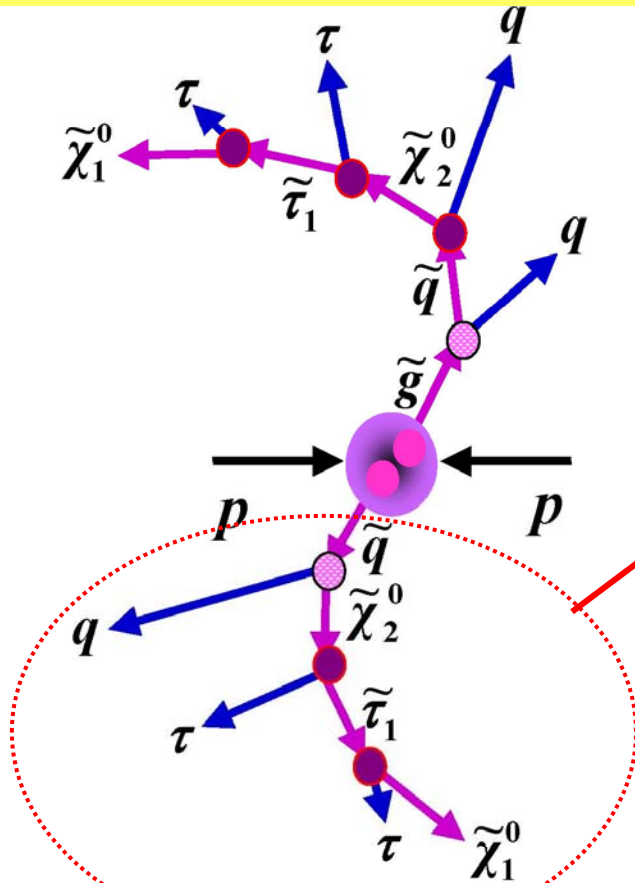


Larger $\tilde{\chi}_2^0$ Mass \rightarrow Larger $M_{\tau\tau}$



Another Mass Peak

$\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tau\tilde{\tau}\tilde{\chi}_2^0$ gives a peak in $M_{j\tau\tau}$



Peak value depends on squark mass

4 Variables and 4 Unknowns

1. Number of events
2. Slope of the P_τ distribution of the softest τ
3. The peak of the $M_{\tau\tau}$ distribution
4. The peak of the $M_{j\tau\tau}$ distribution

Make Simultaneous Measurements

$$M_{\tilde{g}} = 830 \text{ GeV}$$

$$M_{\tilde{\chi}_2^0} = 260 \text{ GeV}$$

$$\Delta M = M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0} = 10.6 \text{ GeV}$$

$$M_{\tilde{\chi}_1^0} = 140.6 \text{ GeV}$$

← Equivalent →
Measurements

$$M_0 = 210 \text{ GeV}$$

$$M_{1/2} = 350 \text{ GeV}$$

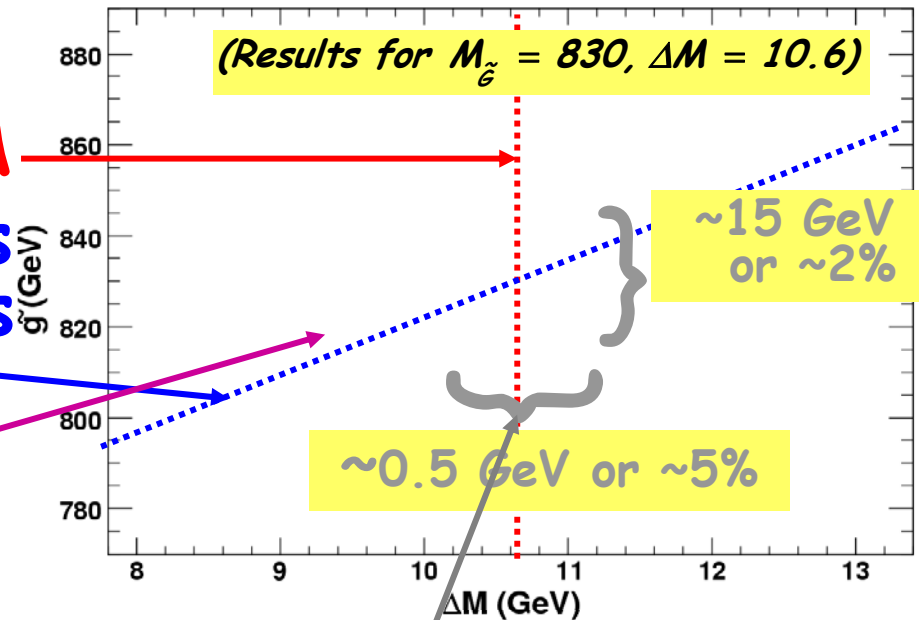
$$M_{\tilde{\chi}_2^0} \sim 0.32 M_{\tilde{g}}$$

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

Measure Parameters
and Test Universality

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

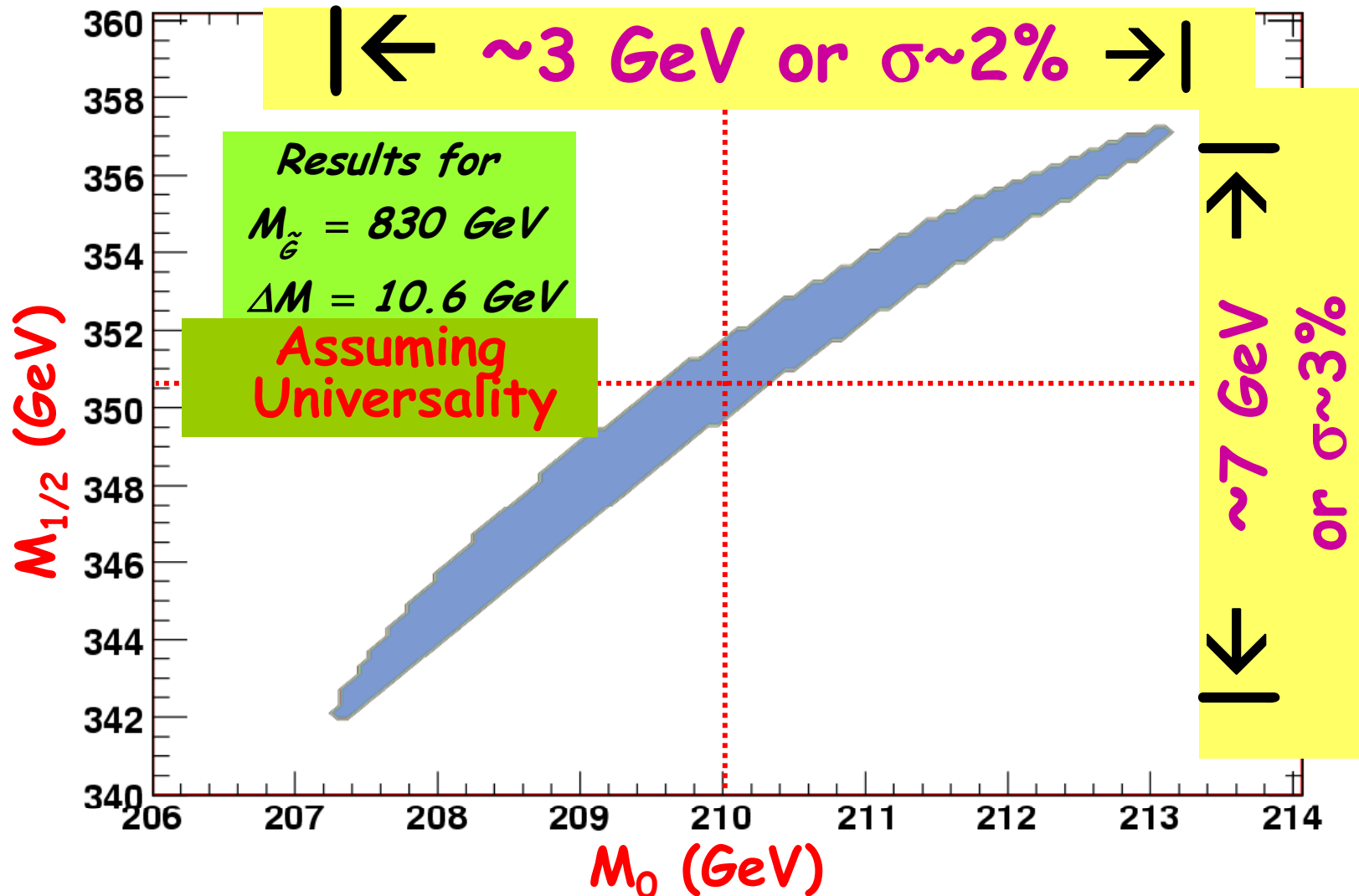


An important measurement without Universality assumptions!



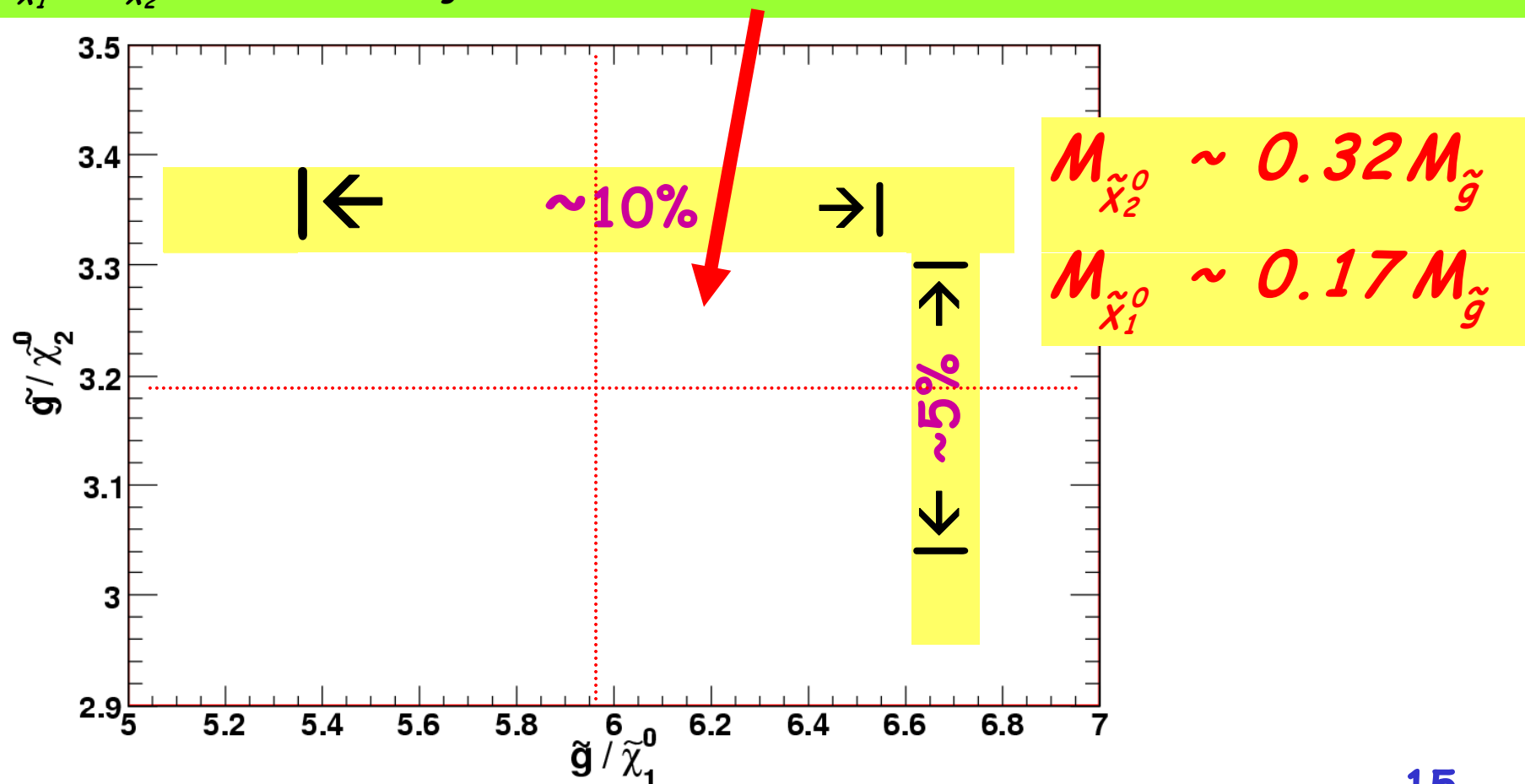
Assuming the Universality Constraints Improves the Measurement

Infer m_0 and $m_{1/2}$



Do we live in a world with Universal Couplings?

