Beyond the Standard Model Physics at the LHC

Peter Richardson
(Cavendish Laboratory and DAMTP, Cambridge)

Outline

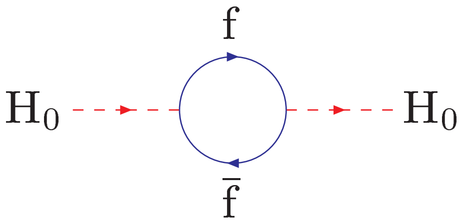
- Need for BSM physics
- SUSY
- SUSY signals
- Extra Dimensions
- Graviton Signals
- Conclusions

Need for BSM physics

- Why do we need physics beyond the Standard Model?
- The Standard Model is in remarkable agreement with all the experimental data.
- However it doesn't explain:
  - The masses of the particles and other parameters of the model.
  - What about gravity?
- These are hard questions and theorists haven't found solutions.
- Instead there's been a great deal of work answering
  - Why is the electroweak scale so much less than the GUT/Planck scales?
- This is called the hierarchy problem.

Hierarchy Problem

- If we look at the Higgs mass there are quantum corrections.



- This gives a correction to the Higgs mass,

$$\delta M^2_{H\,f} = i\frac{|g_f|^2}{4}\int \frac{d^4k}{(2\pi)^4}\frac{\mathrm{tr}\,\left[(\not{k}+\not{p}+m_f)(\not{k}+m_f)\right]}{\left[(k+p)^2-m_f^2\right]\left[k^2-m_f^2\right]}.$$

- Need to introduce an ultra-violet cut-off to regularize the integral

$$\delta M^2_{H\,f} = \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2+6m_f^2\ln\left(\Lambda/m_f\right)\right].$$

Hierarchy Problem

- So either the Higgs mass is the GUT/Planck scale or there is a cancellation

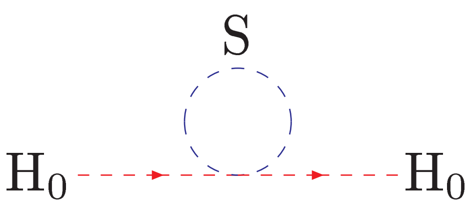
$$M_H^2 = M_{H\text{bare}}^2 + \delta M_H^2,$$

of over 30 orders of magnitude to have a light Higgs.

- This worries a lot of theorists.
- A number of solutions have been proposed.
- I will only discuss two:
  - Supersymmetry;
  - Extra Dimensions.

Supersymmetry

- If there is a scalar loop in the Higgs propagator



- We get a new contribution to the Higgs mass,

$$\delta M^2_{HS} = \frac{\lambda_s}{16\pi^2}\left(\Lambda^2 - 2M_S^2 \ln\left(\Lambda/M_S\right)\right).$$

- So if there are two scalars for every fermion, with the same mass and $\lambda_s = |g_f|^2$ the quadratic dependence cancels.

- Theorists like to have symmetries to explain cancellations like this: Supersymmetry.

- For every fermion degree of freedom there is a bosonic degree of freedom.

Supersymmetric Particles

SM particle	Spin	SUSY particle	Spin
Electron	1/2	Selectron	0
Neutrino	1/2	Sneutrino	0
Up	1/2	Sup	0
Down	1/2	Sdown	0
Gluon	1	Gluino	1/2
Photon	1	Photino	1/2
Z	1	Zino	1/2 Neutralinos
Higgs	0	Higgsino	1/2
W^+	1	Wino	1/2 Charginos
H^+	0	Higgsino	1/2

- One problem, the masses of the SUSY particles are the same as the SM ones.
- But they haven't been observed.
- Need to break SUSY in such a way that the Higgs mass doesn't depend quadratically on the cut-off.
- Called soft SUSY breaking.
- Introduces over 120 parameters into the model.

Supersymmetry breaking

- Need a model of where these parameters come from.
- Can't use the MSSM in simulations: too many parameters.
- Instead use models which predict these parameters from physics at higher energy scales.
- In all these models SUSY is broken in a hidden sector.
- The models differ in how this SUSY breaking is transmitted to the visible sector.

SUGRA

- SUSY breaking is transmitted via gravity.
  - All scalar masses (M_0) unified at the GUT scale.
  - All gaugino masses ($M_{1/2}$) unified at the GUT scale.
  - Universal A and B terms.
  - Use the known value of M_Z to constrain μ and B, leaves $\tan\beta = v_1/v_2$ as a parameter.

- Five parameters give the mass spectrum: M_0, $M_{1/2}$, $\tan\beta$, $\mathrm{sgn}\,\mu$, A.

- Gluino mass correlated with $M_{1/2}$ and slepton mass with M_0.

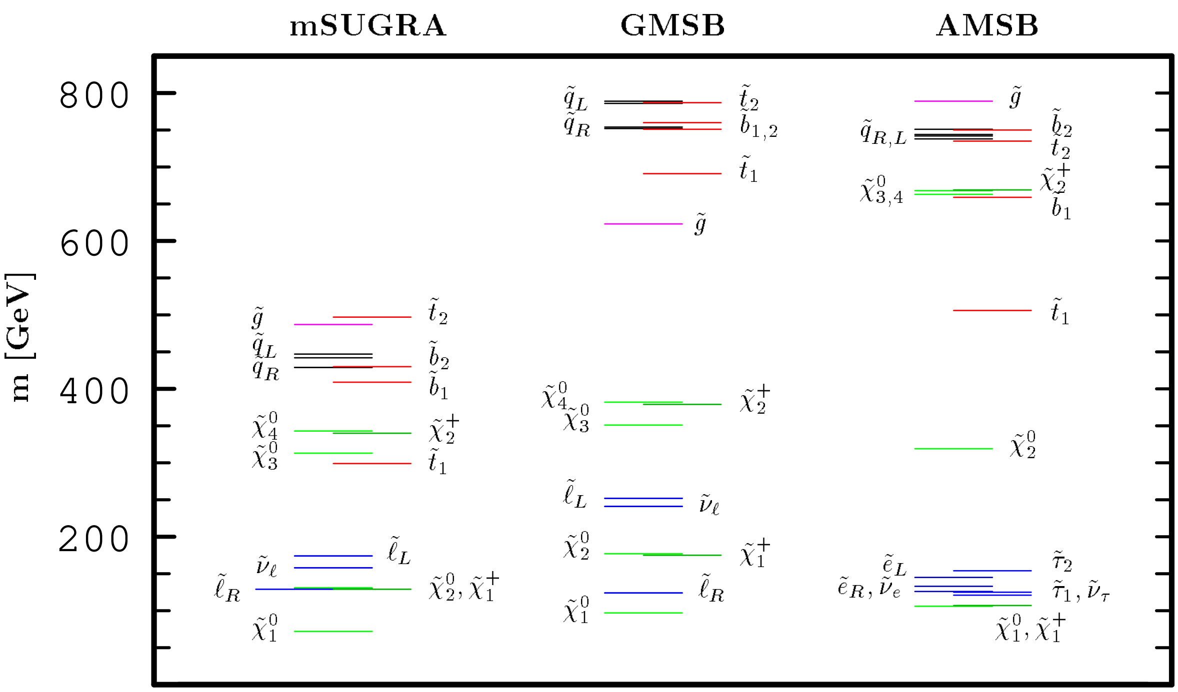
GMSB

- Solves the flavour-changing neutral current problem by using gauge fields instead to gravity to transmit the SUSY breaking.
- Messenger particles, X, transmit the SUSY breaking.
- The simplest choice is a complete $SU(5)$ $\mathbf{5}$ or $\mathbf{10}$ to preserve the GUT symmetry.
- Fundamental SUSY breaking scale $\lesssim 10^{10}$ GeV.
- Gaugino masses occur at 1-loop, $M_{\tilde{g}} \sim \alpha_s N_X \Lambda$.
- Scalar masses at 2-loop, $M_{\tilde{q}} \sim \alpha_s^2 \sqrt{N_X} \Lambda$.
- True LSP almost massless gravitino.
- Lightest superpartner is unstable and decays to gravitino.
- Can be neutral, *e.g.* $\tilde{\chi}_1^0$, or charged, *e.g.* $\tilde{\tau}_1$.

AMSB

- Superconformal anomaly is always present.
- Predicts sparticle masses in terms of $M_{3/2}$.
- Simplest version predicts tachyonic particles.
- Need another SUSY breaking mechanism to get a realistic spectrum.
- *e.g.* Add universal scalar masses (M_0) .
- The model has 4 parameters M_0, $M_{3/2}$, $\tan\beta$ and $\mathrm{sgn}\,\mu$.
- In this model the lightest chargino is almost degenerate with the lightest neutralino.

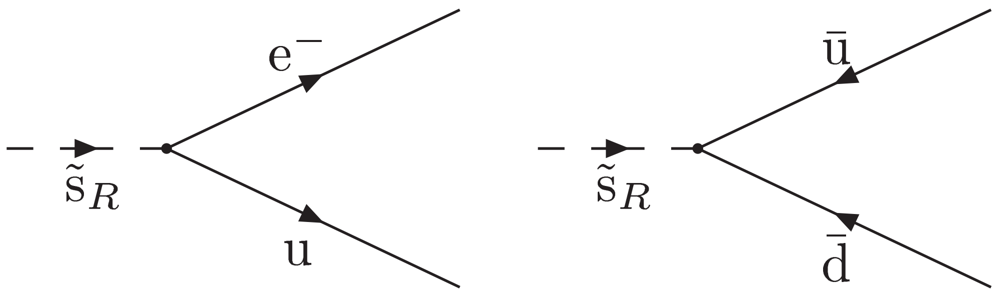
Mass Spectrum



- The mass spectrum in the models is different.
- Main differences:
  - Mass splitting between gluino and electroweak gauginos;
  - Mass splitting of the squarks and sleptons;
  - Nature of the LSP.

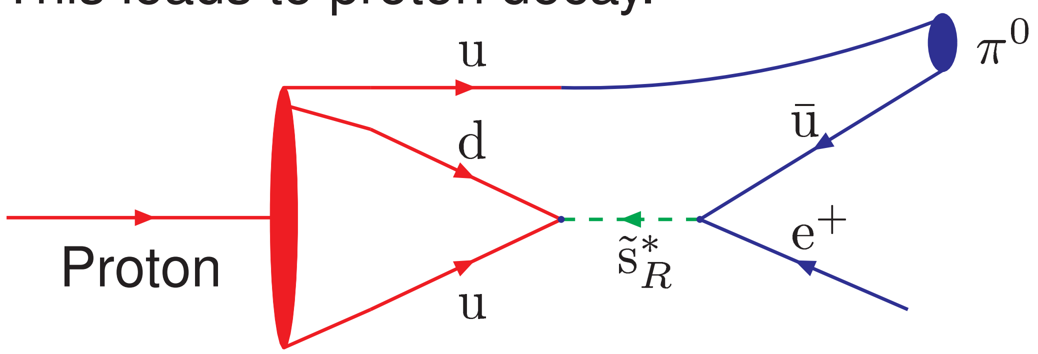
Supersymmetry

- Another problem is that lepton and baryon number are violated.
- The following vertices are present.



Supersymmetry

- This leads to proton decay.



- Limits on the proton lifetime lead to

$$\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \cdot 10^{-27}.$$

- Only natural way is if the LHS is zero.

- We can introduce a symmetry $\mathbf{R_p}$ which prevents both terms,

$$\mathbf{R_p} = (-1)^{3B+L+2S}.$$

  – $\mathrm{R_p} = +1$ Standard Model Particles
  – $\mathrm{R_p} = -1$ SUSY particles

- Instead impose a symmetry forbidding lepton or baryon number violating terms.

SUSY signatures

- These models have very different experimental signatures which must be considered.
- The signals for SUSY depend on the model.
- In R-parity conserving models:
  - Sparticles are only produced in pairs:
  - The LSP is stable, and neutral (cosmology).
- The main signal is missing transverse energy.
- In R-parity violating models:
  - Single Sparticles can be produced;
  - LSP can decay and need not be neutral;
  - Lepton or Baryon Number is Violated.
- The main signal is copious lepton or high p_T jet production.

Characteristic BSM Signals

- Some of the following signals are usually present:
  - Missing transverse energy, $\not\!\!E_T$;
  - Large multiplicity of high p_T jets;
  - Many isolated leptons;
  - Copious b production;
  - Large rate of Higgs production;
  - Isolated photons;
  - Quasi-stable charged leptons.
- Not all present in all models.
- Production of ANY heavy object will give some of these signals.

