A Case Study in LHC SUSY Phenomenology

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OKC Prospects Workshop, 17th September 2010

Introduction

- Will examine the case of 'focus point' SUSY at the LHC
- (Will further assume that the dark matter is comprised of the lightest neutralino)
- This was previously noted as a *difficult* case for the LHC

  - half of the new particles are too heavy to produce at the LHC

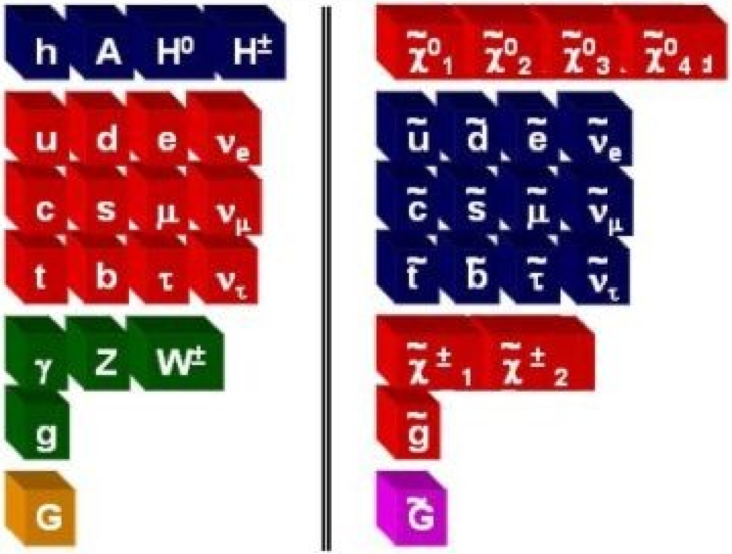
  - can measure the DM particle mass but not the couplings

Outline

- I'll give a quick review of how to measure SUSY at the LHC
- I'll then demonstrate how to improve measurements, including:
  - how to avoid assuming which SUSY particles are being observed
  - how to incorporate the shapes of distributions to improve measurements
- I'll discuss how general these conclusions are

A bluffers guide to supersymmetry

- Supersymmetry (SUSY) is a well-motivated extension of the SM
- It proposes that a fundamental symmetry of nature connects fermions and bosons
- All existing particles have partners with opposite spin statistics called *sparticles*
- In constructing SUSY models, can impose a symmetry called R-parity under which SM particles are even, SUSY particles are odd
- This has two important consequences:
    - we pair produce sparticles at the LHC
    - the lightest sparticle (LSP) is absolutely stable
- Therefore, the LSP is a natural WIMP candidate



Supersymmetry breaking

- Supersymmetry is a broken symmetry; the mechanism of SUSY breaking is currently unknown

    - 'measuring SUSY' actually means 'understanding SUSY breaking sector'

- Full supersymmetric Lagrangian has $\sim$ 105 parameters

    - these reflect our ignorance!
    - many however can be reduced by considering current accelerator constraints

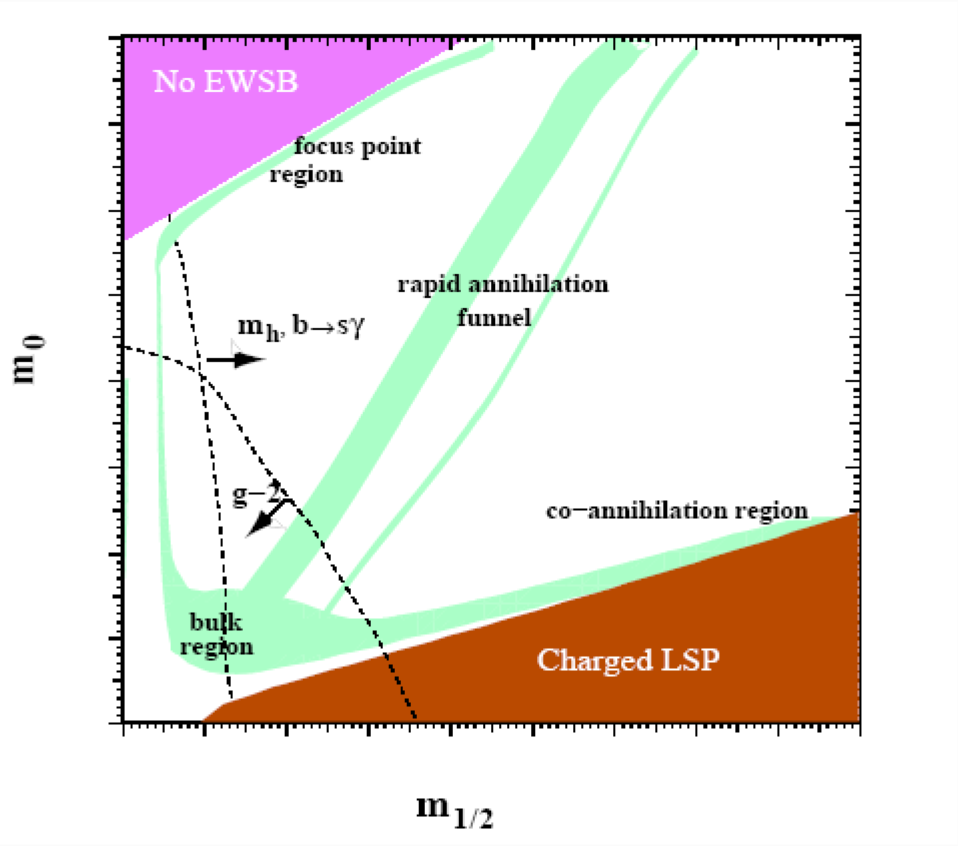
- People normally work with simplified models ($\sim$ 5 parameters):

