Beyond the Standard Model Physics

Outline

- Why BSM Physics?
- Where will we look for it?
  - Precision Experiments
  - Rare Decays
  - Collider Experiments
- What are the options?
  - Grand Unified Theories
  - SUSY
  - Extra Dimensions
- Conclusions

Why BSM Physics?

- **The Standard Model has 19 free parameters:**
  - **3 gauge couplings g_1, g_2, g_3;**
  - **6 quark and 3 lepton masses;**
  - **the Higgs mass and vacuum expectation value(VEV);**
  - **3 mixing angles and 1 phase in CKM matrix;**
  - **the Θ parameter of QCD.**
- **We now need more parameters to incorporate neutrino masses.**
- **What are the values of these parameters?**
  - **Why is the top quark so much heavier that the electron?**
  - **Why is the Θ parameter so small?**
  - **Is there enough CP violation to explain why we are here?**
- **What about gravity?**
- **These are all important questions.**
- **No definite answers to any of them.**

Where will we look for BSM Physics?

- All models of BSM physics predict either new particles or differences from the Standard Model, otherwise they are pretty useless.
- There are a number of ways of looking for BSM effects.
- Collider Experiments
  - If the theory contains new particles these should be produced in collider experiments and decay to give Standard Model particles.
  - Examples include
    * LEP (OPAL, ALEPH, DELPHI, L3) and Tevatron (CDF, D0)
    * In the future LHC (ATLAS, CMS) and NLC?
- Precision Experiments
  - Measure something predicted by the Standard Model to very high accuracy and compare the results with the prediction.
  - Examples include
    * LEP precision Z measurements
    * Brookhaven muon g-2 experiment

- Rare Decays or Processes
  - Measure the cross section or decay rate for some process which the Standard Model predicts to be small (or zero.)
  - Examples include
    * Neutron electric dipole moment experiments
    * Proton Decay experiments
    * Neutrino mixing experiments
    * Rare B and Kaon decay and CP violation experiments (BELLE, BaBar, NA48, KTeV, LHCB, BTeV)

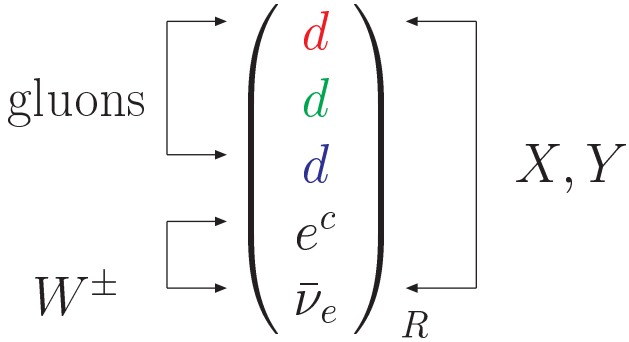
- In many ways these approaches are complimentary.

- Some effects, *e.g.* CP violation, are best studied by dedicated experiments but if the result of these experiments differs from the SM there should be new particles which are observable at collider experiments.

- Rather than talk about these different types of experiment I will present examples of them as I discuss the various different models.

Grand Unified Theories

- **The first attempts to answer these questions were Grand Unified Theories (GUTs.)**
- **The basic idea is that the Standard Model gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ is the subgroup of some larger gauge symmetry.**
- **The simplest group is SU(5), other examples include SO(10).**
- **Let's consider SU(5).**
- **SU(5) has 24 generators $\Rightarrow$ 24 gauge bosons.**
  - **8 gluons of the Standard Model.**
  - **4 Electroweak gauge bosons ($W^{\pm}$, W^0, $B^0 \Rightarrow$ $W^{\pm}$, γ, Z^0)**
- **Therefore there are 12 new gauge bosons**
  - **$X^{\pm\frac{4}{3}}$ and $Y^{\pm\frac{1}{3}}$.**
- **The right-handed down type quarks and left handed leptons form a $\bar{5}$ representation of $SU(5)$.**



- **The rest of the particles form a 10.**

$$\begin{pmatrix} 0 & u^c & -u^c & -u & -d \\ u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ u & u & u & 0 & -e^c \\ d & d & d & e^c & 0 \end{pmatrix}_L$$

- **In this model there are two stages of symmetry breaking.**

- **At the GUT scale the $SU(5)$ symmetry is broken and the X and Y bosons get masses.**

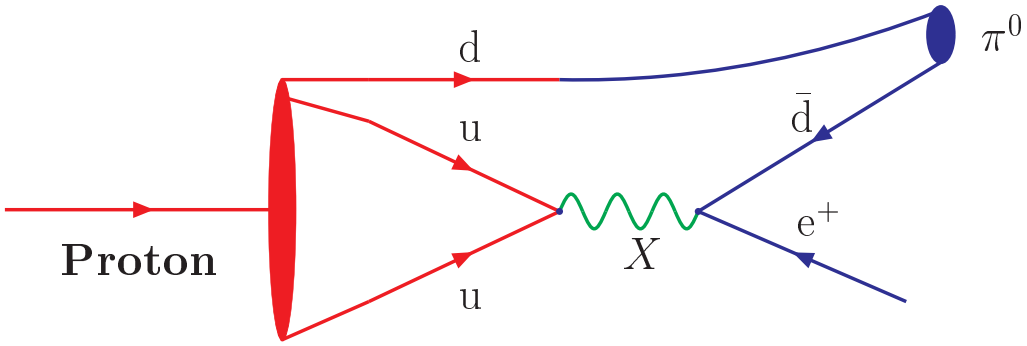
- **At the electroweak scale the $SU(2) \times U(1)$ symmetry is broken as before.**

- **There are three problems with this theory:**
  - **The couplings don't meet at the GUT scale;**
  - **Why is the GUT scale higher than the electroweak scale;**
  - **Proton Decay.**

- **We will come back to the first two of these questions.**

Proton Decay

- **Grand Unified theories predict the decay of the proton via the exchange of X and Y bosons.**



- **We would expect this decay to go like**

$$\Gamma(p \to \pi^0 e^+) \sim \frac{M_p^5}{M_X^4}.$$

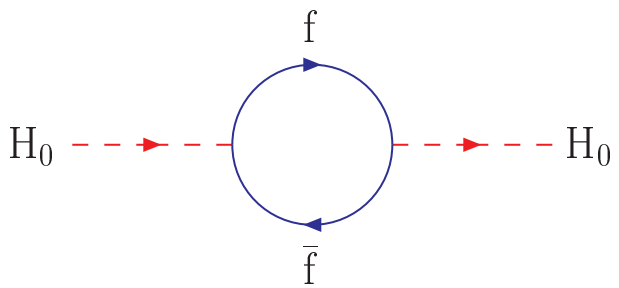
- **There are limits on the proton lifetime from water Čerenkov experiments.**

- **The decay of the proton will produce an electron which is travelling faster than the speed of light in water.**

- **This will give Čerenkov radiation, just as the electron produced in the weak interaction of a neutrino does.**
- **Use this to search for proton decay.**
- **No evidence gives a limit of $\tau_P \geq 1.6 \times 10^{32}$ years.**
- **This means $M_X > 10^{16-17}$GeV.**
- **This is larger than preferred by coupling unification.**

Hierarchy Problem

- **The fact that the electroweak scale is so much less than the GUT scale is called the hierarchy problem.**
- **It is most common to discuss the technical hierarchy problem which is related to the Higgs mass.**
- **If we look at the Higgs mass there are quantum corrections.**



- **This gives a correction to the Higgs mass,**

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

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

$$\delta M_{Hf}^2 = \frac{|g_f|^2}{16\pi^2}\left[-2\Lambda^2+6m_f^2\ln\left(\Lambda/m_f\right)\right].$$

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

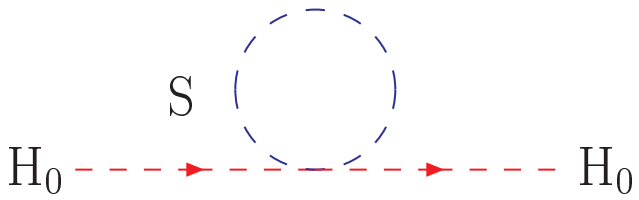
$$M_H^2 = M_{H\,\mathrm{bare}}^2 + \delta M_H^2,$$

  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 consider three:**
  - **Supersymmetry;**
  - **Extra Dimensions;**
  - **Technicolour.**

Supersymmetry

- **If there is a scalar loop in the Higgs propagator**



- **We get a new contribution to the Higgs mass,**

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

- **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	

- All the SM fermions have 2 spin zero partners, called left and right.
- All the SM bosons have 2 spin half partners, called gauginos.
- Need two Higgs doublets to give mass to both the up and down type quarks.

Other reasons for SUSY

- There are major two reasons, in addition to the solution of the hierarchy problem to favour SUSY as an extension of the SM.

- SUSY coupling unification
  - In SUSY GUTS the additional SUSY particles change the running of the couplings and allow the couplings to truly unify at the GUT scale.
  - With increasingly accurate experimental measurements of the strong coupling this is no longer quite true however.

- Coleman-Mandula theorem
  - If we consider extension to the Poincaré group any new generators which transform as bosons lead to a trivial S matrix, *i.e.* scattering only through discrete angles.
  - Later Haag, Lopuszanski and Sohnius showed that SUSY is the only possible extension of the Poincaré group which doesn't give a trivial S matrix.

SUSY Formalism

- A lot of SUSY talks go into a lot of detail about complicated formalisms for deriving a supersymmetrically invariant Lagrangian.
- This can confuse a lot of people and is often not necessary.
- I will NOT go into too many details about these formalisms.
- They are only useful in deriving Lagrangians.
- What I will try to explain is how these formalisms give Feynman rules so you have some idea of what people are showing you in seminars.
- SUSY theorists usually start from the superfield.
- You can think of the superfield as a generalization of a field which contains both a SM particle and its SUSY partner.
- There are two types of superfield.
  - The chiral superfield.
  - The vector superfield.

Chiral Superfields

- **The chiral superfield contains a Weyl fermion and a scalar.**
- **A Weyl fermion only has 1 degrees of freedom,** $e.g.\, e_L$ **or** e_R**.**
- **The scalar is the SUSY partner of the fermion.**
- **There are two types of chiral superfield, left and right.**
- **You may see the field written in a component notation**

$$\begin{aligned}\Phi(x^\mu,\theta,\bar{\theta}) \;=\; & \phi(x)+\sqrt{2}\theta\psi(x)+\theta\theta F(x)+i\partial_\mu\phi(x)\theta\sigma^\mu\bar{\theta} \\ & -\frac{i}{\sqrt{2}}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar{\theta}-\frac{1}{4}\partial^\mu\partial_\mu\phi(x)\theta\theta\bar{\theta}\bar{\theta},\end{aligned}$$

  where $\phi(x)$ **is the scalar field,** $\psi(x)$ **is the Weyl spinor field, and** $F(x)$ **is an auxiliary field.**

- θ **is a two-component spinor.**
- **This is the left chiral superfield. The right field can be found by taking the Hermitian conjugate.**
- **The component fields transform in the following way under a SUSY transformation**

$$\begin{aligned}\delta\phi &= \sqrt{2}\xi\psi; \\ \delta\psi &= \sqrt{2}\xi F+i\sqrt{2}\partial_\mu\phi\sigma^\mu\bar{\xi}; \\ \delta F &= i\sqrt{2}\partial_\mu\psi\sigma^\mu\bar{\xi}.\end{aligned}$$

Chiral Superfields

- The important thing to note is that the auxiliary field only changes by a total derivative.
- This means that we can use the F term of a chiral superfield as a SUSY Lagrangian.
- Together with the property that a product of chiral superfields is also a chiral superfield this allows us to write down part of the Lagrangian.
- In the MSSM the matter and Higgs fields are chiral superfields.
- The following notation or some variant is often used.
  - E_i The right lepton SU(2) singlet chiral superfield for generation i.
  - D_i The right down quark SU(2) singlet chiral superfield for generation i.
  - U_i The right up quark SU(2) singlet chiral superfield for generation i.
  - $H_{1,2}$ The left chiral superfields for the Higgs doublets.
  - L_i The left lepton SU(2) doublet chiral superfield for generation i.
  - Q_i The left quark SU(2) doublet chiral superfield for generation i.

Vector Superfields

- **The vector superfield contains a spin 1 gauge boson and the corresponding gaugino**

$$\begin{aligned} S(x^\mu,\theta,\bar\theta) \;=\; & C(x)+i\theta\chi(x)-i\bar\theta\bar\chi(x)+\frac{i}{2}\theta\theta\left[M(x)+iN(x)\right] \\ & -\frac{i}{2}\bar\theta\bar\theta\left[M(x)-iN(x)\right]+\theta\sigma^\mu\bar\theta V_\mu(x) \\ & +i\theta\theta\bar\theta\left[\bar\lambda(x)+\frac{i}{2}\bar\sigma^\mu\partial_\mu\chi(x)\right]-i\bar\theta\bar\theta\theta\left[\lambda(x)+\frac{i}{2}\sigma^\mu\partial_\mu\bar\chi(x)\right] \\ & +\frac{1}{2}\theta\theta\bar\theta\bar\theta\left[D(x)-\frac{1}{2}\partial_\mu\partial^\mu C(x)\right]. \end{aligned} \tag{2}$$

- **The fields C, M, N and χ can be eliminated by a SUSY gauge transformation.**

- **The important point here is that the D term only changes by a total derivative under a SUSY transform.**

- **Also the product of a left and a right chiral superfield is a vector superfield.**

- **In the MSSM the gauge bosons of the Standard Model and their SUSY partners are represented by vector superfields.**

SUSY Lagrangians

- **We can now write down the simplest SUSY Lagrangian**

$$\mathcal{L} = [\Phi\Phi^\dagger]_{\theta\theta\bar{\theta}\bar{\theta}} = FF^\dagger + \partial_\mu\phi^*\partial^\mu\phi + i\bar{\psi}\bar{\sigma}^\mu\partial_\mu\psi,$$

  This is the Lagrangian for a free Weyl fermion and its scalar superpartner. It this case the equations of motion give $F = 0$.

