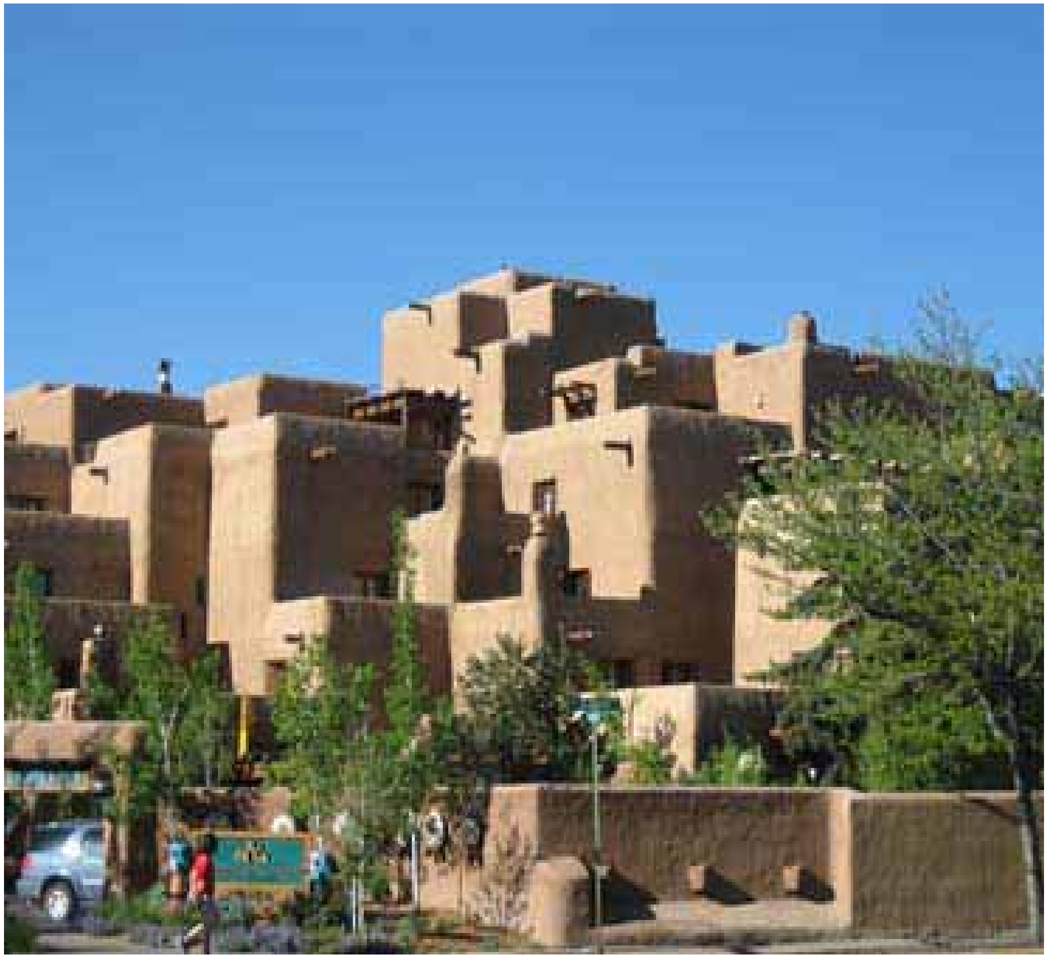
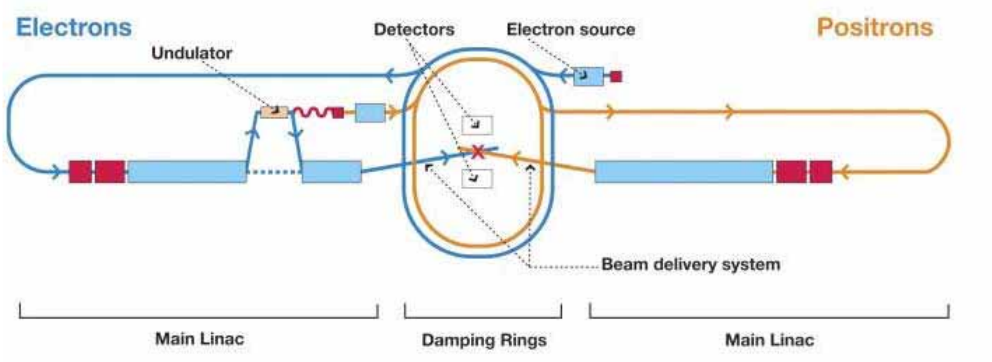
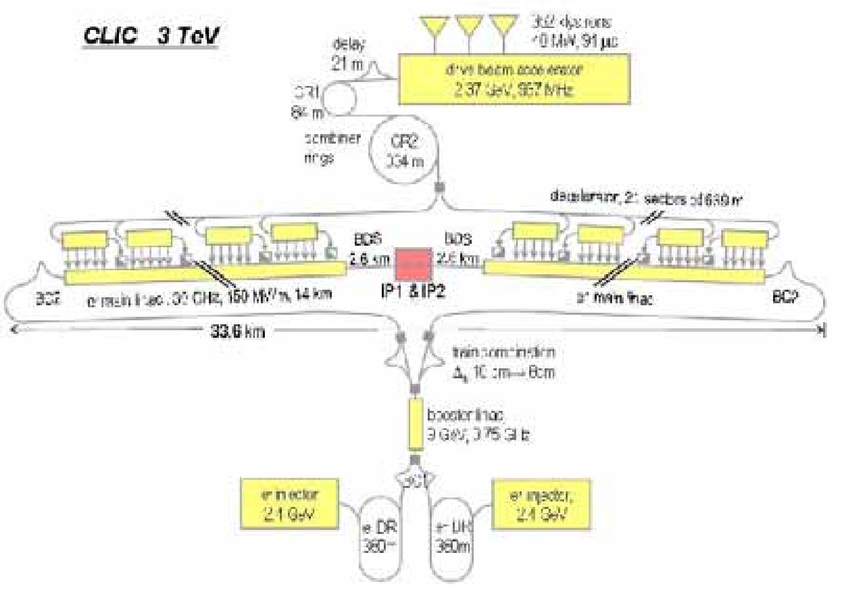
Squarks and Gluinos @ TeV e^+e^- Colliders







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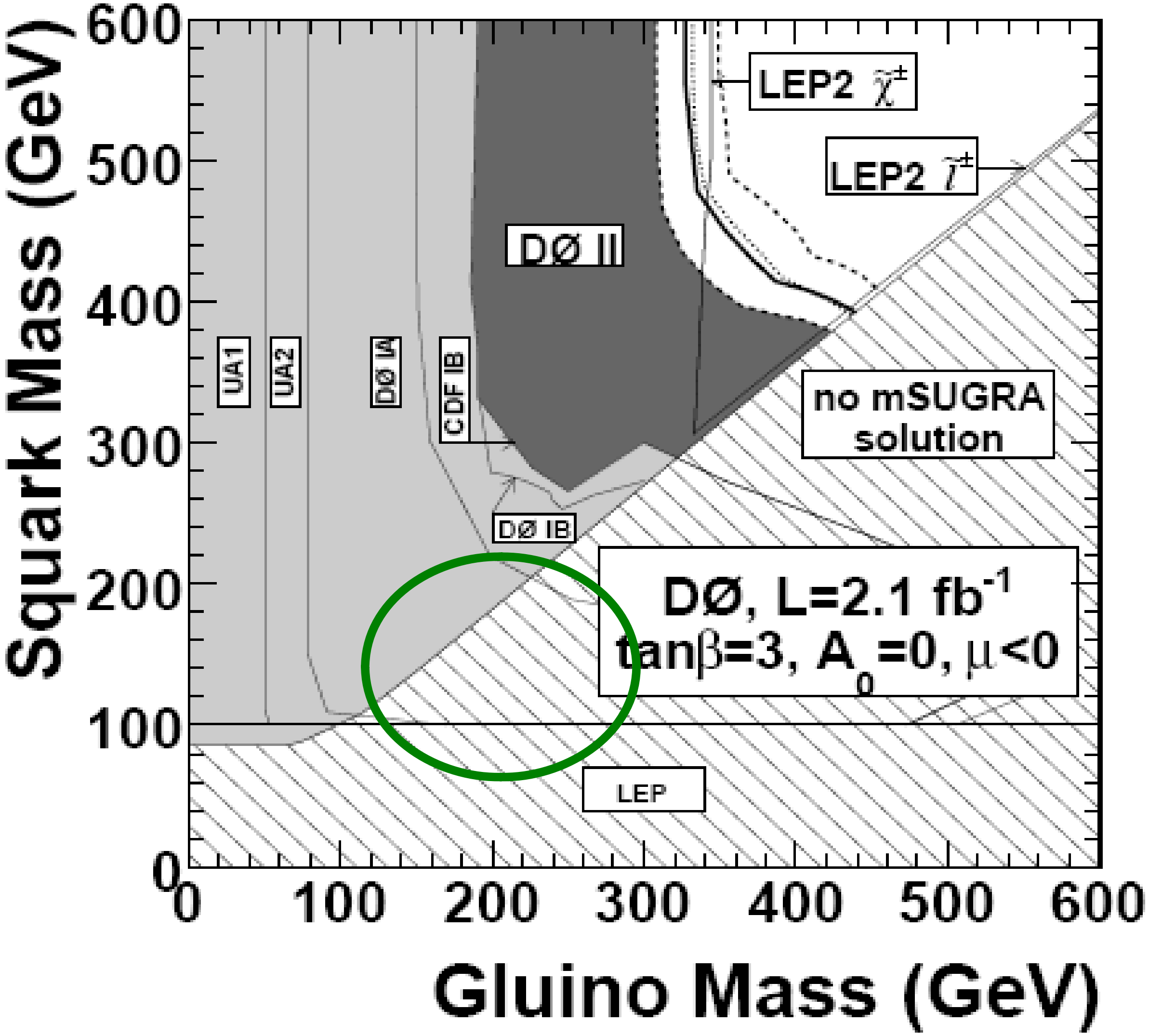
Message # 1 :

It is important to remember that even if the MSSM is realized in nature, it is NOT likely to be the simple mSUGRA scenario & it definitely will NOT be SPS1a’ ! !

Nature is too clever for that….

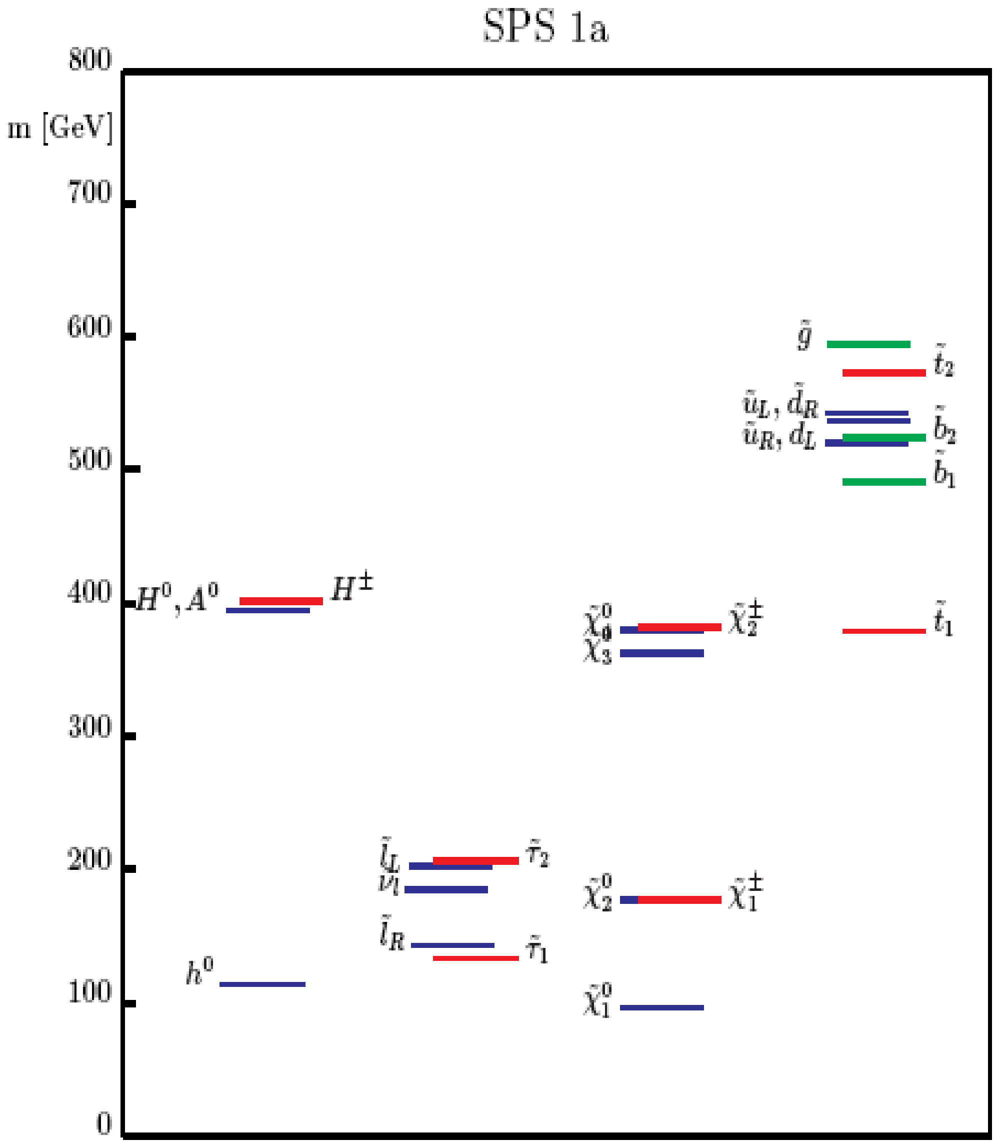
Gluinos & squarks in the 1st & 2nd generation have not been much discussed in the context of TeV e^+e^- colliders for several reasons :

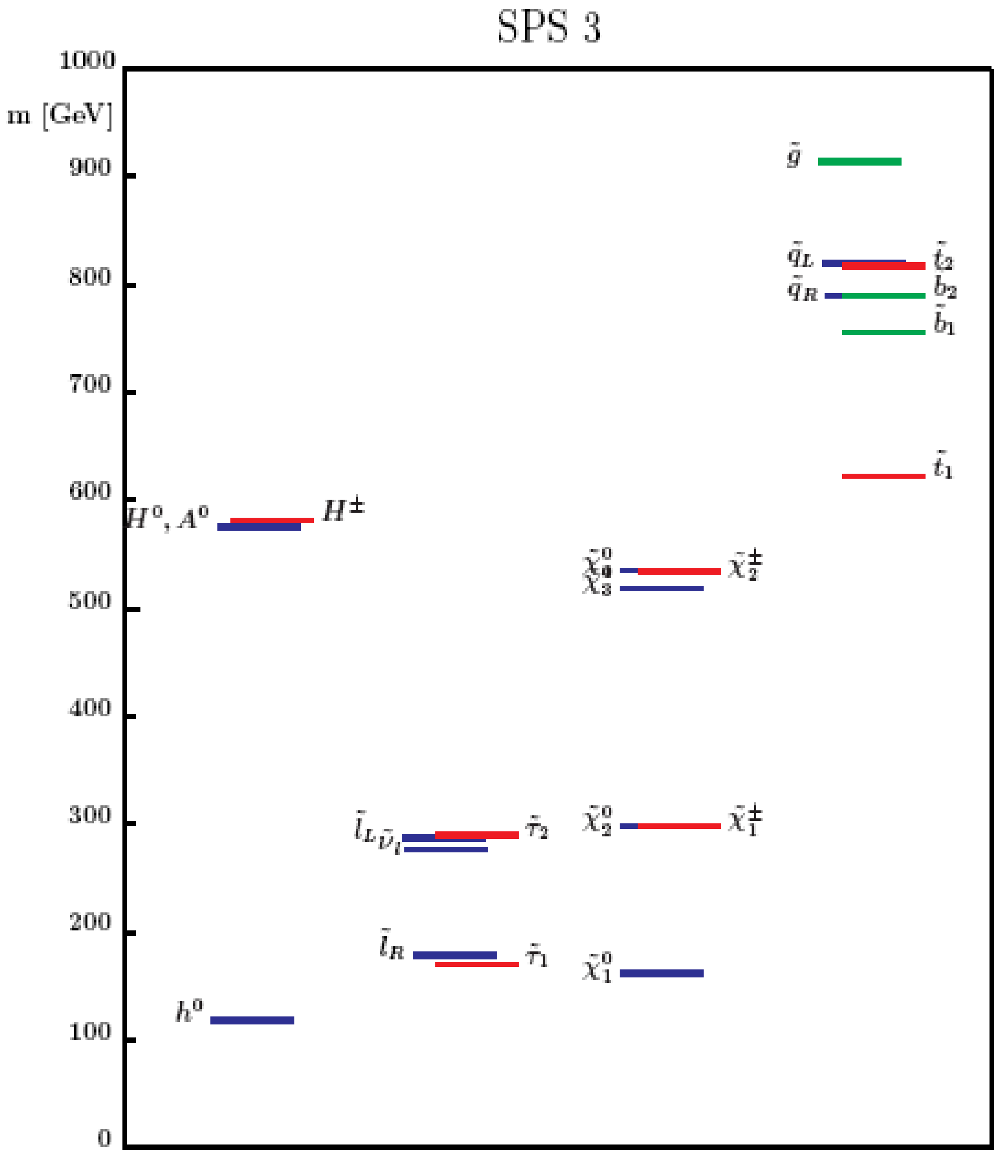


(i) Tevatron searches provide some strong constraints on *mSUGRA..* squarks & gluinos masses >350-400 GeV & so possibly beyond the range of even a 1 TeV collider.

But this result is NOT GENERAL !!!

(ii) Commonly used benchmark points in many past studies always have somewhat heavy squarks & gluinos, e.g., the SPS points, which lie beyond the reach of a 1 TeV collider :





..or, e.g., the ATLAS SUSY (mSUGRA-based!) benchmark points..

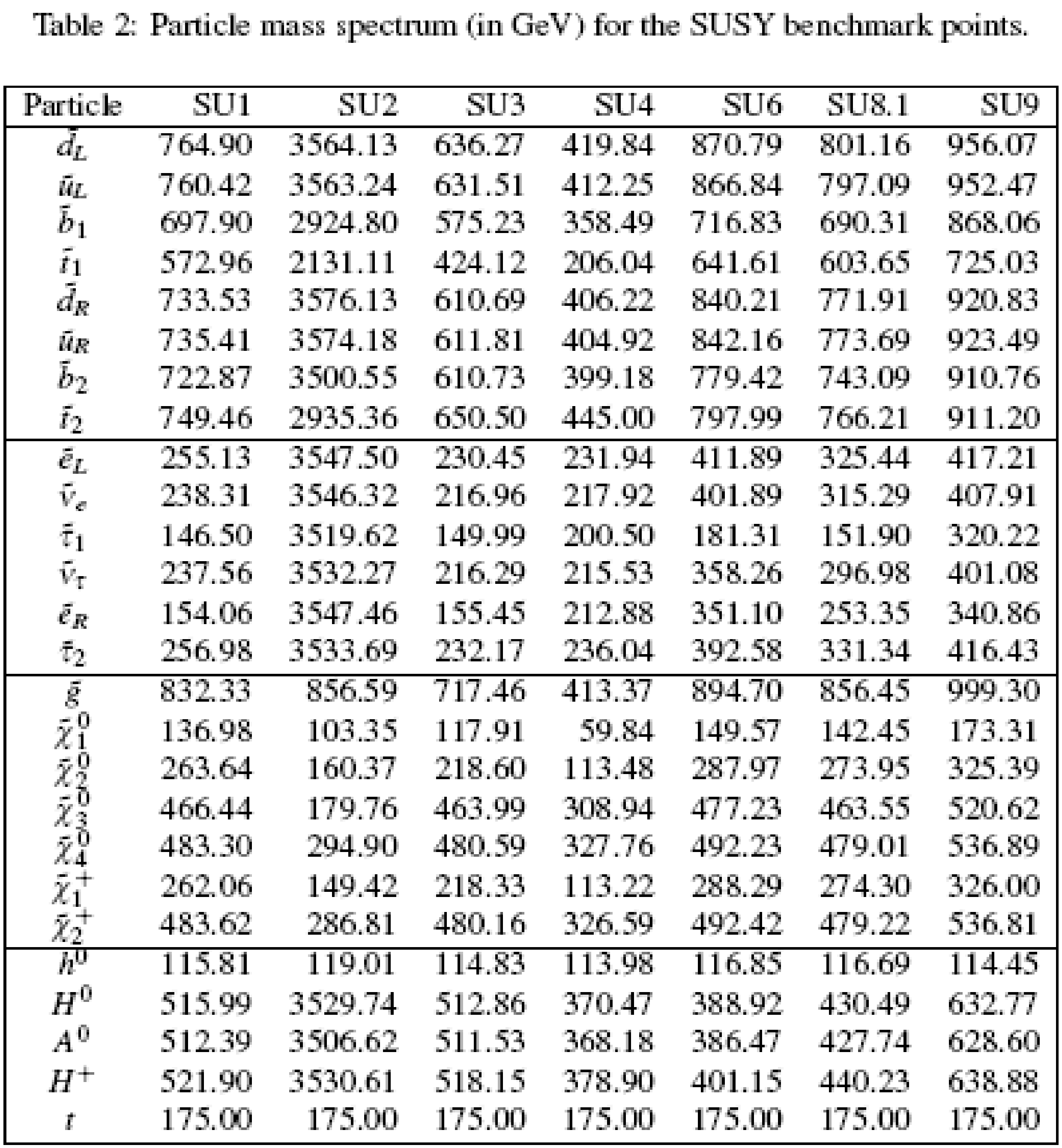
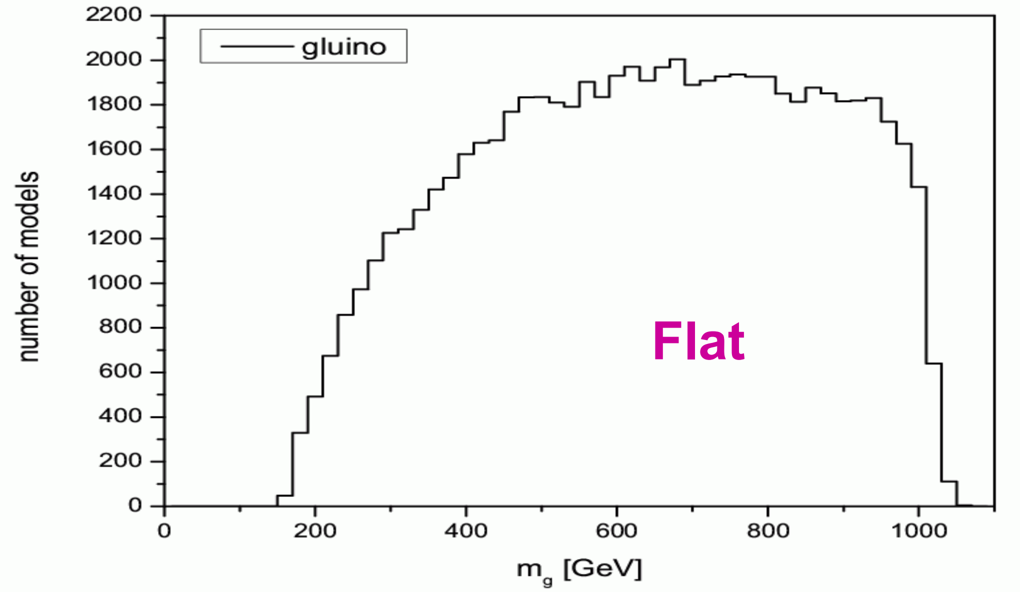


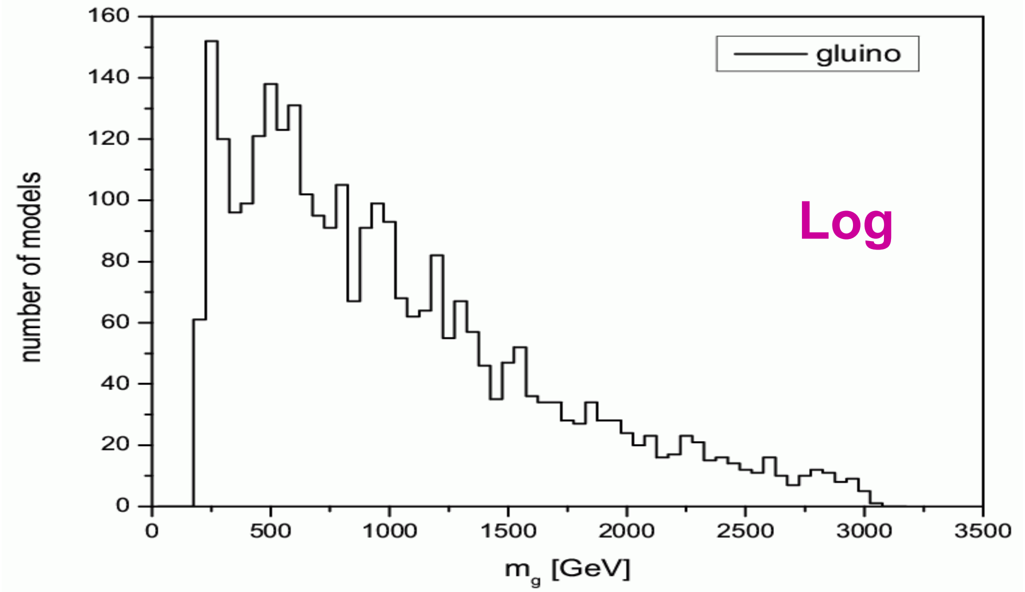
Table 2: Particle mass spectrum (in GeV) for the SUSY benchmark points.

