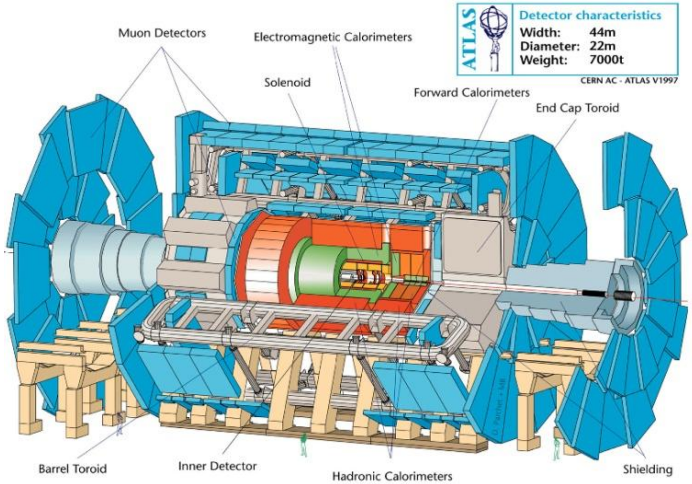
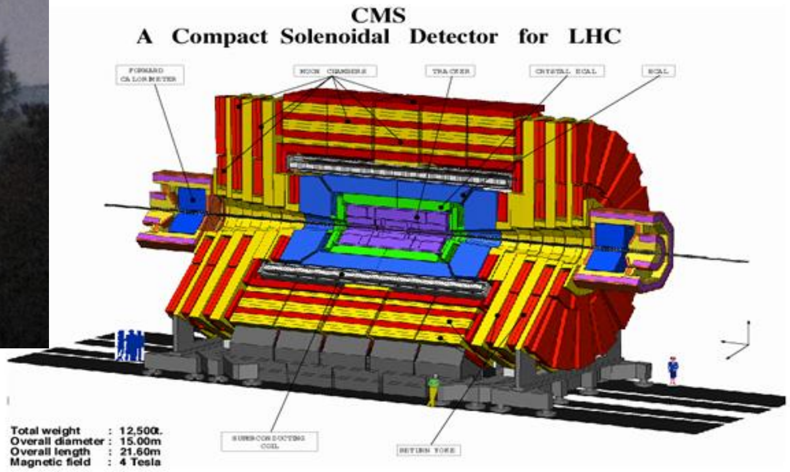
pMSSM SUSY Searches @ 7 TeV



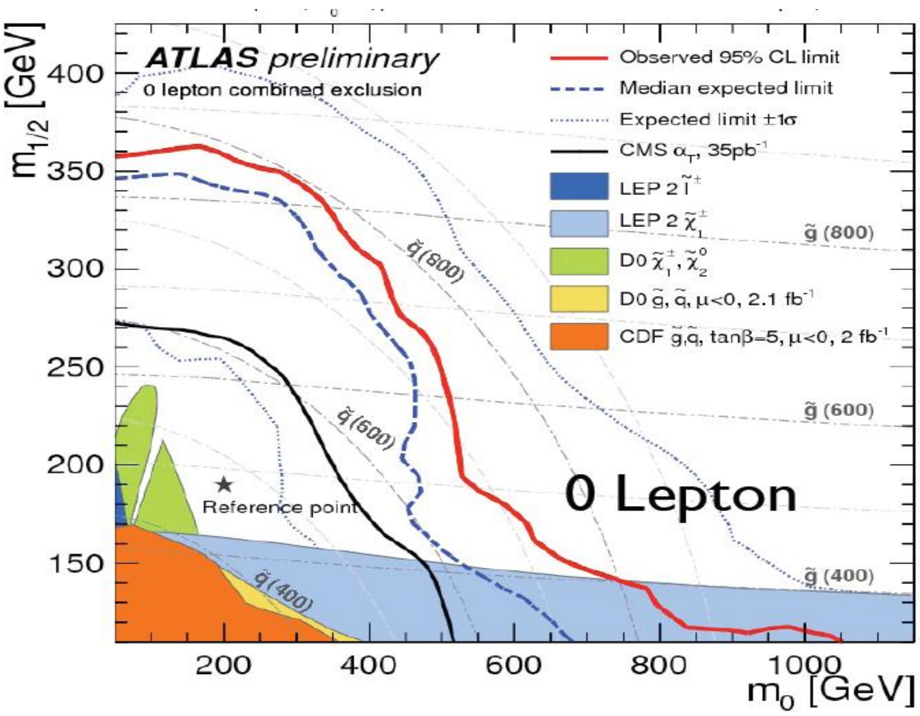


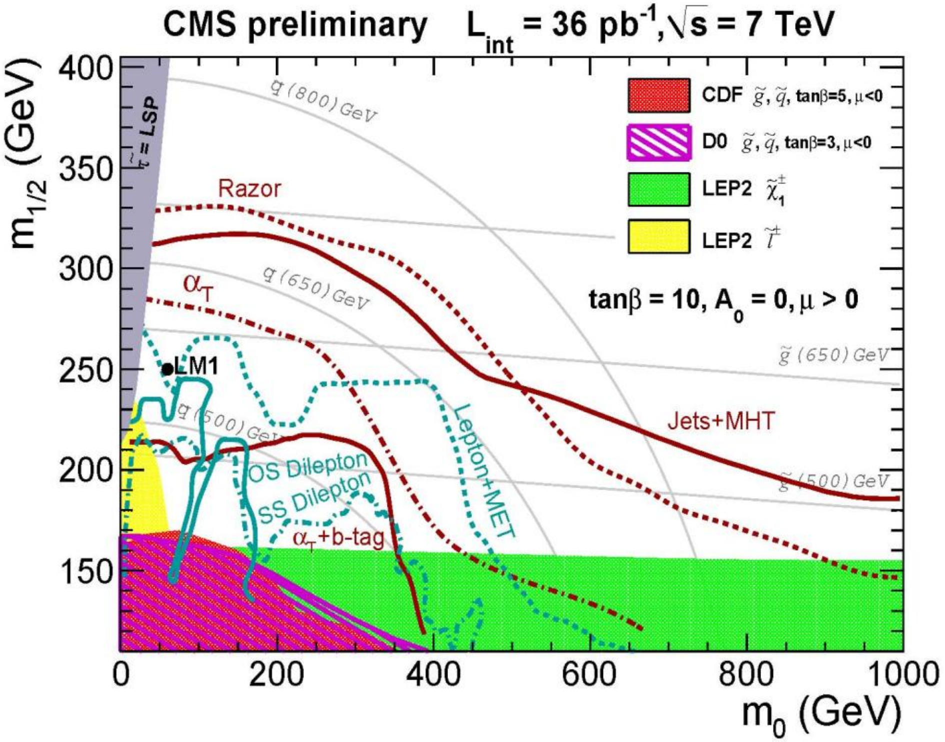
J.A. Conley, J. S. Gainer, J. L. Hewett, M.-P. Le & TGR

arXiv:1009.2539,1103.1697

SLAC NATIONAL ACCELERATOR LABORATORY

T.G. Rizzo 04/13/11

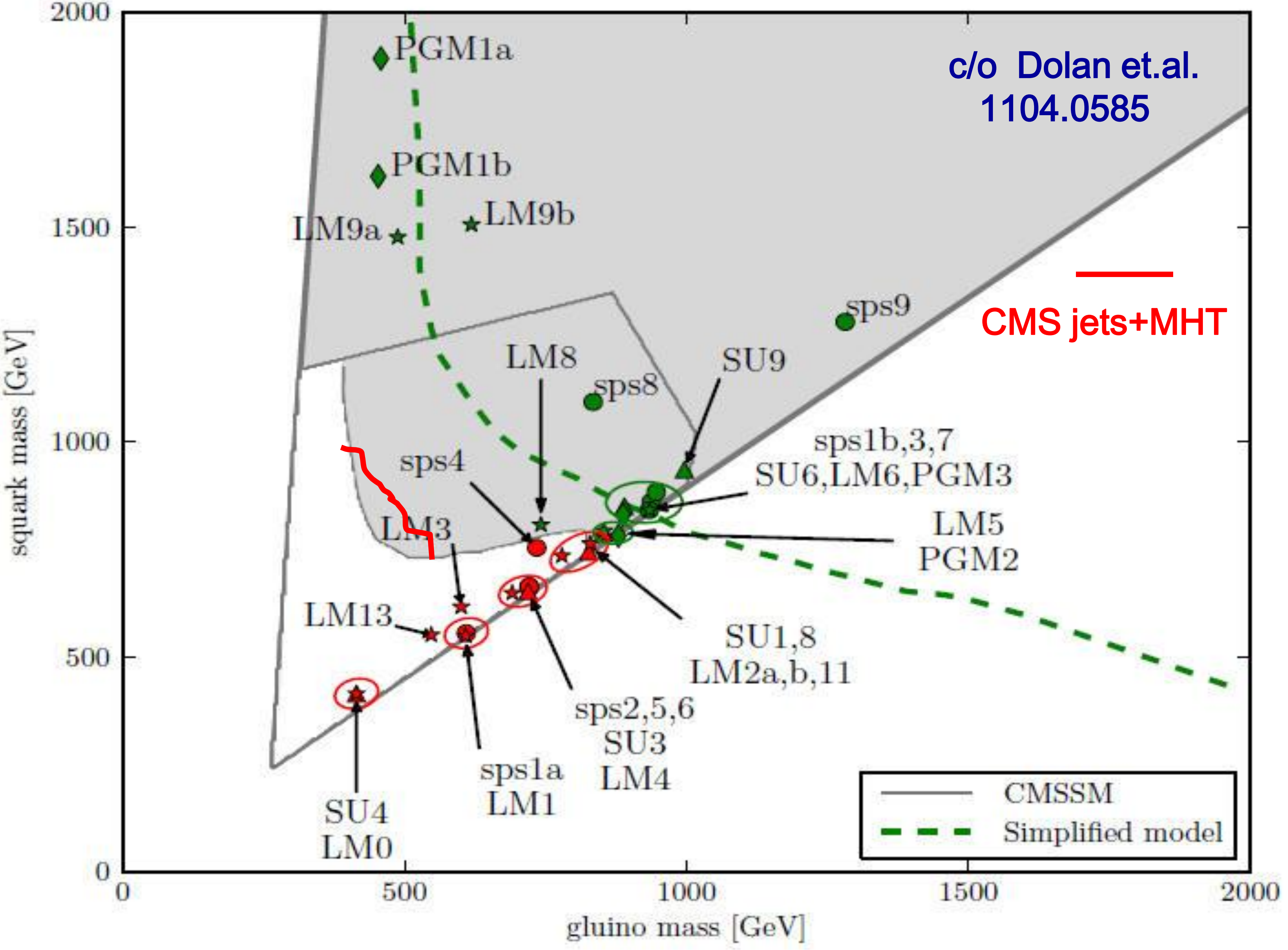




ATLAS & CMS have already made a dent in SUSY space

- However, as these searches proceed we need to be sure that the analyses don't miss anything by assuming specific SUSY breaking mechanisms such as mSUGRA, GMSB, AMSB, etc.

- How do we do this? There are several possible approaches…



c/o Dolan et.al.
1104.0585

Issues:

- The general MSSM is too difficult to study due to the large number of soft SUSY breaking parameters (~ 100).
- Many analyses limited to specific SUSY breaking scenarios having 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

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

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

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

$100\ \text{GeV} \leq M_3 \leq 1\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 1\ \text{TeV}$

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

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

Log Priors

emphasizes lower masses but also extends to higher masses

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

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

$100\ \text{GeV} \leq M_3 \leq 3\ \text{TeV}$

$\sim 0.5\ M_Z \leq M_A \leq 3\ \text{TeV}$

$1 \leq \tan\beta \leq 60$ (flat prior)

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

- Flat Priors : 10^7 points scanned , 68422 survive
- Log Priors : $2\text{x}10^6$ points scanned , 2908 survive

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

Some Constraints

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

- 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* searches & some are quite complicated with many caveats…. These needed to be 'revisited' for the more general case considered here → simulations limit model set size (~1 core-century for set generation)

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)

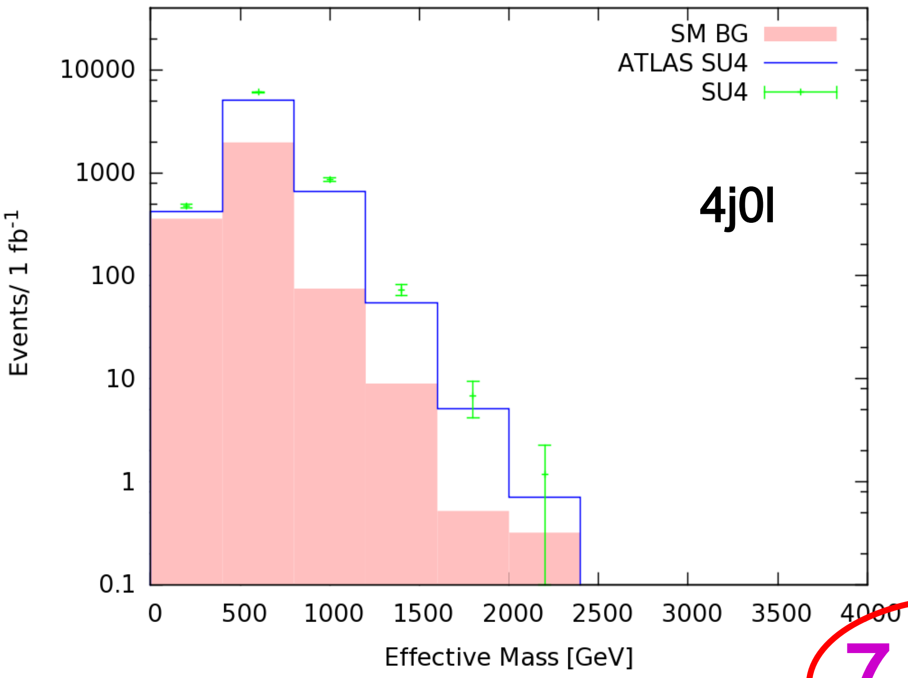
- We used the ATLAS SM backgrounds with their associated systematic errors, search analyses/cuts & criterion for SUSY discovery for comparisons. (→ ATL-PHYS-PUB-2010-010 for 7 TeV, CSC for 14 TeV)

- 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 (~6M K-factors)
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.


SM BG
ATLAS SU4
SU4
4j0l
Events/ 1 fb^{-1}
10000
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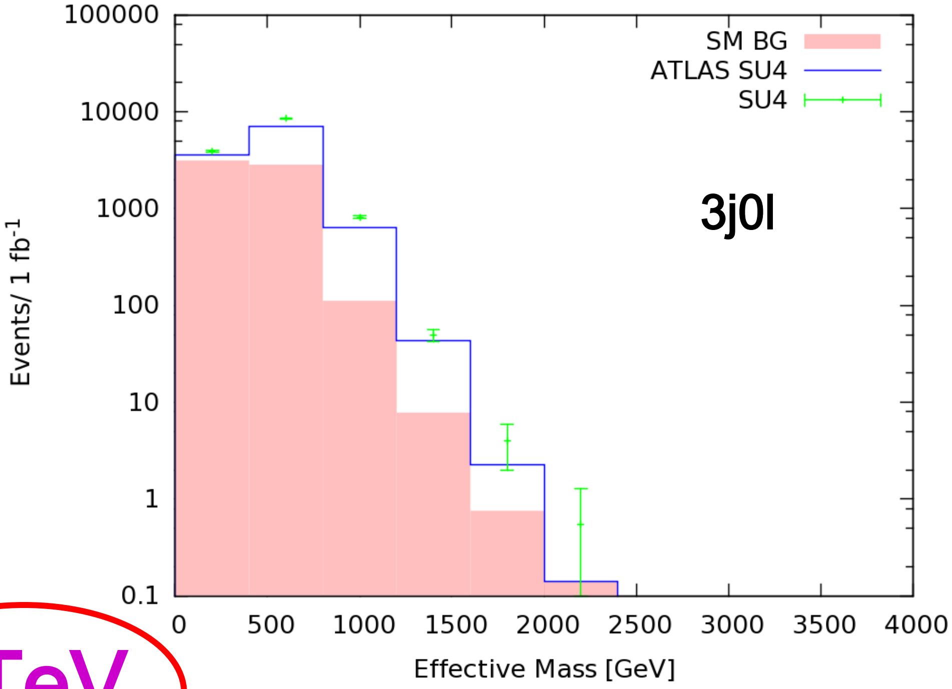
Effective Mass [GeV]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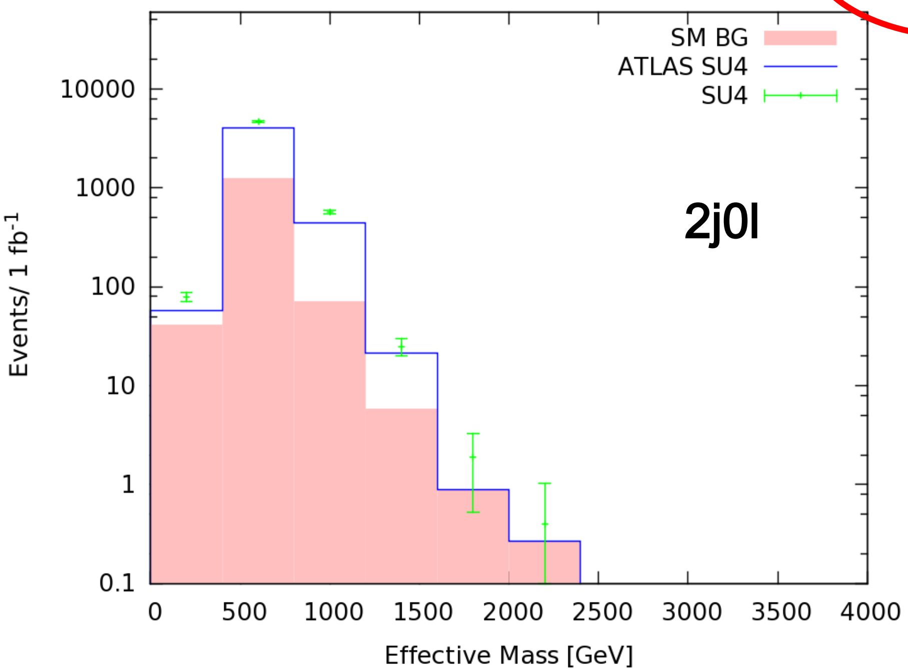
Effective Mass [GeV]

7 TeV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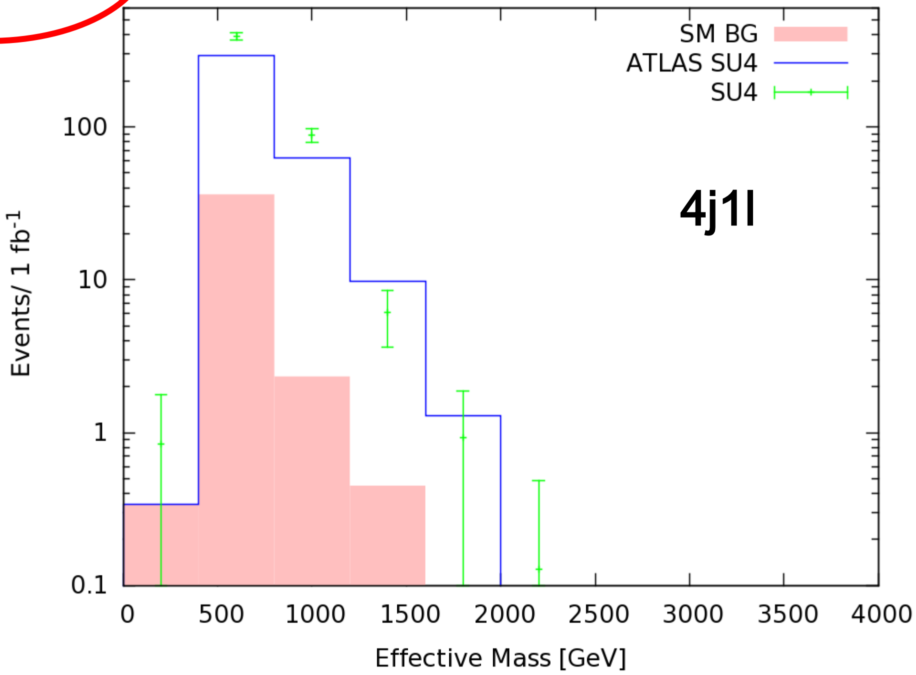
Effective Mass [GeV]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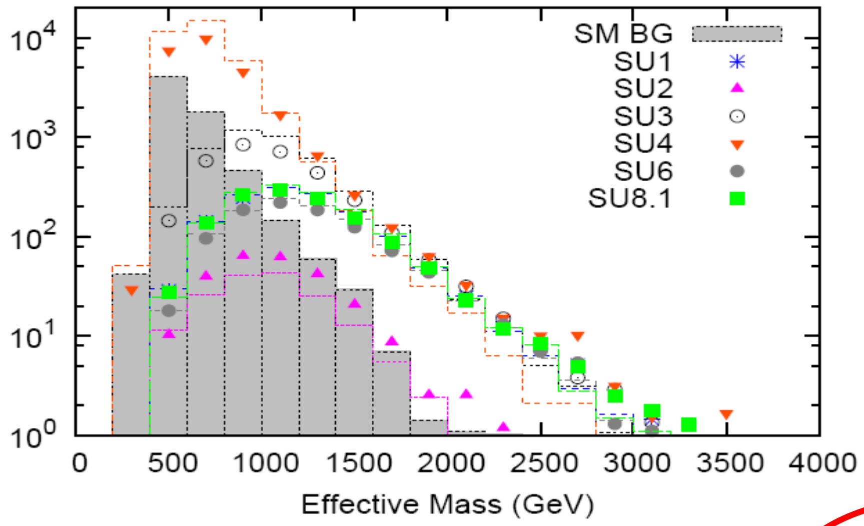
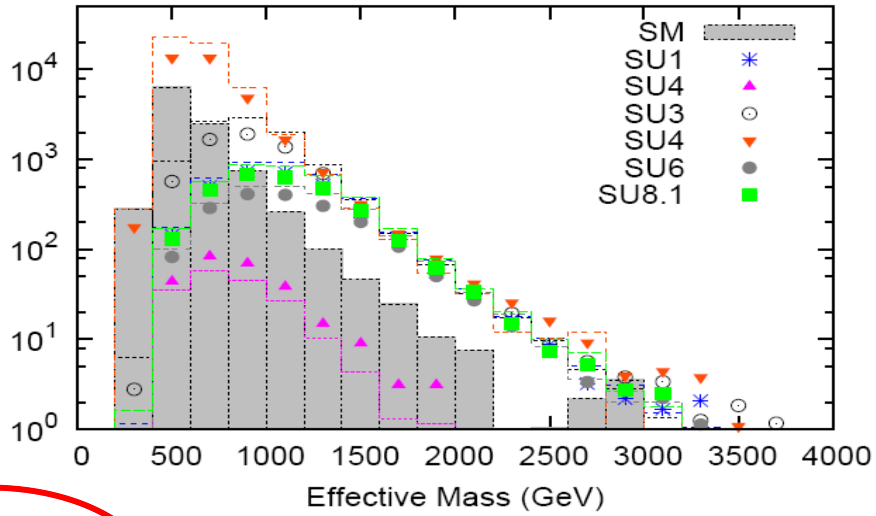
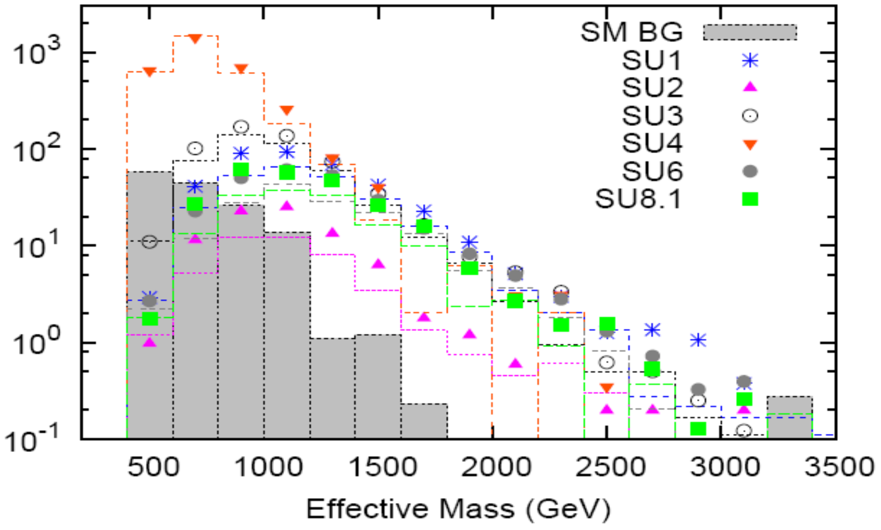


