



SUSY at LHC

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Discovery Time...

We are about to enter into an era of major discovery

Dark Matter: we need new particles to explain the content of the universe

Standard Model: we need new physics

Supersymmetry solves both problems!

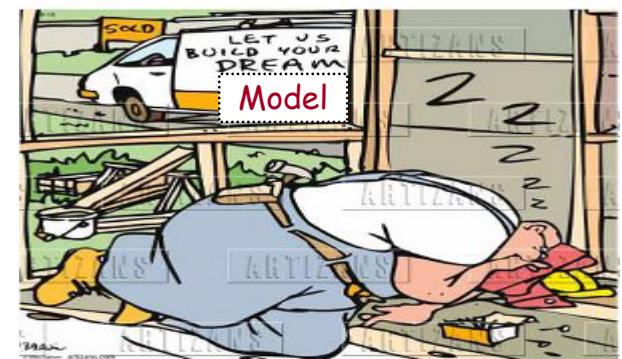
The super-particles are distributed around the weak scale

Our best chance to observe SUSY is at the LHC

LHC: The only experiment which directly probes TeV scale

Future results from Planck, direct and indirect detection in tandem with LHC will confirm a model

SUSY Theory at the LHC



Collision of 2 Galaxy Clusters

splitting normal matter and dark matter apart

– Another Clear Evidence of Dark Matter –

Ordinary Matter

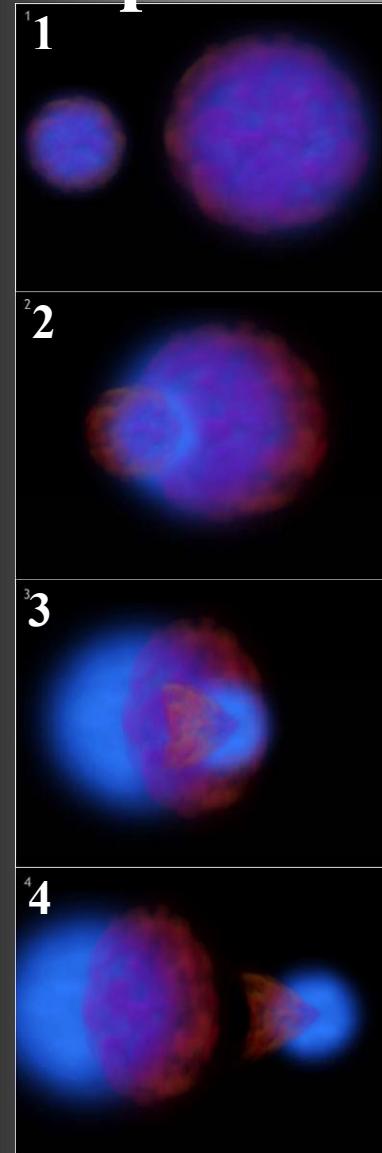
(NASA's Chandra X
Observatory)

(8/21/06)

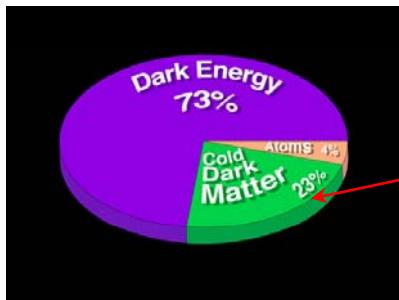
Dark Matter
(Gravitational Lensing)

Approximately
the same size as
the Milky Way

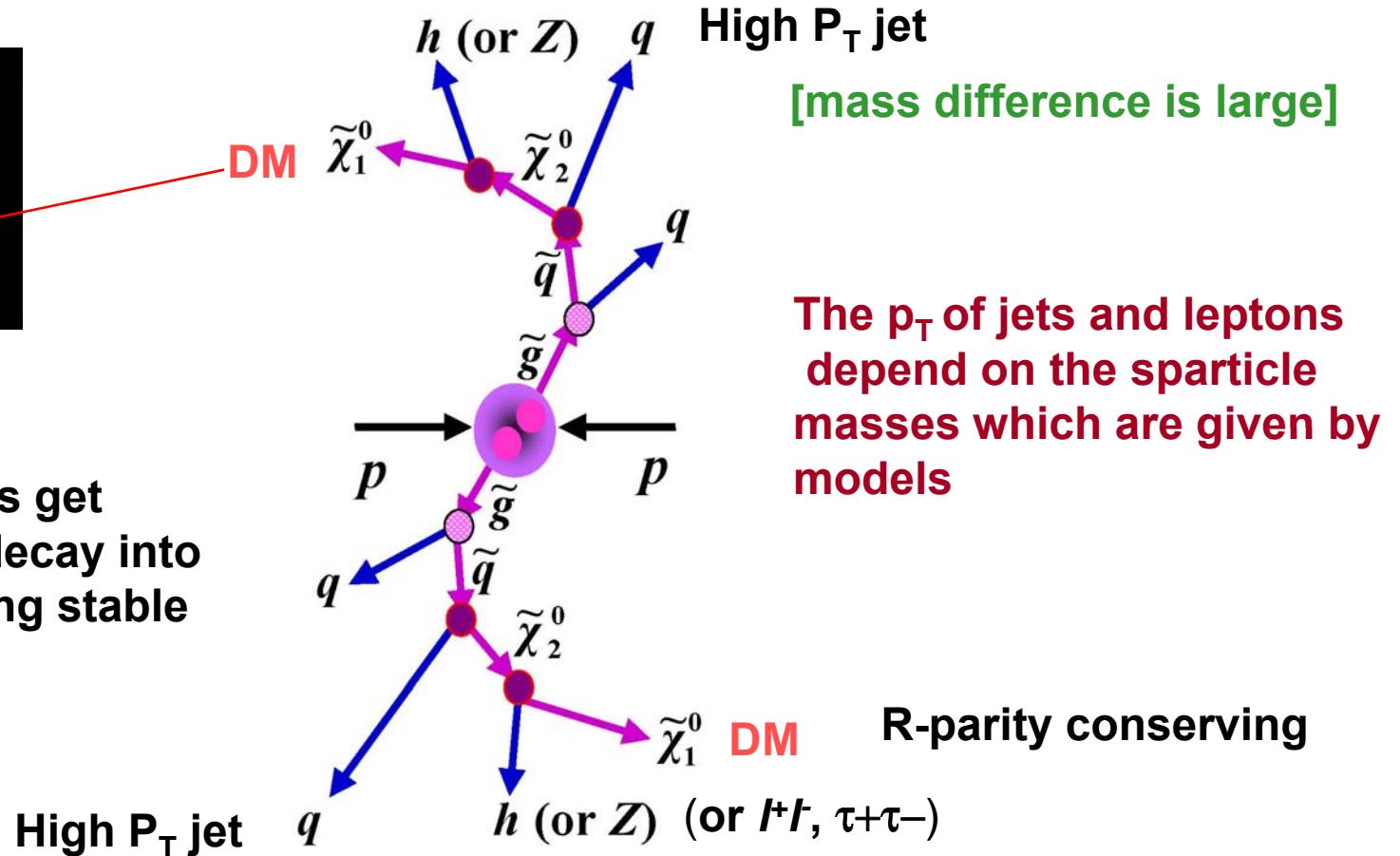
time



SUSY at the LHC



Colored particles get produced and decay into weakly interacting stable particles



The signal : jets + leptons + missing E_T

Example Analysis

Kinematical Cuts and Event Selection

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

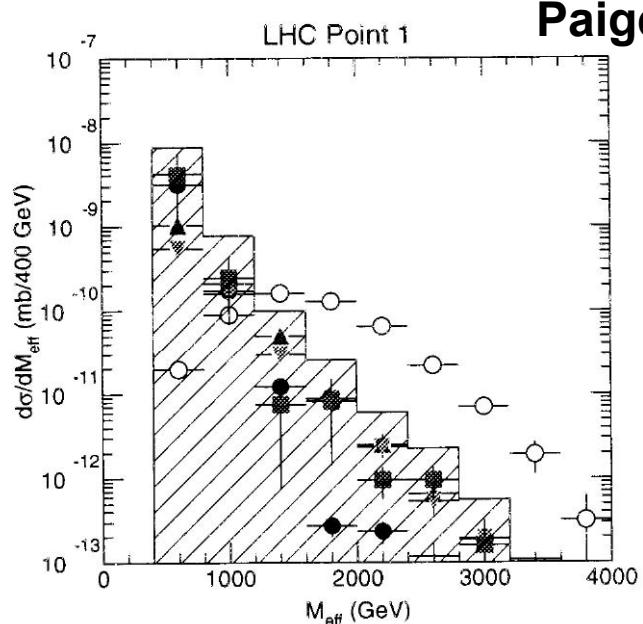


FIG. 1. LHC point 1 signal and standard model backgrounds. Open circles: SUSY signal. Solid circles: $t\bar{t}$. Triangles: $W \rightarrow l\nu, \tau\nu$. Downward triangles: $Z \rightarrow \nu\nu, \tau\tau$. Squares: QCD jets. Histogram: sum of all backgrounds.

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

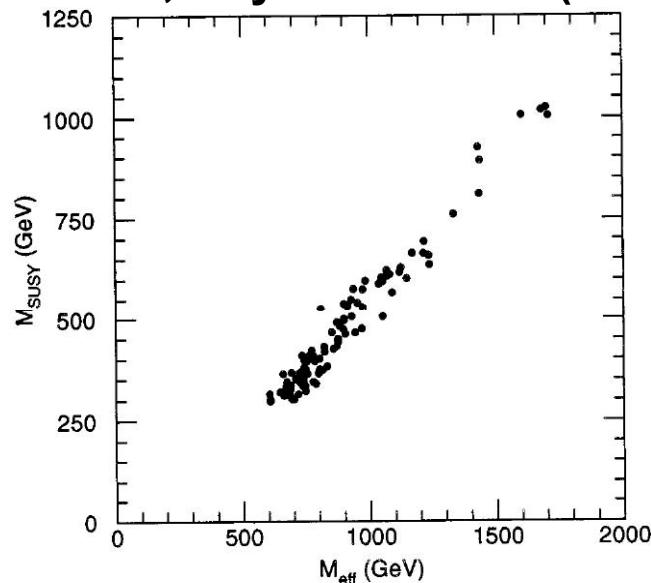
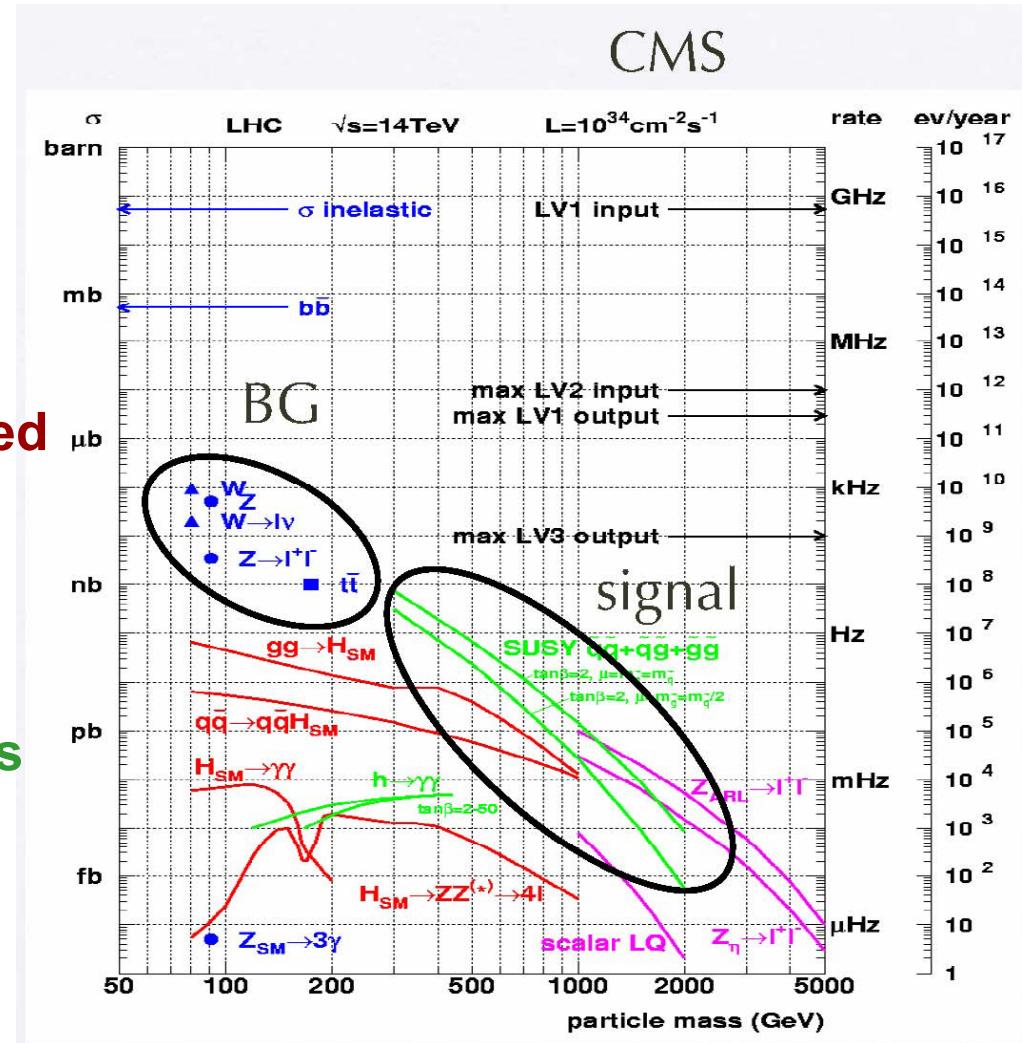


