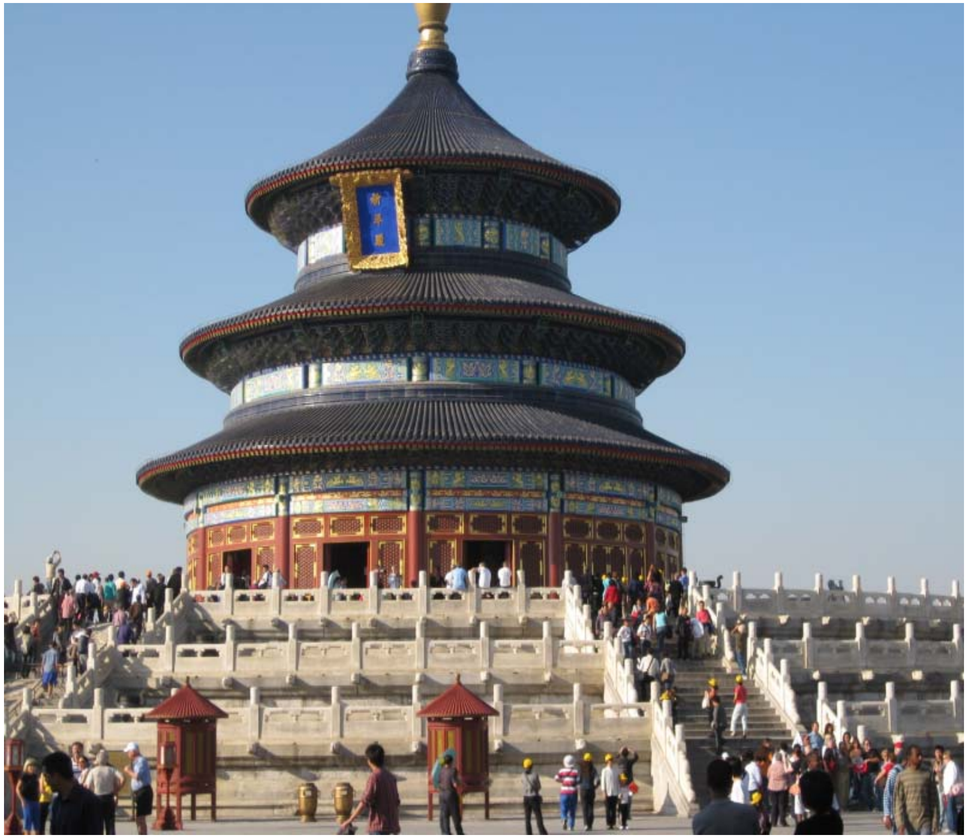
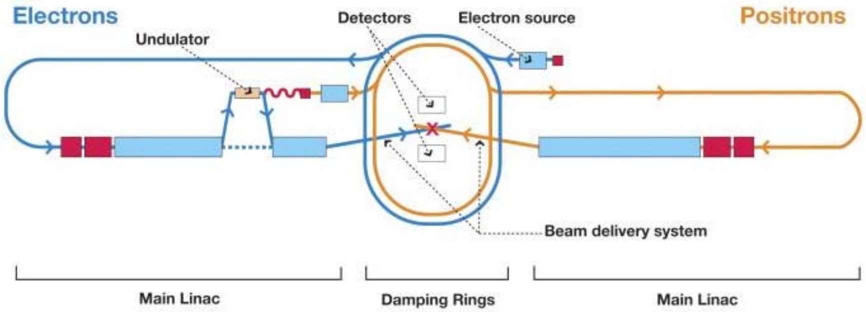
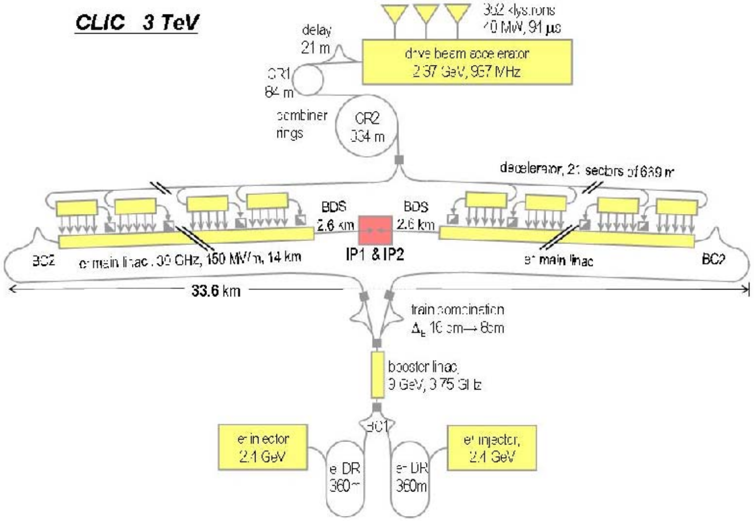
Light Squarks and Gluinos @ TeV e^+e^- Colliders







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3/27/10

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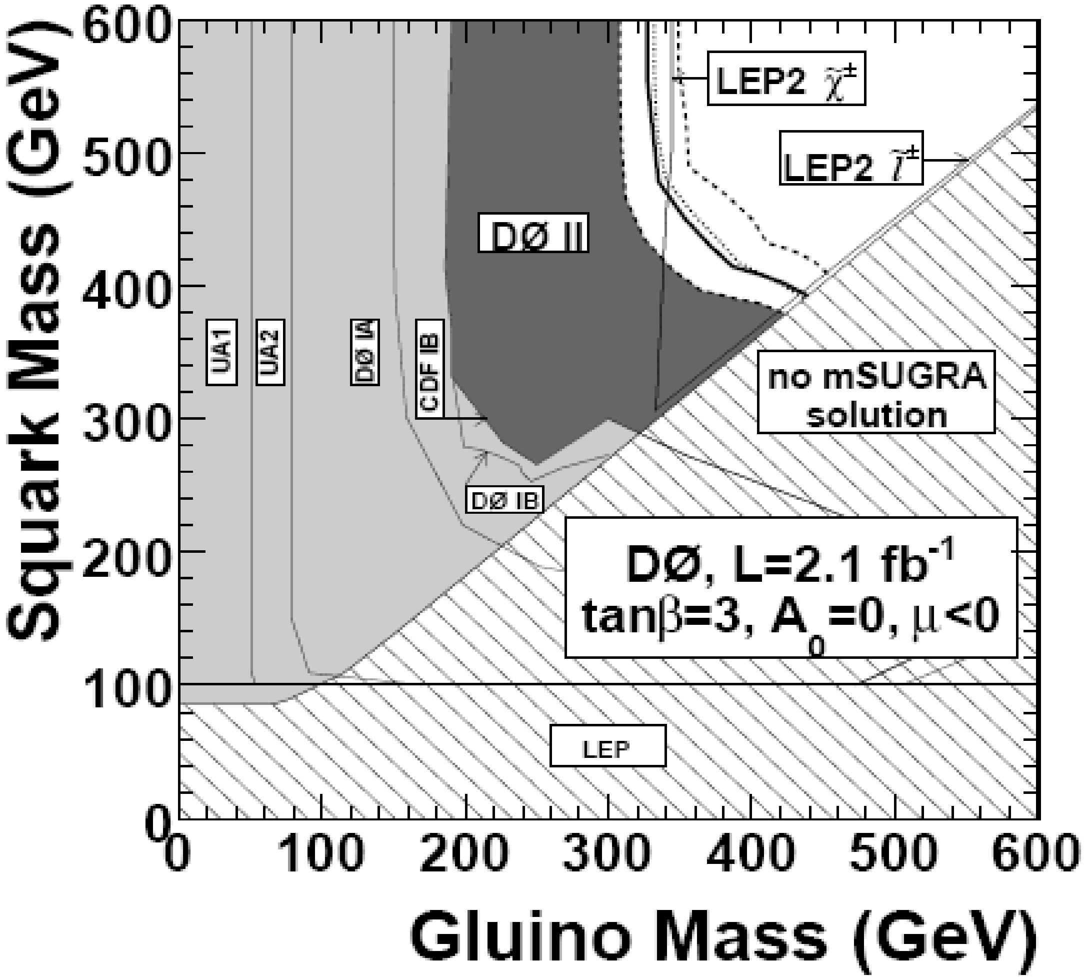
Message # 1 :

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 the SPS1a' point ! !

Nature is too clever for that….

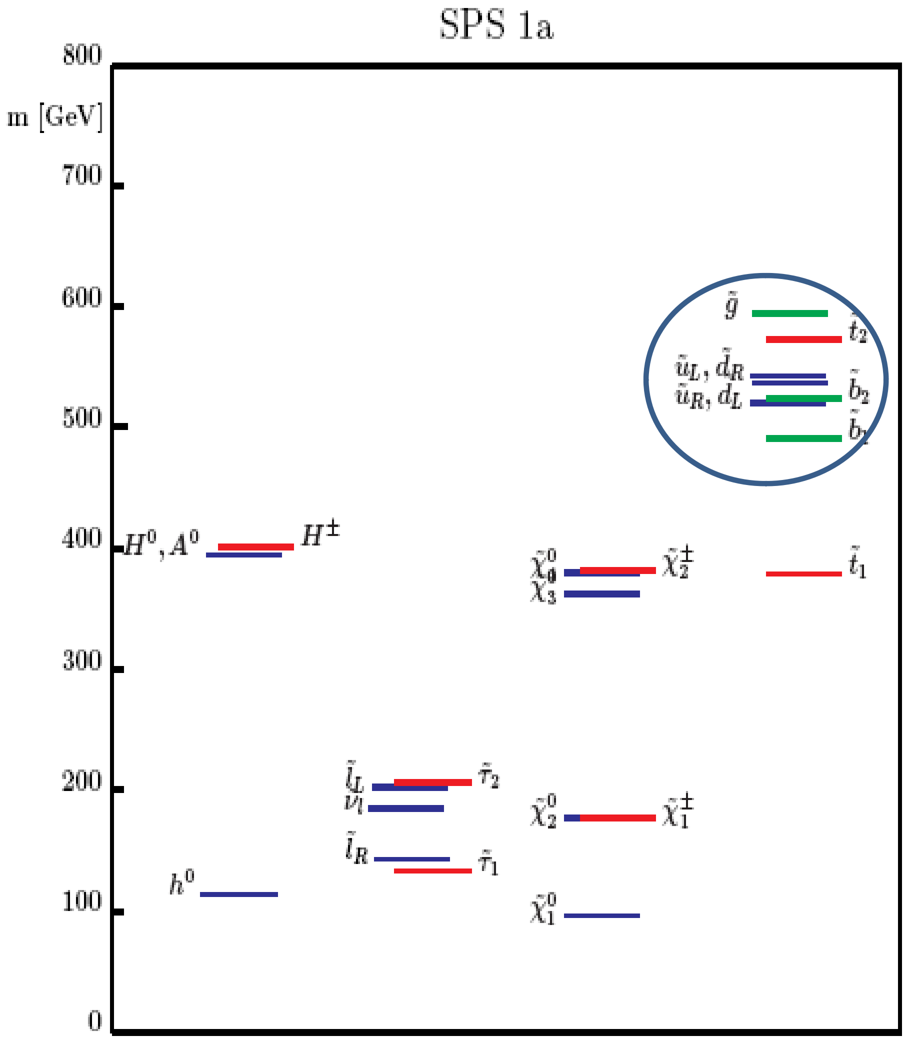
Gluinos & squarks in the 1st & 2nd generation have not been much discussed in the context of ~TeV e^+e^- colliders for several reasons :

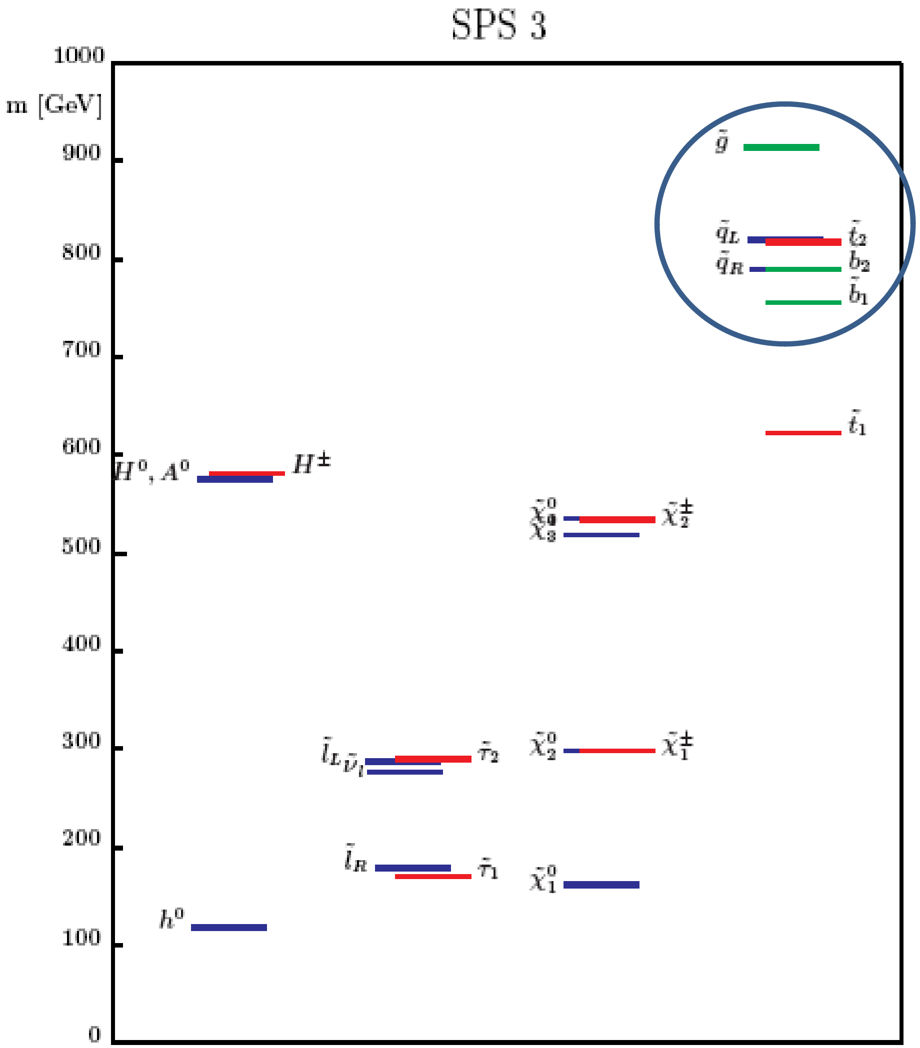


(i) Tevatron searches provide rather strong constraints on *mSUGRA*.. squarks & gluinos masses >350-400 GeV & so they are possibly beyond the range of even a 1 TeV collider.

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..

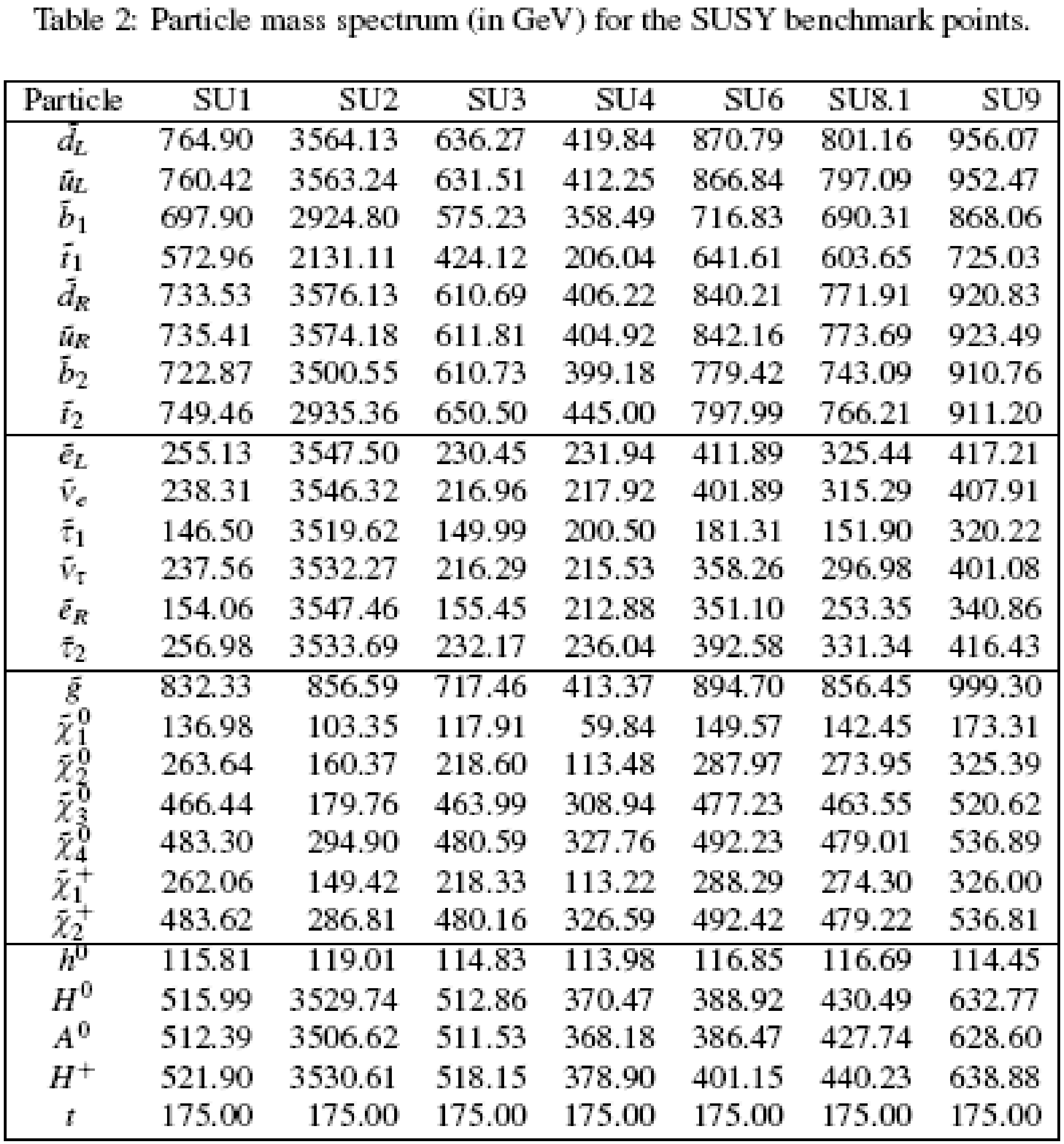
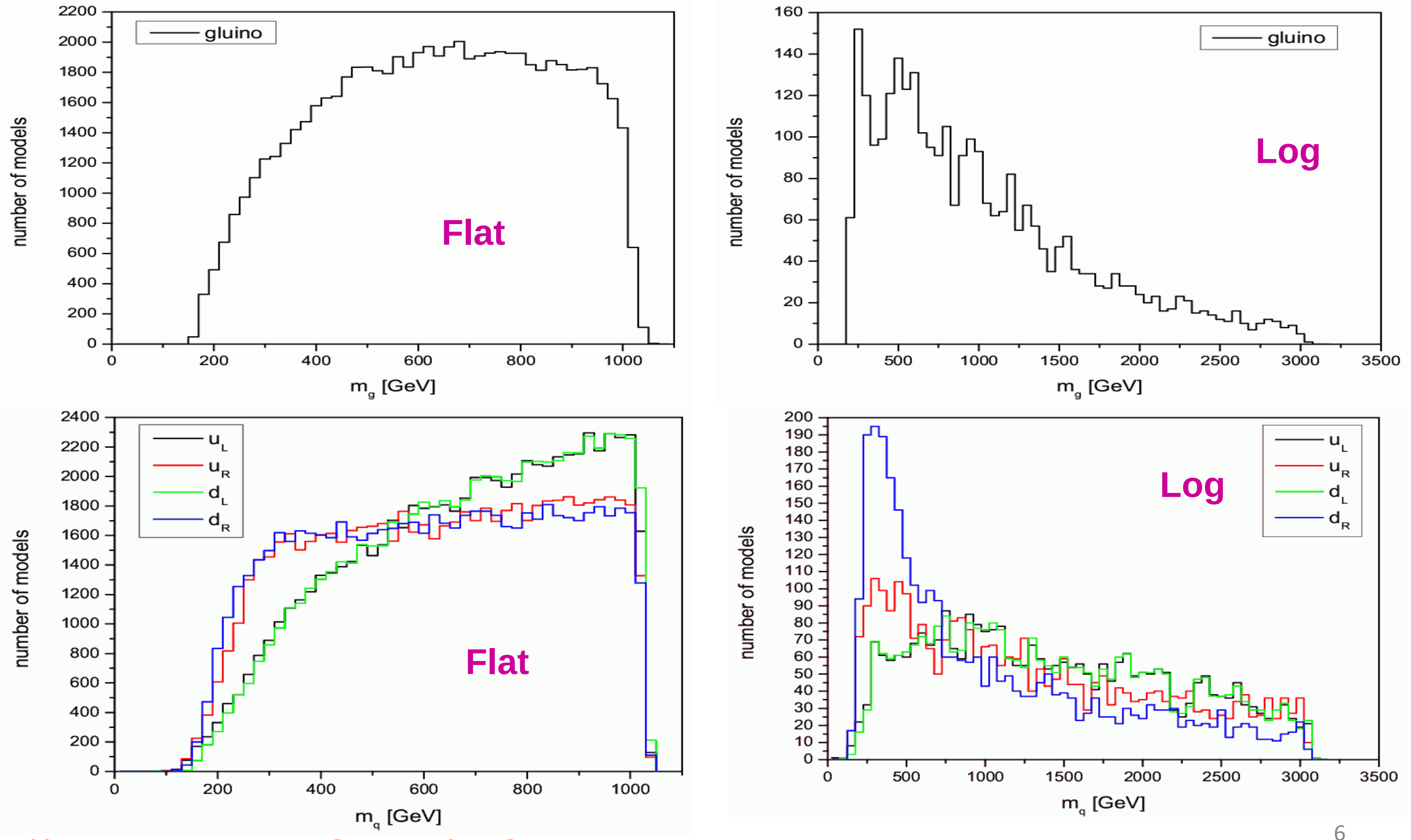


Table 2: Particle mass spectrum (in GeV) for the SUSY benchmark points.

