Signals and Backgrounds for the LHC
SUSY

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SUSY in hadron colliders

Inclusive signatures provide evidence up to $2.5\ \mathrm{TeV}$ for squarks and gluinos.

Everything is produced at once; squarks and gluinos have largest rates.

Production of Sparticles with only E-W couplings (e.g sleptons, Higgs) may be dominated by decays not direct production.

Must use a consistent model for simulation
cannot discuss one sparticle in isolation.

Makes studies somewhat complicated and general conclusions difficult to draw.

LHC Strategies different from Tevatron where weak gaugino production probably dominates

Studies shown here are not optimized

Large event rates are used to cut hard to get rid of standard model background.

Dominant backgrounds are combinatorial from SUSY events themselves.

Studies shown here are not optimized; large event rates are exploited to cut hard to get rid of standard model background.

Full program difficult to estimate, depends on masses and branching ratios

General remarks

Huge number of theoretical models

Most general SUSY model has > 100 parameters Simulation has concentrated on cases that are qualitatively different; some examples were chosen in the expectation that they would be hard.

Model determines the masses, decays and signals.
A Model must be used for simulation in order to understand the problems of reconstruction – Background to SUSY is SUSY itself

Analysis does not depend on a particular model

SUSY production is dominated by gluinos and squarks

Other susy particles produced in their decays

Therefore observation of direct production of sleptons and weak gauginos is difficult but not impossible
Final states with e, μ, τ, γ, $\not{E}_T$ studied

Characteristic SUSY signatures at LHC

Not all present in all models

$\not{E}_T$

High Multiplicity of large p_t jets

Many isolated leptons

Copious b production

Large Higgs production

Isolated Photons

Quasi-stable charged particles

N.B.Production of heavy objects implies subset these signals

Important for triggering considerations

I show only examples, many cases have been studied
(SUGRA, GMSB, broken R parity ....)

Simplest models have few parameters; $m_{1/2}$ and m_0 determine gluino and slepton masses.

SUGRA Model

Grandaddy of SUSY models

Unification all scalar masses (m_0) at GUT scale

Unification all gaugino masses ($m_{1/2}$) at GUT scale

Three more parameters $\tan\beta = v_1/v_2\ sign(\mu)$ (superpotential has $\mu H_1 H_2$) and Trilinear term A, important only for 3rd generation

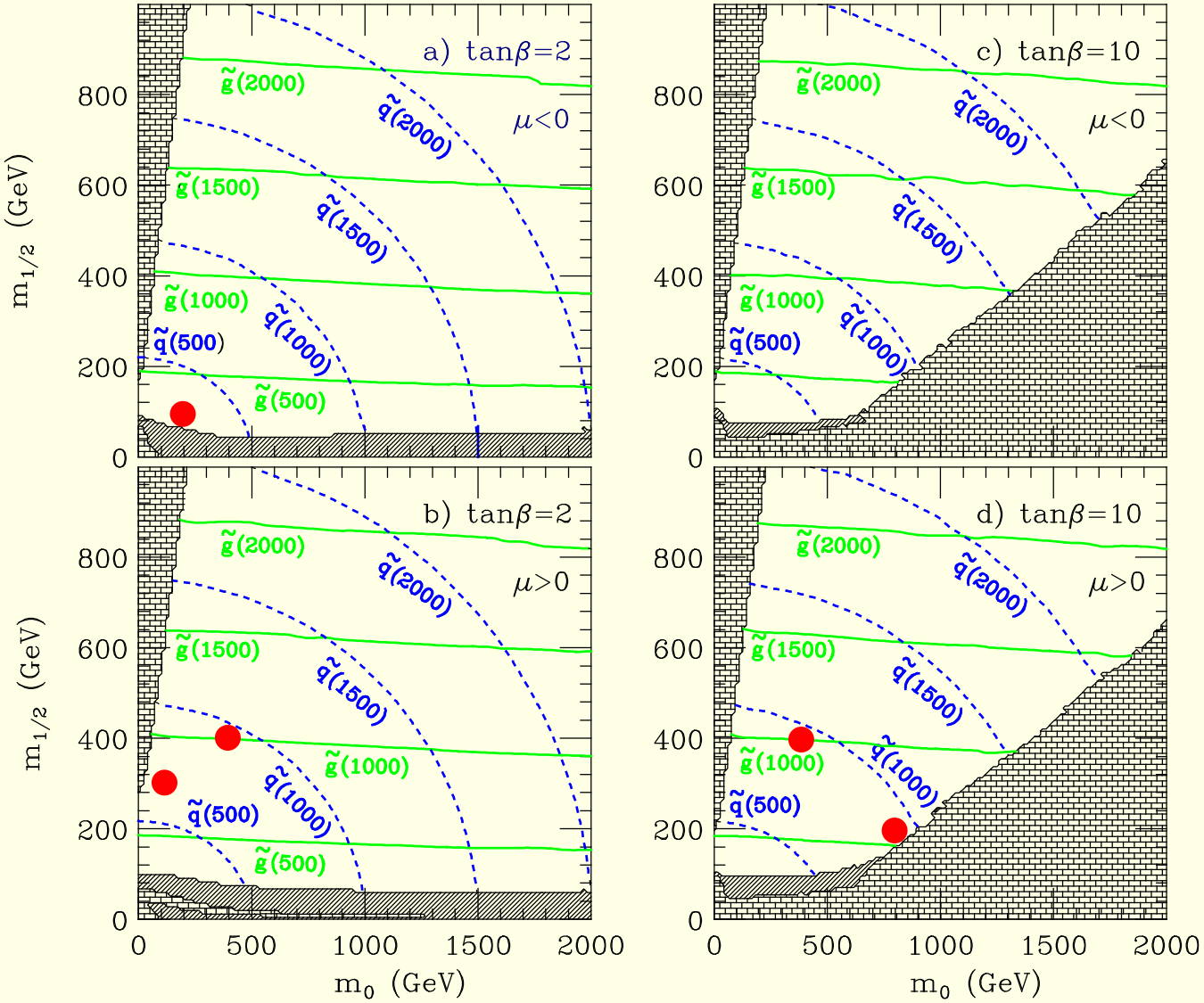
Full mass spectrum and decay table predicted

Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.

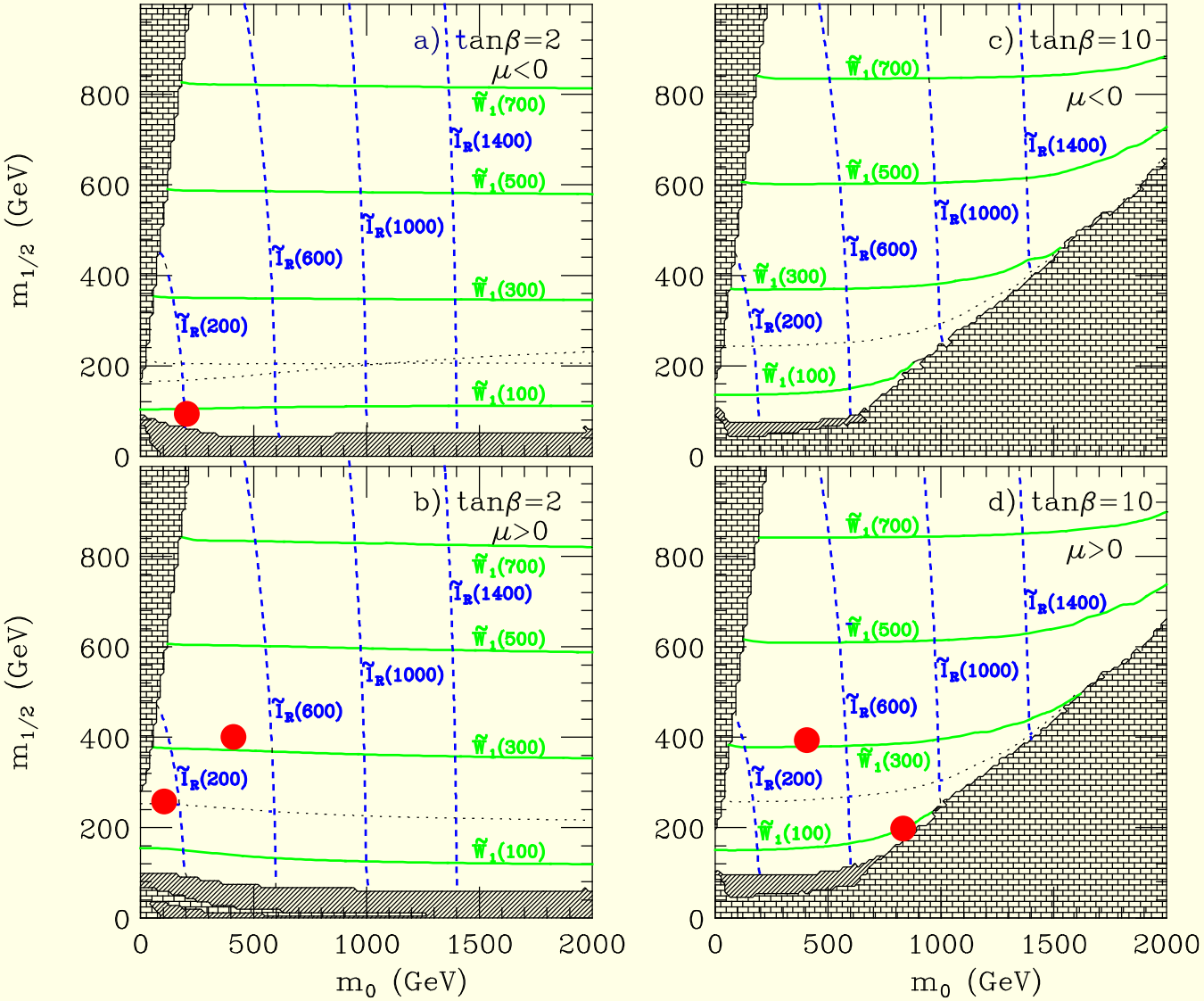
R parity good – neutral LSP stable – all events have 2 LSP's in them
$\Rightarrow$ missing E_T

Gravitino has mass in TeV region: irrelevant to colliders

Can relax unification assumption – more parameters



Contours of fixed *gluino* and squark mass

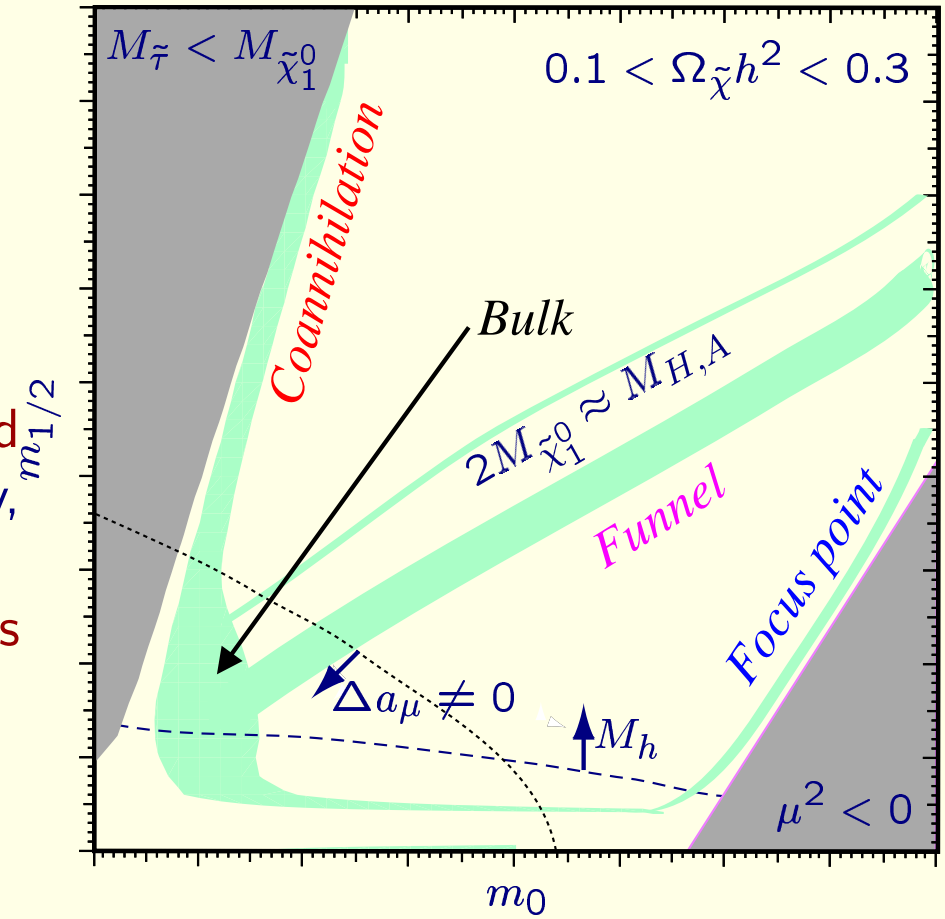


Contours of fixed *wino* and slepton mass

Where to look

Take model seriously: really!?!

Too much dark matter unless
LSP light or annihilation enhanced
usually by some almost degeneracy,
but also by content of LSP
If SUSY explains $(g-2)_\mu$, masses
are small

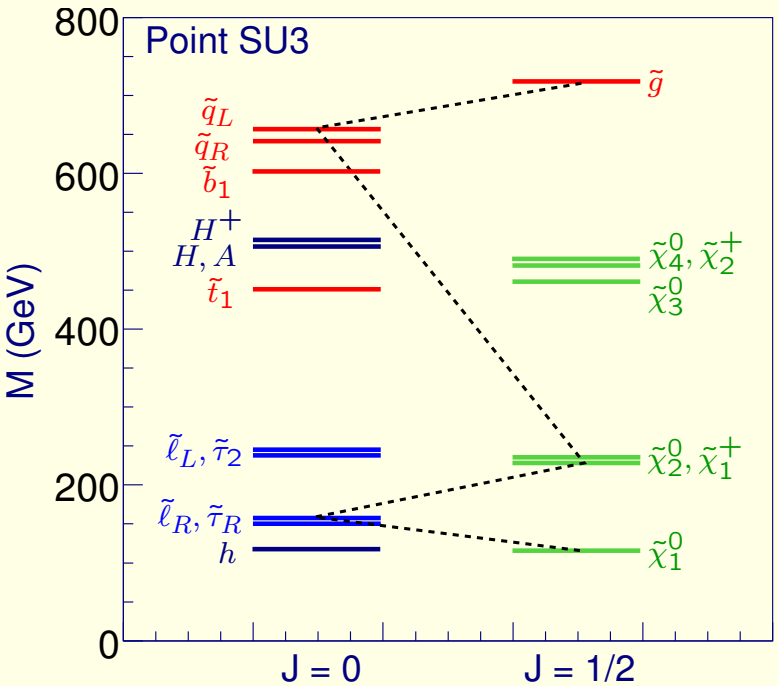


Nomenclature

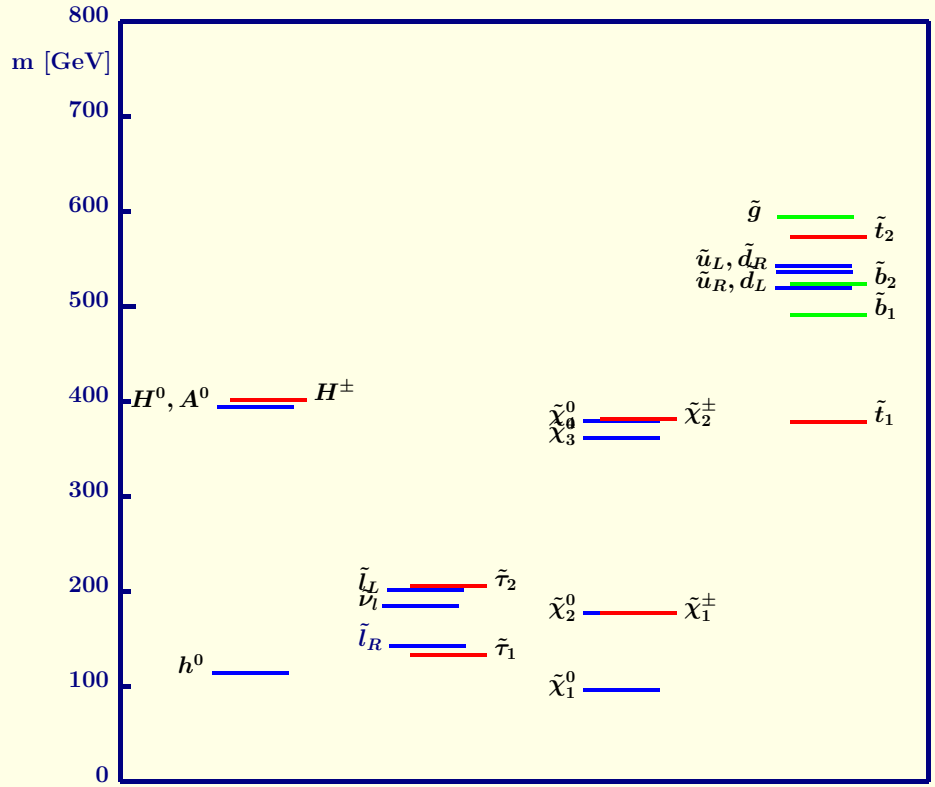
- Bulk region: Masses low $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to e^+e^-$
- Connahilation region: Something almost degenerate with LSP: $\widetilde{\chi}_1^0\tilde{e}_R \to e\gamma$ enhanced
- Higgs pole region: $M_A \sim 2m_{\widetilde{\chi}_1^0}$
- Focus point region: Large m_0, LSP Higgsino, region is sensitive to m_top, may not exist if $m_{top} = 172$. phenomenology of split SUSY is very similar to this region

Caveat emptor: Don't take this too seriously

Two typical spectra



Used in ATLAS studies: important decays shown



SPS1a: used in many LHC/ILC comparisons

Several SUGRA cases studied in detail In one case unification assumptions were relaxed to investigate how signals changed (New signals appeared, old ones stayed) Some cases were restudied assuming that R-Parity was broken

$\Rightarrow$ LSP decayed inside detector.