FIG. 6. Scatterplot of $M_{\text{SUSY}} = \min(M_{\tilde{g}}, M_{\tilde{\chi}})$ vs M_{eff} for randomly chosen SUGRA models having the same light Higgs boson mass within ± 3 GeV as for LHC point 5.

Background

Typical SUSY events are 10^5 events for 10 fb^{-1} , while BG rate is 10^{9-8} for W, Z, t tbar production. The cuts need to be optimized

Large amount of missing energy, high p_T jets, large numbers of jets and leptons are good handles on signal



SUSY Models

MSSM has more than 100 parameters

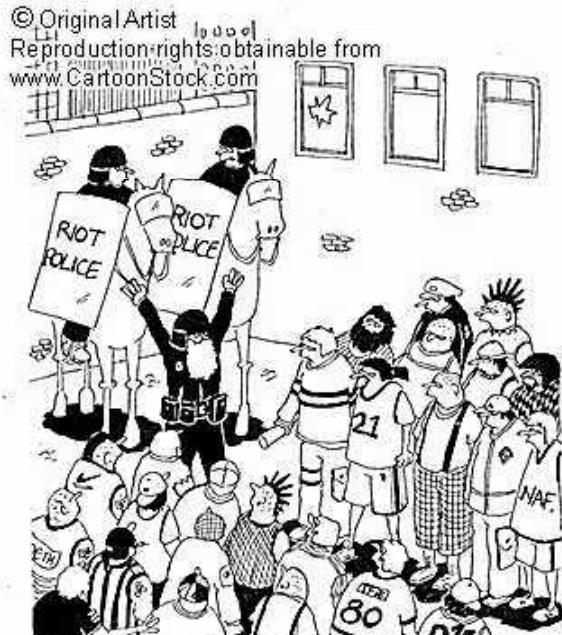
The number of parameters can be reduced in different models

Minimal Model: minimal supergravity (mSUGRA)/CMSSM

Nonuniversal SUGRA model, Anomaly mediated, NMSSM, Compressed- SUSY

Mixed Moduli, Gauge Mediated, non-critical string model, Split SUSY,

Long lived NLSP models, GUT less models, Planck scale SU(5), SO(10) models etc..



Let LHC Decide

**Once SUSY is discovered,
models will be searched
based on typical signals**

These models also will be simultaneously tested at the underground , satellite experiments from their characteristic features.

SUSY Theory at the LHC

Minimal Supergravity (mSUGRA)

Let us use the simplest model to describe the reach of LHC

4 parameters + 1 sign

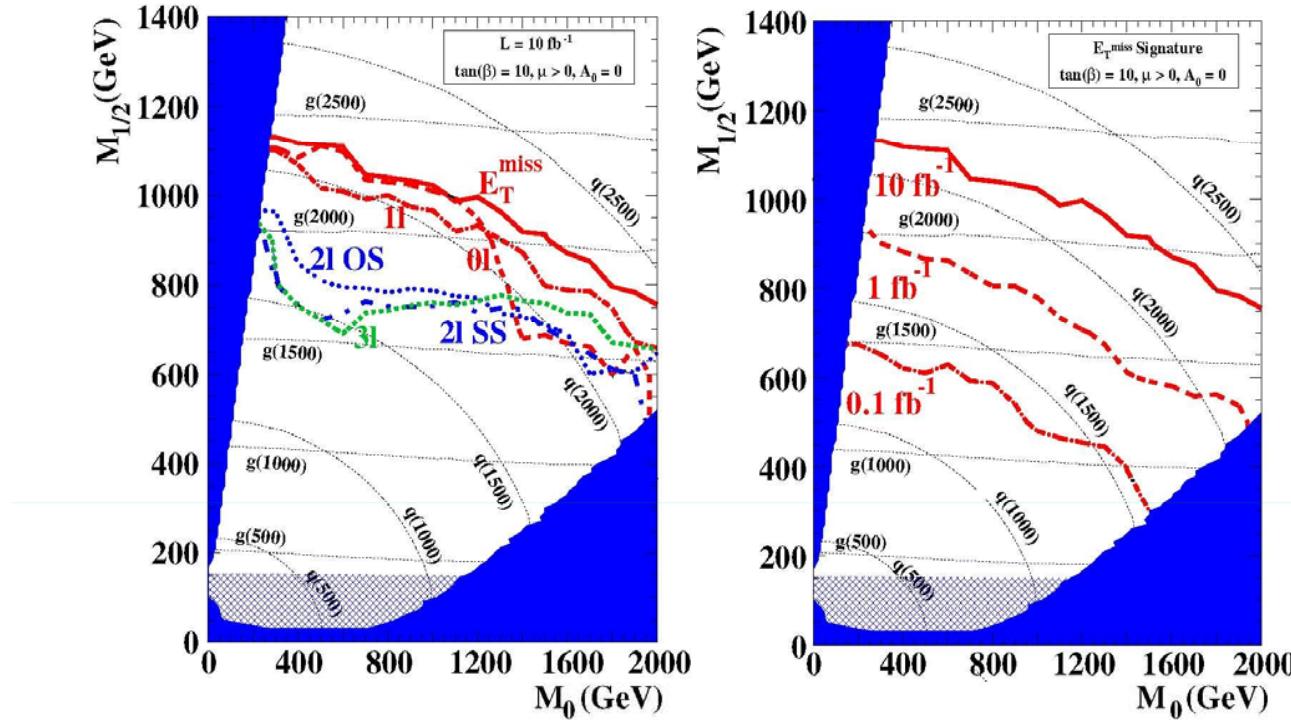
$m_{1/2}$	Common gaugino mass at M_G
m_0	Common scalar mass at M_G
A_0	Trilinear coupling at M_G
$\tan\beta$	$\langle H_u \rangle / \langle H_d \rangle$ at the electroweak scale
sign(μ)	Sign of Higgs mixing parameter ($W^{(2)} = \mu H_u H_d$)

Experimental Constraints

- i. $M_{\text{Higgs}} > 114 \text{ GeV} \quad M_{\text{chargino}} > 104 \text{ GeV}$
- ii. $2.2 \times 10^{-4} < Br(b \rightarrow s \gamma) < 4.5 \times 10^{-4}$
- iii. $0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129$
- iv. $(g-2)_\mu$

Reach at the LHC

Use Jets + leptons + E_T miss discovery channel.



Sensitivity only weakly dependent on A_0 , $\tan(\beta)$ and sign(μ).

Tovey'02

M. Tytgat (SUSY'07)

Measurement of Masses

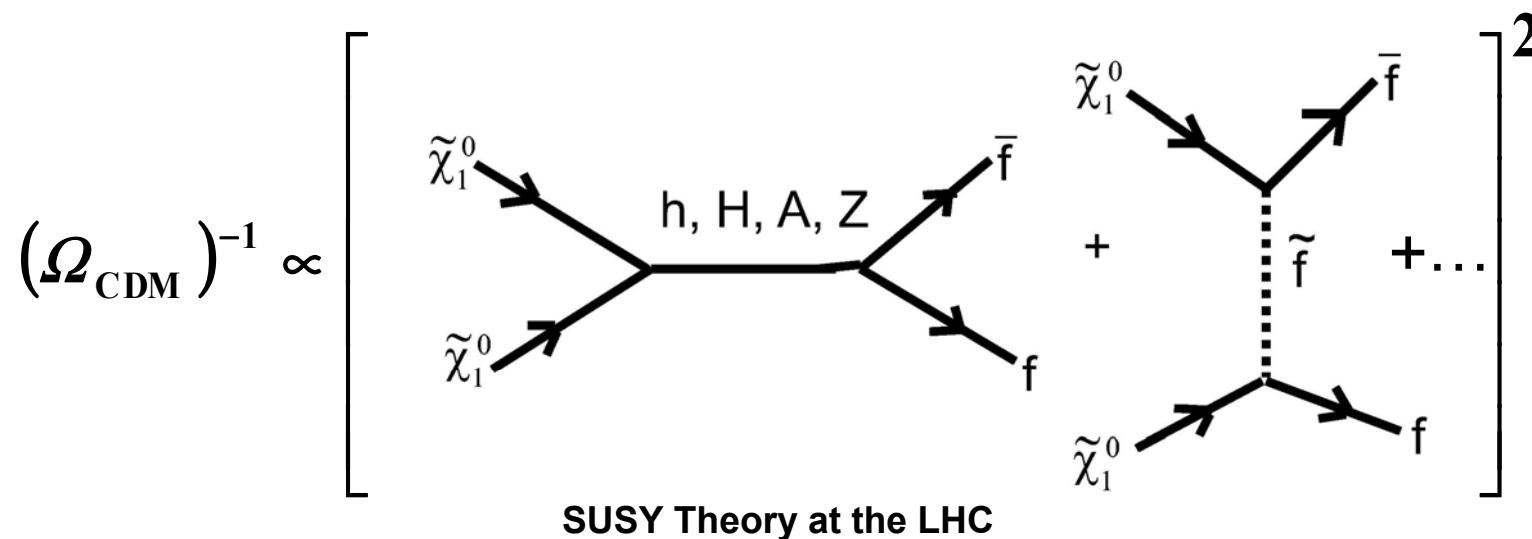
We need to measure the masses of the particles.

Model parameters need to be determined to check the cosmological status. [Allanach, Belanger, Boudjema and Pukhov'04]

If we observe missing energy, then we have a possible dark matter candidate .