- **We then add interactions to it two ways.**
  - **One type of interaction if the interaction of a vector and chiral superfields.This is very complicated and not really necessary for our discussions.**
  - **The other is the interaction of the chiral superfields with each other.**

Superpotential

- **SUSY theorists like to talk about the superpotential.**
- **This is simply the function which when we take the F-term gives the Yukawa interactions and part of the scalar potential.**
- **In general a superpotential of mass dimension 3 is the highest which is renormalizable.**
- **So if we consider just one chiral superfield**

$$\mathbf{W}(\Phi) = \frac{m}{2}\Phi\Phi + \frac{\lambda}{3}\Phi\Phi\Phi.$$

- **This gives the interaction Lagrangian**

$$\begin{aligned}\mathcal{L} &= [W(\Phi)]_{\theta\theta} + \text{h.c.},\\ &= m(\phi F - \frac{1}{2}\psi\psi) + \lambda(\phi^2 F - \phi\psi\psi) + \text{h.c.}\end{aligned}$$

- **So the whole Lagrangian for this simple model is**

$$\begin{aligned}\mathcal{L} &= [\Phi\Phi^\dagger]_{\theta\theta\bar{\theta}\bar{\theta}} + ([W(\Phi)]_{\theta\theta} + \text{h.c.}),\\ &= \partial_\mu\phi^*\partial^\mu\phi + i\bar{\psi}\bar{\sigma}^\mu\partial_\mu\psi - |\lambda\phi^2 + m\phi|^2 - \left(\frac{m}{2}\psi\psi + \lambda\psi\psi\phi + \text{h.c.}\right).\end{aligned}$$

- **After we eliminate F using the equation of motion,**

$$F^\dagger = -m\phi - \lambda\phi^2.$$

MSSM superpotential

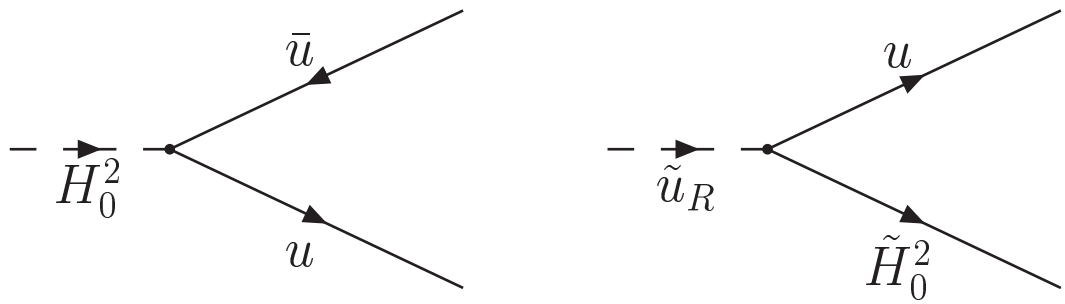
- **The most general renormalizable gauge-invariant superpotential is given by**

$$\mathbf{W} = \mathbf{W}_{\mathrm{MSSM}} + \mathbf{W}_{\not{R}_p}$$

- **where**

$$\begin{aligned}\mathbf{W}_{\mathrm{MSSM}} \;=\; & -h^E_{ij}\varepsilon_{ab}L^a_i H^b_1 \overline{E}_j - h^D_{ij}\varepsilon_{ab}Q^a_i H^b_1 \overline{D}_j \\ & + h^U_{ij}\varepsilon_{ab}Q^a_i H^b_2 \overline{U}_j + \mu\varepsilon_{ab}H^a_1 H^b_2,\end{aligned}$$

  - **The first 3 terms in this superpotential give the Higgs fermion couplings of the SM and the additional interactions required by SUSY.**
  - **The last term mixes the Higgs doublets**

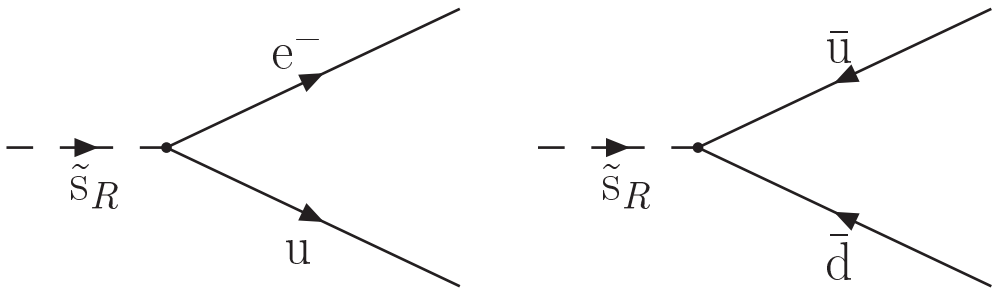


R-parity Violation

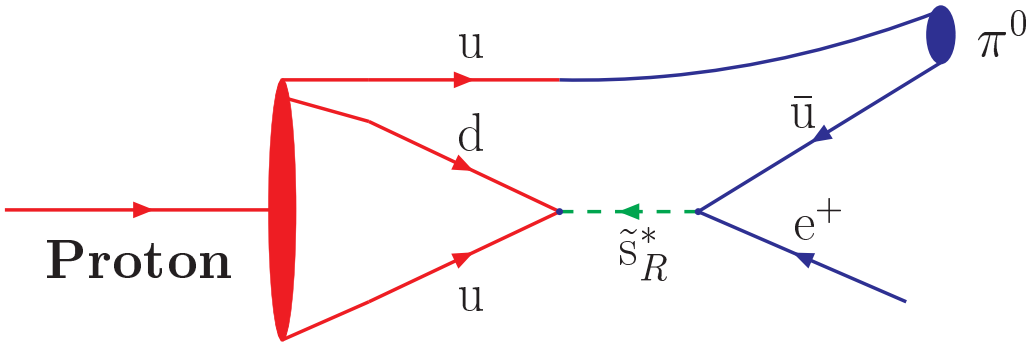
- **and**

$$\mathbf{W}_{\not\mathbf{R_p}} = \frac{1}{2}\lambda_{ijk}\varepsilon^{ab}L_a^i L_b^j \overline{E}^k + \lambda'_{ijk}\varepsilon^{ab}L_a^i Q_b^j \overline{D}^k + \frac{1}{2}\lambda''_{ijk}\varepsilon^{c_1c_2c_3}\overline{U}^i_{c_1}\overline{D}^j_{c_2}\overline{D}^k_{c_3} + \kappa_i\varepsilon^{ab}L_a^i H_b^2,$$

  - **These terms are a problem as they violate lepton or baryon number conservation.**



- **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.**

e.g. Baryon Parity $\begin{array}{lcl} \{Q_i, U_i, D_i\} & \longrightarrow & -\{Q_i, U_i, D_i\} \\ \{L_i, E_i\} & \longrightarrow & \{L_i, E_i\} \end{array}$

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.

The μ problem and NMSSM

- **A lot of theorists worry about the μ term in the superpotential**

$$\mu \varepsilon_{ab} H_1^a H_2^b.$$

- **This is because μ has the dimensions of mass and is not protected by any symmetry from being the GUT scale.**

- **The solution is to add a singlet Higgs field S such that the μ term becomes**

$$\lambda S \varepsilon_{ab} H_1^a H_2^b.$$

- **λ is now a dimensionless coupling and if S develops a VEV we get an effective μ term $\mu = \lambda \langle S \rangle$.**

- **This theory has problems because we should add terms like**

$$\kappa S^3,$$

  to the superpotential.

- **Give cosmological problems.**

- **Lots of models on the market with different discrete symmetries to forbid the problem terms.**

Supersymmetry breaking

- The other major problem is that 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.
- What are these parameters?
  - SUSY breaking masses for the scalars;
  - SUSY breaking masses for the gauginos;
  - A terms which mix three scalars;
  - mixing angles and CP violating phases.

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.**

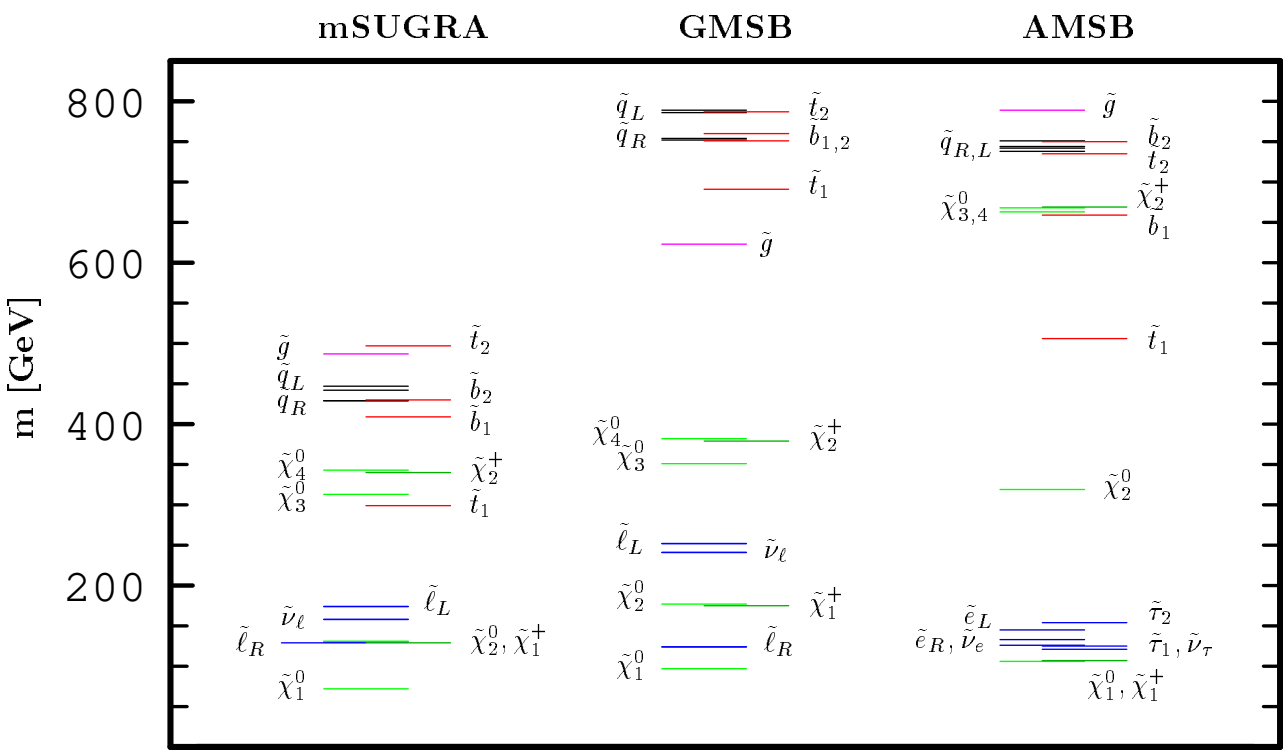
GMSB

- **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 $SU(5)$ 5 or 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.**

Phenomenology

- There is obviously a HUGE amount of phenomenology in these SUSY models.
- I can do no more than scratch the surface.
- I will try and provide an overview.
- I'll start with the collider phenomenology as this is what I'm most familiar with
- I'll then go on and discuss flavour changing neutral currents and rare decays.

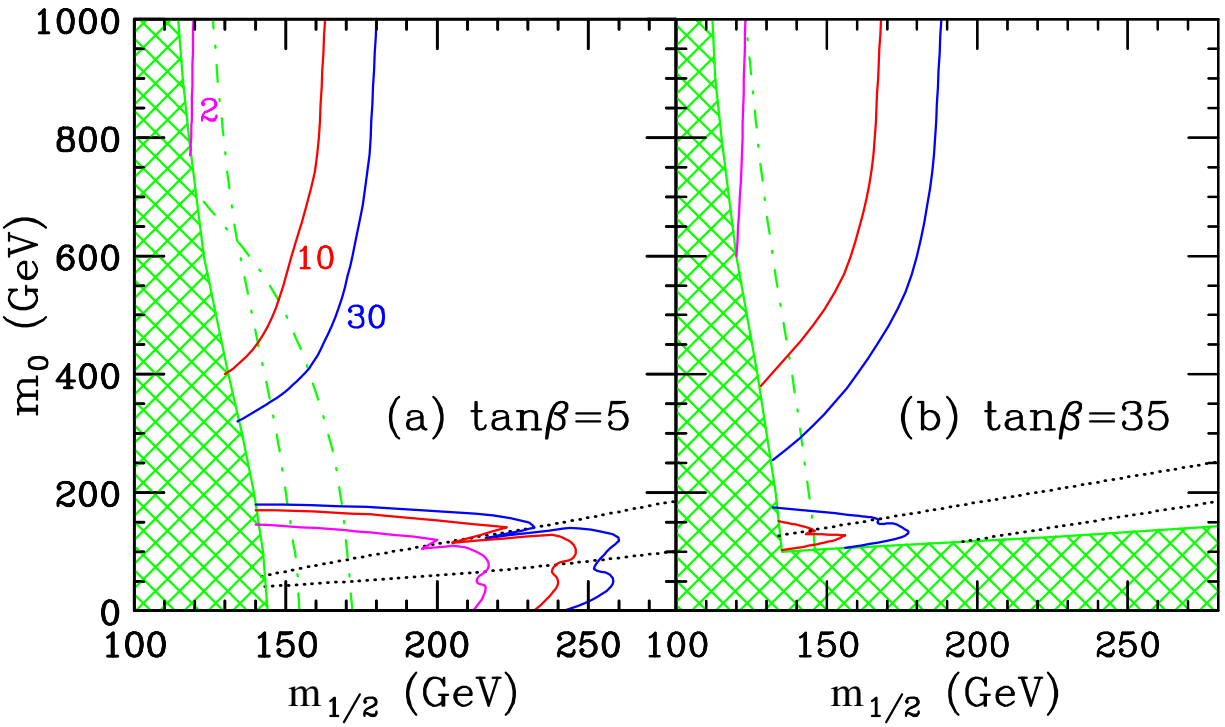
Characteristic BSM Signals

- **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.**

Tevatron

- The Tevatron probably won't have sufficient energy to produce the strongly interacting squarks and gluinos.
- Instead the production of electroweak gauginos may dominate.
- The most promising channel is $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \ell^+ \ell^- \tilde{\chi}_1^0 \ell^\pm \nu$.
- This gives trilepton events which have a relatively low SM background.



