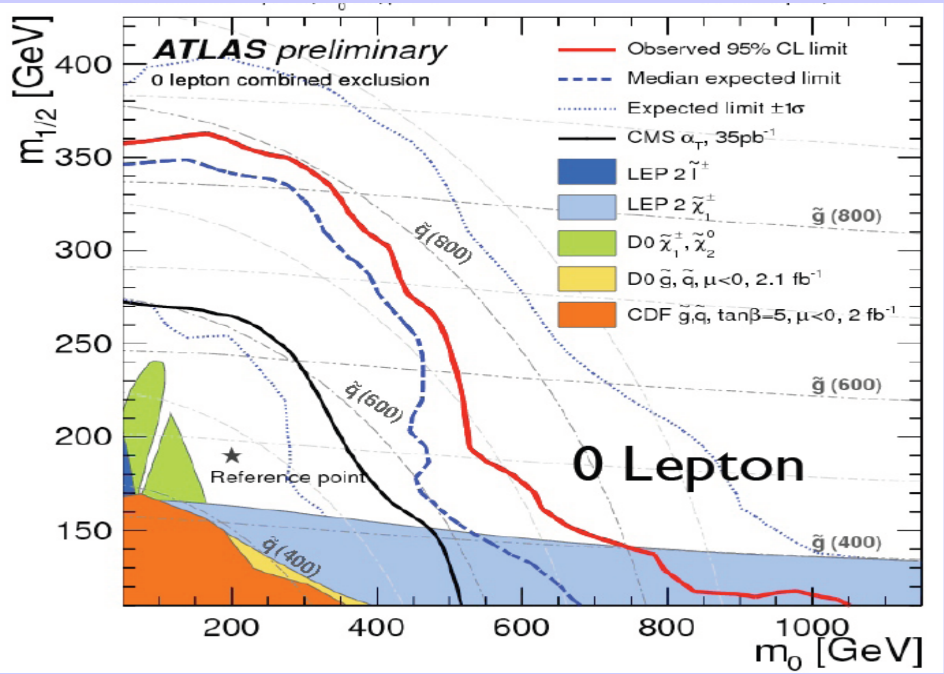
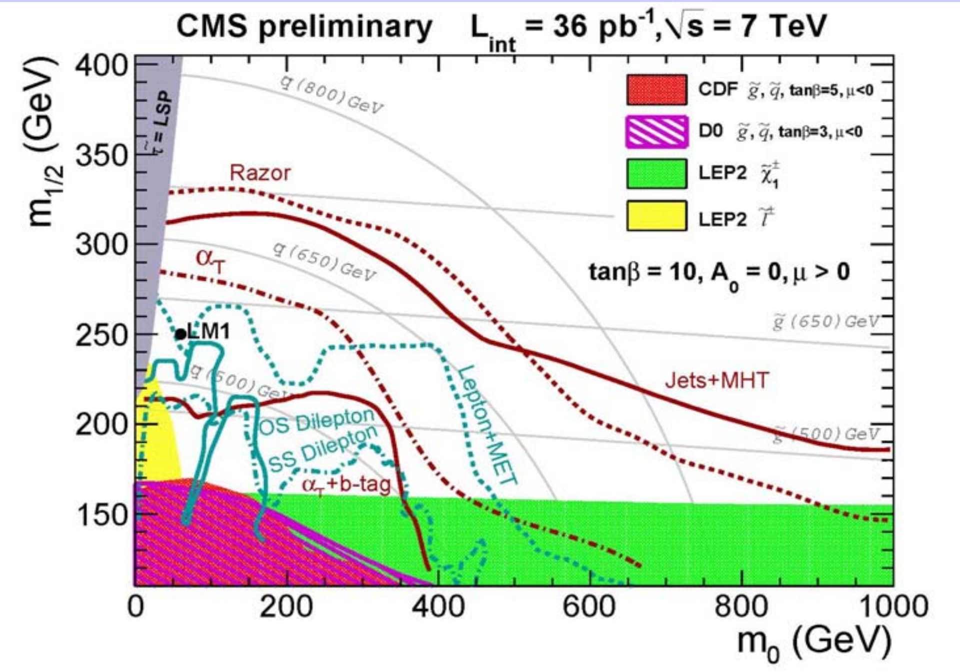
Supersymmetry Without Prejudice

Conley, Gainer, JLH, Le, Rizzo , 1103.1697,1009.2539

ATLAS & CMS have already made a big dent!





- 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 approaches…

Supersymmetry With or Without Prejudice?

- The Minimal Supersymmetric Standard Model has ~120 parameters
- Studies/Searches incorporate simplified versions
  - Theoretical assumptions @ GUT scale
  - Assume specific SUSY breaking scenarios (mSUGRA, GMSB, AMSB…)
  - Small number of well-studied benchmark points
- Studies incorporate various data sets

- Does this adequately describe the true breadth of the MSSM and all its possible signatures?

- The LHC is on, era of speculation will end, and we need to be ready for all possible signals

More Comprehensive MSSM Analysis

Berger, Gainer, JLH, Rizzo, arXiv:0812.0980

- Study Most general CP-conserving MSSM
  - Minimal Flavor Violation
  - Lightest neutralino is the LSP
  - First 2 sfermion generations are degenerate w/ negligible Yukawas
  - No GUT, high-scale, or SUSY-breaking assumptions

- $\Rightarrow$ pMSSM: 19 real, weak-scale parameters

  scalars:

  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}

  gauginos: M_1, M_2, M_3

  tri-linear couplings: A_b, A_t, A_τ

  Higgs/Higgsino: μ, M_A, $\tan\beta$

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

Perform 2 Random Scans

Linear Priors

10^7 points – emphasize moderate masses

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

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

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

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

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

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

Log Priors

$2\text{x}10^6$ points – emphasize lower masses and extend to higher masses

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

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

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

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

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

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

Absolute values account for possible phases
only Arg $(M_i\ \mu)$ and Arg $(A_f\ \mu)$ are physical

Set of Experimental Constraints

- Theoretical spectrum Requirements (no tachyons, etc)
- Precision measurements:
  - $\Delta\rho$, $\Gamma(Z\rightarrow$ invisible)
  - $\Delta(g-2)\mu$
- Flavor Physics
  - $b \rightarrow s\,\gamma$, $B \rightarrow \tau\nu$, $B_s \rightarrow \mu\mu$, Meson-Antimeson Mixing
- Dark Matter
  - Direct Searches: CDMS, XENON10, DAMA, CRESST I
  - Relic density: $\Omega h2 < 0.1210 \rightarrow$ 5yr WMAP data
- Collider Searches: complicated with many caveats!
  - LEPII: Neutral & Charged Higgs searches, Sparticle production
    Stable charged particles
  - Tevatron: Squark & gluino searches, Trilepton search
    Stable charged particles, BSM Higgs searches

Tevatron Squark & Gluino Search

2,3,4 Jets + Missing Energy (D0)

TABLE I: Selection criteria for the three analyses (all energies and momenta in GeV); see the text for further details.

Preselection Cut	All Analyses		
$\not{E}_T$	≥ 40		
|Vertex z pos|	< 60 cm		
Acoplanarity	$< 165°$		
Selection Cut	**"dijet"**	**"3-jets"**	**"gluino"**
Trigger	dijet	multijet	multijet
jet$_1$ p_T [a]	≥ 35	≥ 35	≥ 35
jet$_2$ p_T [a]	≥ 35	≥ 35	≥ 35
jet$_3$ p_T [b]	–	≥ 35	≥ 35
jet$_4$ p_T [b]	–	–	≥ 20
Electron veto	yes	yes	yes
Muon veto	yes	yes	yes
$\Delta\phi(\not{E}_T, \text{jet}_1)$	$\geq 90°$	$\geq 90°$	$\geq 90°$
$\Delta\phi(\not{E}_T, \text{jet}_2)$	$\geq 50°$	$\geq 50°$	$\geq 50°$
$\Delta\phi_{\min}(\not{E}_T, \text{any jet})$	$\geq 40°$	–	–
H_T	≥ 325	≥ 375	≥ 400
$\not{E}_T$	≥ 225	≥ 175	≥ 100

[a] First and second jets are also required to be central ($|\eta_{det}| < 0.8$), with an electromagnetic fraction below 0.95, and to have CPF0 ≥ 0.75.

[b] Third and fourth jets are required to have $|\eta_{det}| < 2.5$, with an electromagnetic fraction below 0.95.

Multiple analyses keyed to look for:
Squarks-> jet +MET
Gluinos -> 2 j + MET

Feldman-Cousins 95% CL
Signal limit: 8.34 events

For each model in our scan we run SuSpect -> SUSY-Hit -> PROSPINO -> PYTHIA -> D0-tuned PGS4 fast simulation and compare to the data

Supersymmetry Without Prejudice @ the LHC

- We passed these 70k MSSM models through the ATLAS SUSY analysis suite (designed for mSUGRA) to explore the sensitivity to this far broader class of SUSY models @ 7&14 TeV

- We employed ATLAS SM backgrounds (Thanks!!!), their associated systematic errors, search analyses/cuts, & statistical criterion for 'discovery'

- We first verify that we can reproduce ATLAS results for their benchmark mSUGRA models with our analysis in each channel

- By necessity there are some differences between us & ATLAS….

ATLAS

ISASUGRA generates spectrum & sparticle decays

NLO cross section using PROSPINO & CTEQ6M

Herwig for fragmentation & hadronization

GEANT4 for full detector sim

FEATURE

SuSpect generates spectra with SUSY-HIT# for decays

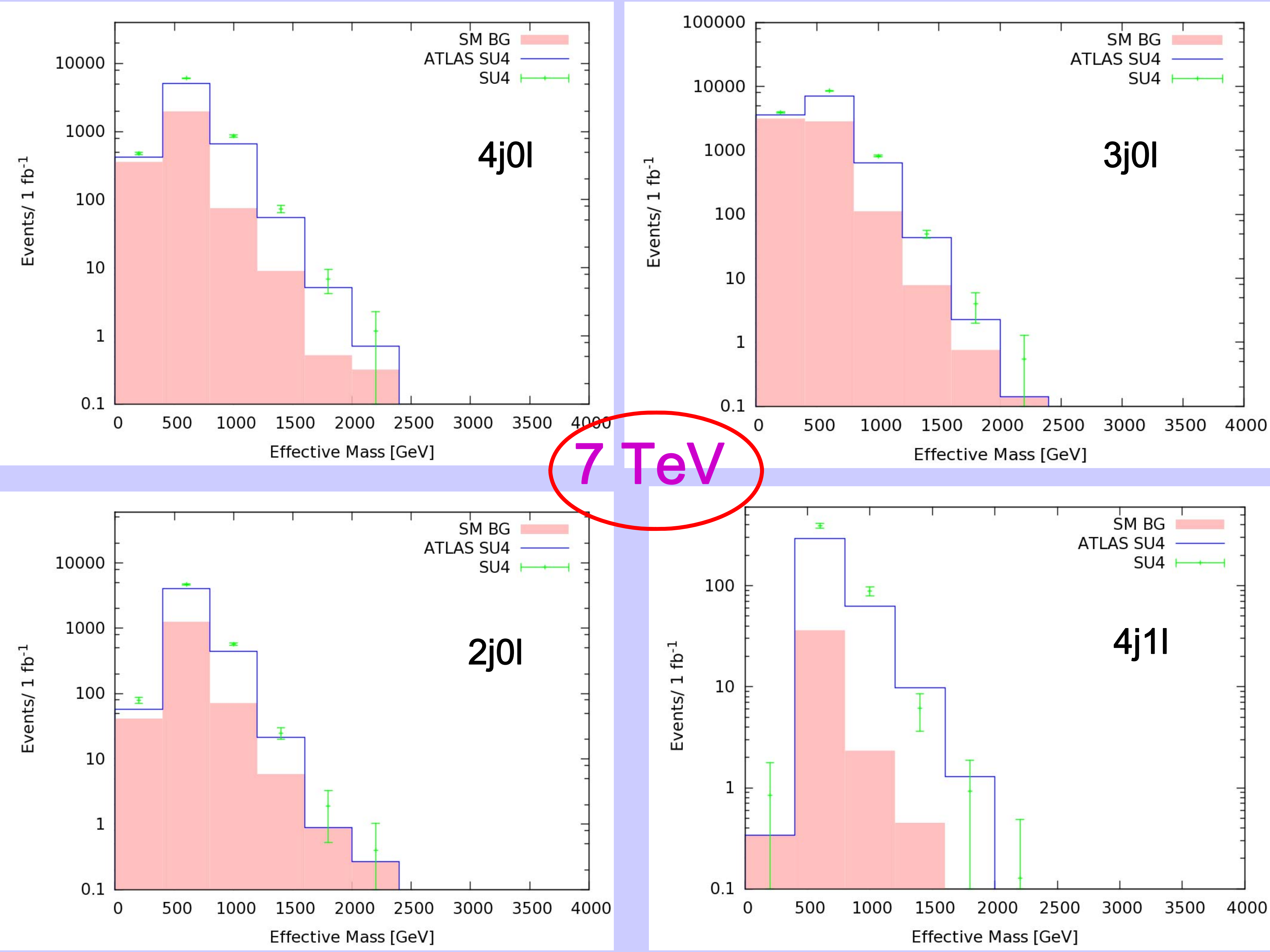
NLO cross section for ~85 processes using PROSPINO** & CTEQ6.6M

