



**Prospects for SUSY using the ATLAS
Detector at the Large Hadron Collider**

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Introduction

SUSY maximal extension of Lorentz group. Inherent to most string theories: currently appear to be our best hope for incorporating gravity

Weak-scale SUSY well motivated as solution to gauge-hierarchy problem, gauge coupling unification etc.

R-parity conserving SUSY also provides good Cold Dark Matter Candidate (CDM now well established by WMAP results).

SUSY one of primary motivations for construction of LHC

MSSM 105 additional free parameters (masses, mixing angles, phases)

Different models / phenomenologies depending on mediation of SUSY breaking: SUGRA, GMSB, AMSB. Constrained models (few parameters)

mSUGRA $m_0, m_{1/2}, A_0, \tan\beta, \text{sgn}(\mu)$

mGMSB $M_{\text{mes}}, N_{\text{mes}}, \Lambda, \tan\beta, \text{sgn}(\mu)$

mAMSB $m_0, m_{\text{aux}}, \tan\beta, \text{sgn}(\mu)$

SUSY at ATLAS

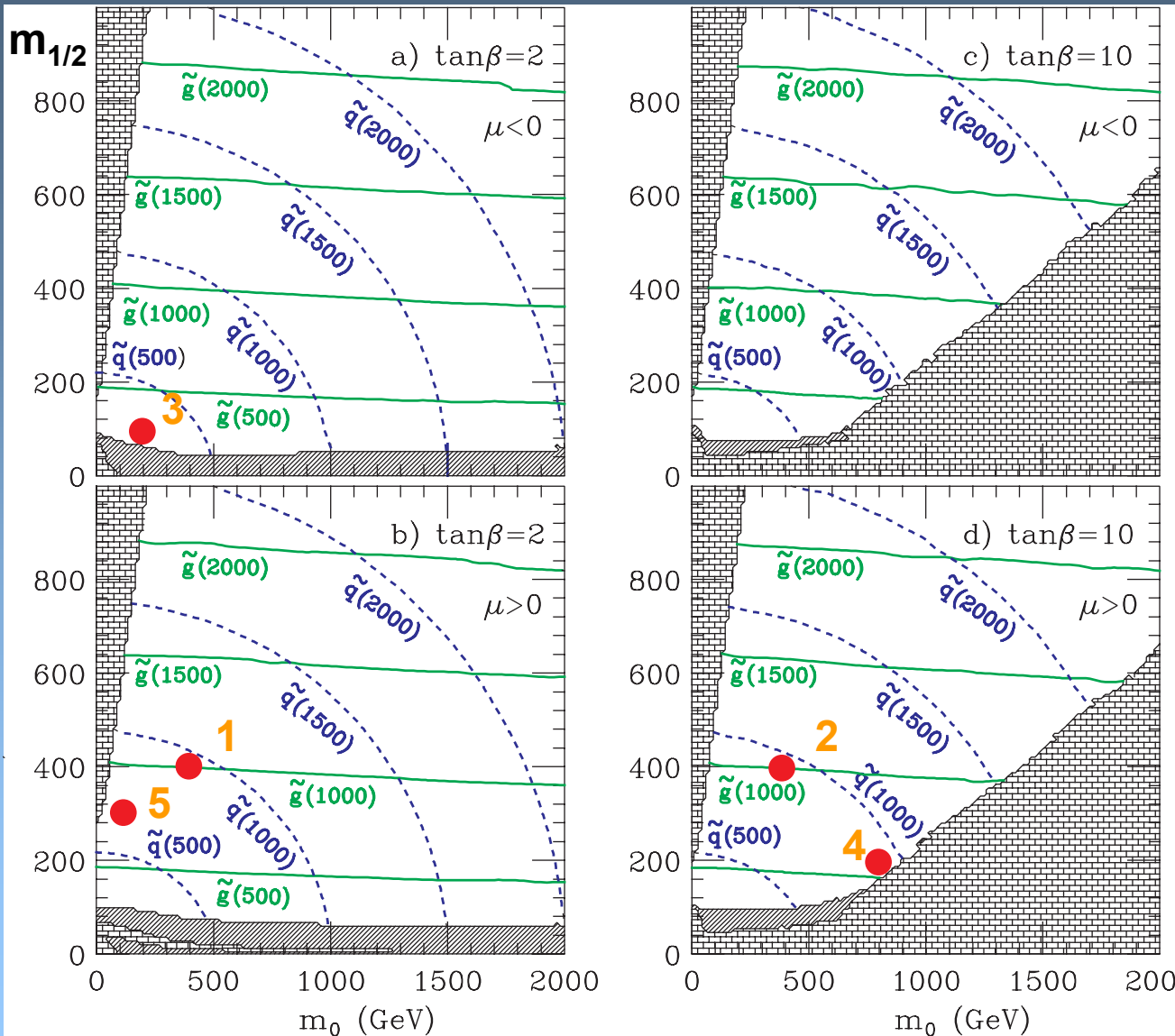
This talk:

- mSUGRA (though some 'model independent' measurements)
- Assume R-Parity conservation \rightarrow missing energy signature
- With appropriate selection criteria (p_T jets, p_T leptons, missing energy) SM background for many SUSY analyses are effectively negligible. Largest potential backgrounds then from competing SUSY decays.

Need to generate full SUSY spectrum for each point in parameter space

- Most analyses rely on fast simulation, or parametrisation of detector response. Some results from full simulation now available (5 fb^{-1}).
- What can be done early on ?
 - Discovery of SUSY (or discovery of non-SM missing energy signal)
 - Determination of SUSY mass scale
 - Determination of SUSY cross-section
 - Initial look at SUSY masses (will likely need much more luminosity)

LHCC SUSY Benchmark Points (1996)



mSUGRA

$m_0, m_{1/2}, A_0, \tan\beta, \text{sgn}(\mu)$

LHCC Point 5:
 $m_0 = 100$ GeV;
 $m_{1/2} = 300$ GeV;
 $A_0 = -300$ GeV;
 $\tan\beta = 2.1$; $\mu > 0$

Cosmologically interesting but higgs mass now excluded by LEP

Modified LHCC Point 5:
 as above but $\tan\beta = 6$

More Recent Benchmark Points (and slopes)

- Post-LEP Benchmarks for Supersymmetry hep-ph/0106204
- Points d'Aix GDR SUSY Workshop Aix-La-Chappele, 2001
- Snowmass (2001) Points and Slopes hep-ph/0202233