LHC

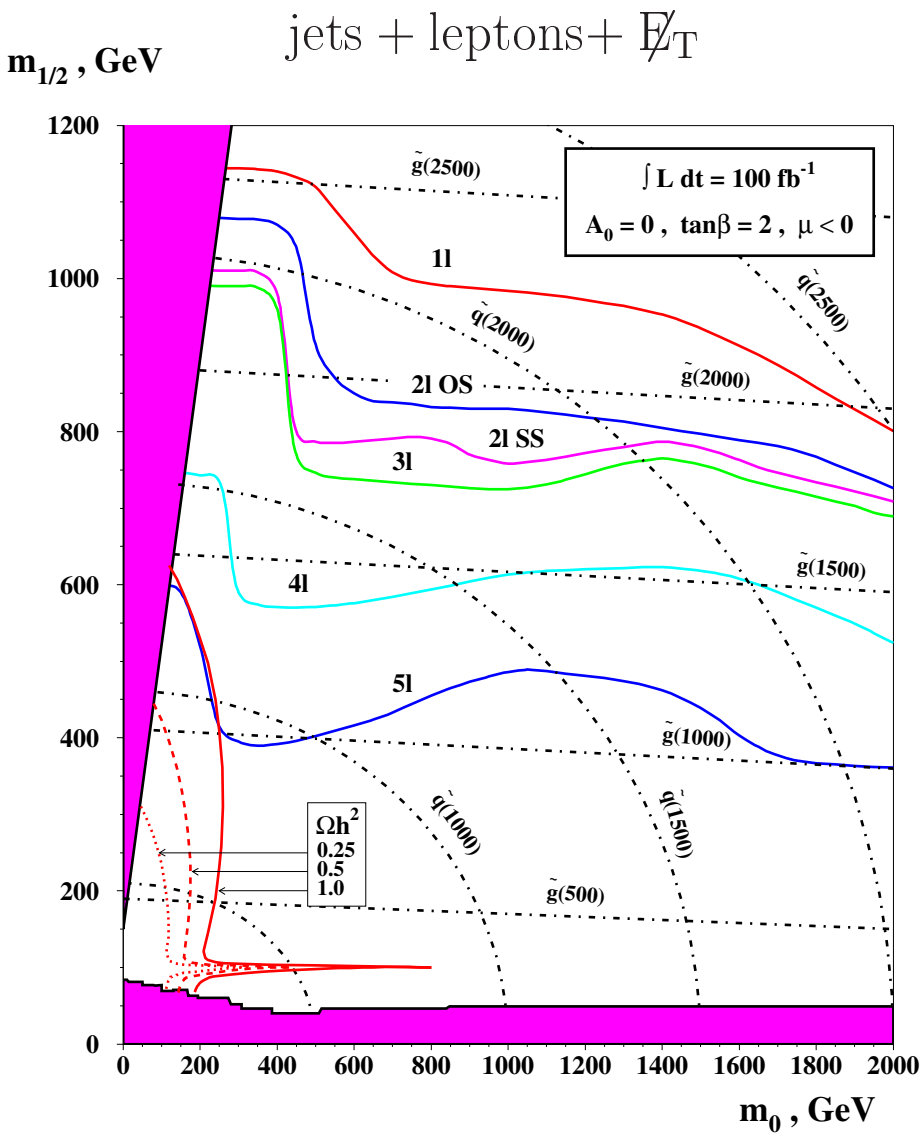
- LHC SUSY studies fall in two categories
  - 'Search studies'
    These are designed to show SUSY can be discovered by looking at inclusive signatures.
  - 'Measurement studies'
    These are designed to show that some parameters of the model, usually masses, can be measured. The aim is to show that 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.*



- **hep-ex/9709032, CMS**

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

Measuring the SUSY scale

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

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

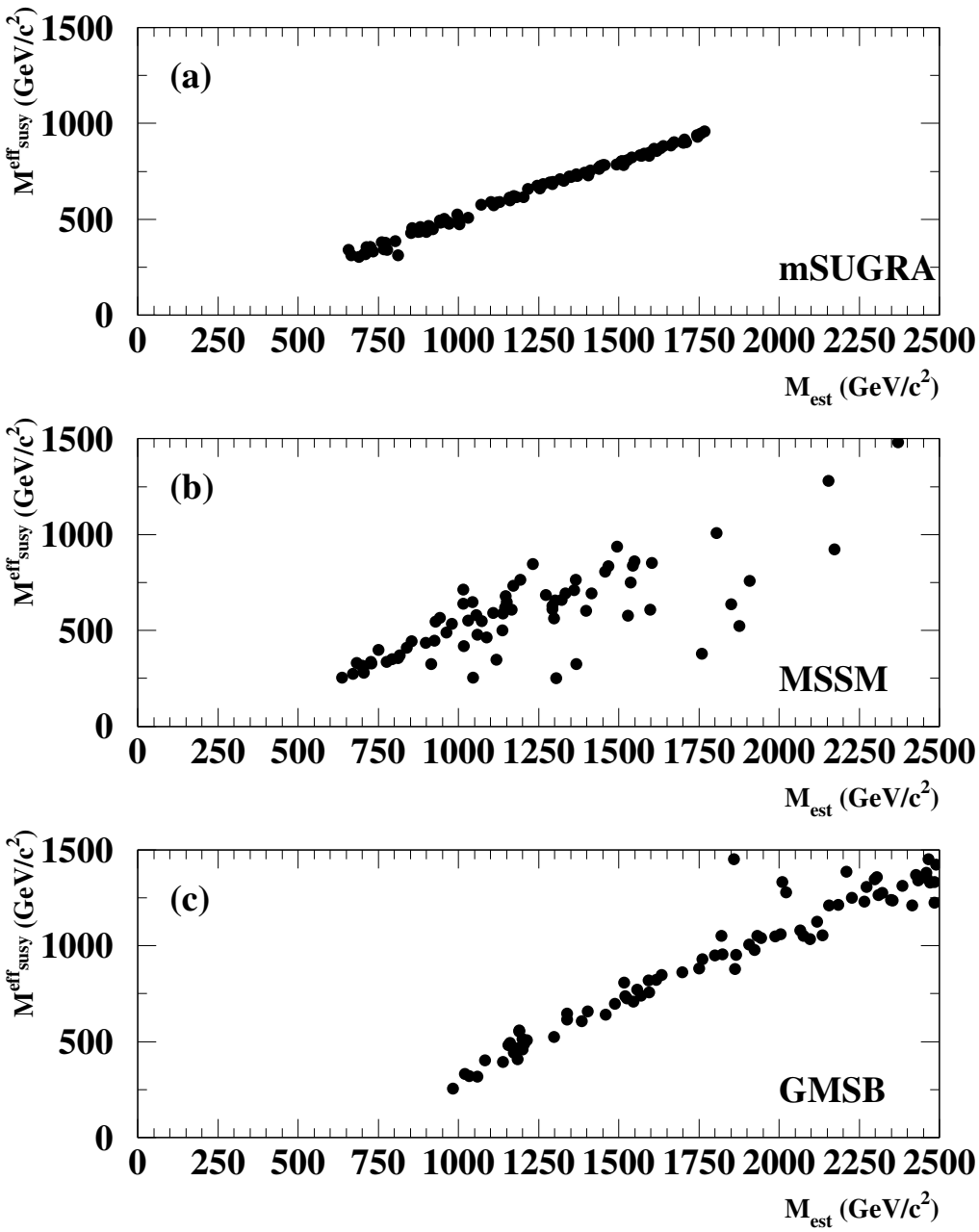
  can be used to measure the SUSY scale.

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

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

- **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

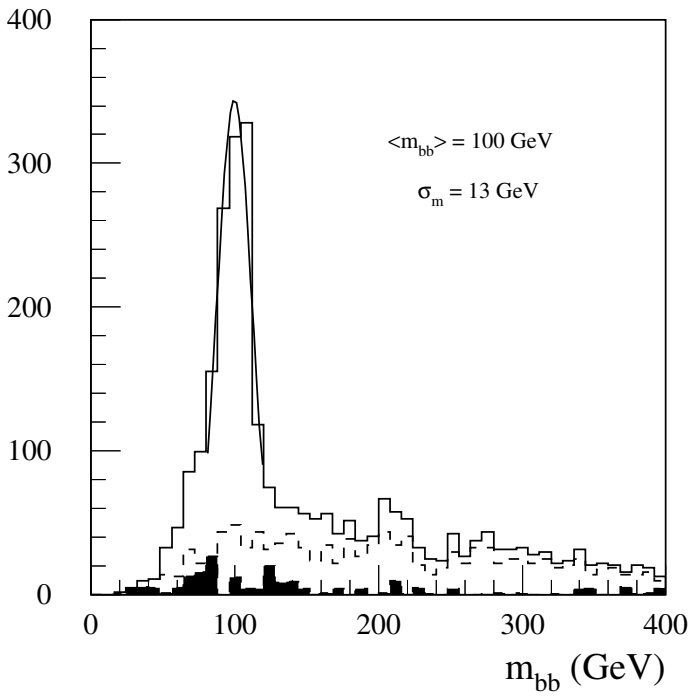
$$\sum_{\text{jets}} |E_T| \qquad \text{or} \qquad \sum_{\text{jets}} |\mathrm{E_T}| + \not{\mathrm{E}}_{\mathrm{T}}.$$

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 $\tilde{\chi}_i^0$ and $\tilde{\chi}_i^\pm$ are produced in their decay, $e.g.\, \tilde{q} \to q\tilde{\chi}_2^0$.**
- **There are two generic features:**
  - **$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ or**
  - **$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+\ell^-$ possibly via an intermediate slepton $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+\ell^-$.**
- **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

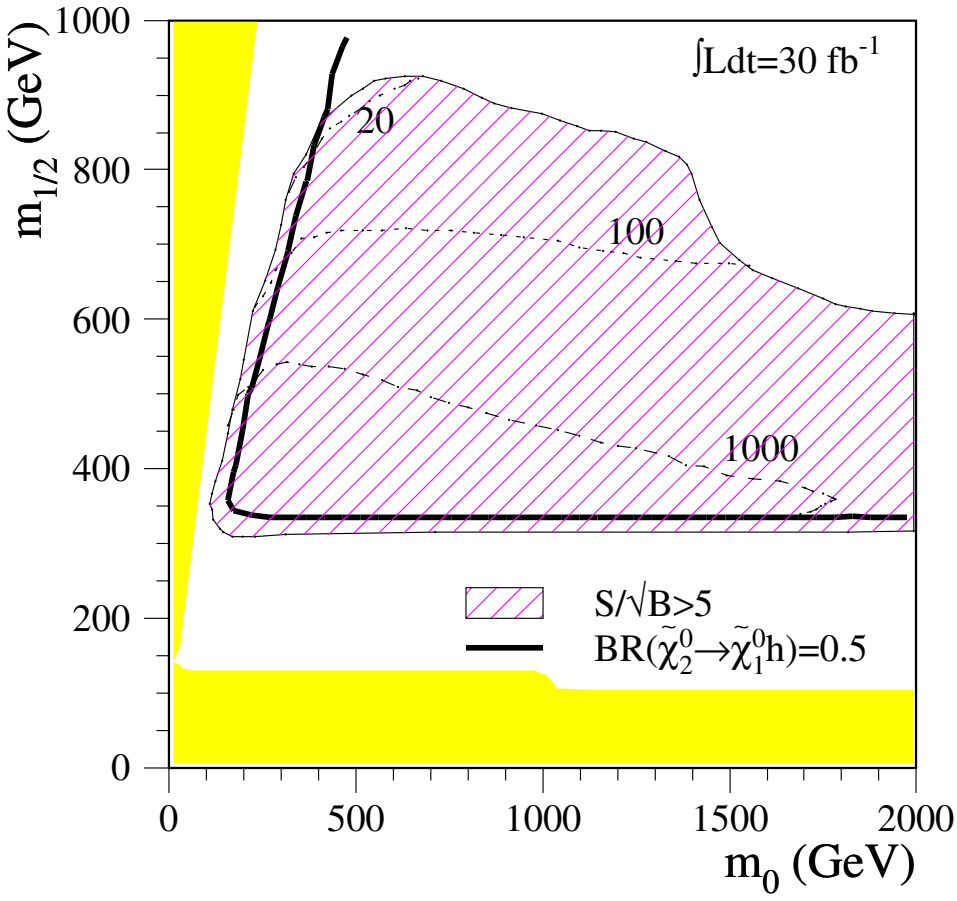
- **If the decay mode $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ exists the Higgs will be discovered in SUSY events.**
- **In this case $\sim$ 20% of SUSY events contain $h \to b\bar{b}$.**



