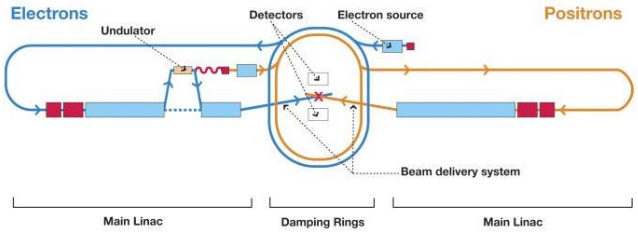
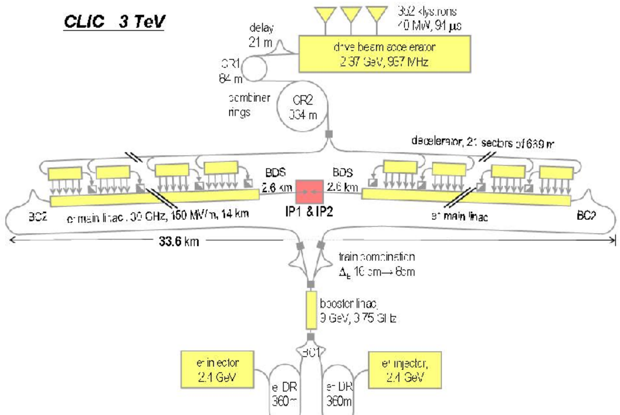
The End of the Beginning: Implications of 7 TeV LHC SUSY Searches for the LC





NATIONAL ACCELERATOR LABORATORY

T.G. Rizzo

03/22/11

THE QUESTIONS:

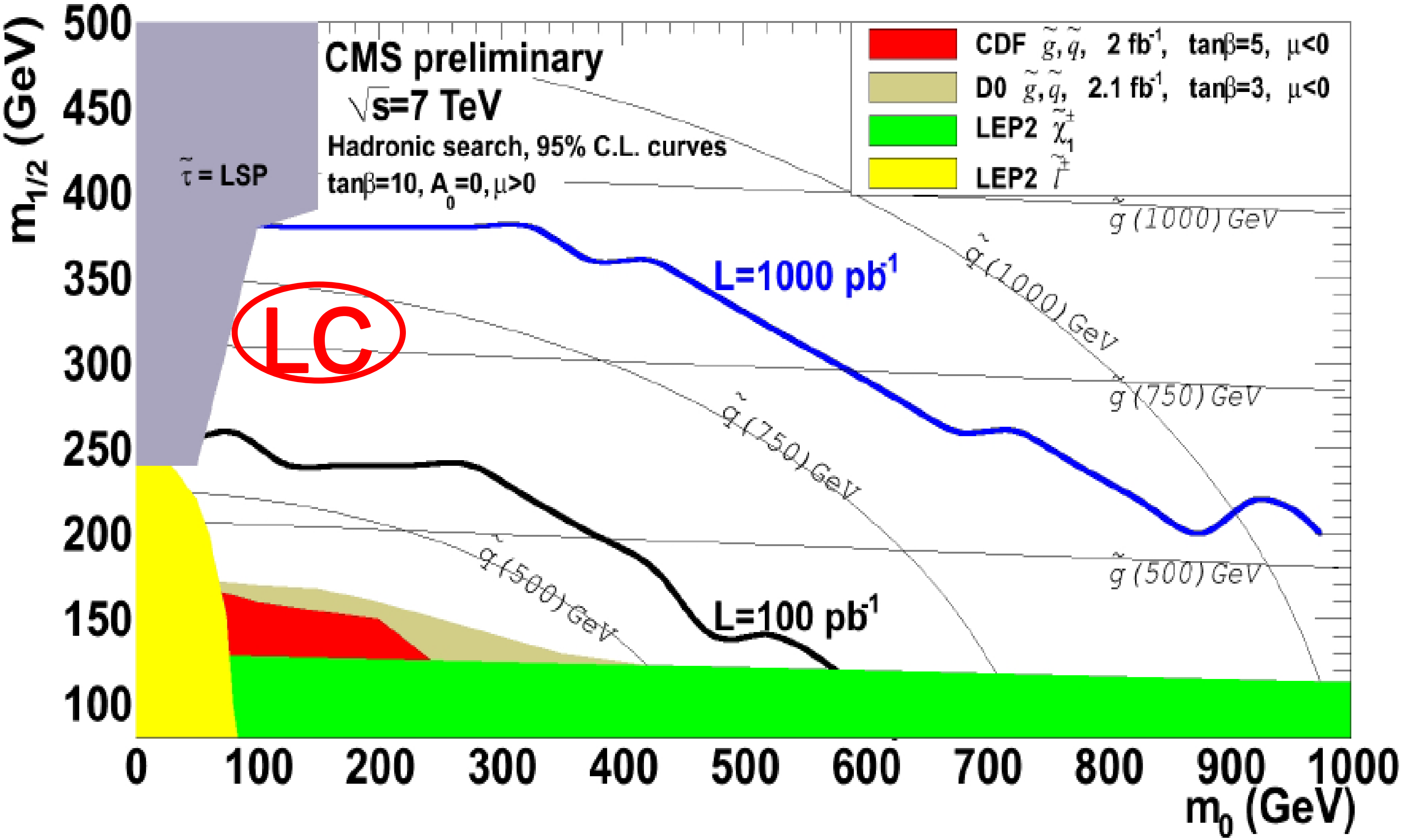
Does SUSY exist & is it 'kinematically accessible' at a 500/1000 GeV LC ??

i.e., can we study both gauginos & sleptons there ?

The LHC should tell us soon…
the answer is currently evolving.

Our long, long (long!) wait is ALMOST over…

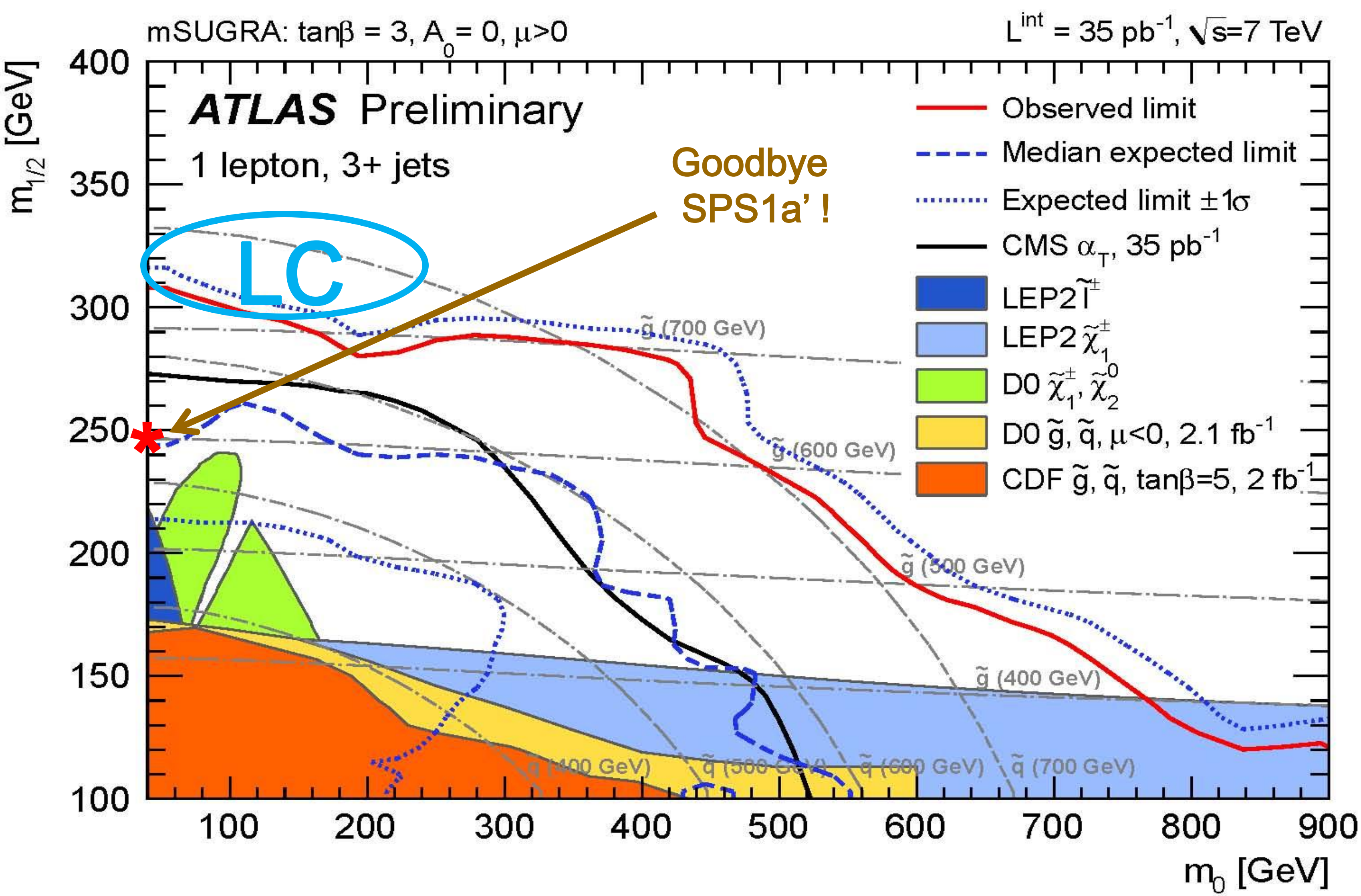
Expectation: If no signal @ 7 TeV w/ >1 fb^{-1}, then LC500 is not a good place to study mSUGRA/CMSSM

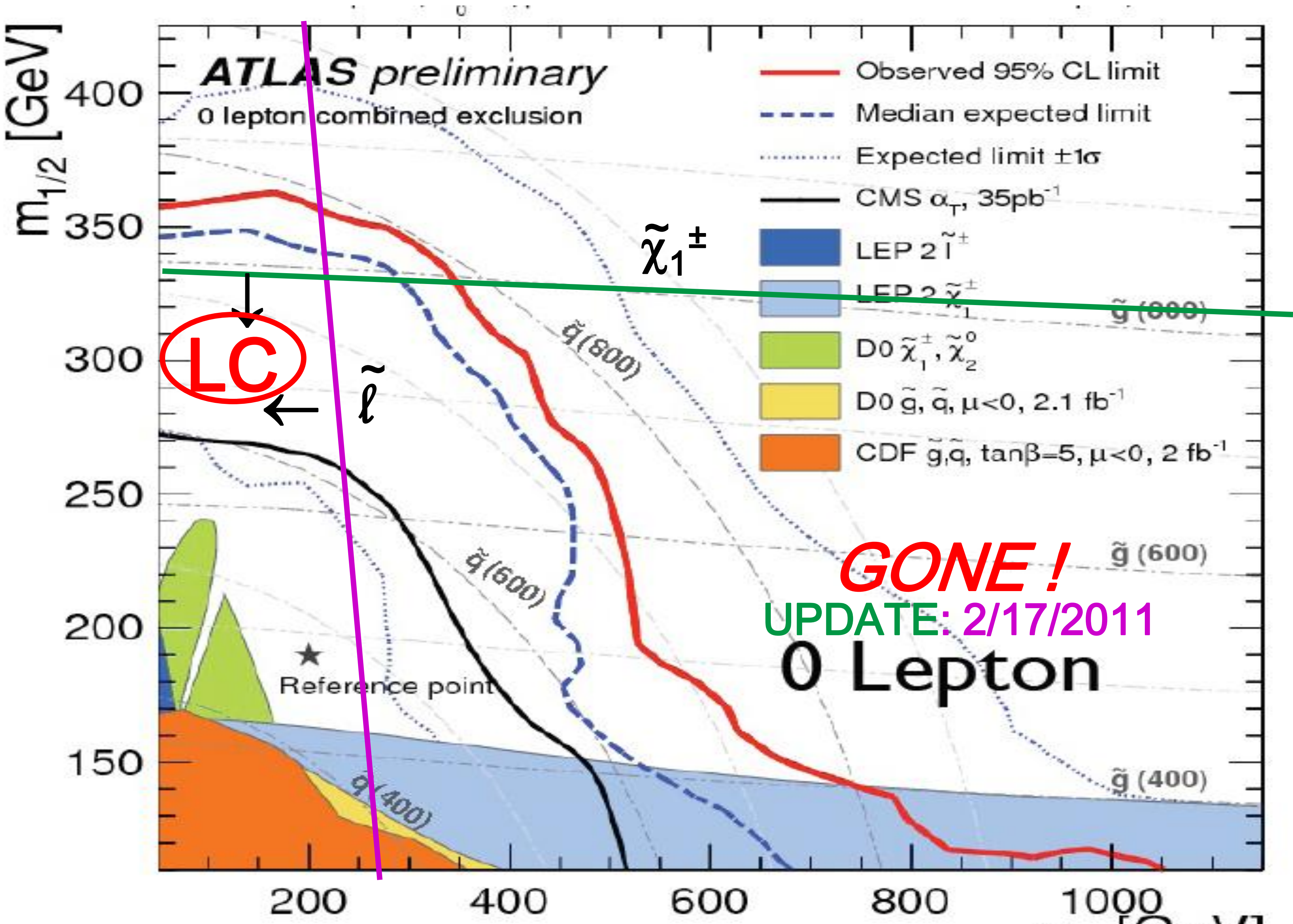


SUSY searches at the LHC have gotten real:

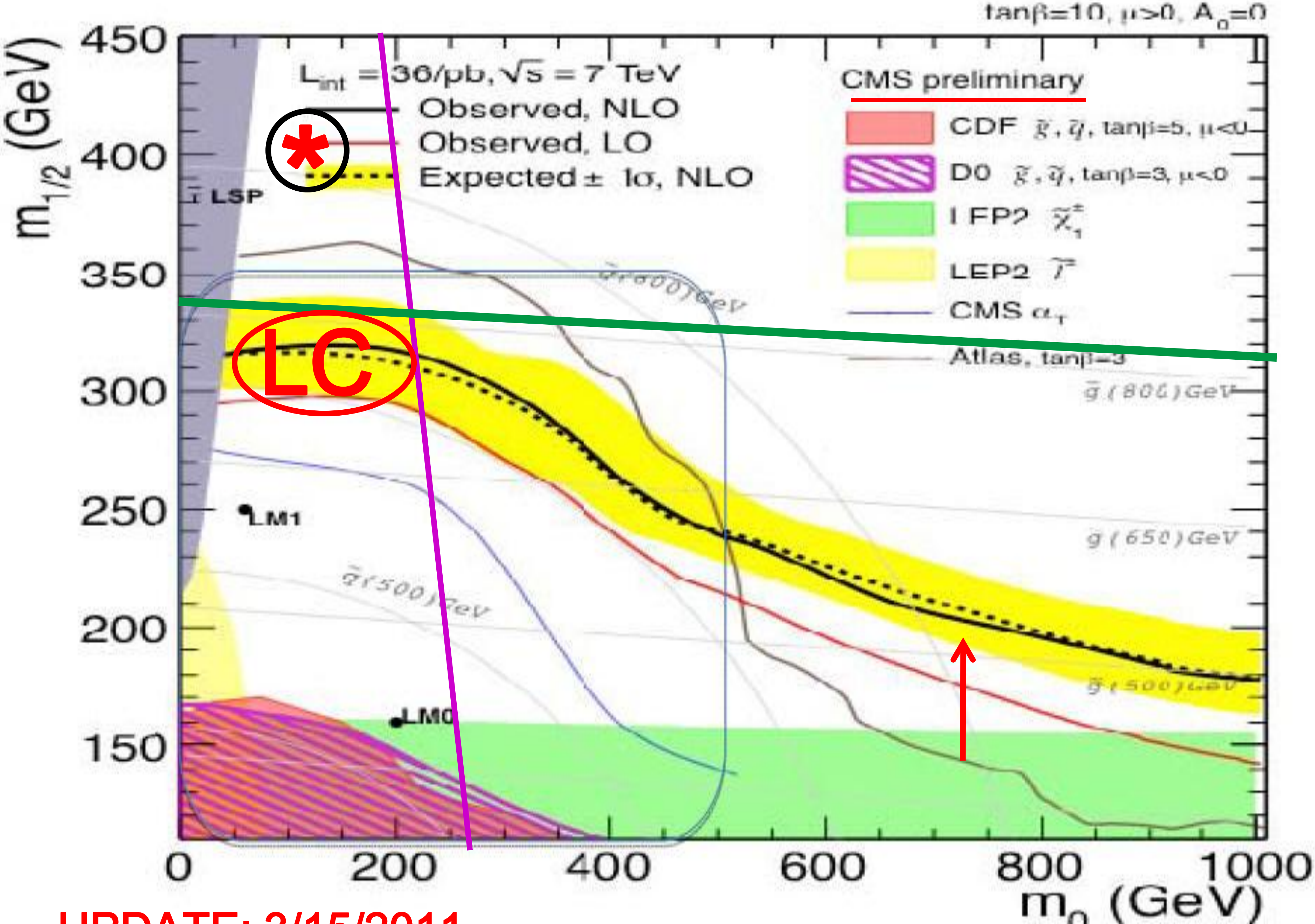
The Amazing Power of √s !

1/27/2011



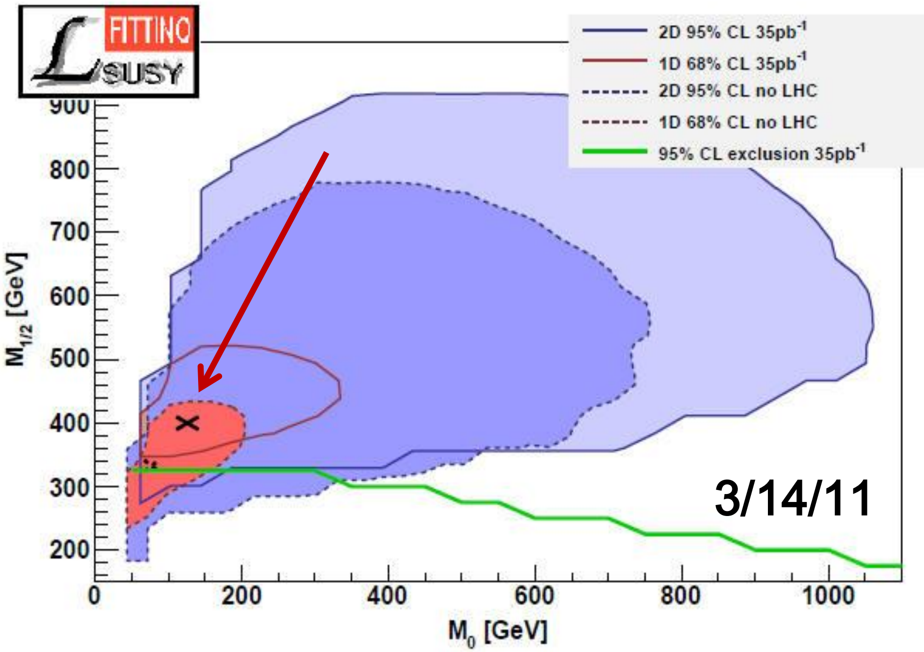


UL region terminated by stau LSP at $m_{1/2}$ ~750 GeV

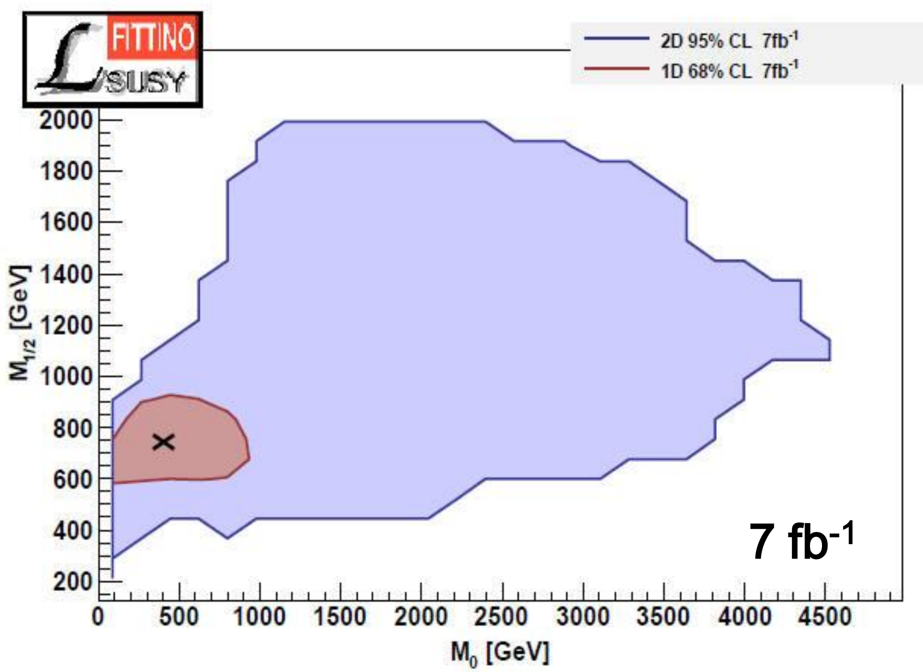


UPDATE: 3/15/2011

mSUGRA FITS



If no signal is found then the mSUGRA global fits to all data will be pushed upwards toward larger & larger masses…



Fits tend to prefer somewhat smaller m_0 values & move to larger $m_{1/2}$ as nothing is seen

→ With only 1 sparticle visible $\tilde{e}_R/\tilde{\tau}_1$ seem to be much more 'likely' than charginos at LC500

P. Bechtle, Moriond11

So for mSUGRA the answer is *in* :

LC500 is NOT a great place to study mSUGRA ..

