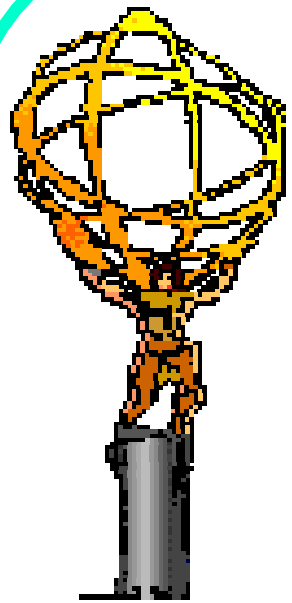
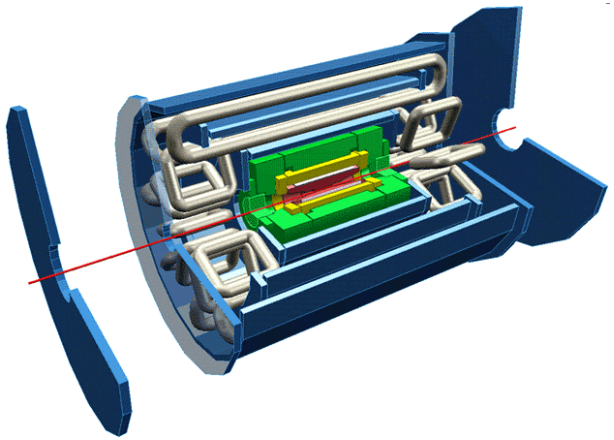
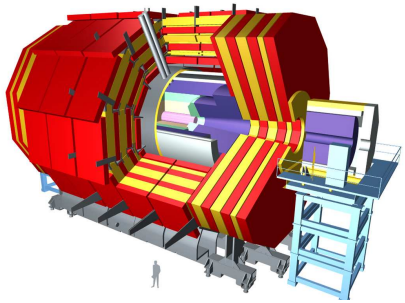
SUSY Searches at the LHC





ATLAS

CMS



- SUSY models
- Strategy for SUSY searches
- SUGRA Models
  - Inclusive signal
  - Precision measurements
  - Overall fit
- GMSB Models
- R-Parity violation
- Conclusions

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SUSY models

SUSY solves hierarchy problem and stabilises the Higgs mass, if the SUSY scale is <1TeV

In the MSSM, R-parity conserved, SUSY broken by adding all mass terms and trilinear A terms => 105 new parameters!

Cannot break SUSY spontaneously with MSSM fields alone => use hidden sector with messenger interaction.

SUGRA => use gravity only at Plank scale

GMSB => use SU(3)xSU(2)xU(1) at low scale

SUGRA models: at GUT scale

- all scalars have mass m_0
- all gauginos/higginos have mass $m_{1/2}$
- all trilinear $H\tilde{f}\tilde{f}$ terms have a common value A_0

Replace B and μ^2 by M_Z and $\tan\beta$ (ratio of Higgs vacuum expectation values)

Five new parameters:

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

Strategy for SUSY Searches

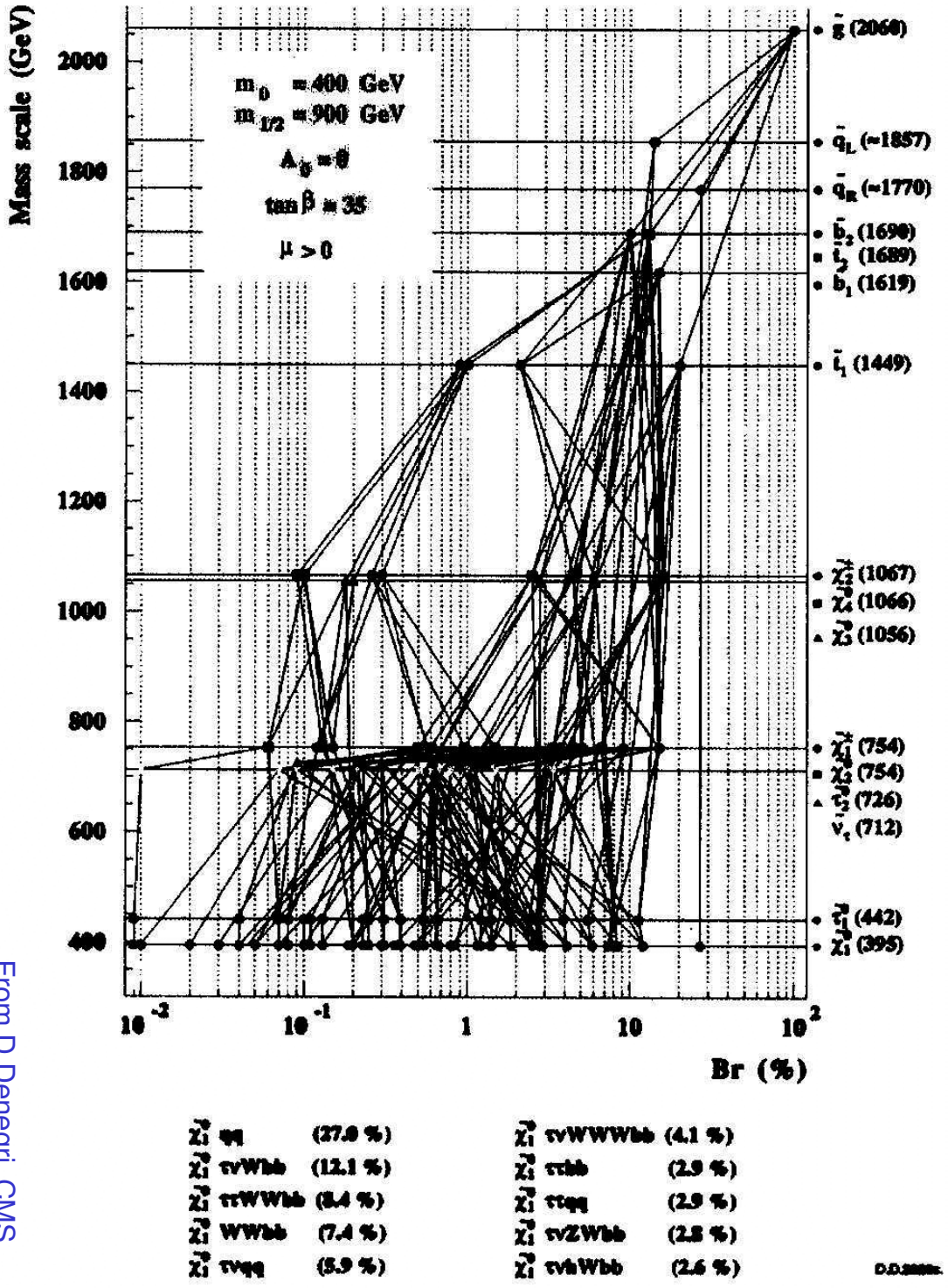
- Search for inclusive signals, measure SUSY mass scale
- Make detailed measurements of exclusive modes, extract kinematic end-points and combinations of masses, in as model independent way as possible
- Input all information into global fits to extract model parameters.

Discovery of SUSY is simple: understanding is not!

Points in SUGRA parameter space analysed by ATLAS

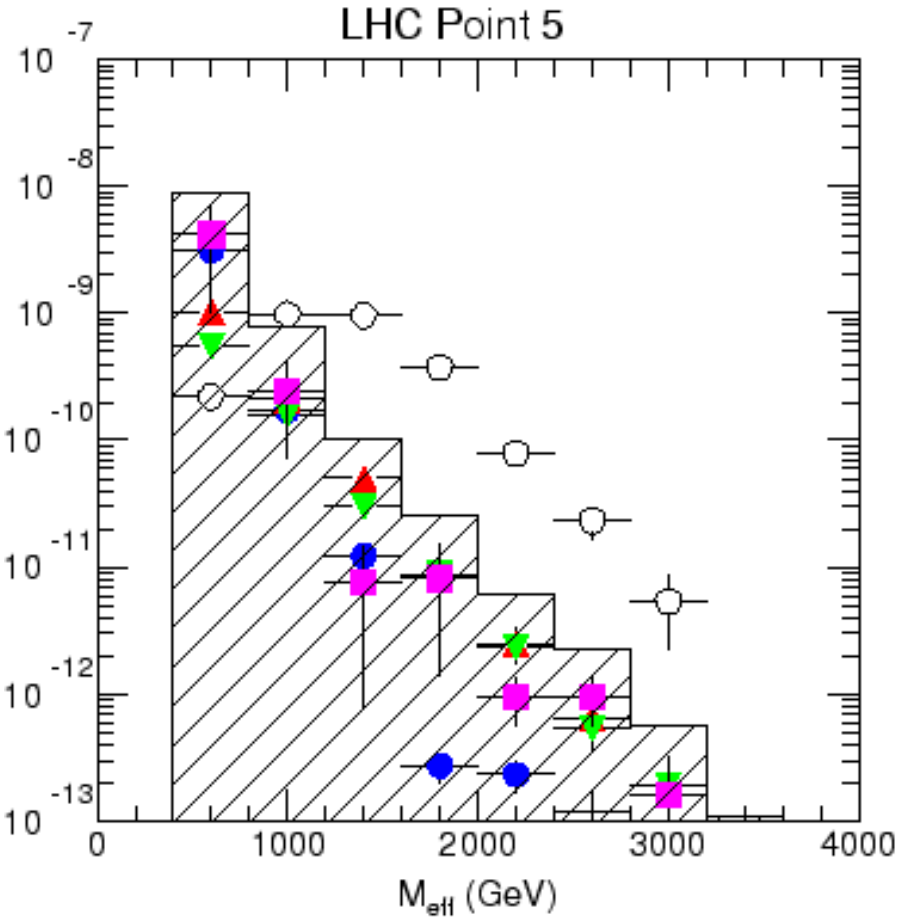
	m_0	$m_{1/2}$	A_0	tanβ	sgn(μ)
1	400	400	0	2	+
2	400	400	0	10	+
3	200	100	0	2	-
4	800	200	0	10	+
5	100	300	300	2.1	+
6	200	200	0	45	-

Decay scheme for a massive gluino at large tanβ



From D.Denegri, CMS

Inclusive SUSY signal at point 5



SUSY can be detected easily in channels with 0-3 leptons, >2 jets and missing E_T .