    - mSUGRA
    - GMSB
    - AMSB, etc,

- All analysis in this talk uses 24 parameter MSSM, even if the benchmark points originally come from mSUGRA

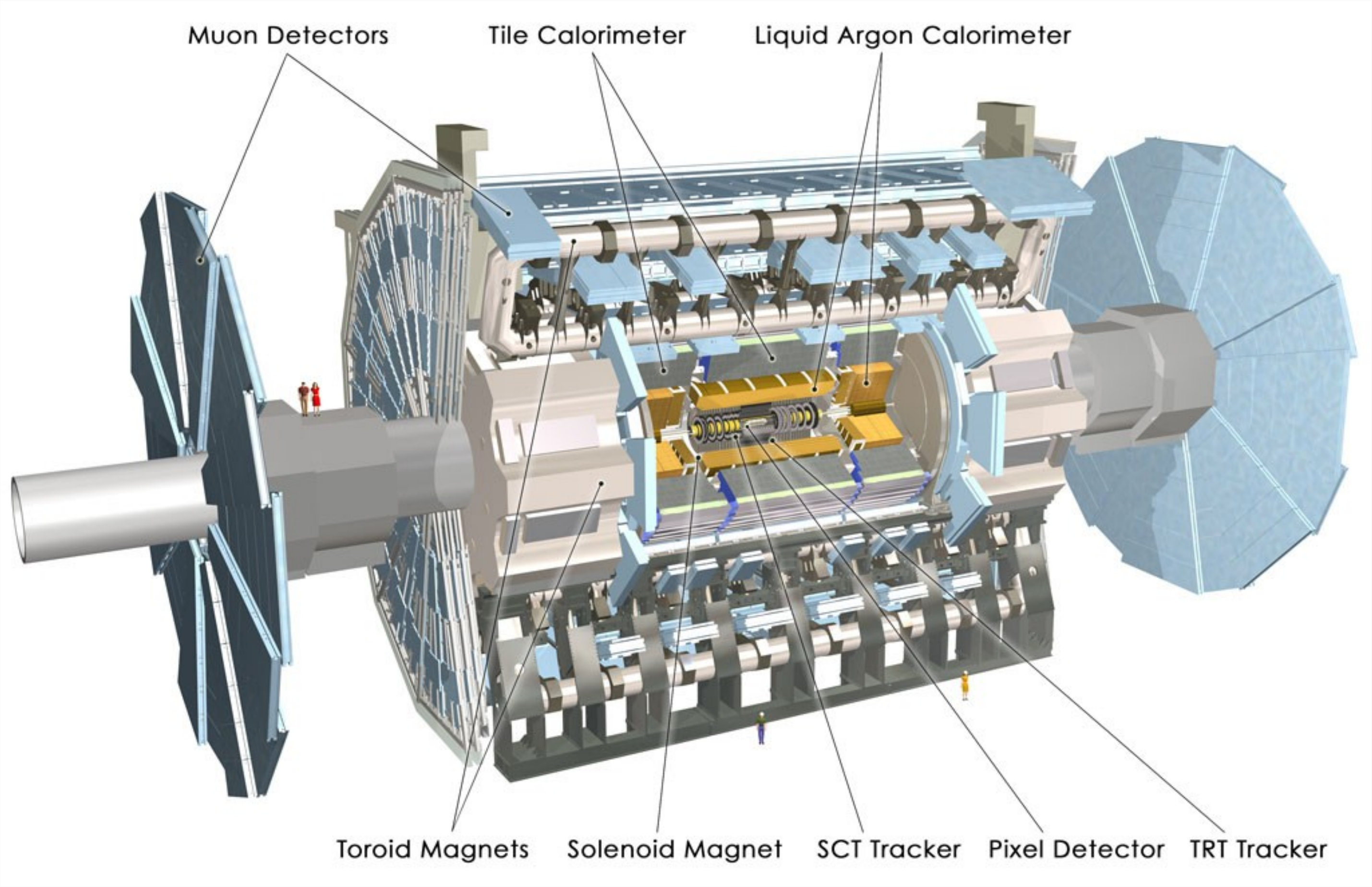
Focus point SUSY

- Benchmark point comes from mSUGRA

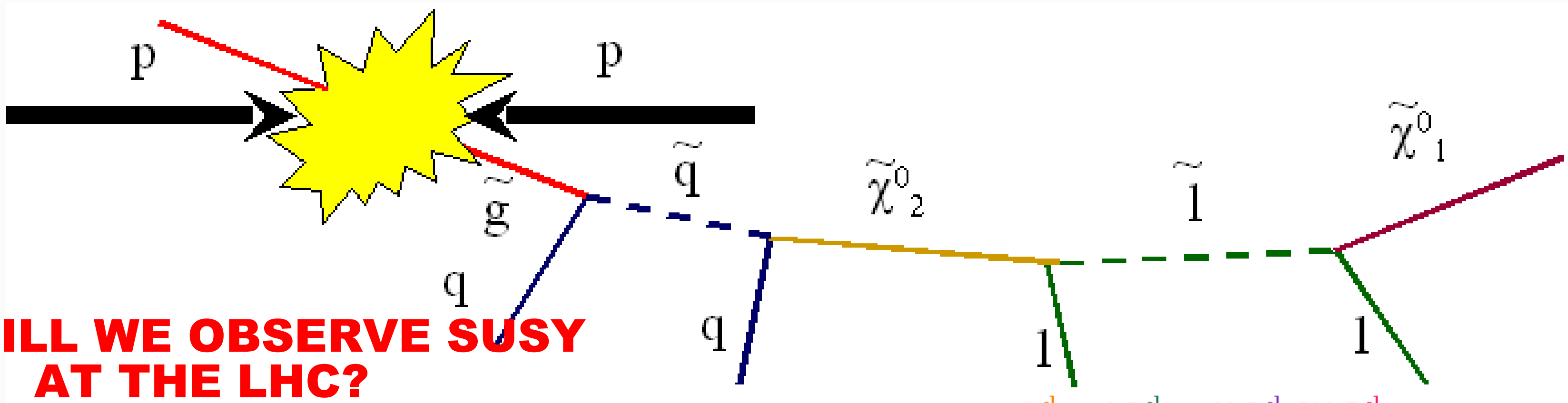


- M_0 can be large without violating any known constraints
- Squarks and sleptons become too heavy to see at the LHC!
- We end up seeing only the neutralinos, charginos, gluino and one or more SUSY Higgs bosons

How to observe SUSY at the LHC (1)



How to observe SUSY at the LHC (2)

