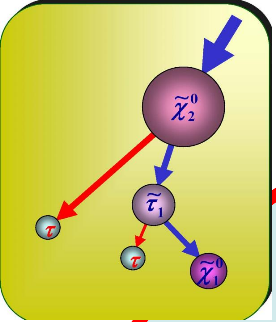


Dark Matter in SUGRA Models and the LHC

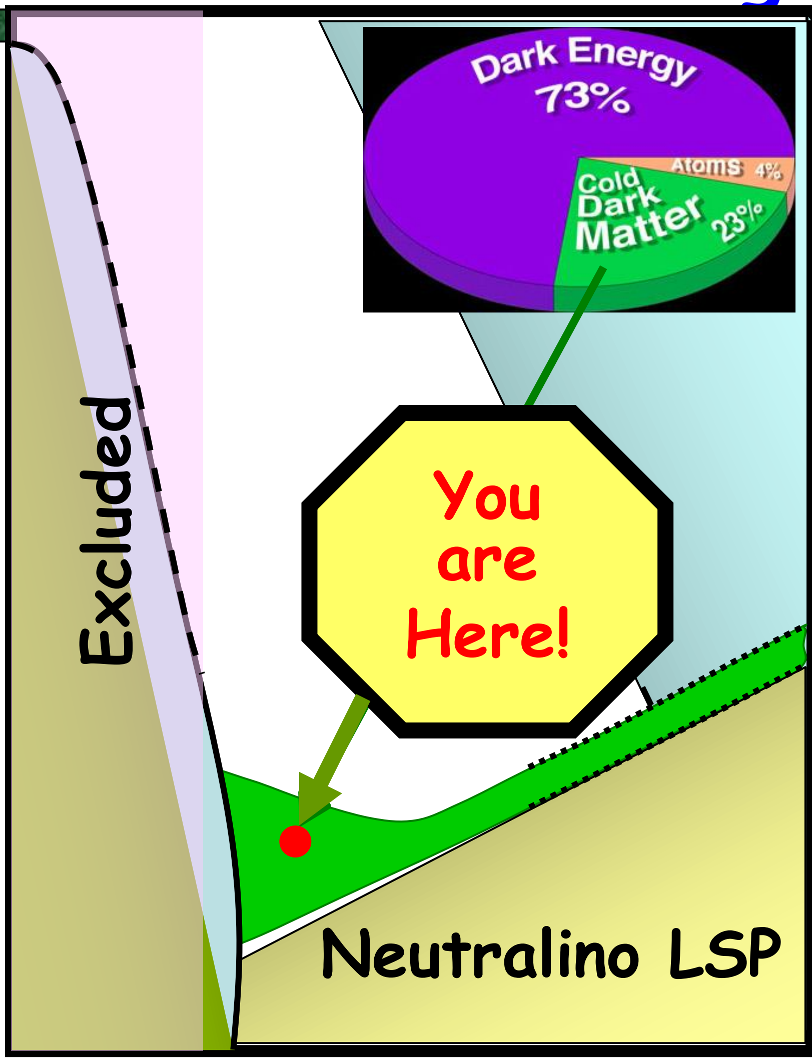
R. Arnowitt, A. Aurisano, B. Dutta, A. Gurrola, T. Kamon, A. Krislock, N. Kolev*, P. Simeon, D. Toback & P. Wagner

Department of Physics, Texas A&M University

*Department of Physics, Regina University

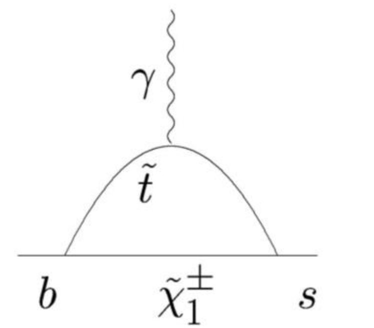
Experimental Constraints on mSUGRA at Large tanβ

Wanted:



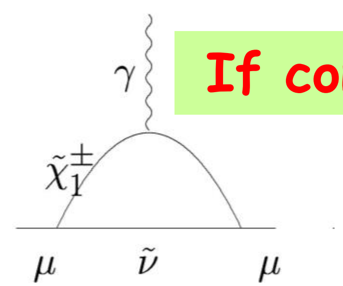
Higgs Mass (M_h)

Branching Ratio $b \to s\gamma$



Magnetic Moment of Muon

If confirmed…

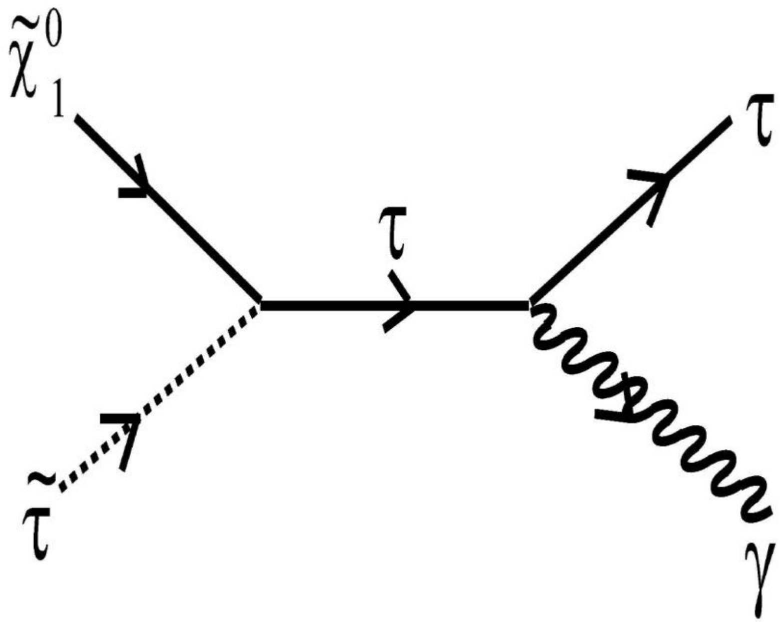


WMAP Dark Matter Favored region

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: ΔM, M_{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

$M_0 = 210\ GeV$

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

$\tan\beta = 40$

$A_0 = 0$

$Sgn(\mu) > 0$

Doesn't affect the phenomenology much after tanβ>15

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

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

$M_{\tilde{\tau}} = 151.2\ GeV$

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

ΔM=10.6 GeV

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

mSUGRA

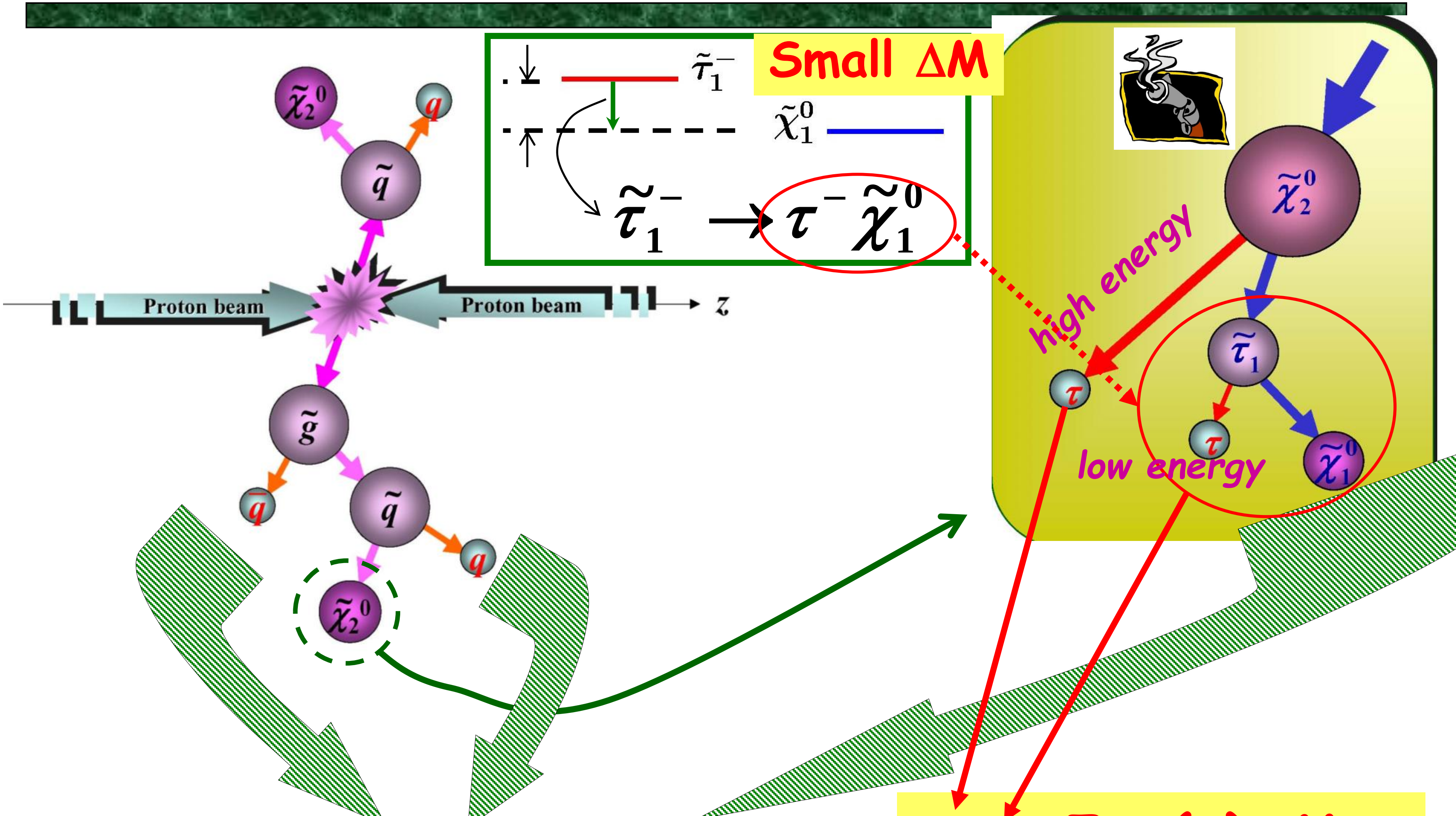
Universality Constraints:

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

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

Want to measure these two values and test these two relations

Identifying Events at the LHC



Trigger on the jets and missing E_T

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

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

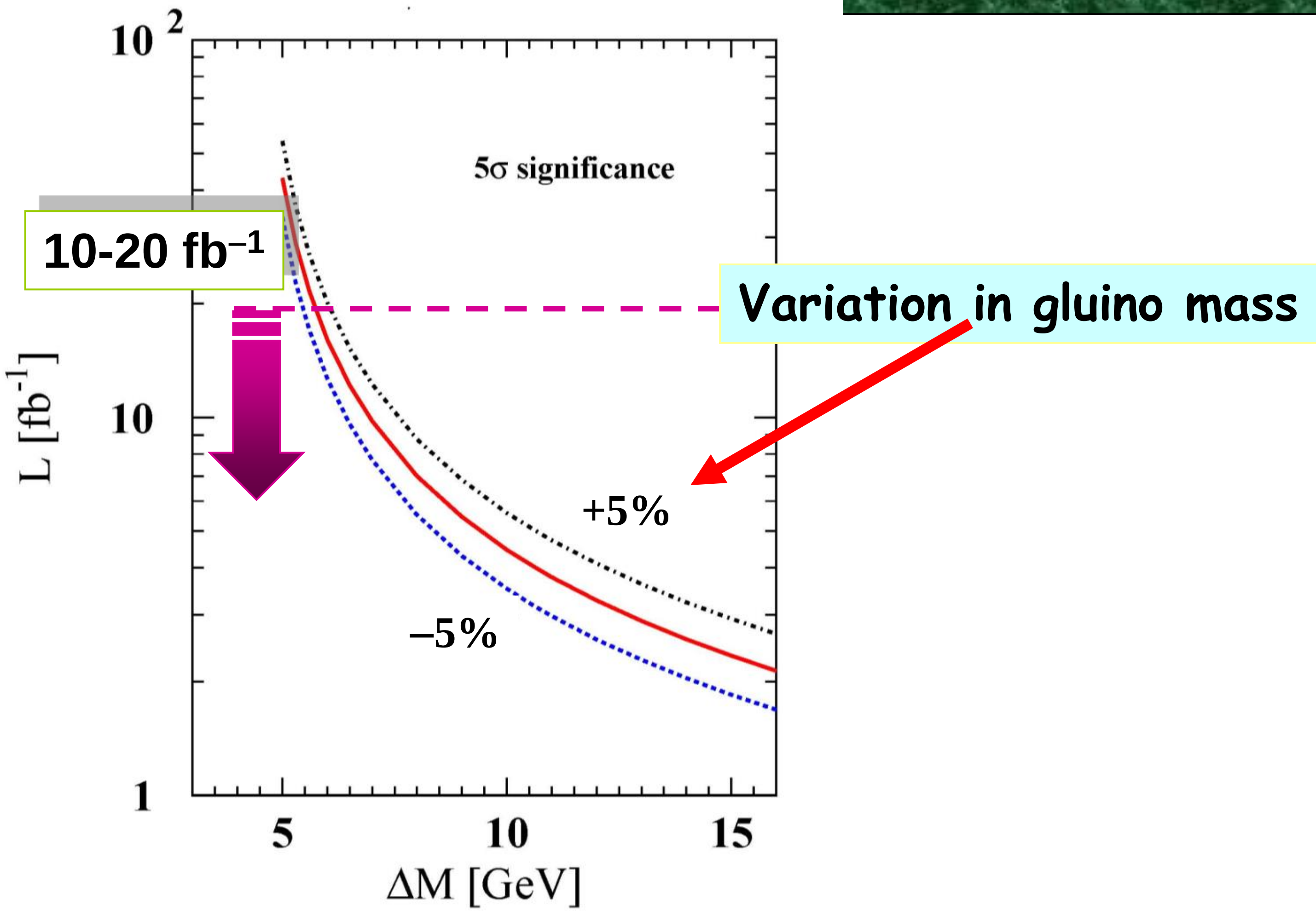
The dominant background is typically ttbar, so we require an extra object and large kinematics to reject it

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

More details in

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

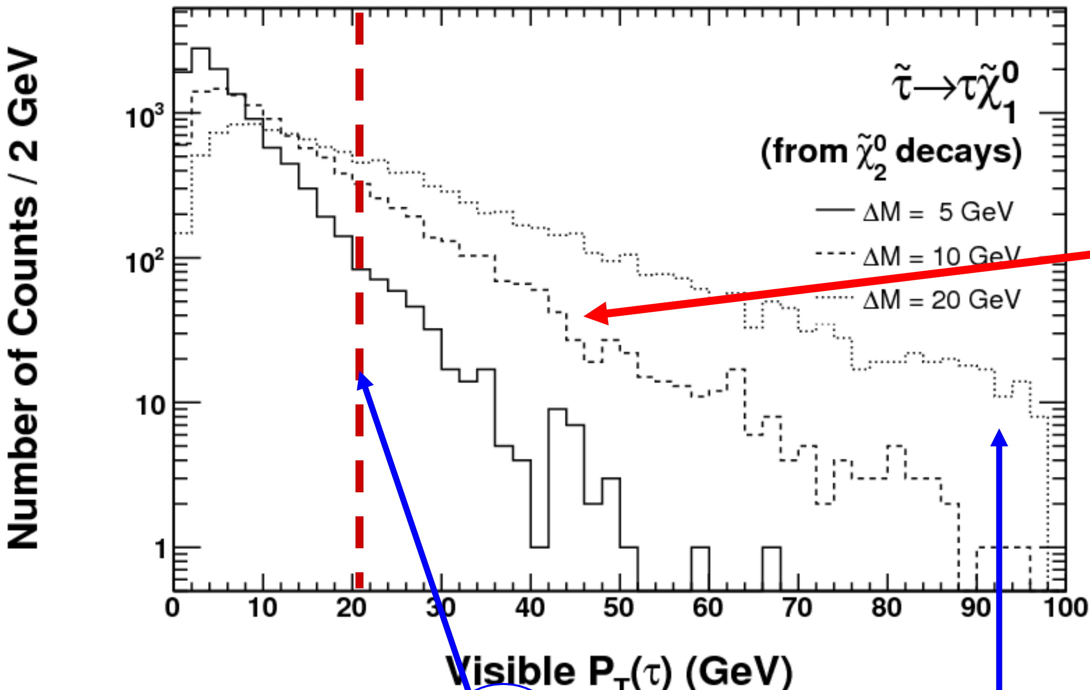
Discovery Luminosity



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

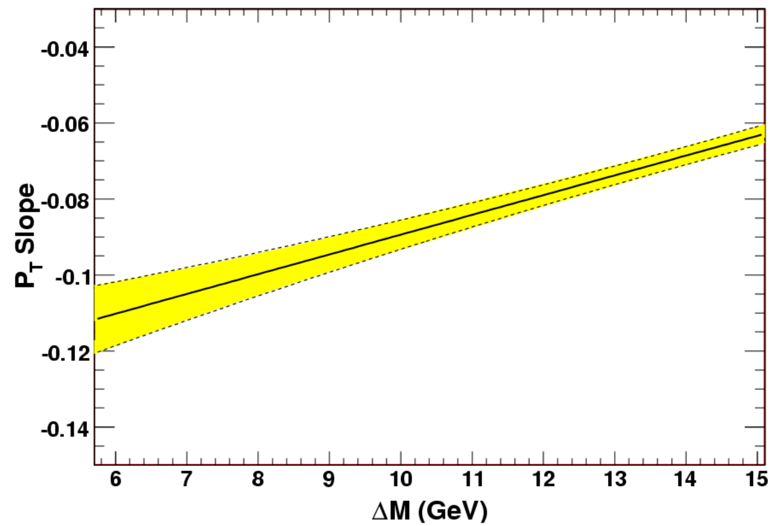
$$\tilde{\tau} \rightarrow \boxed{\tau}\ \tilde{\chi}_1^0$$