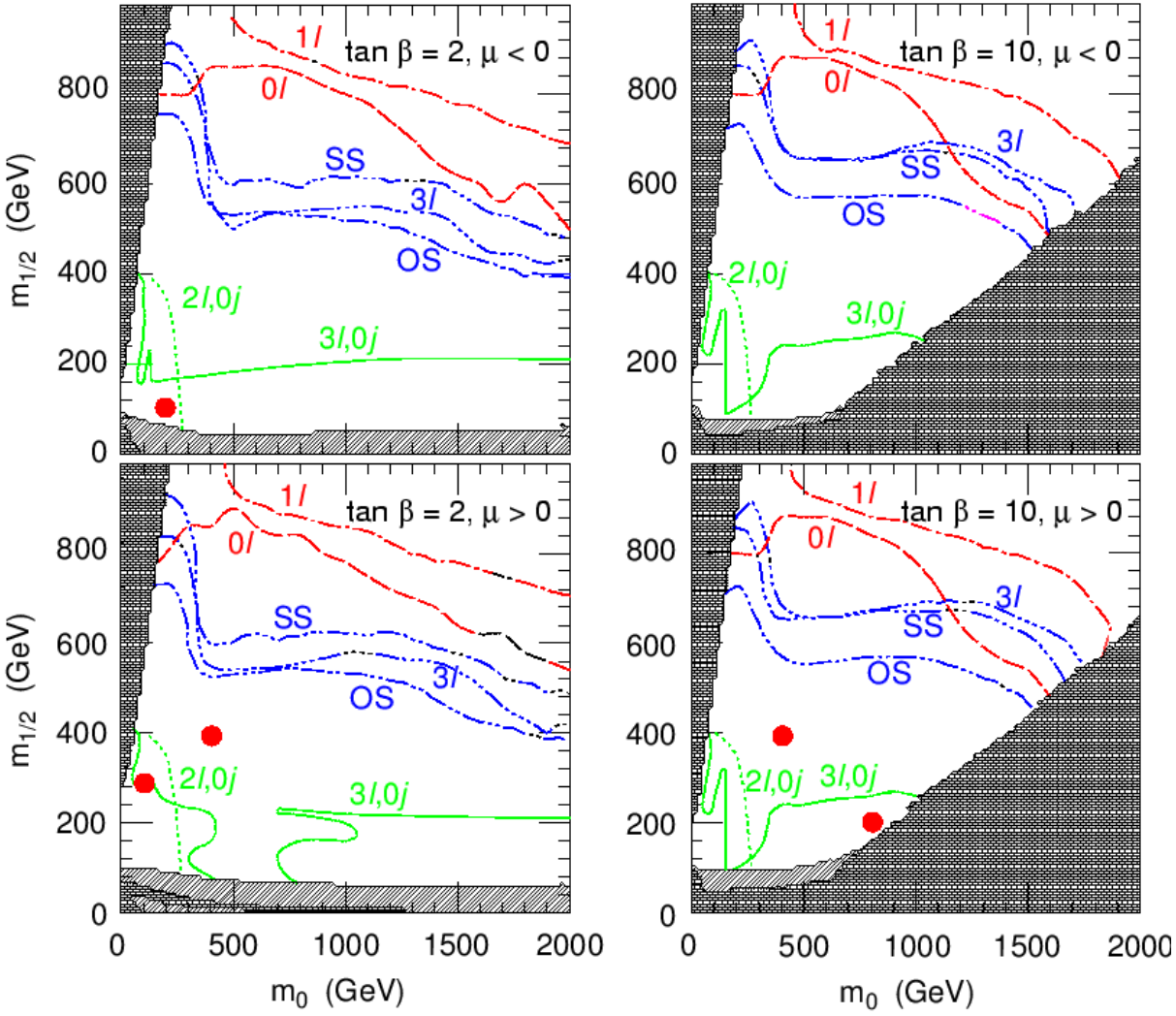
S/B > 10 for large M_{eff}, and accepted cross-section > 1pb

Can detect squark and gluino masses up to 2 TeV in 0 lepton channels and up to >1 TeV in multi-lepton channels.

The peak in M_{eff} gives a good measure of the SUSY mass scale

$$M_{eff} = E_T^{miss} + \sum_{i=1,4} p_T^i$$

Physics reach for SUSY signatures



Reach for $S/\sqrt{B} > 5$, >10 signal events and 10 fb^{-1}

0l: Jets, E_T^{Miss} no leptons

1l: Jets, E_T^{Miss} 1 lepton

SS: same sign leptons

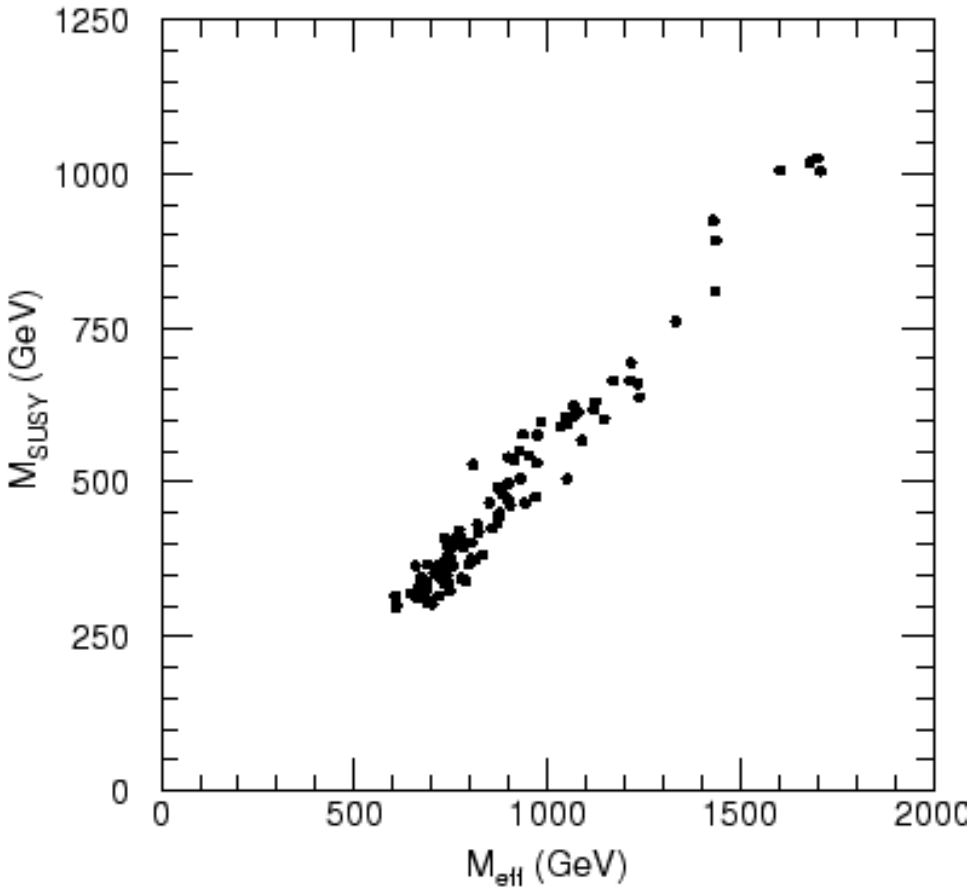
OS: opposite sign leptons

3l: tri-leptons

0j: jet veto

$A_0 = 0$

M_{eff} distribution measures SUSY scale

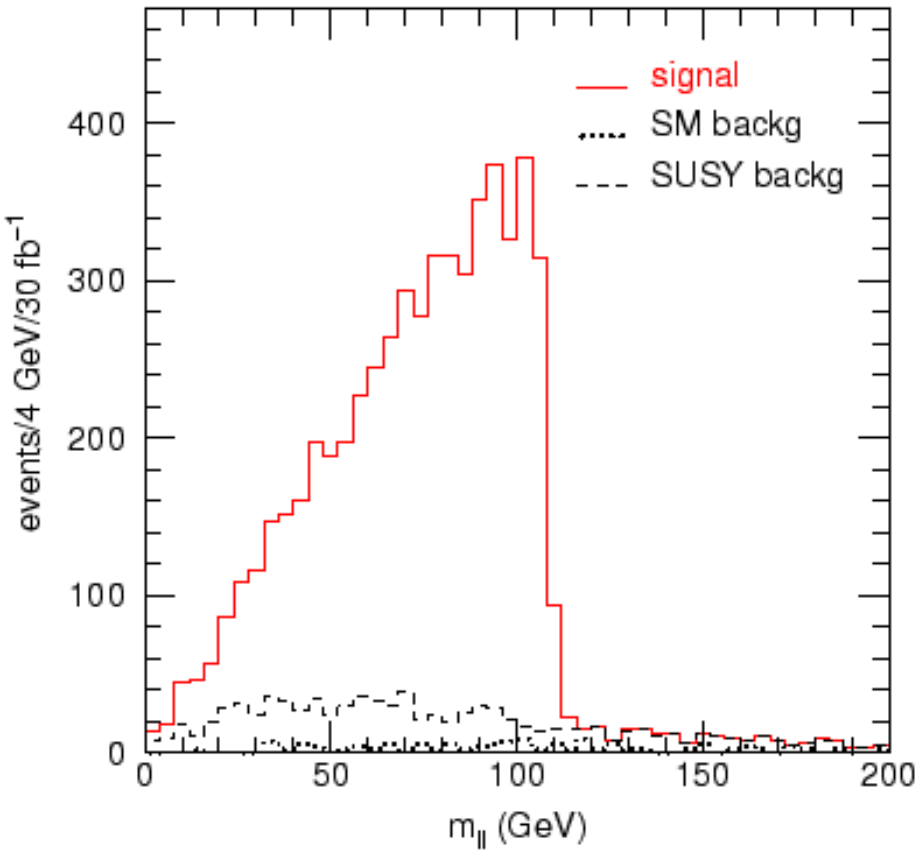


Peak of M_{eff} distribution vs the SUSY mass scale for a set of 100 minimal SUGRA model parameters.

M_{SUSY} is mass of gluino or $\tilde{u}_R$, whichever is lightest.

