Jet Energy Studies at $\sqrt{s} \geq 1$ TeV e^+e^- Colliders II: Light Squark Jets

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07/15

In order to know what jet energies need to be well measured at a TeV LC collider we must make a survey of the range of possibilities from New Physics…Can these energies be large?

The production of new colored objects which decay to quarks and/or gluons can lead to important new signals involving high energy jets which may need to be well-measured.

The most obvious case of this is *light* squark (i.e., the first two generations) production which has NOT been well studied at any realistic level for ILC or CLIC -- so we'll take a (too) quick look here.

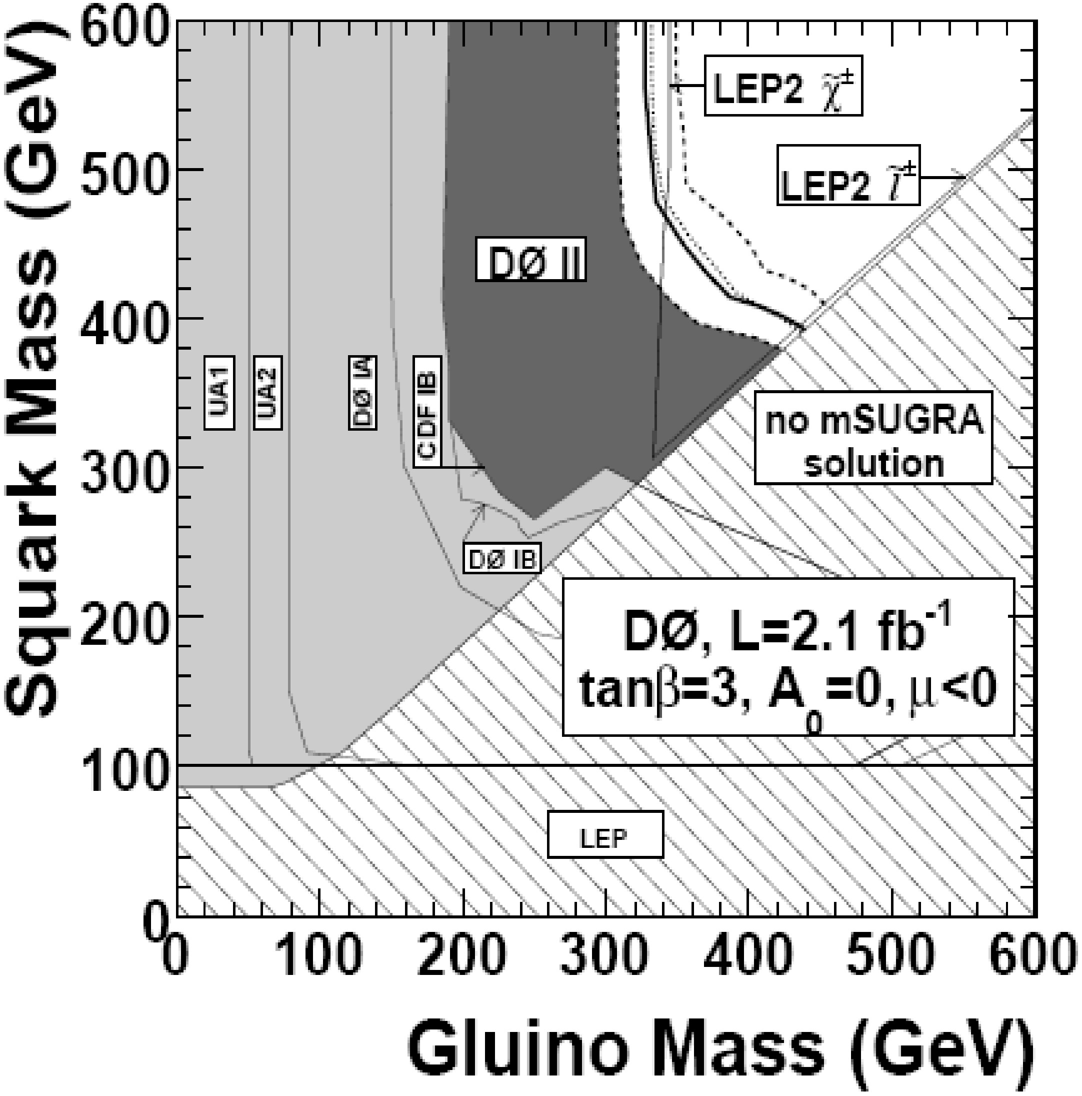
The jet E spectrum produced from the decays of these new states depends on the SUSY mass spectrum & mixing details.

We will look at the jet energy distributions produced at the parton level by light squark decays in 5 SPS models. This will be done using PYTHIA6.324 turning off QCD, ISR and FSR, fragmentation, hadronization, decays of the light particles (i.e., udscbτ), as well as all detector effects (all by request)…. and, of course, no physics backgrounds.

It is not yet clear how generic these results really are from such a limited study since the varieties of SUSY and, more generically, models with new colored states, cover a very wide range of theory space.

Squark masses in all SPS models are in *excess* of 540 GeV so for demonstration purposes we will consider a 2 TeV collider… we can then rescale the jet energies by the ratio of center of mass energies.

While it is unlikely these squarks will be encountered at a 500 GeV machine they may occur at 1 TeV (we'll find out soon from the LHC)…how do they decay ???

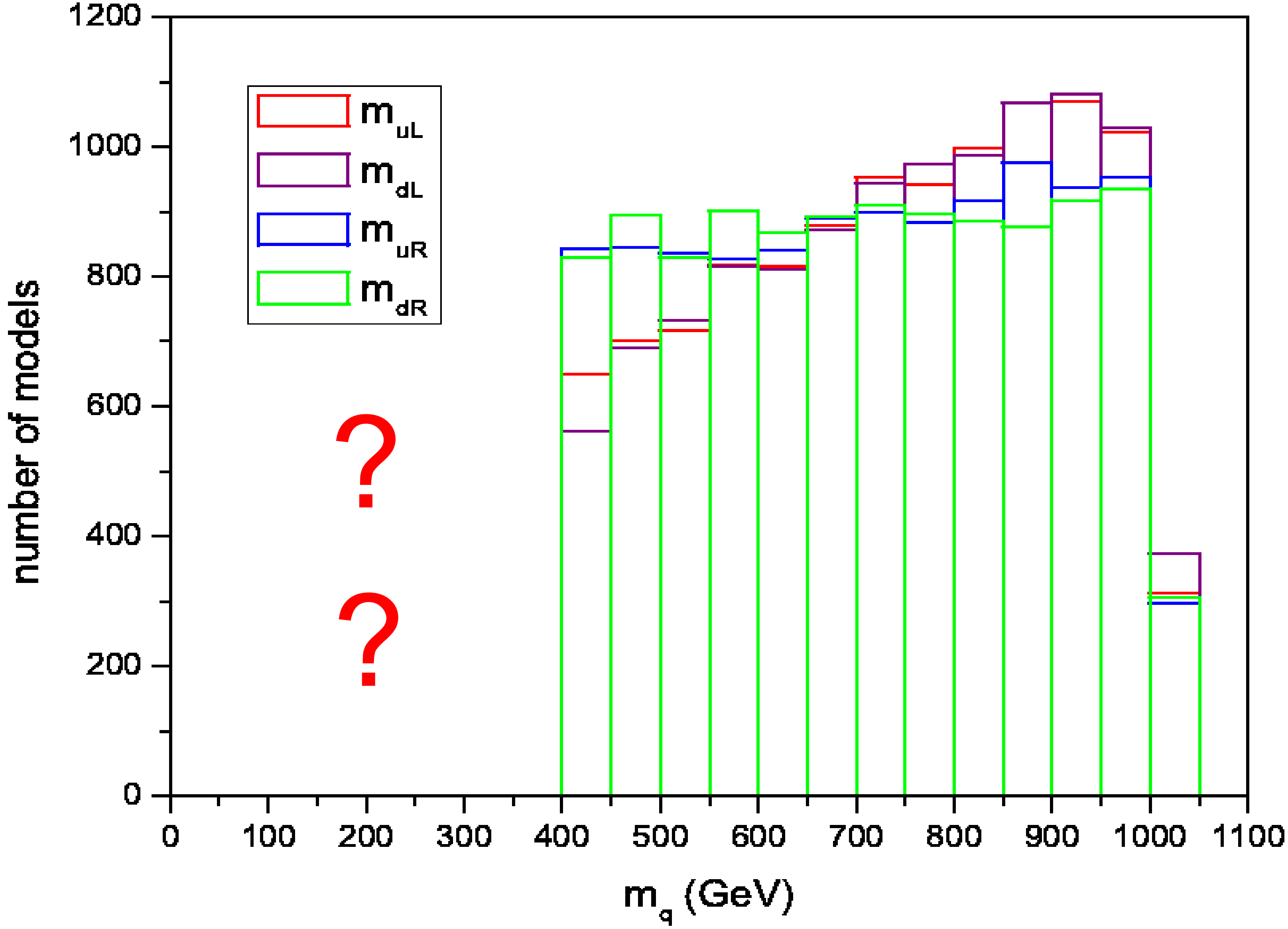


This is for MSUGRA showing > ~380 GeV squarks are still allowed. *However,* in GENERAL, the MSSM may allow even *smaller* mass values (I'll let you know).

Furthermore, their in-accessibility at *500 GeV* means their masses will be quite poorly known after ILC500.

The first ~11k MSSM models….

Berger, Hewett,
Gainer & Rizzo



Squark masses will be poorly determined even *after* LHC & ILC500…

	m_{SPS1a}	LHC	LC	LHC+LC		m_{SPS1a}	LHC	LC	LHC+LC
h	111.6	0.25	0.05	0.05	H	399.6		1.5	1.5
A	399.1		1.5	1.5	$H+$	407.1		1.5	1.5
χ_1^0	97.03	4.8	0.05	0.05	χ_2^0	182.9	4.7	1.2	0.08
χ_3^0	349.2		4.0	4.0	χ_4^0	370.3	5.1	4.0	2.3
$\chi_1^\pm$	182.3		0.55	0.55	$\chi_2^\pm$	370.6		3.0	3.0
$\tilde{g}$	615.7	8.0		6.5					
$\tilde{t}_1$	411.8		2.0	2.0					
$\tilde{b}_1$	520.8	7.5		5.7	$\tilde{b}_2$	550.4	7.9		6.2
$\tilde{u}_1$	551.0	19.0		16.0	$\tilde{u}_2$	570.8	17.4		9.8
$\tilde{d}_1$	549.9	19.0		16.0	$\tilde{d}_2$	576.4	17.4		9.8
$\tilde{s}_1$	549.9	19.0		16.0	$\tilde{s}_2$	576.4	17.4		9.8
$\tilde{c}_1$	551.0	19.0		16.0	$\tilde{c}_2$	570.8	17.4		9.8
$\tilde{e}_1$	144.9	4.8	0.05	0.05	$\tilde{e}_2$	204.2	5.0	0.2	0.2
$\tilde{\mu}_1$	144.9	4.8	0.2	0.2	$\tilde{\mu}_2$	204.2	5.0	0.5	0.5
$\tilde{\tau}_1$	135.5	6.5	0.3	0.3	$\tilde{\tau}_2$	207.9		1.1	1.1
$\tilde{\nu}_e$	188.2		1.2	1.2					

Uses MSUGRA relations

Table 5.25: Errors for the mass determination in SPS1a, taken from [146]. Shown are the nominal parameter values and the error for the LHC alone, the LC alone, and a combined LHC+LC analysis. All values are given in GeV.