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

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

Independent variable: Get more events for large ΔM



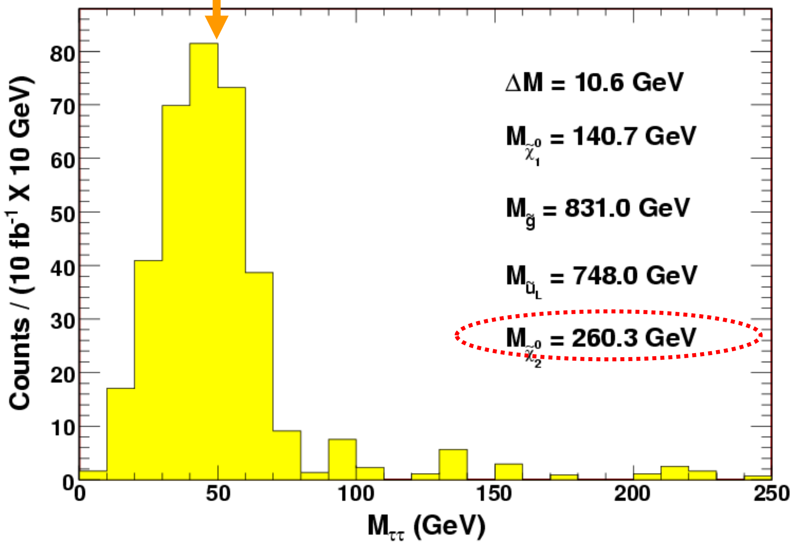
Slope of P_T distribution is largely unaffected by Gluino Mass

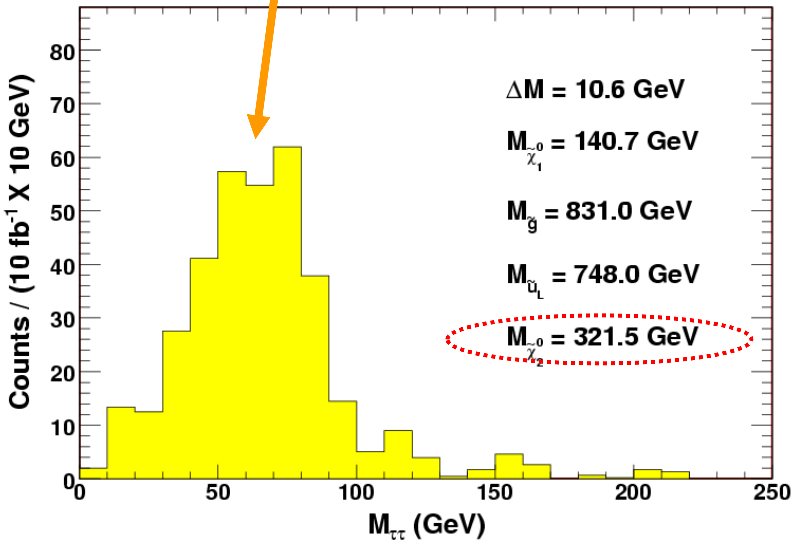
More Observables

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

Clean peak
Even for low
ΔM

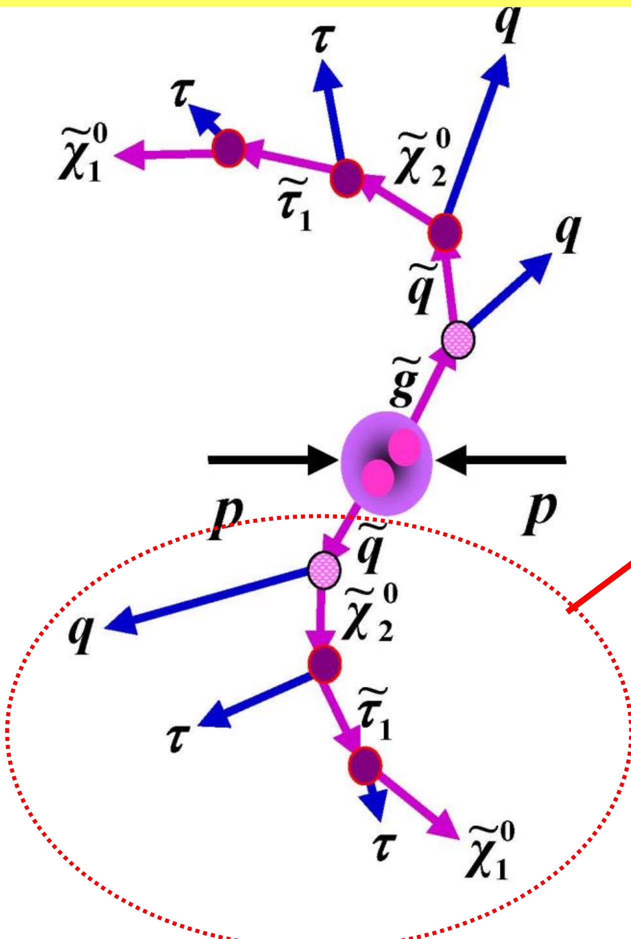
Larger $\tilde{\chi}_2^0$ Mass → Larger $M_{\tau\tau}$

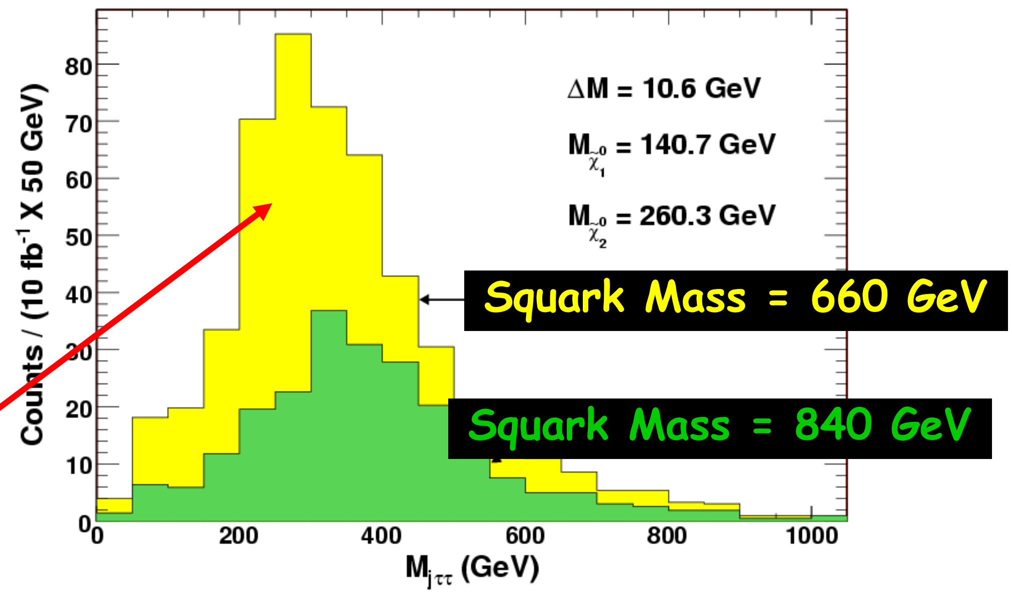




Another Mass Peak

$\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow q\tau\tau\tilde{\chi}_2^0$ 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_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

Make Simultaneous Measurements

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

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

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

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

← Equivalent → Measurements

$M_0 = 210$ GeV

$M_{1/2} = 350$ GeV

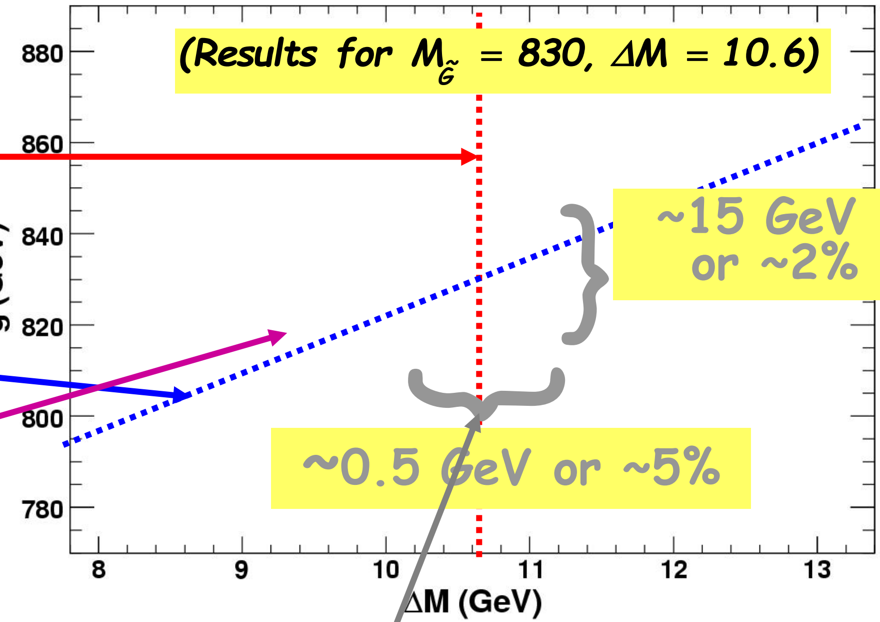
$M_{\tilde{\chi}_2^0} \sim 0.32\, M_{\tilde{g}}$

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

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

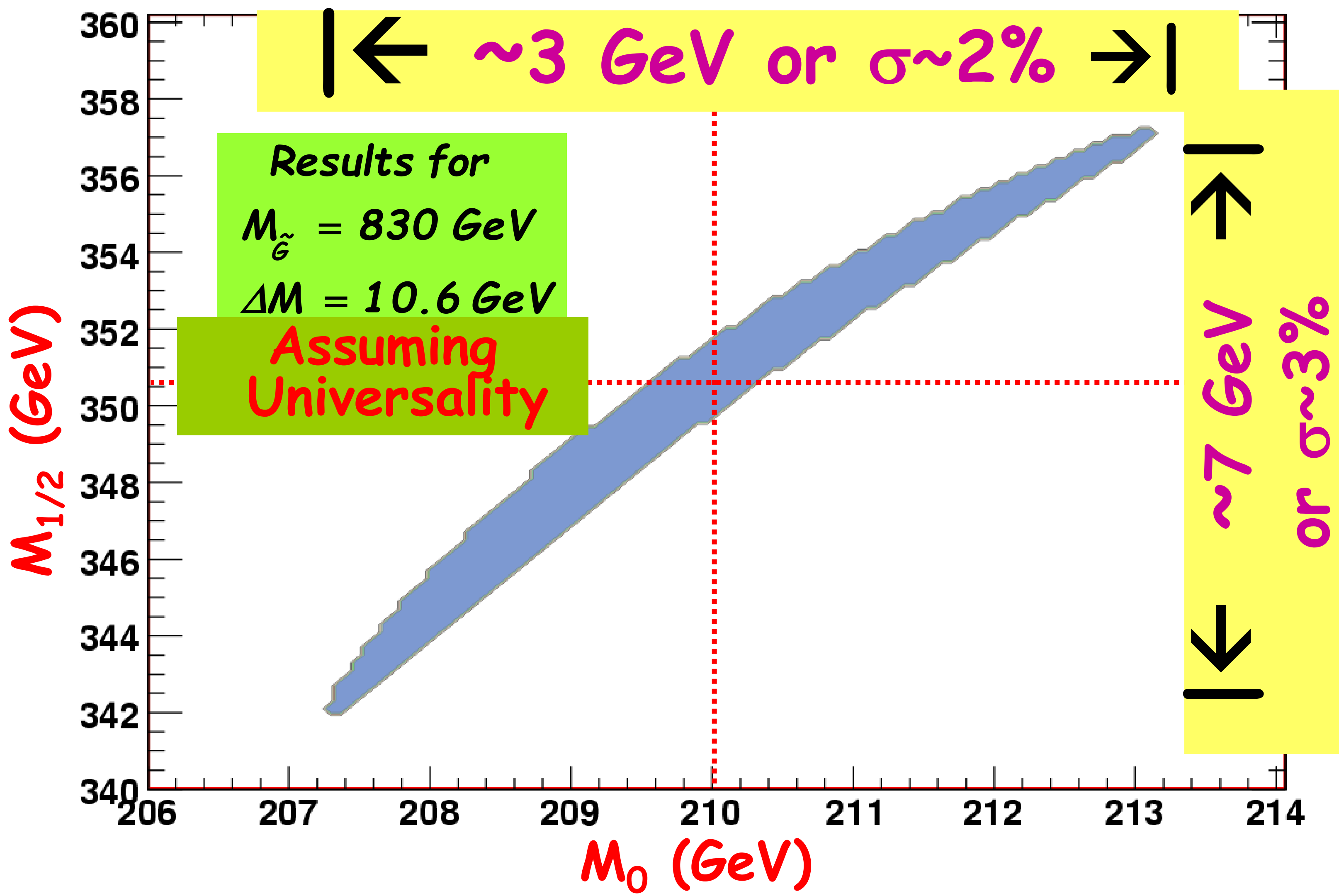


Results for ~300 events
(10 fb^{-1} depending on the Analysis)

An important measurement without Universality assumptions!

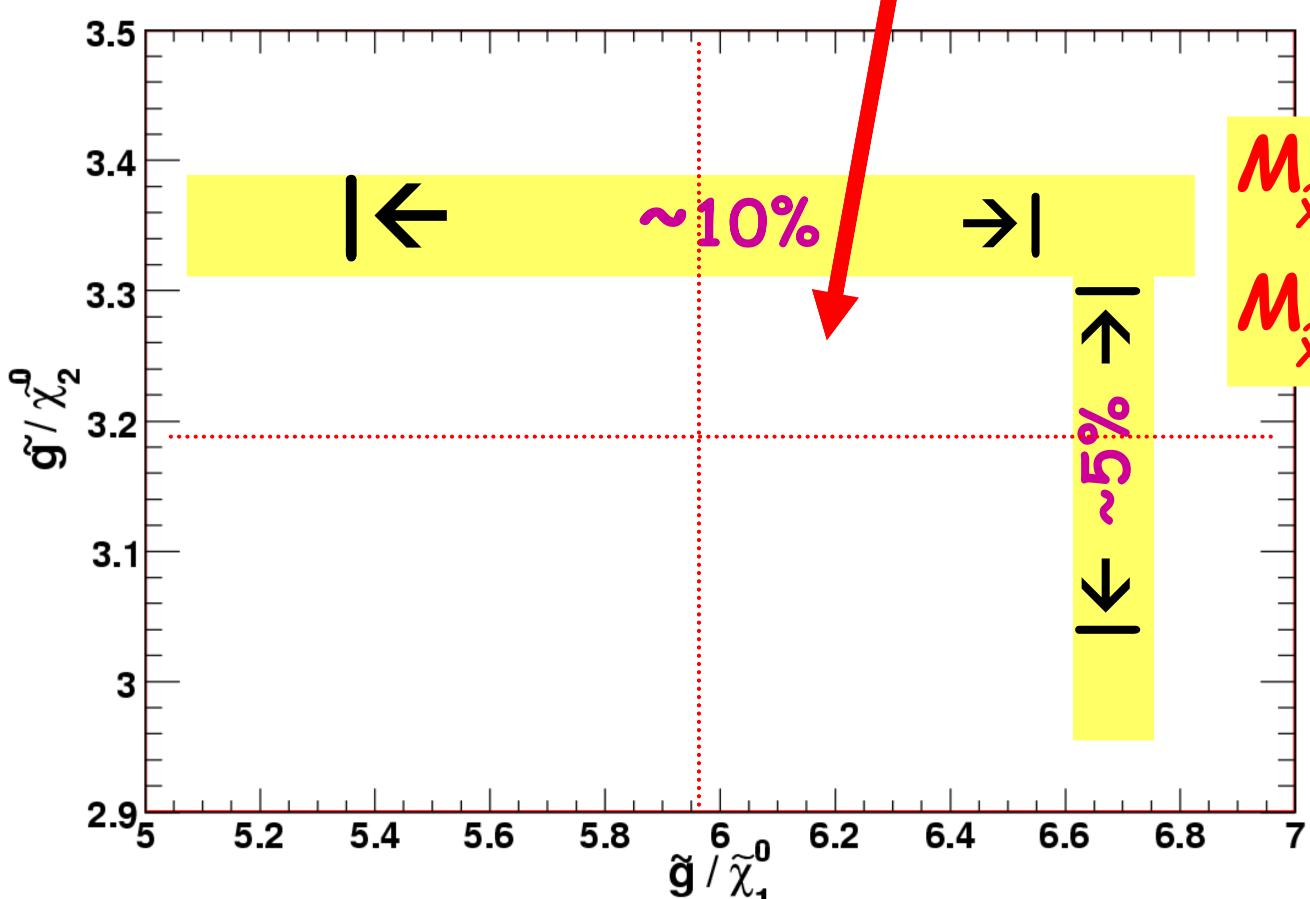
Assuming the Universality Constraints Improves the Measurement