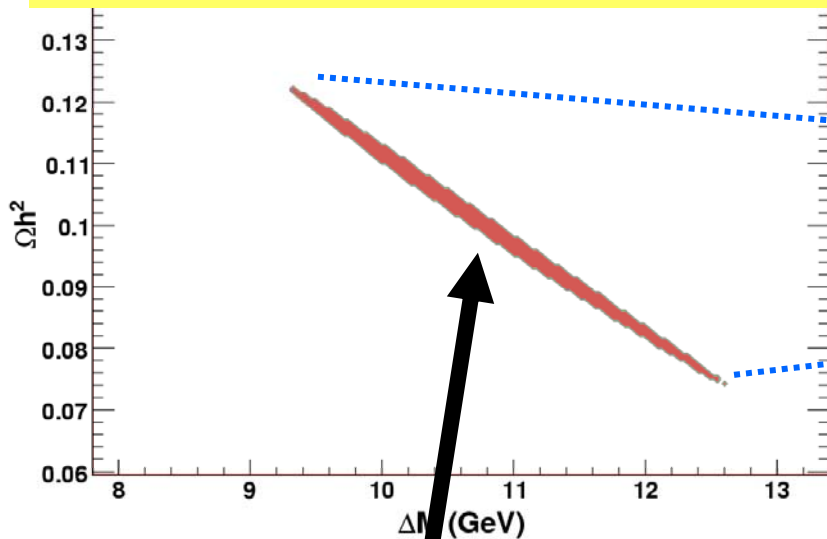
Use all 4 observables to make simultaneous measurements of $M_{\tilde{\chi}_1^0}$, $M_{\tilde{\chi}_2^0}$, ΔM and $M_{\tilde{g}}$ and compare to the mSUGRA Mass Relations



Cosmology Measurements

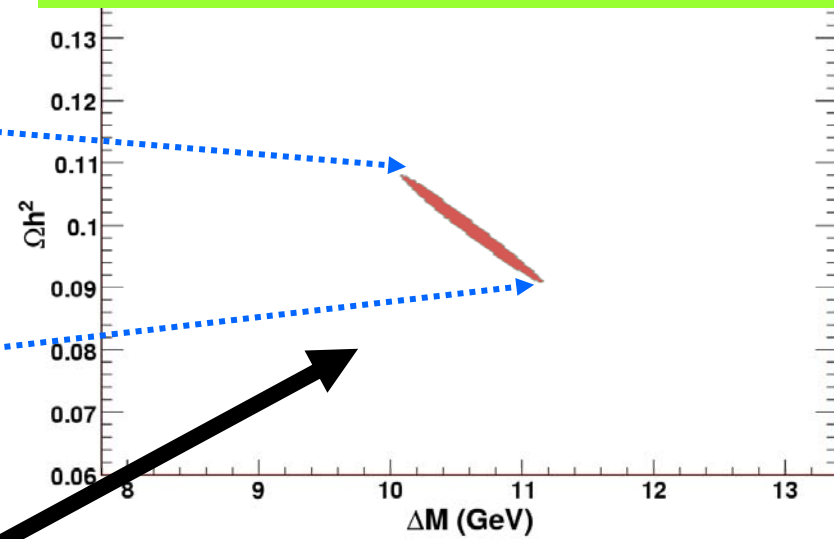
We can measure $\Omega_{\tilde{\chi}_1^0} h^2$ either way

No Universality Assumptions
4 Observables and 4 Unknowns



20%

With Universality Assumptions
4 Observables and 2 Unknowns



10%

Compare to WMAP which is 5%

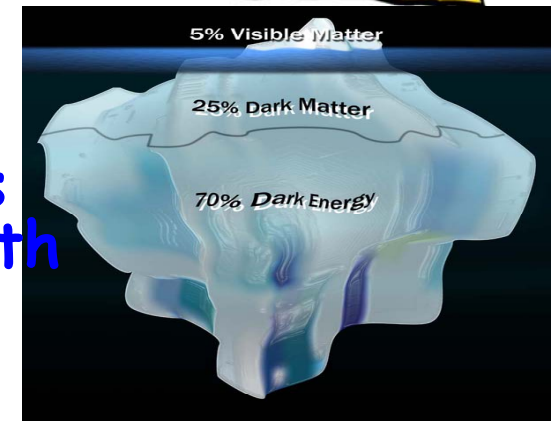
Small ΔM measurement

→ Confidence we are in the co-annihilation region

→ LSP is the Dark Matter

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- ΔM signature with $\sim 10 \text{ fb}^{-1}$ of data in multi- τ 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 ΔM without Universality assumptions, test Universality and make comparisons to the precision WMAP data



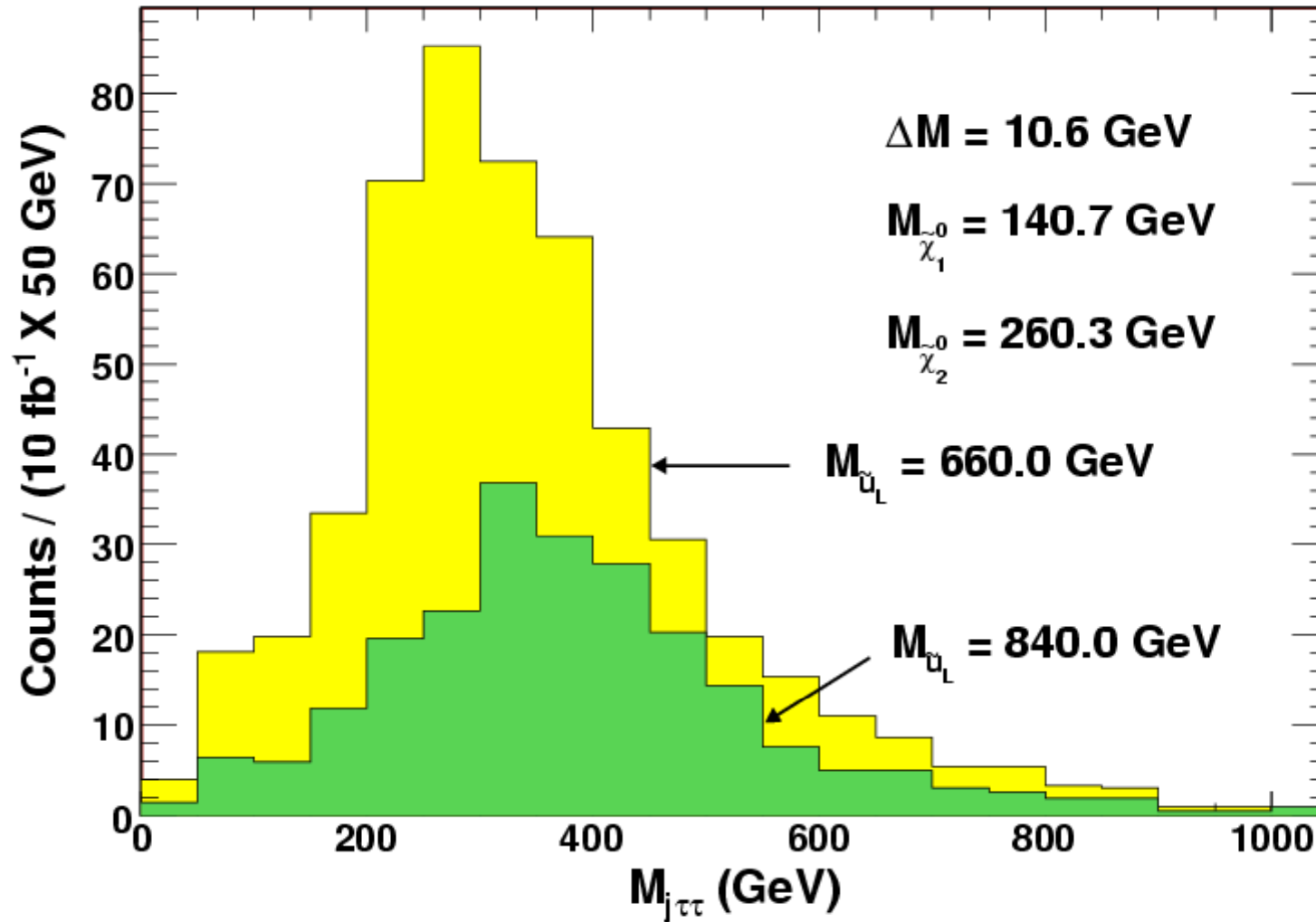


BACKUP Slides

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1	Title
2	Intro with Physics Goals
3	Outline and Overview of Analysis Methods
4	Co-annihilatino and constraints
5	What are we trying to measure: 4 values in mSugra, Ω_{H2}
6	Feynman diagrams and final state
7	Sample of χ^2 , not any tau will do
8	Discovery Lum 1
9	Pt and Nevents, ΔM and M_{gluino} variation
10	χ^2 mass and m_{tautau} variation
11	Squark Mass and $m(j\bar{t})$ variation
12	4 observables and translation, new version of previous slide...
13	ΔM vs M_{gluino} assuming Universalithy
14	M_0 and $M_{1/2}$
15	Test Universality: χ^2 and χ^1
16	Ω_{H2} in both
17	Conclusions

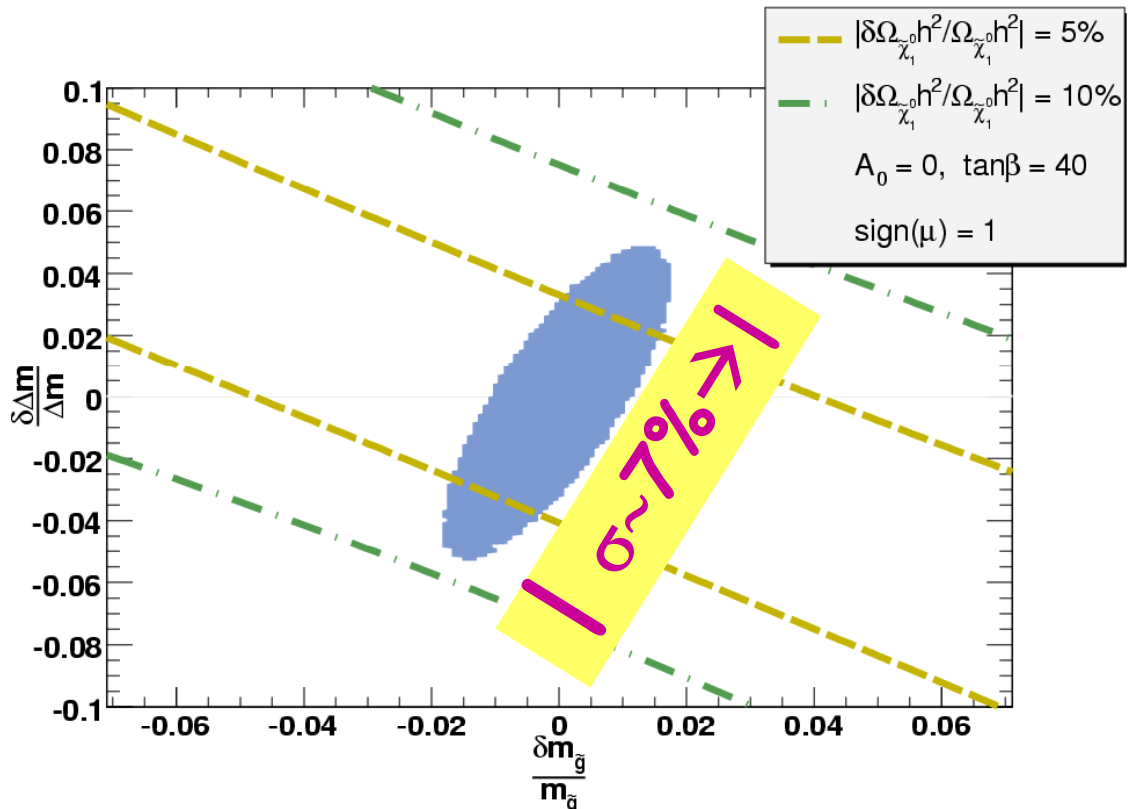


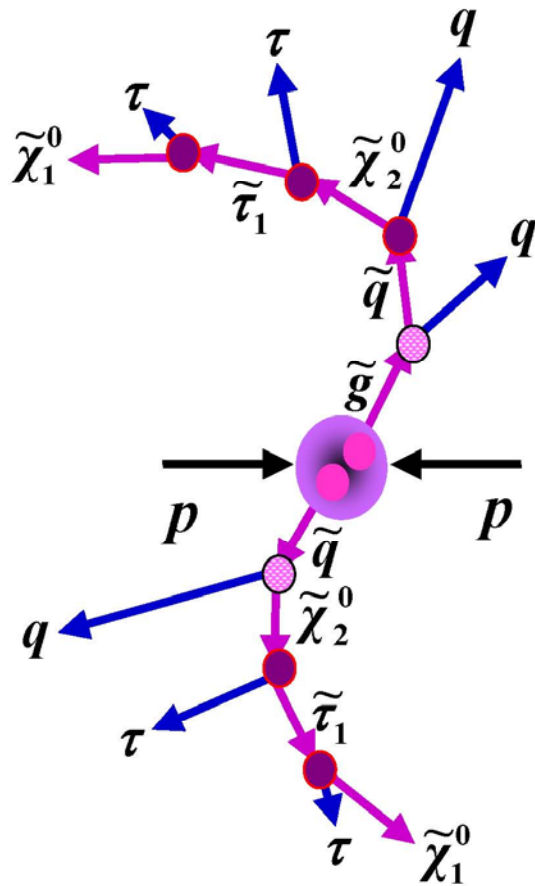
Cosmology Measurements

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%)



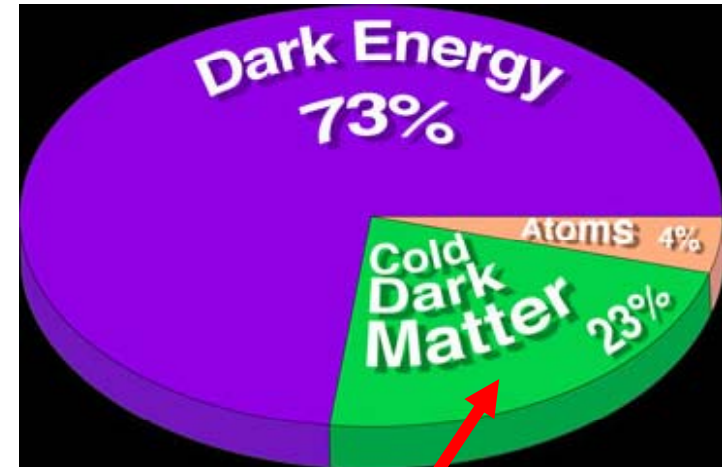




Some caveats

Introduction and Physics Goals

- 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?

