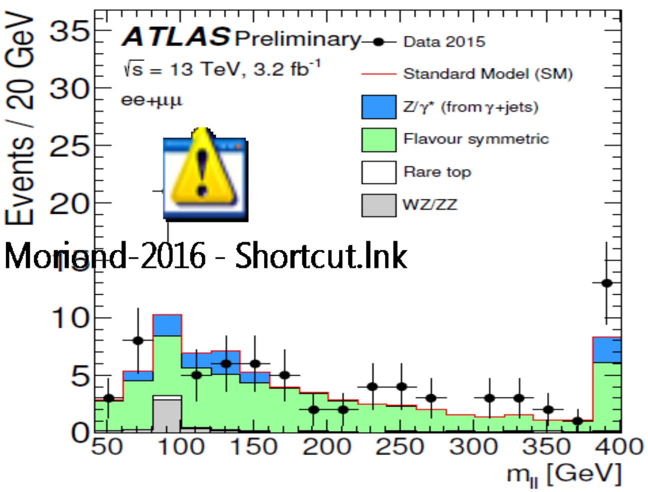
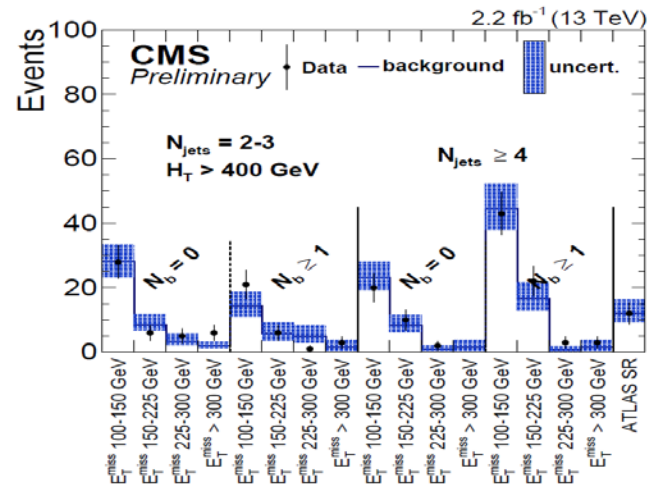
pMSSM SUSY & the ATLAS Z+MET Excess

(Ambulance Chasing from the pre-Diphoton Bump Era)





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1506.05799 + work in progress

3/16/16

Outline & Questions

- What is this excess ?
- Compatibility of ATLAS & CMS @ 8 TeV ?
- Scenarios motivated by the pMSSM (..which is?)
- What properties do ‘successful’ model have?
- What about the13 TeV data?

→ In 8 TeV data, ATLAS observed a 3σ excess in the Z(+jets) +MET search channel:

On-Z Region	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	E_T^{miss} sig. [$\sqrt{GeV}$]	f_{ST}	$\Delta\phi(jet_{12}, E_T^{miss})$
Signal regions								
SR-Z	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	-	-	> 0.4

p_{Tj} > 35 GeV

p_{Tl} > 25,10 GeV

Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ^* + jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

~15-20 excess events?

Signal region	Channel	$\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B	$p(s=0)$	Gaussian significance
SR-Z	$ee + \mu\mu$	1.46	29.6	12^{+5}_{-2}	0.998	0.0013	3.0
	ee	1.00	20.2	8^{+4}_{-2}	0.998	0.0013	3.0
	$\mu\mu$	0.72	14.7	9^{+4}_{-2}	0.951	0.0430	1.7

BUT

→ CMS, with *somewhat different cuts*, saw nothing

- $p_{tj} > 40$ GeV, $p_{Tl} > 20$ GeV
- No H_T cut !

≥2j

E_T^{miss} (GeV)	100–200	200–300	>300
DY background	336 ± 89	28.6 ± 8.6	7.7 ± 3.6
FS background	868 ± 57	45.9 ± 7.3	5.1 ± 2.3
Total background	1204 ± 106	74.5 ± 11.3	12.8 ± 4.3
Data	1187	65	7
GMSB signal yields			
$m_{\tilde{g}} = 900, m_{\tilde{\chi}_1^0} = 150$	22.1 ± 0.4	11.1 ± 0.3	7.2 ± 0.2
$m_{\tilde{g}} = 1100, m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.6 ± 0.05	7.6 ± 0.1

≥3j

E_T^{miss} (GeV)	100–200	200–300	>300
DY background	124 ± 33	12.7 ± 3.8	3.2 ± 1.8
FS background	354 ± 28	26.5 ± 5.4	2.0 ± 1.4
Total background	478 ± 43	39.2 ± 6.6	5.3 ± 2.3
Data	490	35	6
GMSB signal yields			
$m_{\tilde{g}} = 900, m_{\tilde{\chi}_1^0} = 150$	22.0 ± 0.4	11.0 ± 0.3	7.1 ± 0.2
$m_{\tilde{g}} = 1100, m_{\tilde{\chi}_1^0} = 800$	1.1 ± 0.04	1.5 ± 0.05	7.4 ± 0.1

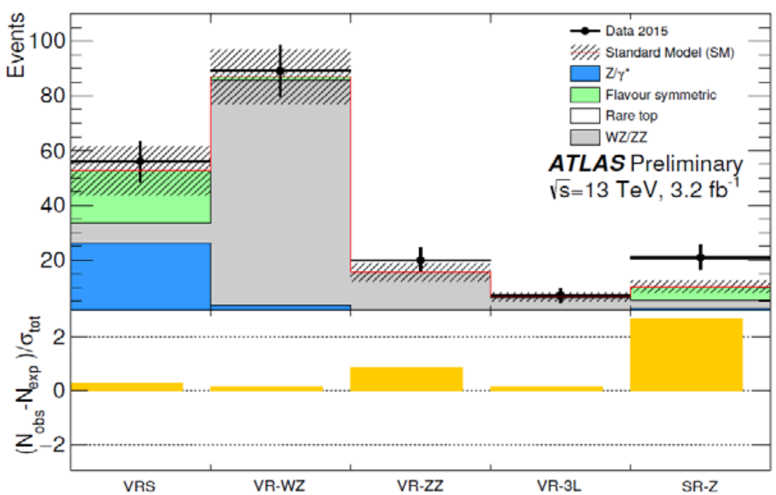
What about the 13 TeV Data ?

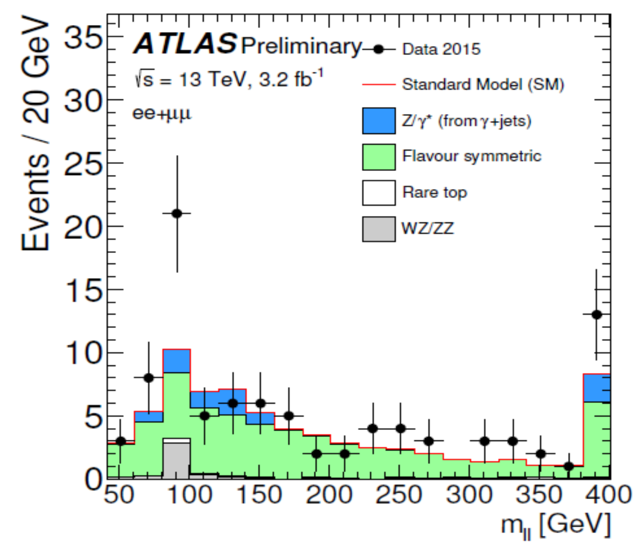
Region	E_T^{miss} [GeV]	H_T [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	SF/DF	$\Delta\phi(\text{jet}_{12}, p_T^{miss})$	$m_T(\ell_3, E_T^{miss})$ [GeV]	$n_{b\text{-jets}}$
Signal regions								
SRZ	> 225	> 600	≥ 2	$81 < m_{\ell\ell} < 101$	SF	> 0.4	-	-