[LHC experiments sensitive only to LSP lifetimes $< 1 \text{ ms}$ ($\ll t_U \sim 13.7 \text{ Gyr}$)]

Using the model parameters we need to calculate relic density



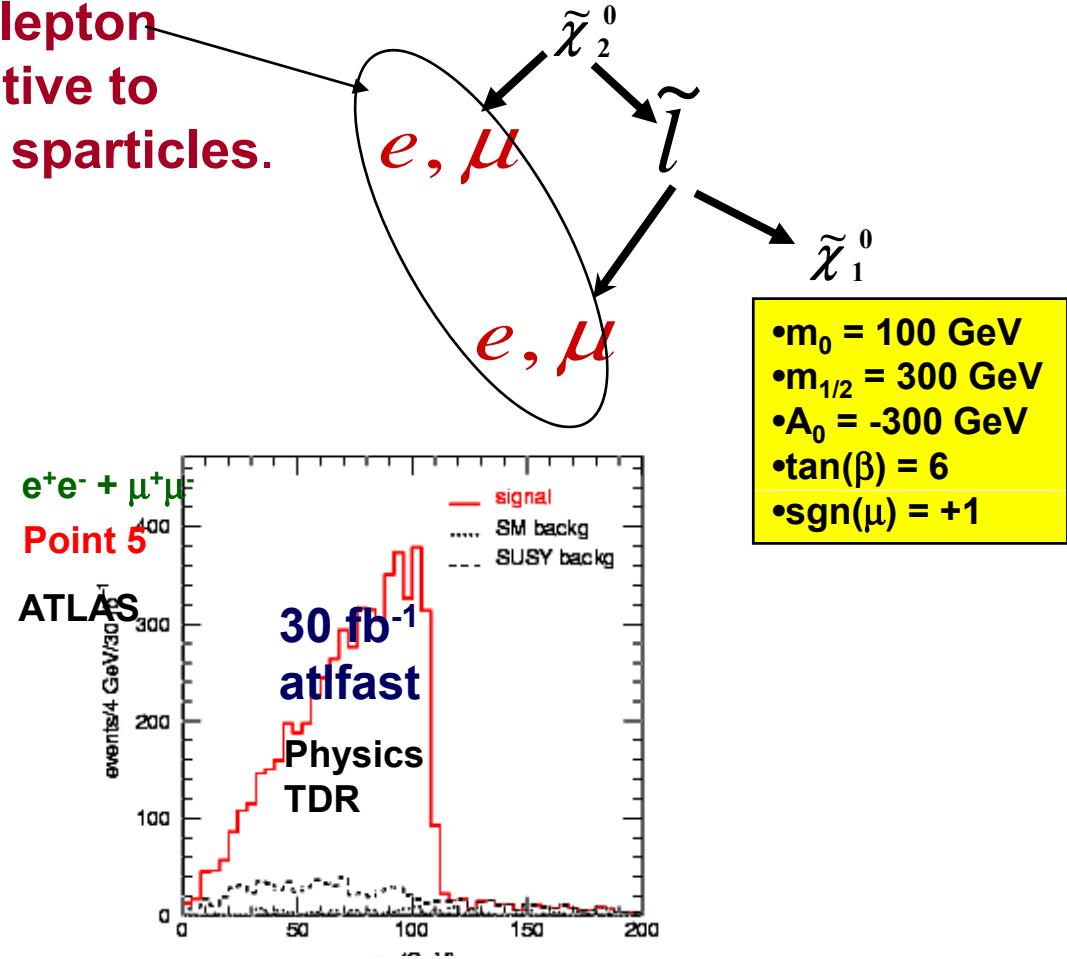
Dilepton Edge Measurement

- Decay of $\tilde{\chi}_2^0$ results into dilepton invariant mass edge sensitive to combination of masses of sparticles.

Can perform SM & SUSY background subtraction using distribution

$$e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$$

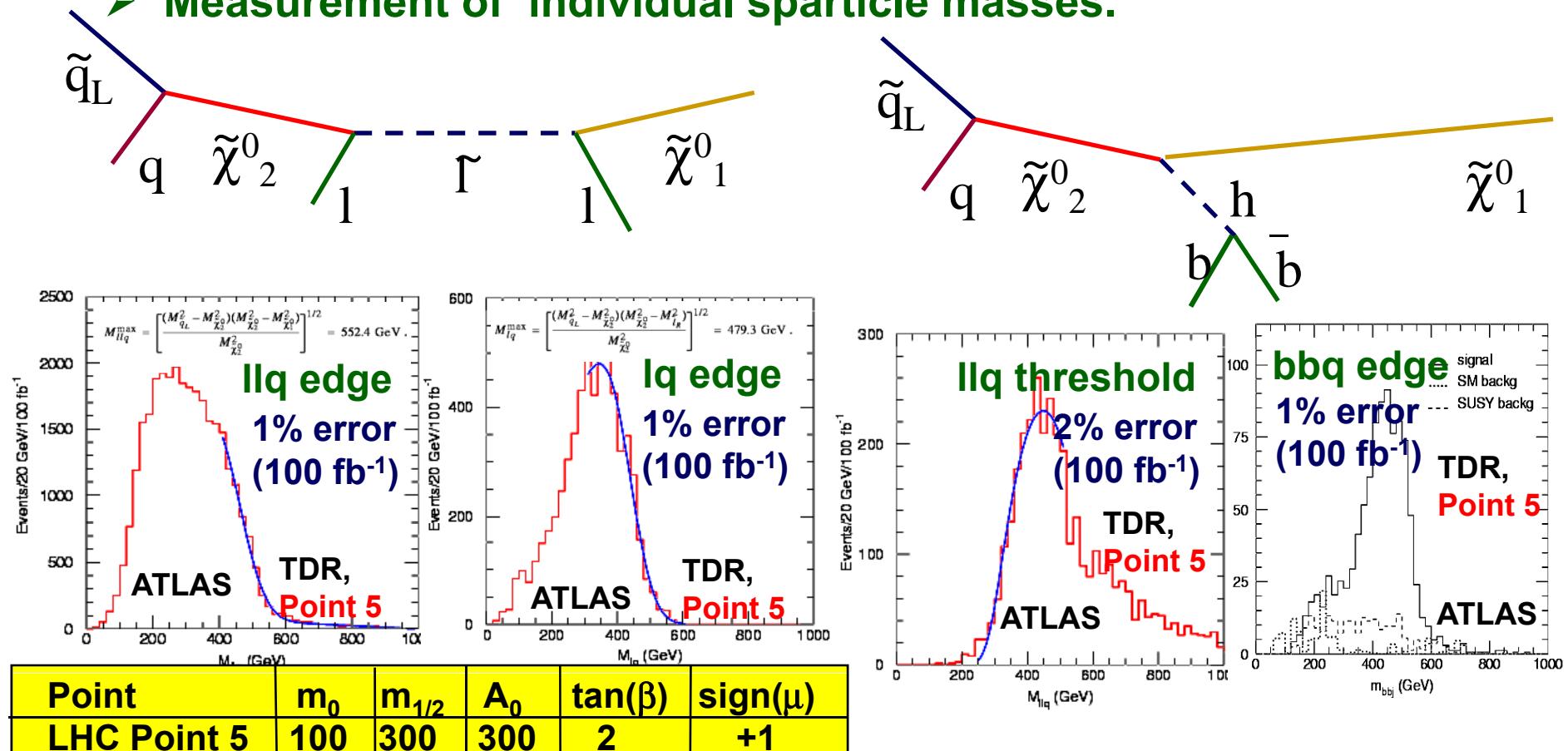
Position of edge measured with precision $\sim 0.5\%$ (30 fb^{-1}).



$$M_{ll}^{\max} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$

Measurements with Squarks

- Use Dilepton edge for reconstruction of decay chain.
- Make invariant mass combinations of leptons and jets.
- multiple constraints on combinations of four masses.
- Measurement of individual sparticle masses.

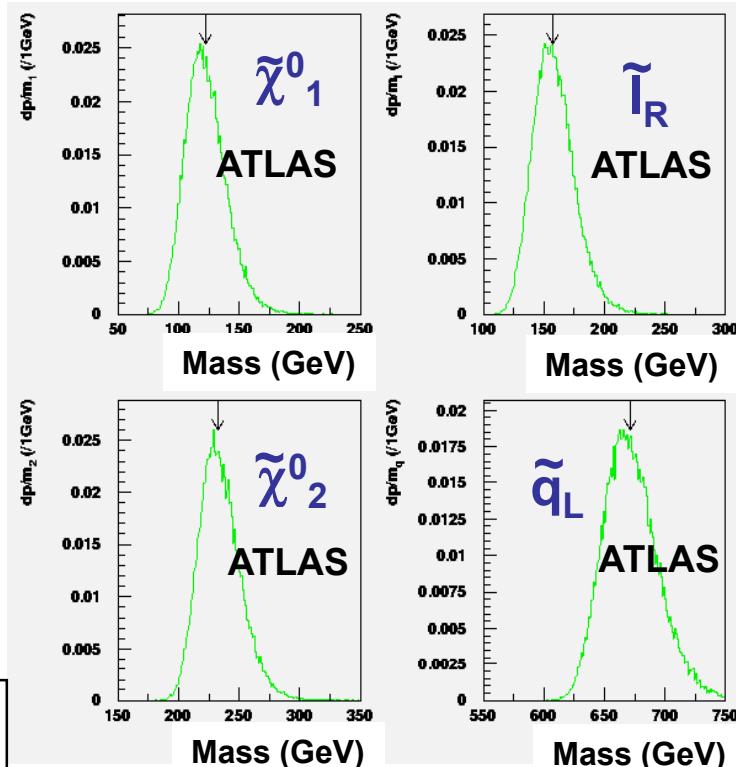


Model Independent Masses

- Measurements from edges from different jet-lepton combinations to obtain ‘model-independent’ mass measurements.

Sparticle	Expected precision (100 fb ⁻¹)
\tilde{q}_L	$\pm 3\%$
$\tilde{\chi}^0_2$	$\pm 6\%$
\tilde{l}_R	$\pm 9\%$
$\tilde{\chi}^0_1$	$\pm 12\%$

LHC
Point 5



Accuracies using many of such observables:

2% (m_0), 0.6% ($m_{1/2}$), 9% ($\tan\beta$), 16% (A_0)

Similar analysis, P. Beagle (SUSY 07); M. Rauch (SUSY 07)

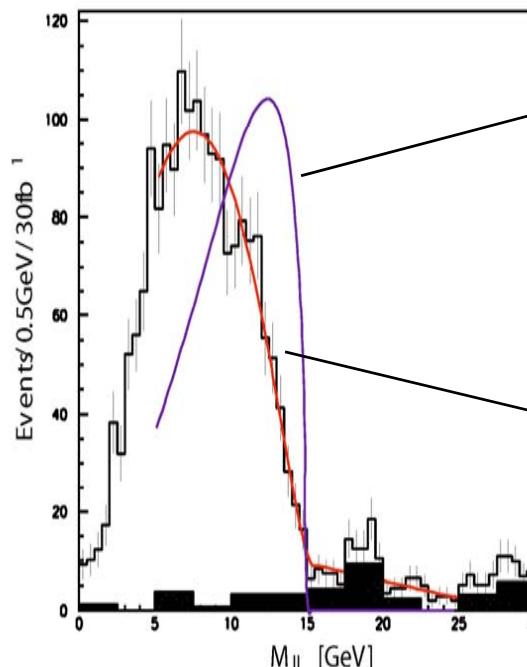
Higgsino vs Gaugino ...