PYTHIA for fragmentation & hadronization

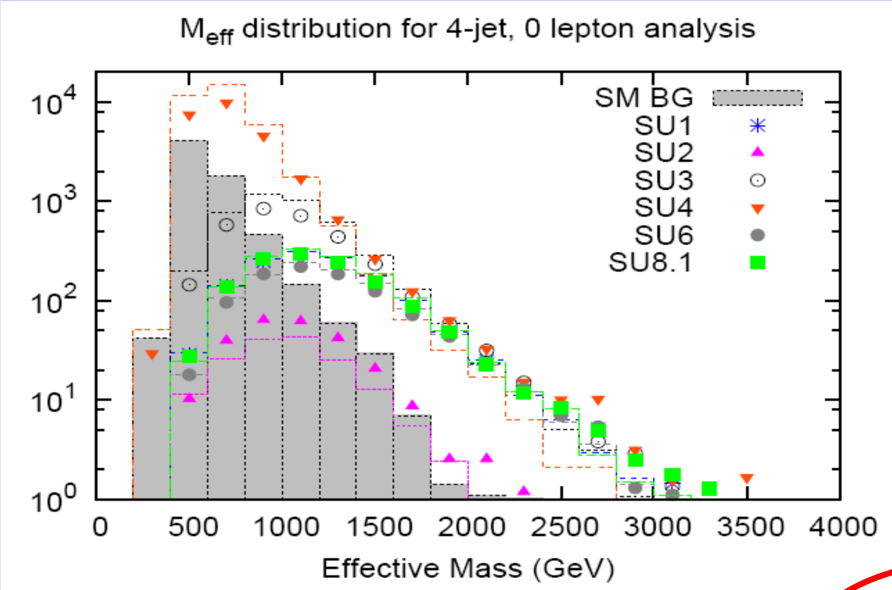
PGS4-ATLAS for fast detector sim

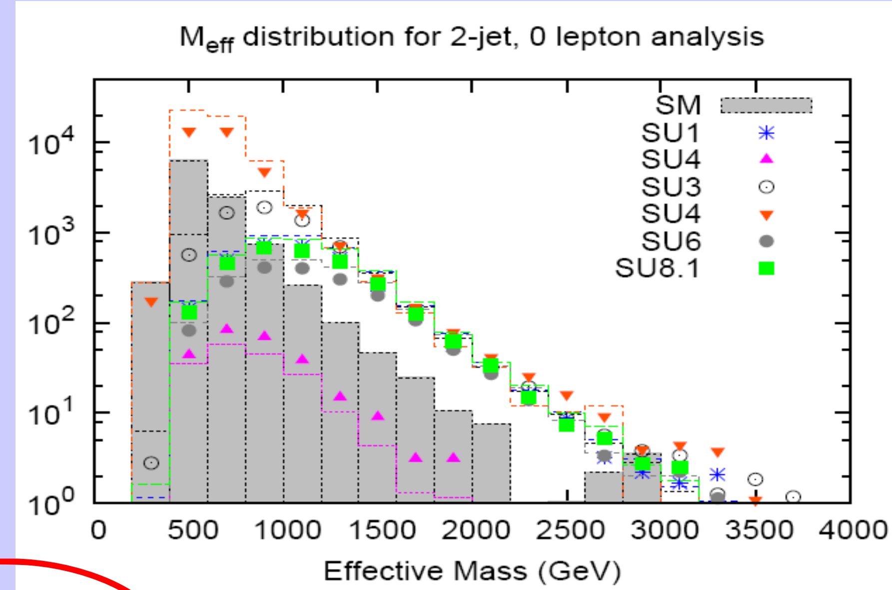
** version w/ negative K-factor errors corrected

version w/o negative QCD corrections & with 1st & 2nd generation fermion masses included as well as explicit small Δm chargino decays

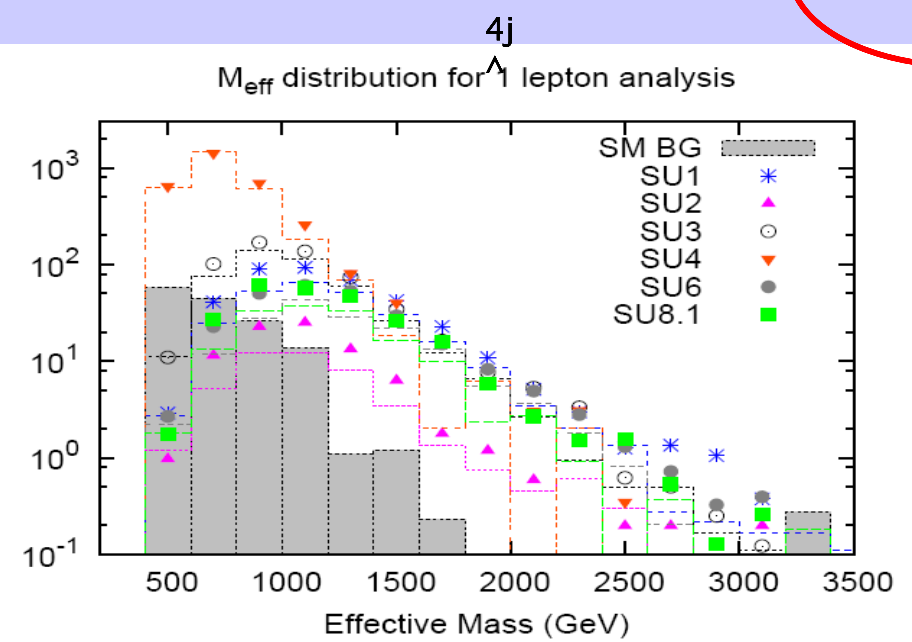


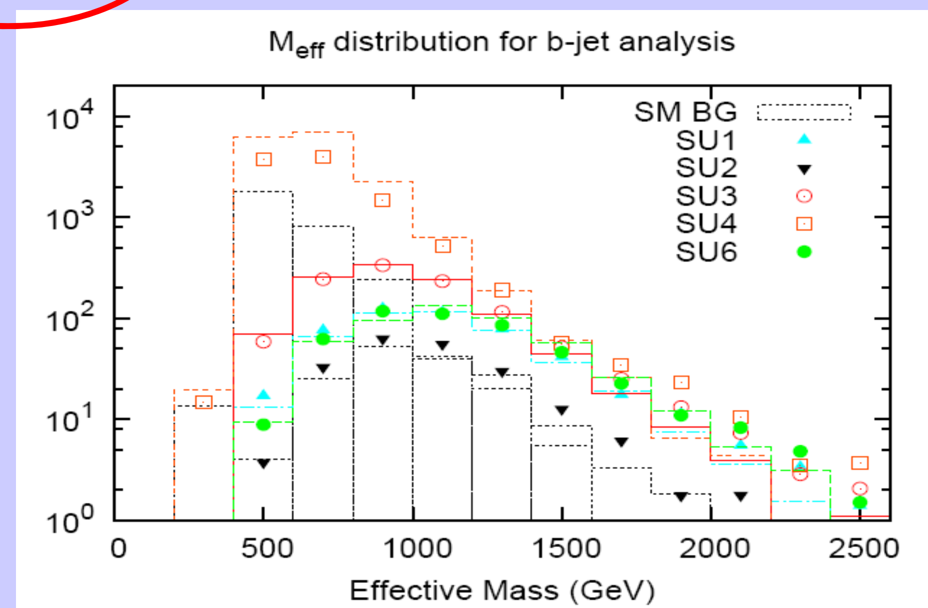
SM BG
ATLAS SU4
SU4
4j0l
Events/ 1 fb-1
Effective Mass [GeV]
3j0l
2j0l
4j1l
7 TeV


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)

→ We do quite well reproducing ATLAS 7 & 14 TeV benchmarks with some small differences due to, e.g., (modified) public code usages

Next Steps:

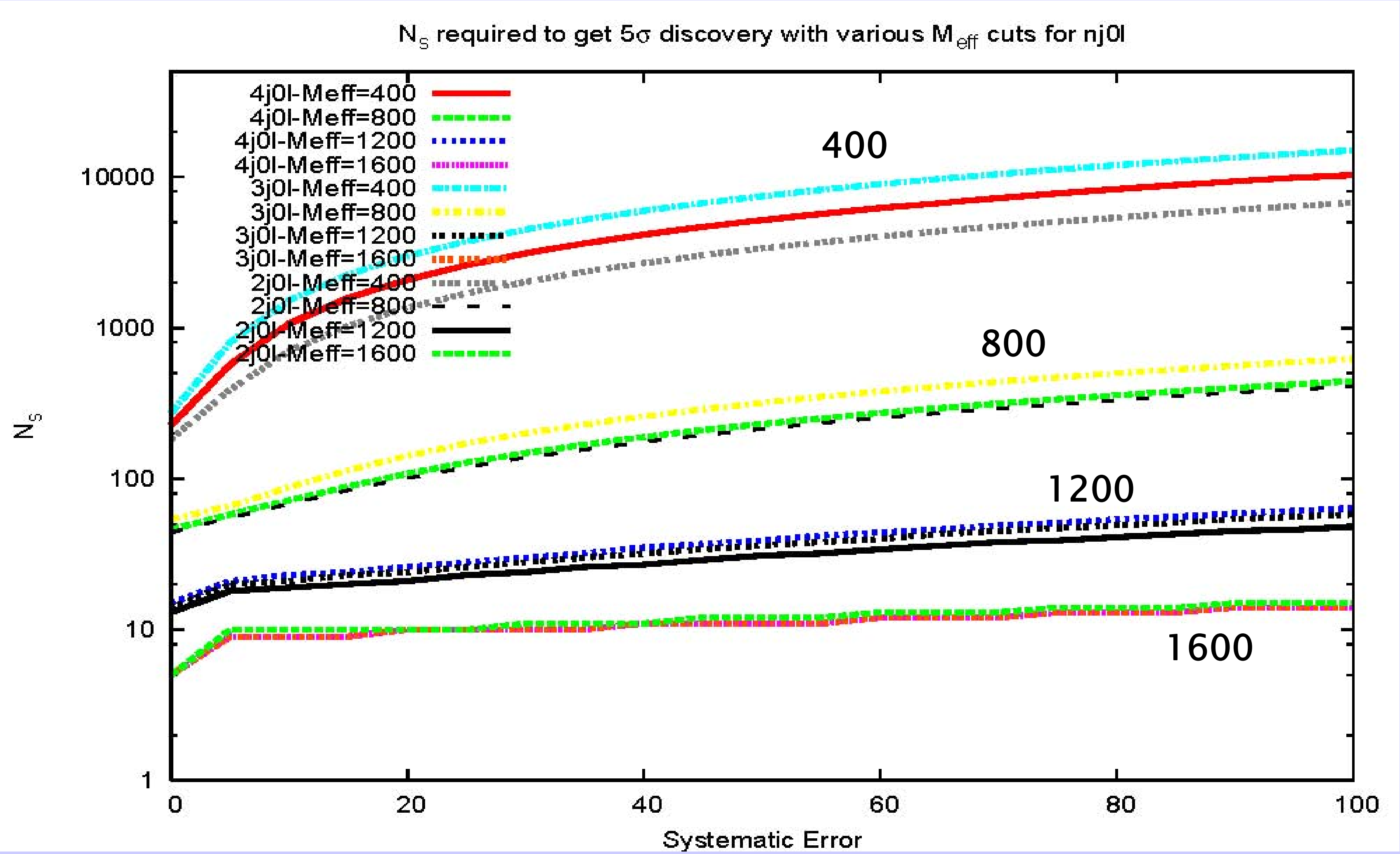
- How well do the ATLAS analyses cover these pMSSM model sets? More precisely, what fraction of these models can be discovered (or not!) by any of the various ATLAS analyses & which ones do the best?

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

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

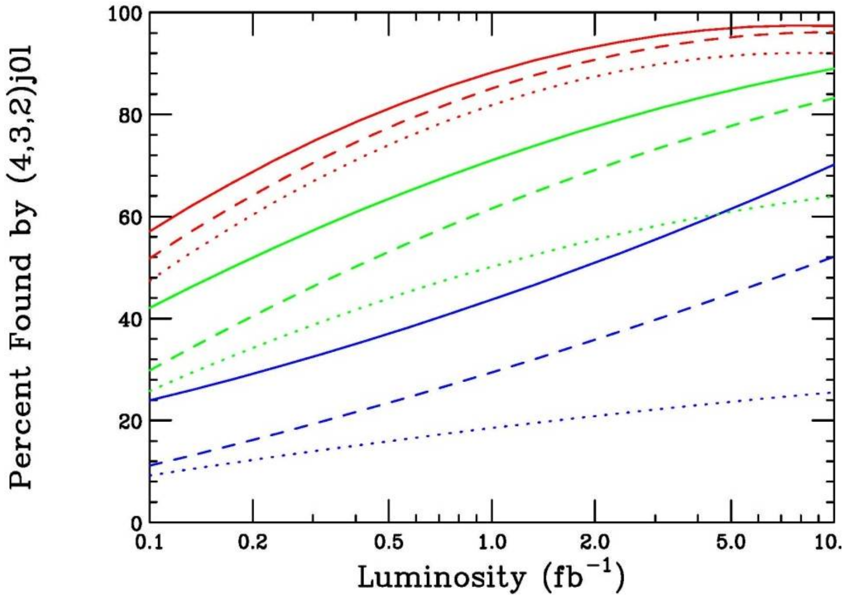
Depends on the M_{eff} cut which is now 'optimized'