→ But remember SUSY ≠ mSUGRA !

- So the more important question is: 'Does a more general version of the MSSM allow for more 'accessible' SUSY at LC500 if the LHC sees nothing during 2011-12 @ 7 TeV ?'
- We can give a partial answer to this question based on a set of more general pMSSM models that were studied in detail for LHC/DM searches…but there's still a lot we don't know…

J.A. Conley, J. S. Gainer, J. L. Hewett, M.-P. Le & TGR
arXiv:1009.2539,1103.1697

Issues:

- The general MSSM is too difficult to study due to the large number of soft SUSY breaking parameters (~ 100).
- Analyses limited to specific SUSY breaking scenarios have only a few parameters…can we be more general ?

Model Generation Assumptions :

- The most general, CP-conserving MSSM with R-parity
- Minimal Flavor Violation at the TeV scale
- The lightest neutralino is the LSP & a thermal relic.
- The first two sfermion generations are degenerate & have negligible Yukawa's.

→ These choices mostly control flavor issues producing a fairly general scenario for collider & other studies

→ the pMSSM with 19 real, TeV-scale parameters…

19 pMSSM Parameters

10 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}

3 gaugino masses: M_1, M_2, M_3

3 tri-linear couplings: A_b, A_t, A_τ

3 Higgs/Higgsino: μ, M_A, $\tan\beta$

How? Perform 2 Random Scans

Flat Priors

emphasizes moderate masses

100 GeV $\leq m_{sfermions} \leq$ 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

emphasizes lower masses but also extends to higher masses

100 GeV $\leq m_{sfermions} \leq$ 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

- Flat Priors : 10^7 models scanned , 68422 survive
- Log Priors : 2×10^6 models scanned , 2908 survive

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

Some Constraints

- W/Z ratio $b \to s \gamma$
- $\Delta(g\text{-}2)_\mu$ $\Gamma(Z \to \text{invisible})$
- Meson-Antimeson Mixing
- $B_s \to \mu\mu$ $B \longrightarrow \tau\nu$

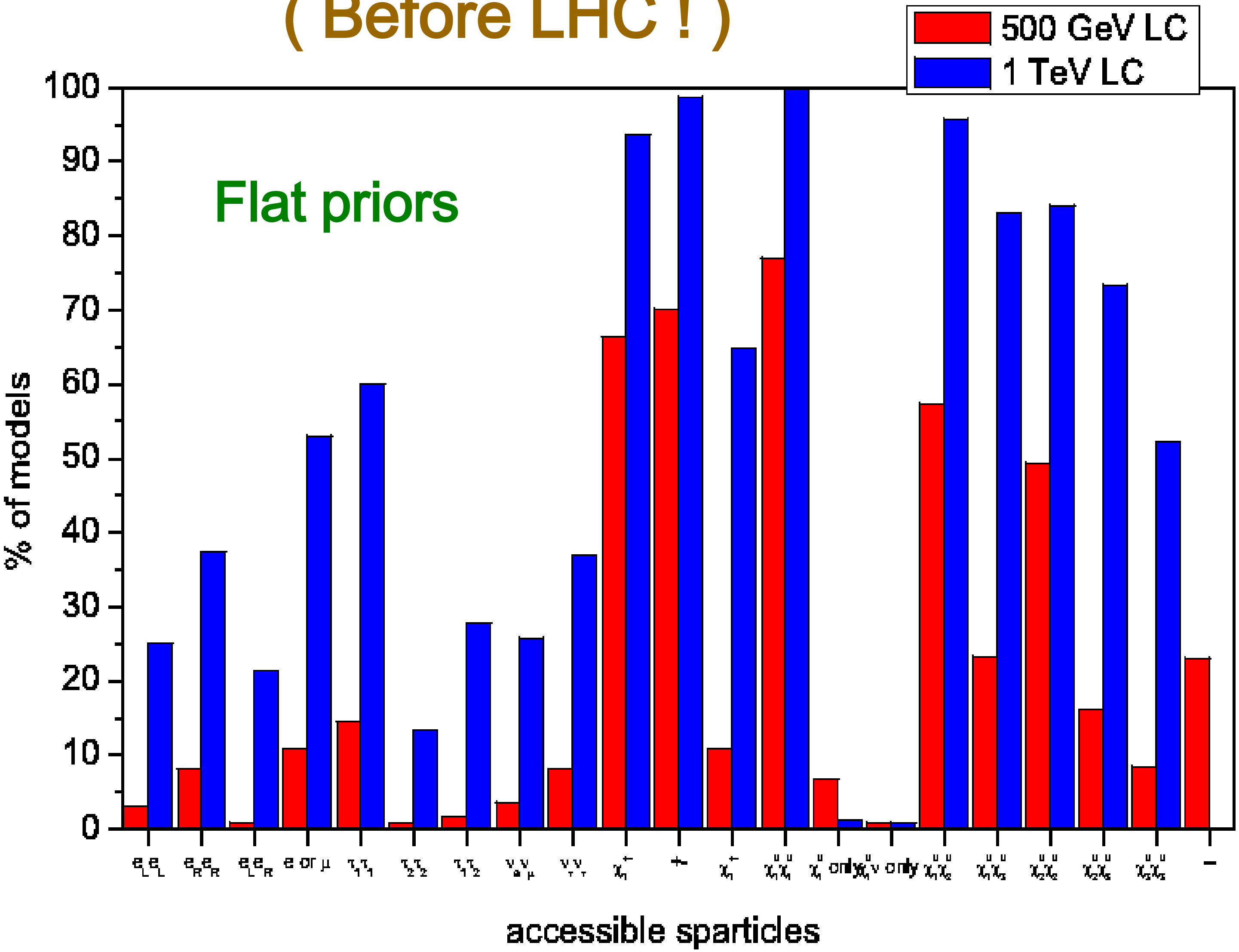
- DM density: $\Omega h^2 < 0.121$. We treat this only as an *upper bound* on the neutralino thermal relic contribution

- Direct Detection Searches for DM (CDMS, XENON…)

- LEP and Tevatron Direct Higgs & SUSY searches : there are *many* of these searches & they are quite complicated with many caveats…. These were 'revisited' for the more general case considered here → simulations limit model set size ~1 core-century for set generation

Model Set Kinematic Accessibility at the ILC : I

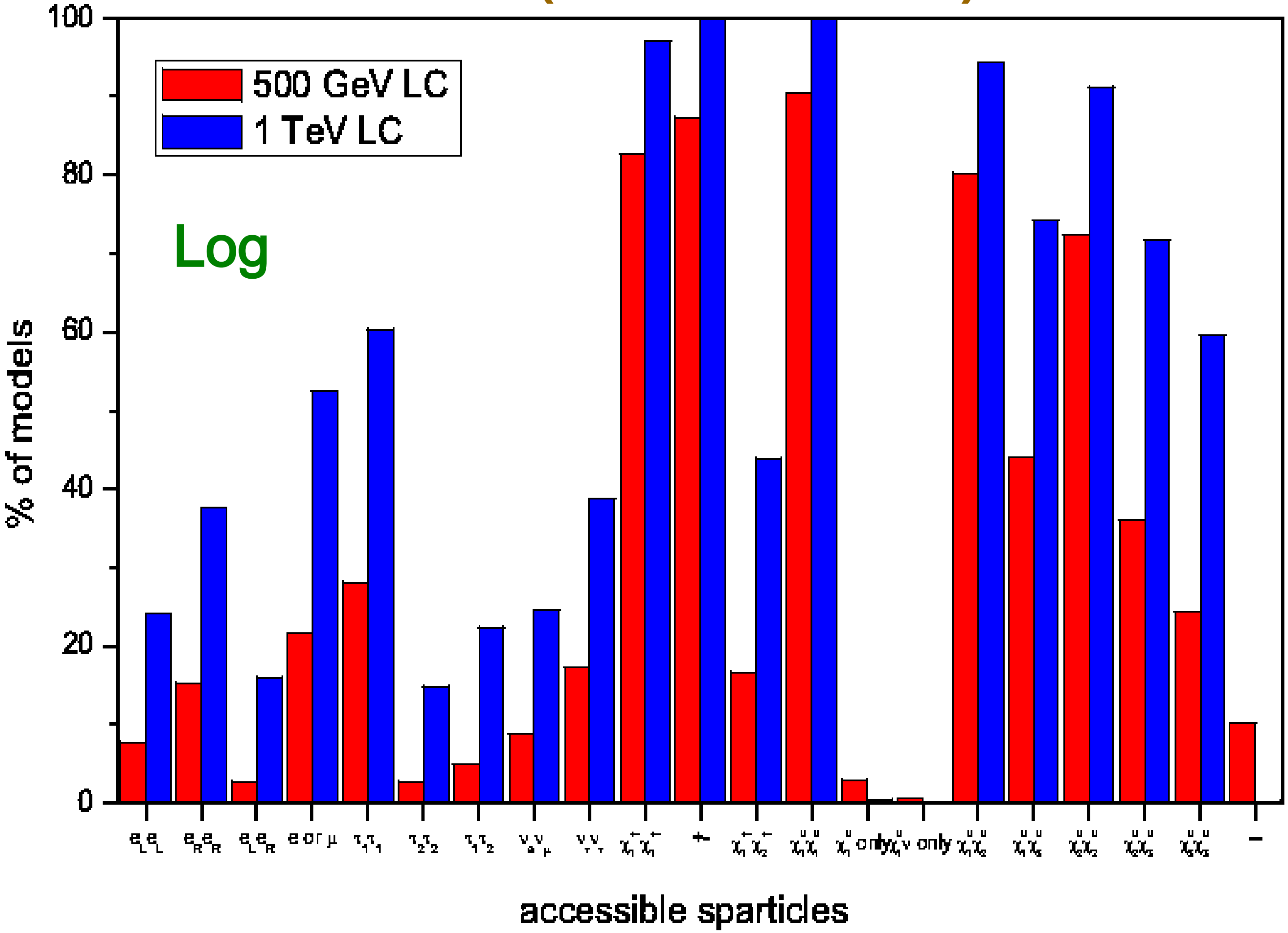
(Before LHC !)



Final State
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
$\tilde{e}_L^\pm\tilde{e}_R^\mp$
$\tilde{\mu}_L^+\tilde{\mu}_L^-$
$\tilde{\mu}_R^+\tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+\tilde{\tau}_1^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
Any charged sparticle
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only
$\tilde{\chi}_1^0 + \tilde{\nu}$ only
$\tilde{\chi}_1^0\tilde{\chi}_2^0$
$\tilde{\chi}_1^0\tilde{\chi}_3^0$
$\tilde{\chi}_2^0\tilde{\chi}_2^0$
$\tilde{\chi}_2^0\tilde{\chi}_3^0$
$\tilde{\chi}_3^0\tilde{\chi}_3^0$
Nothing

Model Set Kinematic Accessibility at the ILC : III

(Before LHC !)



Final State
$\tilde{e}_L^+\tilde{e}_L^-$
$\tilde{e}_R^+\tilde{e}_R^-$
$\tilde{e}_L^\pm\tilde{e}_R^\mp$
$\tilde{\mu}_L^+\tilde{\mu}_L^-$
$\tilde{\mu}_R^+\tilde{\mu}_R^-$
Any selectron or smuon
$\tilde{\tau}_1^+\tilde{\tau}_1^-$
$\tilde{\tau}_2^+\tilde{\tau}_2^-$
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$
Any charged sparticle
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only
$\tilde{\chi}_1^0+\tilde{\nu}$ only
$\tilde{\chi}_1^0\tilde{\chi}_2^0$
$\tilde{\chi}_1^0\tilde{\chi}_3^0$
$\tilde{\chi}_2^0\tilde{\chi}_2^0$
$\tilde{\chi}_2^0\tilde{\chi}_3^0$
$\tilde{\chi}_3^0\tilde{\chi}_3^0$
Nothing

ATLAS SUSY Analyses w/ a Large Model Set

- We passed these points through the ATLAS inclusive MET analyses (@ both 7 &14TeV !), designed for mSUGRA , to explore this broader class of models (~150 core-yrs)

- We used the ATLAS SM backgrounds with their associated systematic errors, search analyses/cuts & criterion for SUSY discovery.

- We verified that we can approximately reproduce the 7 & 14 TeV ATLAS results for their benchmark mSUGRA models with our analysis techniques for each channel. ..BUT beware of some analysis differences:

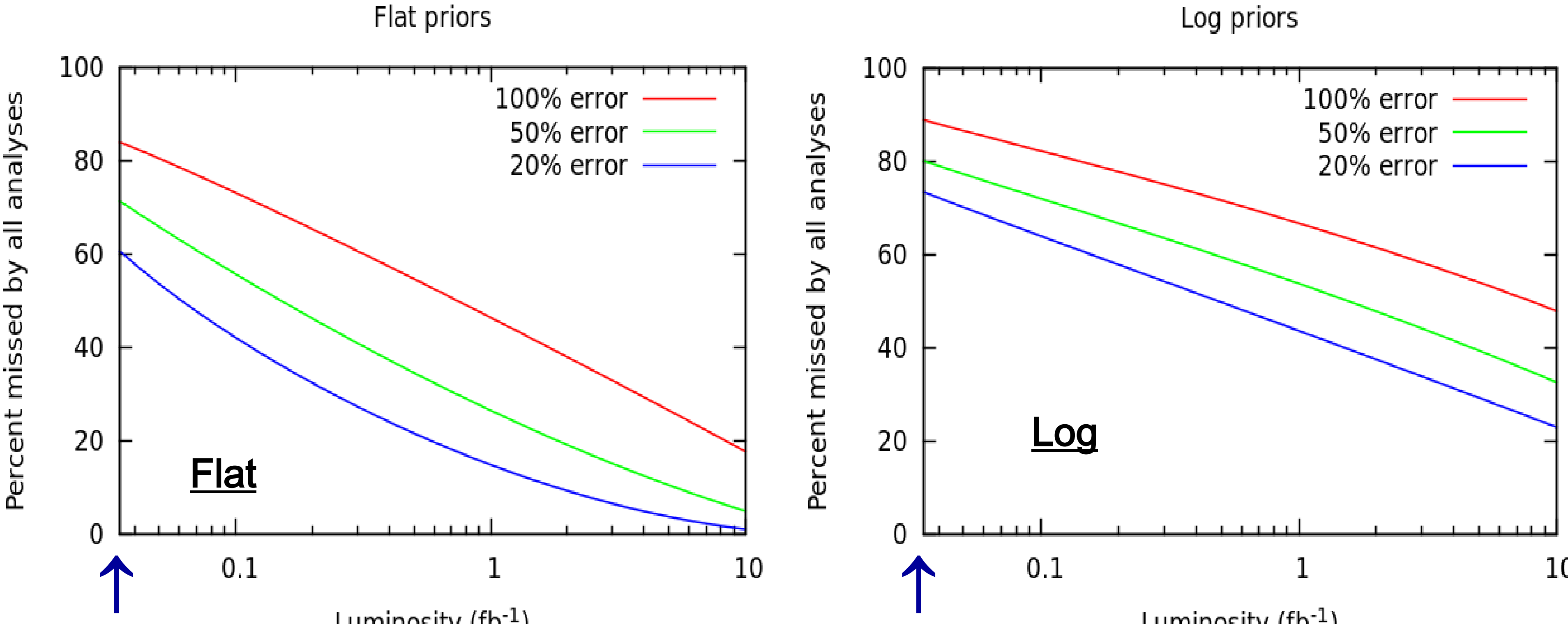
ATLAS	US
ISASUGRA generates spectrum & sparticle decays	SuSpect generates spectra with SUSY-HIT# for decays
Partial NLO cross sections using PROSPINO & CTEQ6M	NLO cross section for all 85 processes using PROSPINO** & CTEQ6.6M
Herwig for fragmentation & hadronization	PYTHIA for fragmentation & hadronization
GEANT4 for full detector sim	PGS4-ATLAS for fast detector simulation

** version w/ negative K-factor errors corrected

version w/o negative QCD corrections, with 1st & 2nd generation fermion masses & other very numerous PS fixes included. e.g., explicit small Δm chargino decays, etc.

How good is the pMSSM coverage @ 7 TeV as the luminosity evolves ??

The coverage is quite good for both model sets !



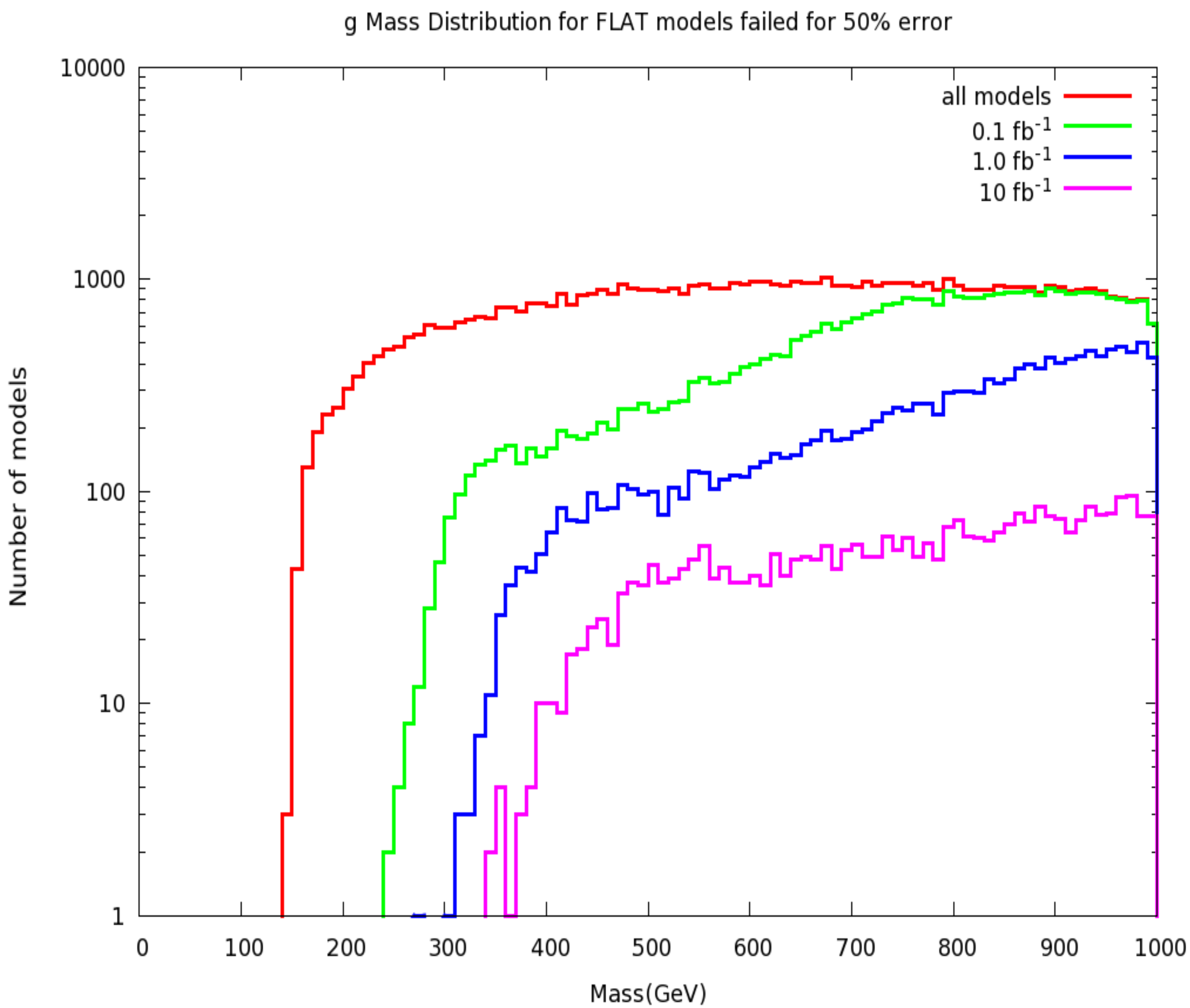
ATLAS pMSSM Model Coverage*
RIGHT NOW for ~35 pb $^{-1}$ @ 7 TeV

δB :	100%	50%	20%
FLAT:	16%	29%	39%
LOG :	11%	20%	27%

Wow! This is actually quite impressive as these LHC SUSY searches are just beginning !