$\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$: Higgsinos, three gaugino masses are very close

$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \quad l^+l^- \quad \text{With } M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0) < M_Z \quad M_{\text{Slepton}} > M_Z$$

Kitano, Nomura'06

The spectrum terminates at $m(l^+l^-)_{\max}$



Gaugino
Like $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$

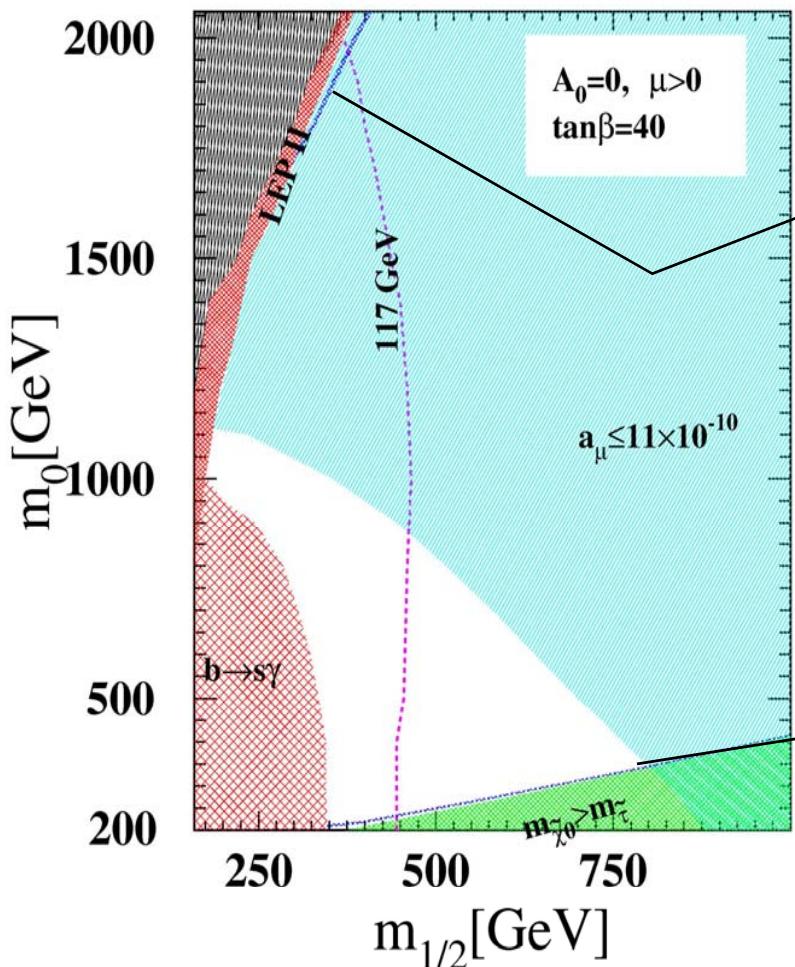
Higgsino

Using other
observables like
 M_{llq} , M_{lq} , M_T , it is
possible to measure
squark and the
neutralino mass with
an accuracy of
2% and 10%

Shapes looks different, 2 scenarios can be distinguished

Dark Matter Allowed Regions

We choose mSUGRA model. However, the results can be generalized.



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

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

[Neutralino-stau coannihilation region]

Bulk region-almost ruled out

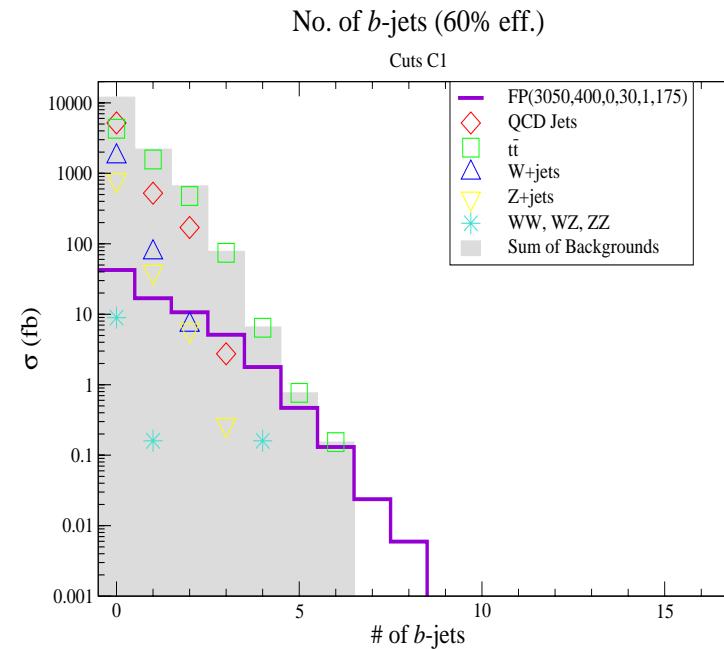
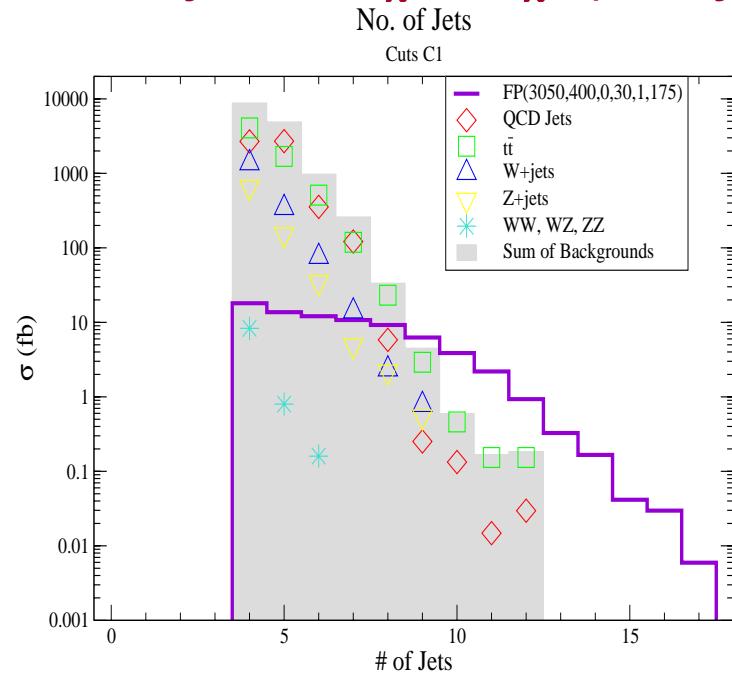
Focus Point : Jets+leptons

**Typical mSUGRA point: $m_0=2910$; $A_0=0$; $m_{1/2}=350$; $\mu>0$; $\tan\beta=30$;
Large sfermion mass, smaller gaugino masses comparatively**

**LHC events characterized by high jet, b-jet, isol. lepton
multiplicity**

Baer, Barger, Shaughnessy, Summy, Wang '07

Gluino decays into $t\bar{t}\chi^0$, $t\bar{b}\chi^+$ (mostly)]



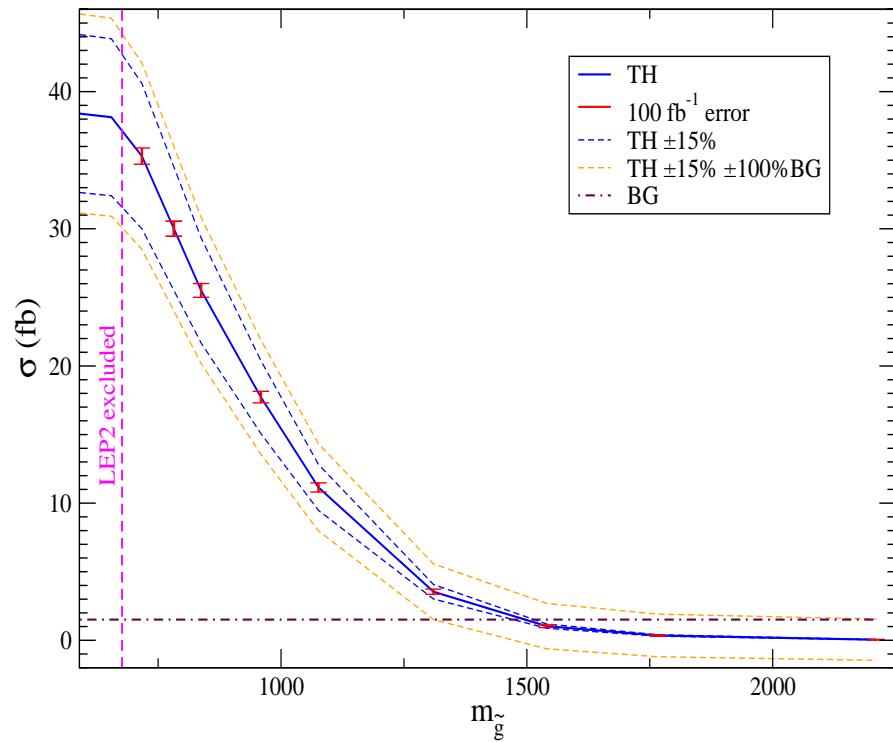
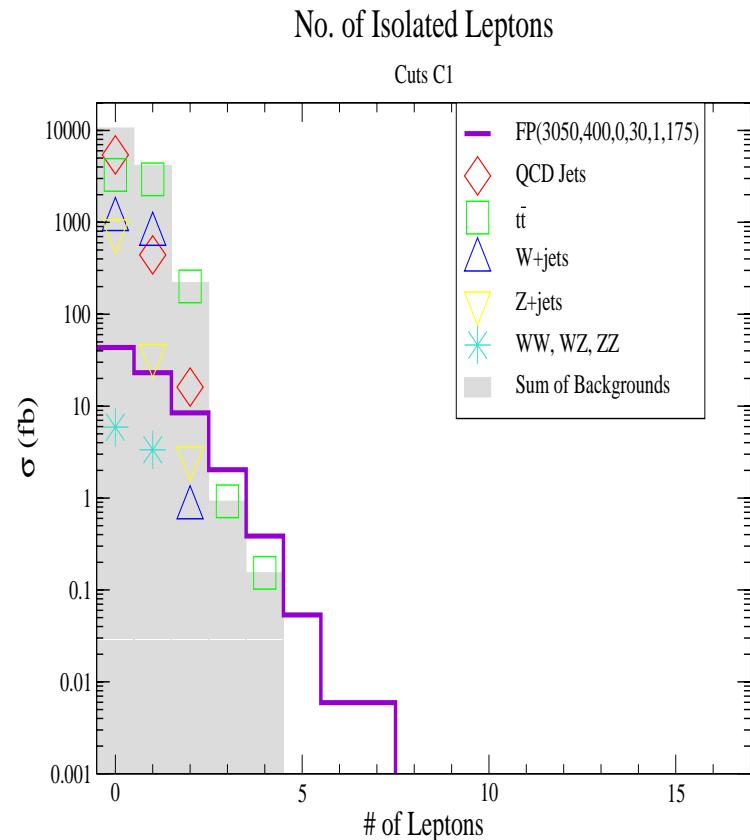
**Higher jet, b-jet, lepton multiplicity requirement increase the
signal over background rate**

Focus Point : Jets+leptons...