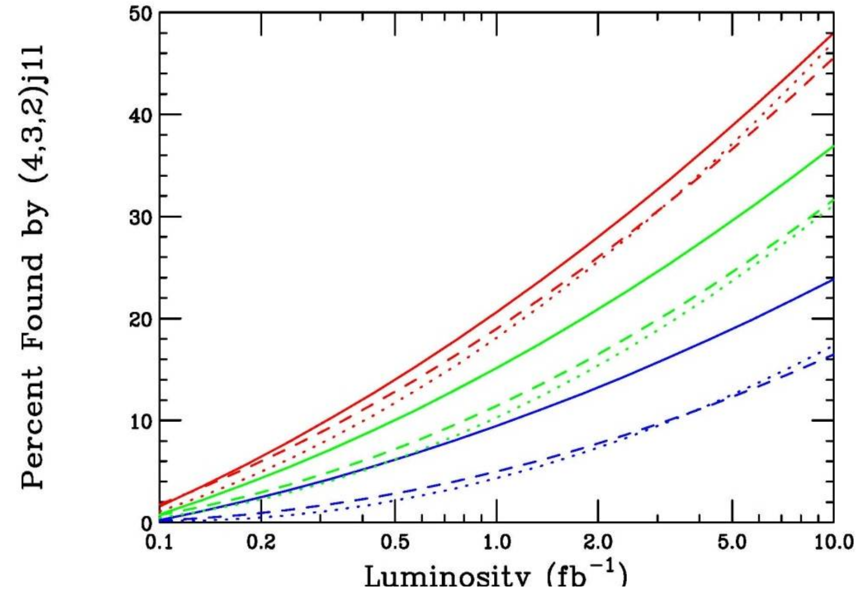
7 TeV



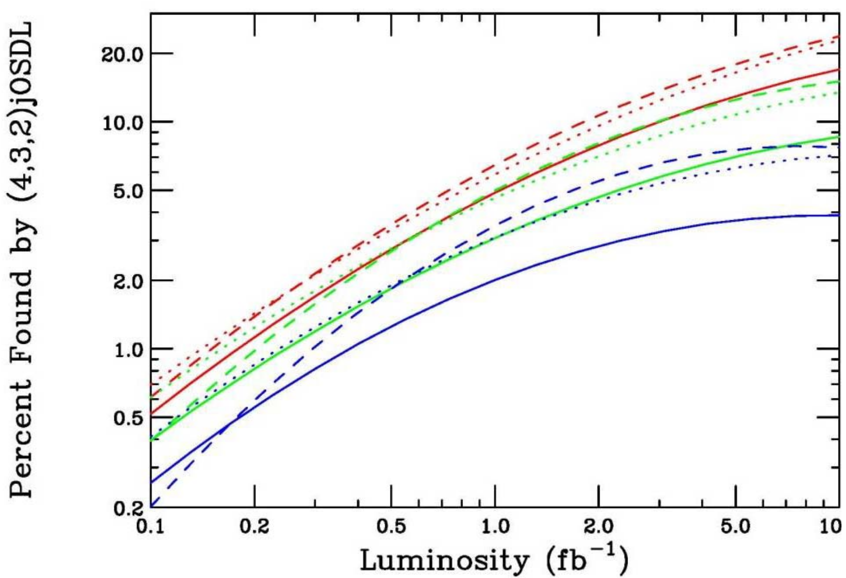
Flat-Priors

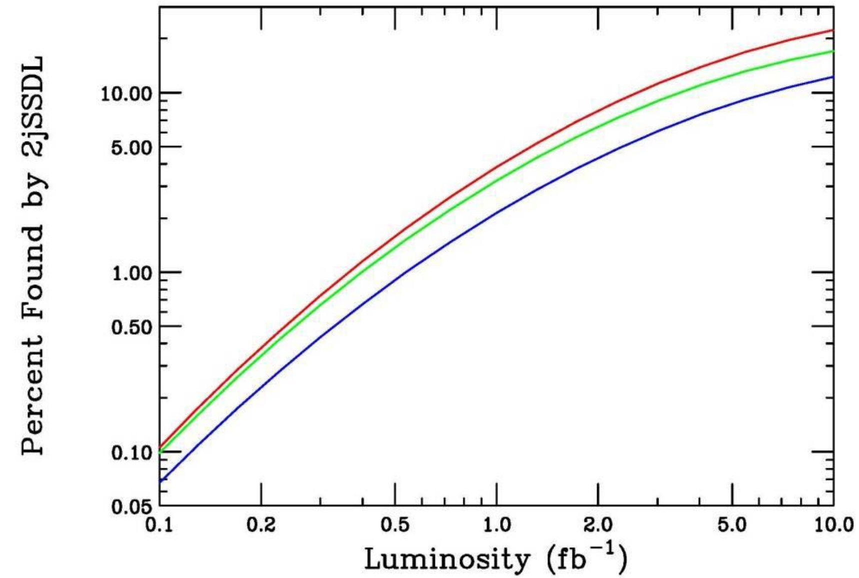
Solid=4j, dash=3j, dot=2j final states





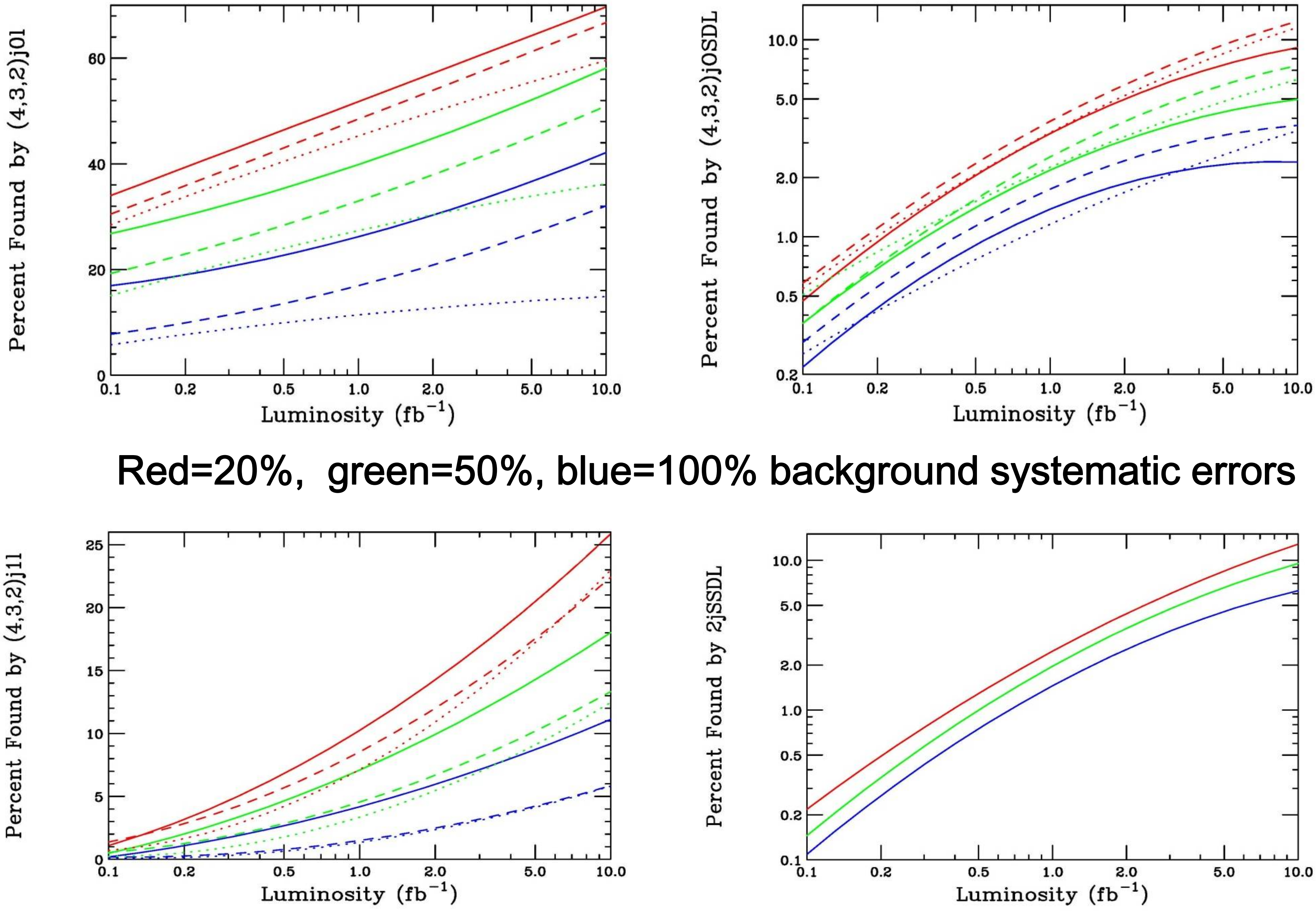
Red=20%, green=50%, blue=100% background systematic errors





Log-Priors

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



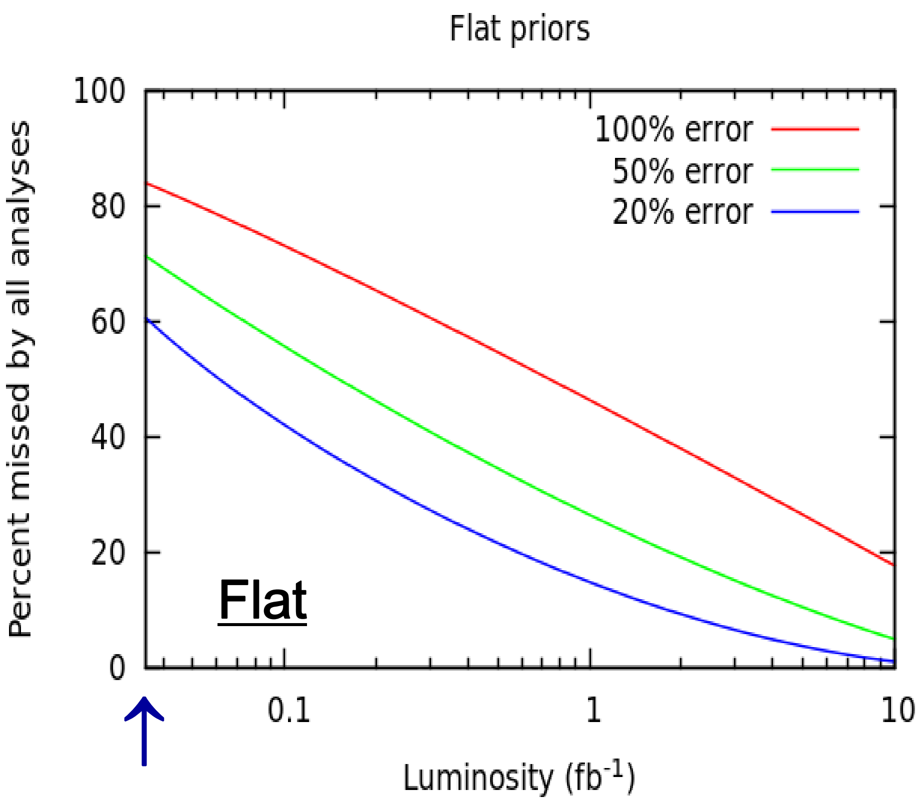
What fraction of models are found by n analyses @7 TeV assuming δB=20% ?

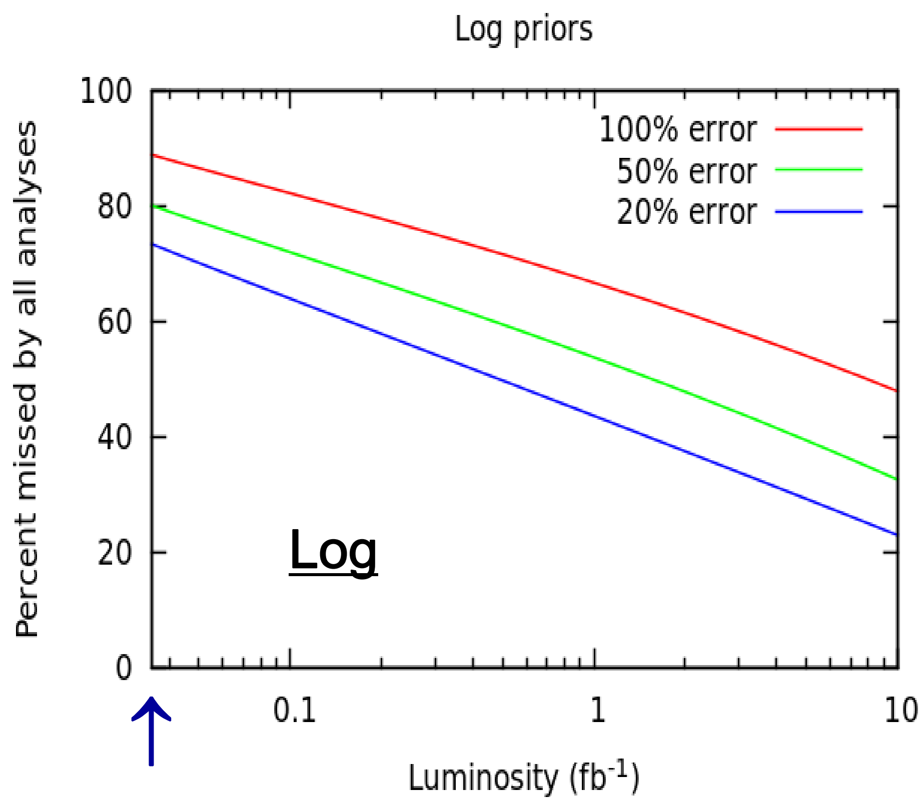
# anl.	Flat $\mathcal{L}_{0.1}$	Flat $\mathcal{L}_1$	Flat $\mathcal{L}_{10}$	Log $\mathcal{L}_{0.1}$	Log $\mathcal{L}_1$	Log $\mathcal{L}_{10}$
→ 0	38.172	7.5501	0.9965	63.64	43.988	22.92
1	9.2928	4.1988	0.90862	5.376	4.8674	5.8482
2	8.7432	4.6665	1.6102	3.6687	5.6665	6.0298
3	41.836	59.878	39.573	26.008	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

The results are highly sensitive to the background uncertainty

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 !

These figures emphasize the importance of decreasing background systematic errors to obtain good pMSSM model coverage. For Flat priors we see that

$L=5(10)\ fb^{-1}$ and $\delta B=100\%$ is 'equivalent' to

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

$L=0.20(0.39)\ fb^{-1}$ and $\delta B=20\%$ (x ~25) !!