M_{eff} distribution for 4-jet, 0 lepton analysis



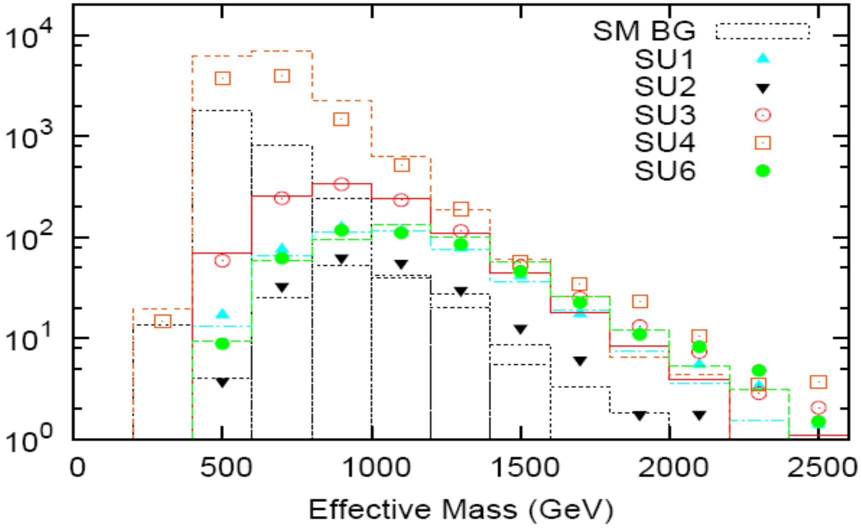
M_{eff} distribution for 2-jet, 0 lepton analysis

14 TeV



4j

M_{eff} distribution for^1 lepton analysis



M_{eff} distribution for b-jet analysis

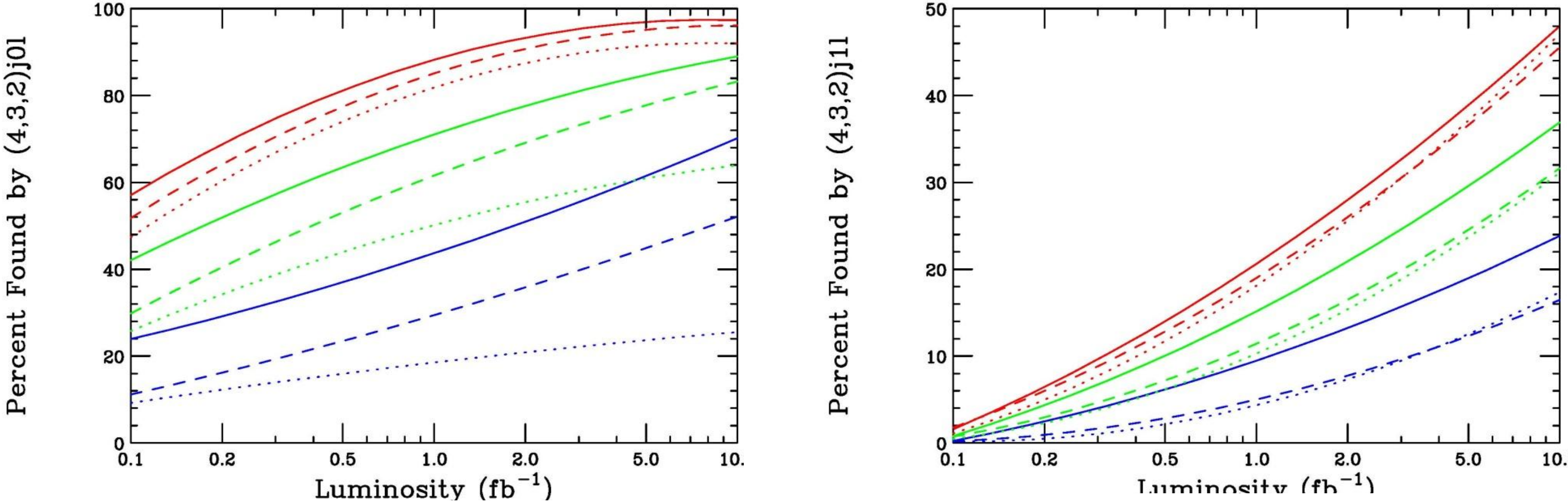
→ We do fairly well reproducing ATLAS 7 & 14 TeV benchmarks but with some differences due to, e.g., (modified) public code usages & PGS vs GEANT4. Having more benchmarks from ATLAS to compare with at 7 TeV would be very useful.

- The first question: 'How well do the ATLAS analyses cover the pMSSM model sets?' More precisely, 'what fraction of these models can be discovered (or not!) by any of the ATLAS analyses & which ones do best?'

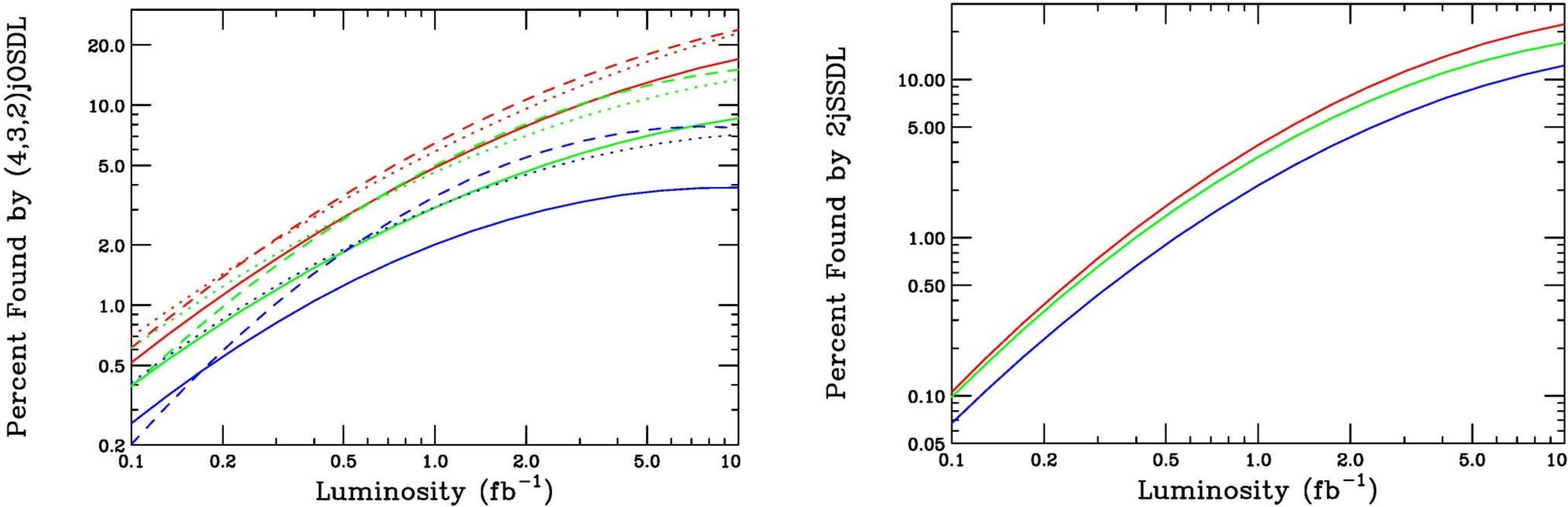
- Then we need to understand WHY some models are missed by these analyses even when high luminosities are available

FLAT

Solid=4j, dash=3j, dot=2j final states

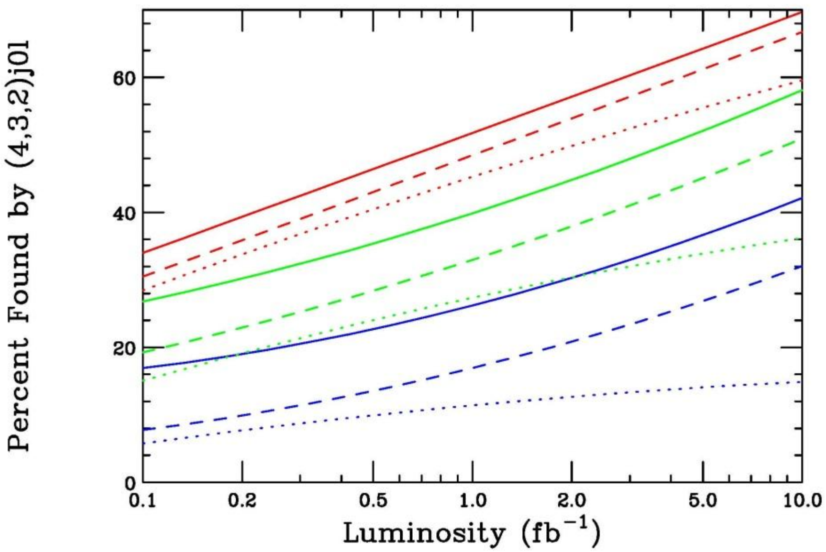


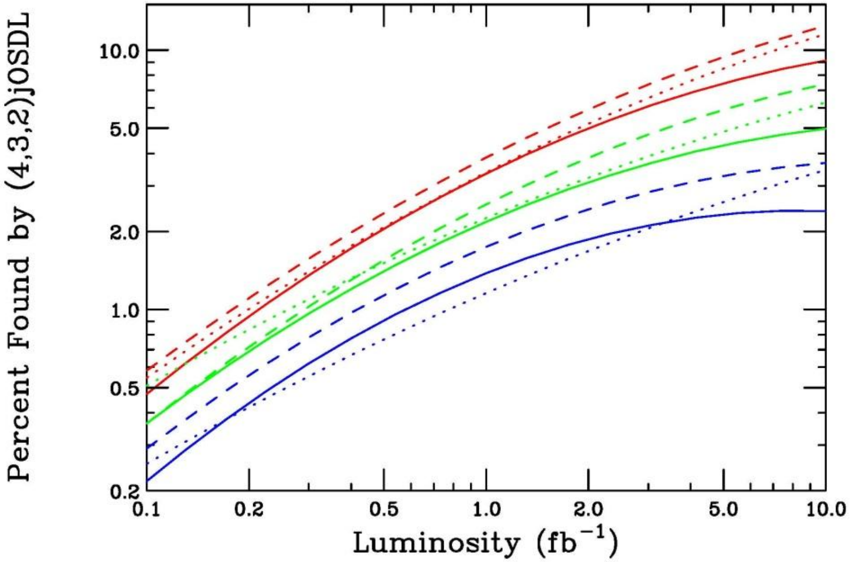
Red=20%, green=50%, blue=100% background systematic errors



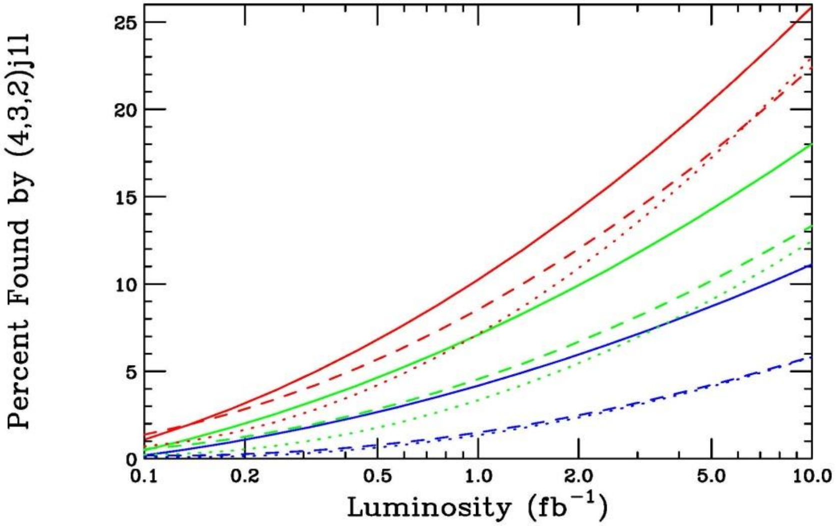
LOG

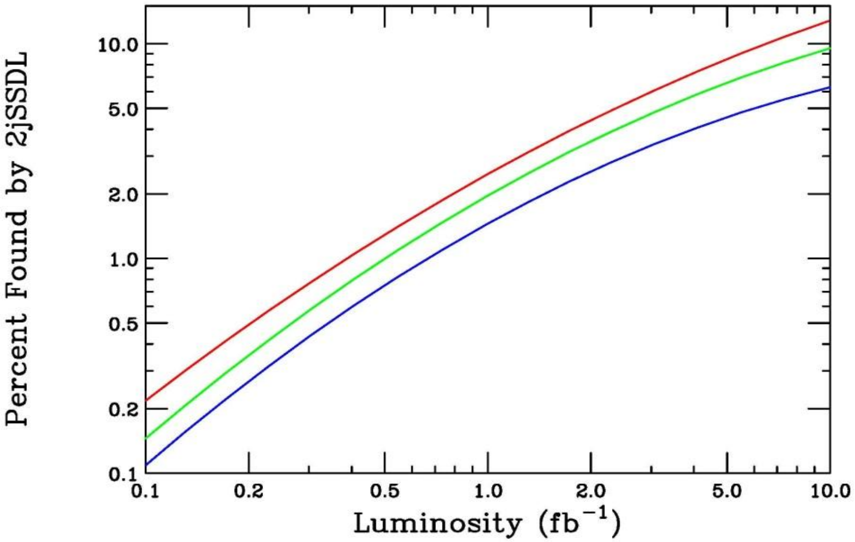
Solid=4j, dash=3j, dot=2j final states



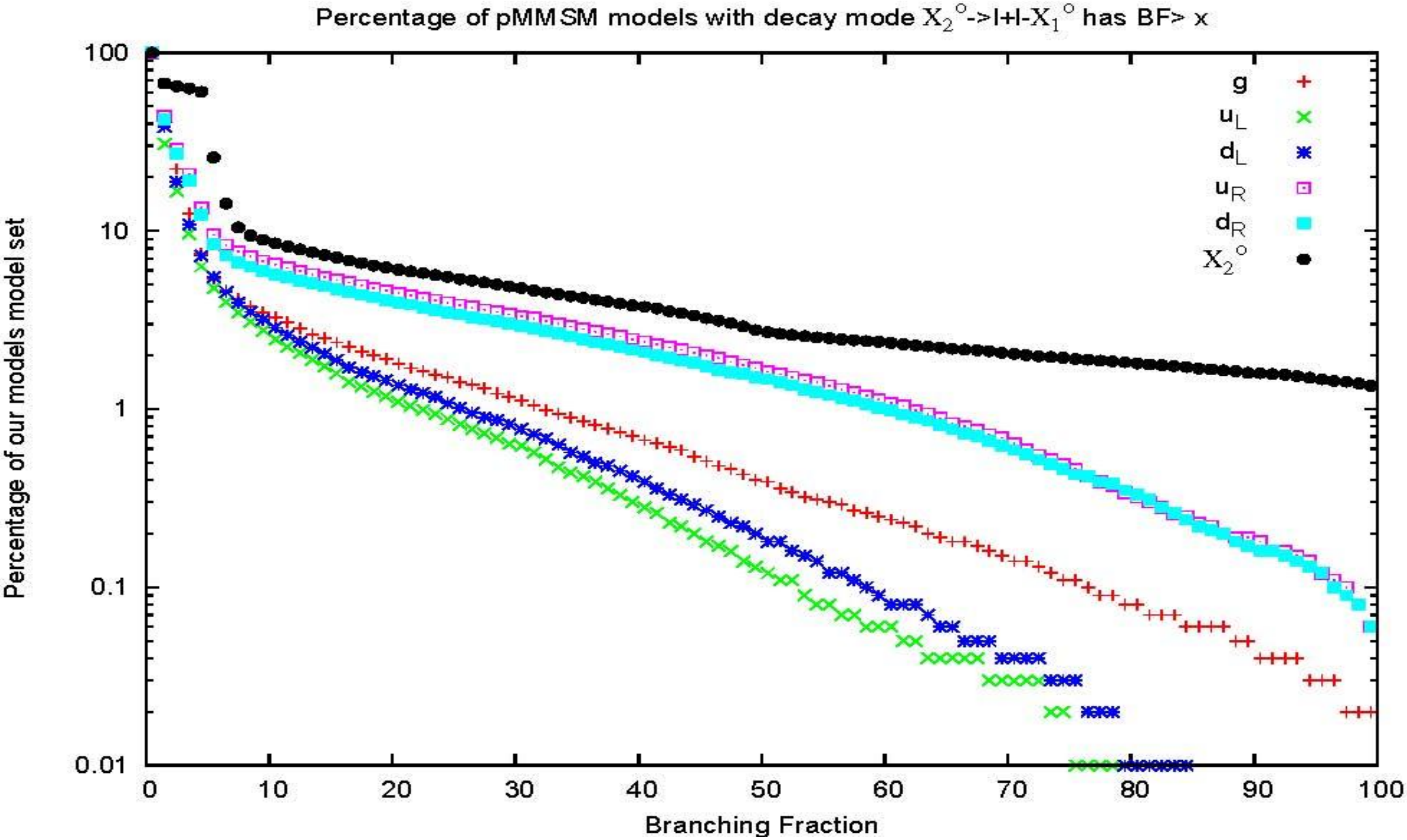


Red=20%, green=50%, blue=100% background systematic errors

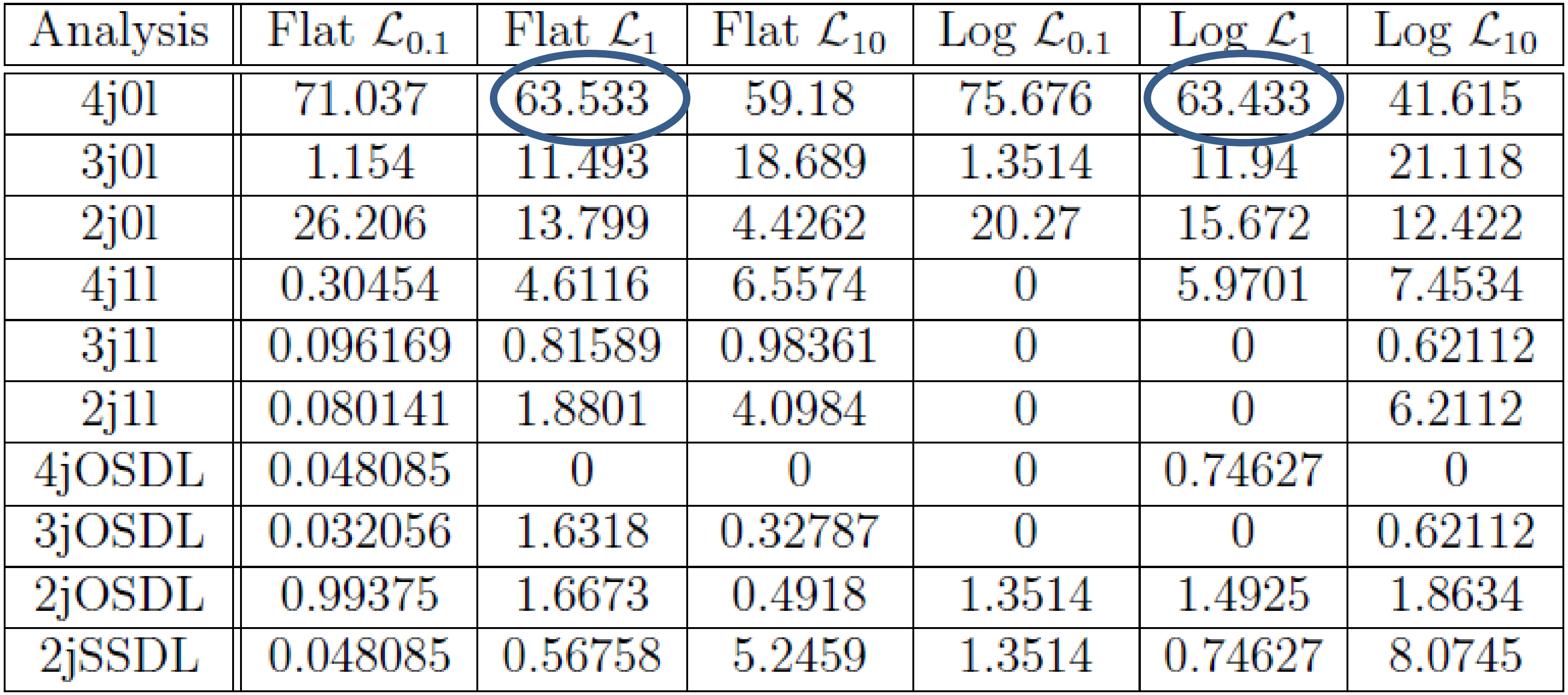




- Note that as the number of required leptons increases the corresponding model ‘coverage’ decreases. Why? The BF to lepton pairs is relatively small in our model sets...e.g. :



Search 'effectiveness': If a model is found by only 1 analysis which one is it??