Strong correlation, with spread of only 10%

$$\tilde{\chi}_2^0 \to \tilde{l}_R^{\pm} l^m \to \tilde{\chi}_1^0 l^+ l^-$$



Dilepton signal at point 5

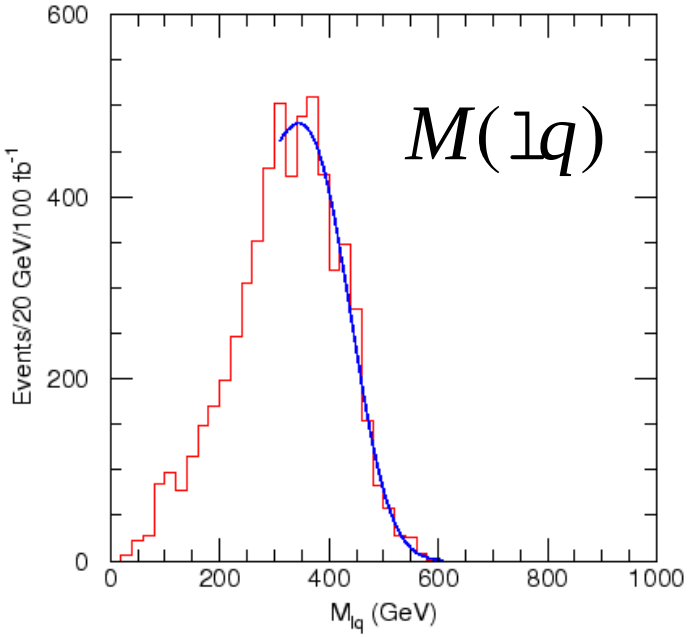
Edge position can be measured to 0.5 GeV with 30 fb^{-1}

5800 signal events, 880 SUSY background, 120 SM background

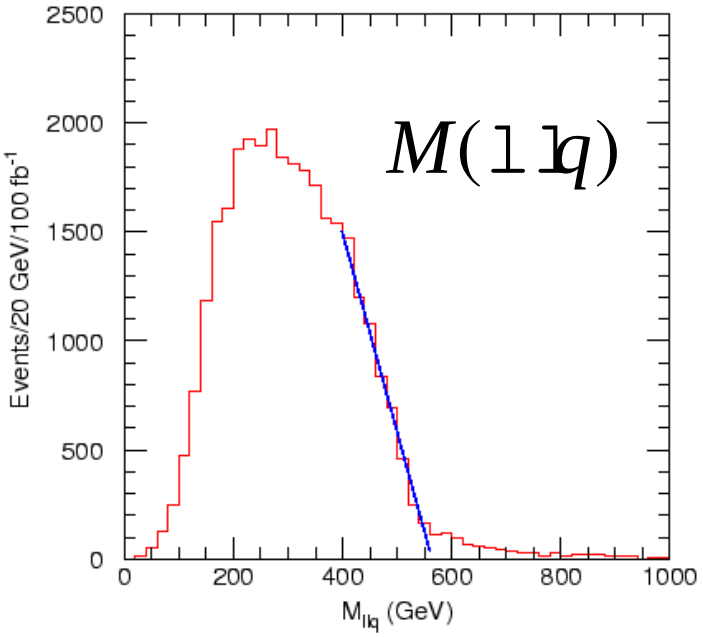
Most background can be subtracted using opposite sign eμ pairs

$$\Rightarrow M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$$

Squark mass reconstruction



$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R^{\pm} l^m q \rightarrow \tilde{\chi}_1^0 l^+ l^- q$$

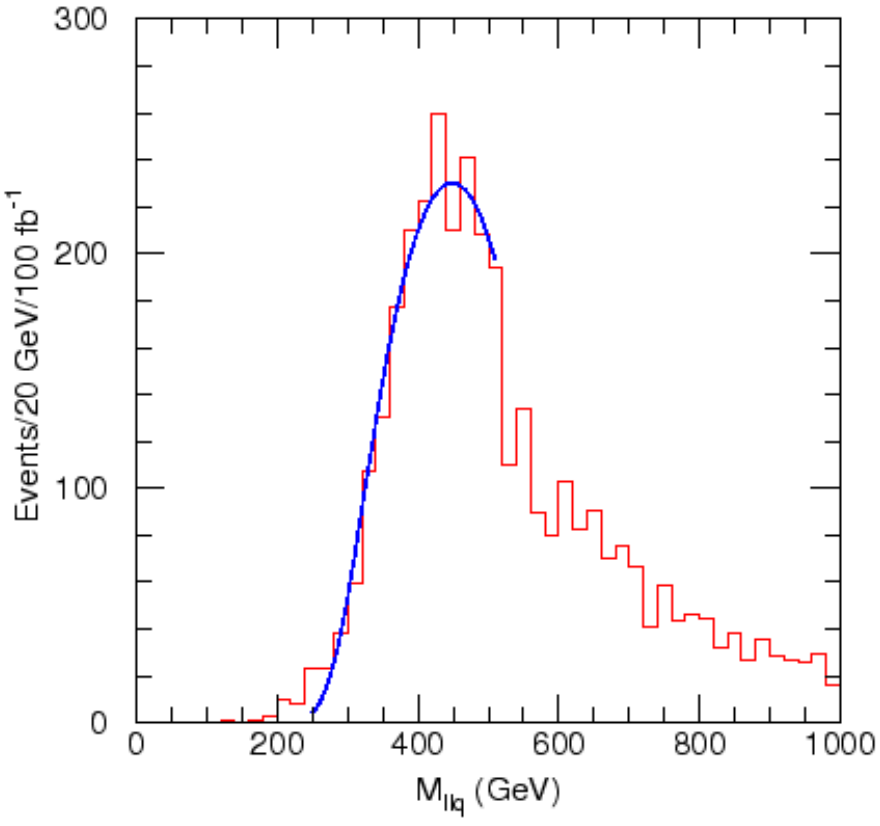


4 unknown masses in decay chain: 2 constraints from $l^{\pm}q$ and l^+l^-q endpoints

Hardest jet usually from squark: combine leptons with hardest two jets in the event. The smaller mass should vanish linearly at 4 body endpoint.

Subtract opposite flavour leptons to remove chargino background.

Squark mass reconstruction: llq threshold



$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R^{\pm} l^m q \to \tilde{\chi}_1^0 l^+ l^- q$$

Dilepton+quark mass also has threshold value which can be measured.

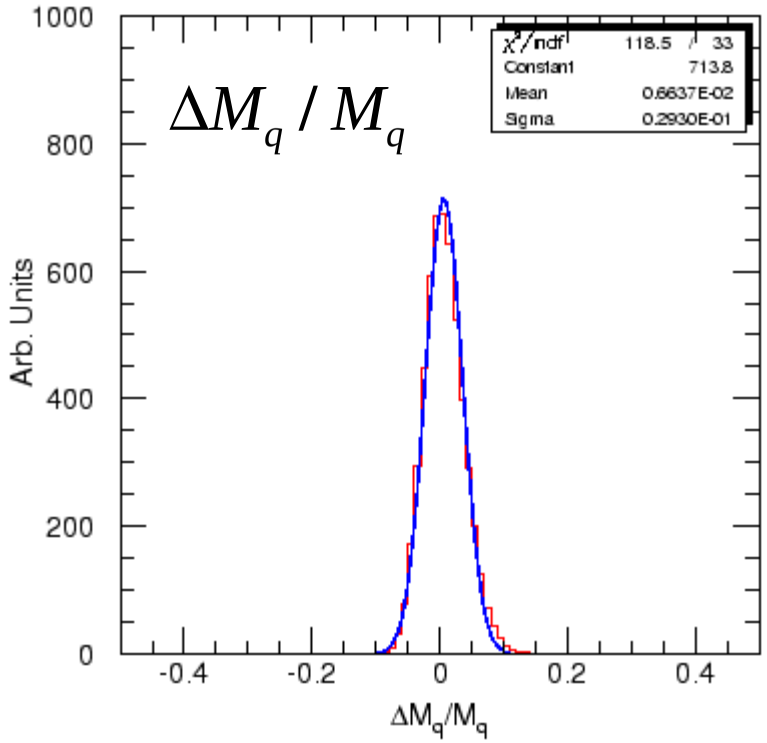
Now have 4 constraints on 4 unknown masses. Also information from

$$q_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 hq$$

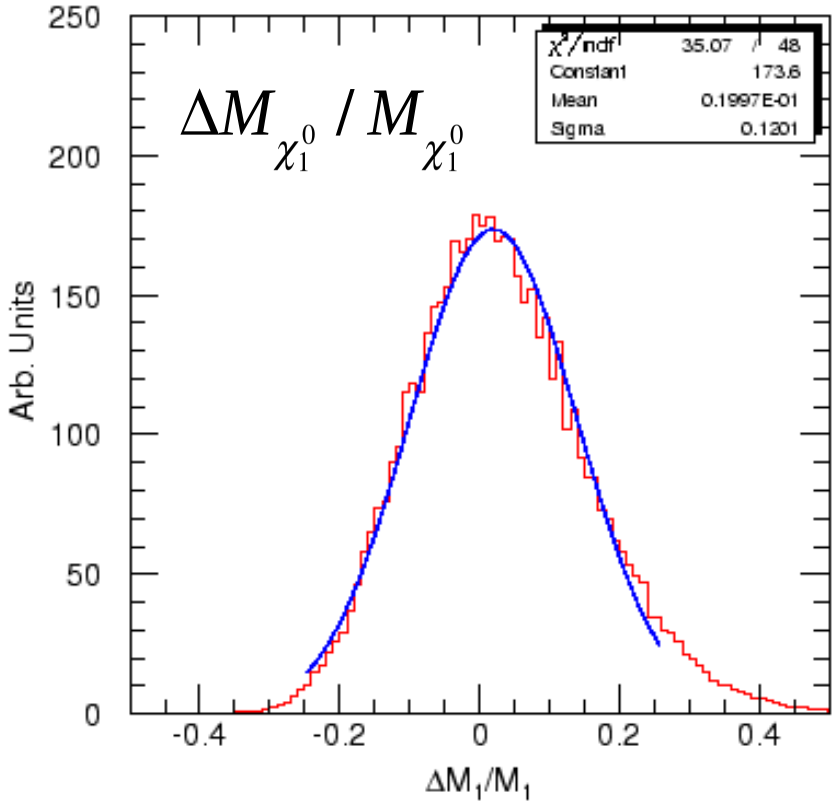
$$h \to b\bar{b}$$

$\Longrightarrow$ Can solve for all SUSY masses

Model independent SUSY masses



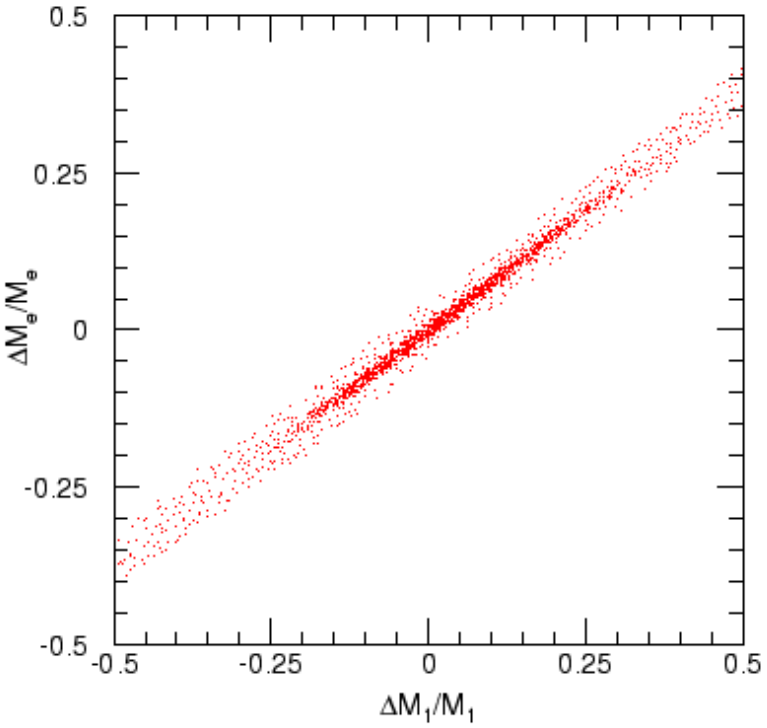
All 4 masses measured from kinematic constraints alone.