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

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

$\delta B = 20\%$

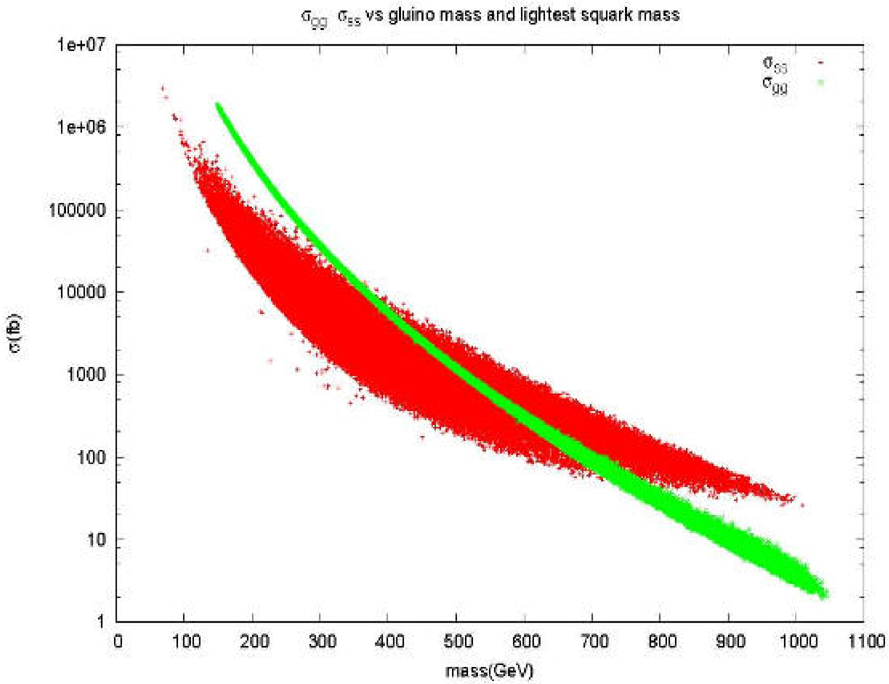
4j0l is the most powerful analysis…

The Undiscovered SUSY

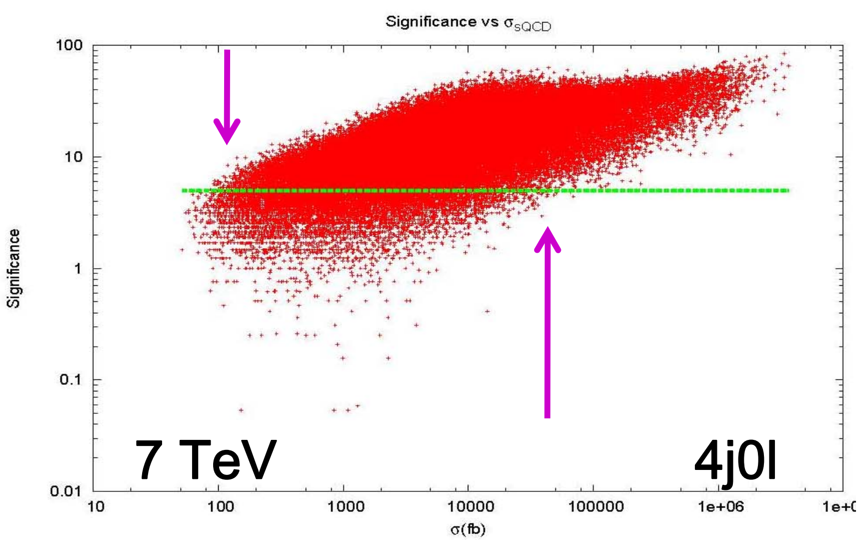
Why Do Models Get Missed by ATLAS?

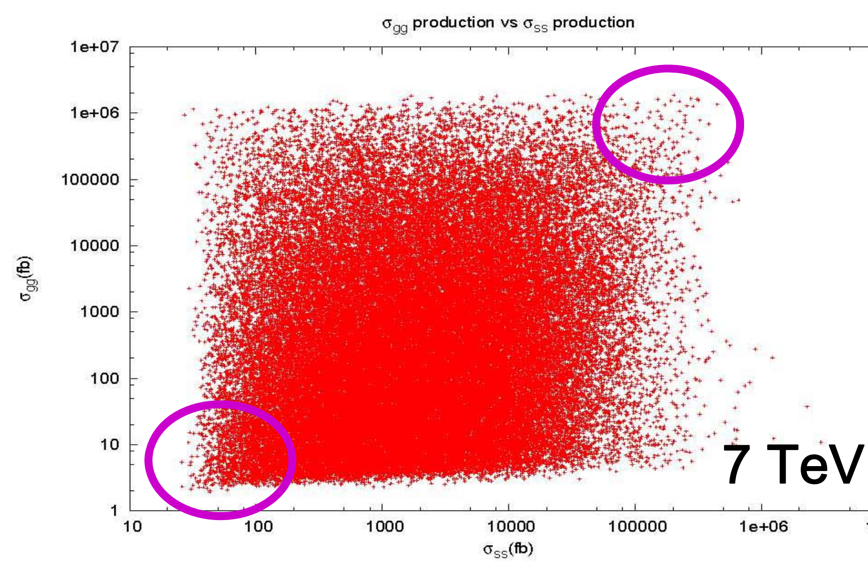
The most obvious things to look at first are :

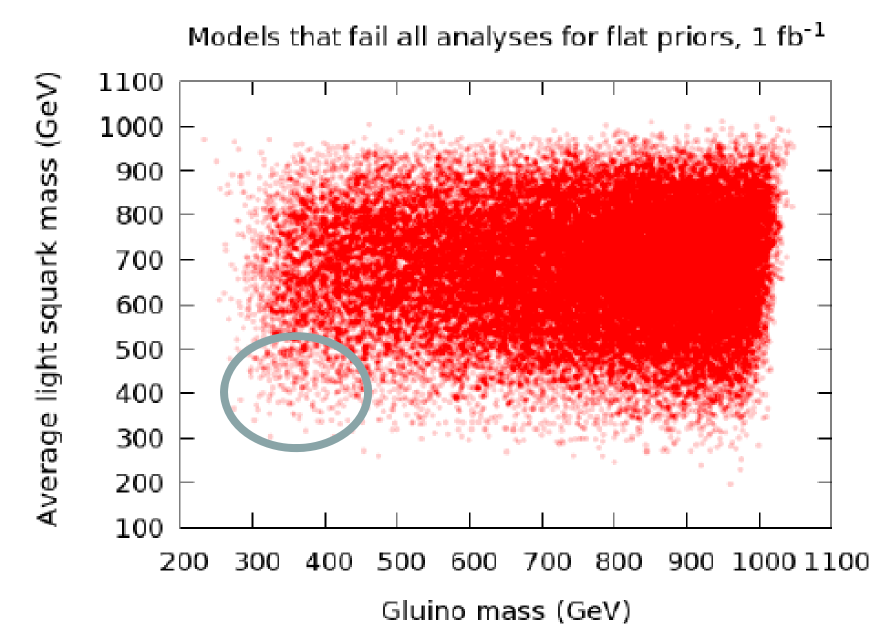
- small signal rates due to suppressed σ's which can be correlated with large sparticle masses
- small mass splittings w/ the LSP (compressed spectra)
- decay chains ending in stable charged sparticles



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.

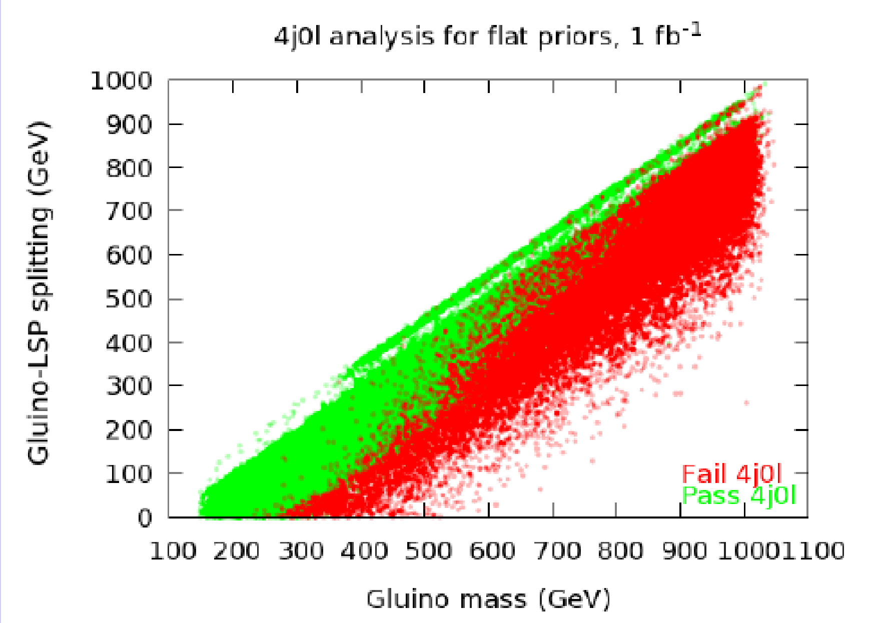


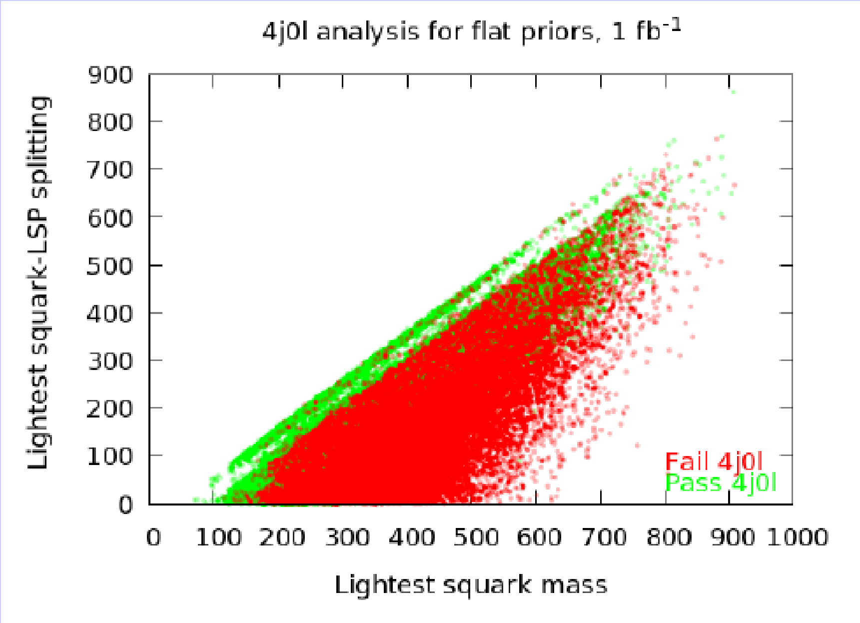




Soft jets & leptons

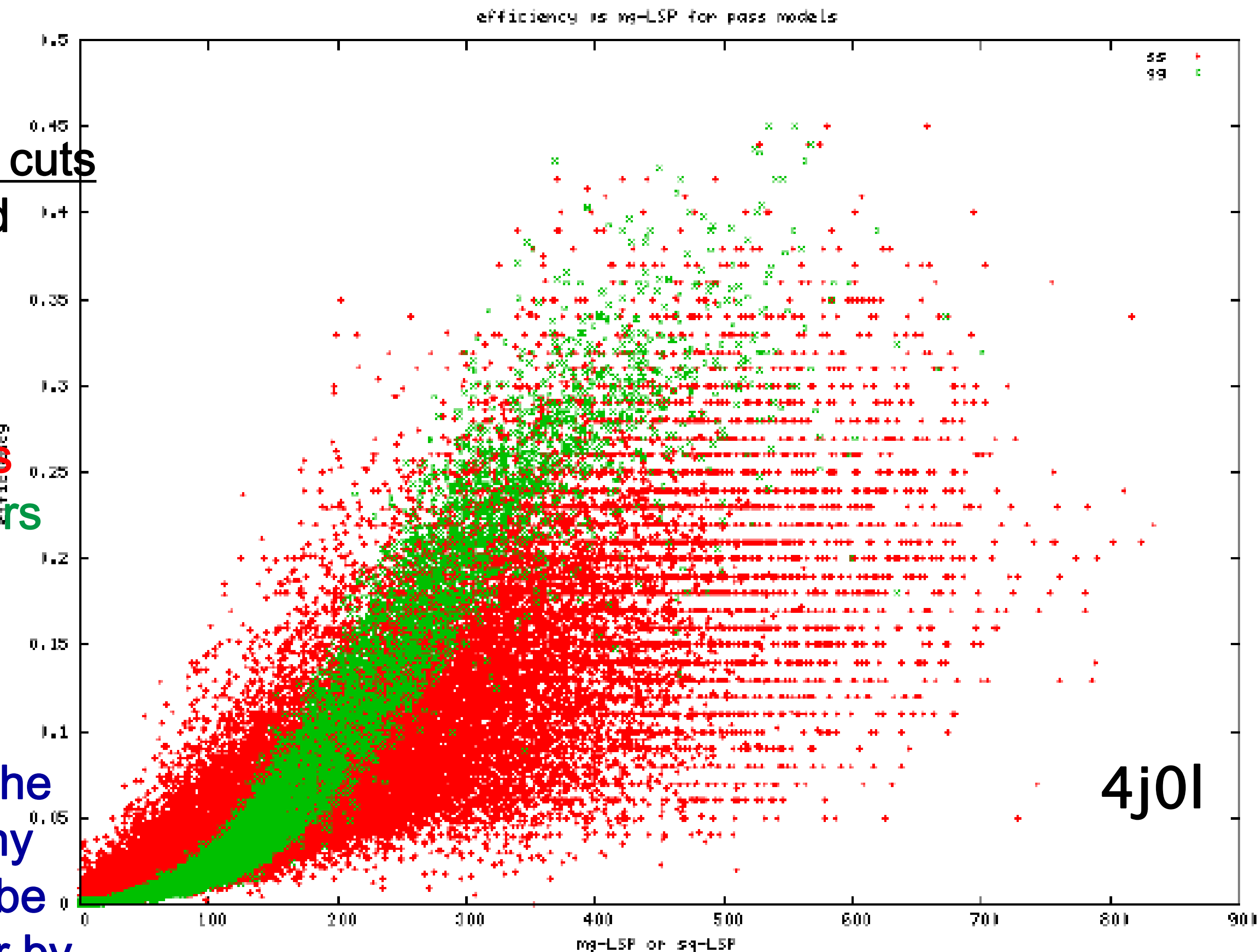
Both 7 & 14 TeV models can be missed due to small mass splittings between squarks and/or gluinos and the LSP → softer jets or leptons not passing cuts. ISR helps in some cases…