SUSY searches

- LHC SUSY studies fall in two categories
  - 'Search studies'
    These are designed to show SUSY can be discovered by looking at inclusive signatures.
  - 'Measurement studies'
    These are designed to show that some parameters of the model, usually masses, can be measured. The aim is to show that an excess of events is SUSY.
- There have been many such studies by both the ATLAS and CMS collaborations.
- I will show examples and try and illustrate the key points.
- Most of the studies assume the full LHC integrate luminosity.
- Hard cuts are applied to reduce the SM background.
- In practice the discovery will probably take less luminosity and have a higher SM background.

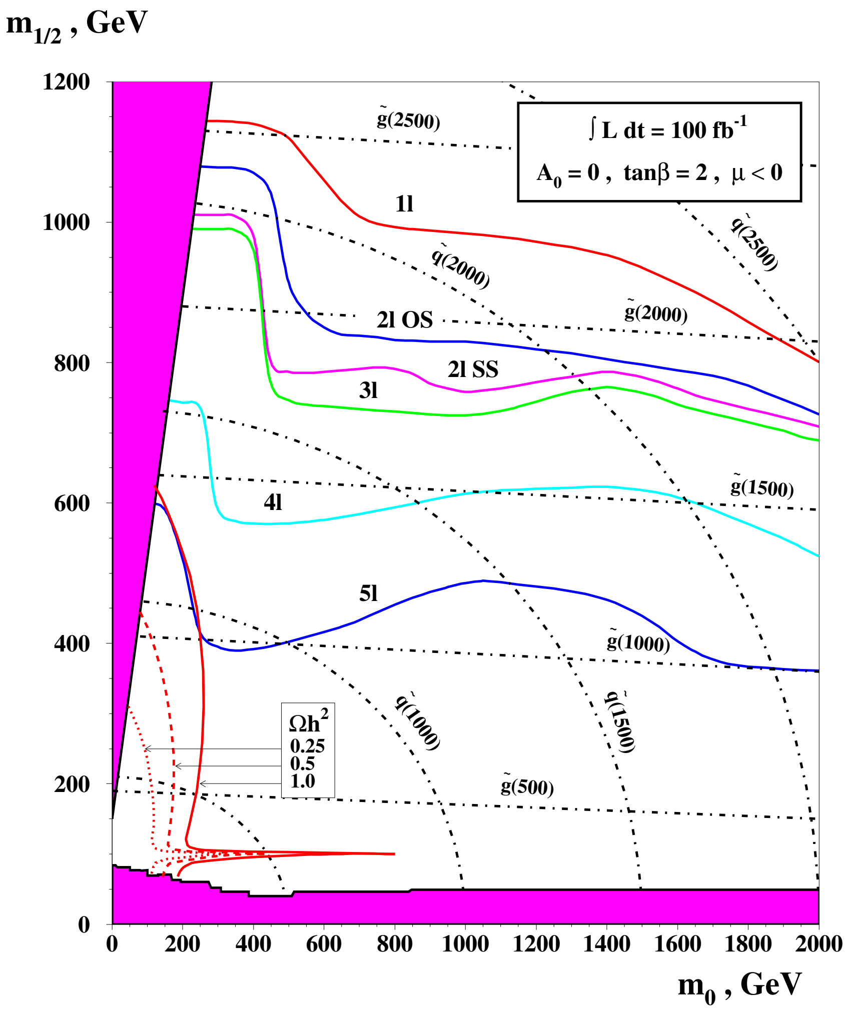
SUSY searches

- All SUSY particle production mechanisms must be simulated at the same time.
- The dominant background to SUSY is usually combinatorial from SUSY events themselves.
- The strongly interacting squarks and gluinos have the highest production rates.
- The production of particles with electroweak couplings may be dominated by the decays of squarks not direct production.

SUSY searches

- Very large range of accessible masses in inclusive signatures *i.e.*

$$\text{jets} + \text{leptons} + \not{E}_T$$



- hep-ex/9709032, CMS

- Covers the interesting theoretical range $M_{\tilde{g}} \lesssim 2.5$ TeV.

Measuring the SUSY scale

- Select events with ≥ 4 jets and $\not{E}_T$.
- The variable

$$M_{\mathrm{eff}} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T$$

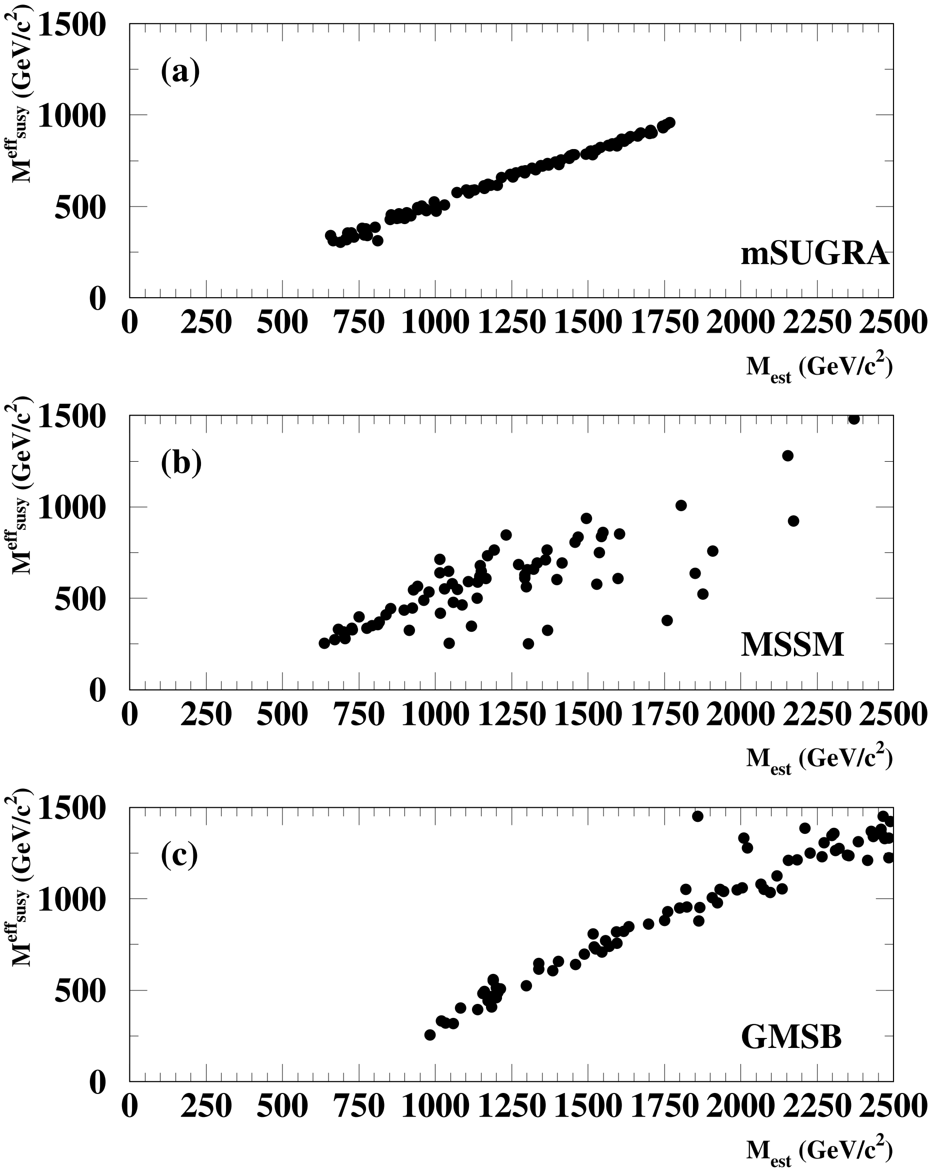
can be used to measure the SUSY scale.

- The peak in the M_{eff} distribution correlates well with the SUSY mass scale

$$M_{\mathrm{SUSY}} = \min(M_{\tilde{\mathrm{u}}}, M_{\tilde{\mathrm{g}}})$$

- Will determine the gluino/squark masses to $\sim 15\%$.
- D.R. Tovey, *Phys. Lett.* **B** 498 (2001) 1.

Measuring the SUSY scale



- The best variables for these analyses are

$$\sum_{\text{jets}} |E_T| \quad \text{or} \quad \sum_{\text{jets}} |\mathrm{E_T}| + \not{E}_{\mathrm{T}}.$$

Characteristic Decays

- There are a number of decays characteristic of SUSY models.

- At the LHC the decay chains usually start with $\tilde{\mathrm{q}}$ or $\tilde{\mathrm{g}}$.

- The electroweak gauginos $\tilde{\chi}^0_i$ and $\tilde{\chi}^\pm_i$ are produced in their decay, *e.g.* $\tilde{q} \to q\tilde{\chi}^0_2$.

- There are two generic features:
  - $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$ or
  - $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+\ell^-$ possibly via an intermediate slepton $\tilde{\chi}^0_2 \to \tilde{\ell}^\pm\ell^\mp \to \tilde{\chi}^0_1\ell^+\ell^-$.

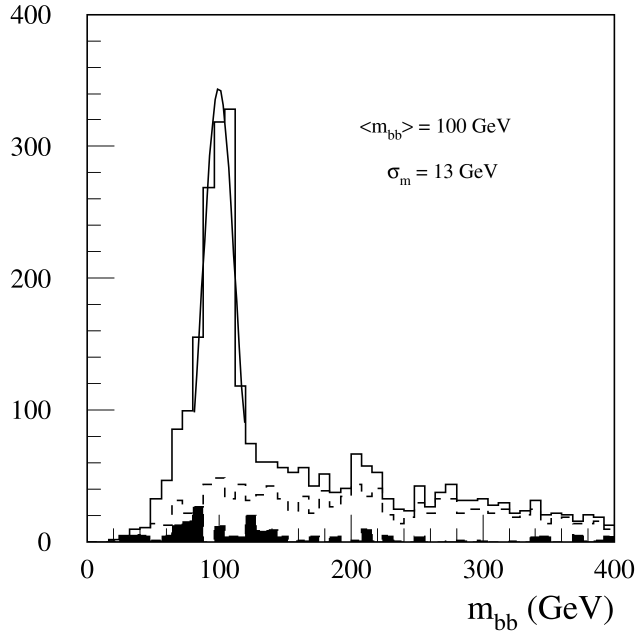
- These characteristic decays are usually used as a starting point for mass measurements.

- Can then measure the masses of other particles by adding more leptons/jets and working up the decay chain.

Decays to Higgs bosons

- If the decay mode $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 h$ exists the Higgs will be discovered in SUSY events.

- In this case $\sim$ 20% of SUSY events contain $h \to b\bar{b}$.

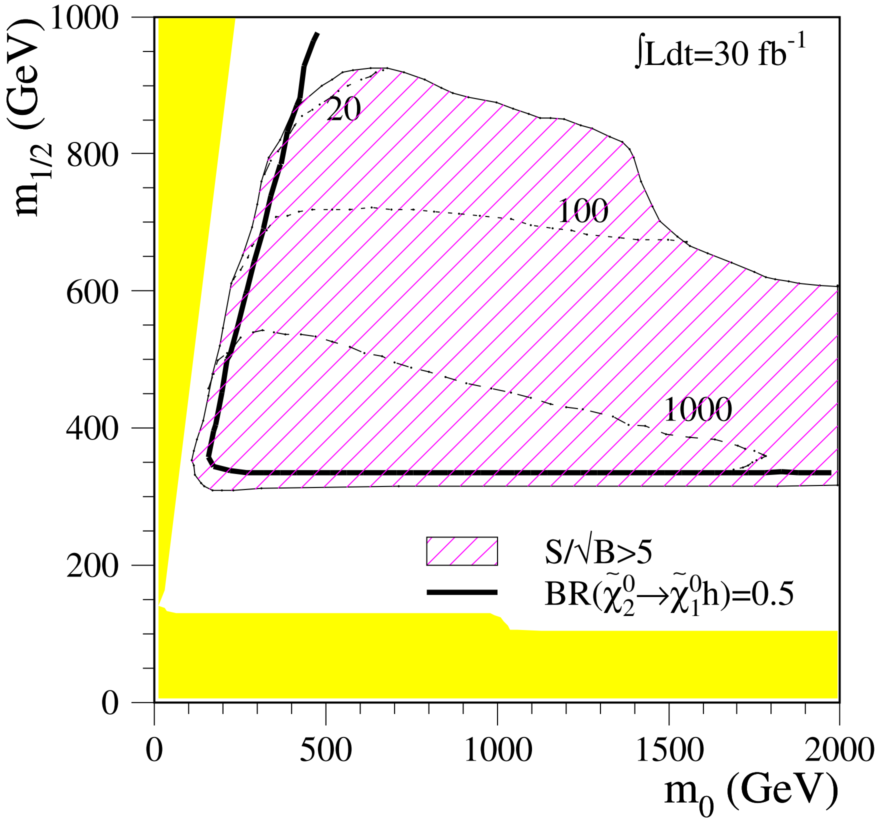


- select events with:
  - $\not{E}_T > 300$ GeV;
  - at least 2 jets with $p_T > 100$ GeV;
  - No isolated leptons;
  - Only 2 b jets with $p_T > 55$ GeV and $|\eta| < 2$.