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



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

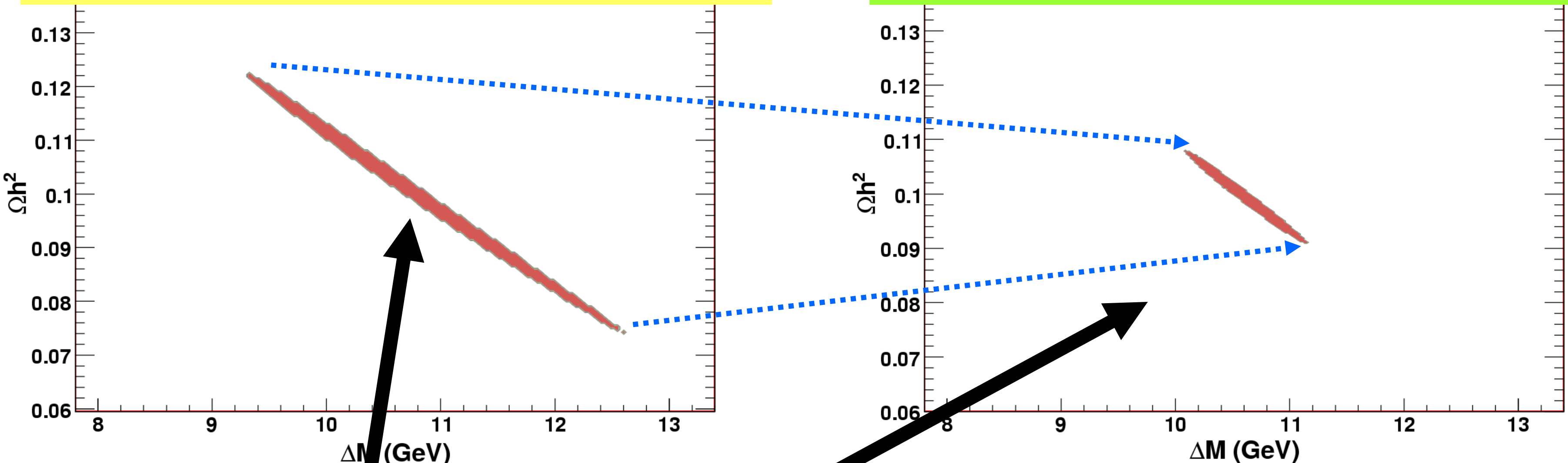
$M_{\tilde{\chi}_1^0} \sim 0.17 M_{\tilde{g}}$

Cosmology Measurements

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

No Universality Assumptions
4 Observables and 4 Unknowns

With Universality Assumptions
4 Observables and 2 Unknowns



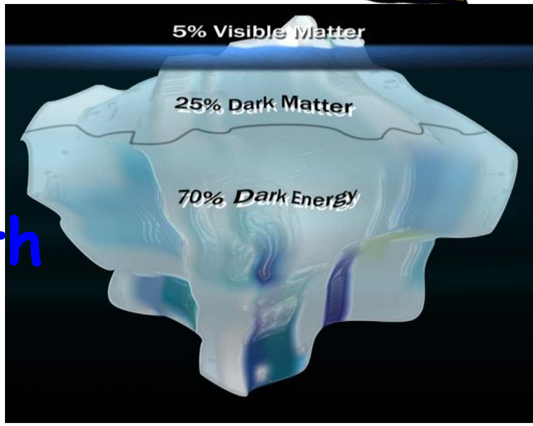
20% *10%*

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

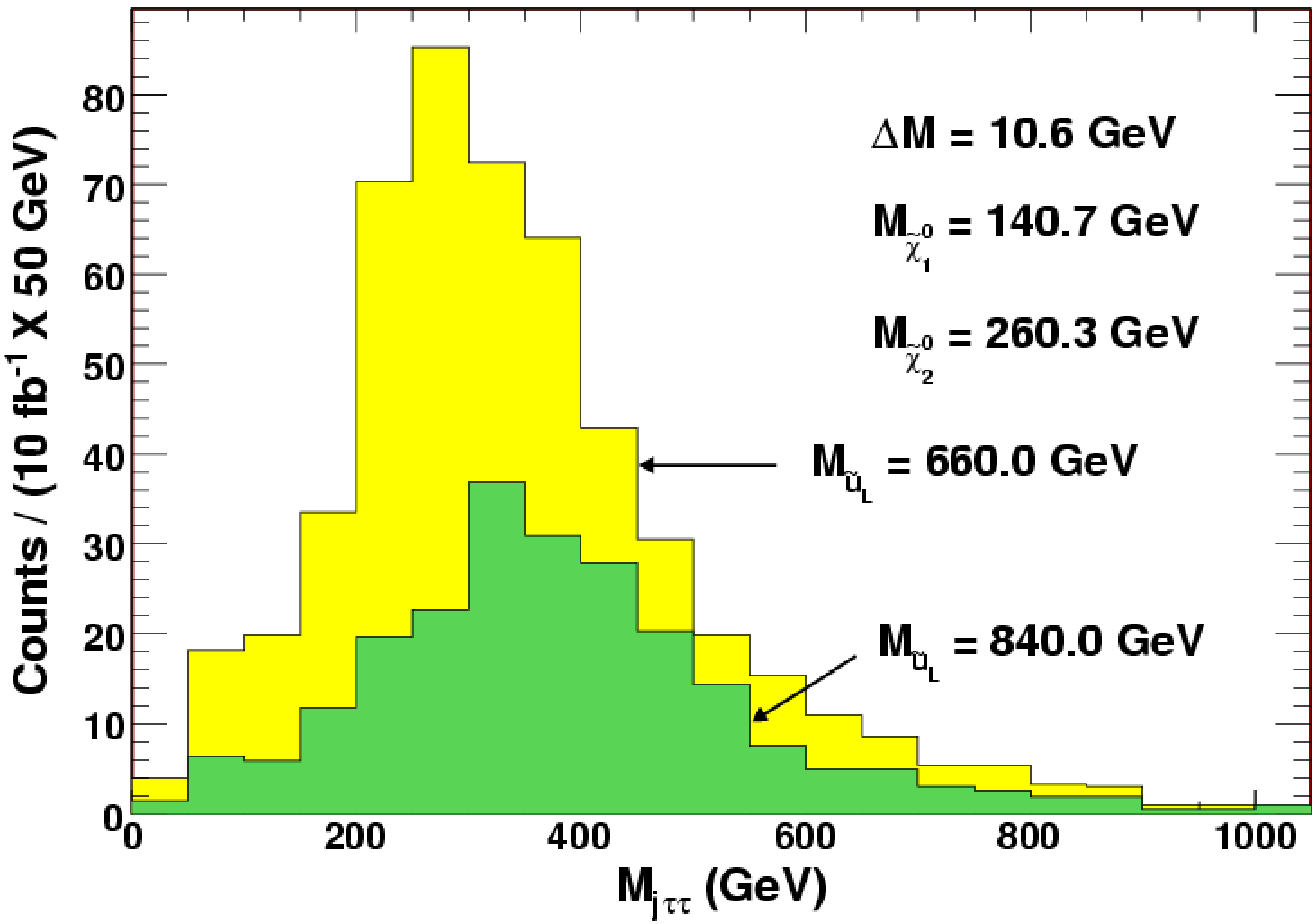


- The LHC should be able to uncover the striking small-ΔM signature with ~10 fb^{-1} of data in multi-τ final states and make high quality measurements with the first few years of running

- 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

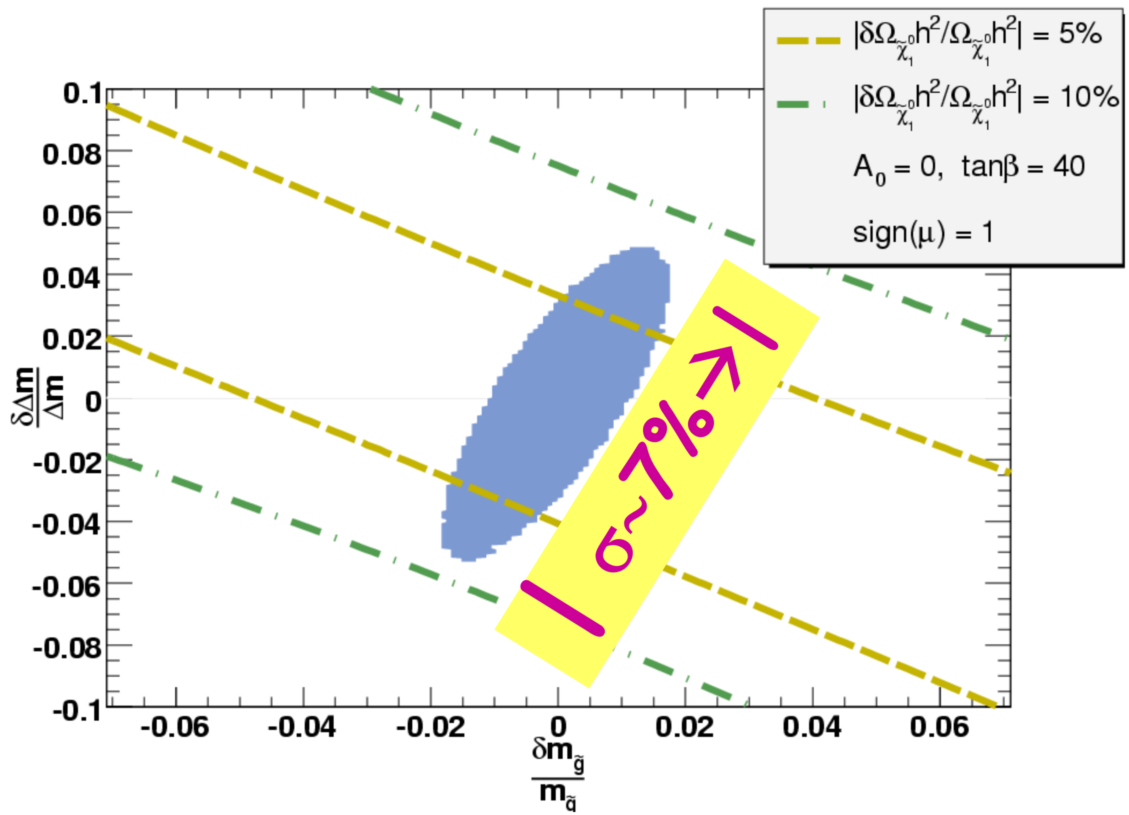
1	Title
2	Intro with Physics Goals
3	Outline and Overview of Analysis Methods
4	Co-annihilatino and constraints
5	What are we trying to measure: 4 values in mSugra, Omegah2
6	Feynman diagrams and final state
7	Sample of Chi2, not any tau will do
8	Discovery Lum 1
9	Pt and Nevents, DeltaM and Mgluino variation
10	Chi2 mass and mtautau variation
11	Squark Mass and m(jtt) variation
12	4 observables and translation, new version of previous slide…
13	DeltaM vs Mgluino assuming Universalithy
14	M0 and M1/2
15	Test Universality: chi2 and chi1
16	Omega H2 in both
17	Conclusions

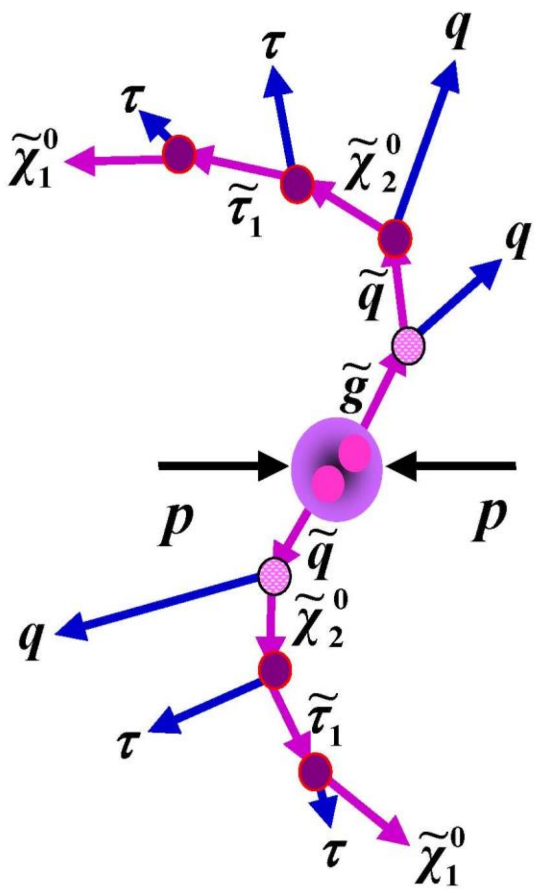

ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{u}_L}$ = 660.0 GeV
$M_{\tilde{u}_L}$ = 840.0 GeV
Counts / (10 fb^{-1} X 50 GeV)
$M_{j\tau\tau}$ (GeV)
0
10
20
30
40
50
60
70
80
0
200
400
600
800
1000

Cosmology Measurements

With the same assumptions we can use ΔM, $M_{\tilde{g}}$ to measure $\Omega_{\tilde{\chi}_1^0} h^2$ to 7%

(Compare to WMAP which is 5%)



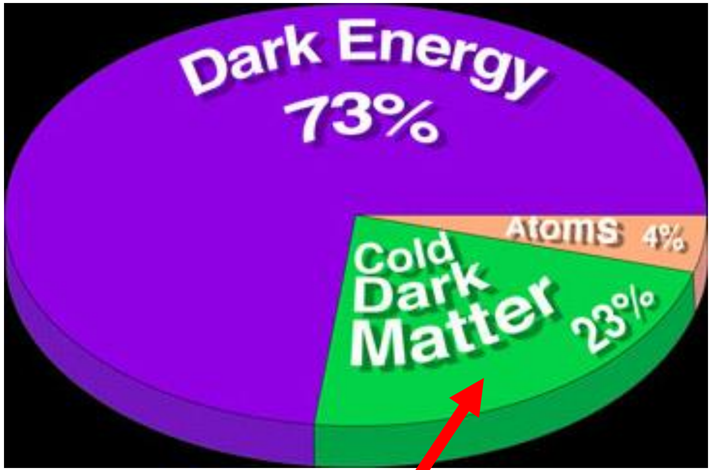


q
τ
τ
$\tilde{\chi}_1^0$
$\tilde{\chi}_2^0$
$\tilde{\tau}_1$
q
$\tilde{q}$
$\tilde{g}$
p
p
$\tilde{q}$
$\tilde{\chi}_2^0$
q
$\tilde{\tau}_1$
τ
τ
$\tilde{\chi}_1^0$

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

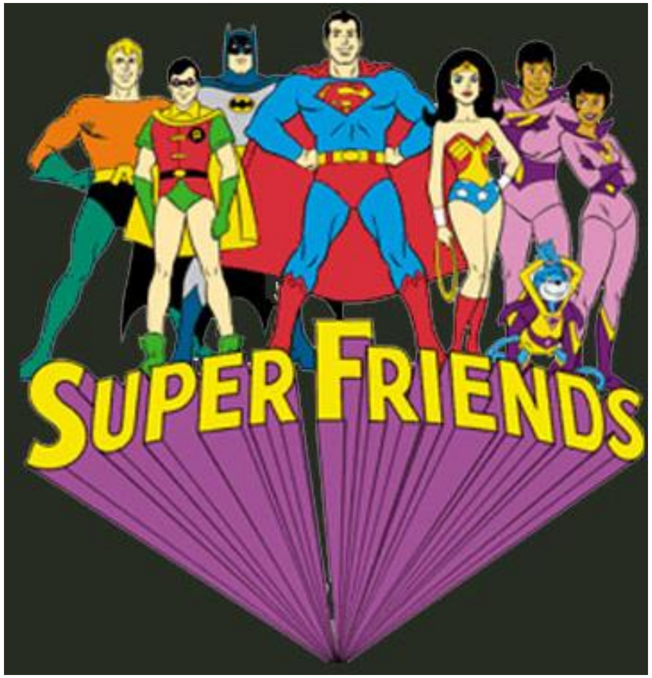
Cosmologists/ Astronomers

Particle Theorists

Particle Experimentalists

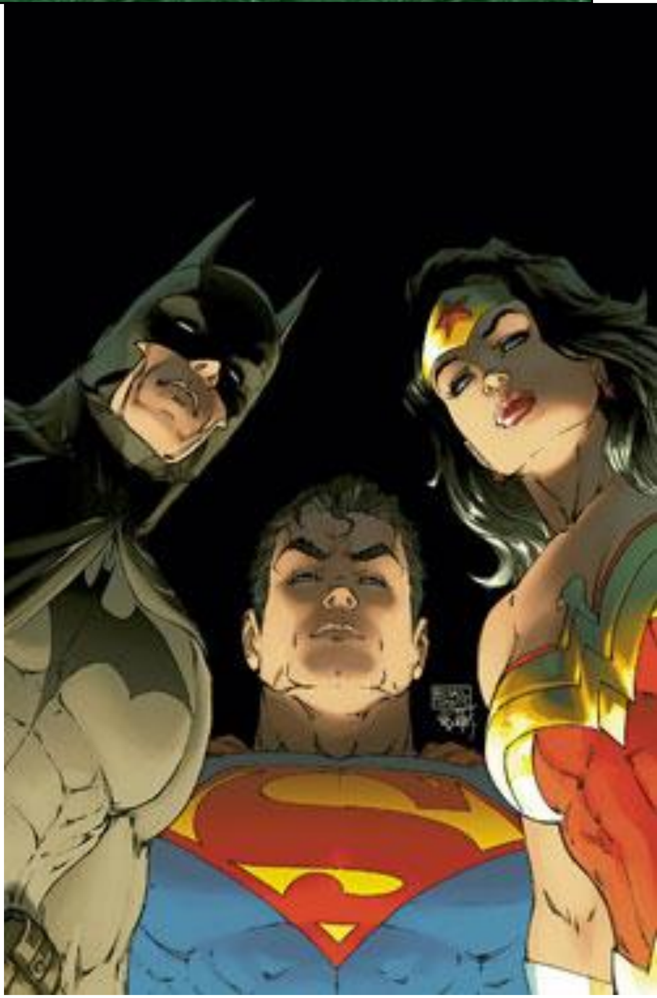
Structure of the Analysis

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

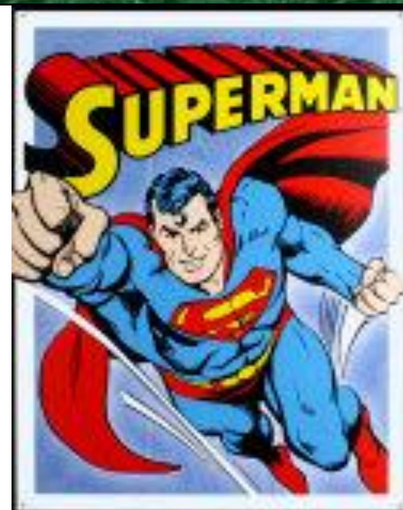


Hypothetical Timeline

- 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

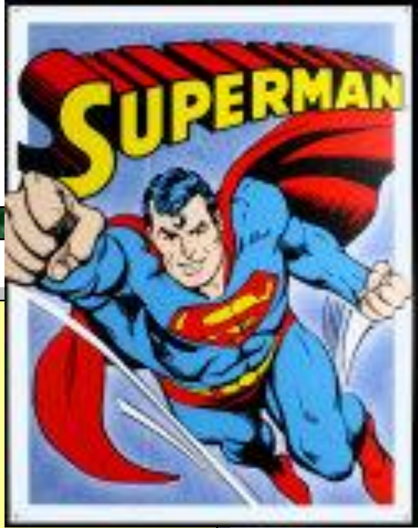


The Players and Their Roles



Astronomy and Cosmology tell us about Dark Matter	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 Ωh^2	Convert the masses into SUSY model parameters and Ωh^2 Do we live in a world with Universal Couplings?	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
sign(μ)	Sign of Higgs mixing parameter ($W^{(2)} = \mu H_1 H_2$)