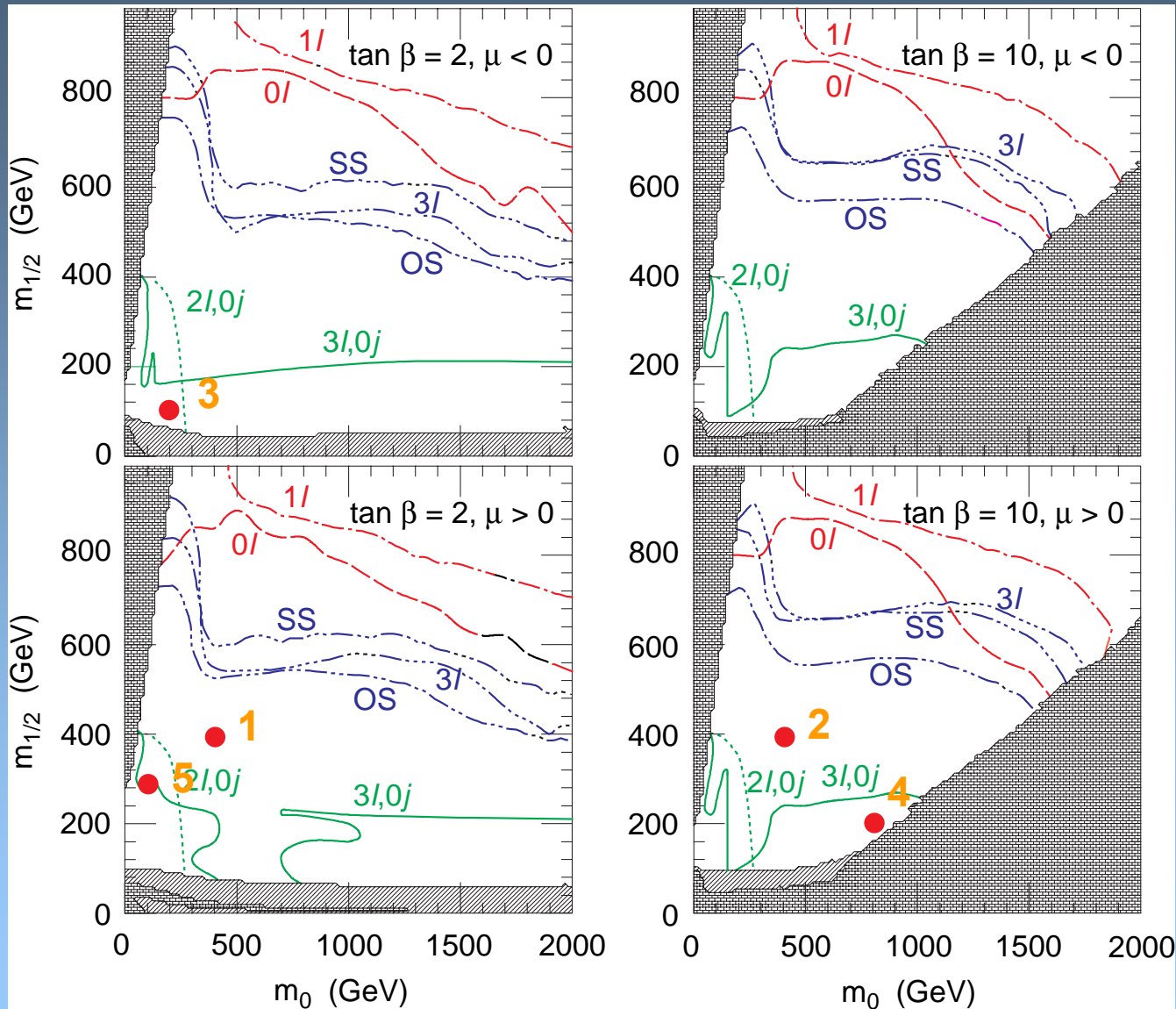
- In each case, points (and slopes in the case of SPS) defined for

- mSUGRA
- mGMSB
- mAMSB

This talk, mostly mSUGRA

- Account for LEP SUSY, Higgs mass constraints,
- Account for $b \rightarrow s \gamma$, $g_{\mu-2}$, LSP relic density $\Omega_{\chi} h^2$
- More recently WMAP results on $\Omega_{\chi} h^2 \rightarrow$ increased interest in focus point and co-annihilation regions.

ATLAS Reach for mSUGRA



**ATLAS Physics
TDR 1999**

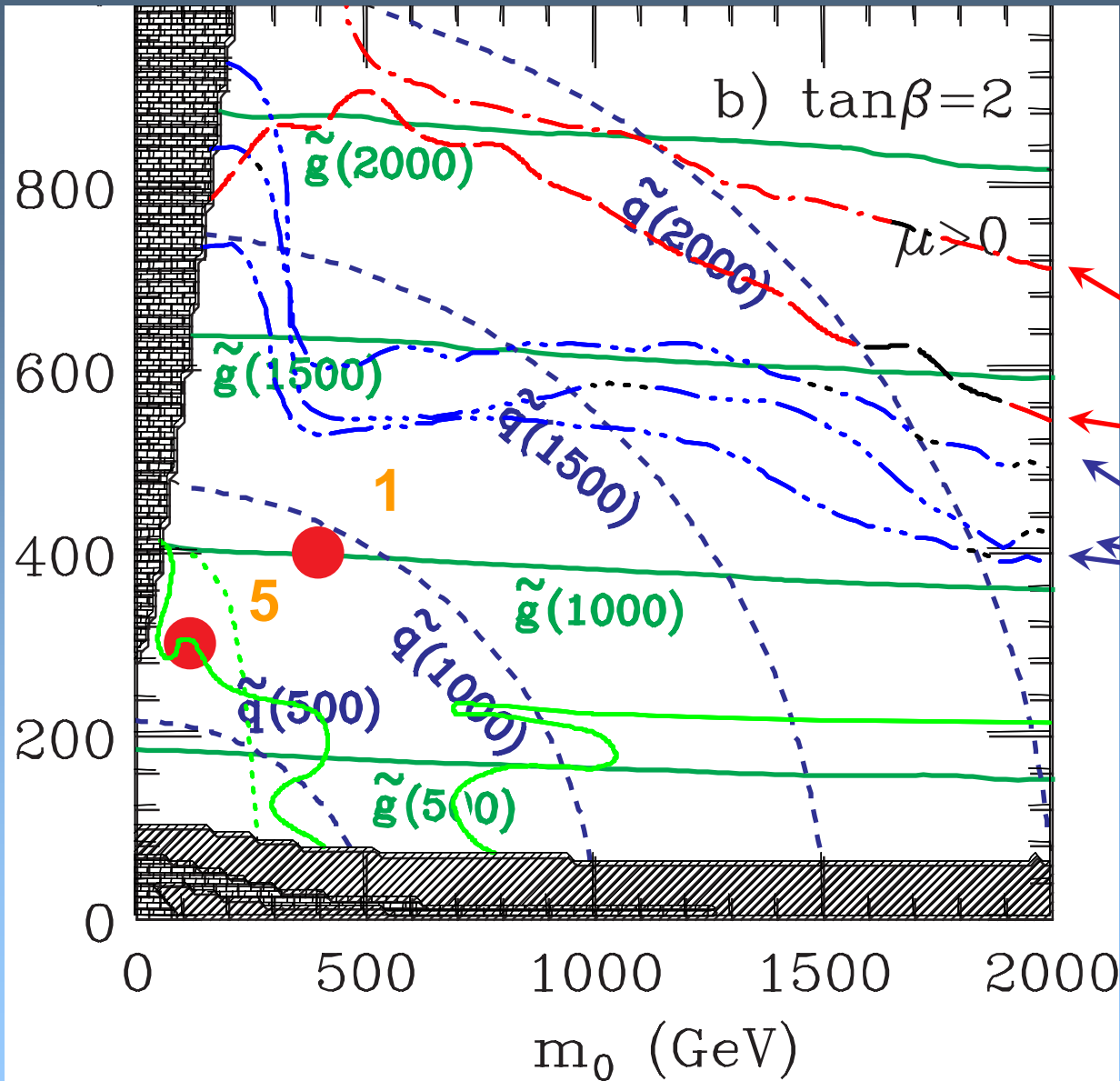
**Jets + n(leptons) +
missing energy**

— $n=0,1$
— $n=2,3$

Reach defined by

- 10 fb^{-1}
- ~ 10 events
- $S/B^{1/2} > 5$

ATLAS mSUGRA Mass Reach



$\tan\beta = 2, \mu > 0$

1 lepton

0 leptons

2 leptons (SS, OS)