Require cuts: $n(j) \geq 7$, $n(b-j) \geq 2$, $A_T \geq 1400 \text{ GeV}$

Gluino mass can be measured with an accuracy 8%

$$E_T^{\text{miss}} + \sum E_T^{\text{jet}} + \sum E_T^{\text{lepton}}$$

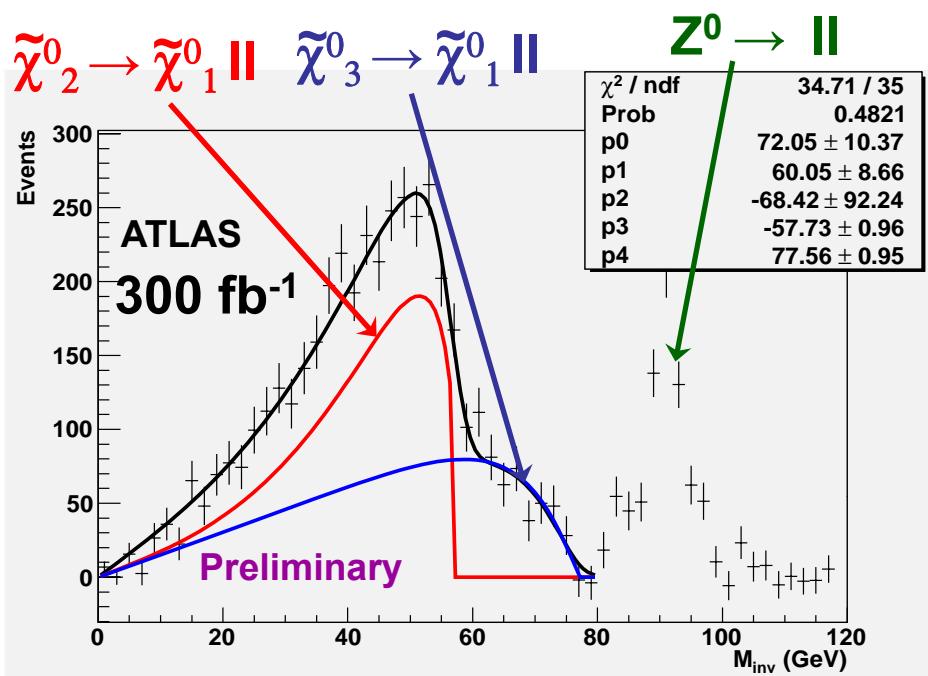


Baer, Barger, Shaughnessy, Summy, Wang '07

Focus Point: Leptons

- Large $m_0 \rightarrow$ sfermions are heavy
- $m_0 = 3550 \text{ GeV}$; $m_{1/2} = 300 \text{ GeV}$; $A_0 = 0$; $\tan\beta = 10$; $\mu > 0$
- Direct three-body decays $\tilde{\chi}_n^0 \rightarrow \tilde{\chi}_1^0 + 2 \text{ leptons}$
- Edges give $m(\tilde{\chi}_n^0) - m(\tilde{\chi}_1^0)$

Tovey, PPC'07



Parameter	Without cuts	Exp. value
M_1	68 ± 92	103.35
$M_2 - M_1$	57.7 ± 1.0	57.03
$M_3 - M_1$	77.6 ± 1.0	76.41

Similar analysis: Error $(M_2 - M_1) \sim 0.5 \text{ GeV}$
G. Moortgat-Pick (SUSY 07)

Bulk Region

The most part of this region in mSUGRA is experimentally (Higgs mass limit, $b \rightarrow s \gamma$) ruled out

Relic density is satisfied by t channel selectron, stau and sneutrino exchange
 Perform the end point analysis to determine the masses

mSUGRA point:

$m_0 = 70$; $A_0 = -300$
 $m_{1/2} = 250$; $\mu > 0$;
 $\tan\beta = 10$;

sparticle	mass
$\tilde{\chi}_1^0$	97.2
$\tilde{\chi}_2^0$	398
\tilde{e}	189
\tilde{g}	607
\tilde{u}_L	533

Nojiri, Polsello, Tovey'05

End pts	value	error
m_{ll}	81.2	0.09
$M_{lq}(\text{max})$	365	2.1
$M_{lq}(\text{min})$	266.9	1.6
$M_{lq}(\text{max})$	425	2.5
$M_{llq}(\text{min})$	207	1.9
$M_{\tau\tau}(\text{max})$	62.2	5.0

The error of relic density: $0.108 \pm 0.01(\text{stat + sys})$

Includes: $(+0.00, -0.002) M(A)$; $(+0.001, -0.011) \tan\beta$; $(+0.002, -0.005) m(\tilde{\tau}_2)$

[With a luminosity 300 fb^{-1} , $\tau\tau$ edge controlled to 1 GeV]

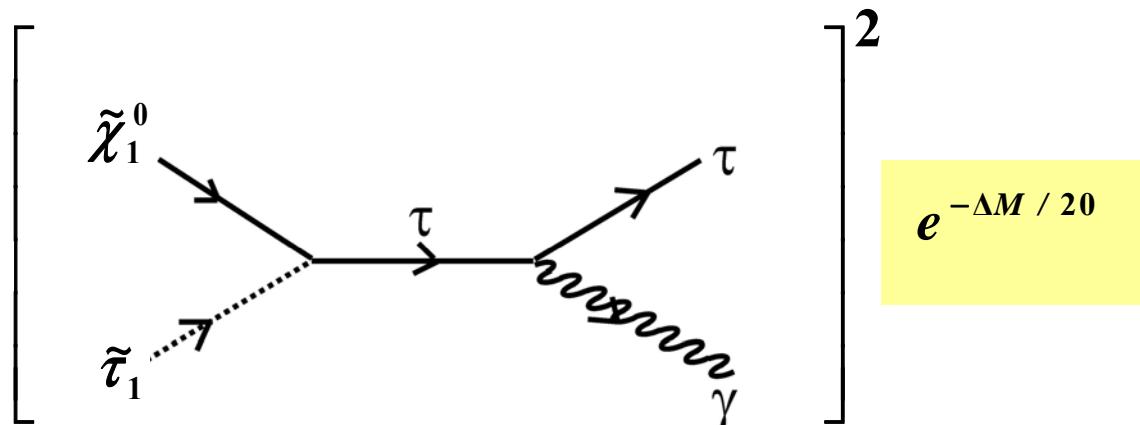
Coannihilation Signatures

Mass of another sparticle comes close to the neutralino:
both of them are thermally available.

This region appears for small m_0 and $m_{1/2}$ values and
therefore will be accessible within a short time

For small $\tan\beta$ this region has e, μ, τ in the signals

For large $\tan\beta$ this region has τ in the signals



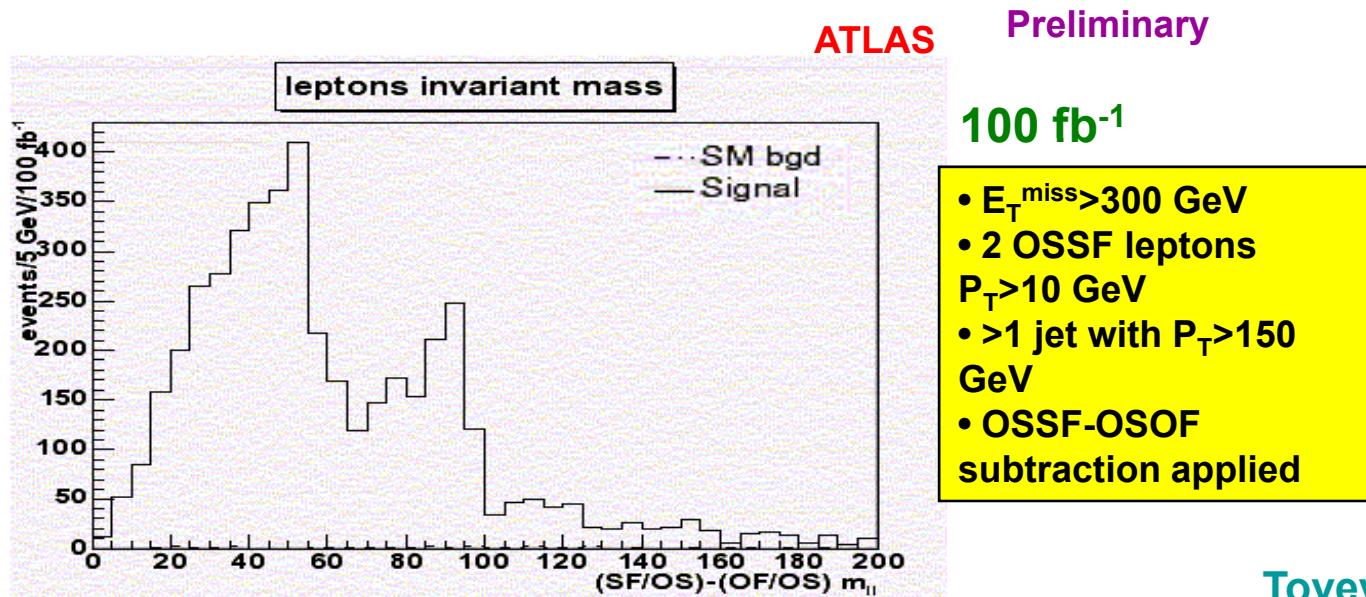
$$e^{-\Delta M / 20}$$

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

Griest, Seckel '91

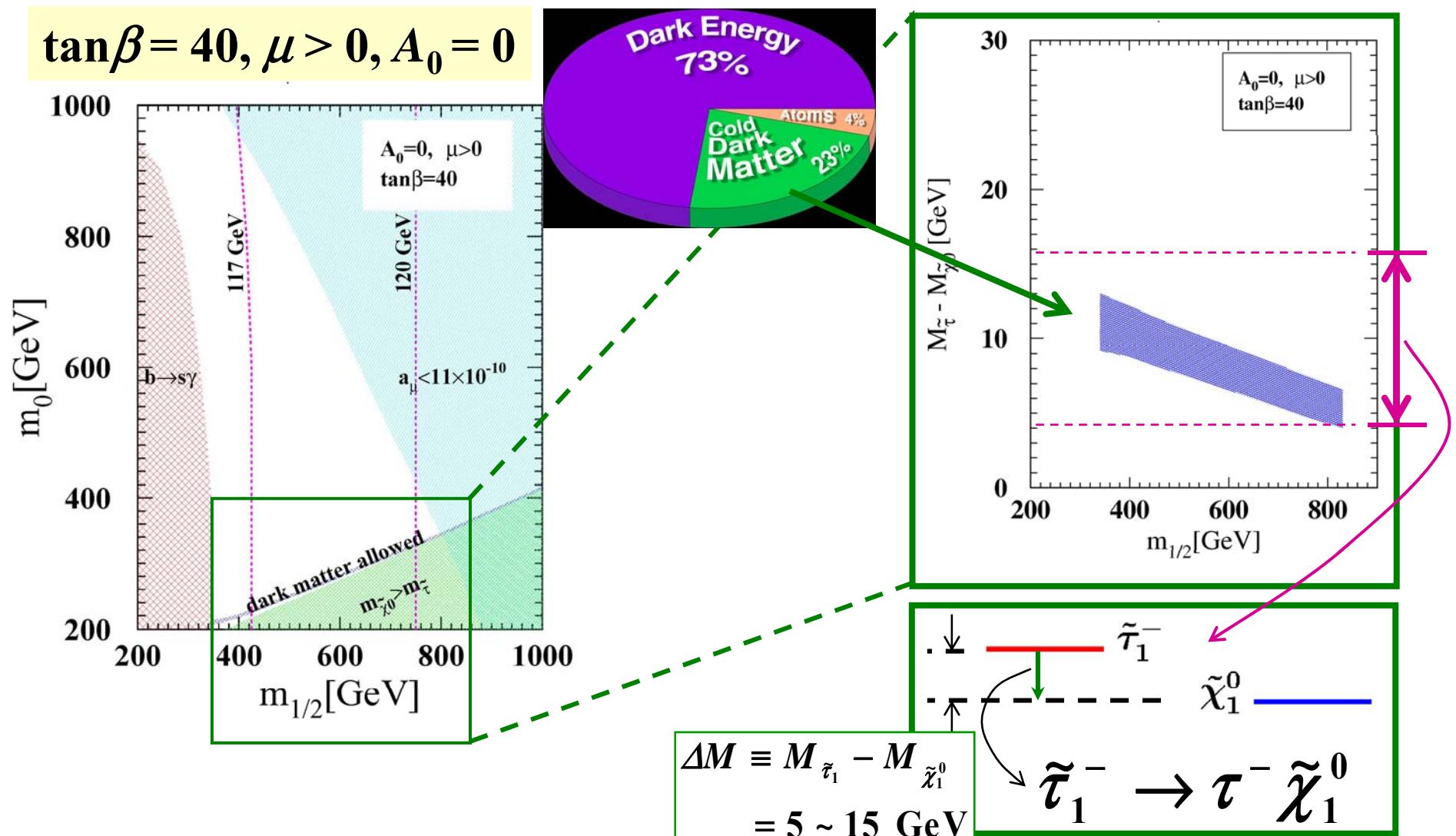
Coann. Signatures ($\tan\beta=10$)