Translation for Experimentalists and Cosmologists:

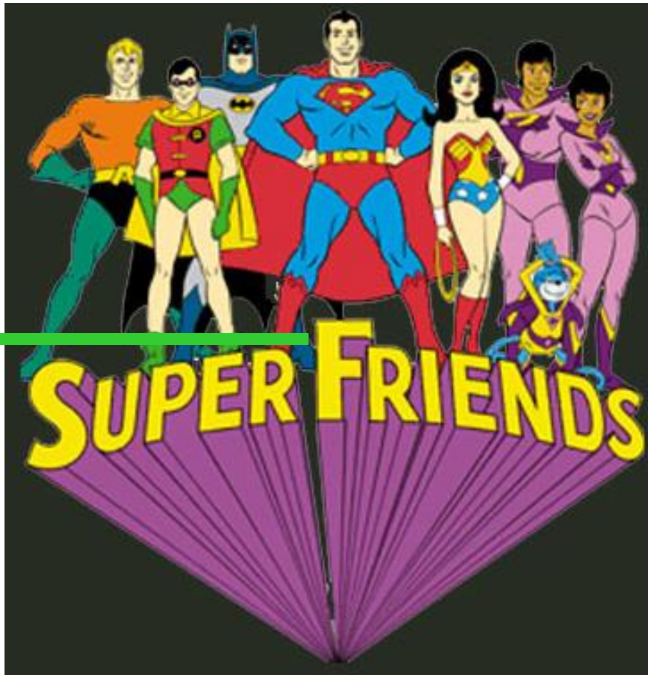
Each combination of these parameters uniquely determines the masses of all the superparticles and the Relic Density ($\Omega_{\tilde{\chi}_1^0} h^2$)

Outline

- Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$
- Identifying events at the LHC
  - Discovery and Experimental Observables
- Measurements of
  - Particle masses: ΔM, 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 both particle physics and cosmology

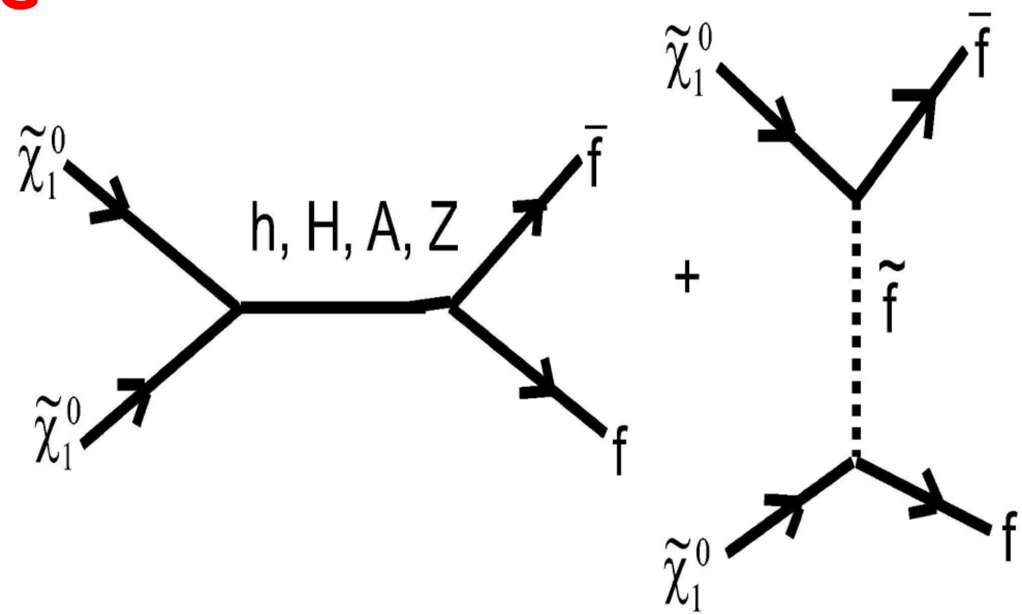


"Vanilla" mSUGRA and Cosmology

mSUGRA parameters uniquely determine the

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

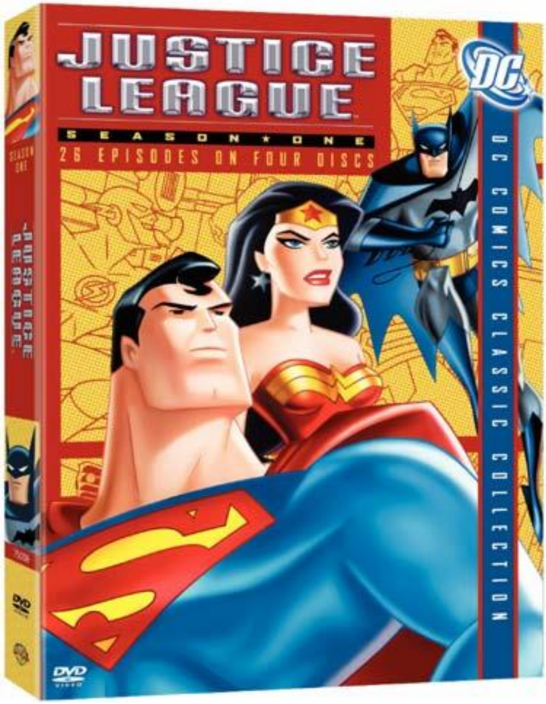
Use WMAP Relic Density measurements to further constrain SUSY parameter space



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

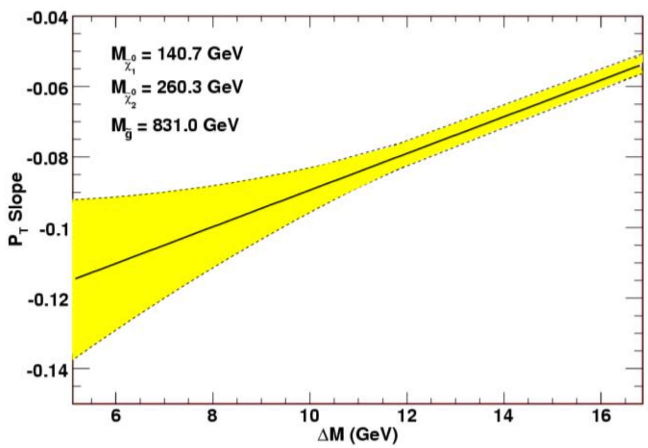
Particle Physicists:

- Non-observation of the Higgs and the Gauginos and their mass limits
- Measurement of branching ratio of the *b-quark→sγ*

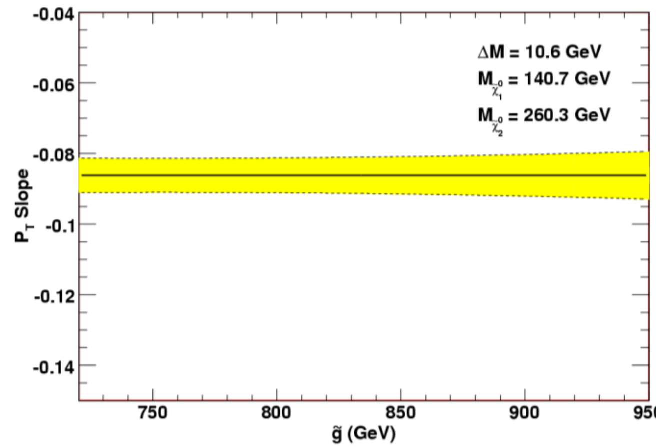
Astronomers and Cosmologists:

- WMAP measurement of the Relic Density

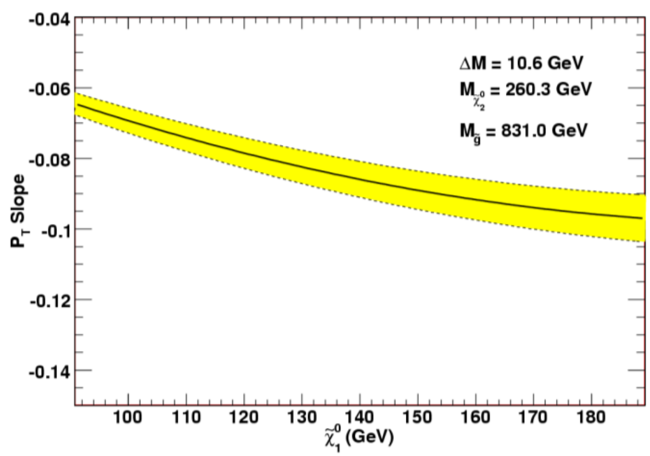
- $M_{Higgs} > 114$ GeV
- $M_{chargino} > 104$ GeV
- $2.2x10^{-4} < Br\ (b \to s\gamma) < 4.5x10^{-4}$
- $a_{\mu}\ x\ 10^{-10} = 27 \pm 10\ (g-2)$
- $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$ (WMAP)



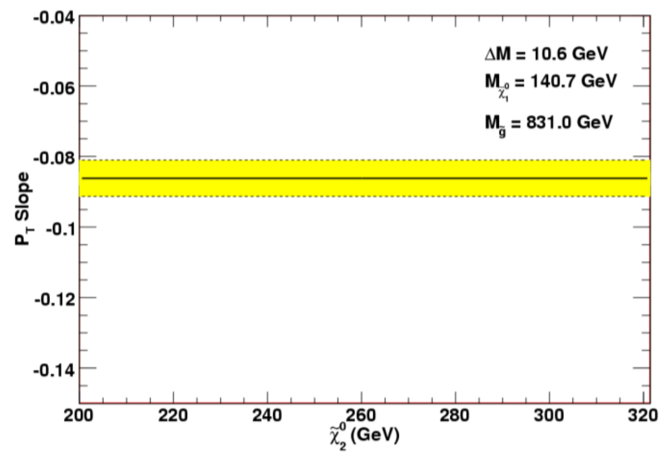
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
P_T Slope
ΔM (GeV)



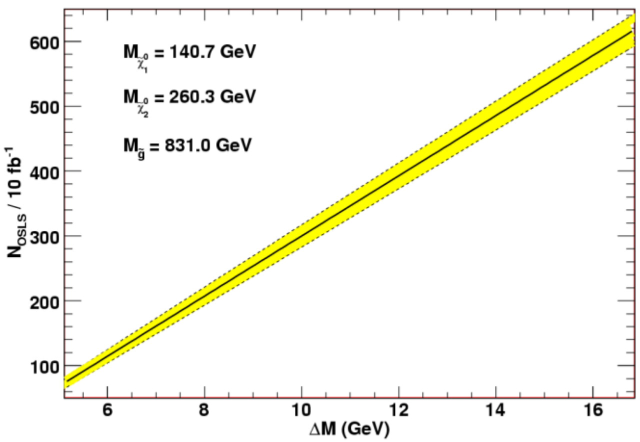
ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
P_T Slope
$\tilde{g}$ (GeV)

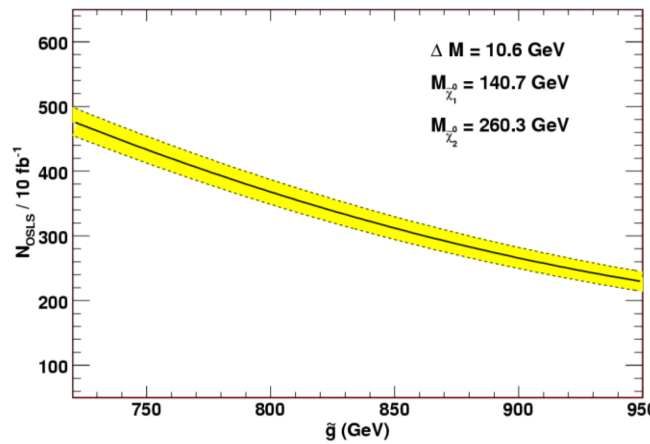


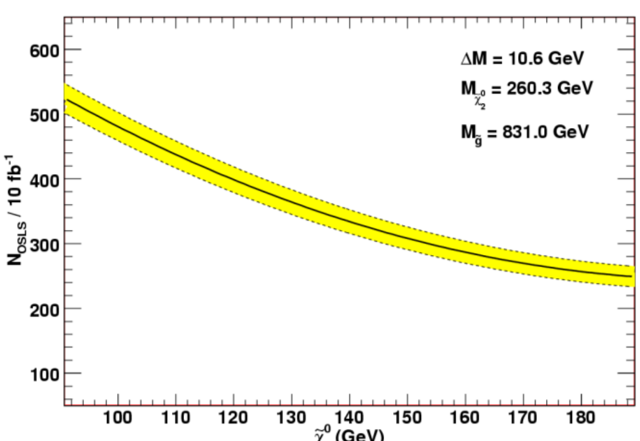
ΔM = 10.6 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
P_T Slope
$\tilde{\chi}_1^0$ (GeV)

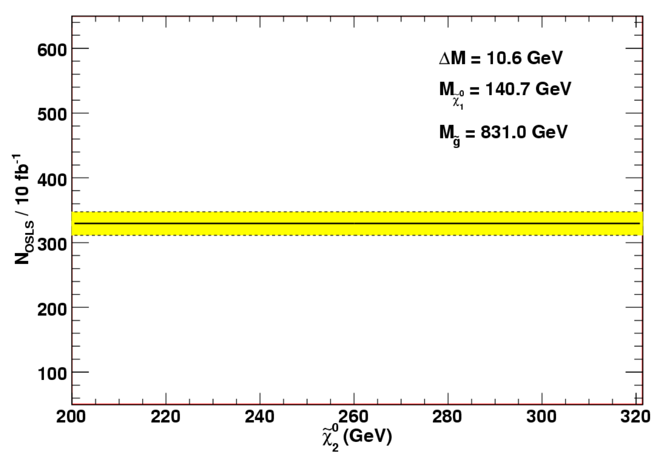


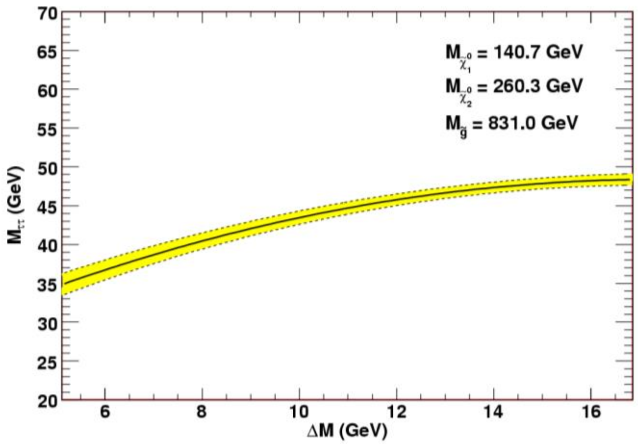
ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{g}}$ = 831.0 GeV
P_T Slope
$\tilde{\chi}_2^0$ (GeV)

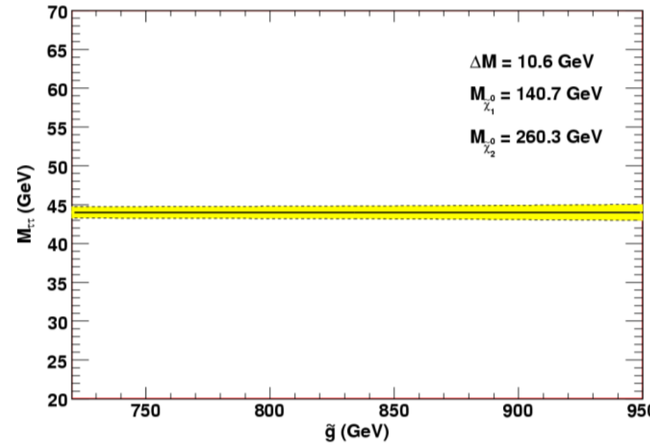

M$_{\tilde{\chi}_1^0}$ = 140.7 GeV
M$_{\tilde{\chi}_2^0}$ = 260.3 GeV
M$_{\tilde{g}}$ = 831.0 GeV
N$_{OSLS}$ / 10 fb^{-1}
ΔM (GeV)