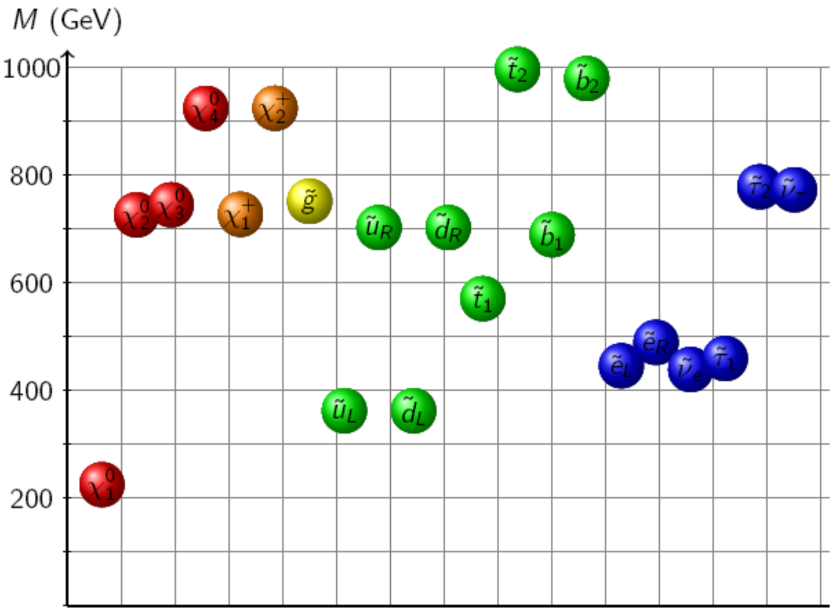
Particle	SU1	SU2	SU3	SU4	SU6	SU8.1	SU9
$\tilde{d}_L$	764.90	3564.13	636.27	419.84	870.79	801.16	956.07
$\tilde{u}_L$	760.42	3563.24	631.51	412.25	866.84	797.09	952.47
$\tilde{b}_1$	697.90	2924.80	575.23	358.49	716.83	690.31	868.06
$\tilde{t}_1$	572.96	2131.11	424.12	206.04	641.61	603.65	725.03
$\tilde{d}_R$	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

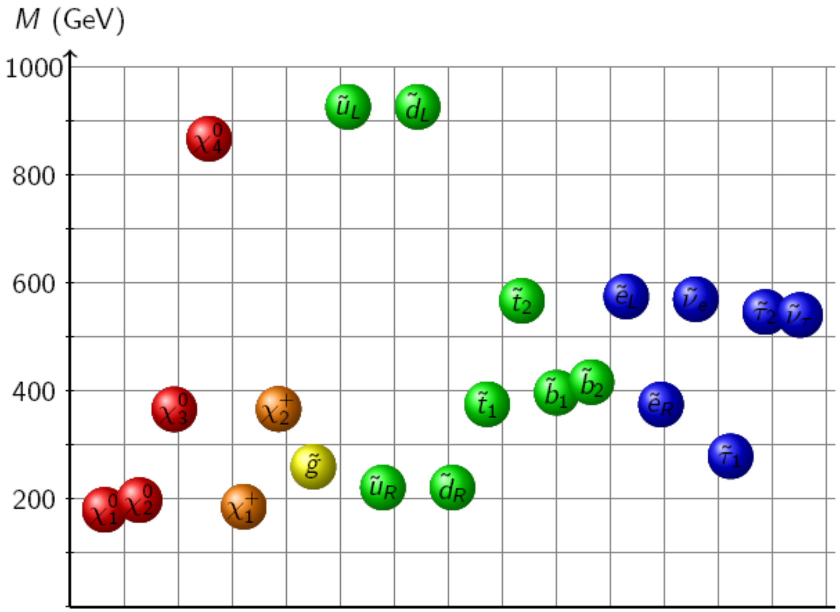
This is a bias based on mSUGRA !!!

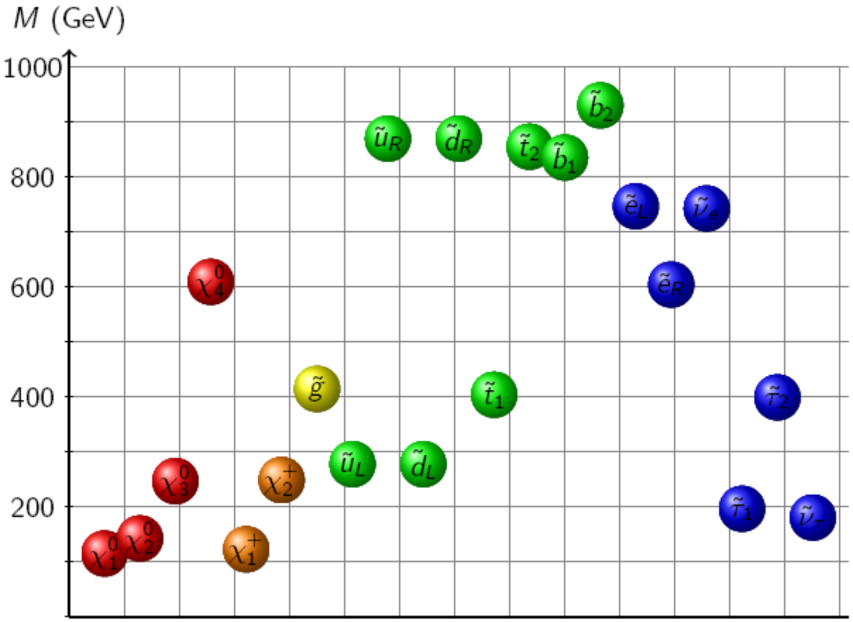
A more general, less prejudiced consideration **of the SUSY parameter space allows for lighter squarks & gluinos that avoid all existing experimental constraints:



** Berger, Hewett ,Gainer & TGR


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


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


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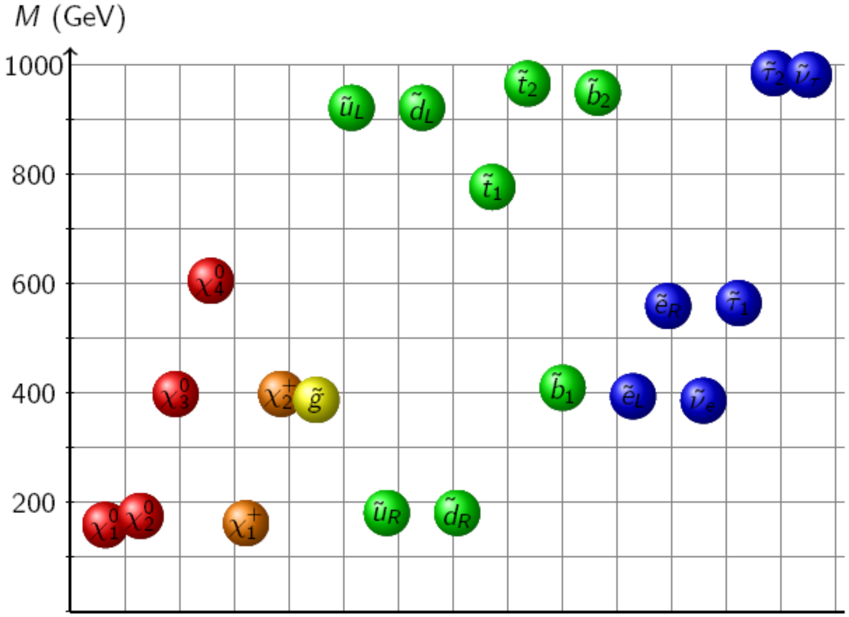
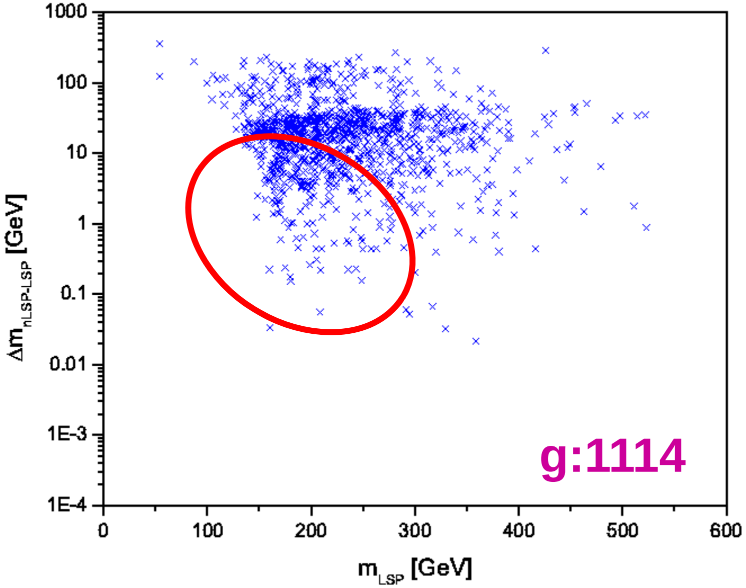
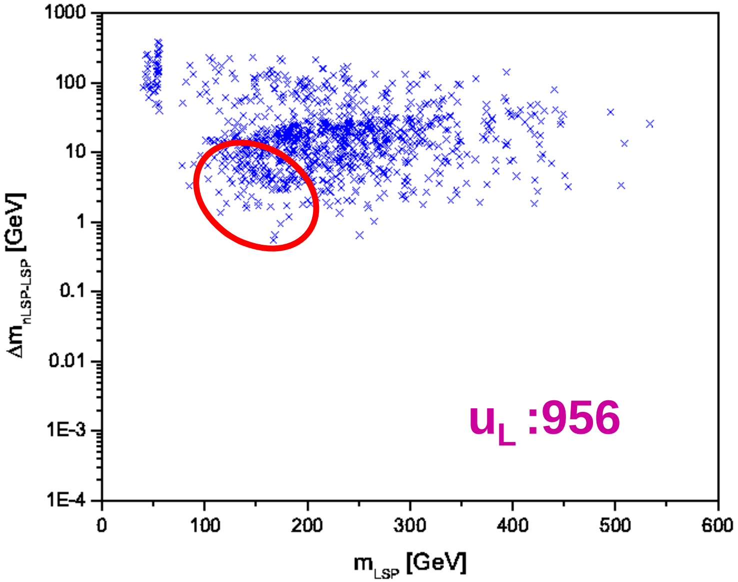
$\tilde{\tau}_1$
$\tilde{\nu}_\tau$

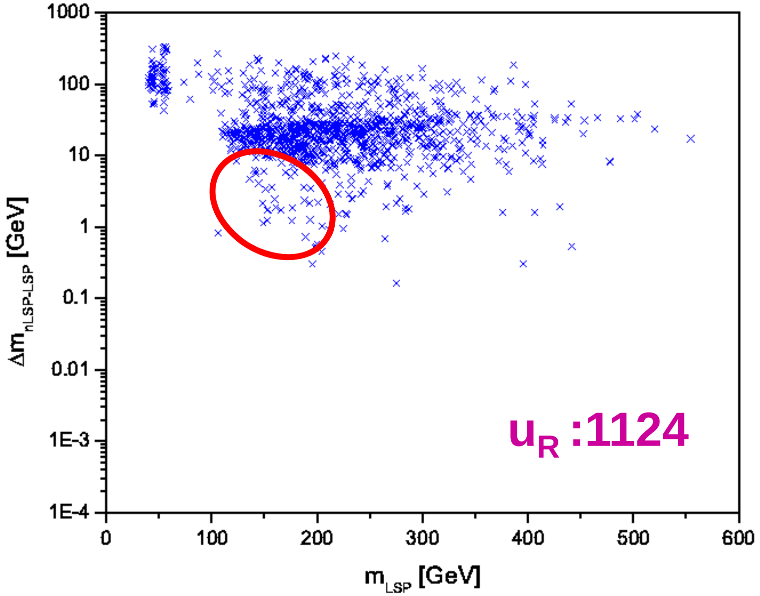

M (GeV)
1000
800
600
400
200
χ_1^0
χ_2^0
χ_3^0
χ_4^0
χ_1^+
χ_2^+
$\tilde{g}$
$\tilde{u}_R$
$\tilde{d}_R$
$\tilde{u}_L$
$\tilde{d}_L$
$\tilde{t}_1$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{b}_2$
$\tilde{e}_L$
$\tilde{\nu}_e$
$\tilde{e}_R$
$\tilde{\tau}_1$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$

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



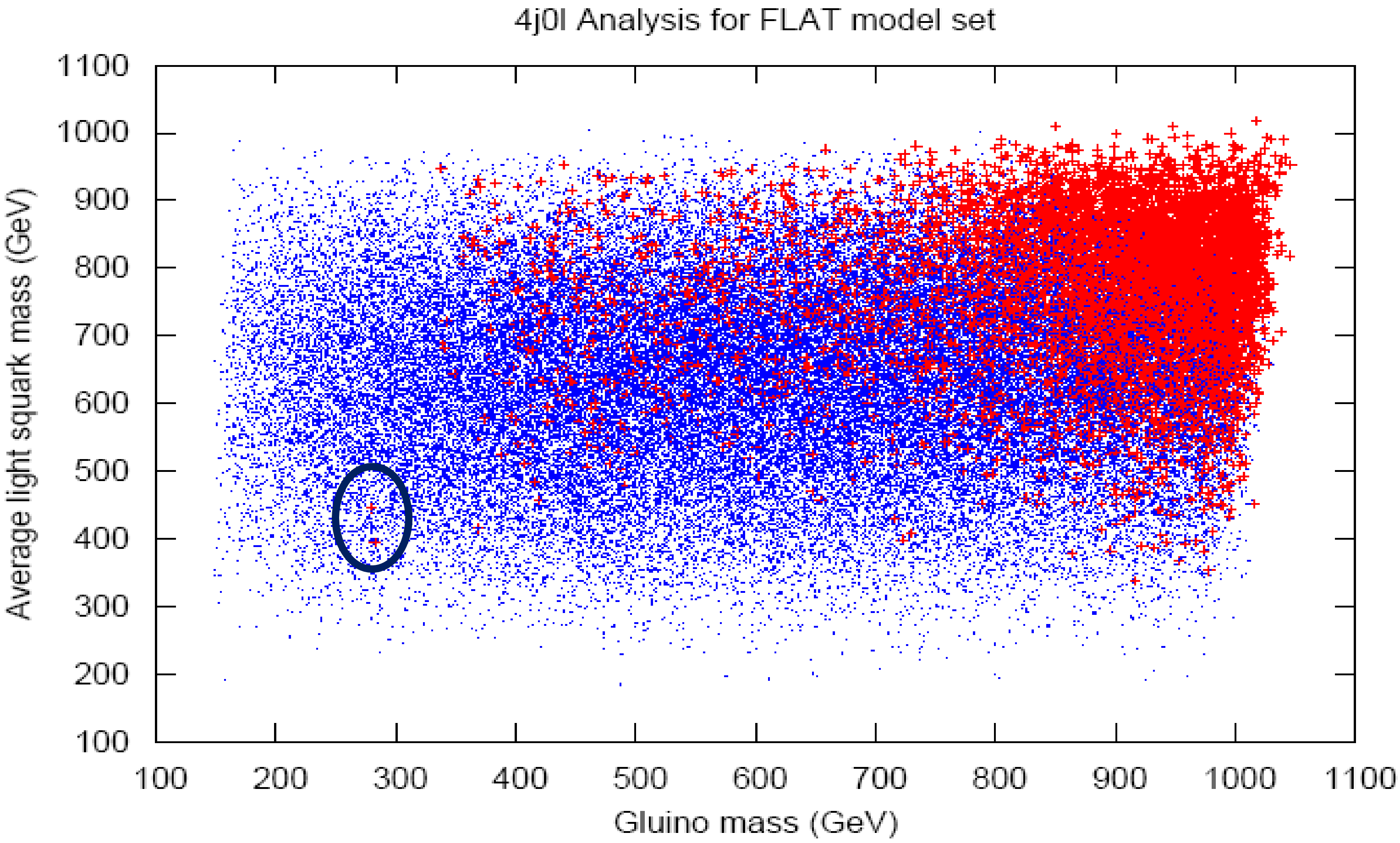
Small mass splittings can lead to soft particles in the final state that have insufficient p_T to pass any SUSY Tevatron search analysis cuts





Message #2: SUSY may be missed @ the LHC

- Squarks & gluinos may BOTH be VERY light yet missed @ LHC !



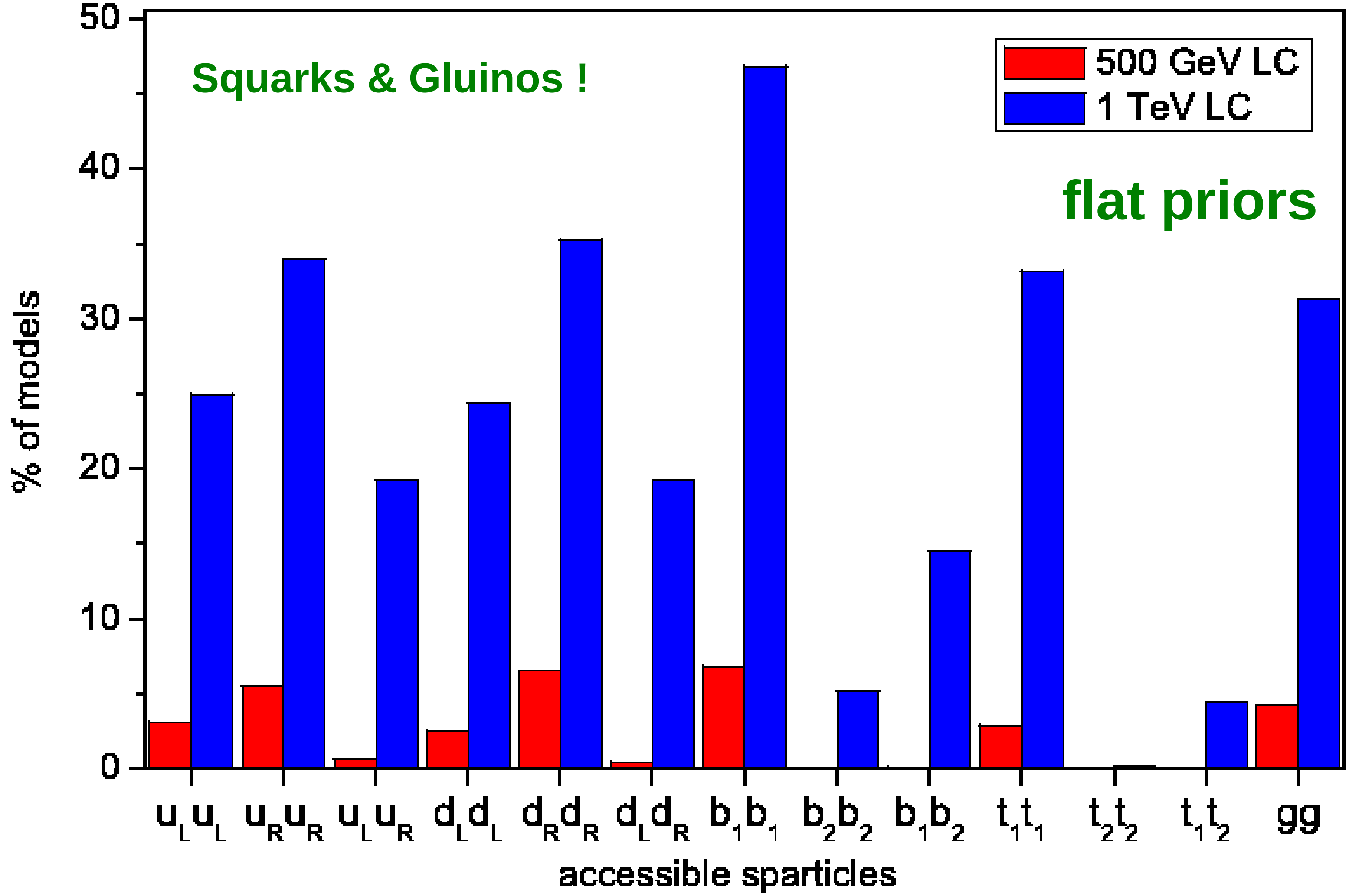
Example: Model 53105

gluino(282.8) → $\tilde{d}_R$ (201.7) j	100%	Δm =81.1 GeV
$\tilde{d}_R$ (201.7) → $\tilde{\chi}_2^0$ (193.8) j	97%	Δm =7.9 GeV
$\tilde{\chi}_2^0$ (193.8) → $\tilde{l}_R^{\pm}$ (163.9) l	100%	Δm =30.0 GeV
$\tilde{l}_R^{\pm}$ (163.9) → $l^{\pm}$ +MET(152.5)	100%	Δm =11.4 GeV