- Graphs from ATLAS Physics TDR.

Decays to Higgs bosons

- This method works over a large region of SUSY parameter space.



- Hatched region has $S/\sqrt{B} > 5$.

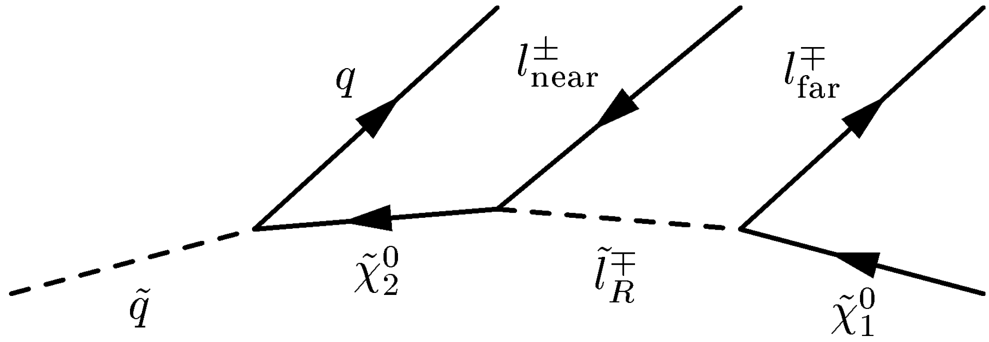
- Over the rest of parameter space the leptonic decay $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ is crucial.

Leptonic Decay chains

- In many models the decay chain,

$$\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\tilde{\ell}^{\pm}\ell^{\mp} \to q\ell^+\ell^-\tilde{\chi}^0_1$$

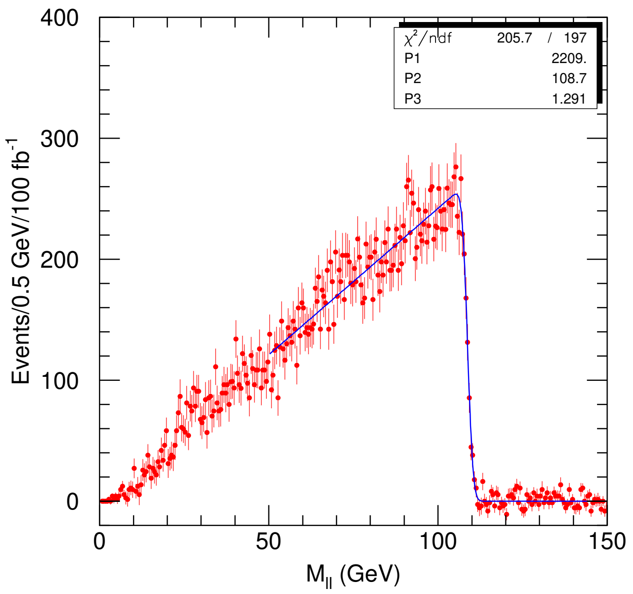
is present.



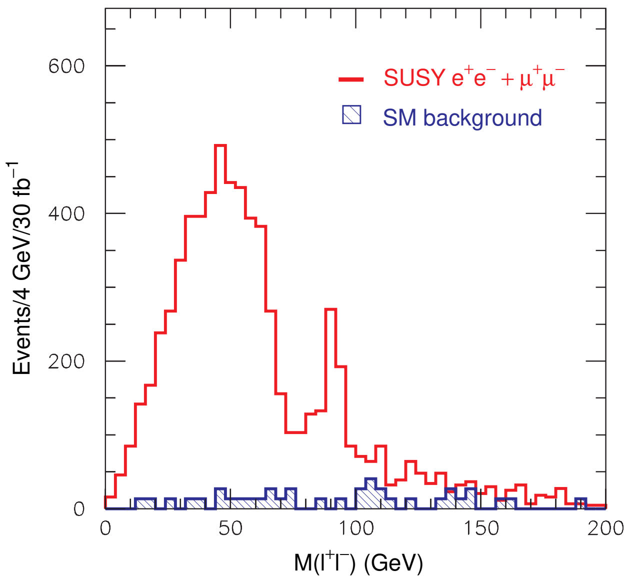
- Start by measuring the decay $\tilde{\chi}^0_2 \to \ell^+\ell^-$.
- Figures taken from ATLAS Physics TDR.

Leptonic Decay Chains

- Via real slepton.



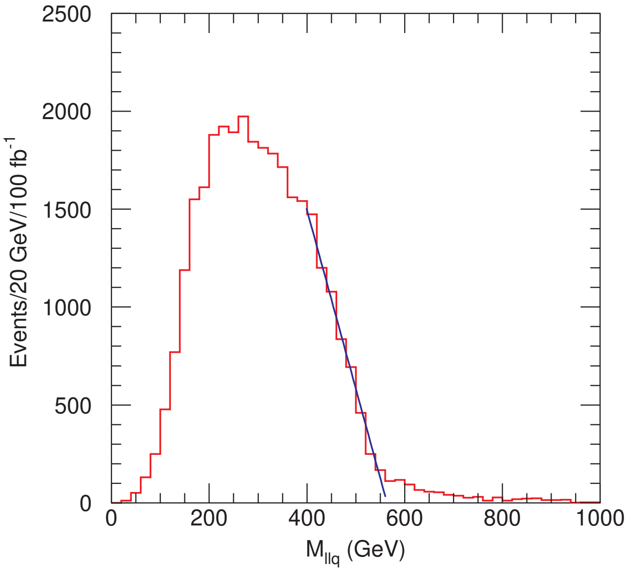
- Via virtual slepton and Z.



- Edge gives $M_{\tilde{\chi}^0_2} - M_{\tilde{\chi}^0_1}$.

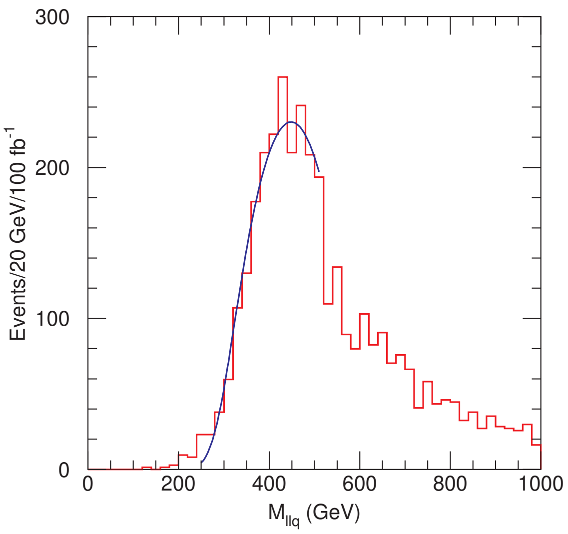
Building on Leptons

- Now add in the jet from the squark decay.
- Require:
  - 2 isolated opposite sign leptons, $p_T > 10$ GeV;
  - ≥ 4 jets one with $p_T > 100$ GeV and rest with $p_T > 50$ GeV;
  - Look at smallest mass combination of $\ell\ell$jet, largest mass combination of $\ell\ell$jet and ℓjet;
  - Together with $\ell\ell$ edge this gives 4 constraints;
  - Solve for the unknown SUSY masses of $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$, $\tilde{q}_L$;
- Smallest mass of $\ell\ell$jet combinations.

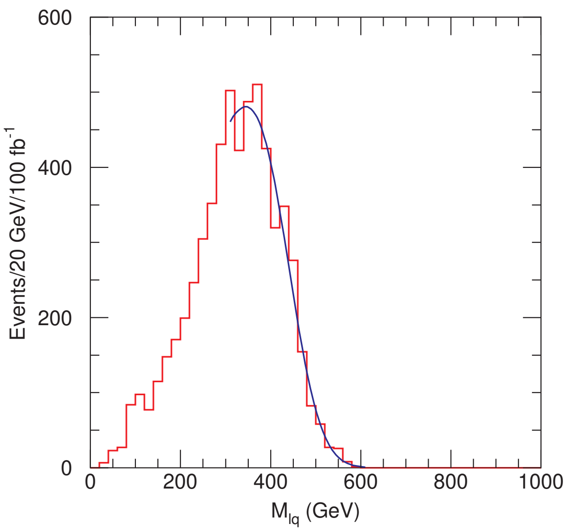


Building on Leptons

- Largest mass of $\ell\ell$jet combinations.



- ℓ jet mass.



- 3%, 6%, 9%, 12% errors on $\tilde{q}_L$, $\tilde{\chi}^0_2$, $\tilde{\ell}_R$ and $\tilde{\chi}^0_1$ masses

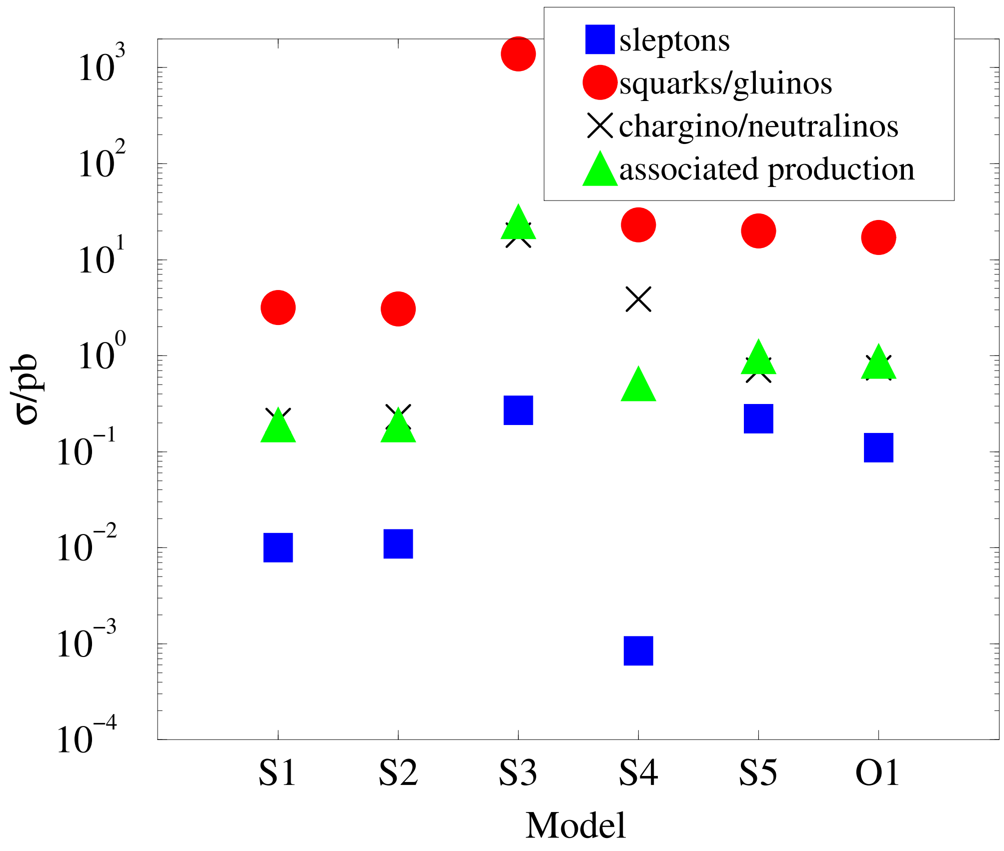
- Taken from ATLAS Physics TDR.