- **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 $S/\sqrt{B} > 5$.**

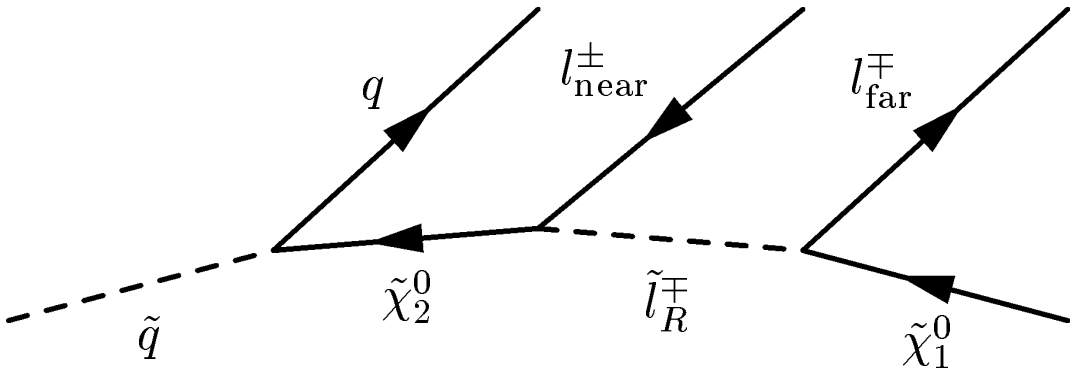
- **Over the rest of parameter space the leptonic decay $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ is crucial.**

Leptonic Decay chains

- **In many models the decay chain,**

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

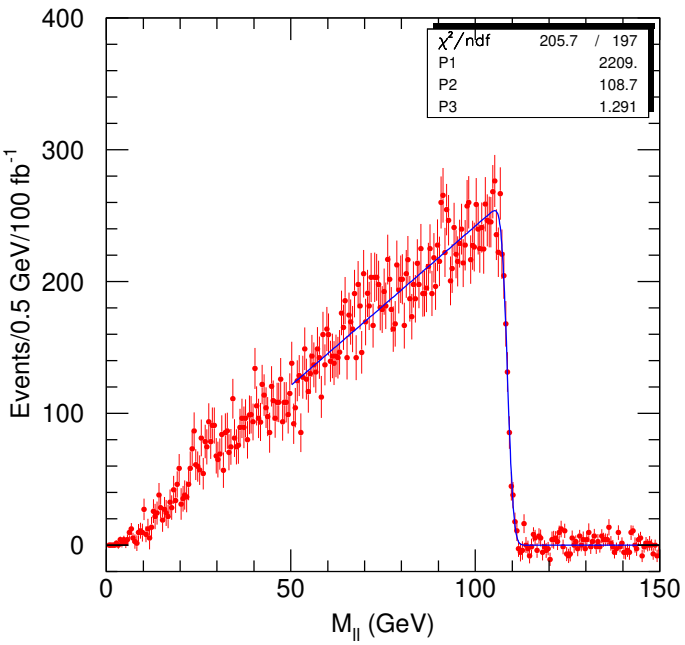
  is present.



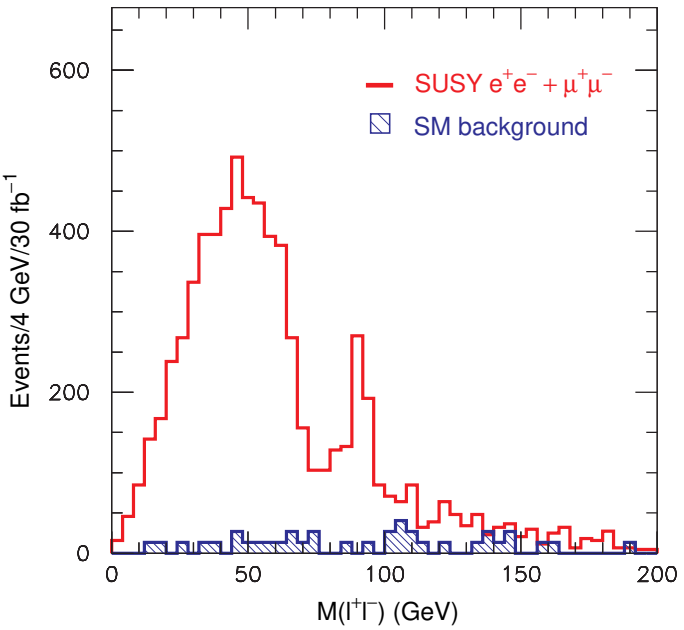
- **Start by measuring the decay $\tilde{\chi}_2^0 \to \ell^+\ell^-$.**
- **Figures taken from ATLAS Physics TDR.**

Leptonic Decay chains

- **Via real slepton.**



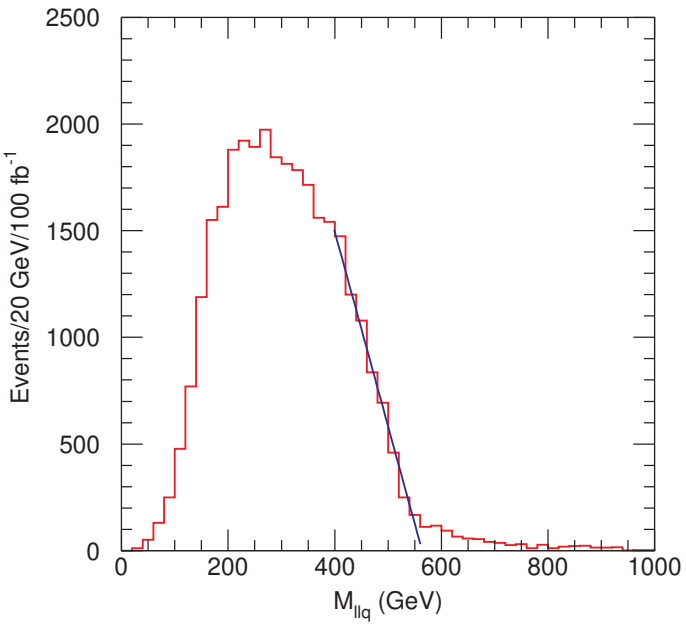
- **Via virtual slepton and Z.**



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

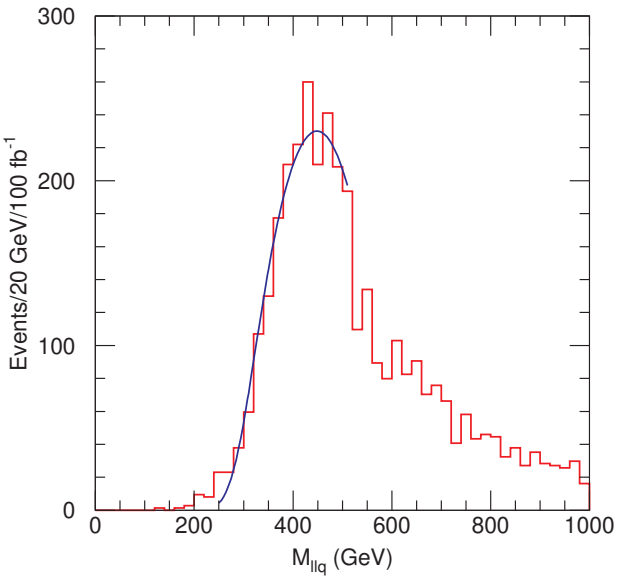
Building on Leptons

- **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.**

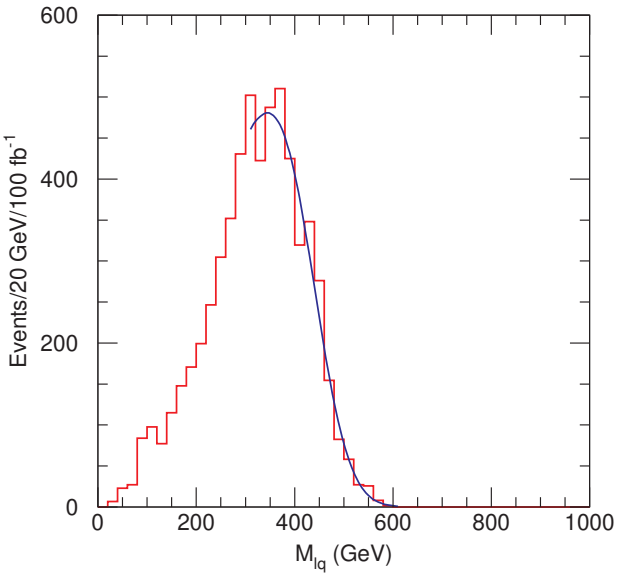


Building on Leptons

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



- **ℓ jet mass.**



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

- **Taken from ATLAS Physics TDR.**

GMSB signals

- **The NLSP is usually the lightest neutralino or stau.**
- **The NLSP then decays producing the gravitino which is the true LSP:**
  - $\tilde{\chi}_1^0 \to \gamma \tilde{G}$**;**
  - $\tilde{\tau}_1 \to \tau \tilde{G}$**.**
- **Both cases have been studied.**
- **Here we will look at a neutralino LSP.**

GMSB with Prompt Photons

- **The signature of $\tilde{\chi}_1^0 \to \gamma \tilde{G}$ is missing transverse energy and two hard photons.**

- **Use the leptonic decay mode of the next-to-lightest neutralino,**

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

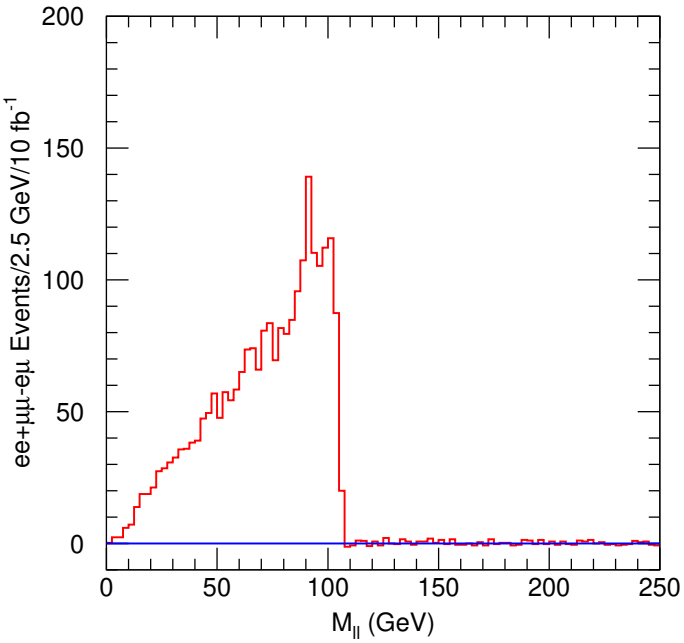
  again.

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

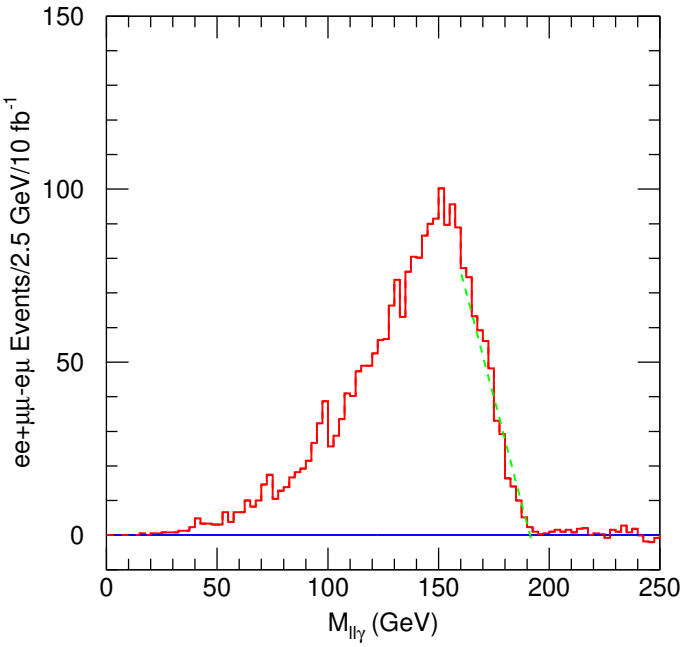
$$\begin{aligned}
M^2_{\tilde{\ell}_R} &= \frac{\left(M^{(1)}_{\ell\gamma}\right)^2 \left(M^{(2)}_{\ell\gamma}\right)^2}{\left(M^{\max}_{\ell\ell}\right)^2} \\
M^2_{\tilde{\chi}_1^0} &= M^2_{\tilde{\ell}_R} - \left(M^{(1)}_{\ell\gamma}\right)^2 \\
M^2_{\tilde{\chi}_2^0} &= M^2_{\tilde{\ell}_R} + \left(M^{(2)}_{\ell\gamma}\right)^2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

GMSB with Prompt Photons

- $\ell\ell$ distribution.

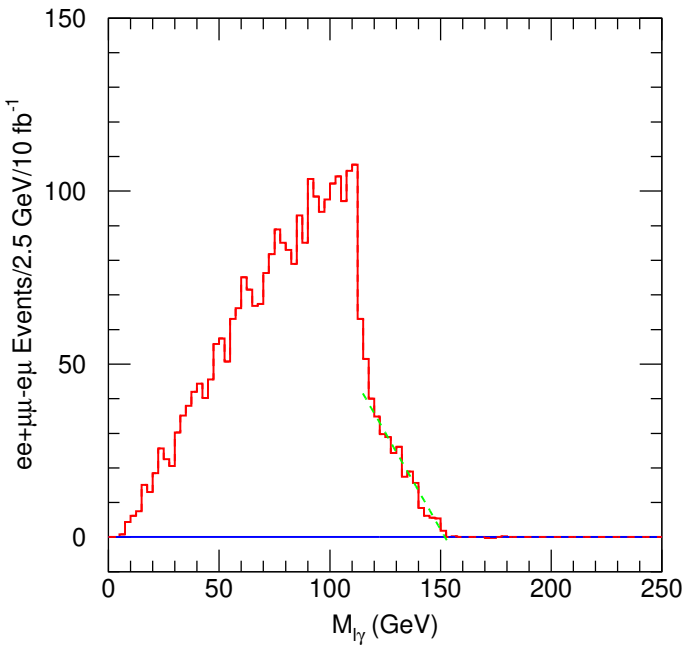


- $\ell\ell\gamma$ distribution.