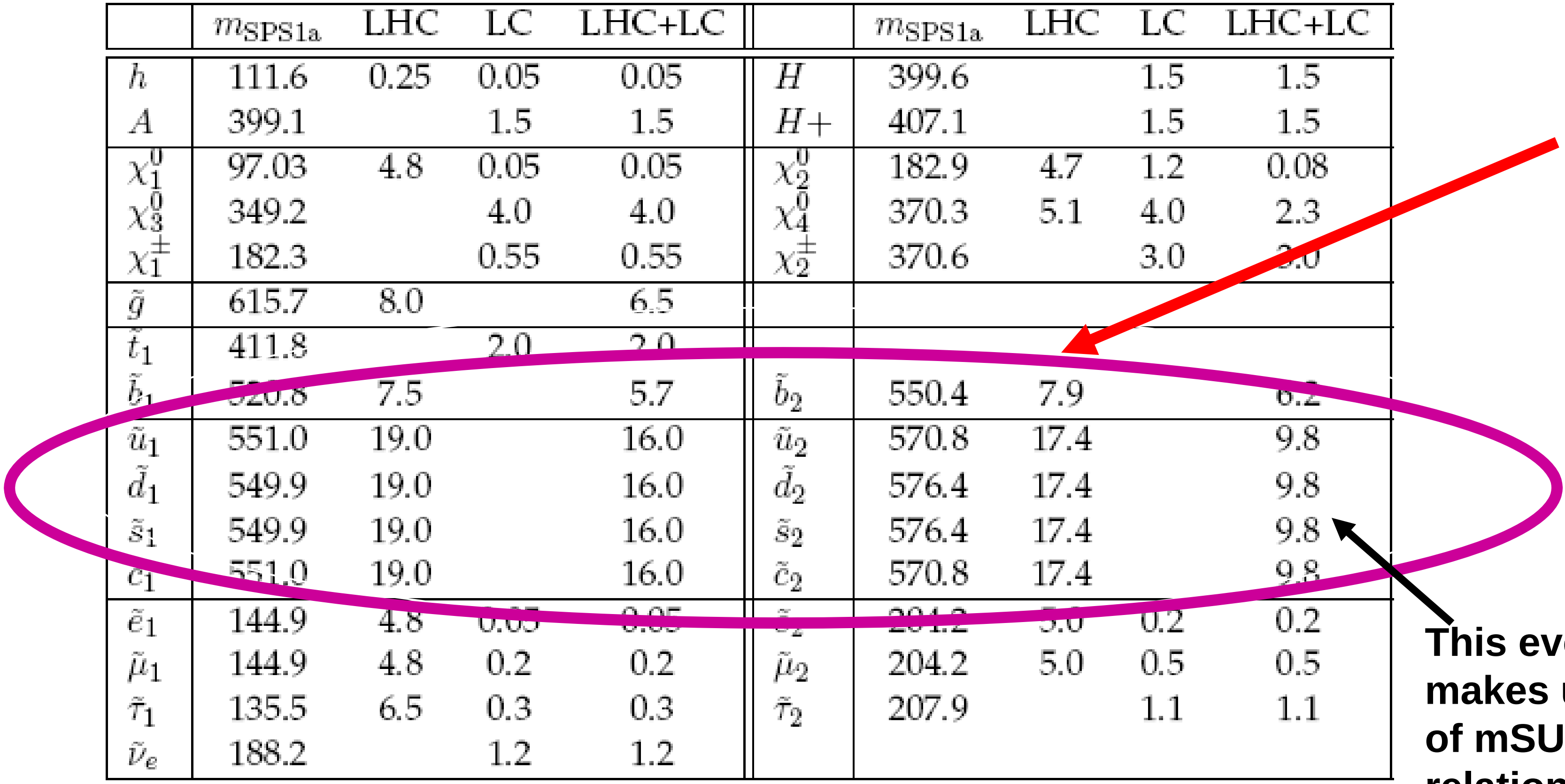
Model *fails* ATLAS analysis cuts due to small mass splittings between the sparticles

→ Sparticles may have ‘commonly discussed’ decay modes yet STILL be missed entirely !

Kinematic Accessibility (M ~ < 1 TeV)



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



	$m_{\rm SPS1a}$	LHC	LC	LHC+LC		$m_{\rm SPS1a}$	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 even makes use of 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

Message #3: we need to think seriously about light squarks and gluinos at TeV & multi-TeV e^+e^- colliders

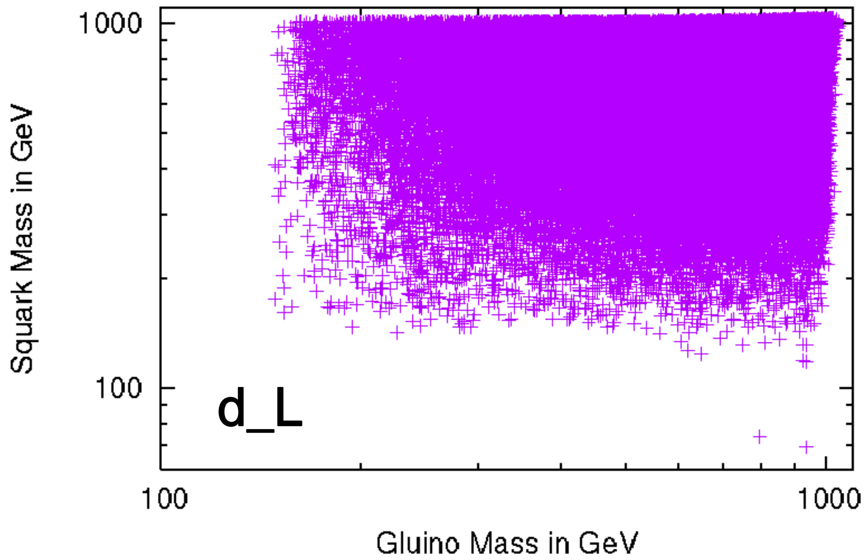
- My purpose here is to ask some questions as a way to stimulate thinking about this subject & not to provide detailed answers…which will require some hard work & LHC data.

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

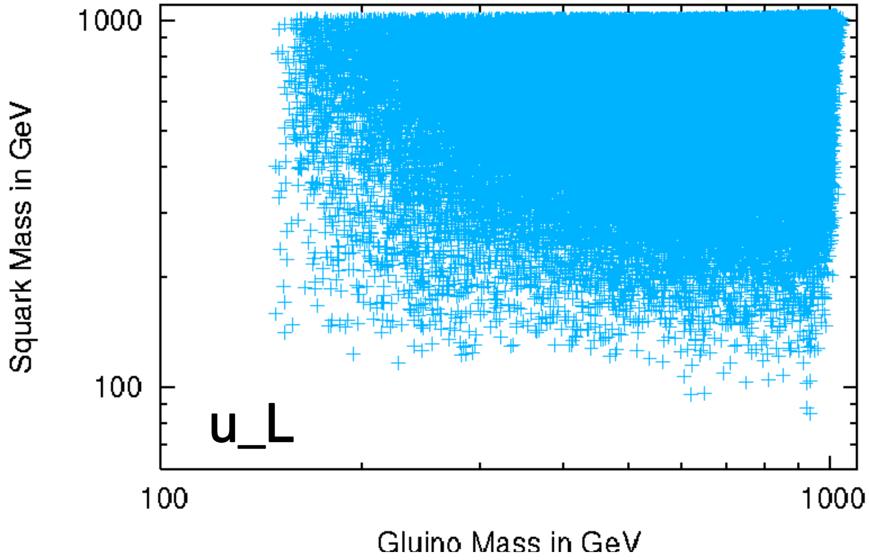
First Question:
Which are lighter
squarks or gluinos?

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

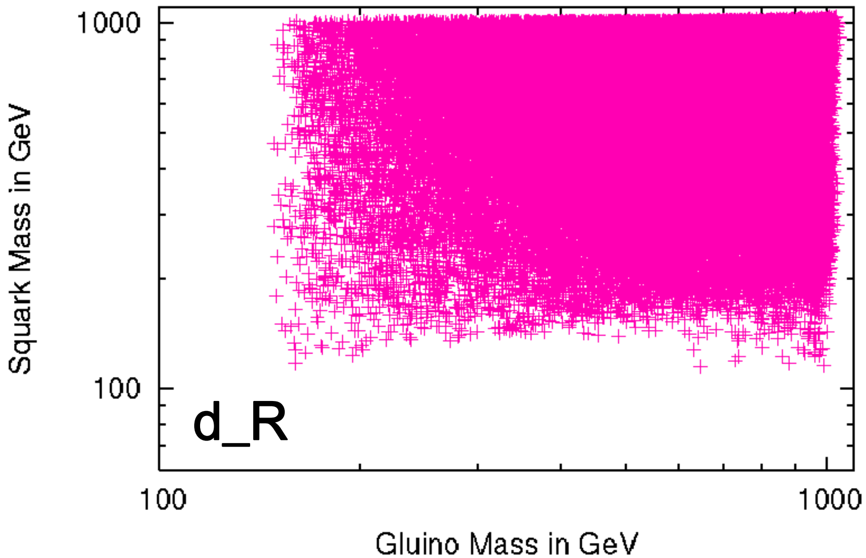
Gluino Mass Versus dl Squark Mass



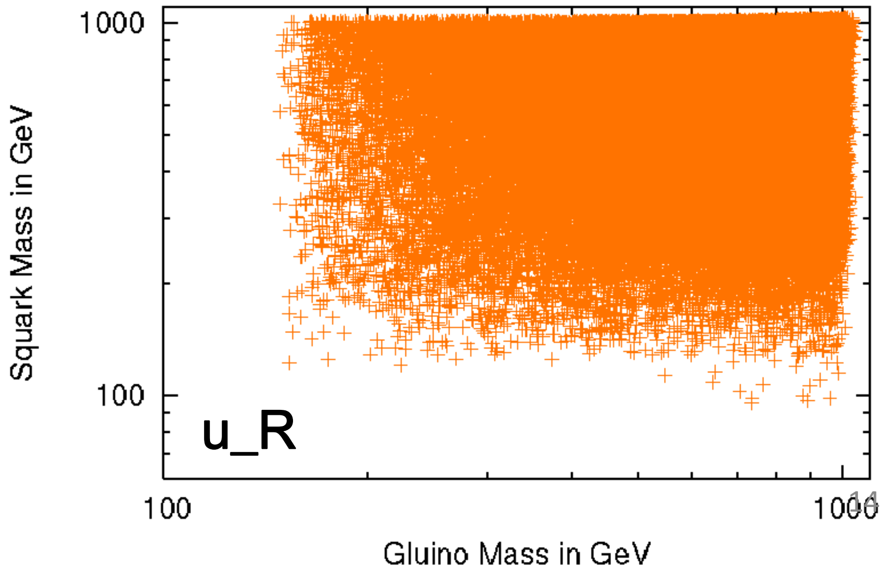
Gluino Mass Versus ul Squark Mass



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 :

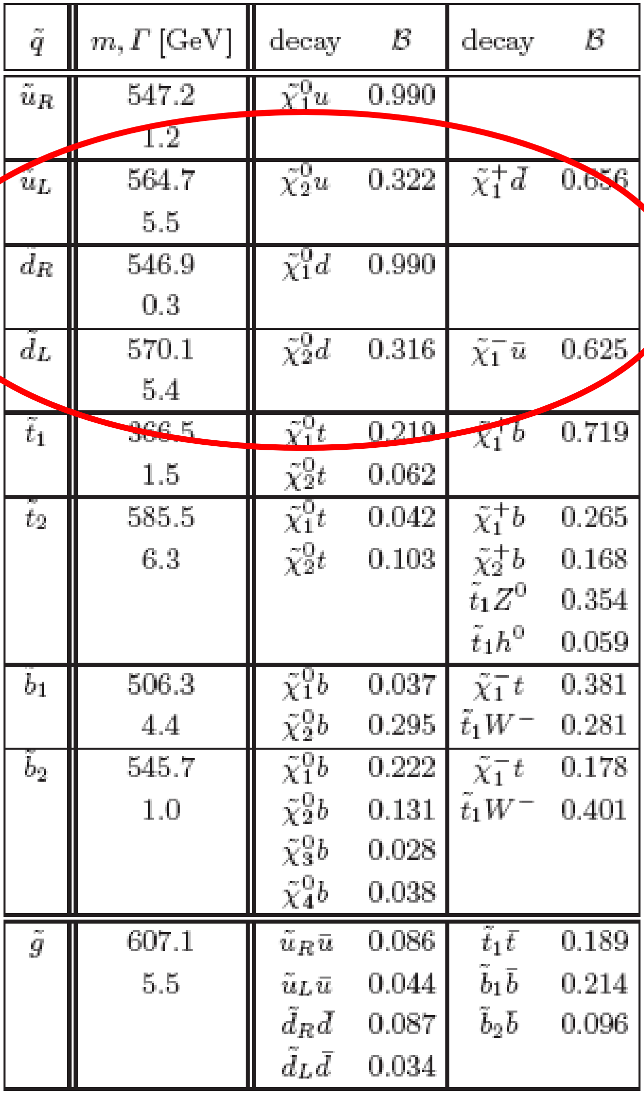
- In the absence of Yukawa couplings (a very good approx.) the squarks in the 1st & 2nd generations do not couple to charged or neutral Higgsinos

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

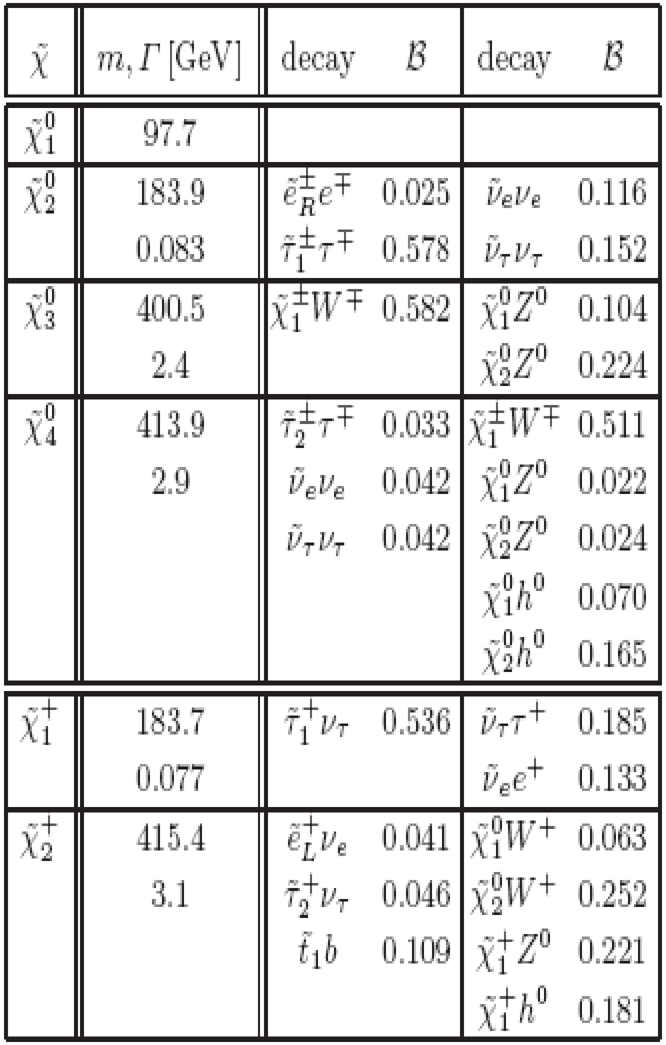
- For LH squarks, decays can occur through both the bino component of χ's as well as the (charged & neutral) wino component.

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 a simple mSUGRA scenario



$\tilde{q}$	m, Γ [GeV]	decay	$\mathcal{B}$	decay	$\mathcal{B}$
$\tilde{u}_R$	547.2 1.2	$\tilde{\chi}_1^0 u$	0.990		
$\tilde{u}_L$	564.7 5.5	$\tilde{\chi}_2^0 u$	0.322	$\tilde{\chi}_1^+ d$	0.656
$\tilde{d}_R$	546.9 0.3	$\tilde{\chi}_1^0 d$	0.990		
$\tilde{d}_L$	570.1 5.4	$\tilde{\chi}_2^0 d$	0.316	$\tilde{\chi}_1^- \bar{u}$	0.625
$\tilde{t}_1$	366.5 1.5	$\tilde{\chi}_1^0 t$ $\tilde{\chi}_2^0 t$	0.219 0.062	$\tilde{\chi}_1^+ b$	0.719
$\tilde{t}_2$	585.5 6.3	$\tilde{\chi}_1^0 t$ $\tilde{\chi}_2^0 t$	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	$\tilde{\chi}_1^0 b$ $\tilde{\chi}_2^0 b$	0.037 0.295	$\tilde{\chi}_1^- t$ $\tilde{t}_1 W^-$	0.381 0.281
$\tilde{b}_2$	545.7 1.0	$\tilde{\chi}_1^0 b$ $\tilde{\chi}_2^0 b$ $\tilde{\chi}_3^0 b$ $\tilde{\chi}_4^0 b$	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	$\mathcal{B}$
$\tilde{\chi}_1^0$	97.7				
$\tilde{\chi}_2^0$	183.9 0.083	$\tilde{e}_R^\pm e^\mp$ $\tilde{\tau}_1^\pm \tau^\mp$	0.025 0.578	$\tilde{\nu}_e \nu_e$ $\tilde{\nu}_\tau \nu_\tau$	0.116 0.152
$\tilde{\chi}_3^0$	400.5 2.4	$\tilde{\chi}_1^\pm W^\mp$	0.582	$\tilde{\chi}_1^0 Z^0$ $\tilde{\chi}_2^0 Z^0$	0.104 0.224
$\tilde{\chi}_4^0$	413.9 2.9	$\tilde{\tau}_2^\pm \tau^\mp$ $\tilde{\nu}_e \nu_e$ $\tilde{\nu}_\tau \nu_\tau$	0.033 0.042 0.042	$\tilde{\chi}_1^\pm W^\mp$ $\tilde{\chi}_1^0 Z^0$ $\tilde{\chi}_2^0 Z^0$ $\tilde{\chi}_1^0 h^0$ $\tilde{\chi}_2^0 h^0$	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	$\tilde{\chi}_1^0 W^+$ $\tilde{\chi}_2^0 W^+$ $\tilde{\chi}_1^+ Z^0$ $\tilde{\chi}_1^+ h^0$	0.063 0.252 0.221 0.181

← ~bino

← ~wino

← ~wino

- Of course, somewhat ‘unusual’ decay chains are possible.

E.g. ,

Gluino $\to \tilde{u}_L$ +j, $\tilde{u}_L \to \tilde{\chi}_1^{\pm}$ j, $\tilde{\chi}_1^{\pm} \to \pi^{\pm}$ + MET (long-lived)*

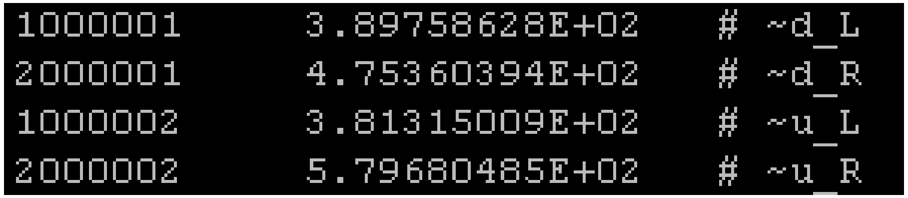
Gluino $\to \tilde{q}$ +j, $\tilde{q} \to \tilde{\chi}_3^0$ +j, $\tilde{\chi}_3^0 \to$ h + MET , h $\to b\bar{b}$

or $\to \tilde{\chi}_1^{\pm}$ W

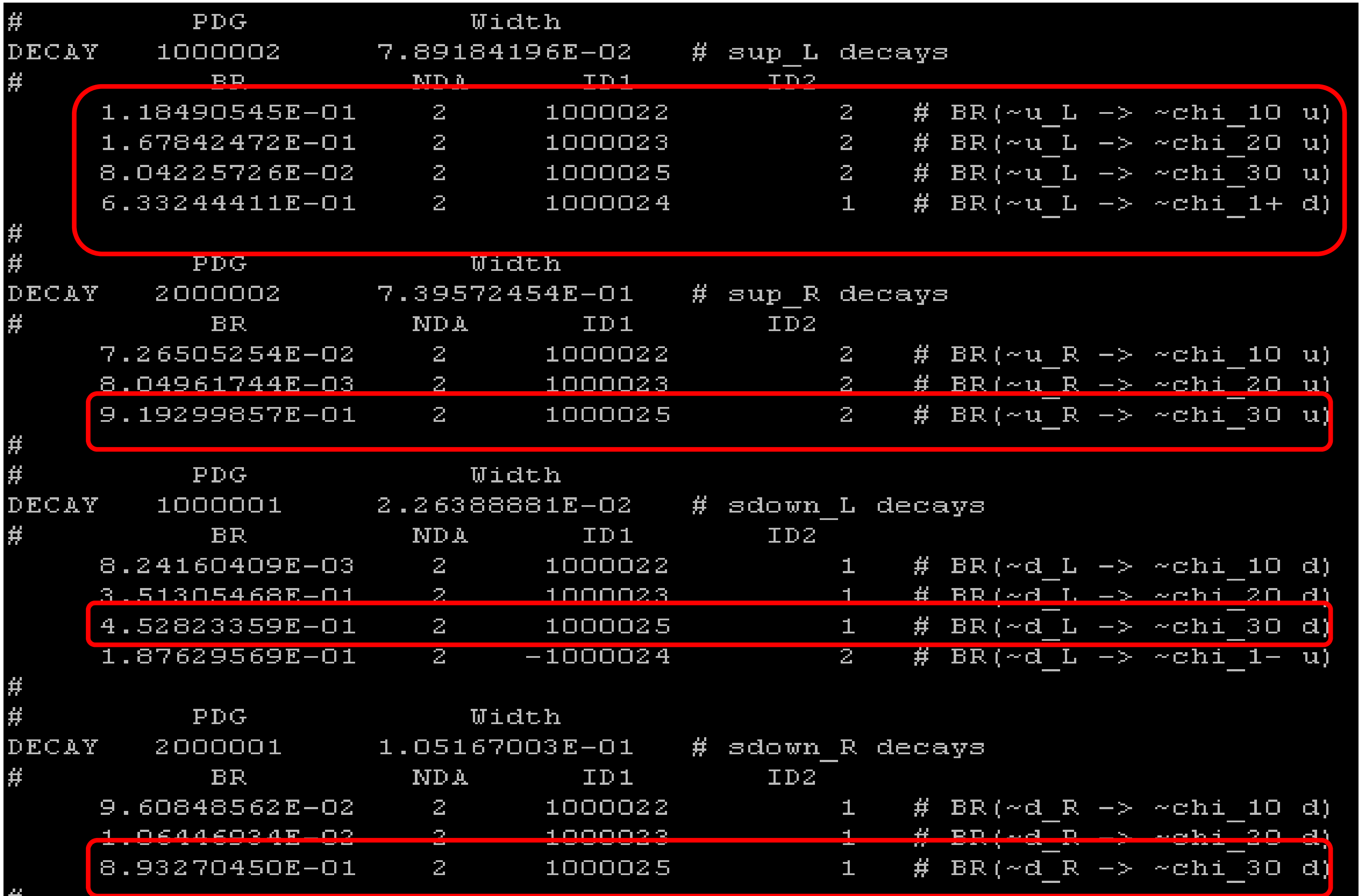
* ‘long-lived’ may be 100μm or many kilometers