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

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

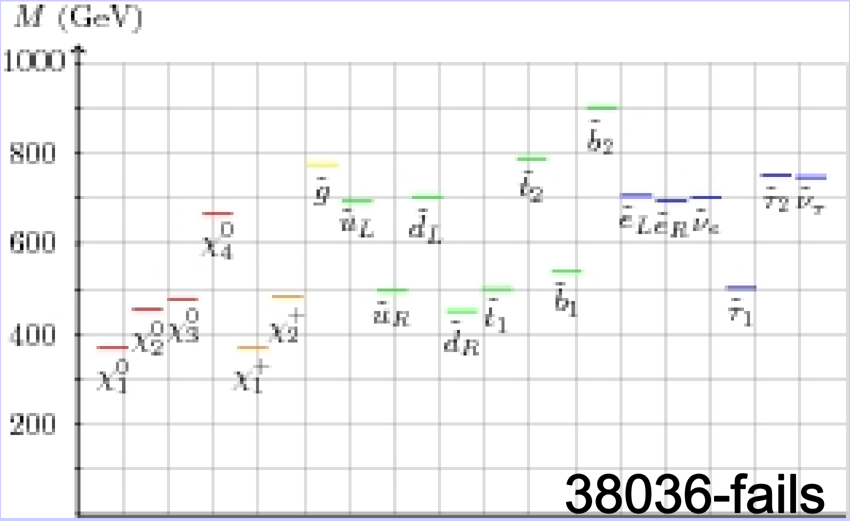


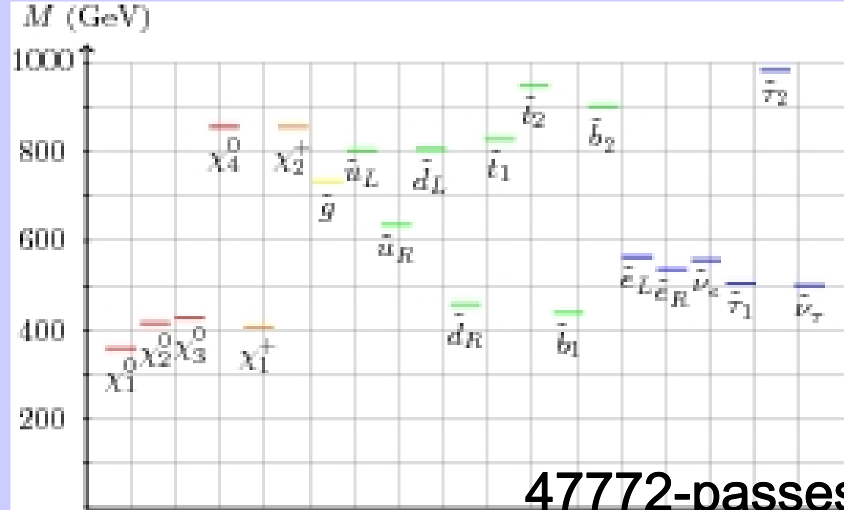
Red=squark pairs
Green=gluino pairs

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

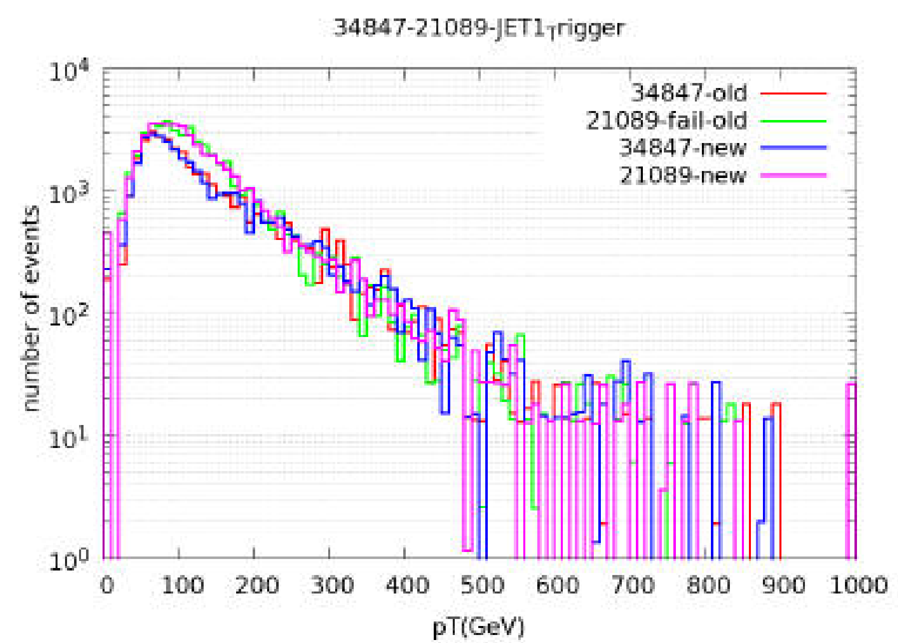


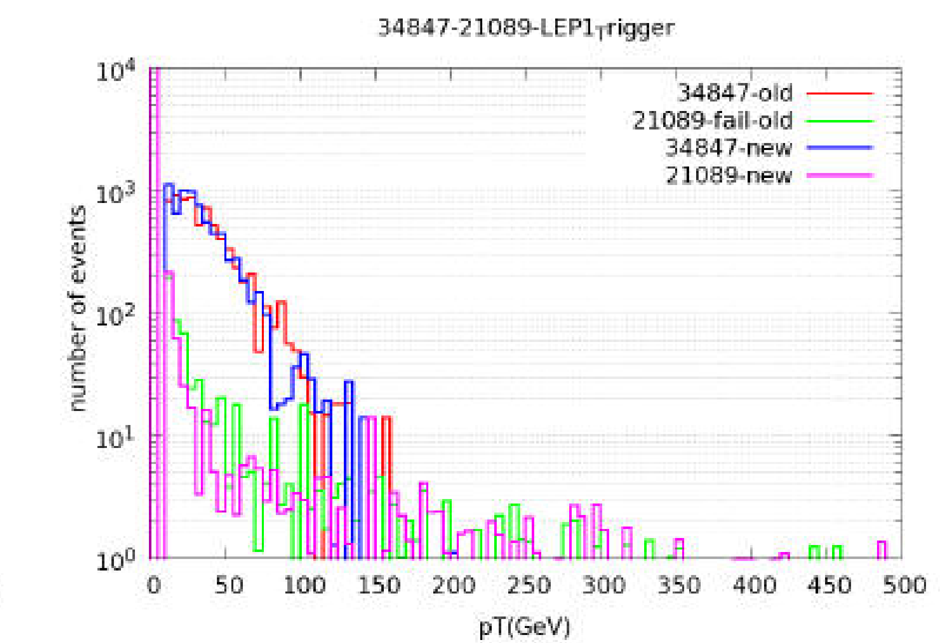


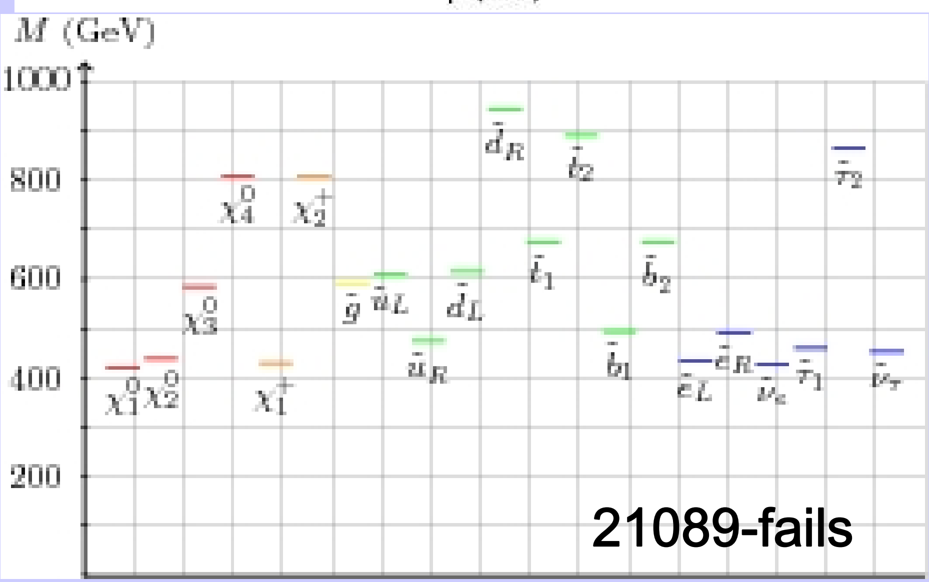
- 38036 (~2.5 pb) fails while 47772 (~1.7 pb) passes all nj0l
- u_R lighter (~500 vs ~635 GeV) & produces larger σ in 38036 & decays ~75% to j+MET
- BUT due to the Δm w/ LSP difference ($\rightarrow$ eff ~13% vs ~3.5%) 38036 fails to have a large enough rate after cuts

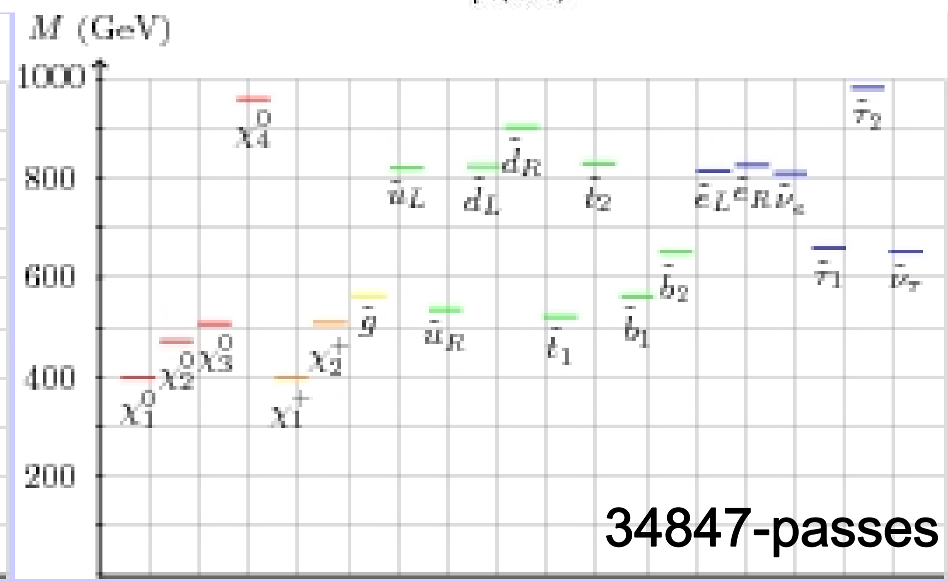
Efficiencies win over cross sections !

Missed vs Found Model Comparisons





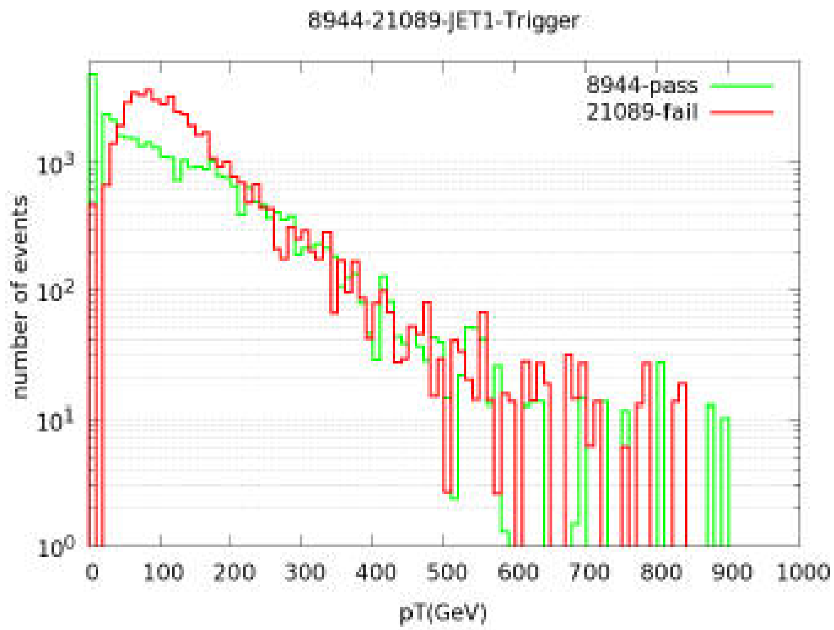


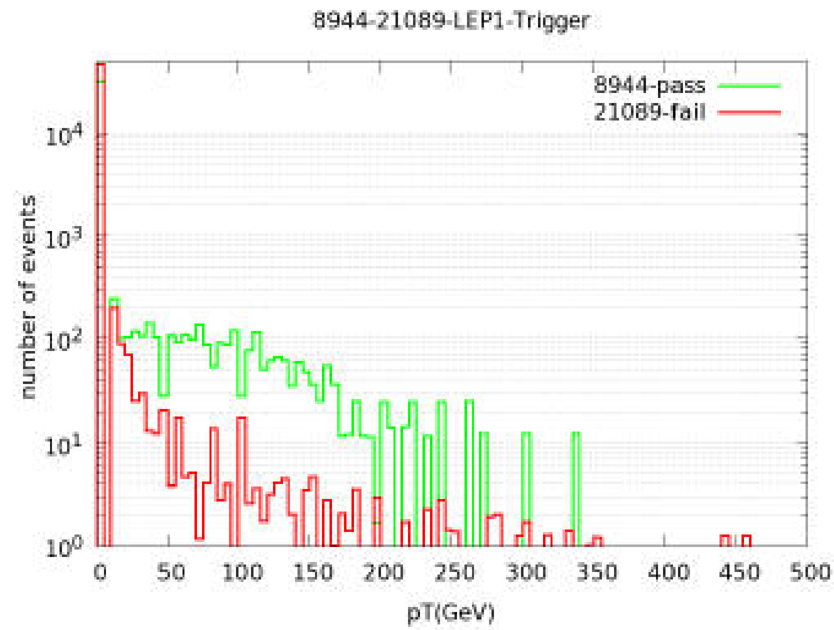


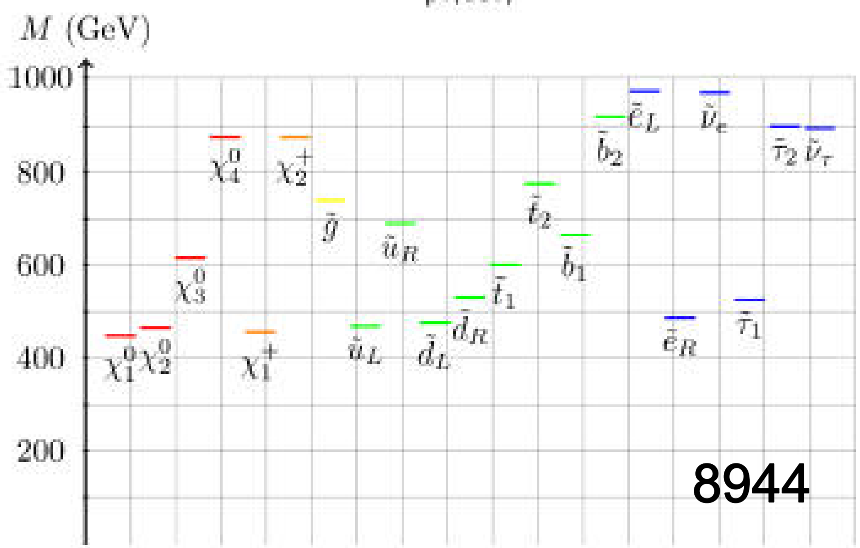
What went wrong ??