Essentials of MSSM Parameters and Mixings

$$\begin{pmatrix} M_2 & M_W\sqrt{2}\sin\beta \\ M_W\sqrt{2}\cos\beta & \mu \end{pmatrix}$$

Wino + charged Higgsino → $\chi^{+}_{1,2}$

bino + neutral wino
and Higgsinos
→ $\chi^{0}_{1,2,3,4}$

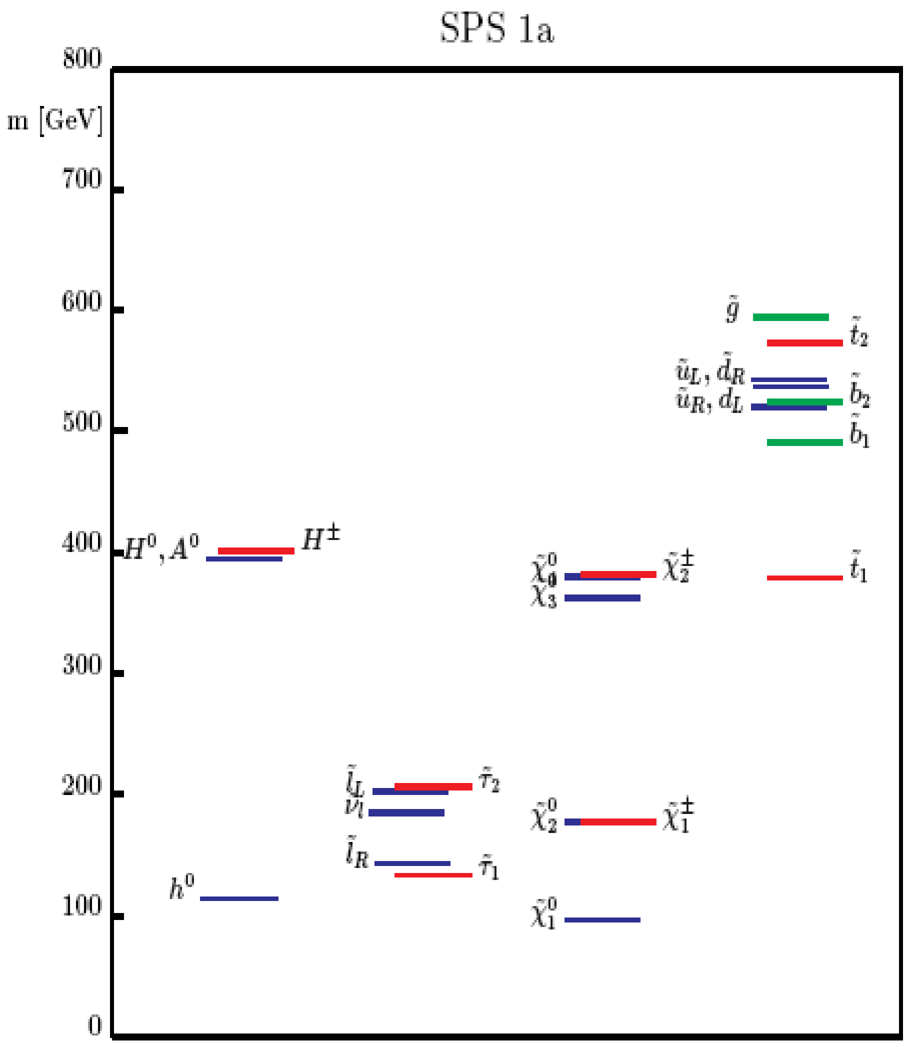
$$\begin{pmatrix} M_1 & 0 & -M_Z s_W \cos\beta & M_Z s_W \sin\beta \\ 0 & M_2 & M_Z c_W \cos\beta & -M_Z c_W \sin\beta \\ -M_Z s_W \cos\beta & M_Z c_W \cos\beta & 0 & -\mu \\ M_Z s_W \sin\beta & -M_Z c_W \sin\beta & -\mu & 0 \end{pmatrix}$$

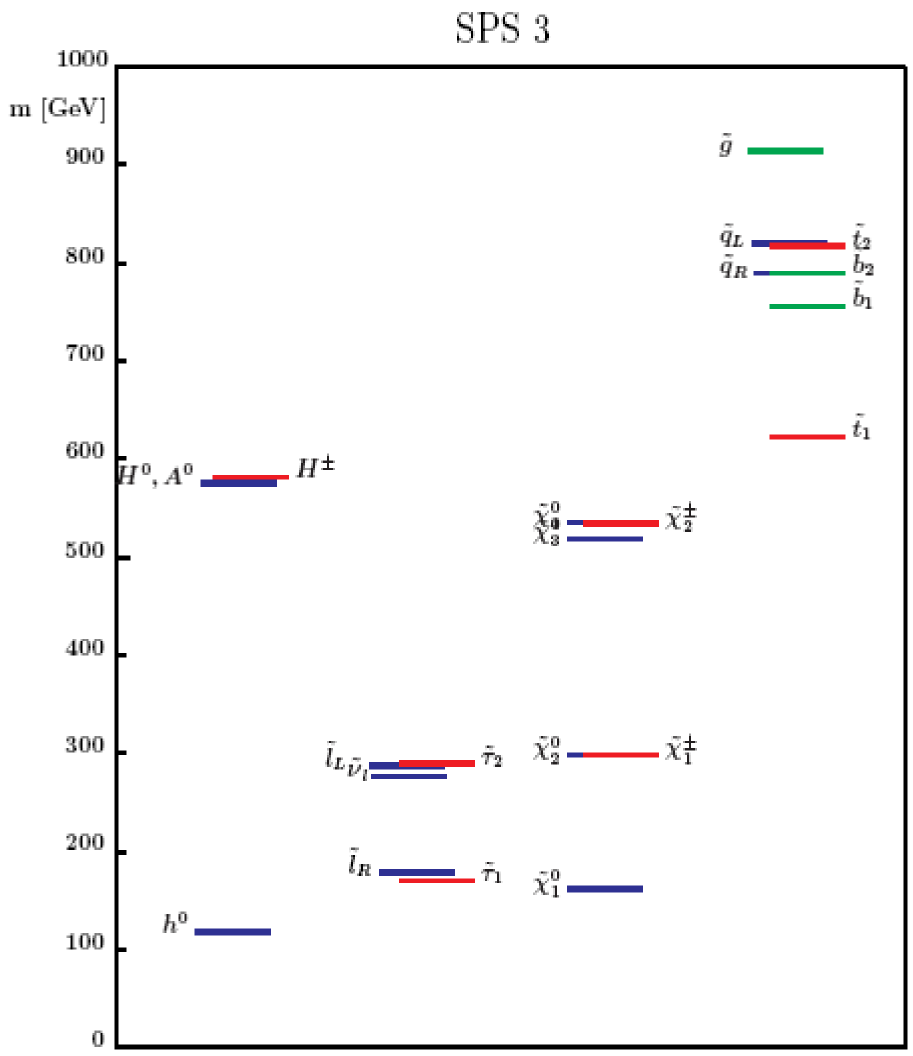
$$M^2_{\tilde{f}} = \begin{pmatrix} M^2_{LL} & m_f X^*_f \\ m_f X_f & M^2_{RR} \end{pmatrix},$$

$$\begin{aligned} M^2_{LL} &= m^2_f + m^2_{L,f} + M^2_Z \cos 2\beta (I^f_3 - Q^f s^2_W), \\ M^2_{RR} &= m^2_f + m^2_{R,f} + M^2_Z \cos 2\beta \, Q^f s^2_W, \\ X_f &= A_f - \mu^* \{\cot\beta, \tan\beta\} \end{aligned}$$

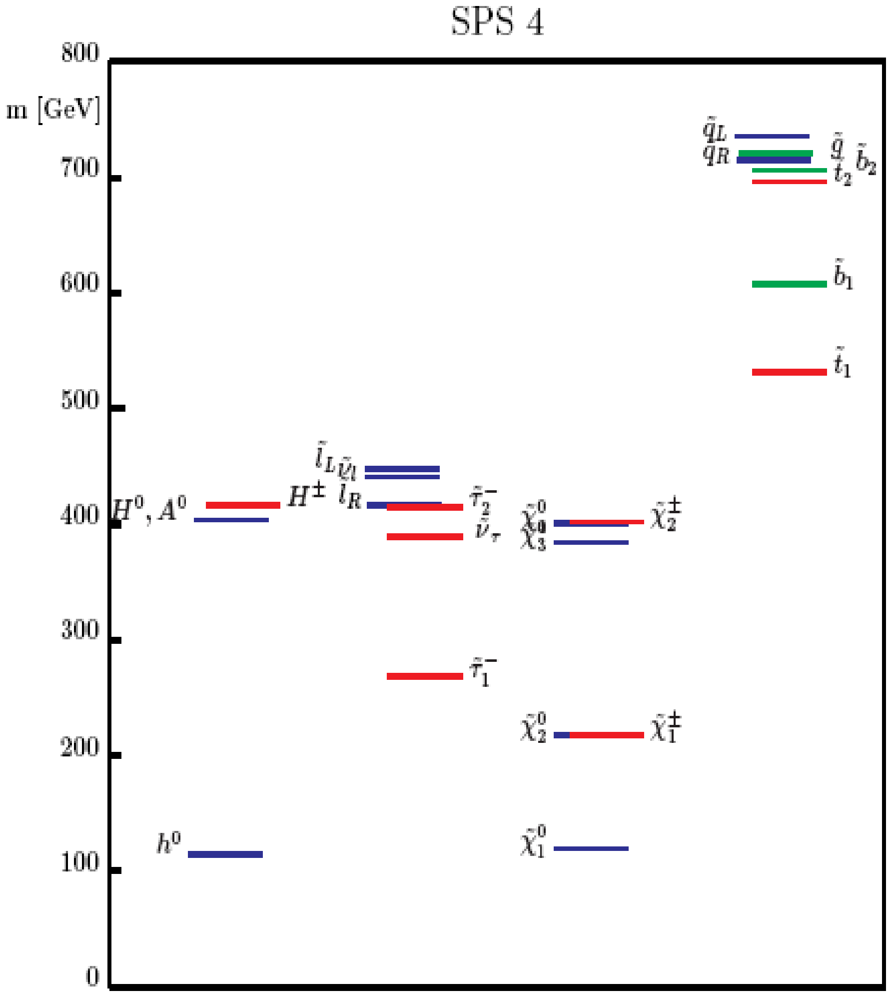
left- and right-sfermions → sfermions$_{1,2}$ …. This mixing is relevant for stops, sbottoms and staus but *not* for the first two generations