- Small slepton-neutralino mass difference gives soft leptons
 - Low electron/muon/tau energy thresholds crucial.
- Study point chosen within region:
 - $m_0=70$ GeV; $m_{1/2}=350$ GeV; $A_0=0$; $\tan\beta=10$; $\mu>0$;
- Decays of χ^0_2 to both I_L and I_R kinematically allowed.
 - Double dilepton invariant mass edge structure;
 - Edges expected at 57 / 101 GeV



Tovey, PPC'07

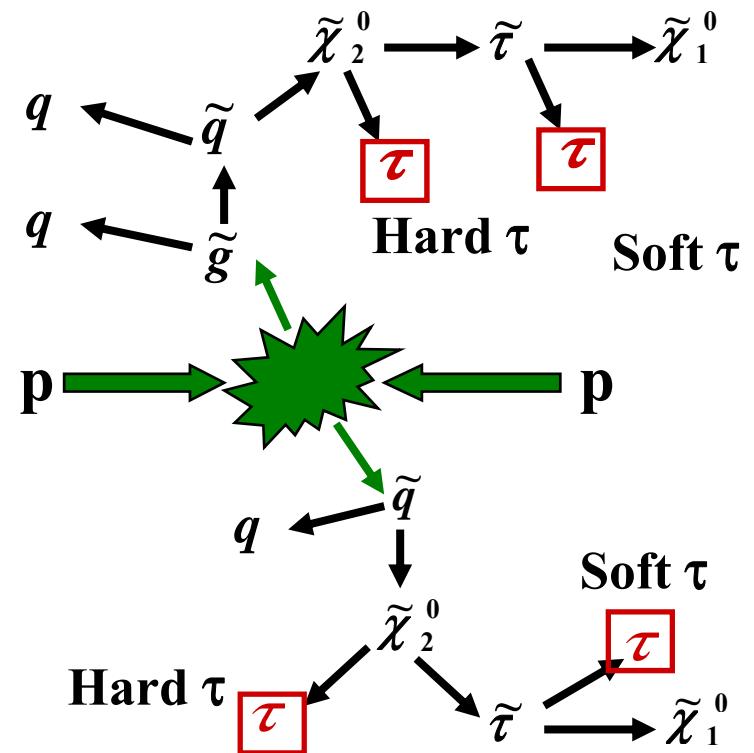
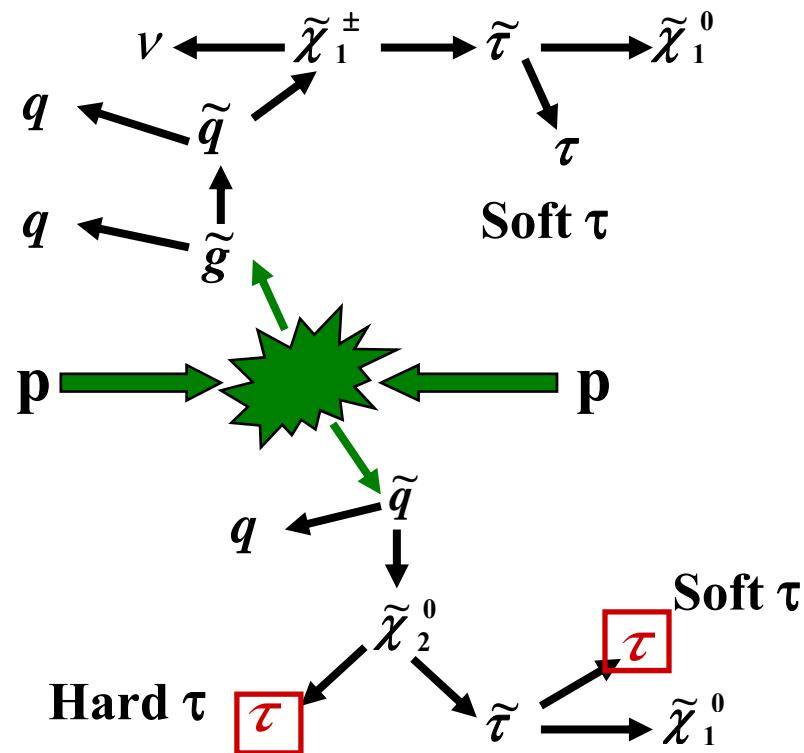
Coannihilation Region ($\tan\beta=40$)



Can we measure ΔM at colliders?

Coann. Signatures ($\tan\beta=40$)

In Coannihilation Region of SUSY Parameter Space:



Final state: $3/4 \tau s + \text{jets} + \text{missing energy}$
 Use hadronically decaying τ

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

Four Observables

1. Sort τ 's by E_T ($E_T^1 > E_T^2 > \dots$) and use OS-LS method to extract τ pairs from the decays
2. Use counting method (N_{OS-LS}) & ditau invariant mass ($M_{\tau\tau}$) to measure mass difference ΔM (between the lightest stau and the neutralino) and gluino mass
3. Measure the P_T of the low energy τ to estimate the mass difference ΔM
D. Toback's talk, parallel session
4. Measure jet- $\tau-\tau$ invariant mass $M_{j\tau\tau}$

Arnowitt, B.D., Kamon, Toback, Kolev,'06; Arnowitt, Arusano,B.D., Kamon, Toback,Simeon,'06; Arnowitt,B.D., Gurrola, Kamon, Krislock, Toback, to appear; D. Toback, talk [this conf]

SUSY Parameters

Since we are using 4 variables, we can measure ΔM , M_{gluino} and the universality relation of the gaugino masses

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

M_{gluino} measured from the M_{eff} method may not be accurate for this parameter space since the tau jets may pass as jets in the M_{eff} observable.

The accuracy of measuring these parameters are important for calculating relic density.

EVENTS WITH CORRECT FINAL STATE : $2\tau + 2j + E_T^{\text{miss}}$

APPLY CUTS TO REDUCE SM BACKGROUND (W+jets, t-tbar,...)

$E_T^{\text{miss}} > 180 \text{ GeV}$, $E_T^{j1} > 100 \text{ GeV}$, $E_T^{j2} > 100 \text{ GeV}$, $E_T^{\text{miss}} + E_T^{j1} + E_T^{j2} > 600 \text{ GeV}$

ORDER TAUS BY P_T & APPLY CUTS ON TAUS: WE EXPECT A SOFT τ AND A HARD τ

$P_T^{\text{all}} > 20 \text{ GeV}$, $P_T^{\tau 1} > 40 \text{ GeV}$

$M_{\tau\tau}^{\text{vis}}$ in ISAJET

Version 7.69 ($m_{1/2} = 347.88$, $m_0 = 201.1$) $\rightarrow M_{\text{gluino}} = 831$

Chose di- τ pairs from neutralino decays with

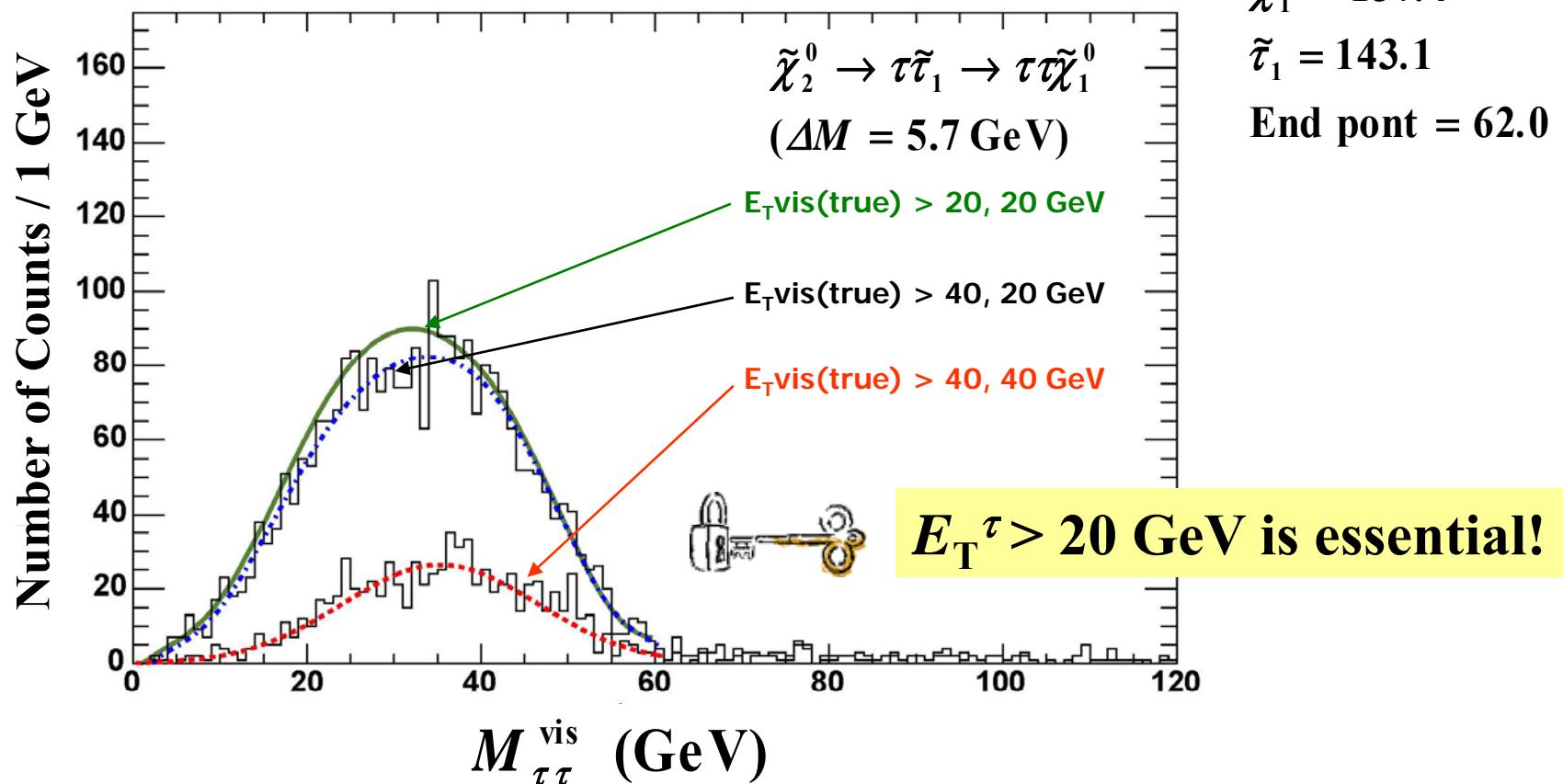
- (a) $|\eta| < 2.5$
- (b) $\tau = \text{hadronically-decaying tau}$