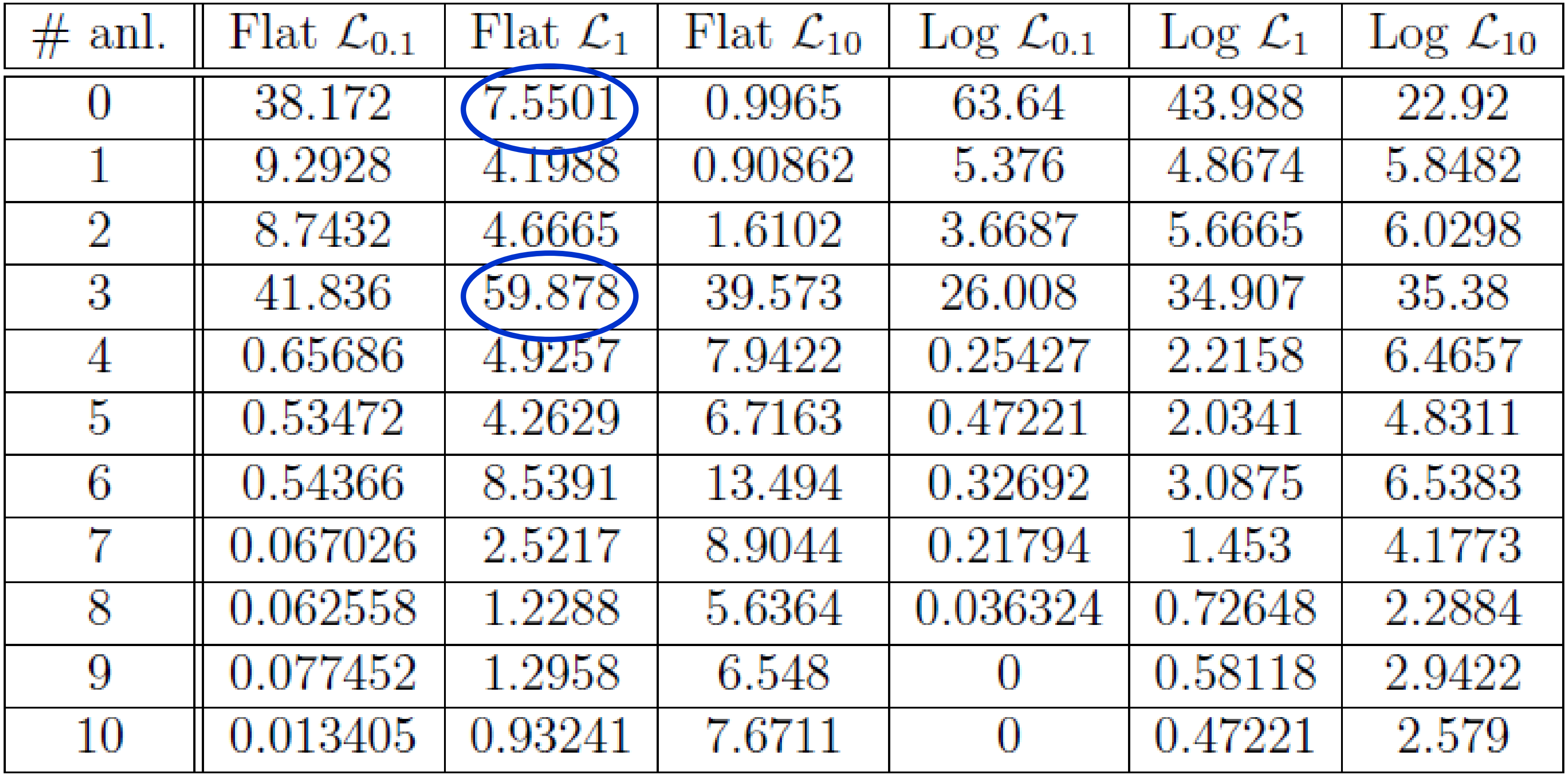


Analysis	Flat $\mathcal{L}_{0.1}$	Flat $\mathcal{L}_{1}$	Flat $\mathcal{L}_{10}$	Log $\mathcal{L}_{0.1}$	Log $\mathcal{L}_{1}$	Log $\mathcal{L}_{10}$
4j0l	71.037	63.533	59.18	75.676	63.433	41.615
3j0l	1.154	11.493	18.689	1.3514	11.94	21.118
2j0l	26.206	13.799	4.4262	20.27	15.672	12.422
4j1l	0.30454	4.6116	6.5574	0	5.9701	7.4534
3j1l	0.096169	0.81589	0.98361	0	0	0.62112
2j1l	0.080141	1.8801	4.0984	0	0	6.2112
4jOSDL	0.048085	0	0	0	0.74627	0
3jOSDL	0.032056	1.6318	0.32787	0	0	0.62112
2jOSDL	0.99375	1.6673	0.4918	1.3514	1.4925	1.8634
2jSSDL	0.048085	0.56758	5.2459	1.3514	0.74627	8.0745

$\delta B = 20\%$

→ → 4j0l is the most powerful analysis…leptons weaker

What fraction of models are found by **n** analyses @7 TeV assuming, e.g., δB=20% ?

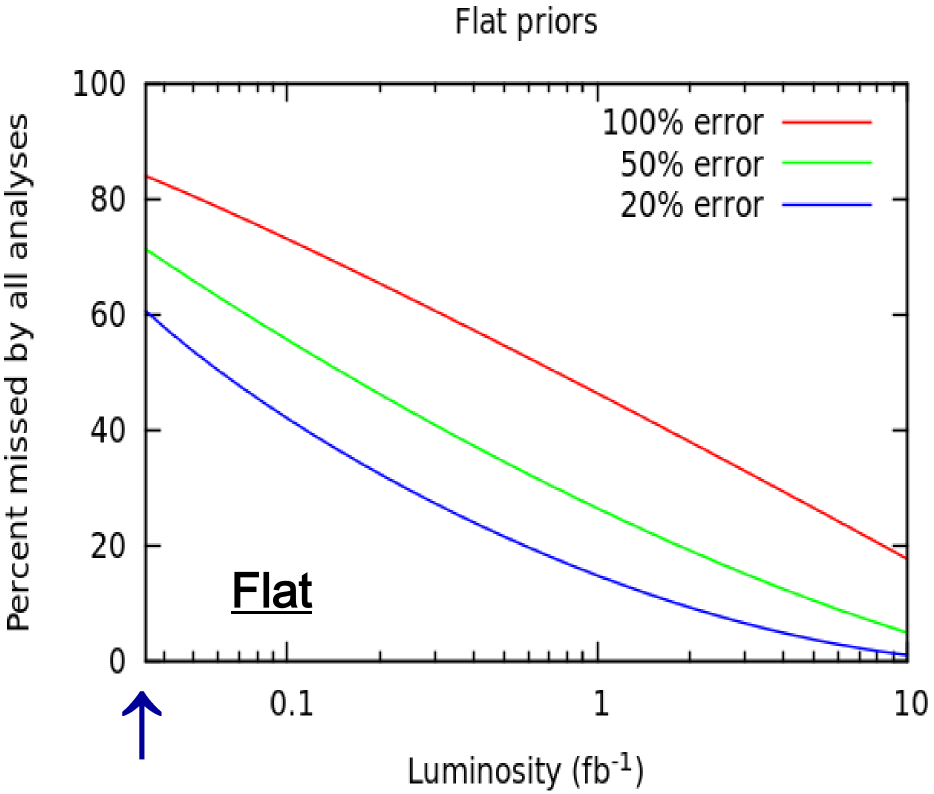


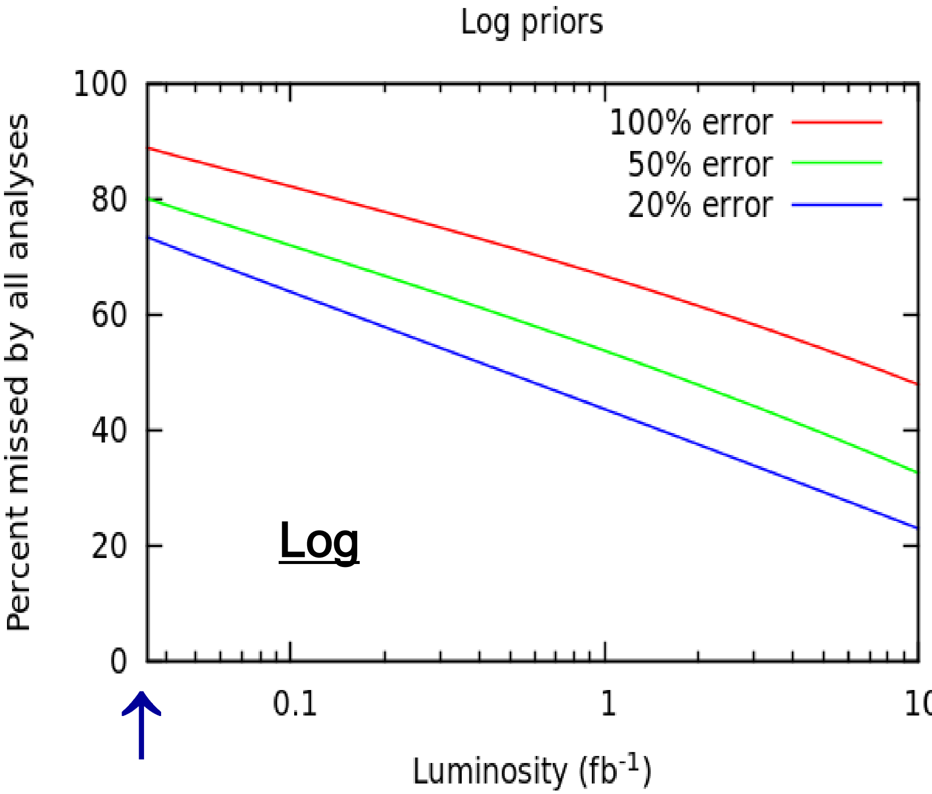
# anl.	Flat $\mathcal{L}_{0.1}$	Flat $\mathcal{L}_1$	Flat $\mathcal{L}_{10}$	Log $\mathcal{L}_{0.1}$	Log $\mathcal{L}_1$	Log $\mathcal{L}_{10}$
0	38.172	7.5501	0.9965	63.64	43.988	22.92
1	9.2928	4.1988	0.90862	5.376	4.8674	5.8482
2	8.7432	4.6665	1.6102	3.6687	5.6665	6.0298
3	41.836	59.878	39.573	26.008	34.907	35.38
4	0.65686	4.9257	7.9422	0.25427	2.2158	6.4657
5	0.53472	4.2629	6.7163	0.47221	2.0341	4.8311
6	0.54366	8.5391	13.494	0.32692	3.0875	6.5383
7	0.067026	2.5217	8.9044	0.21794	1.453	4.1773
8	0.062558	1.2288	5.6364	0.036324	0.72648	2.2884
9	0.077452	1.2958	6.548	0	0.58118	2.9422
10	0.013405	0.93241	7.6711	0	0.47221	2.579

→ → SUSY signals usually seen in multiple analyses

How good is the pMSSM coverage @ 7 TeV as the lumi evolves (assuming a universal background uncertainty)?

The coverage is quite good for both model sets !





- These figures emphasize the importance of decreasing background systematic errors to obtain good pMSSM model coverage. For FLAT priors we see that, e.g.,

L=5(10) fb^{-1} and δB=100% is 'equivalent' to

L=0.65(1.4) fb^{-1} and δB=50% (x ~7) OR to

L=0.20(0.39) fb^{-1} and δB=20% (x ~25) !!

This effect is less dramatic for the LOG case due to the potentially heavier & possibly compressed mass spectrum

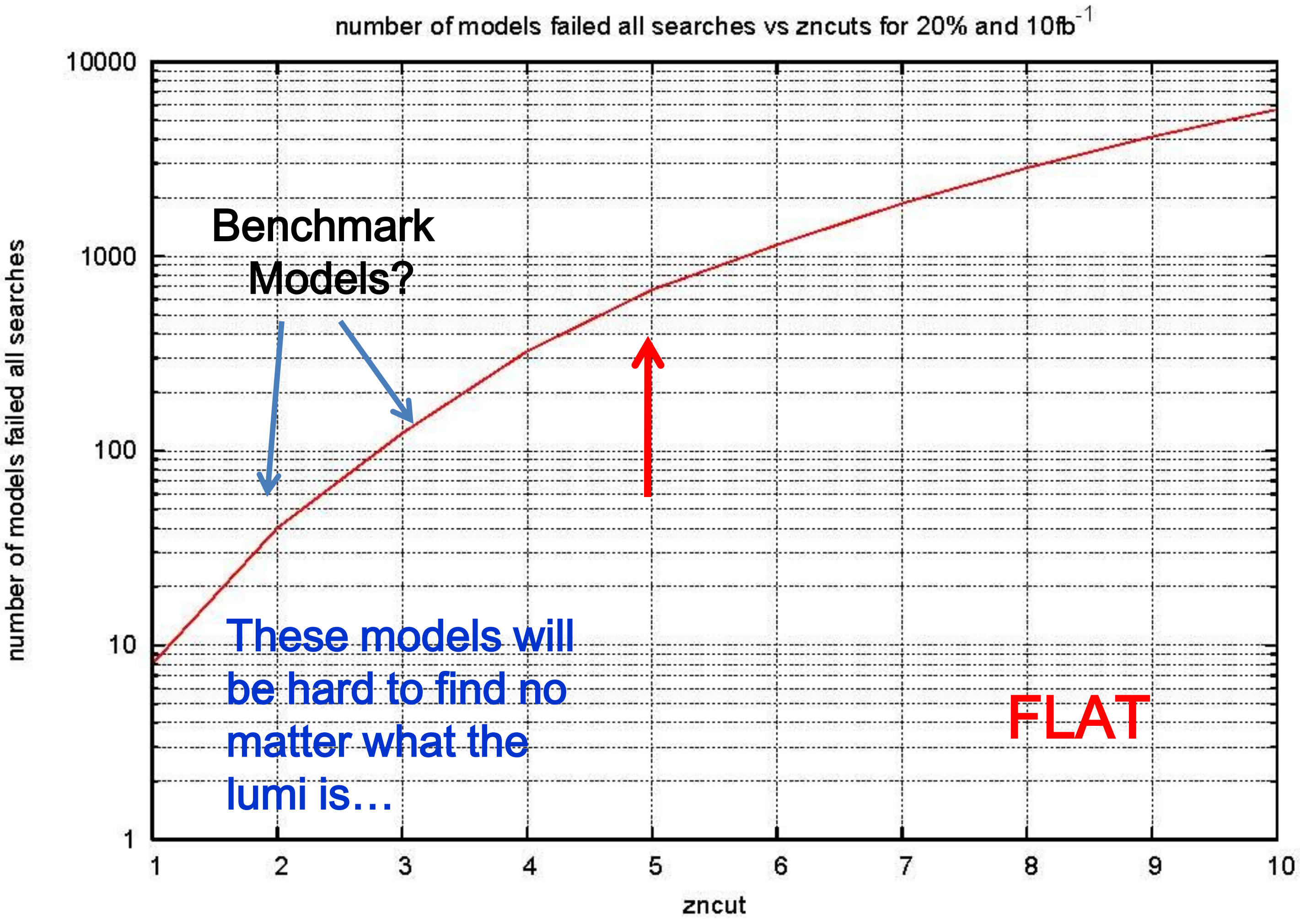
ATLAS pMSSM Model Coverage*
RIGHT NOW for ~35 pb $^{-1}$ @ 7 TeV

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 stated

Aside: How many models will fail to have even one analysis with S > some fixed value by the end of 2012 assuming L=10 fb^{-1} and δB=20%?



Benchmark Models?

These models will be hard to find no matter what the lumi is…

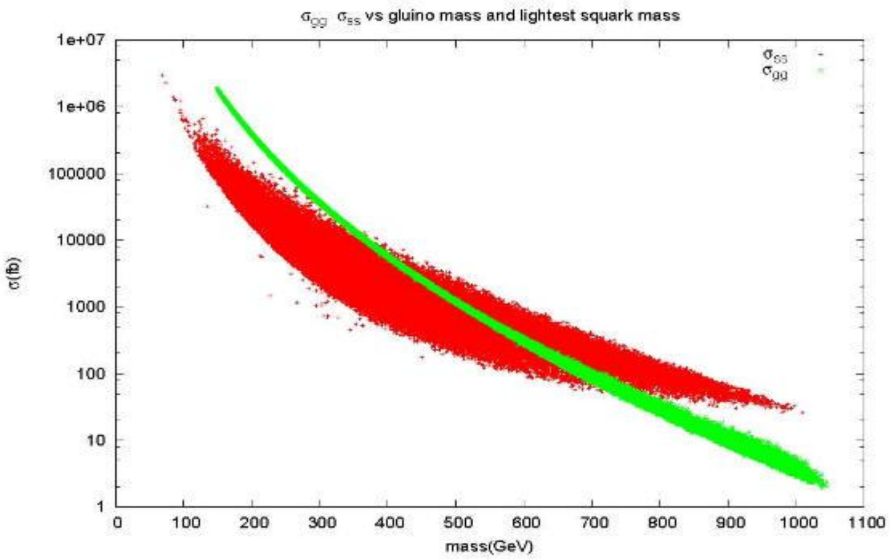
FLAT

The Undiscovered SUSY

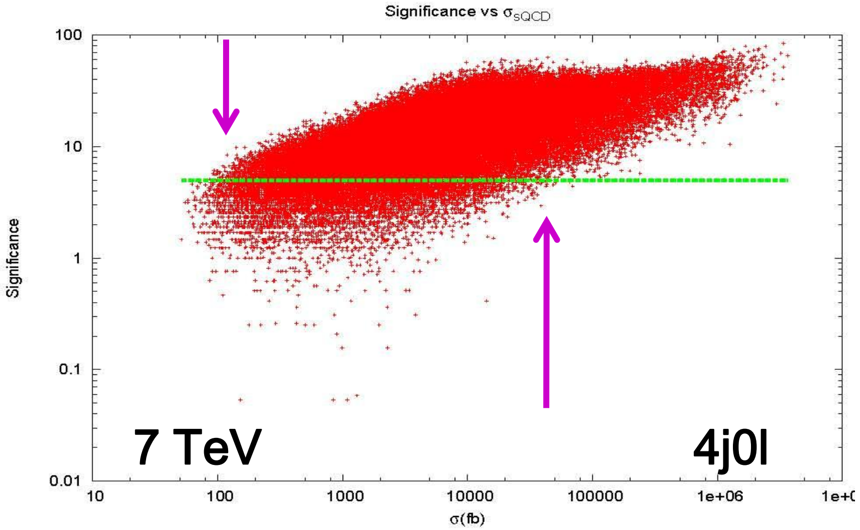
Why Do Models Get Missed by ATLAS?

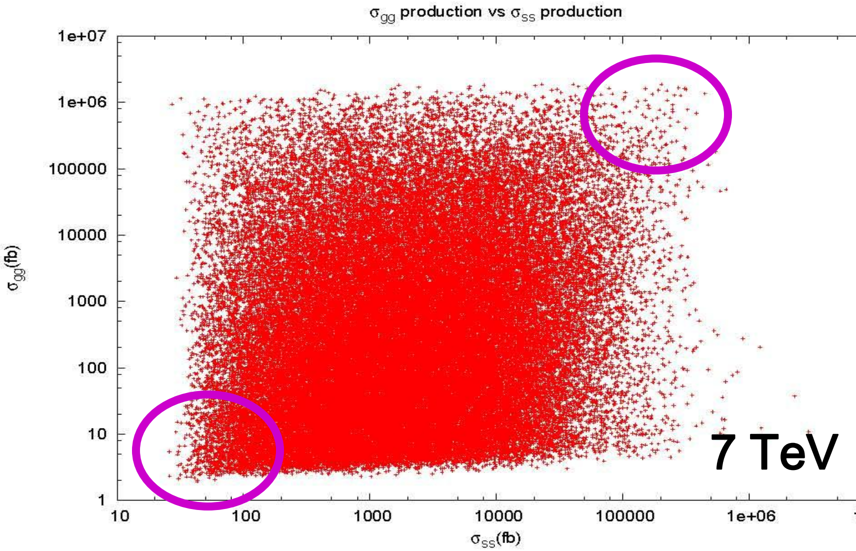
The most obvious things to look at first are :

- small signal rates due to suppressed σ's
- which can be correlated with large sparticle masses
- small mass splittings w/ the LSP (compressed spectra)
- decay chains ending in stable charged sparticles

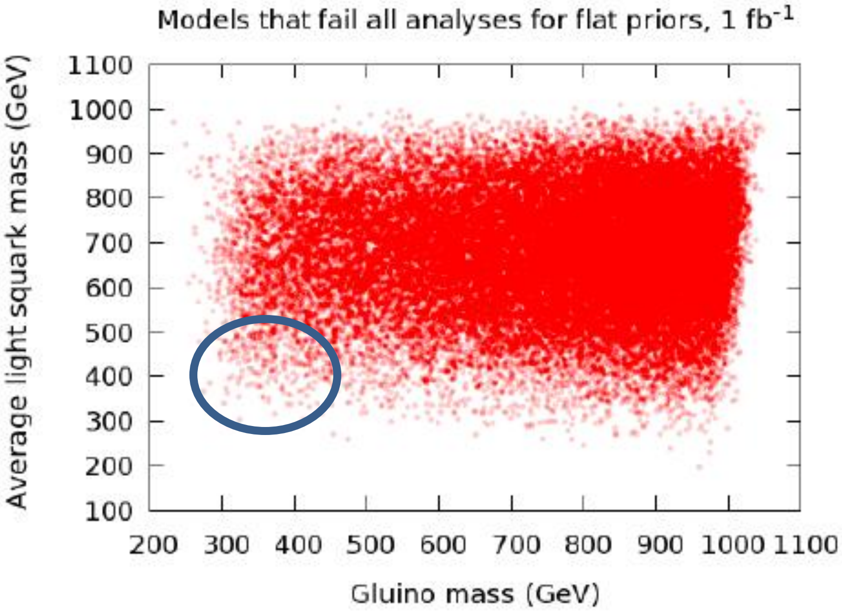


σ's : Squark & gluino production cross sections @ 7 TeV cover a very wide range & are correlated with the search significance. But there are models with σ ~30 pb that are missed by all ATLAS analyses while others with σ below ~100 fb are found.