Model 241

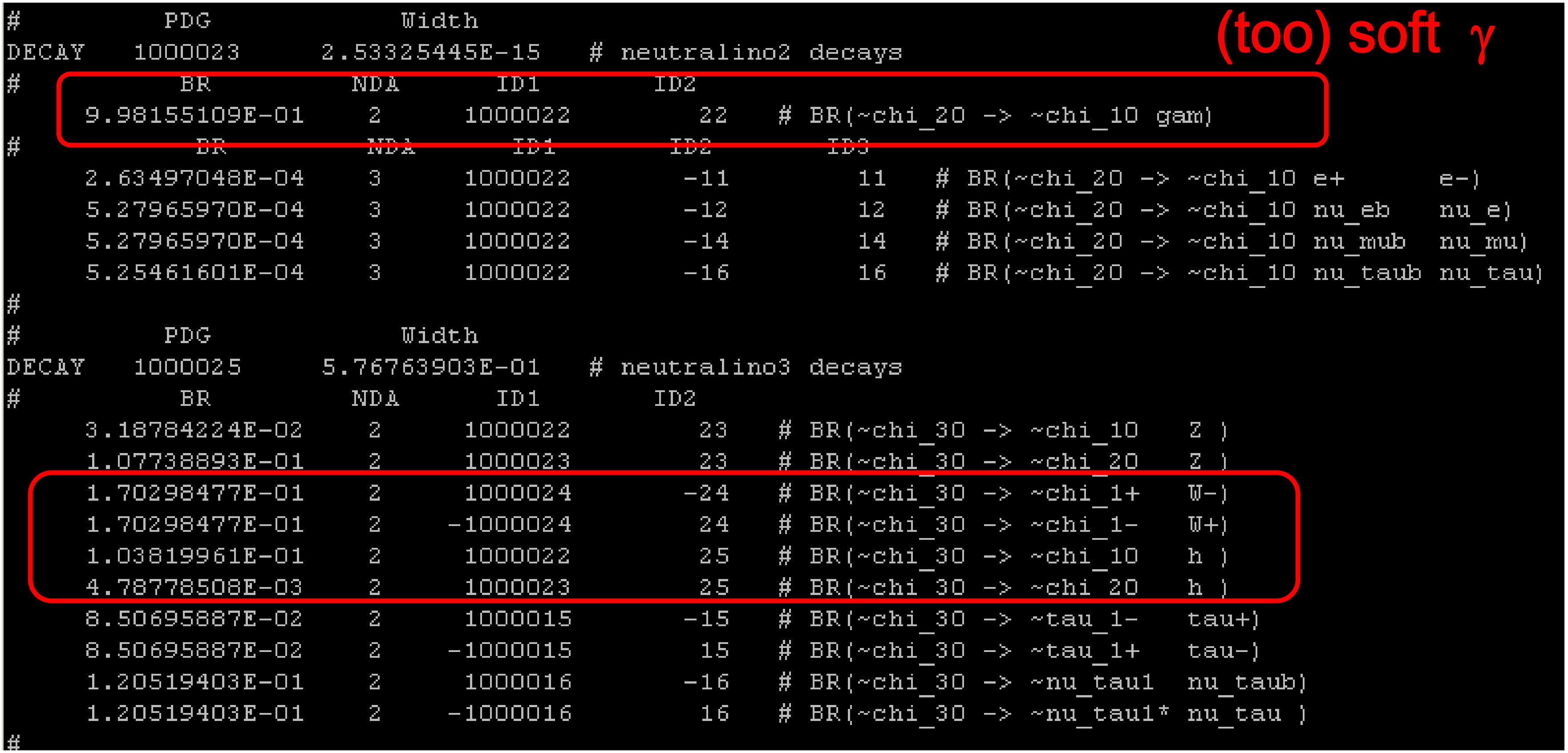
```
 1000021      7.70982319E+02    # ~g
```



```
1000001      3.89758628E+02    # ~d_L
2000001      4.75360394E+02    # ~d_R
1000002      3.81315009E+02    # ~u_L
2000002      5.79680485E+02    # ~u_R
```

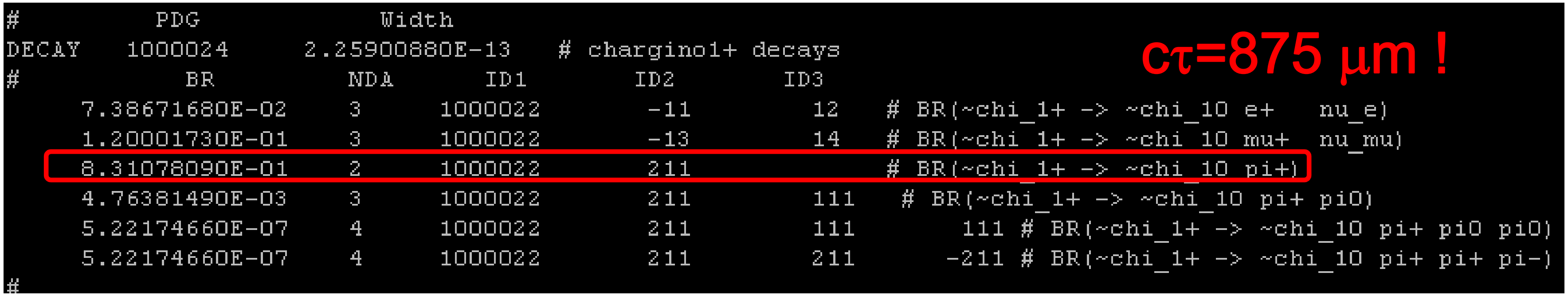


```
#          PDG             Width
DECAY    1000002      7.89184196E-02    # sup_L decays
#          BR          NDA      ID1        ID2
     1.18490545E-01    2      1000022          2    # BR(~u_L -> ~chi_10 u)
     1.67842472E-01    2      1000023          2    # BR(~u_L -> ~chi_20 u)
     8.04225726E-02    2      1000025          2    # BR(~u_L -> ~chi_30 u)
     6.33244411E-01    2      1000024          1    # BR(~u_L -> ~chi_1+ d)
#
#          PDG             Width
DECAY    2000002      7.39572454E-01    # sup_R decays
#          BR          NDA      ID1        ID2
     7.26505254E-02    2      1000022          2    # BR(~u_R -> ~chi_10 u)
     8.04961744E-03    2      1000023          2    # BR(~u_R -> ~chi_20 u)
     9.19299857E-01    2      1000025          2    # BR(~u_R -> ~chi_30 u)
#
#          PDG             Width
DECAY    1000001      2.26388881E-02    # sdown_L decays
#          BR          NDA      ID1        ID2
     8.24160409E-03    2      1000022          1    # BR(~d_L -> ~chi_10 d)
     3.51305468E-01    2      1000023          1    # BR(~d_L -> ~chi_20 d)
     4.52823359E-01    2      1000025          1    # BR(~d_L -> ~chi_30 d)
     1.87629569E-01    2     -1000024          2    # BR(~d_L -> ~chi_1- u)
#
#          PDG             Width
DECAY    2000001      1.05167003E-01    # sdown_R decays
#          BR          NDA      ID1        ID2
     9.60848562E-02    2      1000022          1    # BR(~d_R -> ~chi_10 d)
     1.06446934E-02    2      1000023          1    # BR(~d_R -> ~chi_20 d)
     8.93270450E-01    2      1000025          1    # BR(~d_R -> ~chi_30 d)
#
```



(too) soft γ

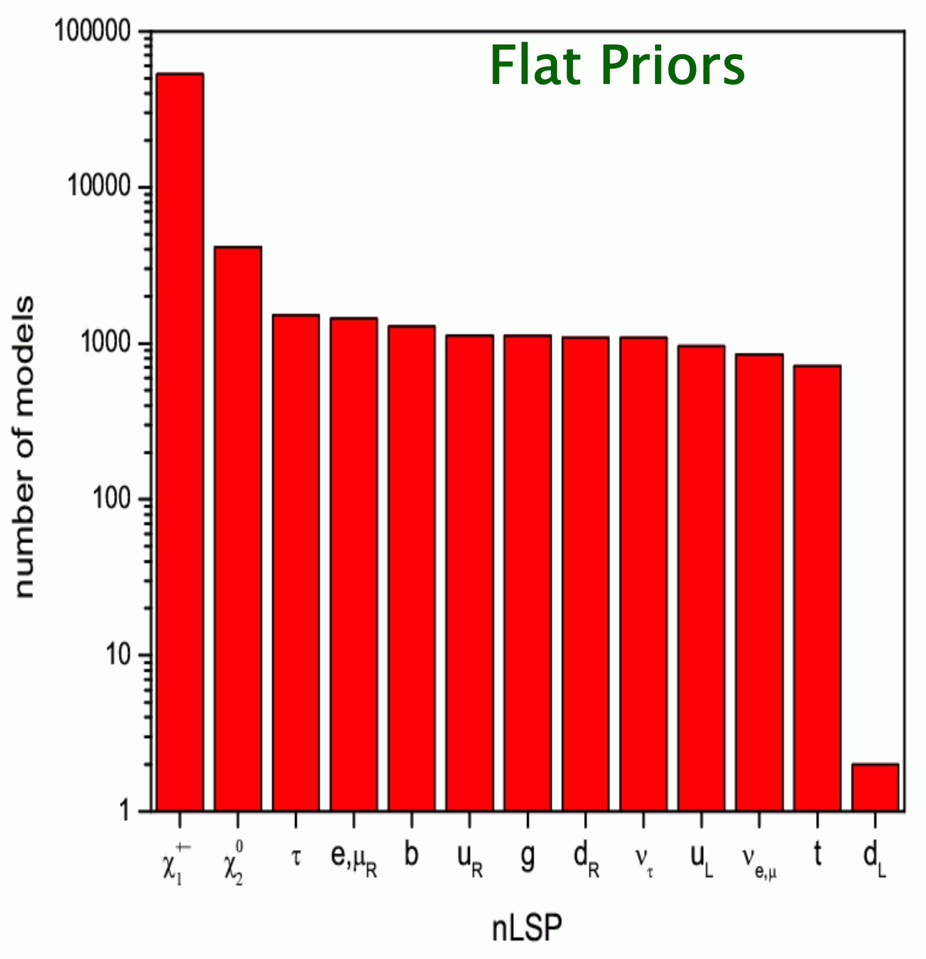
```
#          PDG            Width
DECAY   1000023     2.53325445E-15   # neutralino2 decays
#          BR         NDA      ID1       ID2
     9.98155109E-01    2     1000022        22   # BR(~chi_20 -> ~chi_10 gam)
#          BR         NDA      ID1       ID2       ID3
     2.63497048E-04    3     1000022       -11        11   # BR(~chi_20 -> ~chi_10 e+      e-)
     5.27965970E-04    3     1000022       -12        12   # BR(~chi_20 -> ~chi_10 nu_eb   nu_e)
     5.27965970E-04    3     1000022       -14        14   # BR(~chi_20 -> ~chi_10 nu_mub  nu_mu)
     5.25461601E-04    3     1000022       -16        16   # BR(~chi_20 -> ~chi_10 nu_taub nu_tau)
#
#          PDG            Width
DECAY   1000025     5.76763903E-01   # neutralino3 decays
#          BR         NDA      ID1       ID2
     3.18784224E-02    2     1000022        23   # BR(~chi_30 -> ~chi_10   Z )
     1.07738893E-01    2     1000023        23   # BR(~chi_30 -> ~chi_20   Z )
     1.70298477E-01    2     1000024       -24   # BR(~chi_30 -> ~chi_1+   W-)
     1.70298477E-01    2    -1000024        24   # BR(~chi_30 -> ~chi_1-   W+)
     1.03819961E-01    2     1000022        25   # BR(~chi_30 -> ~chi_10   h )
     4.78778508E-03    2     1000023        25   # BR(~chi_30 -> ~chi_20   h )
     8.50695887E-02    2     1000015       -15   # BR(~chi_30 -> ~tau_1-   tau+)
     8.50695887E-02    2    -1000015        15   # BR(~chi_30 -> ~tau_1+   tau-)
     1.20519403E-01    2     1000016       -16   # BR(~chi_30 -> ~nu_tau1  nu_taub)
     1.20519403E-01    2    -1000016        16   # BR(~chi_30 -> ~nu_tau1* nu_tau )
#
```

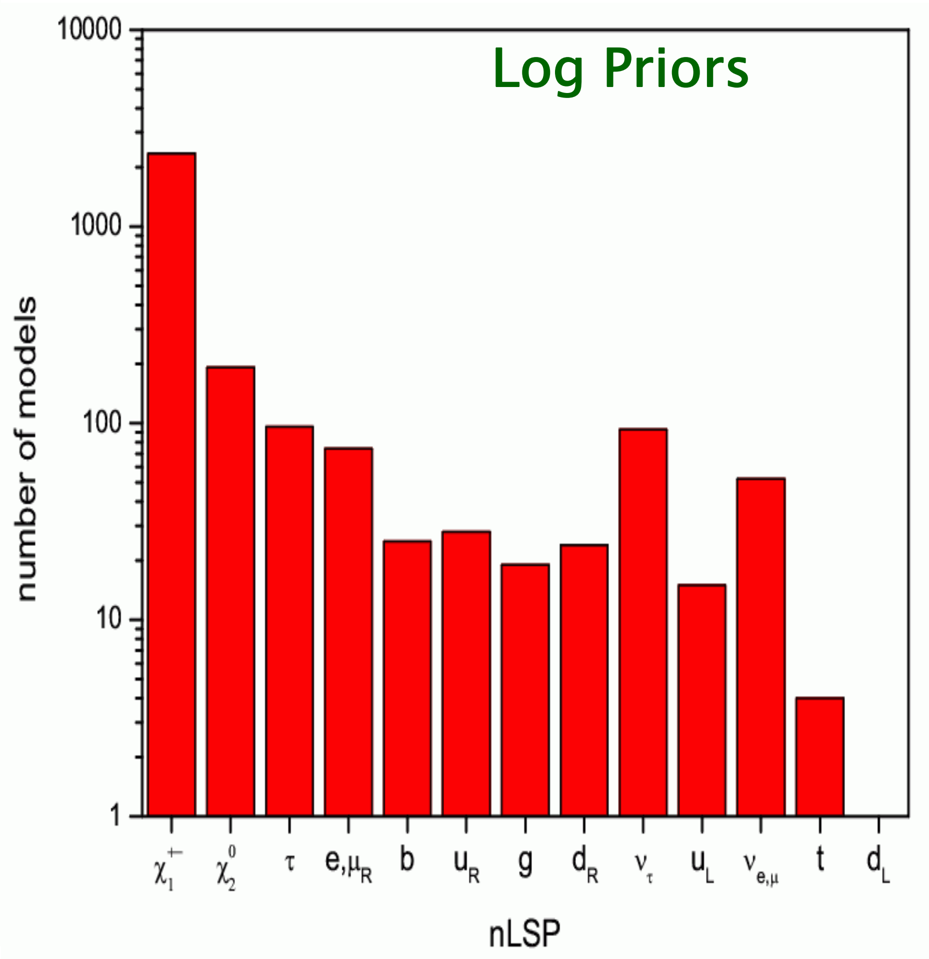


cτ=875 μm !

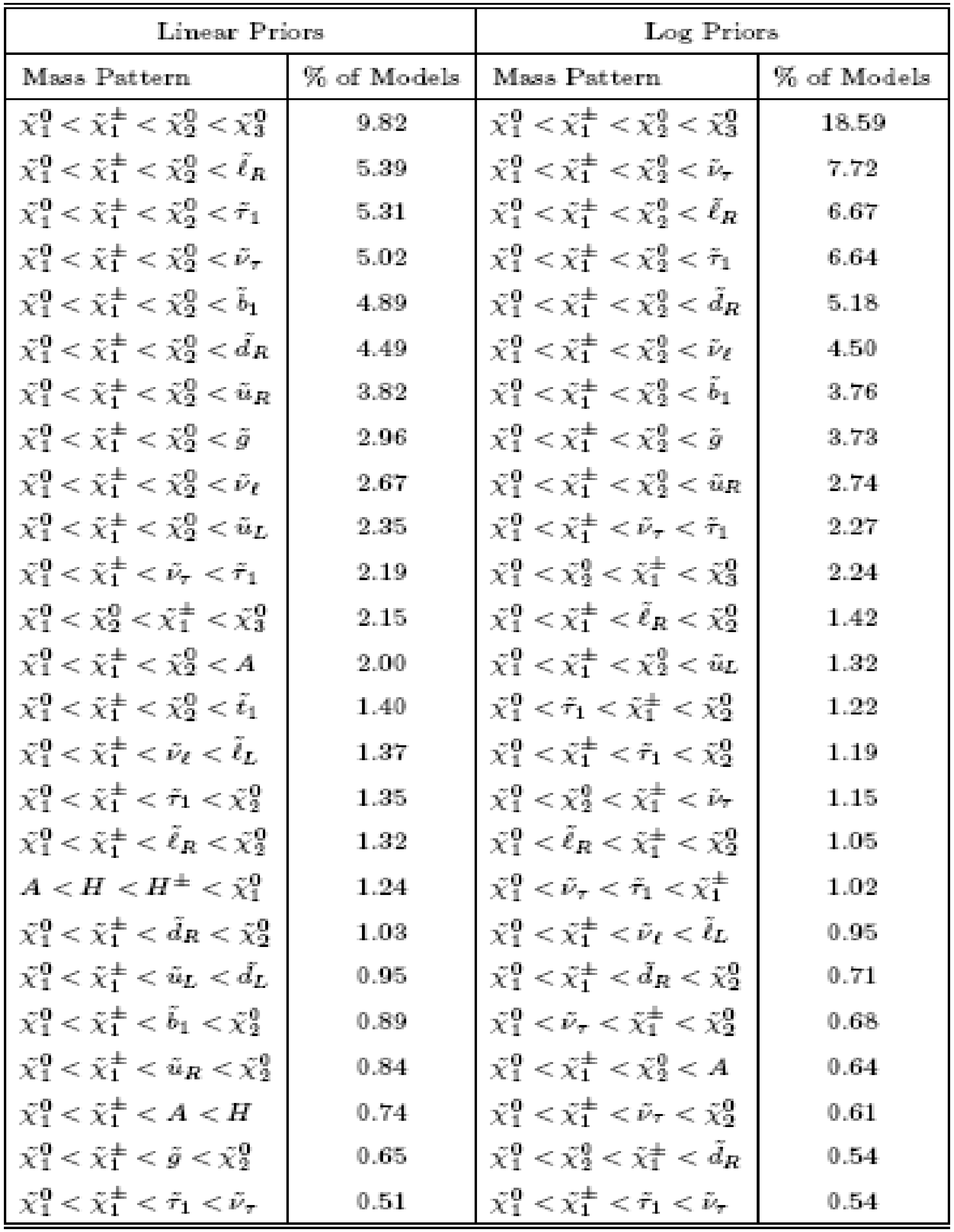
```
#          PDG            Width
DECAY   1000024     2.25900880E-13   # chargino1+ decays
#          BR         NDA      ID1       ID2       ID3
     7.38671680E-02    3     1000022       -11        12   # BR(~chi_1+ -> ~chi_10 e+   nu_e)
     1.20001730E-01    3     1000022       -13        14   # BR(~chi_1+ -> ~chi_10 mu+  nu_mu)
     8.31078090E-01    2     1000022       211             # BR(~chi_1+ -> ~chi_10 pi+)
     4.76381490E-03    3     1000022       211       111    # BR(~chi_1+ -> ~chi_10 pi+ pi0)
     5.22174660E-07    4     1000022       211       111       111 # BR(~chi_1+ -> ~chi_10 pi+ pi0 pi0)
     5.22174660E-07    4     1000022       211       211      -211 # BR(~chi_1+ -> ~chi_10 pi+ pi+ pi-)
#
```

What DOES happen 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 ?????   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.