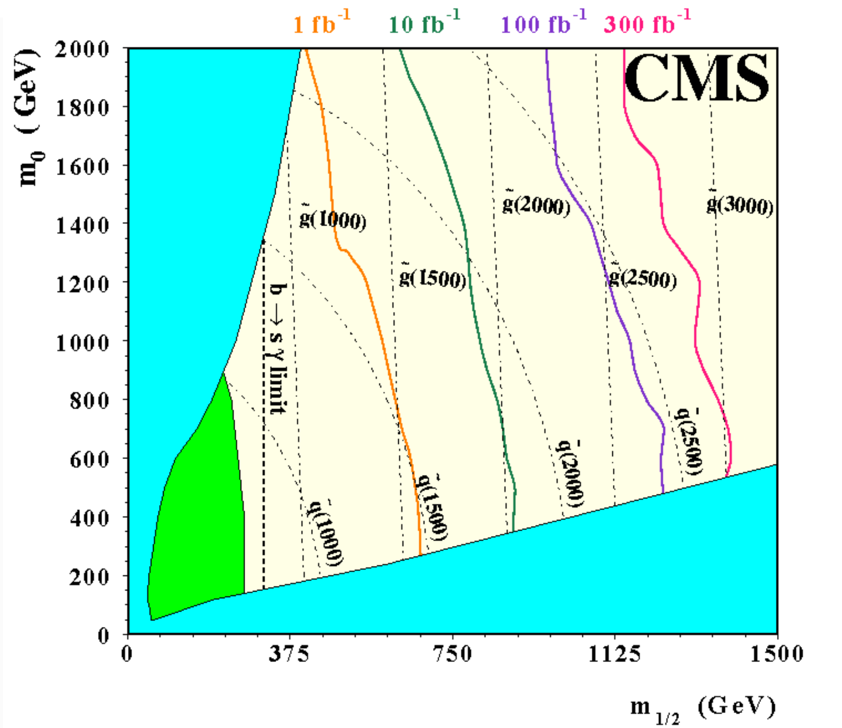


HOW WILL WE OBSERVE SUSY AT THE LHC?

STEP 1

Perform inclusive searches. SUSY events have:

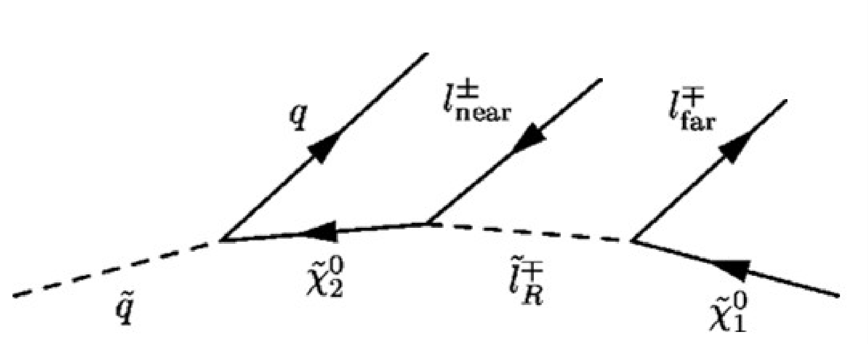
- Large missing energy (due to escaping LSP's)
- High jet multiplicity (from squark and gluino decay)
- Isolated leptons (from slepton and gaugino decay)
- Can plot these distributions and look for an excess over the SM background



How to observe SUSY at the LHC (3)

STEP 2

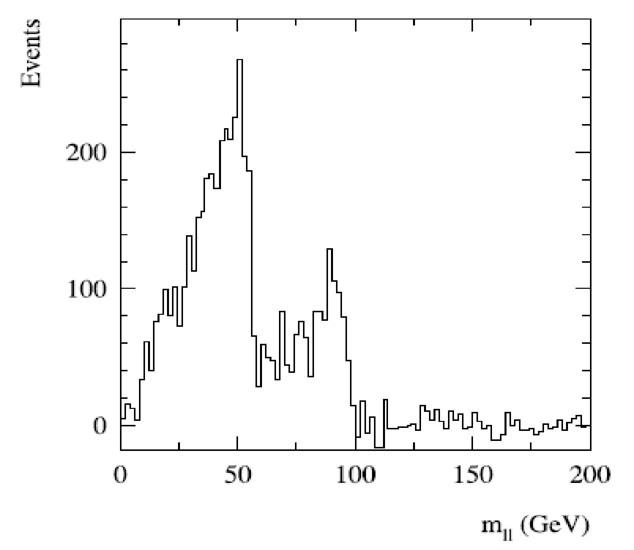
Try and measure weak scale SUSY parameters through exclusive decay measurements.



- Can search for kinematic endpoints in the invariant mass distributions of visible decay products of cascade decays

- Can solve edge equations to reconstruct sparticle mass differences

- Can use mass spectrum to try and reconstruct SUSY parameters if we assume a particular breaking framework (e.g. MSUGRA, pMSSM, etc)



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

General prospects

If we measure lots of endpoints this works well:

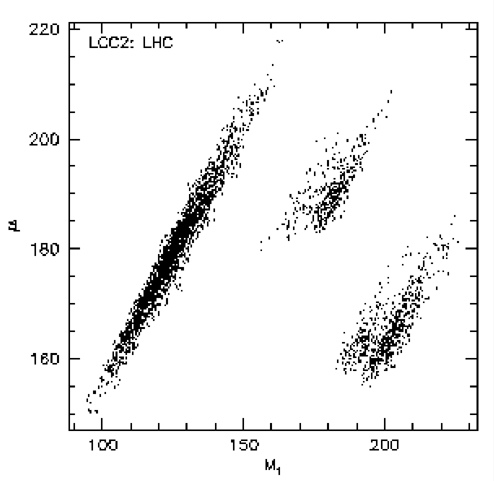
Variable	Value (GeV)	Errors Stat+Sys (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	81.2	0.03	0.08	0.09
$m_{\ell\ell q}^{max}$	425.3	1.4	2.1	2.5
$m_{\ell q}^{low}$	266.9	0.9	1.3	1.6
$m_{\ell q}^{high}$	365.9	1.0	1.8	2.1
$m_{\ell\ell q}^{min}$	207.0	1.6	1.0	1.9
$m(\ell_L) - m(\tilde{\chi}_1^0)$	92.3	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	315.8	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	62.2	5.0	0.3	5.0