GMSB with Prompt Photons

- $\ell\gamma$ distribution.



- Taken from ATLAS Physics TDR.

Squark and Gluino Masses

- **In this model the decay chain**

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

  exists.

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

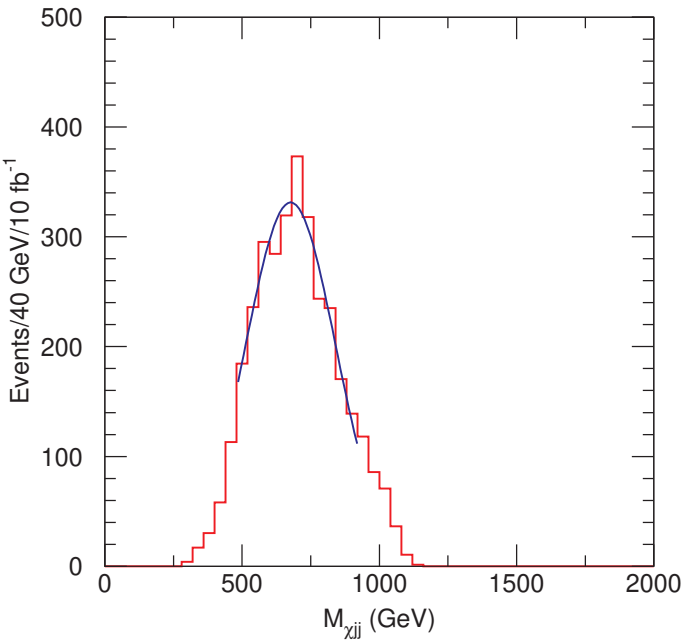
- **Require two reconstructed $\tilde{\chi}_2^0$'s.**

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

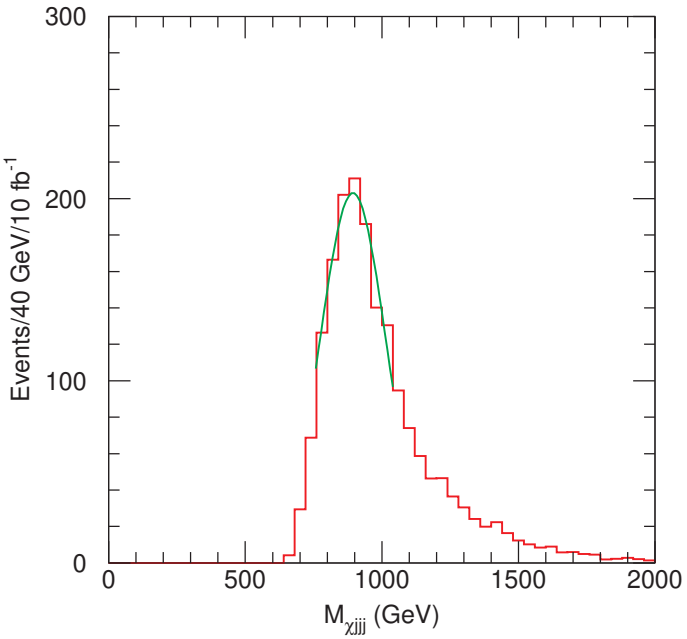
- **Then with third jet for the squark mass.**

Squark and Gluino Masses

- **Gluino Mass.**



- **Squark Mass.**



R-parity violation

- **Provided the $\not{R}_p$ 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 $\not{R}_p$ 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.

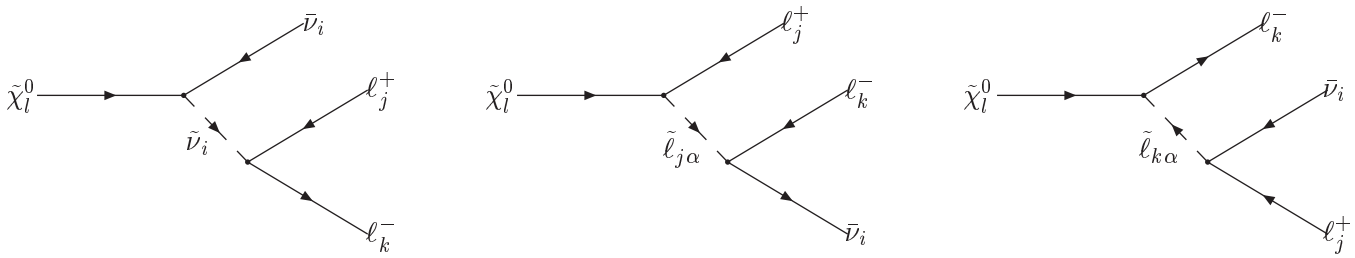
  – UDD LSP decays to quarks.

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

LLE Decays

- **In this model the neutralino decays**

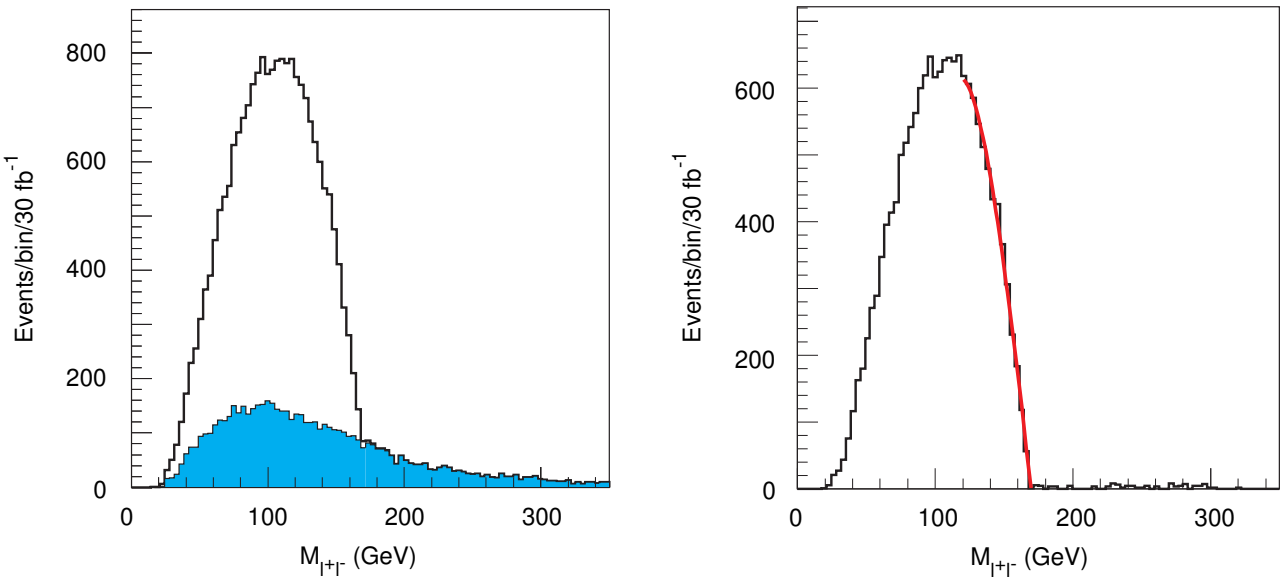
$$\tilde{\chi}_1^0 \longrightarrow \ell^+ \ell^- \nu.$$



- **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

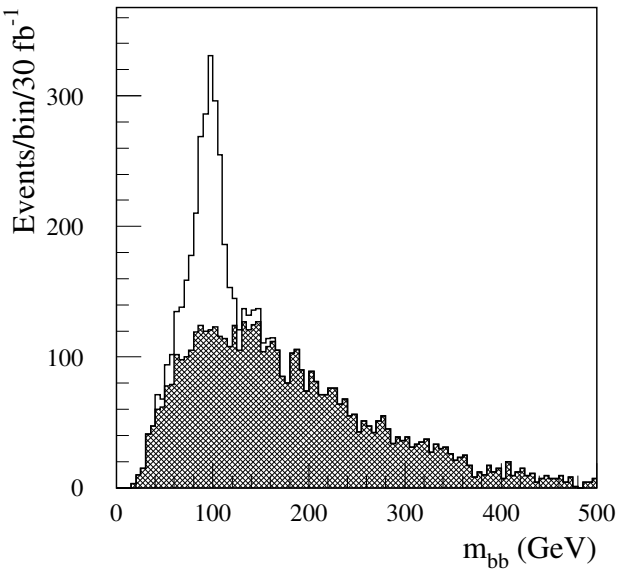
- **The edge in the OSDF lepton mass distribution gives the $\tilde{\chi}_1^0$ mass.**

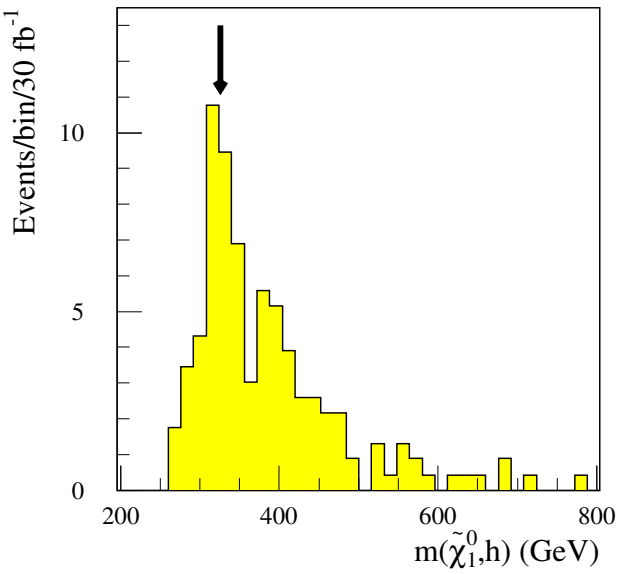


- **Graph shows the result for λ_{122} at SUGRA point 1.**
- **At the point studied the decay $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ occurs.**
- **Therefore can reconstruct the $\tilde{\chi}_2^0$ mass by requiring:**
  - **2 b-jets with $p_T > 30\,\mathrm{GeV}$ and $p_T < 300\,\mathrm{GeV}$;**
  - **$\cos\alpha_{bb} > 0.4$ 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 $\tilde{\chi}_2^0$.

- In this study

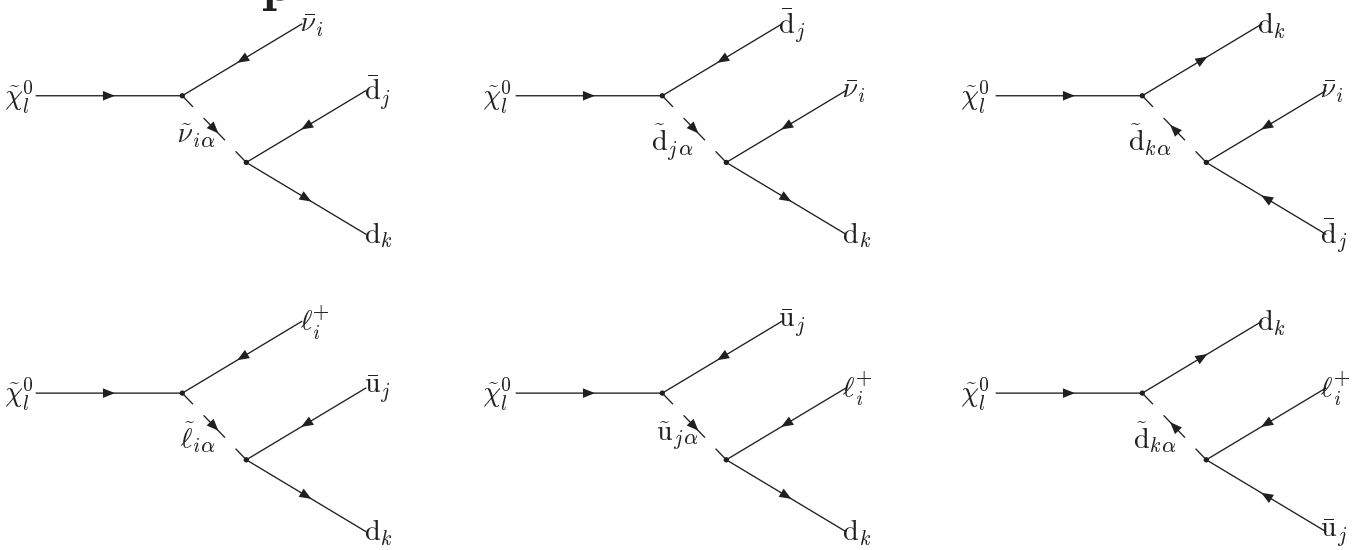
$$M_{\tilde{\chi}_1^0} = 169.8 \pm 0.18\,\mathrm{GeV},$$
$$M_{\tilde{\chi}_2^0} = 326.2 \pm 4.8\,\mathrm{GeV}.$$

- 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.**

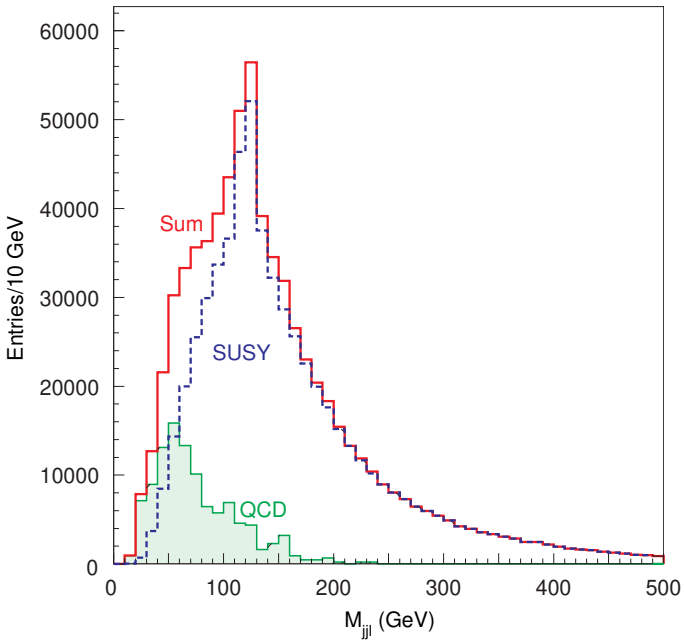
- **Result taken from ATLAS Physics TDR.**