Fractional errors on masses

$\tilde{q}$	$\pm 3\%$	$\tilde{\chi}_2^0$	$\pm 6\%$
$\tilde{l}$	$\pm 9\%$	$\tilde{\chi}_1^0$	$\pm 12\%$

Correlations between mass determinations



Slepton vs neutralino masses

Masses determined by the model independent method are highly correlated.

Errors are controlled by the measured error on the llq threshold.

Fits to SUGRA models

Input measurements and **output parameters** for SUSY fit at Point 5

Sgn(μ) also determined, but data is insensitive to A_0

	Low-Luminosity	Ultimate precision
h mass	92.9±1.0 GeV	92.9±0.2 GeV
Dilepton endpoint	108.92±0.50 GeV	108.92±0.10 GeV
lq endpoint	478.1±11.5 GeV	478.1±5.0 GeV
Ratio of lq /llq endpoints	0.865±0.060	0.865±0.020
llq threshold	271.8±14.0 GeV	271.8±5.4 GeV
hq endpoint	552.5±10.0 GeV	552.5±5.5 GeV
hq threshold	346.5±17.0 GeV	346.5±17.0 GeV

	Low-luminosity	High-Luminosity	Ultimate
m_0	100 +4.1 –2.2 GeV	100.0 ± 1.4 GeV	100.0 ± 1.3 GeV
$m_{1/2}$	300.0 ± 2.7 GeV	300.0 ± 1.7 GeV	300.0 ± 1.5 GeV
tan(β)	2.00 ± 0.10	2.00 ± 0.09	2.00 ± 0.05

Gauge Mediated SUSY Breaking

Possible mechanism for SUSY breaking is in a separate sector, communicated to MSSM particles via SU(3)xSU(2)xU(1) at scale $M_m \ll M_P$

LSP is gravitino with mass « 1GeV

NLSP is neutralino or slepton which can have long lifetime

- $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
- $\tilde{l}_R \rightarrow \tilde{G} l$

Decays may occur outside detector

Parameters of GMSB models

F_m « $(10^{10}\ \mathrm{GeV})^2$	SUSY breaking scale
M_m	Messenger scale
$\Lambda \equiv F_m / M_m$	
N_5	Number of messenger 5-plets
$\tan(\beta)$	
$\mathrm{sgn}(\mu)$	
C_{grav}	Fixes lifetime of decays into gravitinos

GMSB with prompt photons

Choose Cgrav=1

$\Rightarrow \quad \tilde{\chi}_1^0 \to \tilde{G}\gamma$

Dalitz decays can measure $c\tau =$ 1.2mm

Signature is two hard photons with E_t^{miss}

Select:

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm} l^m \to \tilde{\chi}_1^0 l^+ l^- \to \tilde{G} l^+ l^- \gamma$$

Four measurements determine all masses, assuming gravitino mass is small

Gravitino momentum is also determined

$$M^2_{\tilde{l}_R} = \frac{(M^{(1)}_{l\gamma})^2 (M^{(2)}_{l\gamma})^2}{(M^{\max}_{ll})^2}$$

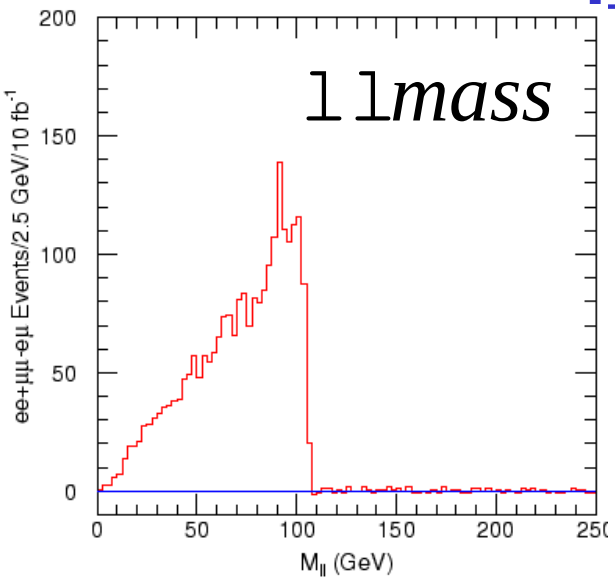
$$M^2_{\tilde{\chi}_1^0} = M^2_{\tilde{l}_R} - (M^{(1)}_{l\gamma})^2$$

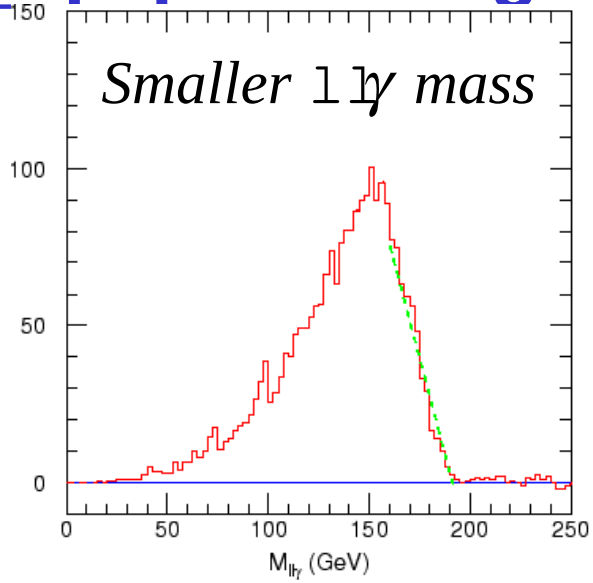
$$M^2_{\tilde{\chi}_2^0} = M^2_{\tilde{l}_R} + (M^{(2)}_{l\gamma})^2$$

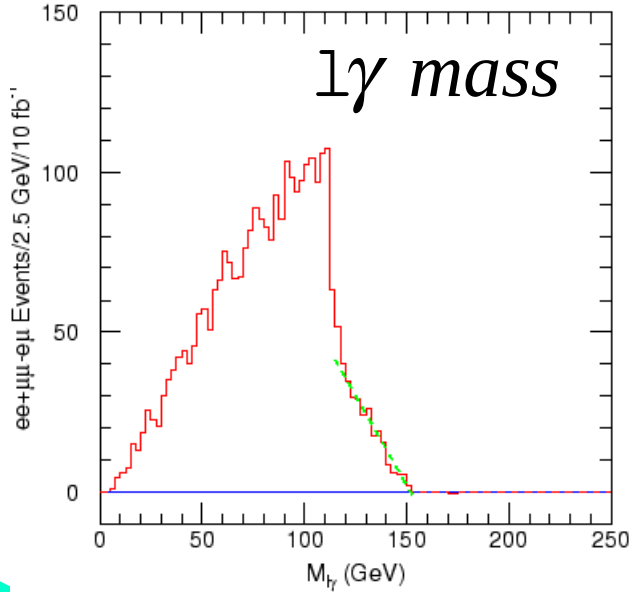
where

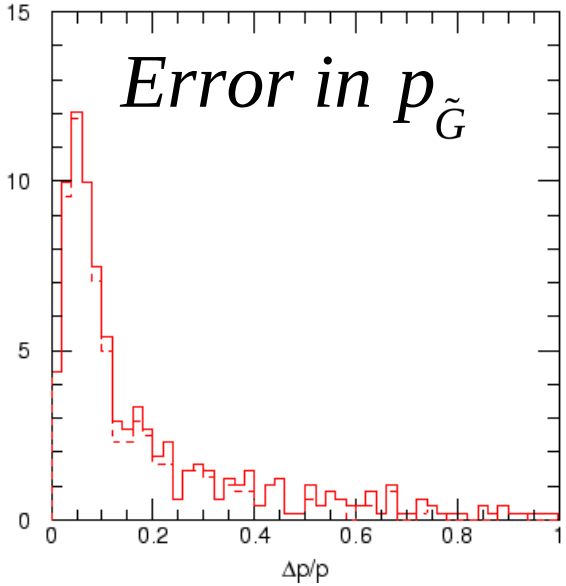
$$(M^{\max}_{ll\gamma})^2 = (M^{(1)}_{l\gamma})^2 + (M^{(2)}_{l\gamma})^2$$

GMSB prompt photon signals









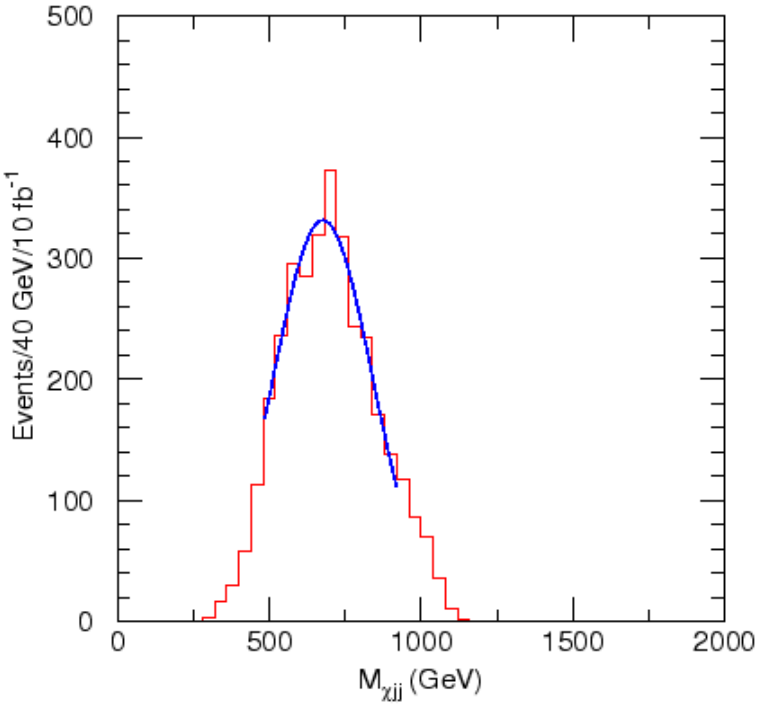
Background subtracted.