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

The Players and their Roles



**Cosmologists/
Astronomers**

Astronomers

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**Particle
Theorists**

Theorists

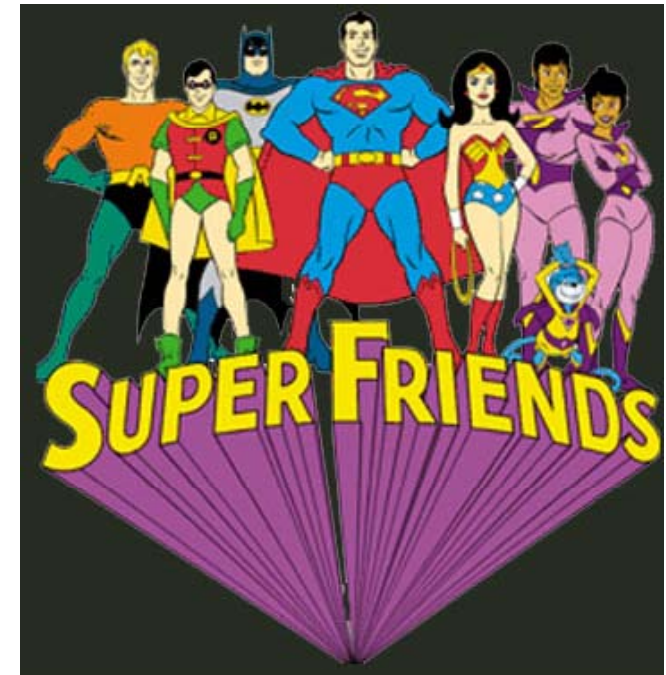
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**Particle
Experimentalists**

Experimentalists

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



The Players and Their Roles



Astronomy and
Cosmology tell us
about Dark Matter

Learn more about
the universe with
two separate
measurements of
 Ωh^2

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Particle Physics Theory
Predicts Supersymmetry
→ Dark Matter Candidate

Convert the masses into
SUSY model parameters
and Ωh^2
Do we live in a world with
Universal Couplings?

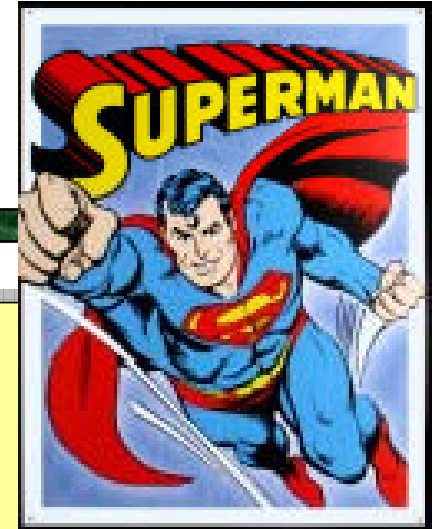
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Experimentalists at
FNAL/LHC do direct
searches for SUSY
particles

Discover SUSY
and measure the
masses of the
superparticles

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
$\text{sign}(\mu)$	Sign of Higgs mixing parameter ($W^2 = \mu H_1 H_2$)

Translation for Experimentalists and Cosmologists:

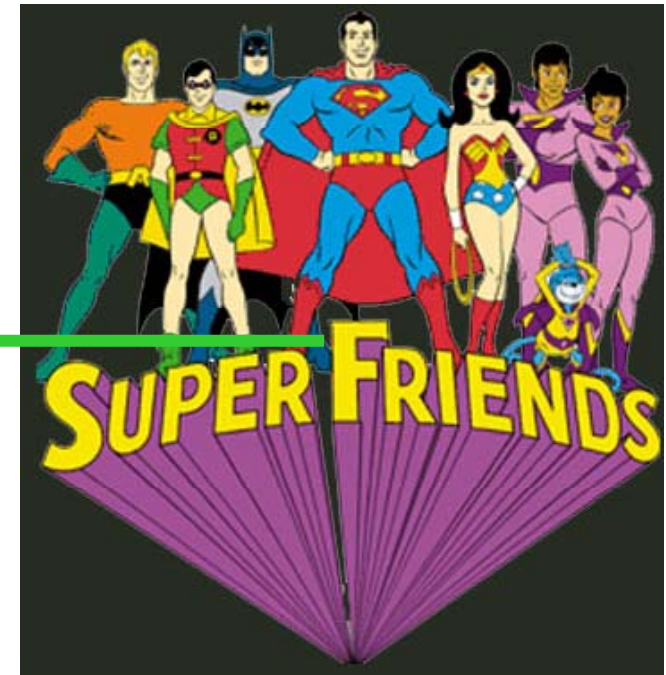
Each combination of these parameters uniquely determines the masses of all the superparticles and the Relic Density ($\Omega_{\tilde{\chi}_1^0} h^2$)

Outline

- **Supersymmetry and the Co-annihilation region**
 - The important experimental constraints
 - A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\text{LSP}}$
- **Identifying events at the LHC** ←
 - Discovery and Experimental Observables
- **Measurements of**
 - Particle masses: ΔM , M_{Gluino} & M_{χ_2}
 - Supersymmetry parameters: M_0 and $M_{1/2}$
 - Cosmological implications: $\Omega_{\text{LSP}} h^2$
- **Conclusions**

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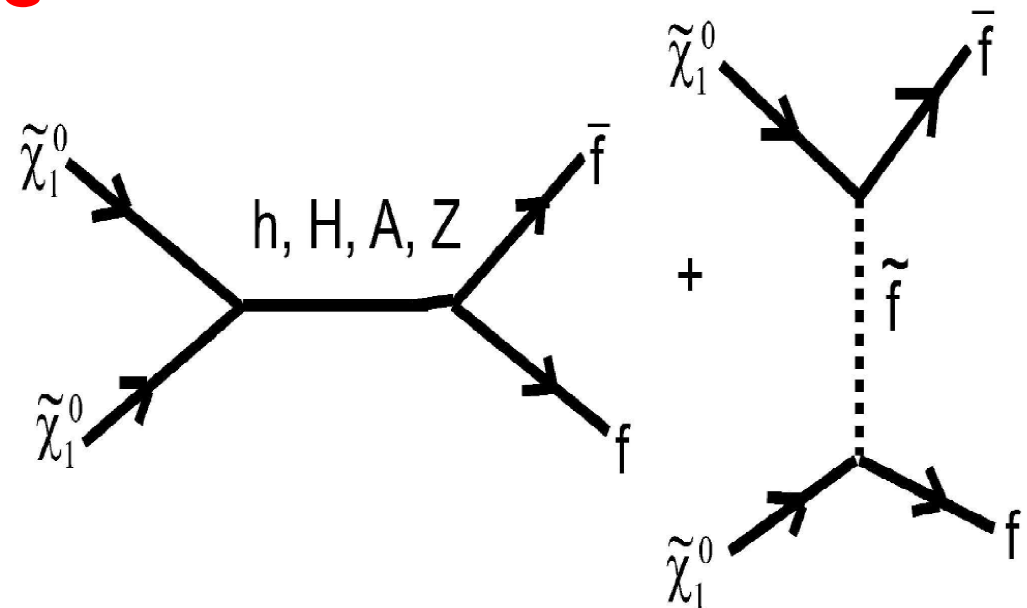
"Vanilla" mSUGRA and Cosmology



mSUGRA parameters uniquely determine the

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

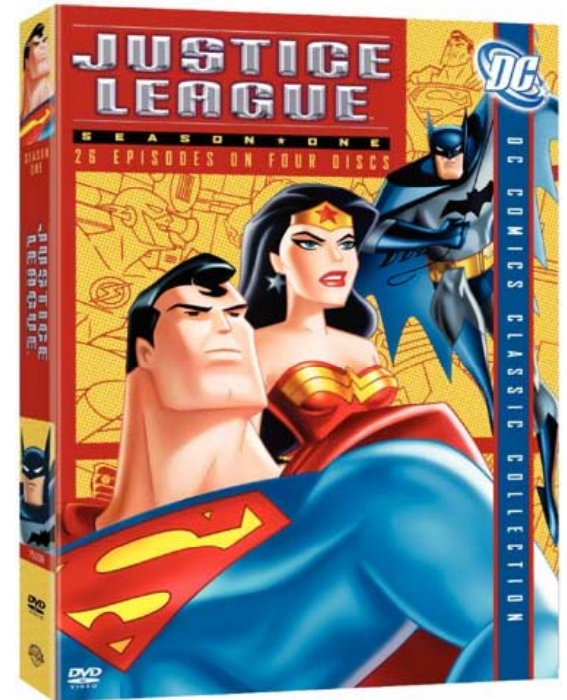
Use WMAP Relic Density measurements to further constrain SUSY parameter space



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



Experimental Constraints

Particle Physicists:

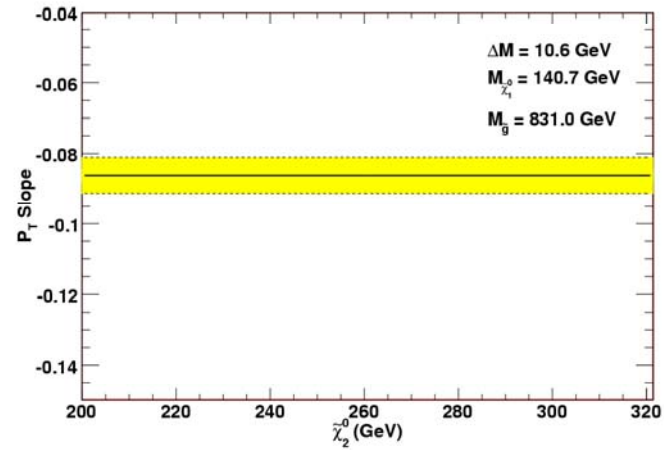
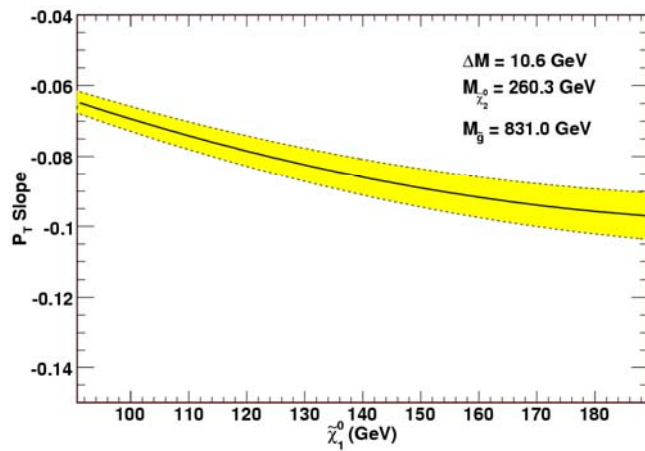
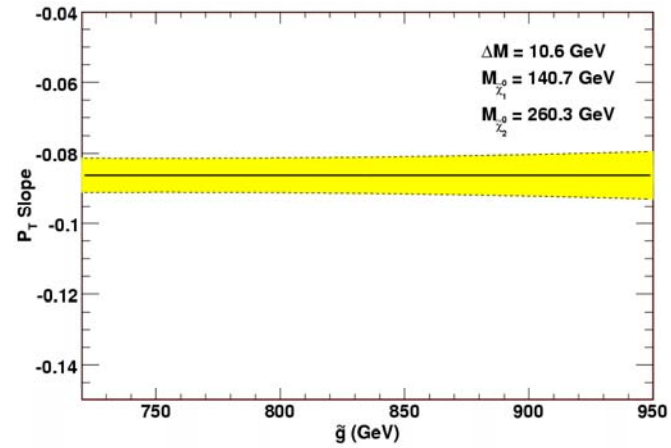
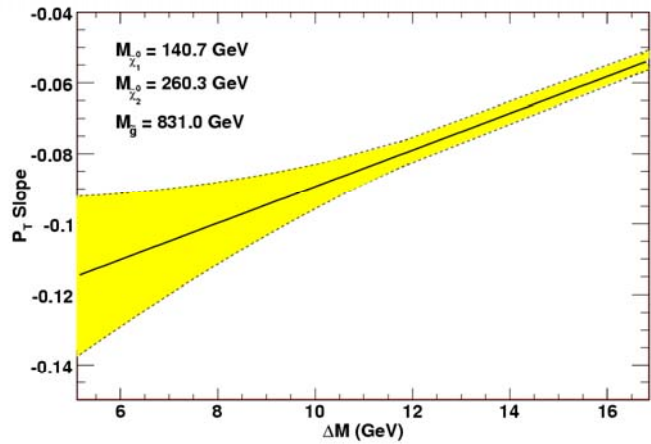
- Non-observation of the Higgs and the Gauginos and their mass limits
- Measurement of branching ratio of the b -quark $\rightarrow s\gamma$