ATLAS @ 13TeV
very similar analysis

	SRZ
Observed events	21
Total expected background events	10.3 ± 2.3
Flavour symmetric ($t\bar{t}$, Wt, WW and $Z \to \tau\tau$) events	5.1 ± 2.0
WZ/ZZ events	2.9 ± 0.8
Z/γ^* + jets events	1.9 ± 0.8
Rare top events	0.4 ± 0.1
p-value	0.013
Significance	2.2
Observed (Expected) S^{95}	$20.0\ (10.2^{+4.4}_{-3.0})$

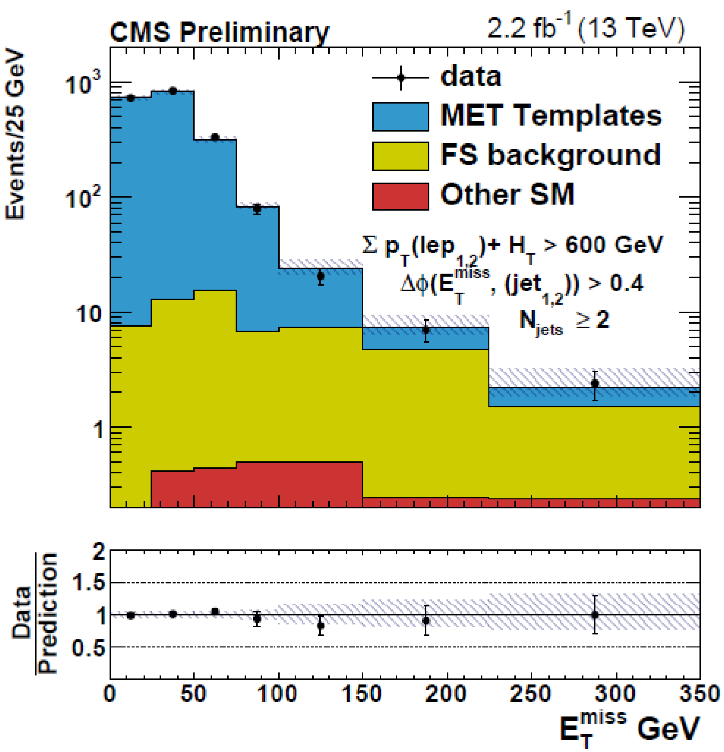
AGAIN there is an excess!

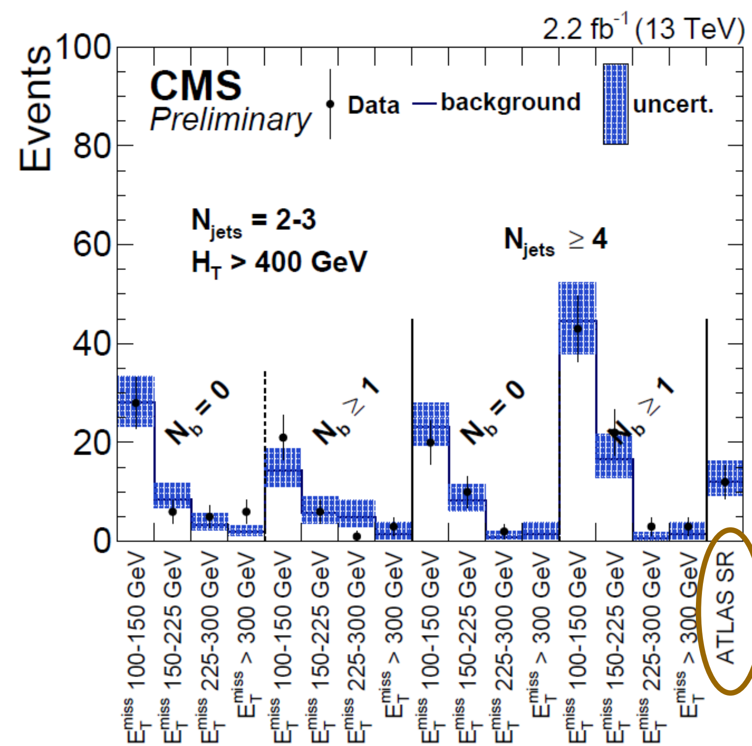




BUT CMS @ 13 TeV now has an 'ATLAS' SR analysis … & they don't see anything. We'll need to be patient to see what happens

ATLAS - SR:				
$H_T+p_T^{l1}+p_T^{l2} > 600$ GeV	$E_T^{miss} > 225$ GeV	$\Delta\phi_{E_T^{miss},j1,j2} > 0.4$	$12.0^{+4.0}_{-2.8}$	12





Issues : Does the CMS 8 TeV analysis preclude a signal in the ATLAS 8 TeV data? Are there models where both results are consistent ? What about 13 TeV?

This is a job for the pMSSM !

Available to us are 2 sets of ~135k and ~186k points in the 19-dimensional pMSSM parameter space that survive the 8 TeV ATLAS analyses* +DM +Flavor +EWK constraints.

Do any of them give large signals? If so, we can use them as seeds to explore the surrounding parameter space

→→ Reminder…what is this pMSSM?

* See, e.g., 1211.7106, 1307.8444 & 1508.06608

The p(henomenological)MSSM

- General CP-conserving MSSM with R-parity
- MFV at the TeV scale (Flavor=CKM)
- Lightest neutralino is the LSP.
- 1st/2nd generation sfermions degenerate
- Ignore 1st/2nd generation A-terms &Yukawa's.
- No assumptions wrt SUSY-breaking

→ the pMSSM with 19 parameters

'Throw darts' into this space.. look at the various predictions --then keep points that survive all constraints

$50\ \text{GeV} \leq |M_1| \leq 4\ \text{TeV}$

$100\ \text{GeV} \leq |M_2, \mu| \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq M_3 \leq 4\ \text{TeV}$

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

$100\ \text{GeV} \leq M_A, l, e \leq 4\ \text{TeV}$

$400\ \text{GeV} \leq q_1, u_1, d_1 \leq 4\ \text{TeV}$

$200\ \text{GeV} \leq q_3, u_3, d_3 \leq 4\ \text{TeV}$

$|A_{t,b,\tau}| \leq 4\ \text{TeV}$

To see how this works in practice for the set of LHC searches, have a look at how ATLAS did this analysis:

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Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A summary of the constraints from the ATLAS experiment on R-parity-conserving supersymmetry is presented. Results from 22 separate ATLAS searches are considered, each based on analysis of up to 20.3 fb^{-1} of proton-proton collision data at centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV at the Large Hadron Collider. The results are interpreted in the context of the 19-parameter phenomenological minimal supersymmetric standard model, in which the lightest supersymmetric particle is a neutralino, taking into account constraints from previous precision electroweak and flavour measurements as well as from dark matter related measurements. The results are presented in terms of constraints on supersymmetric particle masses and are compared to limits from simplified models. The impact of ATLAS searches on parameters such as the dark matter relic density, the couplings of the observed Higgs boson, and the degree of electroweak fine-tuning is also shown. Spectra for surviving supersymmetry model points with low fine-tunings are presented.