$$\tilde{\chi}_2^0 = 264.1$$

$$\tilde{\chi}_1^0 = 137.4$$

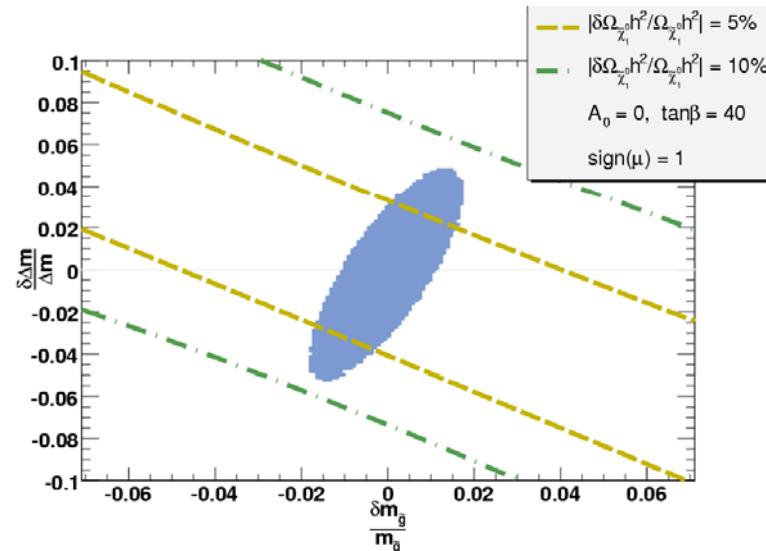
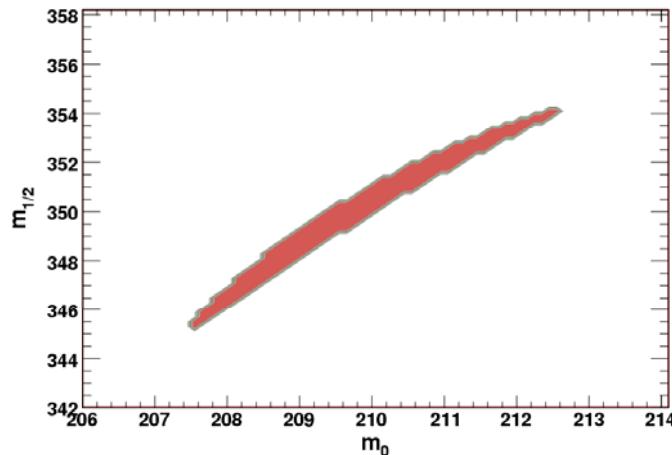
$$\tilde{\tau}_1 = 143.1$$

End point = 62.0



Determination of m_0 , $m_{1/2}$

ΔM and $M_{\text{gluino}} \rightarrow m_0, m_{1/2}, \Omega_{\tilde{\chi}_1^0} h^2$
 (for fixed A_0 and $\tan\beta$)



We determine $\delta m_0/m_0 \sim 1.2\%$ and $\delta m_{1/2}/m_{1/2} \sim 2\%$
 $\delta \Omega h^2/\Omega h^2 \sim 7\% (10 \text{ fb}^{-1})$
 (for $A_0=0$, $\tan\beta=40$)

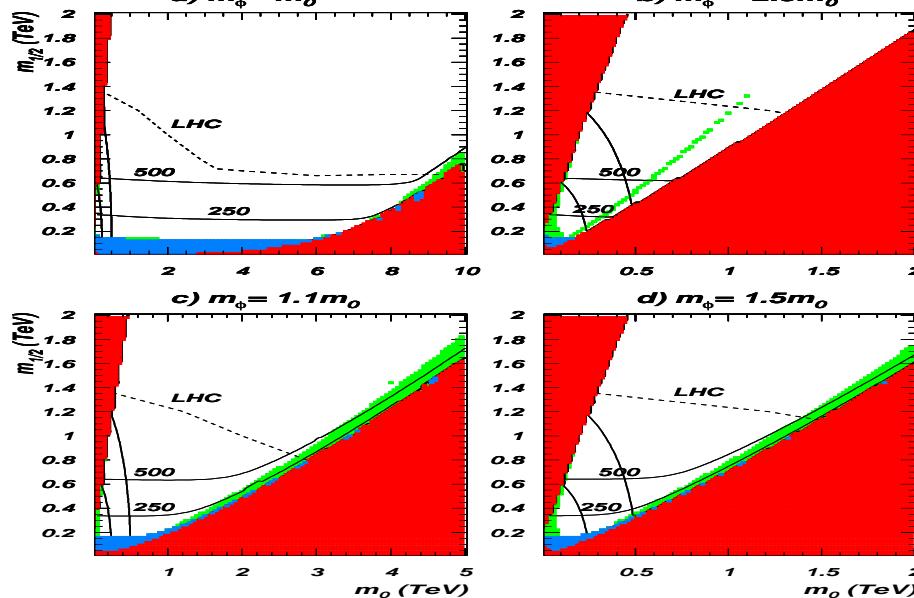
Higgs non-universality

The most common extension of mSUGRA

$$m_{H_1}^2 = m_0^2(1 + \delta_1)$$

$$m_{H_2}^2 = m_0^2(1 + \delta_2)$$

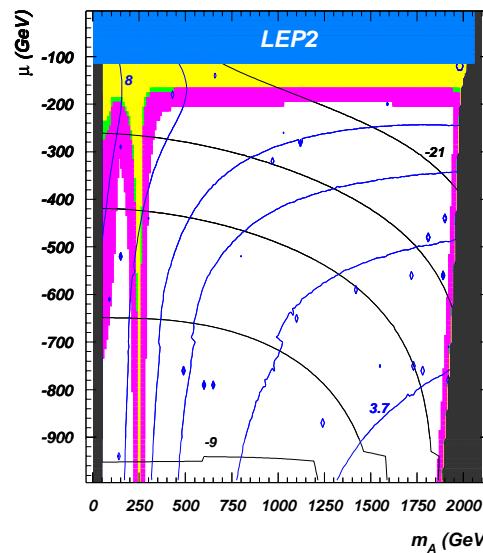
Case 1. $m_{H_1} = m_{H_2}$



Case 2. $m_{H_1} \neq m_{H_2}$

NUHM2: $m_0=300\text{GeV}$, $m_{1/2}=300\text{GeV}$, $\tan\beta=10$, $A_0=0$, $m_{\tilde{t}}=178\text{GeV}$

- $\delta a_\mu \times 10^{10}$ -9, -10, -12, -15, -21
- $\Omega h^2 < 0.094$ (yellow)
- $0.094 < \Omega h^2 < 0.129$ (green)
- $BF(b \rightarrow s\gamma) \times 10^4$ 3.7, 4, 4.5, 5, 6, 8
- $\Omega h^2 > 0.129$ (magenta)



Drees'00;
Baer
Belyaev,
Mustafayev,
Profumo,
Tata'05
Ellis,
Olive,
Santoso'03

LHC signal:

A, H and H^\pm will be relatively light, and more accessible to direct LHC searches

There can be light u_R , c_R squarks, small μ : leads to light $\tilde{\chi}_i^0$ and $\tilde{\chi}_i^\pm$

SUSY Theory at the LHC

Moduli-Mediation

KKLT model: type IIB string compactification with fluxes

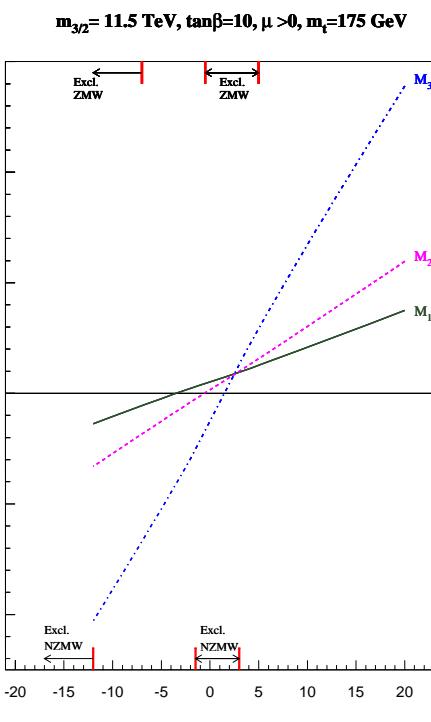
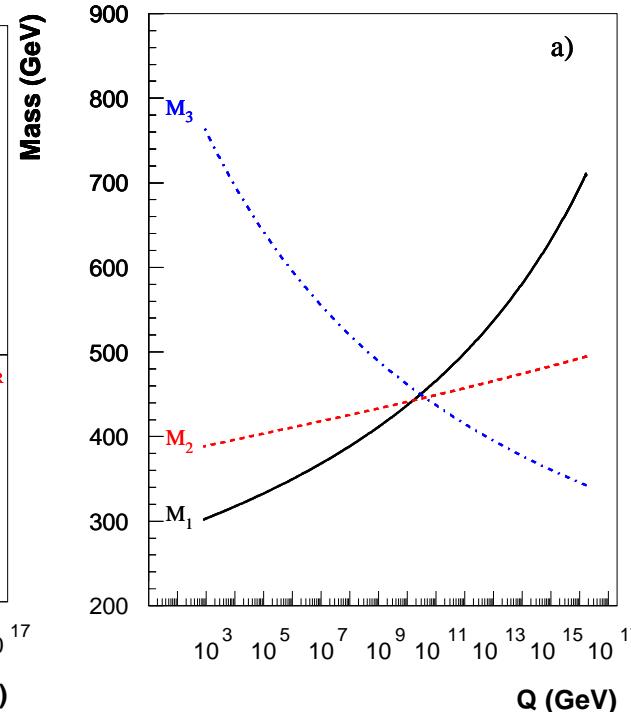
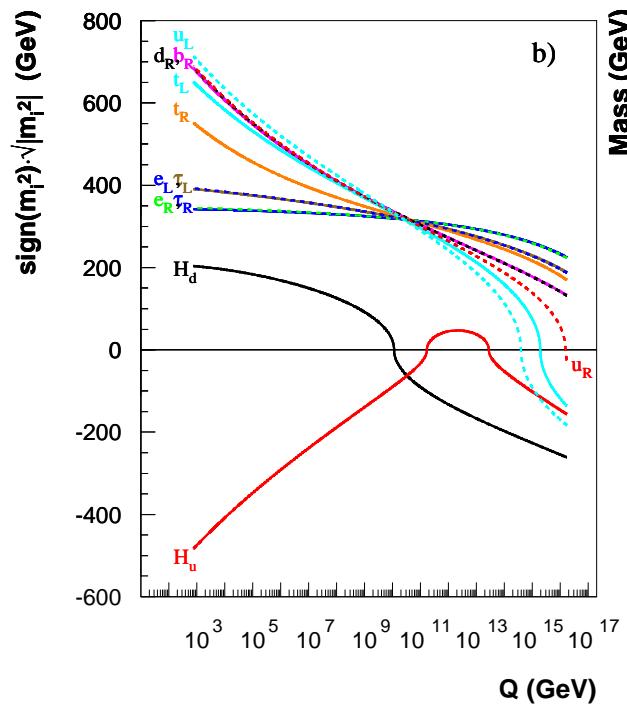
MSSM soft terms have been calculated, Choi, Falkowski, Nilles, Olechowski, Pokorski

Ratio of the modular mediated and anomaly mediated is given by a phenomenological parameter α