Note typically large rates

Table 1: SUGRA parameters for the six LHC points.

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	$\mathrm{sgn}\,\mu$	σ (pb)
1	400	400	0	2.0	$+$	2.9
2	400	400	0	10.0	$+$	2.9
3	200	100	0	2.0	$-$	1300
4	800	200	0	10.0	$+$	28
5	100	300	300	2.1	$+$	15
6	200	200	0	45	$-$	99

Point	1	2	3	4	5	6
$\tilde{g}$	1004	1009	298	582	767	540
$\tilde{\chi}_1^\pm$	325	321	96	147	232	152
$\tilde{\chi}_2^\pm$	764	537	272	315	518	307
$\tilde{\chi}_1^0$	168	168	45	80	122	81
$\tilde{\chi}_2^0$	326	321	97	148	233	152
$\tilde{\chi}_3^0$	750	519	257	290	497	286
$\tilde{\chi}_4^0$	766	538	273	315	521	304
$\tilde{u}_L$	957	963	317	918	687	511
$\tilde{u}_R$	925	933	313	910	664	498
$\tilde{d}_L$	959	966	323	921	690	517
$\tilde{d}_R$	921	930	314	910	662	498
$\tilde{t}_1$	643	710	264	594	489	365
$\tilde{t}_2$	924	933	329	805	717	517
$\tilde{b}_1$	854	871	278	774	633	390
$\tilde{b}_2$	922	930	314	903	663	480
$\tilde{e}_L$	490	491	216	814	239	250
$\tilde{e}_R$	430	431	207	805	157	219
$\tilde{\nu}_e$	486	485	207	810	230	237
$\tilde{\tau}_1$	430	425	206	797	157	132
$\tilde{\tau}_2$	490	491	216	811	239	259
$\tilde{\nu}_\tau$	486	483	207	806	230	218
h^0	111	125	68	117	104	112
H^0	1046	737	379	858	638	157
A^0	1044	737	371	859	634	157
$H^\pm$	1046	741	378	862	638	182

General Features

In general $m_{squark} > m_{slepton}$, $m_{gluino} > m_{\widetilde{W}}$

Splitting between $m_{\widetilde{e_l}}$ and $m_{\widetilde{e_r}}$

Stop is usually lightest squark

Lightest SUSY particle (LSP) stable if R-parity good.

LSP must be neutral if stable

SUSY particles produced in pairs even if R-parity broken.

SUSY production is dominated by gluinos and squarks.

Not necessarily true for Tevatron. Stable LSP $\Rightarrow$ Missing E_T

Background for SUSY usually other SUSY, not Standard Model.

Gauge Mediated Model

Aims to solve FCNC problem by using gauge interactions instead of Gravity to transmit SUSY breaking

Messenger Sector consists of some particles (X) that have SM interactions and are aware of SUSY breaking.

$M_i^2 = M^2 \pm F_A$ Simplest X is complete SU(5) **5** or **10** to preserve GUT

Fundamental SUSY breaking scale $F > F_A$, but $\sqrt{F} \lesssim 10^{10}$ GeV or SUGRA breaking will dominate Gaugino masses at 1-loop

$$M_{\tilde{g}} \sim \alpha_s N_X \Lambda$$

Squark and Slepton masses at 2-loop

$$M_{\tilde{e}} \sim \alpha_W \sqrt{N_X} \Lambda$$

True LSP is a (almost) massless Gravitino

Sparticles decay as in SUGRA, then "NLSP" decays to $\tilde{G}$

lifetime model dependent

NLSP does not have to be neutral

6 parameters

Λ, M, N_5, $\tan\beta$,

$sign\mu$

$10\,\mathrm{TeV} \lesssim \Lambda \equiv F_A/M \lesssim 400\,\mathrm{TeV}$: Scale for SUSY masses.

$M > \Lambda$: Messenger mass scale.

$N_5 \geq 1$: Number of equivalent $5 + \bar{5}$ messenger fields.

$1 \lesssim \tan\beta \lesssim m_t/m_b$: Usual ratio of Higgs VEV's.

$\mathrm{sgn}\,\mu = \pm 1$: Usual sign of μ parameter.

$C_{\mathrm{grav}} \geq 1$: Ratio of $M_{\widetilde{G}}$ to value from F_A, controls lifetime of NLSP.

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	$\mathrm{sgn}\,\mu$	$C_{\mathrm{grav}} \geq 1$	σ (pb)
G1a	90	500	1	5.0	$+$	1.0	7.6
G1b	90	500	1	5.0	$+$	10^3	7.6
G2a	30	250	3	5.0	$+$	1.0	23
G2b	30	250	3	5.0	$+$	5×10^3	23

Sparticle	G1	G2	Sparticle	G1	G2
$\widetilde{g}$	747	713			
$\widetilde{\chi}_1^{\pm}$	223	201	$\widetilde{\chi}_2^{\pm}$	469	346
$\widetilde{\chi}_1^0$	119	116	$\widetilde{\chi}_2^0$	224	204
$\widetilde{\chi}_3^0$	451	305	$\widetilde{\chi}_4^0$	470	348
$\widetilde{u}_L$	986	672	$\widetilde{u}_R$	942	649
$\widetilde{d}_L$	989	676	$\widetilde{d}_R$	939	648
$\widetilde{t}_1$	846	584	$\widetilde{t}_2$	962	684
$\widetilde{b}_1$	935	643	$\widetilde{b}_2$	945	652
$\widetilde{e}_L$	326	204	$\widetilde{e}_R$	164	103
$\widetilde{\nu}_e$	317	189	$\widetilde{\tau}_2$	326	204
$\widetilde{\tau}_1$	163	102	$\widetilde{\nu}_\tau$	316	189
h^0	110	107	H^0	557	360
A^0	555	358	$H^{\pm}$	562	367

Mass spectrum more spread out than in SUGRA

$m(squark)/m(slepton)$ bigger

Anomaly mediated model

Superconformal anomaly always present

predicts sparticle masses in terms of $m_{3/2}$ Randall, Sundrum, Luty, Giudice, Wells, Murayama

Simplest version predicts tachyonic sleptons!

Some other SUSY breaking mechanism must be present to get realistic spectrum

Add universal squark masses (mAMSB) or new very heavy fields (DAMSB) (similar to gauge mediated), both variants are in ISAJET.

AMSB only – Most important feature $M_3 > M_1 > M_2 \Rightarrow$ LSP is a $\tilde{W}^0$ and almost degenerate with $\tilde{\chi}_1^+ \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 \pi^+$ with $c\tau < 10$ cm DAMSB has very short lifetime and bigger mass difference Wells, Paige

Sleptons are lighter than squarks $\tilde{q}_r \rightarrow \tilde{\chi}_2^0 q$ and $\tilde{q}_l \rightarrow \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.

Gravitino mass is $\sim$ TeV, irrelevant to LHC.

AMSB has 4 parameters m_0, $m_{3/2}$, $\tan\beta$, $sign\mu$

DAMSB has 5 parameters M_0, $m_{3/2}$, ,n $\tan\beta$, $sign\mu$. n is the number of new fields at mass M.

$m_{3/2}$ is the gravitino mass

Sparticle	AMSB	DAMSB	Sparticle	AMSB	DAMSB
$\widetilde{g}$	815	500			
$\widetilde{\chi}_1^{\pm}$	101	145	$\widetilde{\chi}_2^{\pm}$	658	481
$\widetilde{\chi}_1^0$	101	136	$\widetilde{\chi}_2^0$	322	152
$\widetilde{\chi}_3^0$	652	462	$\widetilde{\chi}_4^0$	657	483
$\widetilde{u}_L$	754	432	$\widetilde{u}_R$	758	384
$\widetilde{d}_L$	757	439	$\widetilde{d}_R$	763	371
$\widetilde{t}_1$	516	306	$\widetilde{t}_2$	745	454
$\widetilde{b}_1$	670	371	$\widetilde{b}_2$	763	406
$\widetilde{e}_L$	155	257	$\widetilde{e}_R$	153	190
$\widetilde{\nu}_e$	137	246	$\widetilde{\tau}_2$	166	257
$\widetilde{\tau}_1$	140	190	$\widetilde{\nu}_\tau$	137	246
h^0	107	98	H^0	699	297
A^0	697	293	$H^{\pm}$	701	303

Start with SUGRA

- Look for characteristic signals
- jets and missing energy
- these should work anywhere

Inclusive analysis

Select events with at least 4 jets and Missing E_T

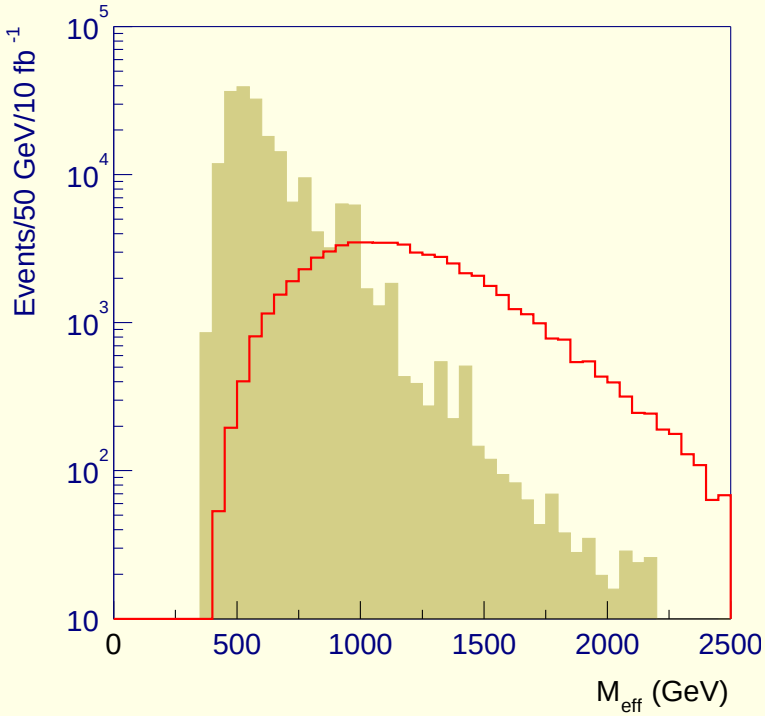
A simple variable

$M_{\rm eff} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not{E}_T$

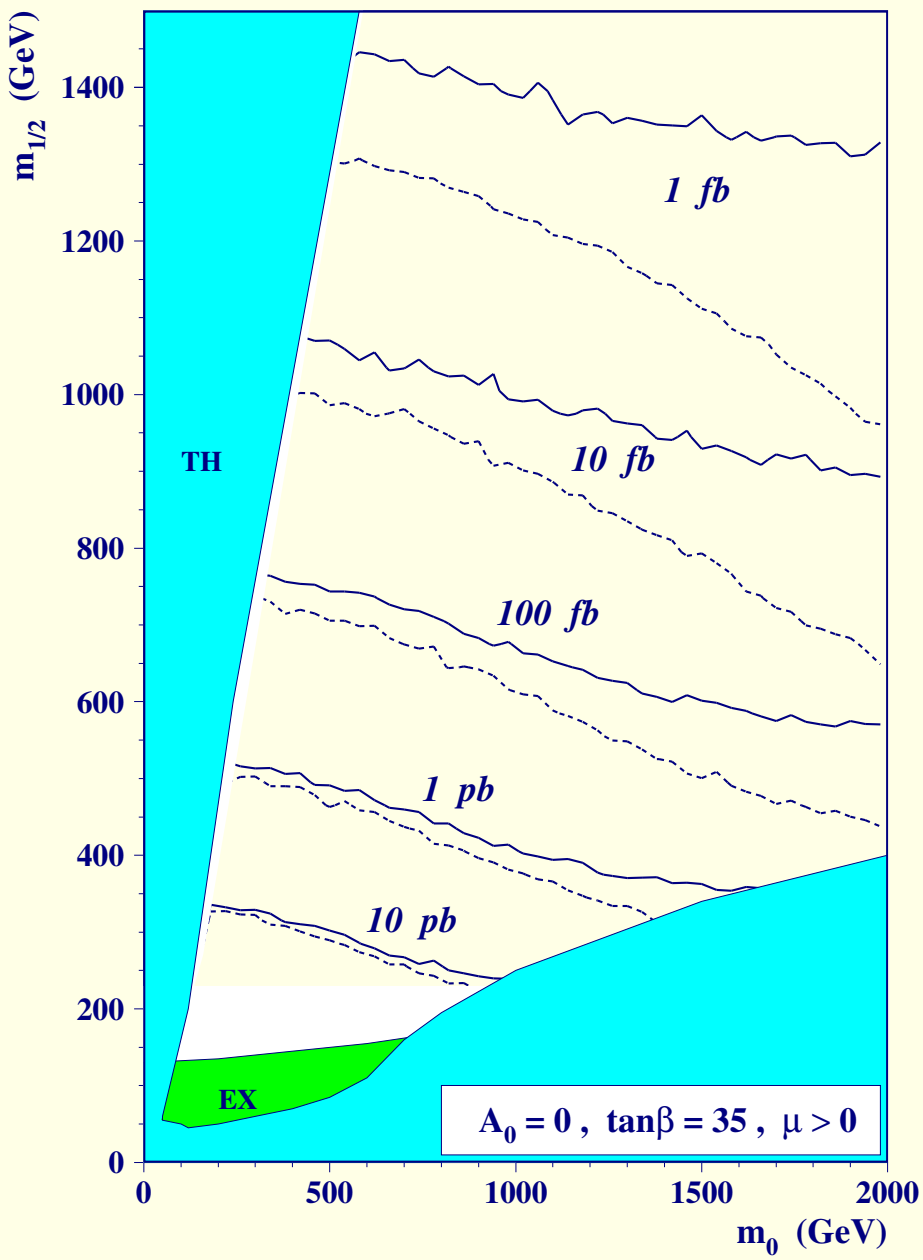
At high $M_{\rm eff}$ non-SM signal rises above background note scale

Peak in $M_{\rm eff}$ distribution correlates well with SUSY mass scale

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

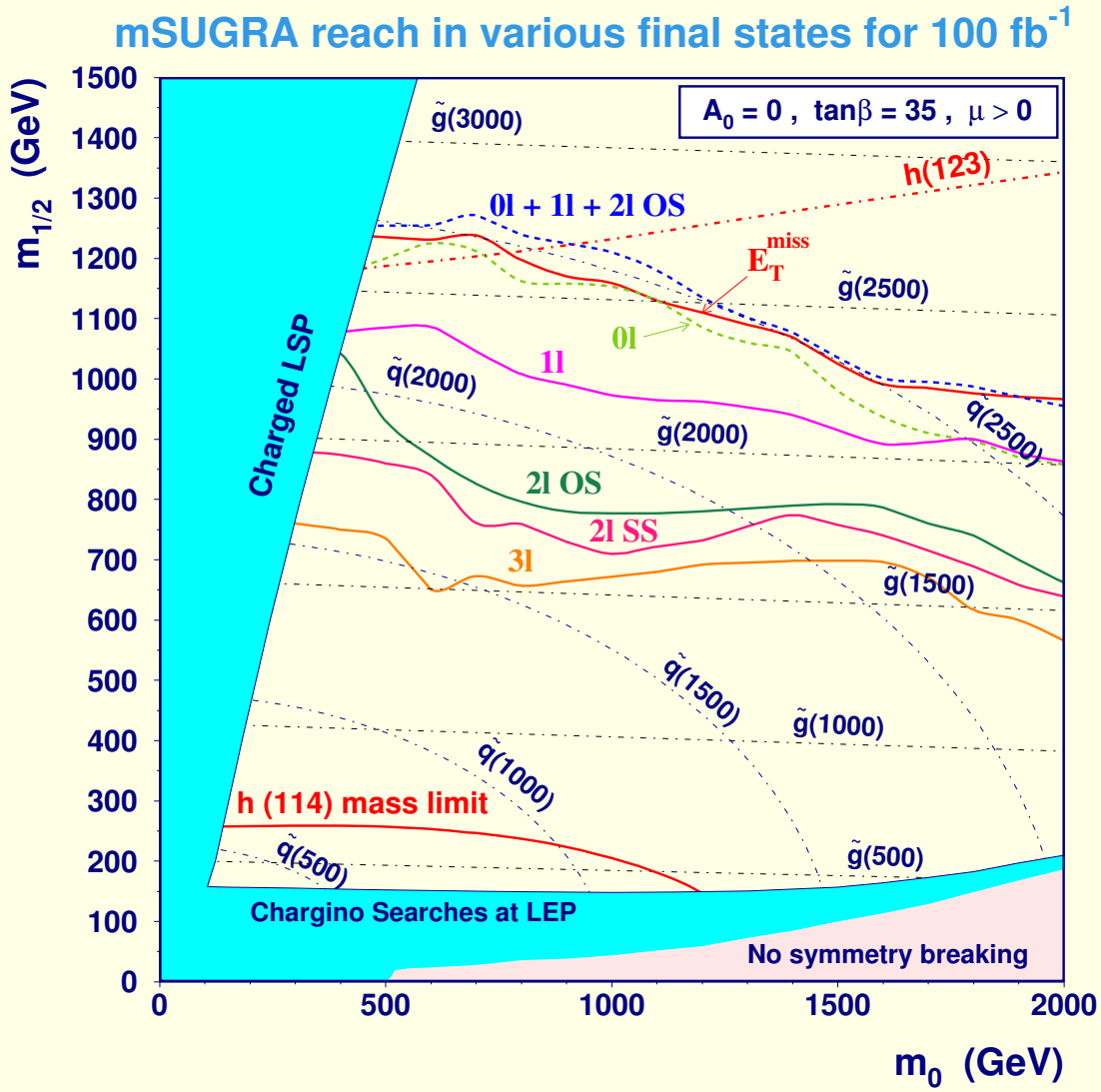


Will determine gluino/squark masses to $\sim 15\%$


$m_{1/2}$ (GeV)
1400
1200
1000
800
600
400
200
0
TH
1 fb
10 fb
100 fb
1 pb
10 pb
EX
$A_0 = 0$, $\tan\beta = 35$, $\mu > 0$
0
500
1000
1500
2000
m_0 (GeV)