- e.g. Co-annihilation region
- Long cascade decays
  - $\Rightarrow$ lots of endpoints
  - $\Rightarrow$ get relic density to ~ 10% !

Nojiri, Polesello, Tovey

hep-ph/0512204

$$\Omega_\chi h^2 = 0.108 \pm 0.01(stat + sys)^{+0.00}_{-0.002}(M(A))^{+0.001}_{-0.011}(\tan\beta)^{+0.002}_{-0.005}(m(\tilde{\tau}_2))$$



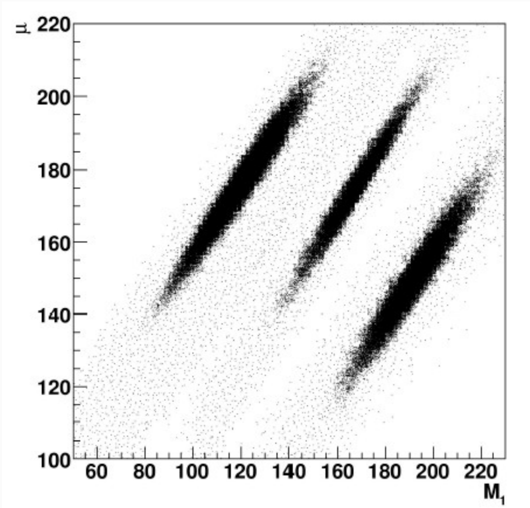
- For the focus points, cascade decays have less particles
- Get fewer mass measurements
- Fail to pin down neutralino couplings
- Get bad relic density predicition!

Baltz, Battaglia, Peskin & Wizansky

hep-ph/0602187

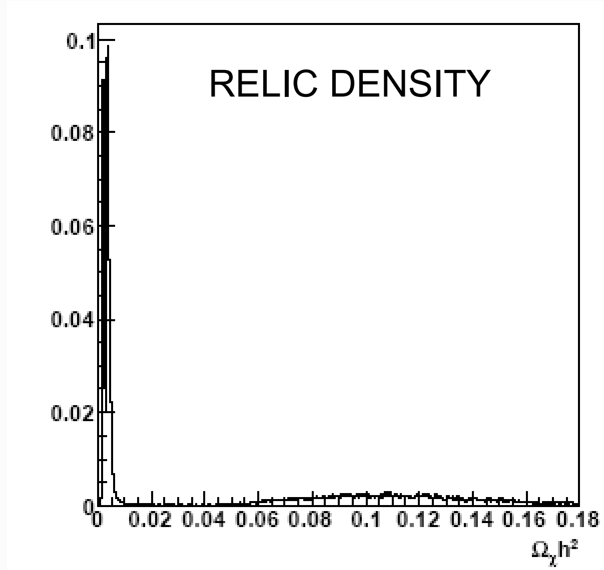
Astrophysical predictions for focus point

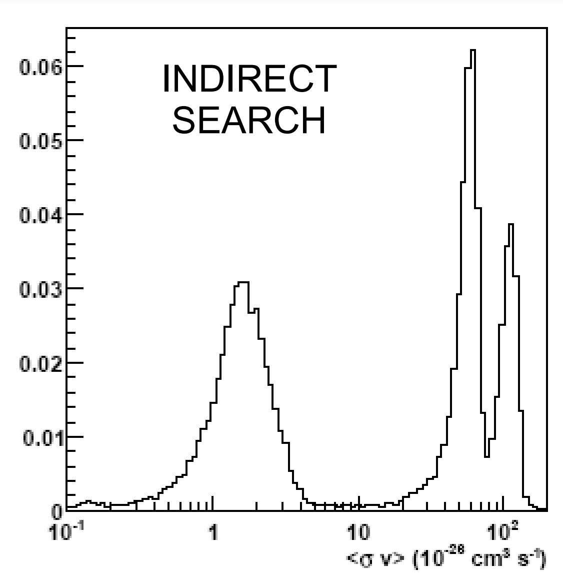
(RESULTS GENERATED USING MULTINEST NESTED SAMPLING ALGORITHM)