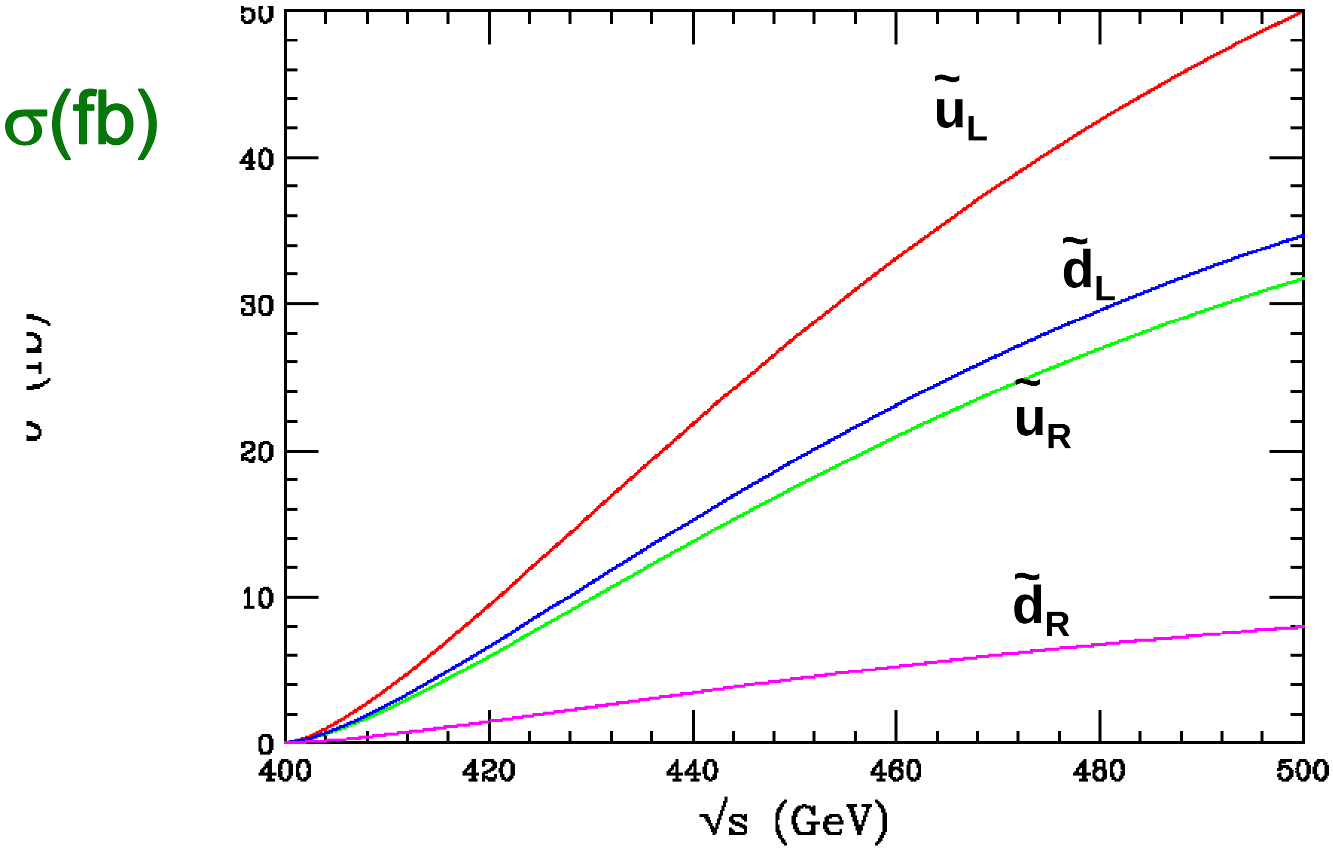
Top 25 most common mass patterns for the 4 lightest SUSY & heavy Higgs particles.

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

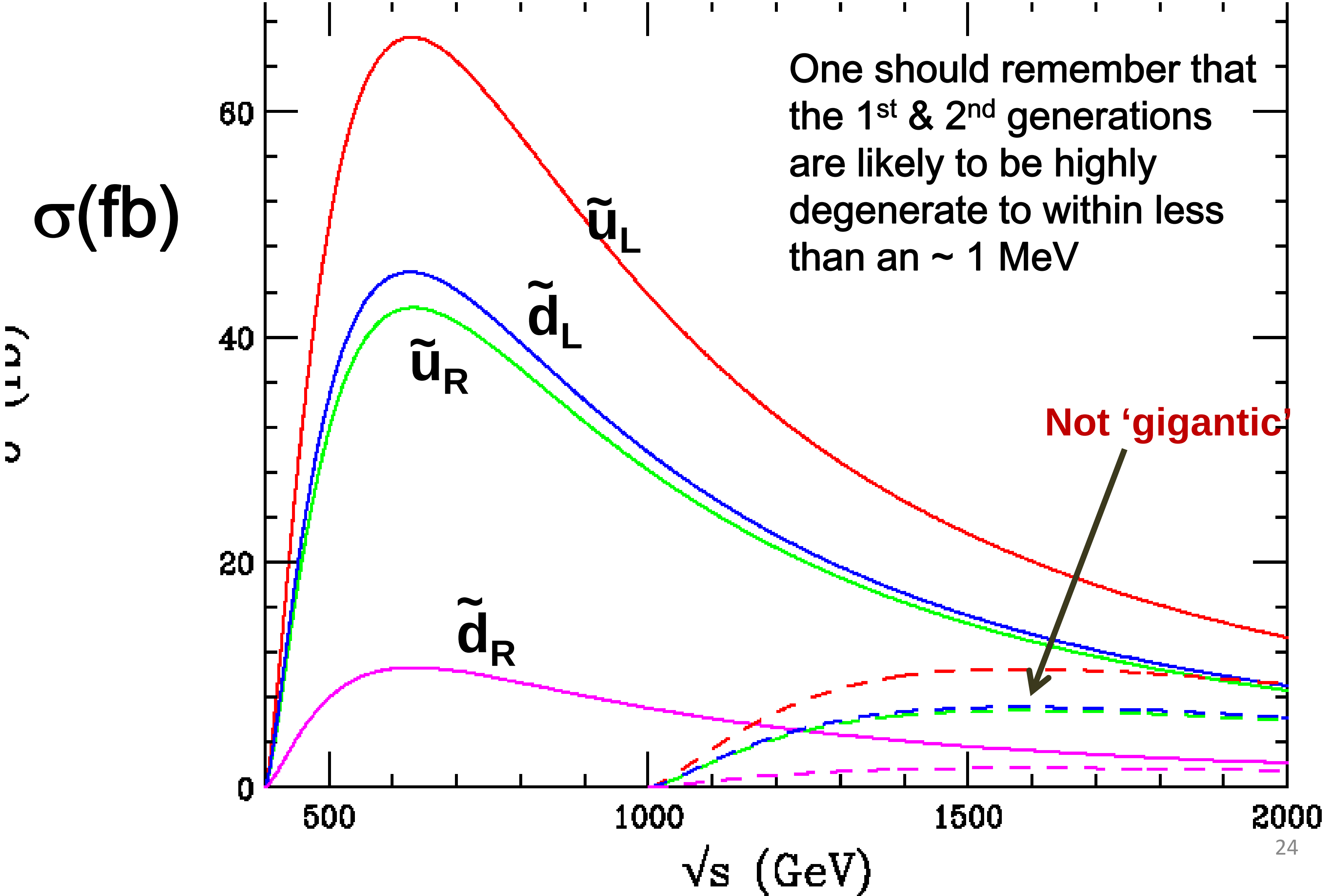
Only ~22 are found in mSUGRA!!

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 SOMEWHAT 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]

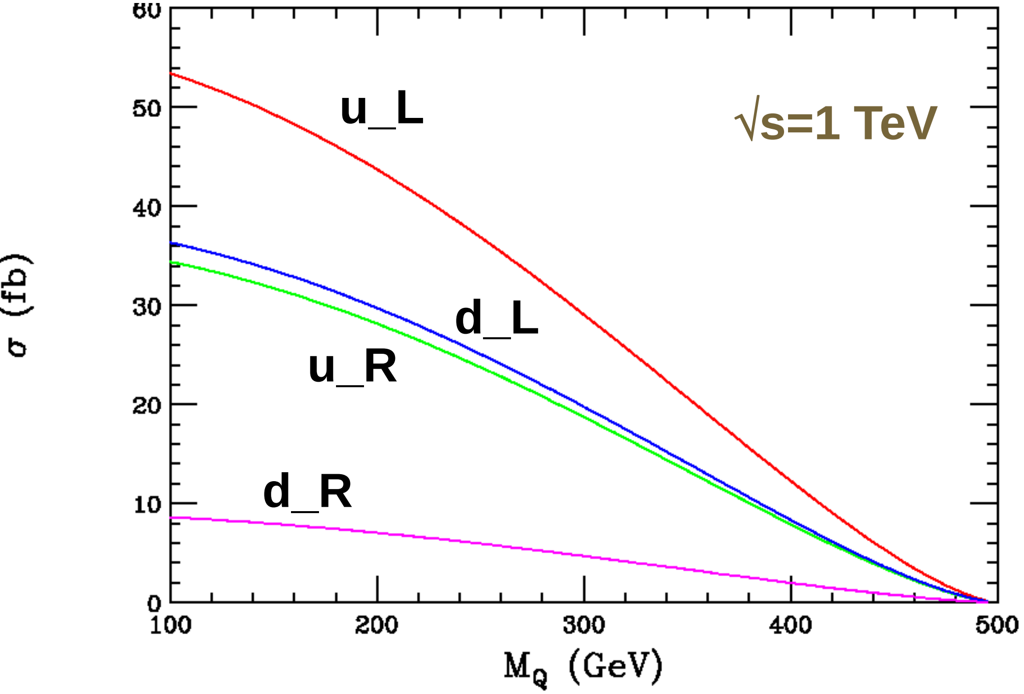


Squark Pair Production in e^+e^-

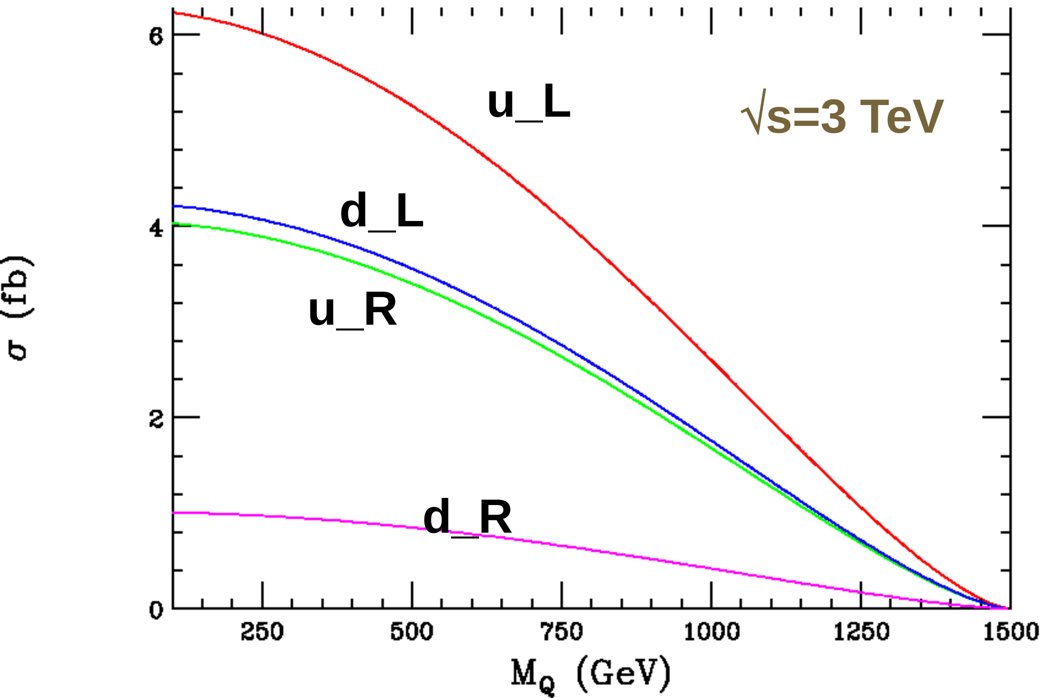


One should remember that the 1st & 2nd generations are likely to be highly degenerate to within less than an ~ 1 MeV

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.

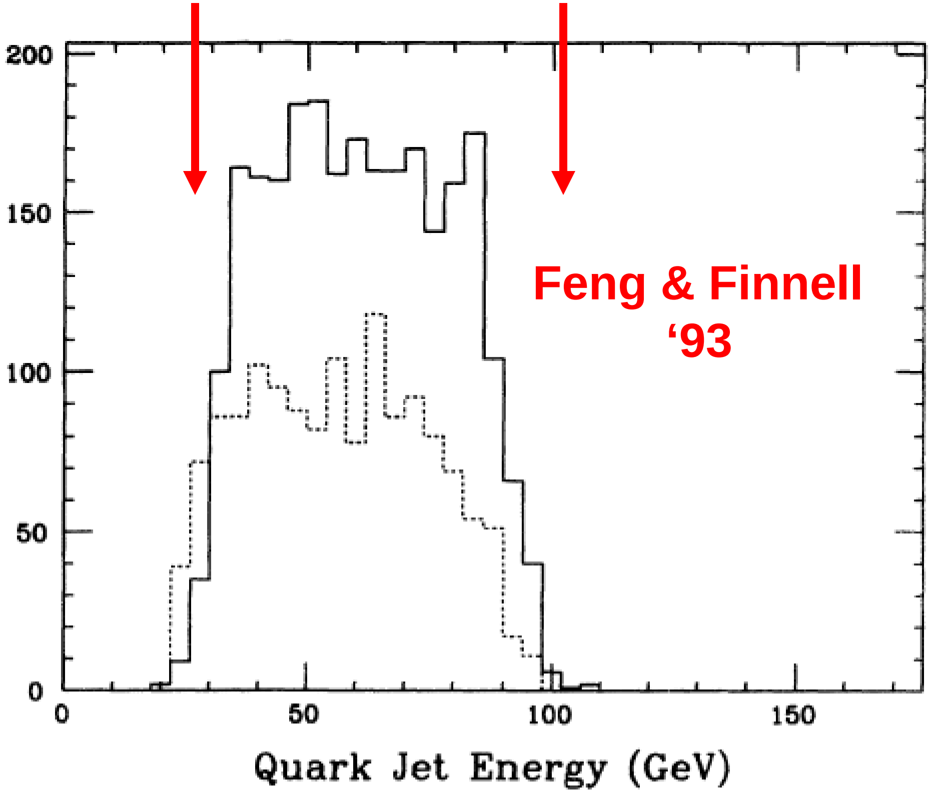


While squark production is largish the real issue is what the squarks end up decaying into…

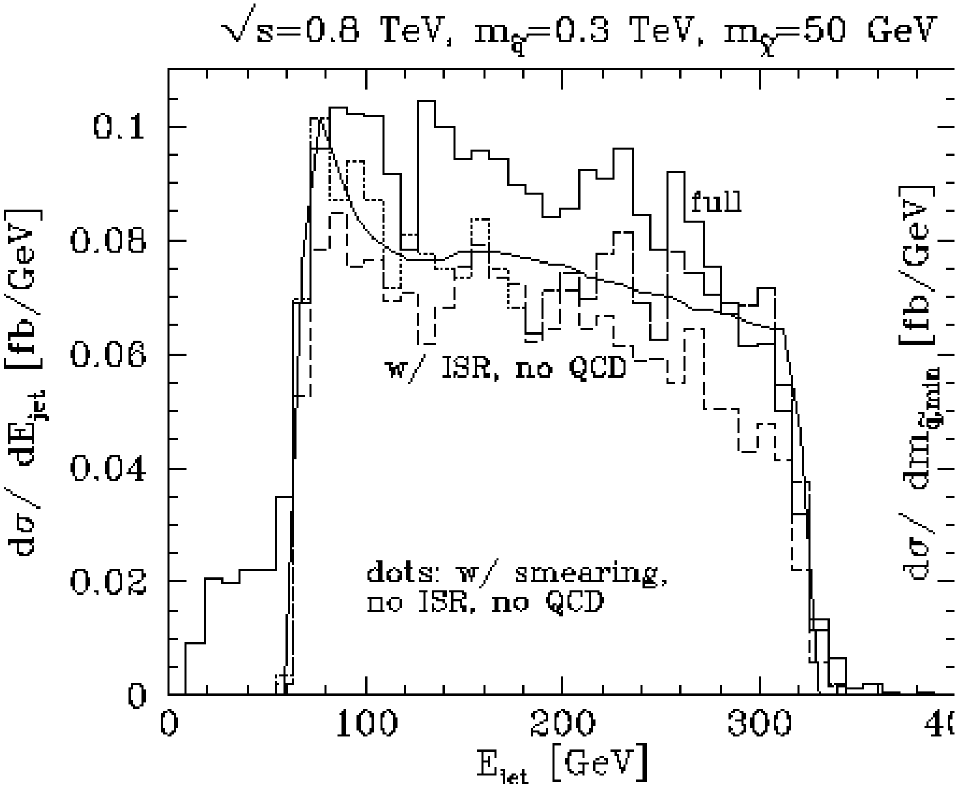
Jet+ME is the SIMPLEST possibility to consider…

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

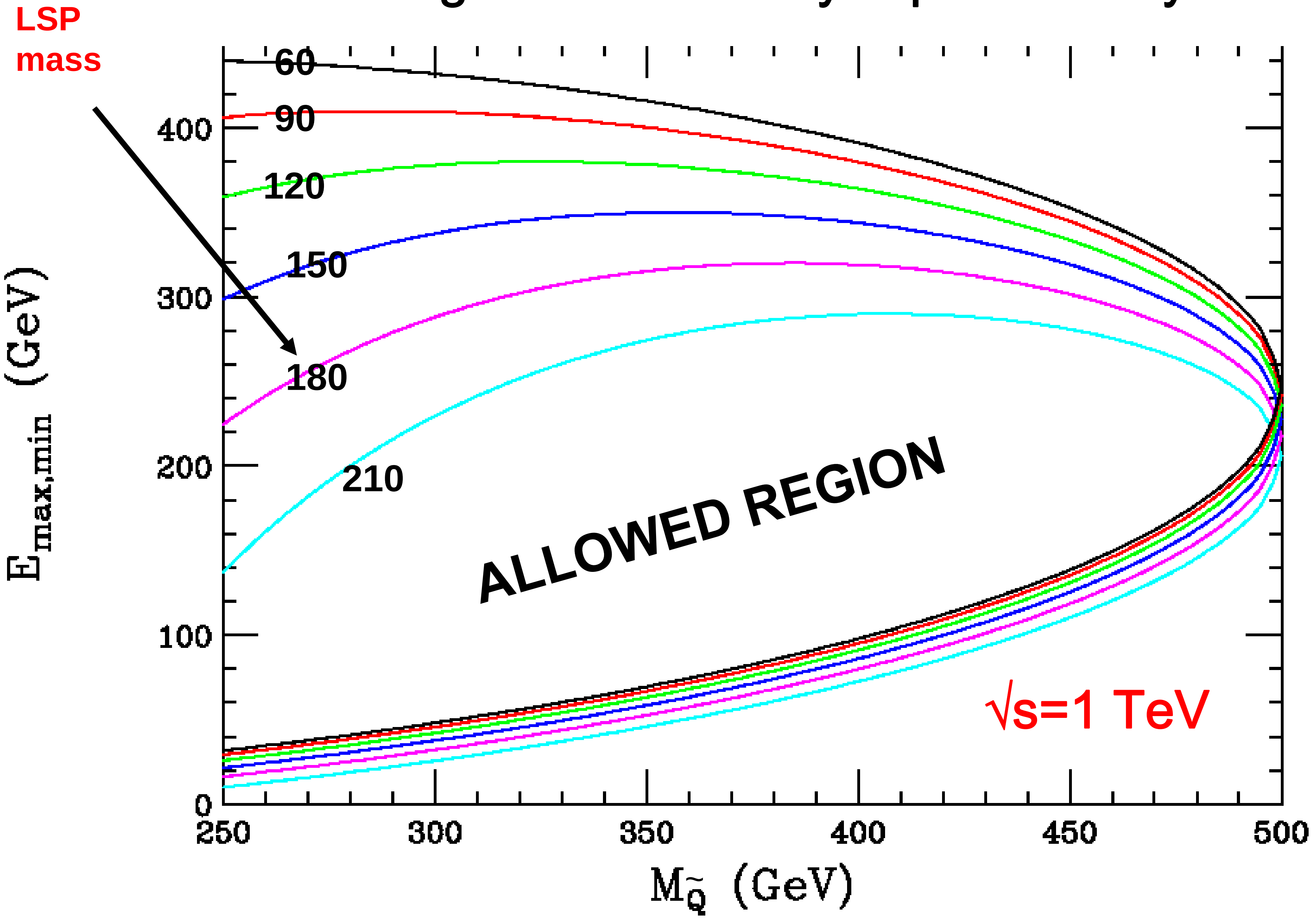


The end points tell us the squark mass

Drees etal. ‘99

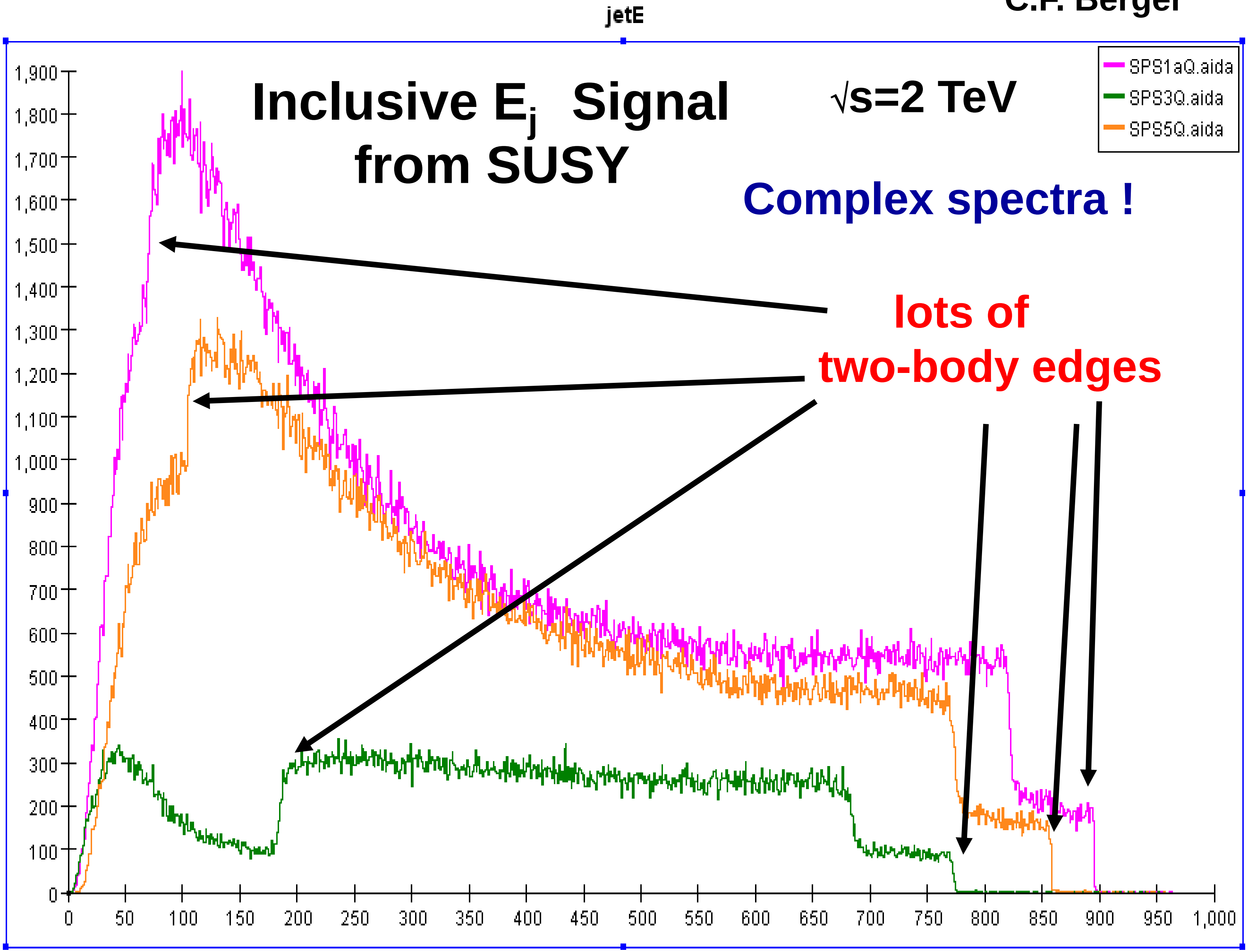
BUT we may have a superposition of many states