- **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.**



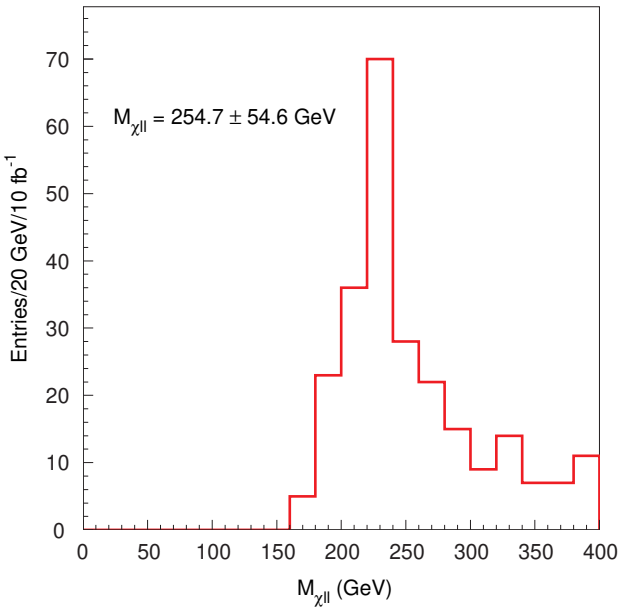
- **The error is $\pm 3\,\mathrm{GeV}$ on the neutralino mass.**

- **This is at SUGRA point 5.**

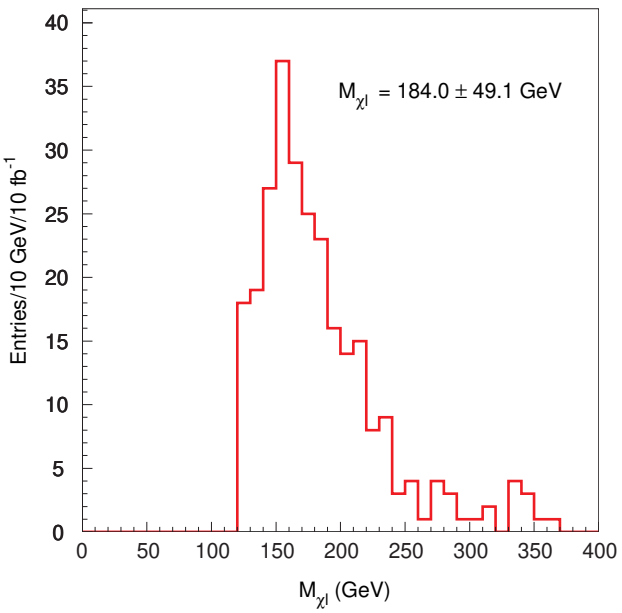
- **At this point the $\tilde{\chi}_2^0$ decays via the mode $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\pm} \ell^{\mp} \to \tilde{\chi}_1^0 \ell^+ \ell^- \tilde{\chi}_1^0$.**

LQD Neutralino Decays

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



- **By combined the $\tilde{\chi}_1^0$ 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**

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

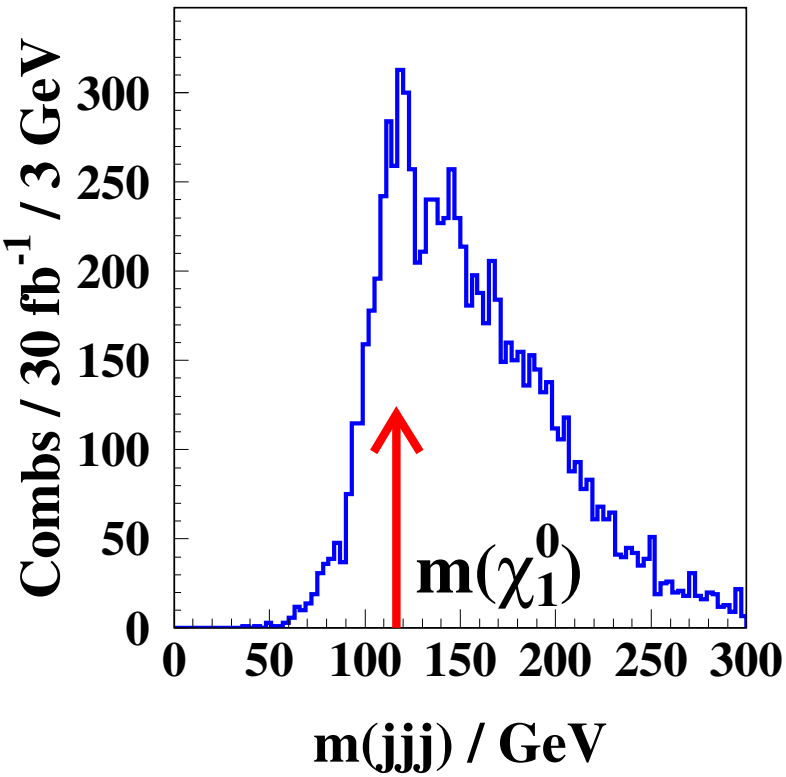
- **λ''_{212} was chosen as it is only limited by perturbativity and is one of the harder signatures, *i.e.* no b tagging.**
- **Each $\tilde{\chi}_1^0$ decays to three quarks.**
- **As the coloured sparticles are predominantly produced the jet multiplicities are large.**

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

- **When λ''_{212} is small two $\tilde{\chi}_1^0$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 $\tilde{\chi}_1^0$ masses for $30\ \mathrm{fb}^{-1}$.**

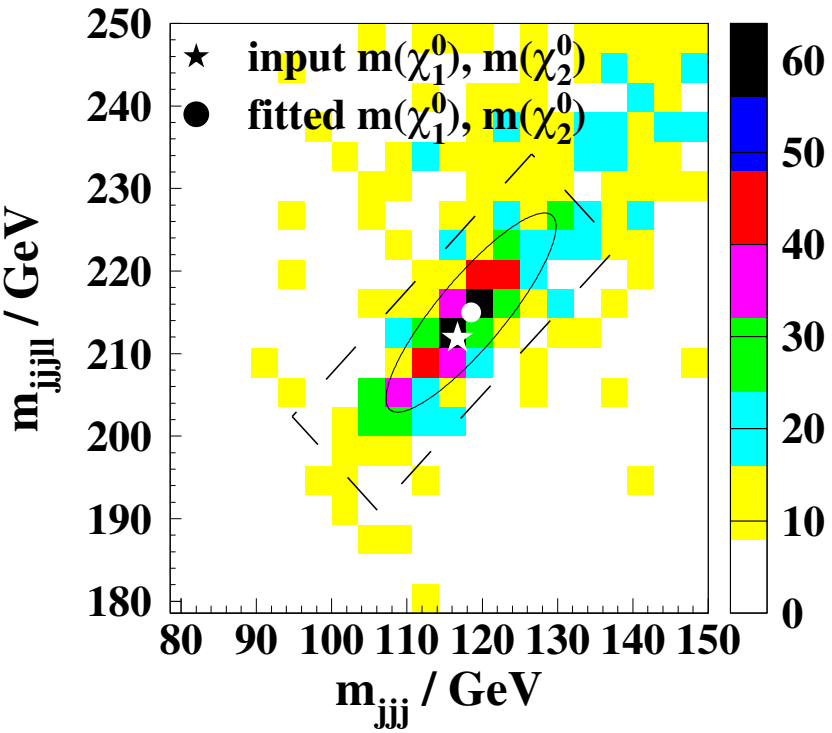


- **There is a combinatoric background below the peak.**

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

Results

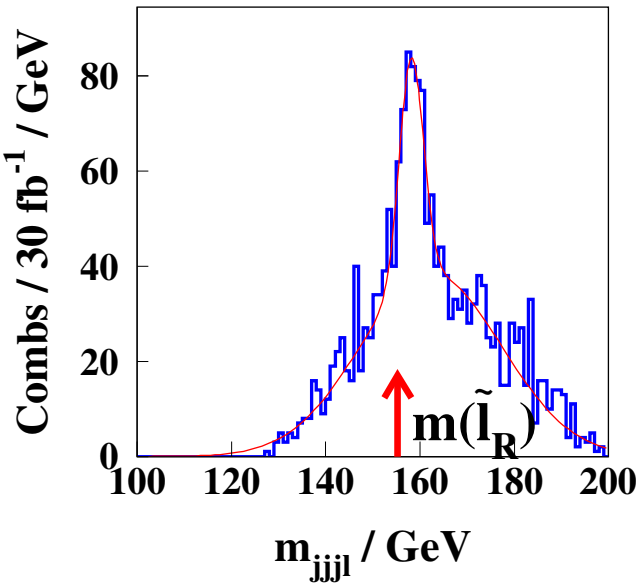
- The requirement that the events contain two leptons preferentially selects the decay chain $\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R l q \rightarrow \tilde{\chi}_1^0 l l q \rightarrow q q q l l q$.
- Use these leptons to reconstruct the $\tilde{\chi}_2^0$ mass.



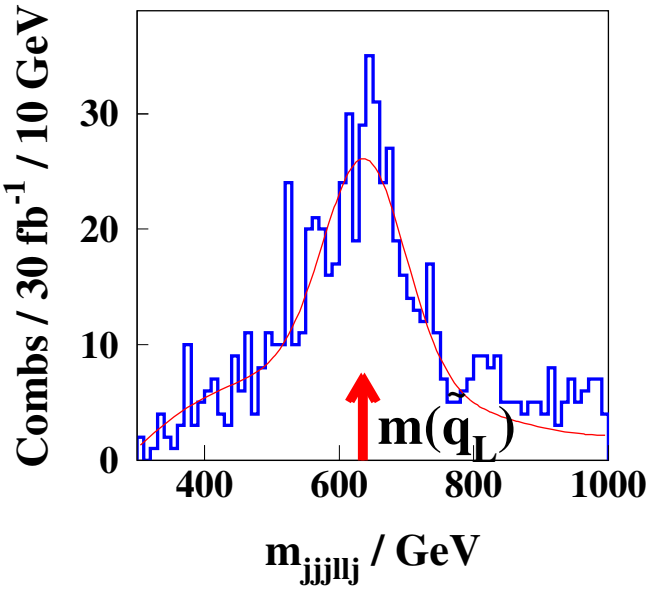
- We can then cut around the peak peak at the $\tilde{\chi}_1^0$,$\tilde{\chi}_2^0$ masses in the mass plane.

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).

NLC

- **At a future linear collider operating at $\sim 0.5 - 1$ TeV the situation is different.**
- **Only the lowest lying SUSY states will probably be accessible.**
- **Will already have some knowledge from the LHC.**
- **There look at gaugino and slepton production.**
- **Use the option of polarizing the beams and scanning the threshold to accurately measure the properties of the particles.**
- ***e.g.* measure the masses to $\sim 0.5\%$ and the $\tilde{\chi}_2^0$ $\tilde{\chi}_1^0$ mass difference to 50 MeV.**

Muon g-2

- **If you measure enough quantities some of them should disagree with the prediction by more the 1 sigma (about 1/3), and some by 2 sigma (4.6%) or 3 sigma (0.3%)**

- **This is why we define a discovery to be 5 sigma** ($6 \times 10^{-5}\%$.)