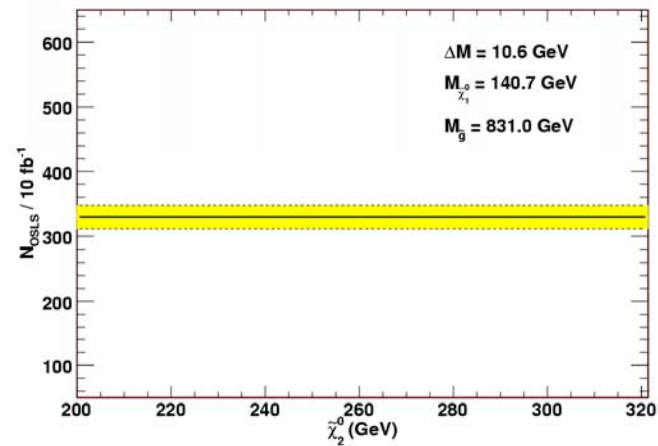
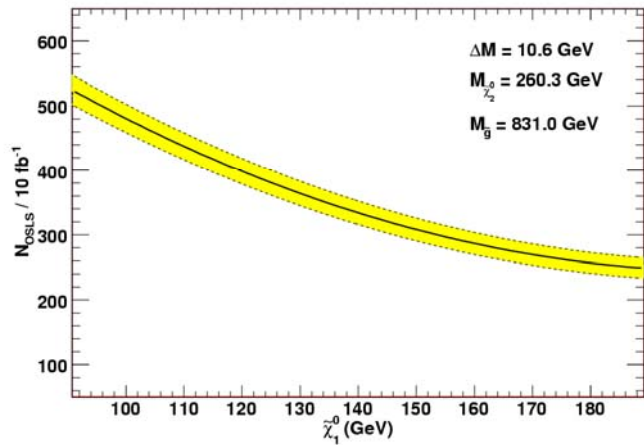
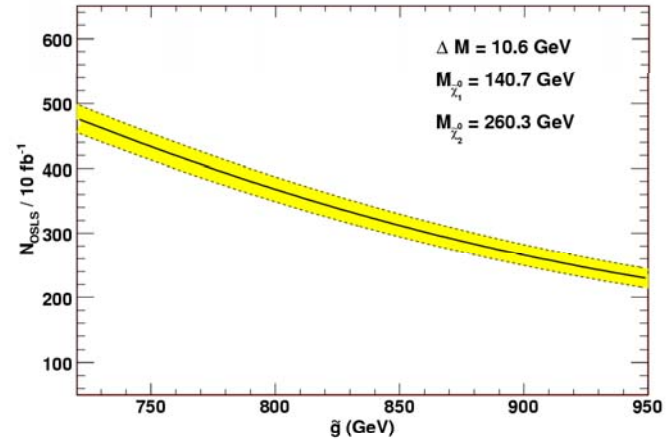
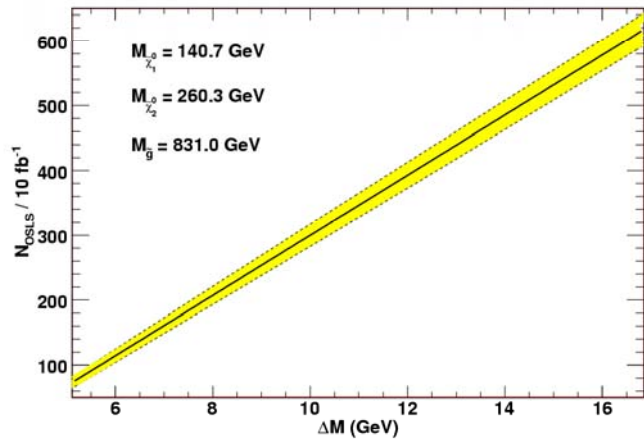
Astronomers and Cosmologists:

- WMAP measurement of the Relic Density

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

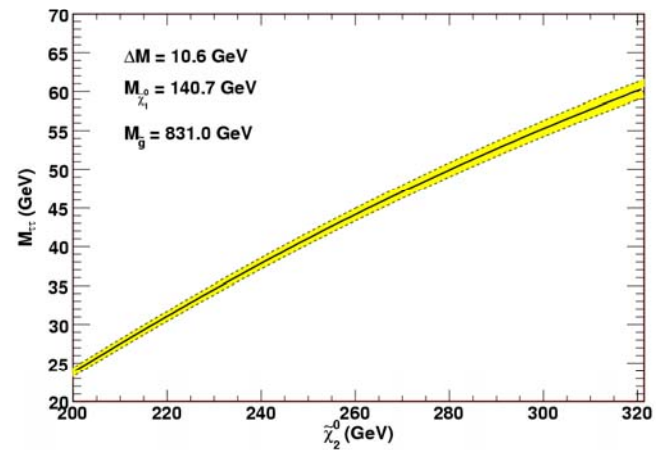
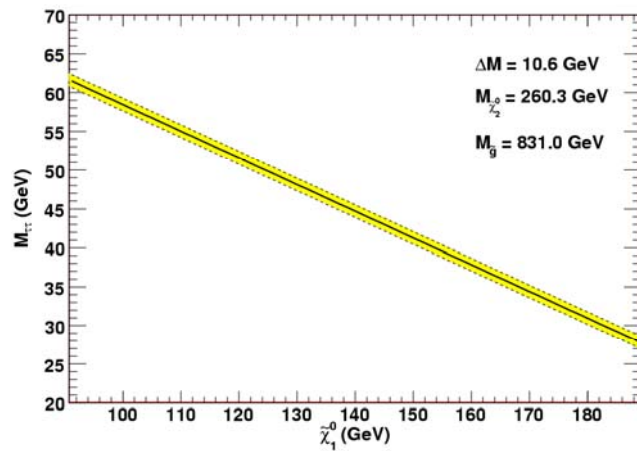
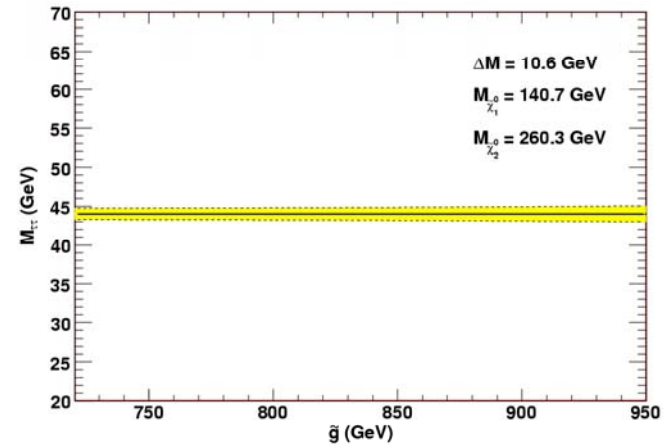
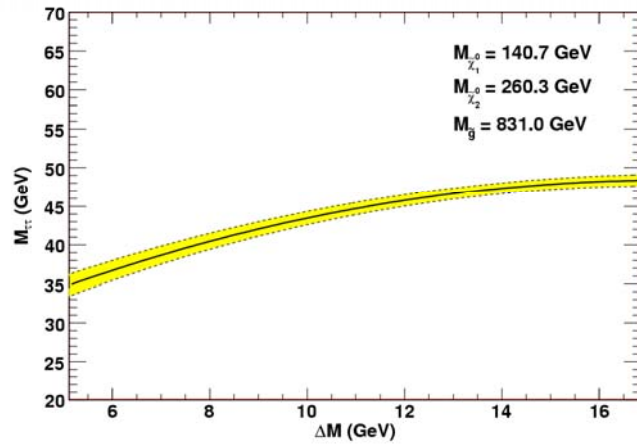


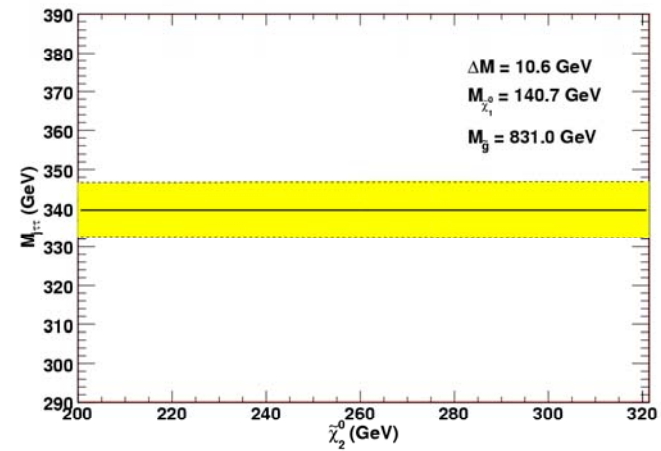
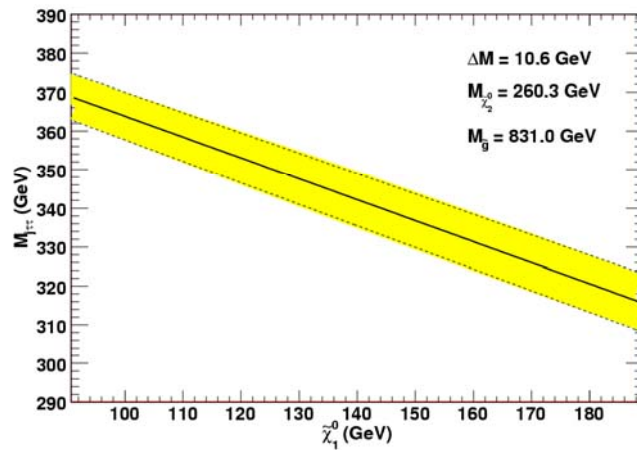
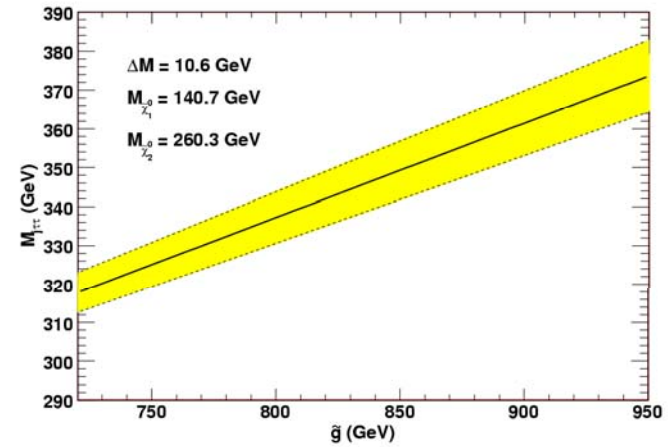
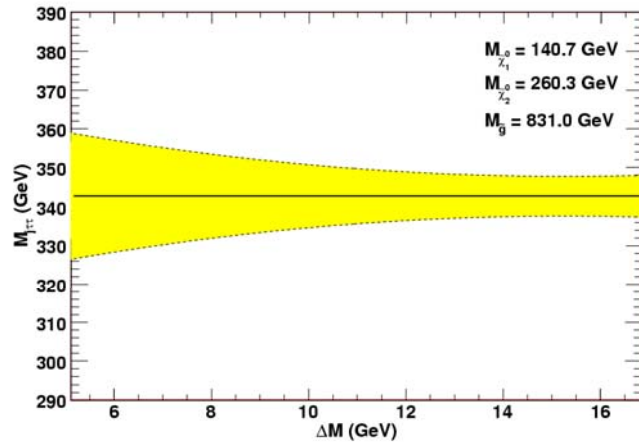


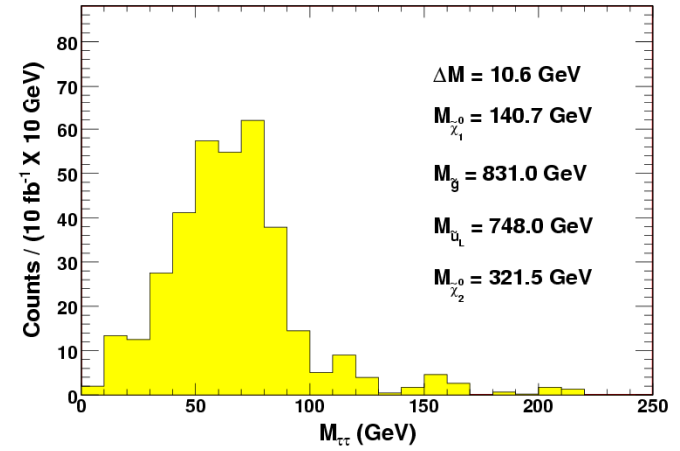
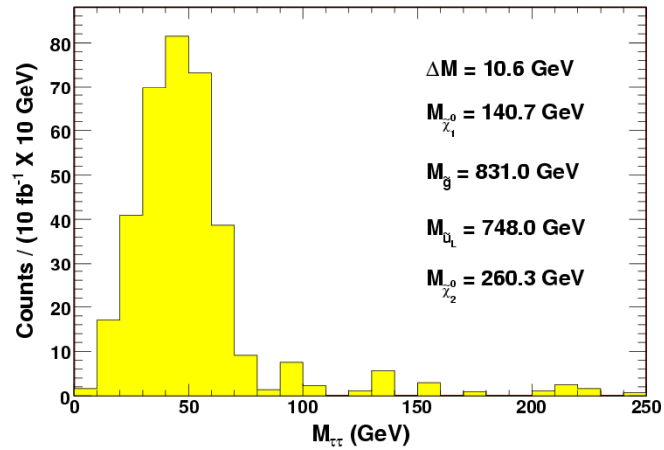