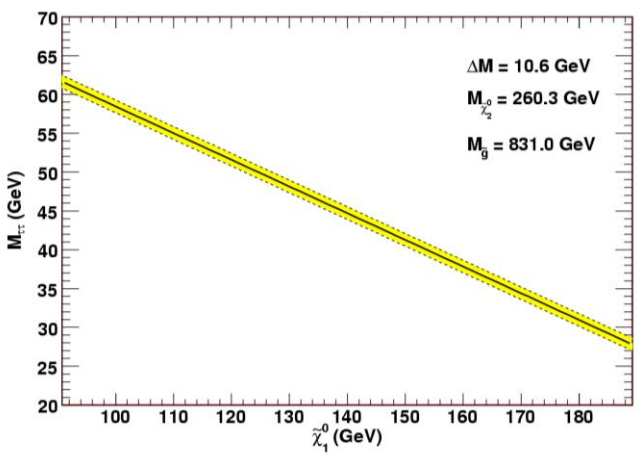

Δ M = 10.6 GeV
M$_{\tilde{\chi}_1^0}$ = 140.7 GeV
M$_{\tilde{\chi}_2^0}$ = 260.3 GeV
N$_{OSLS}$ / 10 fb^{-1}
$\tilde{g}$ (GeV)

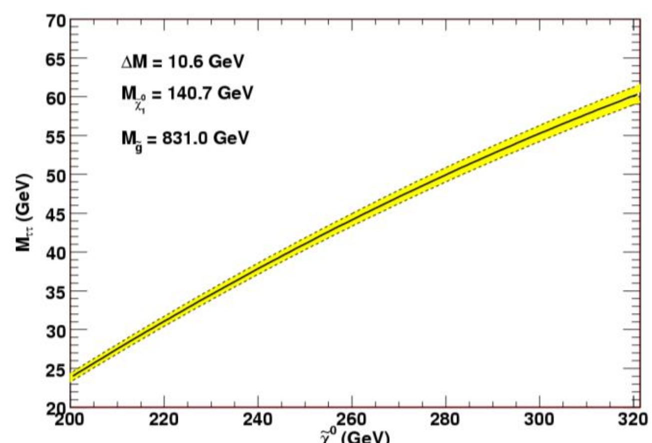

ΔM = 10.6 GeV
M$_{\tilde{\chi}_2^0}$ = 260.3 GeV
M$_{\tilde{g}}$ = 831.0 GeV
N$_{OSLS}$ / 10 fb^{-1}
$\tilde{\chi}_1^0$ (GeV)

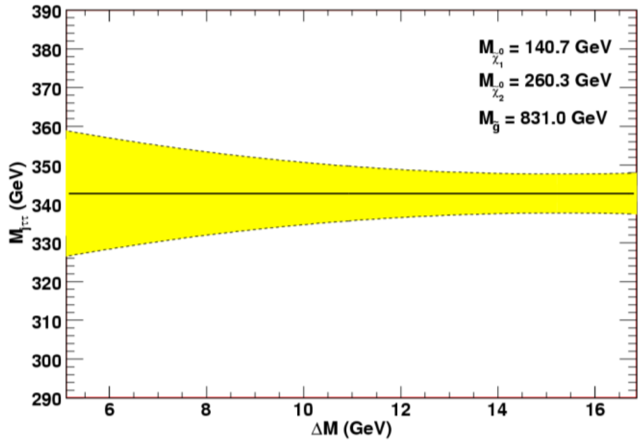

ΔM = 10.6 GeV
M$_{\tilde{\chi}_1^0}$ = 140.7 GeV
M$_{\tilde{g}}$ = 831.0 GeV
N$_{OSLS}$ / 10 fb^{-1}
$\tilde{\chi}_2^0$ (GeV)


$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{\tau\tau}$ (GeV)
ΔM (GeV)

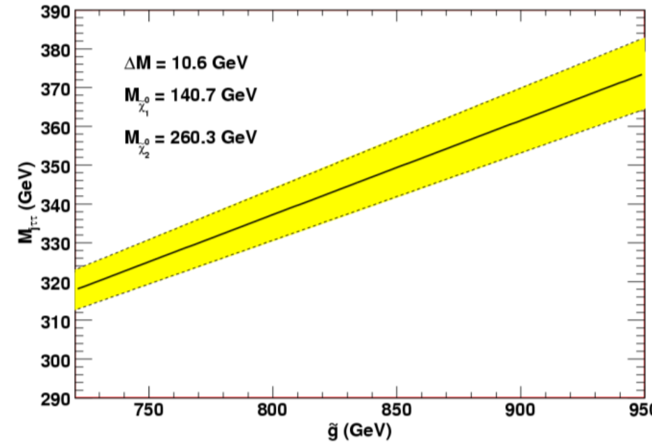

ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tau\tau}$ (GeV)
$\tilde{g}$ (GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{\tau\tau}$ (GeV)
$\tilde{\chi}_1^0$ (GeV)

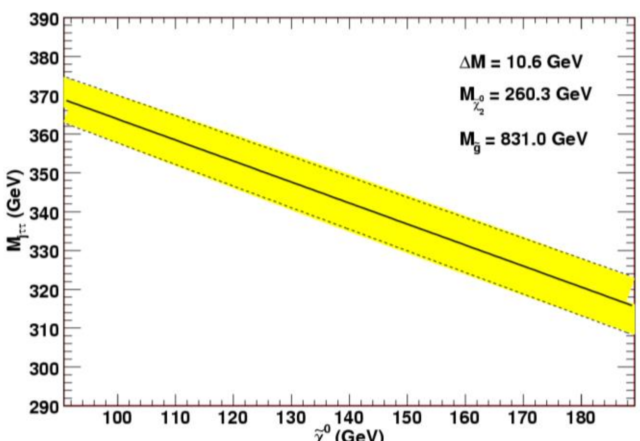

ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{\tau\tau}$ (GeV)
$\tilde{\chi}_2^0$ (GeV)



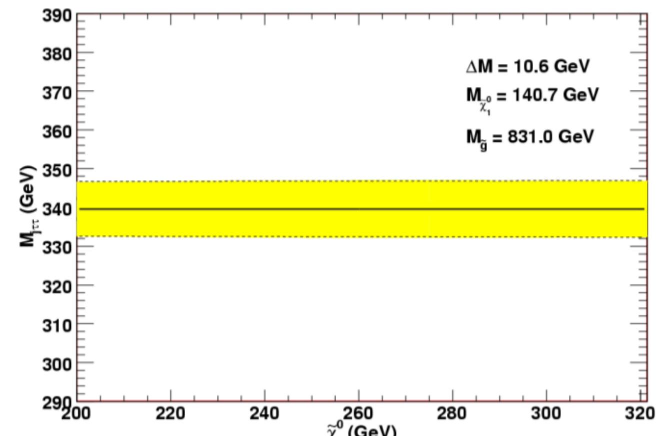
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{j\tau\tau}$ (GeV)
ΔM (GeV)



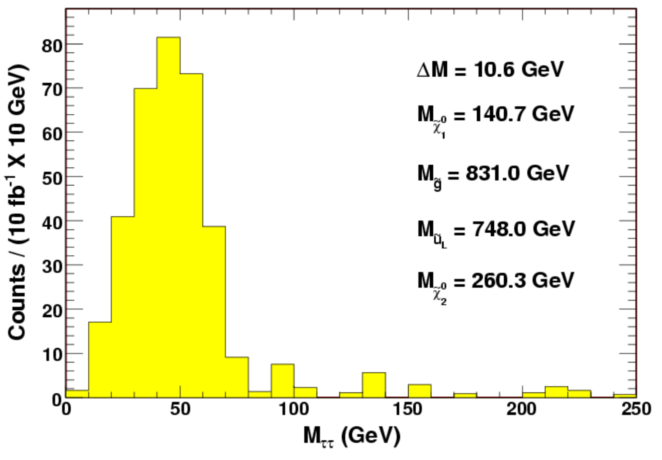
ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{j\tau\tau}$ (GeV)
$\tilde{g}$ (GeV)



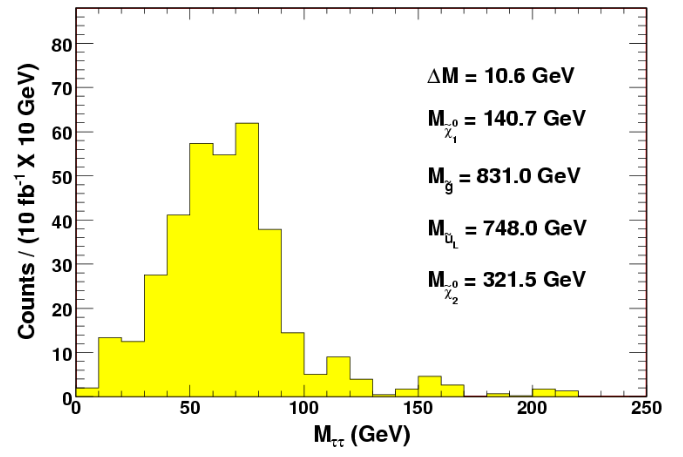
ΔM = 10.6 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{j\tau\tau}$ (GeV)
$\tilde{\chi}_1^0$ (GeV)



ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{j\tau\tau}$ (GeV)
$\tilde{\chi}_2^0$ (GeV)



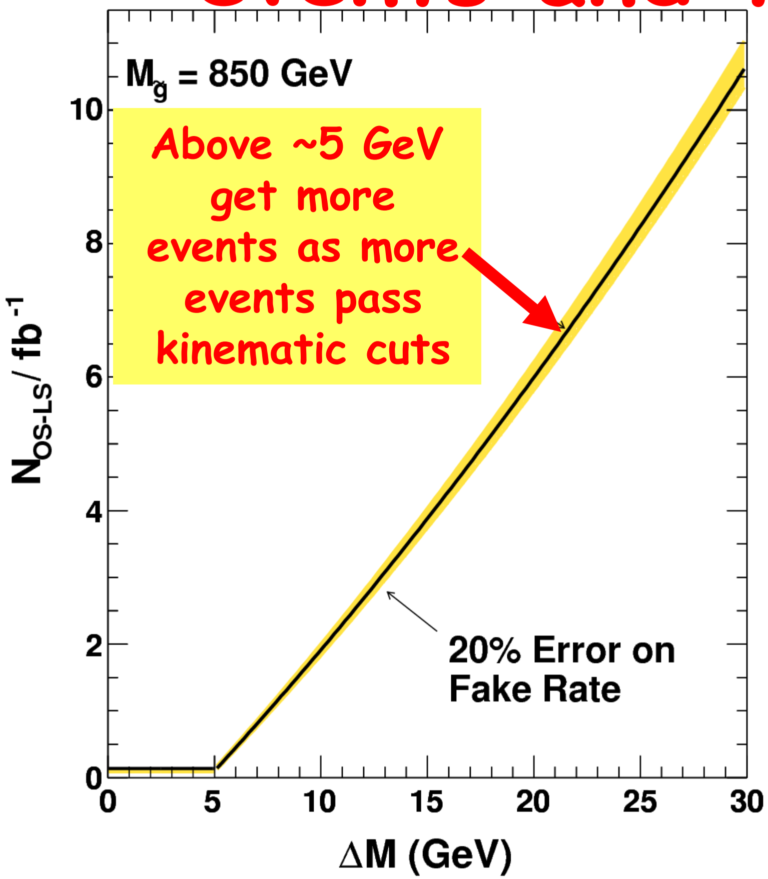
ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{\tilde{u}_L}$ = 748.0 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
Counts / (10 fb^{-1} X 10 GeV)
$M_{\tau\tau}$ (GeV)

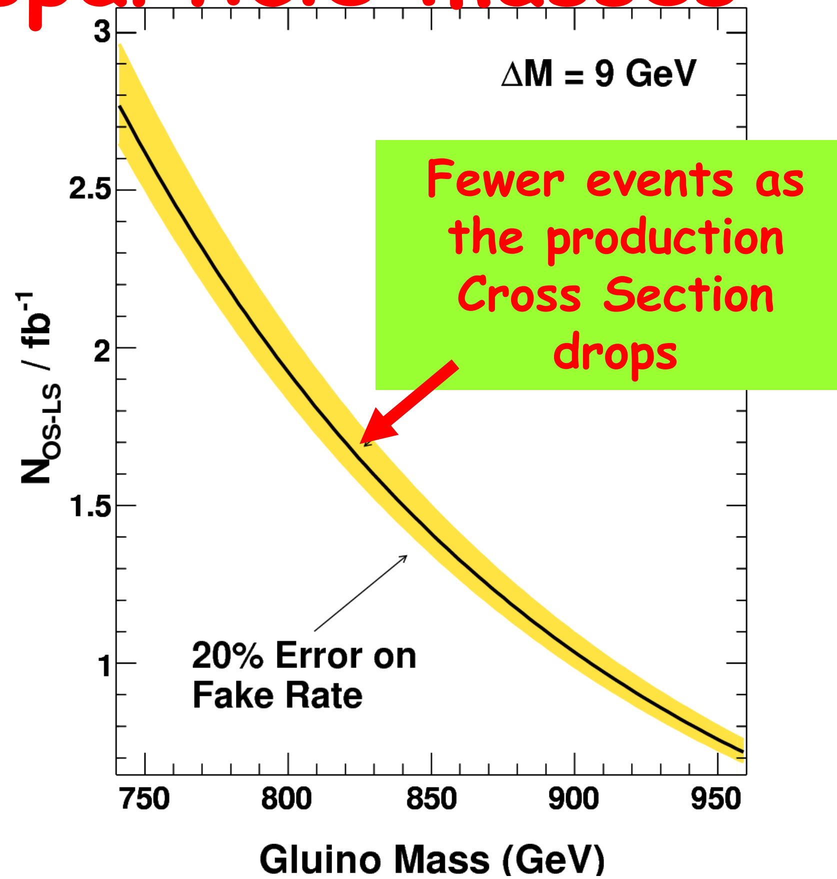


ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{g}}$ = 831.0 GeV
$M_{\tilde{u}_L}$ = 748.0 GeV
$M_{\tilde{\chi}_2^0}$ = 321.5 GeV
Counts / (10 fb^{-1} X 10 GeV)
$M_{\tau\tau}$ (GeV)

Discovery Luminosity

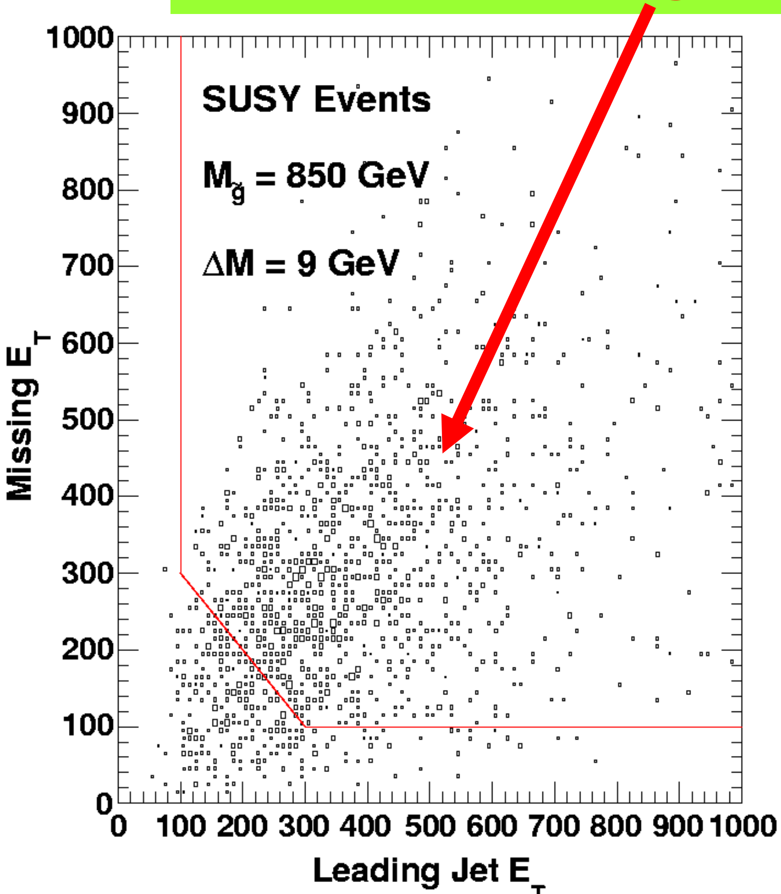
Depends on the number of observable events and the sparticle masses