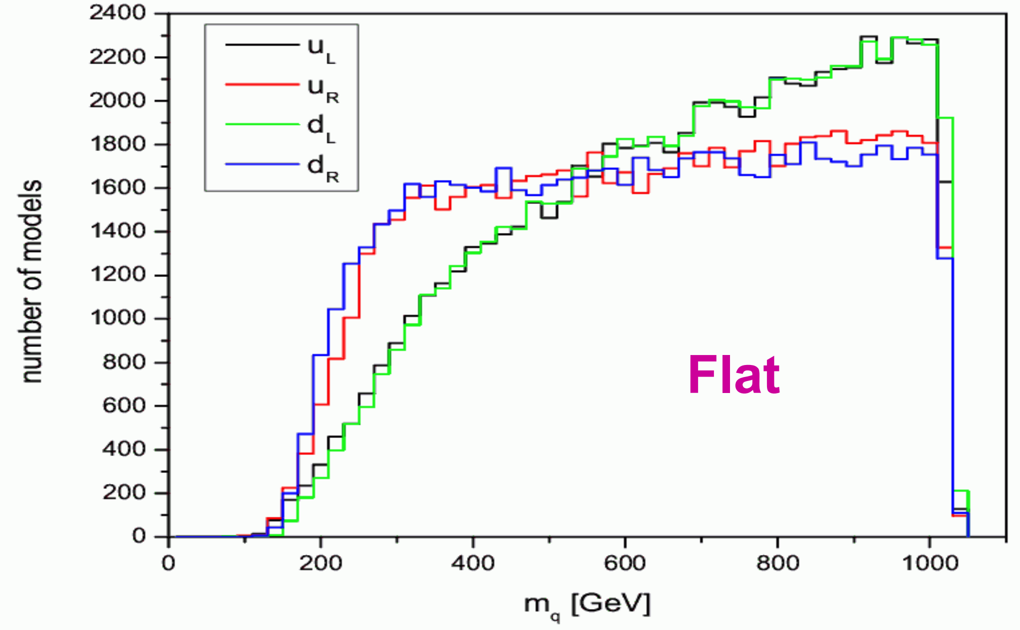
Particle	SU1	SU2	SU3	SU4	SU6	SU8.1	SU9
$\tilde{d}_L$	764.90	3564.13	636.27	419.84	870.79	801.16	956.07
$\tilde{u}_L$	760.42	3563.24	631.51	412.25	866.84	797.09	952.47
$\tilde{b}_1$	697.90	2924.80	575.23	358.49	716.83	690.31	868.06
$\tilde{t}_1$	572.96	2131.11	424.12	206.04	641.61	603.65	725.03
$\tilde{d}_R$	733.53	3576.13	610.69	406.22	840.21	771.91	920.83
$\tilde{u}_R$	735.41	3574.18	611.81	404.92	842.16	773.69	923.49
$\tilde{b}_2$	722.87	3500.55	610.73	399.18	779.42	743.09	910.76
$\tilde{t}_2$	749.46	2935.36	650.50	445.00	797.99	766.21	911.20
$\tilde{e}_L$	255.13	3547.50	230.45	231.94	411.89	325.44	417.21
$\tilde{\nu}_e$	238.31	3546.32	216.96	217.92	401.89	315.29	407.91
$\tilde{\tau}_1$	146.50	3519.62	149.99	200.50	181.31	151.90	320.22
$\tilde{\nu}_\tau$	237.56	3532.27	216.29	215.53	358.26	296.98	401.08
$\tilde{e}_R$	154.06	3547.46	155.45	212.88	351.10	253.35	340.86
$\tilde{\tau}_2$	256.98	3533.69	232.17	236.04	392.58	331.34	416.43
$\tilde{g}$	832.33	856.59	717.46	413.37	894.70	856.45	999.30
$\tilde{\chi}_1^0$	136.98	103.35	117.91	59.84	149.57	142.45	173.31
$\tilde{\chi}_2^0$	263.64	160.37	218.60	113.48	287.97	273.95	325.39
$\tilde{\chi}_3^0$	466.44	179.76	463.99	308.94	477.23	463.55	520.62
$\tilde{\chi}_4^0$	483.30	294.90	480.59	327.76	492.23	479.01	536.89
$\tilde{\chi}_1^+$	262.06	149.42	218.33	113.22	288.29	274.30	326.00
$\tilde{\chi}_2^+$	483.62	286.81	480.16	326.59	492.42	479.22	536.81
h^0	115.81	119.01	114.83	113.98	116.85	116.69	114.45
H^0	515.99	3529.74	512.86	370.47	388.92	430.49	632.77
A^0	512.39	3506.62	511.53	368.18	386.47	427.74	628.60
H^+	521.90	3530.61	518.15	378.90	401.15	440.23	638.88
t	175.00	175.00	175.00	175.00	175.00	175.00	175.00

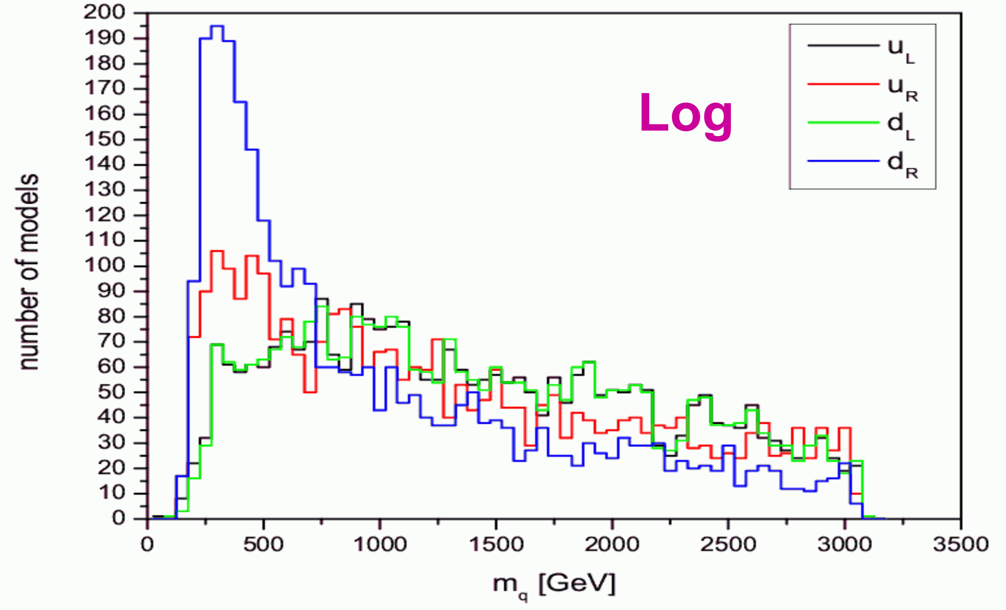
This is a bias !!

A more general, less prejudiced consideration **of the SUSY parameter space allows for lighter squarks & gluinos that avoid all existing experimental constraints:

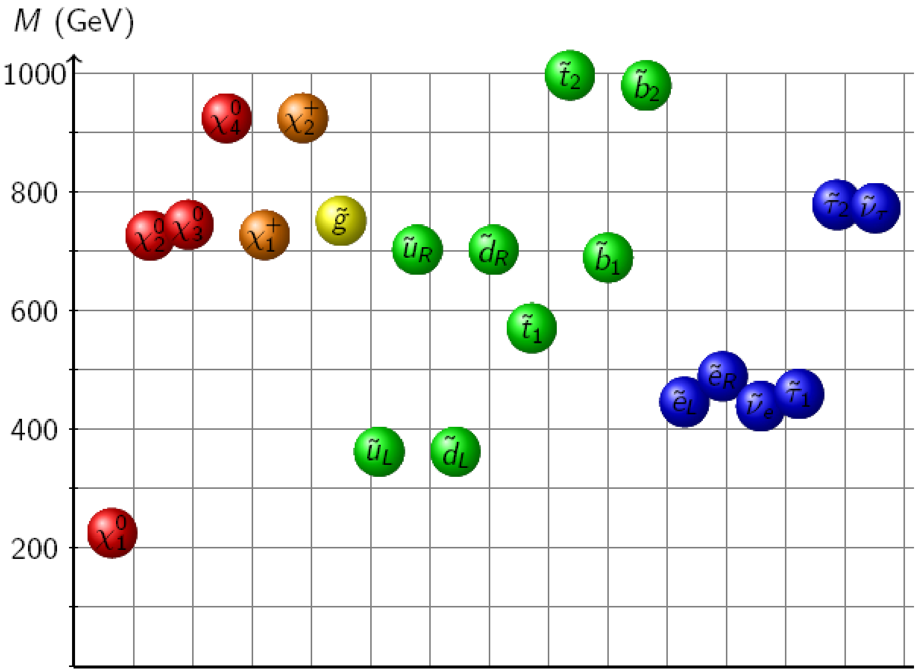








** Berger, Hewett ,Gainer & TGR



M (GeV)
1000
800
600
400
200
χ_4^0
χ_2^+
$\tilde{t}_2$
$\tilde{b}_2$
χ_2^0
χ_3^0
χ_1^+
$\tilde{g}$
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{b}_1$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{t}_1$
$\tilde{e}_R$
$\tilde{e}_L$
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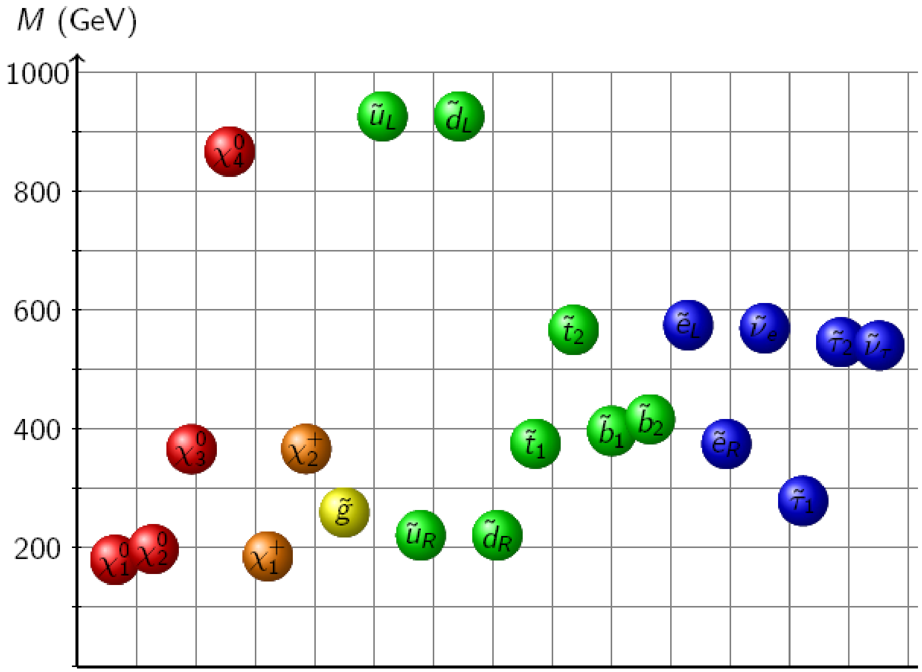
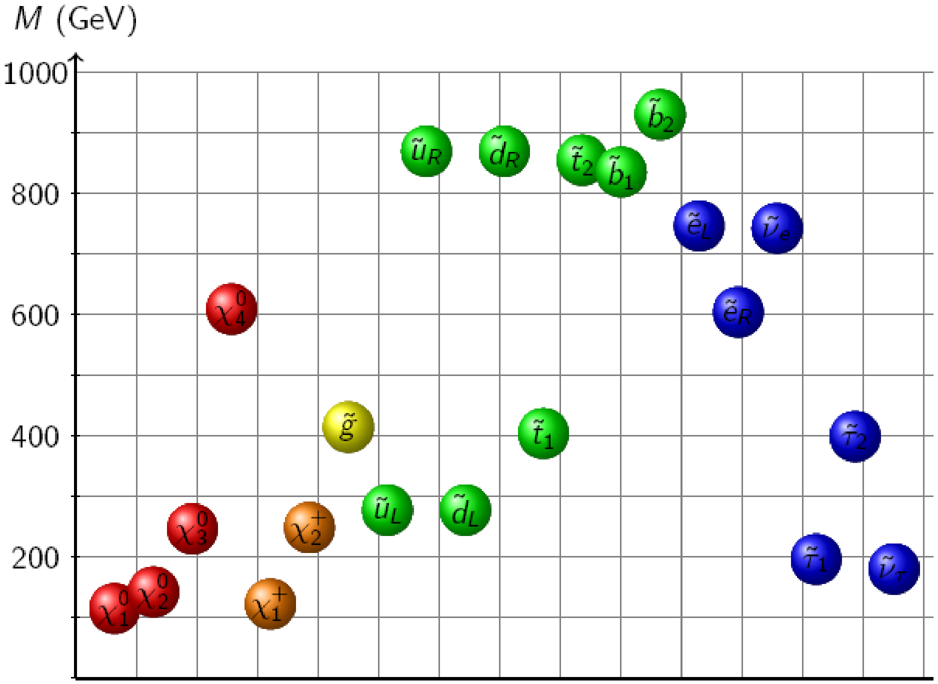
$\tilde{\tau}_1$
$\tilde{u}_L$
$\tilde{d}_L$
χ_1^0



M (GeV)
1000
800
600
400
200
$\tilde{u}_L$
$\tilde{d}_L$
χ_4^0
$\tilde{t}_2$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{b}_2$
$\tilde{b}_1$
χ_3^0
χ_2^+
$\tilde{t}_1$
$\tilde{e}_R$
$\tilde{g}$
$\tilde{\tau}_1$
$\tilde{u}_R$
$\tilde{d}_R$
χ_1^0
χ_2^0
χ_1^+



M (GeV)
1000
800
600
400
200
$\tilde{b}_2$
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{e}_L$
$\tilde{\nu}_e$
χ_4^0
$\tilde{e}_R$
$\tilde{g}$
$\tilde{t}_1$
$\tilde{\tau}_2$
χ_3^0
χ_2^+
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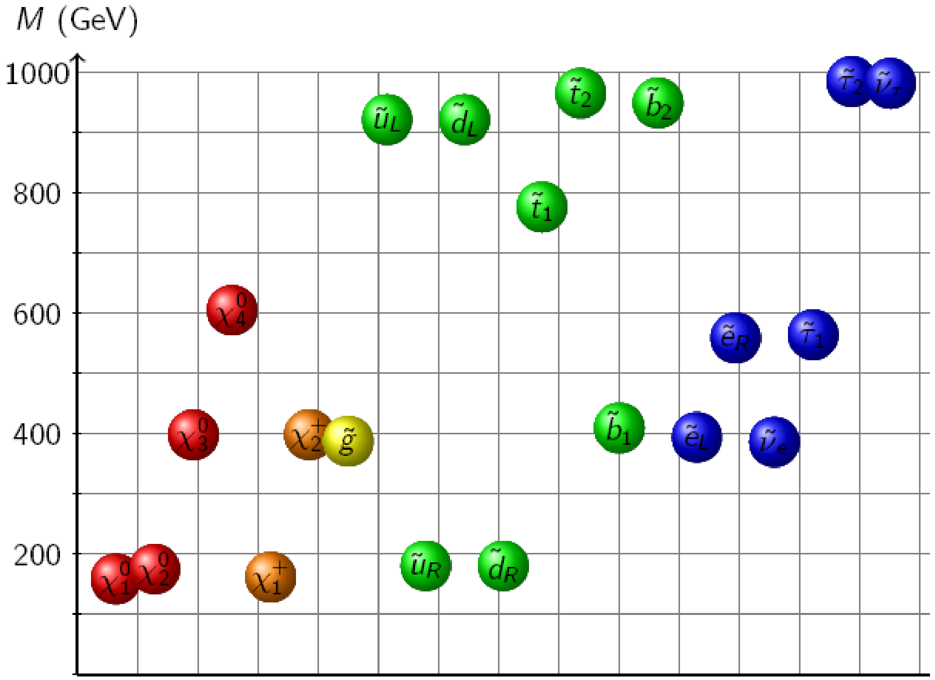
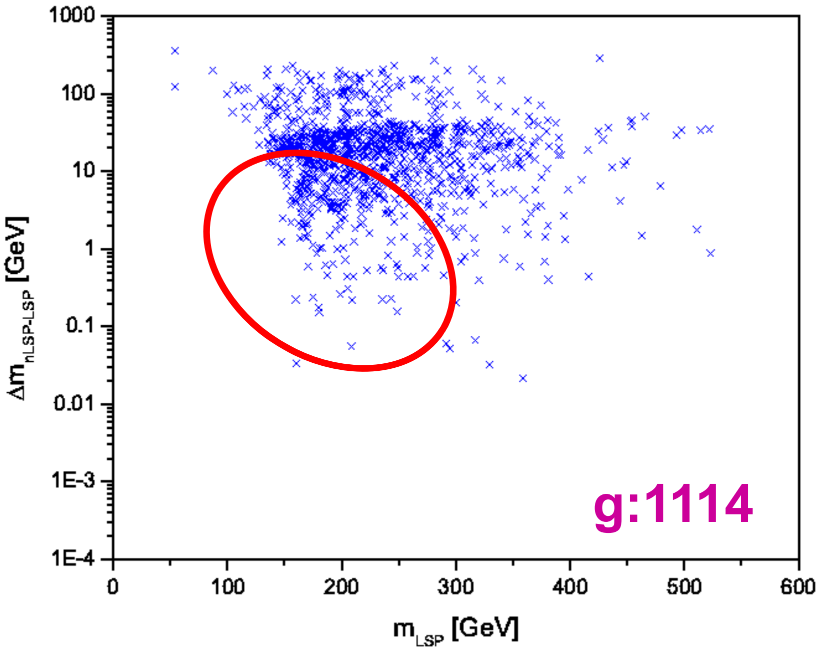
$\tilde{\tau}_1$
$\tilde{\nu}_\tau$
χ_2^0
χ_1^0
χ_1^+

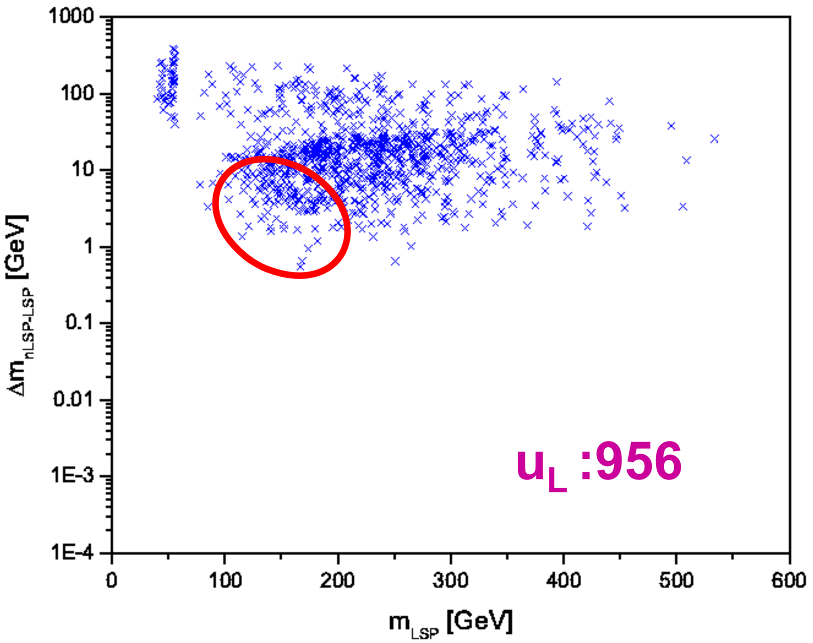


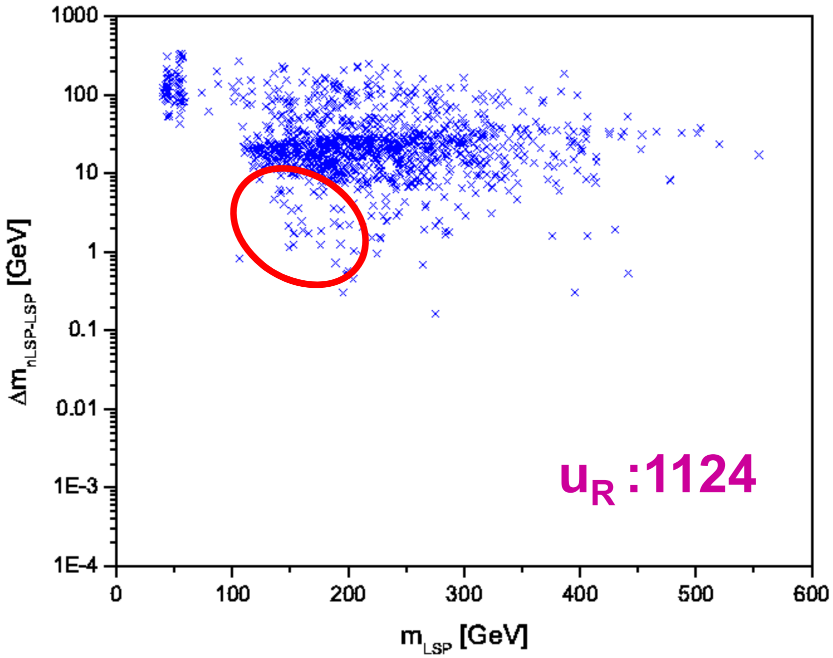
M (GeV)
1000
800
600
400
200
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{t}_2$
$\tilde{b}_2$
$\tilde{u}_L$
$\tilde{d}_L$
$\tilde{t}_1$
χ_4^0
$\tilde{e}_R$
$\tilde{\tau}_1$
$\tilde{b}_1$
χ_3^0
χ_2^+
$\tilde{g}$
$\tilde{e}_L$
$\tilde{\nu}_e$
χ_1^0
χ_2^0
χ_1^+
$\tilde{u}_R$
$\tilde{d}_R$