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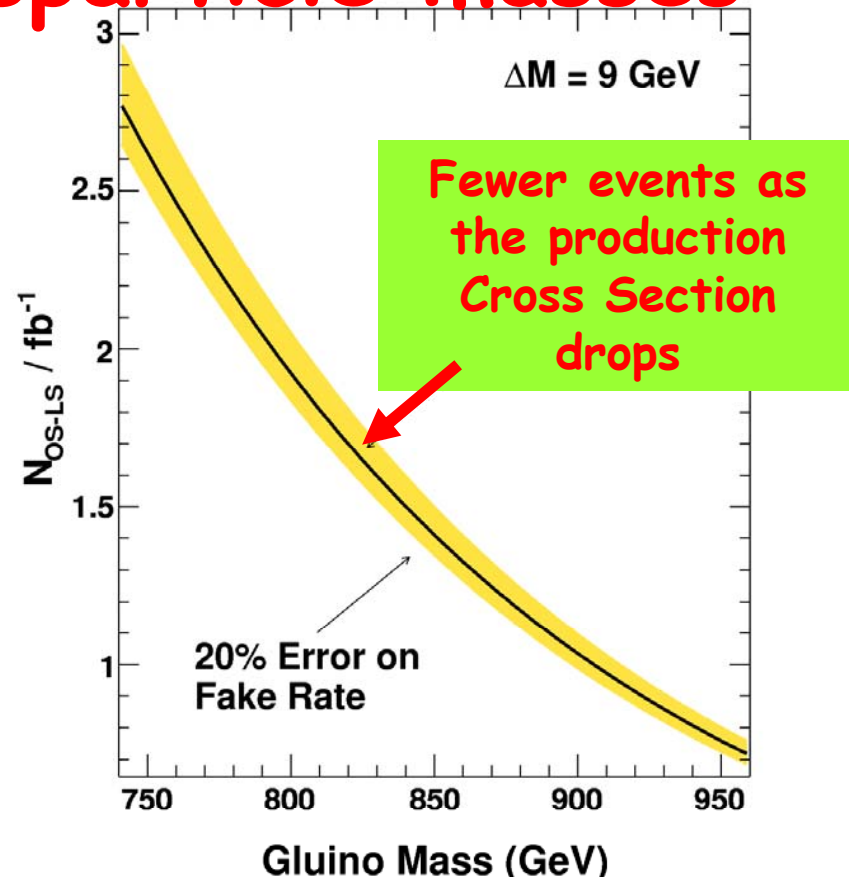
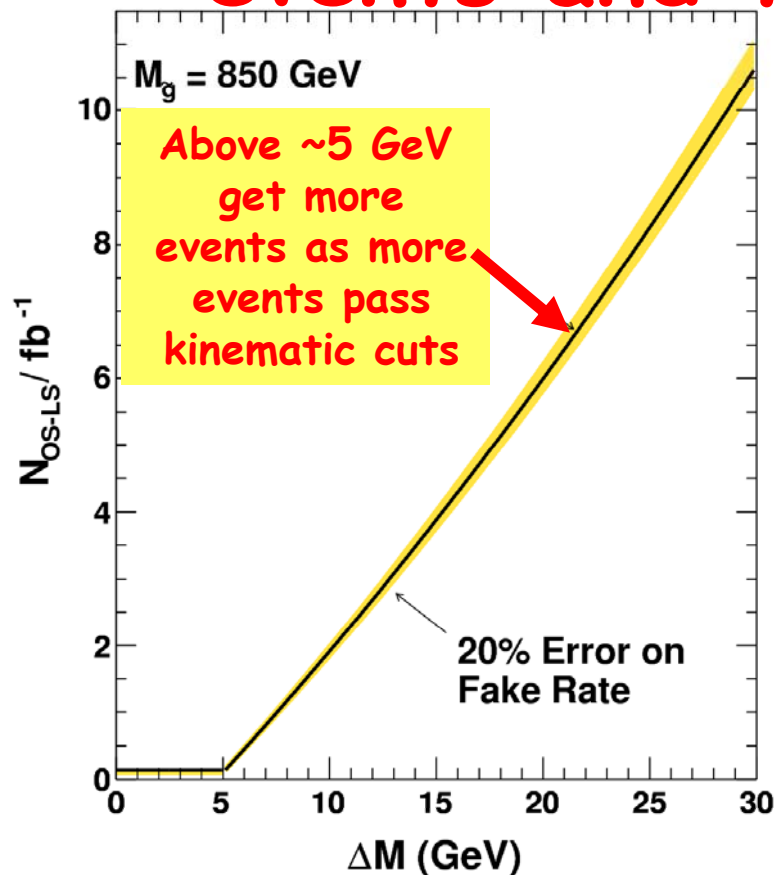






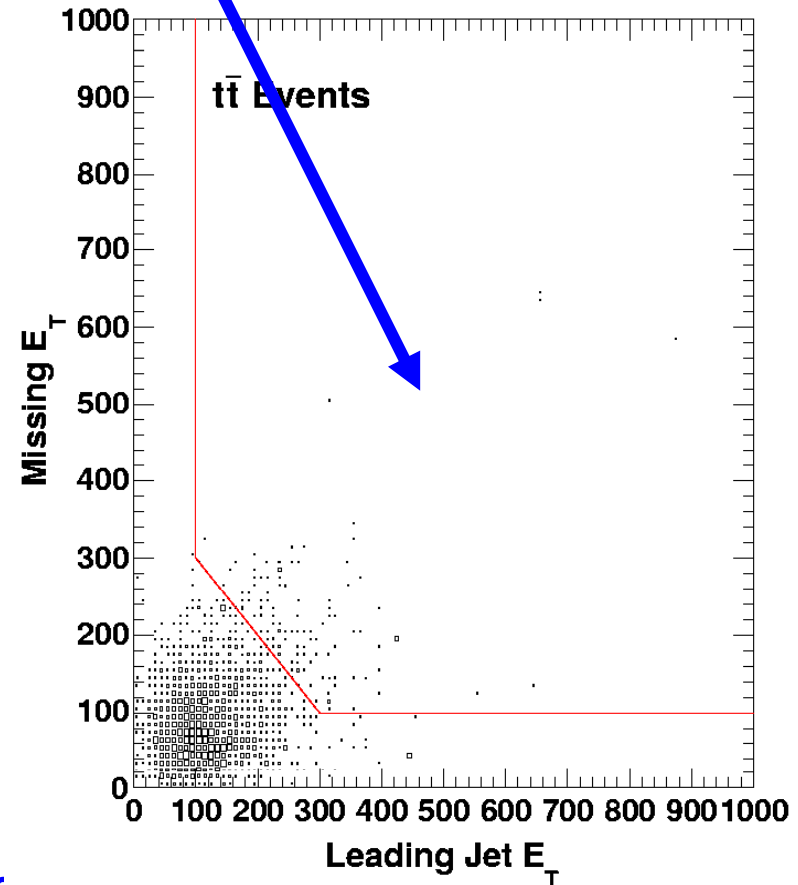
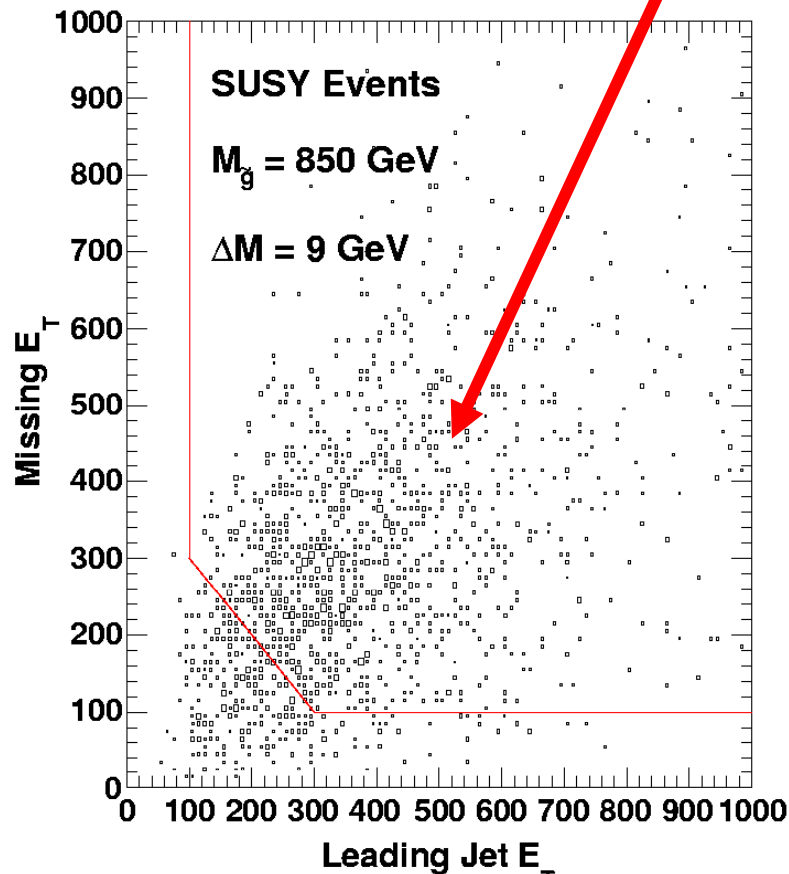
Discovery Luminosity

Depends on the number of observable events and the sparticle masses



Some Technical Details


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

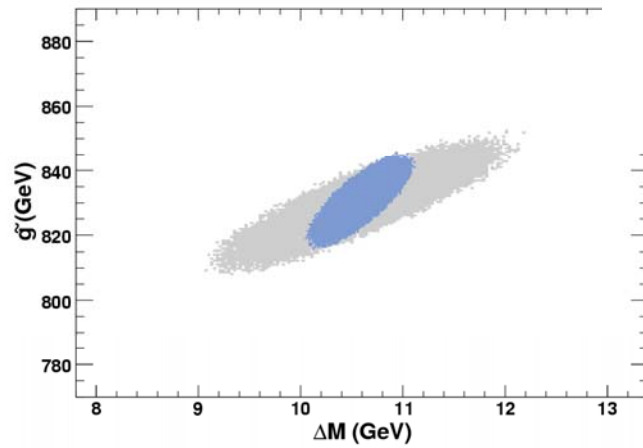
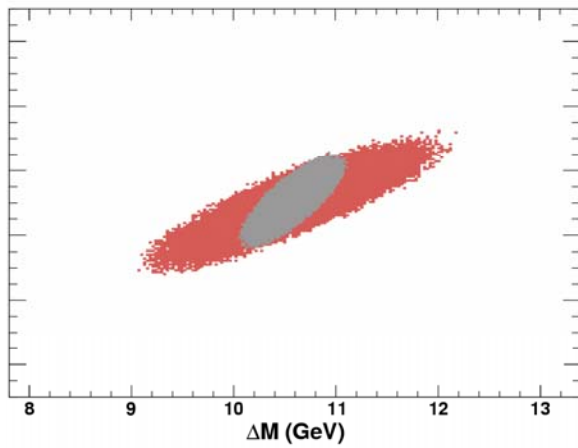
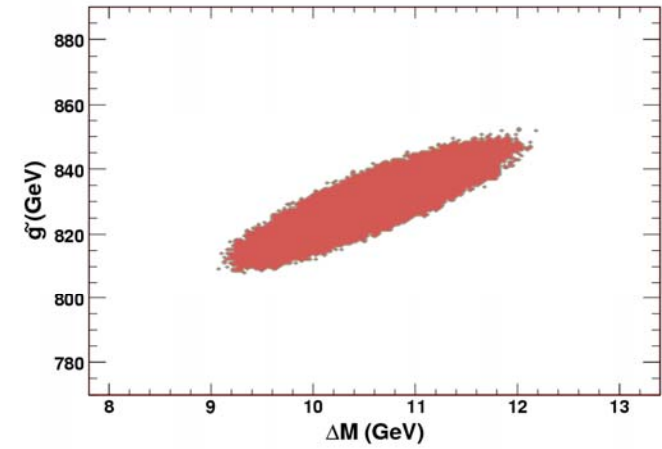
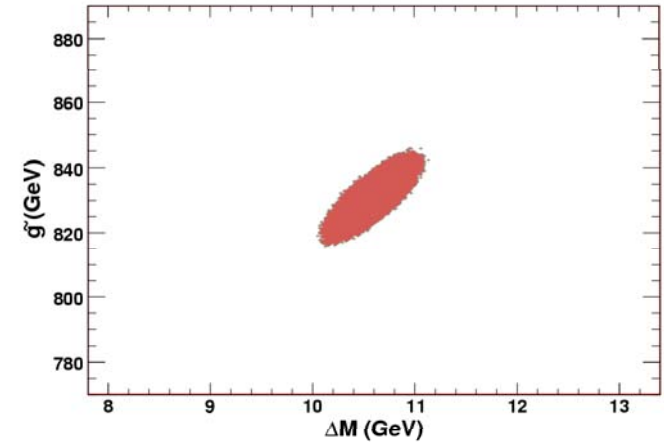


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- **Conclusions**

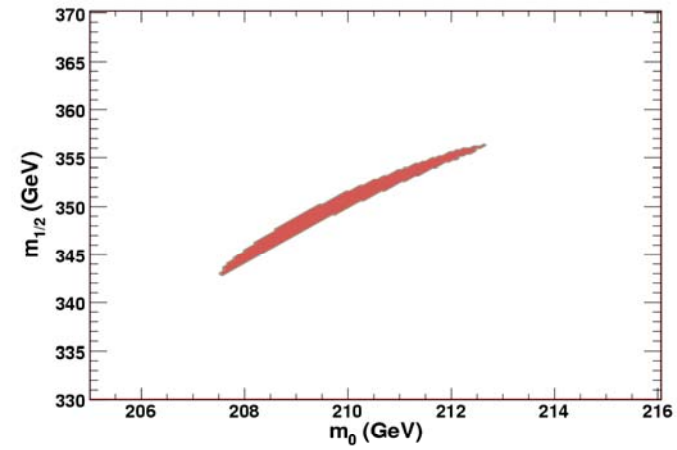
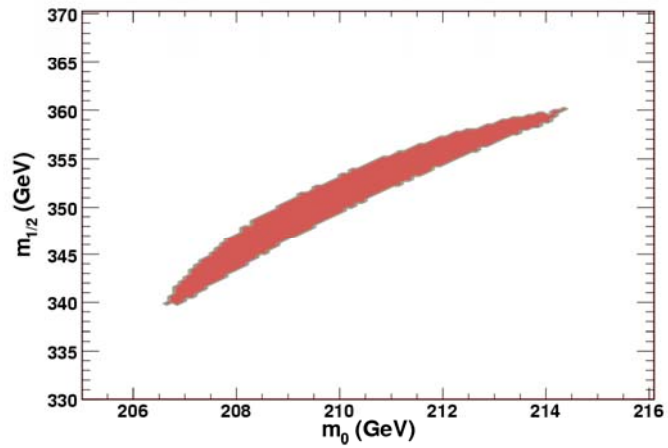
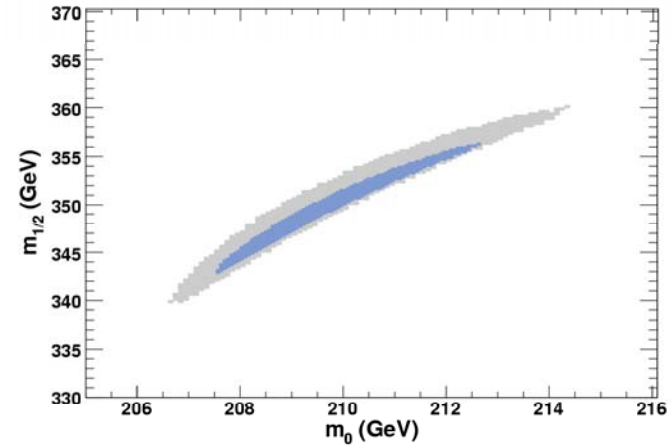