Distinguishing between SUSY models at LHC

Work by Cambridge ATLAS-HERWIG SUSY Group

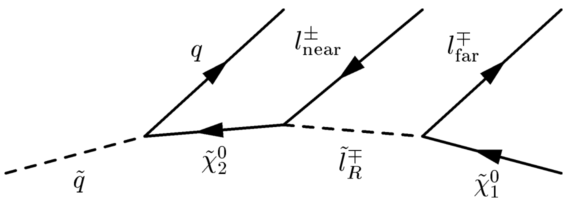
B. Allanach, C. Lester, A. Parker and B. Webber, JHEP 0009:004,2000

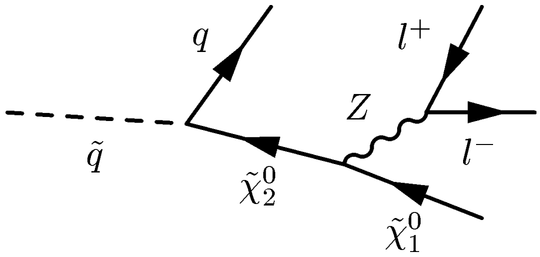
- String-motivated models suggest non-universal SUSY breaking masses.
- the "Optimized" model of Casas, et. al. (O1 Model, hep-ph/9810266) is similar to mSUGRA model S5 but with heavier sleptons.



Distinguishing between SUSY models at LHC

- SUSY masses are obtained from kinematic edges due to decay chains.





- Also used a new variable M_{T2} for finding processes like

$$pp \to \tilde{\ell}^+_R \tilde{\ell}^-_R, \qquad \tilde{\ell}^+_R \tilde{\ell}^-_R \to \ell^+ \tilde{\chi}^0_1 \ell^- \tilde{\chi}^0_1.$$

C.G. Lester and D.J. Summers hep-ph/9906349

$$M^2_{T2}(\chi) = \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max \left\{ m^2_T(p^{l^+}_T, \not{p}_1, \chi), m^2_T(p^{l^-}_T, \not{p}_2, \chi) \right\} \right]$$

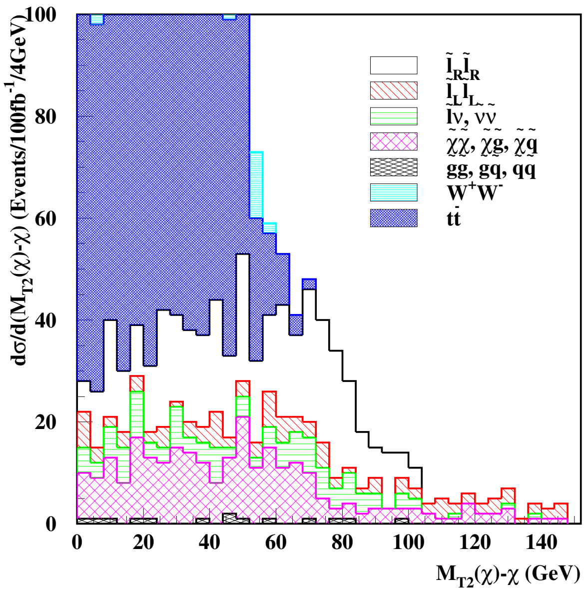
where

$$m^2_T(p^l_T, \not{p}, \chi) \equiv m^2_l + \chi^2 + 2\left(E^l_T E^\chi_T - p^l_T \cdot \not{p}\right)$$

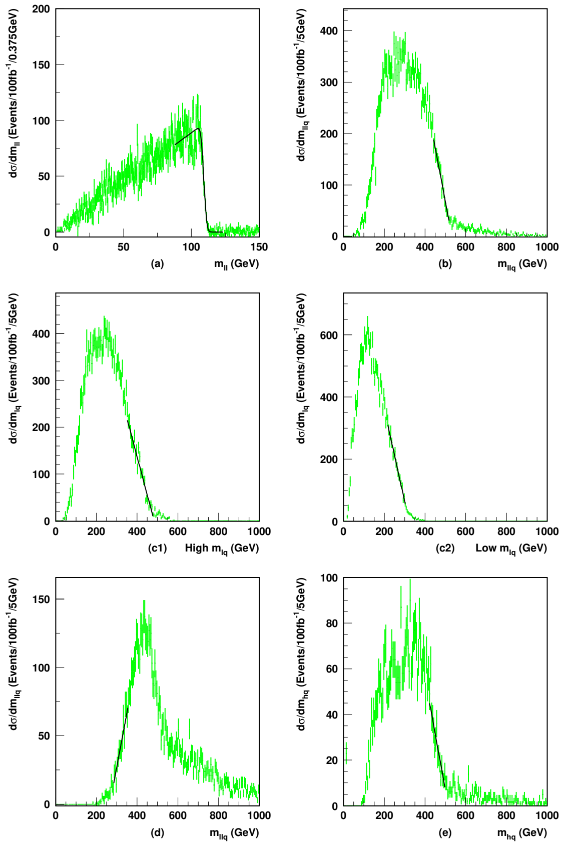
$$E^l_T = \sqrt{{p^l_T}^2 + m^2_l} \quad \text{and} \quad E^\chi_T = \sqrt{\not{p}^2 + \chi^2}$$

Distinguishing between SUSY models at LHC

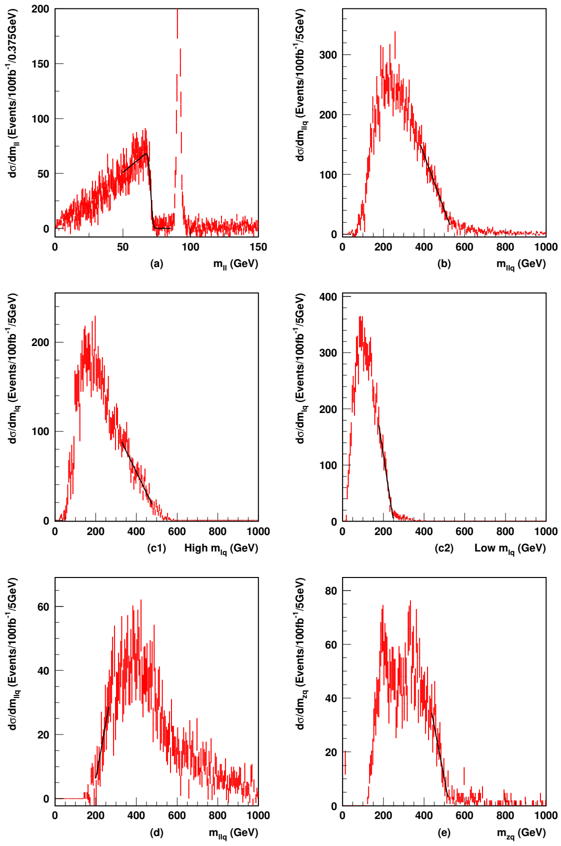
O1 Model



S5 Model



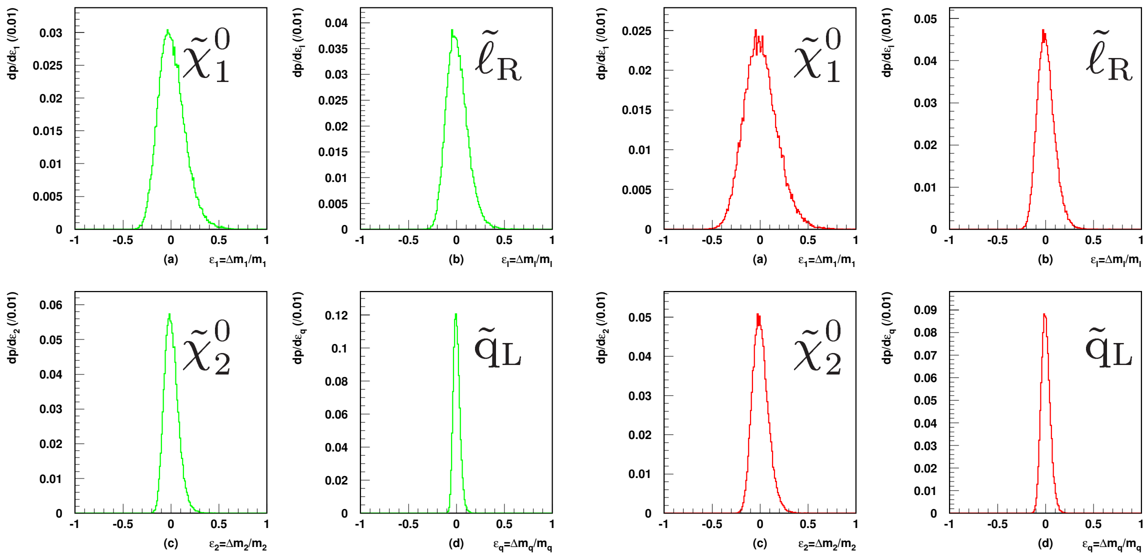
O1 Model



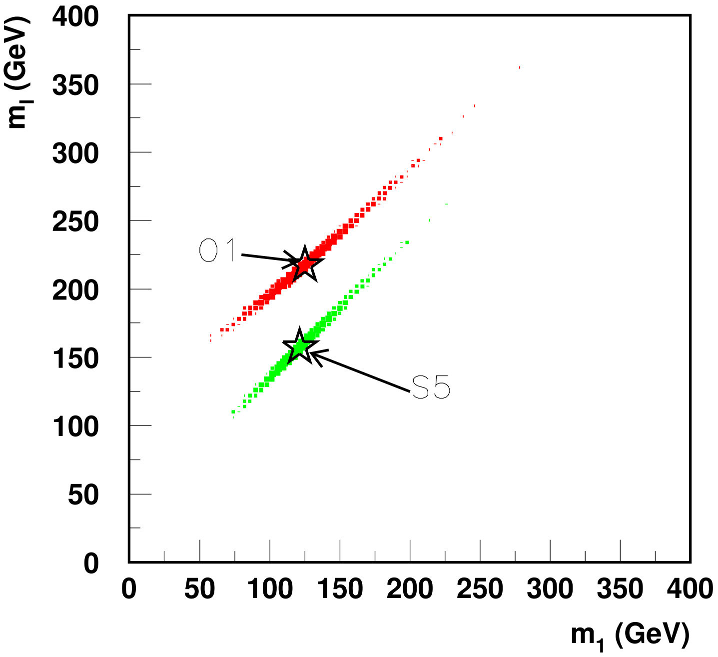
Distinguishing between SUSY models at LHC

- Masses are reconstructed by fitted edge positions.

S5 Model O1 Model



- N.B. distributions 1 years running $\int \mathcal{L} = 100\mathrm{fb}^{-1}$ at high luminosity.



- Models are distinguished even though mass distributions are broad.

GMSB signals

- The NLSP is usually the lightest neutralino or stau.

- The NLSP then decays producing the gravitino which is the true LSP:
  - $\tilde{\chi}^0_1 \to \gamma \tilde{G}$;
  - $\tilde{\tau}_1 \to \tau \tilde{G}$.

- Both cases have been studied.

- Here we will look at a neutralino LSP.

GMSB with Prompt Photons

- The signature of $\tilde{\chi}^0_1 \to \gamma\tilde{G}$ is missing transverse energy and two hard photons.
- Use the leptonic decay mode of the next-to-lightest neutralino,

$$\tilde{\chi}^0_2 \to \tilde{\ell}^\pm\ell^\mp \to \tilde{\chi}^0_1\ell^+\ell^-$$

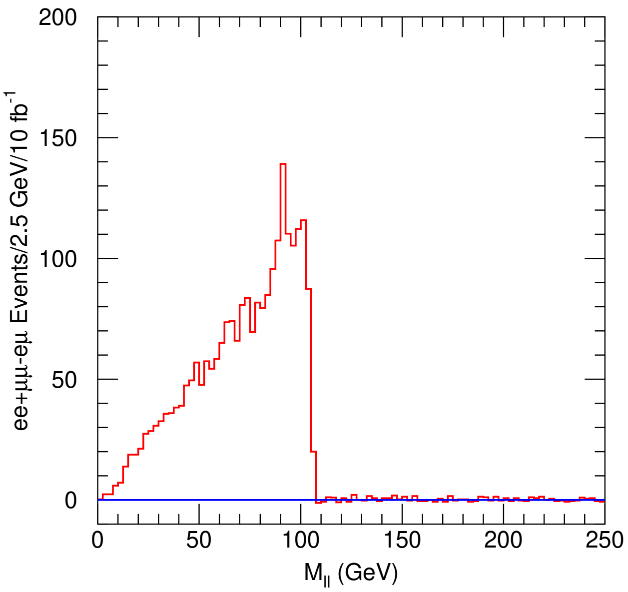
  again.

- Four measurements determine all the masses, neglecting the gravitino mass.