In many cases, but not exclusively, this is due to the small splittings between the squarks and/or gluinos and the LSP…

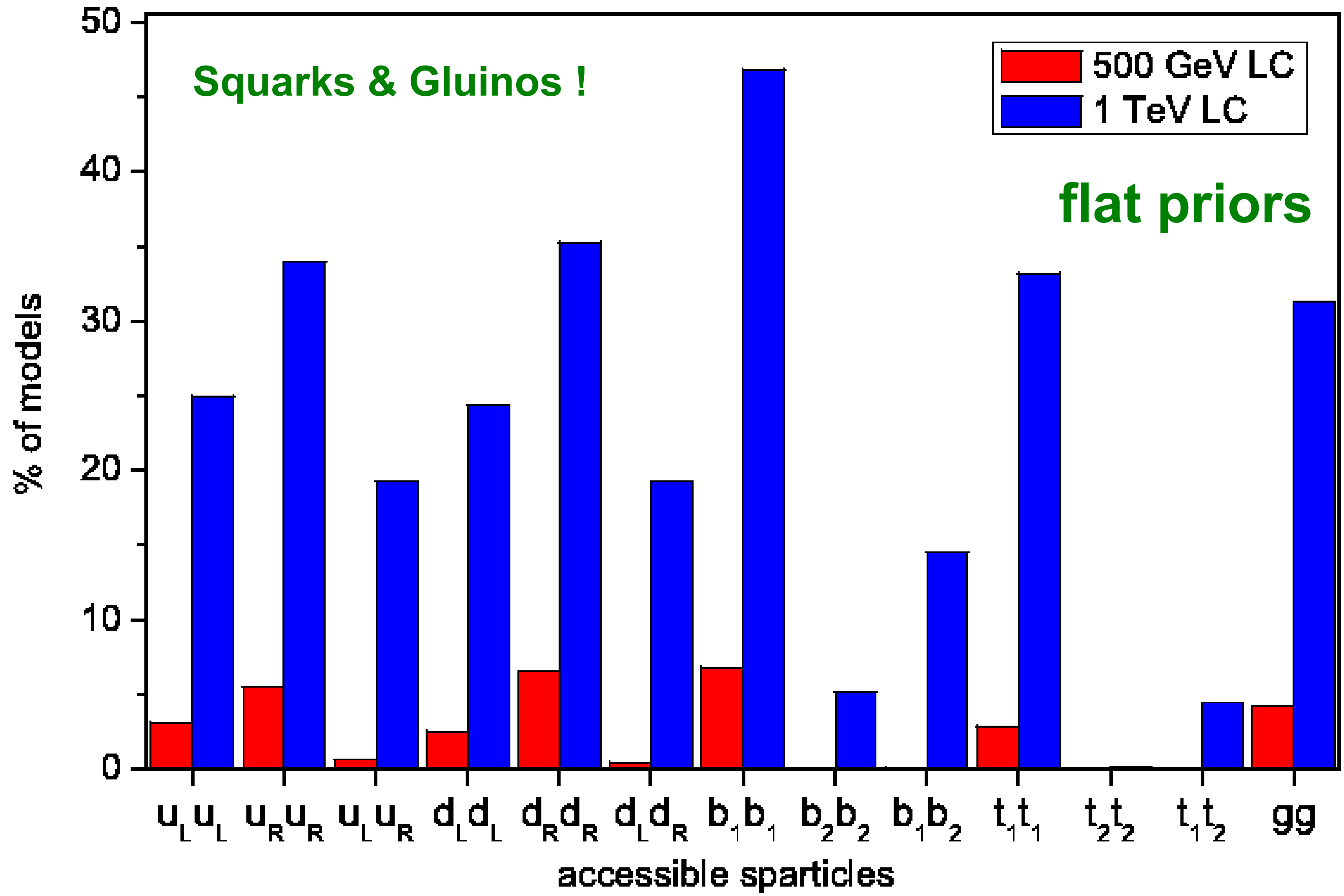


Small mass splittings can lead to soft jets in the final state that have insufficient p_T to pass any SUSY Tevatron search analysis cuts

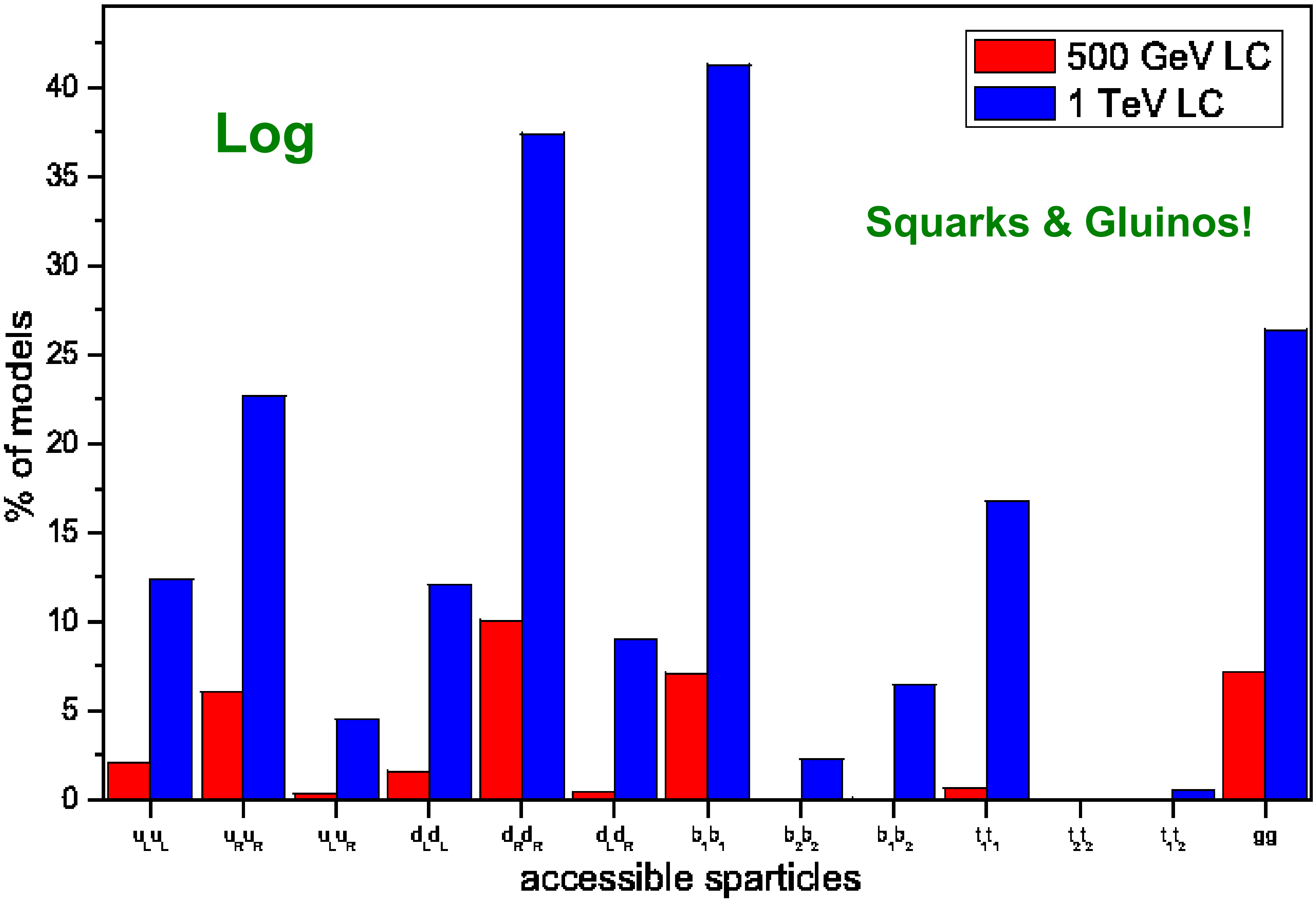




Kinematic Accessibility (M ~ < 1 TeV)



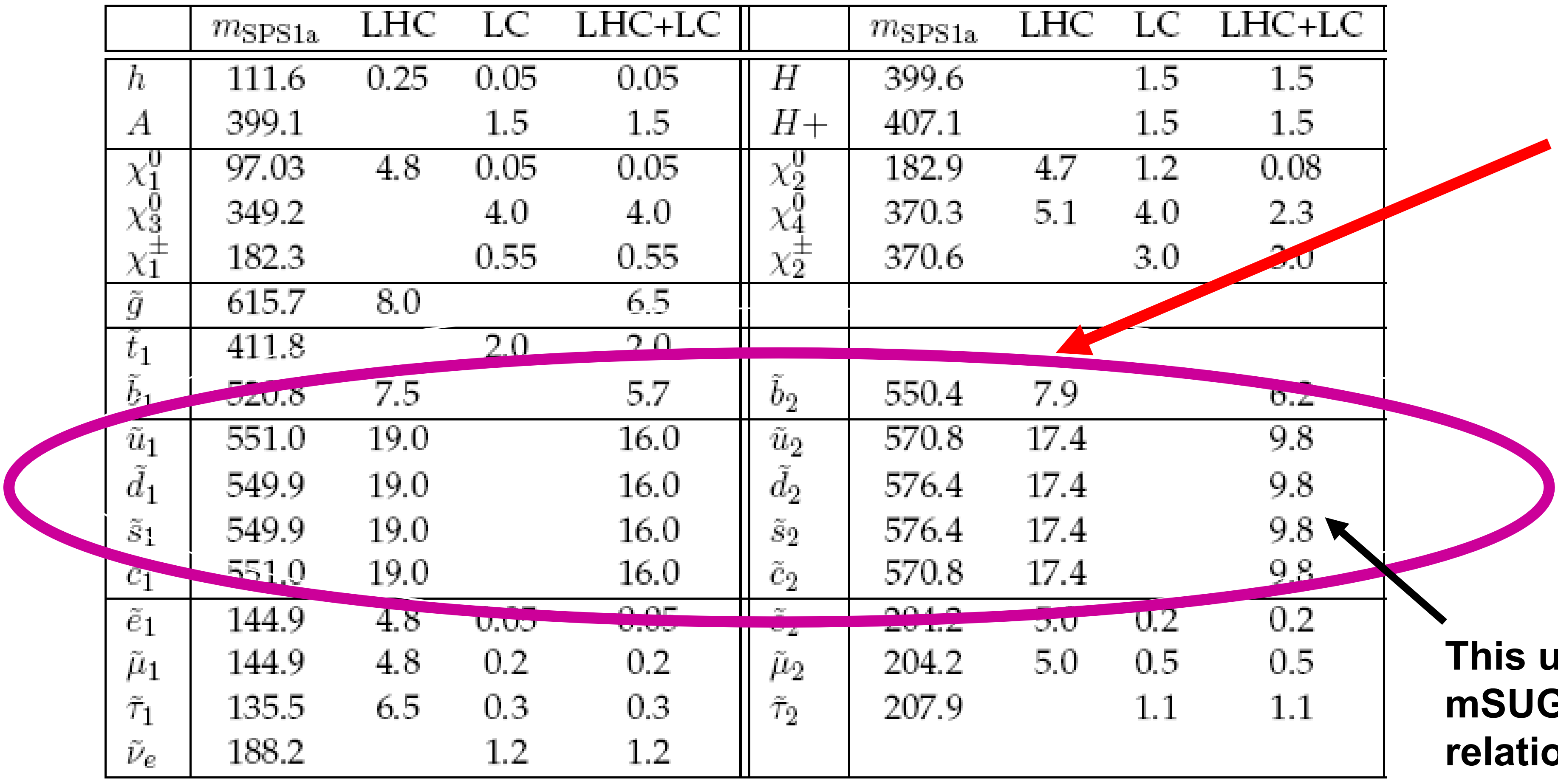
Kinematic Accessibility: M ~ <3 TeV



Log

Squarks & Gluinos!

- **Squark masses will be poorly determined even *after* LHC & ILC500 if they are not directly kinematically accessible…**



	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					

This 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.

The LHC / LC Study Group

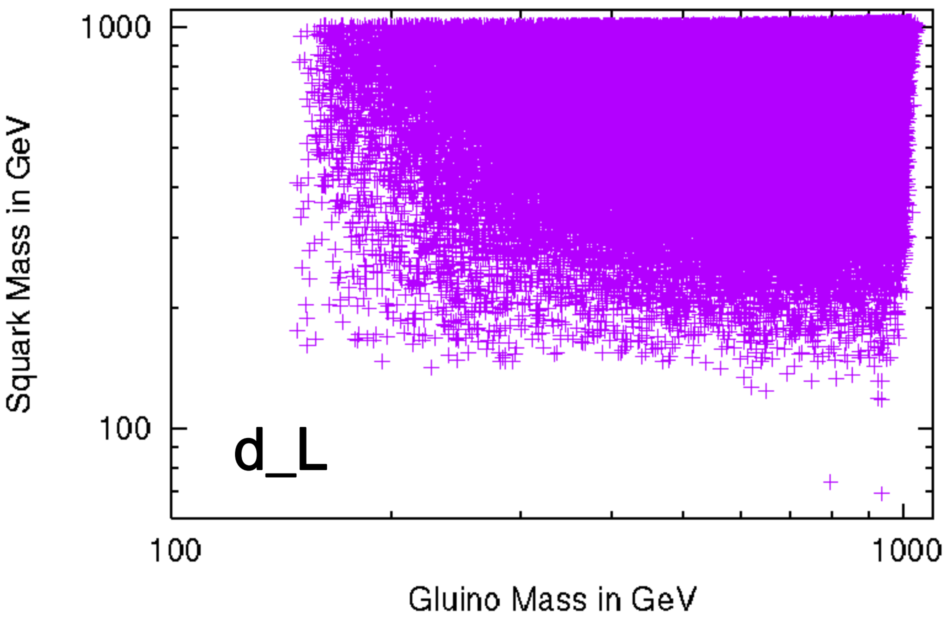
All this suggests that we need to start thinking seriously about squarks and gluinos at TeV & multi-TeV e^+e^- colliders

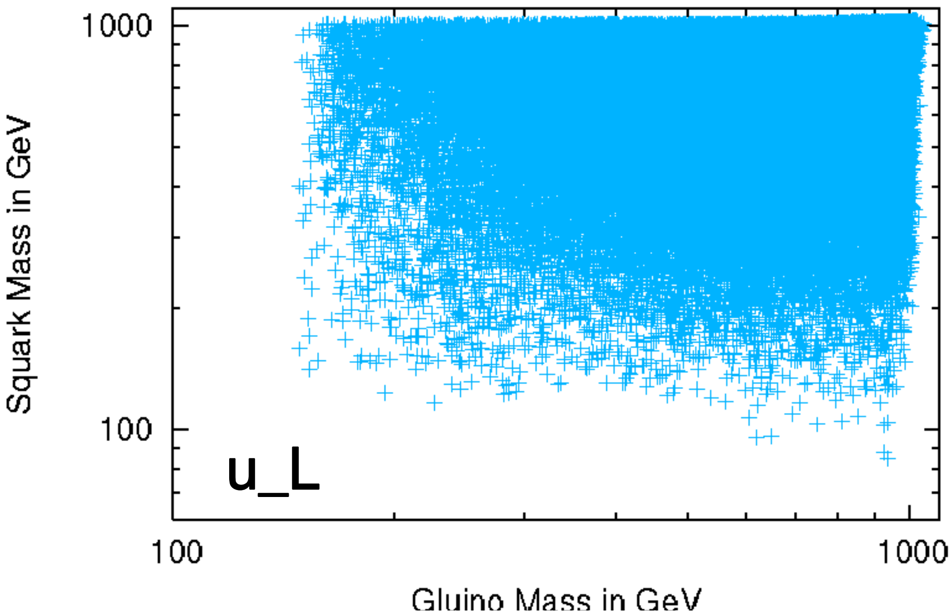
- My purpose here is to ask some questions as a way to begin thinking about this subject & not to provide detailed answers…which will require some hard work & LHC data.

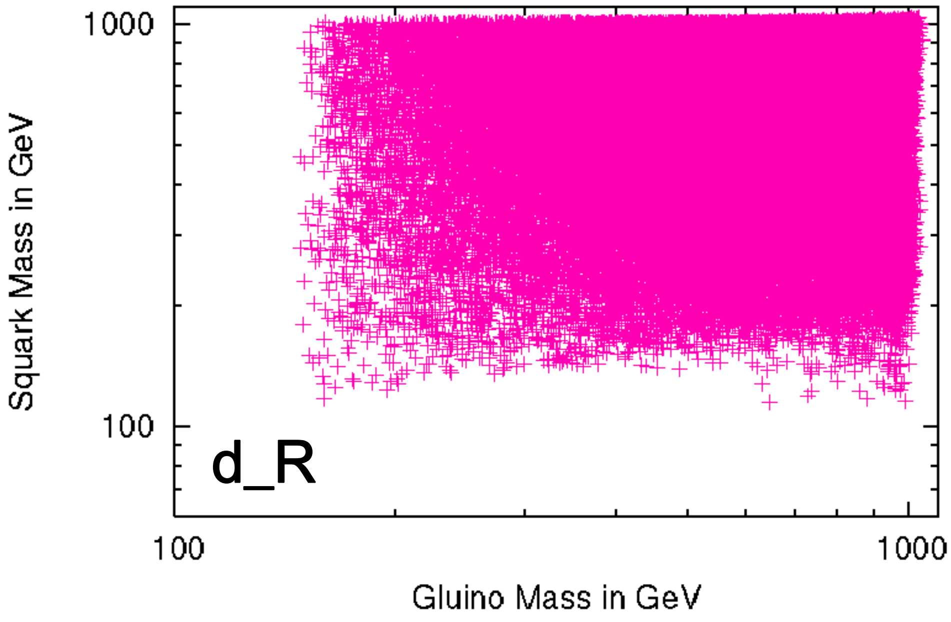
- As you will see there are MANY possibilities to consider. Of course the LHC will hopefully tell us which way to go…

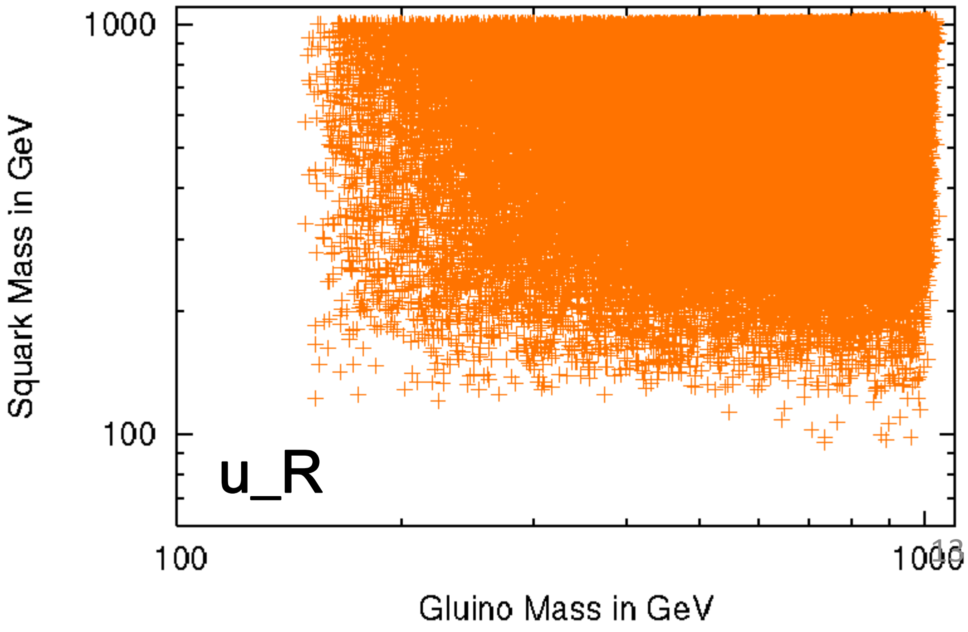
First Question:
Which are lighter
squarks or gluinos?

$M_{\tilde{q}} > m_{\tilde{g}}$ and $m_{\tilde{g}} > M_{\tilde{q}}$ are ~ equally likely


Gluino Mass Versus dl Squark Mass


Gluino Mass Versus ul Squark Mass


Gluino Mass Versus dr Squark Mass


Gluino Mass Versus ur Squark Mass

What processes are relevant for gluino/squark studies?

- If $M_{\tilde{q}} > m_{\tilde{g}}$, $\tilde{q} \to q\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}$
  - e^+e^- → gluino pairs → 4 jets + ME ?
  - e^+e^- → ‘squark + gluino’ → 6 jets + ME ?
  - e^+e^- → squark pairs → 6 jets + ME ?

Depends on who χ is & what it does

- If $m_{\tilde{g}} > M_{\tilde{q}}$, $\tilde{g} \to q\tilde{q}$, $\tilde{q} \to q\tilde{\chi}$
  - e^+e^- → squark pairs → 2 jets + ME ?
  - e^+e^- → ‘squark + gluino’ → 4 jets + ME ?
  - e^+e^- → gluino pairs → 4 jets + ME ?