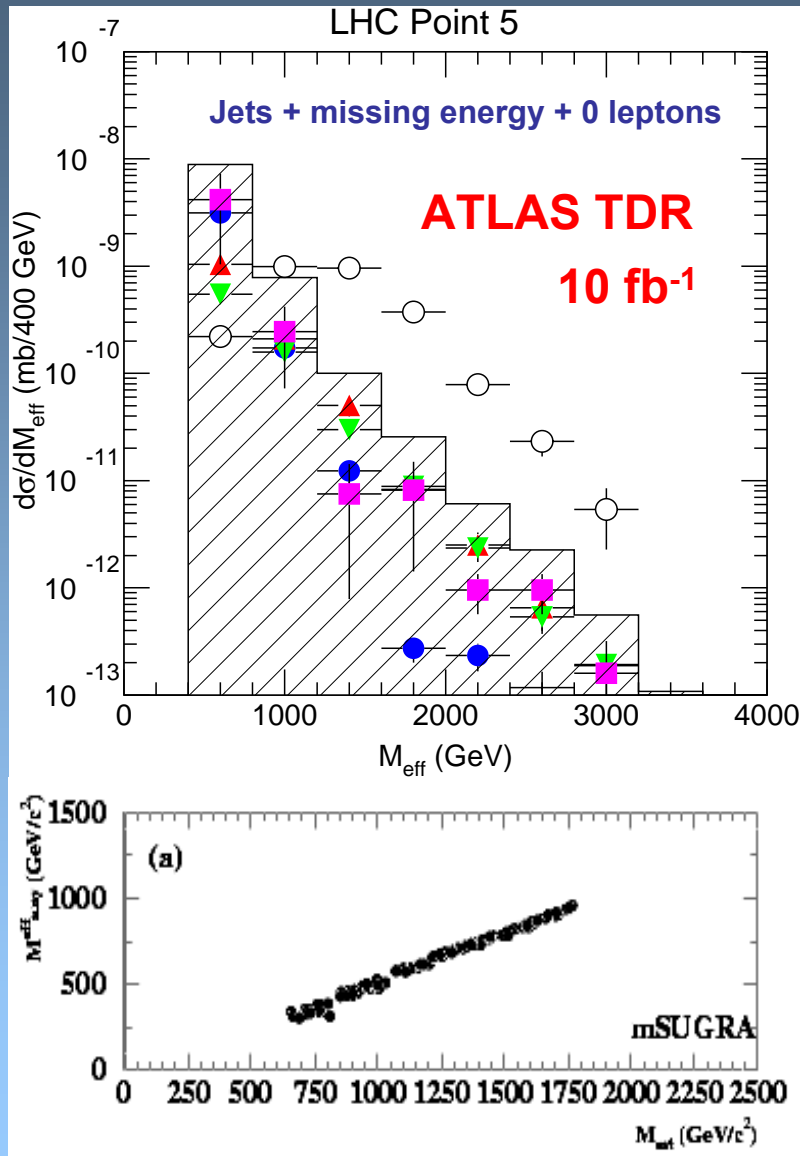
3 leptons

**Jets + n(leptons) +
missing energy:**

Reach to ~ 2 TeV

for $M_{\tilde{g}}, M_{\tilde{q}}$

Determination of SUSY mass scale



$$M_{\text{eff}} = \sum_i |p_T^i| + E_T^{\text{miss}}$$

Peaks at ~ twice SUSY Mass scale

$$M_{\text{SUSY}} \sim \frac{\sum \sigma_i m_i}{\sum \sigma_i}$$

Pseudo 'model independent'

Works also for GMSB, AMSB models
assuming adequate production σ

Normalization strongly correlated to
total SUSY cross-section σ_{SUSY}

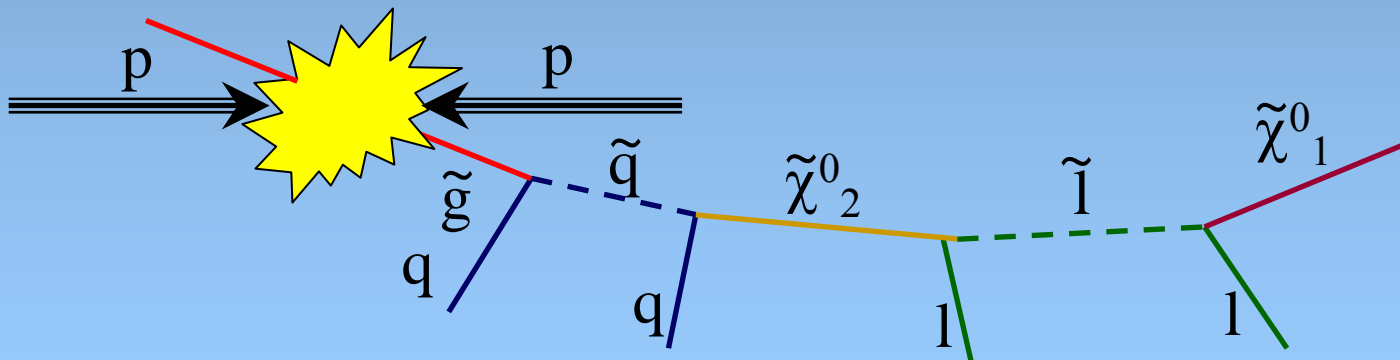
Tovey ATLAS-PHYS-2002-013]
[Hinchliffe et al., Phys Rev D55 (1997) 5520.]