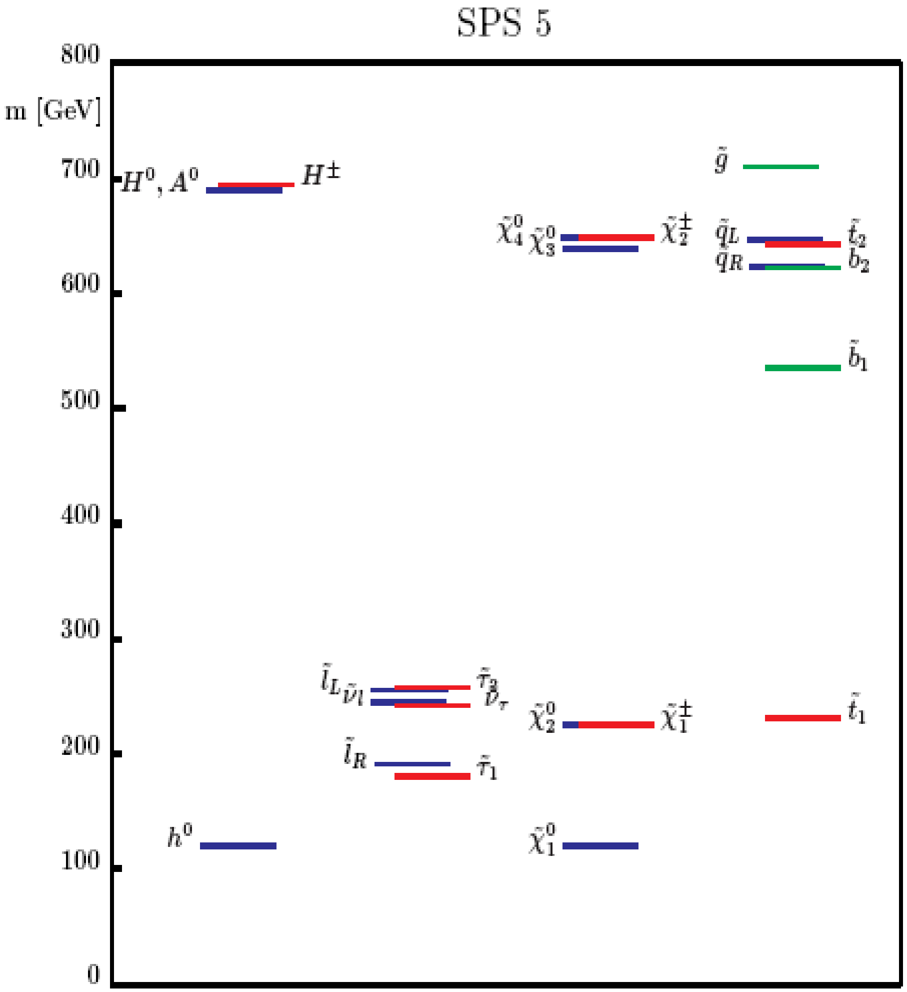
The SUSY spectrum partially determines allowed decay modes





There is a lot of variety in the spectrum details…

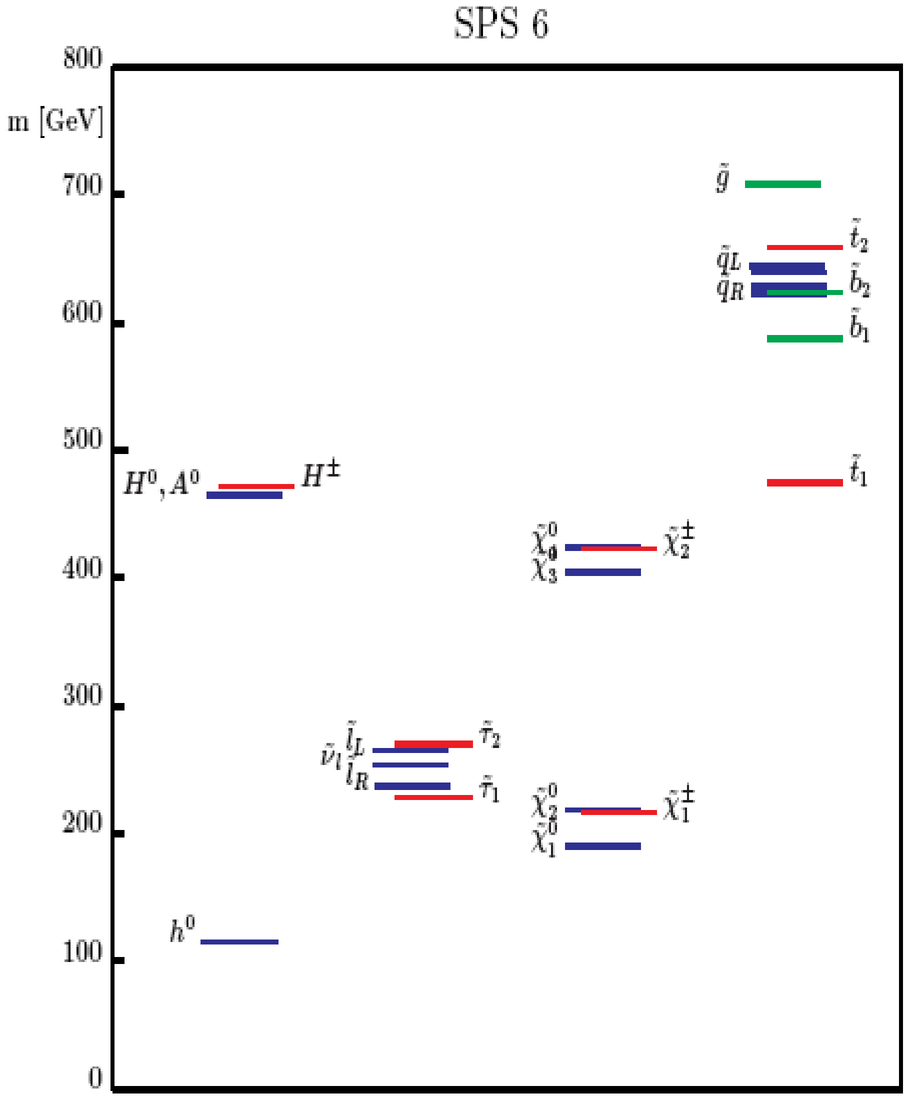


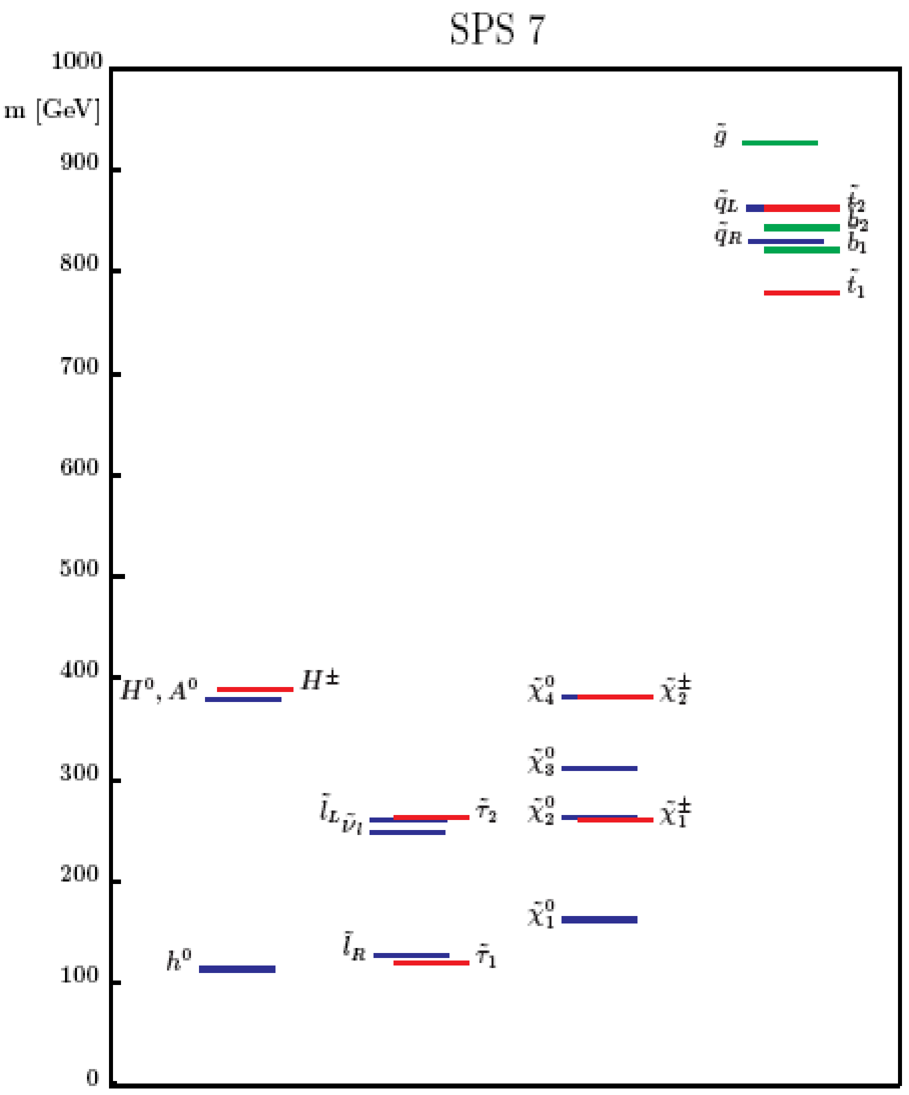


Unfortunately, these MSUGRA models have too many common features so it is hard to generalize just from these few examples

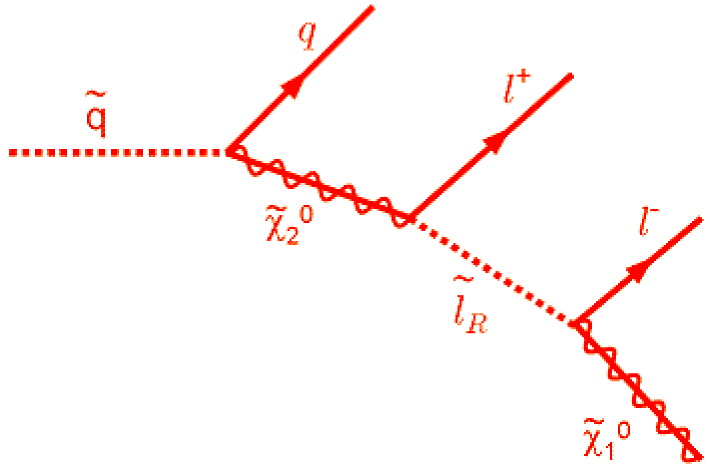
We need a more general study & it’s in progress..

The variety of spectra is truly enormous, e.g., SPS7 is a GMSB scenario whose spectrum appears to be totally different.





While RH-squarks “*generally*“ decay to q+LSP, LH-squarks will *commonly* decay through a weak decay cascade, *provided* the gluino is heavier than the squarks… This is one of the many, many, many possible examples:

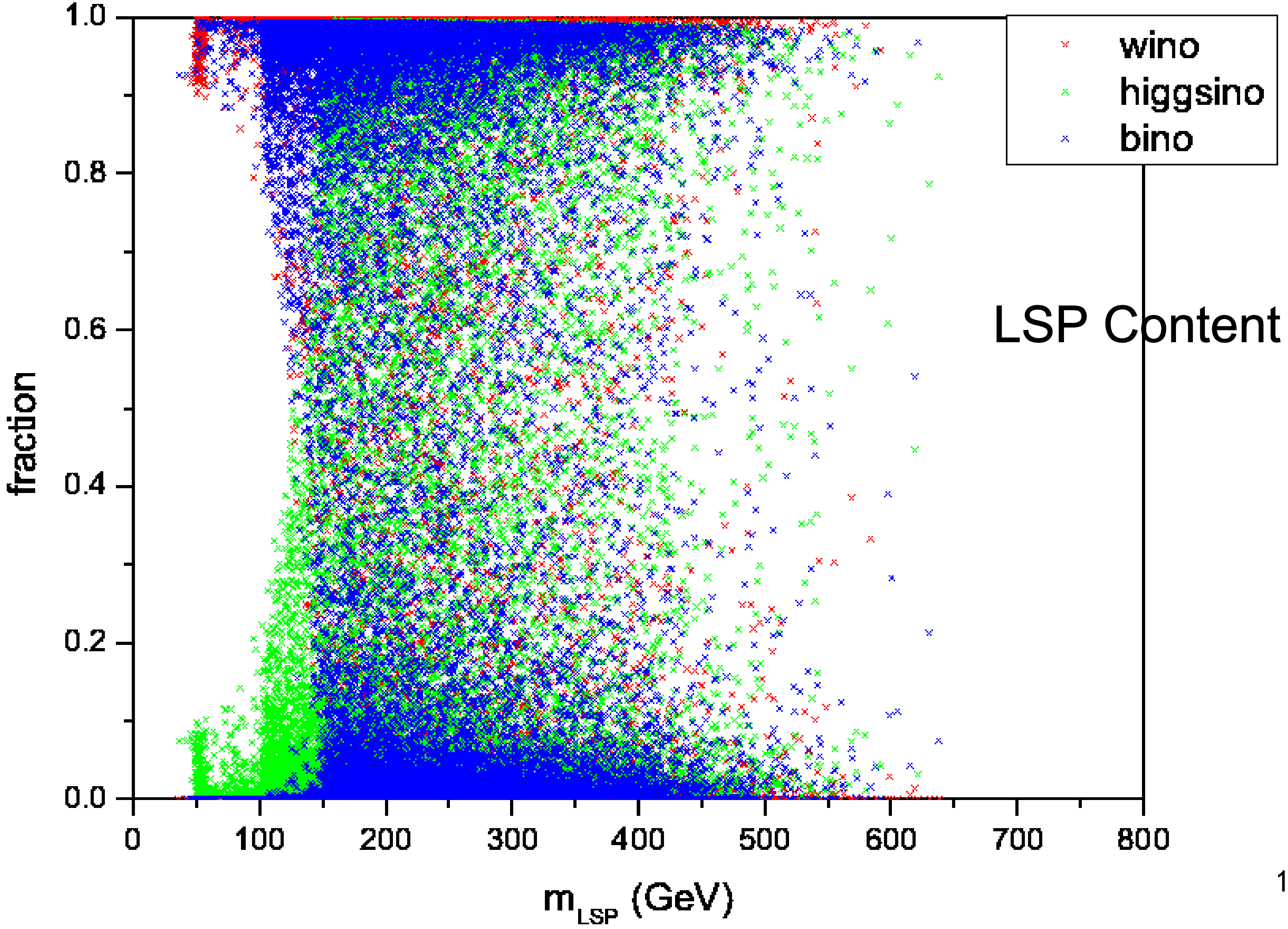


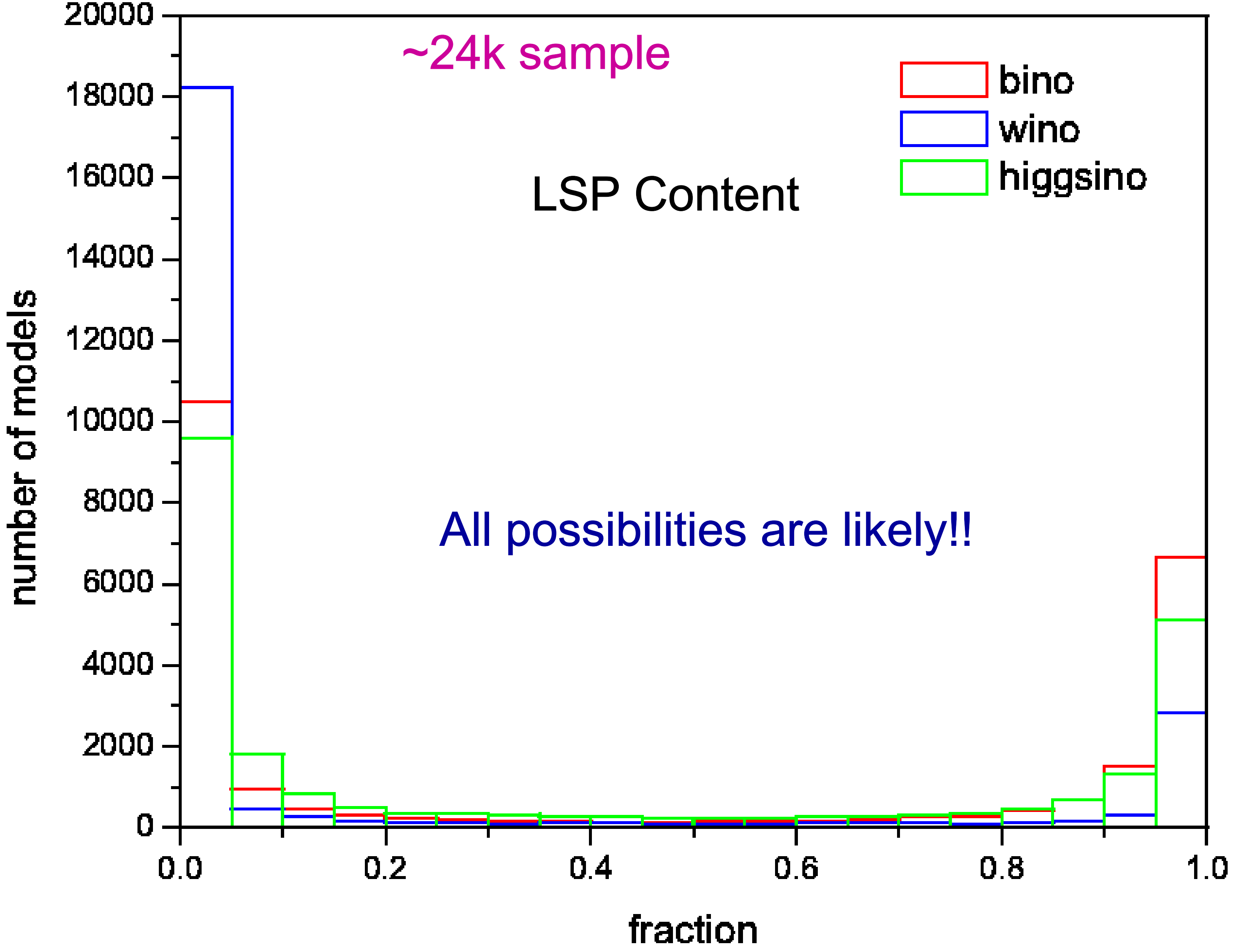
Why is this??

For the first 2 generations the RH-squarks couple only to binos (they have no isospin) while LH-squarks can *also* couple to charged & neutral winos. Higgsino couplings are suppressed by tiny Yukawa couplings…of course the LSP may be a *wino* (as in AMSB) or Higgsino and *not* a bino as is common in MSUGRA.

The first ~24k MSSM models…..

Berger, Gainer,
Hewett & Rizzo




LSP Content

~24k sample

All possibilities are likely!!

Example: SPS1a' Masses and Decay Tables

$\tilde{q}$	m, Γ [GeV]	decay	$\mathcal{B}$	decay	$\mathcal{B}$
$\tilde{u}_R$	547.2 1.2	$\tilde{\chi}^0_1 u$	0.990		
$\tilde{u}_L$	564.7 5.5	$\tilde{\chi}^0_2 u$	0.322	$\tilde{\chi}^+_1 d$	0.656
$\tilde{d}_R$	546.9 0.3	$\tilde{\chi}^0_1 d$	0.990		
$\tilde{d}_L$	570.1 5.4	$\tilde{\chi}^0_2 d$	0.316	$\tilde{\chi}^-_1 \bar{u}$	0.625
$\tilde{t}_1$	366.5 1.5	$\tilde{\chi}^0_1 t$ $\tilde{\chi}^0_2 t$	0.219 0.062	$\tilde{\chi}^+_1 b$	0.719
$\tilde{t}_2$	585.5 6.3	$\tilde{\chi}^0_1 t$ $\tilde{\chi}^0_2 t$	0.042 0.103	$\tilde{\chi}^+_1 b$ $\tilde{\chi}^+_2 b$ $\tilde{t}_1 Z^0$ $\tilde{t}_1 h^0$	0.265 0.168 0.354 0.059
$\tilde{b}_1$	506.3 4.4	$\tilde{\chi}^0_1 b$ $\tilde{\chi}^0_2 b$	0.037 0.295	$\tilde{\chi}^-_1 t$ $\tilde{t}_1 W^-$	0.381 0.281
$\tilde{b}_2$	545.7 1.0	$\tilde{\chi}^0_1 b$ $\tilde{\chi}^0_2 b$ $\tilde{\chi}^0_3 b$ $\tilde{\chi}^0_4 b$	0.222 0.131 0.028 0.038	$\tilde{\chi}^-_1 t$ $\tilde{t}_1 W^-$	0.178 0.401
$\tilde{g}$	607.1 5.5	$\tilde{u}_R \bar{u}$ $\tilde{u}_L \bar{u}$ $\tilde{d}_R \bar{d}$ $\tilde{d}_L \bar{d}$	0.086 0.044 0.087 0.034	$\tilde{t}_1 \bar{t}$ $\tilde{b}_1 \bar{b}$ $\tilde{b}_2 \bar{b}$	0.189 0.214 0.096

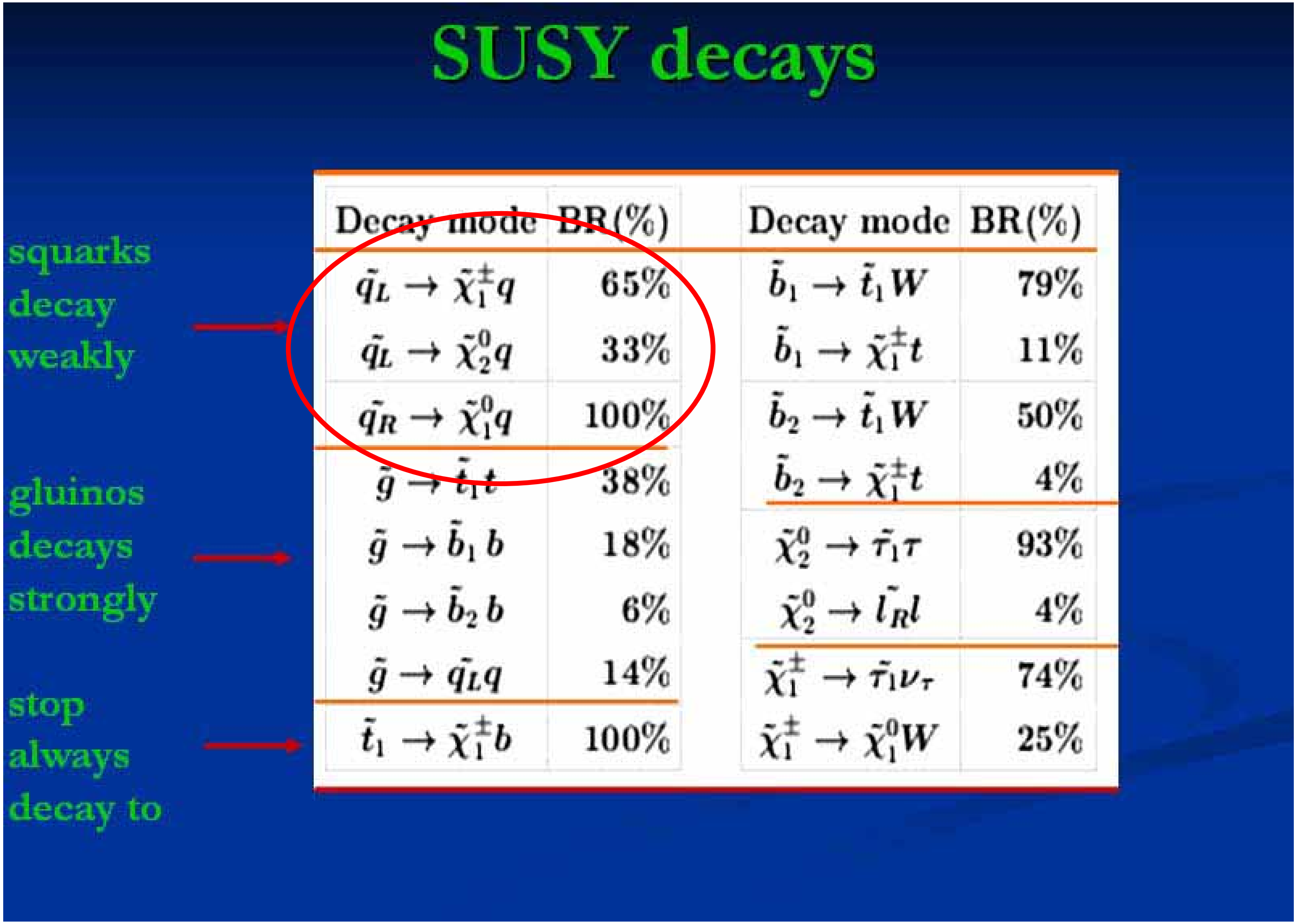
$\tilde{\chi}$	m, Γ [GeV]	decay	$\mathcal{B}$	decay	$\mathcal{B}$
$\tilde{\chi}^0_1$	97.7				
$\tilde{\chi}^0_2$	183.9 0.083	$\tilde{e}^\pm_R e^\mp$ $\tilde{\tau}^\pm_1 \tau^\mp$	0.025 0.578	$\tilde{\nu}_e \nu_e$ $\tilde{\nu}_\tau \nu_\tau$	0.116 0.152
$\tilde{\chi}^0_3$	400.5 2.4	$\tilde{\chi}^\pm_1 W^\mp$	0.582	$\tilde{\chi}^0_1 Z^0$ $\tilde{\chi}^0_2 Z^0$	0.104 0.224
$\tilde{\chi}^0_4$	413.9 2.9	$\tilde{\tau}^\pm_2 \tau^\mp$ $\tilde{\nu}_e \nu_e$ $\tilde{\nu}_\tau \nu_\tau$	0.033 0.042 0.042	$\tilde{\chi}^\pm_1 W^\mp$ $\tilde{\chi}^0_1 Z^0$ $\tilde{\chi}^0_2 Z^0$ $\tilde{\chi}^0_1 h^0$ $\tilde{\chi}^0_2 h^0$	0.511 0.022 0.024 0.070 0.165
$\tilde{\chi}^+_1$	183.7 0.077	$\tilde{\tau}^+_1 \nu_\tau$	0.536	$\tilde{\nu}_\tau \tau^+$ $\tilde{\nu}_e e^+$	0.185 0.133
$\tilde{\chi}^+_2$	415.4 3.1	$\tilde{e}^+_L \nu_e$ $\tilde{\tau}^+_2 \nu_\tau$ $\tilde{t}_1 b$	0.041 0.046 0.109	$\tilde{\chi}^0_1 W^+$ $\tilde{\chi}^0_2 W^+$ $\tilde{\chi}^+_1 Z^0$ $\tilde{\chi}^+_1 h^0$	0.063 0.252 0.221 0.181