Jet flavor tagging may be important here

$\tilde{q} \rightarrow q\tilde{\chi}_i$

This coupling and the χ identity determines what happens at the end of decay chains :

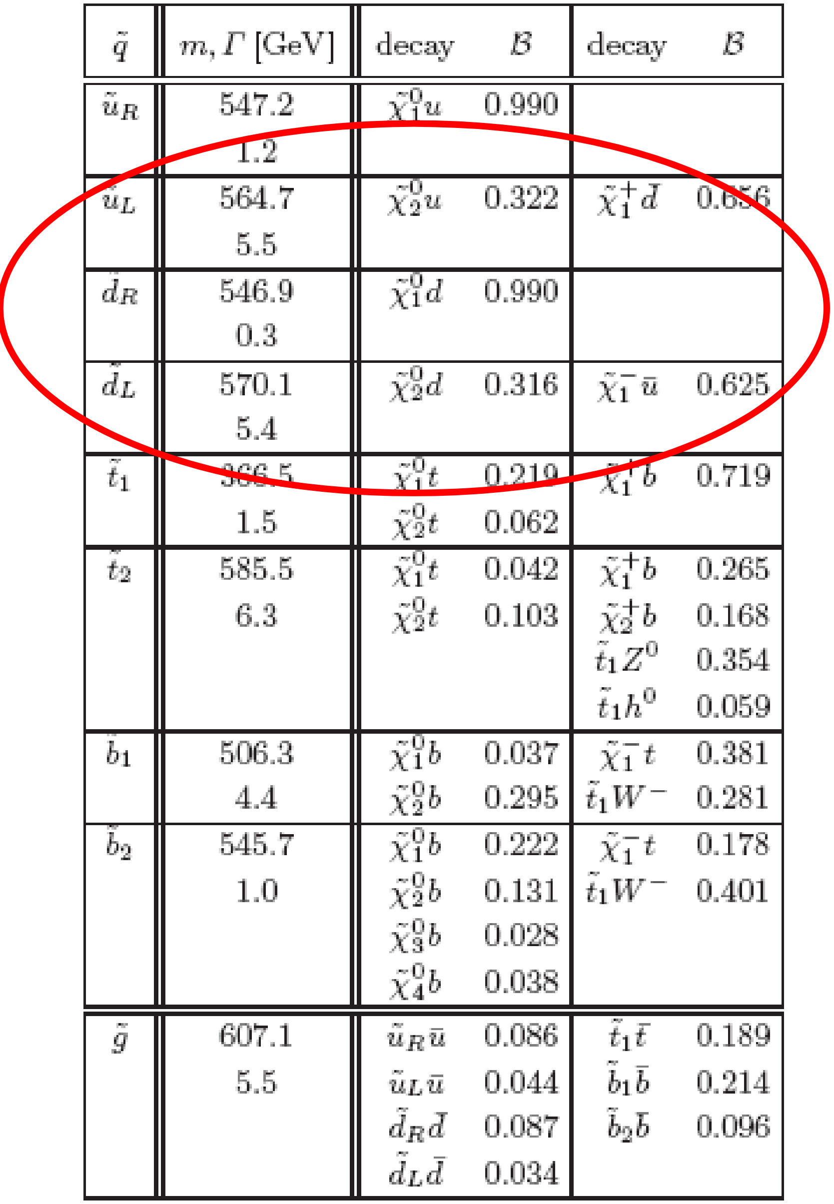
- In the absence of Yukawa couplings (a very good approx.) the squarks in the 1st & 2nd generations do not couple to charged or neutral Higgsinos

- For RH squarks, decays can only occur through the bino component of χ's .

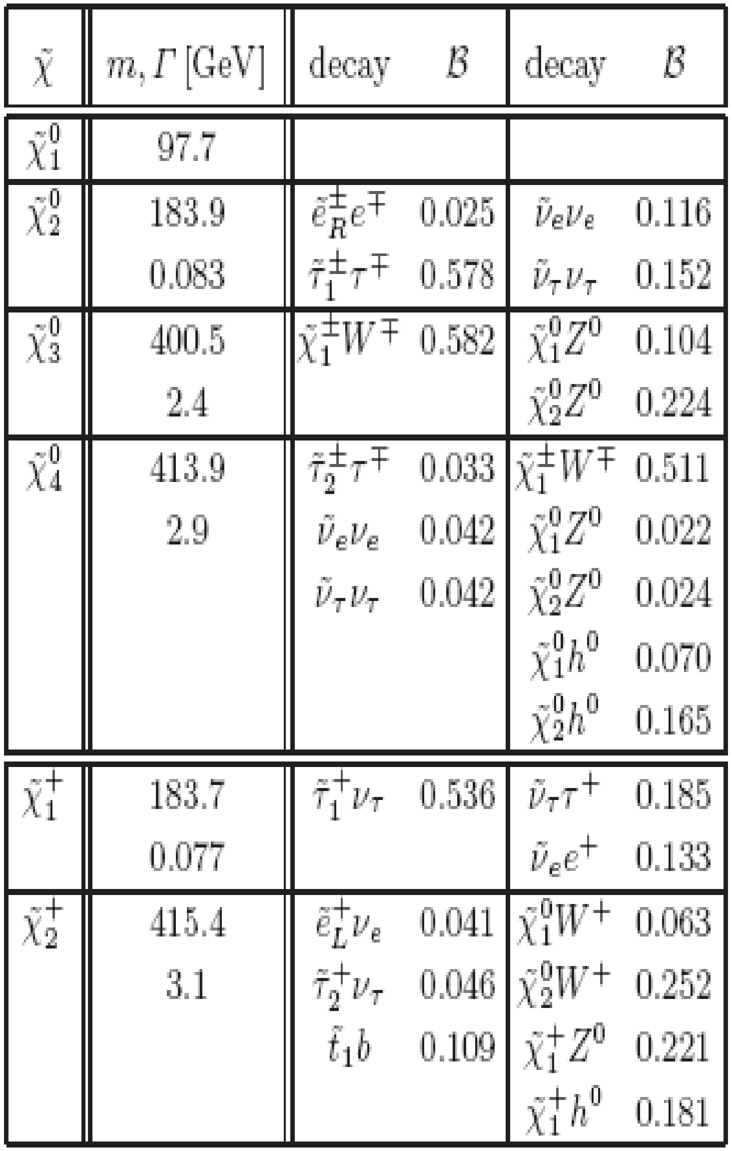
- For LH squarks, decays can occur through both the bino component of χ's as well as the (charged & neutral) wino component.

While χ can lead (directly) to ME (if it is the LSP), precisely how this happens also depends upon the rest of the SUSY spectrum .. What exactly does χ do?

Example: SPS1a' Masses and Decay Tables Typical of an mSUGRA scenario



$\tilde{q}$	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	$\tilde{e}^+_L \nu_e$ $\tilde{\tau}^+_2 \nu_\tau$ $\tilde{t}_1 \bar{b}$	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

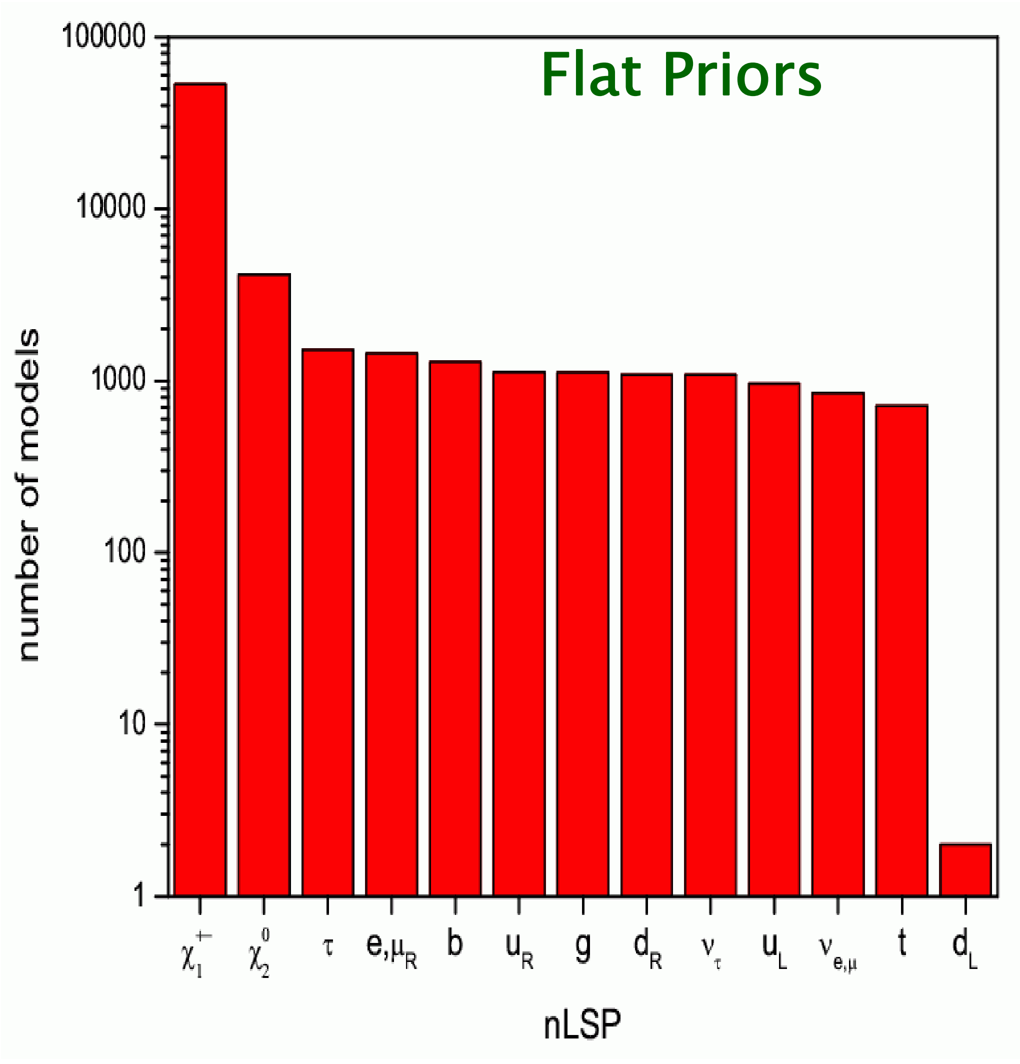
← ~wino

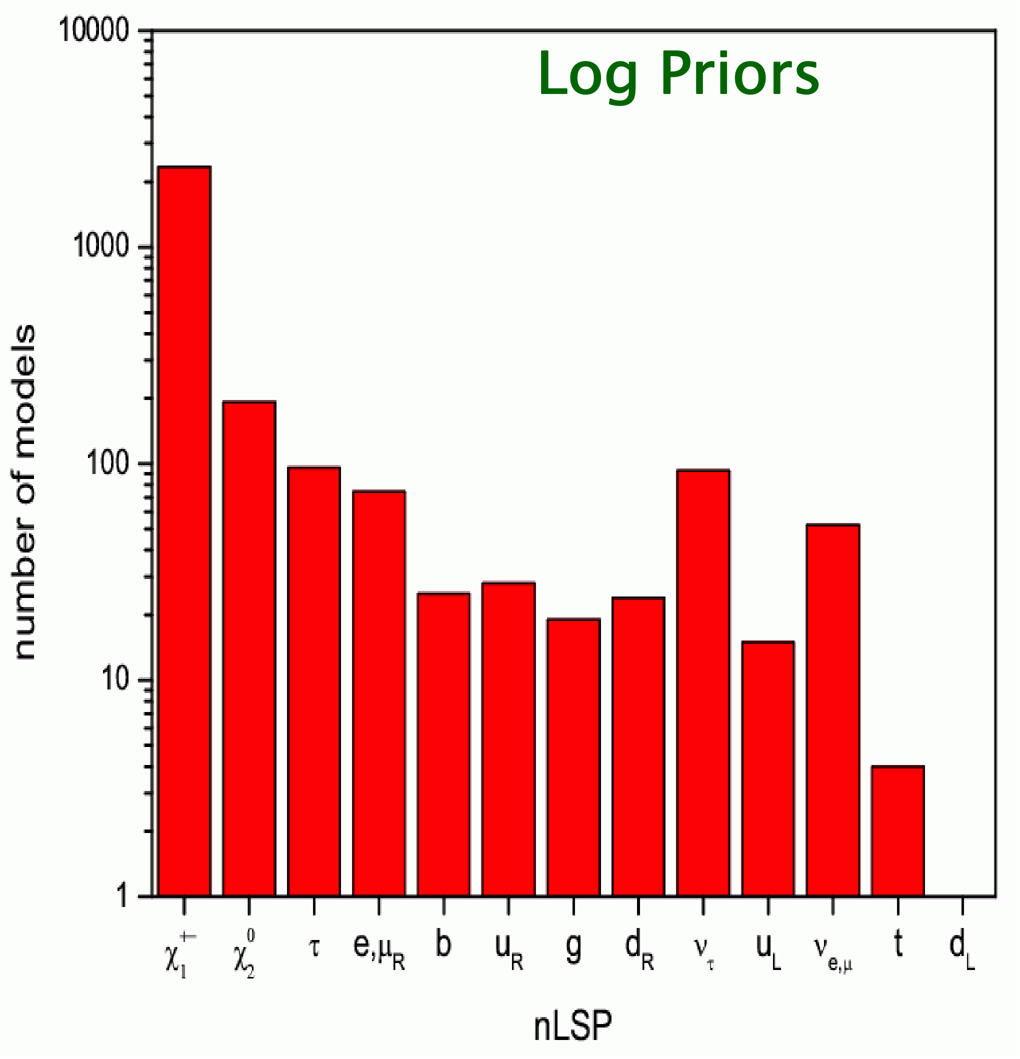
← ~wino

What happens at the end of SUSY decay chains??

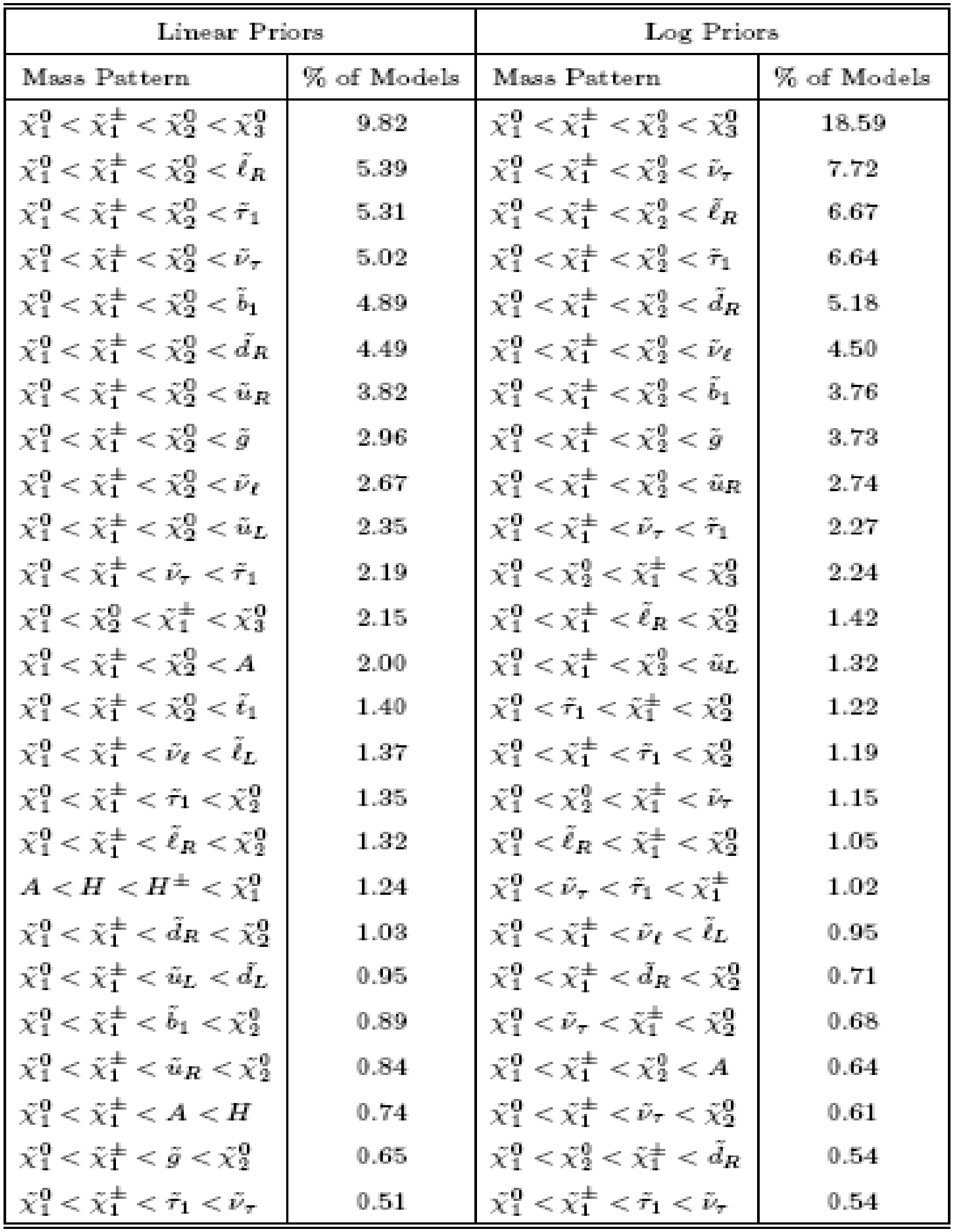
The identity of the nLSP is a critical factor in looking for SUSY signatures..who can play that role here????? Just about

ANY of the 13 possibilities !





Flat **Log**



Linear Priors		Log Priors	
Mass Pattern	% of Models	Mass Pattern	% of Models
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\chi}_3^0$	9.82	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\chi}_3^0$	18.59
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\ell}_R$	5.39	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\nu}_\tau$	7.72
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\tau}_1$	5.31	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\ell}_R$	6.67
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\nu}_\tau$	5.02	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\tau}_1$	6.64
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{b}_1$	4.89	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{d}_R$	5.18
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{d}_R$	4.49	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\nu}_\ell$	4.50
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{u}_R$	3.82	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{b}_1$	3.76
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{g}$	2.96	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{g}$	3.73
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{\nu}_\ell$	2.67	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{u}_R$	2.74
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{u}_L$	2.35	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\tau < \tilde{\tau}_1$	2.27
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\tau < \tilde{\tau}_1$	2.19	$\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_3^0$	2.24
$\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_3^0$	2.15	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\ell}_R < \tilde{\chi}_2^0$	1.42
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < A$	2.00	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{u}_L$	1.32
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < \tilde{t}_1$	1.40	$\tilde{\chi}_1^0 < \tilde{\tau}_1 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0$	1.22
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\ell < \tilde{\ell}_L$	1.37	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\tau}_1 < \tilde{\chi}_2^0$	1.19
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\tau}_1 < \tilde{\chi}_2^0$	1.35	$\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\tau$	1.15
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\ell}_R < \tilde{\chi}_2^0$	1.32	$\tilde{\chi}_1^0 < \tilde{\ell}_R < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0$	1.05
$A < H < H^\pm < \tilde{\chi}_1^0$	1.24	$\tilde{\chi}_1^0 < \tilde{\nu}_\tau < \tilde{\tau}_1 < \tilde{\chi}_1^\pm$	1.02
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{d}_R < \tilde{\chi}_2^0$	1.03	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\ell < \tilde{\ell}_L$	0.95
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{u}_L < \tilde{d}_L$	0.95	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{d}_R < \tilde{\chi}_2^0$	0.71
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{b}_1 < \tilde{\chi}_2^0$	0.89	$\tilde{\chi}_1^0 < \tilde{\nu}_\tau < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0$	0.68
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{u}_R < \tilde{\chi}_2^0$	0.84	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\chi}_2^0 < A$	0.64
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < A < H$	0.74	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\nu}_\tau < \tilde{\chi}_2^0$	0.61
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{g} < \tilde{\chi}_2^0$	0.65	$\tilde{\chi}_1^0 < \tilde{\chi}_2^0 < \tilde{\chi}_1^\pm < \tilde{d}_R$	0.54
$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\tau}_1 < \tilde{\nu}_\tau$	0.51	$\tilde{\chi}_1^0 < \tilde{\chi}_1^\pm < \tilde{\tau}_1 < \tilde{\nu}_\tau$	0.54

SUSY decay chains are very important…especially the end of the chain at any collider experiment.