Exclusive measurements (sparticle masses)

Measurement of SUSY parameters (masses etc)

- Unknown LSP ($\tilde{\chi}_1^0$) mass means no direct reconstruction
- Use cascade decays to determine combinations of masses from endpoints of visible mass distributions

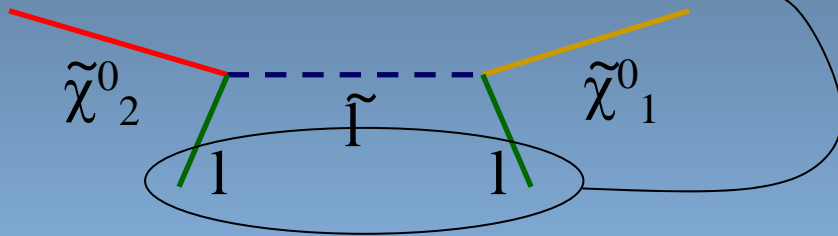
$$\tilde{g} \rightarrow \tilde{q}q \rightarrow qq\tilde{\chi}_2^0 \rightarrow qq\tilde{l} \rightarrow qqll\tilde{\chi}_1^0$$



Dilepton Edge Measurements

Sharp OSSF dilepton invariant mass edge sensitive to combinations of sparticle masses

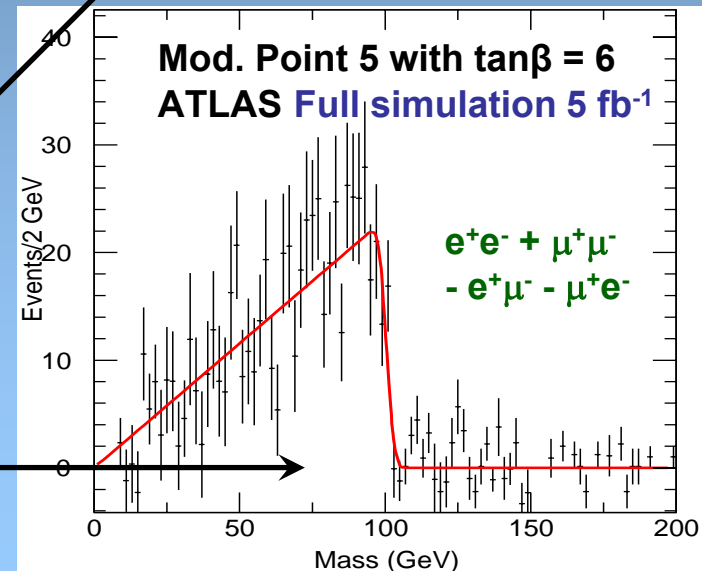
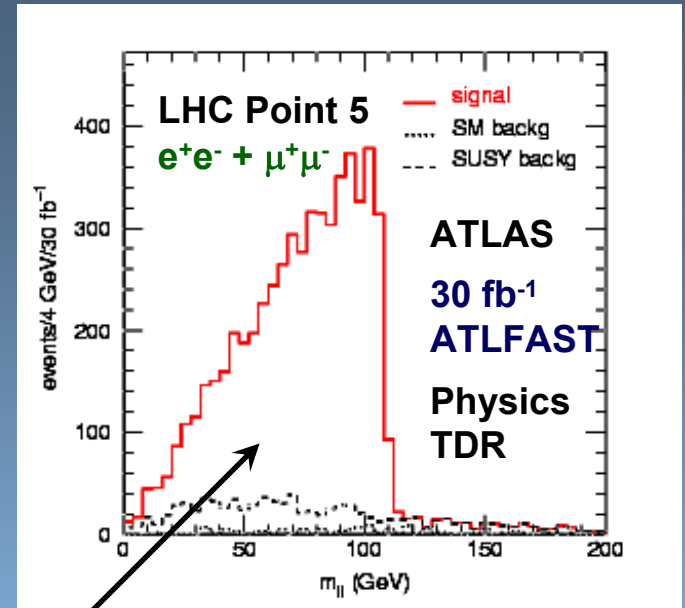
$$M_{ll}^{\max} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}} = 108.93 \text{ GeV}$$



Assumes $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R l \rightarrow \tilde{\chi}_1^0$ kinematically accessible (e.g. LHC Point 5, sps1a).

Edge measured with precision $\sim 0.5 \text{ GeV}$

SM & SUSY background subtraction using OF distribution (here for 5fb^{-1} , full simulation)



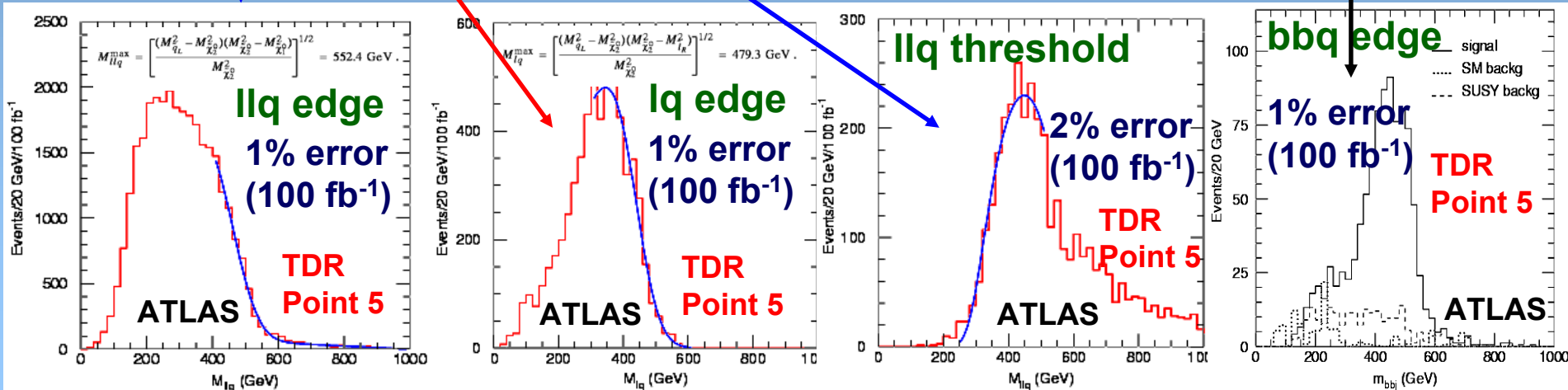
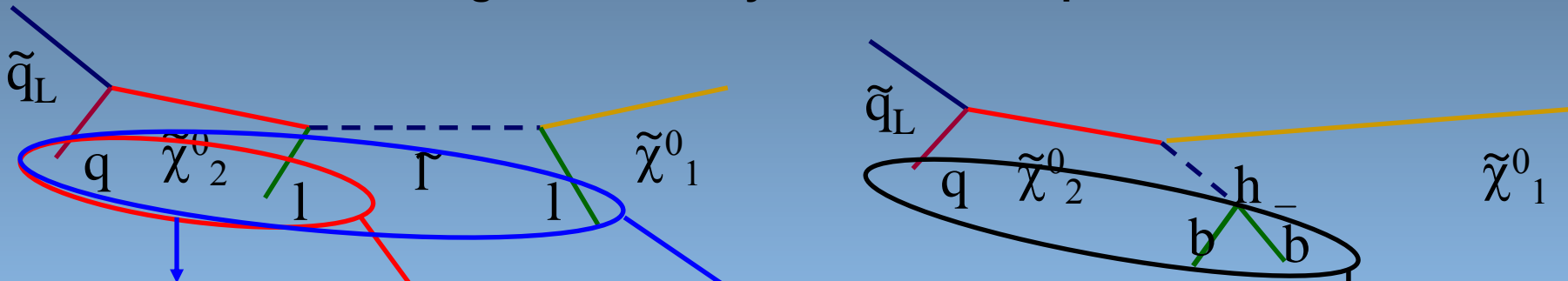
Measurements With Squarks