← ~bino

← ~wino

← ~wino

SPS5 provides another good MSUGRA example



SUSY decays

squarks decay weakly →

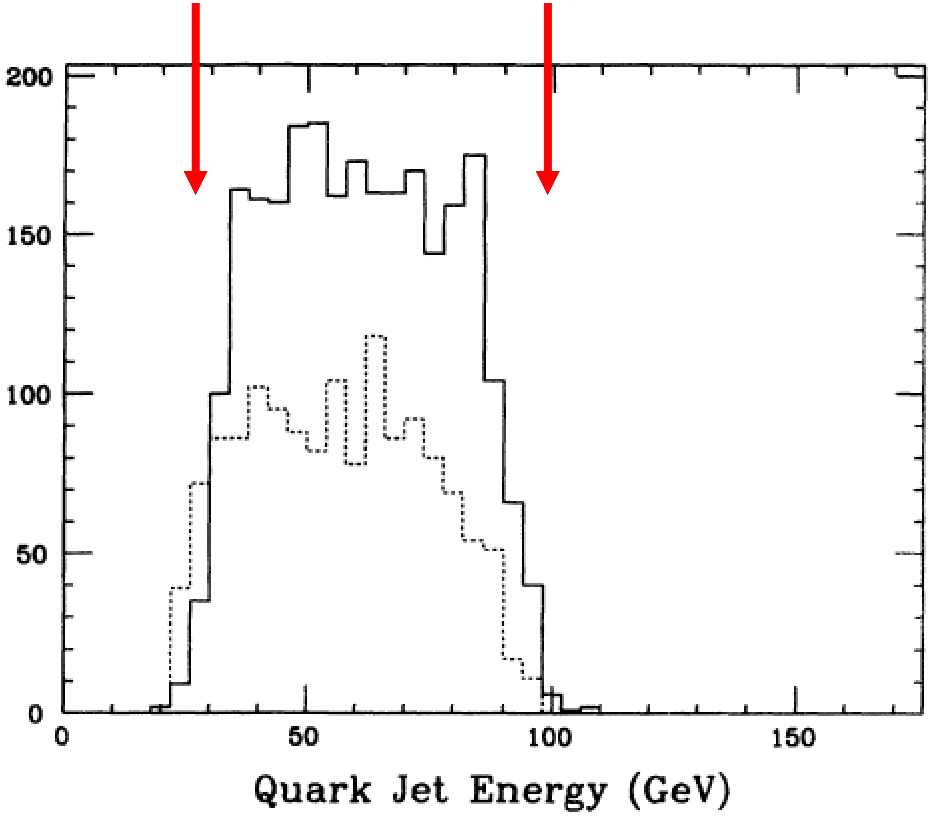
gluinos decays strongly →

stop always decay to →

Decay mode	BR(%)	Decay mode	BR(%)
$\tilde{q}_L \to \tilde{\chi}_1^\pm q$	65%	$\tilde{b}_1 \to \tilde{t}_1 W$	79%
$\tilde{q}_L \to \tilde{\chi}_2^0 q$	33%	$\tilde{b}_1 \to \tilde{\chi}_1^\pm t$	11%
$\tilde{q}_R \to \tilde{\chi}_1^0 q$	100%	$\tilde{b}_2 \to \tilde{t}_1 W$	50%
$\tilde{g} \to \tilde{t}_1 t$	38%	$\tilde{b}_2 \to \tilde{\chi}_1^\pm t$	4%
$\tilde{g} \to \tilde{b}_1 b$	18%	$\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$	93%
$\tilde{g} \to \tilde{b}_2 b$	6%	$\tilde{\chi}_2^0 \to \tilde{l}_R l$	4%
$\tilde{g} \to \tilde{q}_L q$	14%	$\tilde{\chi}_1^\pm \to \tilde{\tau}_1 \nu_\tau$	74%
$\tilde{t}_1 \to \tilde{\chi}_1^\pm b$	100%	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 W$	25%

High Energy Jets From Squarks?

E.g., the simple squark -> q χ two-body decay leads to the familiar `table' structure. The rate depends on the specifics of the mass spectrum as well as the beam polarization.



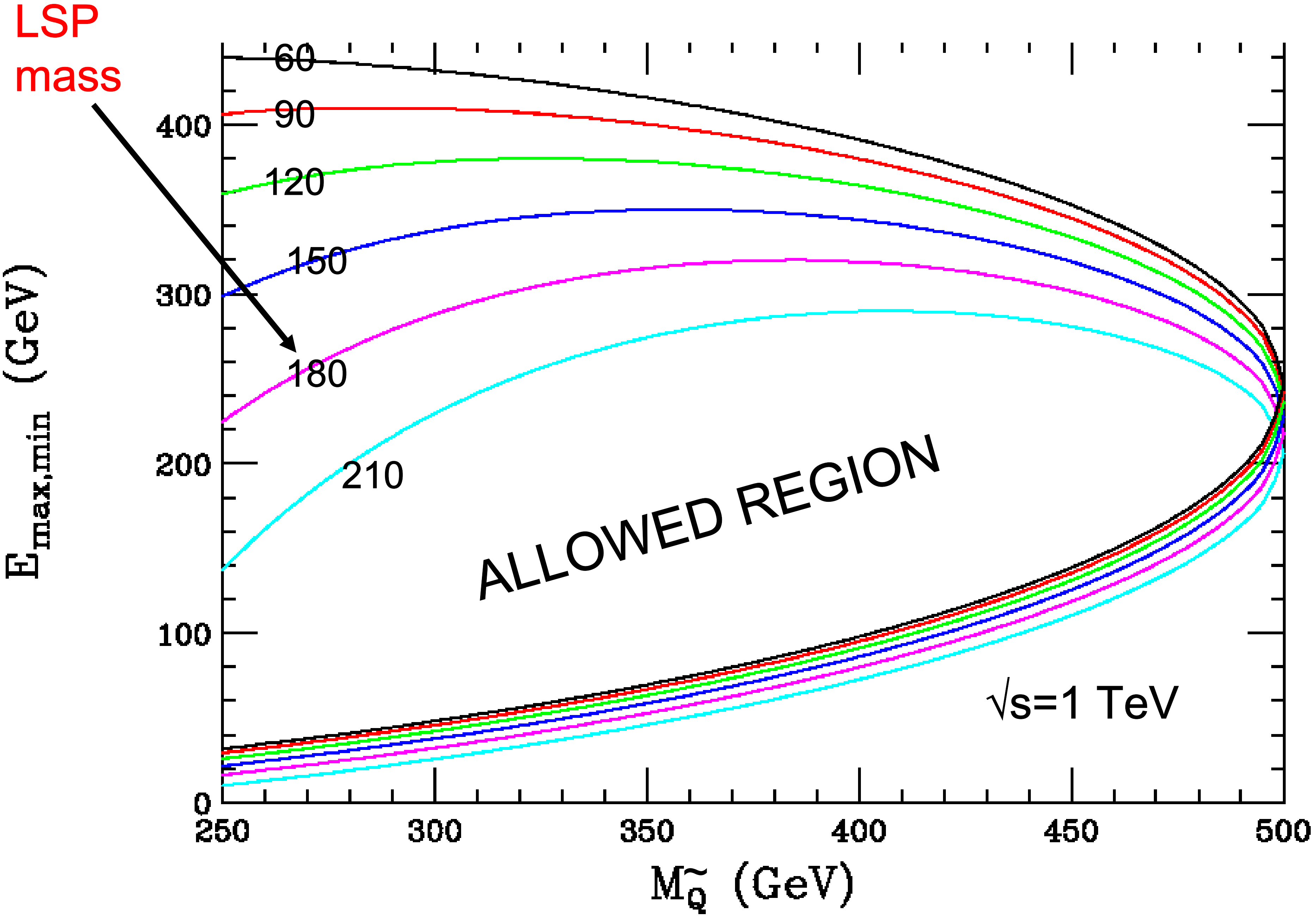
Mixings in the chargino & neutralino sectors are also important in order to determine the full cascade decay chain