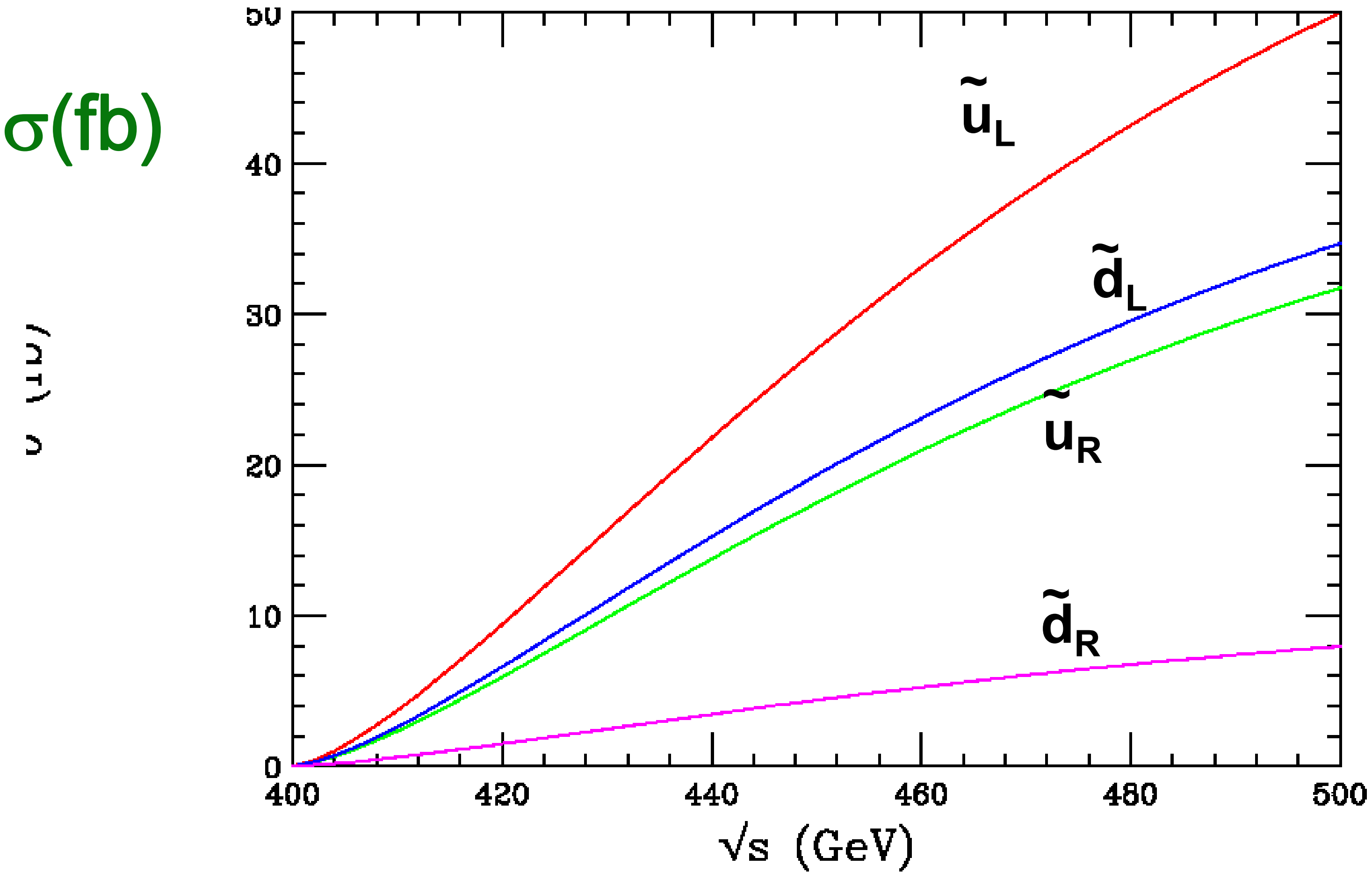
Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

There were 1109 (267) such patterns found for the case of flat (log) priors

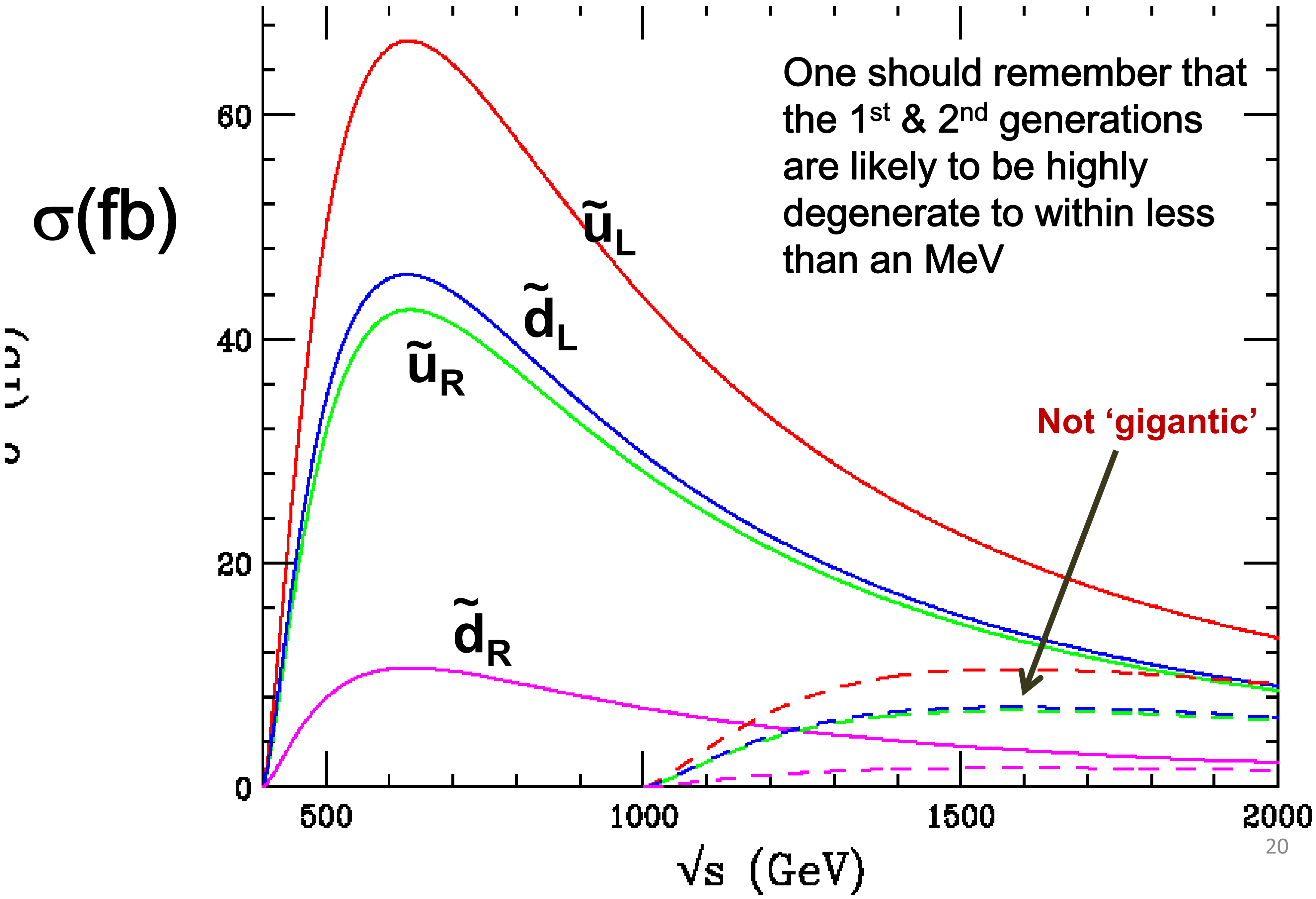
Only ~22 are found to occur in mSUGRA!!

The simplest process to consider is squark pair production with each squark decaying to a jet + ME (i.e., the 2j+ME final state) which is perhaps likely for RH squarks.

In the *absence* of bound state effects, the threshold region is controlled by the p-wave: $d\sigma \sim \beta^3 (1-\cos^2 \theta)$ [squarks are spin-0]

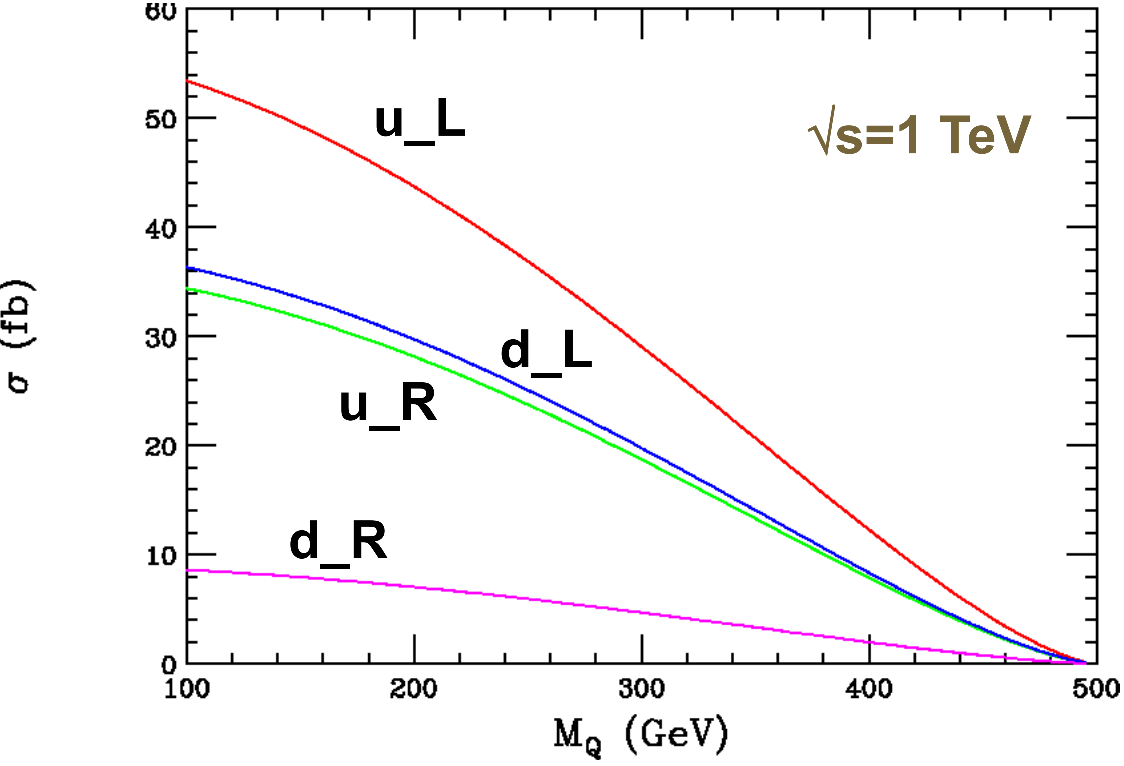


Squark Pair Production in e^+e^-

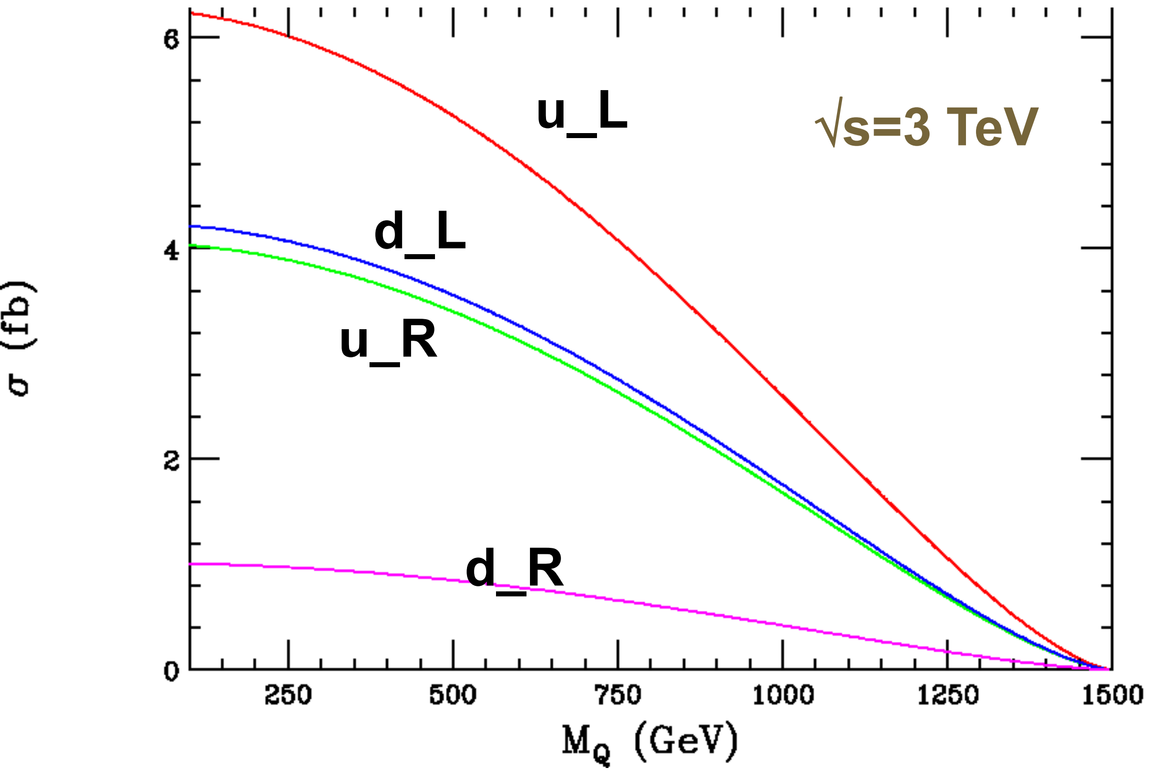


One should remember that the 1st & 2nd generations are likely to be highly degenerate to within less than an MeV

Not ‘gigantic’



The expected degeneracy of the 1st & 2nd generation squarks means that we want good charm tagging in threshold studies to pick out the increased presence of charm jets form squark decays.

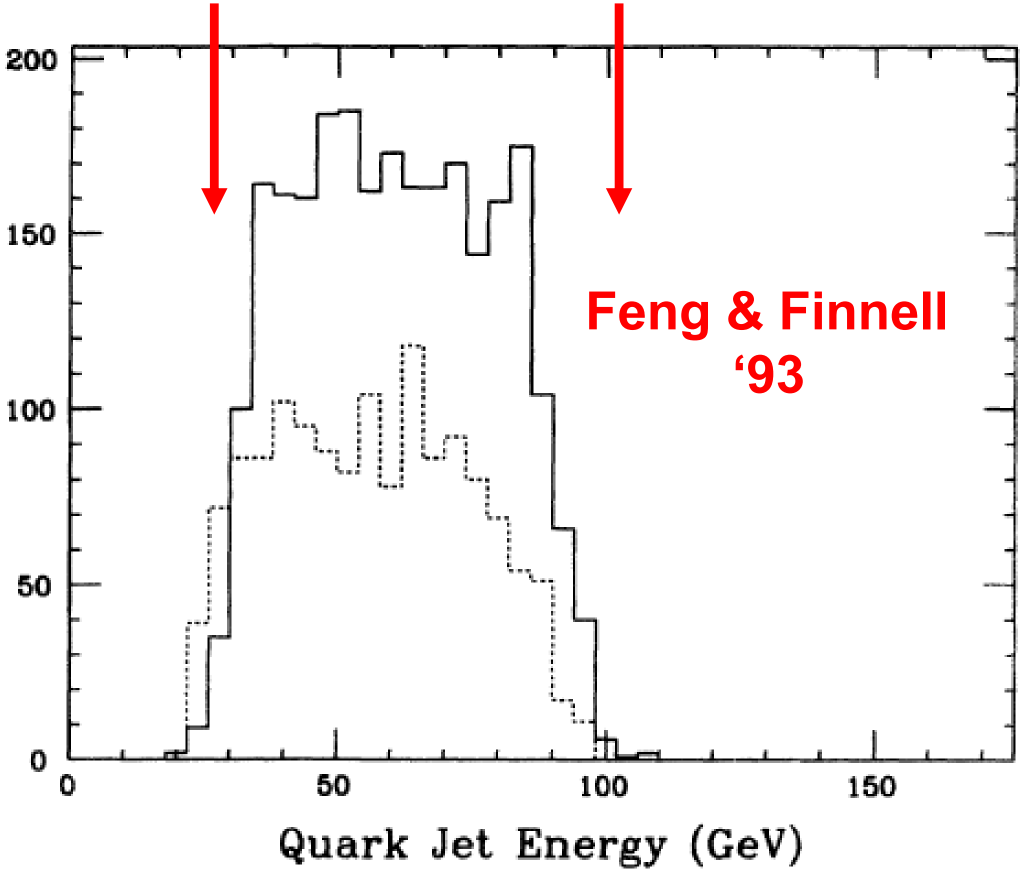


While squark production is largish the real issue is what the squarks end up decaying into…

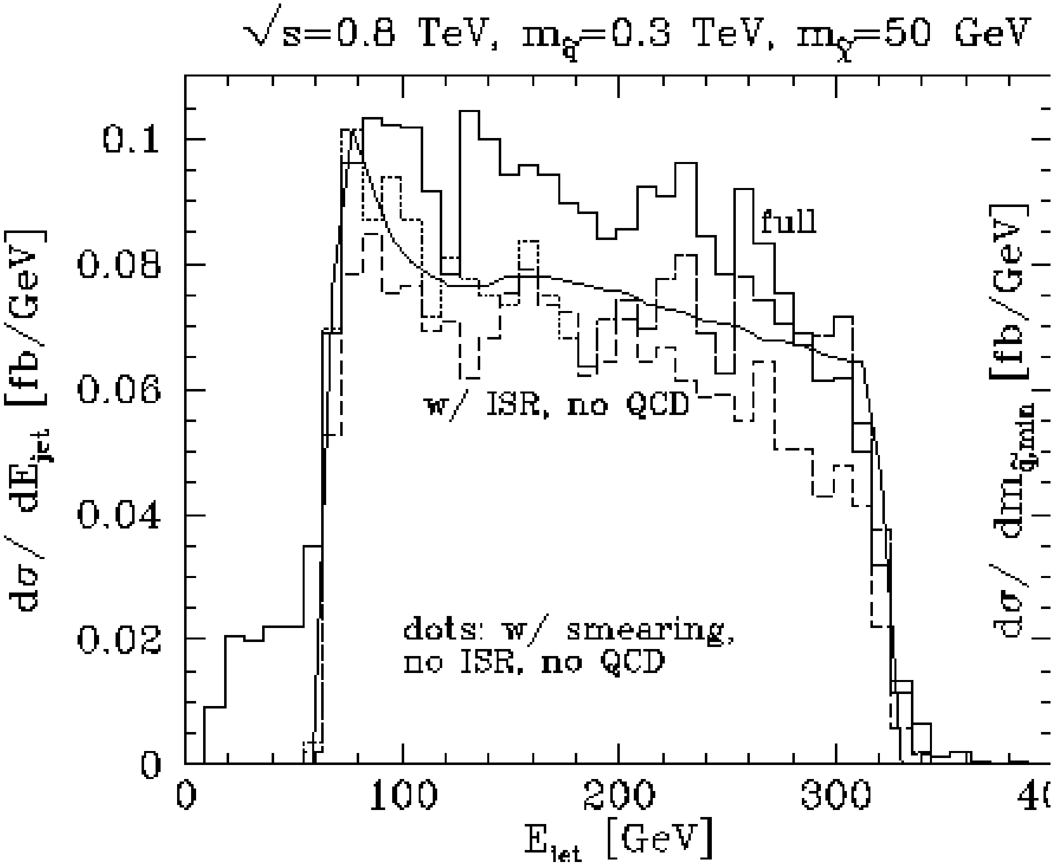
Jet+ME is the SIMPLEST possibility to consider…

High Energy Jets From Squarks?