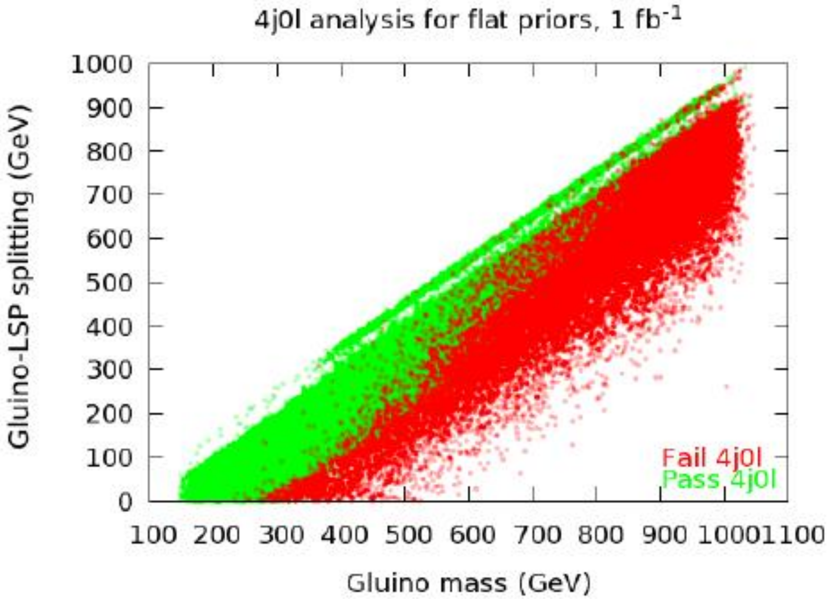


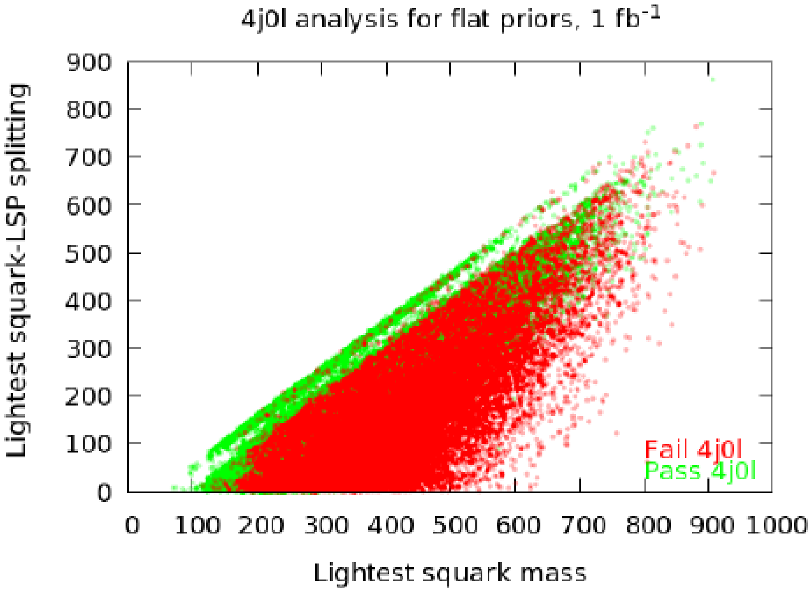
Soft jets & leptons


Models that fail all analyses for flat priors, 1 fb^{-1}

Both 7 & 14 TeV models can be missed due to small mass splittings between squarks and/or gluinos and the LSP → softer jets or leptons not passing cuts. ISR helps in some cases…

7 TeV


4j0l analysis for flat priors, 1 fb^{-1}

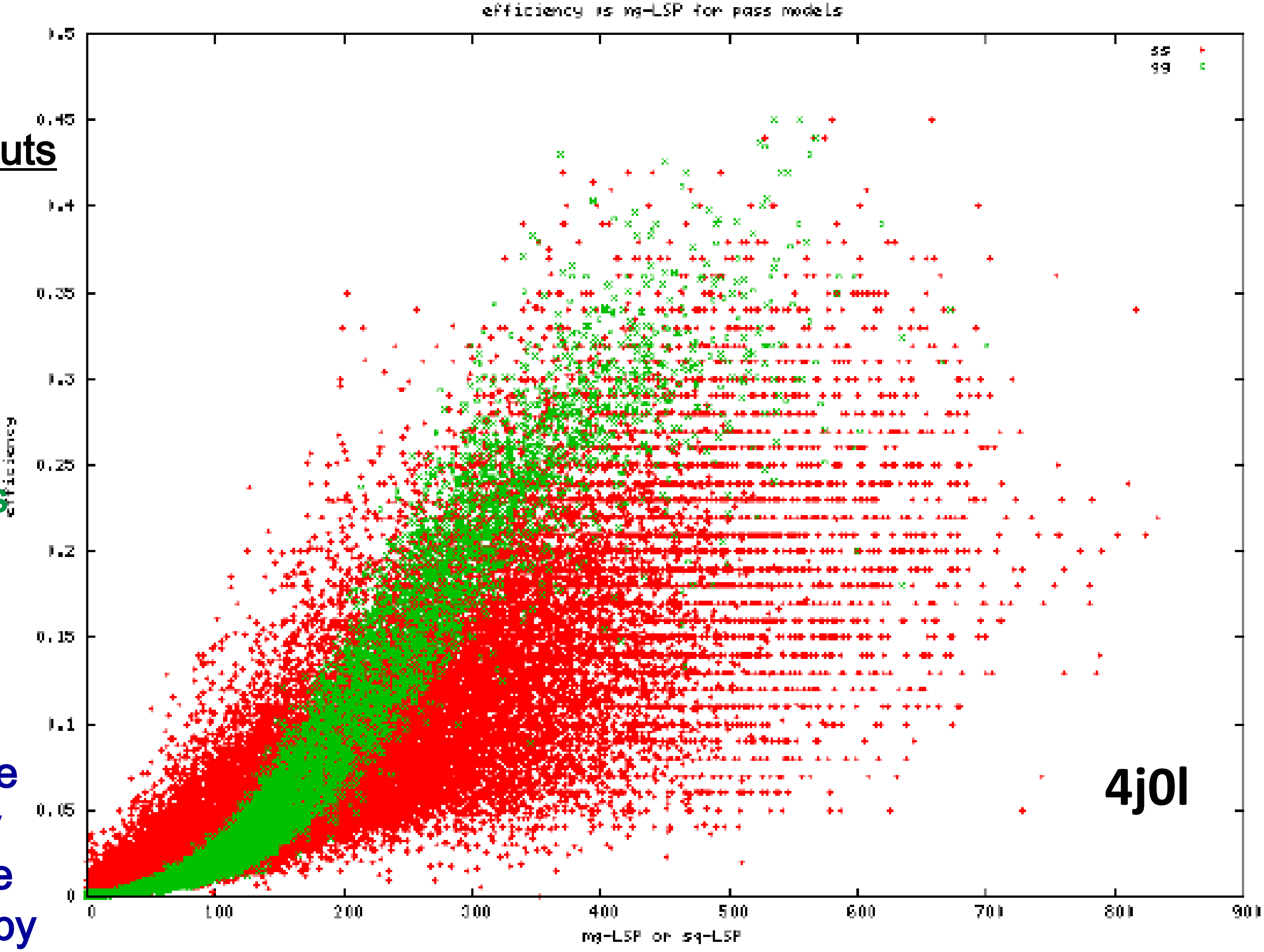

4j0l analysis for flat priors, 1 fb^{-1}

For small mass splittings w/ the LSP a smaller fraction of events will pass analysis cuts

$$\frac{\text{\# of evts passing cuts}}{\text{total generated}}$$

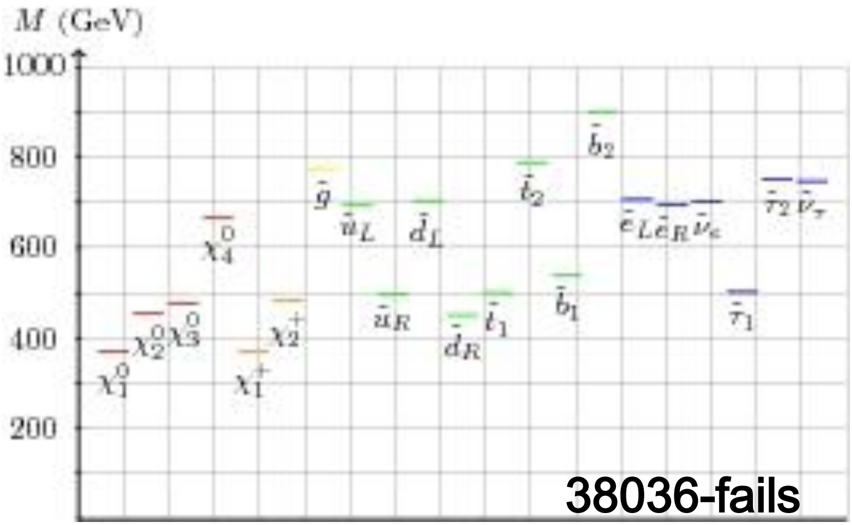
Red=squark pairs
Green=gluino pairs

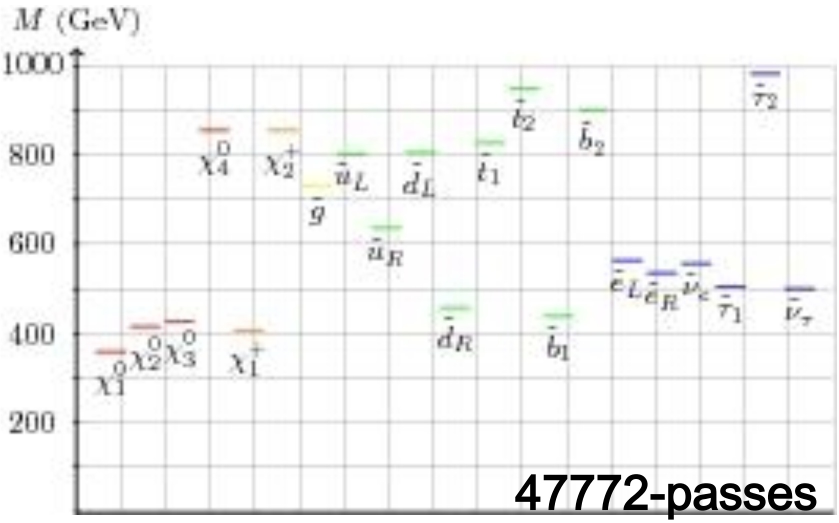
But as seen on the previous slide tiny efficiencies can be compensated for by huge σ's !



Mass Splitting with the LSP

Missed vs Found Model Comparisons





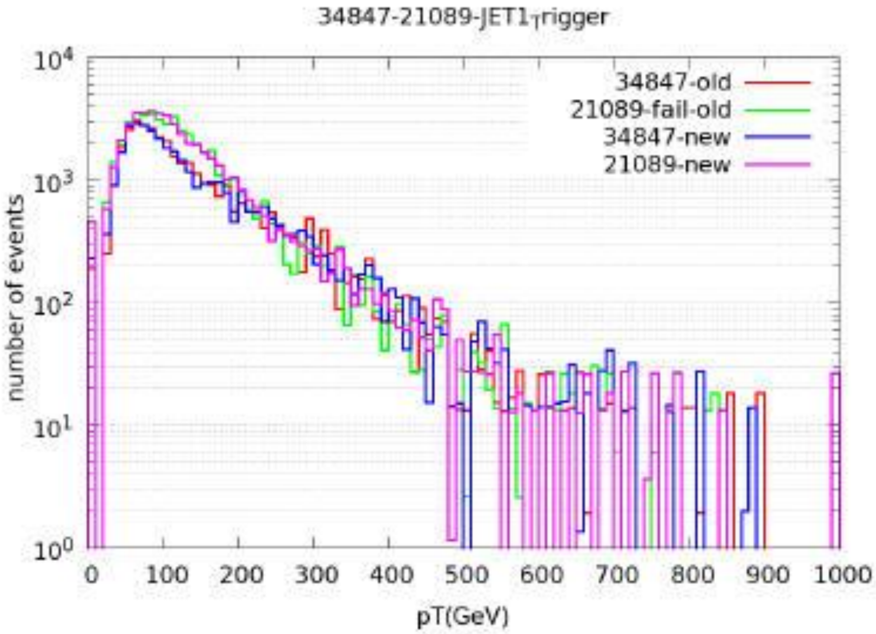
- 38036 (~2.5 pb) fails while 47772 (~1.7 pb) passes all nj0l

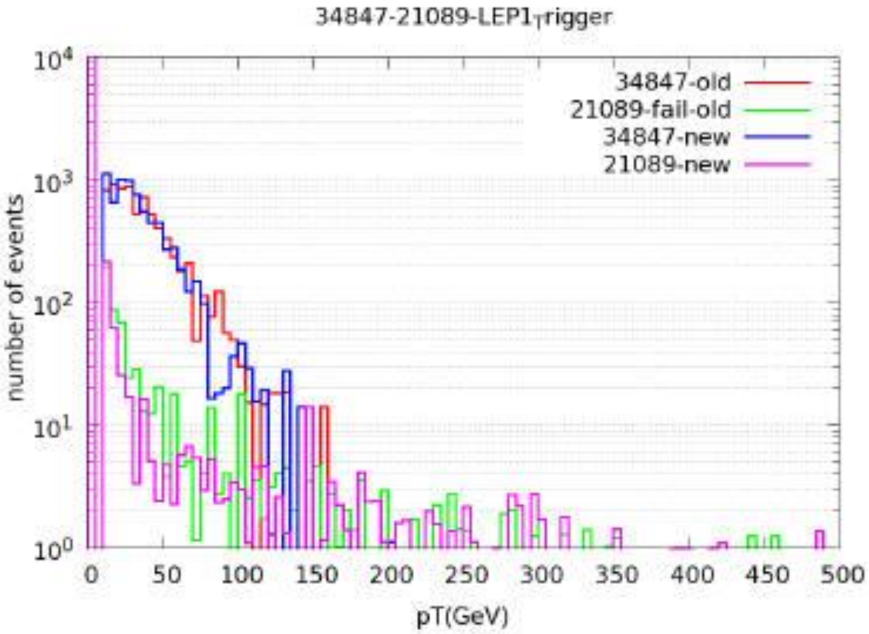
- u_R lighter (~500 vs ~635 GeV) & produces larger σ in 38036 but decays ~75% to j+MET in both models

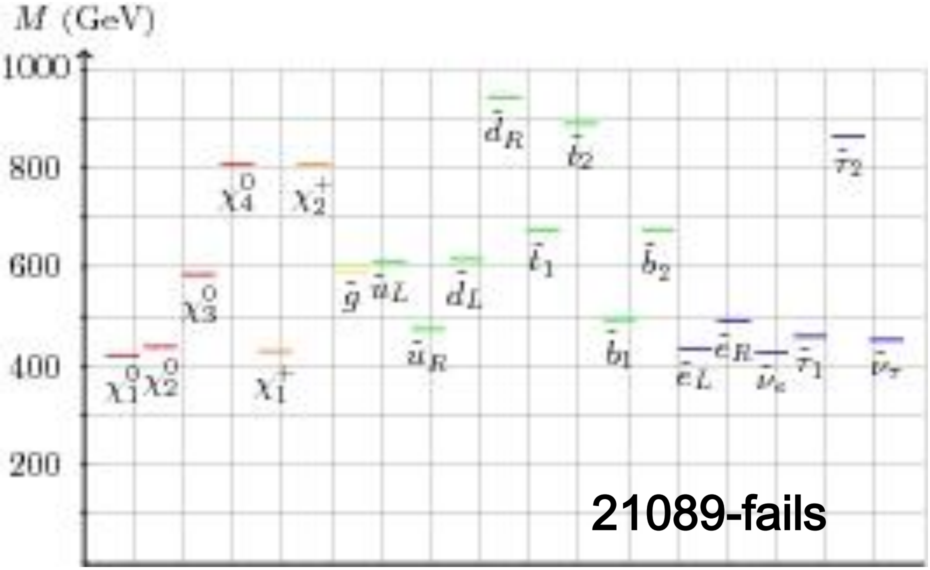
- BUT due to the Δm w/ LSP difference (→ eff ~13% vs ~3.5%) 38036 fails to have a large enough rate after cuts

Efficiencies win over cross sections !

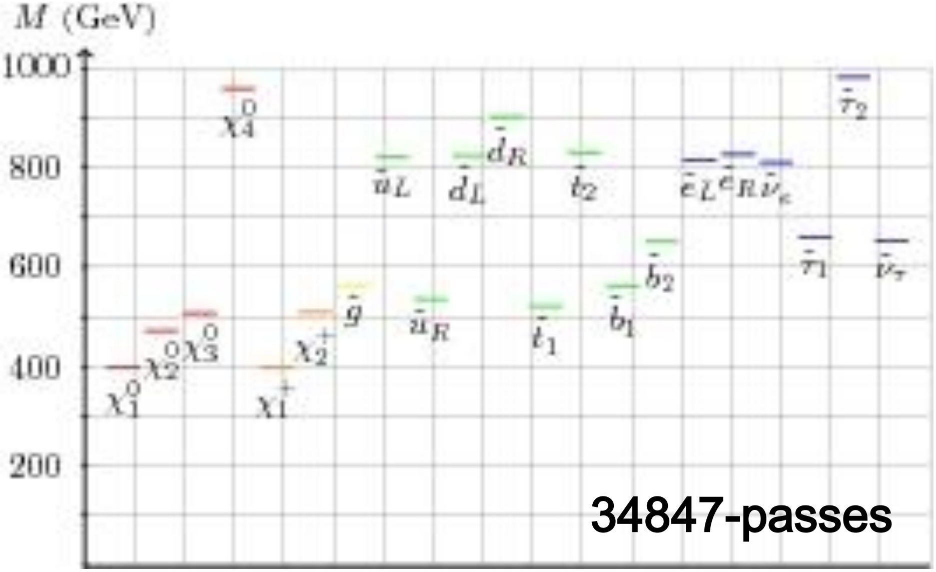
Missed vs Found Model Comparisons







21089-fails



34847-passes

What went wrong ??

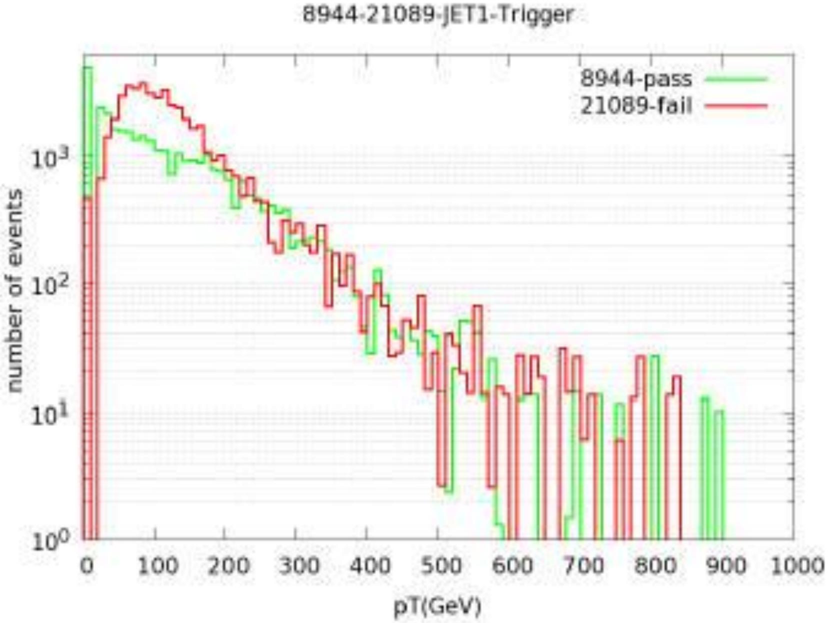
- 21089 (σ ~ 4.6pb) & 34847 (σ ~ 3.3pb) yet both models fail nj0l due to smallish Δm's. BUT 34847 is seen in the lower background channels (3,4)j1l

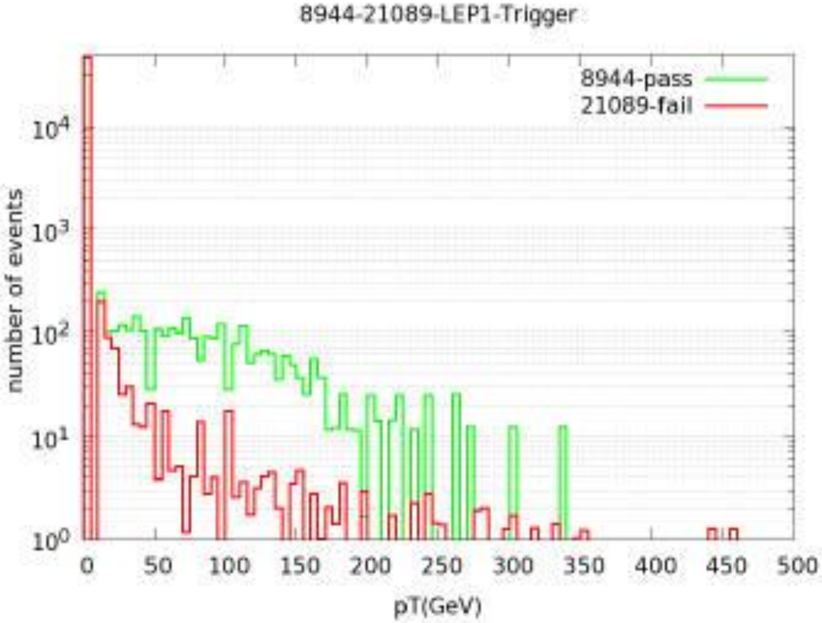
- In 34847, u_R cascades to the LSP via χ_2^0 & the chargino producing leptons via W emission. The LSP is mostly a wino in this case.

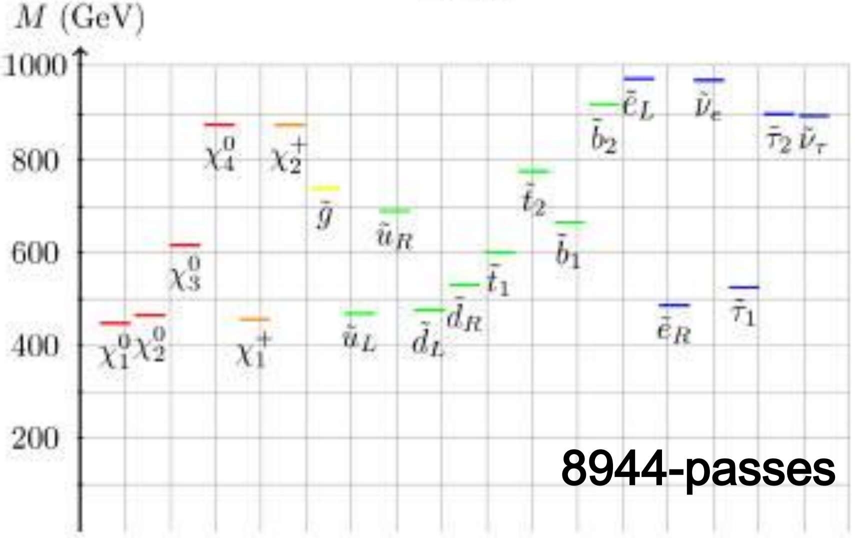
- In 21089, however, u_R can only decay to the lighter ~Higgsino triplet which is sufficiently degenerate as to be incapable of producing high p_T leptons

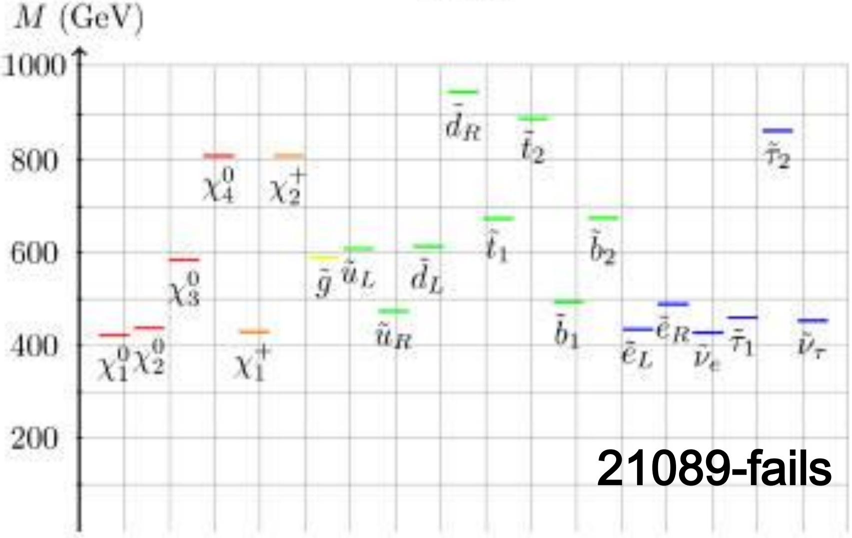
- Note that the jets in both u_R decays have similar p_T's

Missed vs Found Model Comparisons


8944-21089-JET1-Trigger


8944-21089-LEP1-Trigger


8944-passes


21089-fails

What went wrong ??