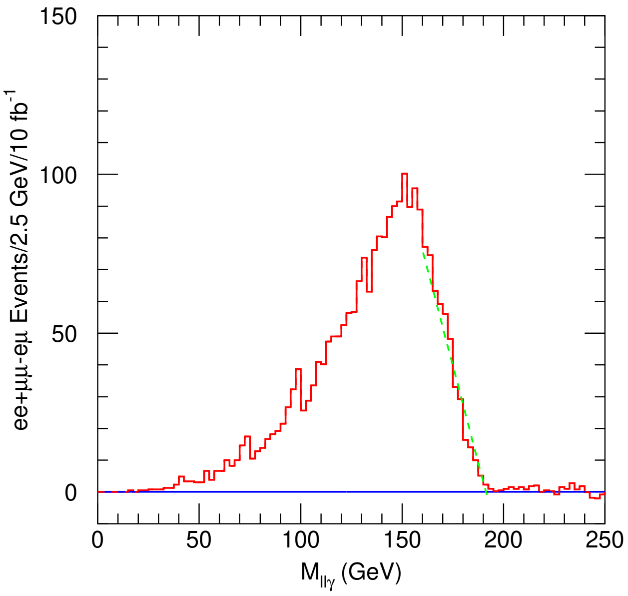
$$\begin{aligned}
M^2_{\tilde{\ell}_R} &= \frac{\left(M^{(1)}_{\ell\gamma}\right)^2\left(M^{(2)}_{\ell\gamma}\right)^2}{\left(M^{\max}_{\ell\ell}\right)^2} \\
M^2_{\tilde{\chi}^0_1} &= M^2_{\tilde{\ell}_R} - \left(M^{(1)}_{\ell\gamma}\right)^2 \\
M^2_{\tilde{\chi}^0_2} &= M^2_{\tilde{\ell}_R} + \left(M^{(2)}_{\ell\gamma}\right)^2
\end{aligned}$$

GMSB with Prompt Photons

- $\ell\ell$ distribution.

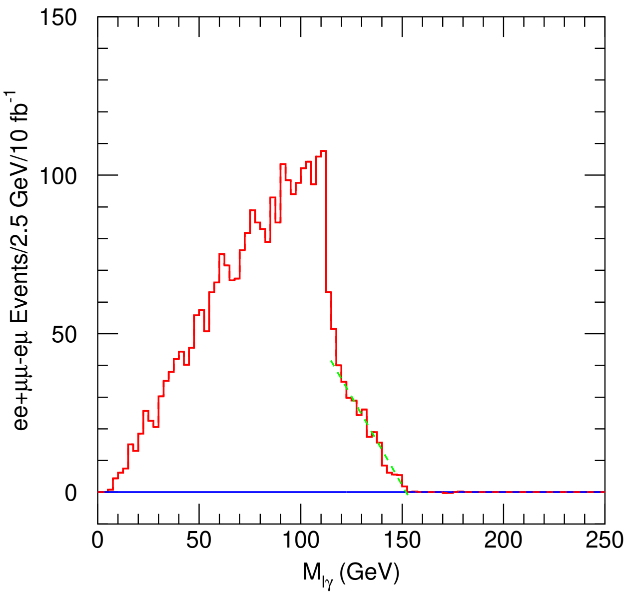


- $\ell\ell\gamma$ distribution.



GMSB with Prompt Photons

- $\ell\gamma$ distribution.



- Taken from ATLAS Physics TDR.

Squark and Gluino Masses

- In this model the decay chain

$$\tilde{\mathrm{q}} \to \mathrm{q}\tilde{\mathrm{g}} \to \tilde{\chi}^0_2\mathrm{q}\bar{\mathrm{q}}\mathrm{q}$$

  exists.

- Build on the measurement of the $\tilde{\chi}^0_2$ decay to measure the squark and gluino masses.

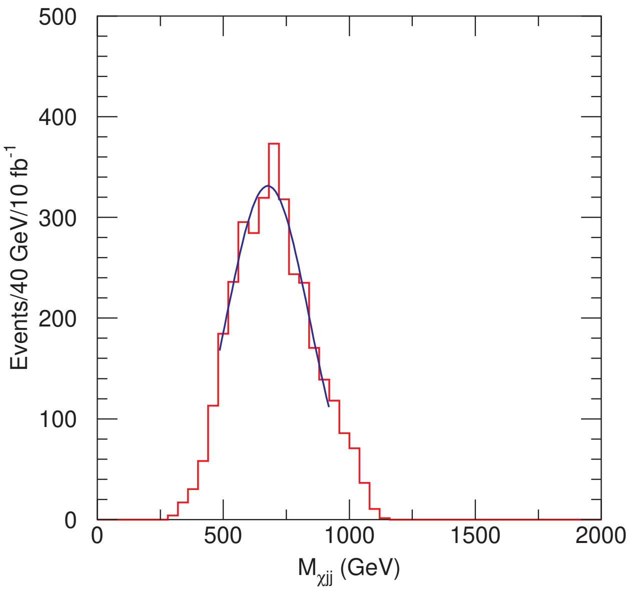
- Require two reconstructed $\tilde{\chi}^0_2$'s.

- Combine each with 2 of hardest 4 jets $\Rightarrow$ gluino mass.

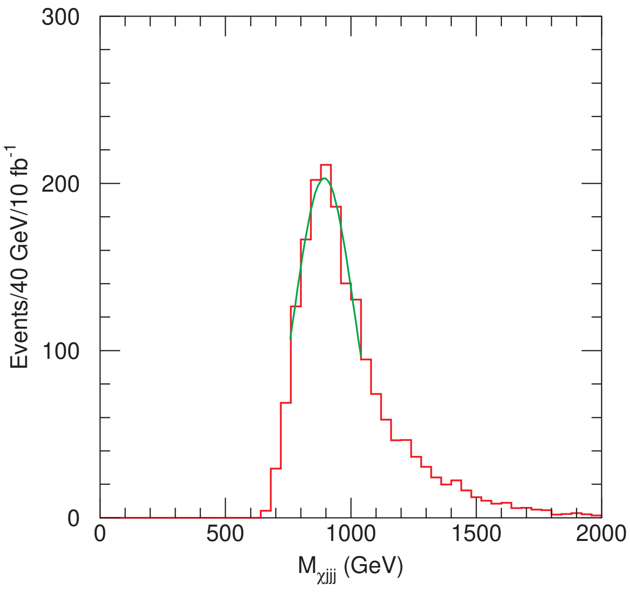
- Then with third jet for the squark mass.

Squark and Gluino Masses

- Gluino Mass.



- Squark Mass.



R-parity violation

- Provided the $\not{R}_{\mathrm{p}}$ coupling is small the main effect is the decay of the LSP.
- If the coupling is $\lesssim 10^{-6}$ the LSP decays outside the detector.
- If the LSP is neutral and decays outside the detector the signatures are the same as the MSSM.
- If the LSP is charged it acts like a muon in the detector but gives more ionization.
- If the coupling is $\gtrsim 10^{-6}$ the LSP decays inside the detector.
- The MSSM decay chains are largely unaffected, but at the end the LSP decays.
- The signature depends on the nature of the $\not{R}_{\mathrm{p}}$ coupling.

R-parity violation

- Most analyses have assumed the $\tilde{\chi}_1^0$ is the LSP although it can be any sparticle.
  - LLE LSP decays to leptons

    Multi-lepton signatures which are visible above the background and the possibility of reconstructing the $\tilde{\chi}_1^0$ mass.

  - LQD LSP decays to lepton or neutrino and jets.

    Again Multi-lepton signatures which should be visible above the background and the possibility of reconstructing the $\tilde{\chi}_1^0$ mass.

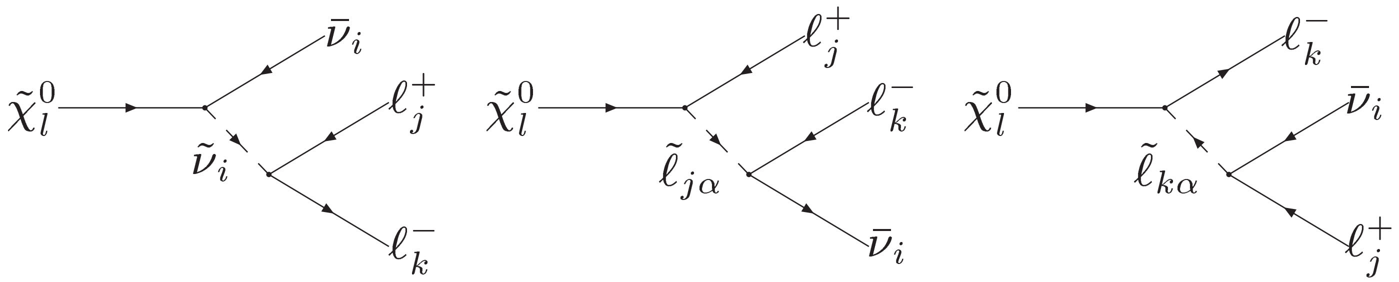
  - UDD LSP decays to quarks.

    This is a potential 'worst case' for the discovery of SUSY at the Tevatron/LHC.

LLE Decays

- In this model the neutralino decays

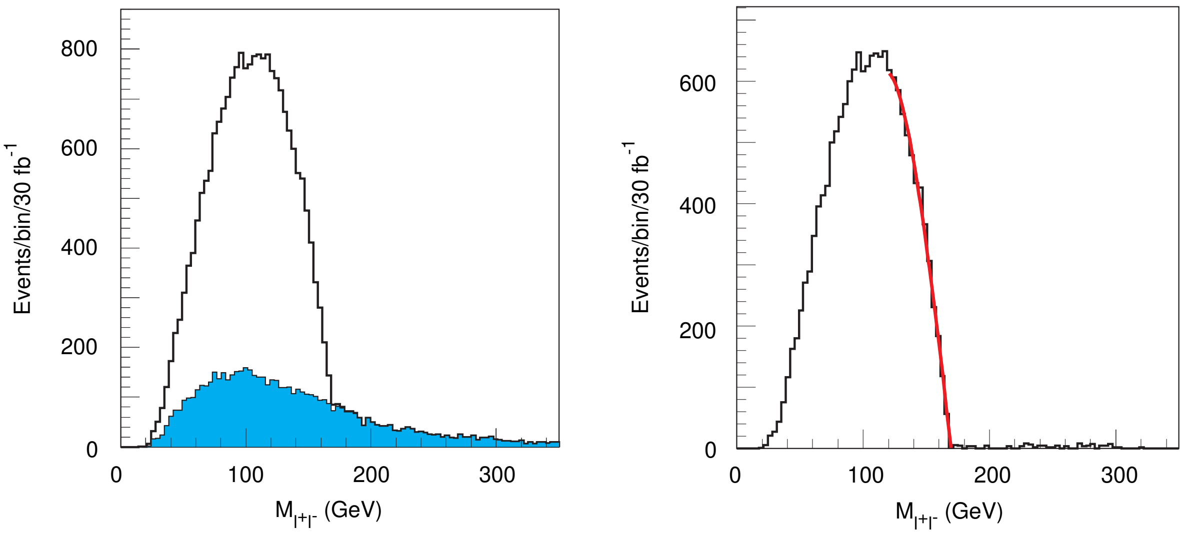
$$\tilde{\chi}_1^0 \longrightarrow \ell^+\ell^-\nu.$$



- In these events two neutralinos are produced.
- This gives at least 4 charged leptons.
- These events are therefore easy to see above the SM background.
- Require:
  - 4 isolated leptons with $p_T > 10\,\mathrm{GeV}$;
  - $\cos\alpha_{ll'} > 0.5$, where $\alpha_{ll'}$ is the angle between leptons in an OSDF pair;
  - $E^T_{\mathrm{miss}} > 50\,\mathrm{GeV}$.

LLE Decays

- The edge in the OSDF lepton mass distribution gives the $\tilde{\chi}^0_1$ mass.



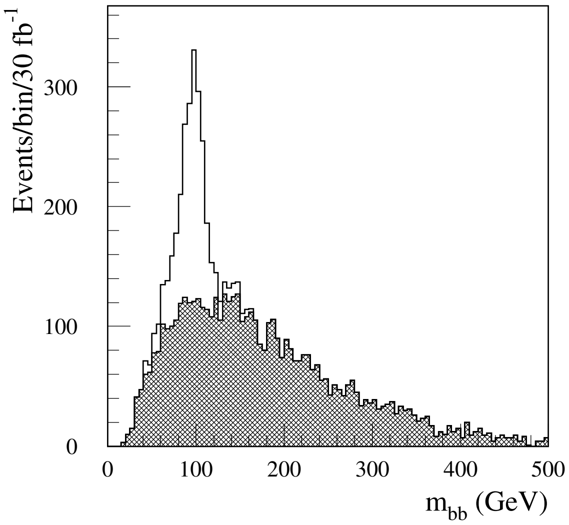
- Graph shows the result for λ_{122} at SUGRA point 1.