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



Feng & Finnell ‘93

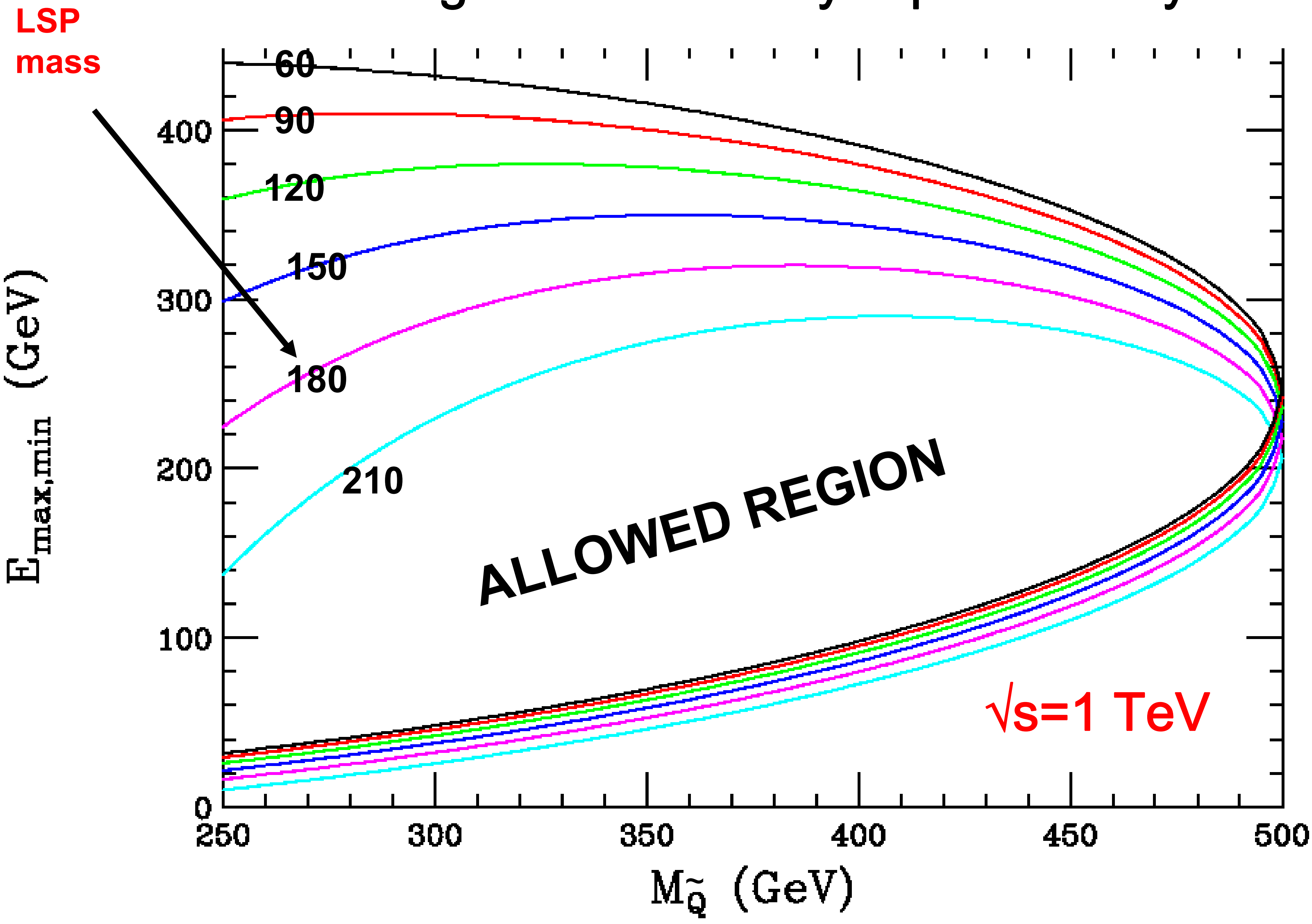


Drees etal. ‘99

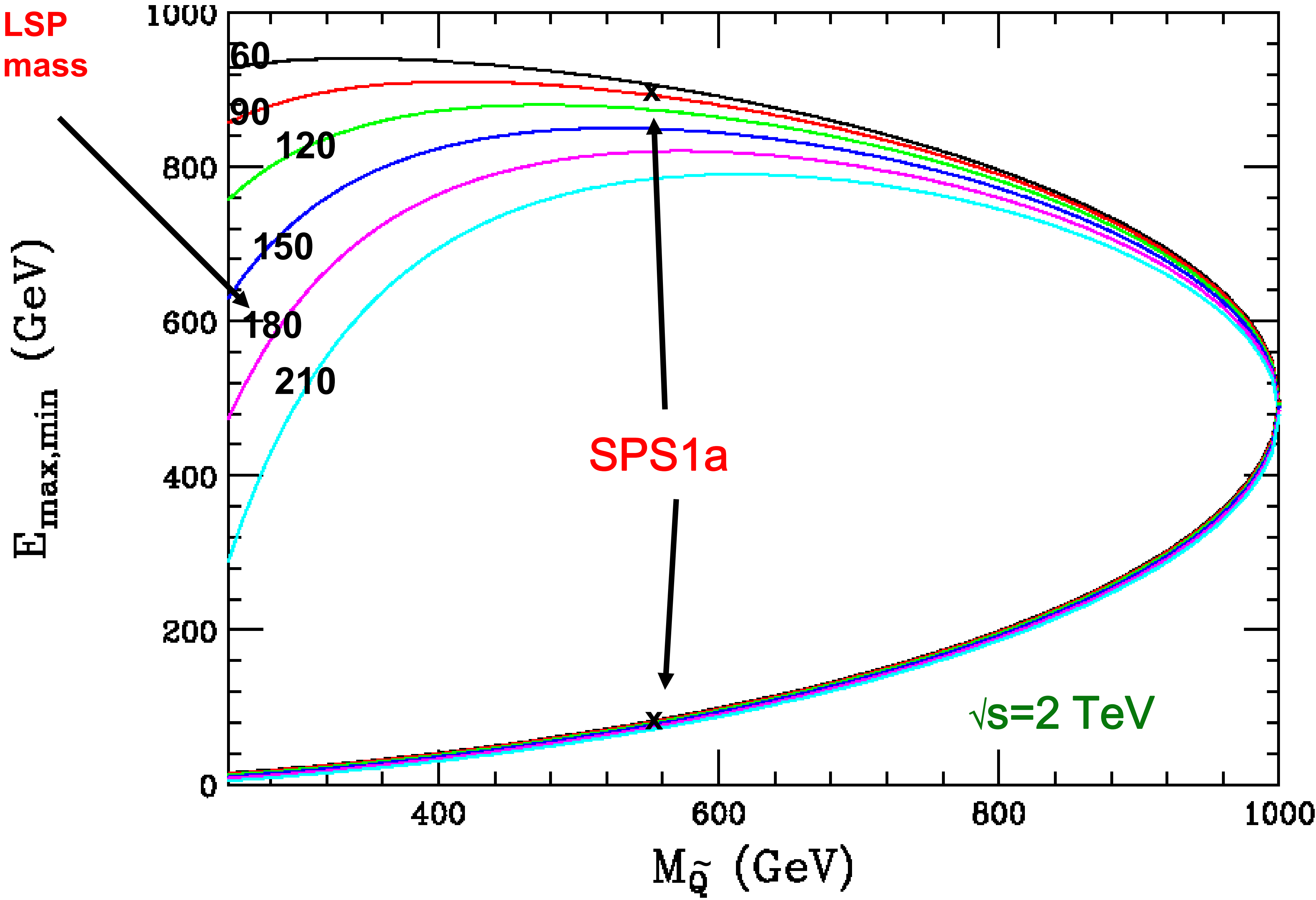
The end points tell us the squark mass

BUT we may have a superposition of many states

Jet Energies in Two-Body Squark Decay



Jet Energies in Two-Body Squark Decay



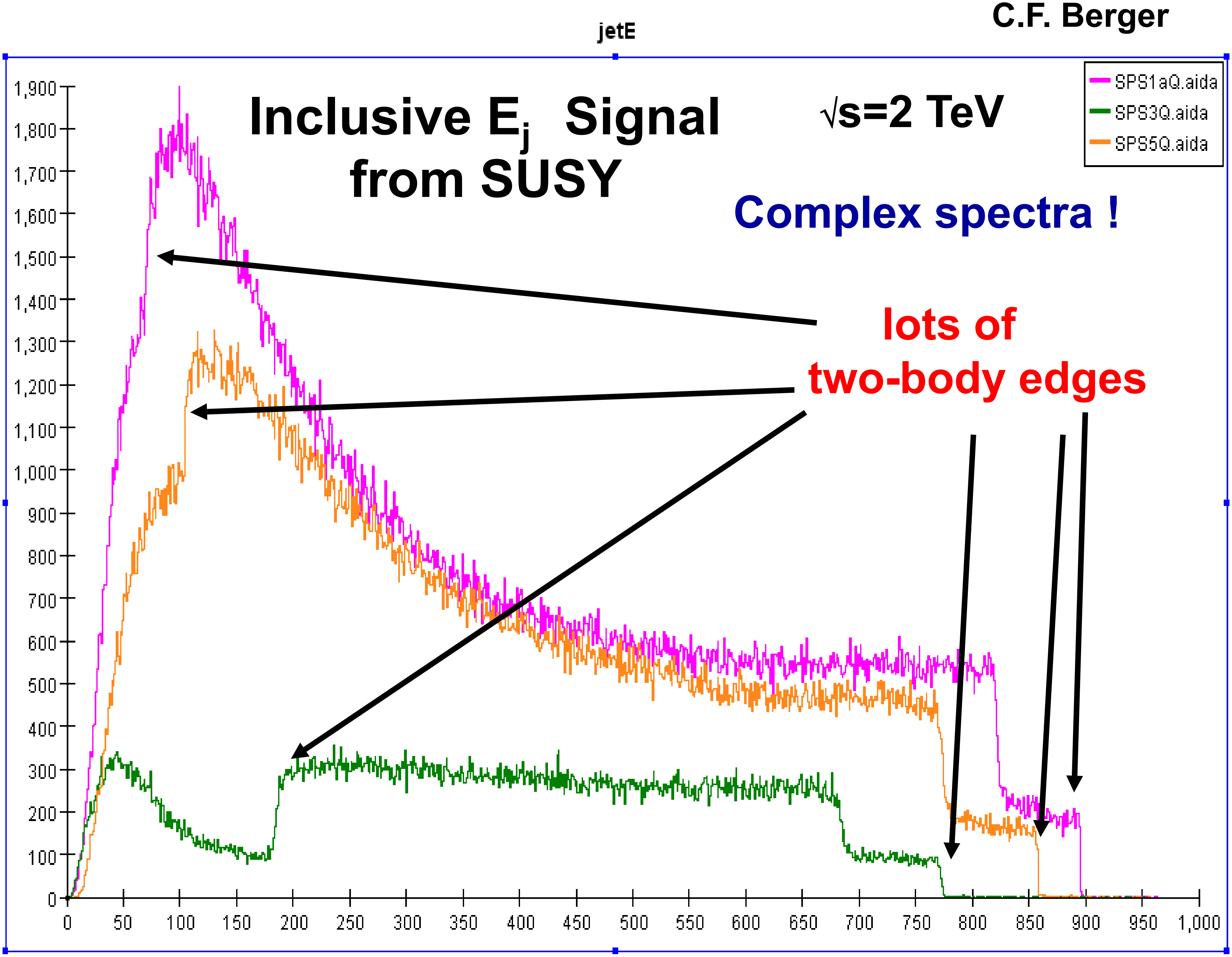
C.F. Berger

Inclusive E_j Signal from SUSY

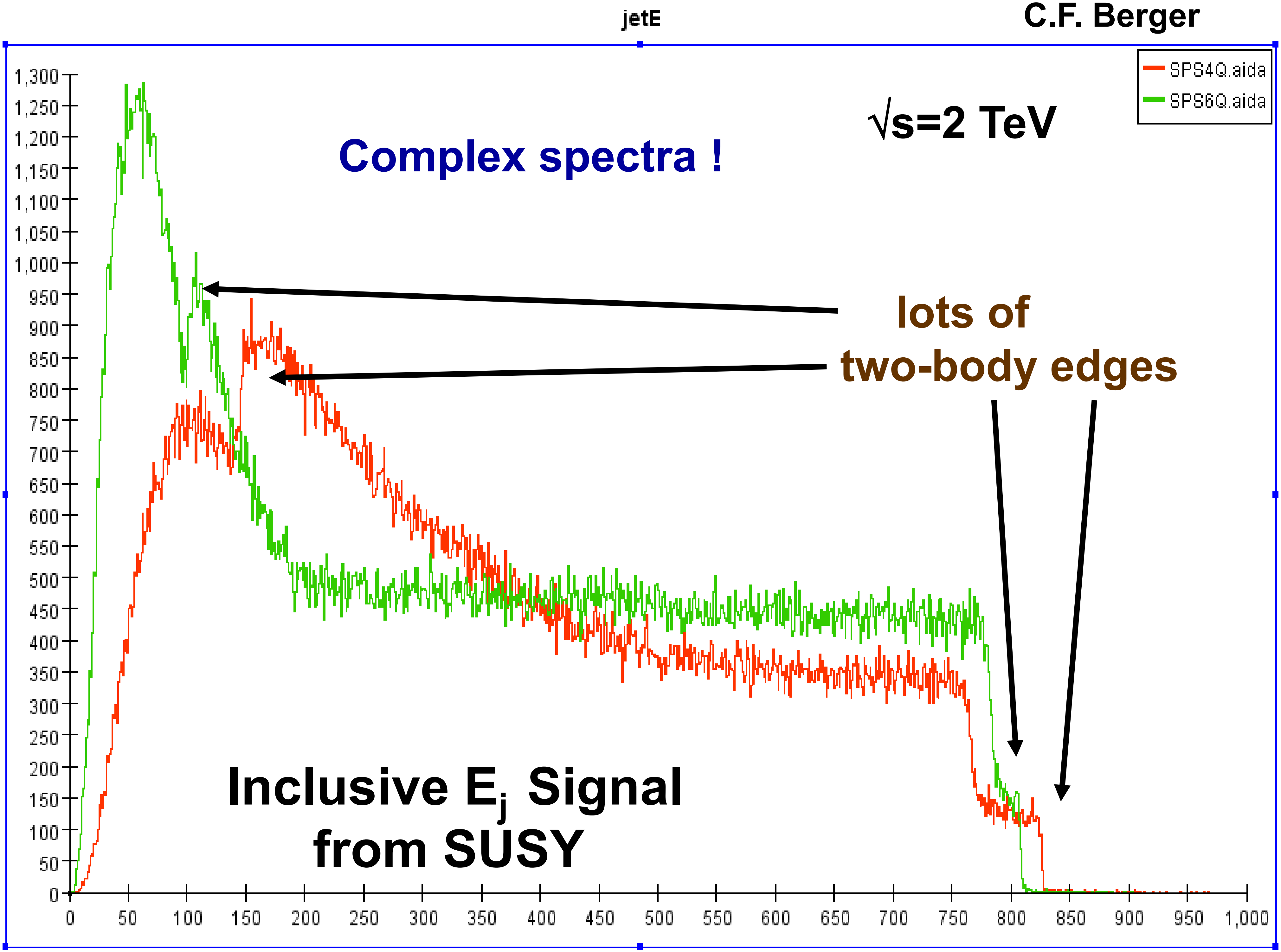
$\sqrt{s}$=2 TeV

Complex spectra !

lots of two-body edges



C.F. Berger



$\sqrt{s}$=2 TeV

Complex spectra !

lots of two-body edges

Inclusive E_j Signal from SUSY

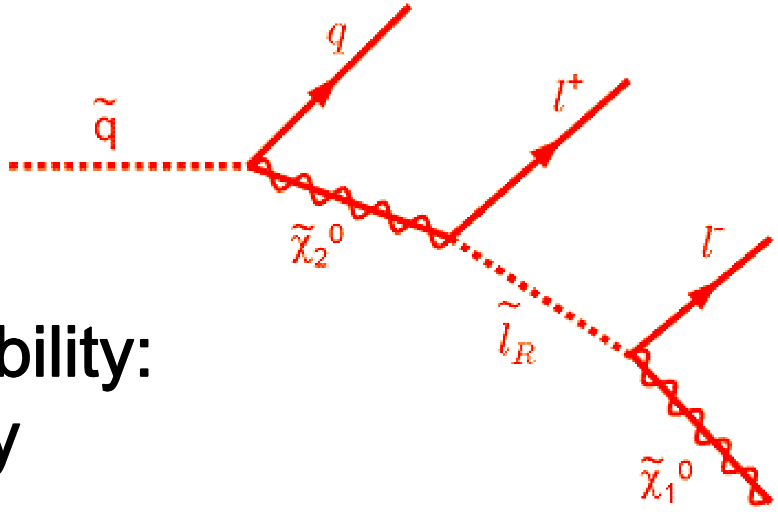
- Backgrounds to this process arise from many SM sources..the most dangerous being $\gamma\gamma \rightarrow jj$ which can have large ME (most others are removable by vetoing W,Z→jj). Jet acoplanarity plus large ME requirements (> 100+ GeV ?) should reduce these $\gamma\gamma$ backgrounds .

- There can also potentially be other backgrounds from SUSY itself depending on the sparticle spectrum as we've seen.

Simulation studies are needed !

→ Of course χ could be more complex: (i) it could be a detector stable chargino leading to a jets + stable charged particles final state or (ii) it could have it's own decay chain via the lighter sleptons or (iii) it may radiatively decay to the LSP via a loop or (iv) … There are MANY possibilities ! Recall this is the SIMPLEST final state….All require simulation studies.

E.g.,



The well-known possibility:
cascade squark decay
through the sleptons

- One should also be mindful of the possibility that gluinos or squarks may be long-lived or even detector-stable , depending upon the details of the SUSY spectrum (e.g., they are the nLSP with a small mass splitting or if squarks are much heavier than gluinos or…), & thus will form R-hadrons.

- This also opens the door to the formation of squarkonia or even gluino-gluino bound states near threshold (but with rates that are p-wave suppressed.)

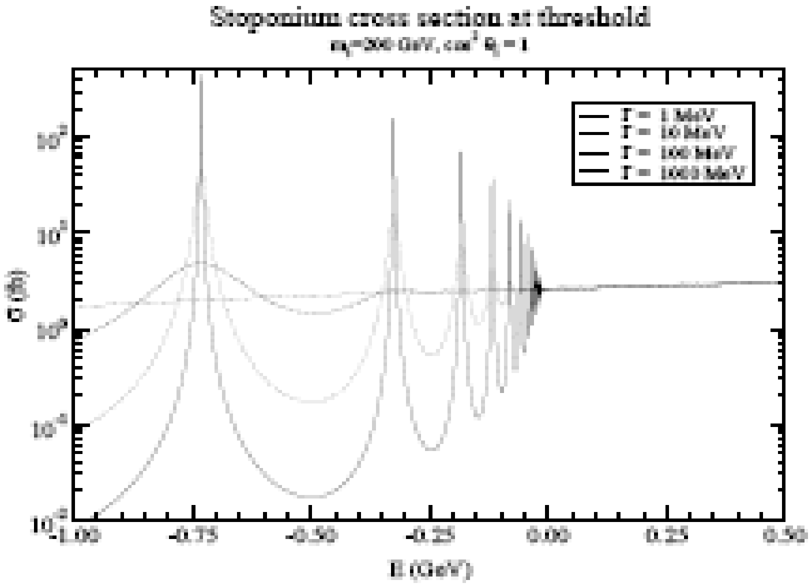


Figure 4: *Cross section at threshold for various decay widths with* $m_{\tilde t} = 200$ *GeV*, $\cos^2\theta_{\tilde t} = 1$. *The centre of mass energy is* $\sqrt{s} = 400$ *GeV at threshold*

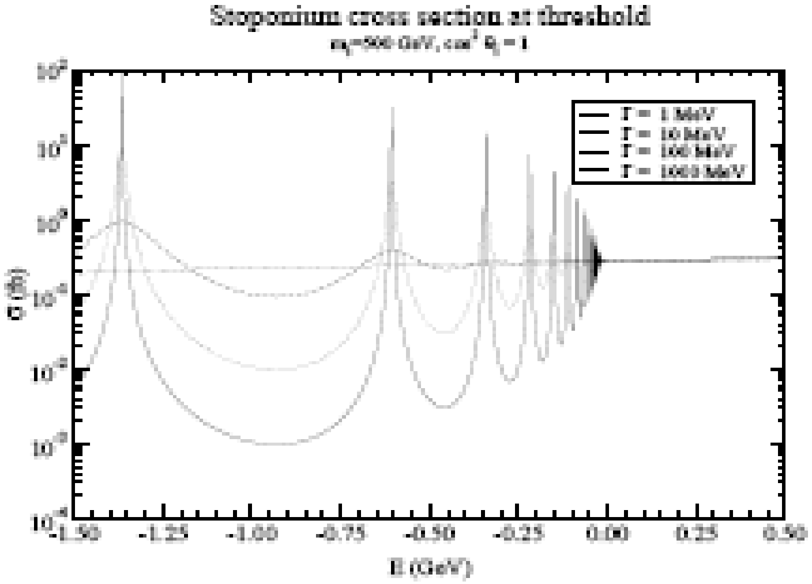


Figure 5: *Cross section at threshold for various decay widths with* $m_{\tilde t} = 500$ *GeV*, $\cos^2\theta_{\tilde t} = 1$. *The centre of mass energy is* $\sqrt{s} = 1000$ *GeV at threshold.*

These have been examined to some extent for the case of stops

It is likely that beam effects will smear such narrow peaks to invisibility …

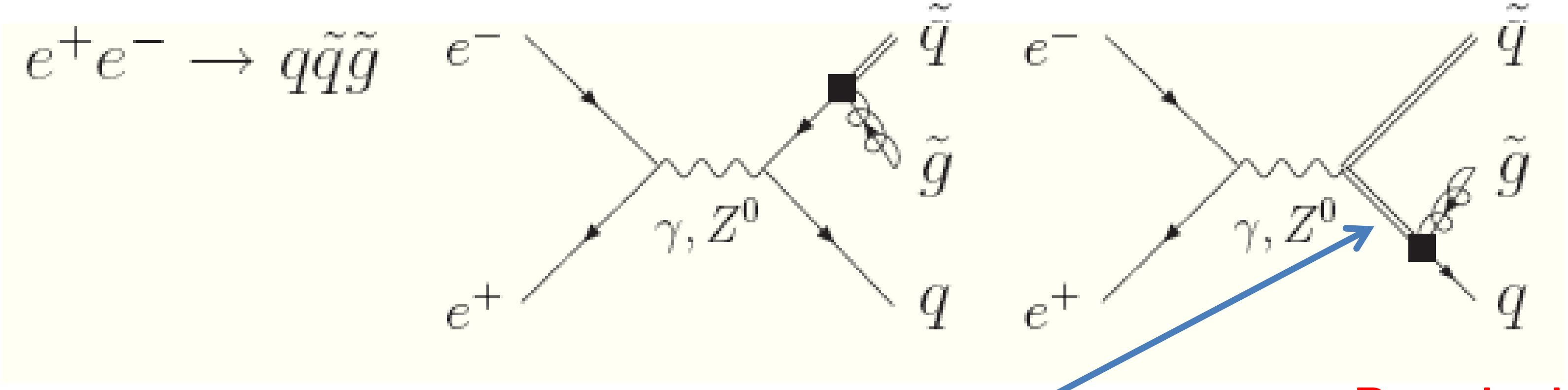
More studies are certainly needed!

Fabiano '01

Clearly, there are very many possible interesting scenarios to consider just in the 1st & 2nd generation squark sector…

The set of possibilities will be drastically reduced by the measurements to be made at the LHC…hopefully beginning soon!

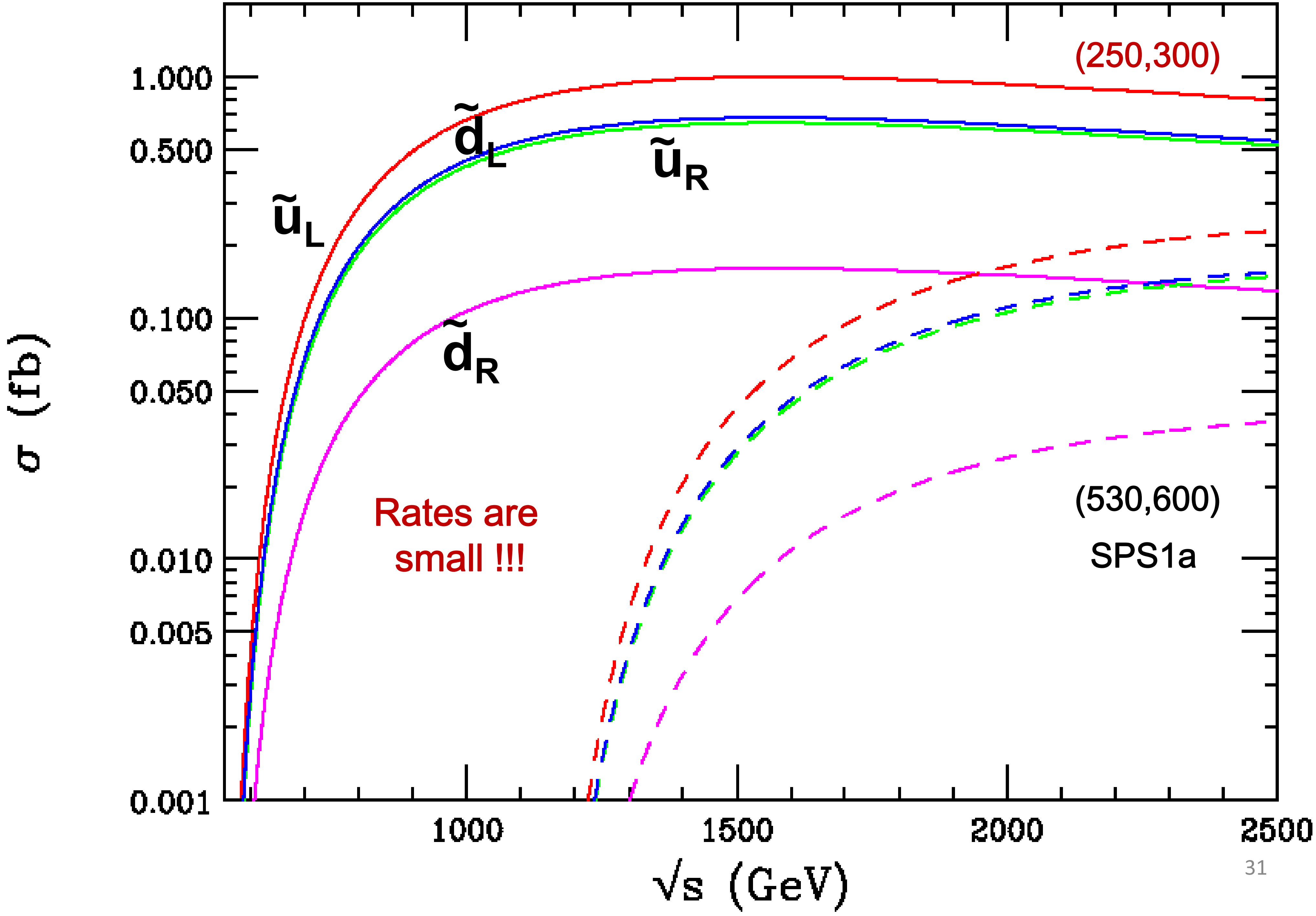
→ **One way to get at gluinos, especially if they are heavier than squarks, is via the 3-body final state:**



Can go on-shell

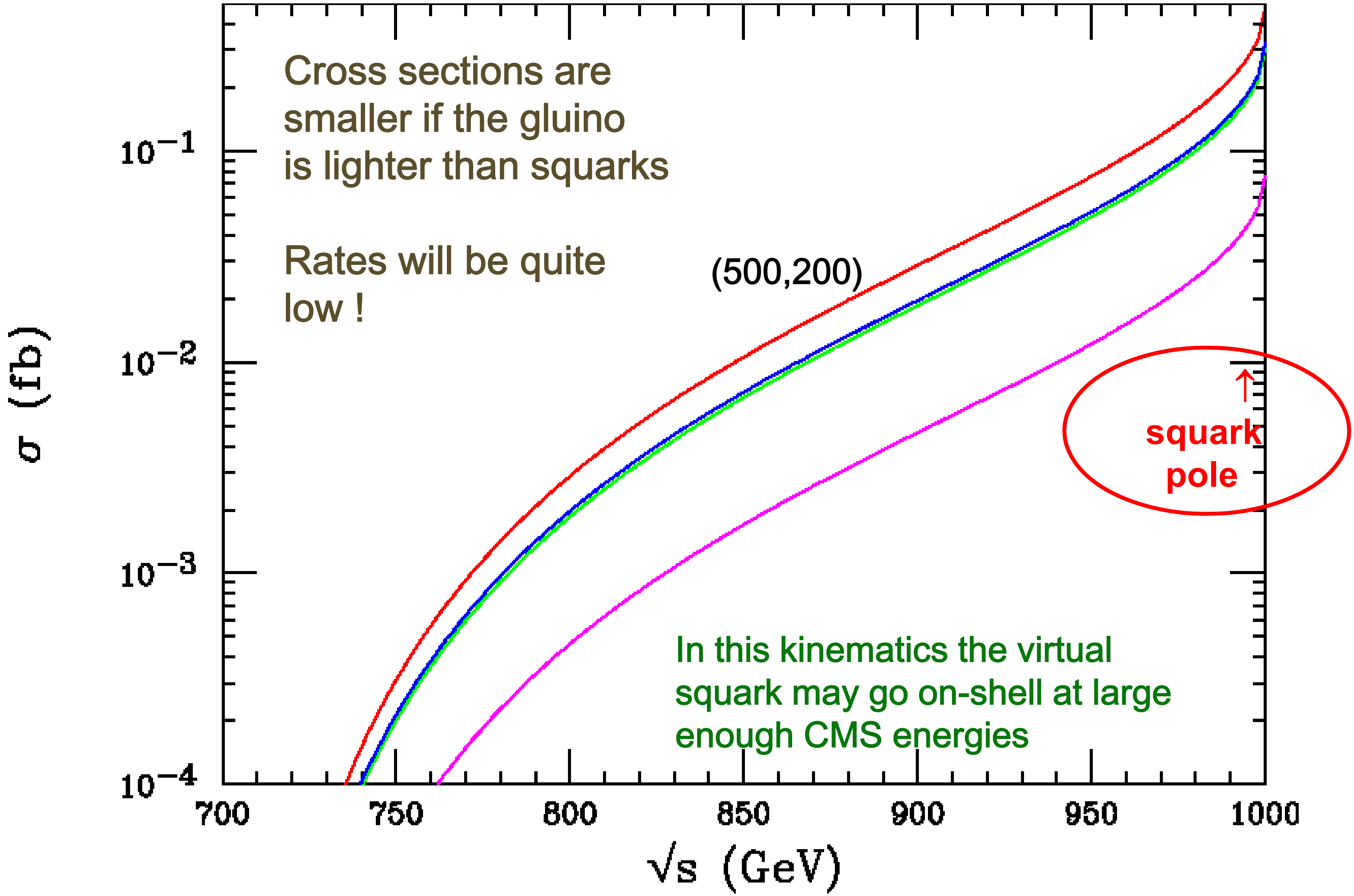
Brandenburg etal '08

Squark + Gluino Production



Rates are small !!!