- 8944 seen in (3,4)OSDL while 21089 is completely missed nj0l fail due to spectrum compression but with very similar colored sparticle total σ = (3.4, 4.6) pb

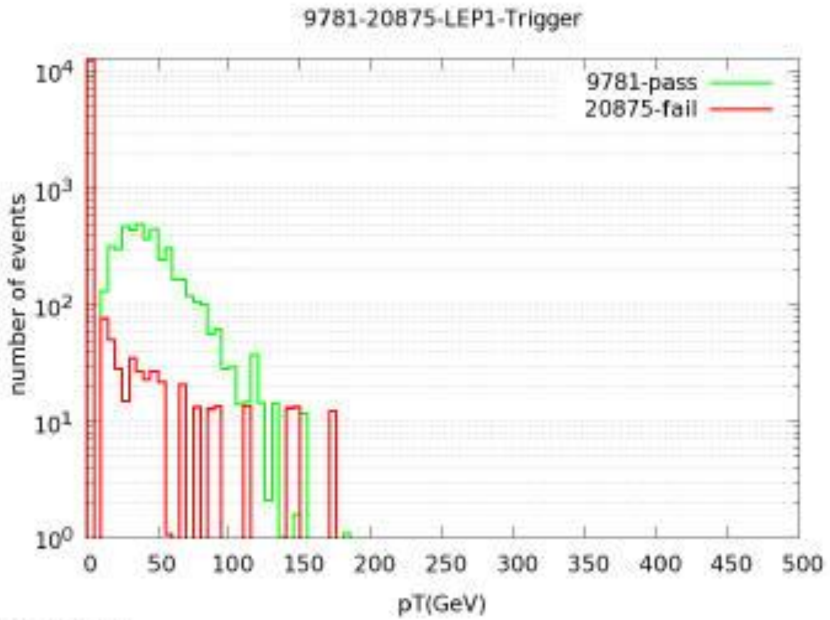
- models have similar gaugino sectors w/ $\chi_{1,2}^0$ Higgsino-like & χ_3^0 bino-like

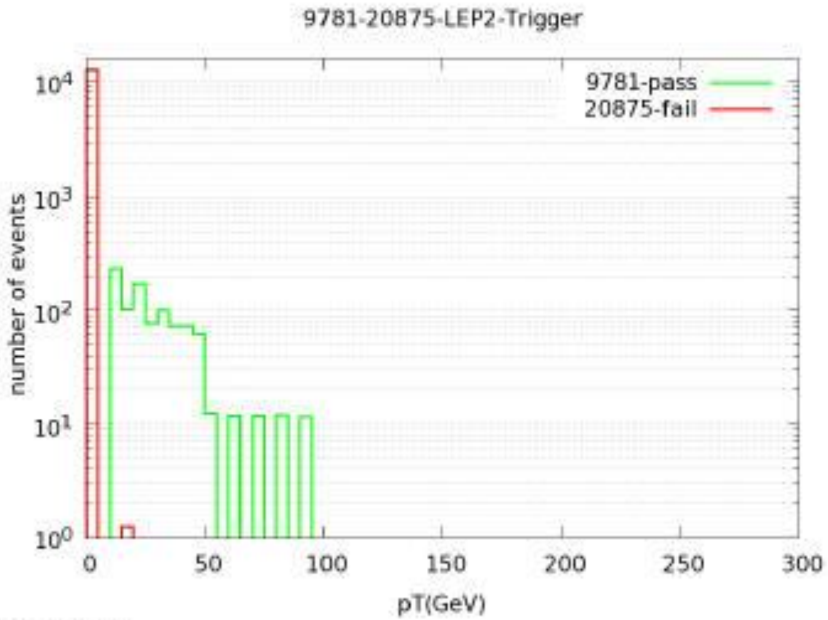
- χ_3^0 can decay thru sleptons to produce OSDL + MET

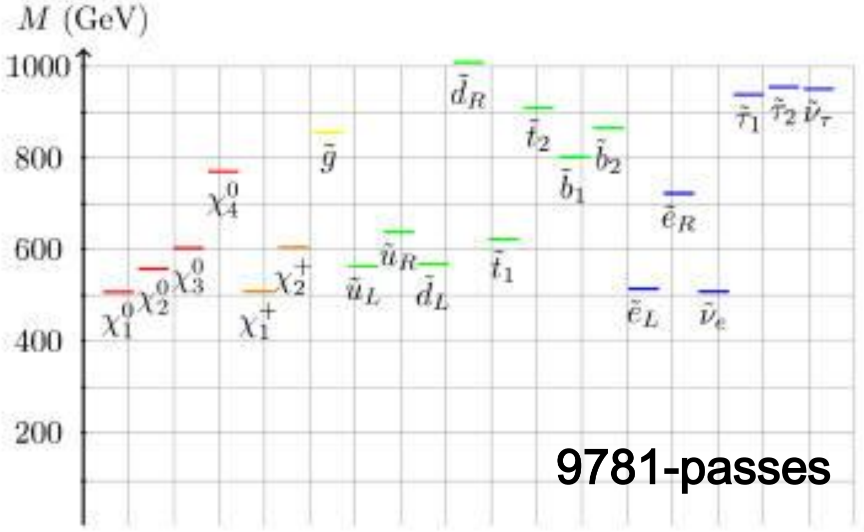
- However in 8944, the gluino is heavier than d_R so that d_R can decay to χ_3^0

- But in 21089, the gluino is lighter than u_R so that it decays into the gluino & not the bino so NO leptons

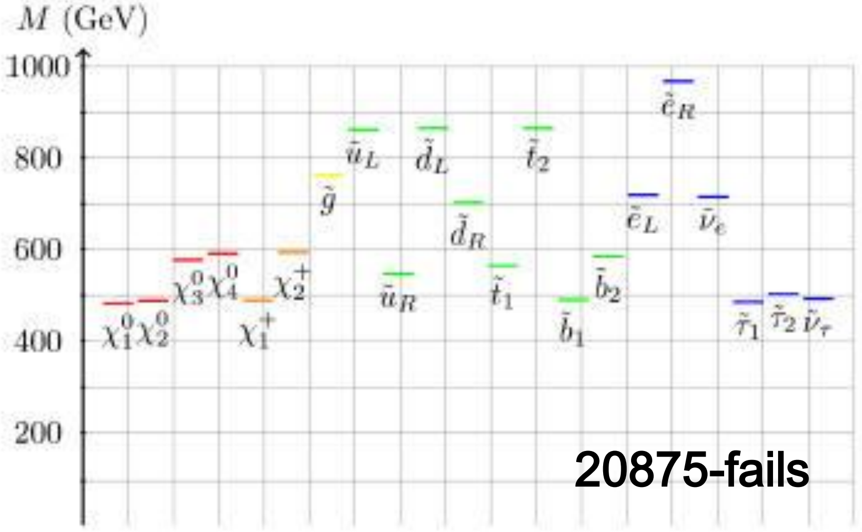
Missed vs Found Model Comparisons







9781-passes



20875-fails

What went wrong ??

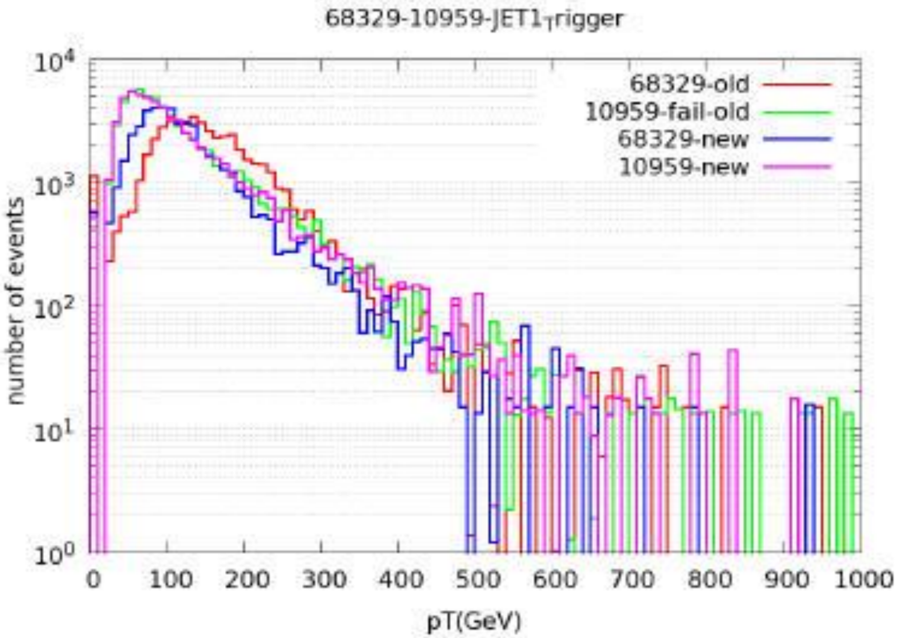
- 9781 seen in 2jSSDL while 20875 is completely missed nj0l fail due to spectrum compression but with very similar colored sparticle total σ = (1.1, 1.3) pb

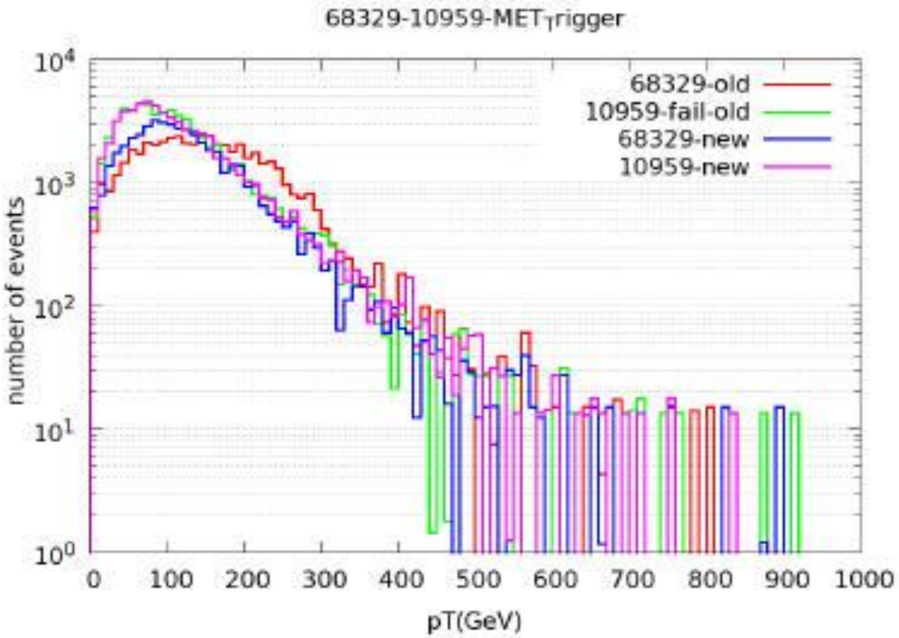
- Both models have highly mixed neutralinos & charginos w/ a relatively compressed spectrum

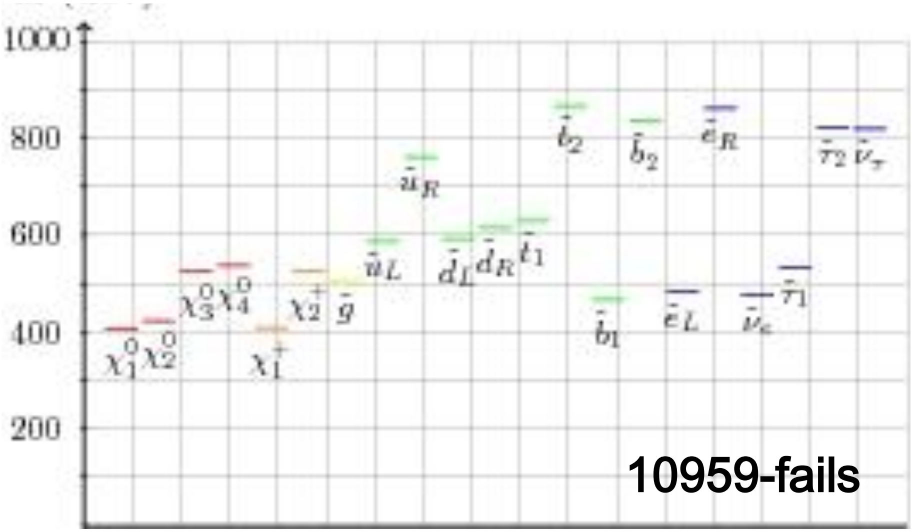
- In model 9781, u_R can decay to j+leptons+MET via the bino part of χ_2^0 through intermediate e,μ sleptons

- But in 20875, these sleptons are too heavy to allow for decay on-shell & only staus are accessible. The resulting leptons from the taus are too soft to pass analysis cuts

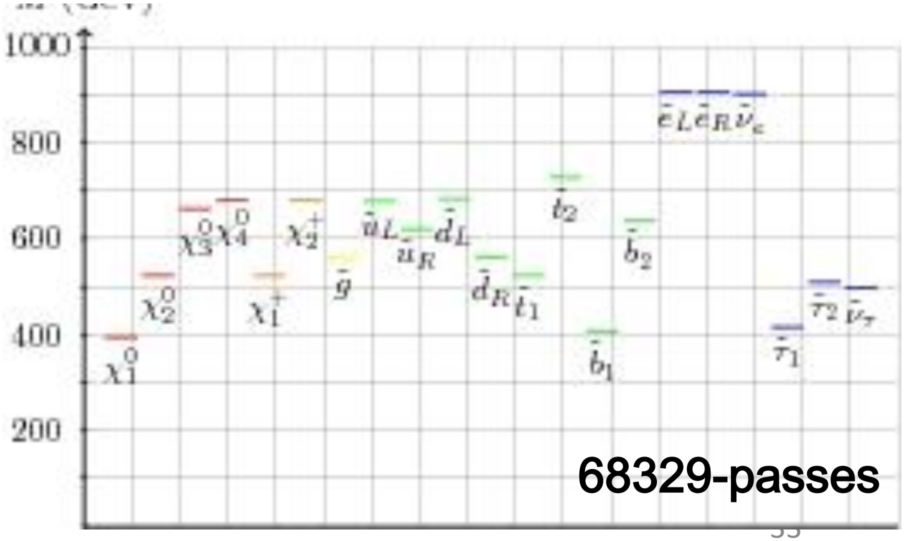
Missed vs Found Model Comparisons







10959-fails

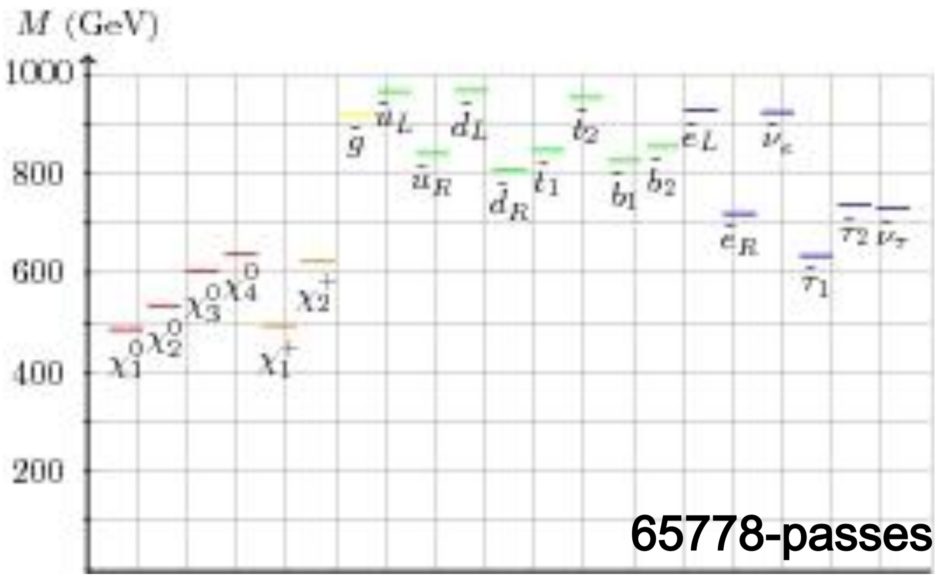


68329-passes

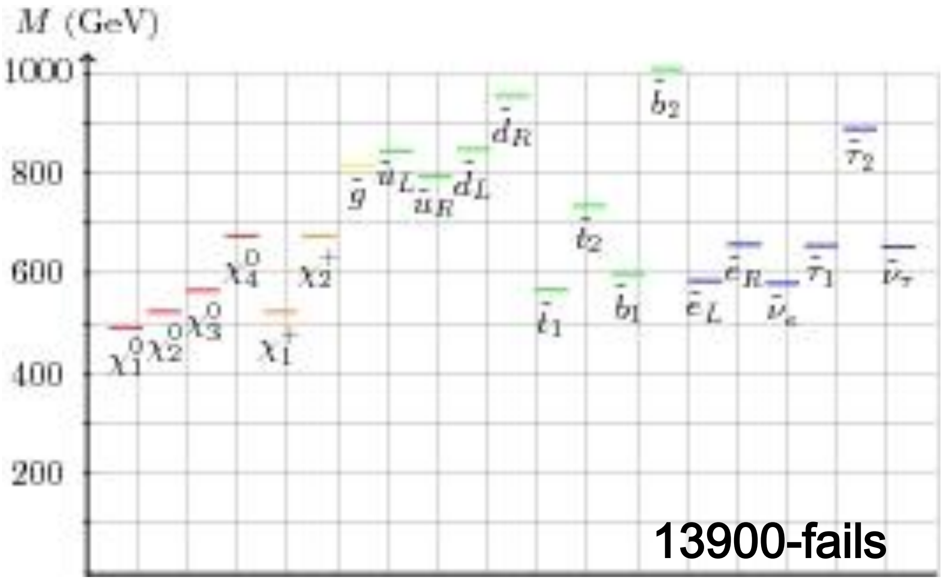
What went wrong ??

- 68329 passes 4j0l (σ~4.6 pb) while 10959 (σ~6.0 pb) fails all
- In 68329, d_R decays to j+MET (B~95%) since the gluino is only ~3 GeV lighter. The gluino decays to the LSP via the sbottom (B~100%) with a Δm~150 GeV mass splitting . The LSP is bino-like in this model
- In 10959, d_R decays via the ~107 GeV lighter gluino (B~99%) and the gluino decays (with Δm ~40 GeV) through sbottom & 2nd neutralino to the (wino-like) LSP (with Δm~ 60 GeV).
- Raising the LSP & b_1 masses in 68239 by 50 GeV (the 2nd set of curves) induces failure due to the new gluino decay path

Missed vs Found Model Comparisons



65778-passes



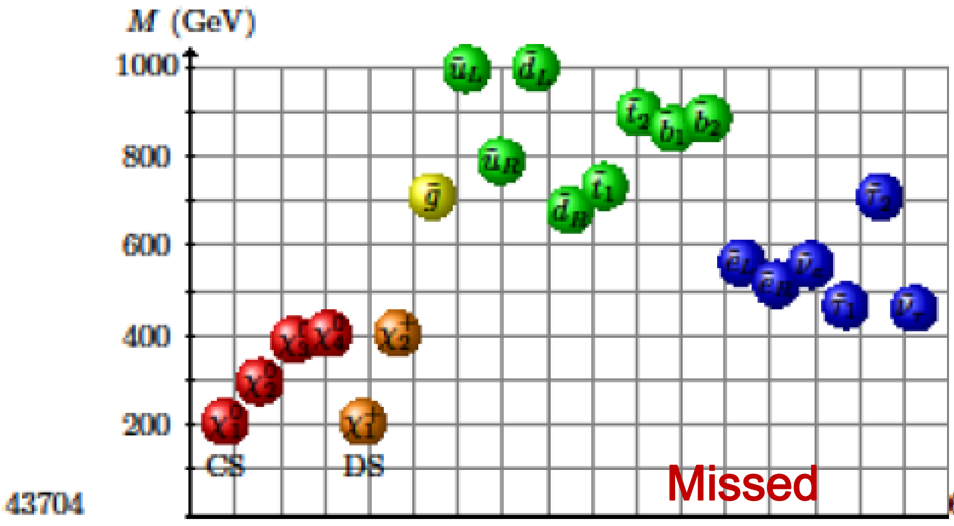
13900-fails

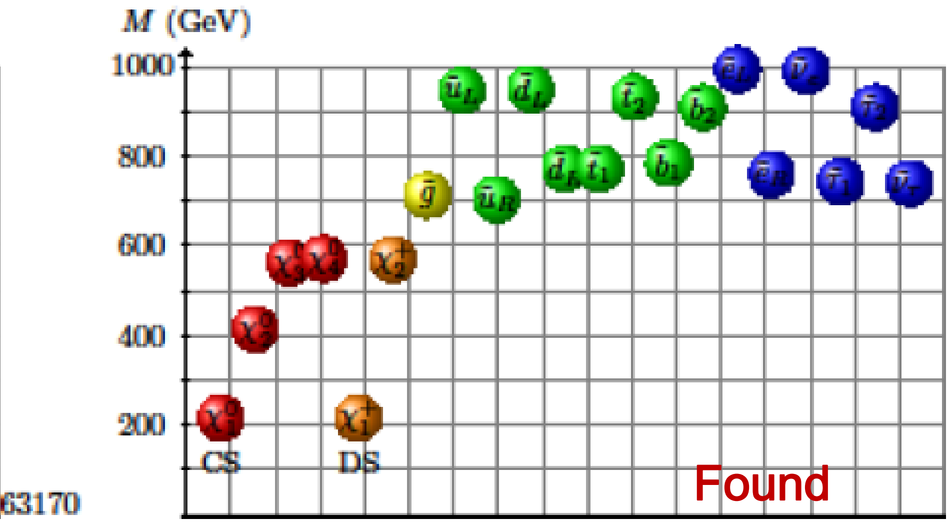
- 13900 & 65778 have heavy spectra & well-mixed gauginos w/ σ ~ 0.36(0.22) pb, too small for nj0l but 65778 seen in 4j1l

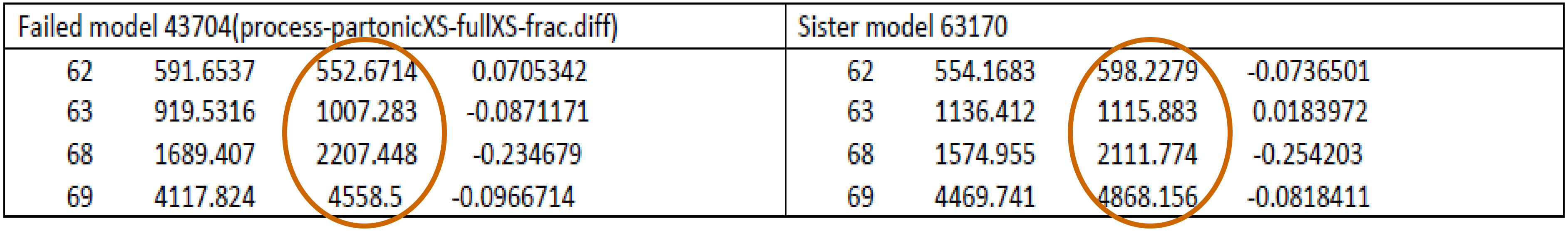
- In 13900 the gluino decays to sbottoms & stops while u_R goes mostly to the LSP, so no leptons

- In 65778, $(d,u)_R$ decay to $j+\chi_{2,4}^0$, then to $W\chi_1^\pm$ w/ B~75% & Δm~160-270 GeV, producing a subsequent hard lepton

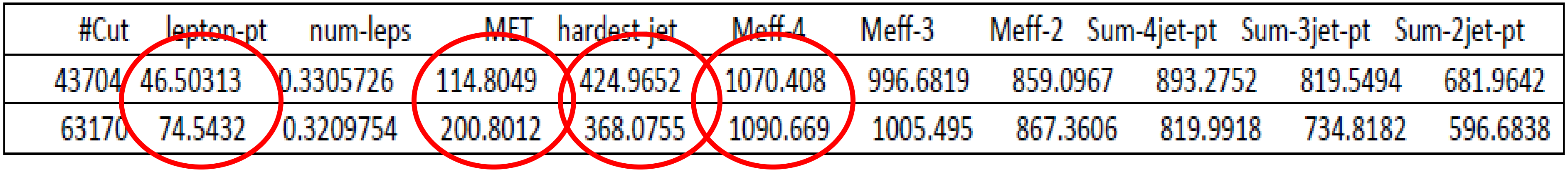
A 14 TeV Example:







Failed model 43704(process-partonicXS-fullXS-frac.diff)				Sister model 63170			
62	591.6537	552.6714	0.0705342	62	554.1683	598.2279	-0.0736501
63	919.5316	1007.283	-0.0871171	63	1136.412	1115.883	0.0183972
68	1689.407	2207.448	-0.234679	68	1574.955	2111.774	-0.254203
69	4117.824	4558.5	-0.0966714	69	4469.741	4868.156	-0.0818411



#Cut	lepton-pt	num-leps	MET	hardest jet	Meff-4	Meff-3	Meff-2	Sum-4jet-pt	Sum-3jet-pt	Sum-2jet-pt
43704	46.50313	0.3305726	114.8049	424.9652	1070.408	996.6819	859.0967	893.2752	819.5494	681.9642
63170	74.5432	0.3209754	200.8012	368.0755	1090.669	1005.495	867.3606	819.9918	734.8182	596.6838

What went wrong ??