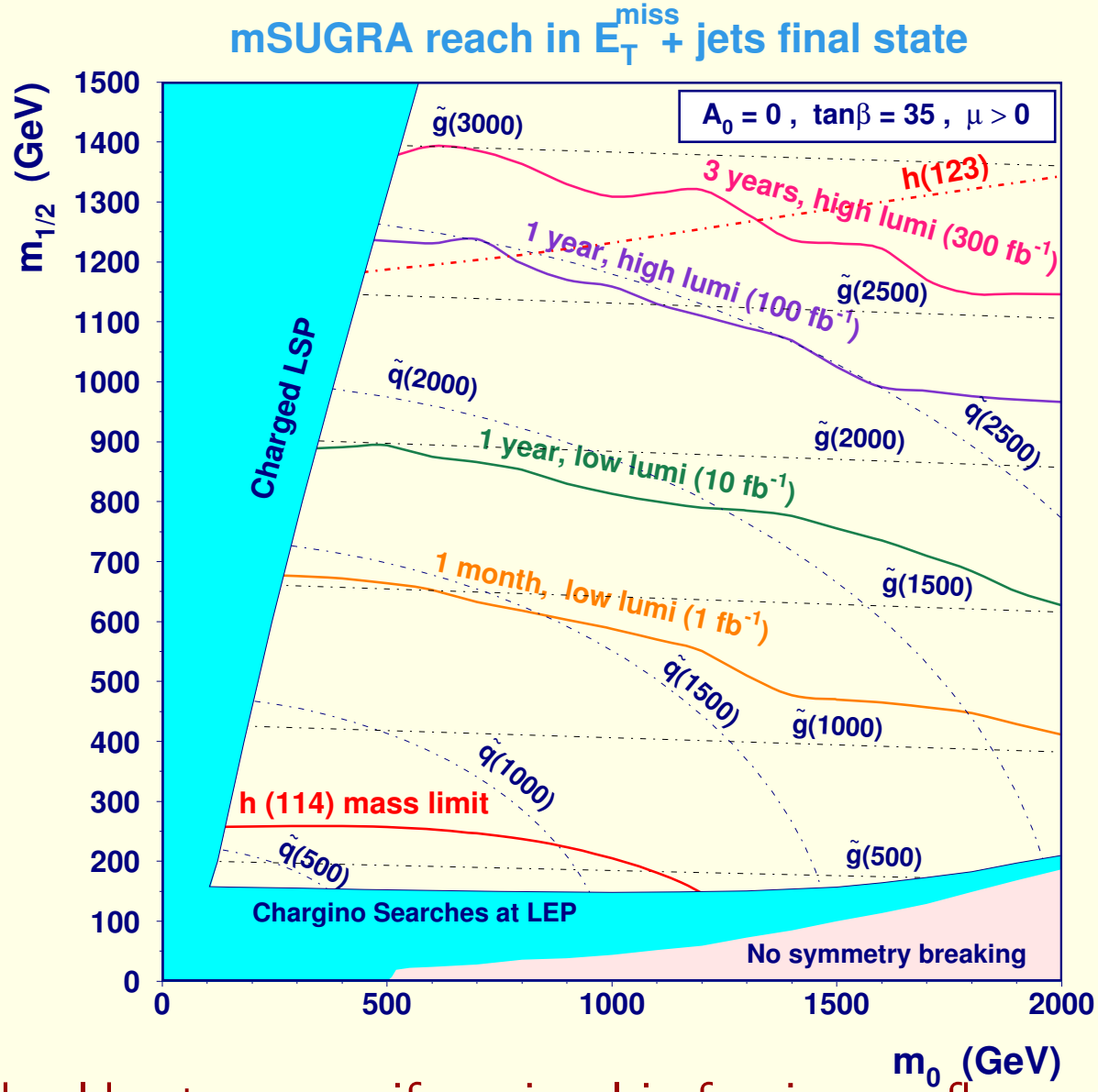
CMS

Can also add lepton(s): More channels more robustness



CMS

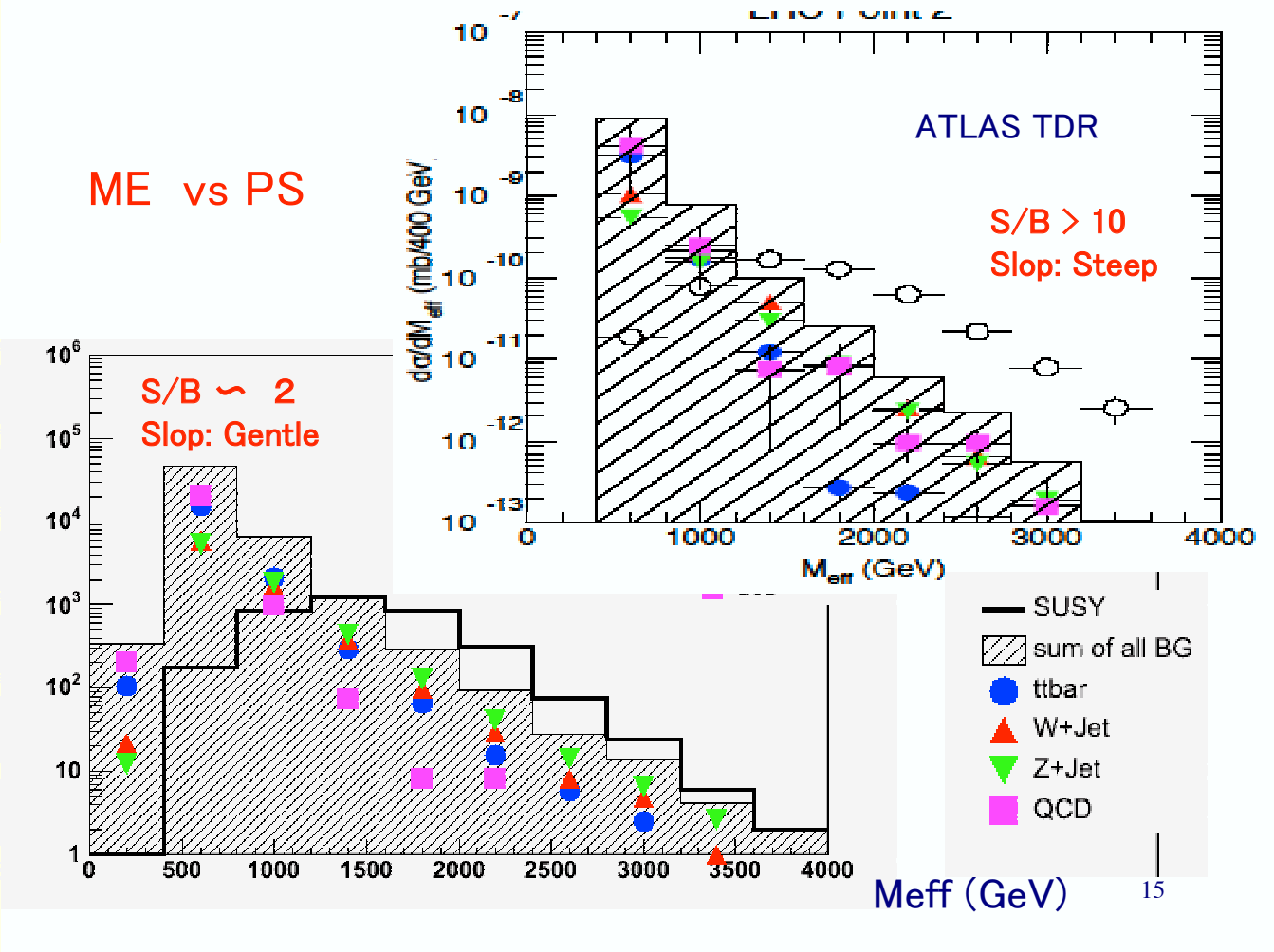
Energy of LHC is most crucial: reach increases slowly with luminosity



Should get nervous if no signal in few inverse fb

How robust is this?

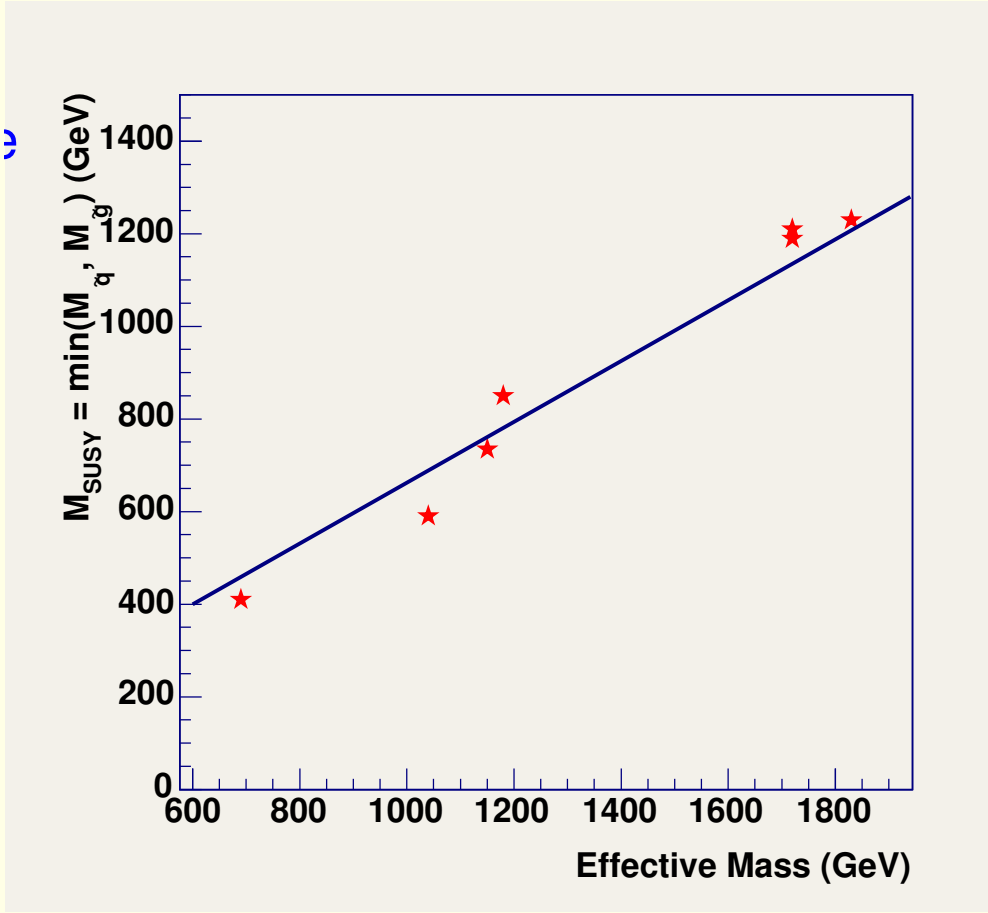
Backgrounds based on showering MC may underestimate multi-jet final states.



May lower reach slightly
Plot shows all jet state
Signal in Lepton+jets+missin
more robust

Asai et al

Peak in $M_{\rm eff}$ distribution correlates well with SUSY mass scale



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

Use this and similar global distributions to establish that new physics exists and determine its mass scale

Method is slightly model dependent

Generalizations to other models

Similar method works in GMSB and MSSM

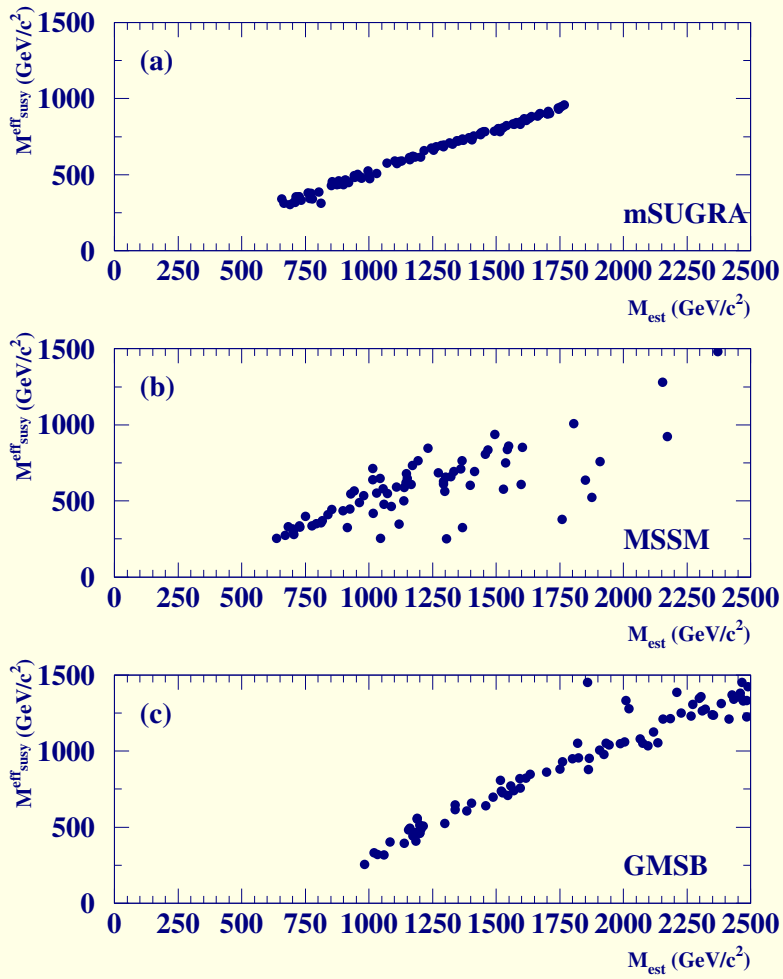
In MSSM, 15 parameters were varied

Events selected to have no isolated leptons, at least 4 jets, large missing E_T

More global variables were used; best is

$$\sum_{jets} |E_T| \text{ or } \sum_{jets} |E_T| + \not{E}_T$$

Error is bigger in MSSM



Model	Var	$\bar{x}$	σ	$\sigma/\bar{x}$	Prec. (%)
mSUGRA	1	1.585	0.049	0.031	2.9
	2	0.991	0.039	0.039	3.8
	3	1.700	0.043	0.026	2.1
	4	1.089	0.030	0.028	2.5
	5	1.168	0.029	0.025	2.1
MSSM	1	1.657	0.386	0.233	23.1
	2	0.998	0.214	0.215	21.1
	3	1.722	0.227	0.132	12.8
	4	1.092	0.143	0.131	12.8
	5	1.156	0.176	0.152	14.8
GMSB	1	1.660	0.149	0.090	8.1
	2	1.095	0.085	0.077	6.6
	3	1.832	0.176	0.096	9.0
	4	1.235	0.091	0.074	6.1
	5	1.273	0.109	0.086	7.9

$\sigma(M_{susy} < 13\%)$

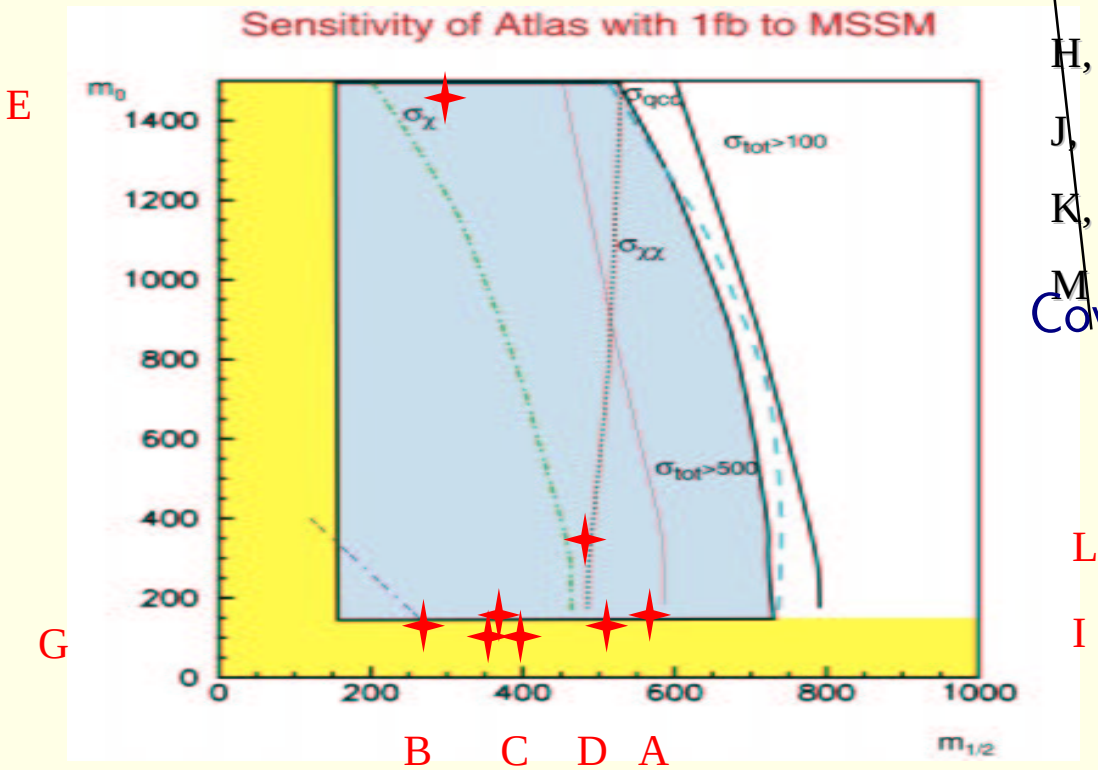
Not optimized

Leptonic channels not used

More work on "global signatures" needed

What about $1\mathrm{fb}^{-1}$

How Useful Is This??



~~F, H, J, K, M~~

Covers "preferred region"

Now for examples of specific final states...