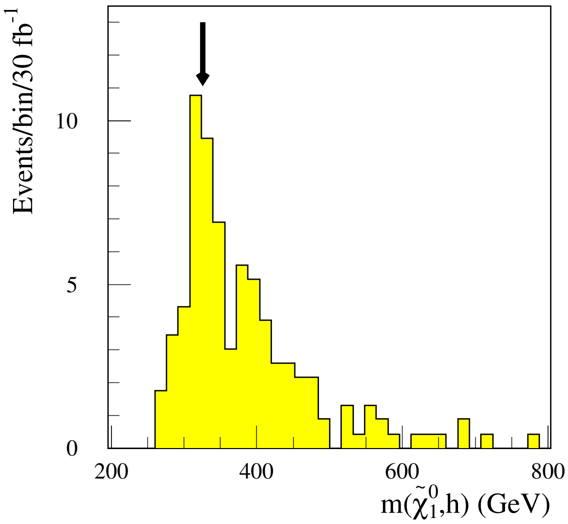
- At the point studied the decay $\tilde{\chi}^0_2 \to h\tilde{\chi}^0_1$ occurs.

- Therefore can reconstruct the $\tilde{\chi}^0_2$ mass by requiring:
  - 2 b-jets with $p_T > 30\,\mathrm{GeV}$ and $p_T < 300\,\mathrm{GeV}$;
  - $\cos\alpha_{bb} > 0.4$ where α_{bb} is the angle between the b-jets.

LLE Decays

- Can reconstruct the Higgs in these events.





- by adding the leptons to the b jets can reconstruct the $\tilde{\chi}^0_2$.

- In this study

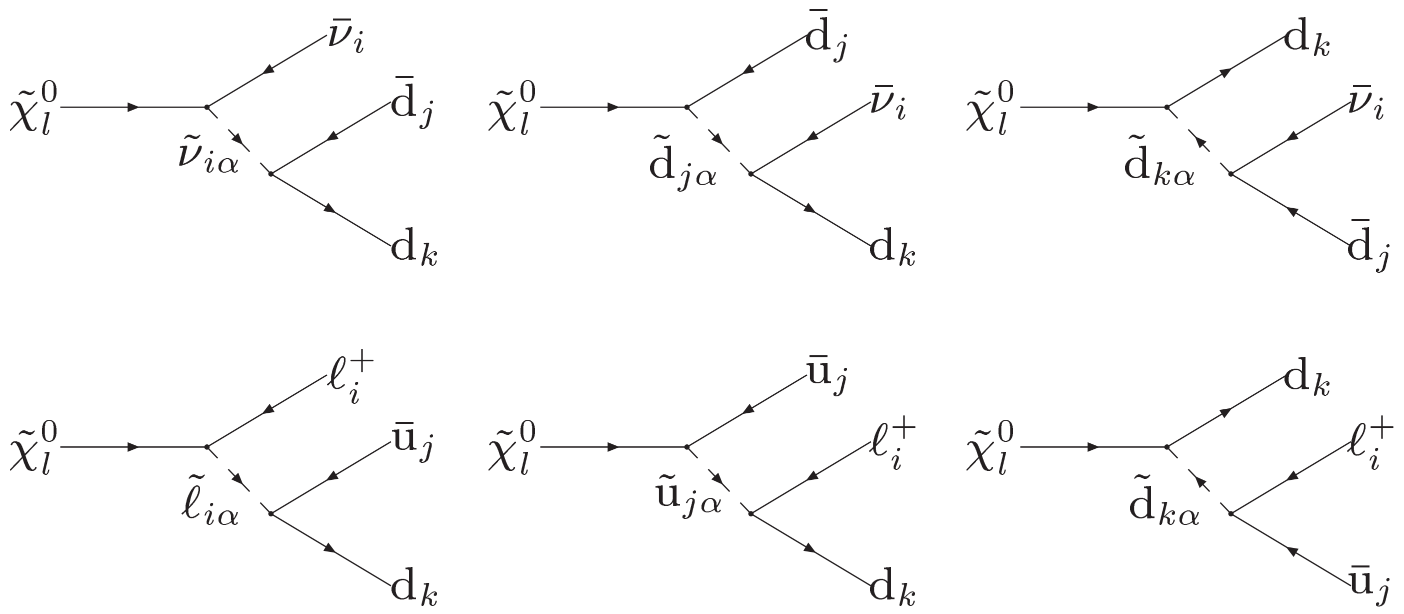
$$
\begin{aligned}
M_{\tilde{\chi}^0_1} &= 169.8 \pm 0.18\,\mathrm{GeV}, \\
M_{\tilde{\chi}^0_2} &= 326.2 \pm 4.8\,\mathrm{GeV}.
\end{aligned}
$$

- Can also reconstruct squarks and charginos.

- Plots taken from ATLAS Physics TDR.

LQD Neutralino Decays

- In this case the neutralino decay gives two jets and a lepton



- Therefore events contain at least four jets and 2 leptons.

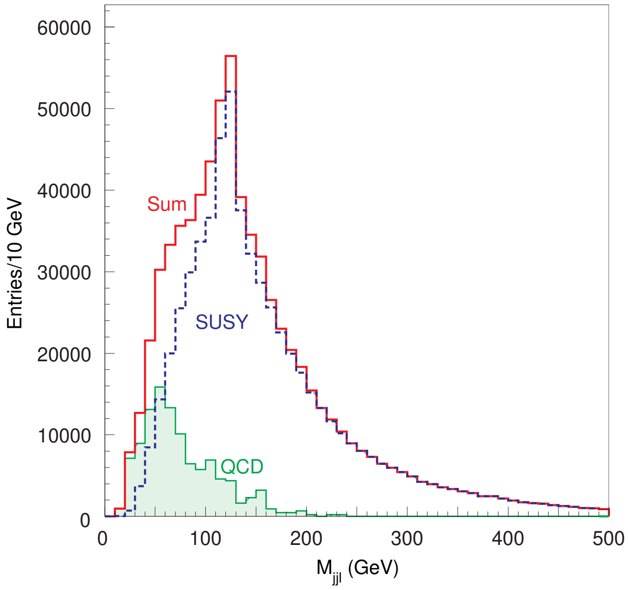
- Result taken from ATLAS Physics TDR.

- Apply the following cuts to reduce the SM background:
  - 6 jets with $p_T > 20\,\mathrm{GeV}$ and 1 with $p_T > 250\,\mathrm{GeV}$;
  - 1 lepton with $p_T > 20\mathrm{GeV}$;
  - sphericity > 0.2 and thrust < 0.9.

LQD Neutralino Decays

- Cuts are then applied to find the right combination of jets and a lepton to reconstruct the neutralino.

- The $\tilde{\chi}_1^0$ mass can be reconstruct from a charged lepton and 2 jets.



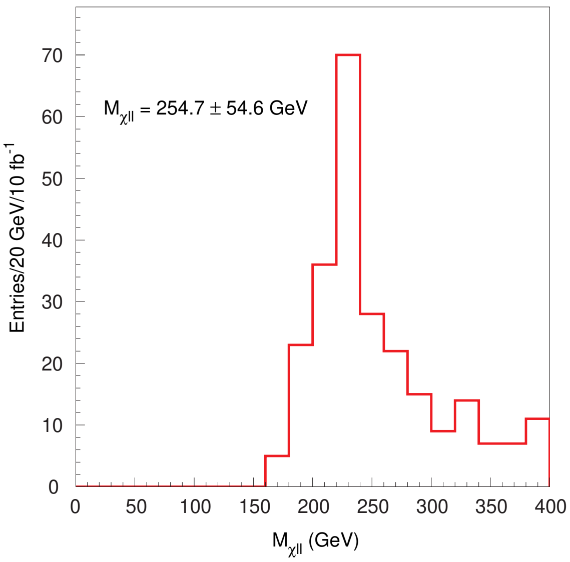
- The error is $\pm 3\,\mathrm{GeV}$ on the neutralino mass.

- This is at SUGRA point 5.

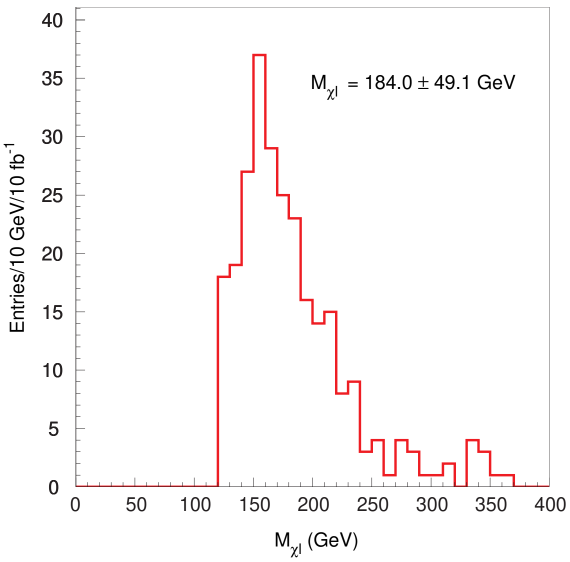
- At this point the $\tilde{\chi}_2^0$ decays via the mode $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm}\ell^{\mp} \to \tilde{\chi}_1^0\ell^+\ell^-\tilde{\chi}_1^0$.

LQD Neutralino Decays

- Therefore by looking for events with 2 more leptons and combining these with nearest $\tilde{\chi}^0_1$ candidate the $\tilde{\chi}^0_2$ can be reconstructed.



- By combined the $\tilde{\chi}^0_1$ candidate with the nearest lepton the $\tilde{\ell}_R$ mass can also be reconstructed.



Baryon Number Violating Neutralino Decays at LHC

Work by Cambridge ATLAS-HERWIG SUSY Group

B. Allanach, A. Barr, L. Drage, C. Lester, D. Morgan, A. Parker, P. Richardson and

B. Webber, JHEP 0103:048,2001

- This is the most experimentally challenging channel for the discovery of SUSY.

- This analysis was performed at the SUGRA Point

$$M_0 = 100 \text{ GeV}, M_{1/2} = 300 \text{ GeV},$$
$$A_0 = 300 \text{ GeV}, \tan\beta = 10, \text{sgn}\,\mu +$$
$$\lambda''_{212} = 0.005.$$

- λ''_{212} was chosen as it is only limited by perturbativity and is one of the harder signatures, *i.e.* no b tagging.

- Each $\tilde{\chi}^0_1$ decays to three quarks.

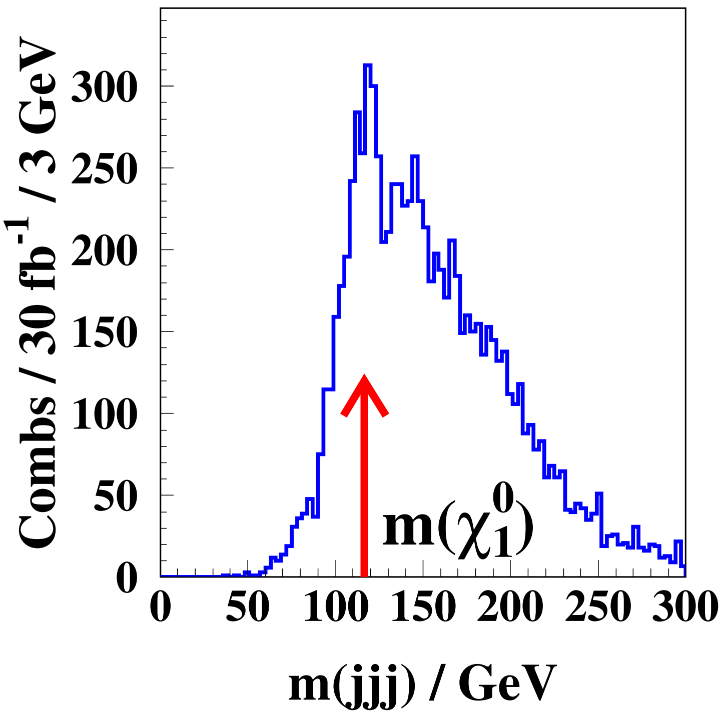
- As the coloured sparticles are predominantly produced the jet multiplicities are large.