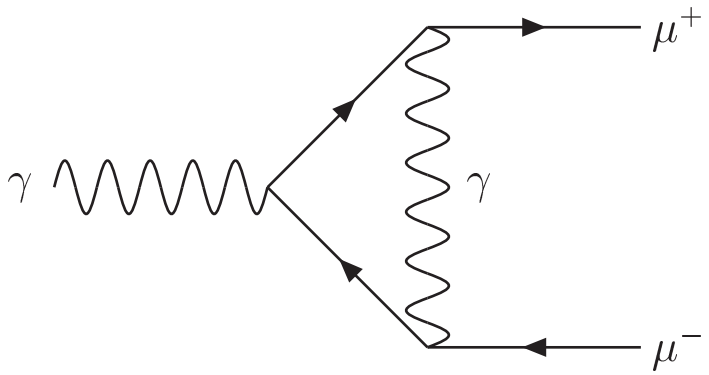
- **One quantity which recently showed such a deviation was the magnetic moment of the muon.**

- **The magnet moment of any fundamental fermion is**

$$\mu = g\left(\frac{e}{2m}\right)\mathbf{S},$$

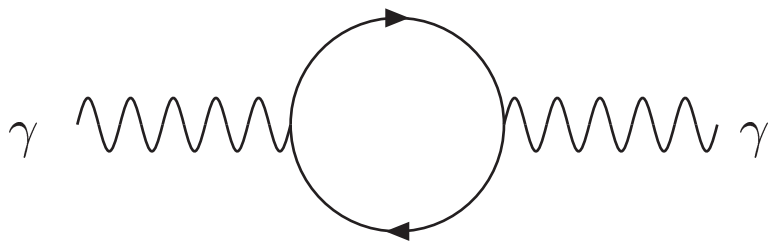
- **The Dirac equation predicts g=2.**

- **However there are quantum corrections.**

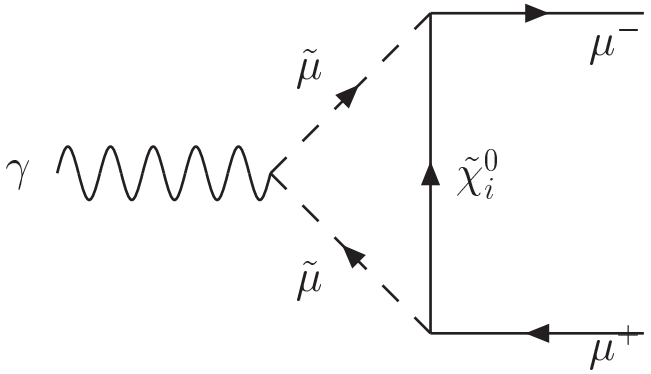


- **The problem is with the higher order corrections.**

- **Quark loops in the photon propagator.**



- **Low energy so can't use perturbative QCD.**
- **Instead use the measured e^+e^- total cross section and the optical theorem.**
- **Gives an experimental error on the theoretical prediction.**
- **Get SUSY corrections from diagrams like.**

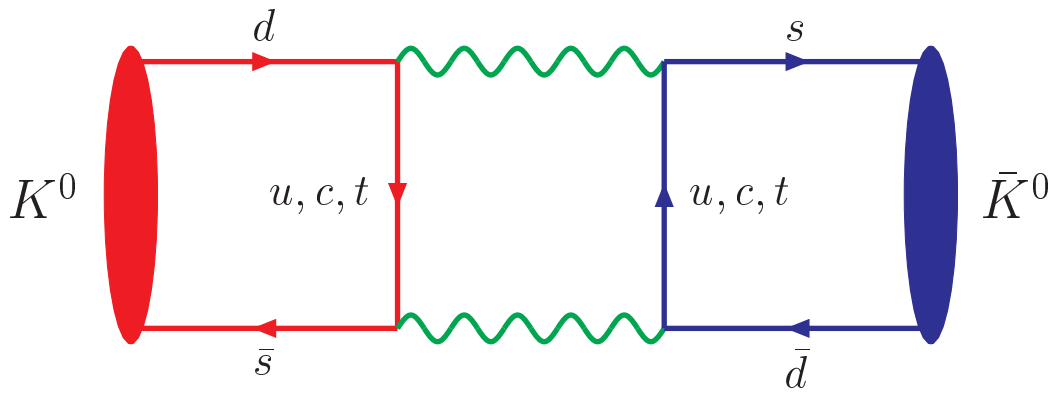


- **The original experimental result disagreed with the SM at 2.6σ,**
- **but an error in the sign in one of the terms, significance now about 1.4σ.**

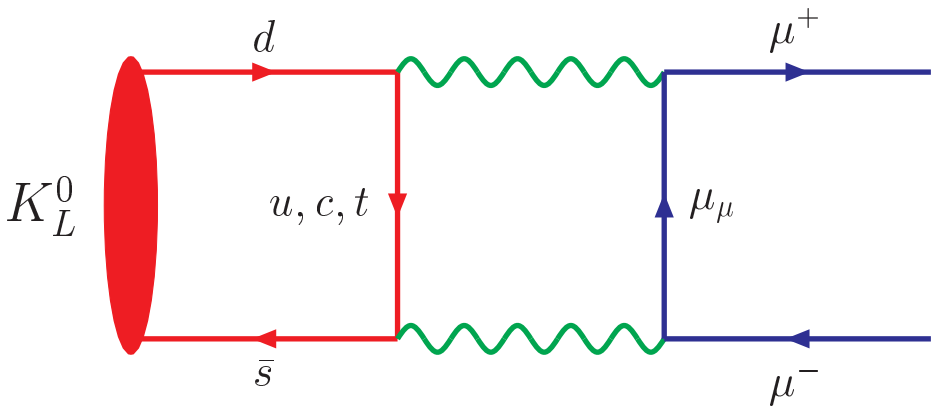
Flavour Changing Neutral Currents

- **In the Standard Model Flavour Changing Neutral Currents are suppressed by the GIM mechanism.**

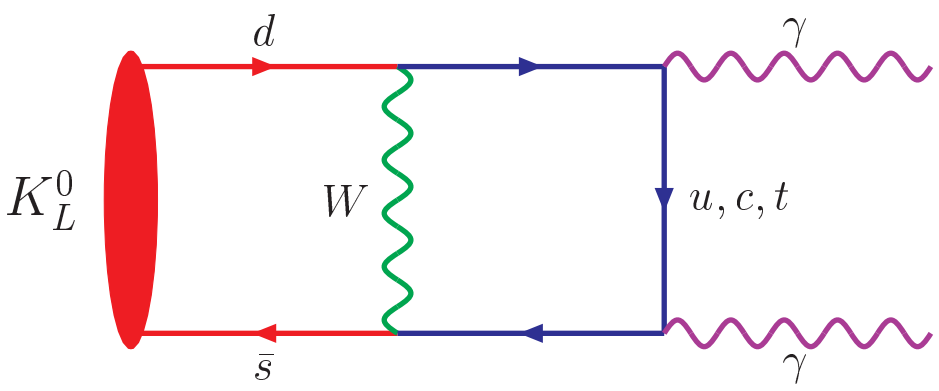
- **Let's consider Kaon mixing**



- **And rare Kaon decays $K_L^0 \to \mu^+\mu^-$**



- **And rare Kaon decays $K_L^0 \to \gamma\gamma$**



Flavour Changing Neutral Currents

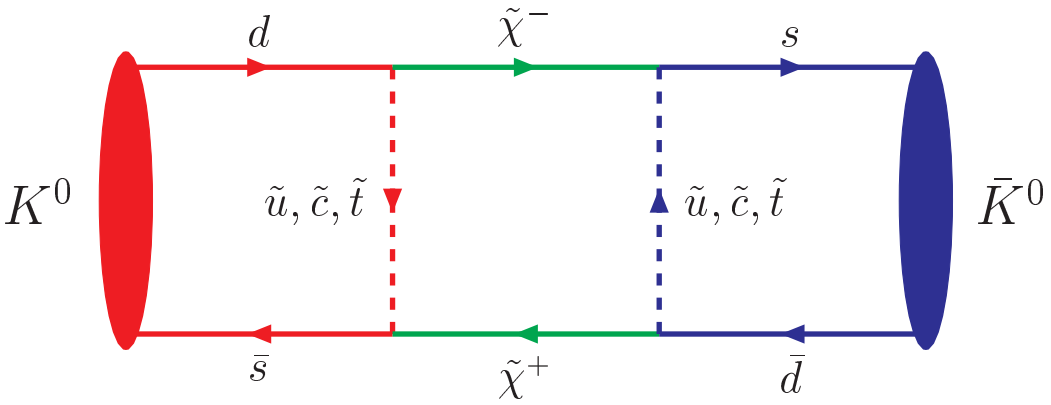
- **Let's only consider two generations for simplicity.**
- **All these diagrams go like**

$$\frac{1}{M_W^2}\frac{m_u^2 - m_c^2}{M^2}$$

  times a factor due to the Cabbibo angle.
- **M is the largest mass left after the removal of 1 W propagator, *i.e.* M_W for $K^0 - \bar{K}^0$ mixing and $K_L^0 \to \mu^+\mu^-$, and m_c for $K_L^0 \to \gamma\gamma$.**
- **This suppression is called the GIM (Glashow-Iliopoulos-Maiani) mechanism.**
- **Explains why $\Gamma(K_L^0 \to \mu^+\mu^-)$ is $\sim 2 \times 10^{-5}\Gamma(K_L^0 \to \gamma\gamma)$.**
- **The current experimental results are in good agreement with the SM.**
- **This often proves a problem in BSM physics as there are often new sources of FCNCs.**

Flavour Changing Neutral Currents in SUSY

- In SUSY theories the SUSY partners also give contributions to FCNCs



- Here the diagrams proportional to the mass difference of the squarks.

- Provide the SUSY breaking masses are flavour independent not a problem, as the mass differences are the same as the SM.

- Also not a problem if no flavour mixing in the model.

- However in general these things are possible and most be considered.

The Theta Problem and the axion

- **The QCD Lagrangian can have a term**

$$\mathcal{L} = \frac{\theta_{\rm QCD}}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu},$$

  where the dual field strength tensor

$$\tilde{F}^a_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\alpha\beta} F^{a,\alpha\beta}.$$

- **We can also get a similar term from rotating the quark masses, due to the anomaly.**

- **Suppose all the quark masses have the same complex phase**

$$|m_i| e^{i\delta} \bar{q}_{Li} q_{Ri}.$$

- **If we make the transformation**

$$q_{Ri} \longrightarrow e^{-i\frac{\delta}{2}\gamma_5} q_{Ri},$$

  then the masses are real.

- **This however gives a contribution to the Lagrangian**

$$\mathcal{L} = -\frac{n\delta}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

- **This gives non-perturbative CP violation in the strong interaction.**

The Theta Problem and the axion

- **In particular the electric dipole moment of the neutron limits $\theta_{\rm QCD} - n\delta \lesssim 10^{-7}$.**
- **Solution have two Higgs doublets**
  - **H_1 only couples to down quarks.**
  - **H_2 only couples to up-type quarks.**
- **Require the Lagrangian respect the Peccei-Quinn symmetry**

$$\begin{aligned} u_R &\to e^{i\theta_u} u_R \\ d_R &\to e^{i\theta_d} d_R \end{aligned}$$

- **The Lagrangian is invariant provided**

$$\begin{aligned} H_1 &\to e^{-i\theta_d} H_1 \\ H_2 &\to e^{-i\theta_u} H_2 \end{aligned}$$

- **but still gives a term via the anomaly.**
- **This allows us to redefine the phase and set $\theta_{QCD} = 0$.**
- **Get two goldstone bosons, one eaten by the Higgs mechanism.**
- **The other is the axion which gets a small mass due to non-perturbative effects.**
- **However we haven't seen it.**

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 $\sim$ 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,

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

- **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 $\sim 1/R^2$.**

- 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.

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

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

Small Extra Dimensions

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

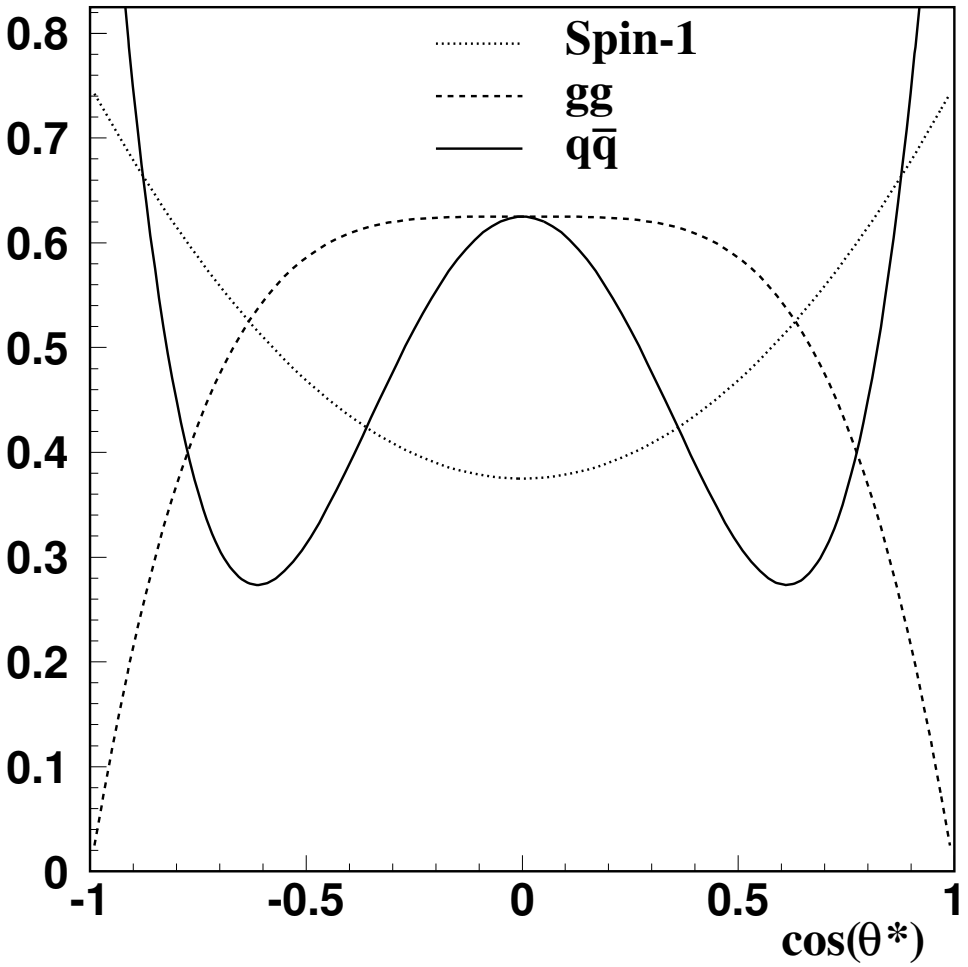
$qq \to G \to f\bar{f}$	$1 - 3\cos^2\theta + 4\cos^4\theta$
$gg \to G \to f\bar{f}$	$1 - \cos^4\theta$
$qq \to G \to BB$	$1 - \cos^4\theta$
$gg \to G \to BB$	$1 + 6\cos^2\theta + \cos^4\theta$