Digression on Simulations

Varying degrees of sophistication

Run an event generator: Makes a list of particles ($e.g$ Pythia)

- "Full simulation"

  Full material description of detector
  Track particle: model its interactions, follow all the secondaries with energy above some threshold
  Translate "hits" into simulated electronic signals
  Now event looks like a real event: reconstruct it using same software
  Advantage: Full description
  Disadvantage: Slow ($\sim$ 15 mins per event), can only be done by experimenter.
  Problems, Low energy hadronic interactions, geometry is hard

- "Fast simulation (theorists version)"

  Assume perfect detector: Apply jet finding algorithm
  Smear, electron, muon, jet momenta and missing ET. using some resolution function

Advantage. Very fast (comparable to generation time), can by done by theorist
Disadvantage: Only as good as resolution function: problems in "tails"

- "Fast simulation (experimenters version)"

  Response of individual particles is parametrized.
  Might use "full" for some particles ($e.g.$ Photons) and parametrized for others (pions)
  May use full reconstruction.

In practice all are used: Theorists version is often good enough for evaluating a model

Characteristic SUSY Decays

Illustrate techniques by choosing examples from case studies.

Both $\widetilde{q}$ and $\widetilde{g}$ produced; one decays to the other

Weak gauginos ($\widetilde{\chi_i^0}, \widetilde{\chi_i^\pm}$) then produced in their decay. *e.g.* $\widetilde{q_L} \to \widetilde{\chi}_2^0 q_L$

Two generic features
$\chi_2^0 \to \chi_1^0 h$ or
$\chi_2^0 \to \chi_1^0 \ell^+\ell^-$ possibly via intermediate slepton $\chi_2^0 \to \widetilde{\ell^+}\ell^- \to \chi_1^0 \ell^+\ell^-$
Former tends to dominate if kinematically allowed.

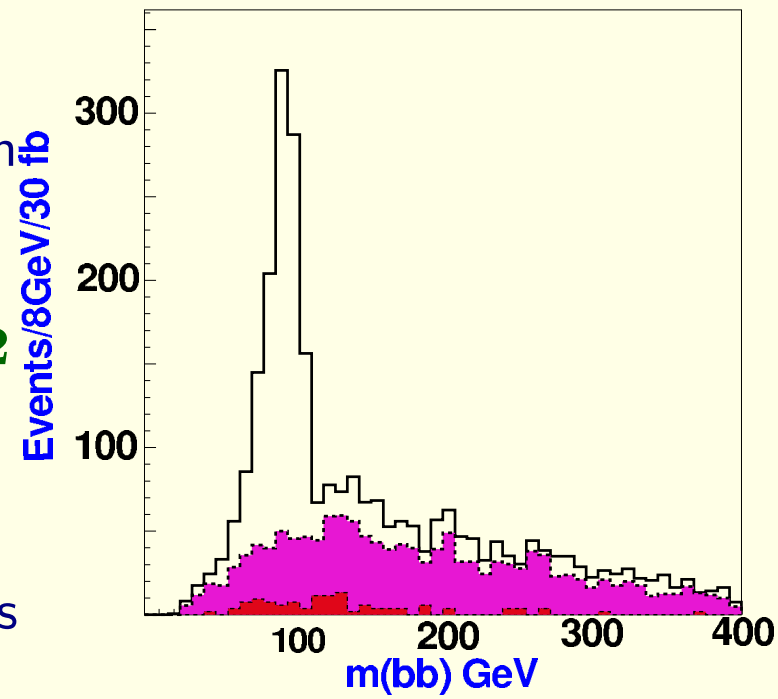
Use these characteristic decays as a starting point for mass measurements

Many SUSY particles can then be identified by adding more jets/leptons

Decays to Higgs bosons

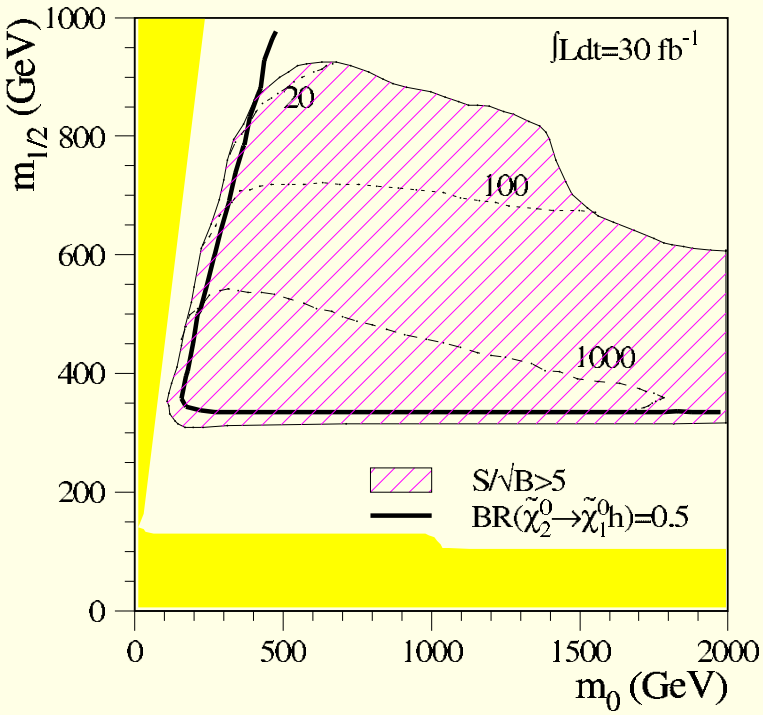
If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

Event selection
$\not{E}_T > 300\,\mathrm{GeV}$
≥ 2 jets with $p_T > 100\,\mathrm{GeV}$ and ≥ 1 with $\mid \eta \mid < 2$
No isolated leptons (suppresses $t\bar{t}$)
Only 2 b-jets with $p_{T,b} > 55$ GeV and $\mid \eta \mid < 2$
$\Delta R_{b\bar{b}} < 1.0$ (suppresses $t\bar{t}$)
Clear peak in $b\bar{b}$ mass
Very small standard model background (pale)
Dominant background is other SUSY decays (dark)



Generally applicable

This method works over a large region of parameter space in the SUGRA Model
Hatched region has $S/\sqrt{B} > 5$
Contours show number of reconstructed Higgs
Channel is closed at low $m_{1/2}$



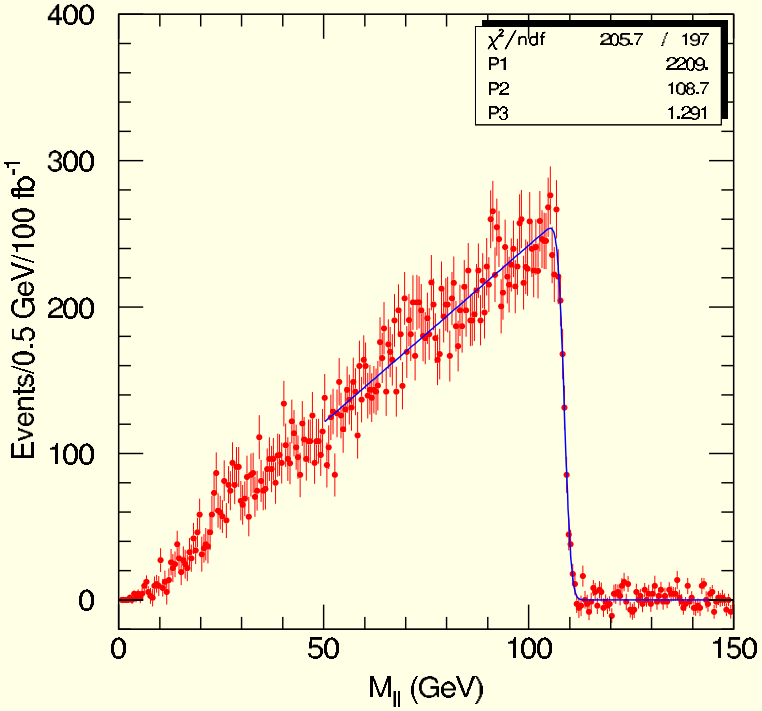
Over rest of parameter space, leptons are the key...

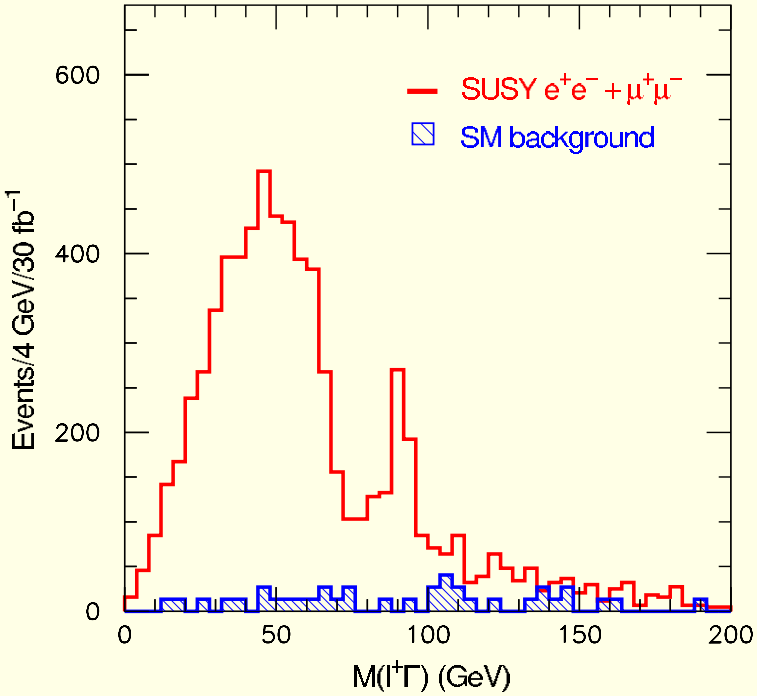
Starting with Leptons

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons

Key decays are $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$ and $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$

Mass of opposite sign same flavor leptons is constrained by decay





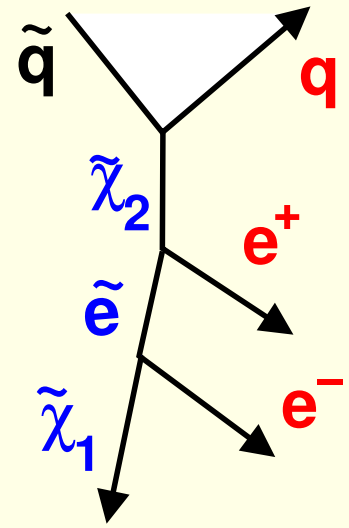
Decay via real slepton: $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$

Plot shows $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$

Decay via virtual slepton: $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$ and Z from other SUSY particles

Building on Leptons

Decay $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\ell\tilde{\chi}_1^0$



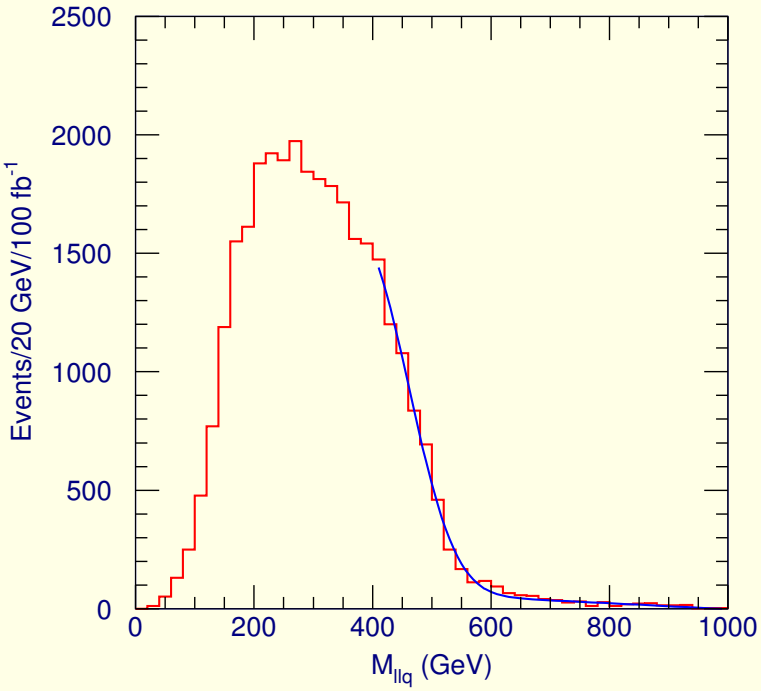
Identify and measure decay chain

- 2 isolated opposite sign leptons; $p_t > 10$ GeV
- ≥ 4 jets; one has $p_t > 100\ GeV$, rest $p_t > 50$ GeV
- $\not{E}_T > max(100, 0.2M_{eff})$

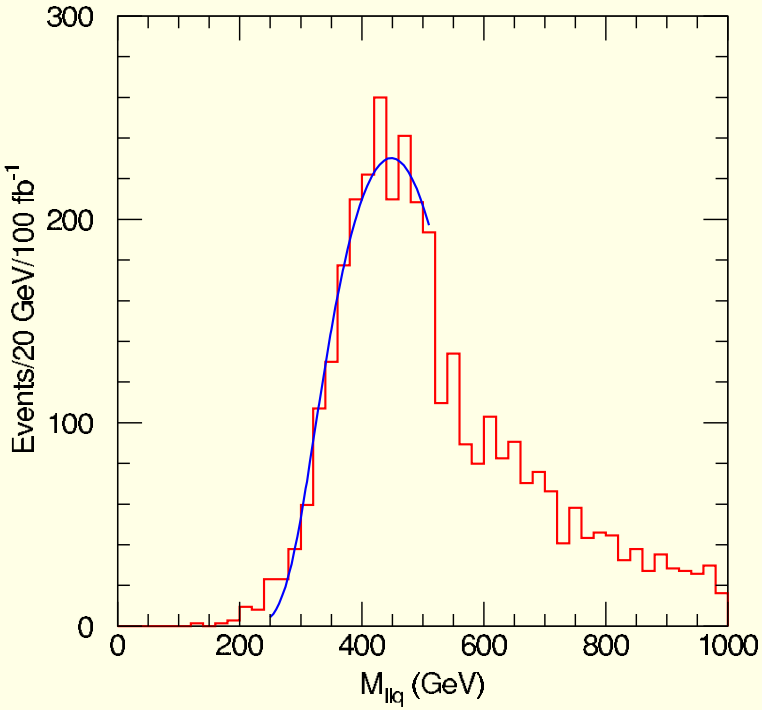
Mass of $q\ell\ell$ system has max at

$$M_{\ell\ell q}^{\max} = [\frac{(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2)(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2)}{M_{\tilde{\chi}_2^0}^2}]^{1/2} = 552.4\,\mathrm{GeV}$$

and min at 271 GeV



smallest mass of possible $\ell\ell jet$ combinations



largest mass of possible $\ell\ell jet$ combinations

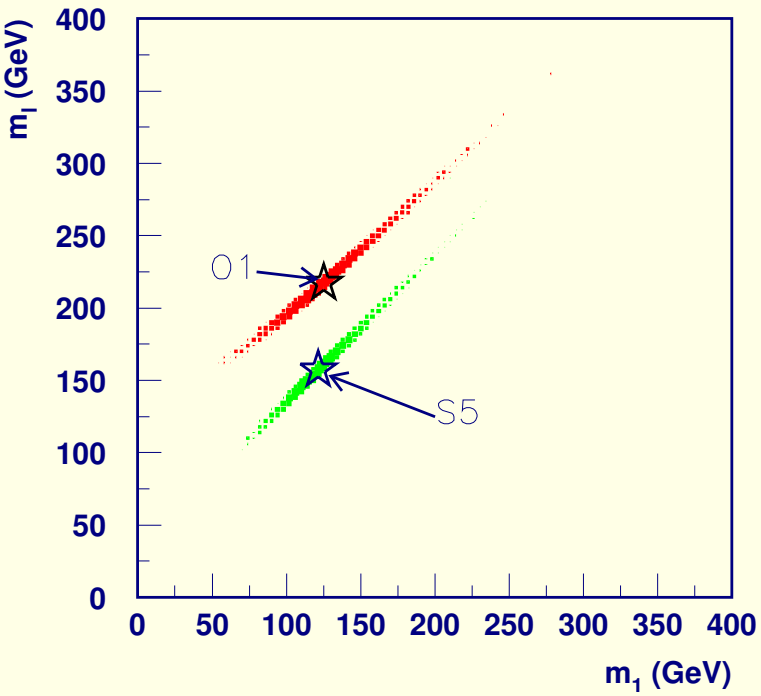
Kinematic structure clearly seen

Can also exploit ℓjet mass

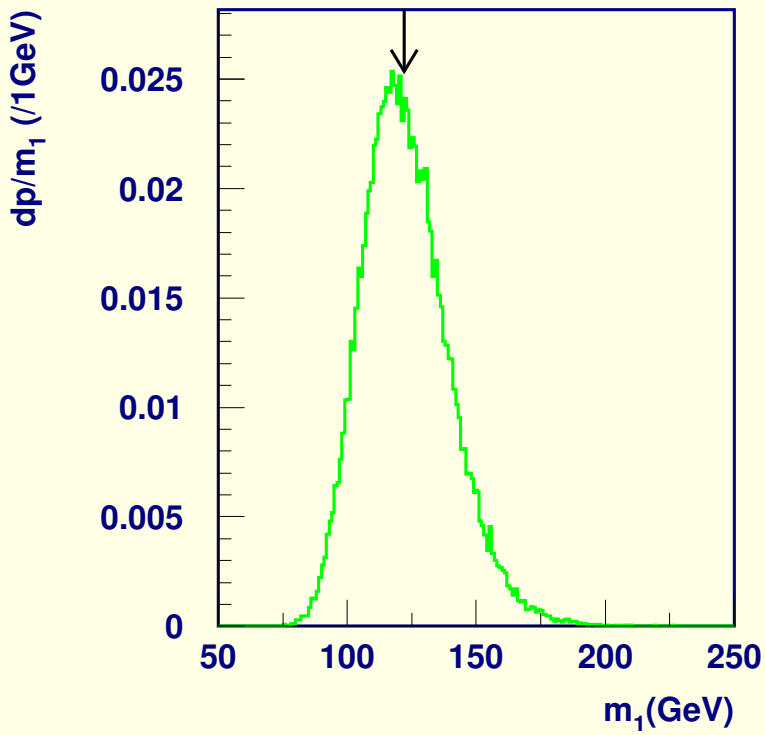
Can now solve for the masses. Note that no model is needed

Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses
4 Unknowns, $m_{\tilde{q_L}}, m_{\tilde{e_R}}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$

Errors are 3%, 9%, 6% and 12% respectively



correlations $m_{\tilde{e_R}}$ vs. $m_{\tilde{\chi}_1^0}$



LSP mass

Mass of unobserve
determined
Errors are strong
and a precise i
determination of
reduces the errors on

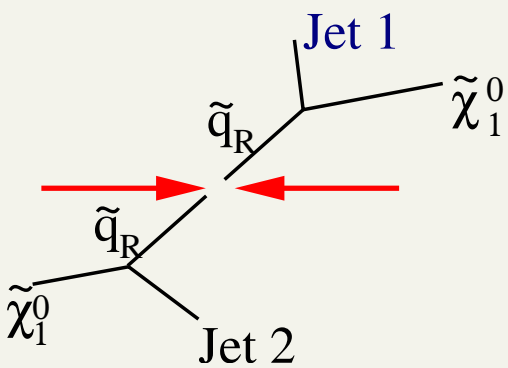
Right squarks

s-tranverse mass. Definition

- Select Events:

$pp \to X + \tilde{q}_R \tilde{q}_R \to X + q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$

  - 2 Jets with P_T >200GeV
  - Δ(j1-j2)>1
  - Missing E_T >400GeV



- Partition $\vec{\not{E}}_T = \vec{\not{E}}_{T,1} + \vec{\not{E}}_{T,2}$ in all possible ways and compute:

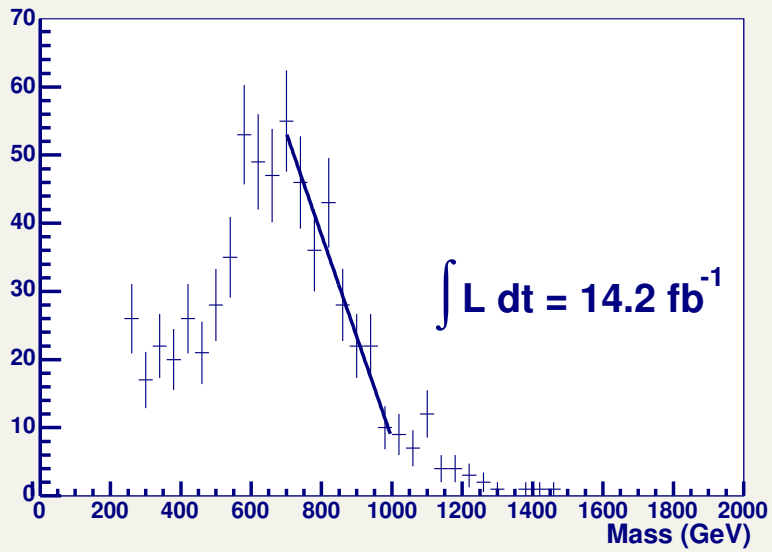
$$M_T^2 = \min_{\vec{\not{E}}_{T,1},\vec{\not{E}}_{T,2}} \left[\max\{m_T^2(P_{T,j1}, \not{E}_{T,1}, M_{\tilde{\chi}_1^0}), m_T^2(P_{T,j2}, \not{E}_{T,2}, M_{\tilde{\chi}_1^0})\}\right]$$

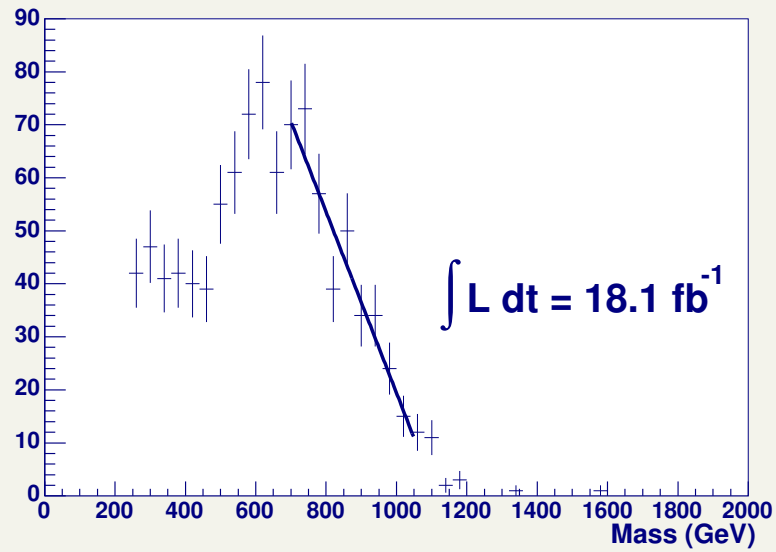
- M_T^2 depends on the choice of $M(\tilde{\chi}_1^0)$

s-tranverse mass for the SU5 point

Fit the end-point with a straight line and extrapolate to the x-axis
Use "true" value of M$(\tilde{\chi}_1^0)$

(Ola Kristoff Oye)





From the fit: $M(\tilde{q}_R) = 1056 \pm 181$GeV
Generator: $M(\tilde{q}_R) = 1190$GeV

From the fit: $M(\tilde{q}_R) = 1113 \pm 164$GeV
Generator: $M(\tilde{q}_R) = 1210$GeV

Again Limited by LSP mass uncertainty

Final states with taus

Large $\tan\beta$ implies that $m(\tilde{\tau}) < m(\tilde{\mu})$

Taus may be the only produced leptons in gaugino decay.

Leptonic tau decays are of limited use – where did lepton come from?

Use Hadronic tau decays, using jet shape and multiplicity for ID and jet rejection.

Full simulation study used to estimate efficiency and rejection

Rely on Jet and $E_t(miss)$ cuts to get rid of SM background

Measure "visible" tau energy

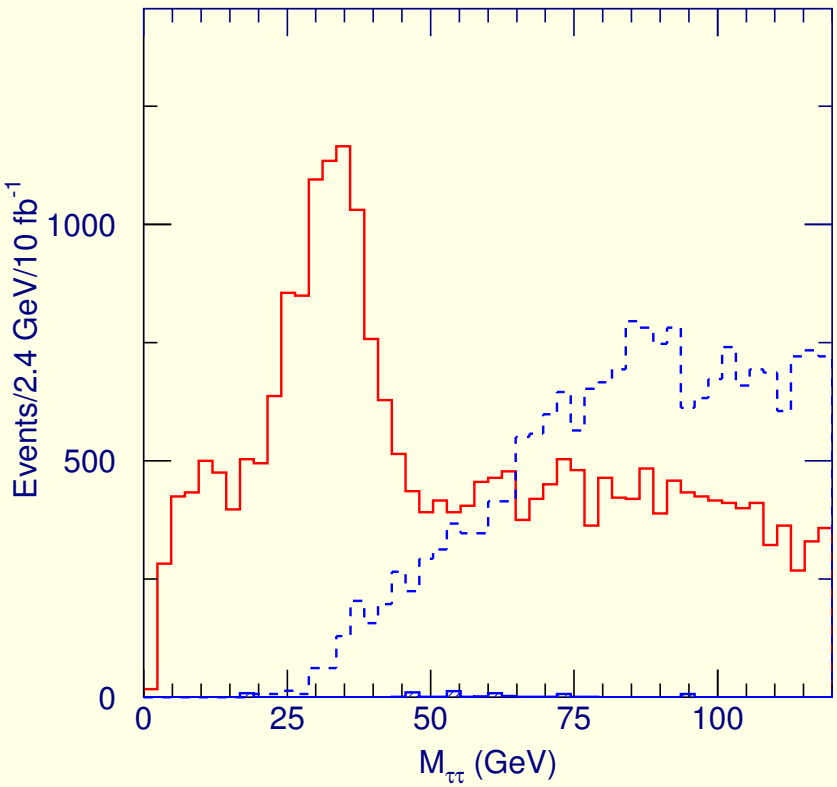
Event selection

≥ 4 jets, one has $p_t > 100$ GeV, rest $p_t > 50$ GeV

No isolated leptons with $p_t > 10$ GeV

$\not{E}_T > max(100, 0.2M_{eff})$

Look at mass of observed tau pairs



Real signal visible above fakes (dashed) and SM (solid)

Can use peak position to infer end point in decay $\tilde{\chi}_2^0 \to \tau\tau\tilde{\chi}_1^0$ (61 GeV)

Estimate 5% error

Large $\tan\beta \Rightarrow$ light sbottom – Look for these

$$\tilde{g} \to b\tilde{b} \to bb\tau^{\pm}\tau^{\mp}\tilde{\chi}_1^0$$

Previous sample with 2 $b-$jets having $p_t > 25$ GeV

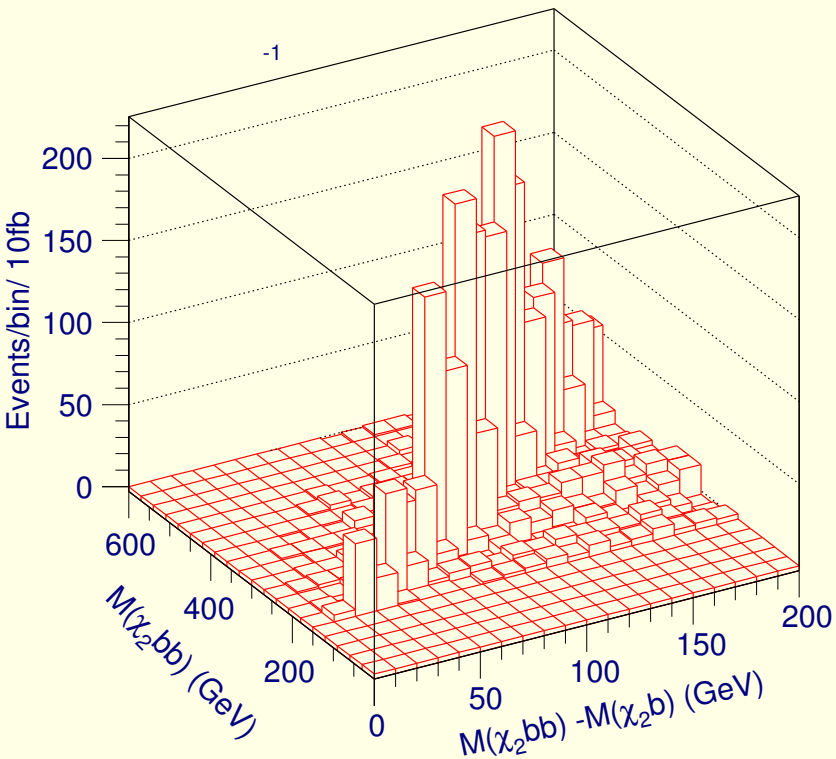
Lots of missing E_T: tau decays and $\tilde{\chi}_1^0$'s

Select $40 < m_{\tau\tau} < 60$ GeV

Combine with b jets

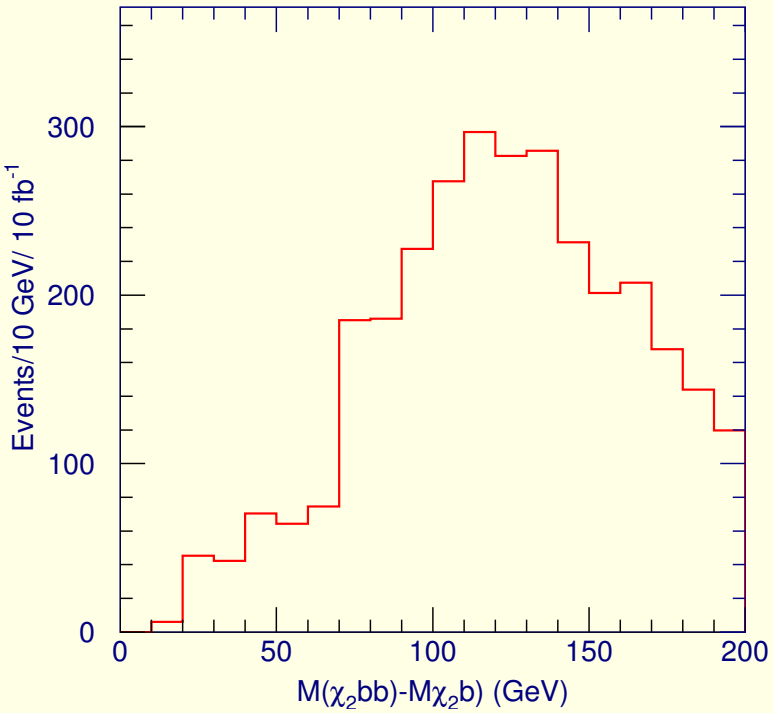
Look at $\tau\tau bb$ and $\tau\tau b$: should approximate gluino and sbottom use partial reconstruction technique assuming mass of $\tilde{\chi}_1^0$

Peaks are low; should be expected due to missing energy

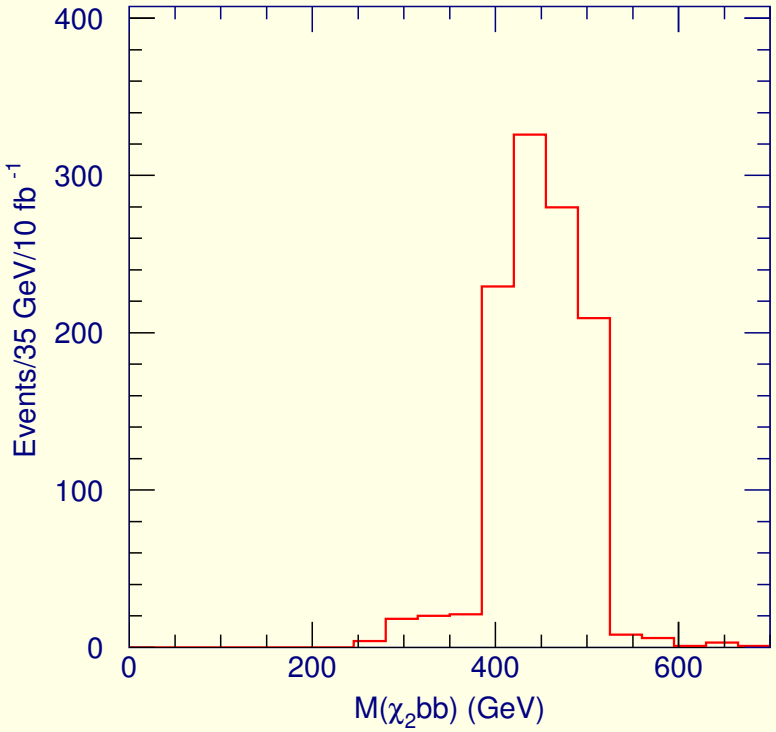


Plot of $m(\tilde{\chi}_2^0 bb)$ vs $m(\tilde{\chi}_2^0 bb) - m(\tilde{\chi}_2^0 b)$

Projections



gluino-sbottom
should be 160 GeV



gluino
540 GeV

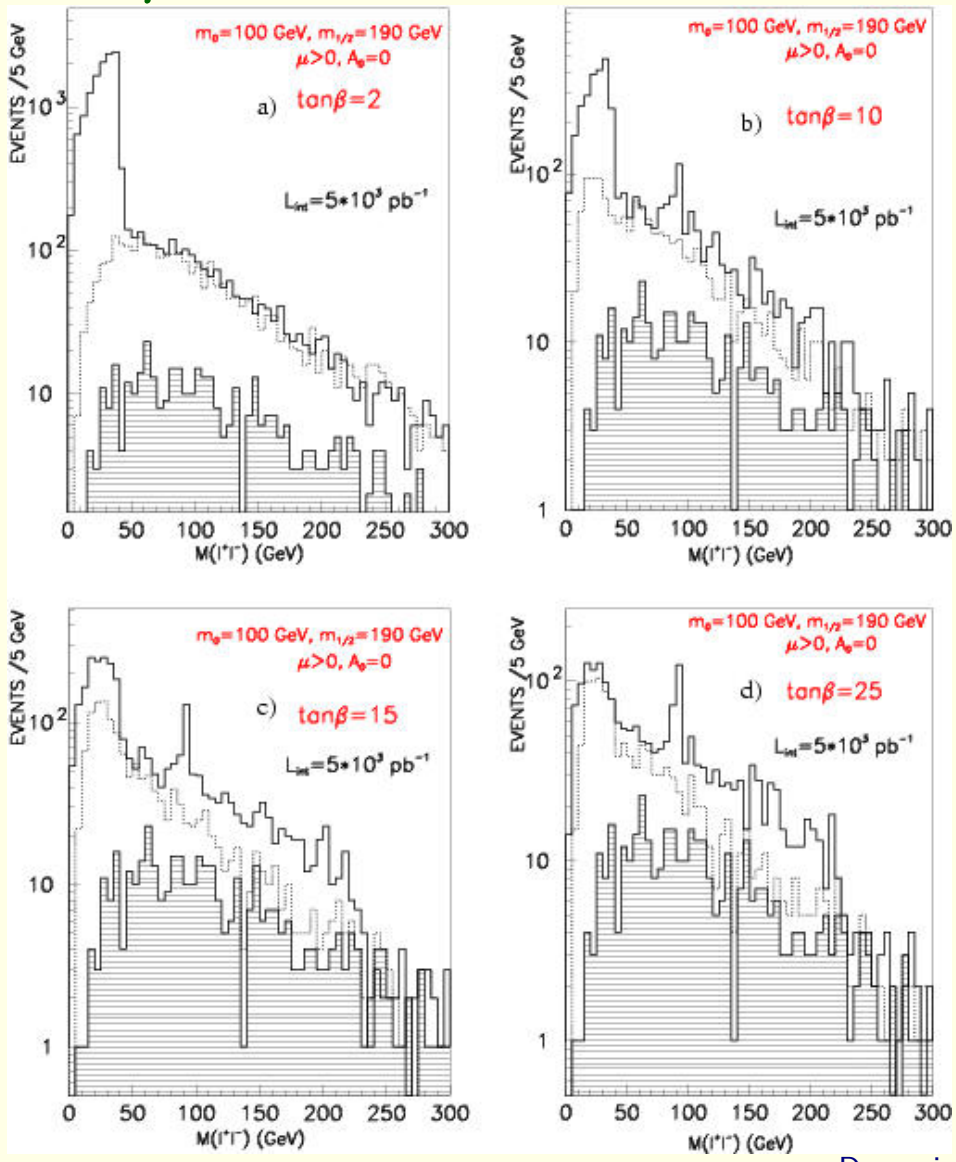
Lepton Universality

$e/\mu/\tau$ universality must be tested Large $\beta \Rightarrow m_{\tilde{\tau}} < m_{\tilde{e}}$