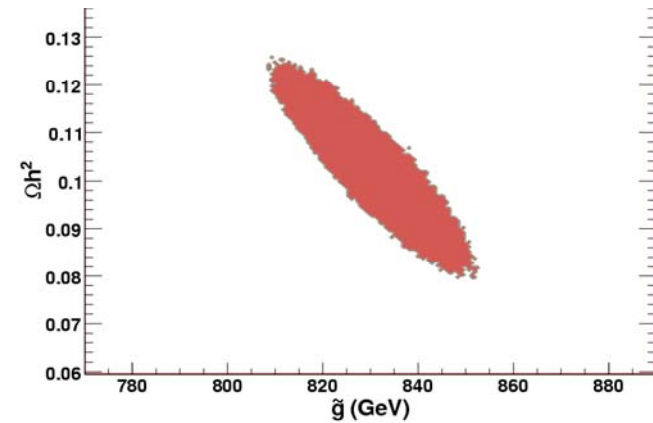
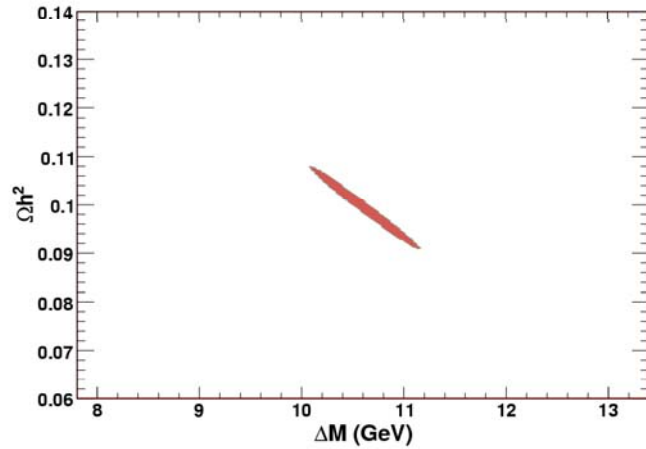
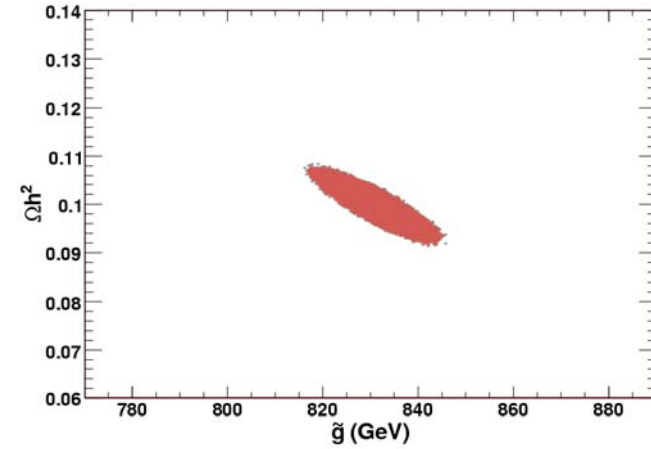
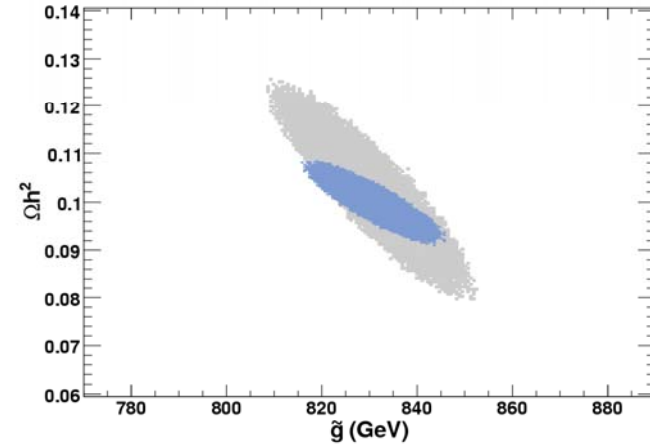
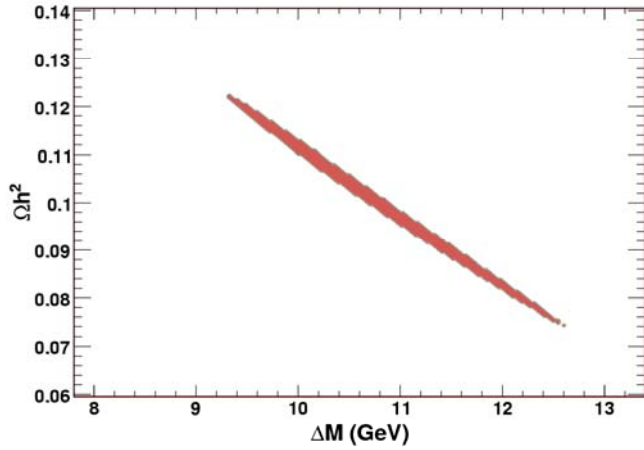
July 28th 2007

Dave Toback *et. al.*, Texas A&M University

LHC

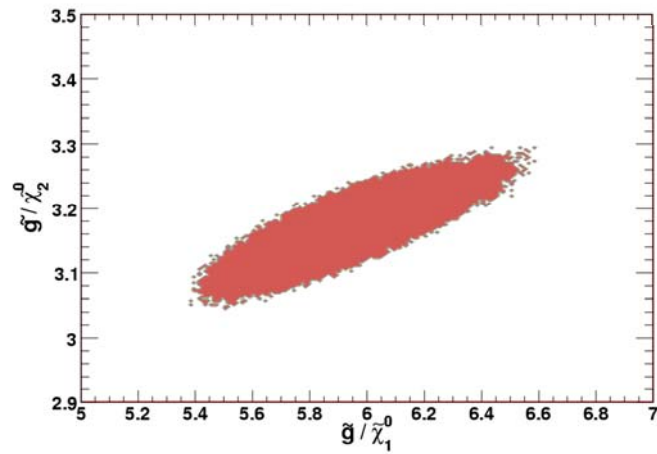
44





SUSY 2007
July 28th 2007

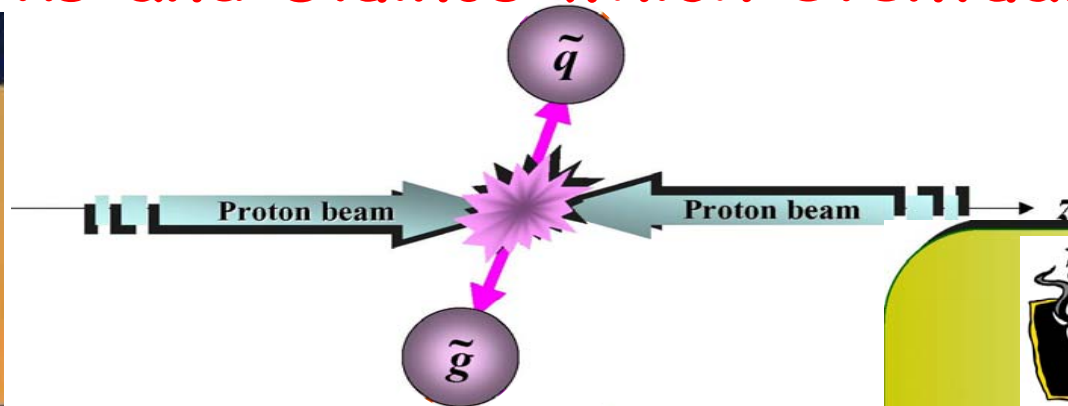
Dark Matter in SUGRA Models
Dave Toback *et. al.*, Texas A&



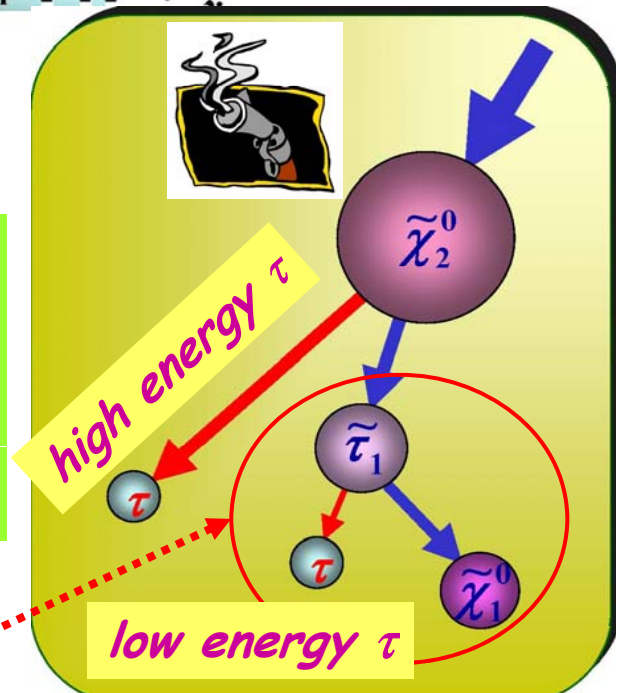
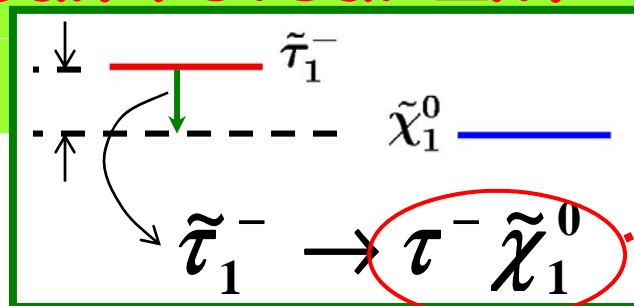


A Smoking Gun at the LHC?

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, 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



Highest SUSY Particle



Lightest Neutralino



$\tilde{\chi}_1^0$



Cold Dark Matter

Small $\tilde{\tau}$ Mass

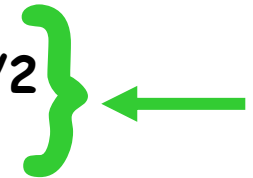
In mSUGRA models the mass of the lightest $\tilde{\tau}$ can be close to the $\tilde{\chi}_1^0$ mass because of the Renormalization Group Equations (RGEs) for small m_0

For small mass difference we can get the right relic density

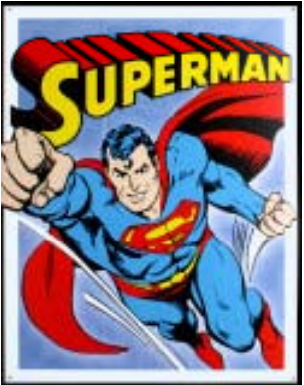
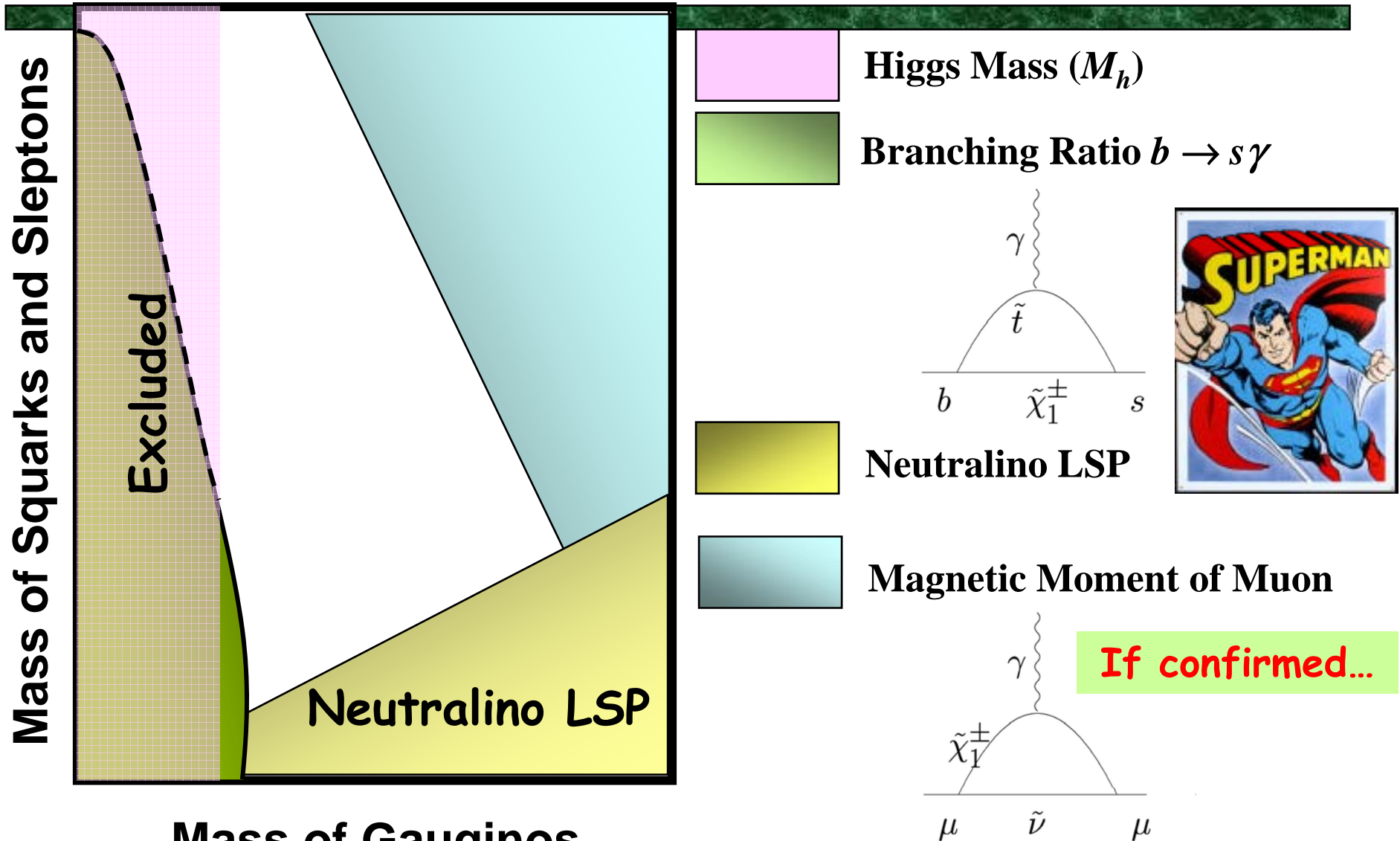
$$\begin{aligned}\Delta M &\equiv M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} \\ &= 5 \sim 15 \text{ GeV}\end{aligned}$$