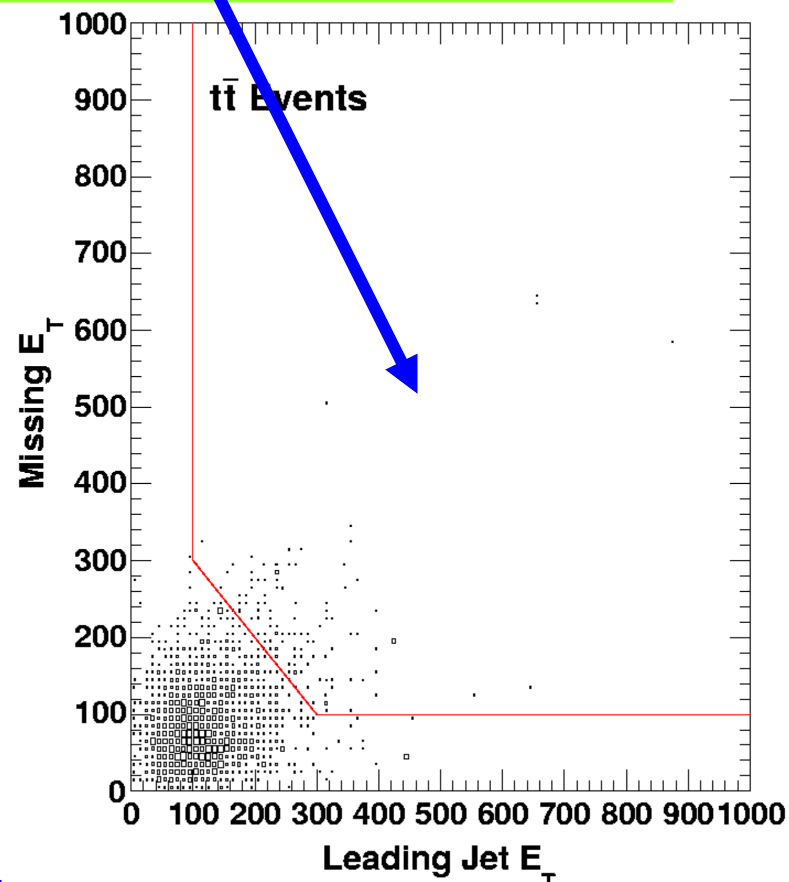




Some Technical Details

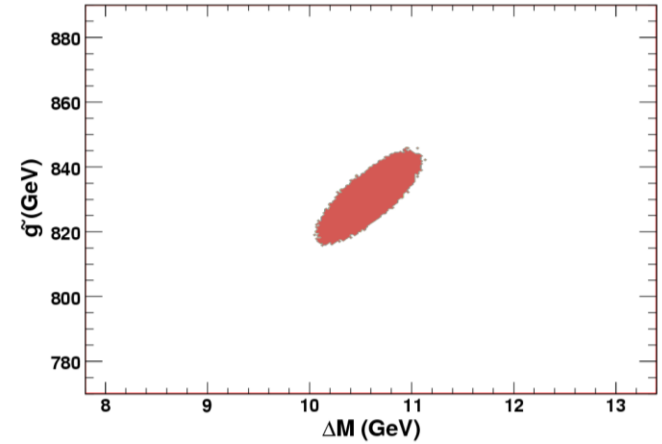
Use event kinematics to separate SUSY from $t\bar{t}$



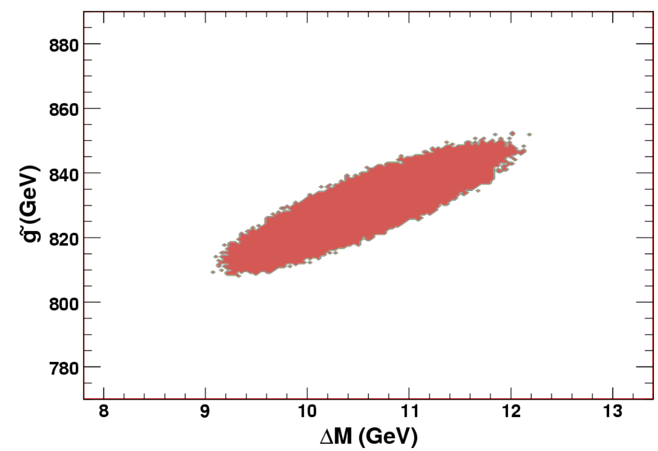


Outline

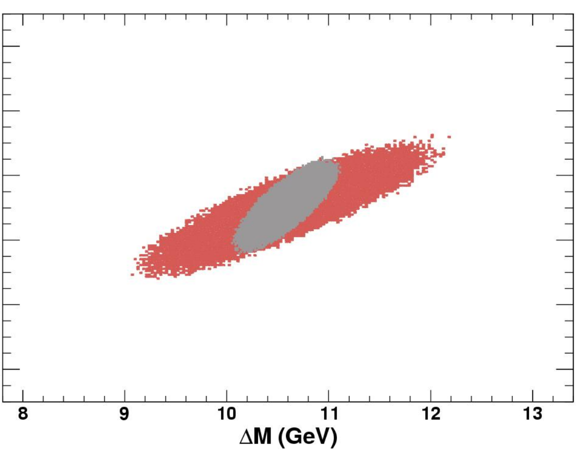
- Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$
- Identifying events at the LHC
  - Discovery and Experimental Observables
- Measurements of ←
  - Particle masses: ΔM, M_{Gluino} & $M_{\chi 2}$
  - Supersymmetry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



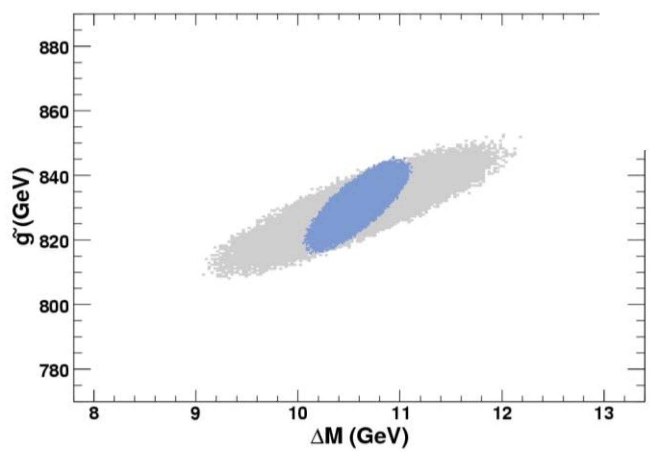
880
860
840
820
800
780
g̃ (GeV)
8
9
10
11
12
13
ΔM (GeV)



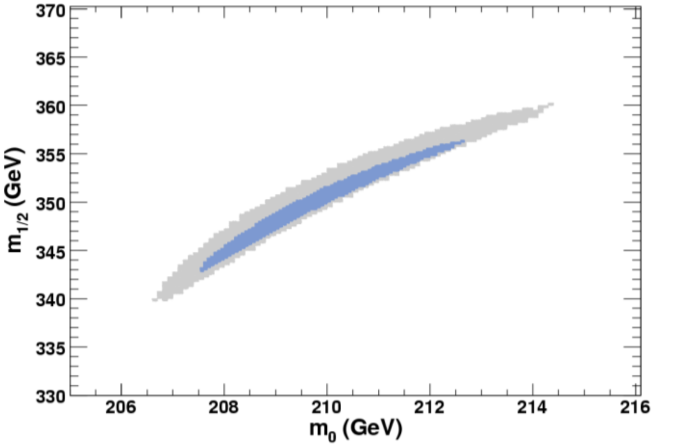
880
860
840
820
800
780
g̃ (GeV)
8
9
10
11
12
13
ΔM (GeV)

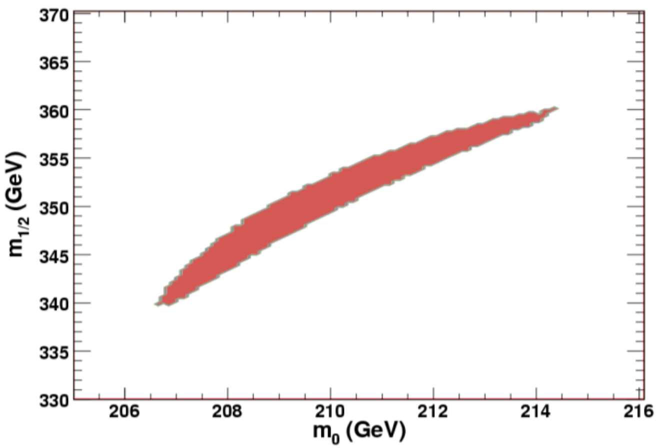


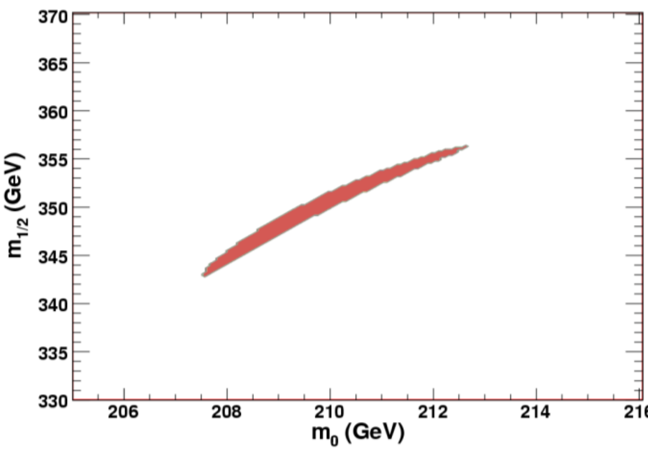
8
9
10
11
12
13
ΔM (GeV)

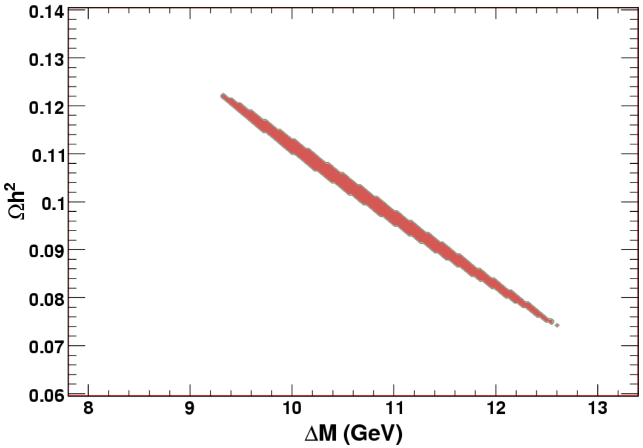


880
860
840
820
800
780
g̃ (GeV)
8
9
10
11
12
13
ΔM (GeV)

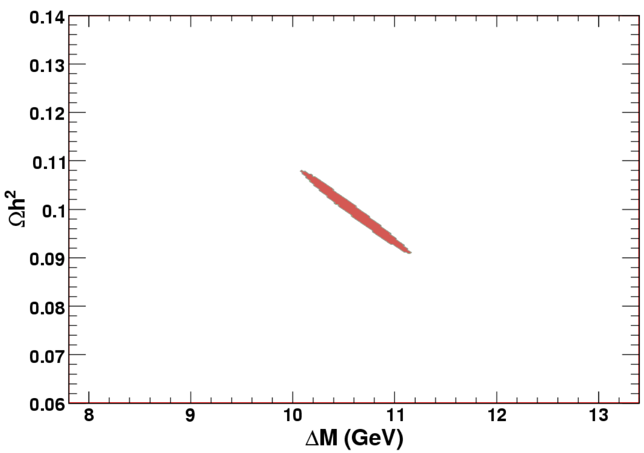

370
365
360
355
350
345
340
335
330
206
208
210
212
214
216
m_0 (GeV)
$m_{1/2}$ (GeV)


370
365
360
355
350
345
340
335
330
206
208
210
212
214
216
m_0 (GeV)
$m_{1/2}$ (GeV)

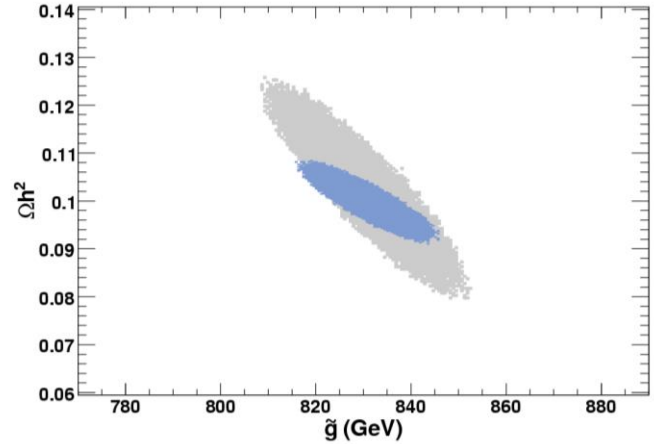

370
365
360
355
350
345
340
335
330
206
208
210
212
214
216
m_0 (GeV)
$m_{1/2}$ (GeV)



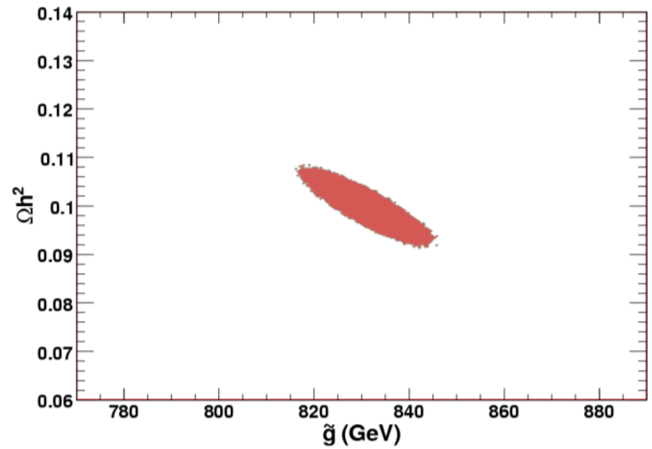
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
Ωh^2
8
9
10
11
12
13
ΔM (GeV)



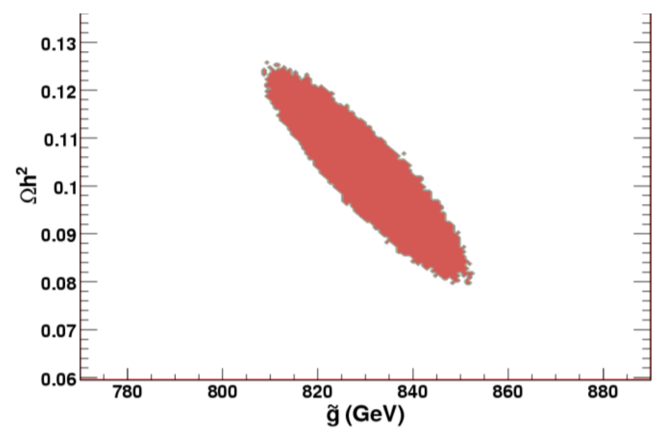
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
Ωh^2
8
9
10
11
12
13
ΔM (GeV)



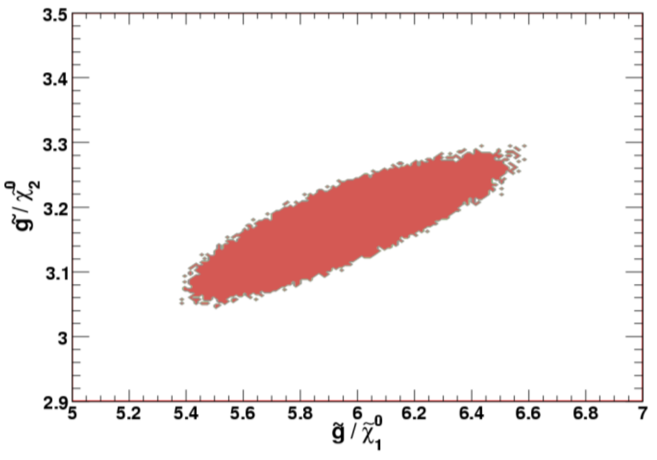
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
Ωh^2
780
800
820
840
860
880
$\tilde{g}$ (GeV)



0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
Ωh^2
780
800
820
840
860
880
$\tilde{g}$ (GeV)

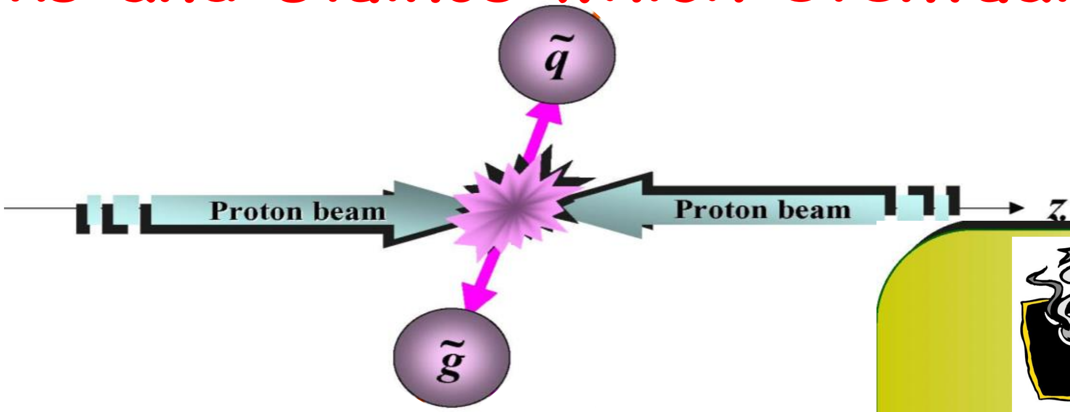


0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
Ωh^2
780
800
820
840
860
880
$\tilde{g}$ (GeV)

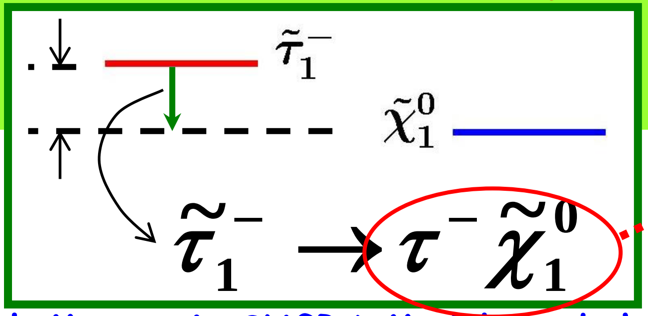

3.5
3.4
3.3
3.2
3.1
3
2.9
5
5.2
5.4
5.6
5.8
6
6.2
6.4
6.6
6.8
7
$\tilde{g} / \tilde{\chi}_1^0$
$\tilde{g} / \tilde{\chi}_2^0$

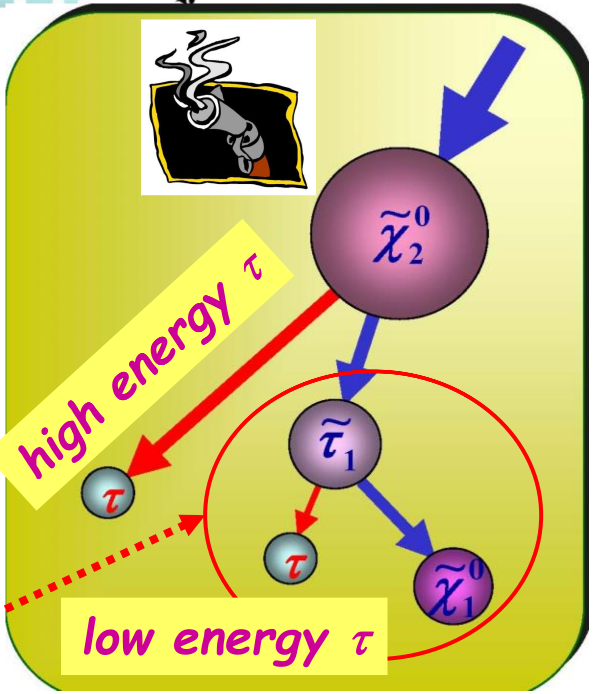
A Smoking Gun at the LHC?