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 1508.06608

doi:10.1007/JHEP10(2015)134

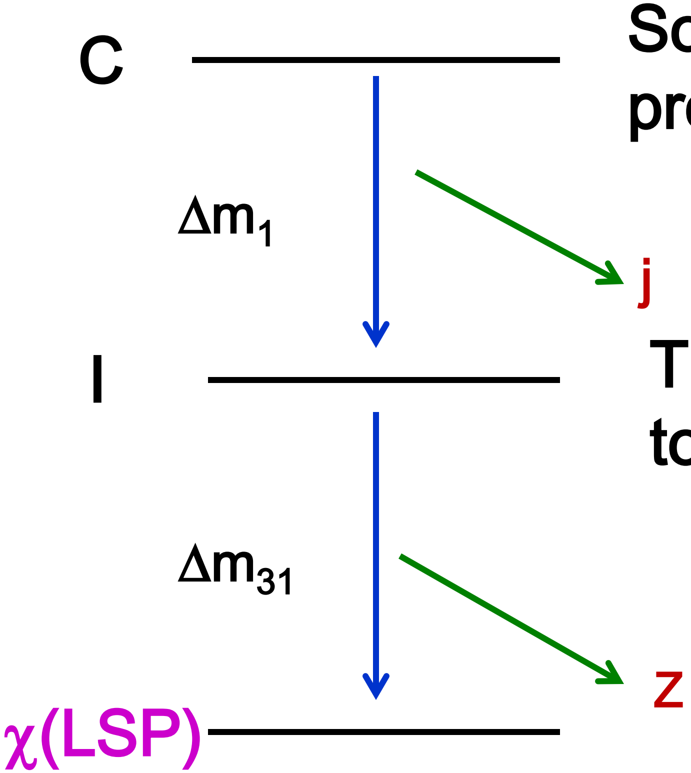
JHEP10(2015)134

The subspace of points that explains the 8 TeV excess is shaped by the following 3 (obvious) requirements:

- Generating enough Z+MET events in ATLAS
- Satisfying the null CMS search
- Satisfying the null (0,1)-l + jets searches by ATLAS

What is the nature of these models?

We imagine a simplified SUSY spectrum that looks like a cascade: C→ I (+j) → LSP (+Z)

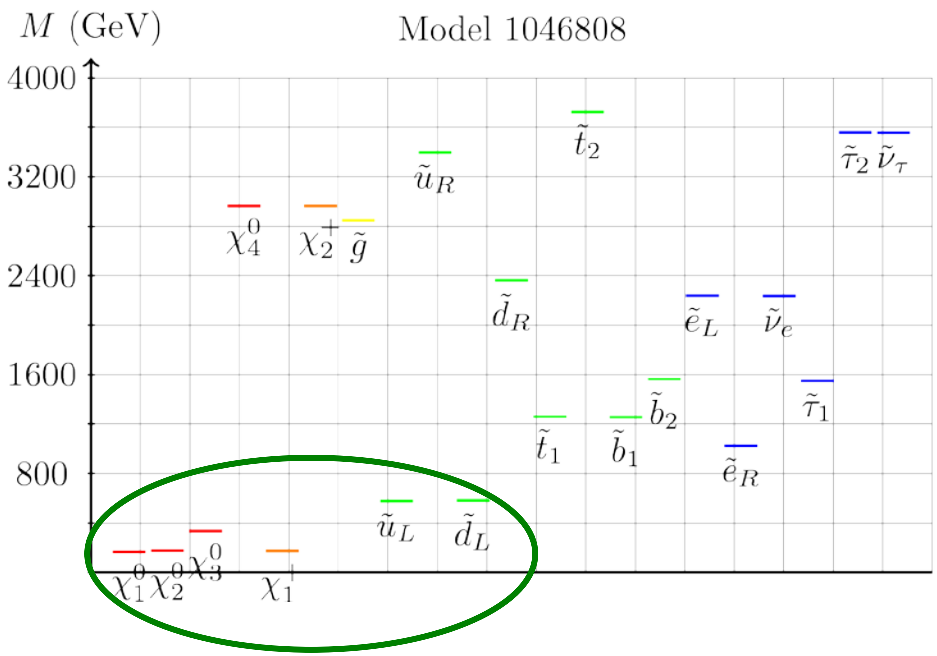


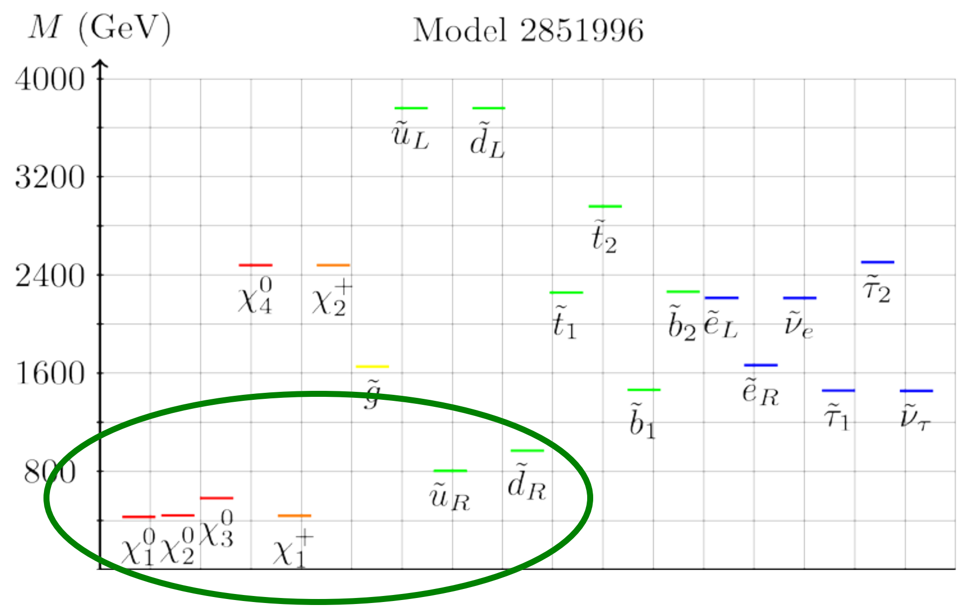
Some colored sparticle initiates cascade to provide a large enough σ & the jets

The intermediate color-singlet state decays to the LSP (→ MET) emitting the Z

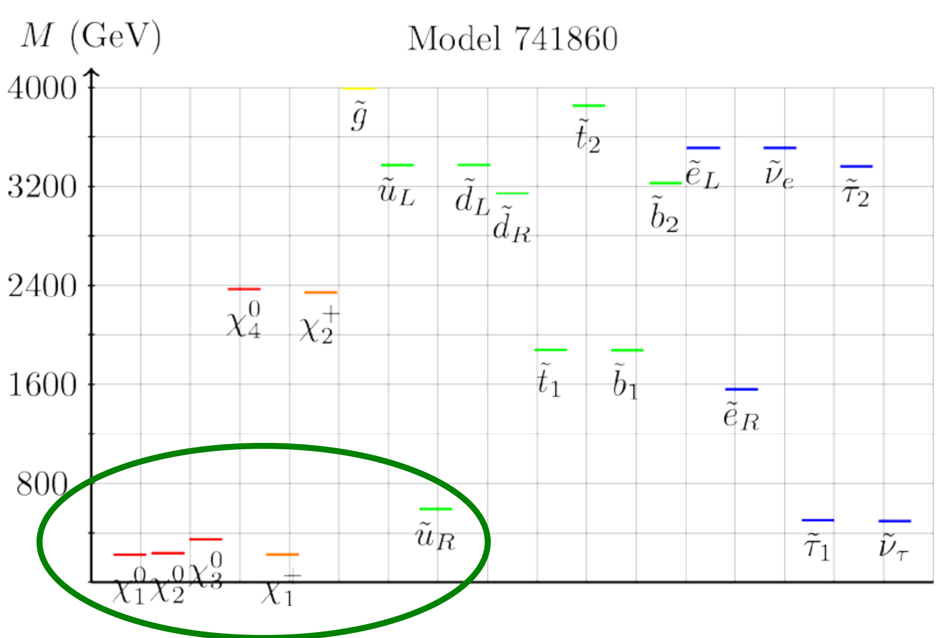
→ Direct C → LSP +j decays must be suppressed to pass the 0l+jets analysis