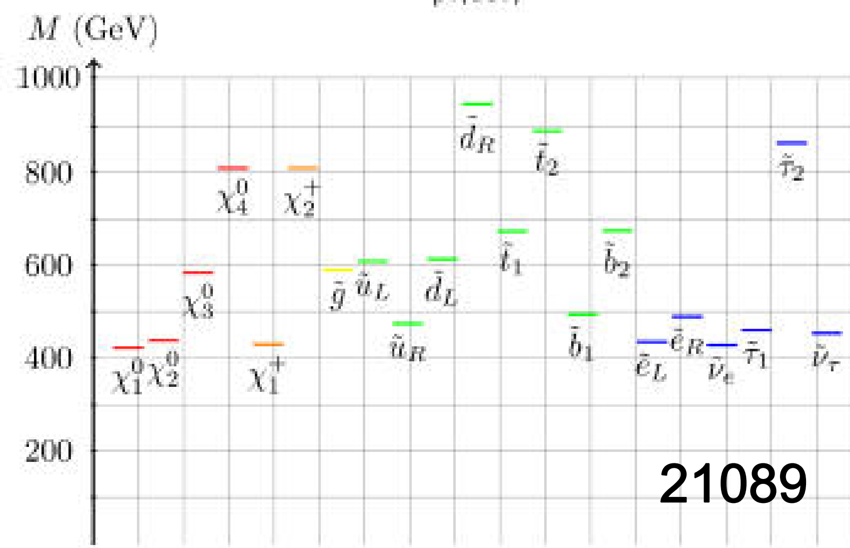
- 21089 (σ ~ 4.6pb) & 34847 (σ ~ 3.3pb) yet both models fail nj0l due to smallish Δm's. BUT 34847 is seen in the lower background channels (3,4)j1l
- In 34847, u_R cascades to the LSP via χ_2^0 & the chargino producing leptons via W emission. The LSP is mostly a wino in this case.
- In 21089, however, u_R can only decay to the lighter ~Higgsino triplet which is sufficiently degenerate as 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









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

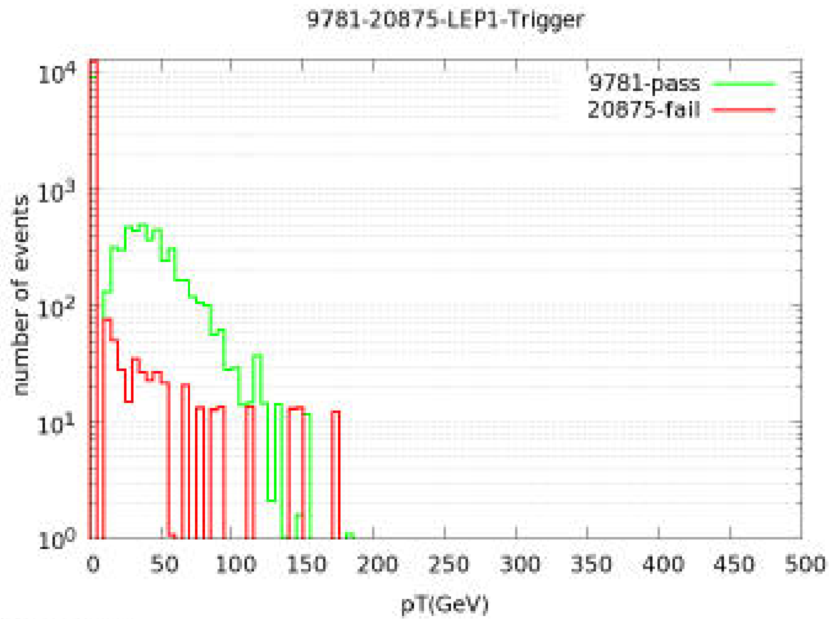
- models have similar gaugino sectors w/ $\chi_{1,2}^0$ Higgsino-like & χ_3^0 bino-like

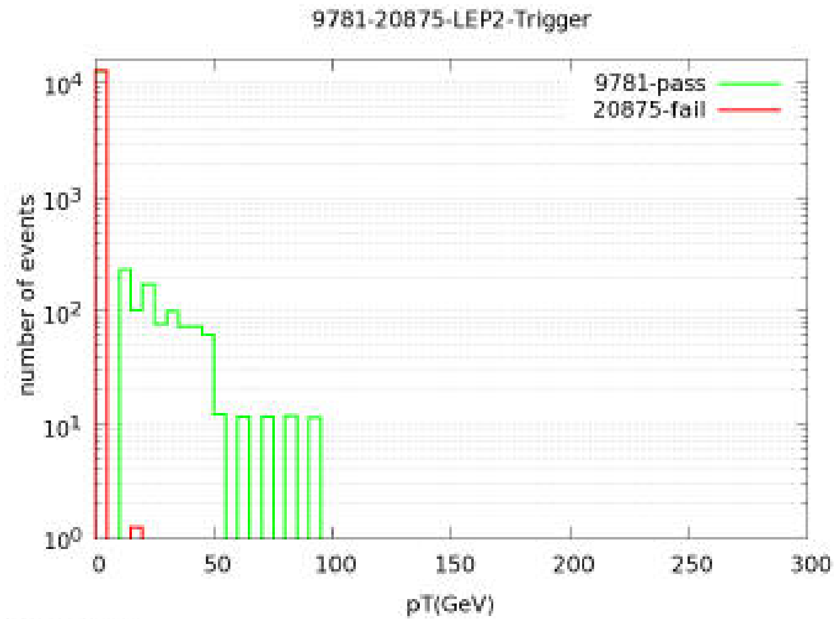
- χ_3^0 can decay thru sleptons to produce OSDL + MET

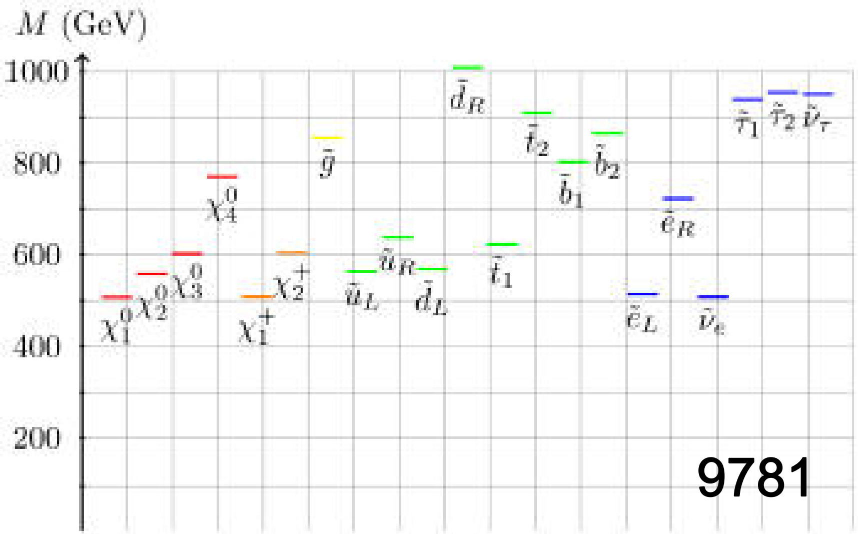
- However in 8944, the gluino is heavier than d_R so that d_R can decay to χ_3^0

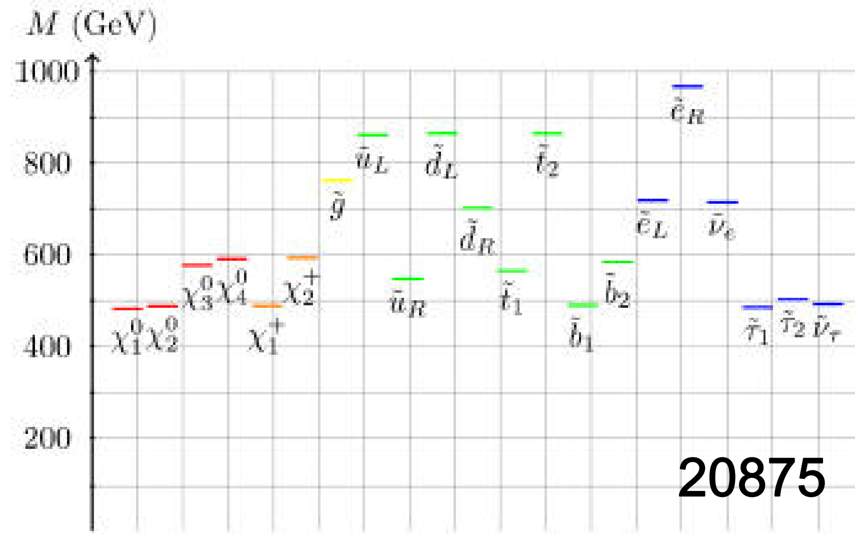
- But in 21089, the gluino is lighter than u_R so that it decays into the gluino & not the bino so NO leptons

Missed vs Found Model Comparisons









What went wrong ??

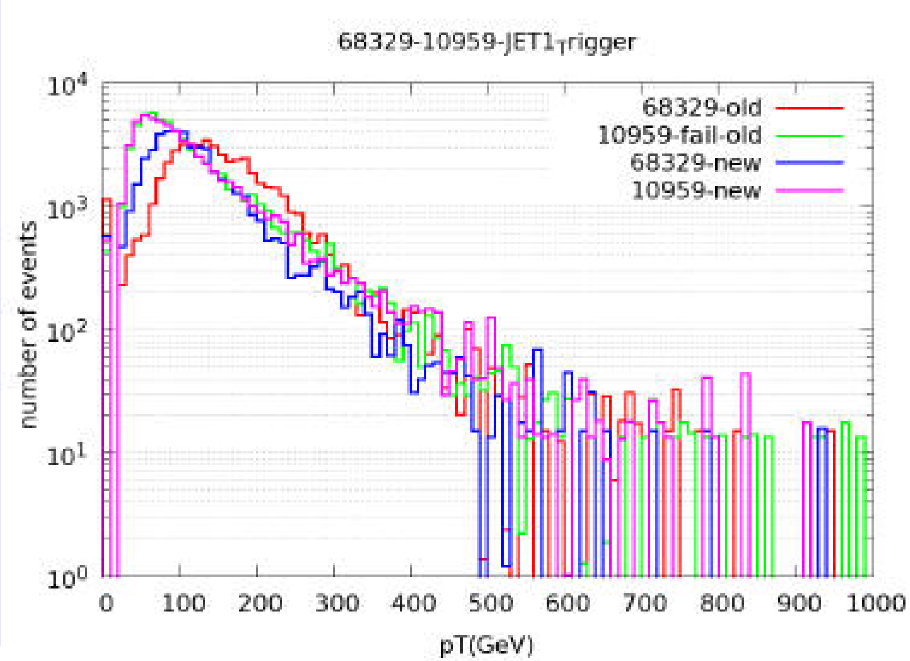
- 9781 seen in 2jSSDL while 20875 is completely missed
  nj0l fail due to spectrum compression but with very similar colored sparticle total σ = (1.1, 1.3) pb

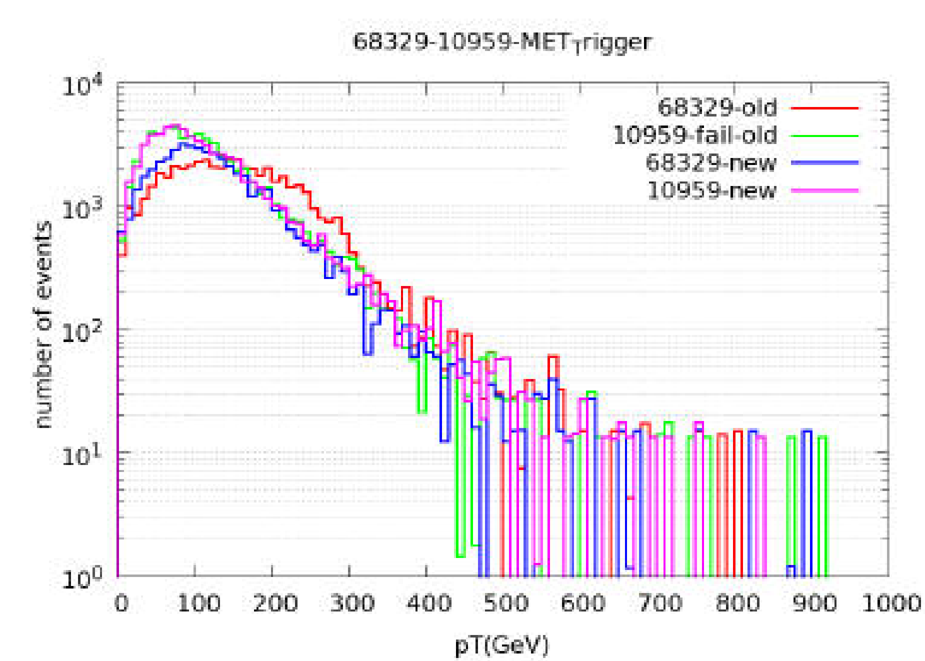
- Both models have highly mixed neutralinos & charginos w/ a relatively compressed spectrum