In 43704: gluinos→ d_R →χ_2^0 →W + ‘stable’ chargino (~100%)
(Zanesville, OH) as the χ_2^0 –LSP mass splitting is ~91 GeV

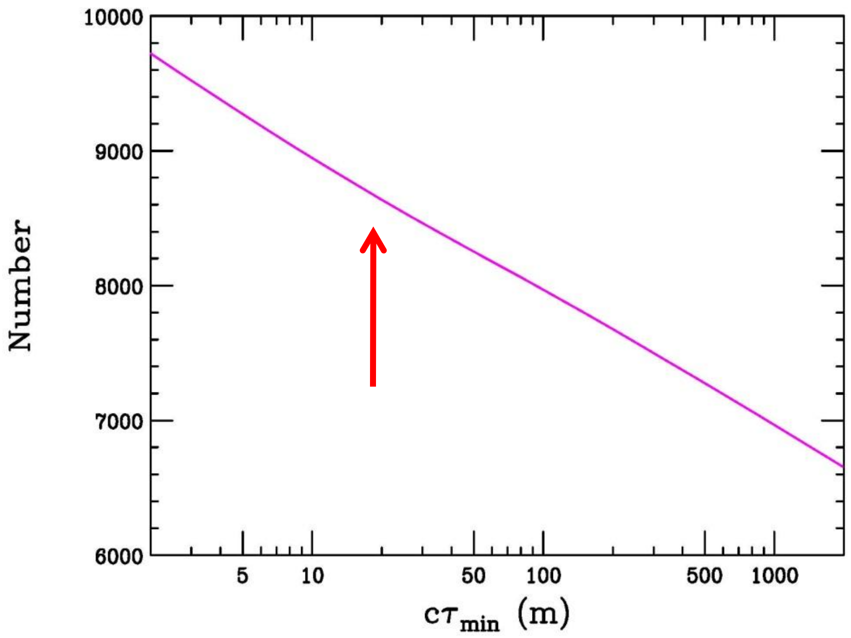
In 63170: gluinos→ u_R →χ_2^0 → Z/h + LSP (~30%) as the
(St. Louis, MO) χ_2^0 –LSP mass splitting is larger ~198 GeV

- Again: a small spectrum change can have a large effect on the signal observability!
- → Searches for stable charged particles in complex cascades may fill in some gaps as they are common in our model sets

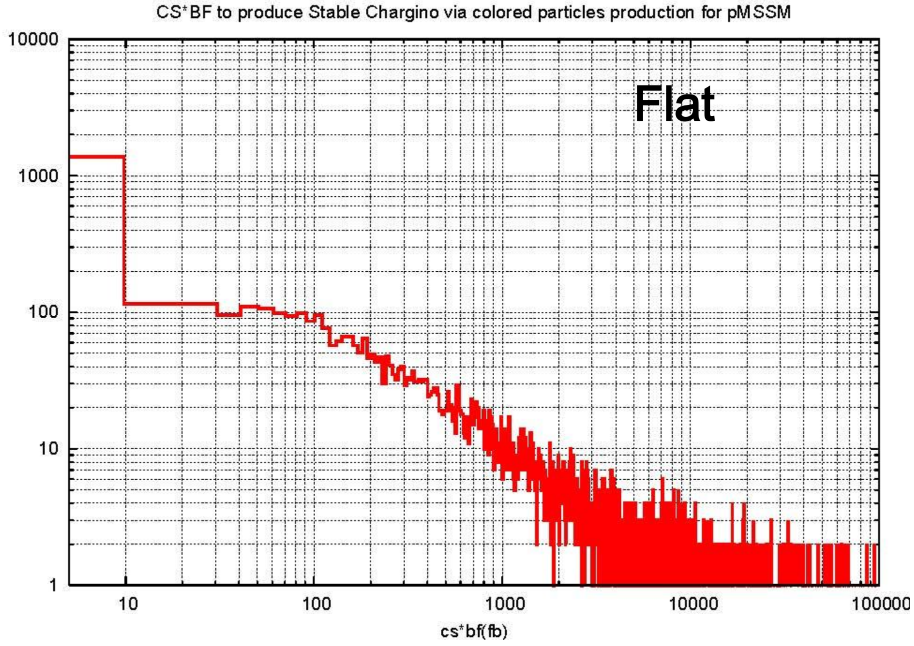
‘Stable’ Charged Particles in Cascades

→ Mostly long-lived charginos produced in gluino/squark initiated decay chains

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



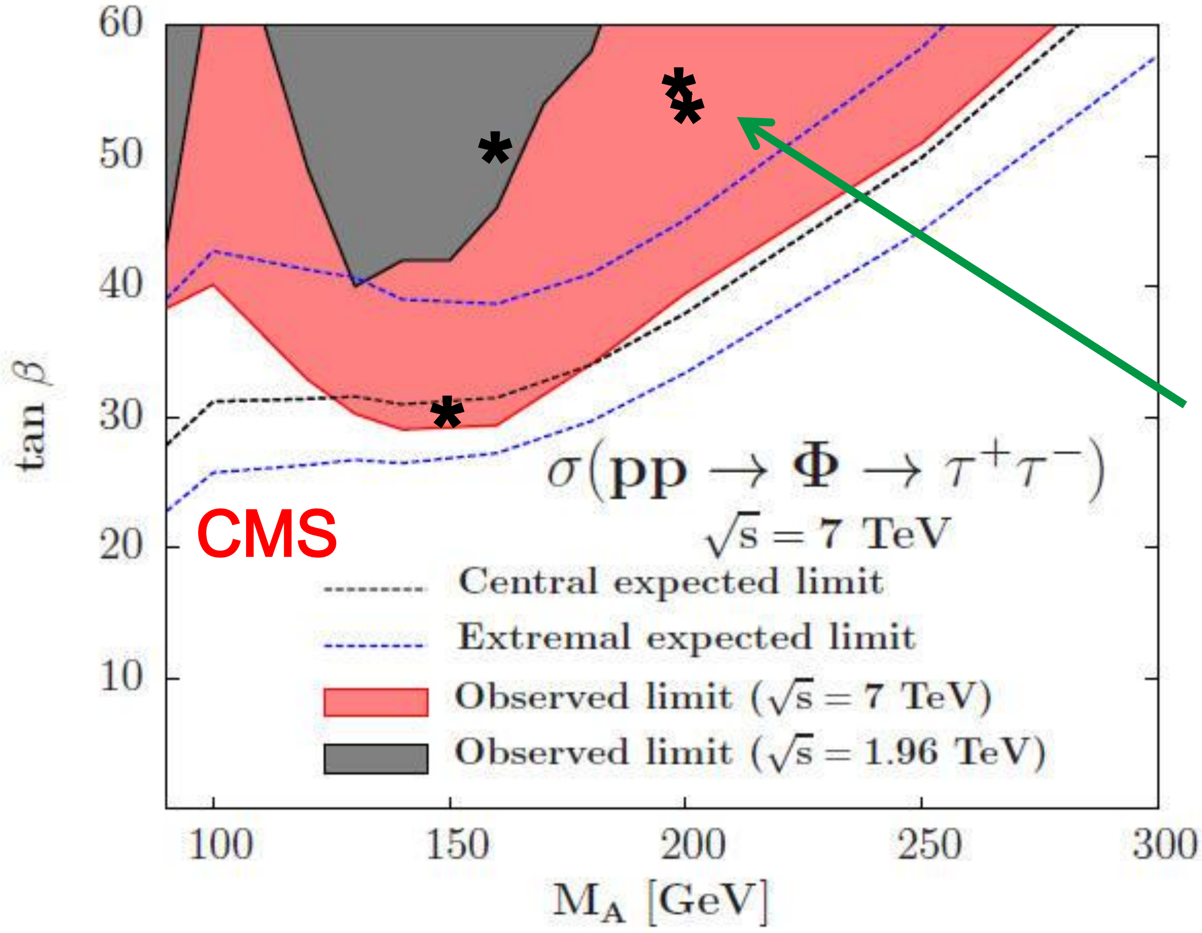
Unboosted Minimum Decay Length



Estimated σB

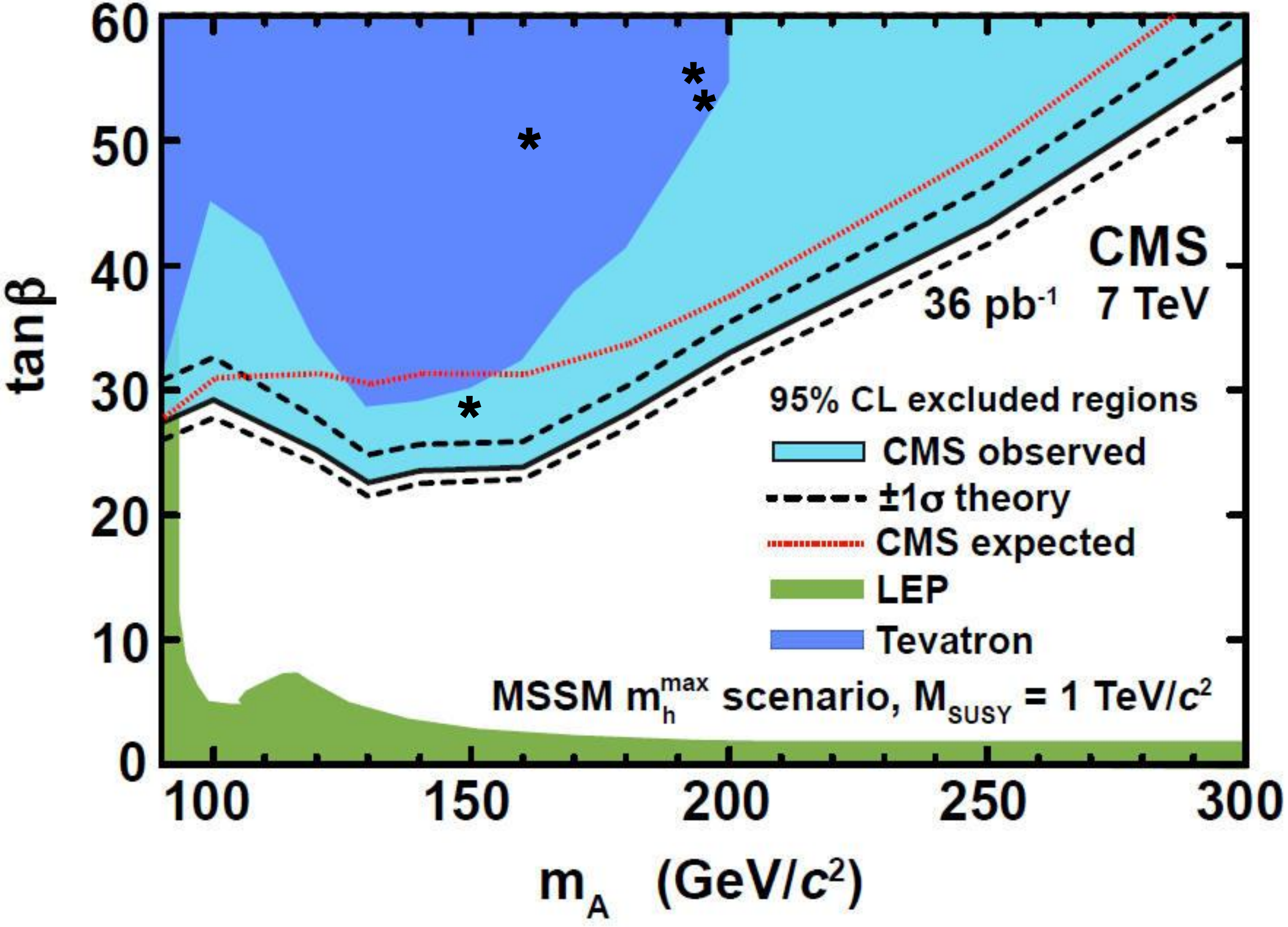
Impact of Higgs Searches

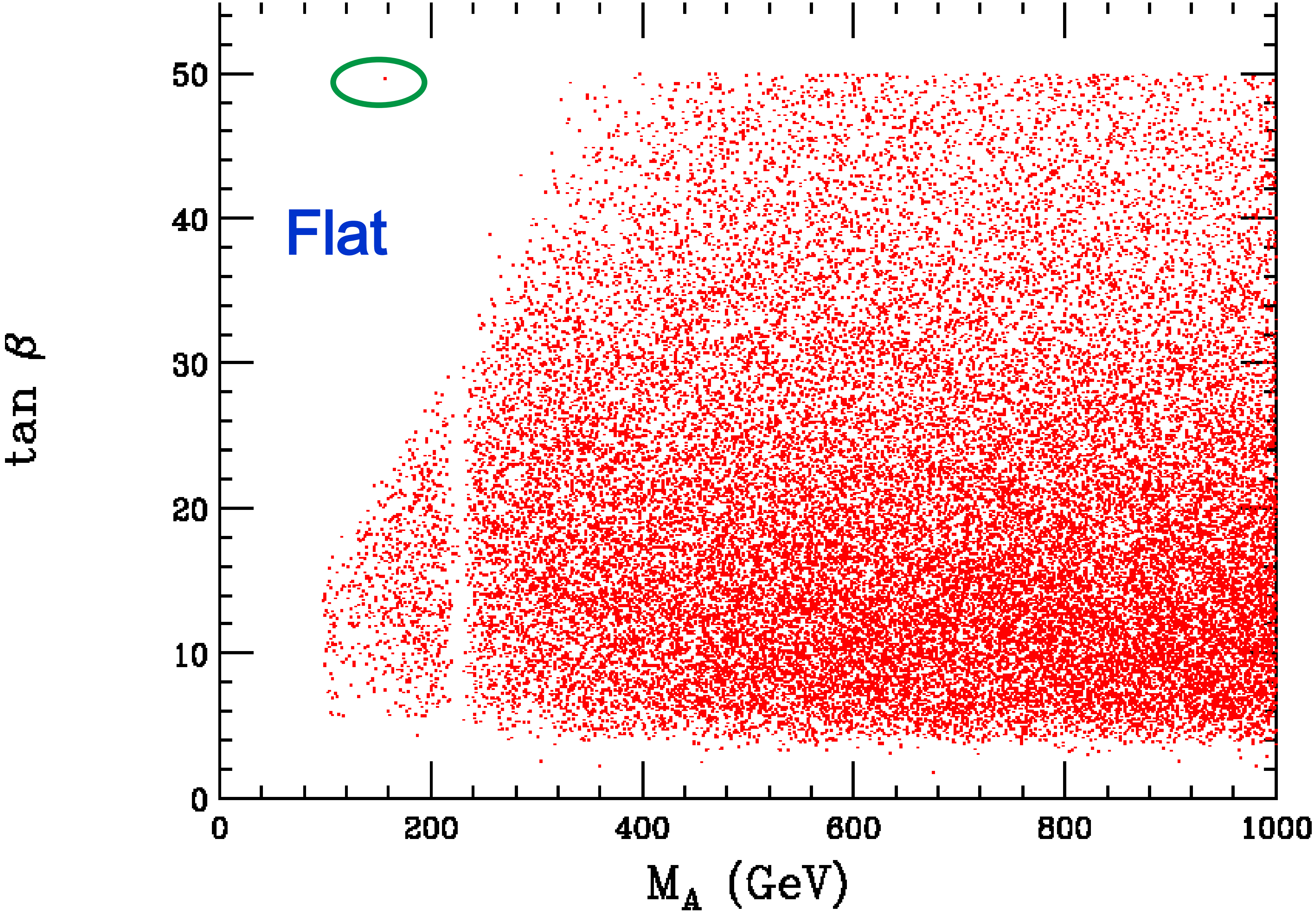
Searches for the various components of the SUSY Higgs sector also can lead to very important constraints on SUSY parameter space.



So far with ~35 pb^{-1} these searches have excluded only **4** of our models (due to the existing strong flavor constraints) but these searches are just beginning ..

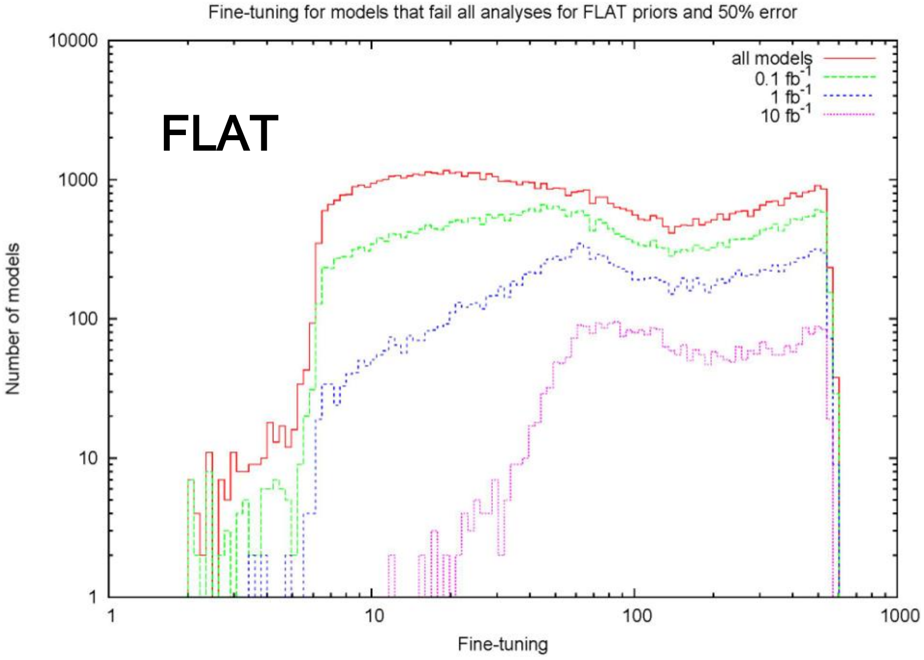
Baglio & Djouadi 1103.6247

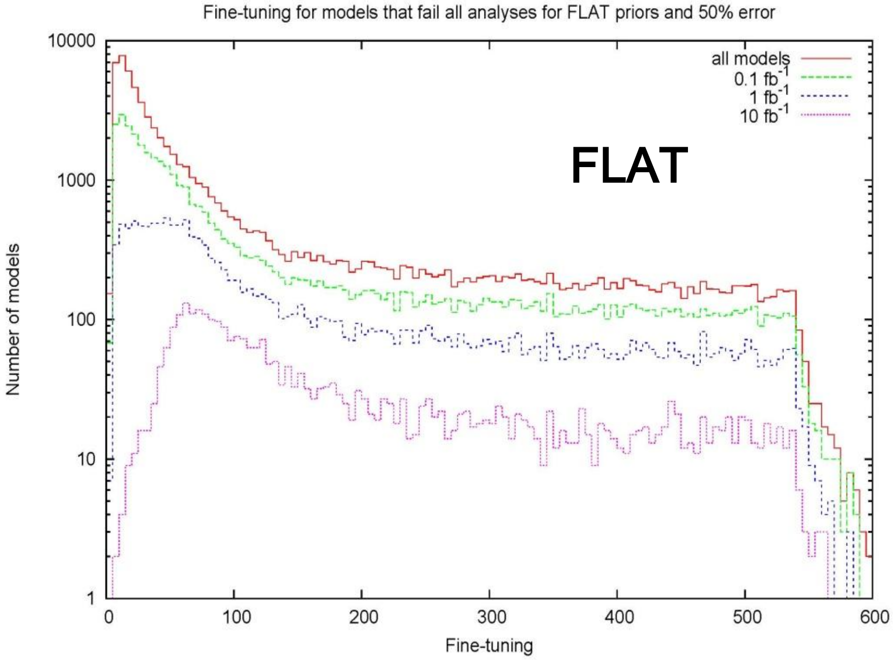

60
50
40
30
20
10
0
tanβ
100
150
200
250
300
m_A (GeV/c²)
CMS
36 pb⁻¹ 7 TeV
95% CL excluded regions
CMS observed
±1σ theory
CMS expected
LEP
Tevatron
MSSM m_h^max scenario, M_SUSY = 1 TeV/c²
*
*
*
*


Flat
tan β
M_A (GeV)
0
10
20
30
40
50
0
200
400
600
800
1000

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 our pMSSM model sets??





Summary & Conclusions

- ATLAS searches at both 7 &14 TeV (& any value in between) with ~10 fb^{-1} will do quite well at discovering or excluding most of our FLAT pMSSM models & not at all badly with our LOG prior set

- With ~35 pb^{-1} , a reasonable fraction of our model sets have already been 'covered' !