Choi, Jeong, Okumura, Falkowski, Lebedev, Mambrini, Kitano, Nomura

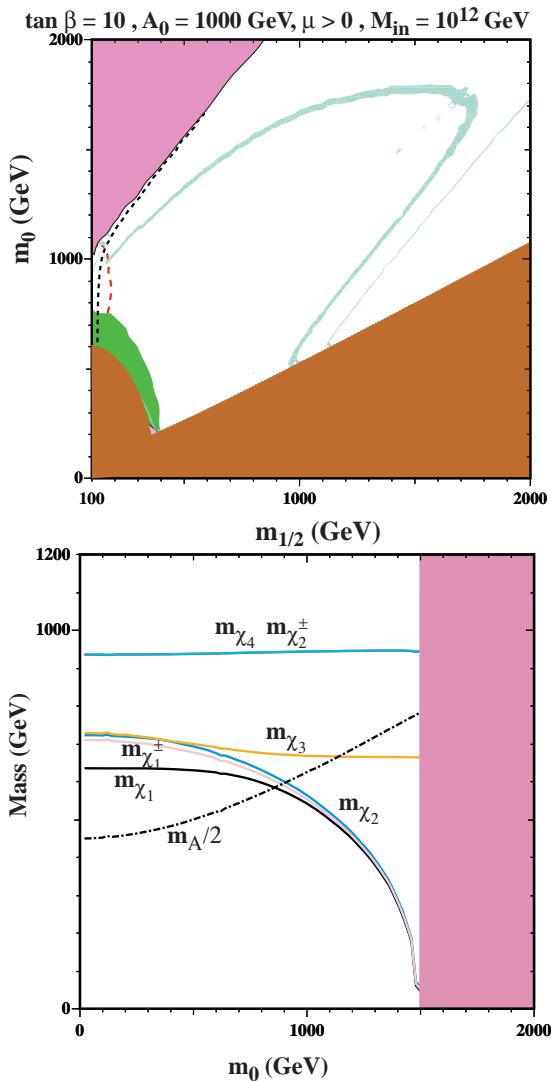
$$\alpha=6, m_{3/2}=12 \text{ TeV}, \tan\beta=10, \mu>0, m_t=175 \text{ GeV}$$

$$\alpha=6, m_{3/2}=12 \text{ TeV}, \tan\beta=10, \mu>0, m_t=175 \text{ GeV}$$

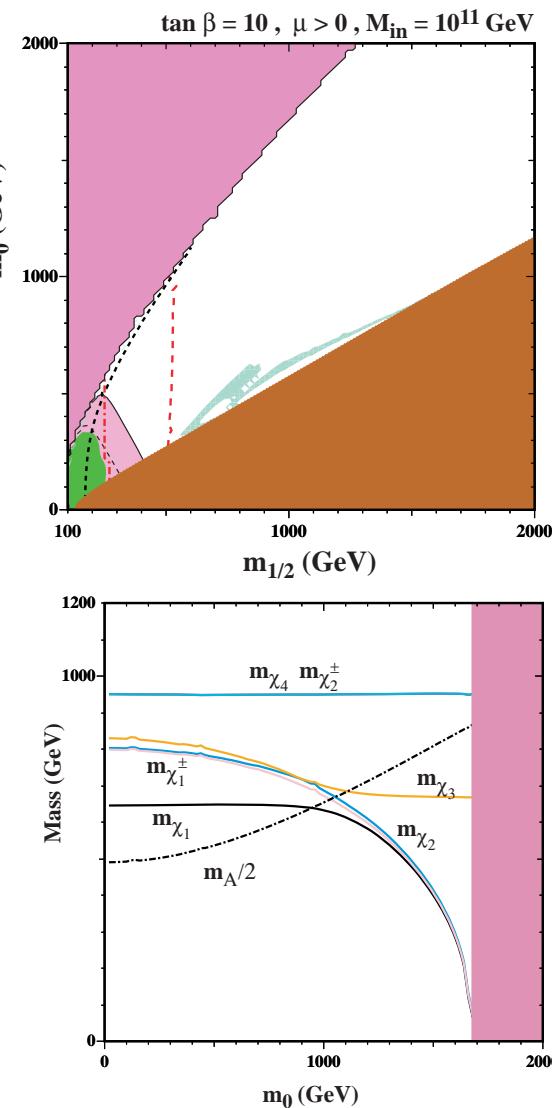


Baer, Park, Tata, Wang'06,07

GUT-less and Moduli Mediation



GUT-less



MM-AMSB

Ellis,
Olive,
Sandick'07

μ is smaller
in the GUT -
less case
for this
Example.

Other Examples...

Bino-wino Coannihilation,

Mixed Wino coannihilation

In these cases, the lightest chargino and the second lightest neutralino are very close to the lightest neutralino

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$: decay opens up along with other three body decay modes

Baer et. al.'05

Long-lived charged particles:

Gravitino LSP (mass around 100 GeV...) and sleptons NLSP

One can find that the sleptons to decay after a long time

Feng, Su, Takayama, '04

Stop NLSP: stop \rightarrow charm + $\tilde{\chi}_1^0$

Gladyshev, Kazakov, Paucar'05'07

NMSSM: This model can have extra Z', sneutrino as dark matter candidate,
In the context of intersecting Brane Models [Kumar, Wells' 06]

Signal: $qq \rightarrow qqW+W-, qqZZ \rightarrow qqH1,2 \rightarrow qqA1A1; A1A1 \rightarrow bb\tau+\tau-$

SUSY Theory at the LHC

Moretti et al '06

Other Examples...

“Compressed” MSSM:

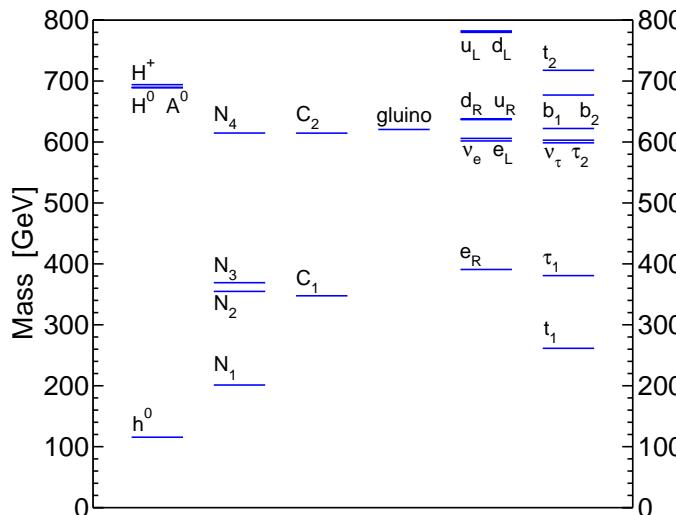
Martin,’07; Baer et al,’07

$$- m_{H_u}^2 = 1.92 M_3^2 + 0.16 M_2 M_3 - 0.21 M_2^2 - 0.33 M_3 A_t - 0.074 M_2 A_t + \dots$$

Naturalness argument : M_3 is small, use $M_3 < (M_2, M_1)$ at the GUT scale

Relic density is satisfied by neutralino annihilation via $t - t\bar{t}$ production, stop coannihilation etc.

A typical sample of “compressed” mass spectrum with $\Omega h^2 = 0.11$



The GUT scale parameters are $M_{1,2,3} = 500, 750, 250$, $A_0 = -500$, $m_0 = 342$ GeV

Reduction of leptons in the signal.

Inflation and MSSM : Flat directions LLE, UDD etc. Smaller sparticle masses are needed once the constraints from n_s , δ_H are included

Little Hierarchy : Smaller stop mass is needed

Allahverdi, Dutta, Mazumdar, 07

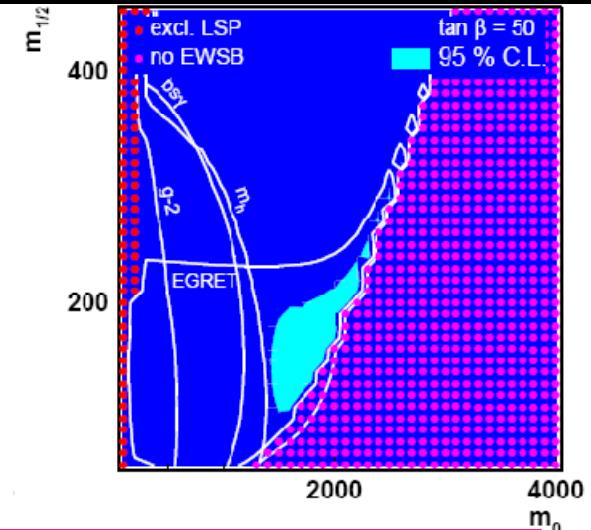
Ratazzi et al’06, Dutta, Mimura’07

Conclusion

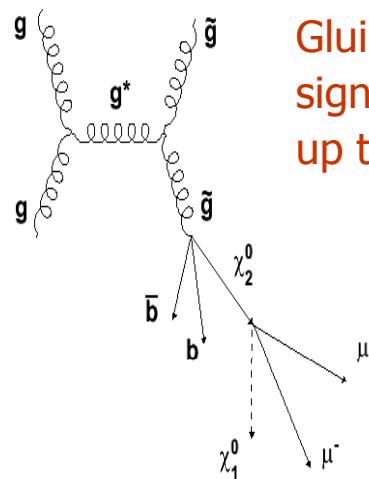
EGRET excess of diffuse galactic gamma rays is explained as a signal of supersymmetric dark matter annihilation

De Boer, Sander, Zhukov
Gladyshev, Kazakov'05,'06

Fitted SUSY parameters
 $m_0 = 1400 \text{ GeV}$ $\tan\beta = 50$
 $m_{1/2} = 180 \text{ GeV}$ $A_0 = 0.5m_0$



ATLAS



Gluino decays have a clear signature ($4\mu + 4\text{jets} + P_T$ + up to 4 secondary vertices).

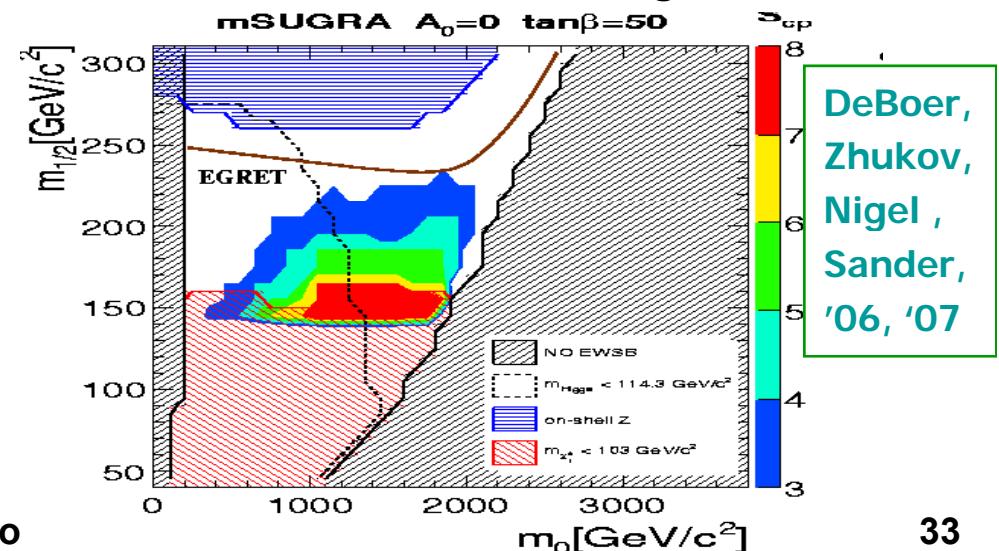
Expected # of events for ATLAS after 1 year of running with LHC luminosity $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ is around 150

Bednyakov, Budagov, Gladyshev,
Kazakov, Khoriauli, Khramov,
Khubua'06'07

SUSY Theo

CMS tri-lepton discovery potential

$XX \rightarrow 3 \text{ leptons}$
significance



Conclusion

LHC is a great machine to discover supersymmetry which would solve problems in particle physics and cosmology

Signature contains missing energy (R parity conserving) many jets and leptons : **Discovering SUSY should not be a problem!**

Once SUSY is discovered, attempts will be made to connect particle physics to cosmology

The masses and parameters will be measured, models will be investigated

Four different cosmological motivated regions of the minimal SUGRA model have distinct signatures

Based on these measurement, the dark matter content of the universe will be calculated to compare with WMAP/PLANCK data.

Conclusion...

I hope not...