* Fraction of models that SHOULD have been found but weren't if all ATLAS analyses were performed as planned

• What do LHC searches do? If nothing is found they just 'remove' models from the 'allowed' set until few remain



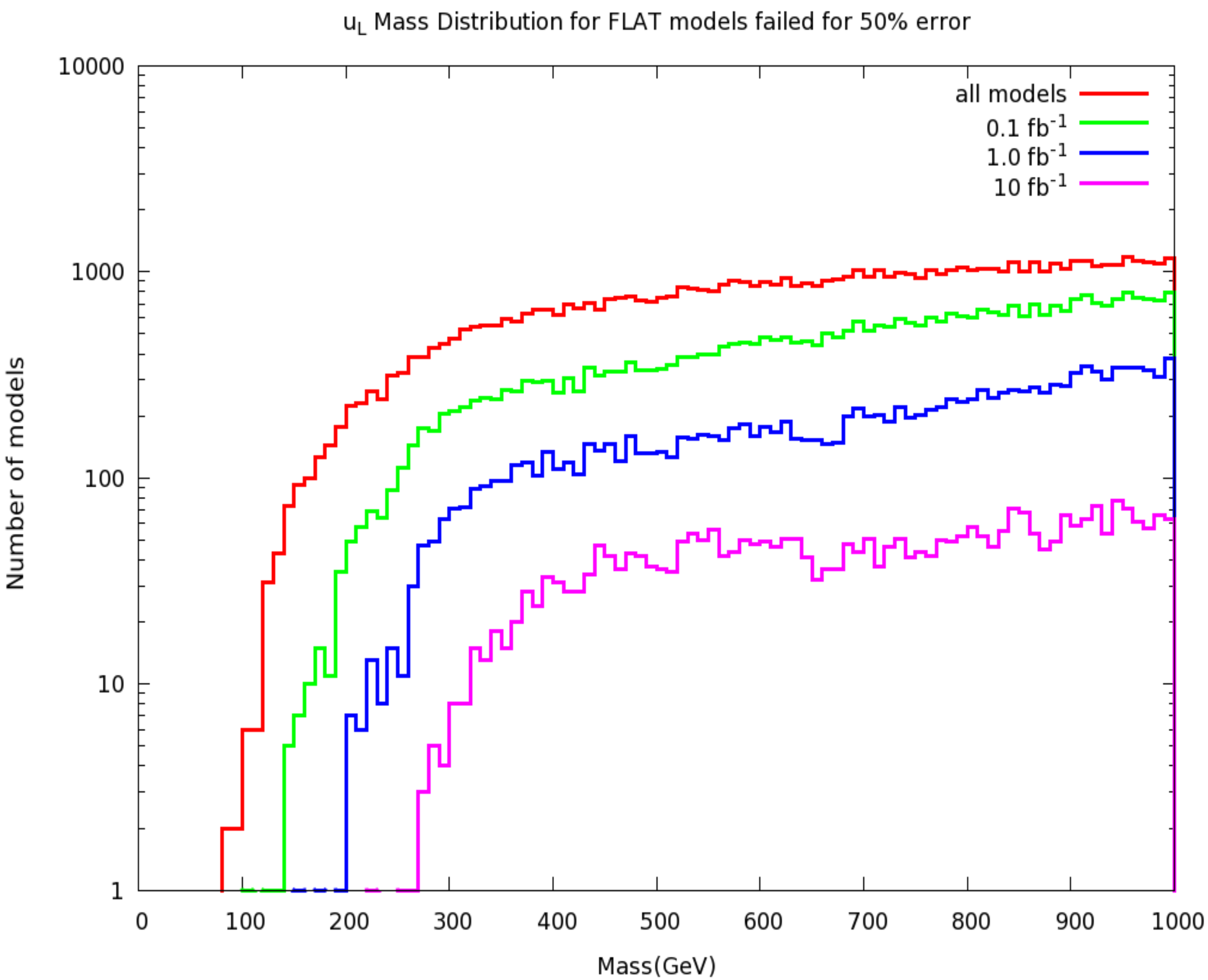
LHC SUSY searches are preferentially sensitive to squarks & gluinos

Here we see the gluino population falling as models are 'removed' ..

More models w/ lighter gluinos are removed

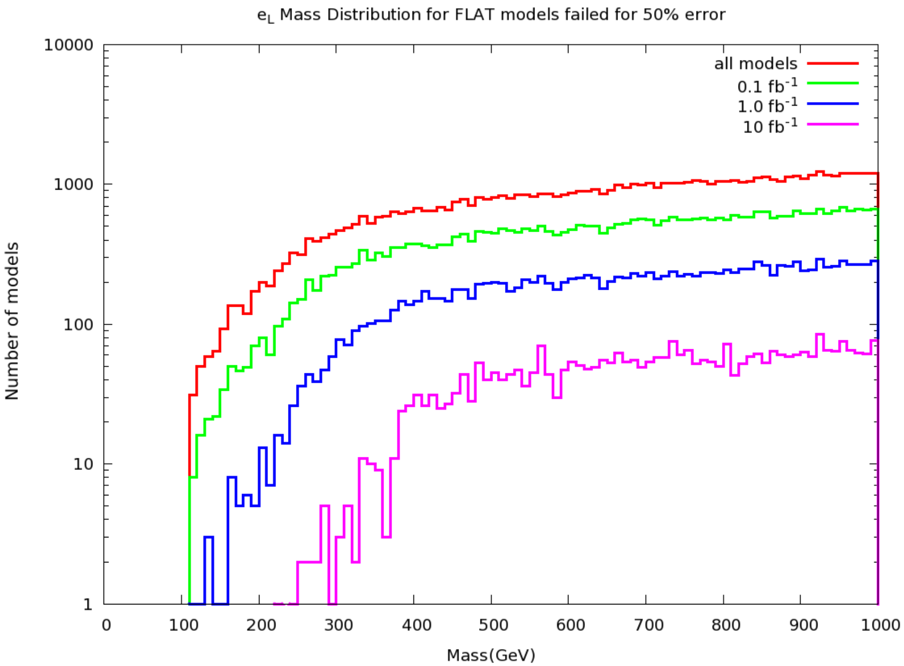
What about the other sparticles?

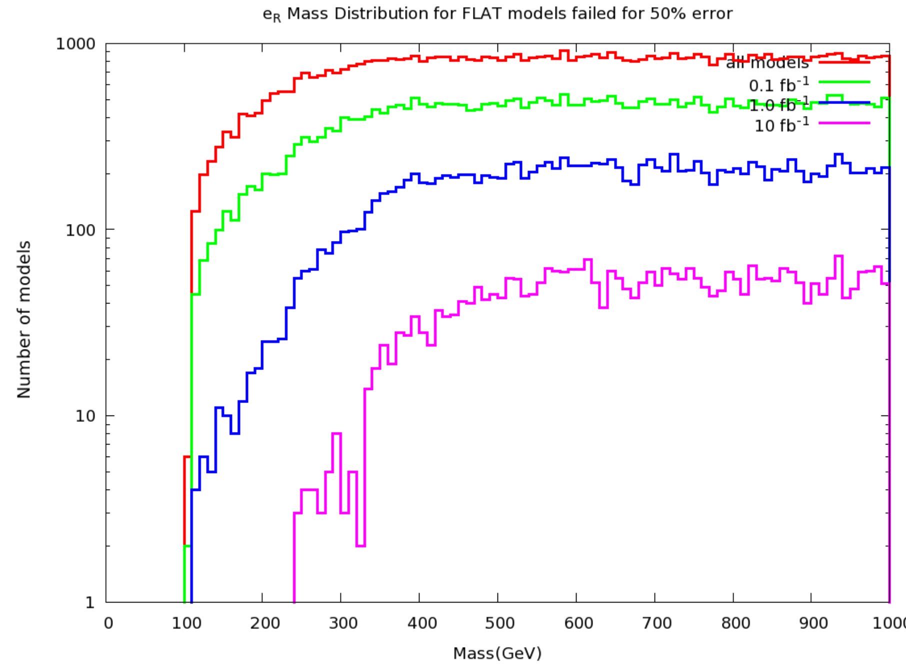
For the other colored sparticles we would expect to see the same effect as there is nothing special about gluinos.



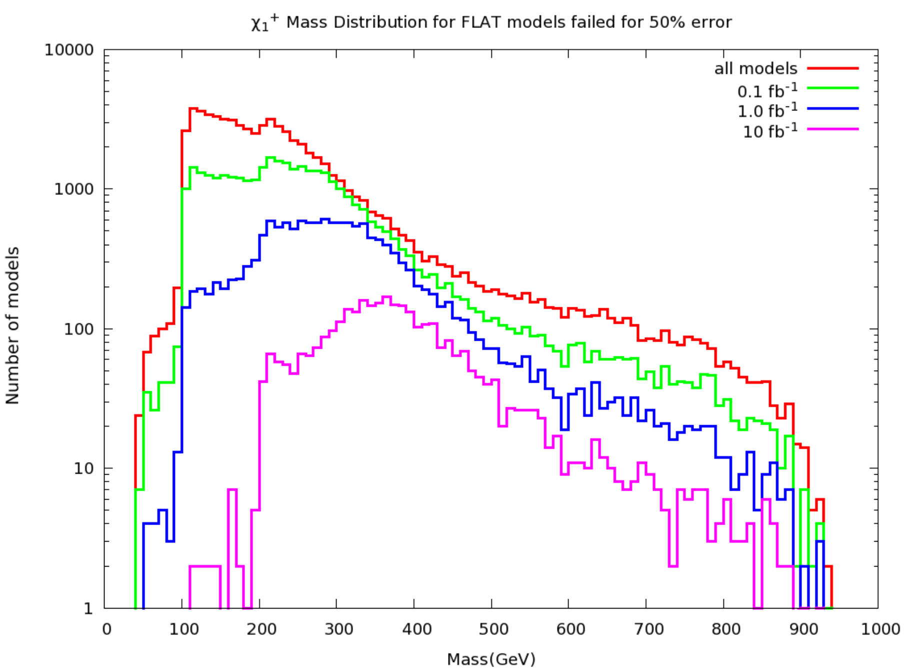
For squarks we also see the depletion of lighter states as the LHC lumi goes up.

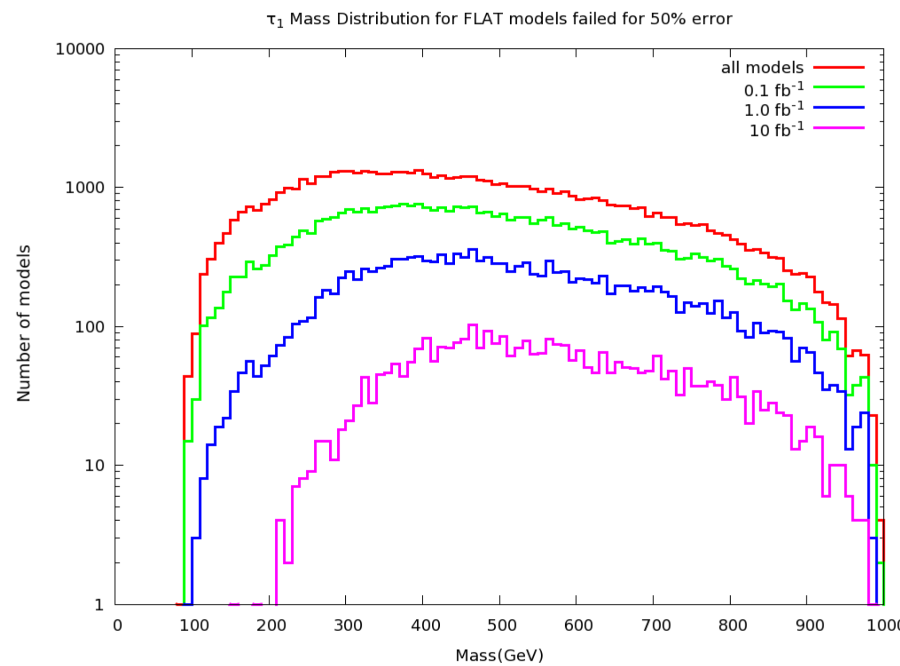
But what about color singlets at they are not (much) directly produced at the LHC & are most relevant for the LC ?

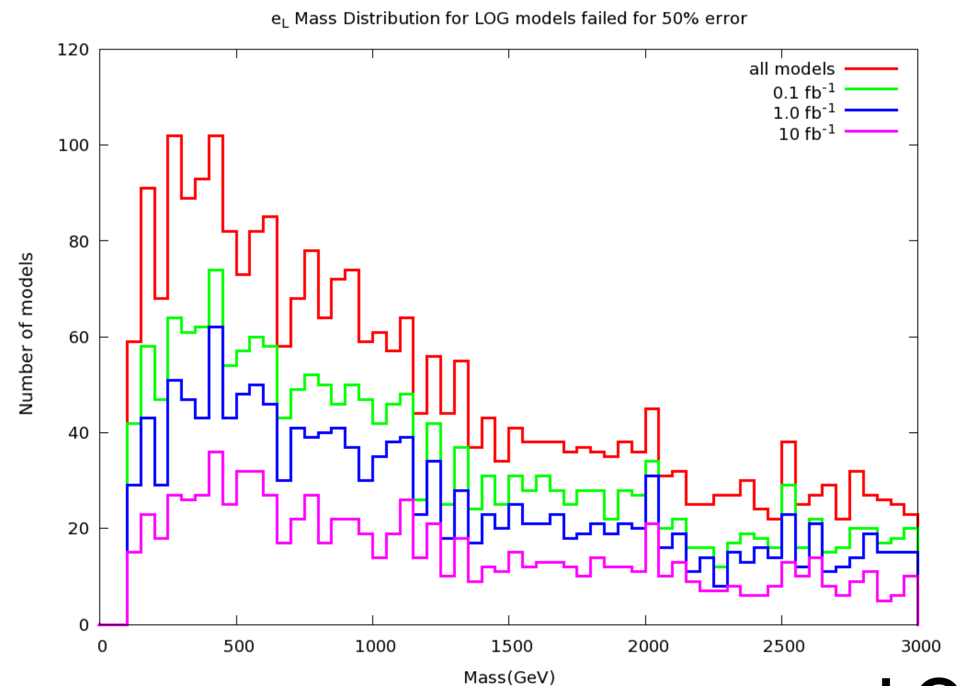

e_L Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000

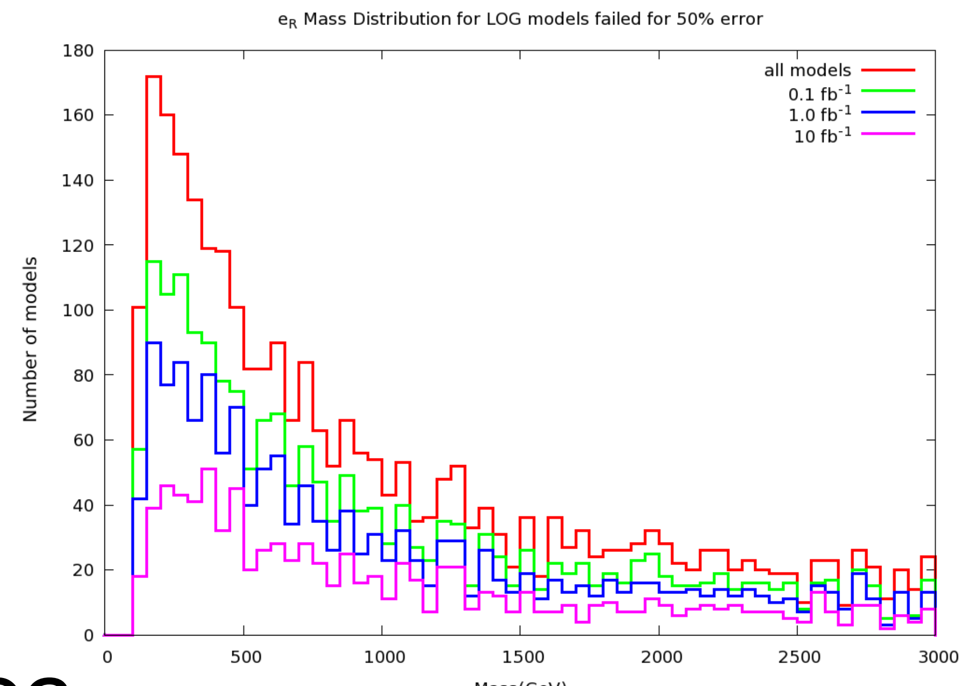

e_R Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
1
10
100
1000
0
100
200
300
400
500
600
700
800
900
1000

FLAT

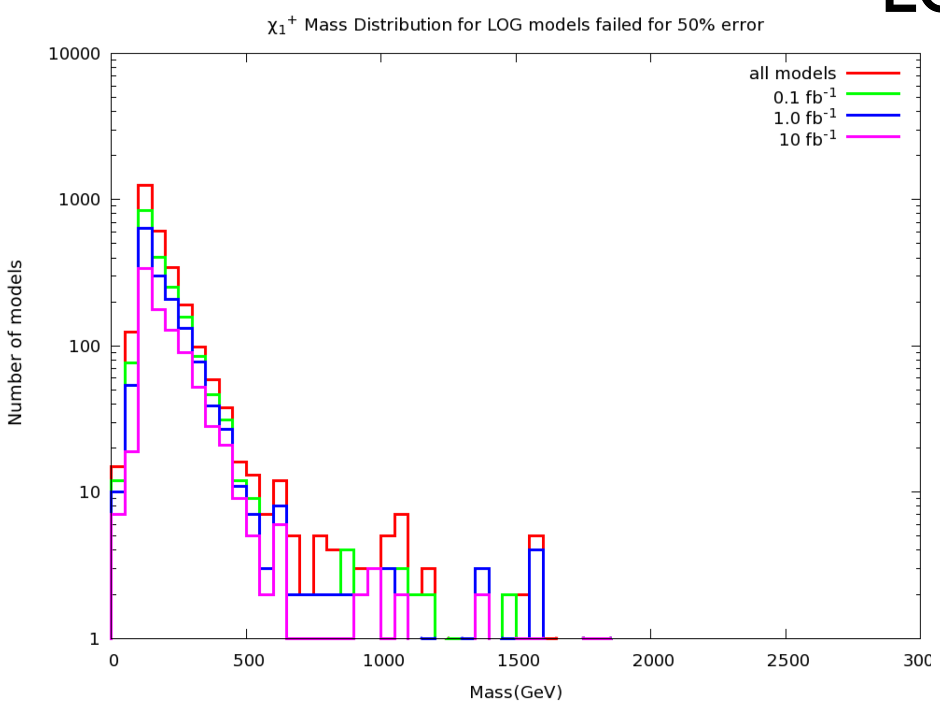

χ1+ Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000

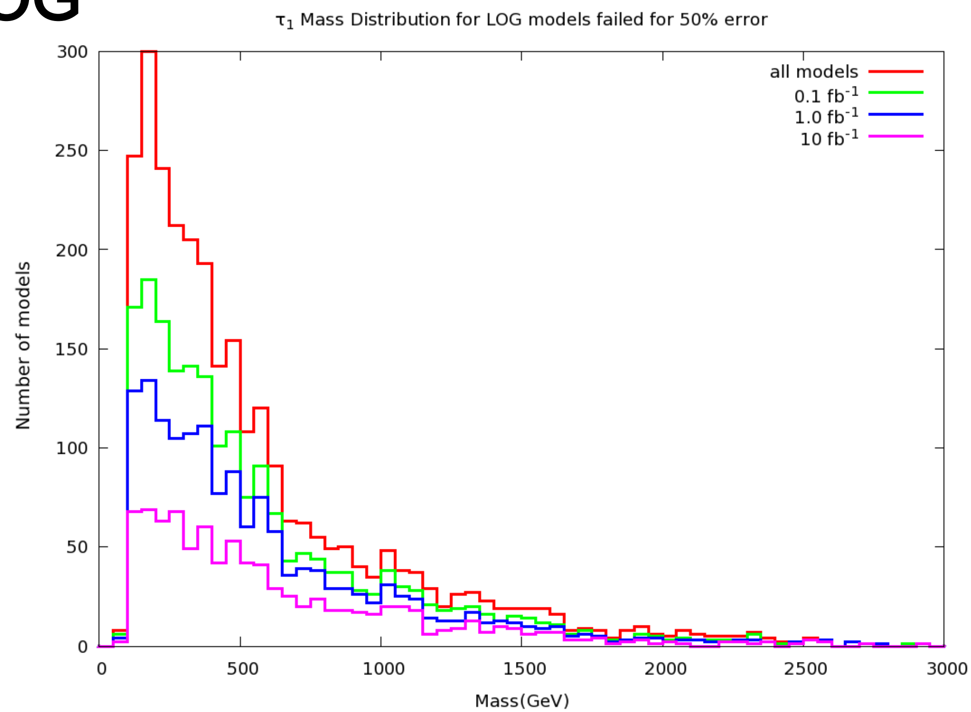

τ1 Mass Distribution for FLAT models failed for 50% error
all models
0.1 fb-1
1.0 fb-1
10 fb-1
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000


e_L Mass Distribution for LOG models failed for 50% error
Number of models
Mass(GeV)
all models
0.1 fb^-1
1.0 fb^-1
10 fb^-1


e_R Mass Distribution for LOG models failed for 50% error
Number of models
Mass(GeV)
all models
0.1 fb^-1
1.0 fb^-1
10 fb^-1