- Reducing SM background uncertainties is quite important in enhancing model coverage..

- Models 'missed' due to either compressed spectra *or* because of low MET cascades ending in 'stable' charginos *or*…
There are actually MANY reasons that models are missed.

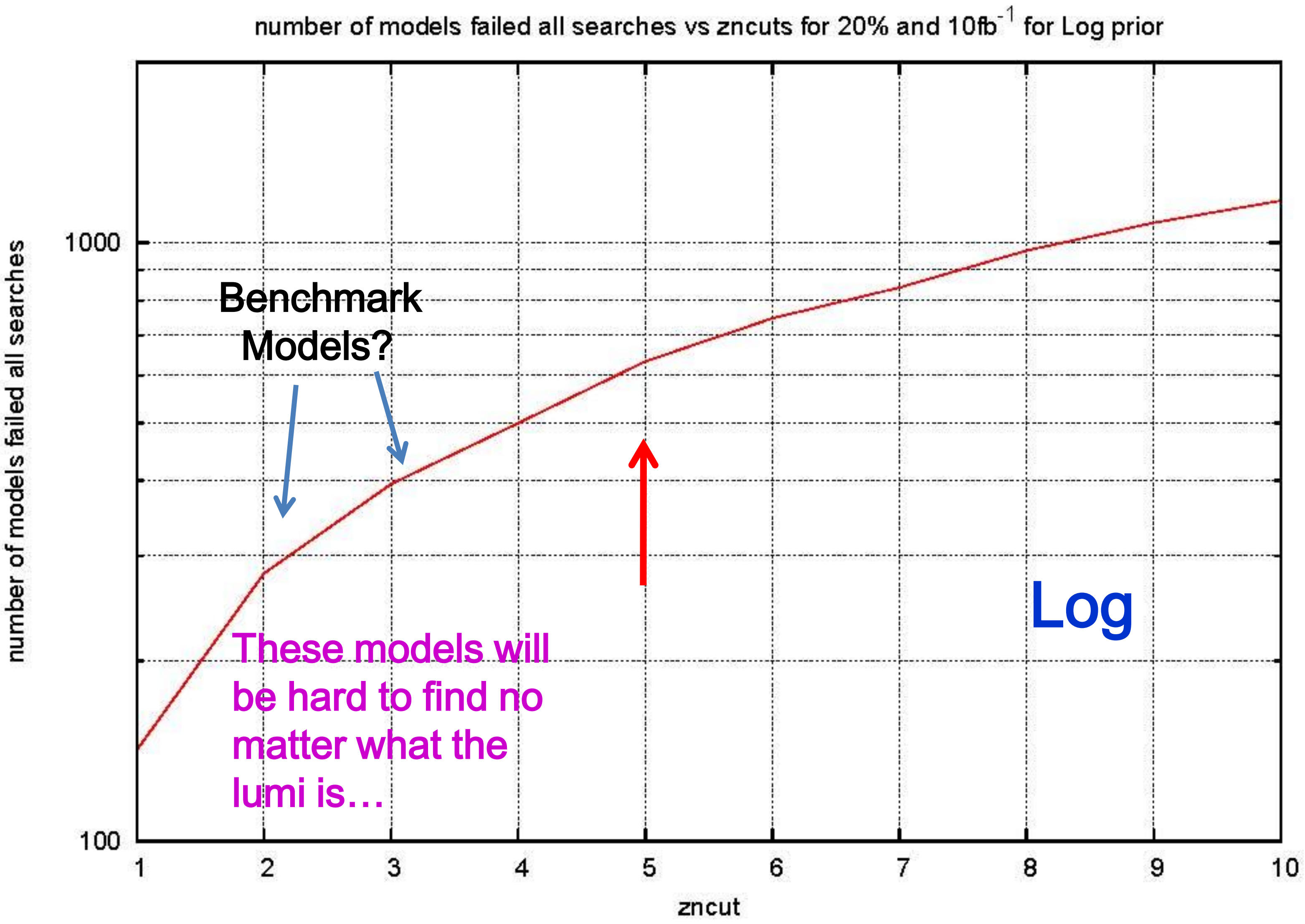
Summary & Conclusions (cont.)

- Searches in other channels, e.g., stable charged particles & Higgs, will play an important role in covering our pMSSM model set space

- Quite commonly small changes in the sparticle spectrum can lead to very significant changes in signal rates & will then substantially alter the chances for SUSY discovery for our models

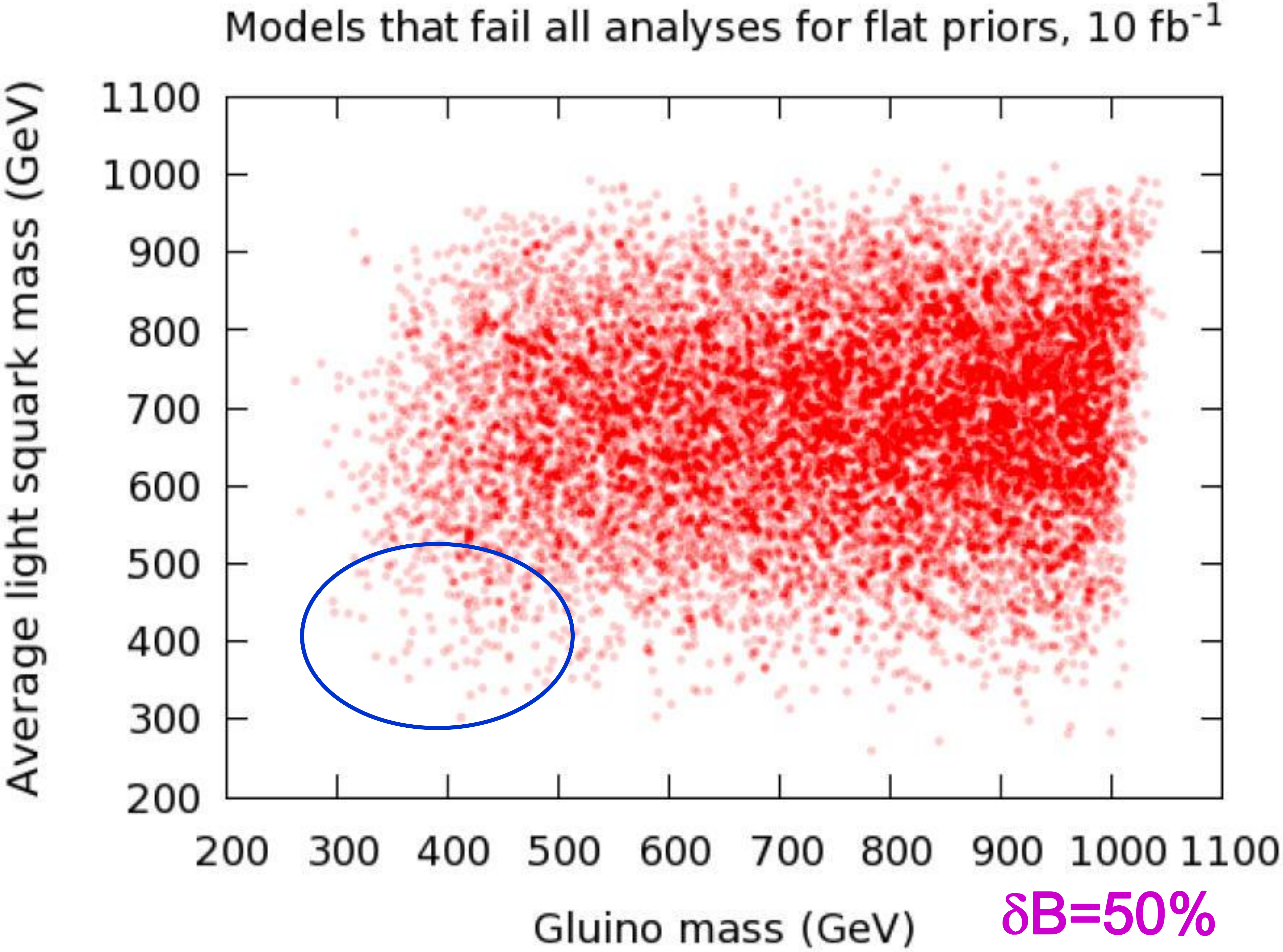
BACKUP SLIDES

This same behavior is observed in the Log prior case



Benchmark Models?

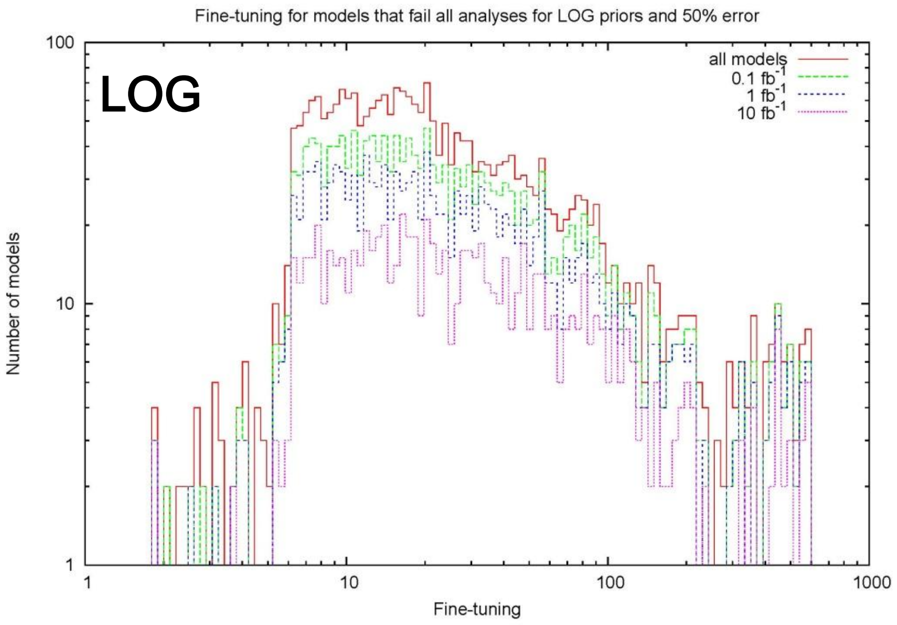
These models will be hard to find no matter what the lumi is…

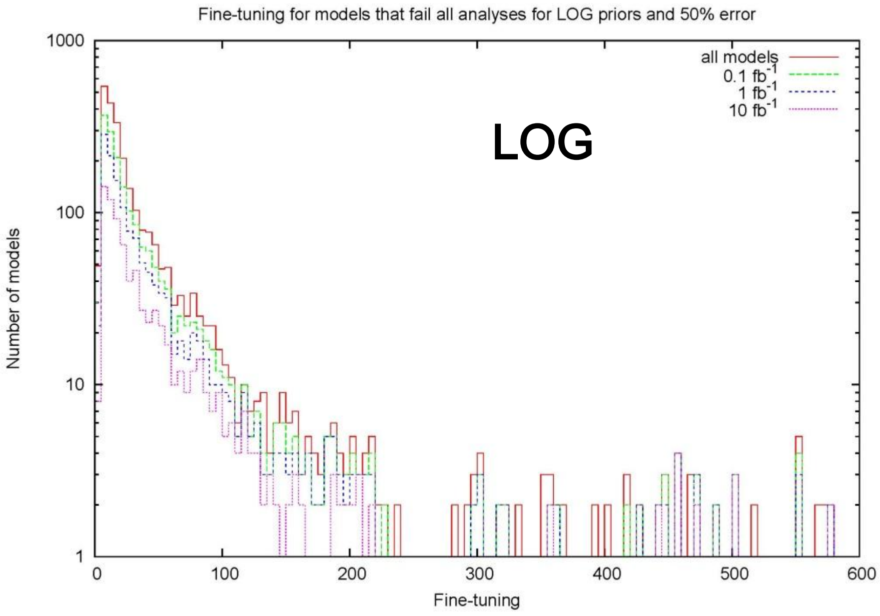

Models that fail all analyses for flat priors, 10 fb^{-1}
Average light squark mass (GeV)
1100
1000
900
800
700
600
500
400
300
200
200
300
400
500
600
700
800
900
1000
1100
Gluino mass (GeV)

δB=50%

→ Models w/ low tuning do appear to ‘suffer’ more than those w/ larger values from null SUSY searches

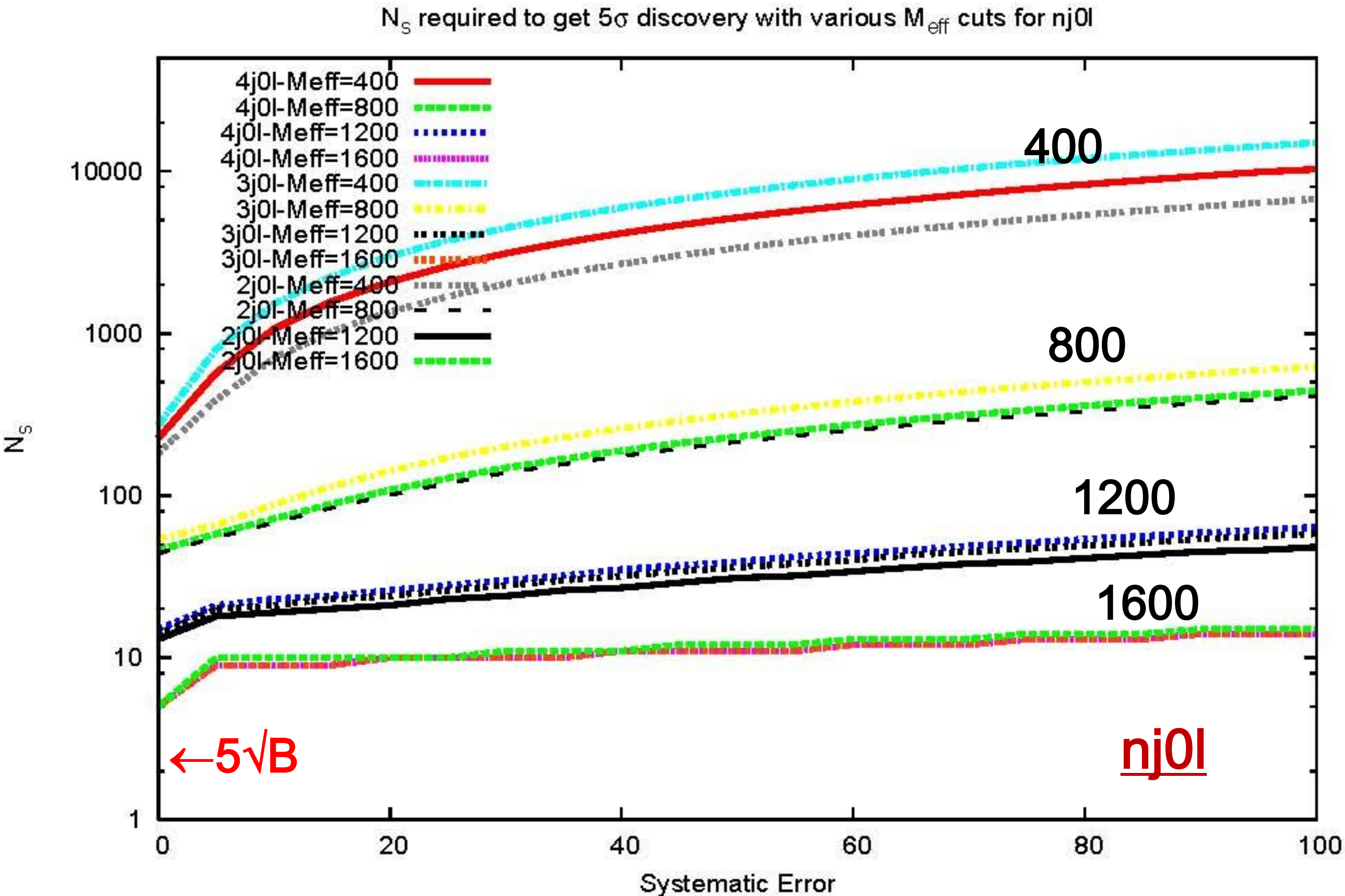
- The amount of fine tuning in the LOG prior set is somewhat less influenced by null ATLAS searches due to spectrum differences , i.e., compression plus mass stretch-out



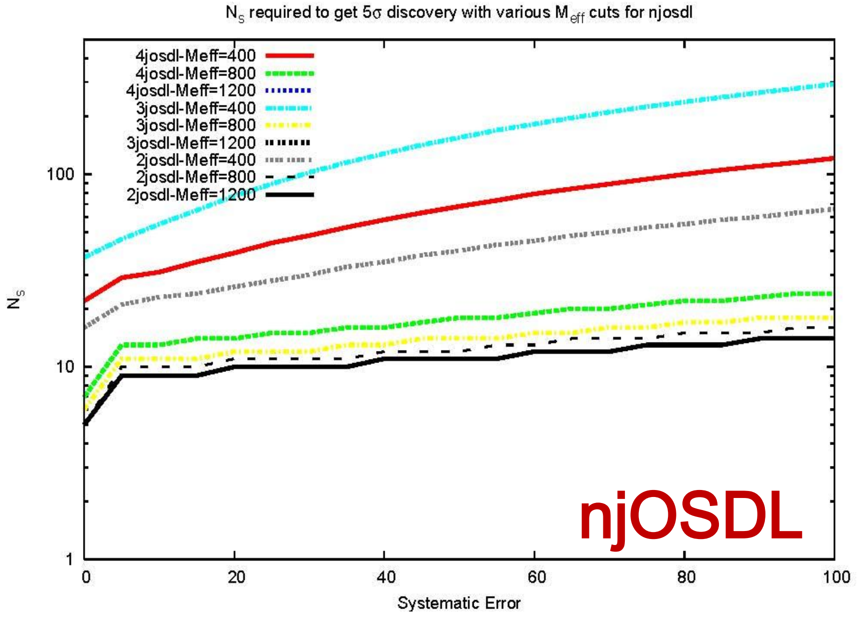


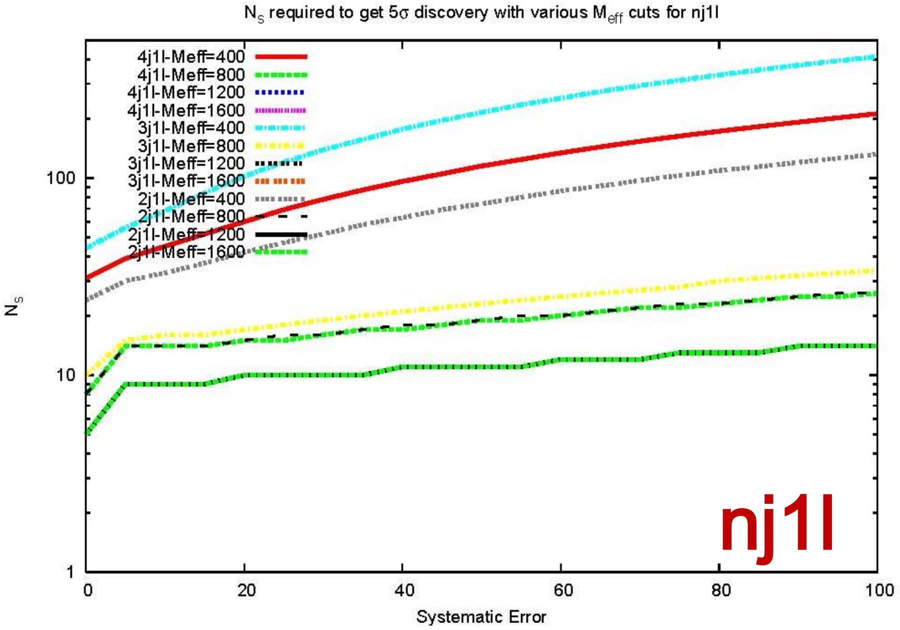
- How many signal events do we need to reach S=5?