The observed production & decay will have all modes contributing simultaneously

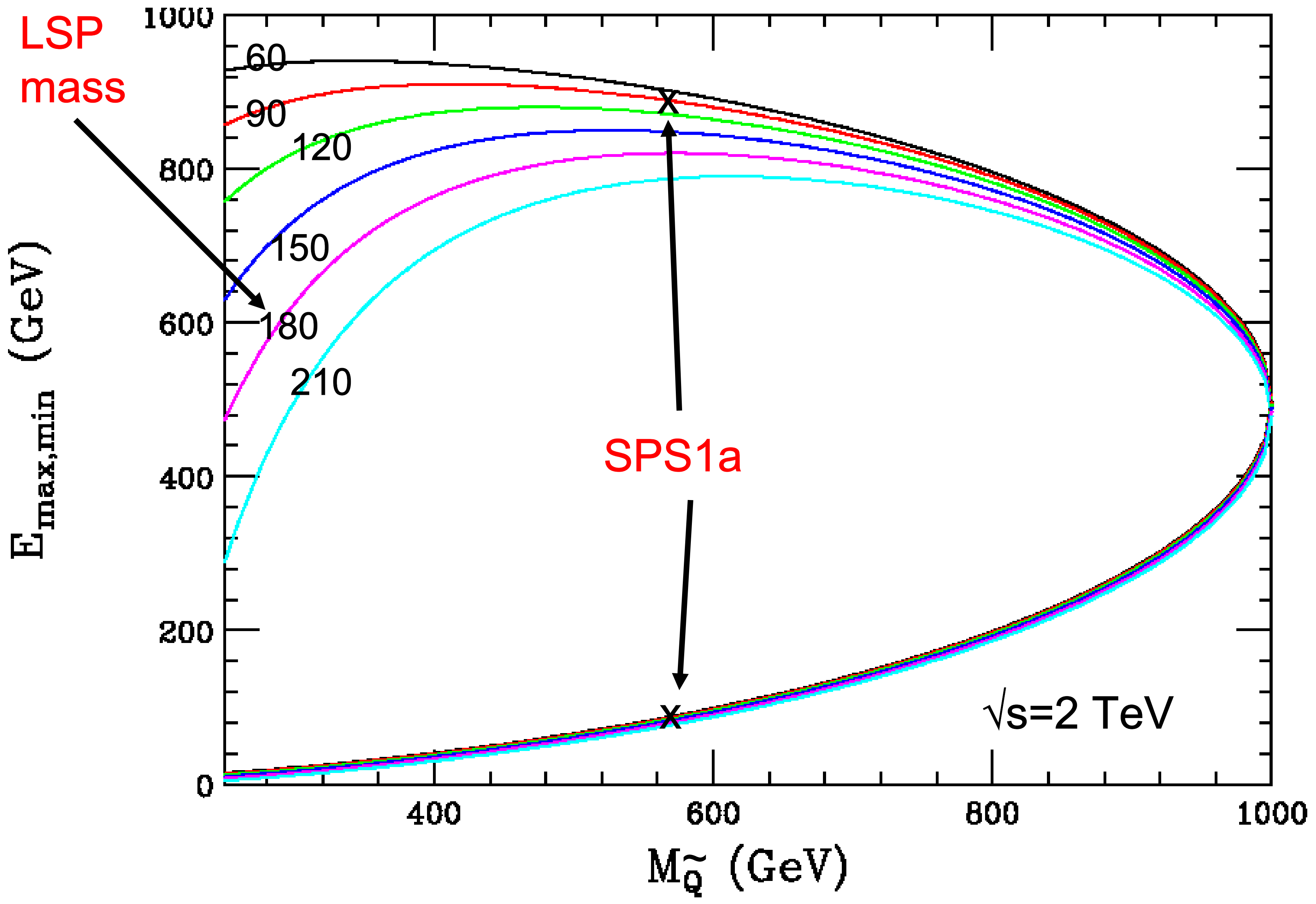
The end points tell us the squark mass

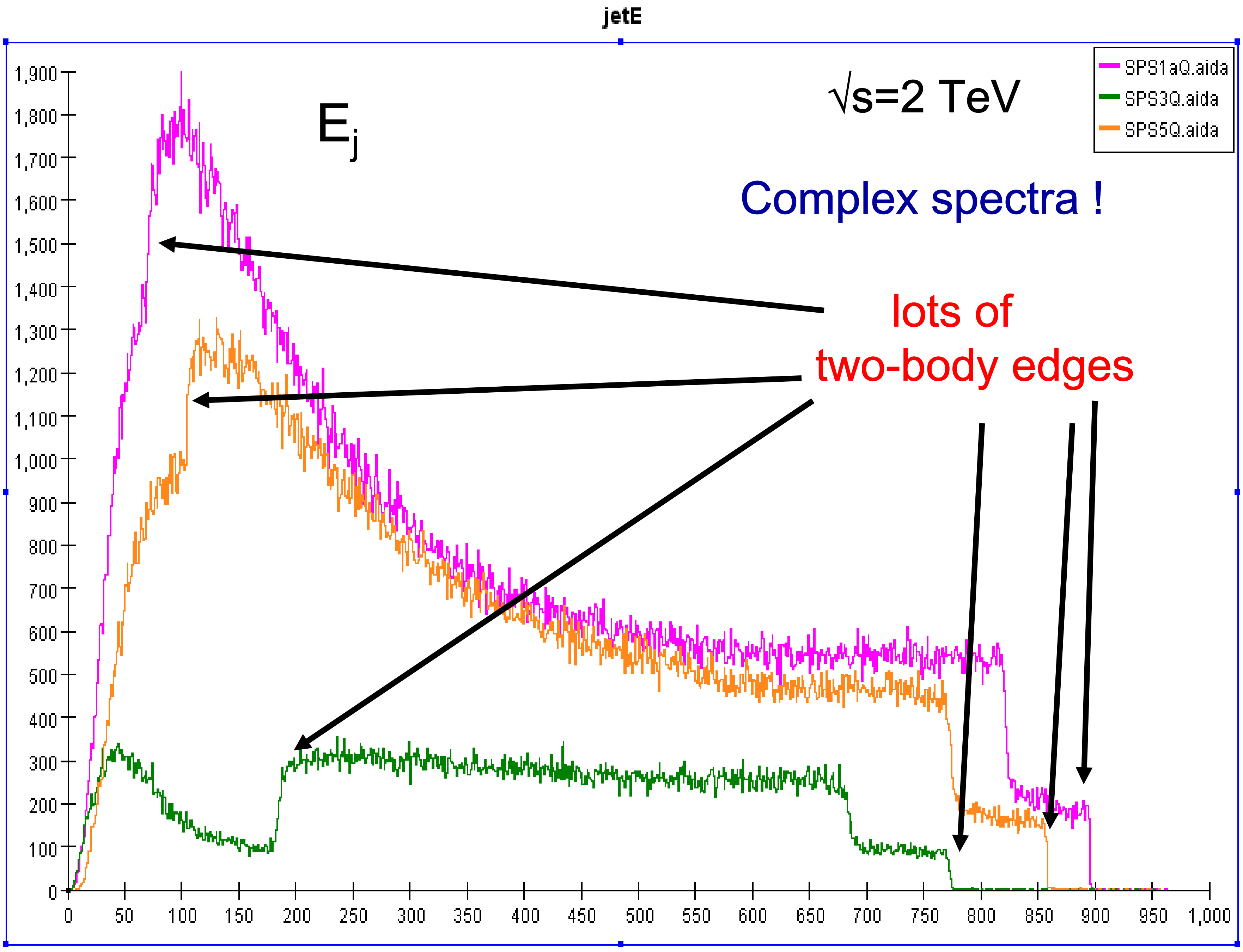
Feng & Finnell '93

Jet Energies in Two-Body Squark Decay



Jet Energies in Two-Body Squark Decay

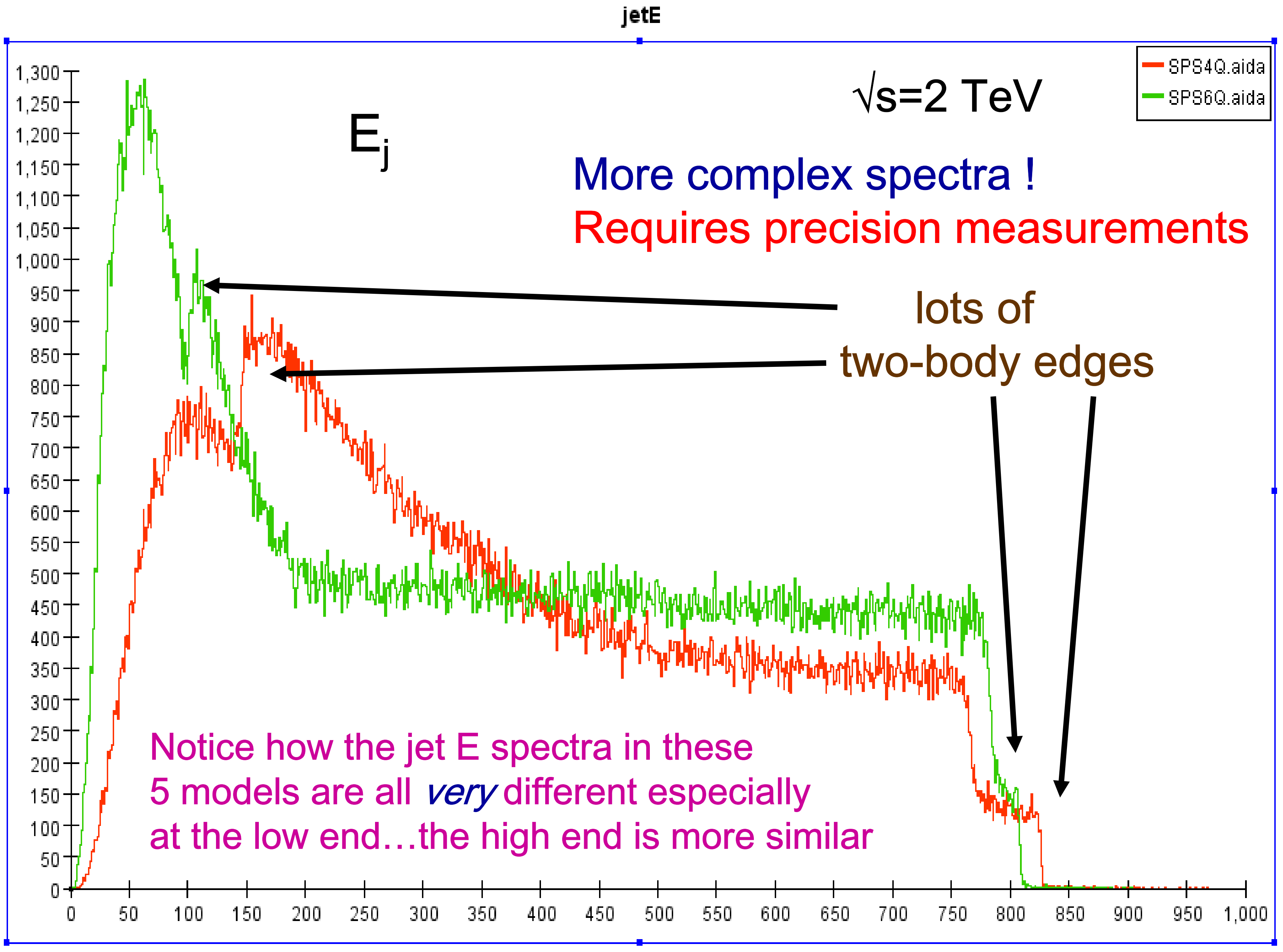




$\sqrt{s}=2$ TeV

Complex spectra !