Expect larger rate of $\tau^+\tau^-$ and hence μ^+e^-

Plot of invariant mass distributions μ^+e^- (dashed) and $\mu^+\mu^-$ (solid) from SUSY cascades *vs.* $\tan\beta$

$\mu^+\mu^-$ structure less distinct at large $\tan\beta$



Denegri, Majerotto, Rurua

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Explicit flavor violation is also possible

Neutrino oscillations imply lepton number is violated

Atmospheric muon neutrino deficit implies $\nu_{mu} \leftrightarrow \nu_\tau$ with maximal mixing

In a SUSY model, expect significant flavor violation in slepton sector

Simplest model of lepton number violation involves addition of right handed neutrino N with SUSY conserving Majorana mass mNN and coupling to lepton left doublet and Higgs of the form LNH

Including only $\mu \leftrightarrow \tau$ mixing gives

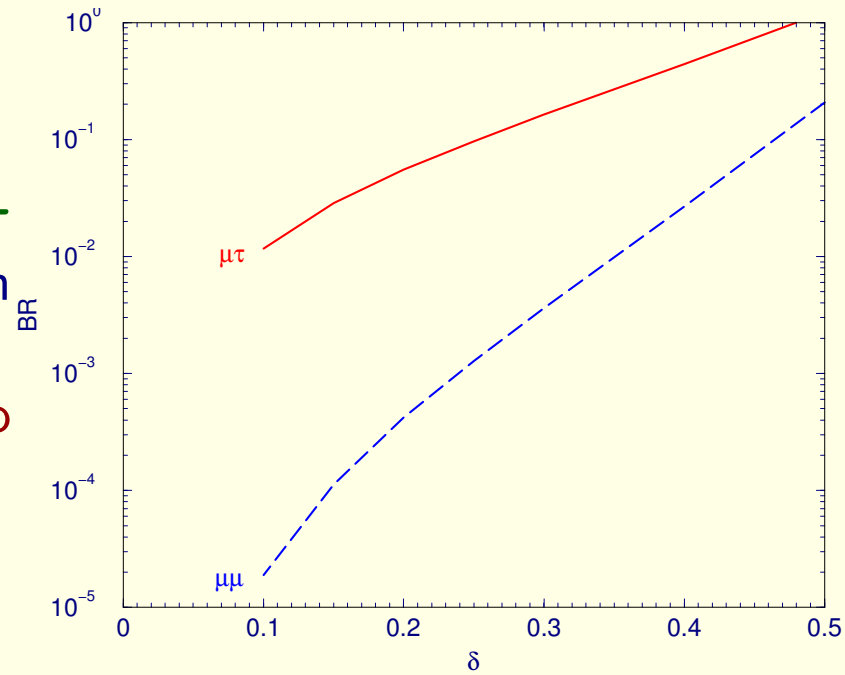
$$M^2_{\widetilde{\ell\ell}} = \begin{bmatrix} M_L^2 + D_L & 0 & 0 & 0 & 0 & 0 \\ 0 & M_L^2 + D_L & M^2_{\mu\tau} & 0 & 0 & 0 \\ 0 & M^2_{\mu\tau} & M^2_{\tau_L} + D_L & 0 & 0 & m_\tau \bar{A}_\tau \\ 0 & 0 & 0 & M_R^2 + D_R & 0 & 0 \\ 0 & 0 & 0 & 0 & M_R^2 + D_R & 0 \\ 0 & 0 & m_\tau \bar{A}_\tau & 0 & 0 & M^2_{\tau_R} + D_R \end{bmatrix}$$

Atmospheric neutrinos suggest maximal mixing $i.e.$ $\delta = \mathcal{O}(1)$

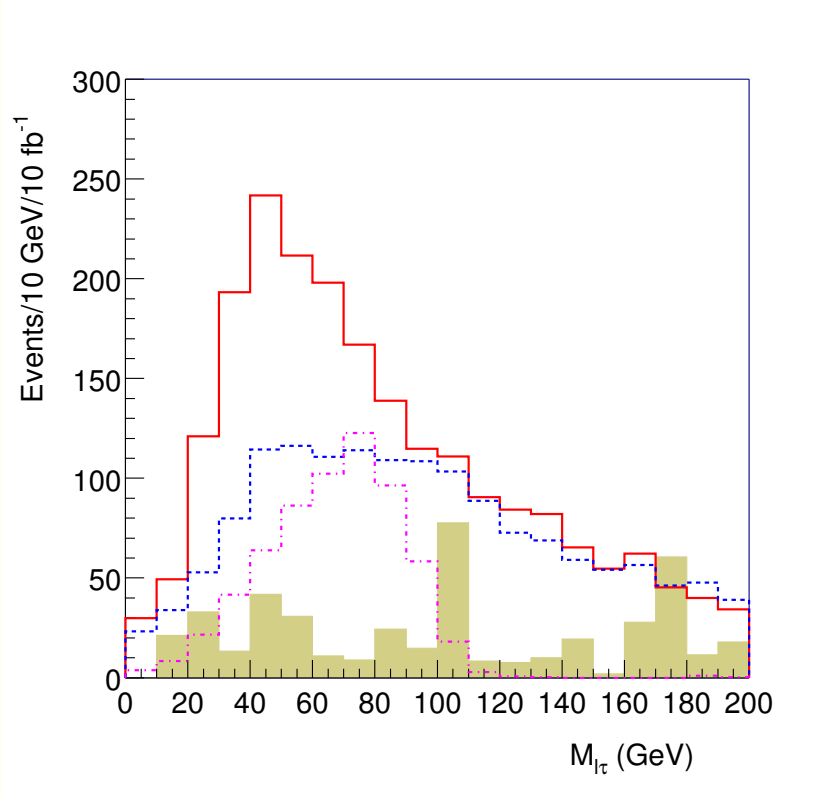
Two types of flavor violation production ($\widetilde{\chi}_2^0 \to \tilde{\tau}\mu$) and decay ($\tilde{\tau} \to \widetilde{\chi}_1^0\mu$).

Branching ratio for $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\mu\tau$ and for $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\mu\mu$ through an intermediate $\tilde{\tau}_1$

Must use hadronic tau decays to distinguish



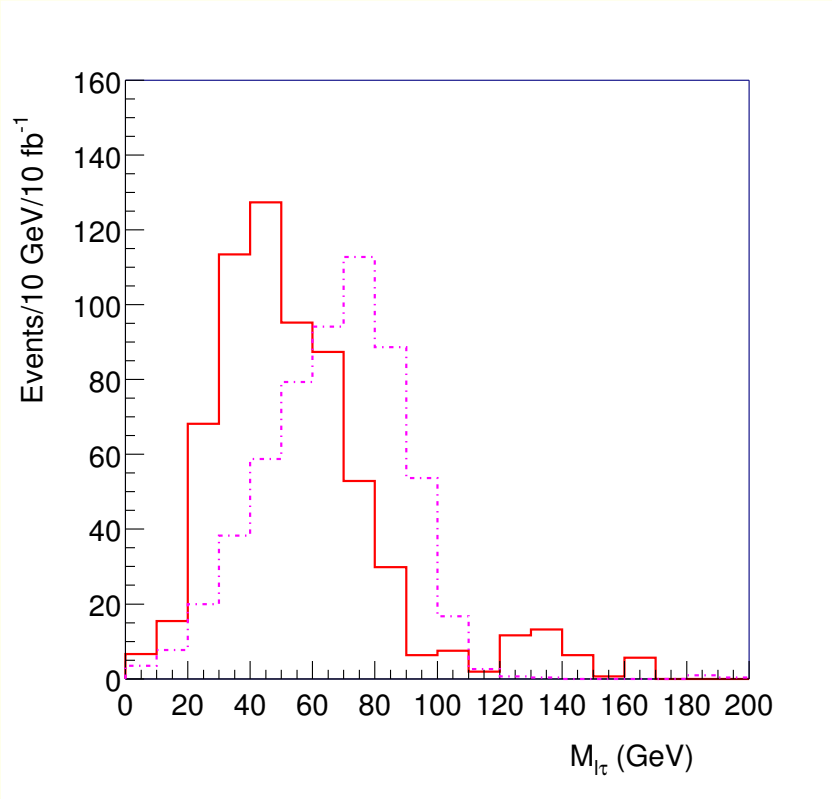
Signal for lepton number violation comes by comparing $\mu\tau_h$ and $e\tau_h$ final states



$\ell^{\pm}\tau_h^{\mp}$ signal (red), $\ell^{\pm}\tau_h^{\pm}$ signal (blue), $\mu^{\pm}\tau_h^{\mp}$ from LFV decays with $BR = 10\%$ (magenta), and Standard Model $\ell^{\pm}\tau_h^{\mp}$

Lepton number violating decay $\widetilde{\chi}_2^0 \to \mu\tau_h\widetilde{\chi}_1^0$ give harder $\mu\tau$ mass distribution than that from $\widetilde{\chi}_2^0 \to \tau\tau\widetilde{\chi}_1^0 \to \mu\tau_h\widetilde{\chi}_1^0$

Subtraction removes background



$\ell^{\pm}\tau_h^{\mp} - \ell^{\pm}\tau_h^{\pm}$ (red) and $\mu^{\pm}\tau_h^{\mp}$ from LFV decays with $BR = 10\%$ (magenta)
Signal is established from $E = N(\mu^{\pm}\tau_h^{\mp}) - N(e^{\pm}\tau_h^{\mp})$
10 fb^{-1} and 5σ implies BR=2.3% or $\delta \sim 0.1$ well within value needed for neutrino data

Sensitive provided that $\tilde{\chi}_2^0$ production is large enough (large fraction of parameter space More sensitive than $\mu \to e\gamma$

R-parity broken

Implies either Lepton number or Baryon number is violated and LSP decays

Either $\tilde{\chi}_1^0 \to qqq$, or $\tilde{\chi}_1^0 \to q\bar{q}\ell$ or $\tilde{\chi}_1^0 \to \ell^+\ell^-\nu$

First two have no $\not{E}_T$, last 2 have more leptons and are straightforward

First case is hardest, Global S/B is worse due to less $\not{E}_T$ Example, SUGRA with $\tilde{\chi}_1^0 \to qqq$ Leptons are essential to get rid of QCD background

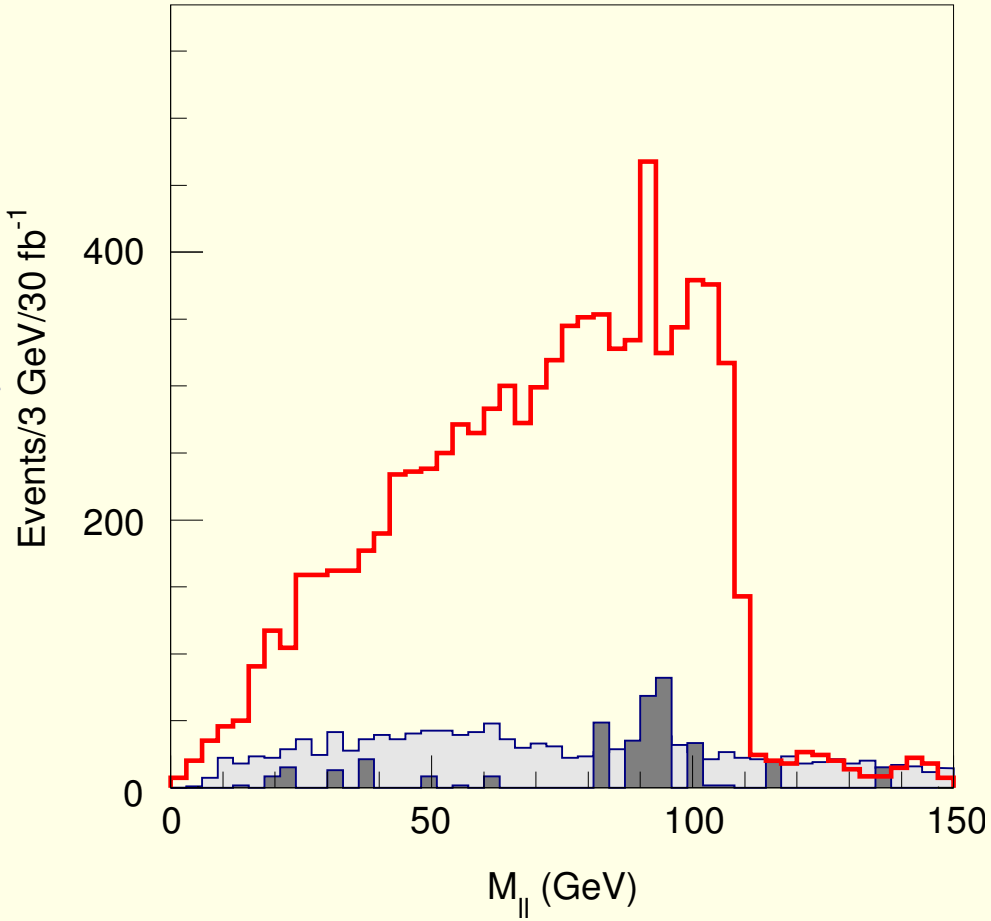
≥ 8 jets with $p_t > 50$ GeV

2 OSSF isolated leptons.

$S_T > 0.2$, selects "ball like" events

$\Sigma_{jets+leptons} E_T > 1$ TeV

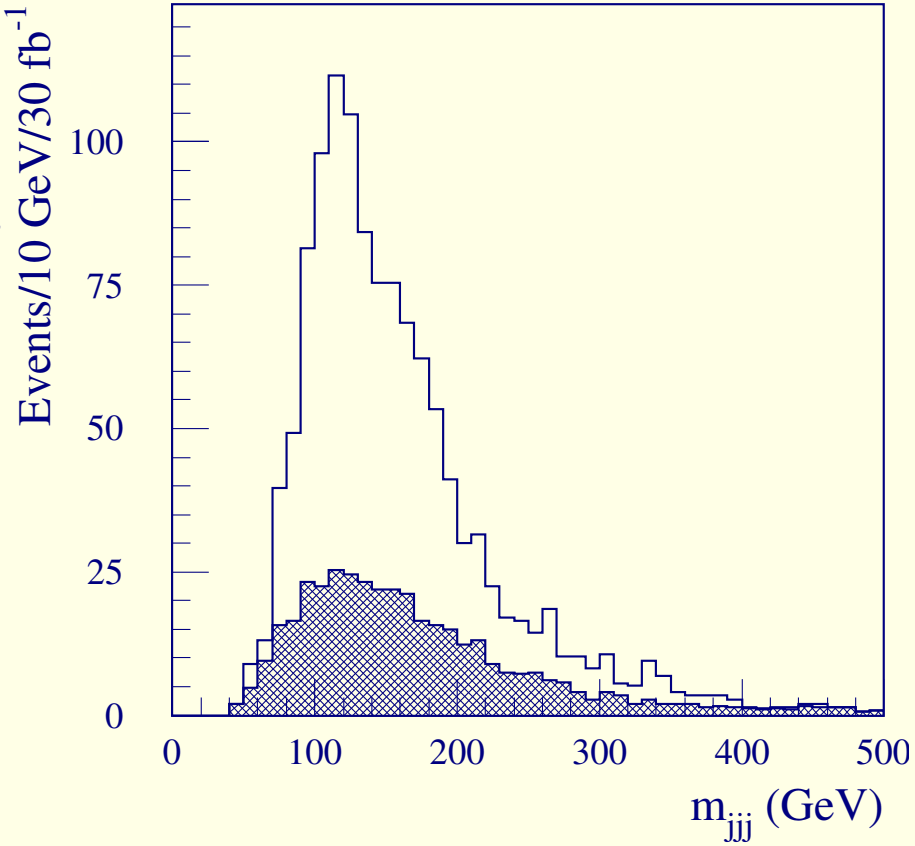
Dilepton mass still shows clear structure with small background from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



As nothing is lost, should be possible to reconstruct $\tilde{\chi}_1^0$

Difficult because jet multiplicity is very high and $\tilde{\chi}_1^0$ mass is usually small, so jets are soft