Outline

- **Supersymmetry and the Co-annihilation region**
 - The important experimental constraints
 - A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\text{LSP}}$
- **Identifying events at the LHC**
 - Discovery and Experimental Observables
- **Measurements of**
 - Particle masses: ΔM , M_{Gluino} & M_{χ_2}
 - Supersymmetry parameters: M_0 and $M_{1/2}$
 - Cosmological implications: $\Omega_{\text{LSP}} h^2$
- **Conclusions**



Particle Physics Constrained Region



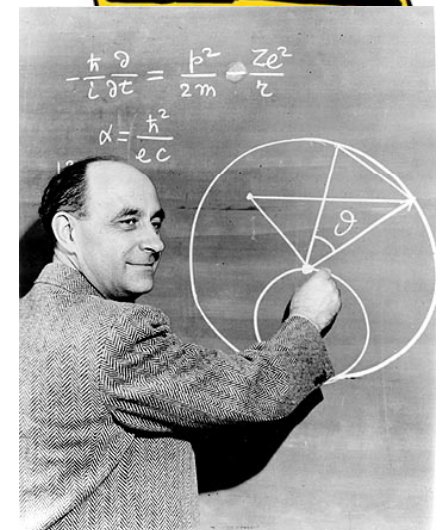
What if the Co-Annihilation Region is realized in Nature?

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?



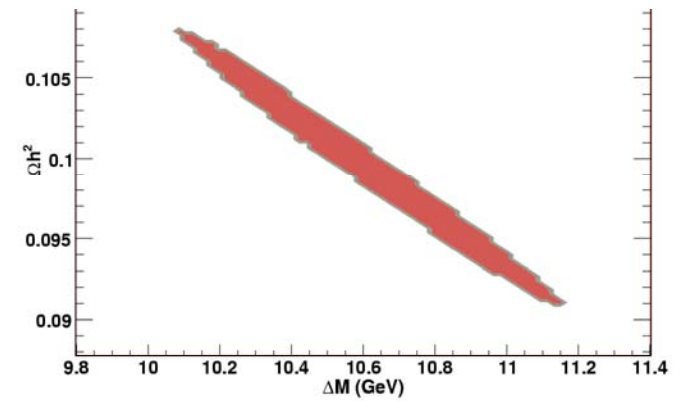
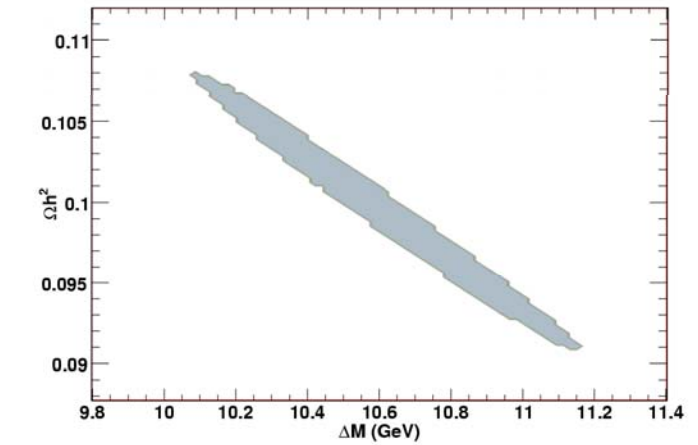
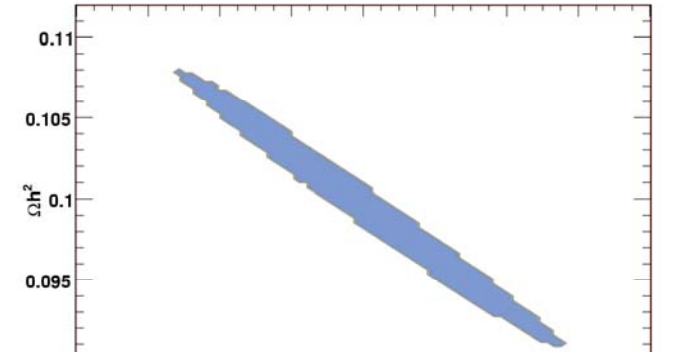
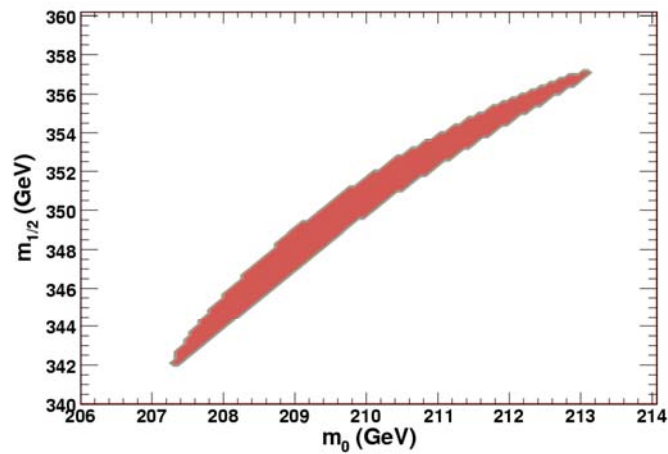
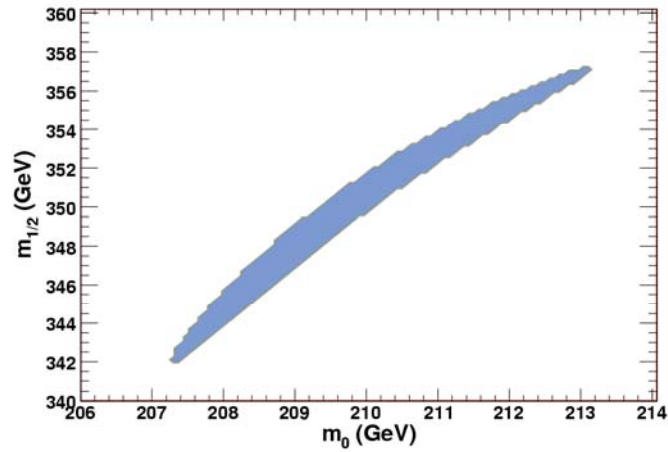
Aside on our Assumptions...

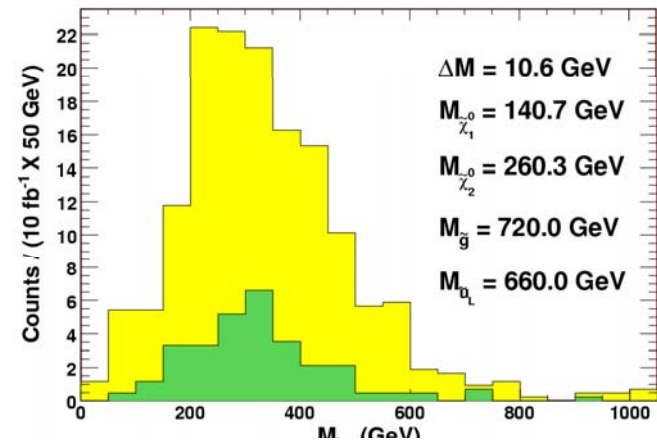
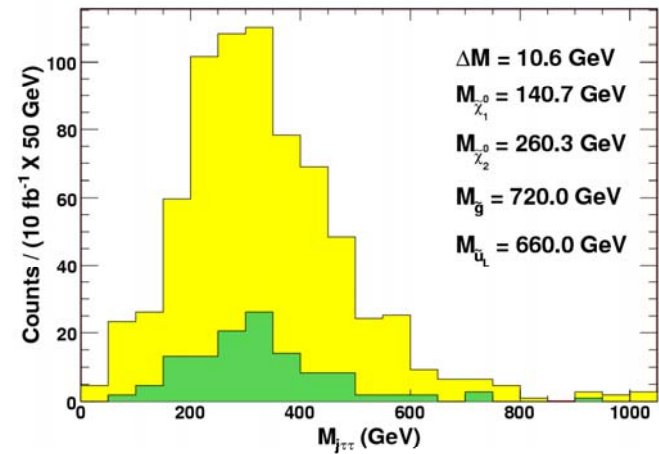
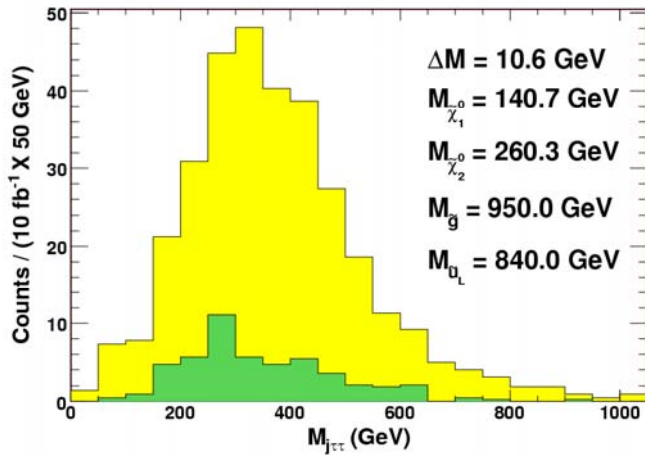
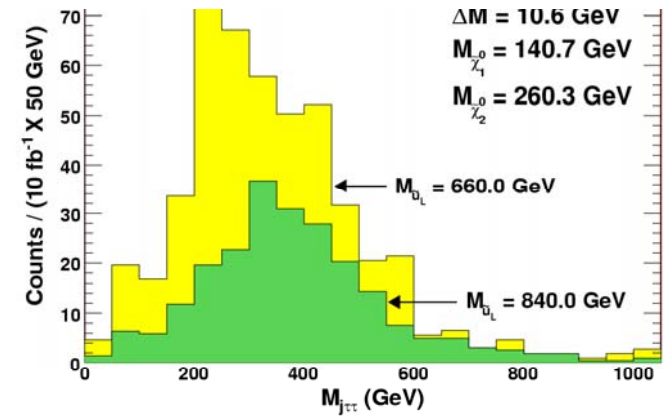
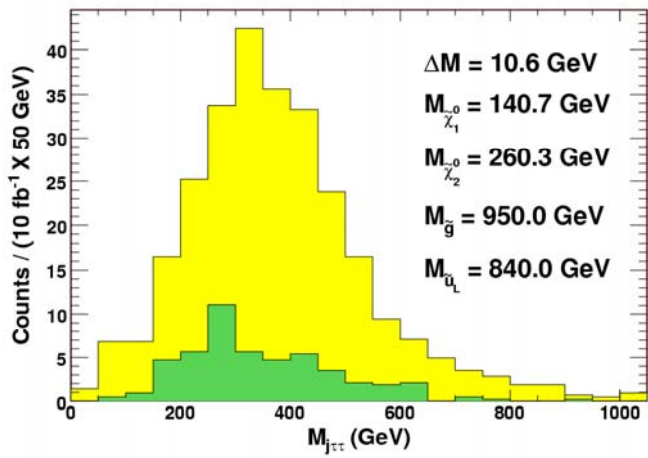
The WMAP constraints limits the parameter space to 3 regions that should all be studied:

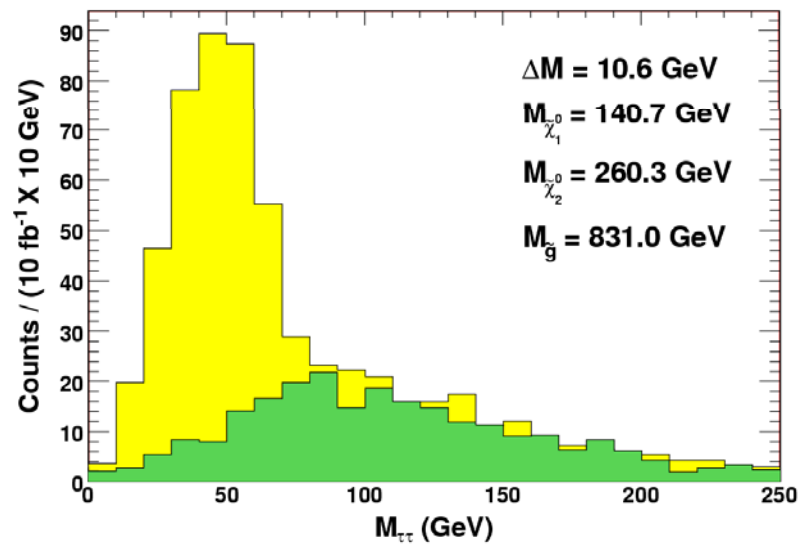
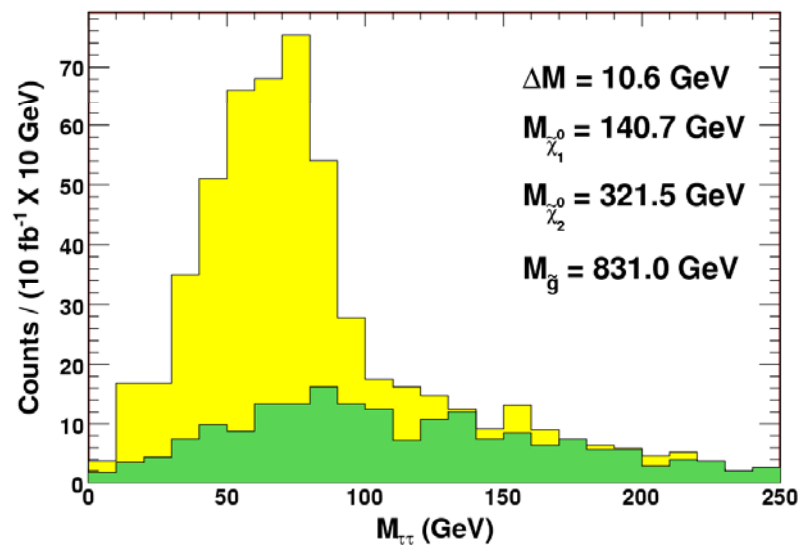
1. The stau-neutralino co-annihilation region

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

Concentrate on this region for the rest of this talk...