- **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**

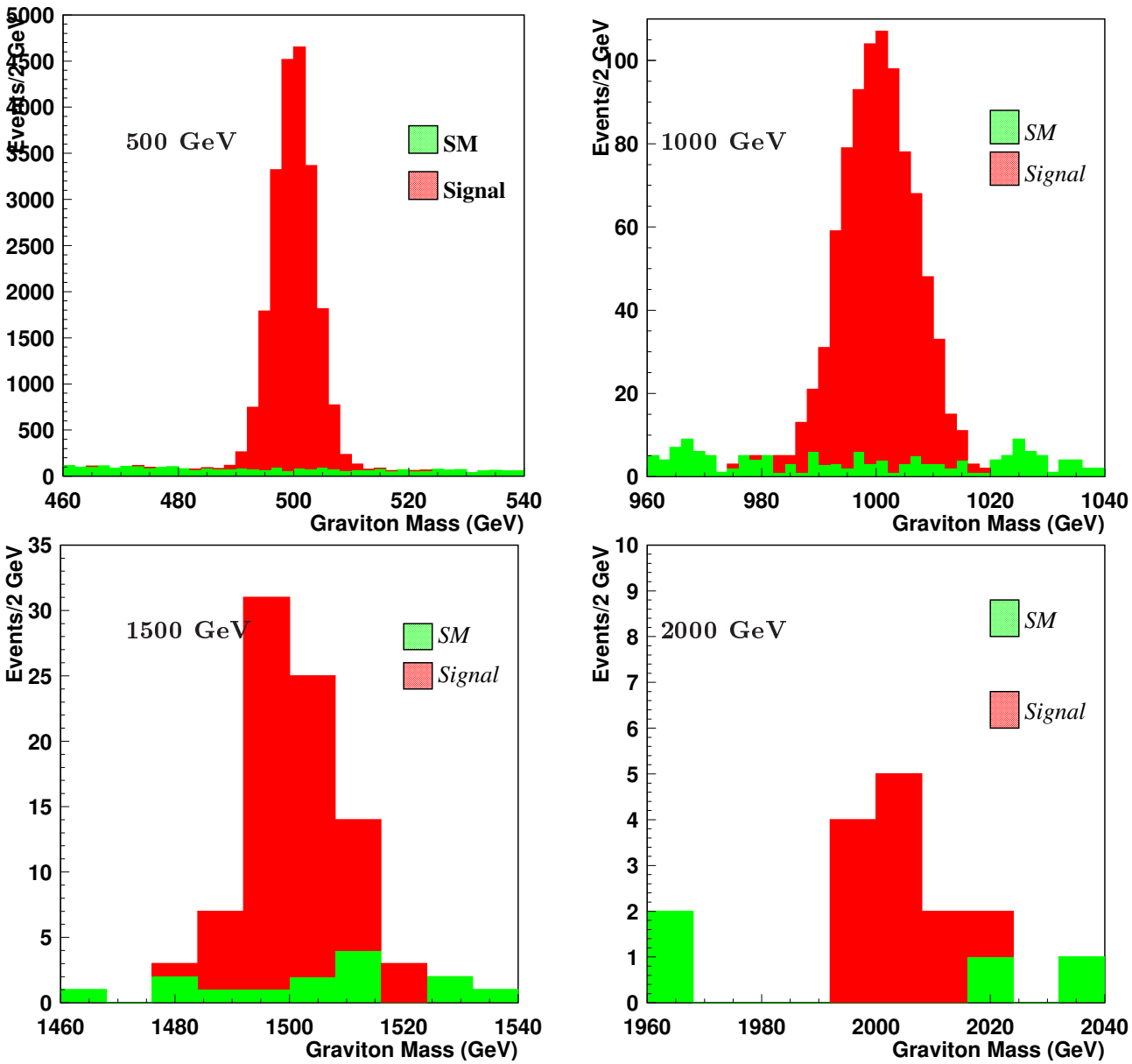
$$\frac{\Delta E}{E} = \frac{12\%}{\sqrt{E}} + \frac{24.5\%}{E_T} + 0.7\%.$$

- **Mass resolution**

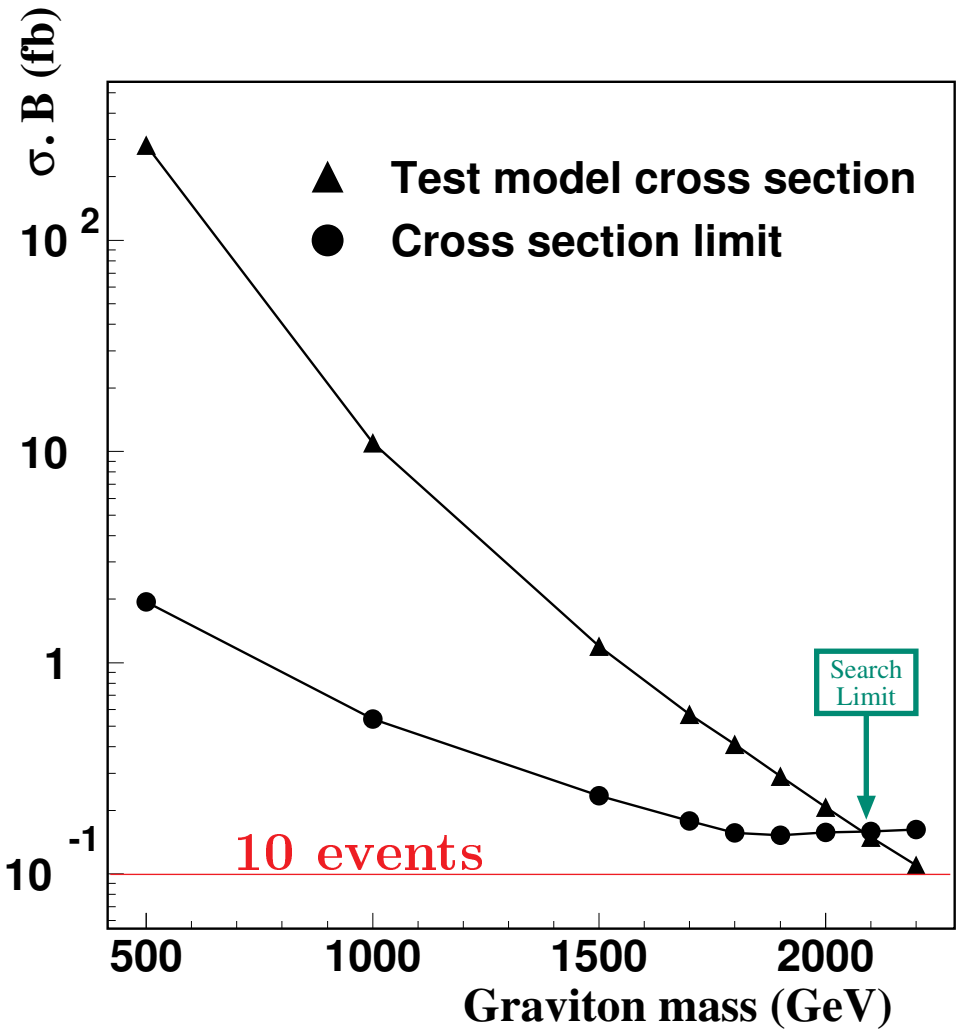
$$\frac{\sigma_m}{m}(500\ GeV) = 0.8\%.$$

Graviton Resonance

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



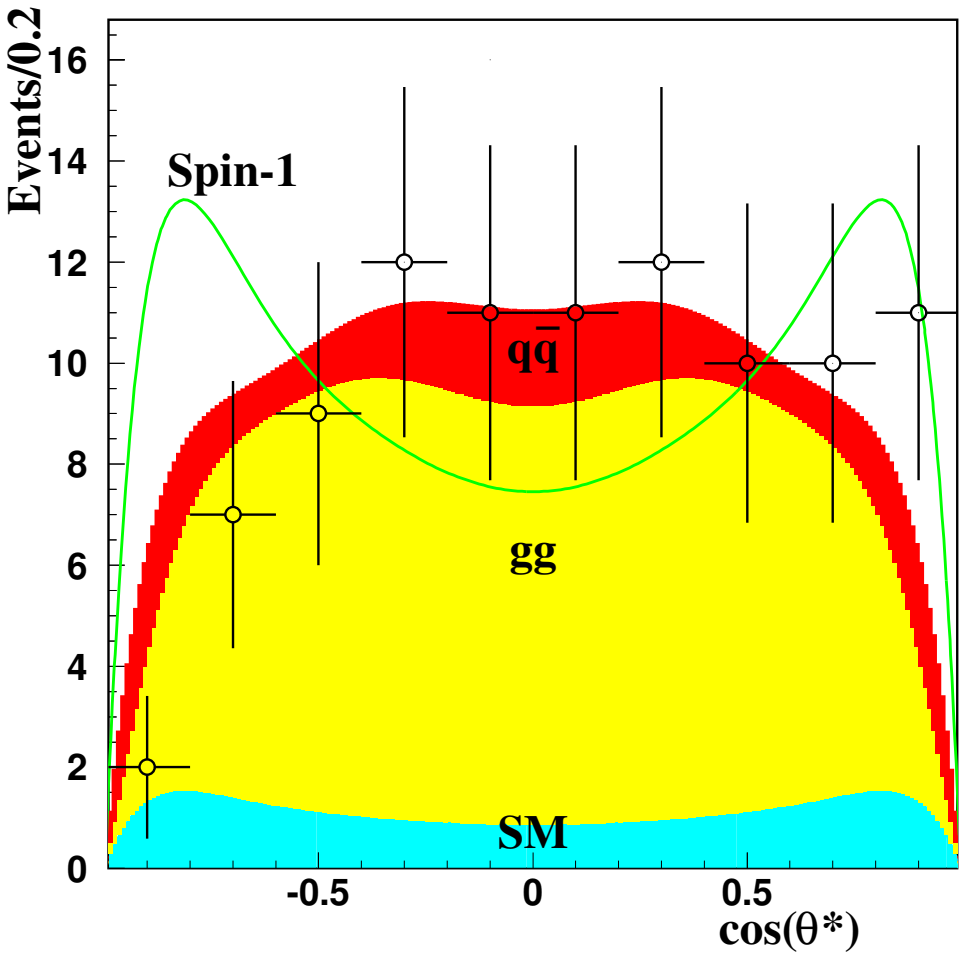
Production Cross Section



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

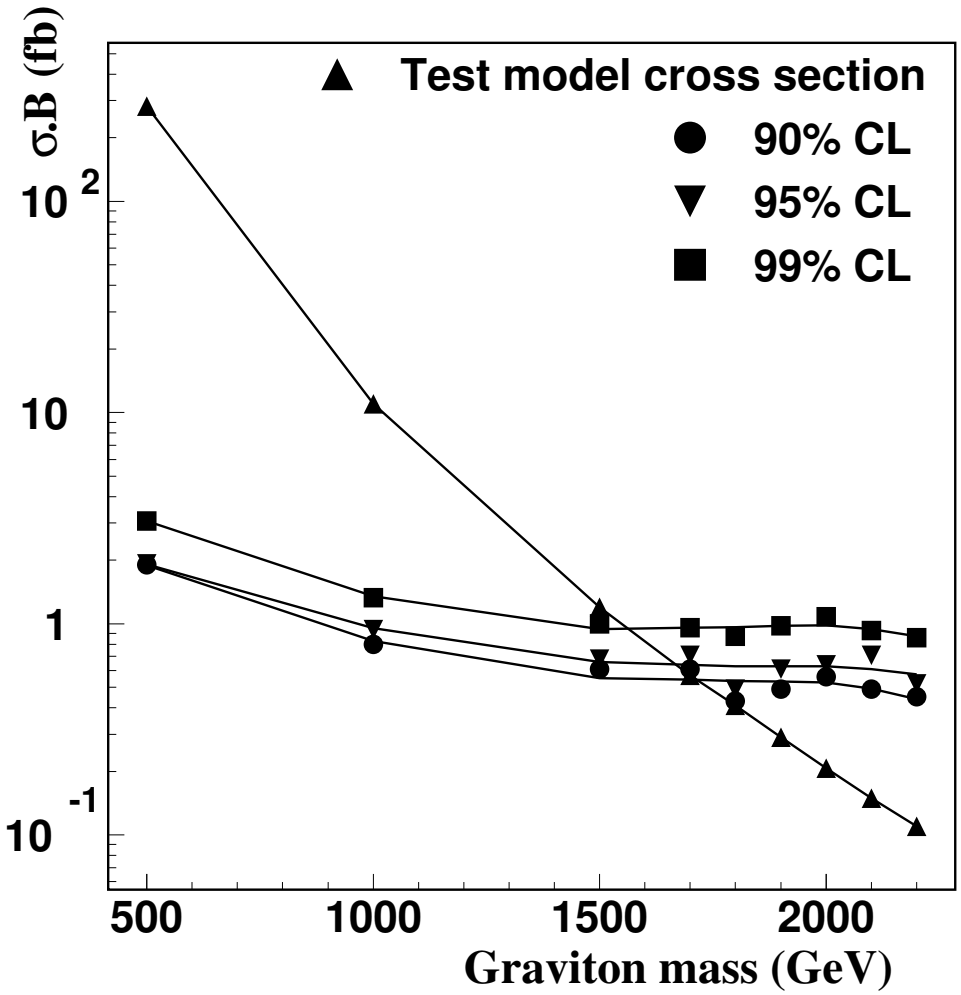
Determining the Spin

- 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:**
  - $G \to \mu^+\mu^-$
  - $G \to \gamma\gamma$
  - $G \to \text{jetjet}$
  - $G \to WW$
- **Tests the universality of the coupling.**

Technicolour

- Postulate a new set of gauge interactions Technicolour.
- This acts on new technifermions.
- We think of this interaction like QCD.
- The technifermions form bound states, the lightest being technipions.
- By the Higgs mechanism these technipions give the longitudinal components of the $W^{\pm}$ and Z bosons.
- Still need to find a way to give the fermions masses, called Extended Technicolour.
- It has proved hard to construct realistic models which aren't already ruled out.
- Has fallen out of fashion in recent years.

Conclusions

- **BSM physics is a field which needs experimental confirmation.**
- **Until we see something its just a set of nice ideas.**
- **I've tried to give you some idea of the various models which are being looked at.**
- **I hope this will enable you to understand more of the seminars.**