LOG


χ_1^+ Mass Distribution for LOG models failed for 50% error
Number of models
Mass(GeV)
all models
0.1 fb^-1
1.0 fb^-1
10 fb^-1


τ_1 Mass Distribution for LOG models failed for 50% error
Number of models
Mass(GeV)
all models
0.1 fb^-1
1.0 fb^-1
10 fb^-1

	$\sqrt{s}=500$ GeV		$\sqrt{s}=1$ TeV	
Sparticle	Flat	Log	Flat	Log
$\tilde{e}_L$	107	101	3052	347
$\tilde{e}_R$	260	209	3938	565
$\tilde{\tau}_1$	730	381	7431	869
$\tilde{\tau}_2$	30	36	1288	207
$\tilde{\nu}_e$	151	117	3168	356
$\tilde{\nu}_\tau$	386	236	4366	553
$\tilde{\chi}_1^0$	5487	1312	14,510	1539
$\tilde{\chi}_2^0$	2738	1035	10,714	1395
$\tilde{\chi}_3^0$	429	352	5667	903
$\tilde{\chi}_4^0$	10	18	1267	202
$\tilde{\chi}_1^\pm$	4856	1208	13,561	1495
$\tilde{\chi}_2^\pm$	94	54	3412	456
$\tilde{g}$	0	0	1088	65
$\tilde{d}_L$	35	11	2459	117
$\tilde{d}_R$	220	96	3630	526
$\tilde{u}_L$	52	16	2545	123
$\tilde{u}_R$	124	64	3581	273
$\tilde{b}_1$	289	75	5553	590
$\tilde{b}_2$	1	0	409	21
$\tilde{t}_1$	93	9	3727	217
$\tilde{t}_2$	0	0	2	0

LC Implications

← In the set of 14623 (1546) FLAT(LOG) models NOT found at 7 TeV w/ 1 fb^{-1} & $\delta B=50\%$ we find there are….

This doesn't look too bad for 500 GeV or 1 TeV !

But →

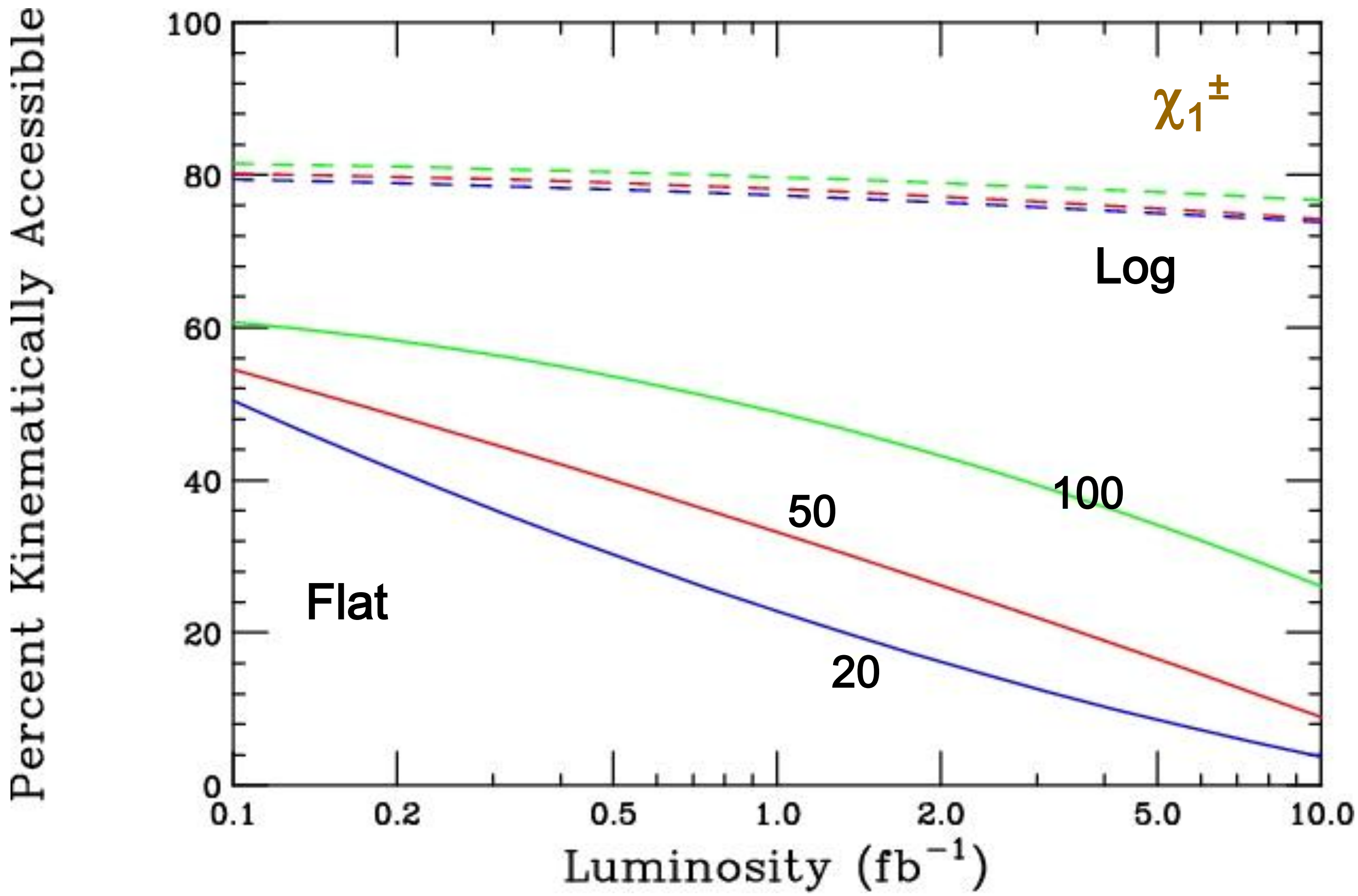
	$\sqrt{s} = 500$ GeV		$\sqrt{s} = 1$ TeV	
Sparticle	Flat	Log	Flat	Log
$\tilde{e}_L$	0	37	63	142
$\tilde{e}_R$	0	72	53	223
$\tilde{\tau}_1$	2	142	165	338
$\tilde{\tau}_2$	0	11	9	69
$\tilde{\nu}_e$	0	42	64	146
$\tilde{\nu}_\tau$	0	85	81	236
$\tilde{\chi}_1^0$	26	507	587	626
$\tilde{\chi}_2^0$	4	397	352	557
$\tilde{\chi}_3^0$	0	136	57	357
$\tilde{\chi}_4^0$	0	5	5	66
$\tilde{\chi}_1^\pm$	25	467	505	608
$\tilde{\chi}_2^\pm$	0	17	16	170
$\tilde{g}$	0	0	27	5
$\tilde{d}_L$	0	3	73	24
$\tilde{d}_R$	1	18	63	157
$\tilde{u}_L$	0	5	81	24
$\tilde{u}_R$	0	14	86	79
$\tilde{b}_1$	0	20	103	189
$\tilde{b}_2$	0	0	3	4
$\tilde{t}_1$	1	2	94	58
$\tilde{t}_2$	0	0	0	0

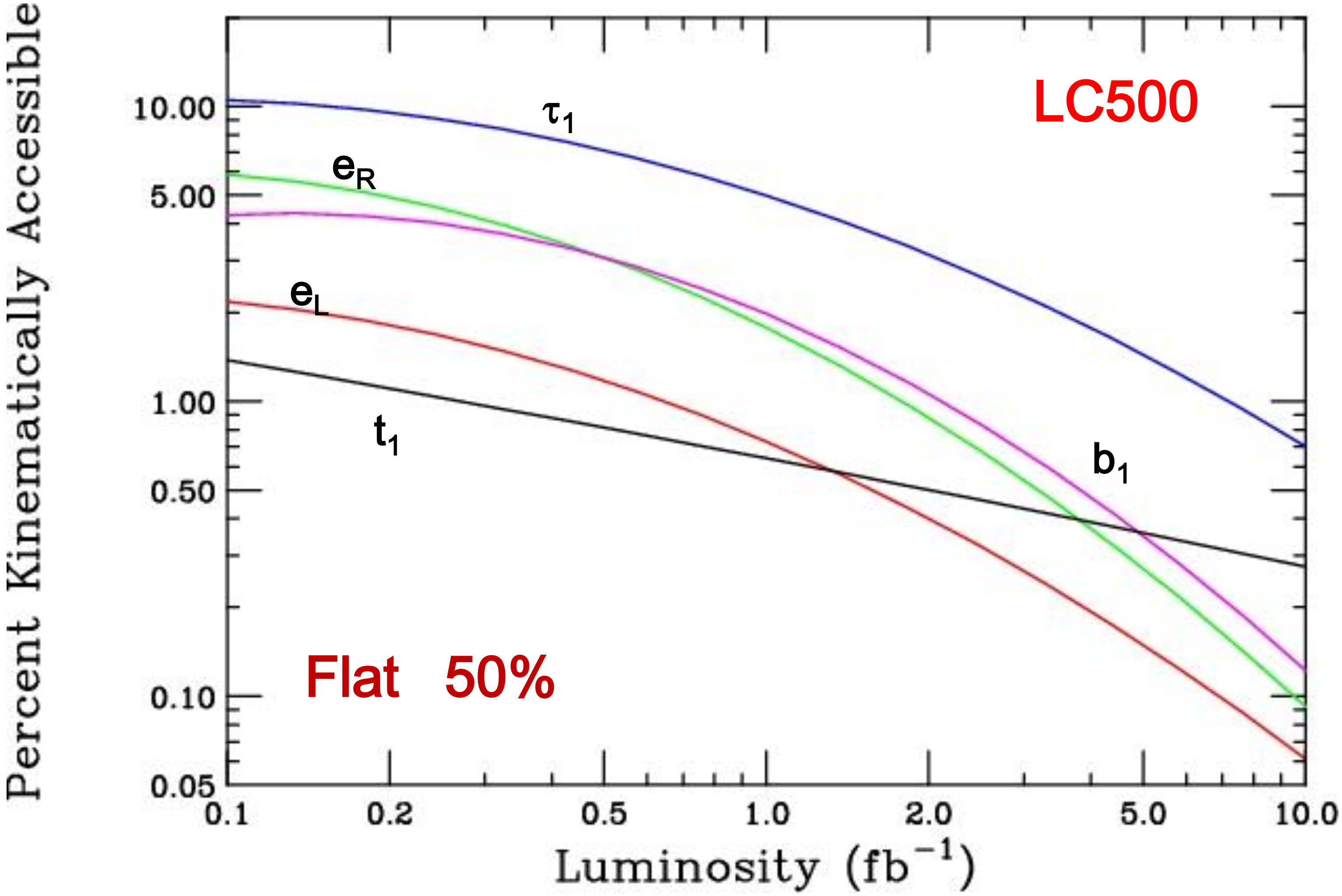
In the set of 672(663) FLAT(LOG) models NOT found @ 7 TeV w/ 10 fb^{-1} and δB=20% there are a lot fewer !

← Not a whole lot in the FLAT case at 500 GeV ! …so the SUSY @ the LC window depends where we end up & the spectrum shape details

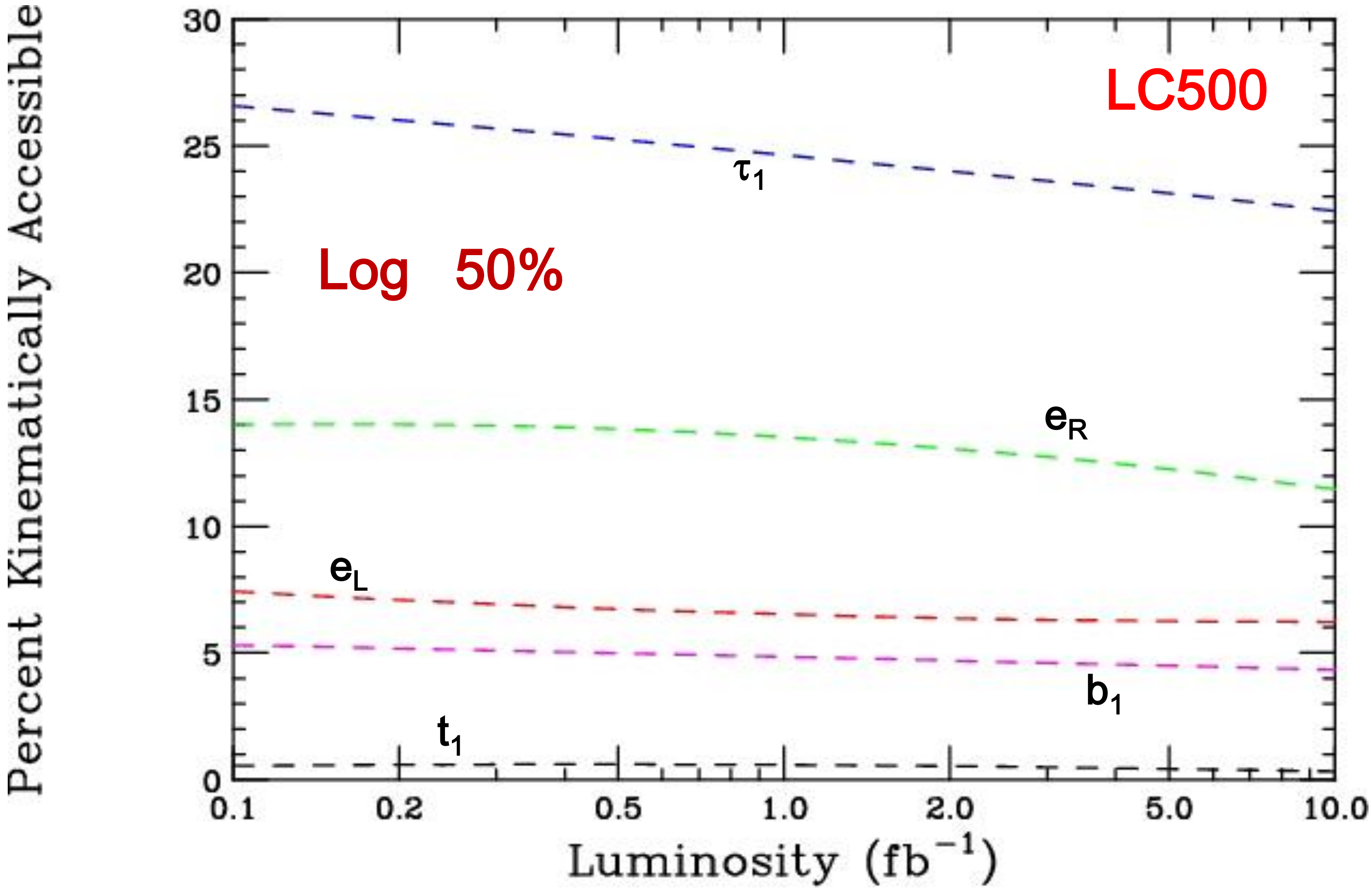
However, a 1TeV LC is vastly BETTER !

- Of course what's REALLY important is the fraction of the 'undiscovered' models which have kinematically accessible sparticles at the LC…



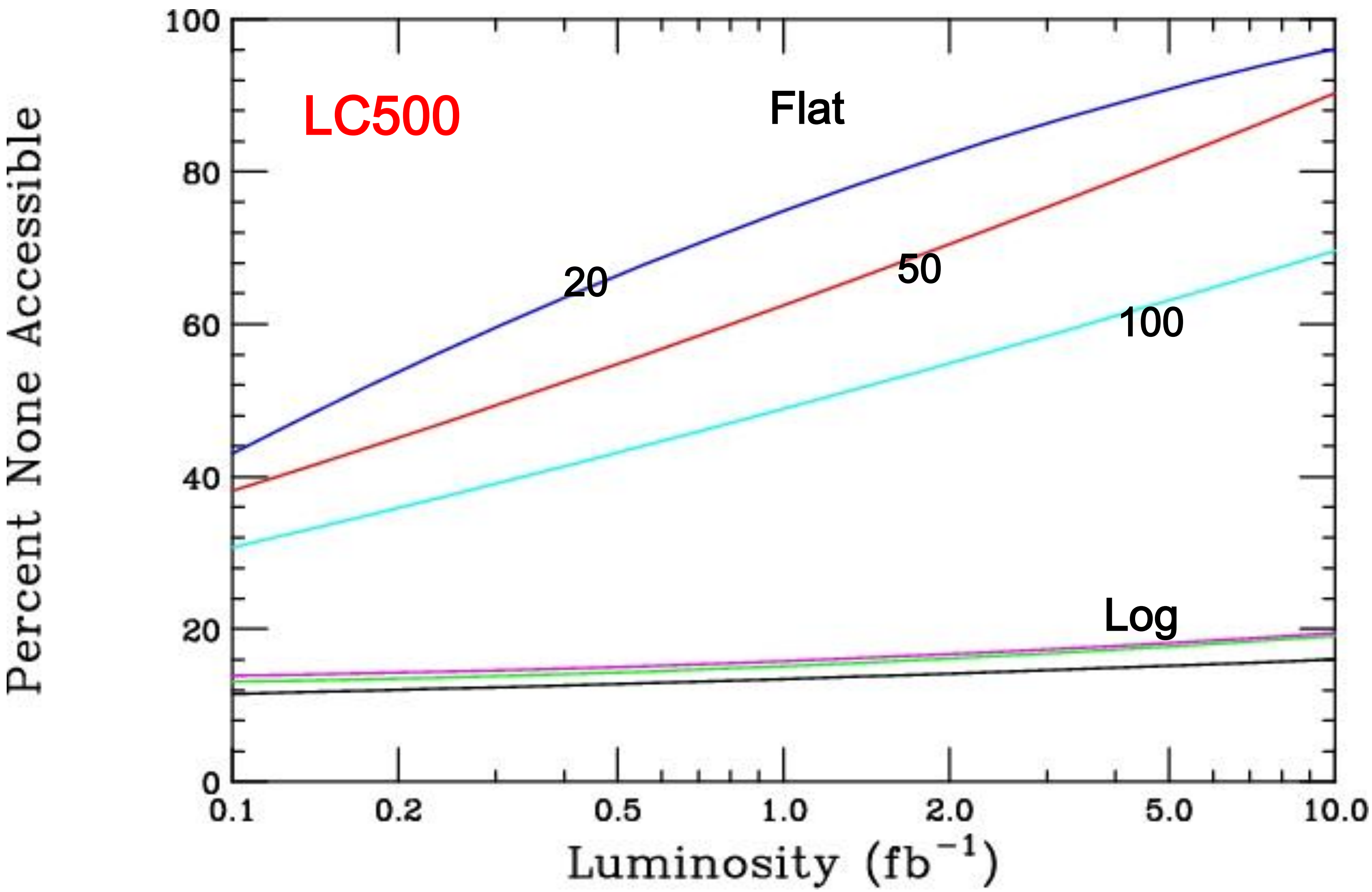


As the lumi increases the fraction of flat prior models with LC500 observable sparticles becomes very small <1%. However…