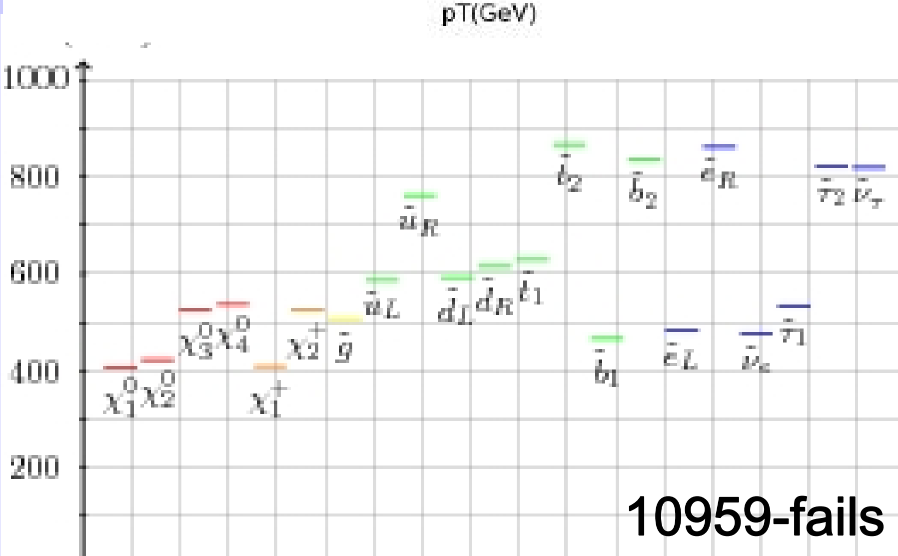
- In model 9781, u_R can decay to leptons+MET via the bino part of χ_2^0 via intermediate e,μ sleptons

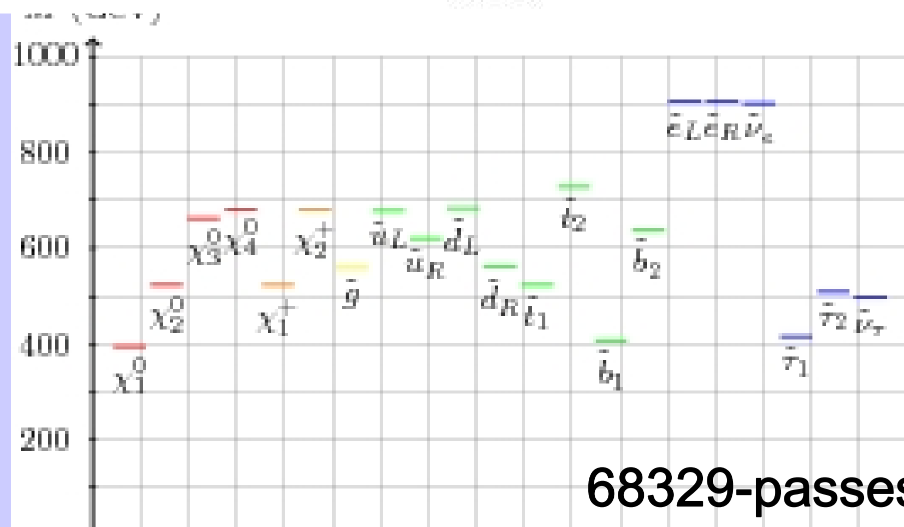
- But in 20875, these sleptons are too heavy to allow for decay on-shell & only staus are accessible. The resulting leptons from the taus are too soft to pass analysis cuts

Missed vs Found Model Comparisons





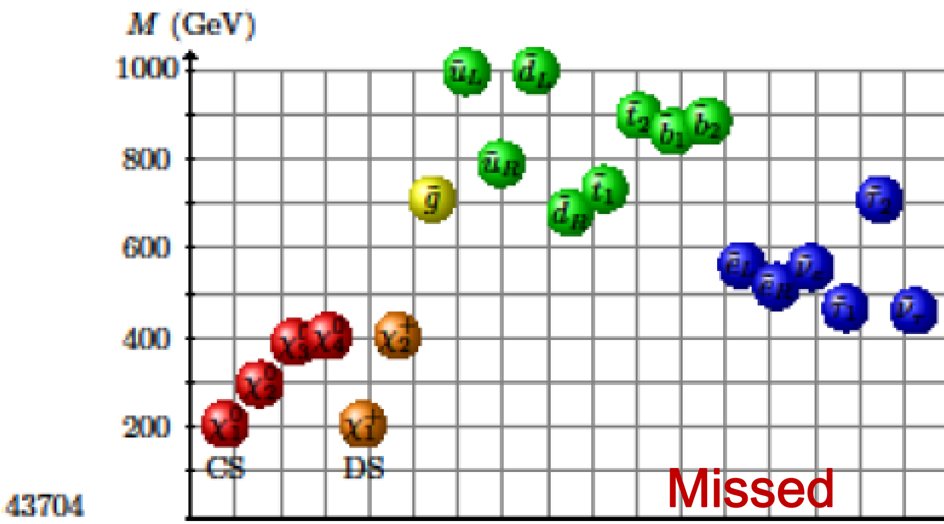


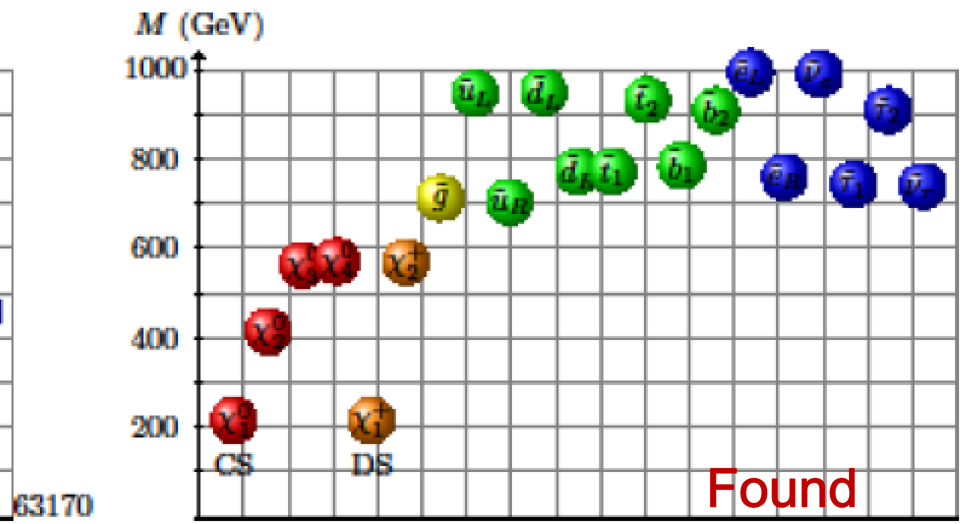


What went wrong ??

- 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 & 2^{nd} neutralino to the (wino-like) LSP (with Δm~ 60 GeV).
- Raising the LSP & b_1 masses in 68239 by 50 GeV (the 2^{nd} set of curves) induces failure due to the new gluino decay path

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$\rightarrow$ d_R $\rightarrow \chi_2^0$ $\rightarrow$W + 'stable' chargino (~100%)
(Zanesville, OH) as the χ_2^0 –LSP mass splitting is ~91 GeV

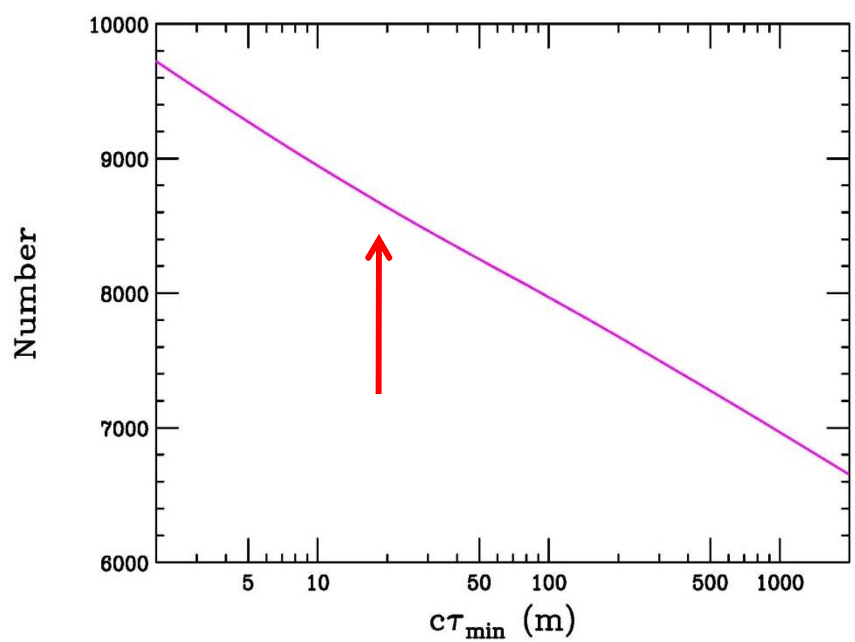
In 63170: gluinos$\rightarrow$ u_R $\rightarrow \chi_2^0$ $\rightarrow$ Z/h + LSP (~30%) as the
(St. Louis, MO) χ_2^0 –LSP mass splitting is larger ~198 GeV

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

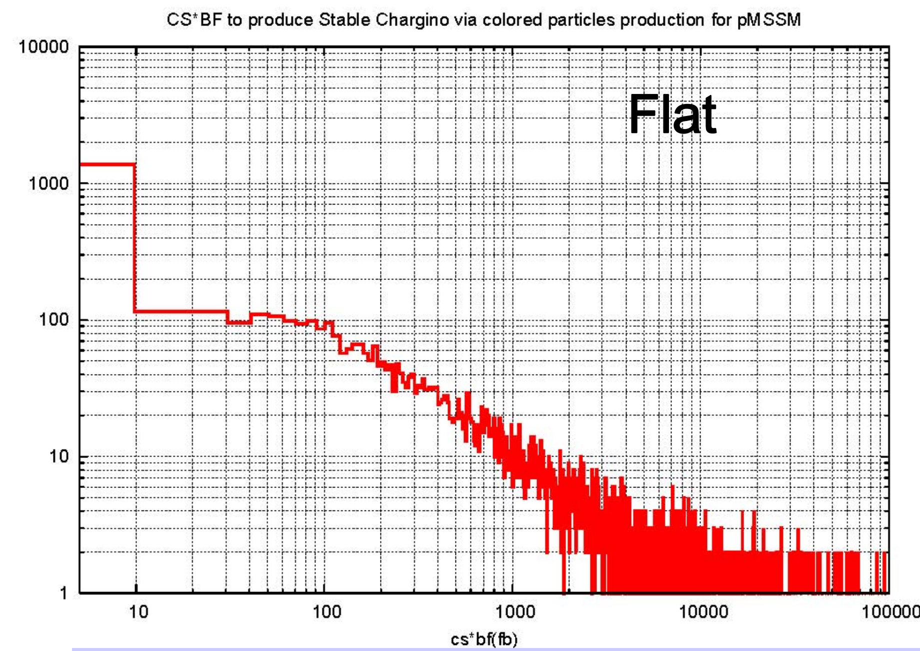
'Stable' Charged Particles in Cascades

→ Mostly long-lived charginos produced in long decay chains

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



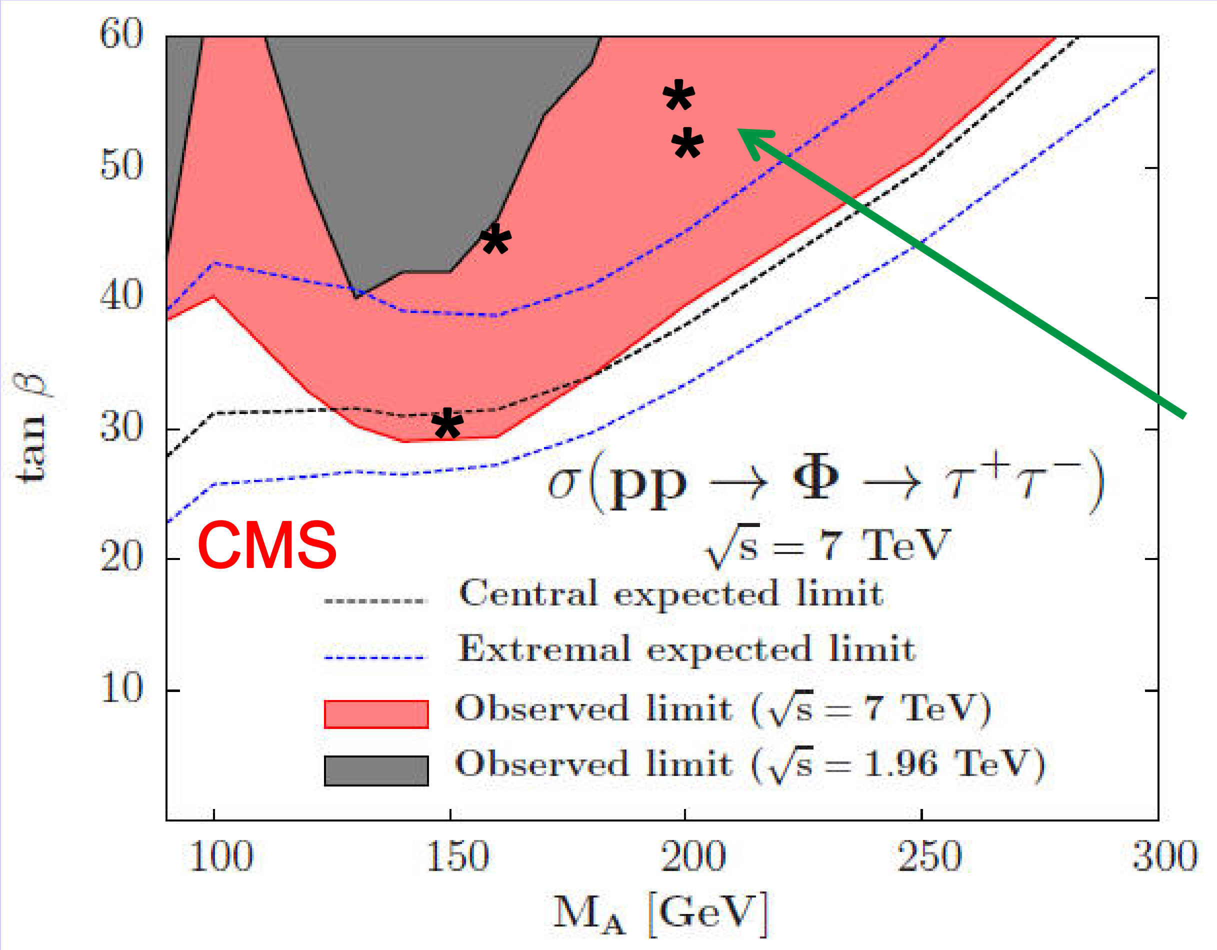
Unboosted Minimum Decay Length



Estimated σB

Impact of Higgs Searches

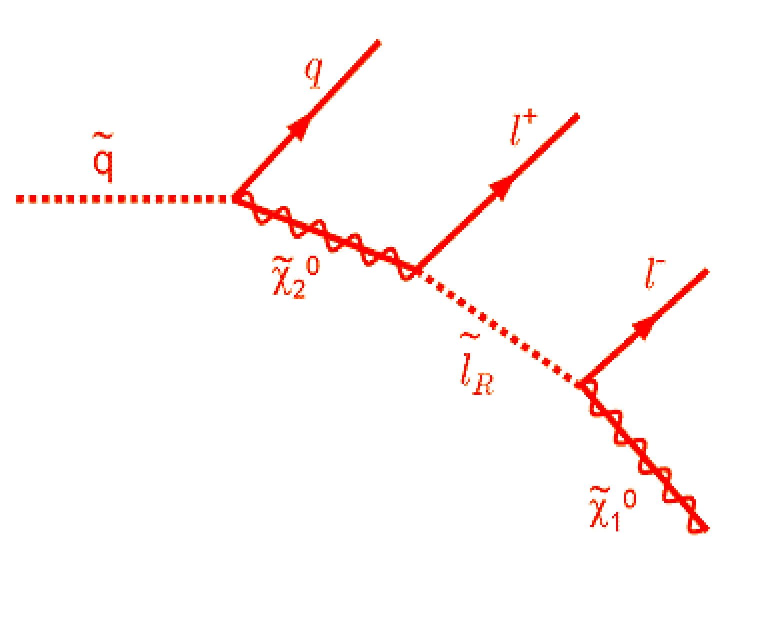
Searches for the various components of the SUSY Higgs sector also can lead to very important constraints on SUSY parameter space.