lots of
two-body edges



E_j

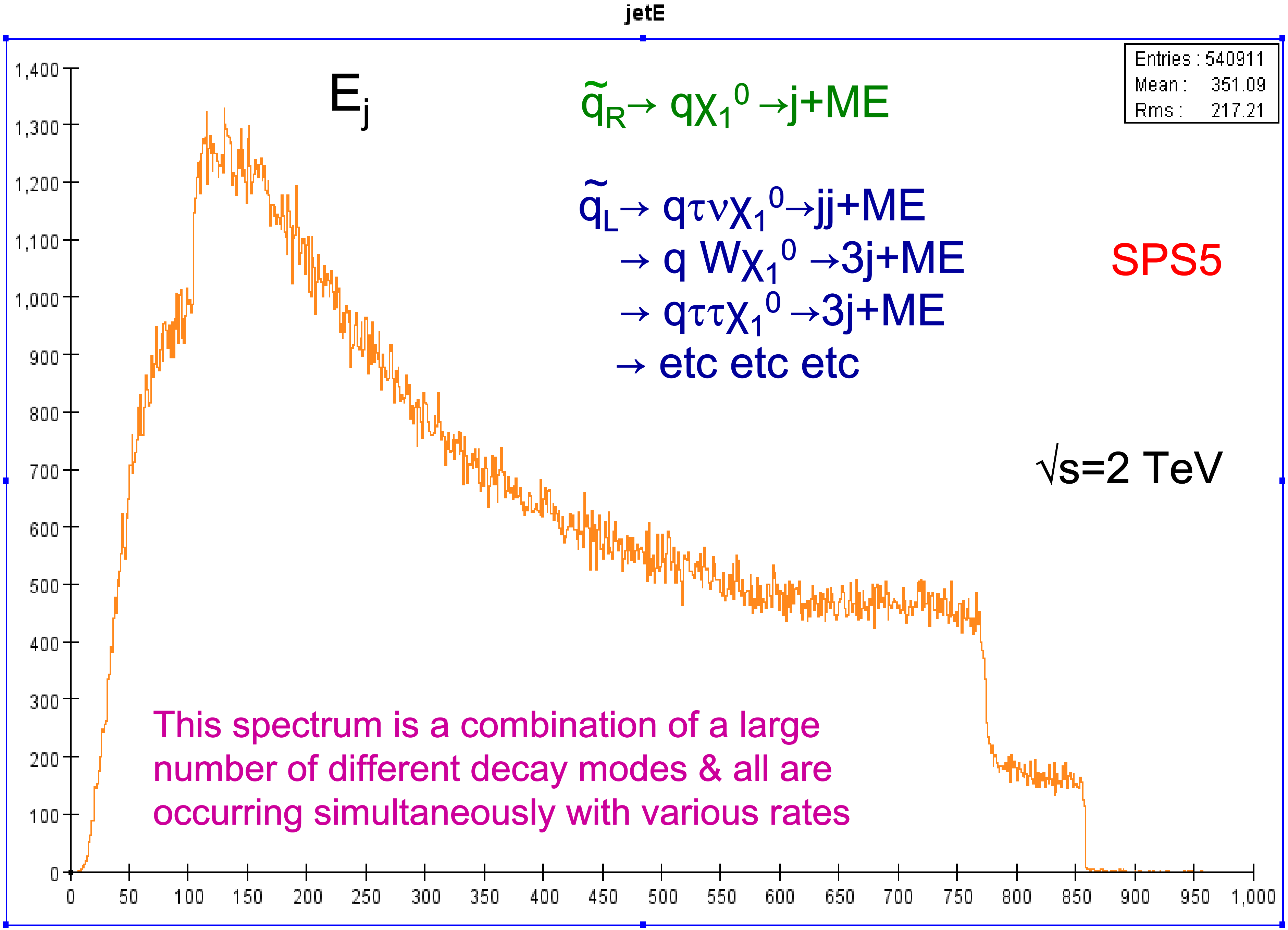
$\sqrt{s}$=2 TeV

More complex spectra !

Requires precision measurements

lots of
two-body edges

Notice how the jet E spectra in these
5 models are all *very* different especially
at the low end…the high end is more similar



E_j

$\tilde{q}_R \rightarrow q\chi_1^0 \rightarrow j+ME$

$\tilde{q}_L \rightarrow q\tau\nu\chi_1^0 \rightarrow jj+ME$

$\rightarrow q\, W\chi_1^0 \rightarrow 3j+ME$

$\rightarrow q\tau\tau\chi_1^0 \rightarrow 3j+ME$

→ etc etc etc

SPS5

$\sqrt{s}=2$ TeV

This spectrum is a combination of a large number of different decay modes & all are occurring simultaneously with various rates

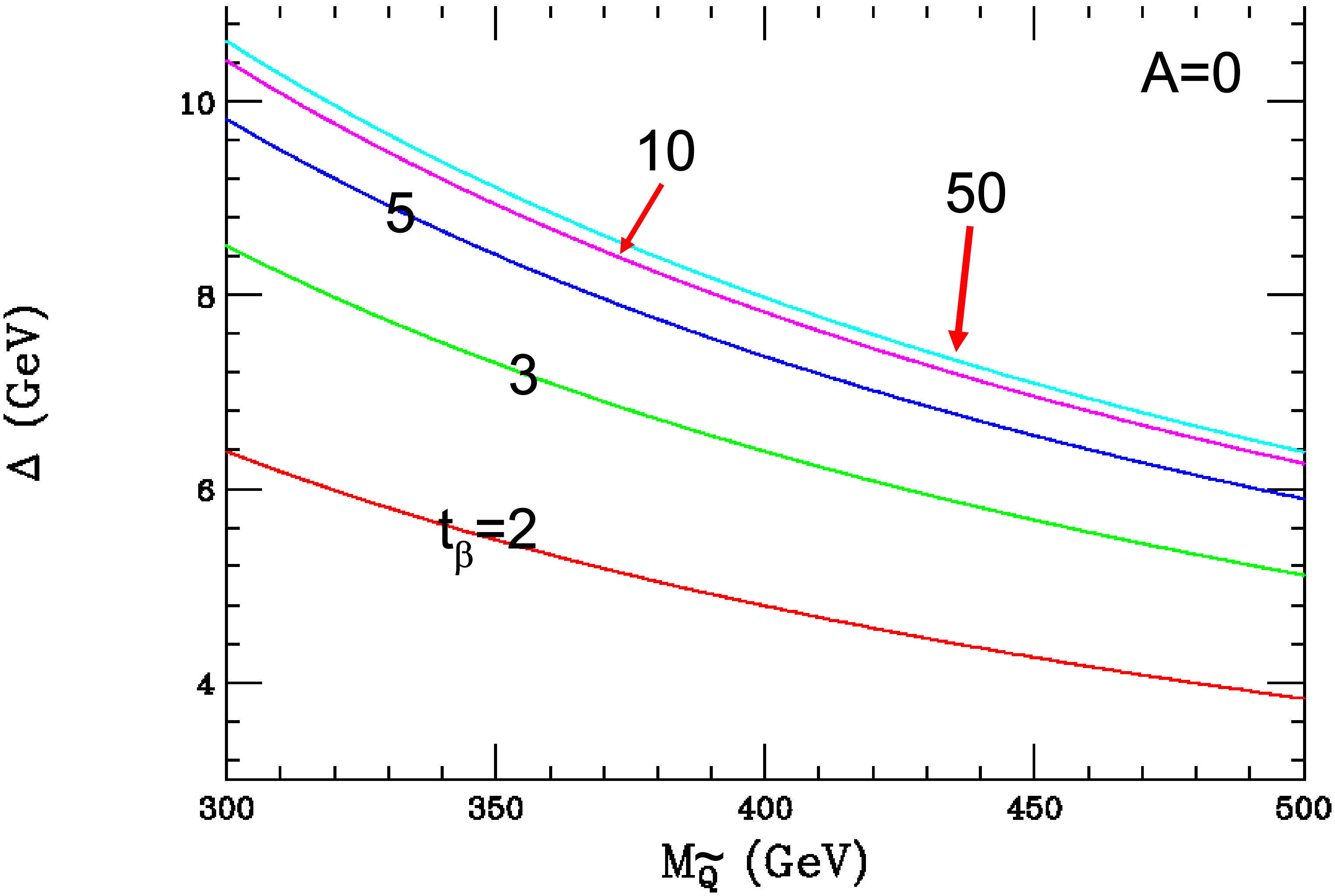
An Aside on Backgrounds:

In a *real* analysis of this two-body decay mode, most all of both the SUSY as well as SM backgrounds can be removed by (i) demanding only two acoplanar jets with large $\Delta\phi$ and no leptons or photons, (ii) $E_{miss} > 150$ GeV, (iii) removing events with dijet pair masses less than 100 GeV.

All in all this signal is *far* cleaner than the corresponding one for selectrons and certain chargino modes.

d_L-u_L squark mass splitting

Can this be measured??? Jet E resolution may be important



Small
mass
splitting
for
large
masses

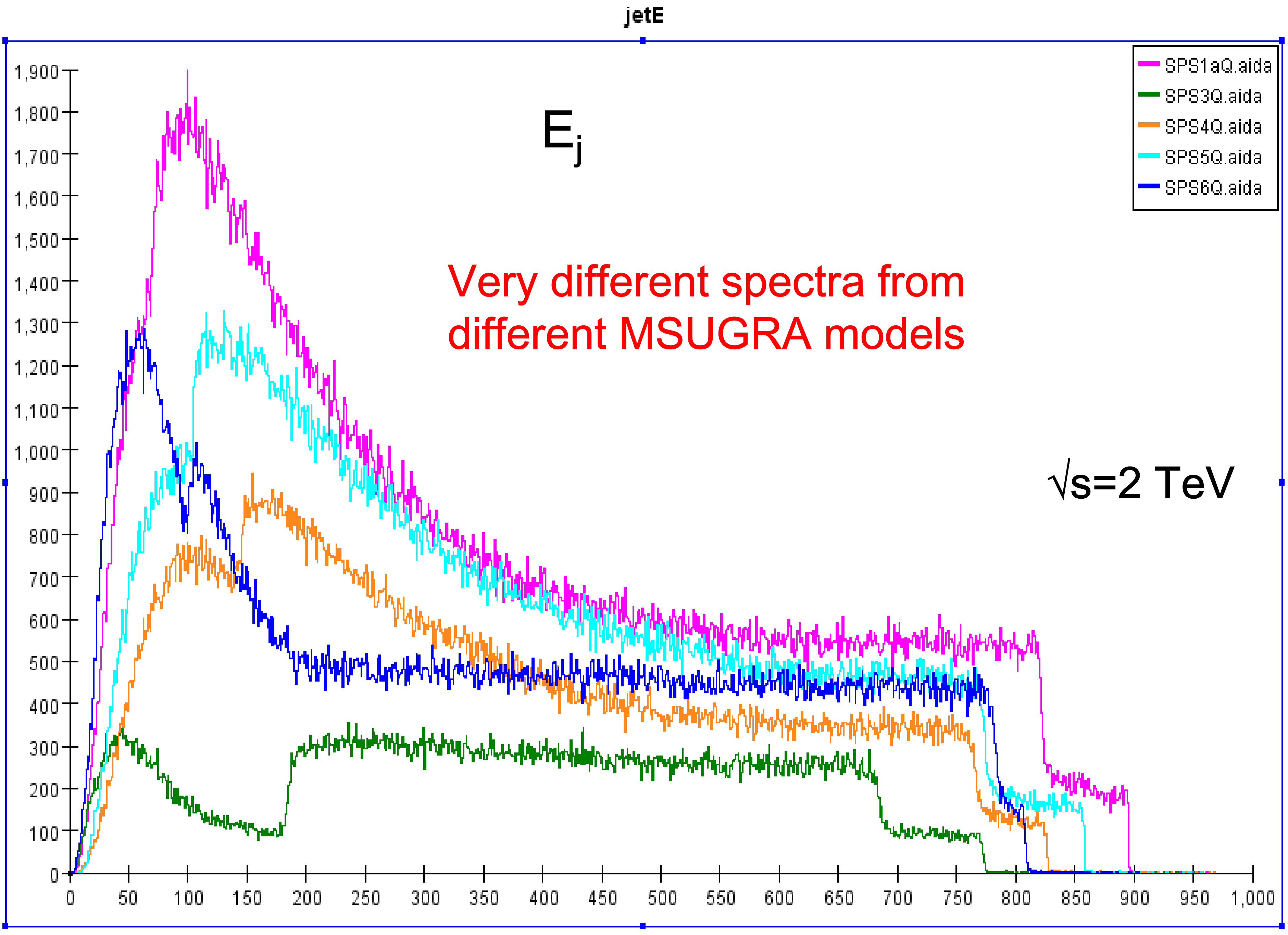
Summary

- The study of the first two generation squark properties at a LC would add very important information about SUSY breaking physics and the nature of the high scale underlying theory.

- The decays of squarks naturally lead to a rich spectrum of jets in the final state from various competing modes. Some of these jets can be hard, approaching the beam energy, particularly for two-body decays to j+LSP. MSUGRA (as well as other SUSY breaking scenarios, but not, e.g., in AMSB) *almost* universally leads to such final states for RH udsc squarks. However, this does depend on the details of the spectrum and the mixing in the gaugino sector.