Dilepton edge point starting point for reconstruction of decay chain

Make invariant mass combination of leptons and jets

Yields multiple constraints on combinations of four masses

Combined constraints give sensitivity to individual sparticle masses



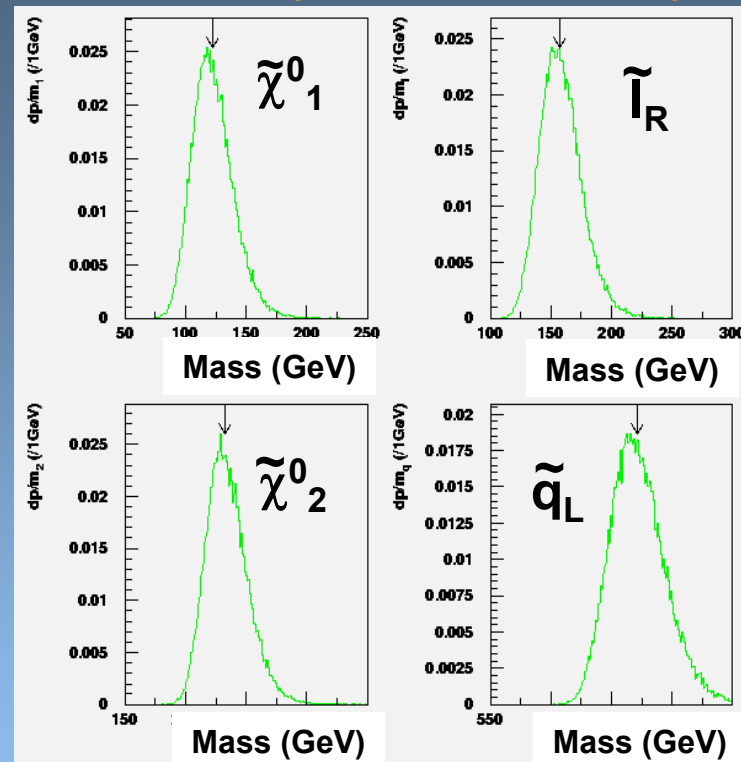
'Model-Independent' Masses

Combine measurements from edges from different jet/lepton combinations to obtain 'model-independent' mass measurements. [Allanach et al., hep-ph/0007009]

ATLAS (LHC SUSY Point 5)

Related edge	Kinematic endpoint
l^+l^- edge	$(m_{\tilde{l}}^{\text{max}})^2 = (\xi - \tilde{l})(\tilde{l} - \bar{\chi})/\tilde{l}$
l^+l^-q edge	$(m_{\tilde{l}q}^{\text{max}})^2 = \begin{cases} \max \left[\frac{(\bar{q}-\xi)(\xi-\tilde{l})}{\xi}, \frac{(\tilde{q}-\tilde{l})(\tilde{l}-\bar{\chi})}{\tilde{l}}, \frac{(\tilde{q}-\xi)(\xi-\tilde{l})}{\xi} \right] \\ \text{except for the special case in which } \tilde{l}^2 < \tilde{q}\bar{\chi} < \xi^2 \text{ and} \\ \xi^2\bar{\chi} < \tilde{q}\tilde{l}^2 \text{ where one must use } (m_{\tilde{q}} - m_{\tilde{\chi}_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{\text{max}})^2 = X + (\tilde{q} - \xi) \left[\xi + X - \tilde{q} + \sqrt{(\xi - X - \tilde{q})^2 - 4X\tilde{q}} \right] / (2\xi)$
l^+l^-q threshold	$(m_{\tilde{l}q}^{\text{min}})^2 = \begin{cases} [2\tilde{l}(\tilde{q} - \xi)(\xi - \bar{\chi}) + (\tilde{q} + \xi)(\xi - \tilde{l})(\tilde{l} - \bar{\chi}) \\ -(\tilde{q} - \xi)\sqrt{(\xi + \tilde{l})^2(\tilde{l} + \bar{\chi})^2 - 16\xi\tilde{l}\bar{\chi}}] / (4\xi) \end{cases}$
$l_{\text{near } \tilde{q}}^{\pm}$ edge	$(m_{\text{near } \tilde{q}}^{\text{max}})^2 = (\tilde{q} - \xi)(\xi - \tilde{l})/\xi$
$l_{\text{far } \tilde{q}}^{\pm}$ edge	$(m_{\text{far } \tilde{q}}^{\text{max}})^2 = (\tilde{q} - \xi)(\tilde{l} - \bar{\chi})/\tilde{l}$
$l^{\pm}\tilde{q}$ high-edge	$(m_{\tilde{l}(\tilde{q}, \tilde{q}_l)}^{\text{max}})^2 = \max \left[(m_{\text{near } \tilde{q}}^{\text{max}})^2, (m_{\text{far } \tilde{q}}^{\text{max}})^2 \right]$
$l^{\pm}\tilde{q}$ low-edge	$(m_{\tilde{l}(\tilde{q}, \tilde{q}_l)}^{\text{min}})^2 = \min \left[(m_{\text{near } \tilde{q}}^{\text{max}})^2, (\tilde{q} - \xi)(\tilde{l} - \bar{\chi}) / (2\tilde{l} - \bar{\chi}) \right]$
M_{T2} edge	$\Delta M = m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$

Table 4: The absolute kinematic endpoints of invariant mass quantities formed from decay chains of the types mentioned in the text for known particle masses. The following shorthand notation has been used: $\bar{\chi} = m_{\tilde{\chi}_1^0}^2$, $\tilde{l} = m_{\tilde{l}}^2$, $\xi = m_{\tilde{\chi}_1^{\pm}}^2$, $\bar{q} = m_{\tilde{q}}^2$ and X is $m_{\tilde{q}}^2$ or $m_{\tilde{\chi}_1^0}^2$ depending on which particle participates in the branched decay.



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

Right-handed Squark Mass

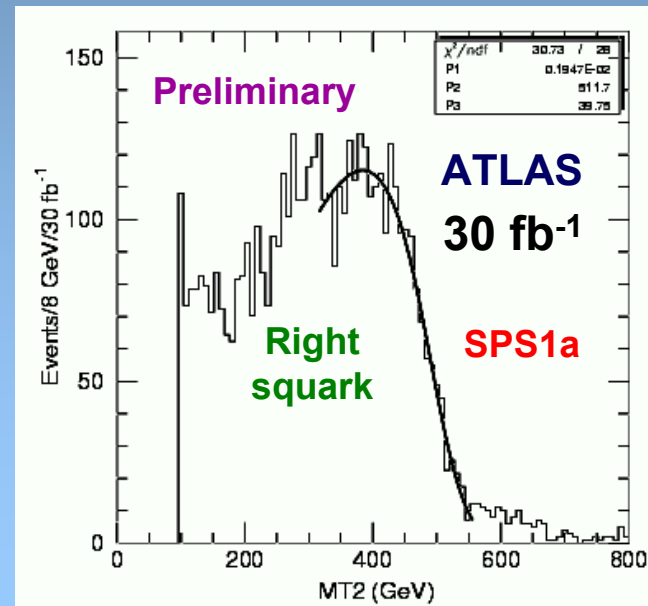
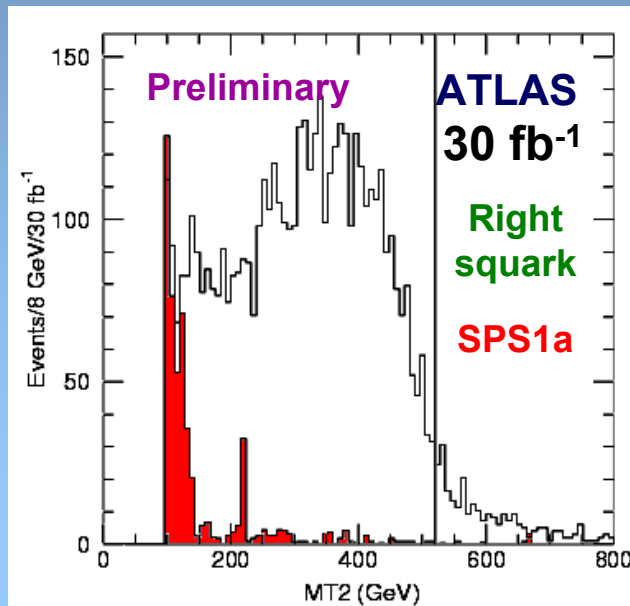
Typically BR ($\tilde{q}_R \rightarrow \tilde{\chi}^0_1 q$) > 99%. (no dilepton chain through $\tilde{\chi}^0_2$)