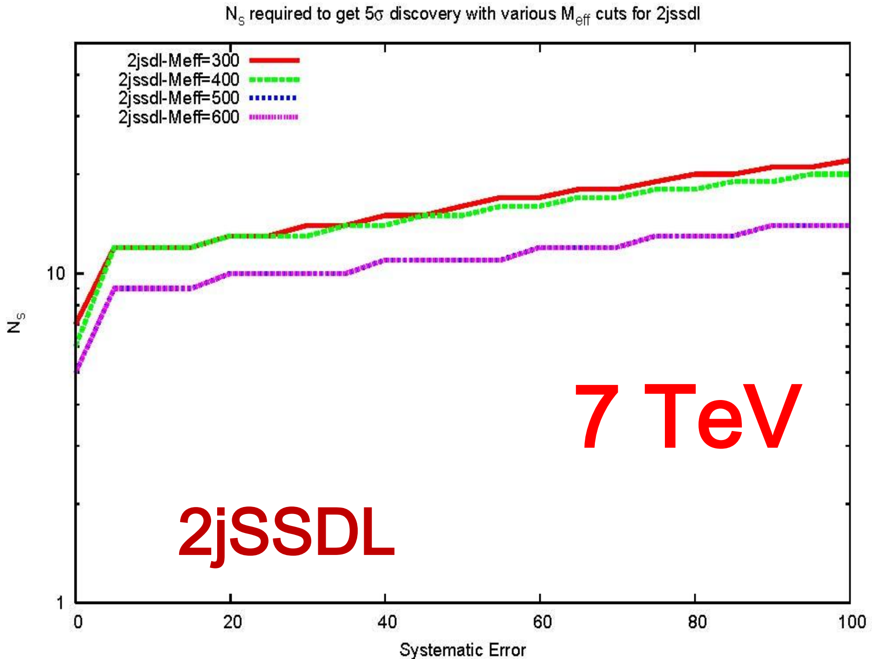
Depends on the M_{eff} ‘cut’ which is now ‘optimized’ @ 7 TeV

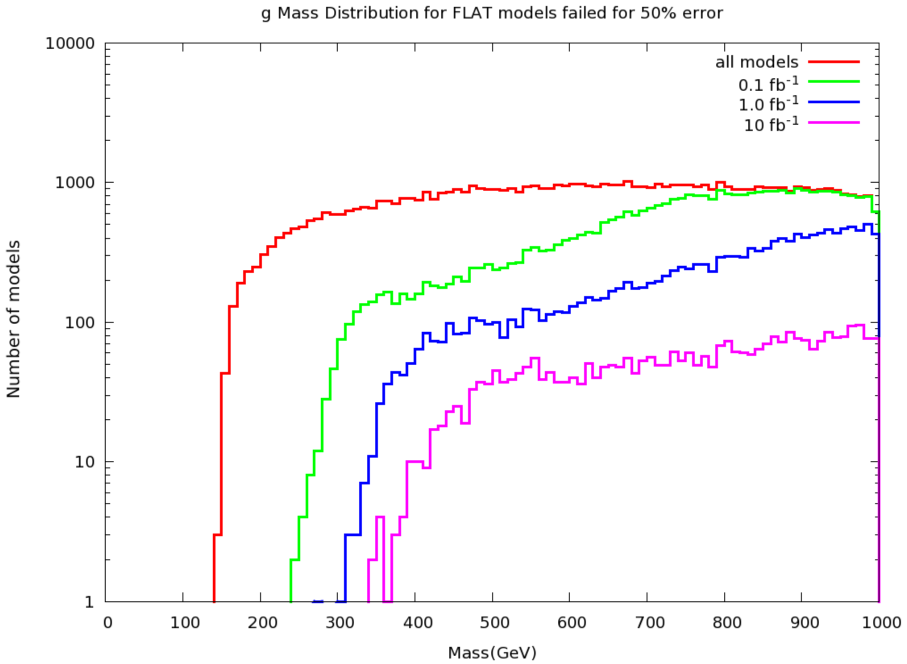


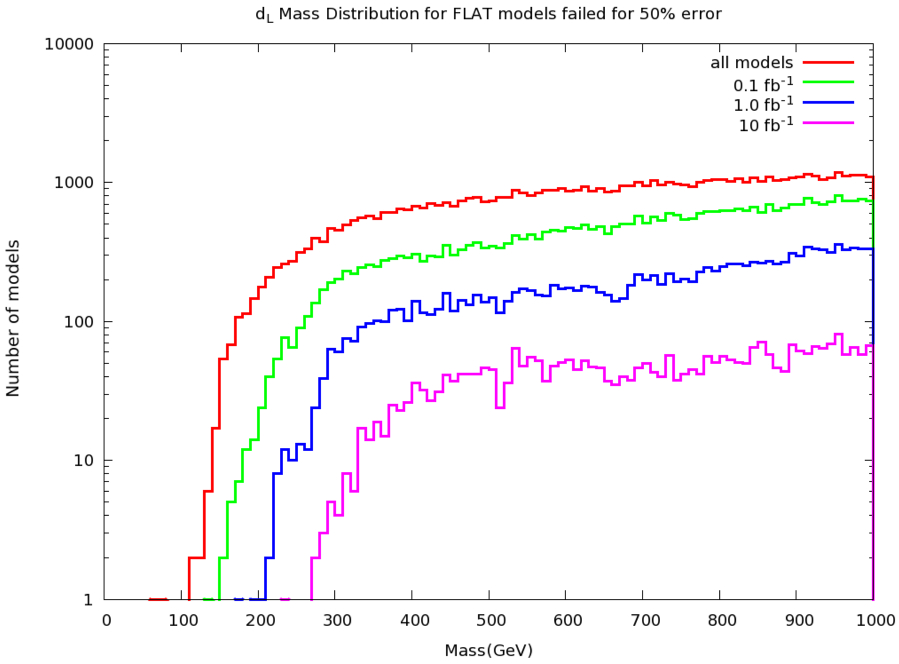
- The size of the background systematic error can play a very significant role in the pMSSM model coverage especially for nj(0,1)l …

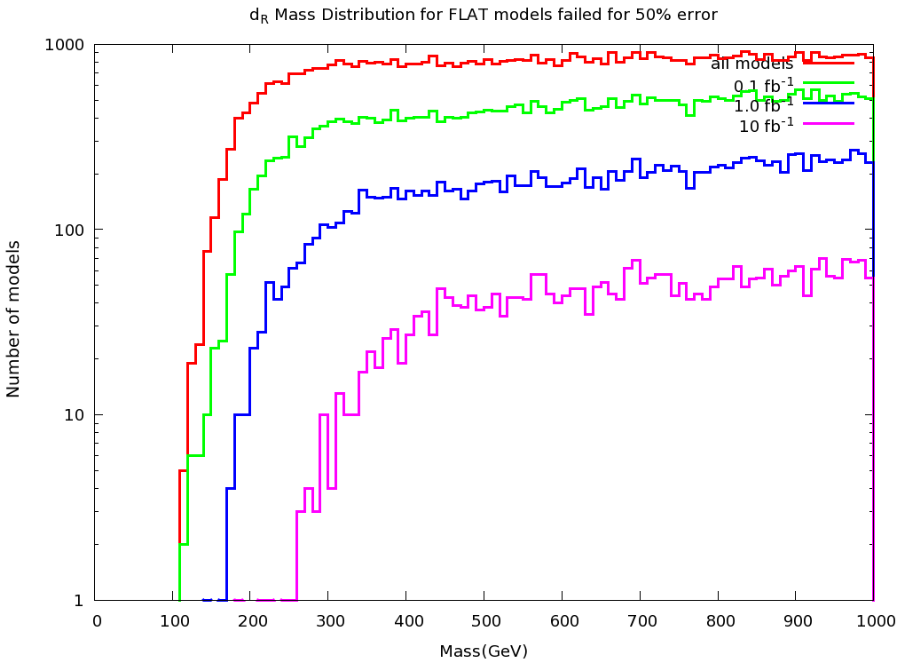

N_S required to get 5σ discovery with various M_{eff} cuts for njosdl

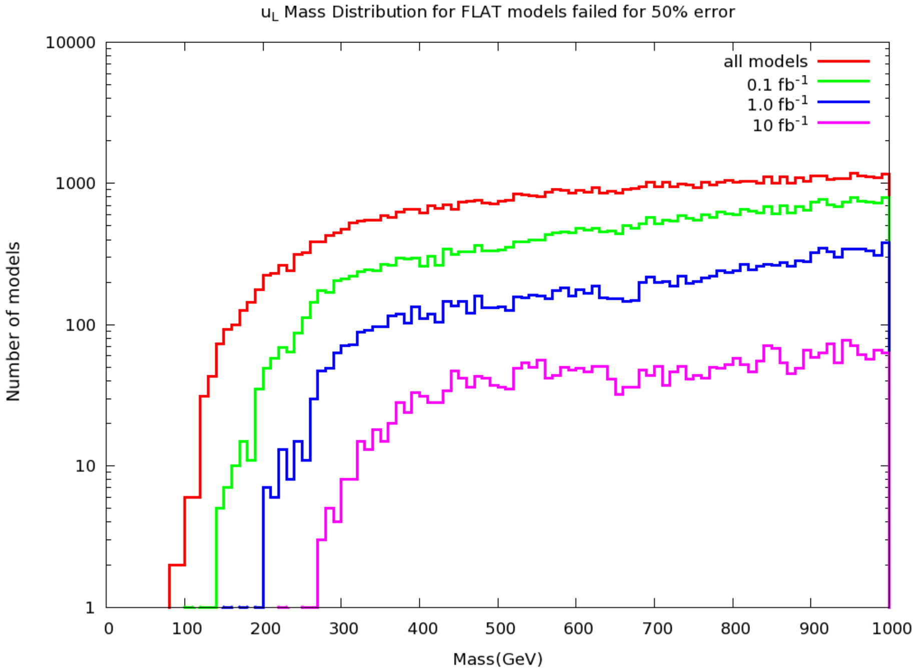

N_S required to get 5σ discovery with various M_{eff} cuts for nj1l

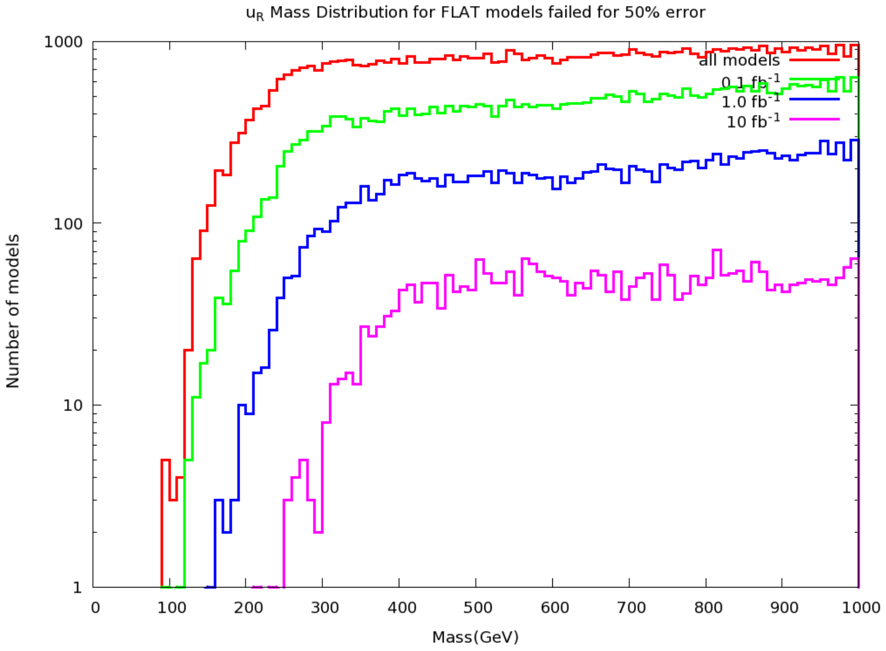

N_S required to get 5σ discovery with various M_{eff} cuts for 2jssdl

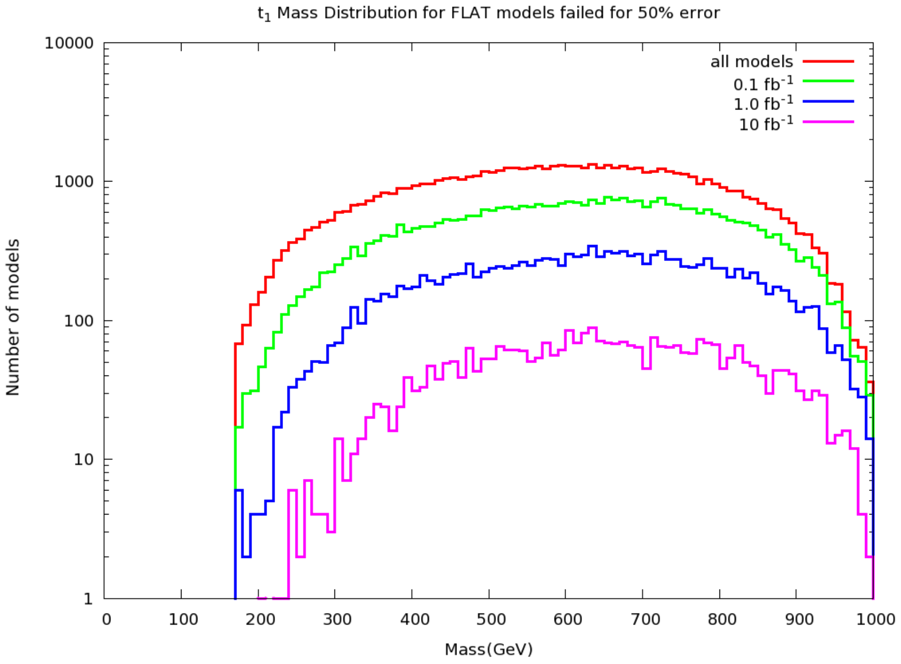

g Mass Distribution for FLAT models failed for 50% error
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}

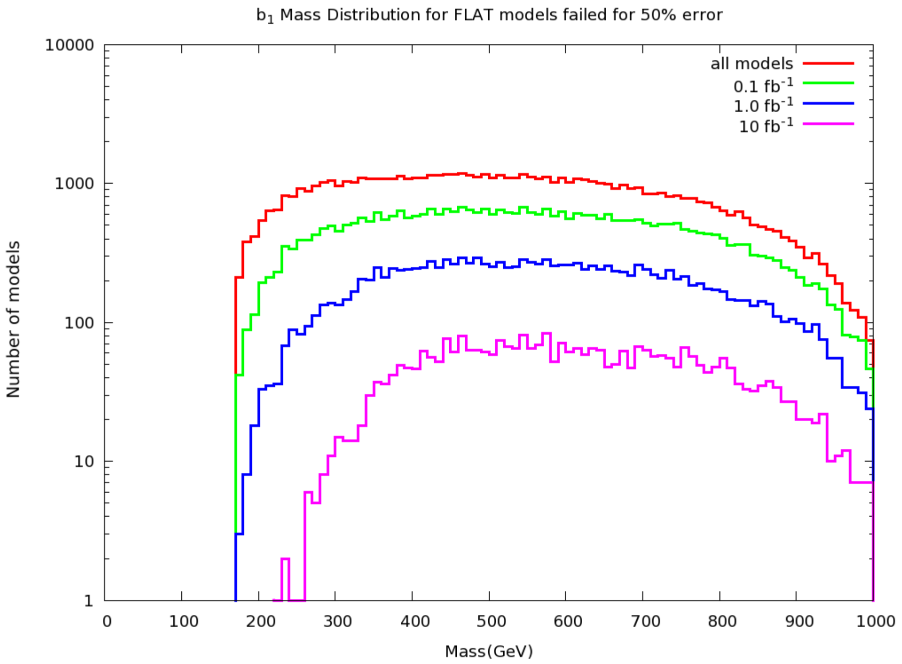

d_L Mass Distribution for FLAT models failed for 50% error
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}

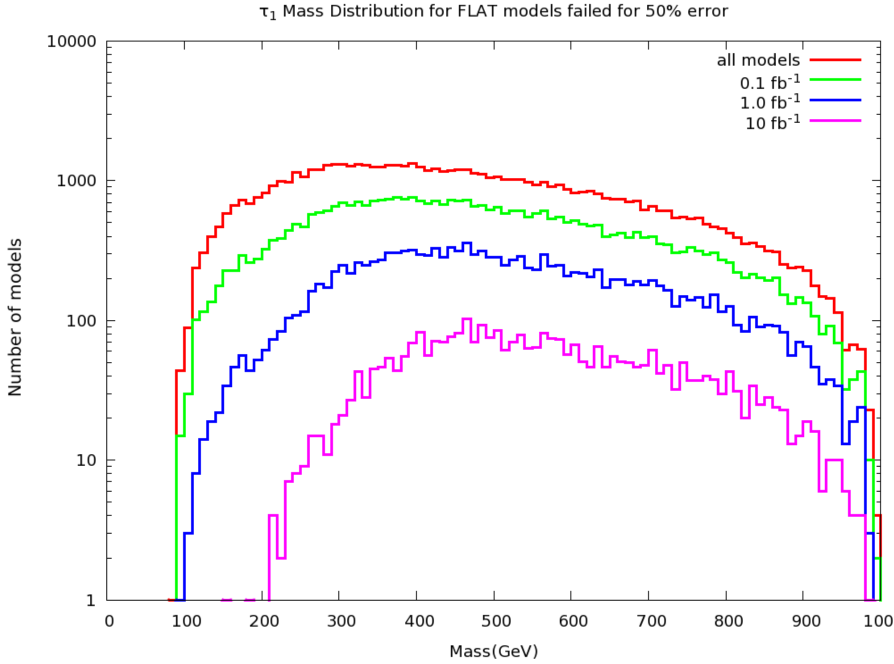

d_R Mass Distribution for FLAT models failed for 50% error
Number of models
Mass(GeV)
1
10
100
1000
0
100
200
300
400
500
600
700
800
900
1000
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}

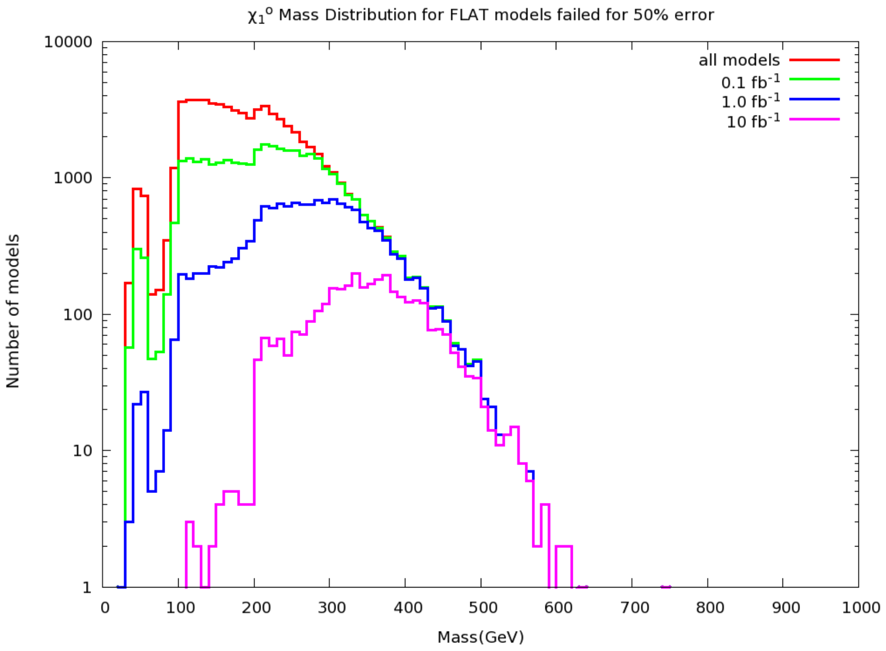

u_L Mass Distribution for FLAT models failed for 50% error
Number of models
Mass(GeV)
1
10
100
1000
10000
0
100
200
300
400
500
600
700
800
900
1000
all models
0.1 fb^{-1}
1.0 fb^{-1}
10 fb^{-1}


u_R Mass Distribution for FLAT models failed for 50% error

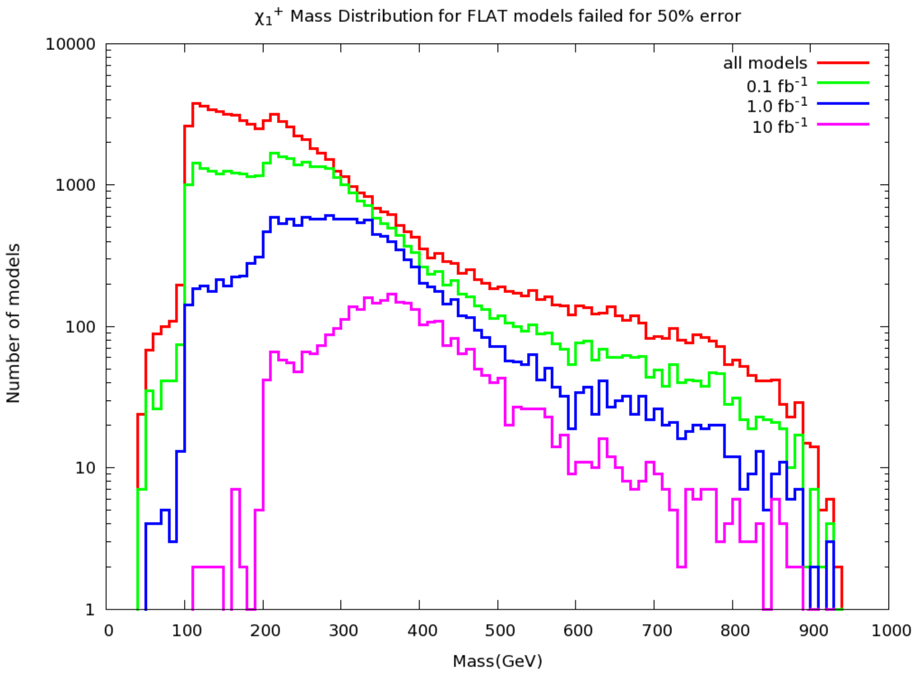

t_1 Mass Distribution for FLAT models failed for 50% error


b_1 Mass Distribution for FLAT models failed for 50% error

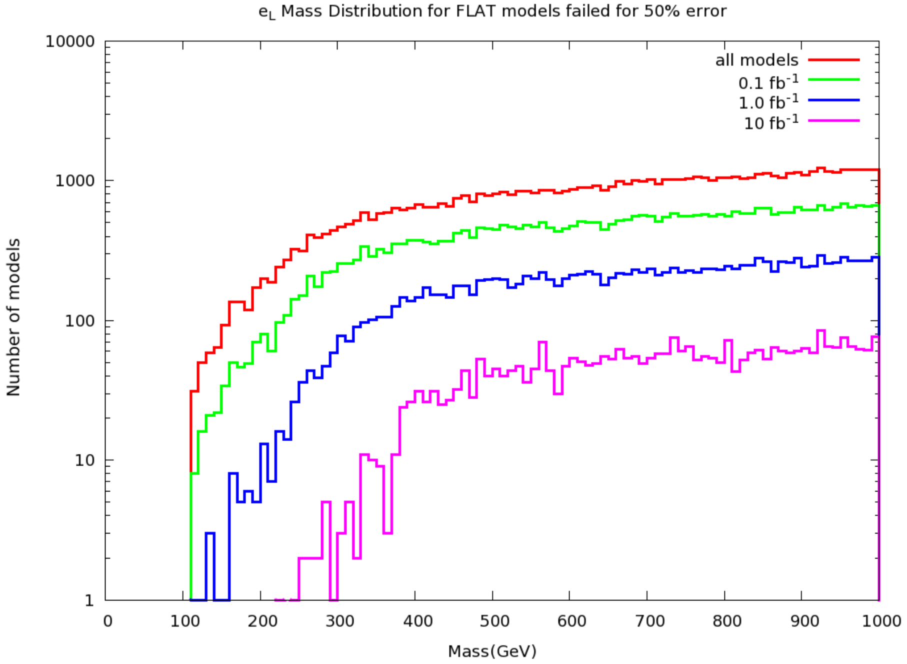

τ_1 Mass Distribution for FLAT models failed for 50% error



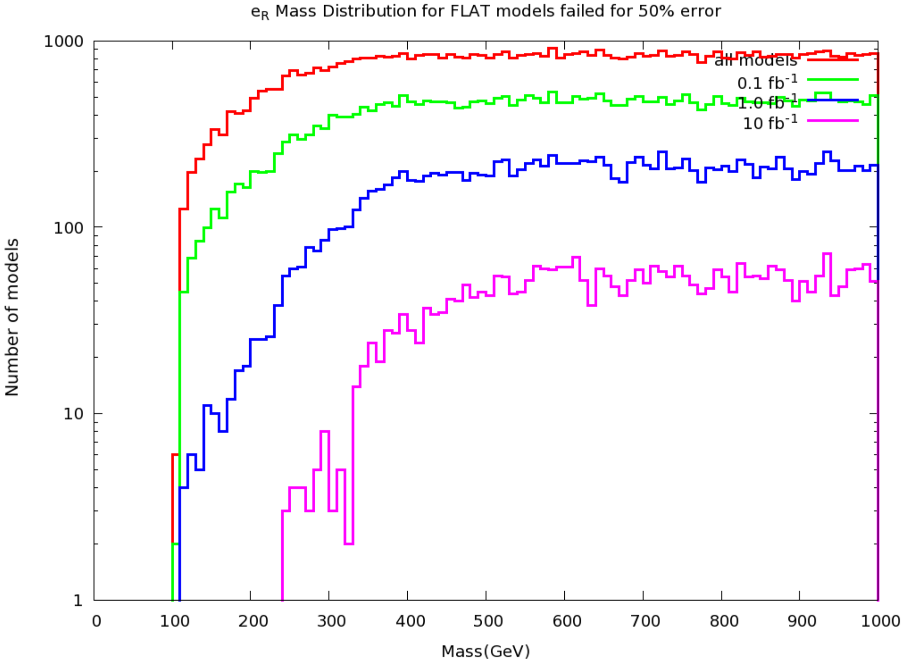
χ_1^o Mass Distribution for FLAT models failed for 50% error



χ_1^+ Mass Distribution for FLAT models failed for 50% error



e_L Mass Distribution for FLAT models failed for 50% error



e_R Mass Distribution for FLAT models failed for 50% error