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

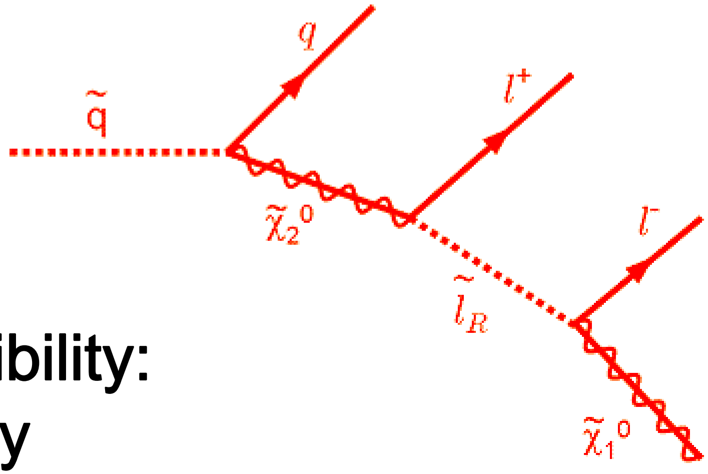
- Backgrounds to this process arise from many SM sources..the most dangerous, $\gamma\gamma \rightarrow jj$ has large ME (most others are removed by vetoing W,Z→jj). Jet acoplanarity plus large ME requirements (> 100+ GeV ?) should reduce these .

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

Simulation studies will be needed !

→ Of course χ could be more complex: (i) a detector stable chargino leading to a jets + stable charged particles final state
(ii) have it's own decay chain via the lighter sleptons
(iii) it may radiatively decay to the LSP via a loop or …
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 … soft guys?

- One should remember 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 ….), & 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.)

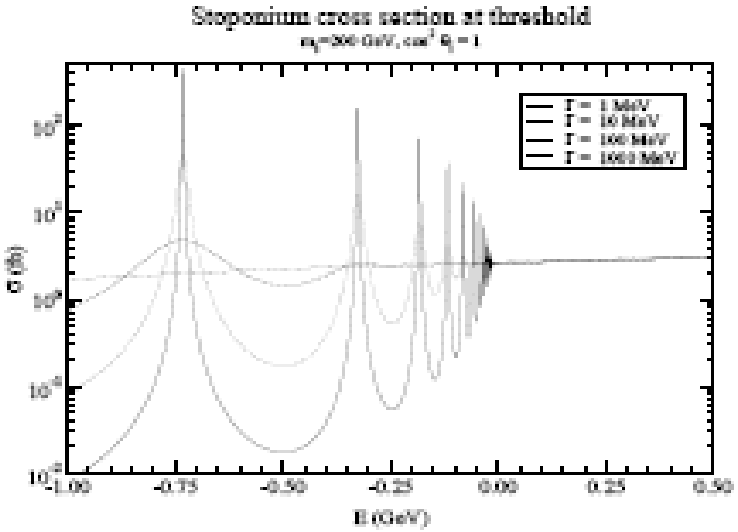
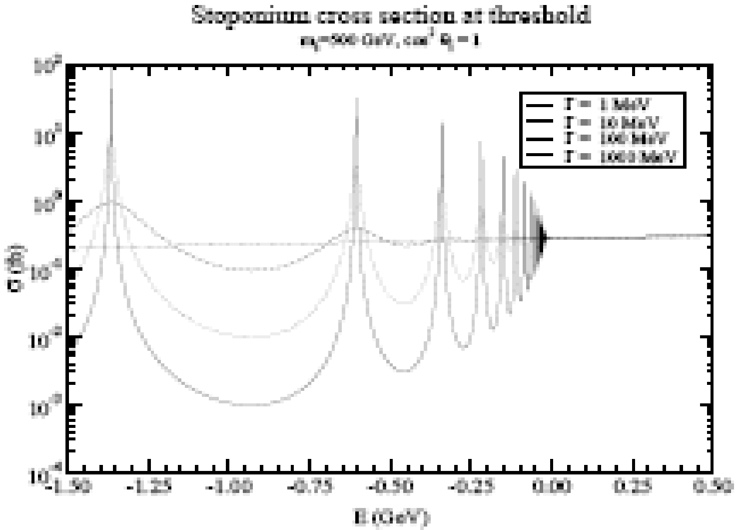


Figure 4: *Cross section at threshold for various decay widths with* $m_{\tilde t}$ = 200 *GeV*, $\cos^2\theta_{\tilde t} = 1$. *The centre of mass energy is* $\sqrt{s}$ = 400 *GeV at threshold*

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 will certainly needed!

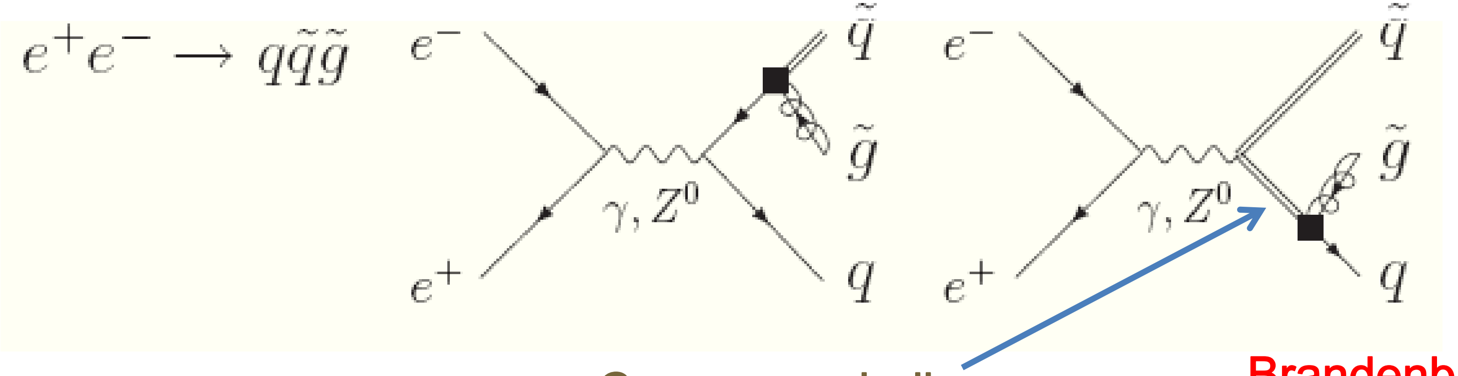
Fabiano '01

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.*

Clearly, there are very many 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 soon!

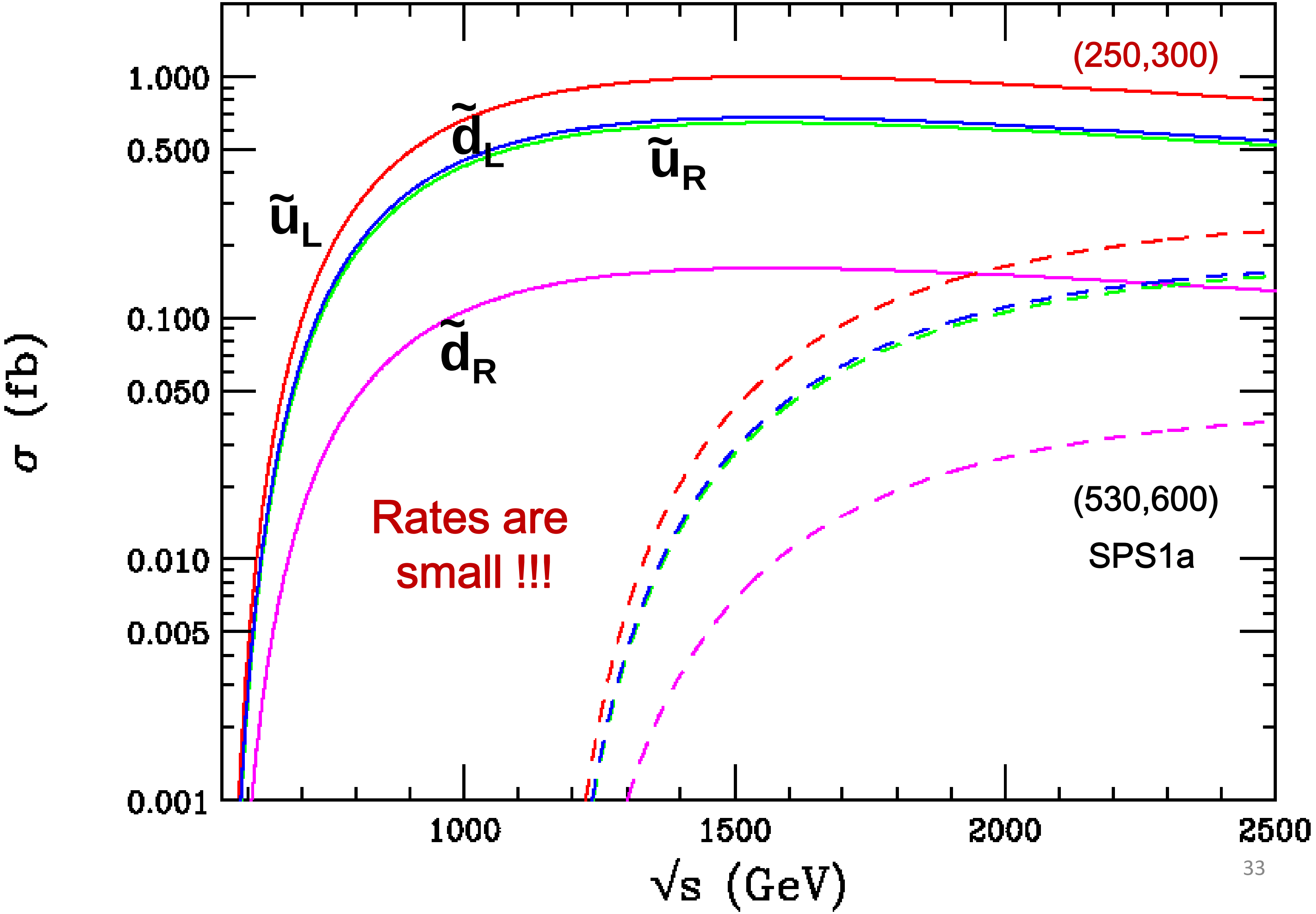
→ **One way to get at gluinos, especially if they are heavier than squarks, is via the 3-body final state:**



Can go on-shell

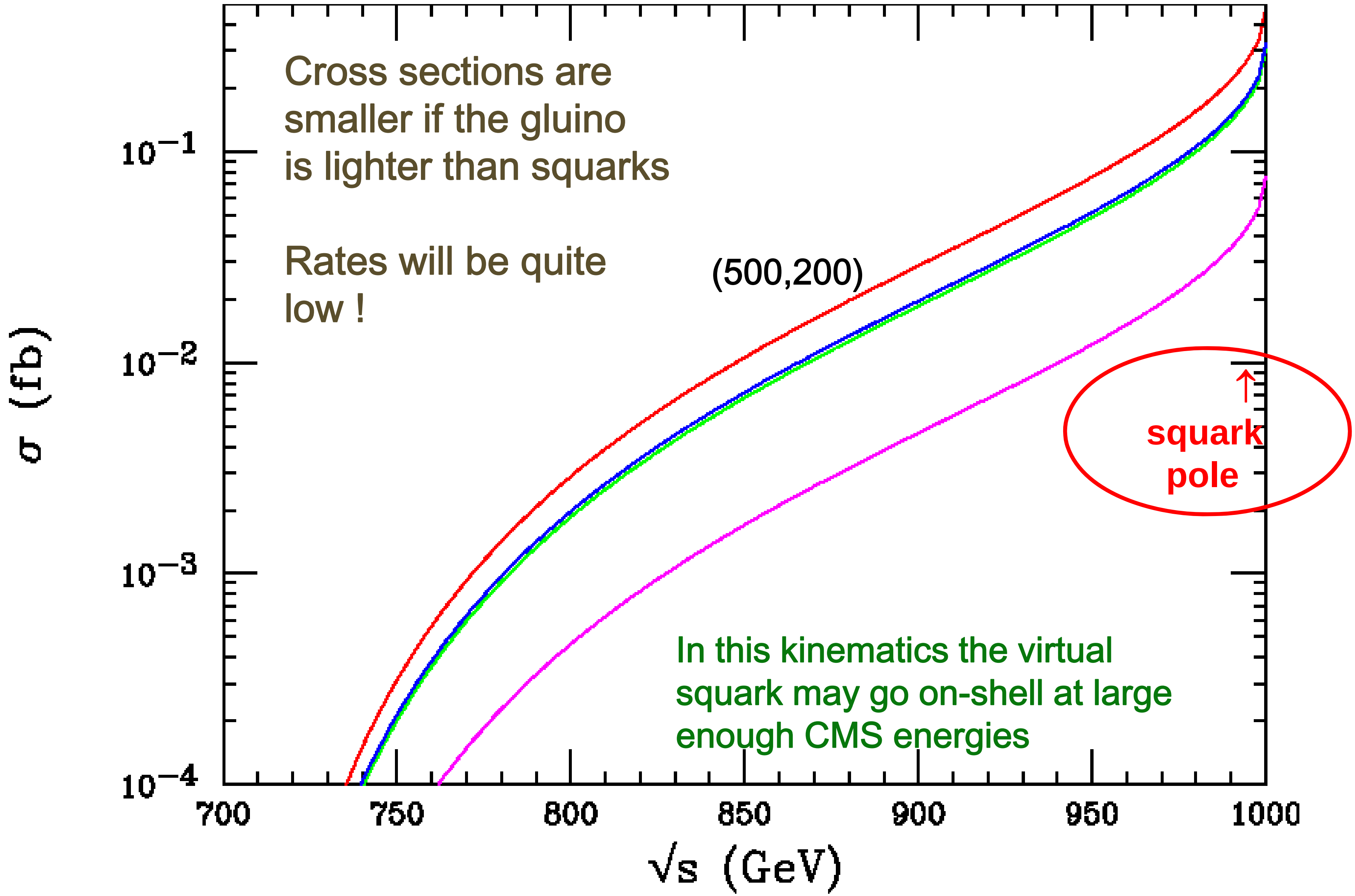
Brandenburg etal '08

Squark + Gluino Production



Rates are small !!!

Squark + Gluino Production



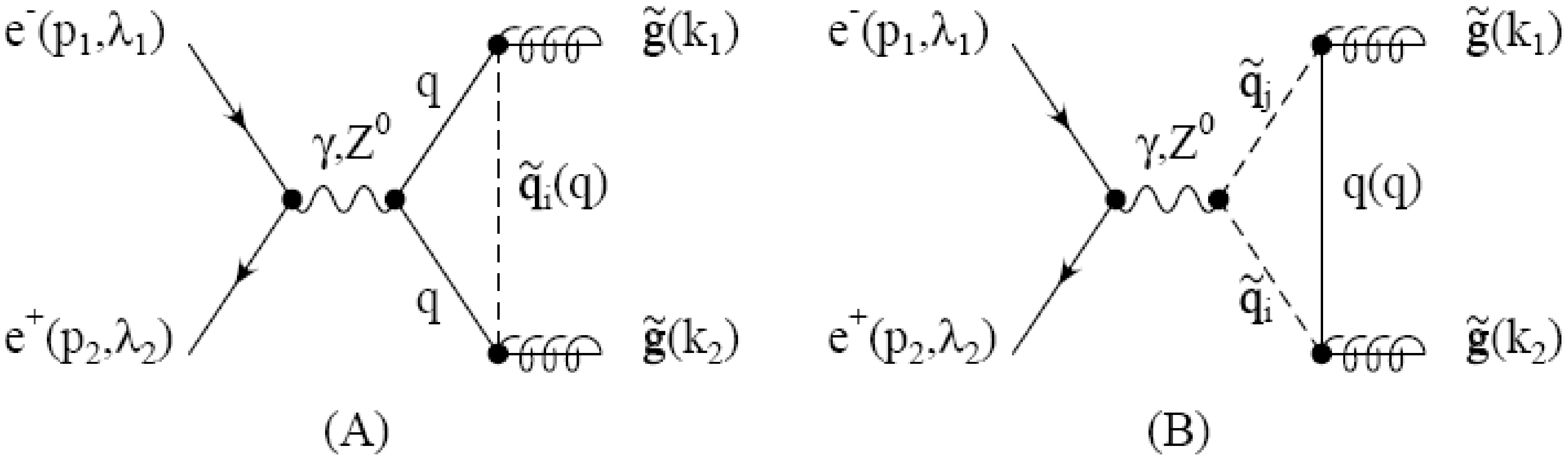
Cross sections are smaller if the gluino is lighter than squarks

Rates will be quite low !

↑ **squark pole**

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

→ For direct production of gluino pairs squark /quark loops are required which involves the entire strongly interacting sector 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….

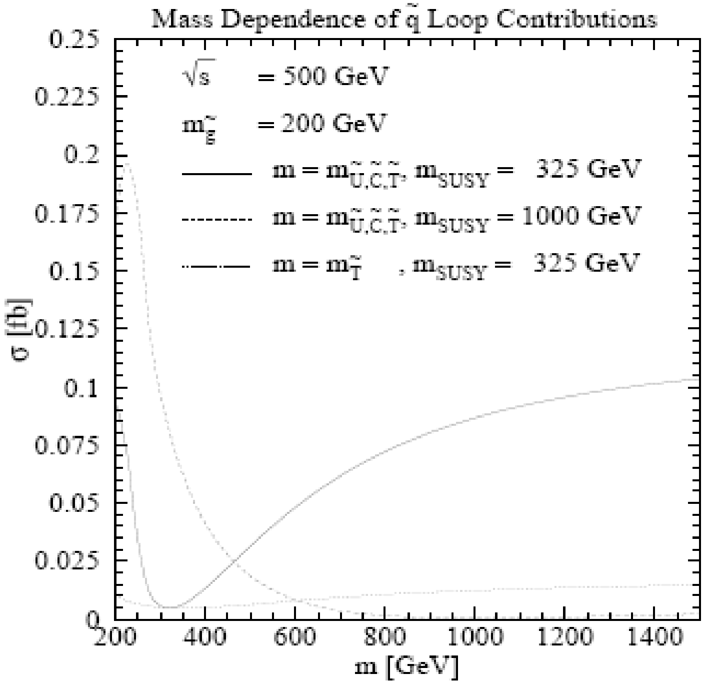
$$d\sigma_{\lambda 1,\lambda 2} \sim [A(1-4\lambda_1\lambda_2) + B(2\lambda_1-2\lambda_2)] \quad \underline{\beta^3} \; (1+\cos^2\theta)$$

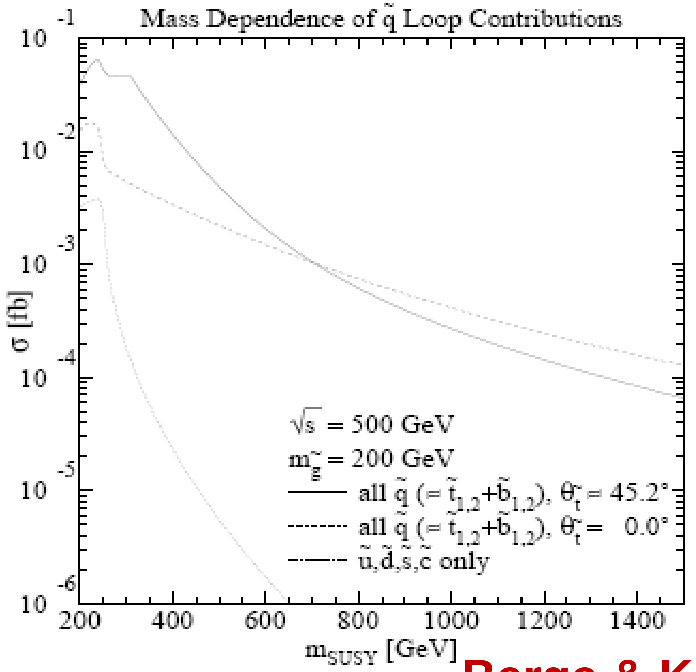
→ Gluinos are spin-1/2 Majorana fields

- For ‘significant’ rates it is favorable to remove degeneracies between the squarks which are common in mSUGRA. This is because 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 LH-doublets. Large rates favor lighter squarks.