Squark + Gluino Production

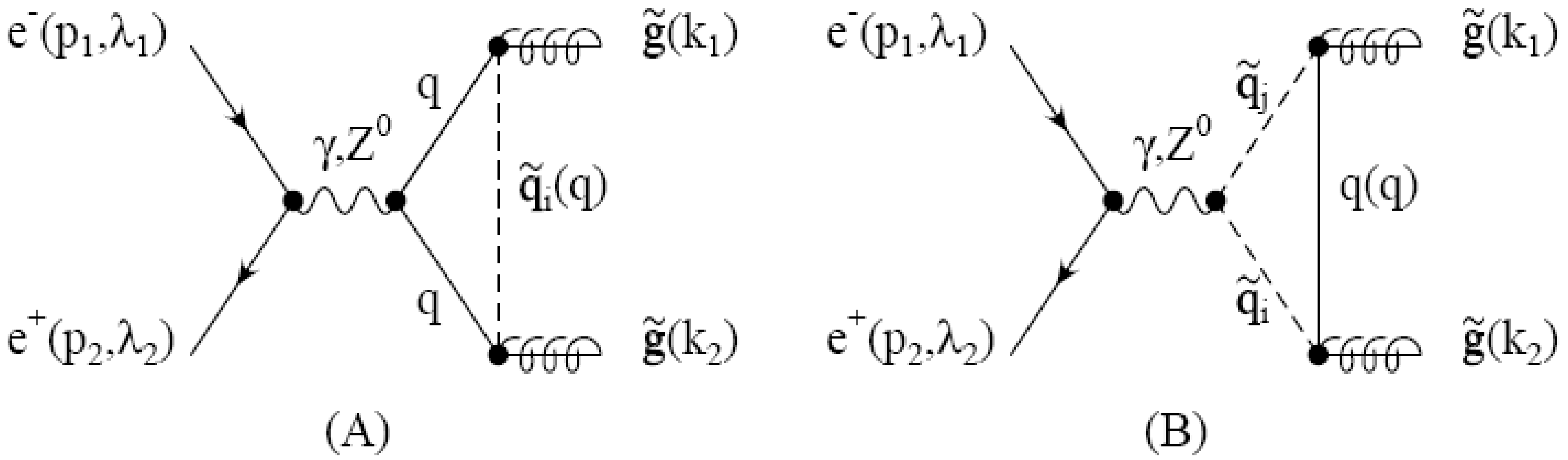


Cross sections are smaller if the gluino is lighter than squarks

Rates will be quite low !

In this kinematics the virtual squark may go on-shell at large enough CMS energies

→ For direct production of gluino pairs we need to go through squark /quark loops which involves the entire strongly interacting sector of the MSSM including squark mixing etc. & also leads to very small production rates (~ <0.1-1 fb) :



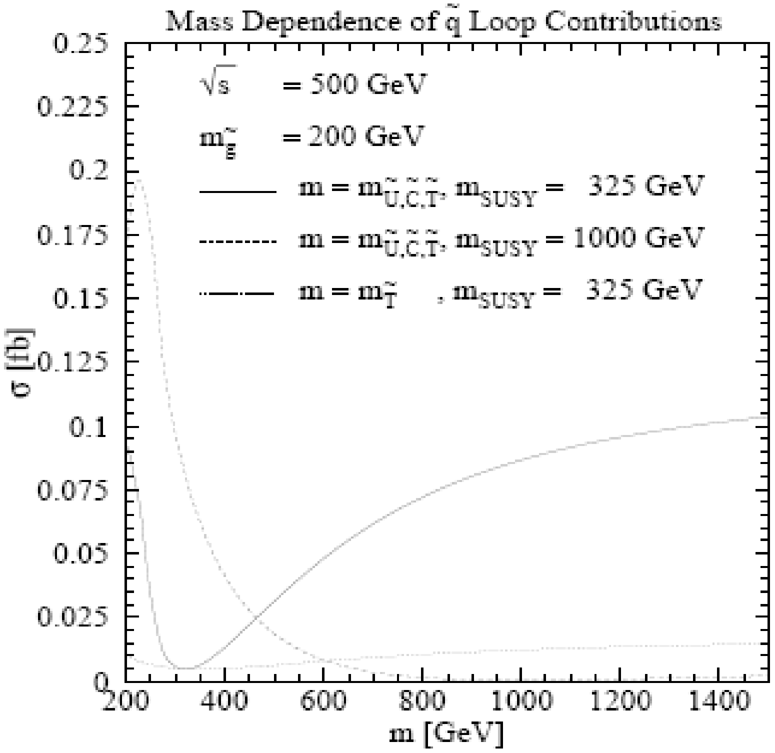
Berge & Klasen

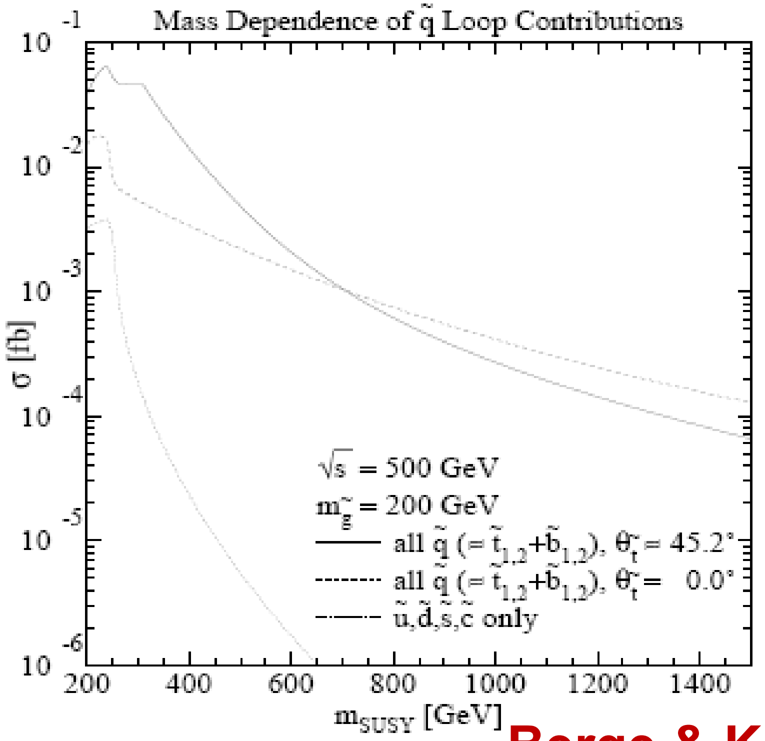
There are in general MANY parameters here & the studies so far have been somewhat limited -- mostly to mSUGRA-like scenarios . This needs to be revisited just to understand rates.

$$d\sigma_{\lambda 1,\lambda 2} = [A(1-4\lambda_1\lambda_2) + B(2\lambda_1-2\lambda_2)] \quad \underline{\beta^3} \, (1+\cos^2\theta)$$

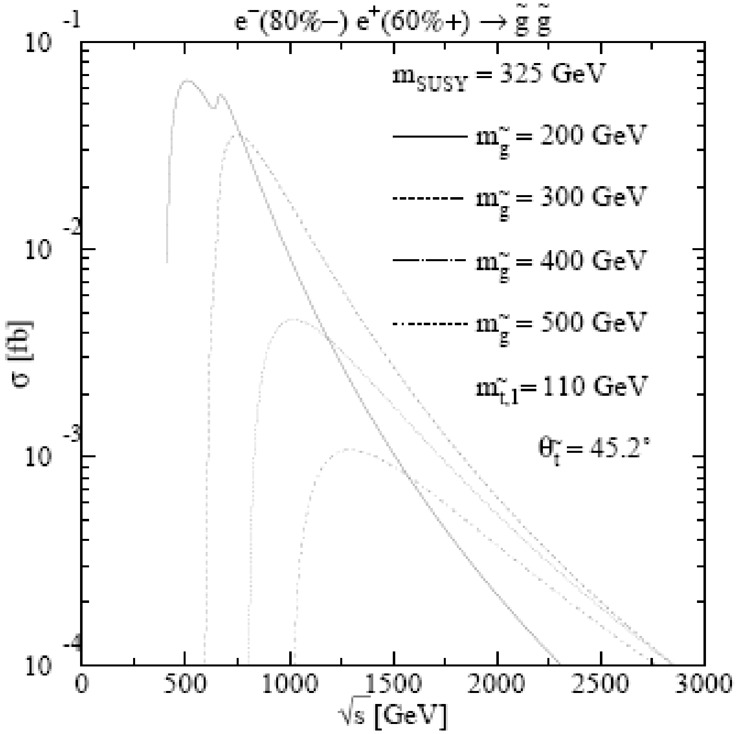
→ Gluinos are spin-1/2 Majorana fields

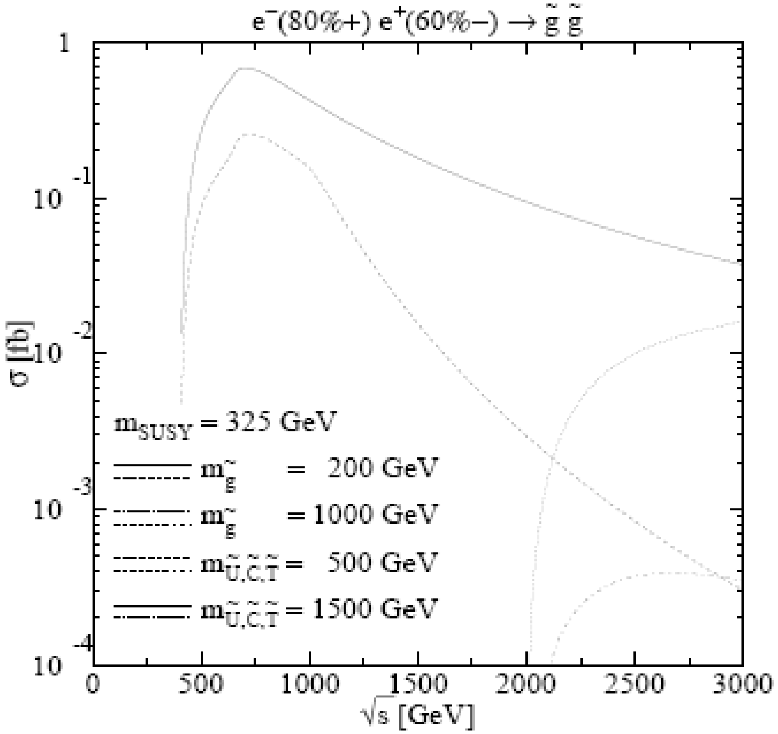
- In order to get ‘significant’ rates it is favorable to remove any degeneracies between the squarks which are common in mSUGRA. The reason for this is that that the contributions of LH- and RH-squarks tend to cancel as also do the two individual contributions of the LH-squarks within each of the individual doublets. This favors lighter squarks.
- In mSUGRA this means that stops produce the largest contributions…but this will not necessarily be the case in the general MSSM.
- Numerical scans of the MSSM parameters would be useful..





Berge & Klasen





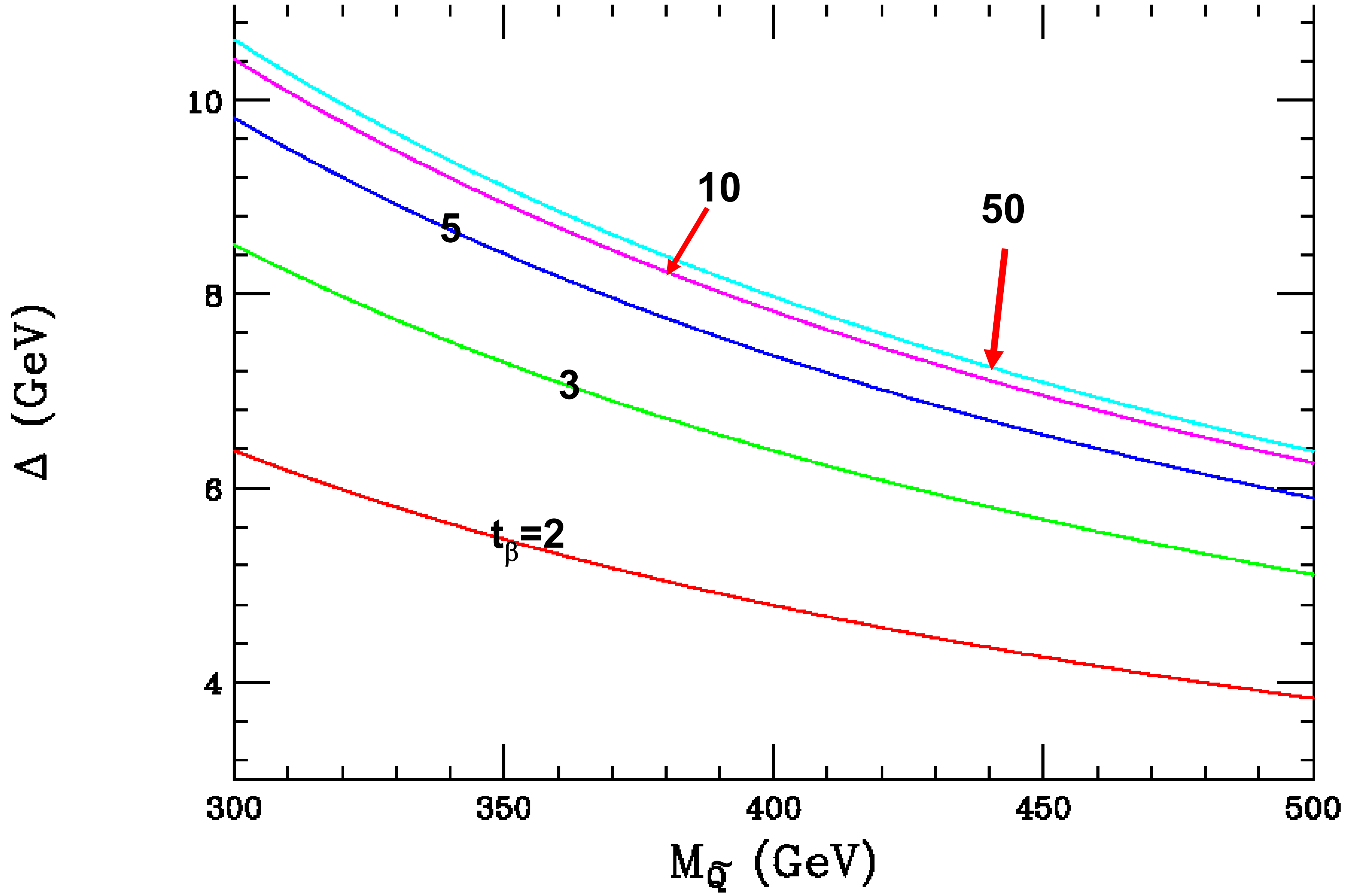
As seen above, the LHC mass determinations for squarks will not be so great…but precision measurements of squark & gluino masses do give us some insight into the MSSM parameters themselves so it is important to know them as well as possible. A good example of this is the mass splitting between the LH d- & u-squarks:

$$M_{dL}^2 - M_{uL}^2 = M_W^2 (t_\beta^2 - 1) / (t_\beta^2 + 1)$$

This is the same tree-level result as in the slepton sector in the MSSM providing a cross-check on our understanding of soft SUSY breaking. Note that at tree-level the LH d-squarks are always heavier than the corresponding LH u-squarks…

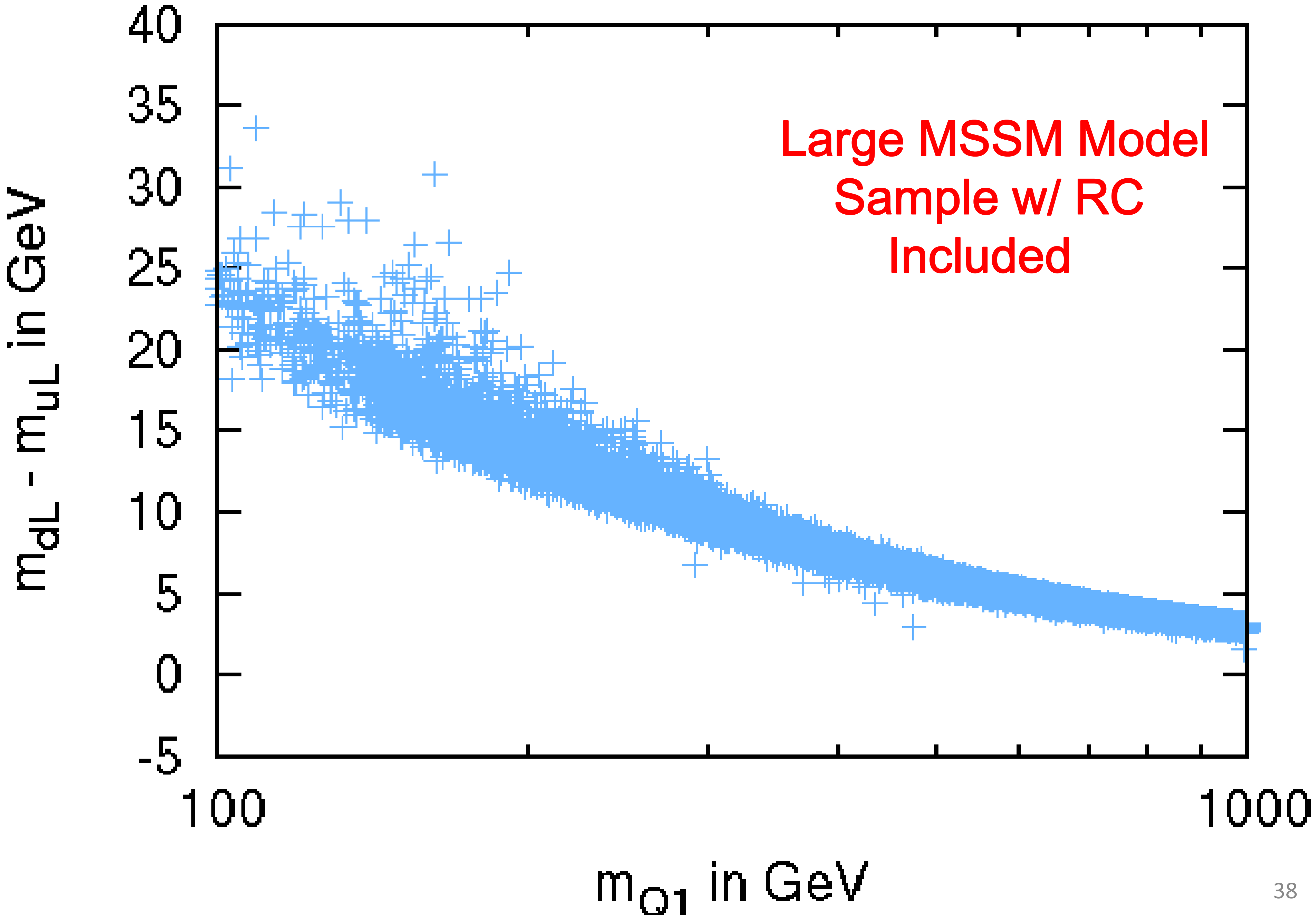
Tree-level d_L-u_L Squark Mass Splitting

Can this be precisely measured at threshold???



Small mass splitting for large masses

Squark Mass Splitting



Large MSSM Model
Sample w/ RC
Included

Some Further Comments

- It is clear from the above that even the few studies that have been done for squarks & gluinos have been somewhat limited in scope & have concentrated on the mSUGRA scenario almost exclusively. This needs to change.
- $\gamma\gamma$ -induced squark & gluino production is also interesting since far larger cross sections are possible but there is no time to discuss those processes here . They also need some further study.
- Even within the MSSM SUSY context we should prepare for the unexpected.

Summary

- 1st & 2nd generations squarks & gluinos have not been well studied at TeV e^+e^- colliders even though they may be kinematically accessible…

- Generally, squarks are more easily studied than gluinos which are produced at lower rates. We will be fortunate if squarks are heavier as they then source gluinos.