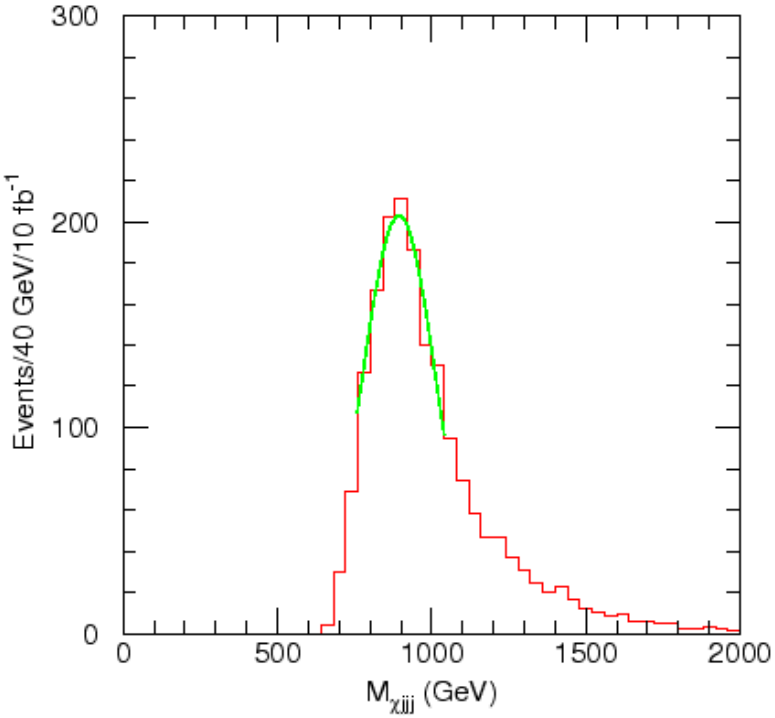
$$M_{l\gamma}^{(1)} = \sqrt{M_{\tilde{l}_R}^2 - M_{\tilde{\chi}_1^0}^2} = 112.7\,\text{GeV}$$

$$M_{l\gamma}^{(2)} = \sqrt{M_{\tilde{\chi}_2^0}^2 - M_{\tilde{l}_R}^2} = 152.6\,\text{GeV}$$

Gluino and squark masses at GMSB 1a

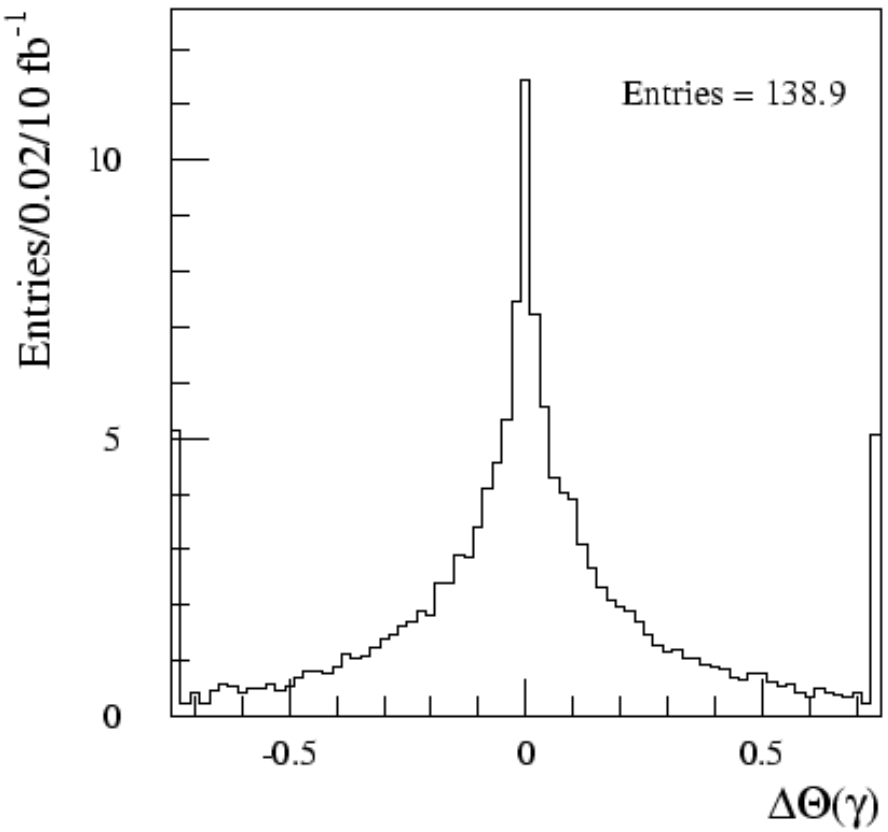
$$\tilde{q} \rightarrow \tilde{g}q \rightarrow \tilde{\chi}_2^0 q\bar{q}q$$





Require two reconstructed χ^0_2. Combine each with 2 of hardest 4 jets for gluino mass, and then with third jet for squark mass

GMSB: Long lived neutralinos



With $C_{grav}=10^3$ neutralino $c\tau$ =1.1km

Signatures similar to SUGRA but decay to gravitino+photon can be detected

ATLAS measures angle with EM calo

(Can also measure time delay)

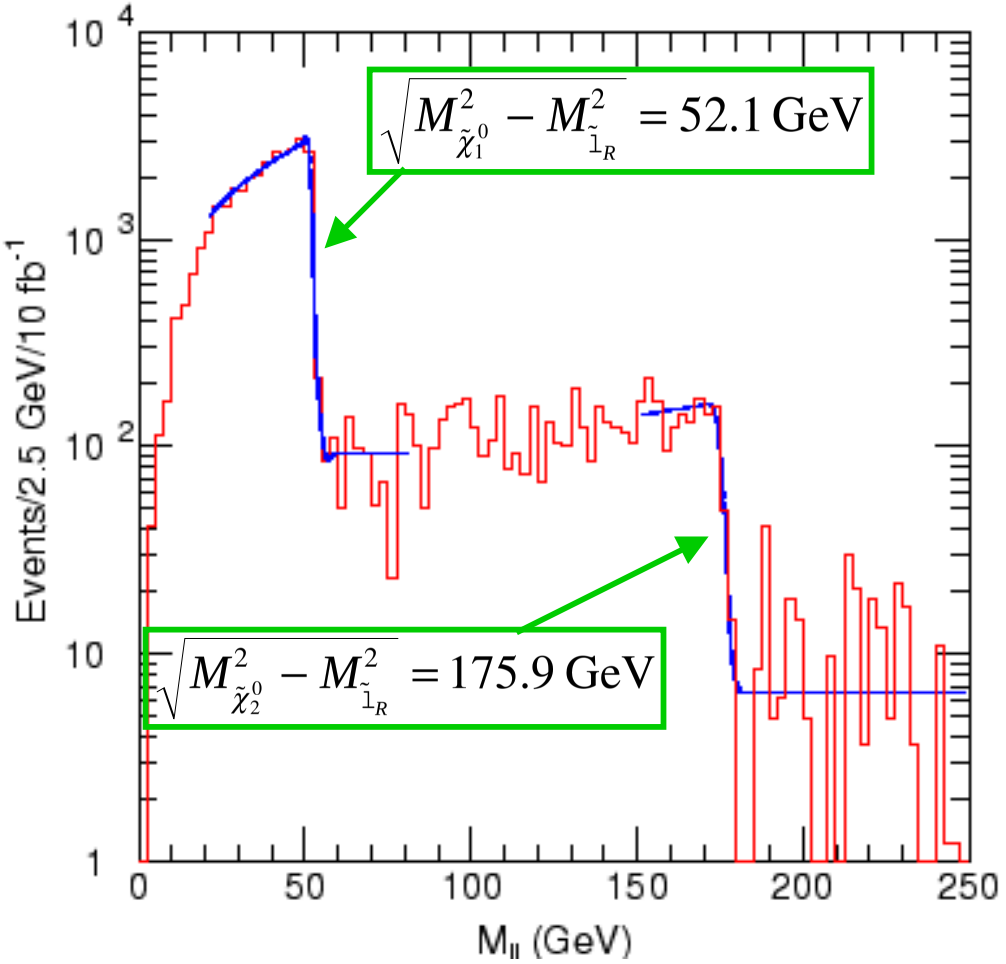
5σ significant non-pointing gives 82% efficiency.

Requiring p_T>20GeV, isolated photons gives overall signal efficiency of 52%

For 30pb^{-1}, get $c\tau$>100km at 95%CL and $C_{grav}>10^8$

Corresponds to $\Lambda>10^4$

GMSB with shortlived sleptons



Dilepon mass spectrum

If N_5>1, NLSP's are right-handed sleptons.

For C_{grav}=1 get

$$\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_1 \rightarrow l\tilde{G}$$