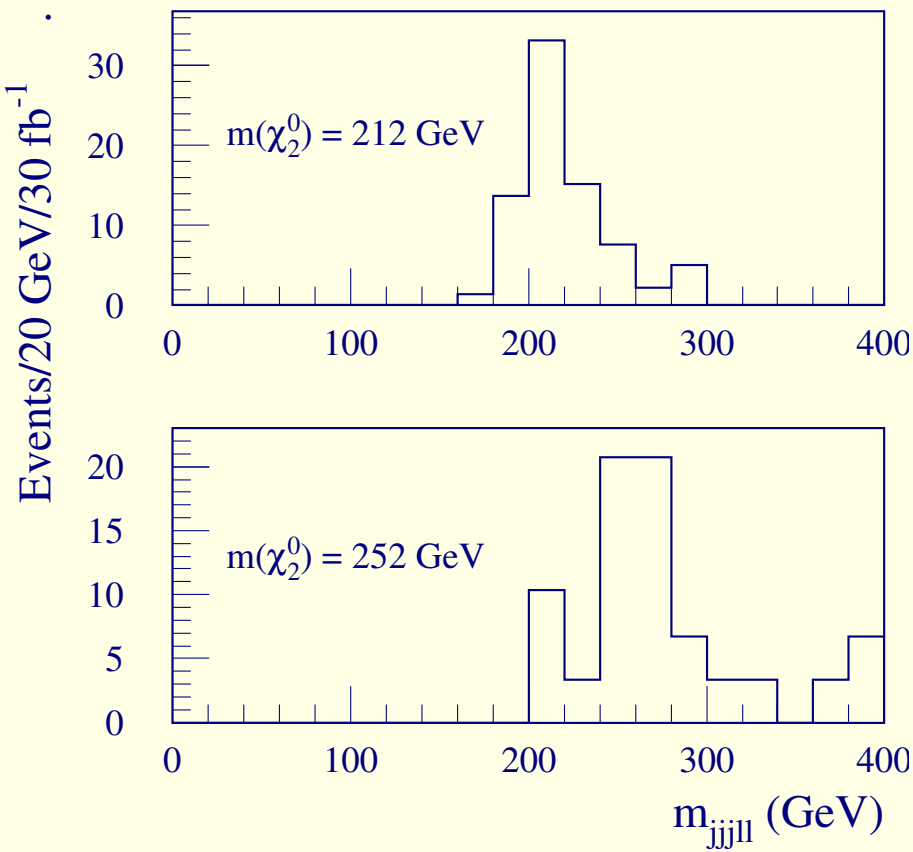
≥ 8 jets with $p_t > 17.5$ GeV, ≤ 8 jets with $p_t > 25$ GeV
2 jets with $p_t > 100(200)$ GeV and $|\eta| < 2$
1 or 2 leptons with $p_t > 20$ GeV
Sphericity cut
combine 6 slowest jets into 2 sets of 3;
require $M(jjj)_1 - M(jjj)_2 < 20$ GeV



Nominal mass 122 GeV

Can cut around peak and combine with either leptons or quarks

reconstruct $\tilde{q_R} \to q\tilde{\chi}_1^0(\to qqq))$ and $\chi_2^0 \to \ell\ell\tilde{\chi}_1^0$



Plot shows $\tilde{\chi}_2^0$

Note that tight cuts imply low event rate (analysis not optimized)

New signals in GMSB

Lightest superpartner is unstable and decays to Gravitino ($\tilde{G}$)

Either neutral

$\chi_1^0 \to \gamma\tilde{G}$: $c\tau \sim C^2(100\ \text{GeV}/M_{\chi_1^0})^5(\Lambda/180\text{TeV})^2(M_M/180\text{TeV})^2$mm

$\Rightarrow$ extra photons or similar signals to SUGRA depending on lifetime

Or charged

Almost always slepton: $\tilde{e_R} \to e\widetilde{G}$

No Missing E_T if $c\tau$ large, events have a pair of massive stable charged particles ("G2b")

Large lepton multiplicity if $c\tau$ small ("G2a").

Discovery and measurement in these cases is trivial

In case "G2b", every decay product can be measured

In case "G1a" $\widetilde{G}$ momenta can be inferred and events fully reconstructed.

GMSB case 1a: Event selection (not optimized)

Decay $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0 \to \ell^+\ell^-\gamma\tilde{G}$ is key
Lifetime of $\tilde{\chi}_1^0$ is short

Find jets

$$M_{\rm eff} \equiv \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}\,.$$

Require

$M_{\rm eff} > 400\,{\rm GeV}$;

$\not{E}_T > 0.1 M_{\rm eff}$.

Looking for

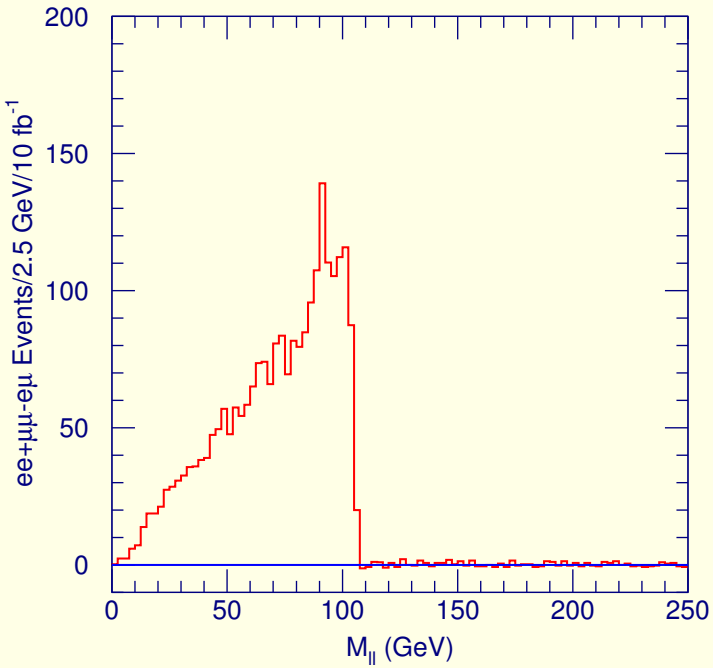
$$\tilde{\chi}_2^0 \to \tilde{\ell}^\pm\ell^\mp \to \tilde{\chi}_1^0\ell^\pm\ell^\mp \to \tilde{G}\gamma\ell^\pm\ell^\mp\,,$$

Electrons and photons : $p_T > 20\,{\rm GeV}$

Muons : $p_T > 5\,{\rm GeV}$.

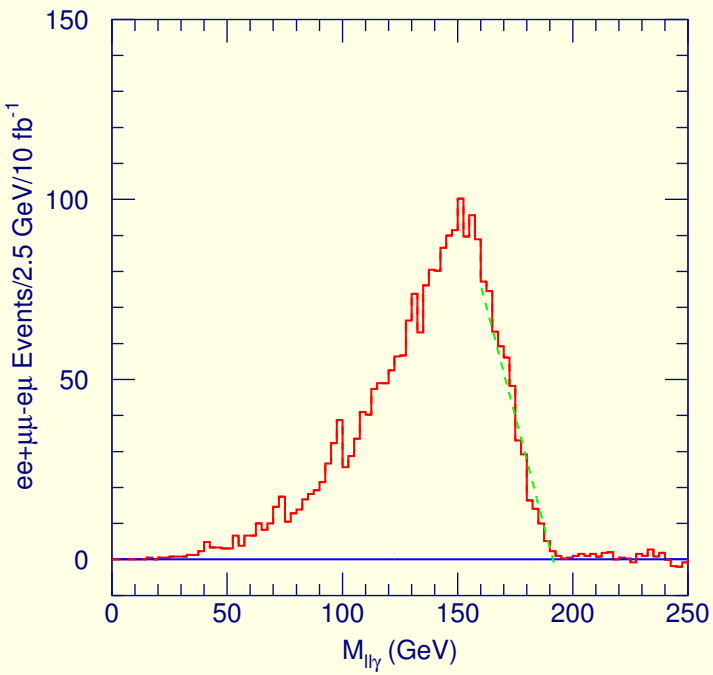
Require at least 2 photons and two leptons.

Dilepton mass distribution, flavor subtracted $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$



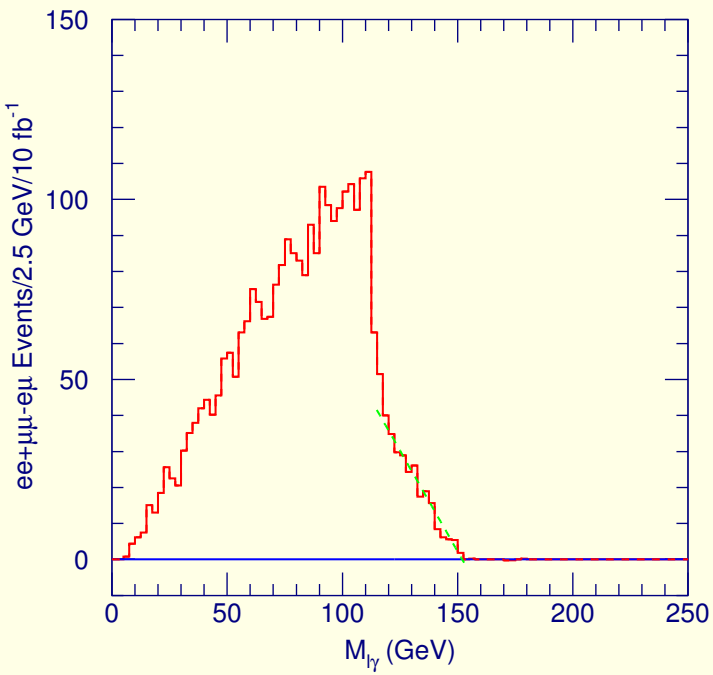
End is at

$$M_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{M_{\tilde{\ell}_R}}{M_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{\ell}_R}}\right)^2} = 105.1$$



Form $\ell^+\ell^-\gamma$ mass and take smallest combination. Linear vanishing at

$$\sqrt{M^2_{\tilde{\chi}^0_2} - M^2_{\chi^0_1}} = 189.7\,\mathrm{GeV}\,,$$



Form $\ell^{\pm}\gamma$ mass also. Two structures at

$$\sqrt{M^2_{\tilde{\ell}_R} - M^2_{\chi^0_1}} = 112.7\,\mathrm{GeV}$$

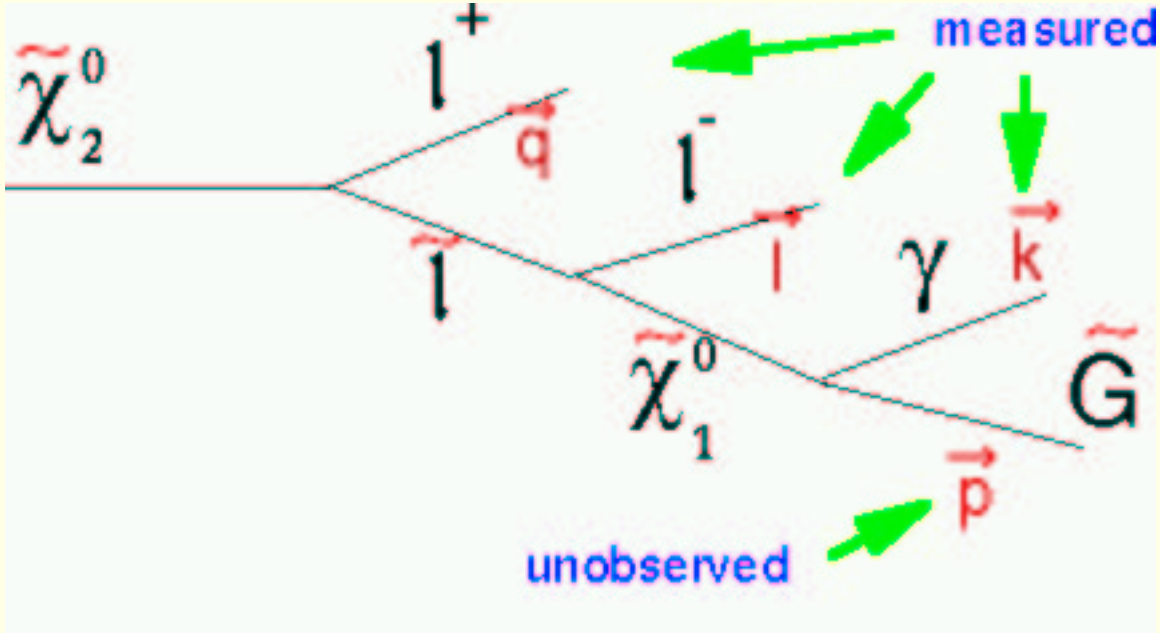
and

$$\sqrt{M^2_{\chi^0_2} - M^2_{\tilde{\ell}_R}} = 152.6\,\mathrm{GeV}$$

These four measurements are sufficient to determine the masses of the particles ($\widetilde{\chi}_2^0$, $\widetilde{\ell}_R$, and $\widetilde{\chi}_1^0$) in this decay chain without assuming any model of SUSY breaking.

Now use this to reconstruct the decay chain and measure the $\widetilde{G}$ momenta despite the fact that there are two in each event and both are invisible!

Full reconstruction of SUSY events



Know masses $\Rightarrow$ can calculate p assuming $p^2 = 0$:

$$
\begin{aligned}
2p_0k_0 - 2\vec{p}\cdot\vec{k} &= M^2_{\tilde{\chi}^0_1} \\
2p_0l_0 - 2\vec{p}\cdot\vec{l} &= M^2_{\tilde{\ell}_R} - M^2_{\tilde{\chi}^0_1} - 2k\cdot l \\
2p_0k_0 - 2\vec{p}\cdot\vec{q} &= M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_R} - 2(k+l)\cdot q
\end{aligned}
$$

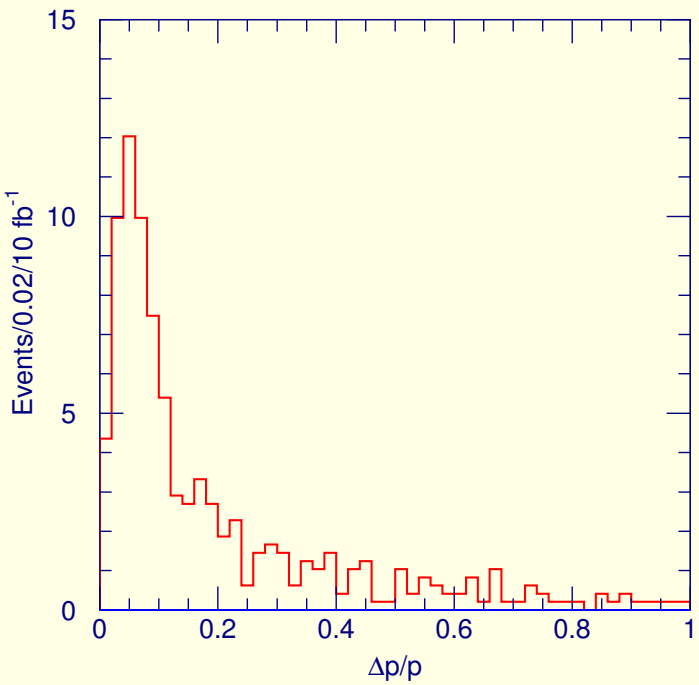
0C fit with 2×2 solutions.

Event has two of these decays so require 4 leptons and 2 gammas

Calculate missing E_T
Form a χ^2 using measured missing E_T to resolve ambiguities

$$\chi^2 = \left(\frac{\not{E}_x - p_{1x} - p_{2x}}{\Delta \not{E}_x}\right)^2 + \left(\frac{\not{E}_y - p_{1y} - p_{2y}}{\Delta \not{E}_y}\right)^2 .$$

use $\Delta \not{E}_x = \Delta \not{E}_x = 0.6\sqrt{E_T} + 0.03 E_T$.



Compare to generated $\widetilde{G}$ momenta
Plot shows all solutions with $\chi^2 < 10$
$\Delta \vec{p} = \vec{p}_{\tilde{G}} - \vec{p}_{reconst}$
$\Delta|\vec{p}|/|\vec{p}| \sim 10\%$

Squark and Gluino Masses

Use measured $\widetilde{\chi}_2^0$ momenta and combine with jets

$\widetilde{q} \to \widetilde{g}q \to \widetilde{\chi}_2^0 \overline{q} q q$

Require at least 4 jets with $p_T > 75\,\mathrm{GeV}$

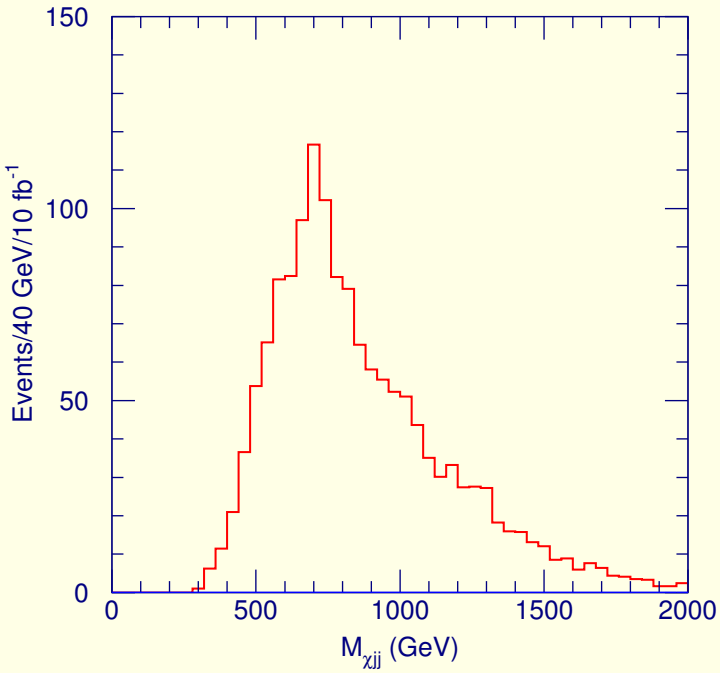


Figure shows mass of $\widetilde{\chi}_2^0$+2 jets;
peak is below gluino mass (747 GeV);
no correction applied for small jet cone.

Much easier than the SUGRA cases; masses measured directly

Measuring the fundamental scale of SUSY breaking

Lifetime of $\tilde{\chi}_1^0 \to \tilde{G}$ is important as it measures the fundamental scale of SUSY breaking

Measure lifetime of χ_1^0 ($\to \tilde{G}\gamma$) using Dalitz decay $\chi_1^0 \to e^+e^-\gamma\tilde{G}$

Works for short lived $\tilde{\chi}_1^0$

Statistics limited ($\sim$few-K events)

Measure lifetime of χ_1^0 ($\to \tilde{G}\gamma$): photon pointing.