Although there are several possibilities, we find a rather unique spectrum-type from the model scan



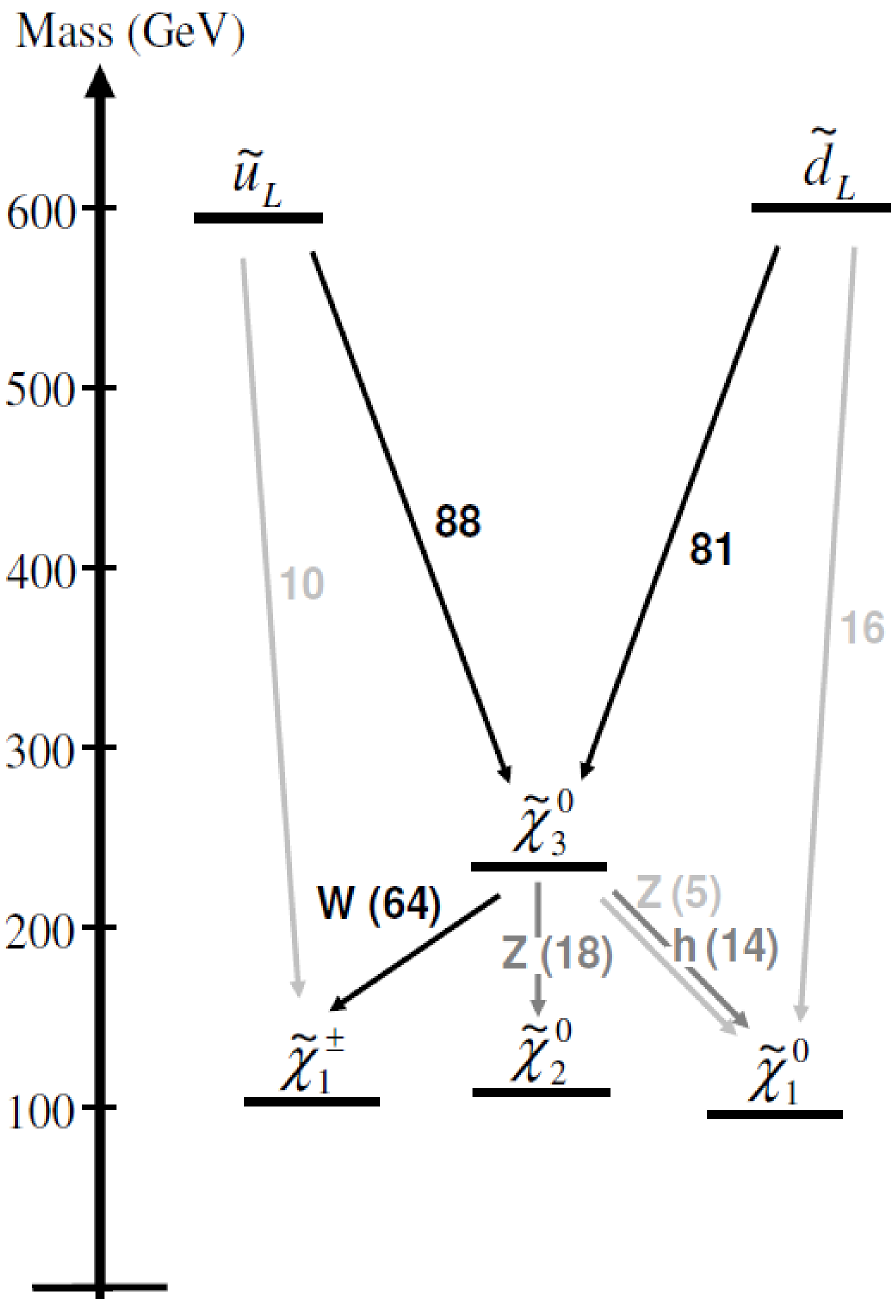


Here are a few ‘passing’ pMSSM model spectra



Squarks → Bino → Higgsino

Roughly (but not completely) the rest of the spectrum is decoupled.. but does play some role



A typical decay pattern of one of the sample passing pMSSM models

Using the pMSSM models that 'worked' as seeds we can explore the model space around them to see what parameters are required.

- It is useful to separate the C=Q,u,d cases as they have different σ's & decays (if the spectrum is not quite decoupled)