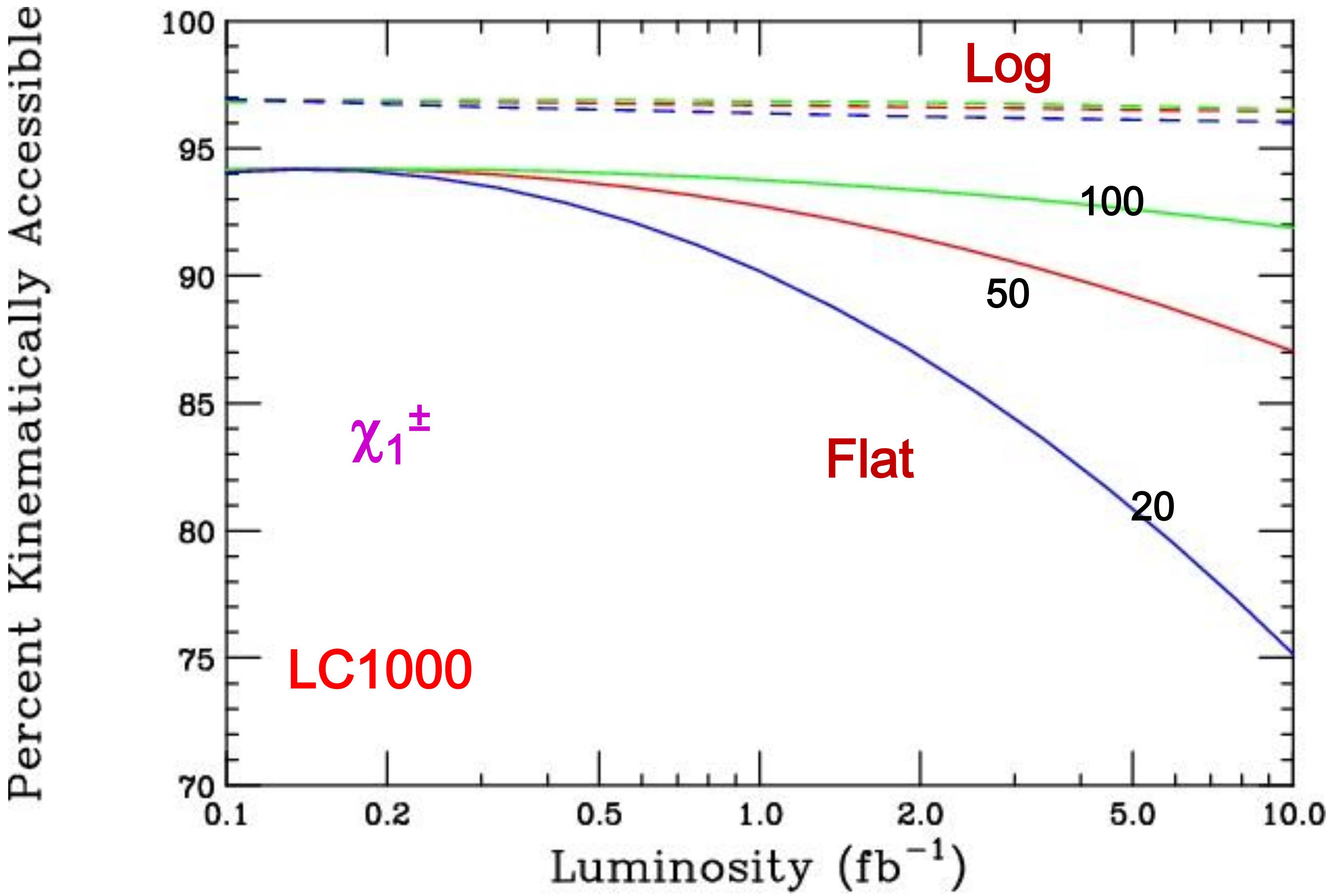


As the lumi increases the fraction of log prior models with LC500 observable sparticles declines quite slowly !

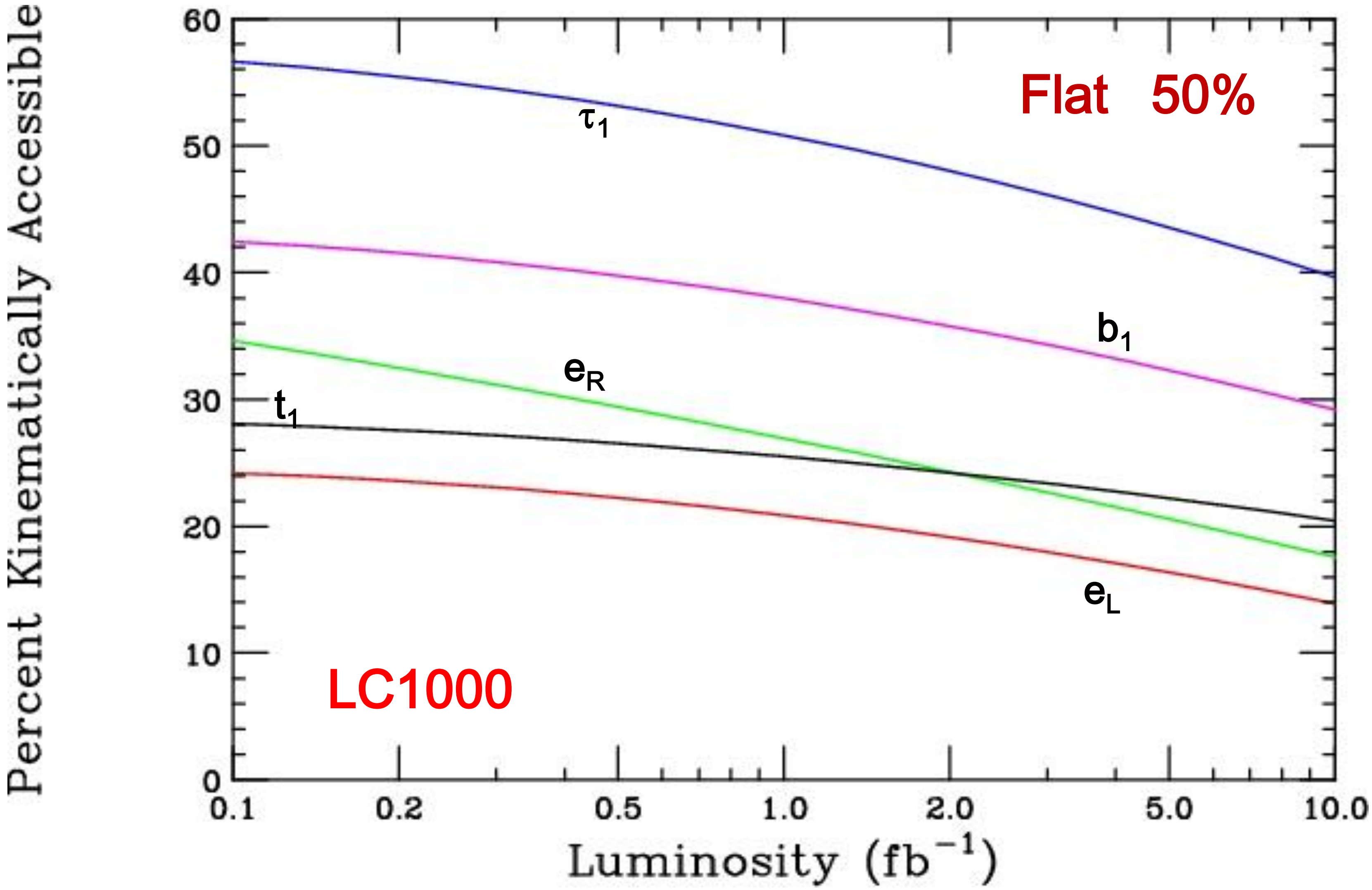
The fraction of models with NO sparticles accessible at LC500 grows rapidly for the flats but almost not at all for the logs

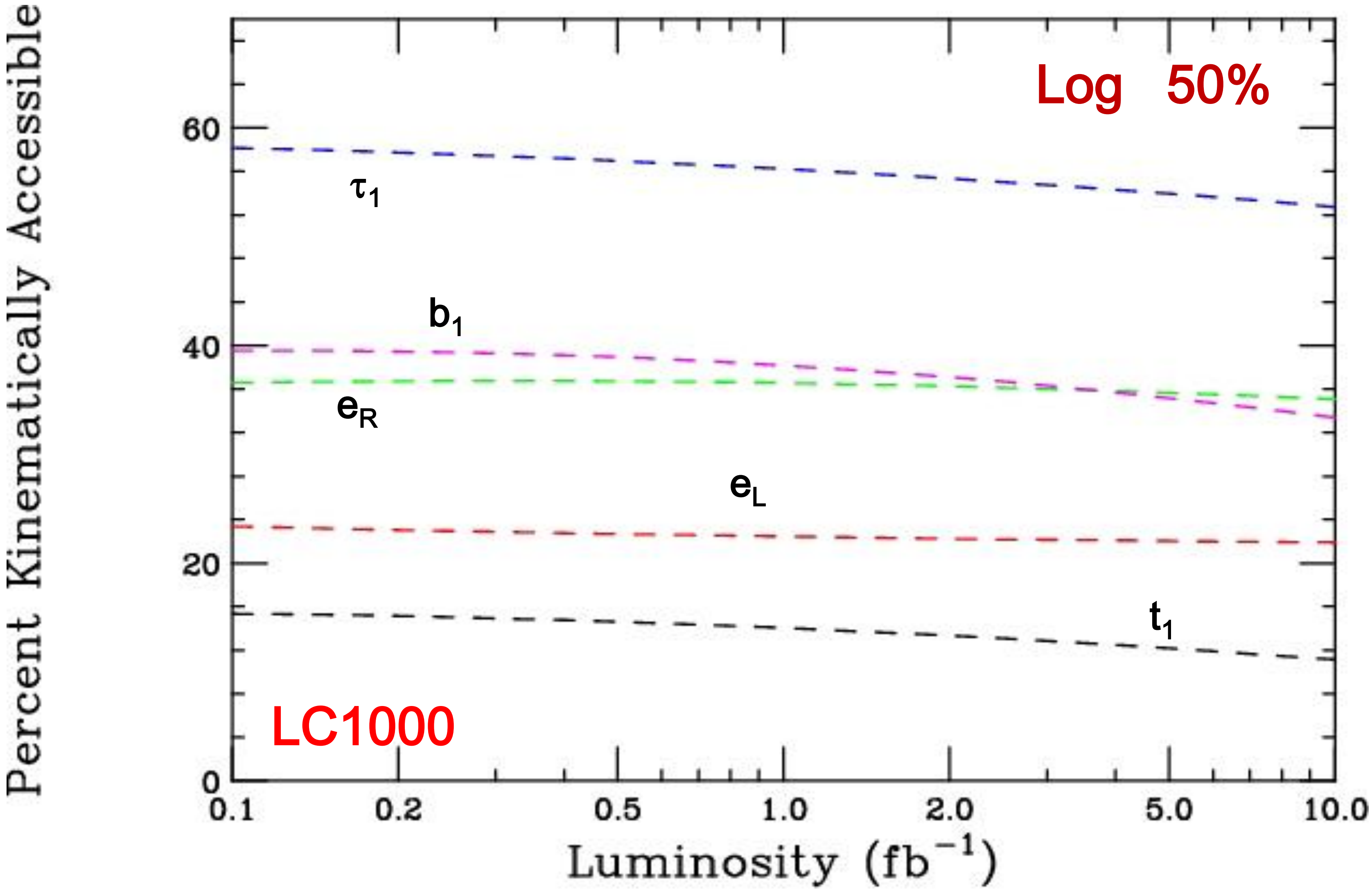


Things do change a lot at LC1000… a very large fraction of models have accessible charginos.



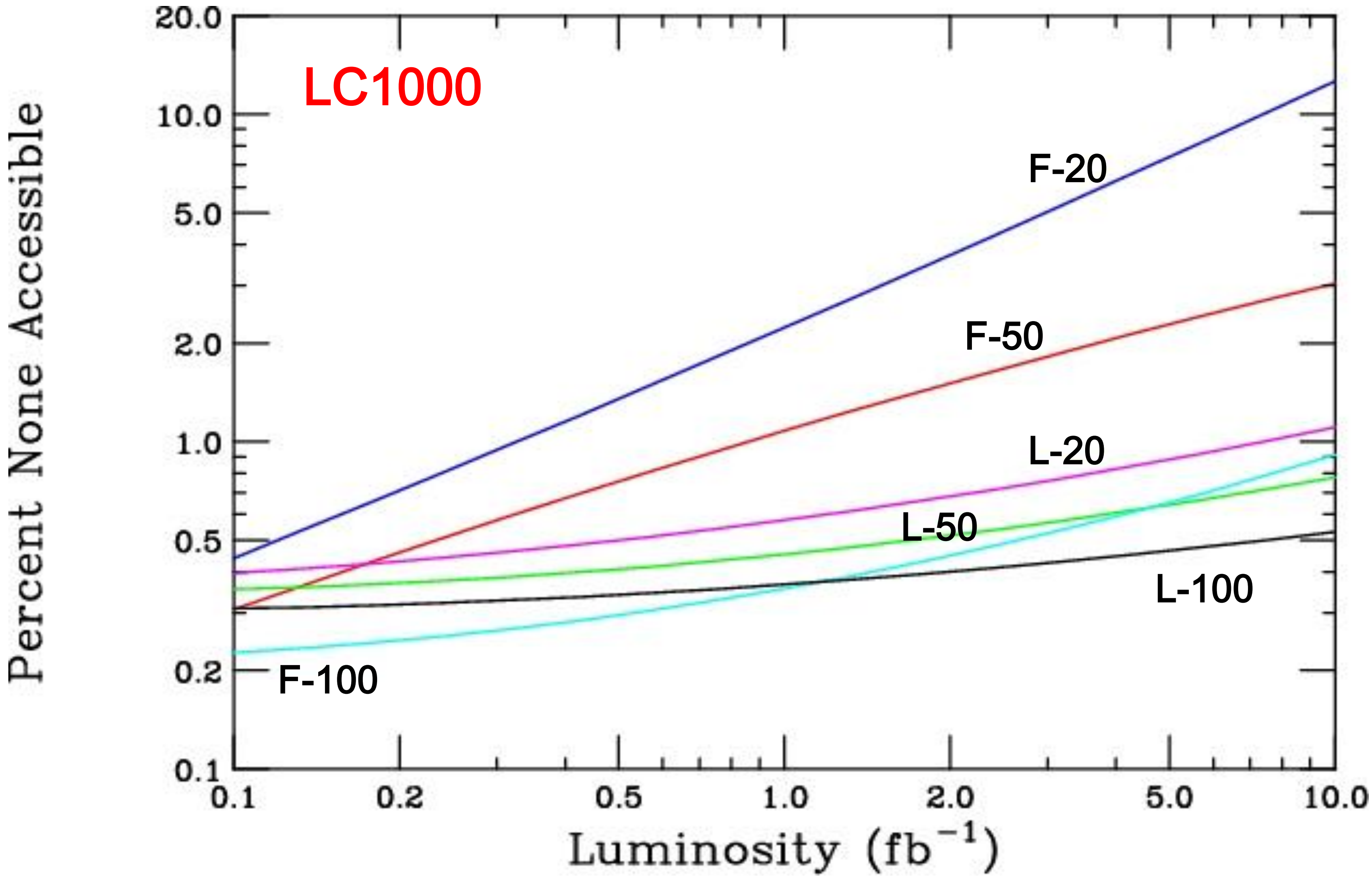
Other sparticles are also reasonably accessible at LC1000





For the Log case many sparticles are accessible at LC1000

The fraction of models w/o any SUSY accessible is small



- If nothing is seen, just how visible SUSY may or may not be at LC500 will depend on 2 factors that we presently don't know:

(i) What luminosity/background systematics will be achieved during the 2011-12(13) run? (We just need to wait to find out…)

(ii) How are the many sparticles in the SUSY spectrum distributed ? (i.e., just how is SUSY broken..who knows?)

→ We can say that if nature is anything like the Flat prior case then LC500 will NOT be a good place for SUSY studies

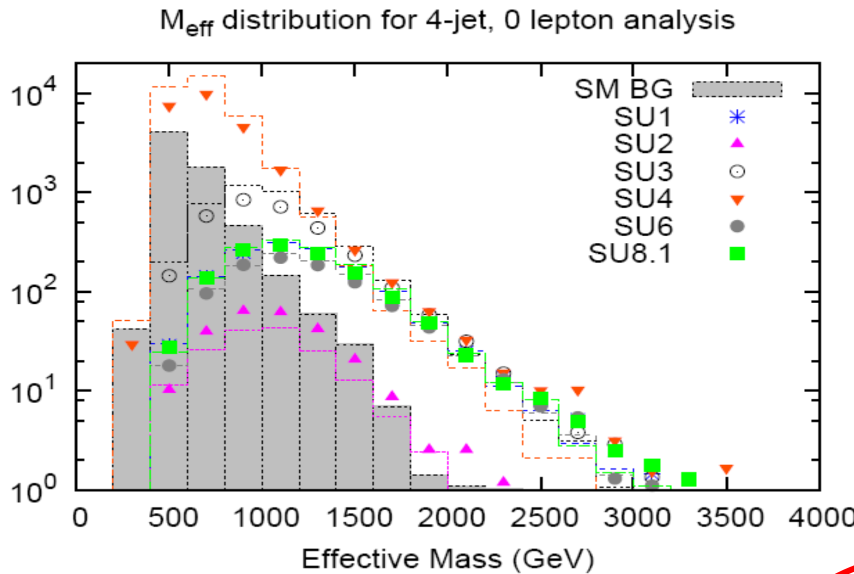
Summary & Conclusions

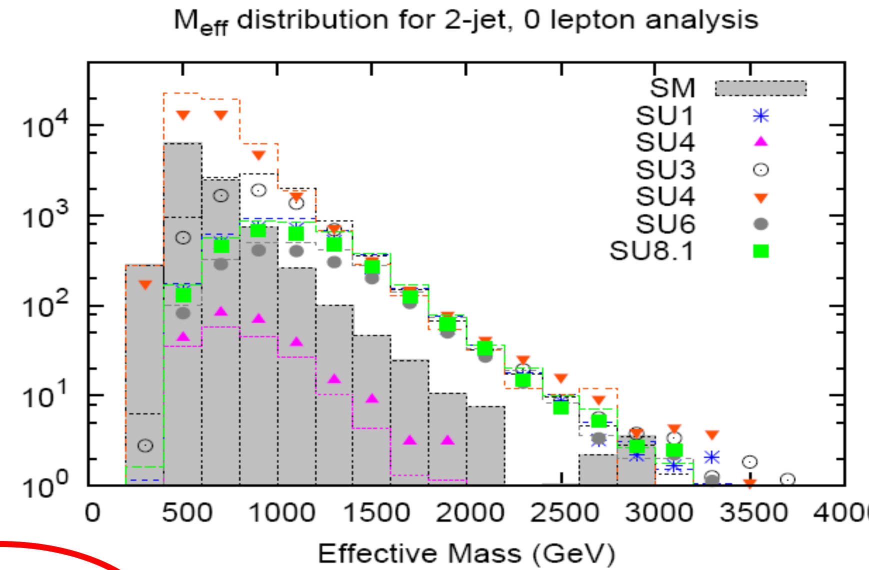
- LHC explorations of SUSY are underway & a fair bit of the mSUGRA parameter space is already excluded
- With ~35 pb^{-1}, a reasonable fraction of our pMSSM model space has also been 'covered' !
- Combined chargino + slepton studies at LC500 in mSUGRA are excluded; if only one, staus more likely than charginos
- At best, LC500 looks 'iffy' for pMSSM SUSY studies BUT we don't know either the final performance of the LHC or what the sparticle spectrum looks like
- We're anxious for more data…remember search caveats!