Outline of the Talk

- **Co-annihilation Signals at the LHC**

- A Smoking Gun: Small $\Delta M = M_{\text{stau}} - M_{\tilde{\nu}_\tau}$

- **Experimental Observables and Discovery**



- **Measurements**

- Particle masses: ΔM , M_{Gluino} , M_{χ_2} , M_{χ_1}

- Supersymmetry parameters: M_0 and $M_{1/2}$

- Do we live in a mSUGRA model?

- Cosmological implications

- **Conclusions**

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

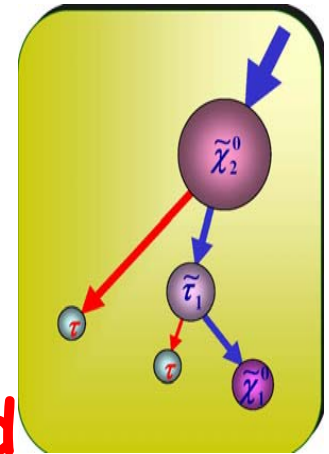
-
- Combine next two
 - Sample of χ^2 , not just any tau will do

Not just any τ will do!



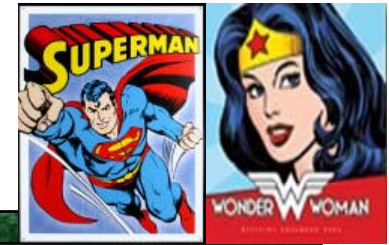
Our τ 's are special!

1. χ_2 decays produce a pair of opposite sign τ 's
 - Many SM and SUSY backgrounds, jets faking τ 's will have equal number like-sign as opposite sign
2. Each χ_2 produces one high energy τ and one low energy τ
3. The invariant mass of the τ -pair reflects the mass of the SUSY particles and their mass differences

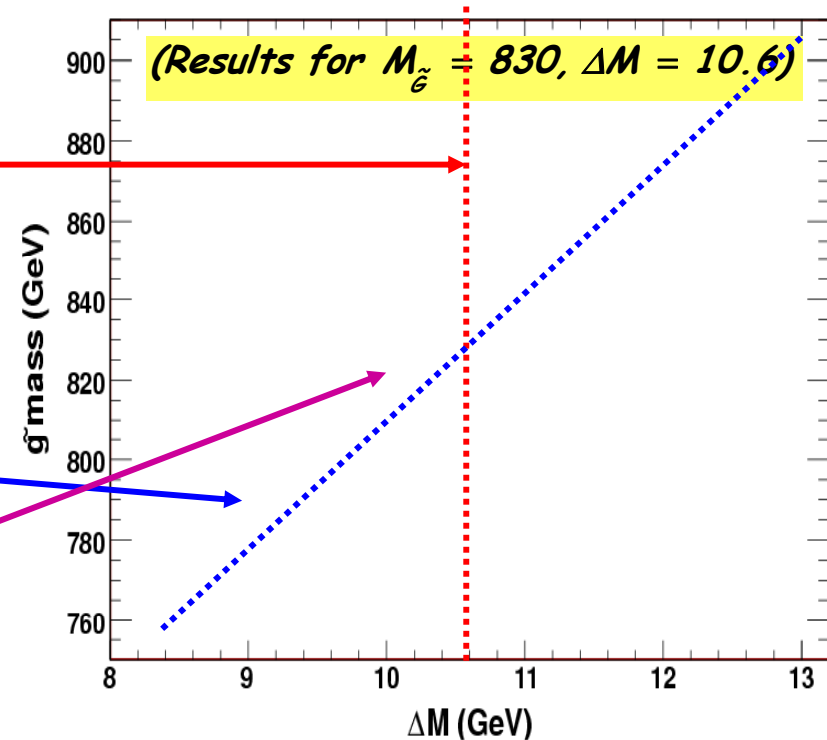


$$M_{\tau\tau} \propto M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}}$$

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

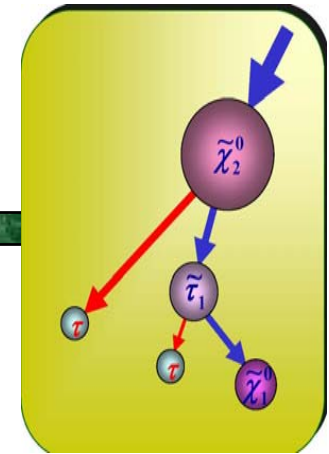


An important measurement without Universality assumptions!

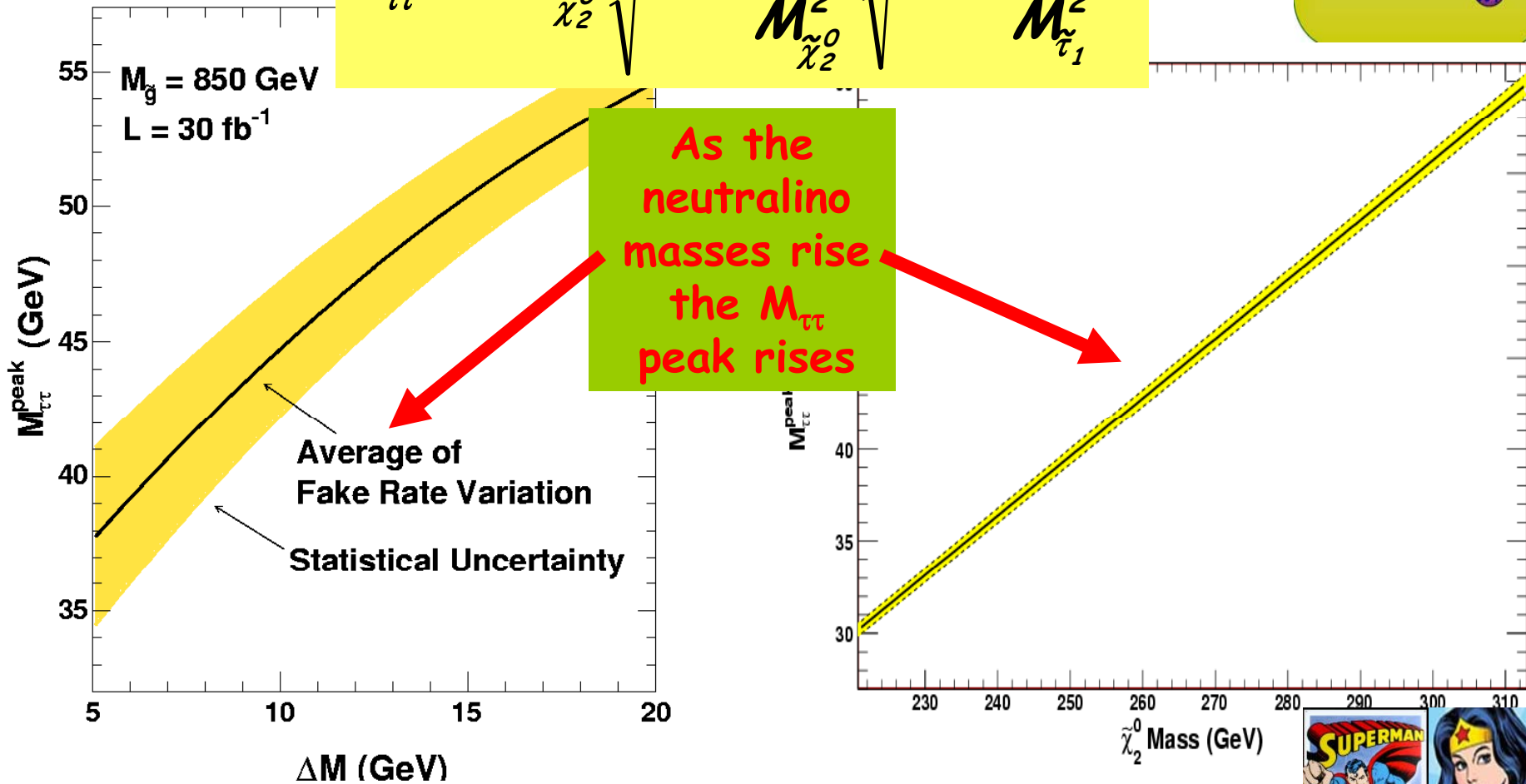
Results for ~ 300 events (10 fb^{-1} depending on the Analysis)



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



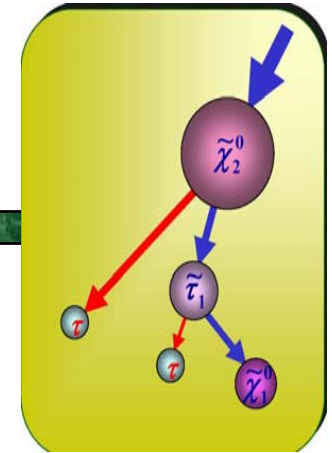
$$M_{\tau\tau} \propto M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}}$$



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



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

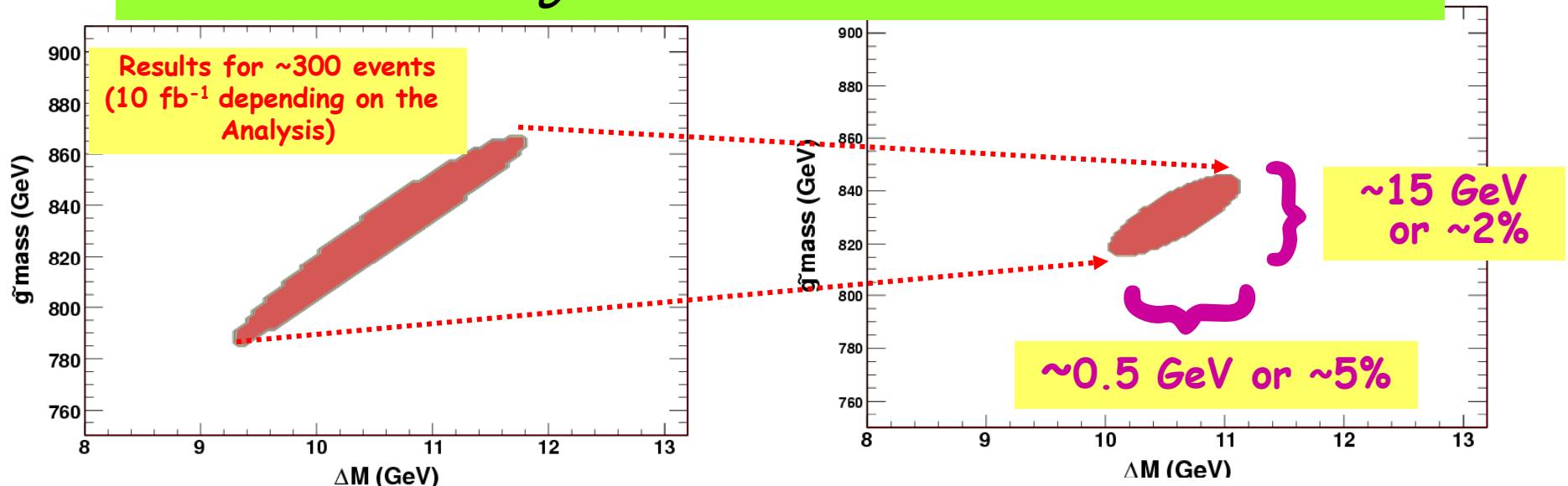


As the
squark mass
rises the
 $M_{j\tau\tau}$ peak
rises



What if we Assume the Universality Relations?

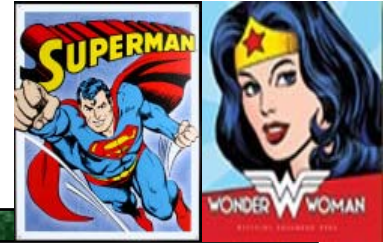
Use Events, $M_{\tau\tau}$ and Slope to measure ΔM , $M_{\tilde{g}}$ and $M_{\tilde{\chi}_2^0}$ simultaneously
 (Results for $M_{\tilde{G}} = 830 \text{ GeV}$, $\Delta M = 10.6 \text{ GeV}$)



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

Measuring the SUSY Masses



For our sample of events we can make four measurements

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

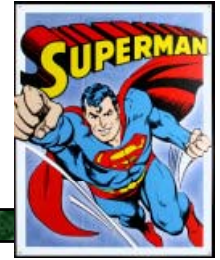
Since we are using 4 variables, we can measure 4 things

Since A , $\tan\beta$ and $\text{sign}(\mu)$ don't change the phenomenology much (for large $\tan\beta$) we choose to use our three variables to determine ΔM , M_{gluino} and the χ_2 and χ_1 Masses

Model parameters

Universality Test

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!