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

Lighest 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

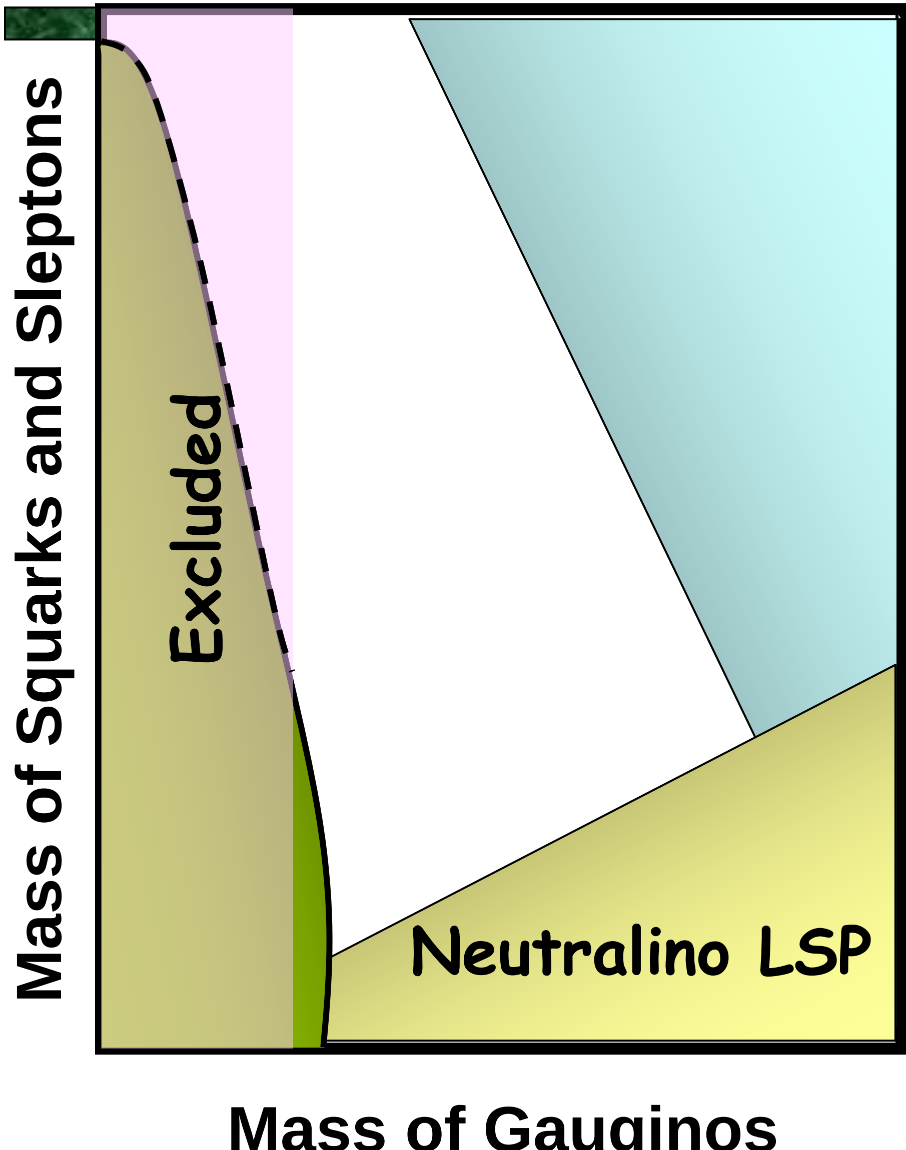
For small mass difference we can get the right relic density

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

Outline

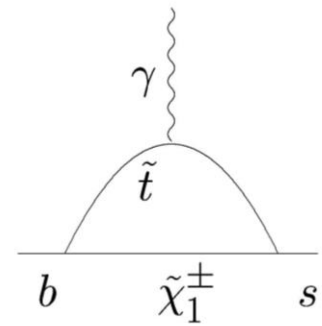
- Supersymmetry and the Co-annihilation region
  - The important experimental constraints
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$
- Identifying events at the LHC
  - Discovery and Experimental Observables
- Measurements of
  - Particle masses: ΔM, M_{Gluino} & $M_{\chi 2}$
  - Supersymmetry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

Particle Physics Constrained Region



Higgs Mass (M_h)

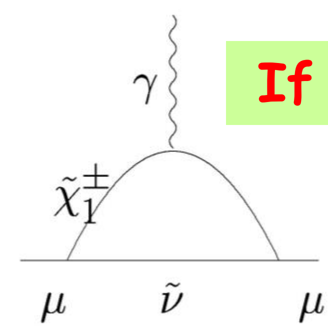
Branching Ratio $b \to s\gamma$



Neutralino LSP

Magnetic Moment of Muon

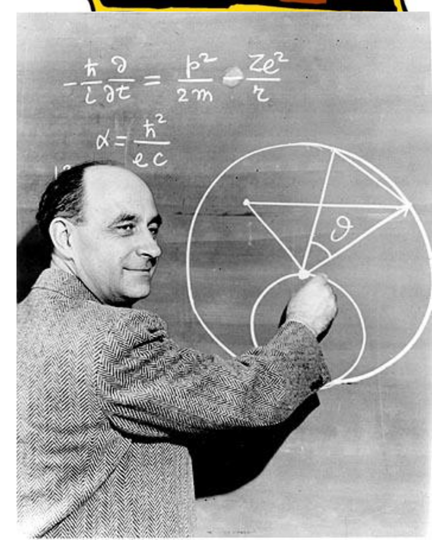
If confirmed…



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?



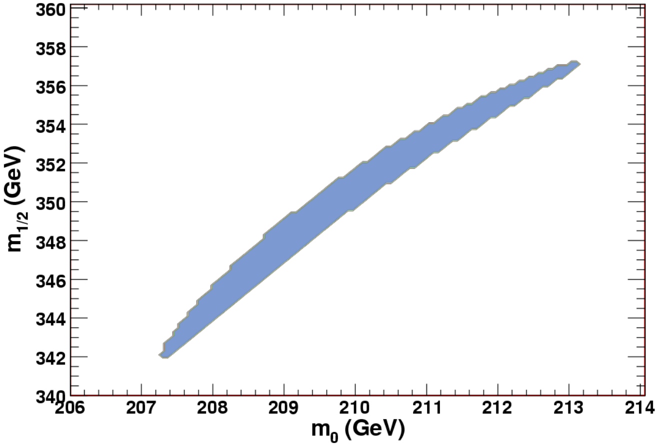
Aside on our Assumptions…

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

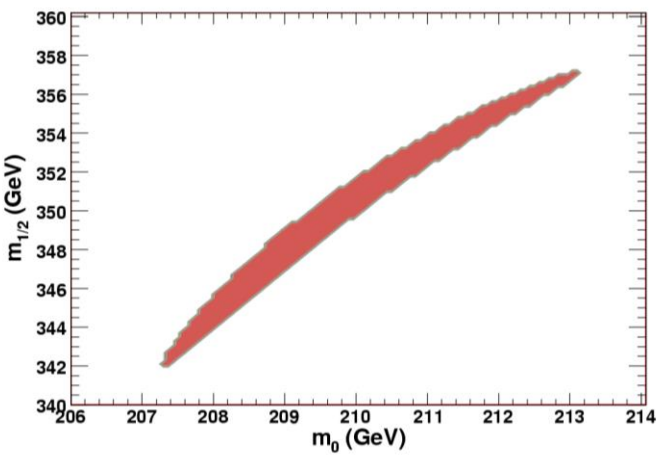
1. The stau-neutralino co-annihilation region

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

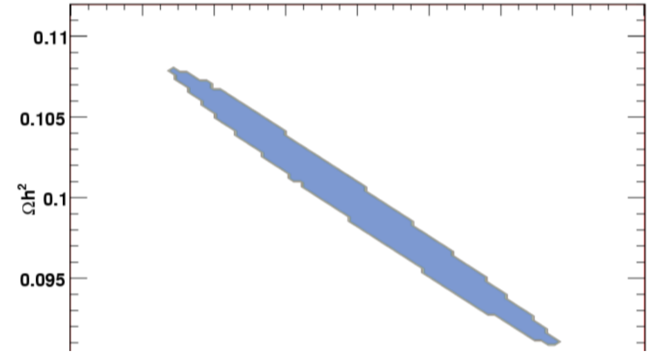
Concentrate on this region for the rest of this talk…



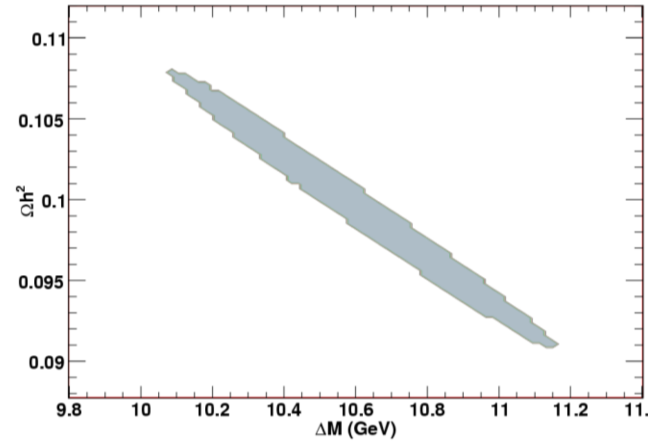
m1/2 (GeV)
m0 (GeV)



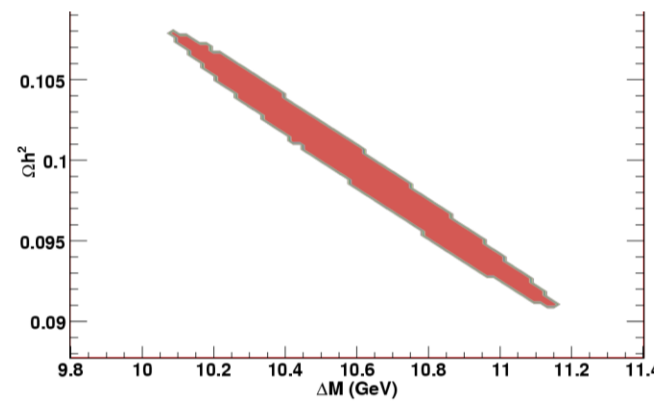
m1/2 (GeV)
m0 (GeV)



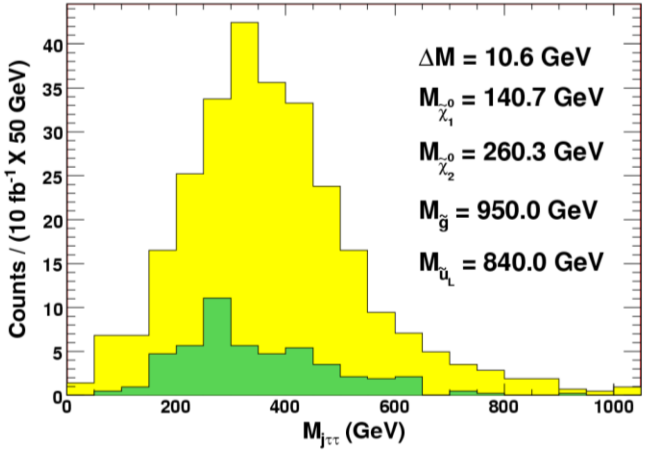
Ωh2

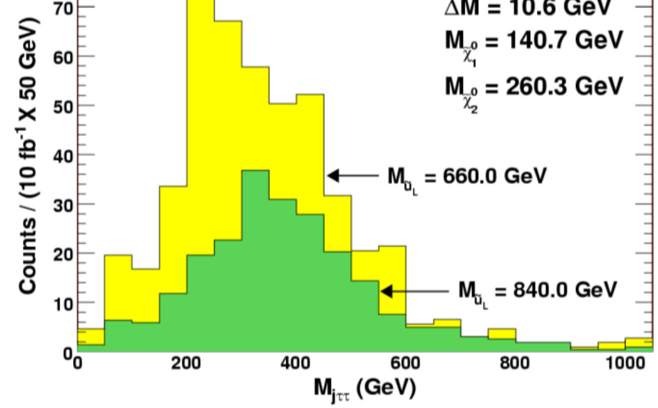


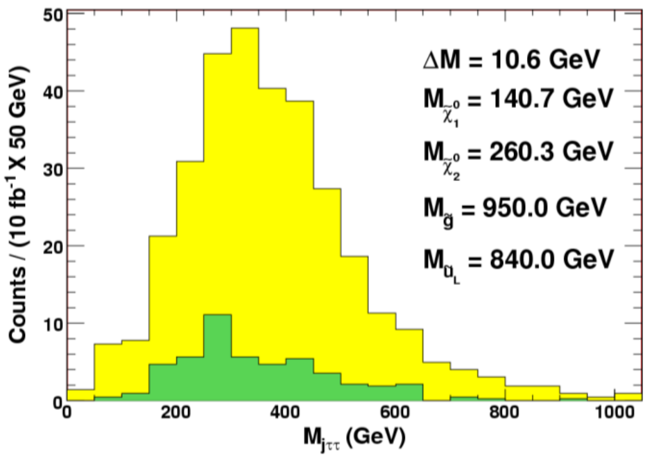
Ωh2
ΔM (GeV)

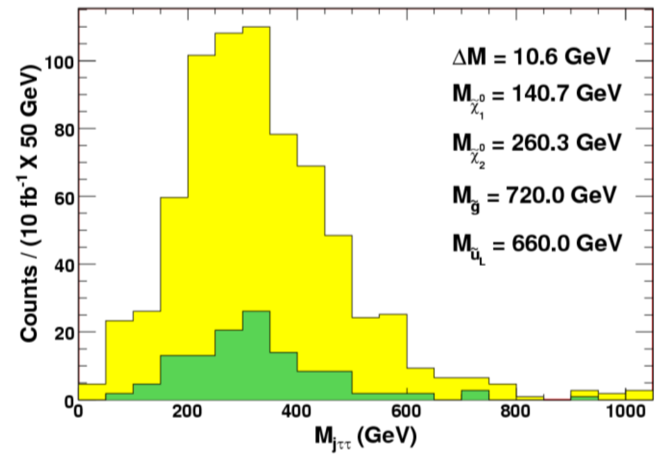


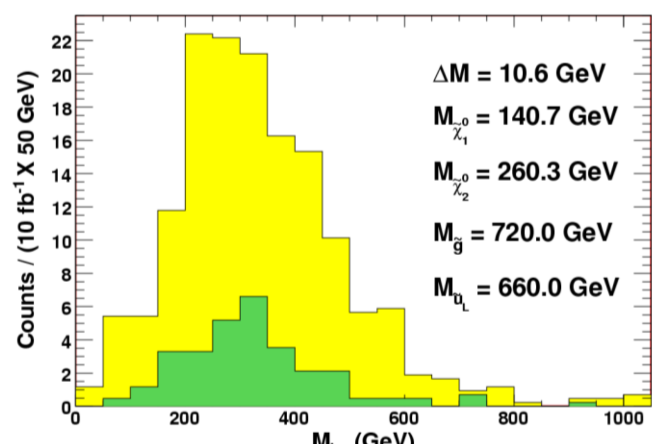
Ωh2
ΔM (GeV)