Search for events with 2 hard jets and lots of E_T^{miss} .

Reconstruct mass using 'stransverse mass'

$$m_{T2}^2 = \min_{q_T^{\chi(1)} + q_T^{\chi(2)} = E_T^{\text{miss}}} [\max\{m_T^2(p_T^{j(1)}, q_T^{\chi(1)}; m_\chi), m_T^2(p_T^{j(2)}, q_T^{\chi(2)}; m_\chi)\}]$$

- Needs $\tilde{\chi}^0_1$ mass measurement as input



statistical
precision
~ 4 GeV

Mass Relation Method

Other analysis techniques exist that do not rely on endpoint measurements

$$\tilde{g} \rightarrow \tilde{b}b \rightarrow \tilde{\chi}_2^0 bb \rightarrow \tilde{l}bbl \rightarrow \tilde{\chi}_1^0 bbl$$

[Nojiri et al, hep-ph/0402295]

Assume $\tilde{\chi}_2^0, \tilde{\chi}_1^0, \tilde{l}_R$ masses known from other measurements (as described)

Six unknowns $M_{\tilde{g}}, M_{\tilde{b}}, p_{\tilde{\chi}_1^0}$ for five equations:

Combine two events: 10 equations for 10 unknowns (2 masses common)

Does not rely on having events near the endpoint

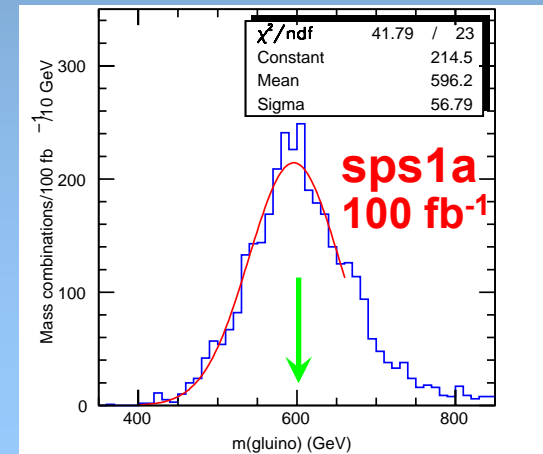
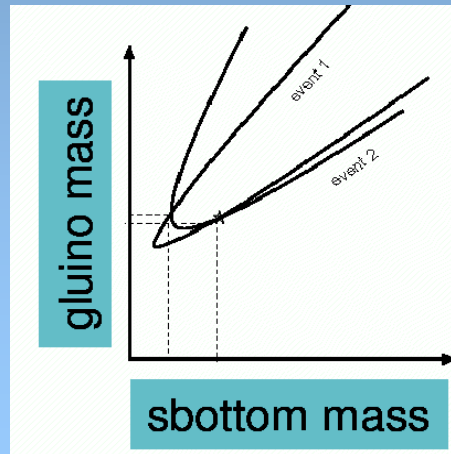
$$M_{\tilde{\chi}_1^0}^2 = p_{\tilde{\chi}_1^0}^2$$

$$M_{\tilde{l}}^2 = (p_{\tilde{\chi}_1^0} + p_{\tilde{l}})^2$$

$$M_{\tilde{\chi}_2^0}^2 = (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2})^2$$

$$M_{\tilde{b}}^2 = (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2} + p_{\tilde{b}_1})^2$$

$$M_{\tilde{g}}^2 = (p_{\tilde{\chi}_1^0} + p_{\tilde{l}_1} + p_{\tilde{l}_2} + p_{\tilde{b}_1} + p_{\tilde{b}_2})^2$$



Measurement of Lightest Chargino Mass

Mass of lightest chargino very difficult to measure as does not participate in standard dilepton SUSY decay chain

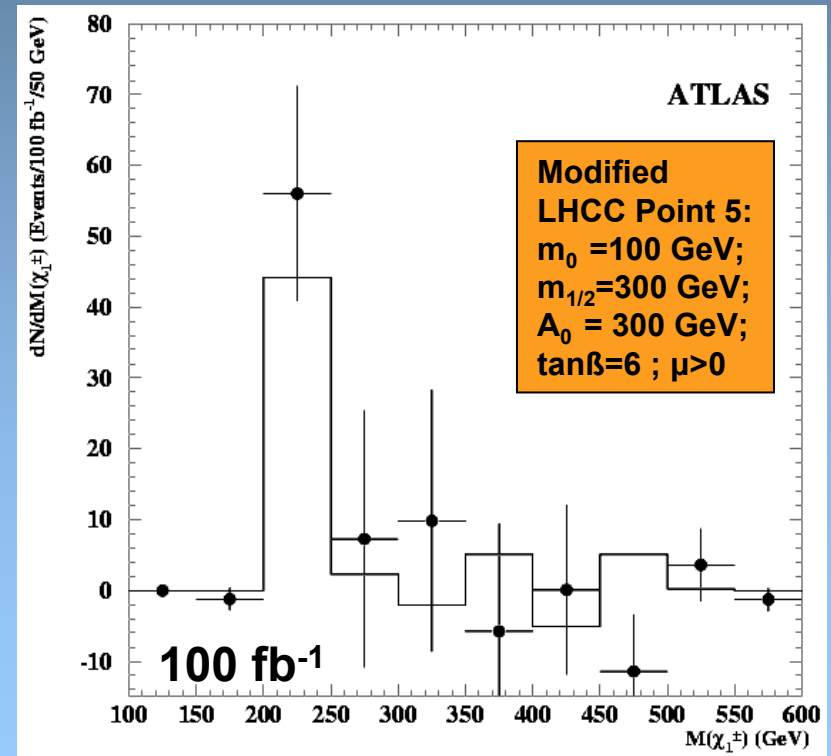
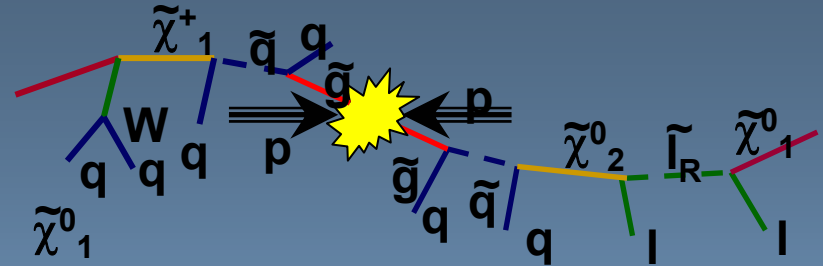
Use decay $\tilde{\chi}_1^+ \rightarrow W^+ \tilde{\chi}_1^0$ with dilepton decay chain on other 'leg' of the event