Angular resolution of photons from primary vertex (ATLAS)

$\Delta\theta \sim 60mr/\sqrt{E}$ Detailed study of efficiency for non-pointing photons

Important for long lived $\tilde{\chi}_1^0$

Decays are uniformly distributed in the detector

Cross check from time delay of decay

Failure to see photons $\Rightarrow c\tau > 100$ km or $\sqrt{F} \geq 10^4$ TeV

Mass measurement of quasi-stable sleptons – ATLAS

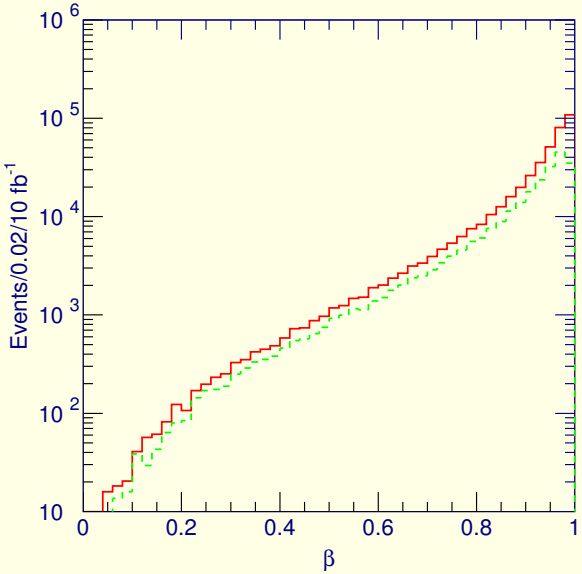
Sleptons are produced at the end of decay chains $\Rightarrow$ large velocity

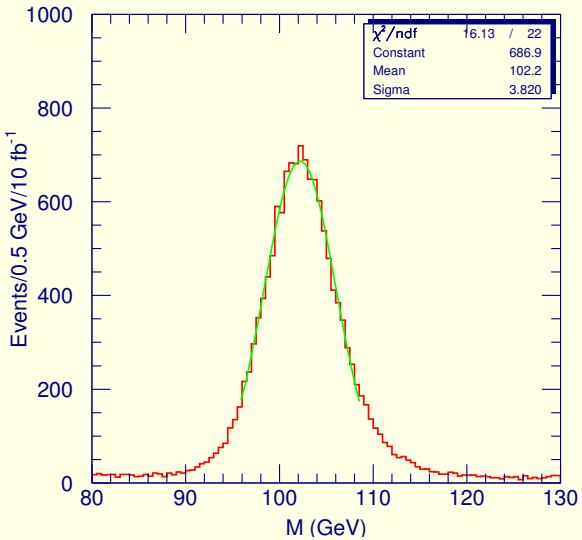
Most of these will pass the Muon Trigger

Measure the velocity using TOF in Muon system, then infer mass

Time resolution $\sim \mathbf{65}$ ns

$\Rightarrow \boldsymbol{\Delta M/M} \sim \mathbf{3\%}$ for $\boldsymbol{M} = \mathbf{100}$ GeV

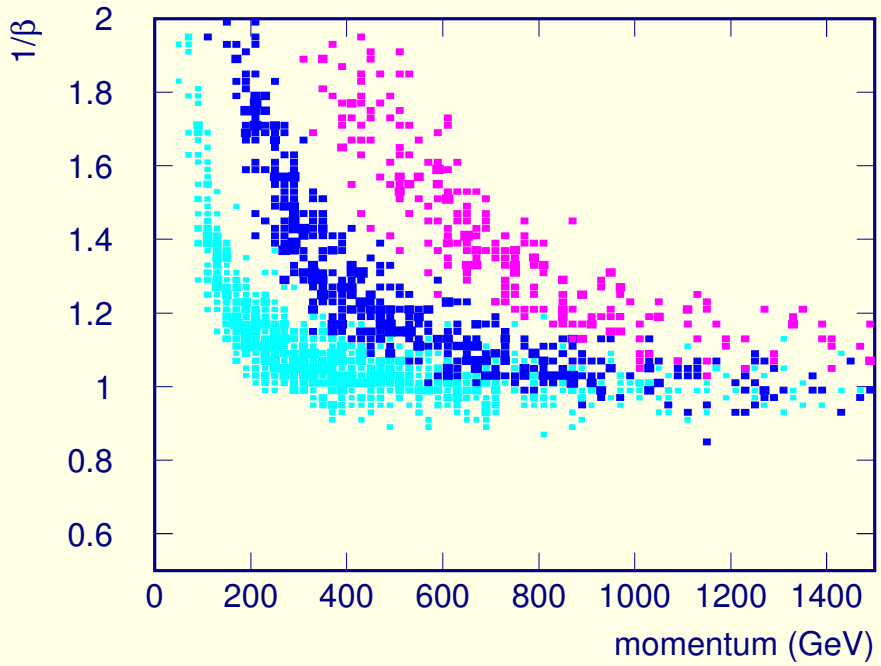


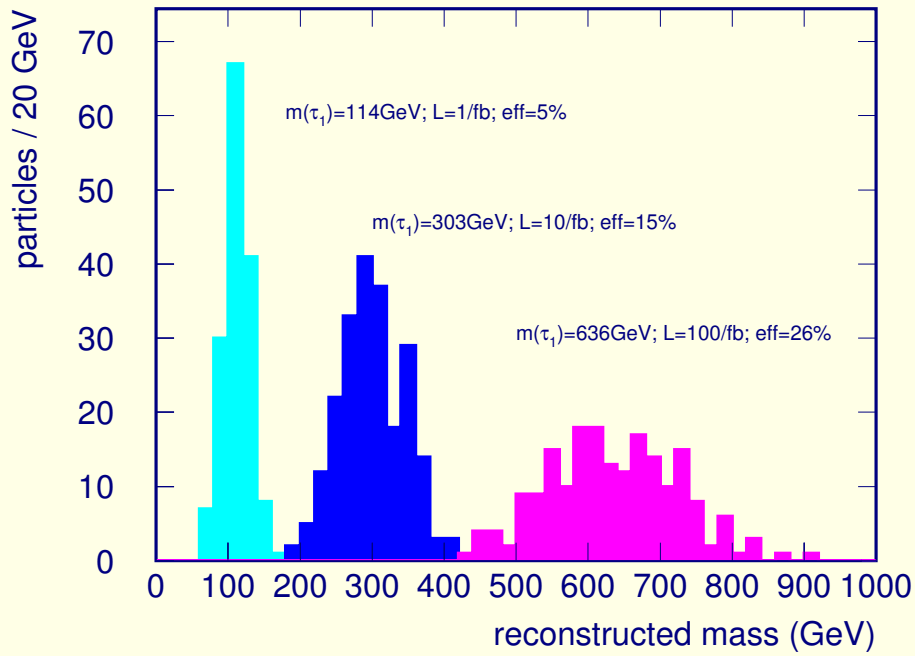


velocity $\boldsymbol{\Delta M/M}$

How well does this work in CMS?

Three cases studied $m_{stau} = 104, 303, 636$ GeV



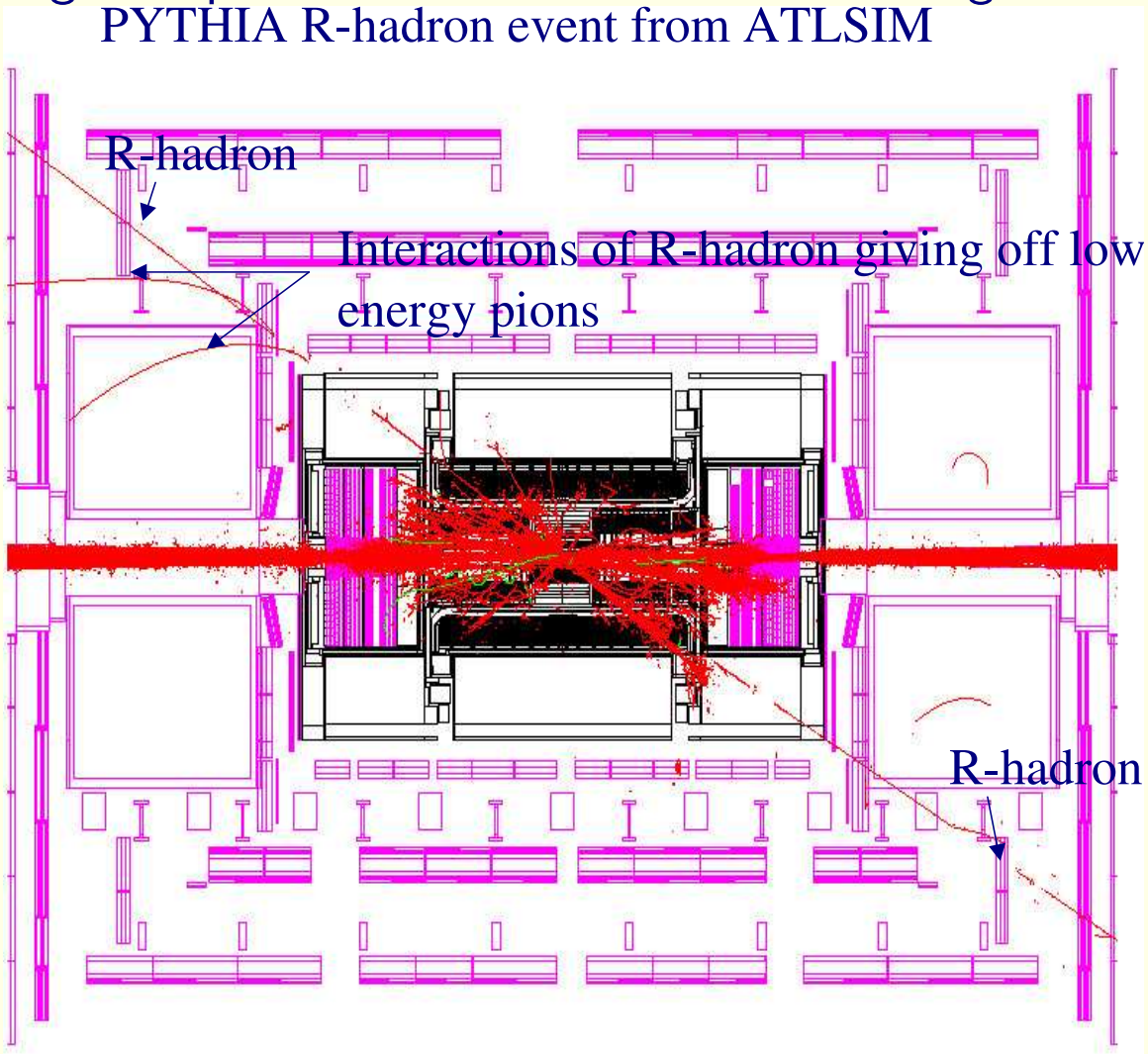


AMSB

Look at paper of Wells and Paige

Odd Ball: R-hadron (split susy)

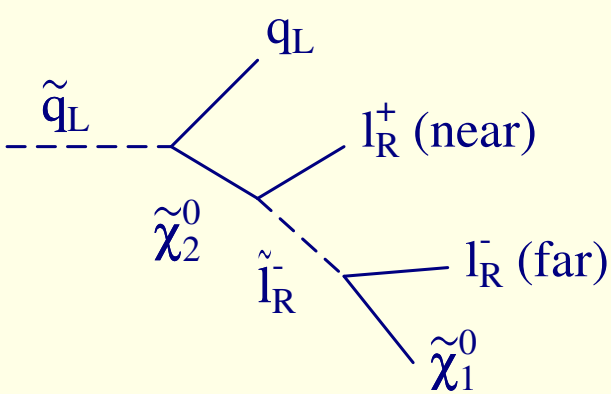
Long lived or quasi stable gluino produces "cannon ball" that charge exchanges as it



passes through detector

Spin measurements at LHC?

Conventional wisdom says that you need LC for this but...



Angle between q and e^- in $\tilde{\chi}_2^0$ rest frame is sensitive to spin correlations.

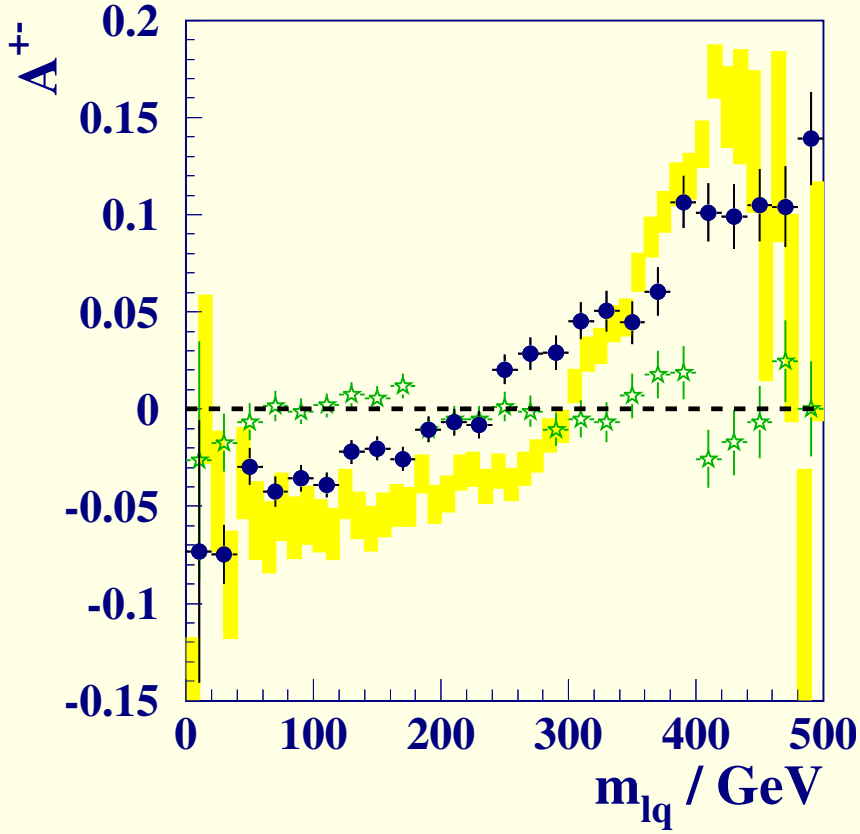
But effect washes out if we do not know which lepton comes out first: Use kinematics

But effect washes out if average over q and $\overline{q}$: LHC is a pp machine: more $\tilde{q}$ than $\tilde{\overline{q}}$

Form an asymmetry from invariant mass distribution of lepton and jet

$$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$$

Green:spin correlation off
Yellow: No detector ($\times 0.6$)
Needs at least $100\mathrm{fb}^{-1}$



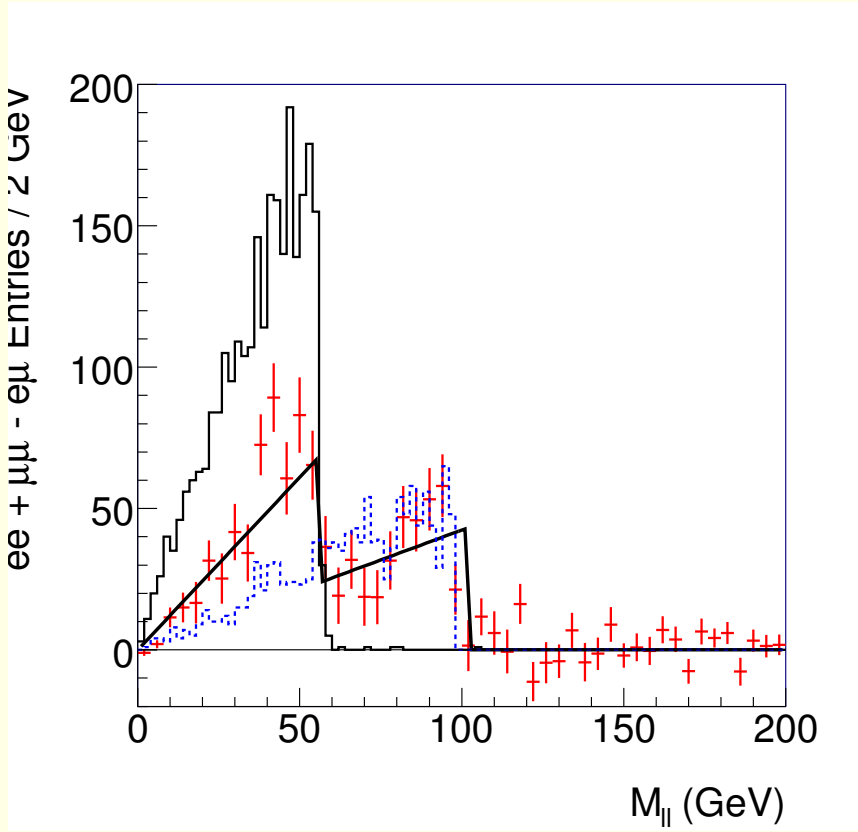
Barr

Difficult cases I: Small mass gaps

Co-annihilation region: Near degeneracy between LSP and sleptons.Soft leptons and more messy decays.

$\tilde{q}_L \to q\tilde{\chi}_2^0$ then $\tilde{\chi}_2^0(260) \to \tilde{\ell}_R(153)\ell \to \ell\ell\tilde{\chi}_1^0(136)$ and $\tilde{\chi}_2^0 \to \tilde{\ell}_L(255)\ell \to \ell\ell\tilde{\chi}_1^0(136)$

Leptons can still be found despite small mass gaps



ATLAS

Conclusions

- Serious thinking has started about what might be done at 10^{35} and what machine and detector upgrades are needed.

Discovery cannot be far off

"The train is already late" (Altarelli): Fine tuning is a problem already.

We expected gauginos in the LEP range

Tevatron "window" is small but low masses are more likely

Discovery cannot be far off

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An era is about to end

Low energy SUSY has provided employment for $> \mathbf{20}$ years

It will be discovered or die in the next 6 years.