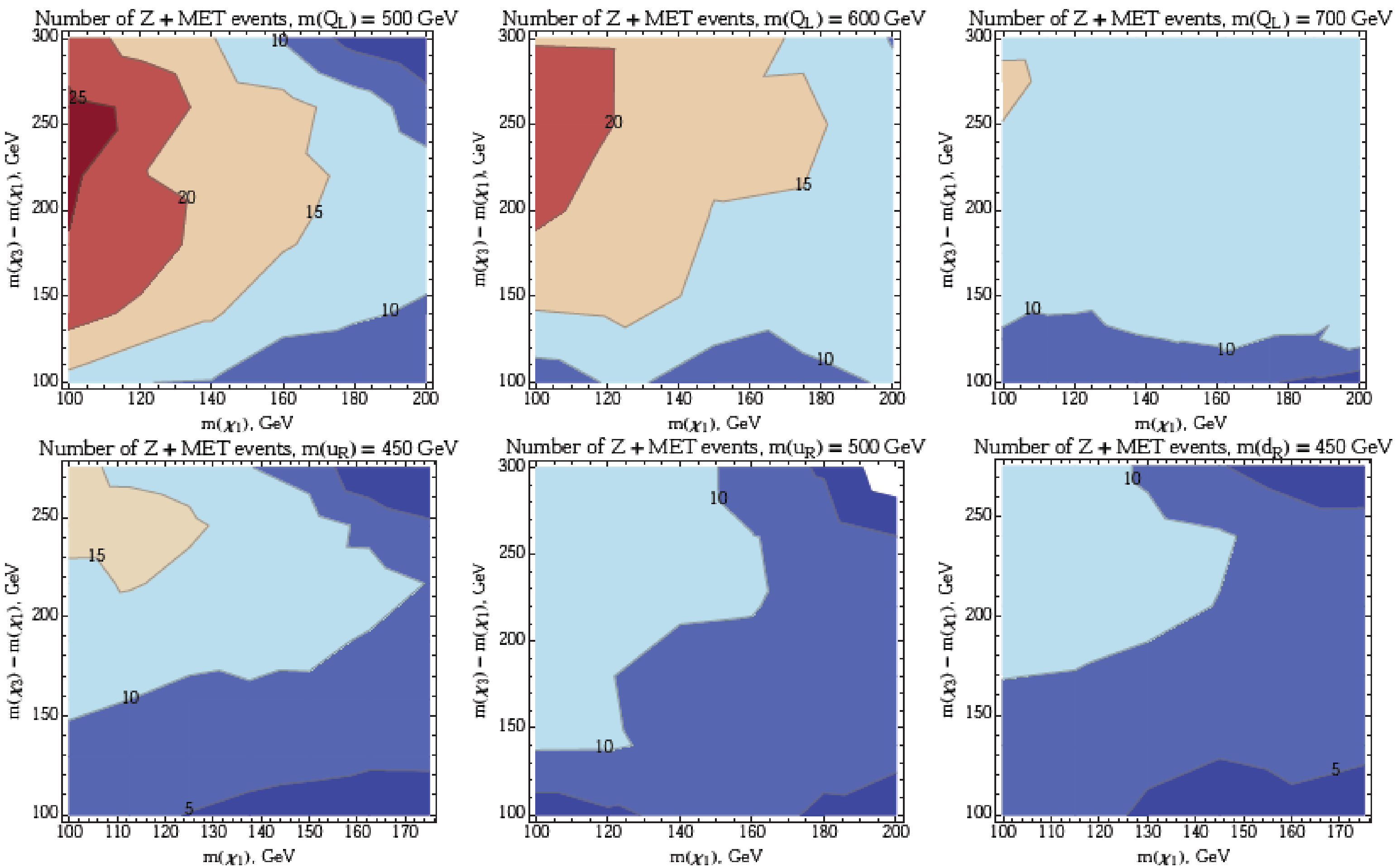


Figure 3: Signal event rate contours for the ATLAS Z+MET analysis in the $\chi_3^0 - \chi_1^0$ mass difference and χ_1^0 mass plane. The top three panels correspond to the case of $\tilde{Q}_L = 500\,, 600\,, 700$ GeV from left to right, while the bottom panels are for $\tilde{u}_R = 450\,, 500$ GeV and $\tilde{d}_R = 450$ GeV, left to right.

These plots tell us that:

- Lighter squarks are preferred to get a large rate & Q, u, d are preferred (in that order) as they give larger σ's for the same fixed mass .
- Δm_{31} >~ 150 GeV are preferred (a surprise?). This allows for decays through the 125 GeV scalar but also more visible decay products. (The precise rates depends on Q, u, or d). This is a 'test' channel for this scenario.
- Light Higgsino LSPs below ~170 GeV are preferred
- Scans tell us more details

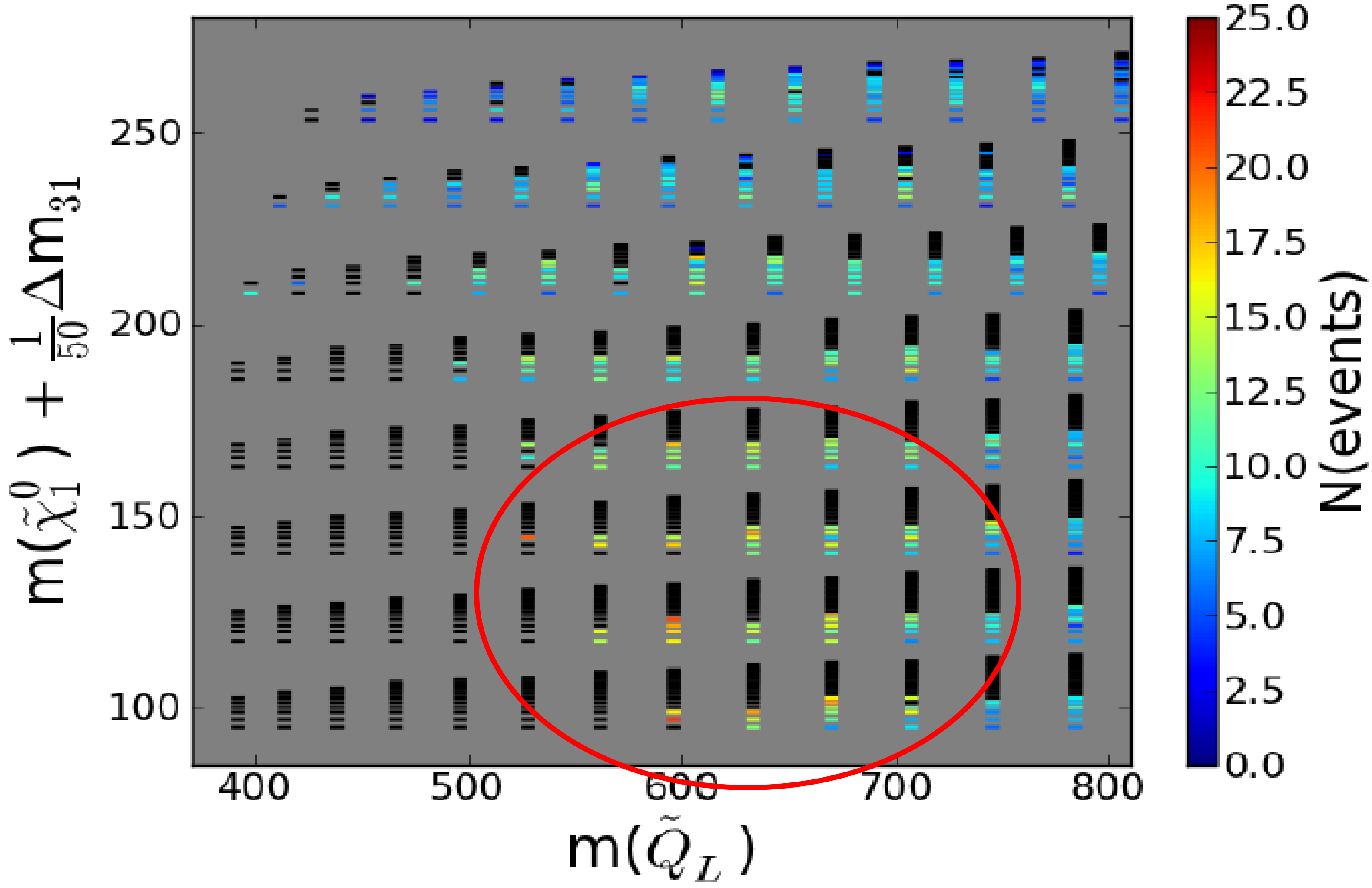
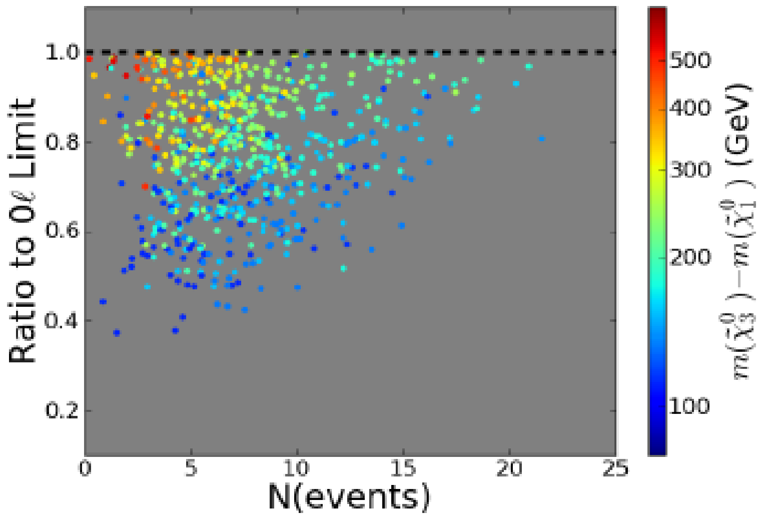
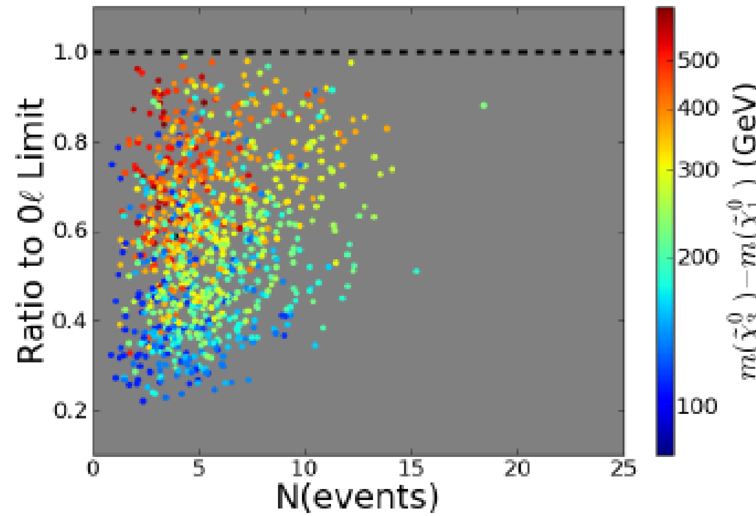