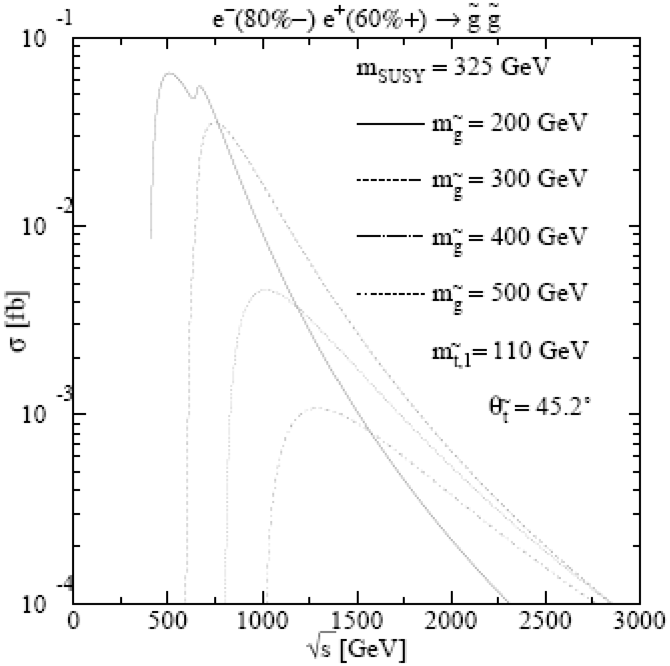
- In mSUGRA this means that stops produce the largest contributions…but this will not necessarily be the case in the general MSSM.

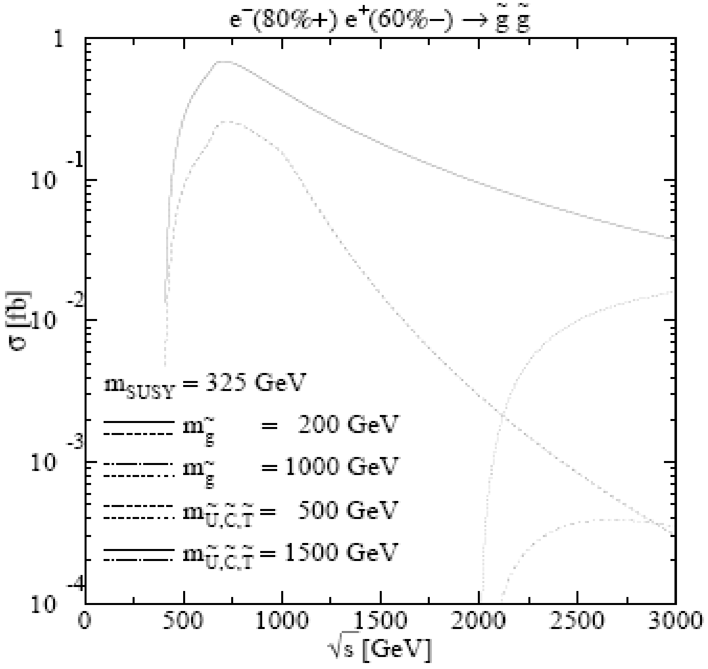
- Numerical scans of the MSSM parameters would be useful..


Mass Dependence of $\tilde{q}$ Loop Contributions


Mass Dependence of $\tilde{q}$ Loop Contributions

Berge & Klasen


$e^-(80\%-)\ e^+(60\%+) \rightarrow \tilde{g}\,\tilde{g}$

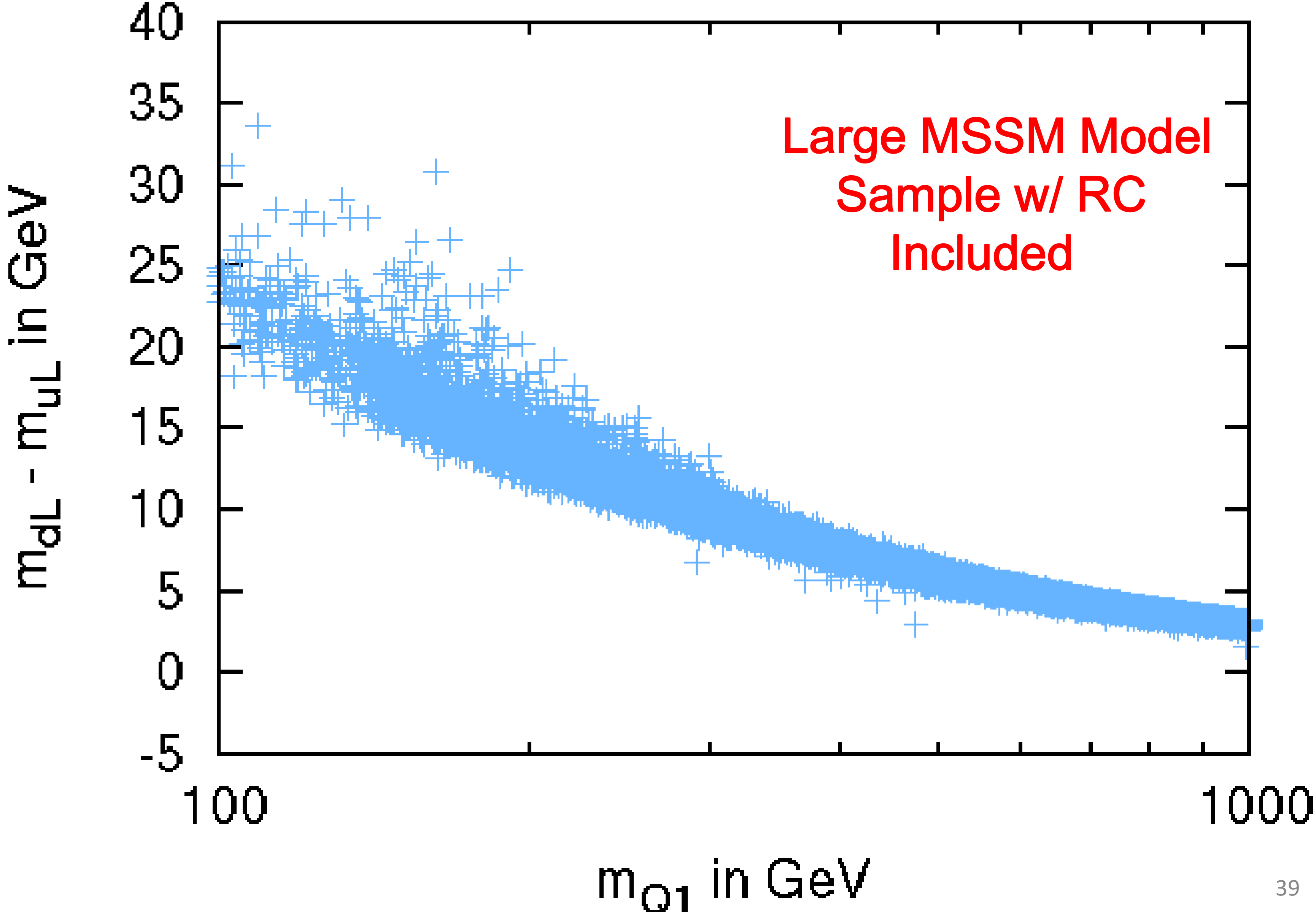

$e^-(80\%+)\ e^+(60\%-) \rightarrow \tilde{g}\,\tilde{g}$

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

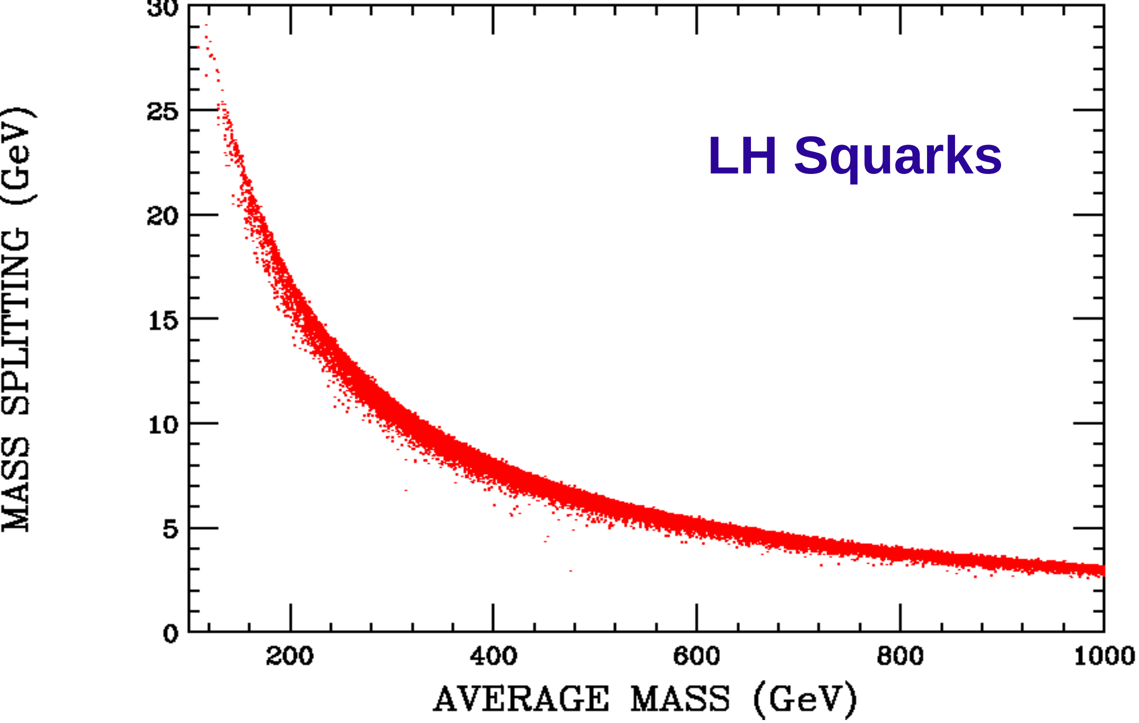
$$M_{dL}^2 - M_{uL}^2 = M_W^2 (t_\beta^2 - 1) / (t_\beta^2 + 1)$$

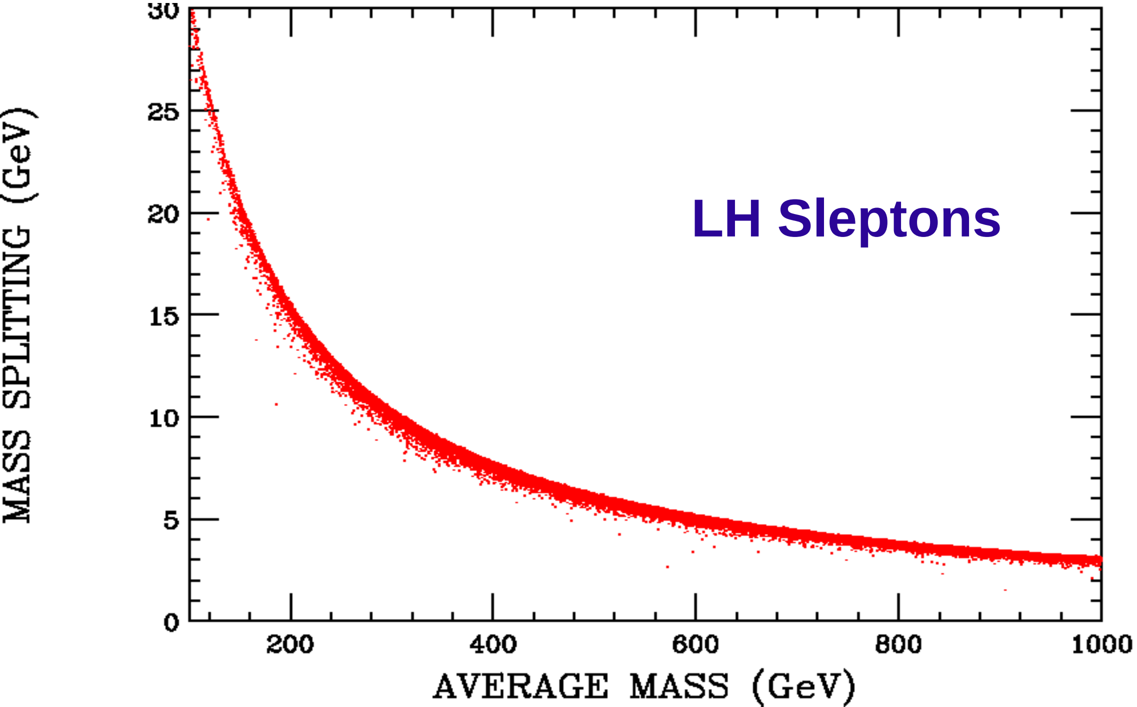
This is the same tree-level result as in the slepton sector in the MSSM providing a cross-check on our understanding of soft SUSY breaking. Note that at tree-level the LH d-squarks are always heavier than the corresponding LH u-squarks…

Squark Mass Splitting



Large MSSM Model Sample w/ RC Included





LH squark and LH slepton mass splittings within the doublet are almost identical up to small EWK & loop corrections. If one sees a violation of this it will imply important new physics beyond the MSSM

Message #4: Life w/ SUSY Can Be Complicated

- It is clear from the above that even the few studies done for light 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 will need some further study …

- Even within the MSSM SUSY context we should prepare for the unexpected.

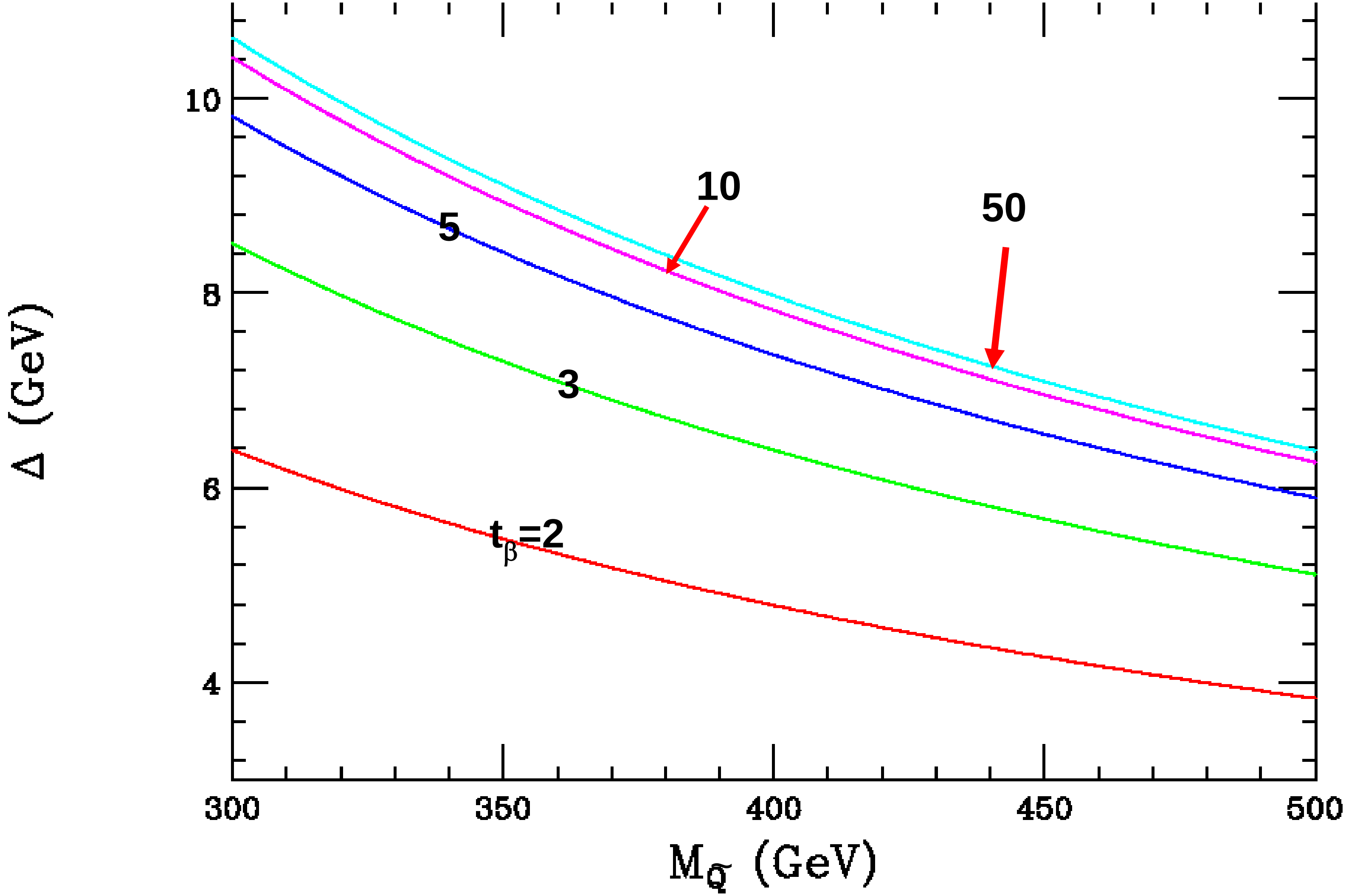
Summary

- 1st & 2nd generations squarks & gluinos have not been well studied at TeV e^+e^- colliders even though they may be kinematically accessible… LHC will hopefully tell us!
- 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 BUT may miss SUSY !
- Squarks & gluinos can/will be very interesting at these colliders w/ many possibilities to consider…GET READY!

BACKUP

Tree-level d_L-u_L Squark Mass Splitting

Can this be precisely measured at threshold???