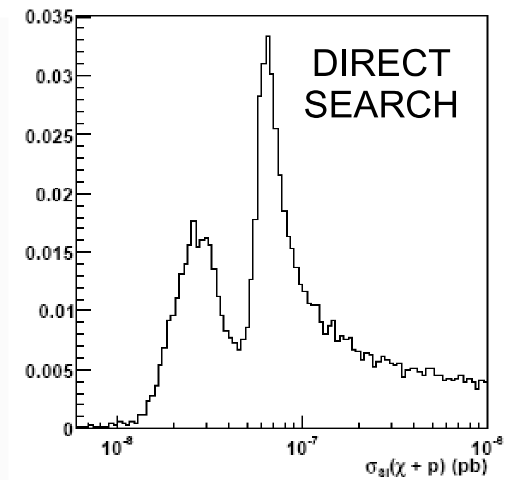


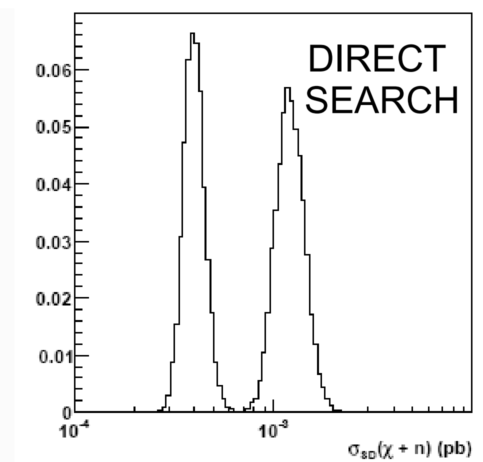
White, Feroz
JHEP 1007:064,2010

Observable	Value
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	59.5 ± 0.5 GeV
$m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_1^0}$	85.3 ± 1.5 GeV
$m_{\tilde{g}}$	850 ± 85 GeV
m_h	118.72 ± 0.25 GeV
$m_{\tilde{\chi}_1^0}$	106 ± 11 GeV









What went wrong?

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta s_W & m_Z \sin\beta s_W \\ 0 & M_2 & m_Z \cos\beta c_W & -m_Z \sin\beta c_W \\ -m_Z \cos\beta s_W & m_Z \cos\beta c_W & 0 & -\mu \\ m_Z \sin\beta s_W & -m_Z \sin\beta c_W & -\mu & 0 \end{pmatrix}$$

- The neutralino couplings are determined by a 4 by 4 mixing matrix
- We measured *two* mass differences, plus some idea of the overall mass scale
- It's obvious why it didn't work
- We can expect similar results in *any* SUSY model with heavy scalars

A solution

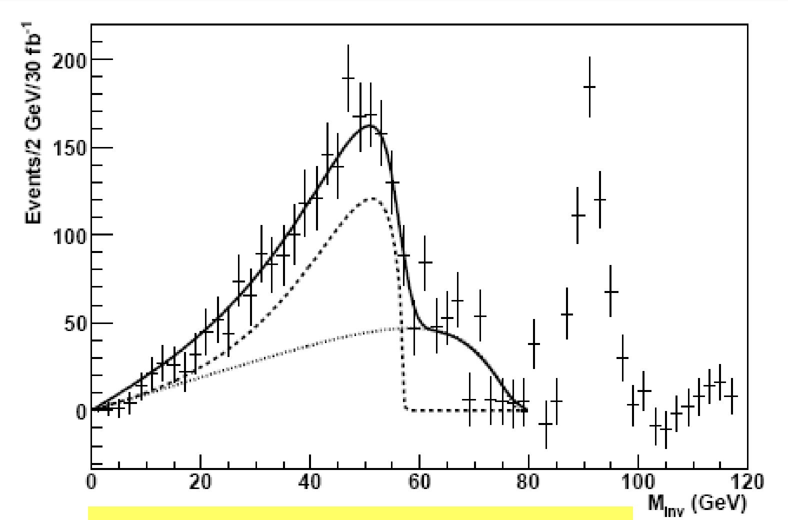
- The answer is quite simple- don't only use mass measurements
- The LHC will also have measured:

  - the shape of the dilepton distribution

  -the ratio of the number of events in each bump

  - lots of inclusive information

- Lots of information on neutralino mixing is contained in the shape of the dilepton plot:



Sanctis et al, Eur. Phys.J.C52:743-758,2007

- If I tune the components of the neutralinos, the number of events in each bump changes
- A previous ATLAS study demonstrates that you can extract this number from the integral of a fit to the distribution shape (shown)
- The dilepton plot is a very clean distribution where backgrounds can be reduced by flavour subtraction

Details

- Can run fits in parameter space using shape information, but need to be able to calculate likelihood quickly
- Assuming you have identified the correct neutralinos causing the endpoints, the ratio of events in each bump is given by:

$$\frac{BR(\tilde{g} \to ... \to \tilde{\chi}_2^0 + X) \times BR(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 l^+ l^-)}{BR(\tilde{g} \to ... \to \tilde{\chi}_3^0 + X) \times BR(\tilde{\chi}_3^0 \to \tilde{\chi}_1^0 l^+ l^-)}$$

- This however *assumes* information about neutralino mixing
- In the general case, we instead have:

$$\frac{BR(\tilde{g} \to ... \to \tilde{\chi}_p^0 + X) \times BR(\tilde{\chi}_p^0 \to \tilde{\chi}_q^0 l^+ l^-)}{BR(\tilde{g} \to ... \to \tilde{\chi}_r^0 + X) \times BR(\tilde{\chi}_r^0 \to \tilde{\chi}_s^0 l^+ l^-)}$$

- For any given point:

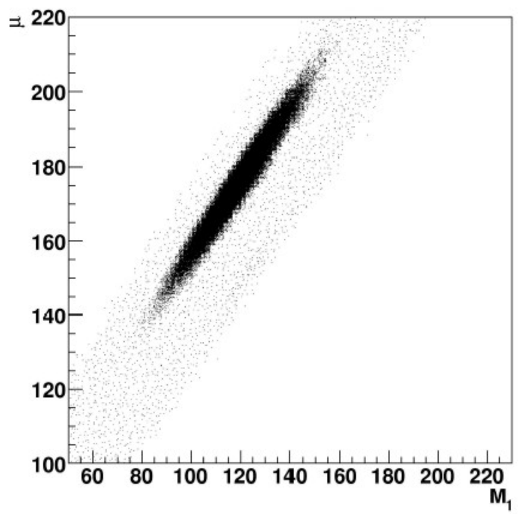
  - work out all branching ratio ratios of this form

  - assume the two highest caused the endpoints, and use them in likelihood

  - reject points with three endpoints or the wrong endpoint being tallest

Results

- We can constrain neutralino mixing ⇒ get WIMP mass *and* couplings



White, Feroz
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$m_{\tilde{g}}$	850 ± 85 GeV
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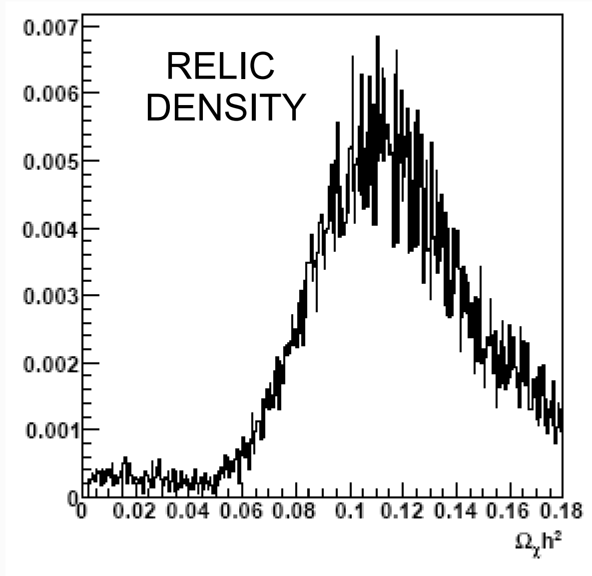
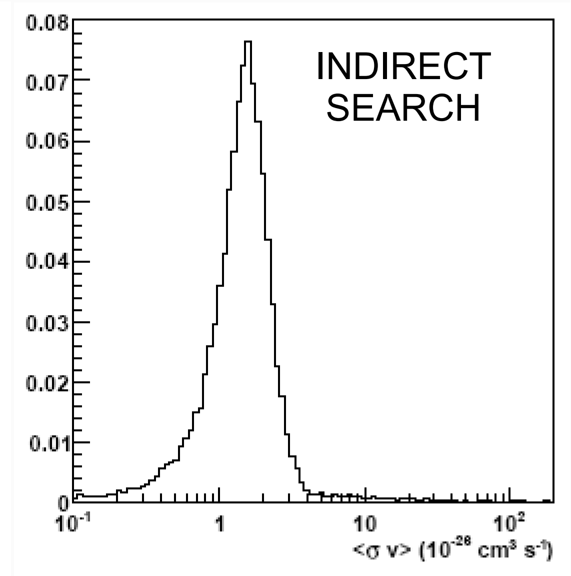
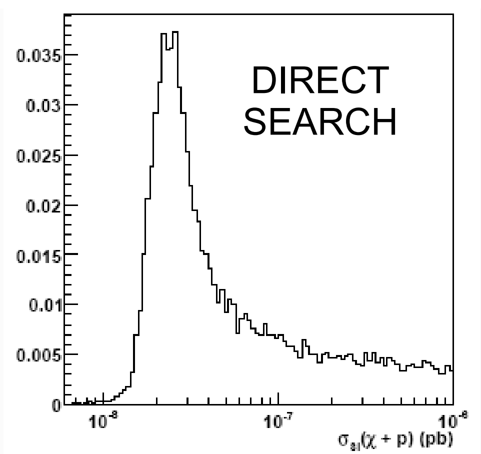
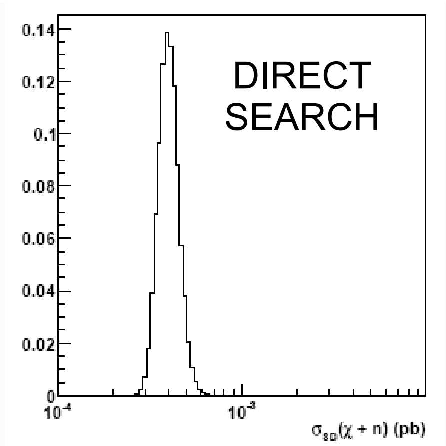
$m_{\tilde{\chi}^0_1}$	106 ± 11 GeV
N_p/N_r	1.5 ± 0.3