"Now this is not the end.
It is not even the beginning of the end.
But it is, perhaps, the end of the beginning".

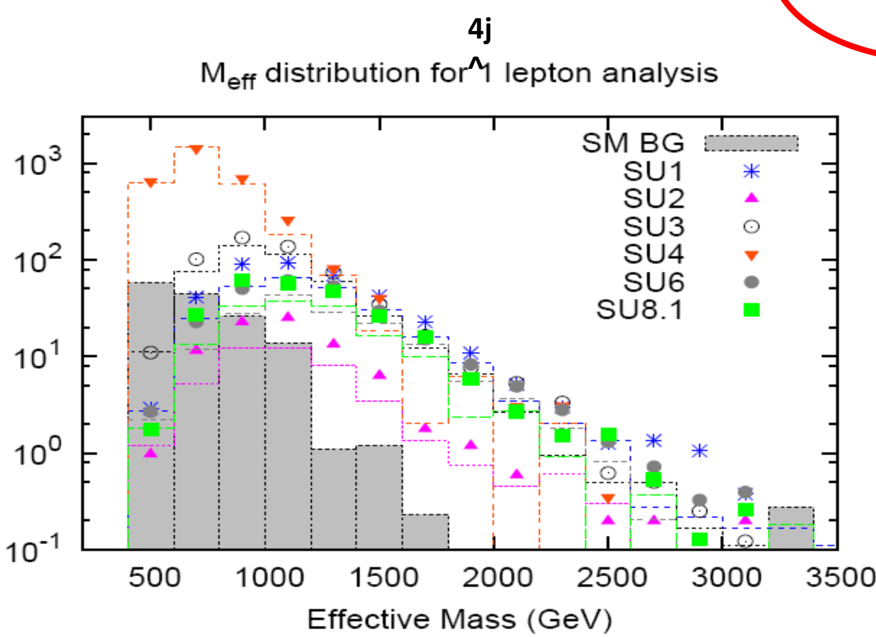
c/o A. Strumia
@ Moriond 2011

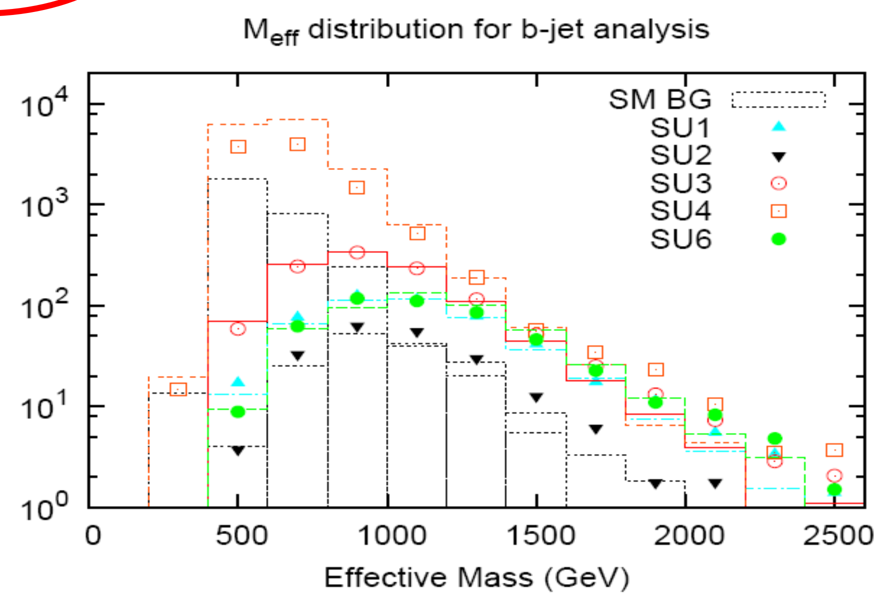
BACKUP SLIDES

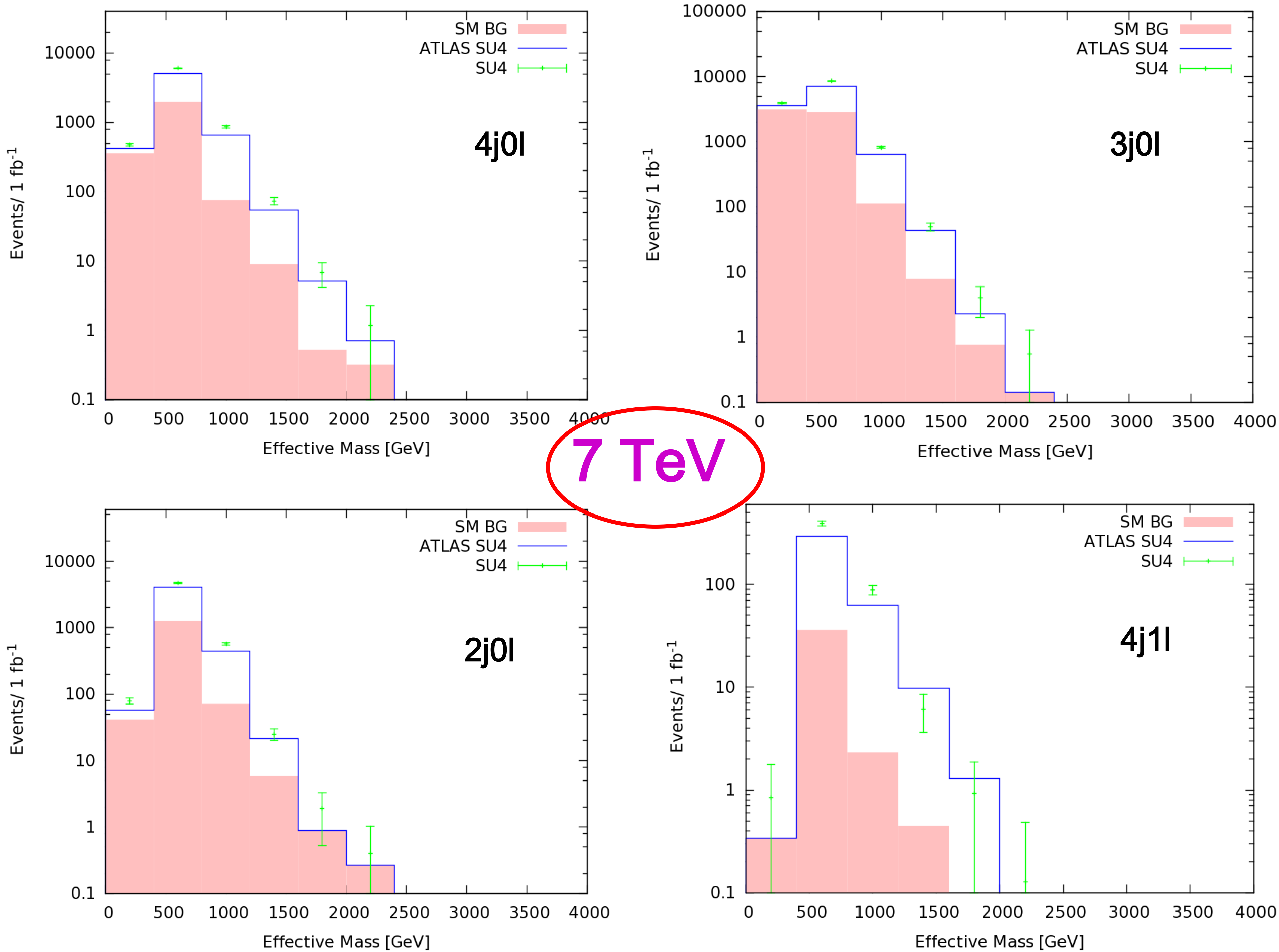

M_eff distribution for 4-jet, 0 lepton analysis
SM BG
SU1
SU2
SU3
SU4
SU6
SU8.1
Effective Mass (GeV)


M_eff distribution for 2-jet, 0 lepton analysis
SM
SU1
SU4
SU3
SU4
SU6
SU8.1
Effective Mass (GeV)

14 TeV


4j
M_eff distribution for ^1 lepton analysis
SM BG
SU1
SU2
SU3
SU4
SU6
SU8.1
Effective Mass (GeV)

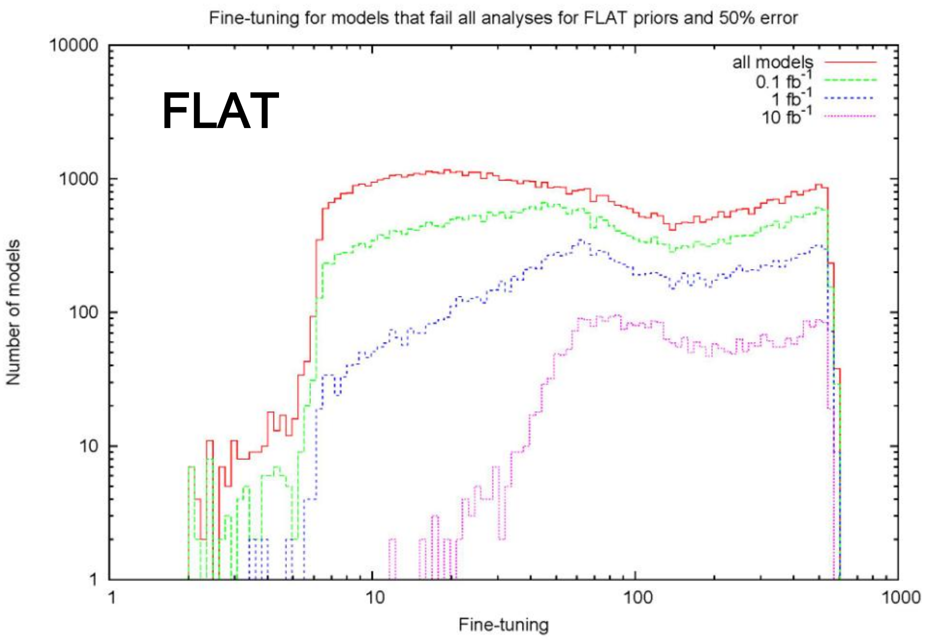

M_eff distribution for b-jet analysis
SM BG
SU1
SU2
SU3
SU4
SU6
Effective Mass (GeV)

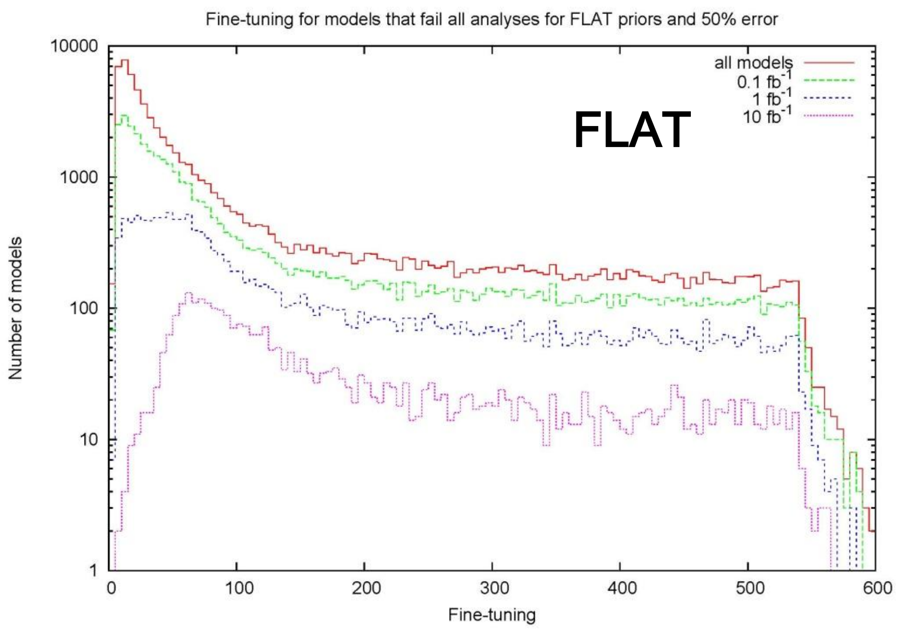


SM BG
ATLAS SU4
SU4
4j0l
3j0l
2j0l
4j1l
7 TeV
Events/ 1 fb-1
Effective Mass [GeV]
0.1
1
10
100
1000
10000
100000
0
500
1000
1500
2000
2500
3000
3500
4000

Fine-Tuning SUSY ?

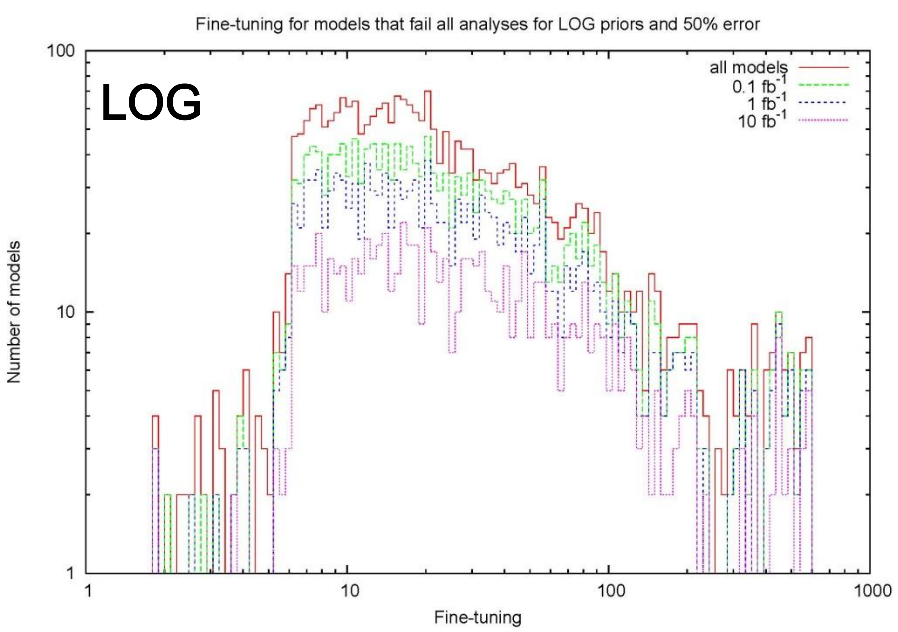
- It is often claimed that if the LHC (@7 TeV) does not find anything then SUSY must be VERY fine-tuned & so 'less likely'. Is this true for the pMSSM??

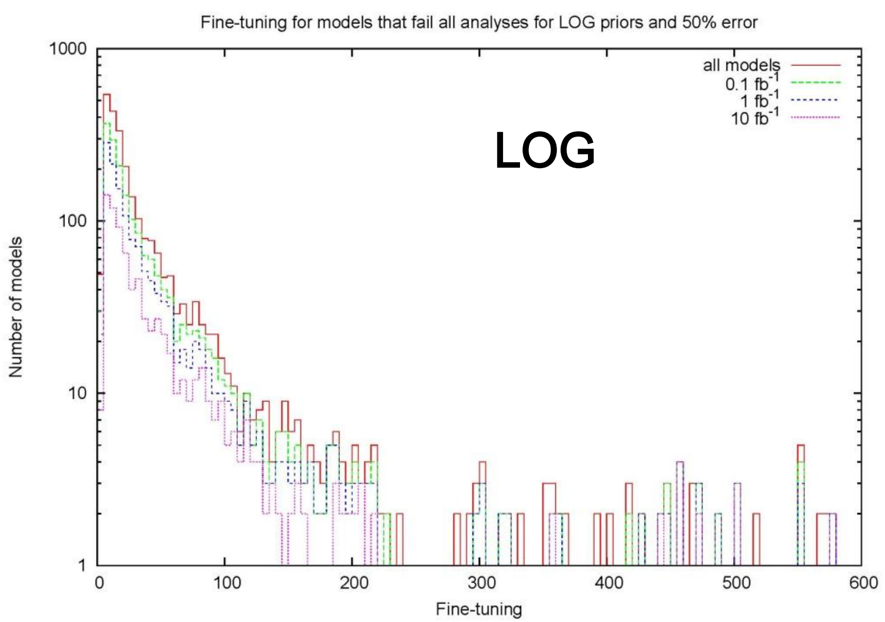




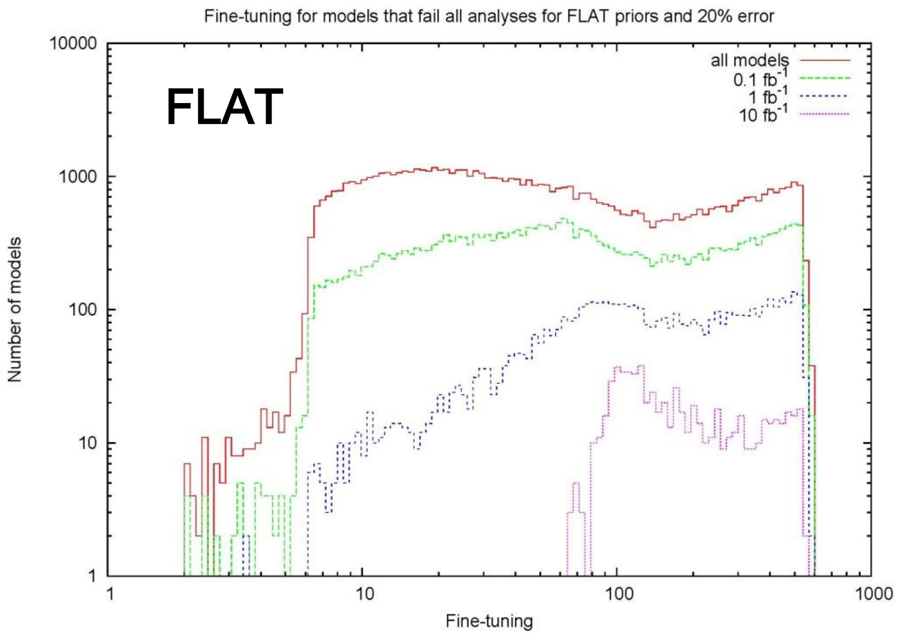
→ It is certainly true that models w/ low tuning do appear to 'suffer' more than those w/ larger values from null SUSY searches

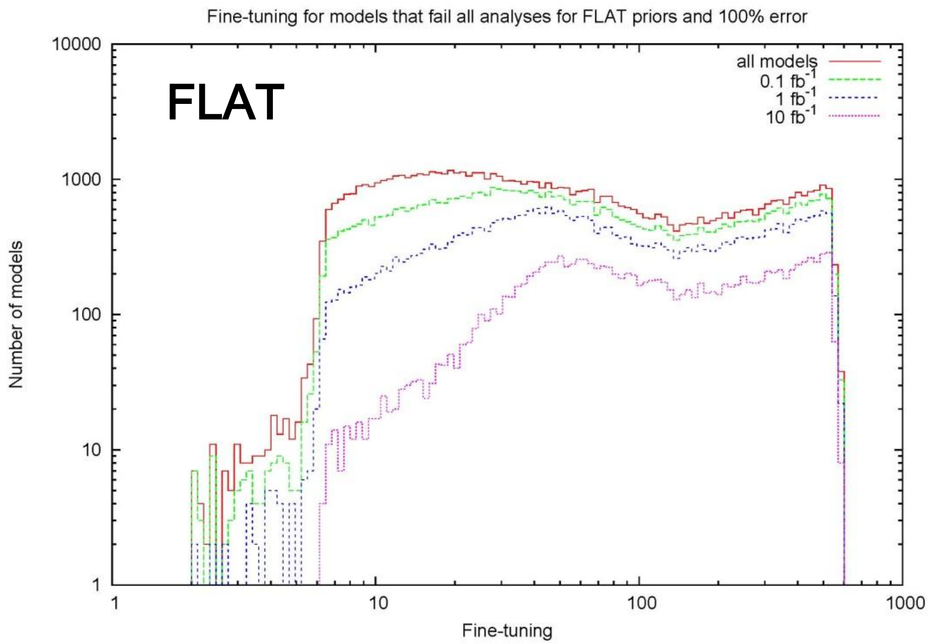
- The amount of fine tuning in the LOG prior set is somewhat less influenced by null ATLAS searches due to spectrum differences





• However, we see that models w/ low tuning <u>DO</u> survive..how many will depend on the exact lumi & systematic errors achieved by ATLAS searches. Note the variation w/ the background systematic errors..the fewer surviving models, the more fine-tuned they are