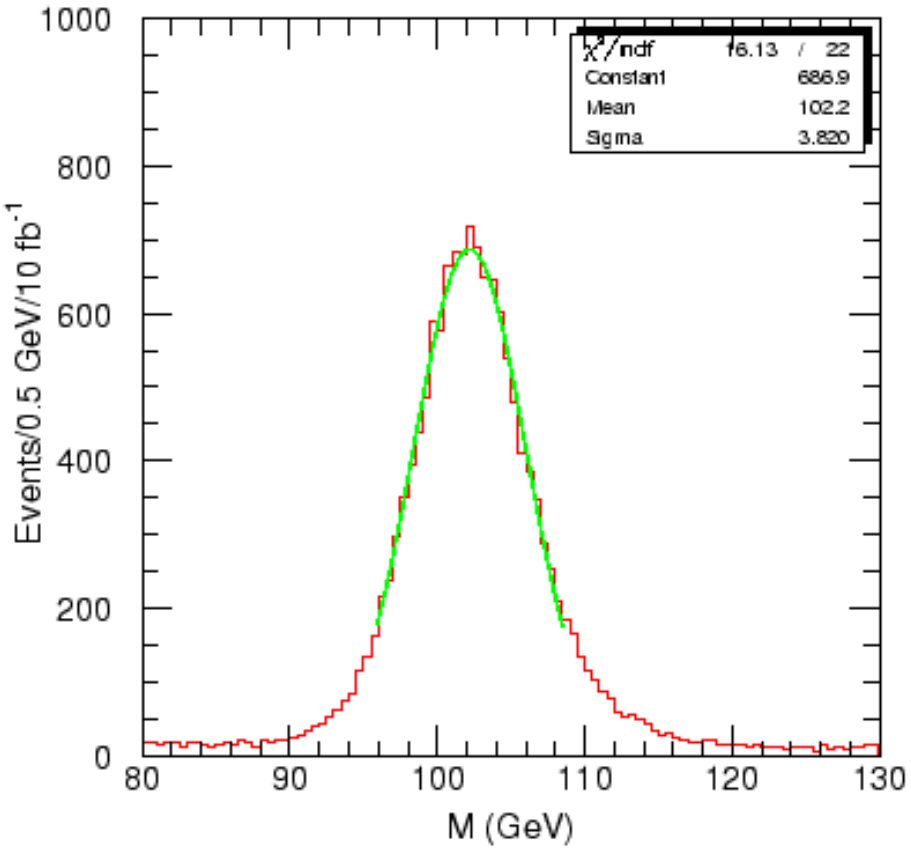
Production cross section=23pb

Many signatures with leptons and missing p_T

Simple to discover SUSY in this case

Many mass measurements possible

GMSB with longlived sleptons



ATLAS: Slepton mass = 102.2 GeV.
Time resolution =1ns

With $N_5>1$ and $C_{grav}>1$, NLSP is the stau, which decays via

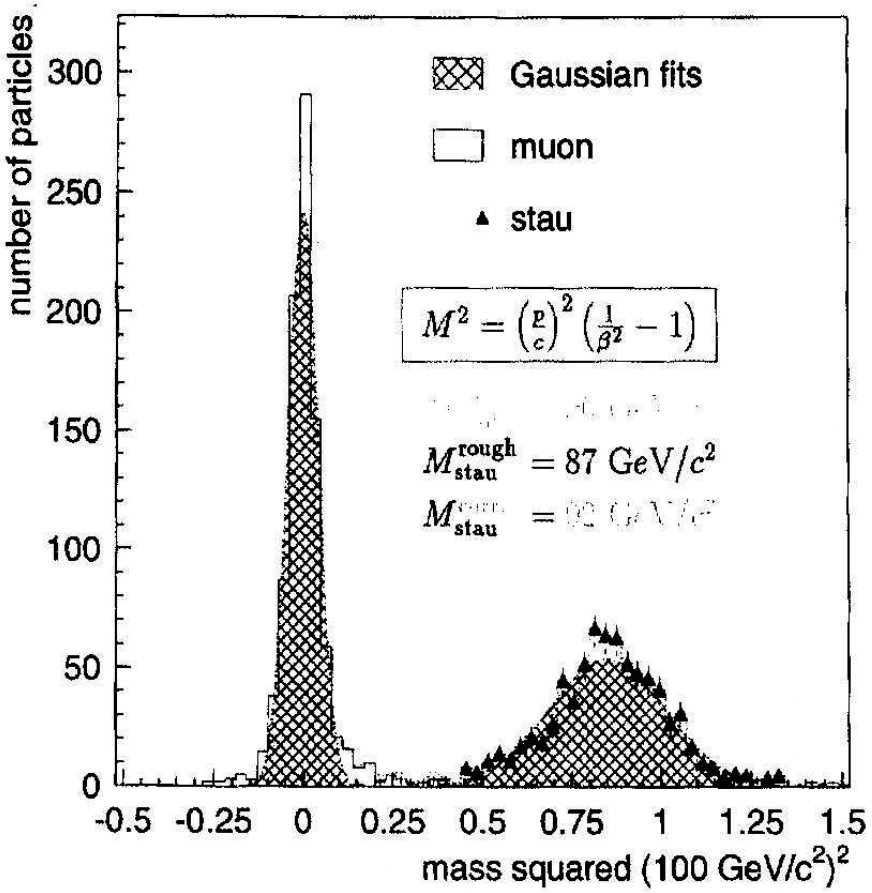
$$\tilde{\tau}_1 \rightarrow \tau\tilde{G}$$

with $c\tau$=1km

Signature is two heavy quasistable particles in each event.

Detect in muon system by time of flight!

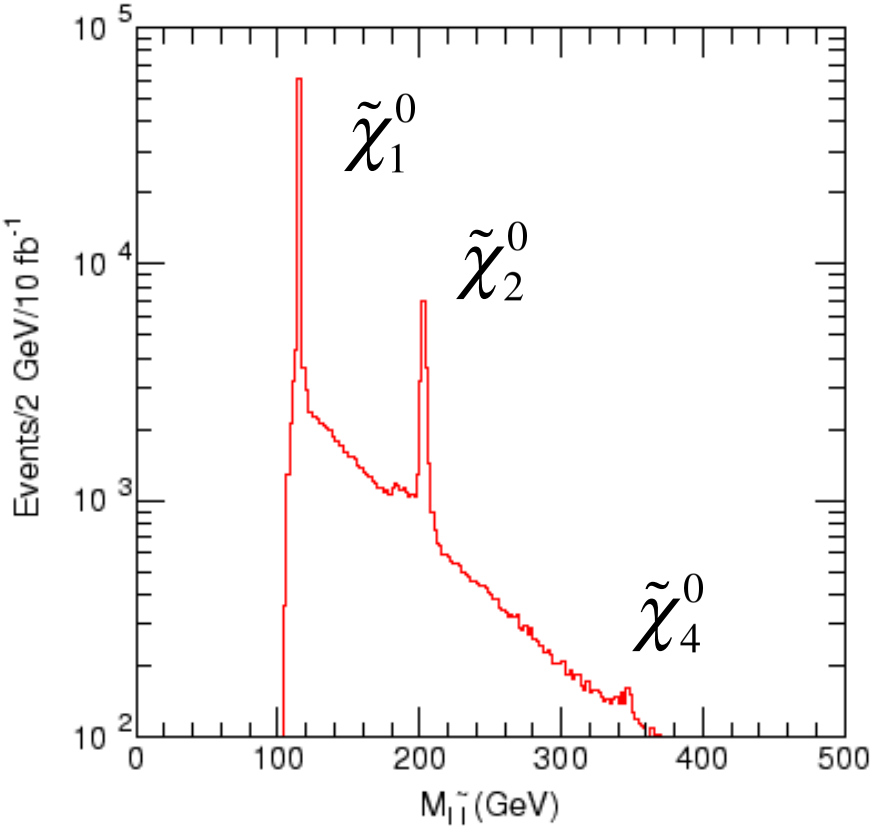
Mass^2 of $\tilde{\tau}_1$ (NLSP in GMSB) with $c\tau \simeq 10$ m in CMS drift tubes



- Time of flight measurement enable us to find (exclude) pair produced heavy long–lived charged particles from LEP2, Tevatron limit (~ 100 GeV) to LHC kinematical limit (~ 1 TeV), if the cross sections are at the level of femtobarns or greater.

  (But exact exclusion limits should be evaluated.)

GMSB: neutralino reconstruction



Neutralino decays

$$\tilde{\chi}_i^0 \rightarrow \tilde{l}_R l$$

can be fully reconstructed.

Events with at least 3 (s)lepton candidates. Combine sleptons with leptons (p_T>10 GeV)

No TOF cuts since SM background negligible.

GMSB fits

Fits for the GMSB parameters normally determine Λ, N_5 and sgn(μ) well for one year of running at low luminosity.

	Prompt γ	Stable χ	Slepton	Stable Slepton
Λ	$90\pm1.7\times10^3$		30000 ± 540	30000 ± 250
M_m	$50\pm17\times10^4$	$\Lambda N_5=90000$	$250\pm60\times10^3$	$250\pm32\times10^3$
N_5	1.00 ± 0.014	±880	3.0 ± 0.05	3.0 ± 0.02
$\tan(\beta)$	5.0 ± 1.3	$5.0^{+2.7}_{-1.8}$	5.0 ± 1.0	5.0 ± 0.3

ATLAS results for $30pb^{-1}$

ANOMALY MEDIATED SUSY BREAKING

hep-ph/0001249

$M(\tilde{\chi}_1^\pm) \simeq M(\tilde{\chi}_1^0)$ $\qquad \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \pi^\pm$

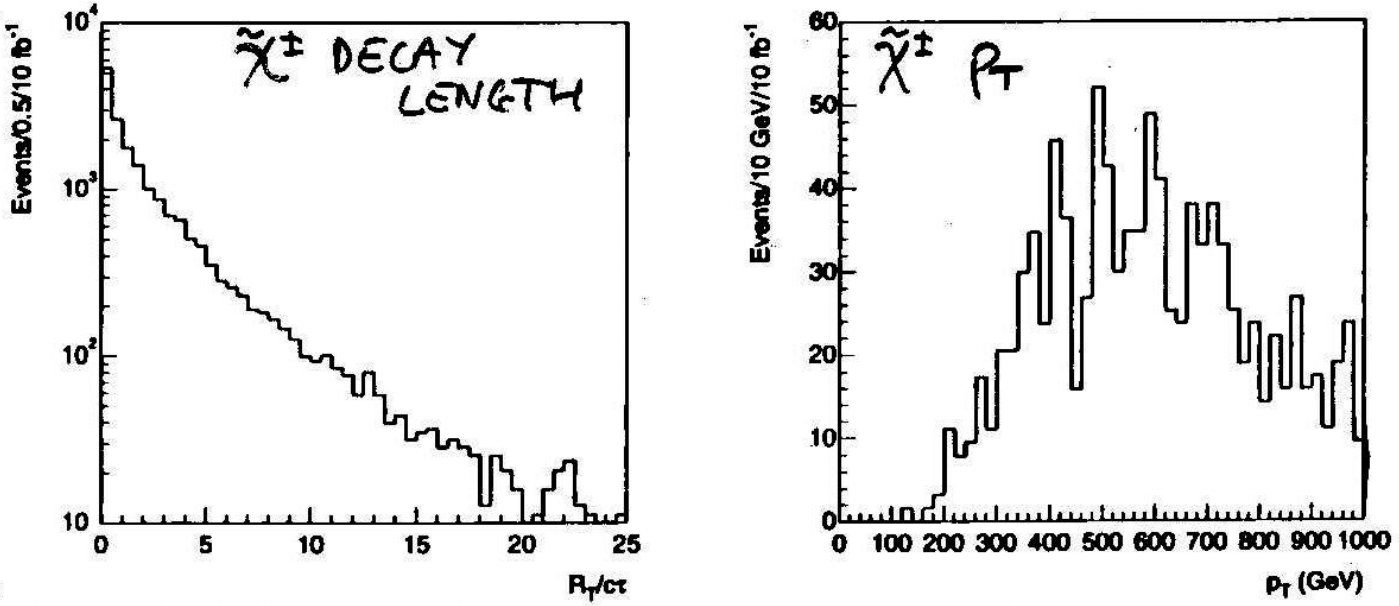


Figure 7: Left: Radial track length distributions for $\tilde{\chi}_1^\pm$ in the barrel region, $|\eta| < 1$. Right: p distribution for $\tilde{\chi}_1^\pm$ with $R_T > 10c\tau$.

R-parity violating models

R-parity can be broken by three distinct interaction terms, parameterised by λ,λ' and λ''

$$\lambda \neq 0: \quad \tilde{\chi}_1^0 \to l^+ l^- \nu \quad \text{Lepton number violated}$$

$$\lambda' \neq 0: \quad \tilde{\chi}_1^0 \to q\bar{q}\nu, q\bar{q}l \quad \text{Lepton number violated}$$

$$\lambda'' \neq 0: \quad \tilde{\chi}_1^0 \to qqq \quad \text{Baryon number violated}$$