Figure 4: Results from the simplified spectra scan for a parent Q_L-squark in the $\tilde{Q}_L$ and $\chi_1^0 + (1/50)\Delta m_{31}$ mass plane. The vertical bars represent the coarse grid in our scan, with the value of the mass splitting Δm_{31} increasing for successively higher slices of the bar. The color code indicates the predicted event rate for the ATLAS 20 fb^{-1} Z+MET channel. Black slices in a vertical bar correspond to points excluded by any of the simulated searches.

How deeply are the ATLAS (0,1)-l +jets & the CMS Z+MET searches cutting into the desired region of parameter space?

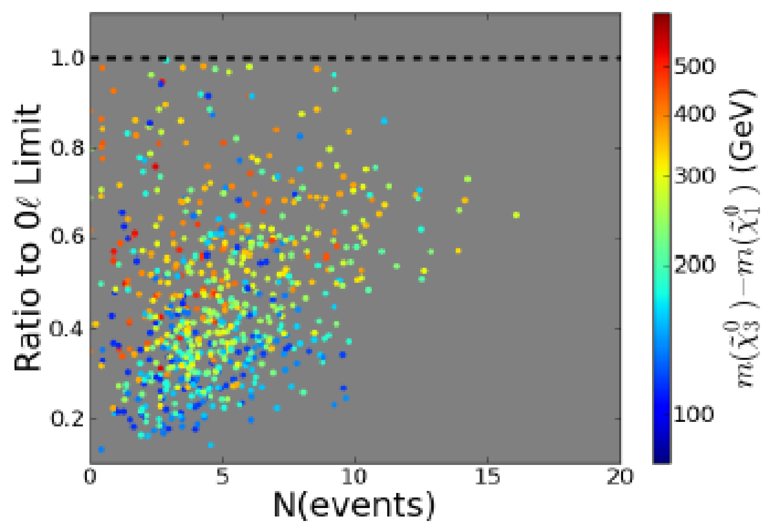


Q



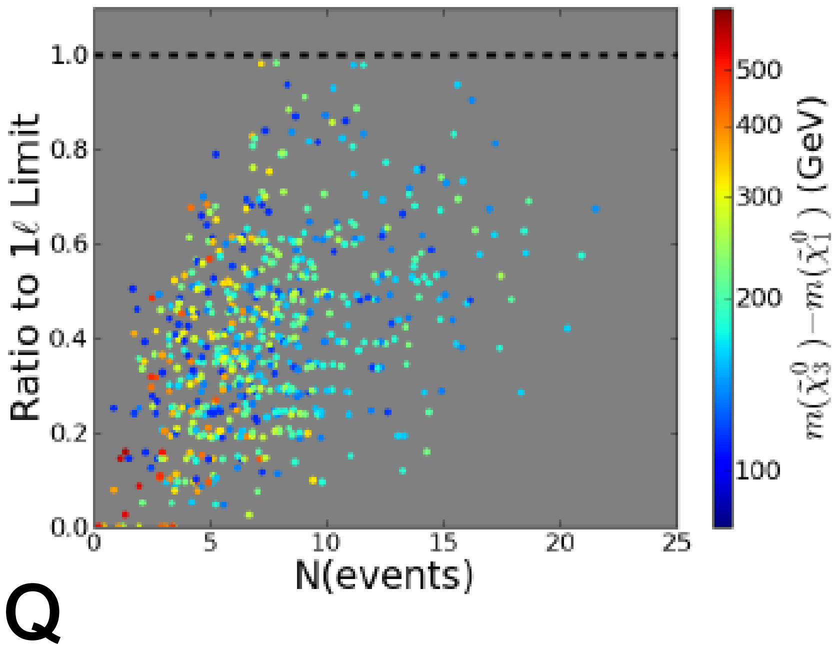
u

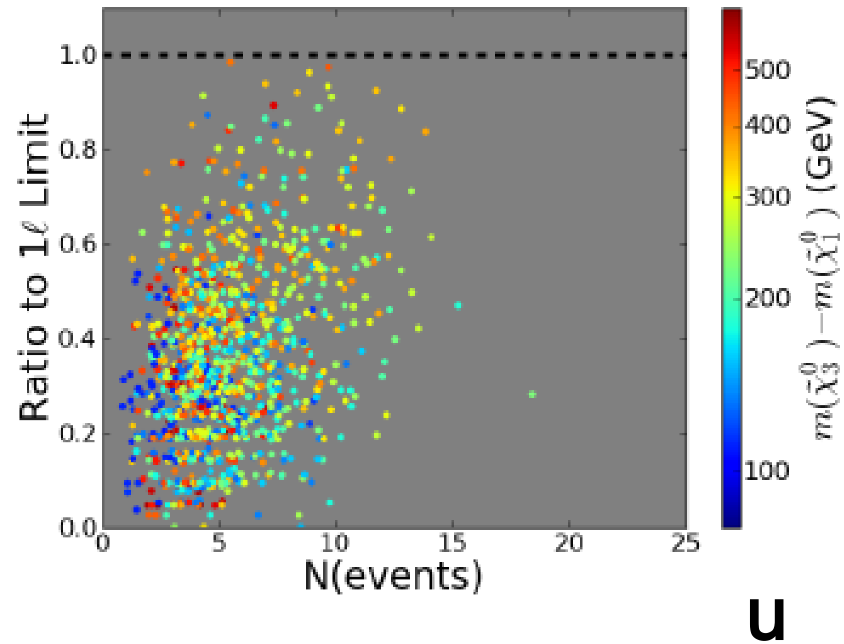
d

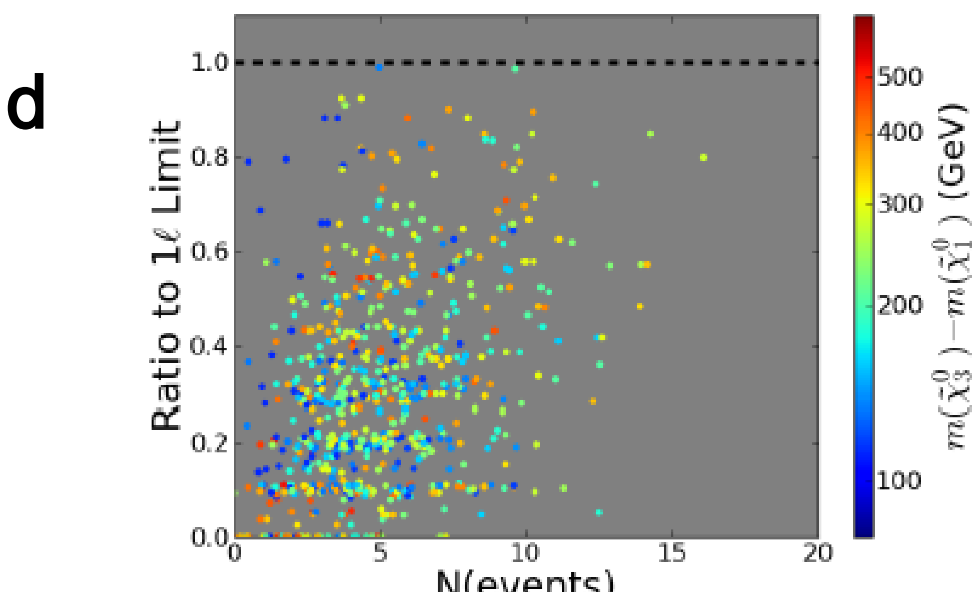


Note clustering near the upper boundary !