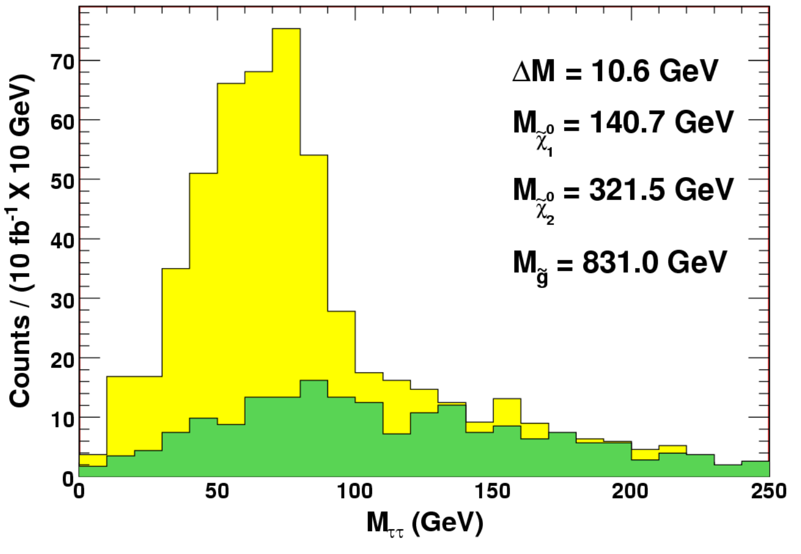

ΔM = 10.6 GeV
$M_{\tilde{\chi}^0_1}$ = 140.7 GeV
$M_{\tilde{\chi}^0_2}$ = 260.3 GeV
$M_{\tilde{g}}$ = 950.0 GeV
$M_{\tilde{u}_L}$ = 840.0 GeV
Counts / (10 fb^{-1} X 50 GeV)
$M_{j\tau\tau}$ (GeV)

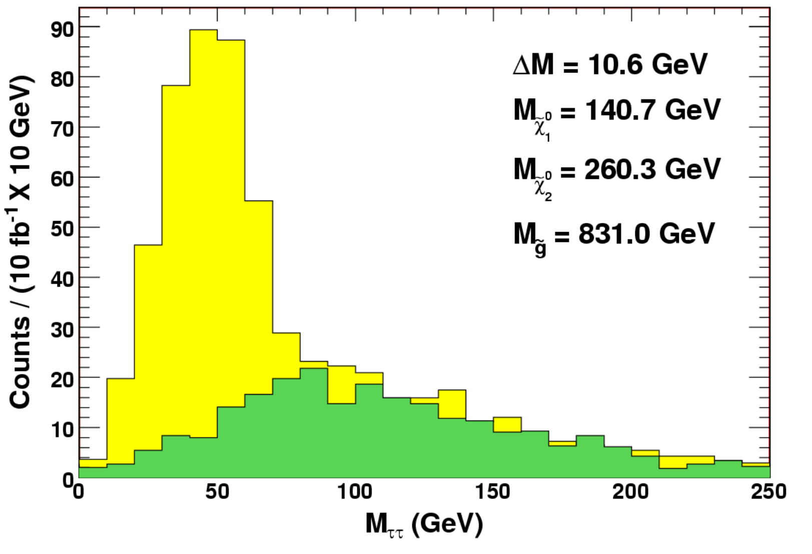

ΔM = 10.6 GeV
$M_{\tilde{\chi}^0_1}$ = 140.7 GeV
$M_{\tilde{\chi}^0_2}$ = 260.3 GeV
$M_{\tilde{u}_L}$ = 660.0 GeV
$M_{\tilde{u}_L}$ = 840.0 GeV
Counts / (10 fb^{-1} X 50 GeV)
$M_{j\tau\tau}$ (GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}^0_1}$ = 140.7 GeV
$M_{\tilde{\chi}^0_2}$ = 260.3 GeV
$M_{\tilde{g}}$ = 950.0 GeV
$M_{\tilde{u}_L}$ = 840.0 GeV
Counts / (10 fb^{-1} X 50 GeV)
$M_{j\tau\tau}$ (GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}^0_1}$ = 140.7 GeV
$M_{\tilde{\chi}^0_2}$ = 260.3 GeV
$M_{\tilde{g}}$ = 720.0 GeV
$M_{\tilde{u}_L}$ = 660.0 GeV
Counts / (10 fb^{-1} X 50 GeV)
$M_{j\tau\tau}$ (GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}^0_1}$ = 140.7 GeV
$M_{\tilde{\chi}^0_2}$ = 260.3 GeV
$M_{\tilde{g}}$ = 720.0 GeV
$M_{\tilde{u}_L}$ = 660.0 GeV
Counts / (10 fb^{-1} X 50 GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 321.5 GeV
$M_{\tilde{g}}$ = 831.0 GeV
Counts / (10 fb^{-1} X 10 GeV)
$M_{\tau\tau}$ (GeV)


ΔM = 10.6 GeV
$M_{\tilde{\chi}_1^0}$ = 140.7 GeV
$M_{\tilde{\chi}_2^0}$ = 260.3 GeV
$M_{\tilde{g}}$ = 831.0 GeV
Counts / (10 fb^{-1} X 10 GeV)
$M_{\tau\tau}$ (GeV)

Outline of the Talk

- Co-annihilation Signals at the LHC
  - A Smoking Gun: Small $\Delta M = M_{stau} - M_{LSP}$

- Experimental Observables and Discovery
- Measurements
  - Particle masses: ΔM, M_{Gluino}, $M_{\chi 2}$, $M_{\chi 1}$
  - Supersymmetry parameters: M_0 and $M_{1/2}$
  - Do we live in a mSUG
  - Cosmological implicati
- Conclusions

Particle Physics

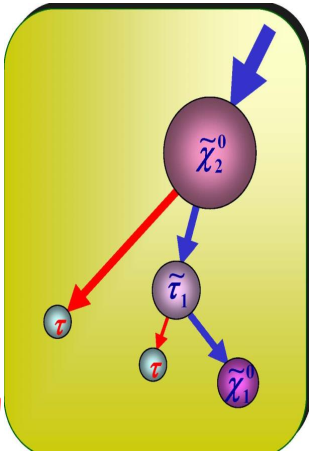
The lightest $\tilde{\tau}$ is a good candidate

- Combine next two
- Sample of Chi2, 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

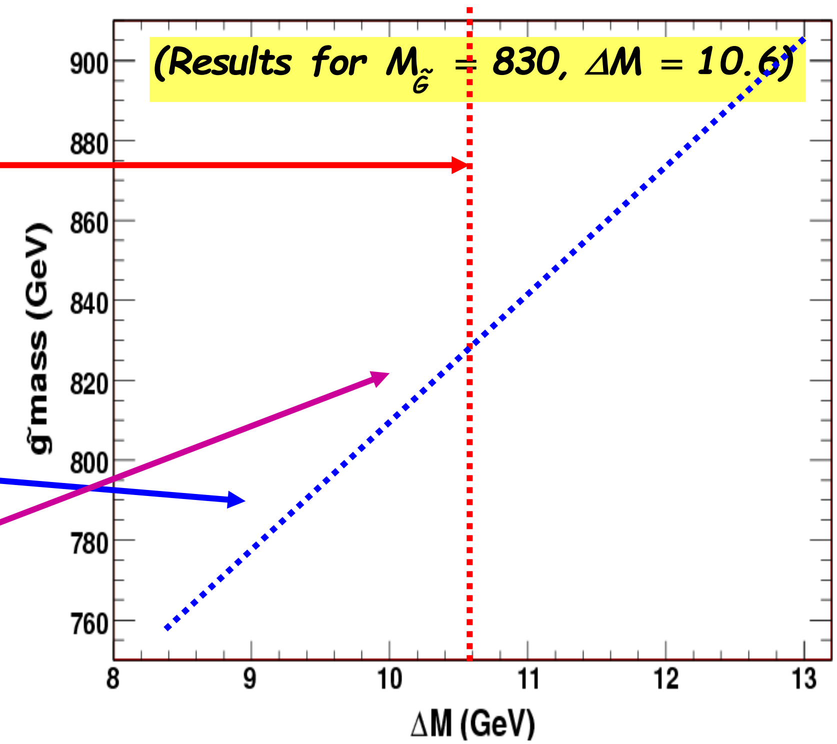


2. Each χ_2 produces one *high energy τ* and one *low energy τ*
3. The invariant mass of the τ-pair reflects the mass of the SUSY particles and their mass differences

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

Measure ΔM and the Gluino Mass

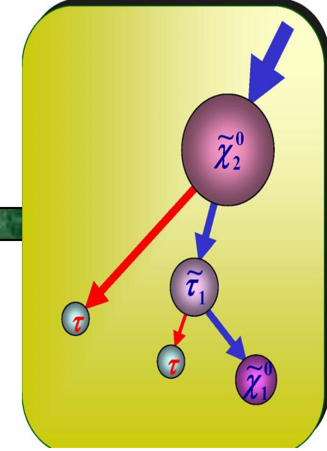
- The slope of the P_T distribution of the τ's only depends on the ΔM
- The event rate depends on both the Gluino mass and ΔM
- Can make a simultaneous measurement



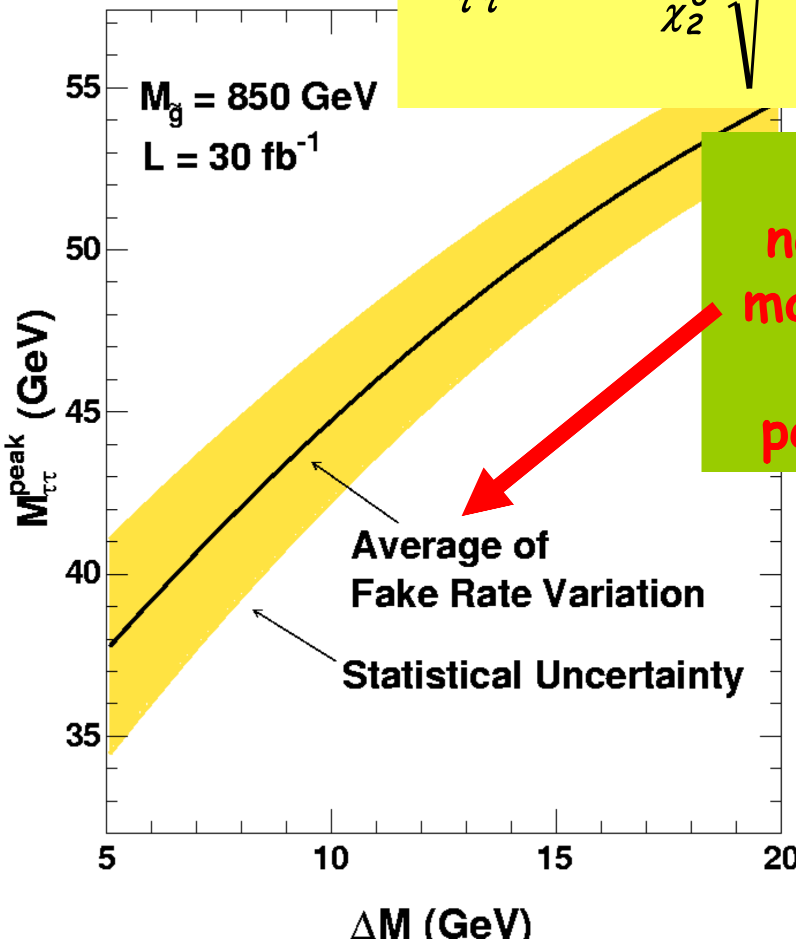
Results for ~300 events
(10 fb^{-1} depending on the Analysis)

An important measurement without Universality assumptions!

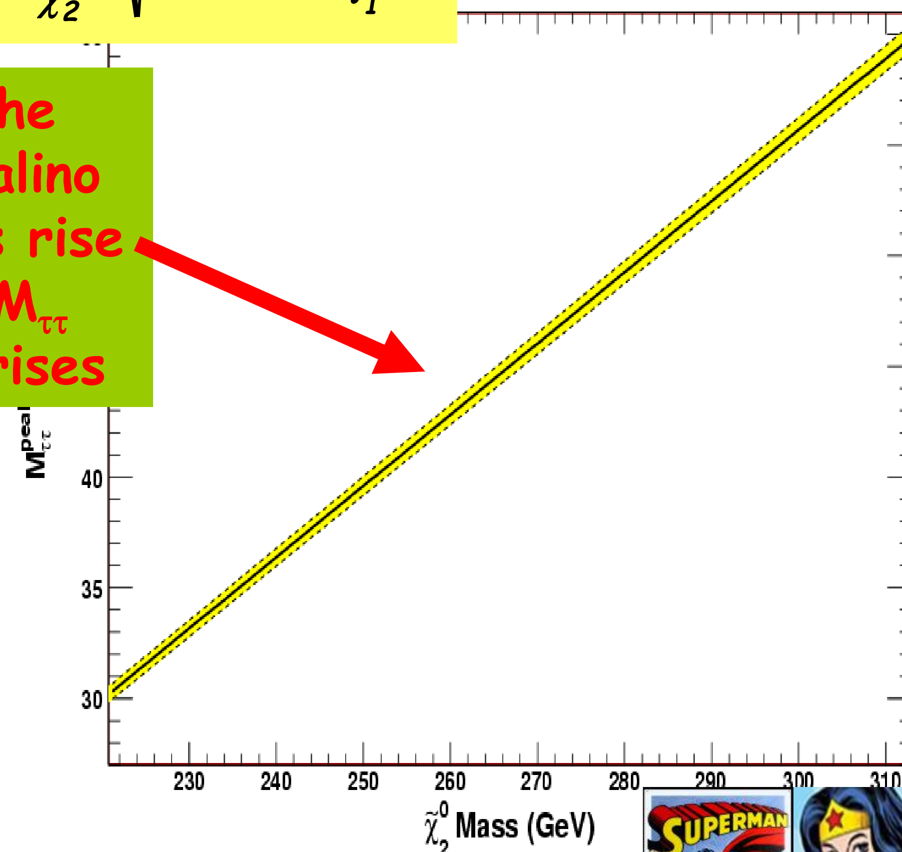
Add in the Peak of $M_{\tau\tau}$



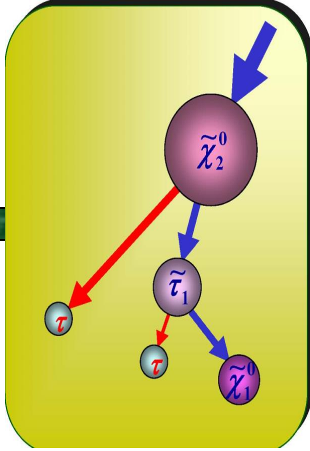
$$M_{\tau\tau} \propto M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}}$$



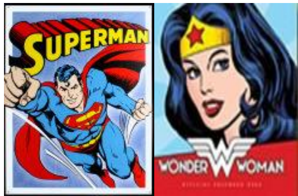
As the neutralino masses rise the $M_{\tau\tau}$ peak rises



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



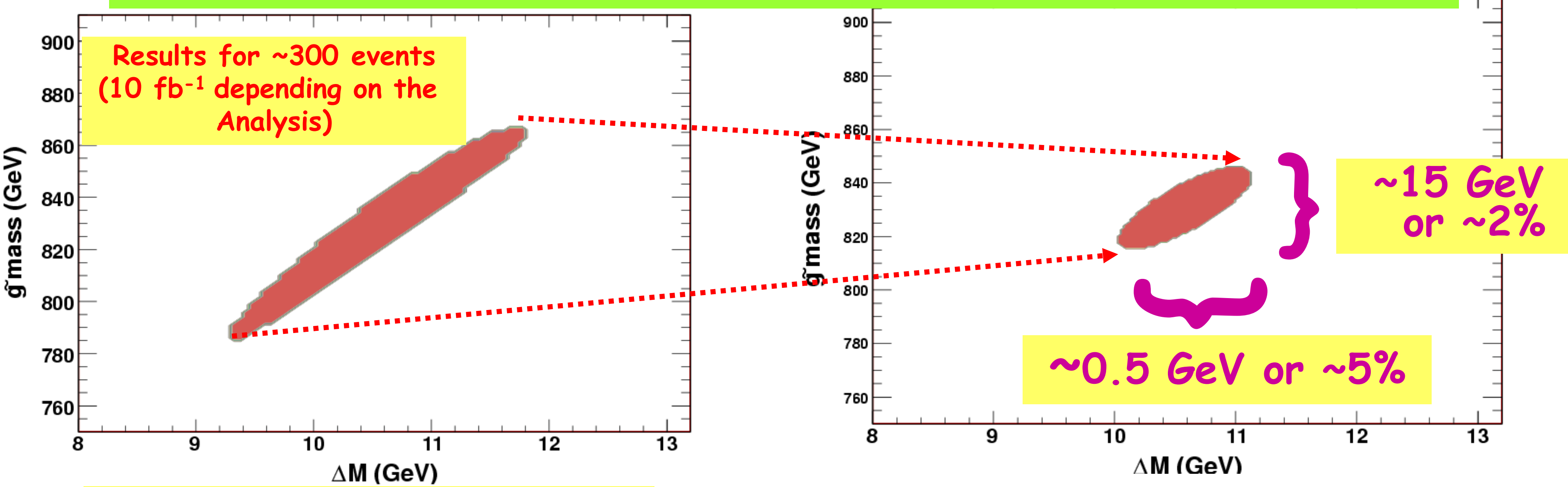
As the squark mass rises the $M_{j\tau\tau}$ peak rises



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 GeV, ΔM = 10.6 GeV)



Analysis only assumes

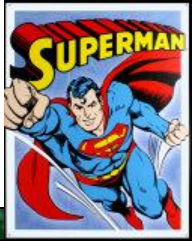
$$M_{\tilde{\chi}_1^0} \sim 0.17\, M_{\tilde{g}}$$

Analysis assumes

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

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

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 sign(μ) 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!