Use kinematics to calculate $M(\tilde{\chi}_1^+)$

Use sideband subtraction technique obtain peak at true $M(\tilde{\chi}_1^+)$ [218 GeV]

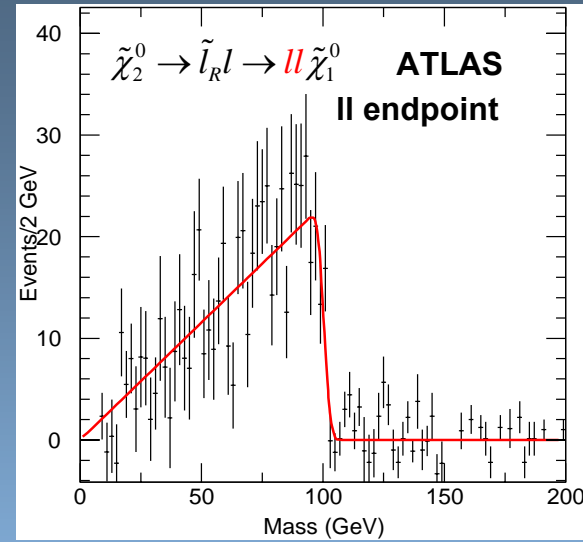
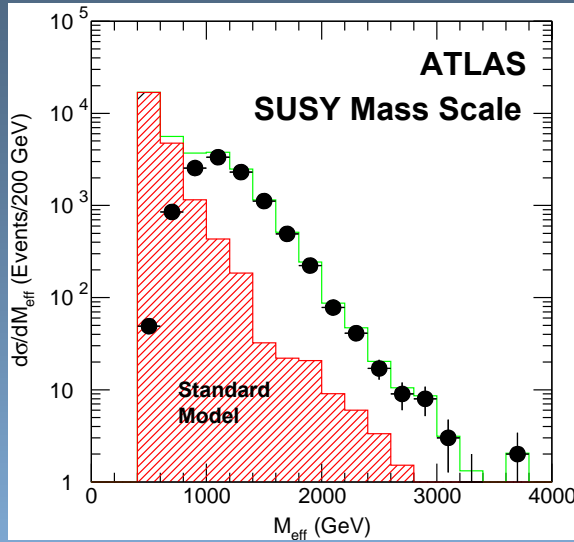
~ 3 σ significance for 100 fb⁻¹.

Requires known $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L$ masses

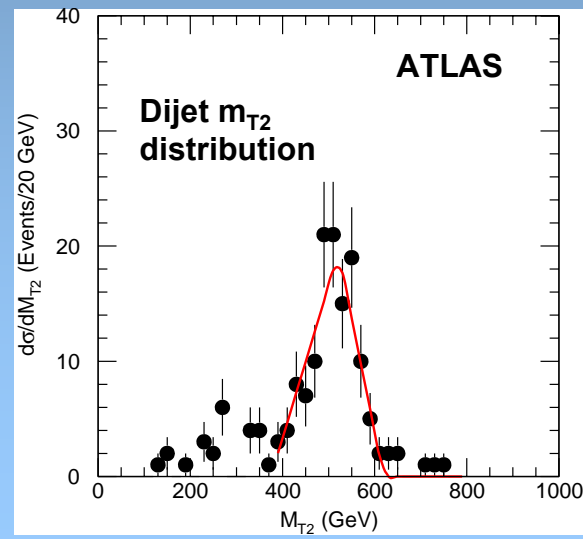
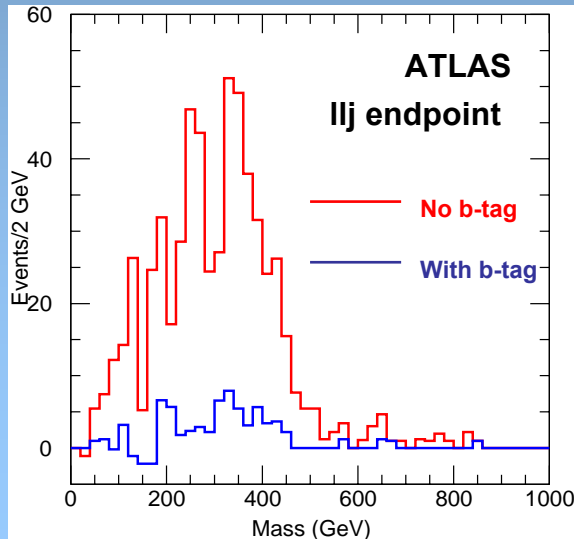


ATLAS SUSY Full Simulation 5fb⁻¹

Modified
LHCC Point 5:
 $m_0 = 100$ GeV;
 $m_{1/2} = 300$ GeV;
 $A_0 = 300$ GeV;
 $\tan\beta = 6$; $\mu > 0$