Detection of the $\tilde{\chi}^0_1$

- When λ''_{212} is small two $\tilde{\chi}^0_1$s are produced.
- So search for two combinations of three jets with:
  - $\delta m_{jjj} = |m^a_{jjj} - m^b_{jjj}| < 20$ GeV where a and b are the neutralino candidates.
  - Only consider $8 \leq N_{\rm jet} \leq 10$.
  - Transverse sphericity> 0.2, thrust< 0.9.
  - $m_{T,\rm cent} > 1000$ GeV where $m_{T,\rm cent} = \sum \left[p_T^{\rm jet} + p_T^{\rm lept}\right]$.
  - at least 2 leptons with $p_T > 15$ GeV & $|\eta| < 2$.
- Since the cross section is dominated by squark and gluino production $\approx$ 95% of the events contain hard jets from squark decays. Require:
  - $E_T^{h1} > 200$ GeV and $E_T^{h2} > 100$ GeV
- Only consider the other jets to reduce combinatorics.

Results

- Reconstructed $\tilde{\chi}^0_1$ masses for $30\ \mathrm{fb}^{-1}$.

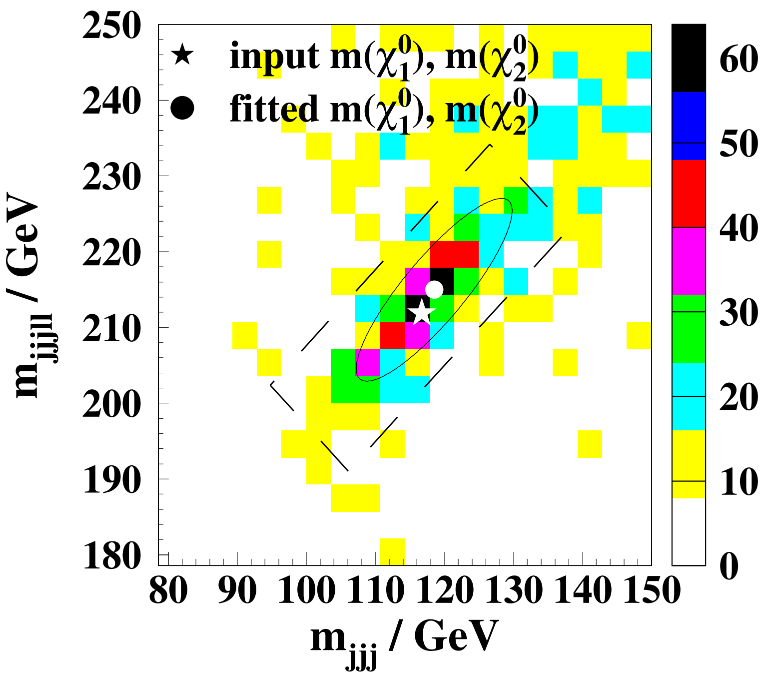


- There is a combinatoric background below the peak.

- The shape of this background is defined by the cuts.

Results

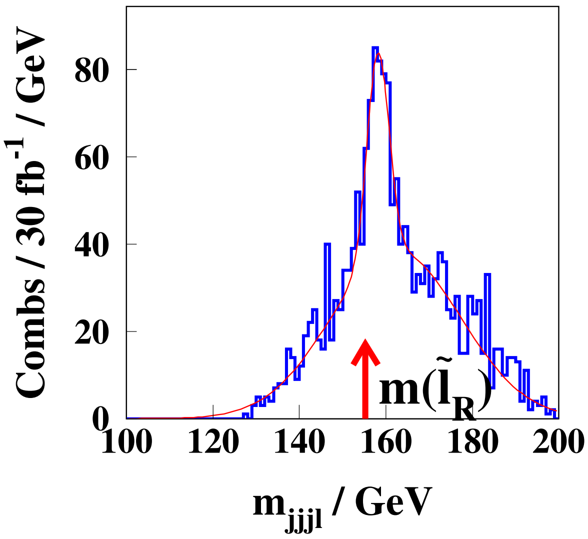
- The requirement that the events contain two leptons preferentially selects the decay chain $\tilde{q}_L \to \tilde{\chi}^0_2 q \to \tilde{l}_R l q \to \tilde{\chi}^0_1 llq \to qqqllq$.
- Use these leptons to reconstruct the $\tilde{\chi}^0_2$ mass.



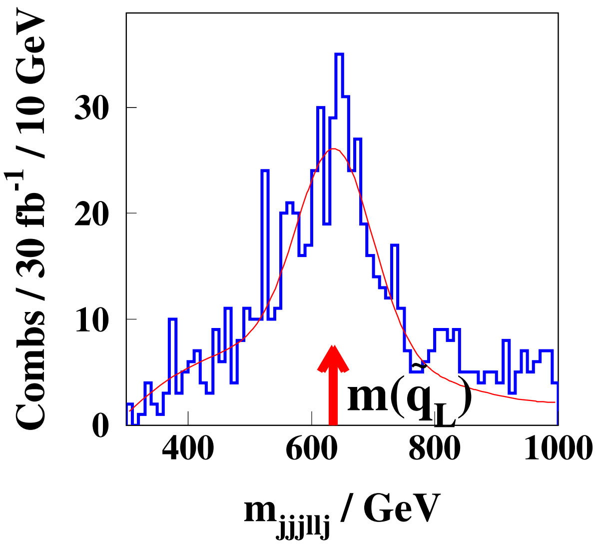
- We can then cut around the peak peak at the $\tilde{\chi}^0_1$,$\tilde{\chi}^0_2$ masses in the mass plane.

Results

- Can also reconstruct the $\tilde{\ell}_R$.



- and $\tilde{q}_L$ masses.



- It is also possible to use non-isolated muons and b-tagging to identify the flavour structure of the coupling.

- Allanach *et. al.* JHEP 0109:021, (2001).

Extra Dimensions

- Many theorists believe there are more than 4 dimensions.
- String theories can only exist in 10/11 dimensions.
- The hierarchy problem can be solved in these models in one of two ways:
  - There is an extra dimension with size ~ 1mm.

$$M^2_{\text{Planck}} \sim M^{n+2} R^n$$

    - The Planck mass is then of order 1 TeV.
    - Hence the hierarchy problem is non-existent.
  - Small extra dimensions
    - The extra dimension is warped.
    - The model has two branes.
    - We live on one and the other is at the Plank scale.
    - The Higgs VEV is suppressed by a warp factor,

$$\exp(-kr_c\pi).$$

Extra Dimensions

- The phenomenology of the small and large extra dimension models are very different.

- We can see this with a simple example.

- Consider a scalar field in 5-dimensions

$$\left(\frac{\partial^2}{\partial t^2} - \nabla_5^2 + m^2\right)\Phi(x,y,z,x_5,t) = 0.$$

where

$$\nabla_5^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} + \frac{\partial^2}{\partial x_5^2}$$

- If the 5-th dimension is circular,

$$\Phi(x,y,z,x_5,t) = \sum_n \Phi_n(x,y,z,t)\exp(inx_5/R).$$

- The equation of motion therefore becomes,

$$\sum_n \left(\frac{\partial^2}{\partial t^2} - \nabla_4^2 + m^2 + \frac{n^2}{R^2}\right)\Phi_n(x,y,z,t).$$

- Tower of states with mass splitting $\sim 1/R^2$.

Extra Dimensions

- These are called Kaluza-Klein excitations.
- In extra dimension models only the graviton exists in the extra dimension.
- So we get towers of gravitons.
- Large Extra Dimensions
  - The mass splitting is small.
  - All the gravitons contribute to a given process.
  - Gives deviations from the SM prediction for SM processes.
- Small Extra Dimensions
  - The mass splitting is large.
  - Gives resonant graviton production.
- The phenomenology is therefore very different.

Resonant Graviton production

Work by Cambridge ATLAS-HERWIG SUSY Group

B. Allanach, K. Odagiri, A. Parker and B. Webber, JHEP 0009:019, 2000.

- There are many models.

- This analysis is model independent, considered Randall and Sundrum type models as a test case.

- In this model the gravitons have KK excitations with scale

$$\Lambda_\pi = \bar{M}_{\rm Planck} \exp(-kr_c\pi).$$

- This gives a spectrum of graviton resonances which can be detected.

- First resonance has mass

$$m_1 = kx_1 \exp(-kr_c\pi) = 3.83\frac{k}{\bar{M}_{\rm Planck}}\Lambda_\pi,$$

where

$$0.01 \le \frac{k}{\bar{M}_{\rm Planck}} \le 1.$$

Small Extra Dimensions

- Model implemented in HERWIG.
- Interfaced to ATLAS simulation (ATLFAST) for detector simulation.
- Coupling $1/\Lambda_\pi$.
- The worst case is when $\frac{k}{\bar{M}_{\rm Planck}} = 0.01$.
- The angular distribution of the decay products in CM frame are

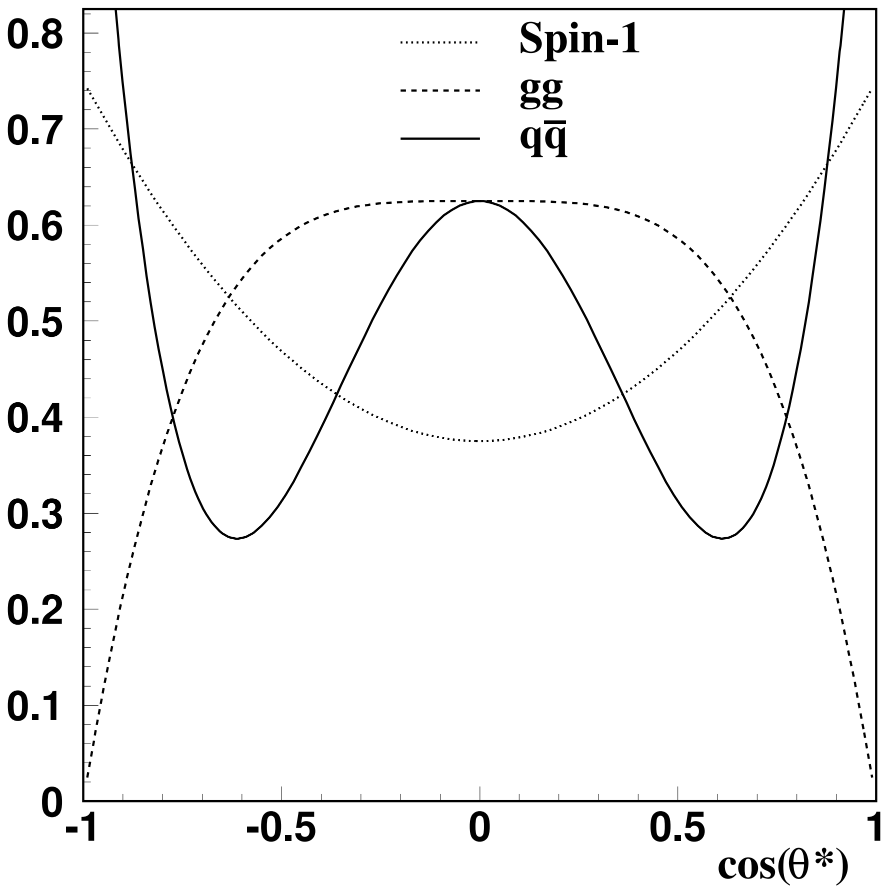
$$
\begin{array}{ll}
qq \to G \to f\bar{f} & 1 - 3\cos^2\theta + 4\cos^4\theta \\
gg \to G \to f\bar{f} & 1 - \cos^4\theta \\
qq \to G \to BB & 1 - \cos^4\theta \\
gg \to G \to BB & 1 + 6\cos^2\theta + \cos^4\theta
\end{array}
$$

- Can distinguish from Drell-Yan with

$$1 + \cos^2\theta.$$

Small Extra Dimensions

- The angular distributions are very different depending on the spin of the resonance.



- Gives information on the spin and couplings of the resonance.

Small Extra Dimensions

- Best channel is $G \to e^+e^-$. Good energy and angular resolution.

  Jets good rate, poor resolution and high background.
  Muons worse mass resolution as high mass.
  Z/W rate and reconstruction problems.

- Main background is Drell-Yan.

- Acceptance for leptons $|\eta| < 2.5$.

- Tracking and identification efficiency included.