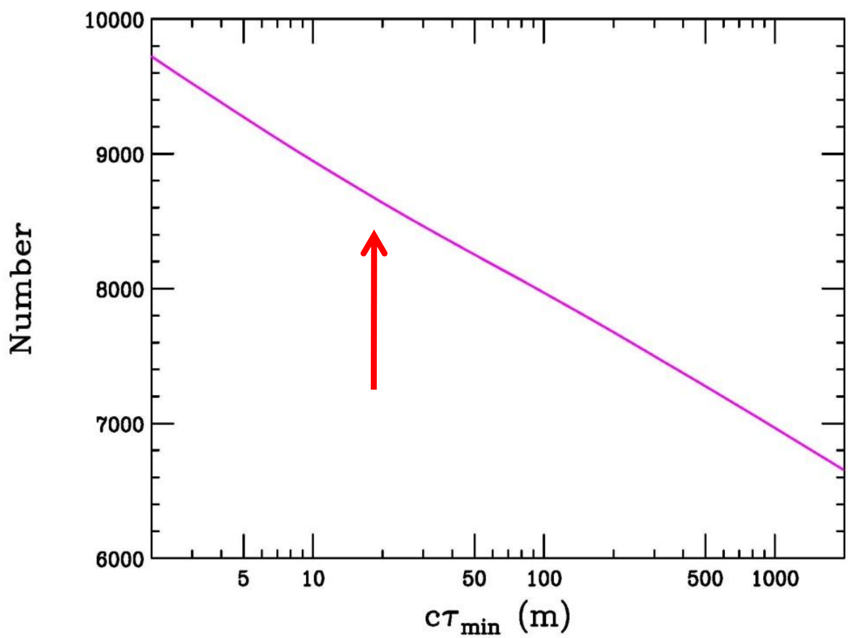




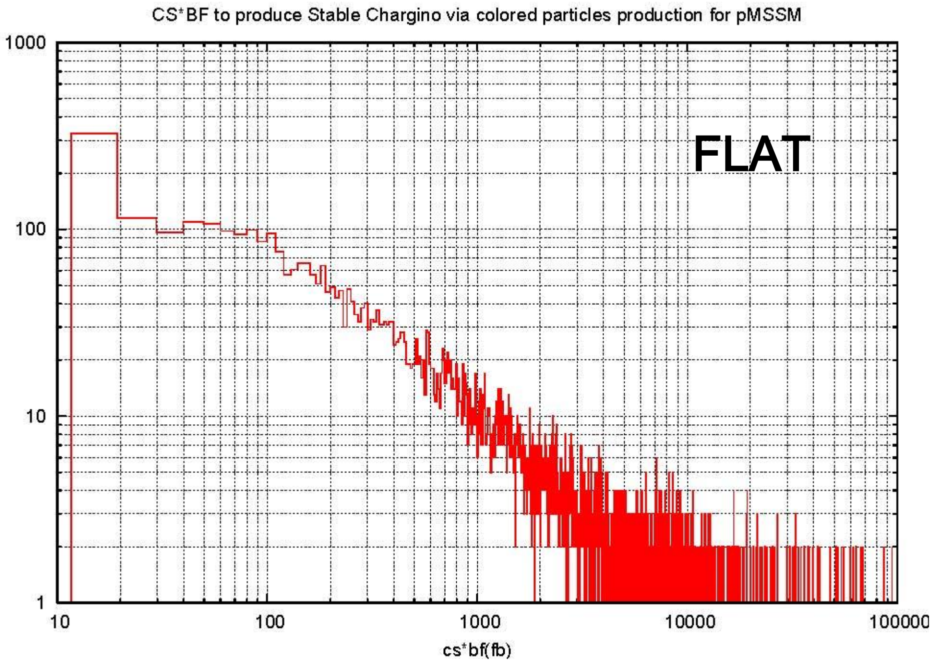
‘Stable’ Charged Particles in Cascades

→ Mostly long-lived charginos produced in long decay chains

~84% of these $\chi_1^{\pm}$ with cτ>20m have σB>10 fb @ 7 TeV



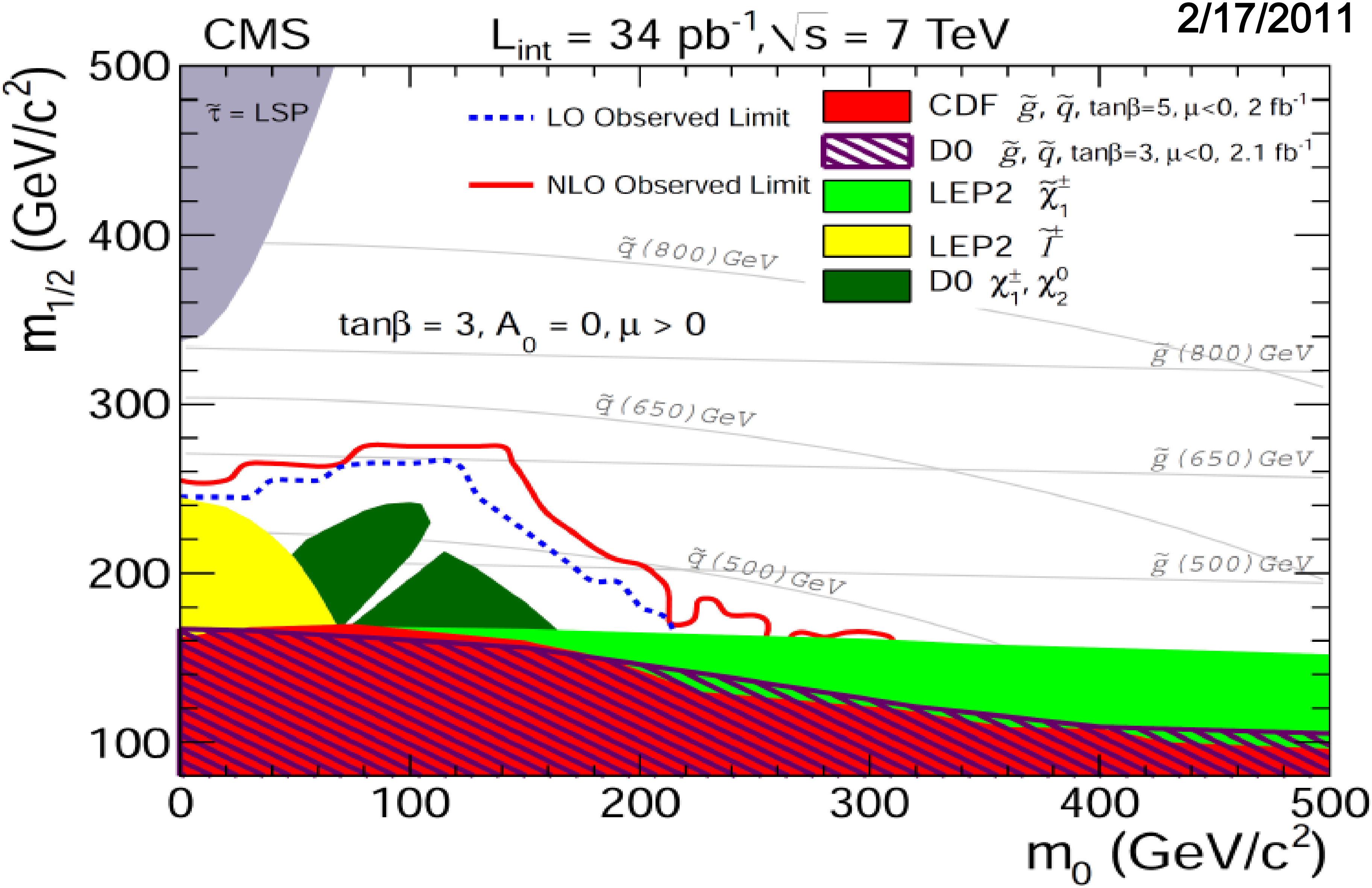
Unboosted Minimum Decay Length



Estimated Cross Section

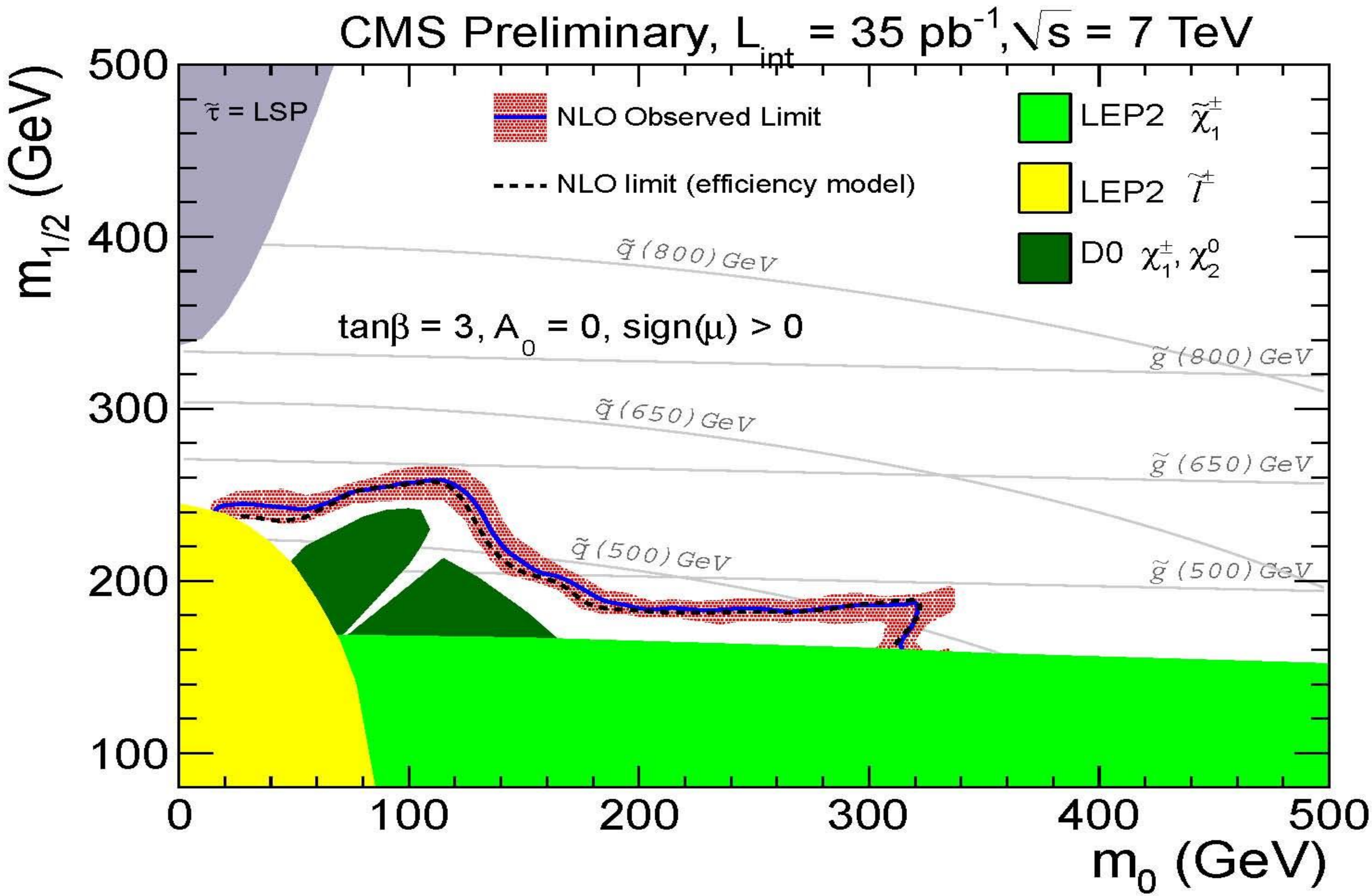
2jOSDL..more icing on the cake…

2/17/2011

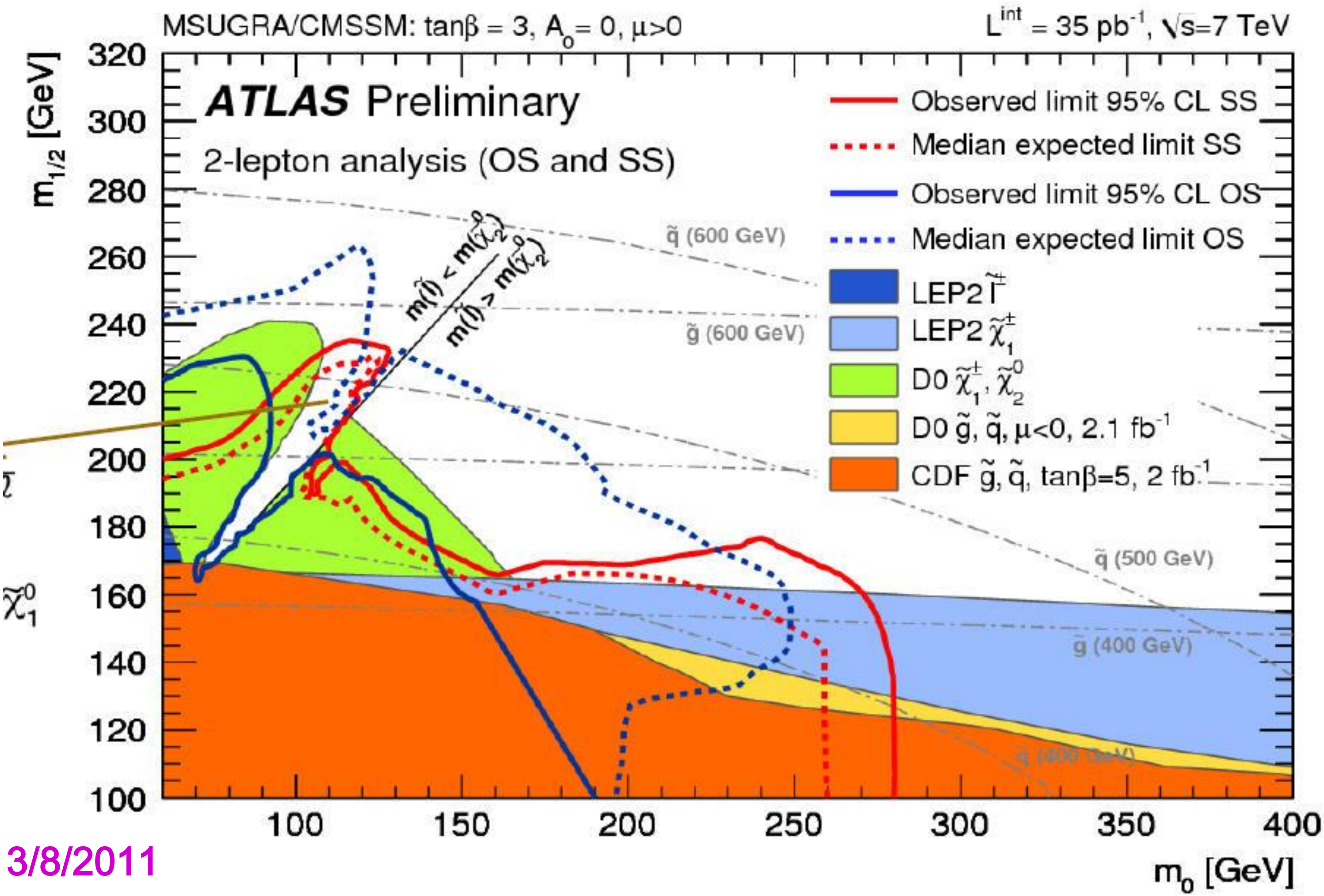


SSDL..even more icing on the cake…

3/6/2011

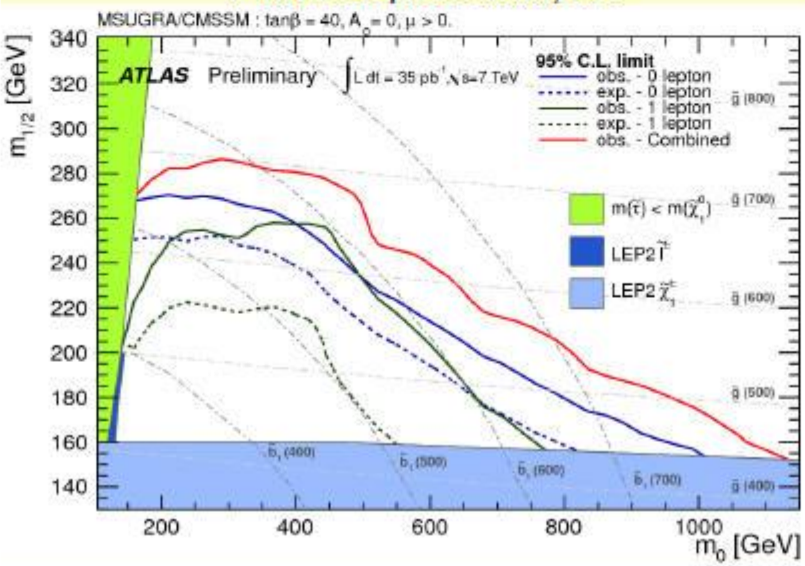


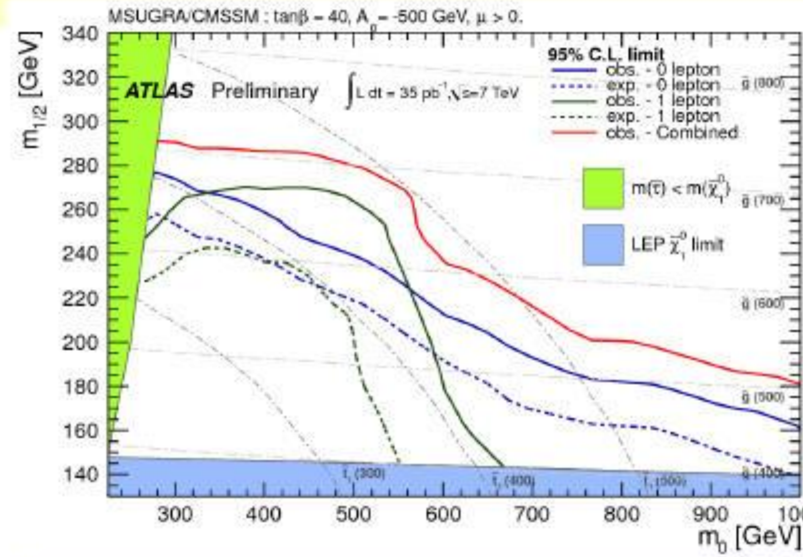
..& the results keep right on coming !