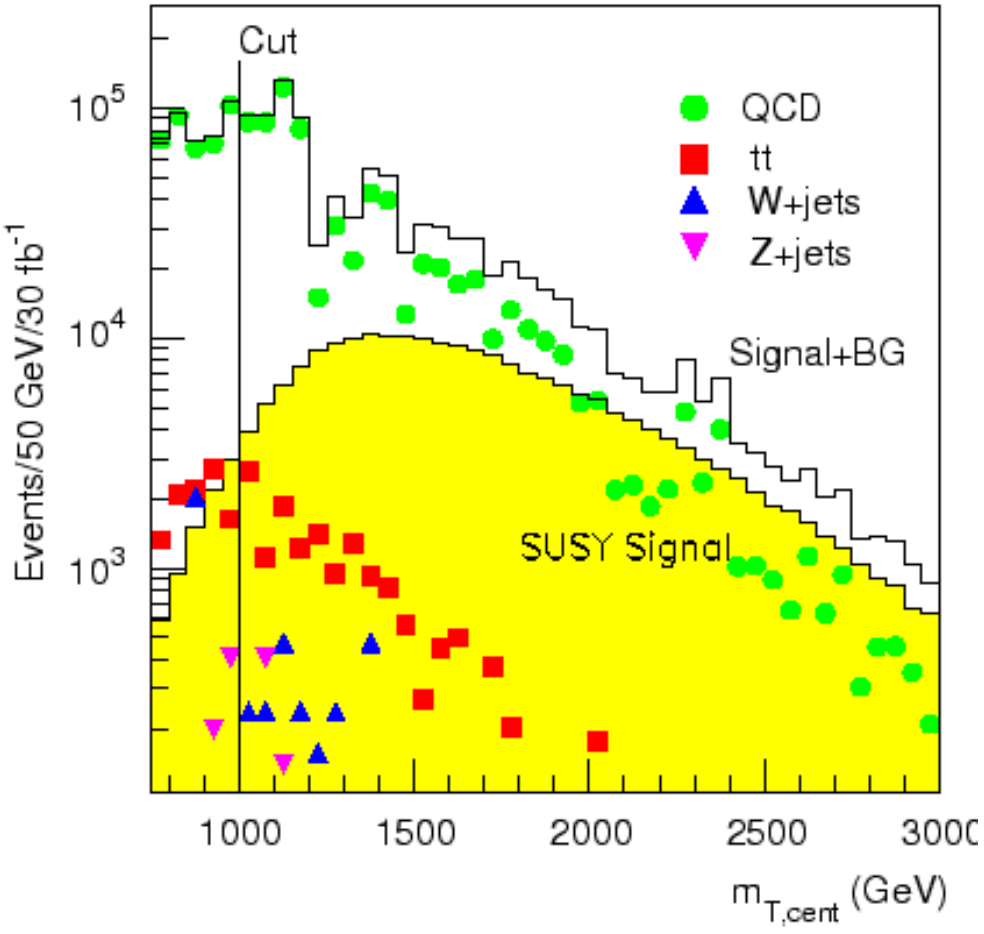
For $\lambda<10^{-6}$ LSP decays outside detector, no new signatures

For $10^{-6} < \lambda<10^{-2}$ LSP decays inside detector.

For $\lambda>10^{-2}$ all SUSY decay chains can be modified.

Studies only consider moderate λ values with prompt LSP decays.

Baryon number violation $\tilde{\chi}_1^0 \rightarrow cds$



Most difficult case: no E_T^{miss} signature, no special quark flavours or lepton tags.

Define mass scale with

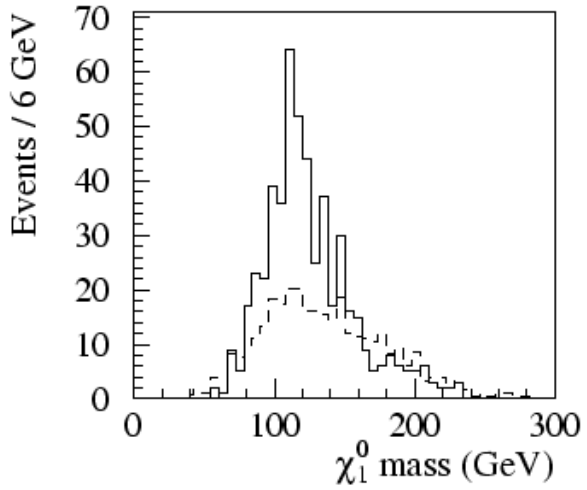
$$M_{T,cent} = \sum_{\eta<2} p_T^{jet} + \sum_{\eta<2} p_T^{lepton}$$

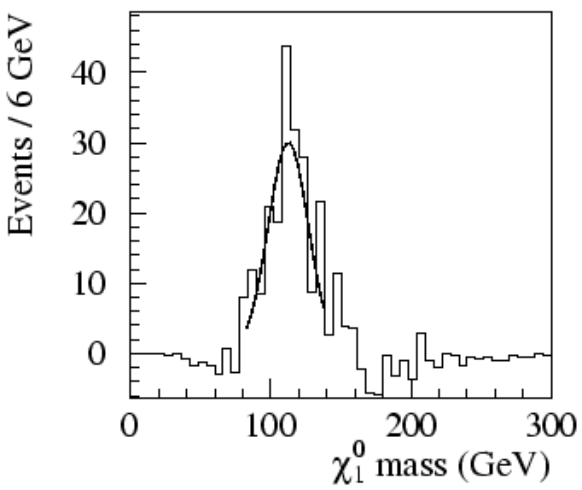
for events with >8 jets (p_T>50 GeV)
>1 jet (p_T>100 GeV)
S_T>0.2, thrust>0.9

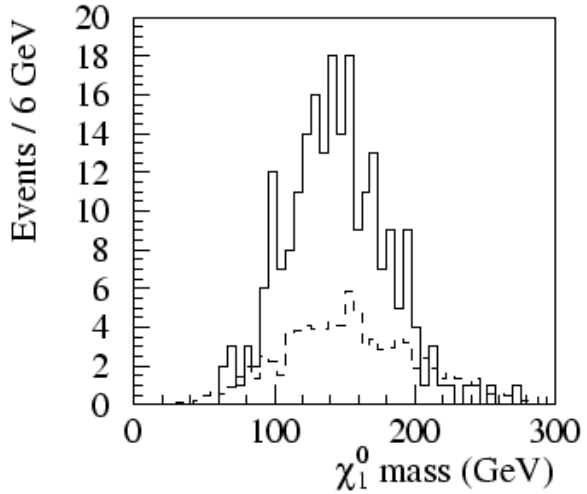
S/B <1: need to require leptons in events from χ^0_2 decays

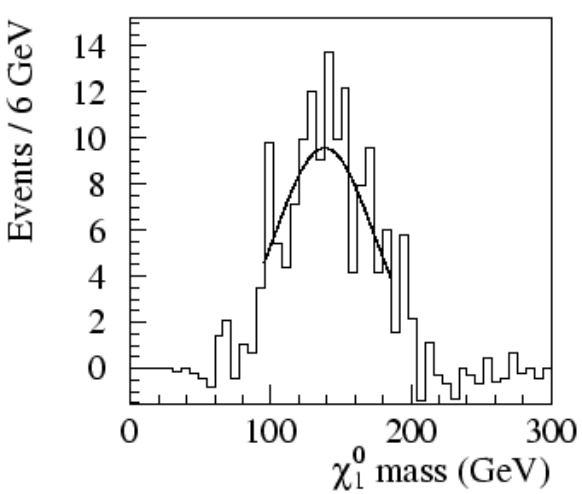
Baryon number violation

$$\tilde{\chi}_2^0 \to \tilde{l}_R^{\pm} l^m \to \tilde{\chi}_1^0 l^+ l^-$$









Channel provides lepton signature ⇒

Reconstruct χ^0_1 in 3 jets

Require two χ^0_1 in each event with masses within 20 GeV.

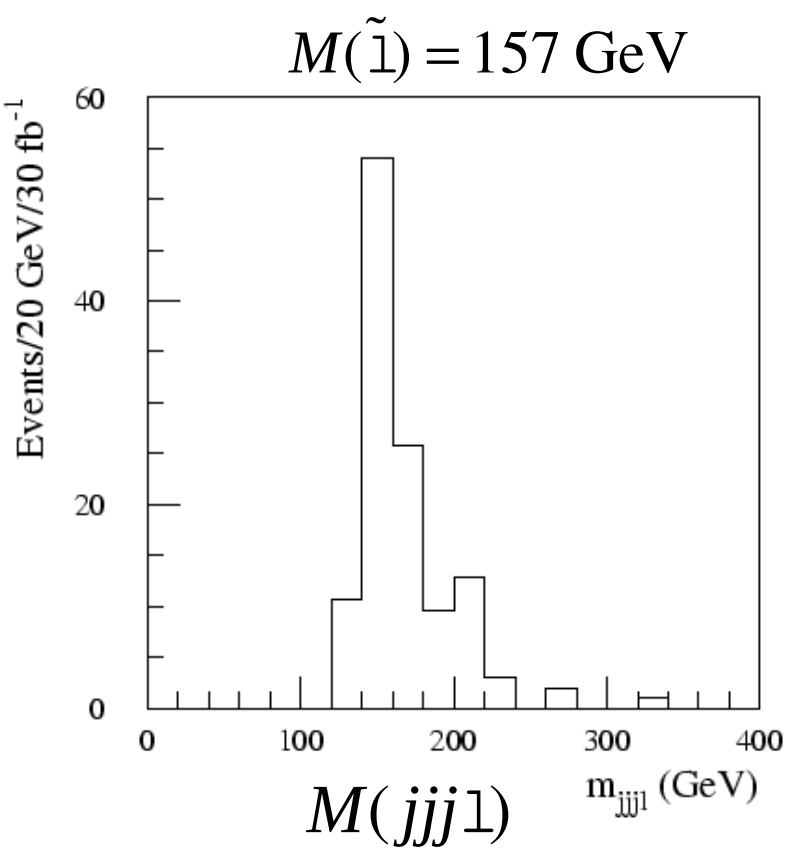
Measure combinatoric background from events with badly matching masses.

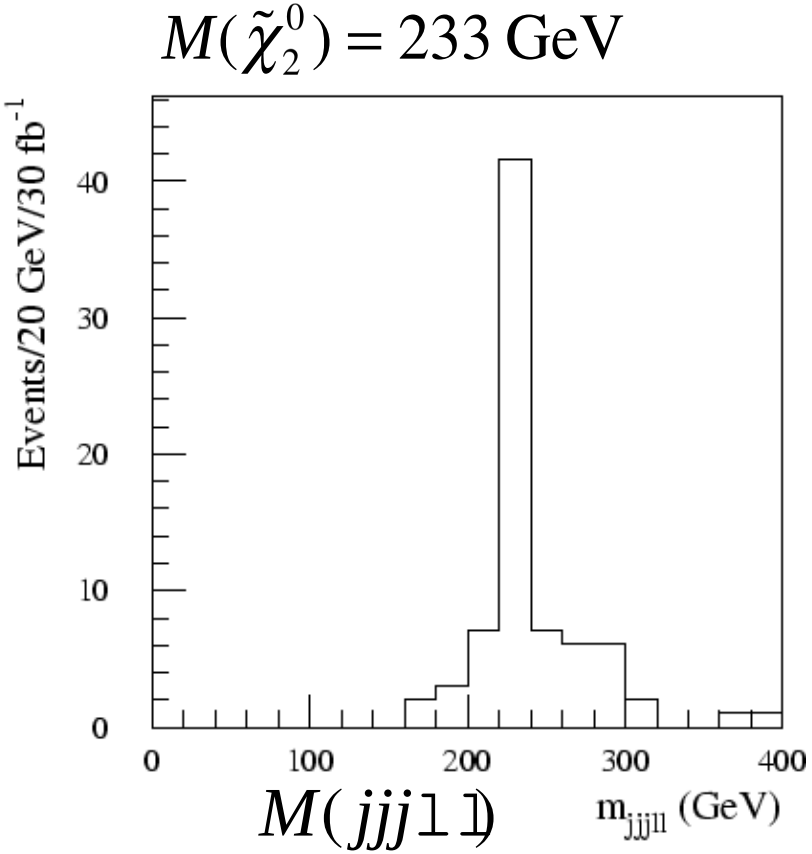
Measure χ^0_1 mass to about 3 GeV.