CDMS Exclusion Limit

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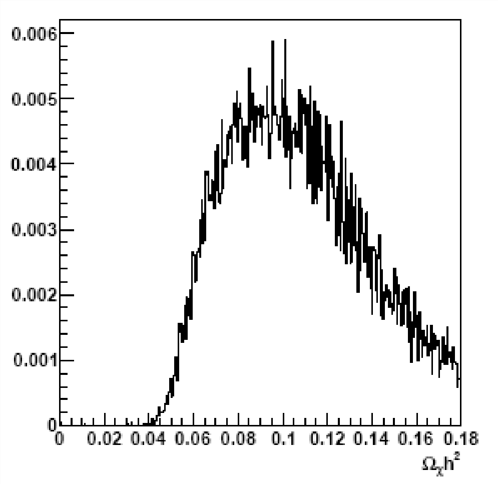
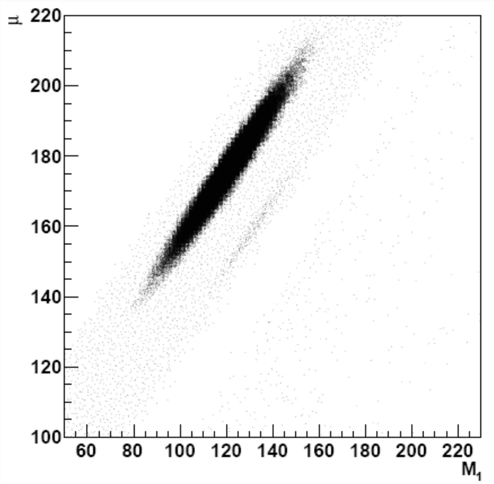


- In fact get very similar results using standard measurements and the CDMS exclusion limit (with a realistic astrophysical uncertainty).

- We get an improved relic density prediction as a result however

- A good example of how direct search data are competing with the LHC to constrain SUSY

- We can expect *much better* direct exclusion limits by the time the LHC is capable of providing any of the measurements in this talk



How general is this?

- The results also indicate that the 'correct' particles caused the endpoints

- In fact we get the same result with the ratio measurement (not shown)

  - points where e.g. the χ_4,χ_3 mass difference matches the observed value necessarily have a lower number of events in the plot

  - can expect similar behaviour in any model with heavy scalars

- Could generalise to other models by adding cross-section information (work in progress)

  - we were helped by having heavy squarks and sleptons since all of our decay chains were headed by gluinos

  - in a general case, would have to account for extra particles up the chain

Summary

- Have shown how using simple extra observables from the LHC can improve measurements of neutralino mixing parameters

  - this is particularly significant for dark matter studies

- Can easily generalise the techinque here to other models (work in progress)

- SUSY models with heavy scalars could be a lot easier to analyse at the LHC than we previously thought