Reconstructed
 100.25 ± 1.14 GeV
Expected
 100.31 GeV

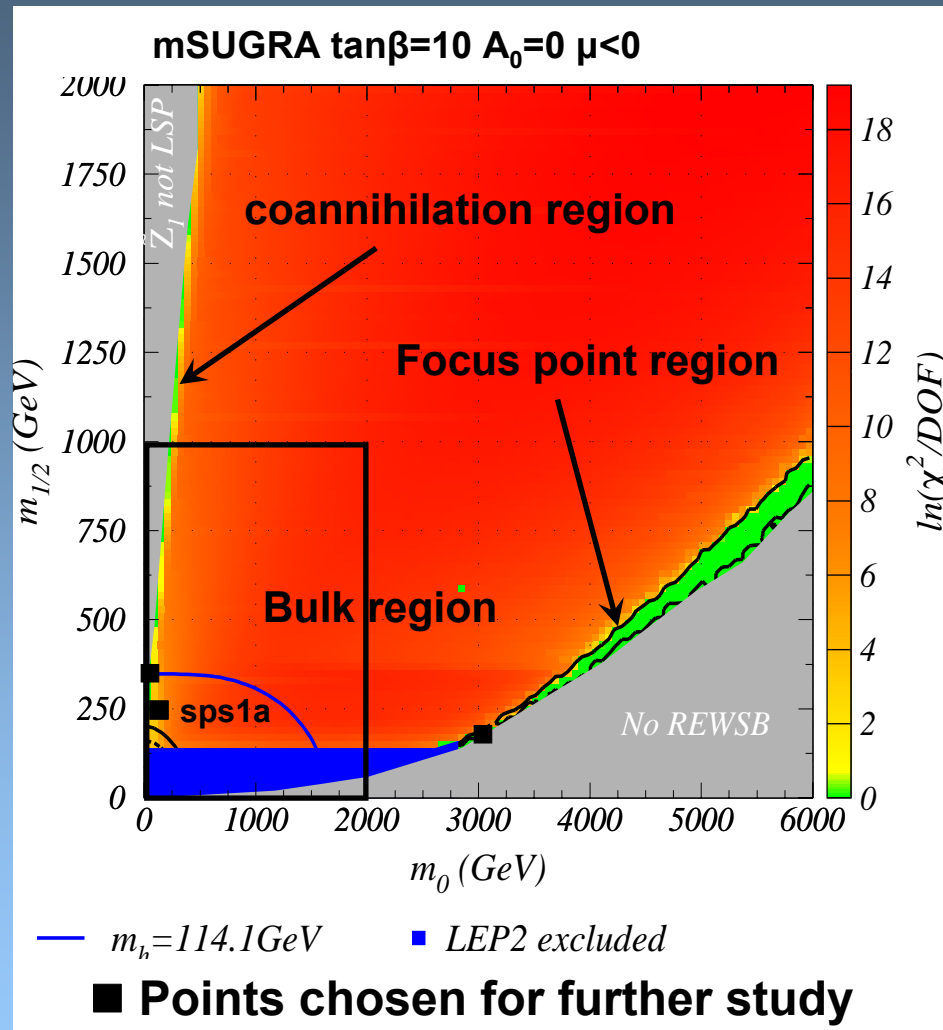


Reconstructed
 619.6 ± 8.2 GeV
Expected
 612 GeV

Reconstructed
 560 GeV
Expected
 590 GeV

Reconstructed
 422 ± 9 GeV
Expected
 501 GeV

Special Regions (Focus Point, Coannihilation)



WMAP results severely constrain mSUGRA parameter space

$$\Omega_{\text{CDM}} h^2 = 0.1126^{+0.0161}_{-0.0181}$$

Favoured regions $(m_0, m_{1/2})$ are

Coannihilation region

sleptons almost degenerate with LSP \rightarrow slow leptons

Dilepton studies underway

Focus point region

Low \tilde{q}, \tilde{g} cross-sections

High squark, slepton masses

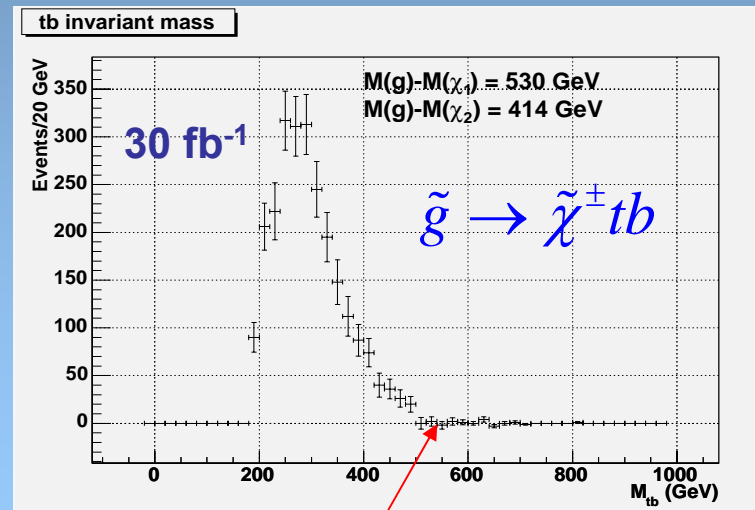
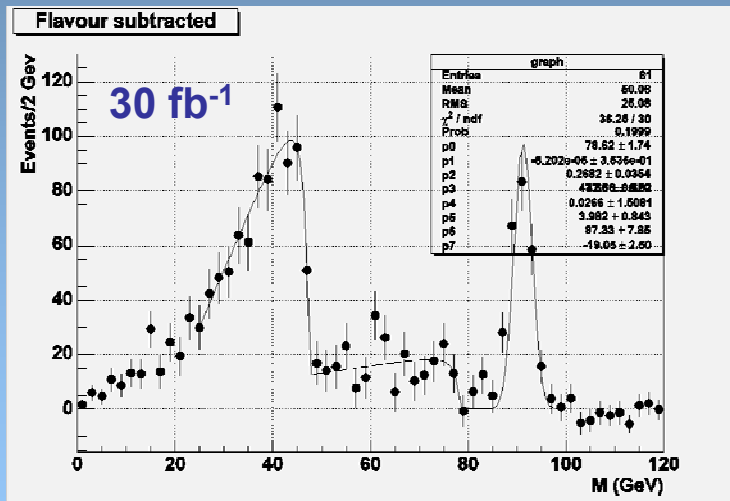
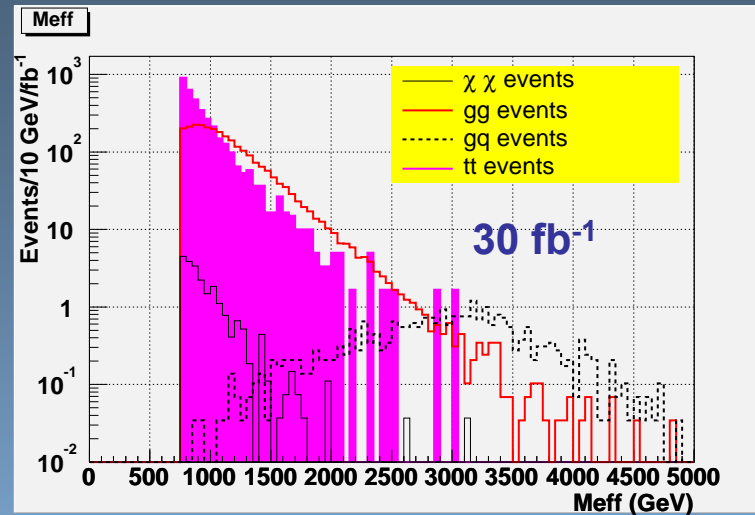
Investigation of these points in progress

ATLAS Studies at Focus Point

Difficult due to very heavy squarks, sleptons, low squark/gluino cross-sections

Neutralino/chargino production abundant but without large jets + missing energy signal (M_{eff})

Dilepton edge analysis for direct $\tilde{\chi}_n^0 \rightarrow \tilde{\chi}_1^0 ll$ decays. Combination with jets for \tilde{g} mass reconstruction under investigation



Light g reconstruction via three body decay

$$\tilde{g} \rightarrow \tilde{\chi} qq^{(\prime)} \quad M(\tilde{g}) - M(\chi_1^\pm) = 530 \text{ GeV}$$

Summary

If TeV scale SUSY exists, it should be discovered at the LHC.

How well we can measure the model parameters depends how lucky we are (and perhaps how clever)

Most studies so far have use mSUGRA, fast simulation

Studies of mGMSB and mASMB models also underway

Lots of work on using taus (not discussed here)

Lots of interesting kinematic reconstruction techniques

Need more work on fully simulated events (including pileup in the case of analyses relying on high-luminosity running). But results from analysis of fully reconstructed data in line with results from fast simulations.

Need more investigation of focus-point and coannihilation regions
and need to wait until sometime in 2008