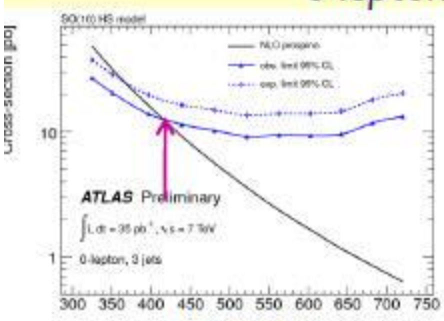
Specific SUSY models

0- and 1-lepton analyses

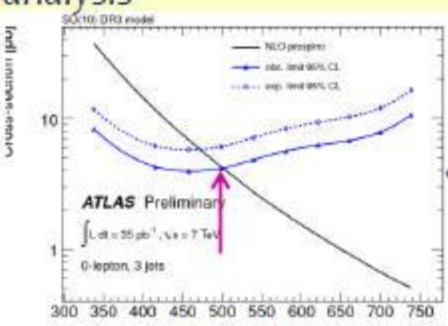




0-lepton analysis

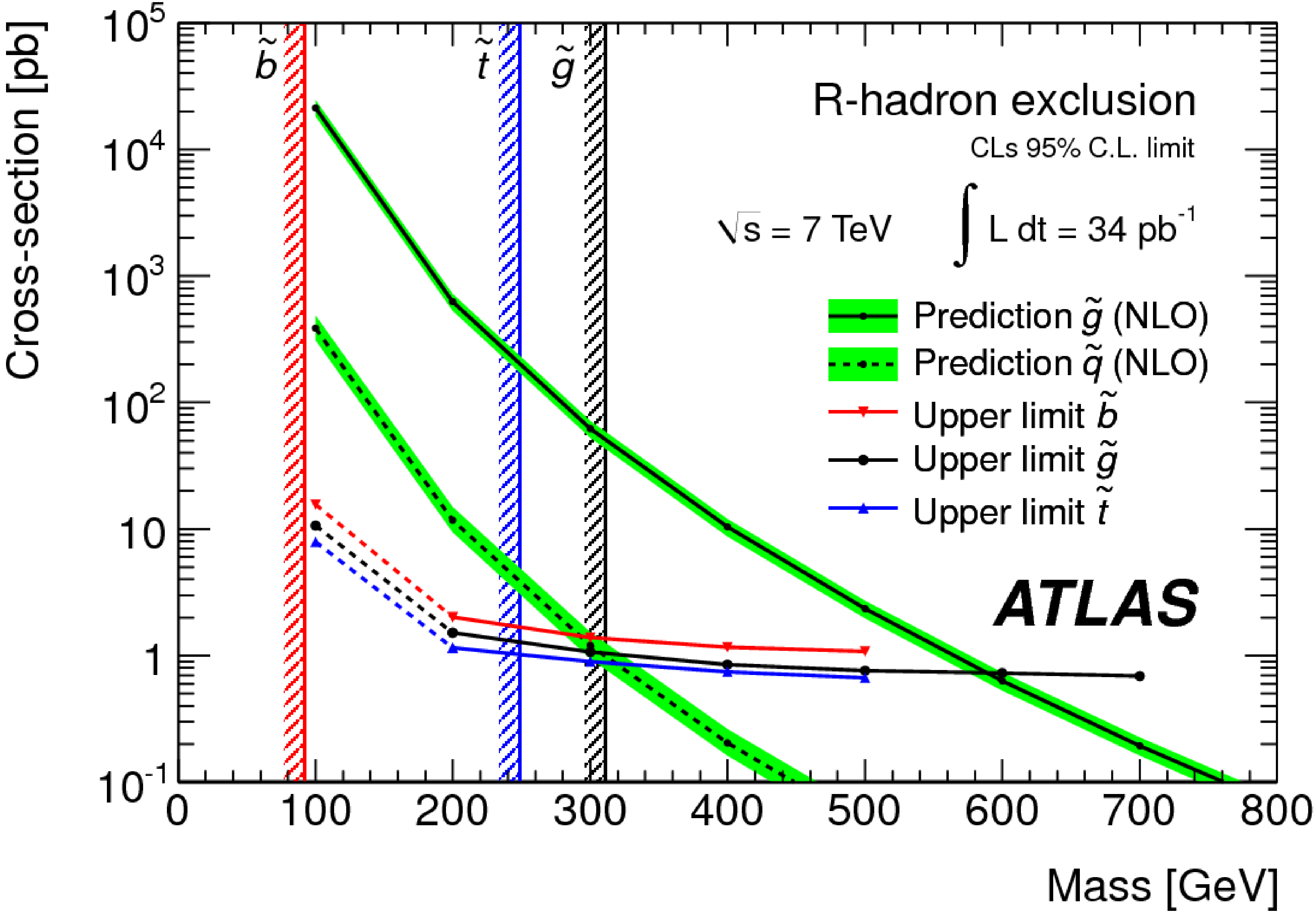


HS-model

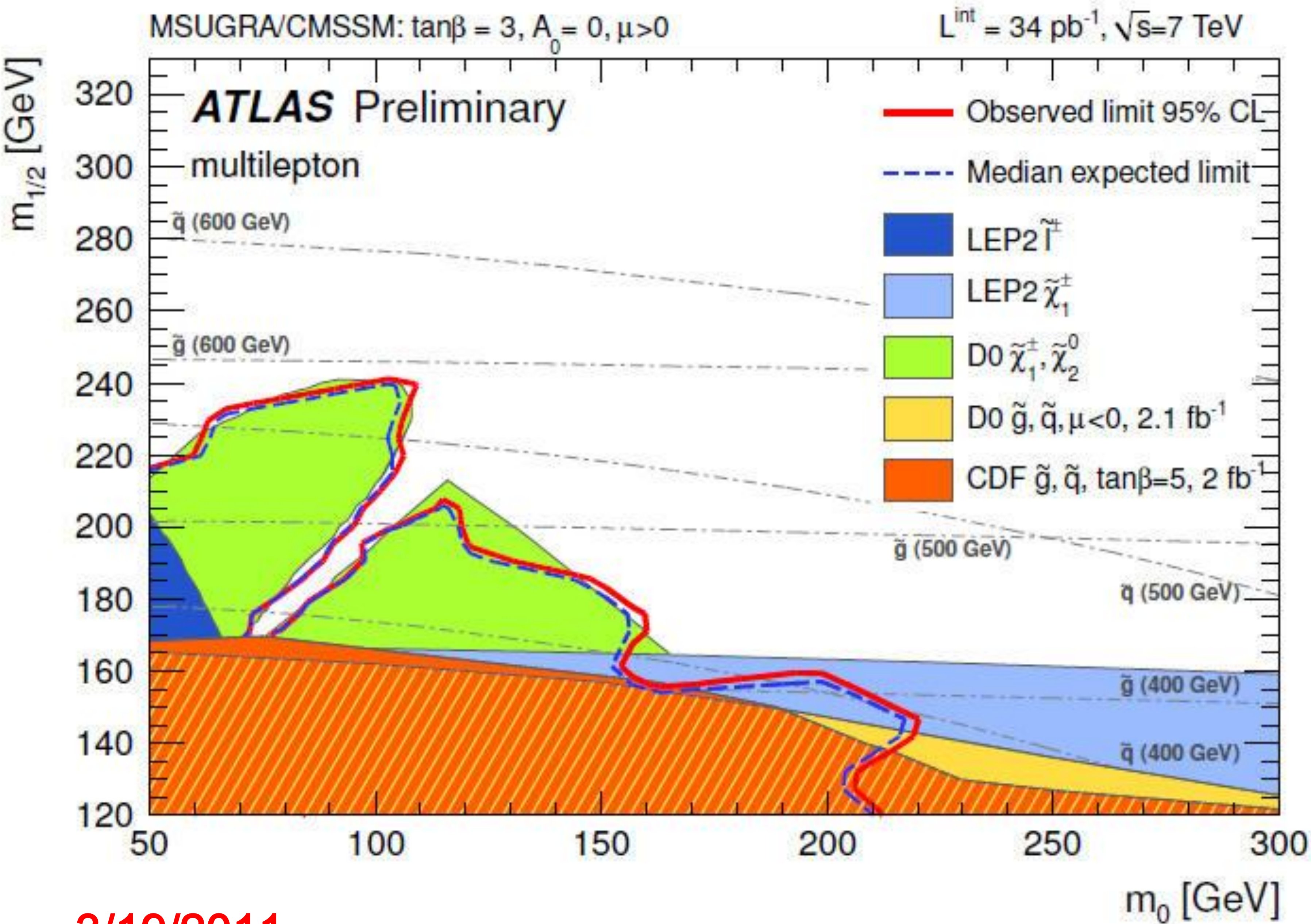


DR3-model

- **mSUGRA:** large tan β or low A_o values:
  - For each $(m_o, m_{1/2})$ sbottom/stop masses lower than in low tan β scenarios
  - **Exclude gluino masses up to 500 GeV for m_o < 1 TeV**
- **SO(10) models:** gluino pair production one of the dominant processes:
  - Gluino → $b\bar{b}\chi^o_1$ (DR3) or $b\bar{b}\chi^o_2$ (HS)
  - **Exclude masses up to 500(420) GeV**



Cross-section [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
$\tilde{b}$
$\tilde{t}$
$\tilde{g}$
R-hadron exclusion
CLs 95% C.L. limit
$\sqrt{s}$ = 7 TeV
$\int L\,dt = 34\ pb^{-1}$
Prediction $\tilde{g}$ (NLO)
Prediction $\tilde{q}$ (NLO)
Upper limit $\tilde{b}$
Upper limit $\tilde{g}$
Upper limit $\tilde{t}$
ATLAS
0
100
200
300
400
500
600
700
800
Mass [GeV]

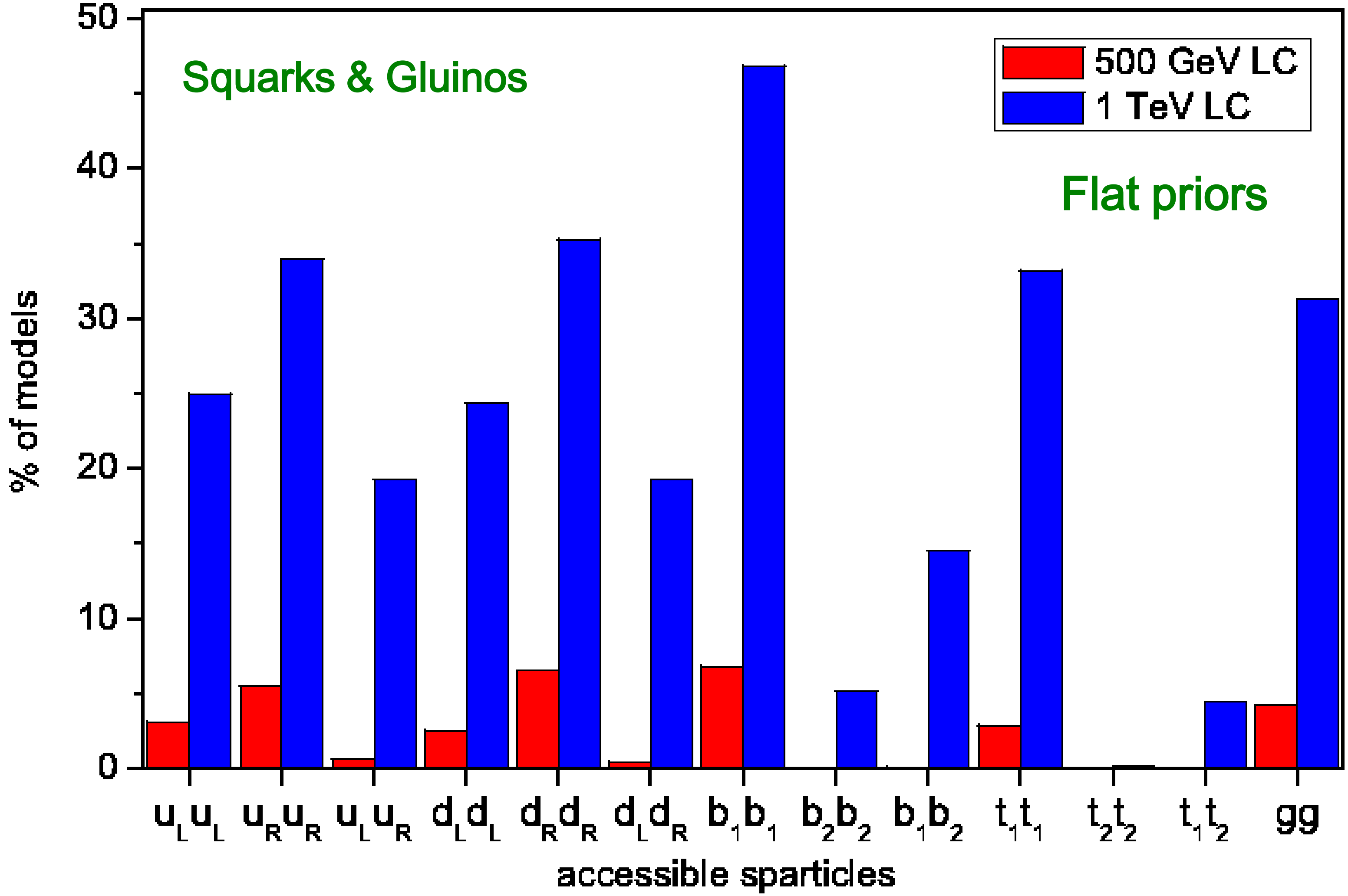


MSUGRA/CMSSM: tanβ = 3, A_0 = 0, μ>0
L^{int} = 34 pb^{-1}, $\sqrt{s}$=7 TeV
ATLAS Preliminary
multilepton
Observed limit 95% CL
Median expected limit
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
D0 $\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$
D0 $\tilde{g}, \tilde{q}$, μ<0, 2.1 fb^{-1}
CDF $\tilde{g}, \tilde{q}$, tanβ=5, 2 fb^{-1}
$\tilde{q}$ (600 GeV)
$\tilde{g}$ (600 GeV)
$\tilde{g}$ (500 GeV)
$\tilde{q}$ (500 GeV)
$\tilde{g}$ (400 GeV)
$\tilde{q}$ (400 GeV)
$m_{1/2}$ [GeV]
m_0 [GeV]

3/19/2011

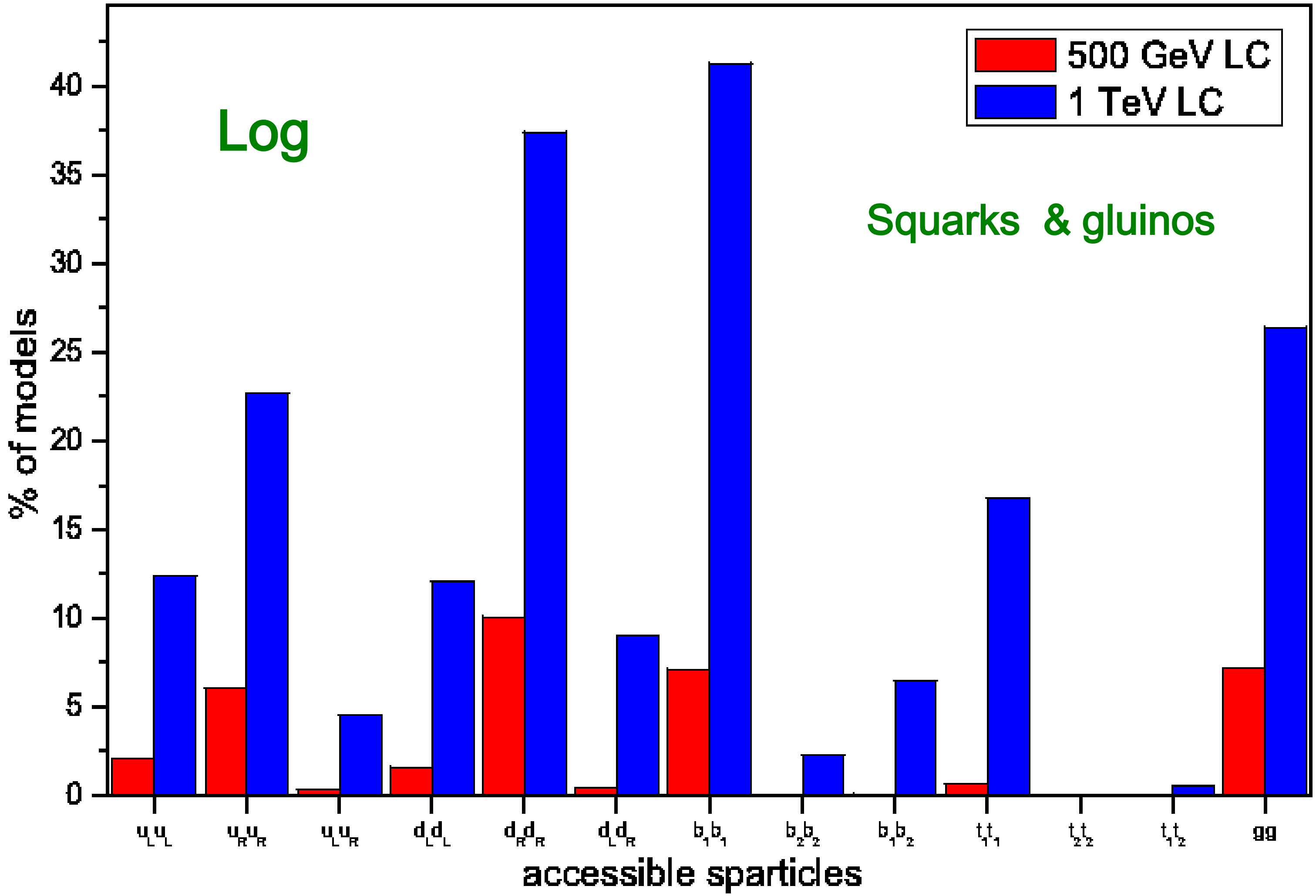
Model Set Kinematic Accessibility at the ILC : II

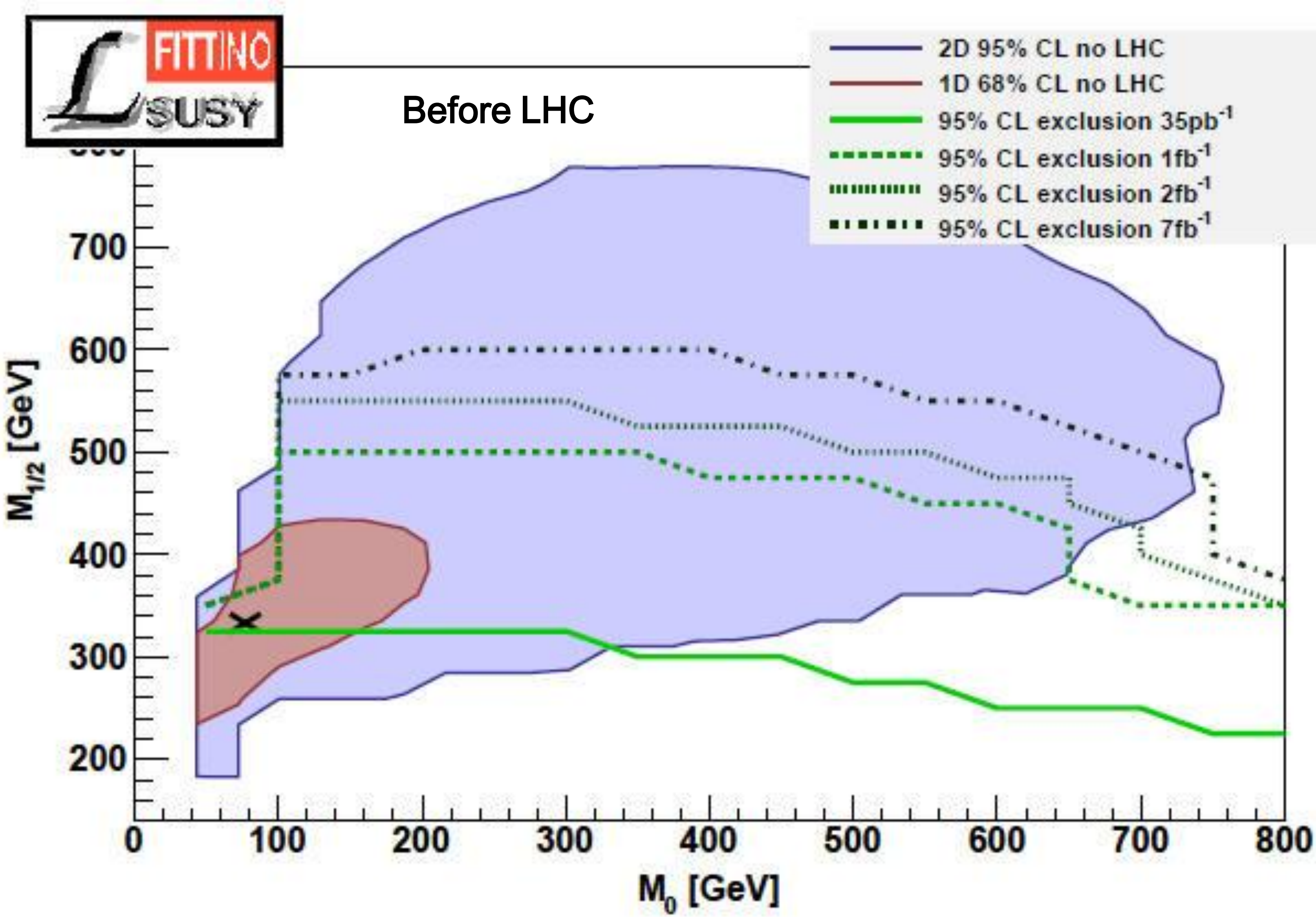
(Before LHC)



Model Set Kinematic Accessibility at the ILC : IV

(Before LHC)




FITTINO
SUSY
Before LHC
2D 95% CL no LHC
1D 68% CL no LHC
95% CL exclusion 35pb-1
95% CL exclusion 1fb-1
95% CL exclusion 2fb-1
95% CL exclusion 7fb-1
700
600
500
400
300
200
M1/2 [GeV]
0
100
200
300
400
500
600
700
800
M0 [GeV]