Small
mass
splitting
for
large
masses

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

2×10^6 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

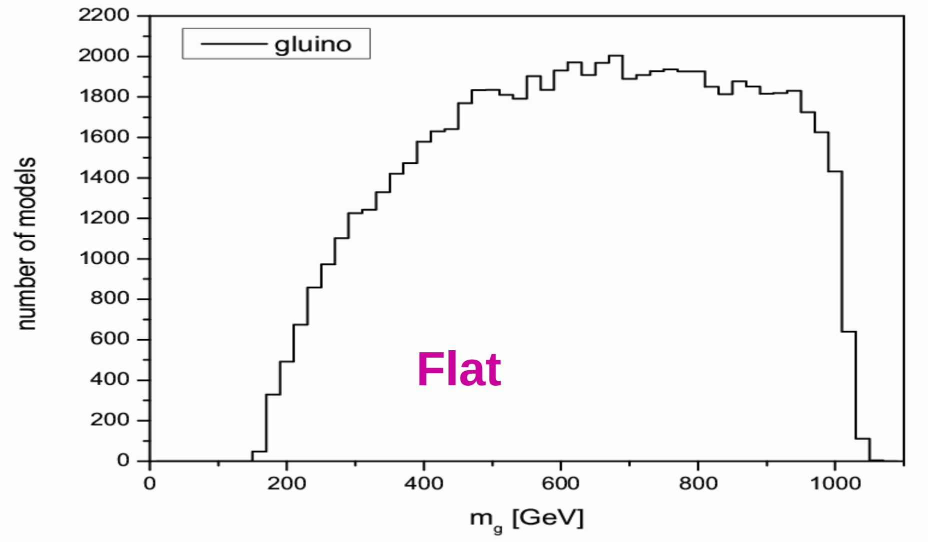
$1 \leq \tan\beta \leq 60$

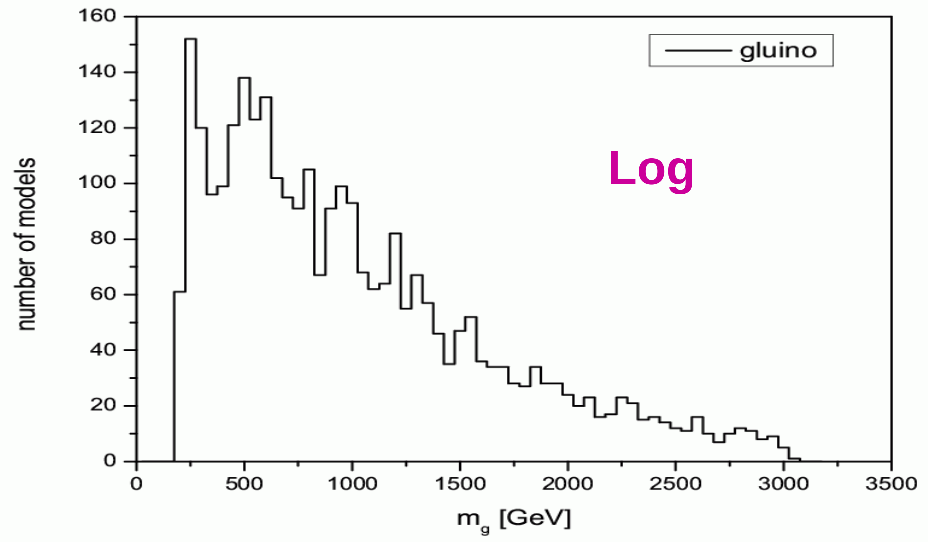
10 GeV $\leq |A_{t,b,\tau}| \leq$ 3 TeV

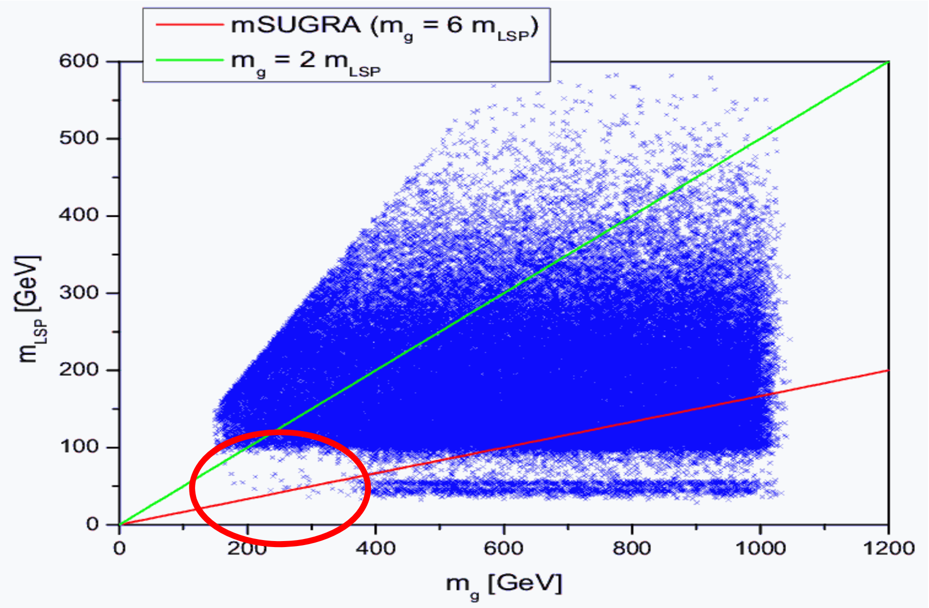
→Comparison of these two scans will show the prior sensitivity.

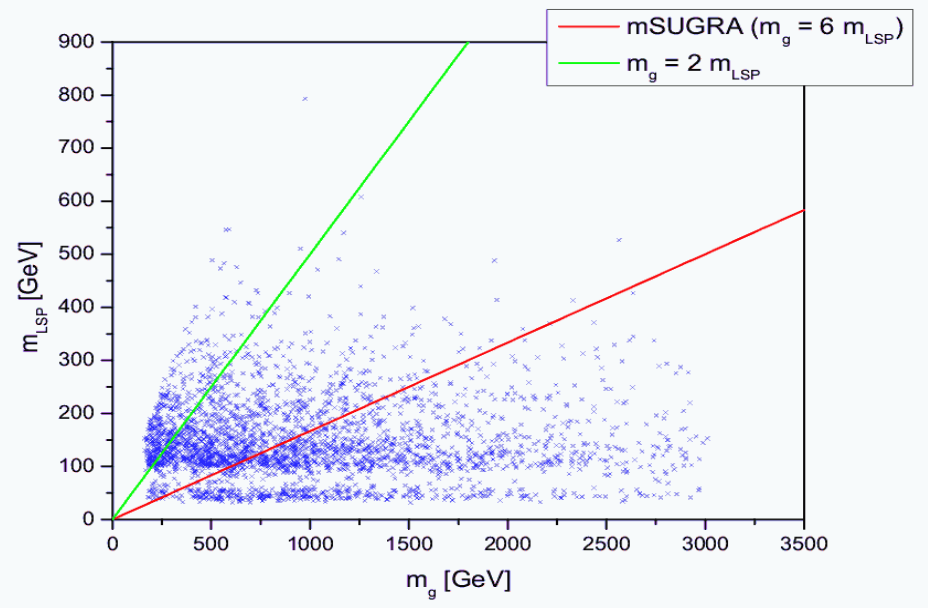
→This analysis required ~ 1 processor-century of CPU time... this is the real limitation of this study.

Gluino Can Be Light !!

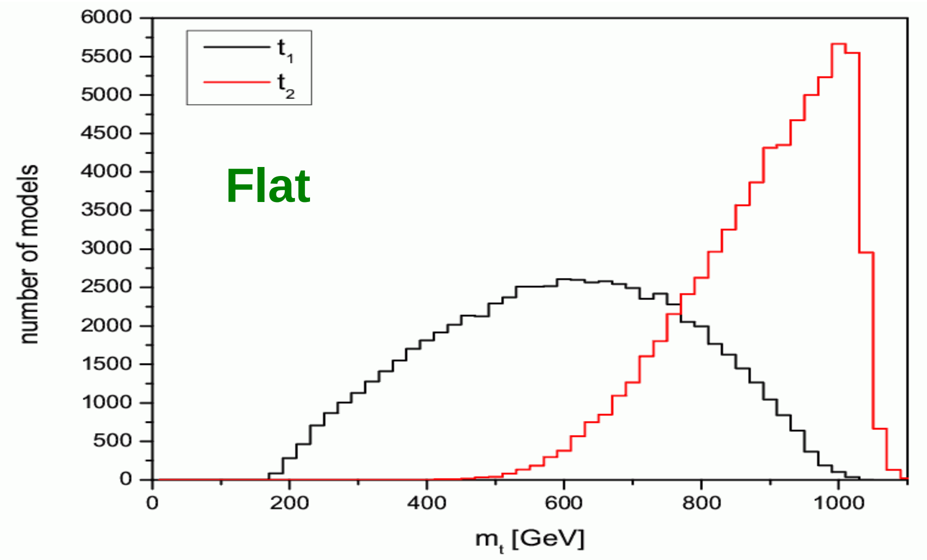


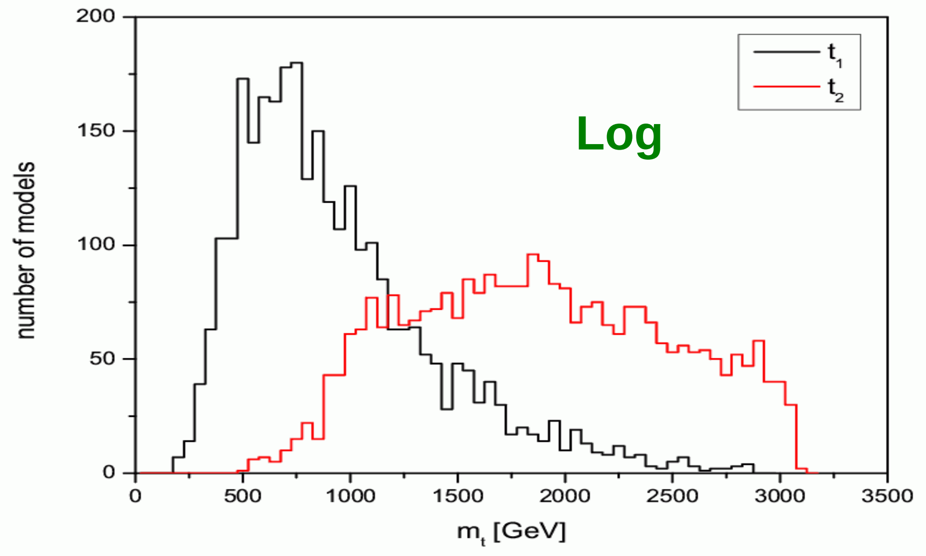


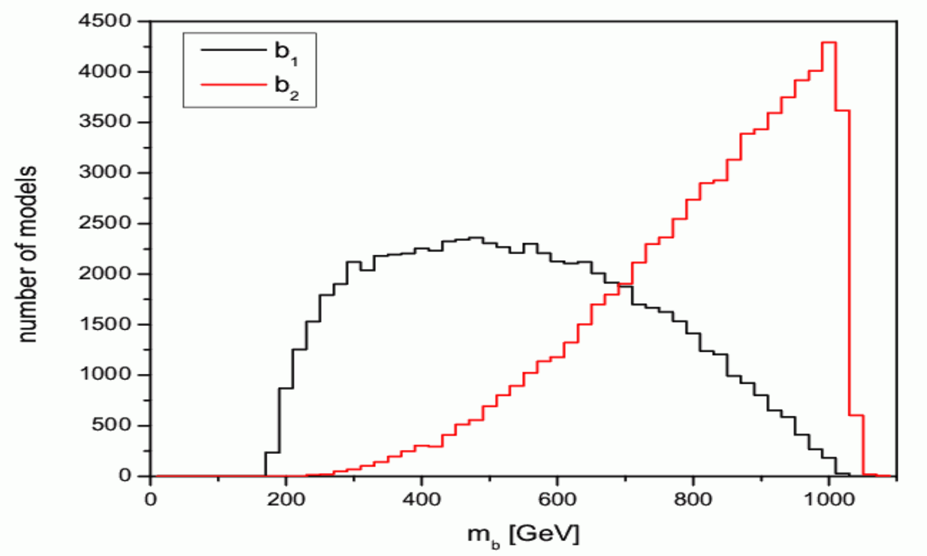


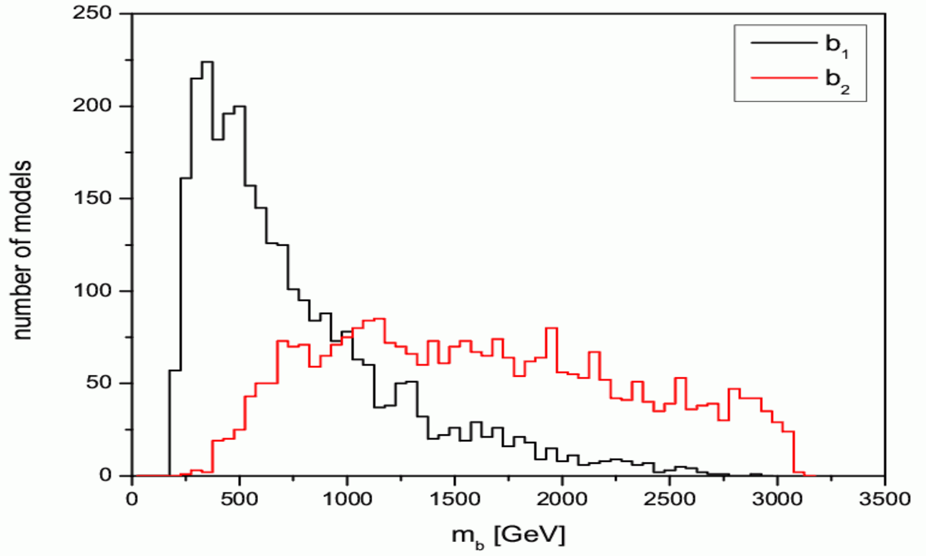


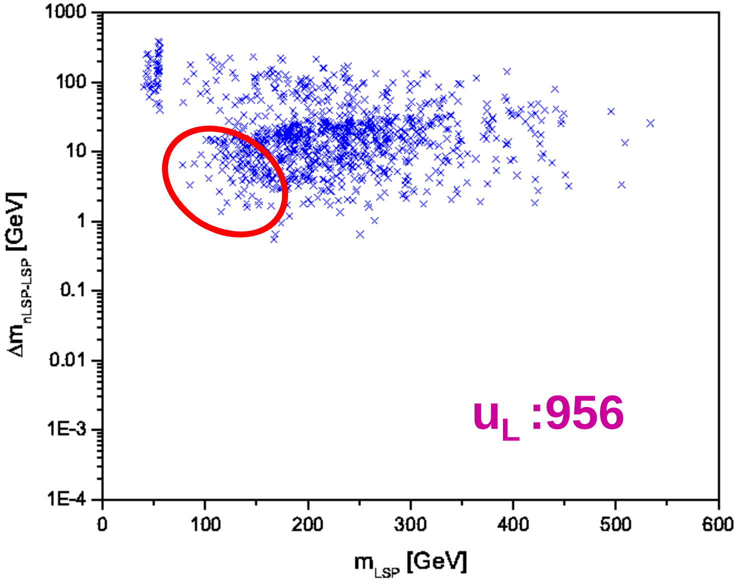
Distribution of Sparticle Masses By Species

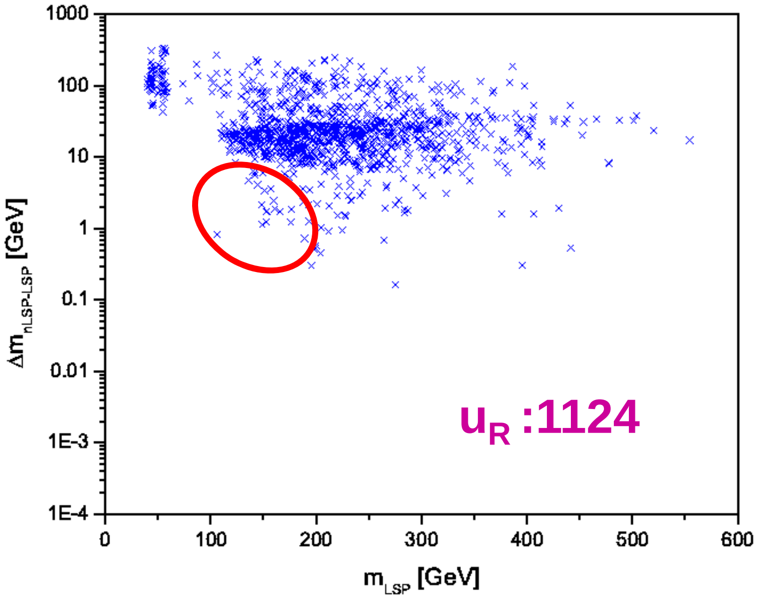









u_L :956
$\Delta m_{nLSP-LSP}$ [GeV]
m_{LSP} [GeV]
1000
100
10
1
0.1
0.01
1E-3
1E-4
0
100
200
300
400
500
600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m_{LSP} [GeV]
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0.01
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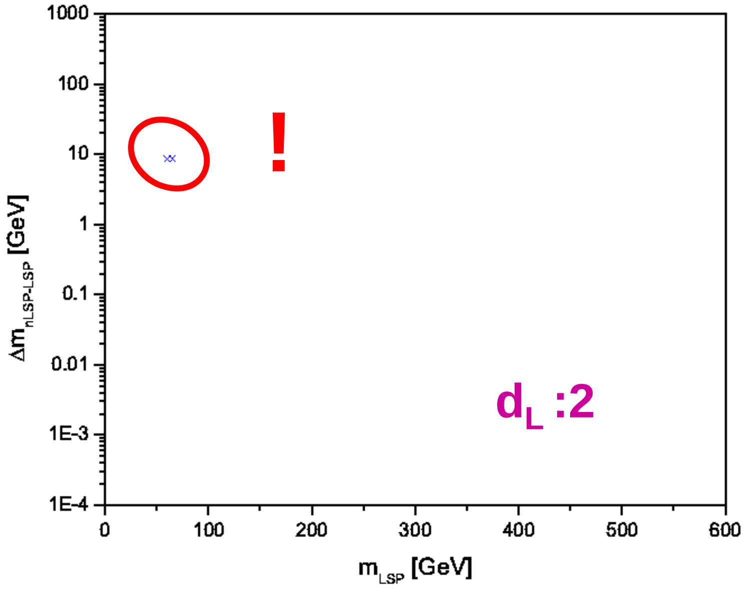
1E-4
0
100
200
300
400
500
600


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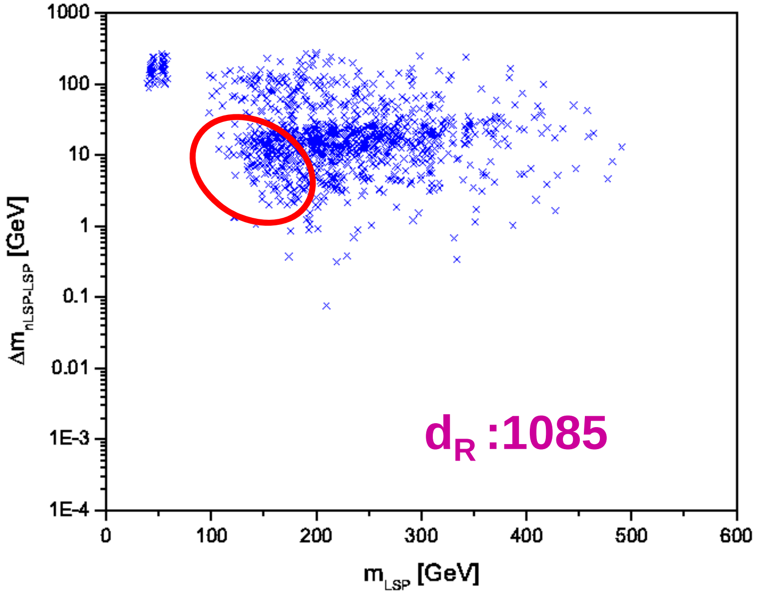
1E-4
0
100
200
300
400
500
600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m_{LSP} [GeV]
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0.01
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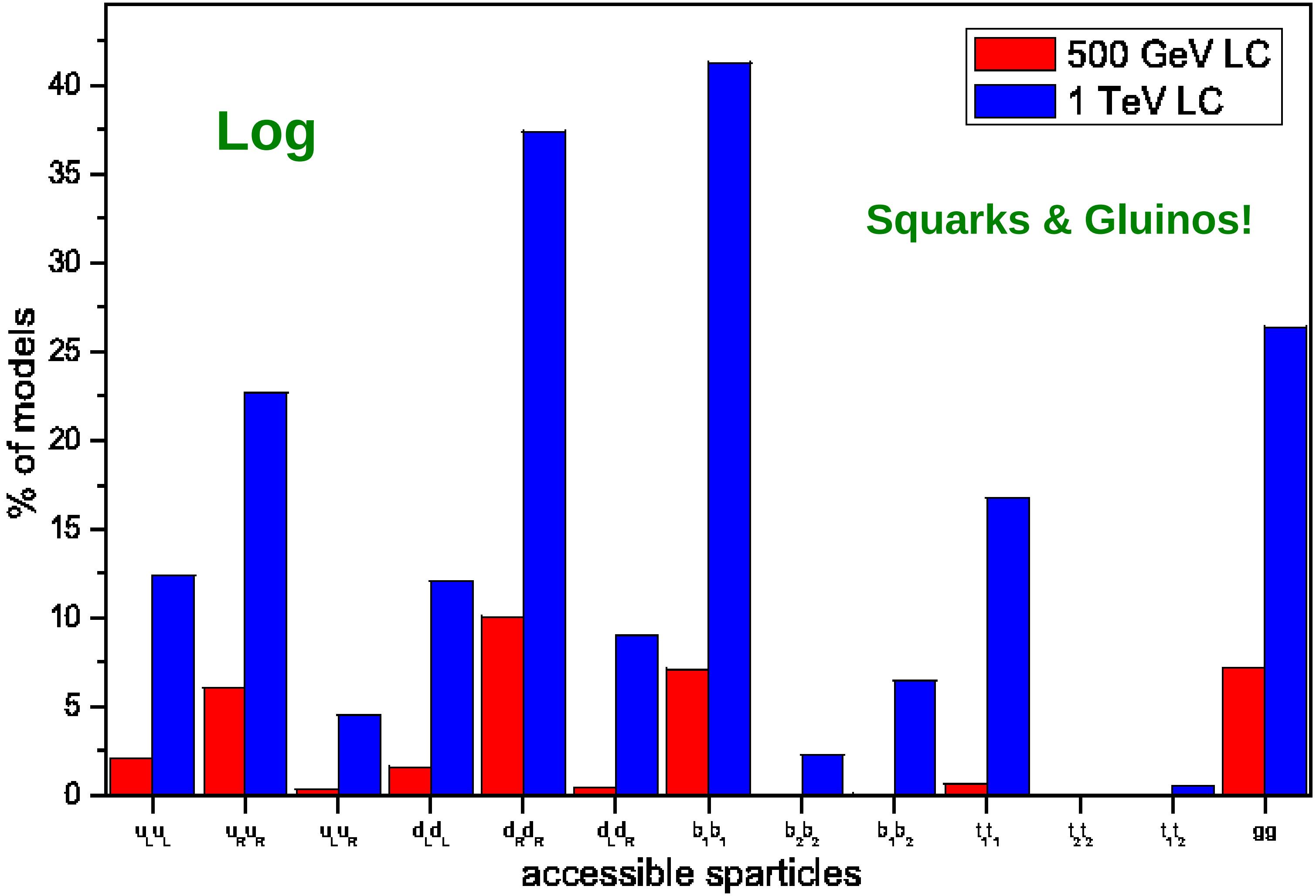
1E-4
0
100
200
300
400
500
600

Kinematic Accessibility: M ~ <3 TeV



Log

Squarks & Gluinos!

Jet Energies in Two-Body Squark Decay