- Model-independent studies are lacking as are detailed studies of 1st & 2nd generation squark production at a LC

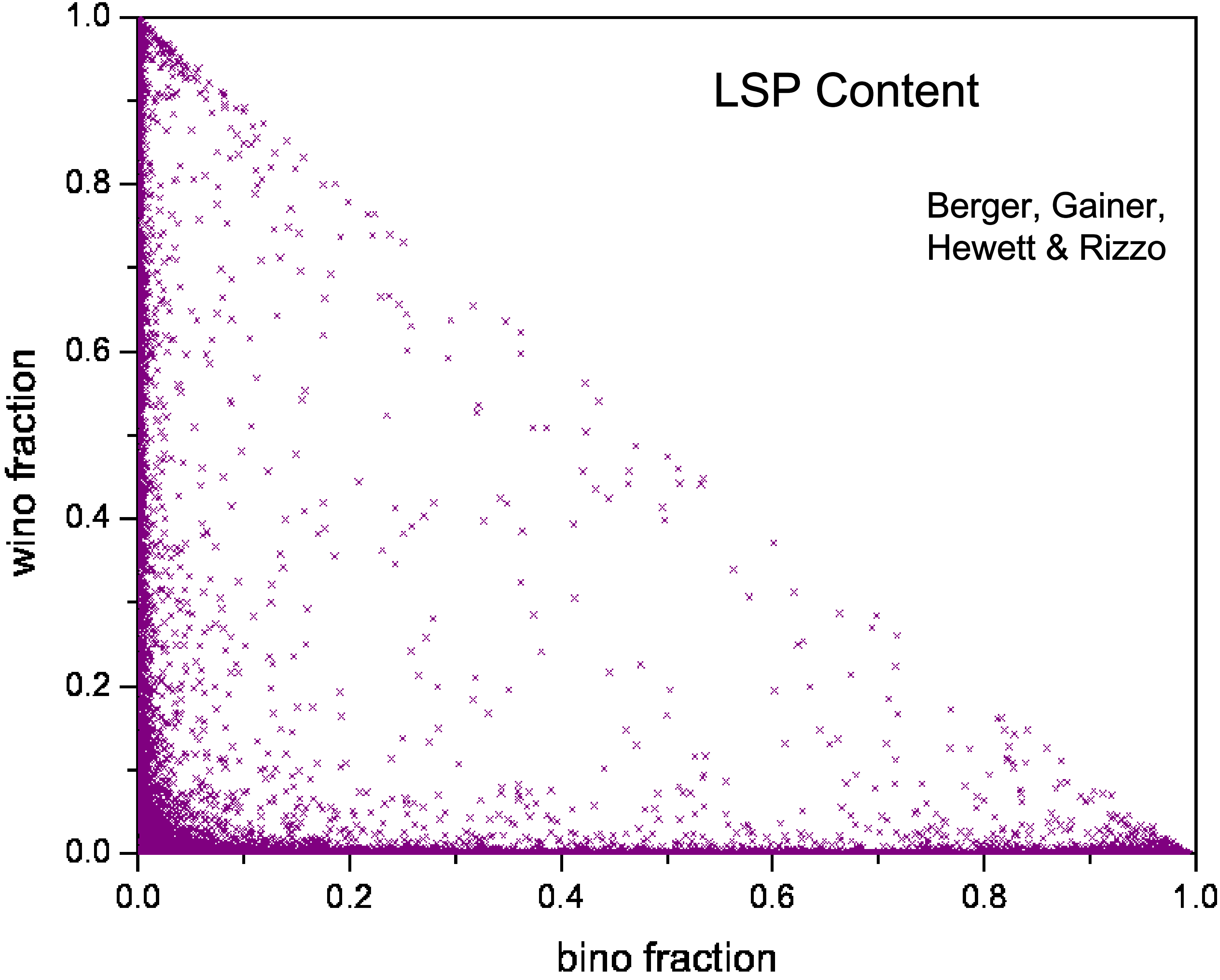
BACKUP SLIDES

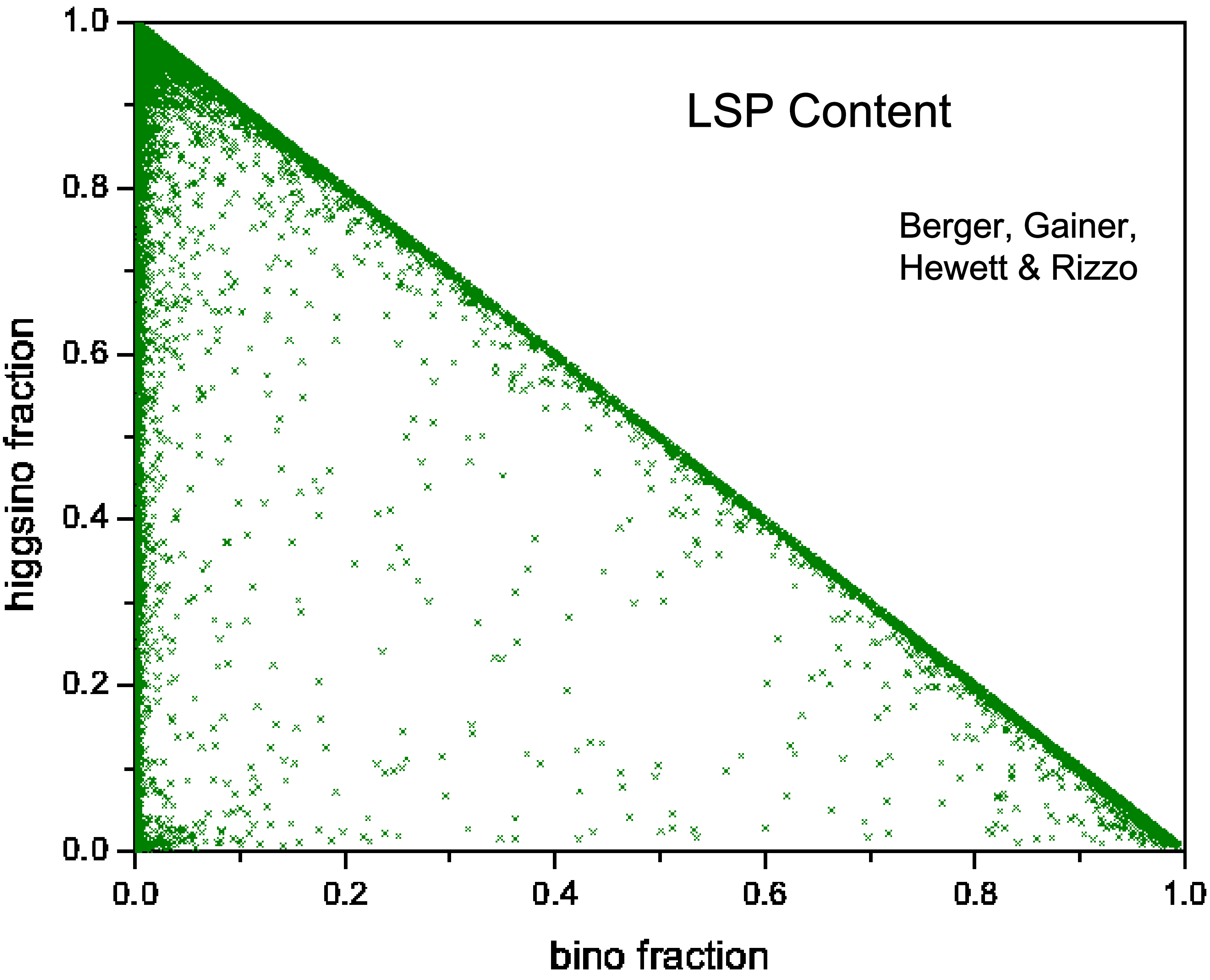


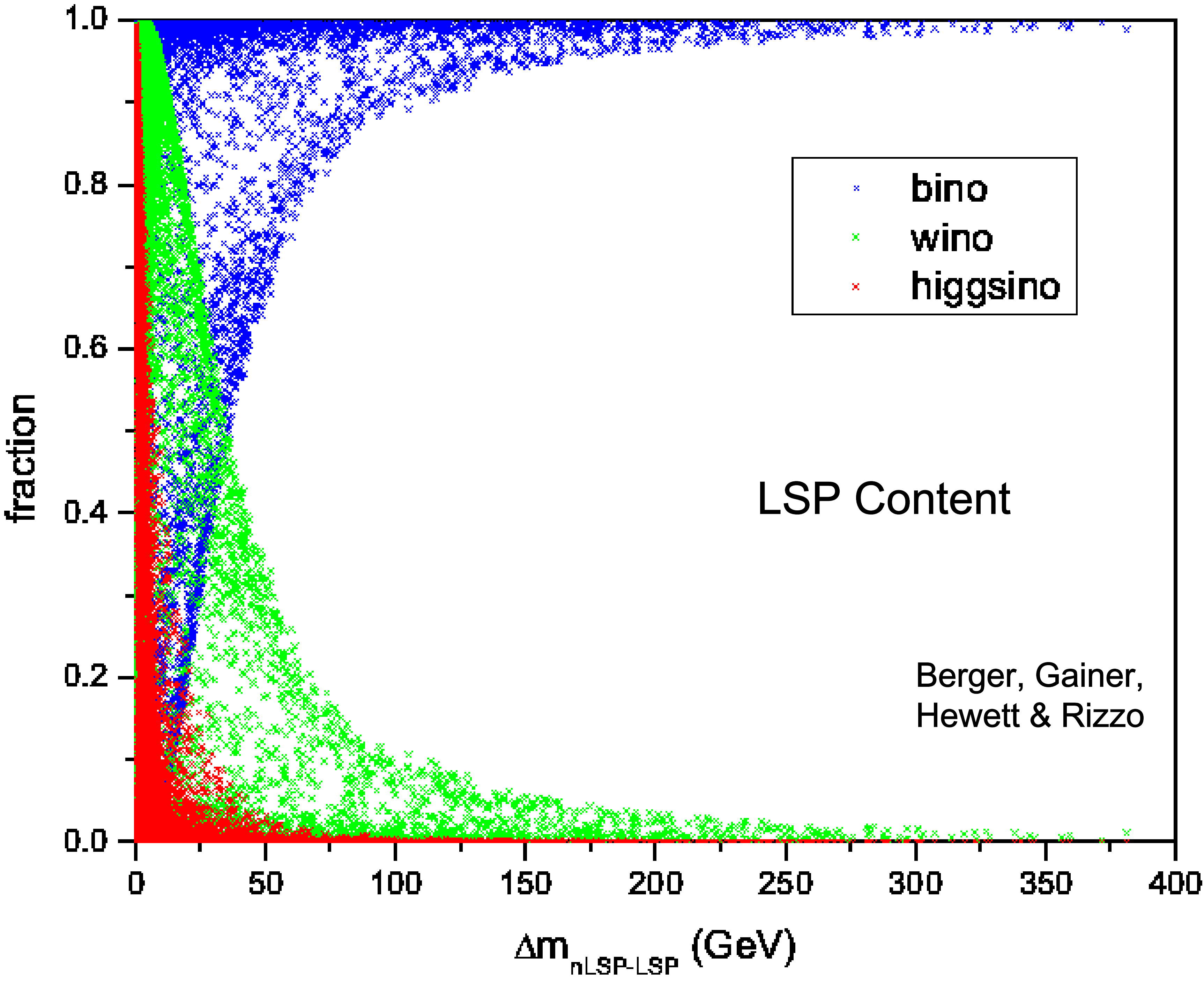
E_j

Very different spectra from different MSUGRA models

$\sqrt{s}=2$ TeV


LSP Content
Berger, Gainer,
Hewett & Rizzo
wino fraction
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
bino fraction


LSP Content
Berger, Gainer,
Hewett & Rizzo
higgsino fraction
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
bino fraction


bino
wino
higgsino
LSP Content
Berger, Gainer,
Hewett & Rizzo
fraction
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350
400
$\Delta m_{nLSP-LSP}$ (GeV)