- Energy resolution

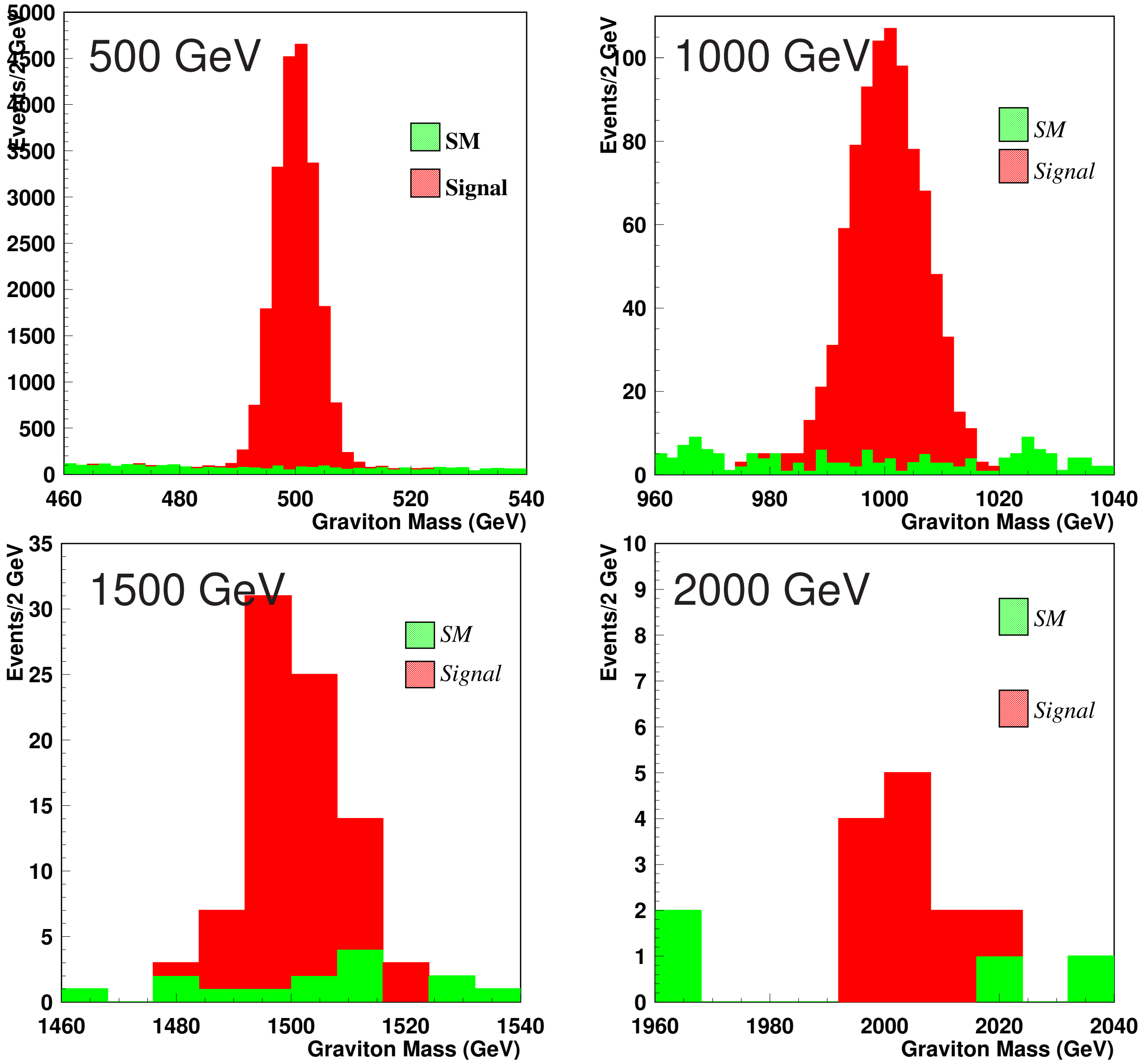
$$\frac{\Delta E}{E} = \frac{12\%}{\sqrt{E}} + \frac{24.5\%}{E_T} + 0.7\%.$$

- Mass resolution

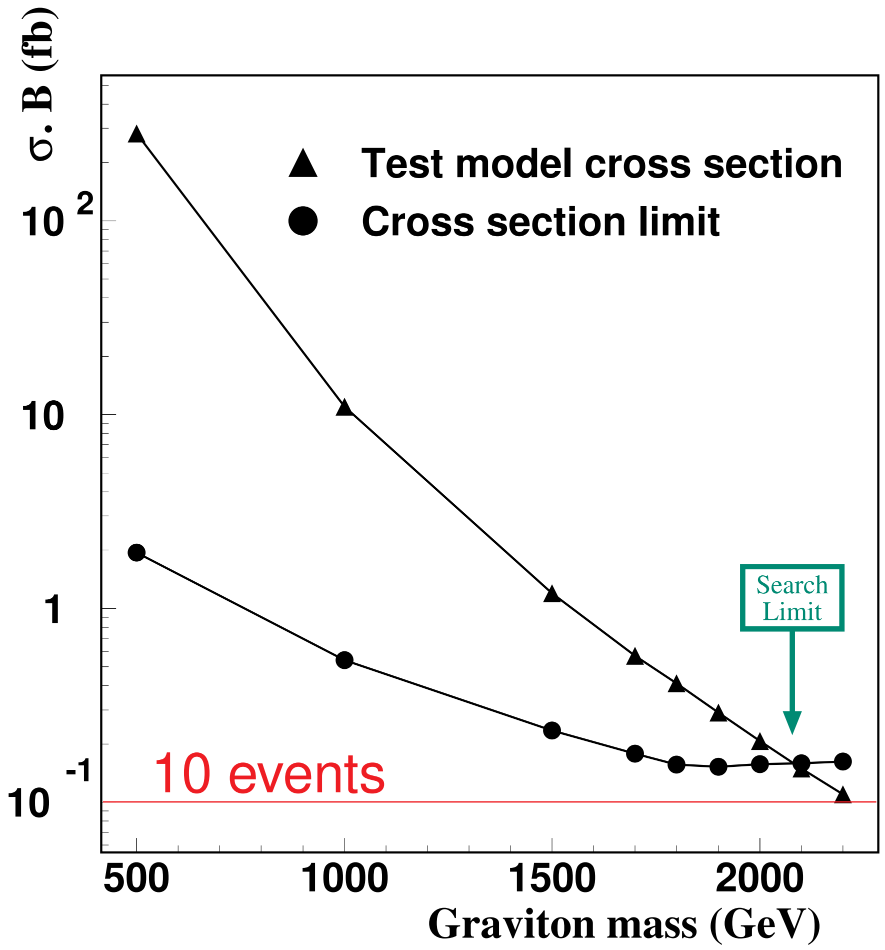
$$\frac{\sigma_m}{m}(500\ GeV) = 0.8\%.$$

Graviton Resonance

- Graviton resonance is prominent above SM background for $100\ \mathrm{fb}^{-1}$ integrated luminosity.
- Drell-Yan background can be measured and subtracted from the sidebands.



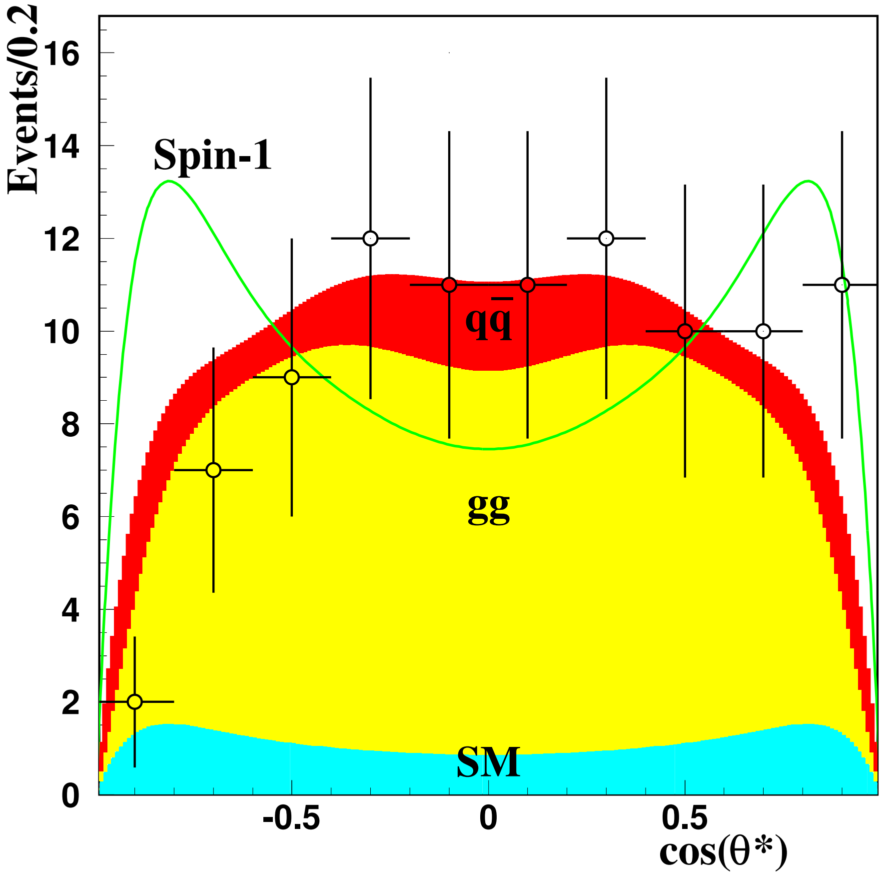
Production Cross Section



- The search limit is at 2080 GeV for a signal of 10 events and $S/\sqrt{B} > 5$.

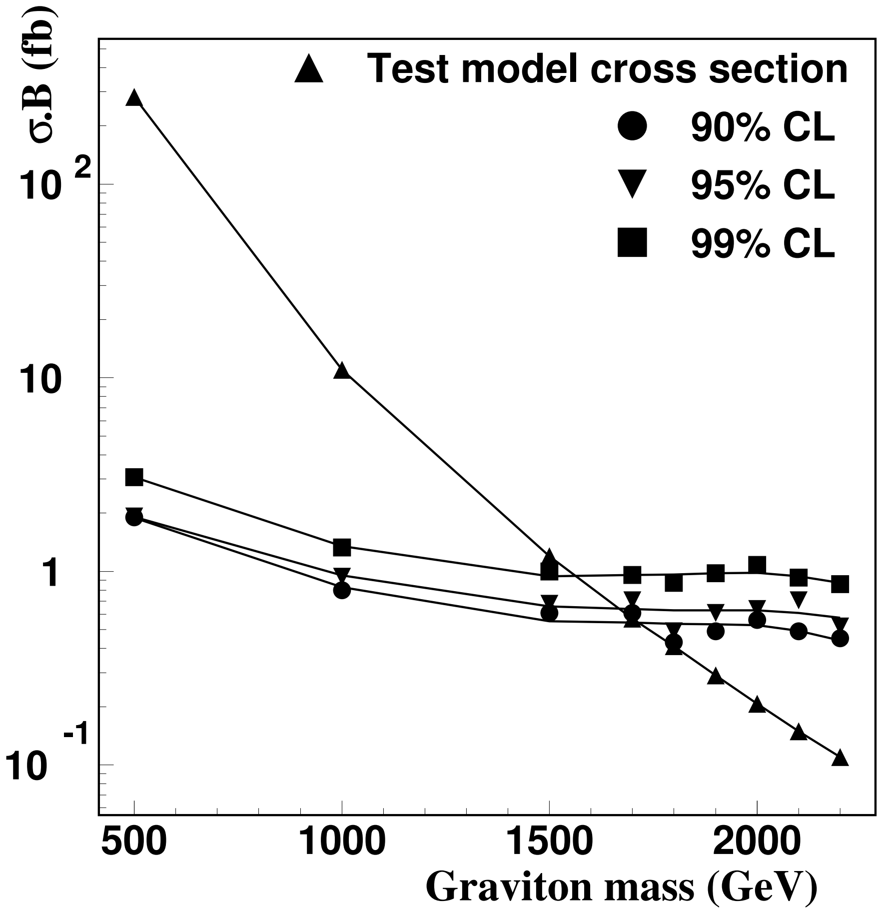
Determining the spin

- The angular distribution changes with graviton mass.
- Production more from $q\bar{q}$ as mass increases due to the PDFs.
- For a graviton mass of 1.5 TeV.



- Production dominantly from gluon fusion.
- Acceptance removes events at high $\cos\theta^*$.

Determining the spin



- Model independent minimum cross sections needed to distinguish spin-2 from spin-1 at 90, 95 and 99% confidence.

- Assumes 100 fb^{-1} integrated luminosity.

- For the test model the spin-2 nature can be established at 90% confidence up to 1720 GeV.

Other Decay Modes

- Can also observe other decays modes:
  - $G \to \mu^+\mu^-$
  - $G \to \gamma\gamma$
  - $G \to \mathrm{jetjet}$
  - $G \to WW$
- Tests the universality of the coupling.

Conclusions

- There are many models of new physics.
- If these models have anything to do with electroweak symmetry breaking they have observable signals at the LHC.
- If there is new physics at the TeV scale the LHC should observe something.
- It may be hard to interpret what a signal is.