- Although multijet final states will clearly be the result of squark & gluino production, what else may happen also depends upon the MSSM model details & ME may not be present. The LHC should tell us one way or the other.

- Squarks & gluinos can/will be very interesting at these colliders w/ many possibilities to consider…GET READY!

BACKUP

FEATURE Analysis Assumptions :

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale
- The lightest neutralino is the LSP.
- The first two sfermion generations are degenerate (sfermion type by sfermion type).
- The first two generations have negligible Yukawa's.
- No assumptions about SUSY-breaking or GUT

This leaves us with the pMSSM:

→ the MSSM with 19 real, TeV/weak-scale parameters…

What are they??

19 pMSSM Parameters

sfermion masses: m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}

gaugino masses: M_1, M_2, M_3

tri-linear couplings: A_b, A_t, A_τ

Higgs/Higgsino: μ, M_A, $\tan\beta$

Note: These are TeV-scale Lagrangian parameters

How? Perform 2 Random Scans

Linear Priors

10^7 points – emphasizes moderate masses

100 GeV $\leq m_{\text{sfermions}} \leq$ 1 TeV

50 GeV $\leq |M_1, M_2, \mu| \leq$ 1 TeV

100 GeV $\leq M_3 \leq$ 1 TeV

~0.5 $M_Z \leq M_A \leq$ 1 TeV

$1 \leq \tan\beta \leq 50$

$|A_{t,b,\tau}| \leq$ 1 TeV

Log Priors

$2\text{x}10^6$ points – emphasizes lower masses but extends to higher masses

100 GeV $\leq m_{\text{sfermions}} \leq$ 3 TeV

10 GeV $\leq |M_1, M_2, \mu| \leq$ 3 TeV

100 GeV $\leq M_3 \leq$ 3 TeV

~0.5 $M_Z \leq M_A \leq$ 3 TeV

$1 \leq \tan\beta \leq 60$

10 GeV $\leq |A_{t,b,\tau}| \leq$ 3 TeV

→Comparison of these two scans will show the prior sensitivity.

→This analysis required ~ 1 processor-century of CPU time... this is the real limitation of this study.

Constraints

- $-0.0007 < \Delta\rho < 0.0026$ (PDG'08)

- $b \to s\,\gamma$: $B = (2.5 - 4.1) \times 10^{-4}$; (HFAG) + Misiak etal. &
  Becher & Neubert

- $\Delta(g-2)_\mu$??? $(30.2 \pm 8.8) \times 10^{-10}$ (0809.4062)
  $(29.5 \pm 7.9) \times 10^{-10}$ (0809.3085)
  $[\sim 14.0 \pm 8.4] \times 10^{-10}$ [Davier/BaBar-Tau08]
  → $(-10$ to $40) \times 10^{-10}$ to be conservative..

- $\Gamma(Z \to$ invisible$) < 2.0$ MeV (LEPEWWG)

- Meson-Antimeson Mixing $0.2 < R_{13} < 5$

- **$B \to \tau\nu$** **$B = (55$ to $227) \times 10^{-6}$** **Isidori & Paradisi, hep-ph/0605012 & Erikson etal., 0808.3551 for loop corrections**

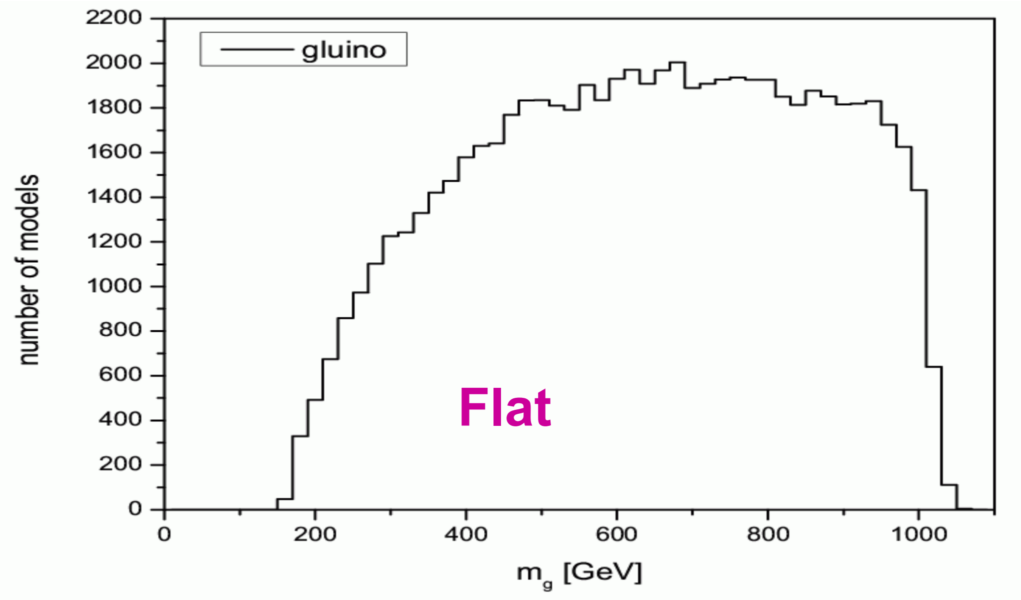
- $B_s \to \mu\mu$ $B < 4.5 \times 10^{-8}$ (CDF + D0)

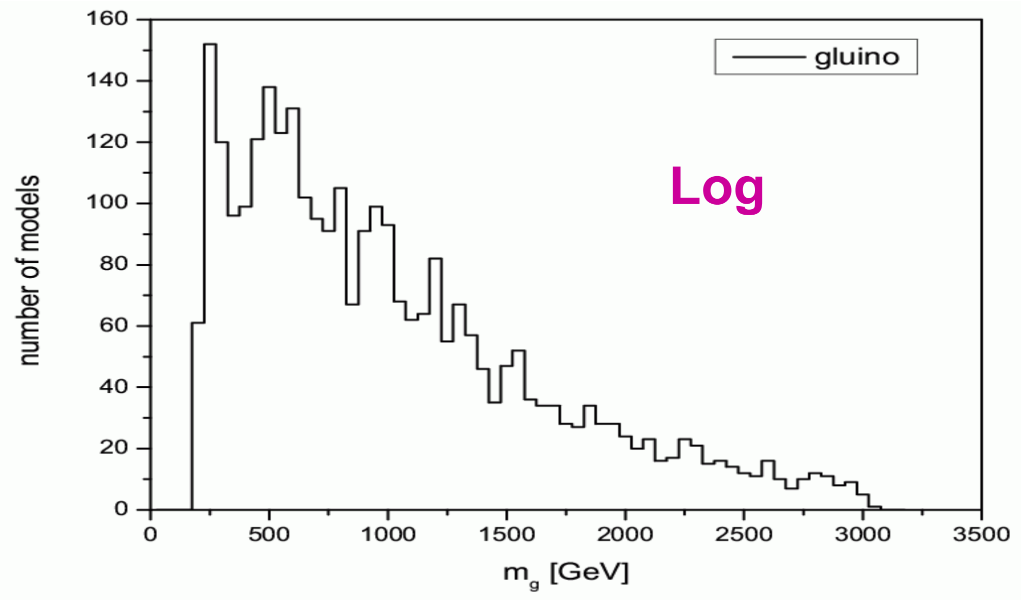
- **Direct Detection Searches for Dark Matter (e.g., CDMS, ..)**

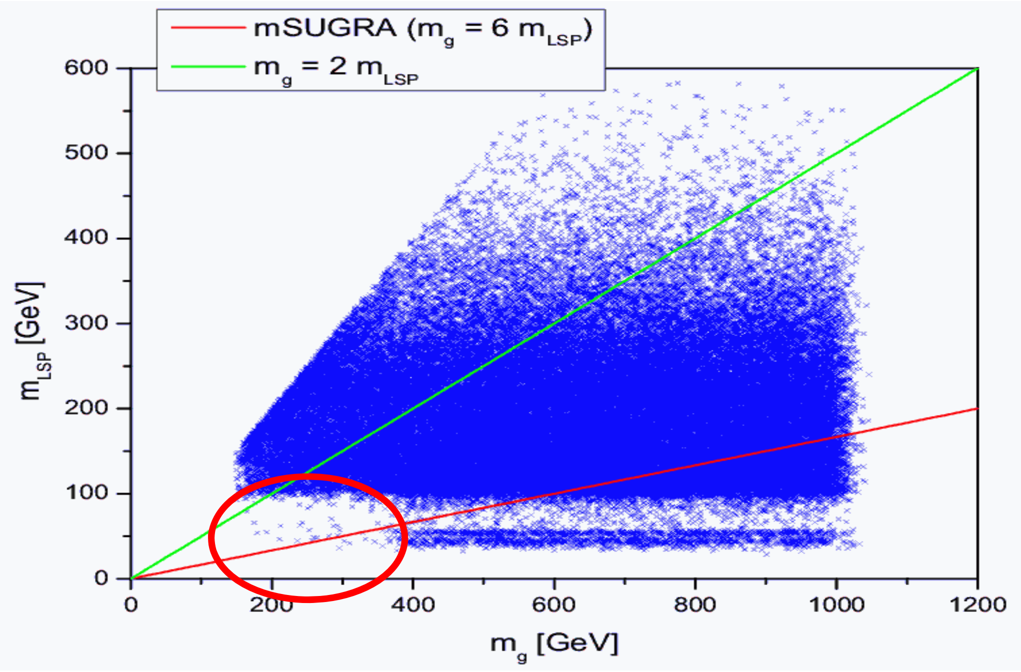
- **Dark Matter density: $\Omega h^2 < 0.1210$ → 5yr WMAP data +….**
  We treat this only as an *upper bound* density to allow for multi-component DM

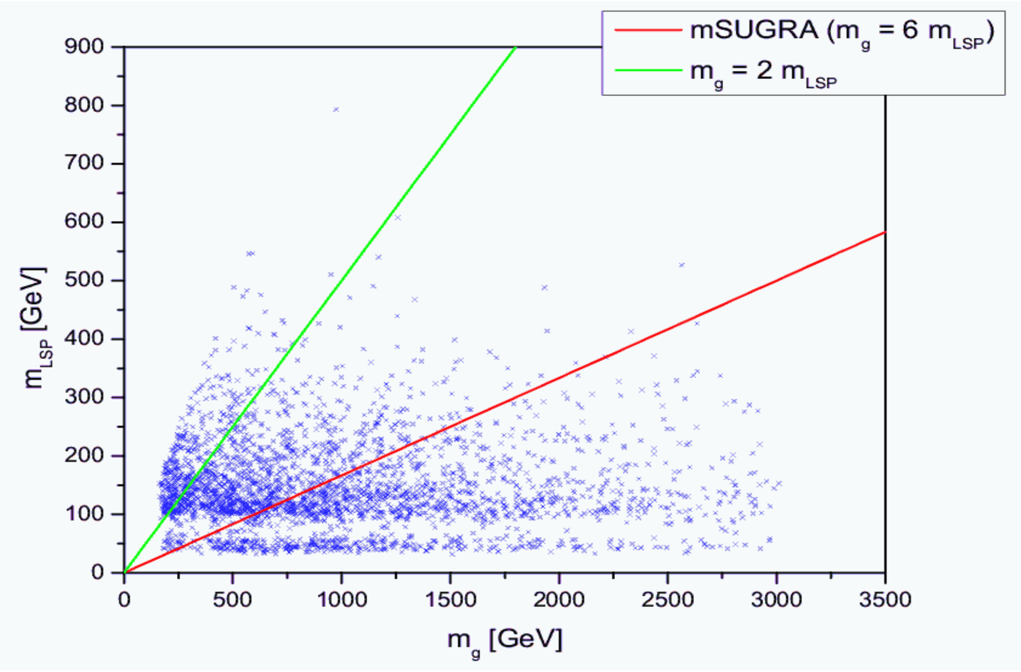
- **LEP and Tevatron Direct Higgs & SUSY searches : there are *many* of these searches some requiring detector simulations**

Gluino Can Be Light !!

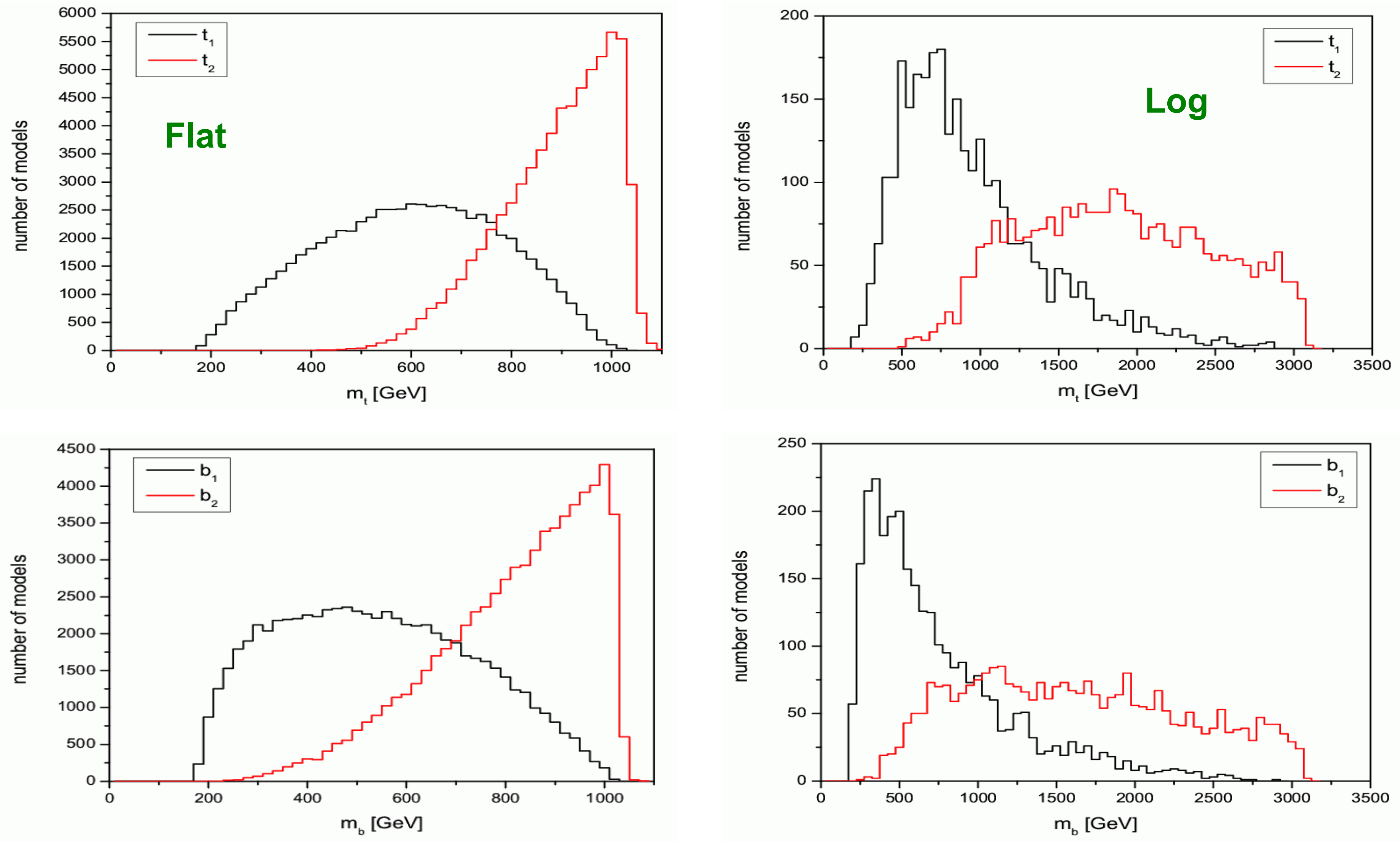


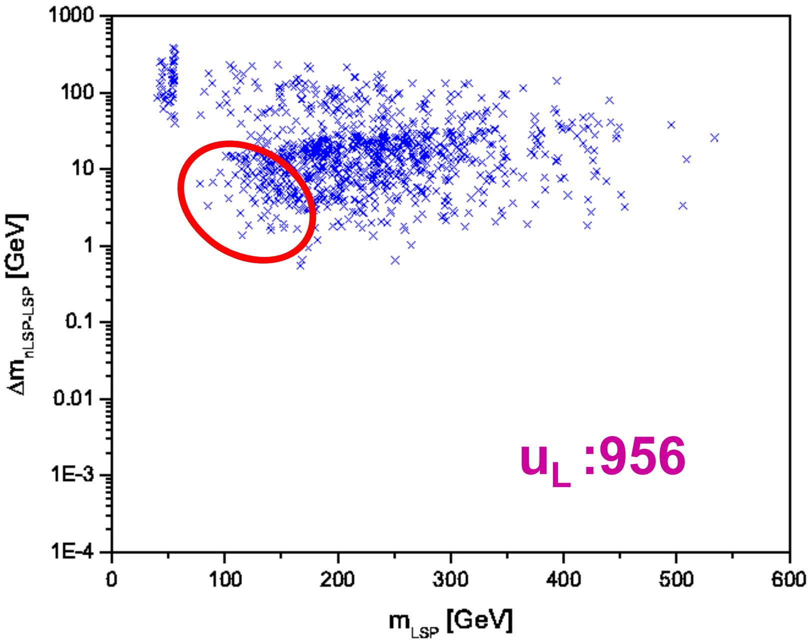


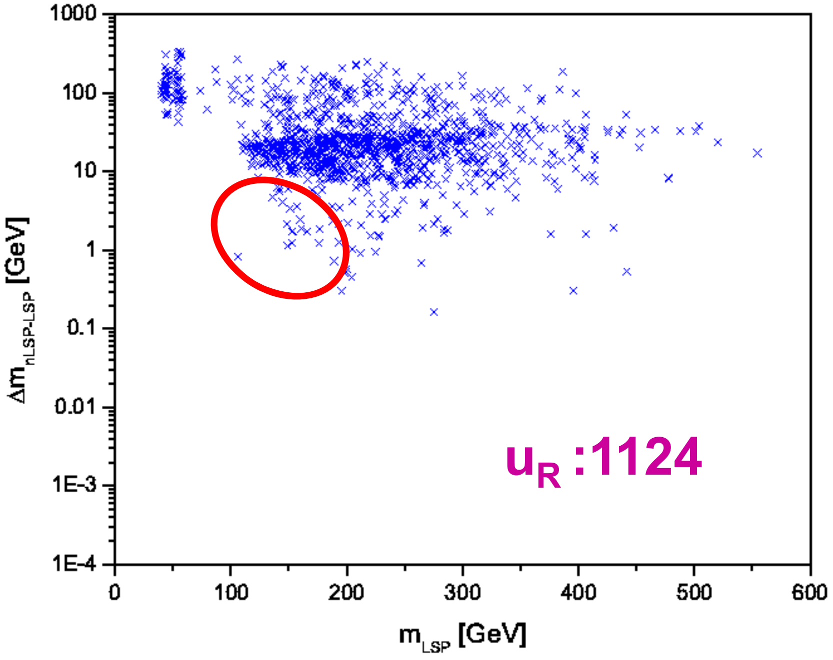


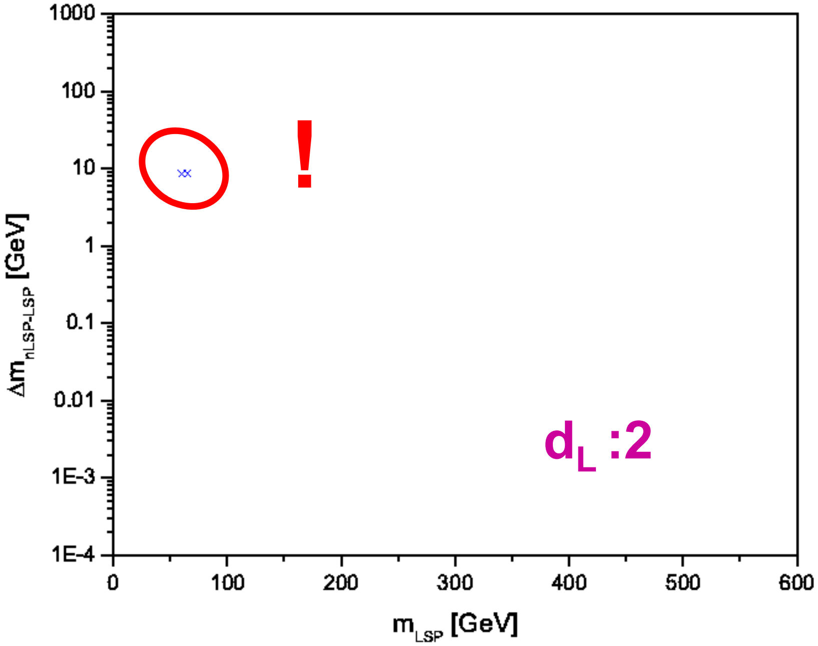


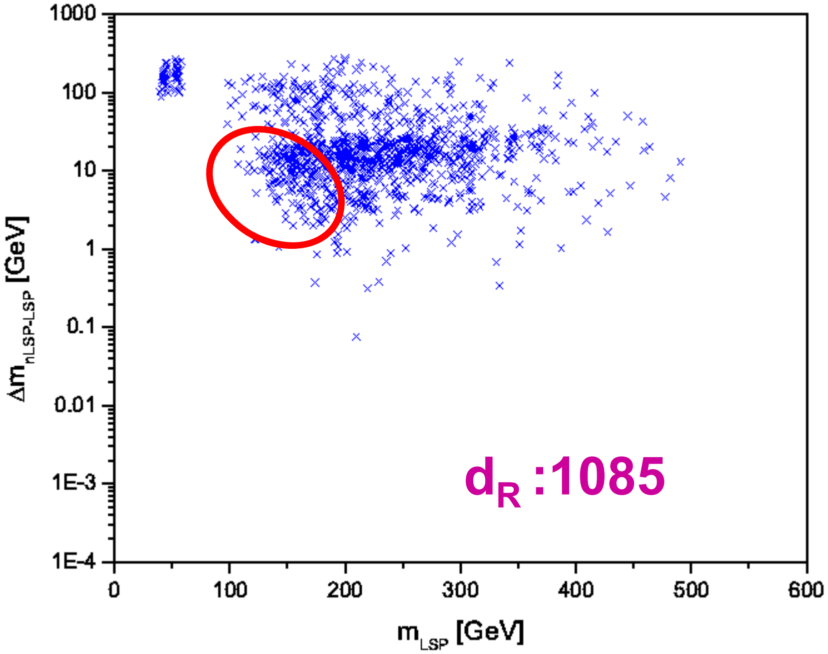
Distribution of Sparticle Masses By Species




$\Delta m_{nLSP-LSP}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]
u_L :956


$\Delta m_{nLSP-LSP}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]
u_R :1124


$\Delta m_{nLSP-LSP}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]
!
d_L :2


$\Delta m_{nLSP-LSP}$ [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600
m_{LSP} [GeV]
d_R :1085