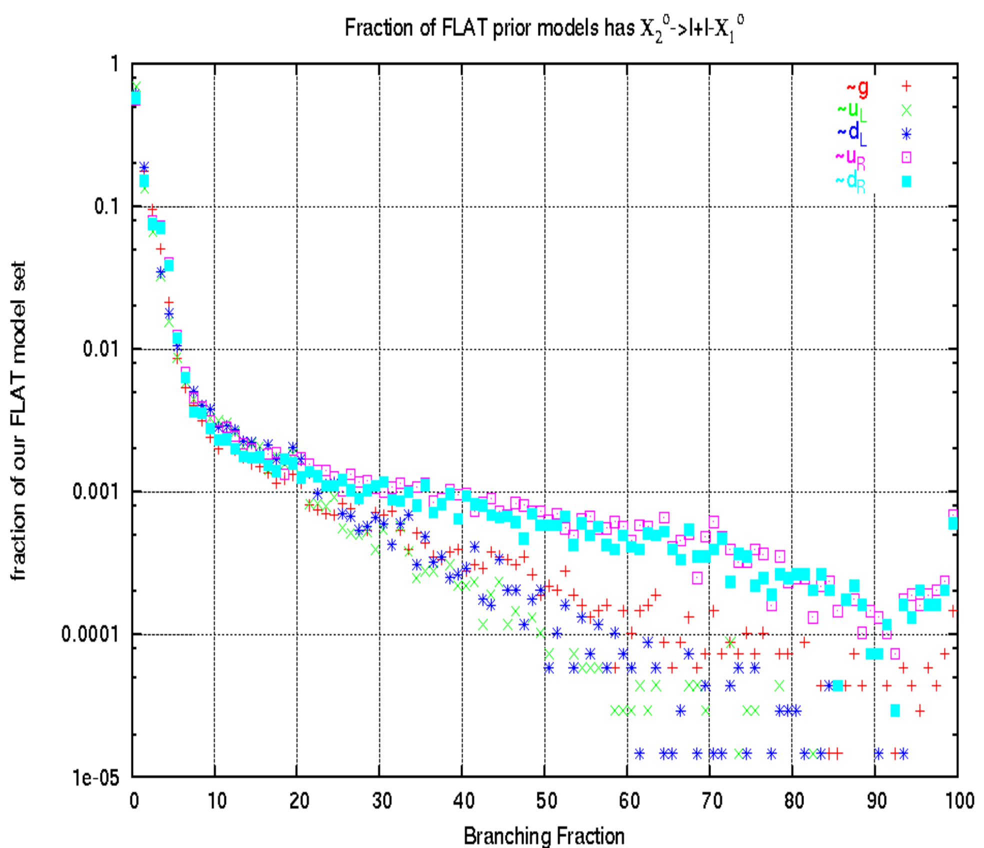


So far with ~35 pb^{-1} these searches have excluded only 4 of our models (due to the existing strong flavor constraints) but these searches are just beginning ..

Baglio & Djouadi 1103.6247

How often do these 'famous' decay chains occur in ourmodel set??





It appears that this is not GENERALLY a common mode in our sample

Summary & Conclusions

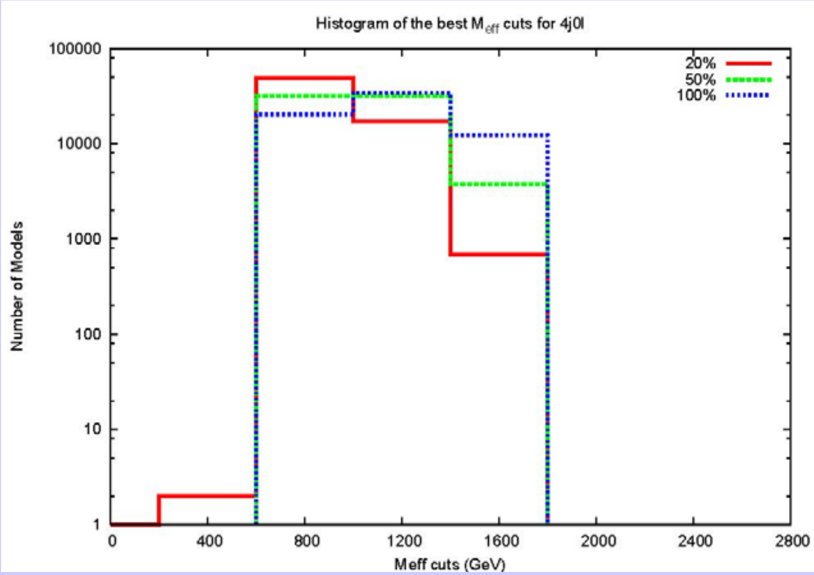
- ATLAS searches at both 7 &14 TeV (& any value in between) with ~10 fb^{-1} will do quite well at 'discovering' most of the Flat pMSSM models & not at all badly with the Log prior set

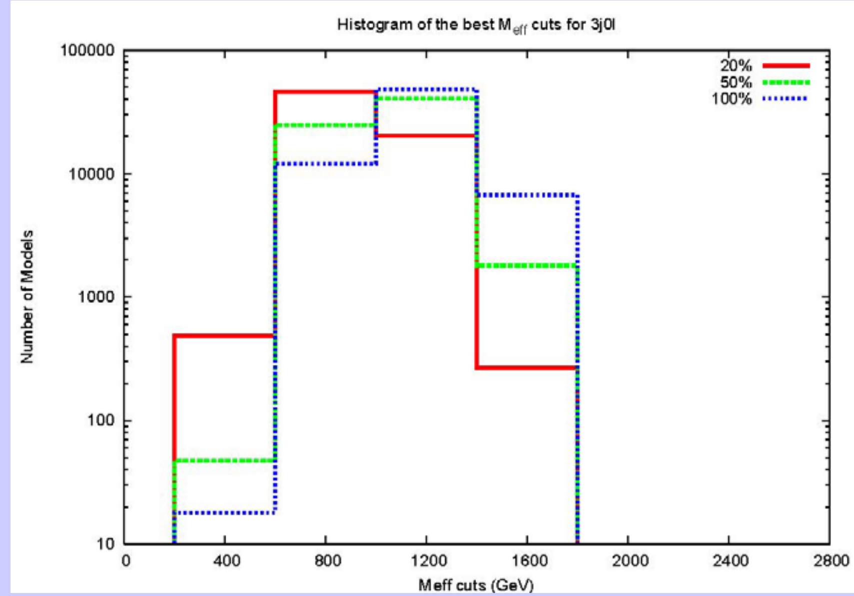
- With ~35 pb^{-1} , a reasonable fraction of this model space has already been 'covered' !

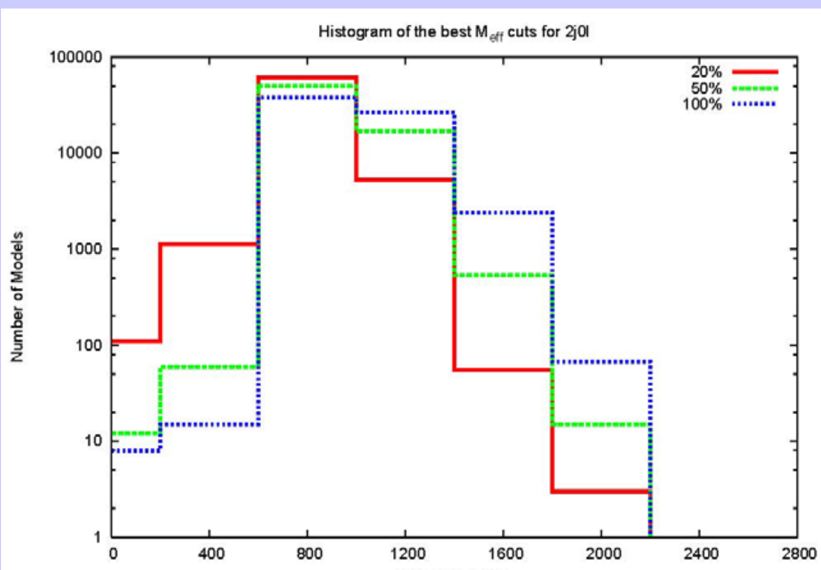
- Reducing SM background uncertainties is crucial to enhancing model coverage..

- Models 'missed' primarily due to either compressed spectra *or* because of low MET cascades ending in 'stable' charginos *or*…

- Small spectrum changes CAN be very important !

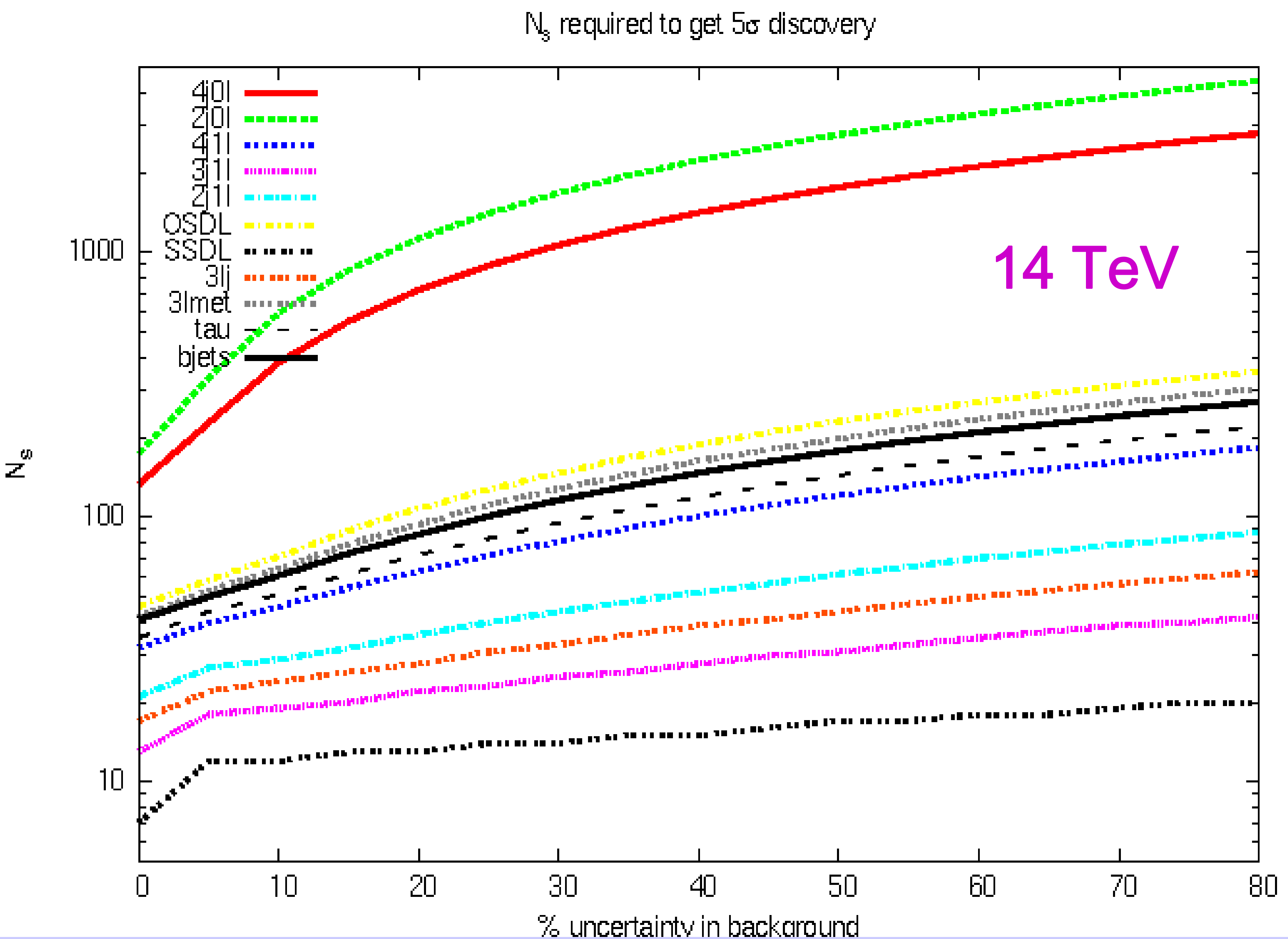






As the background uncertainty grows, harder M_{eff} cuts are needed to achieve maximum model significance in all of the various search channels.

Note that the M_{eff} cut is less important for final states with fewer jets. This persists even in analyses with leptons.



N_s required to get 5σ discovery
4l0l
2l0l
4l1l
3l1l
2l1l
OSDL
SSDL
3lj
3lmet
tau
bjets
14 TeV
1000
100
10
N_s
0
10
20
30
40
50
60
70
80
% uncertainty in background