Then reconstruct slepton and χ^0_2 masses

Baryon number violation

$\tilde{\chi}_2^0 \to \tilde{l}_R^{\pm} l^m \to \tilde{\chi}_1^0 l^+ l^-$

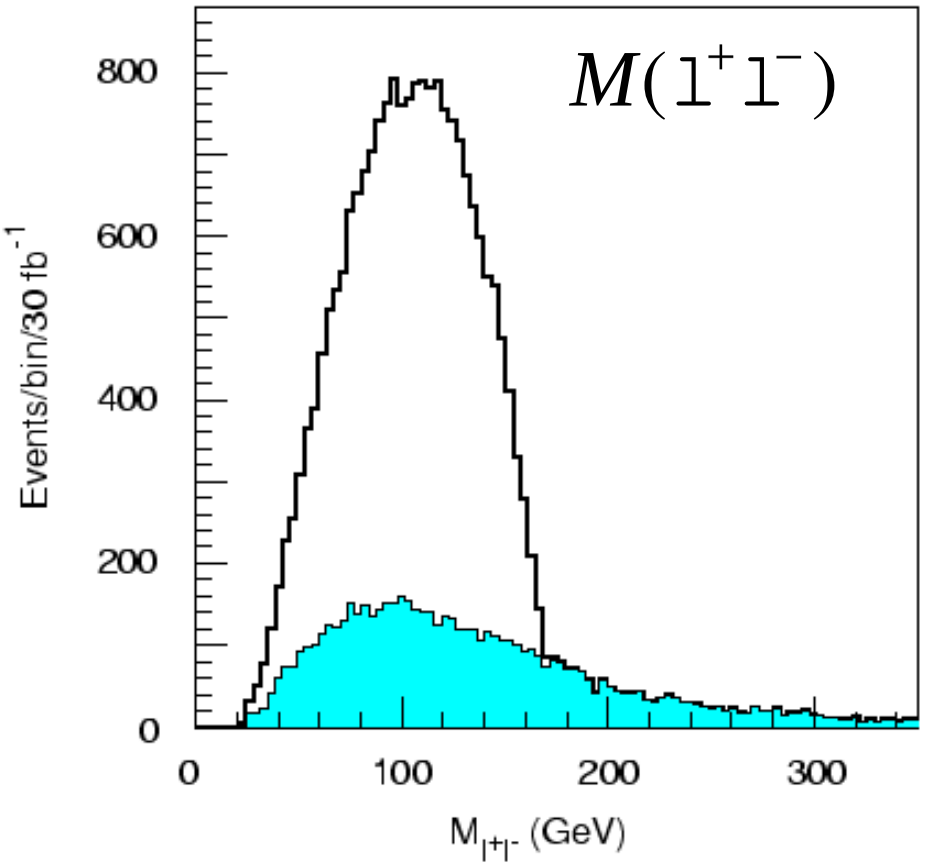




Add reconstructed χ^0_1 candidates to one and two leptons to form slepton and χ^0_2 masses

Lepton number violation

$$\tilde{\chi}_1^0 \rightarrow \nu_{e(\mu)} + \mu^{\pm}(e^{\pm}) + \mu^{m}$$



Each event contains ≥4 leptons

Require ≥4 leptons (p_T>10 GeV)

cosθ>0.5 between l pairs

E_T^{miss} >50 GeV

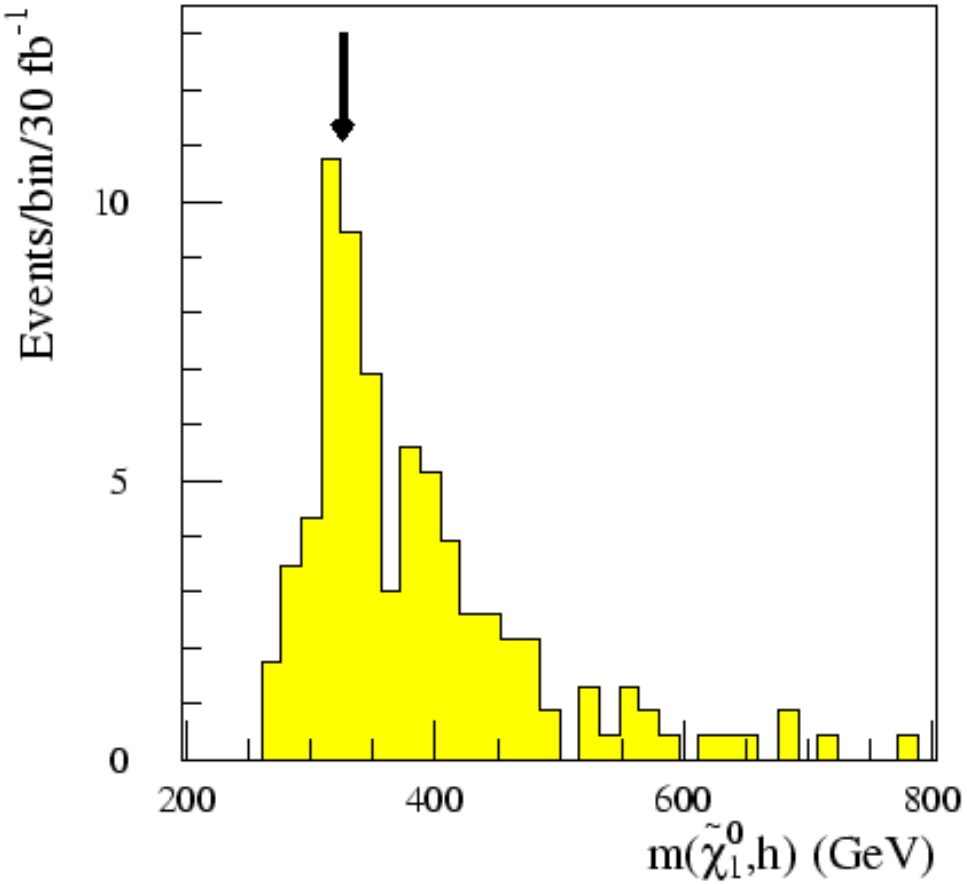
Plot mass of OS-DF lepton pairs: clear edge with endpoint at χ^0_1 mass

Measure m(χ^0_1)=169.8±0.18 GeV

χ^0_1 candidates within 50 GeV of the edge are used in other mass reconstructions.

Lepton number violation

$$\tilde{\chi}_1^0 \rightarrow \nu_{e(\mu)} + \mu^{\pm}(e^{\pm}) + \mu^{m}$$



Combine χ^0_1 candidates with Higgs candidates reconstructed in bb mode

Search for

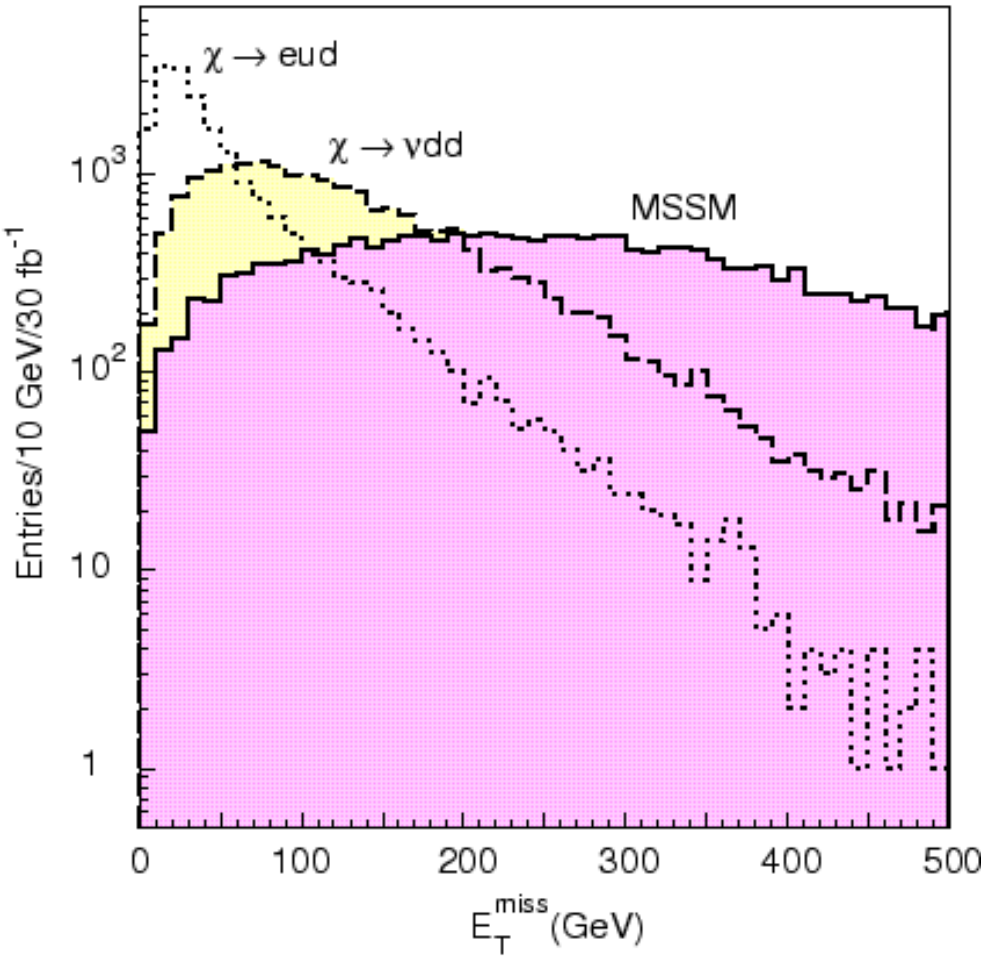
$$\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$$

Measure m(χ^0_2)=326.2±4.8 GeV

Can also reconstruct chargino, slepton and squark masses.

Lepton number violation

$$\tilde{\chi}_1^0 \to q\bar{q}\,l, \quad q\bar{q}\,\nu$$



qql case is simple: signature includes two leptons per event, and χ^0_1 can be fully reconstructed.

qqν case has small E_T^{miss}, but extra leptons are produced in cascades.

Can extract SUSY signal from combination of E_T^{miss}, high jet multiplicity and lepton tag.

Conclusions

- SUSY will be easy to detect if the mass scale is in the LHC reach.
- The main background to SUSY processes is other SUSY processes
- The challenge is to unravel the underlying model
- A range of models has been explored by the experiments, including non-Universal SUGRA, R-parity violation, and GMSB
- In all cases, a wide range of precise measurements are possible and model parameters can generally be extracted accurately

The LHC data will keep the experimentalists profitably employed for many years!