0-lepton

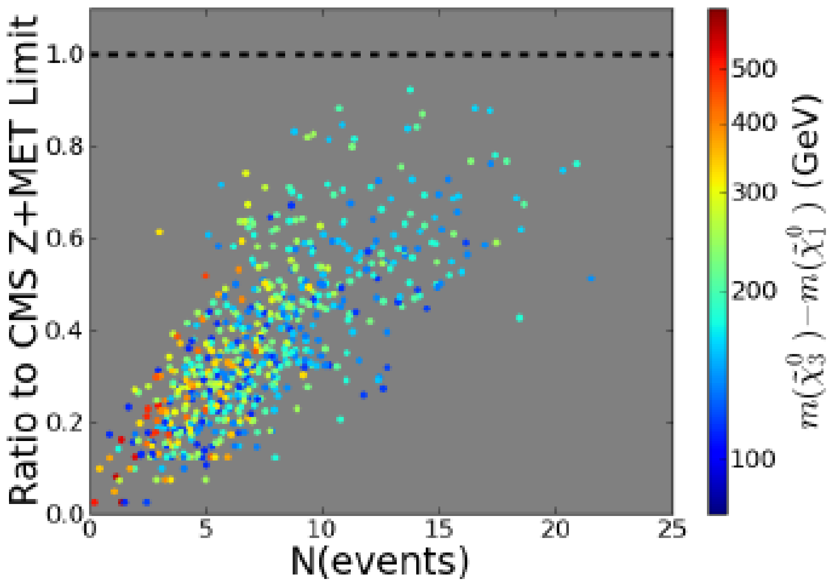




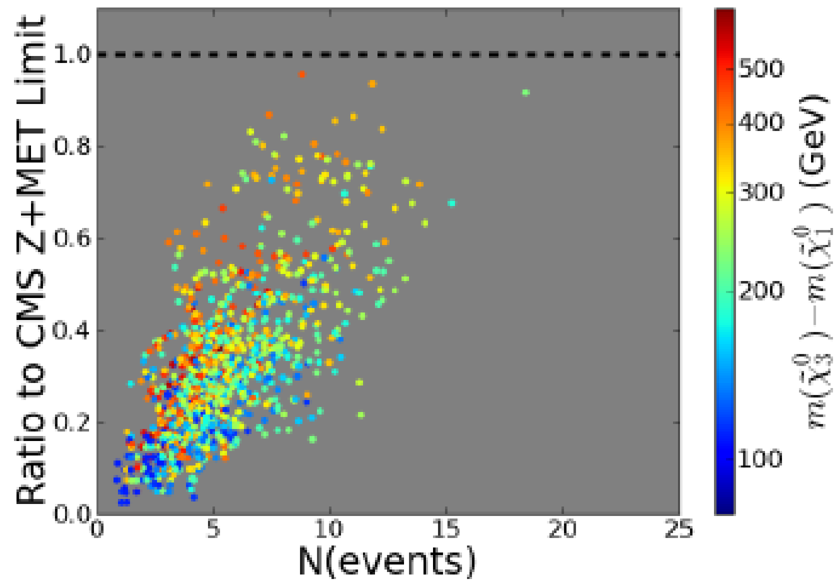


Less clustering near the upper boundary

1-lepton

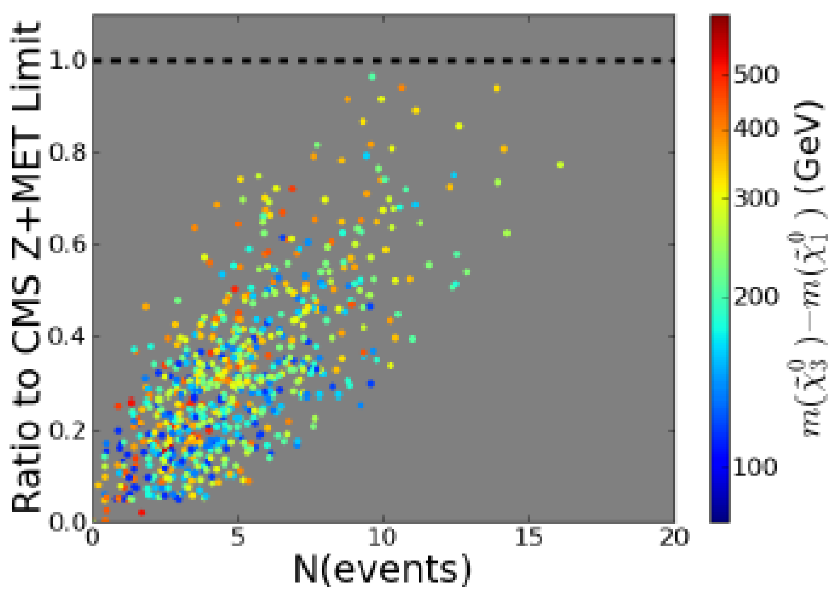


Q



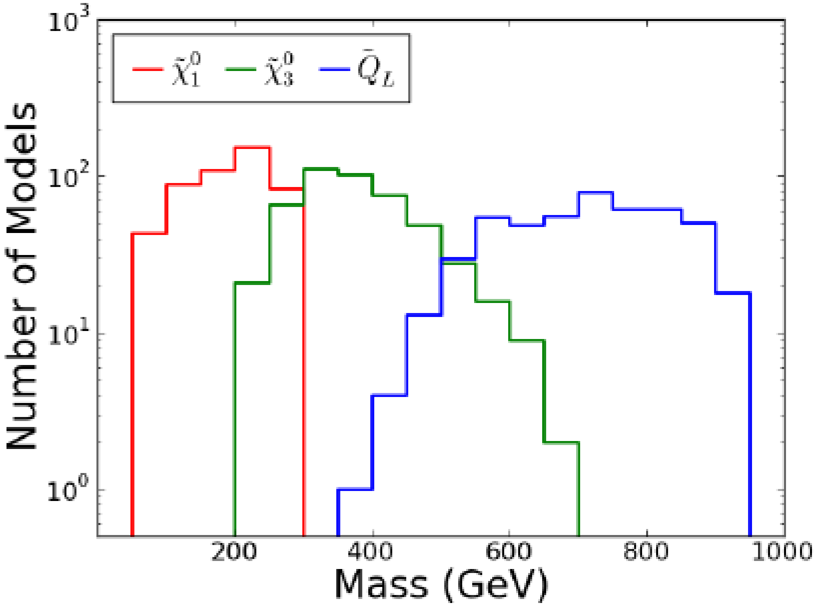
u

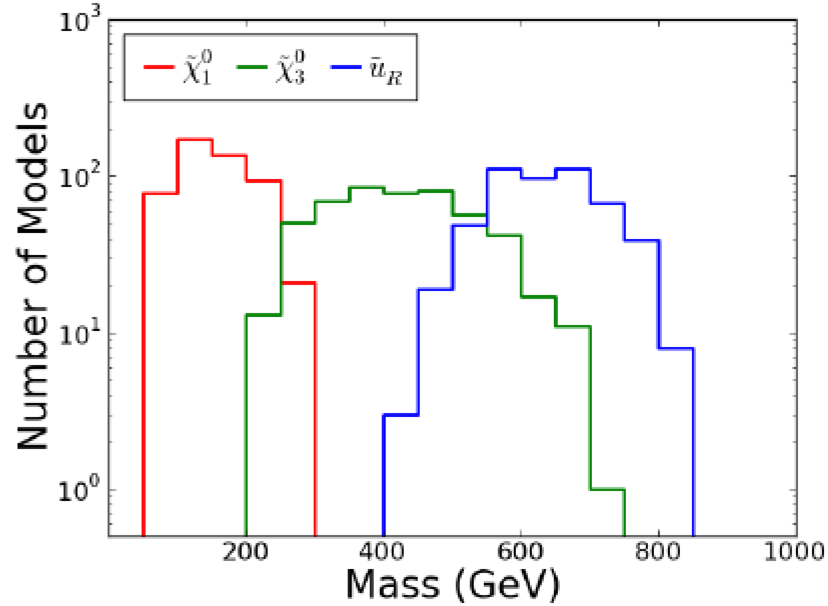
d



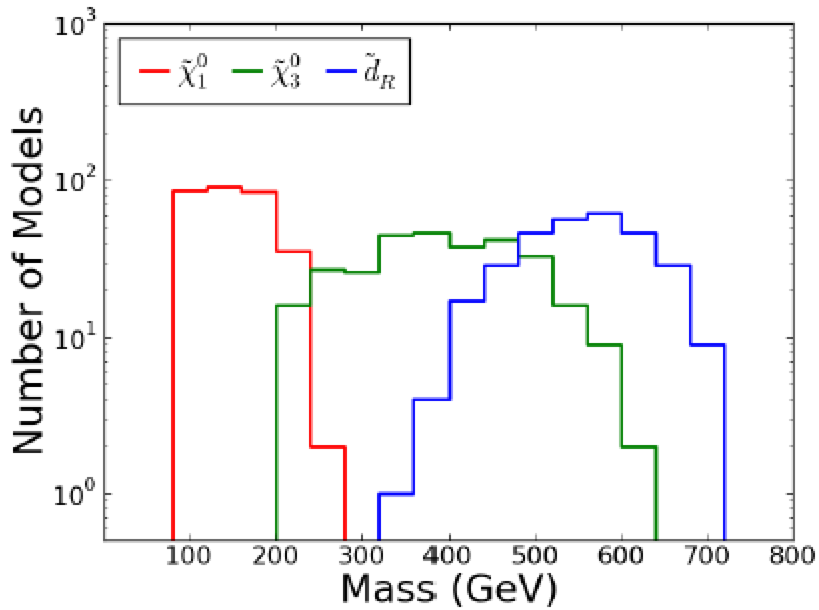
Little clustering near the upper boundary

CMS





Mass Distributions

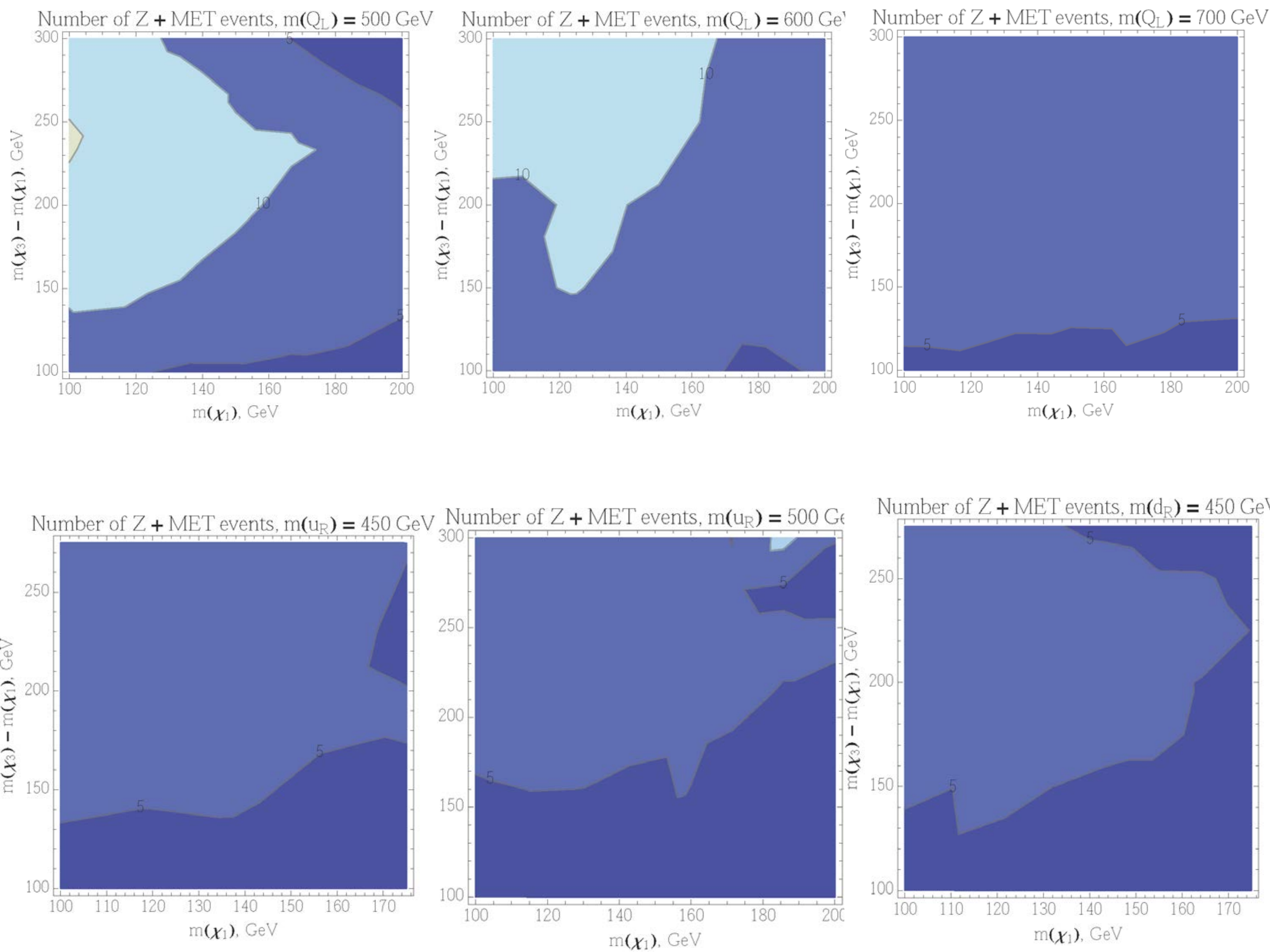


What Do the Models Predict for 13 TeV ?

- Going to 13 TeV enhances the squark production σ's by a factor of ~4 so we should expect enhanced signal rates
- There are new 13 TeV SUSY constraints to satisfy
- Unfortunately, we only have incomplete (very!) preliminary results ready for 13 TeV (next slide)

So I can't comment in detail on this (yet)

- Given the ~ATLAS signal region employed by CMS & their null results we can't draw any consistent experimental conclusions either until more data is available..



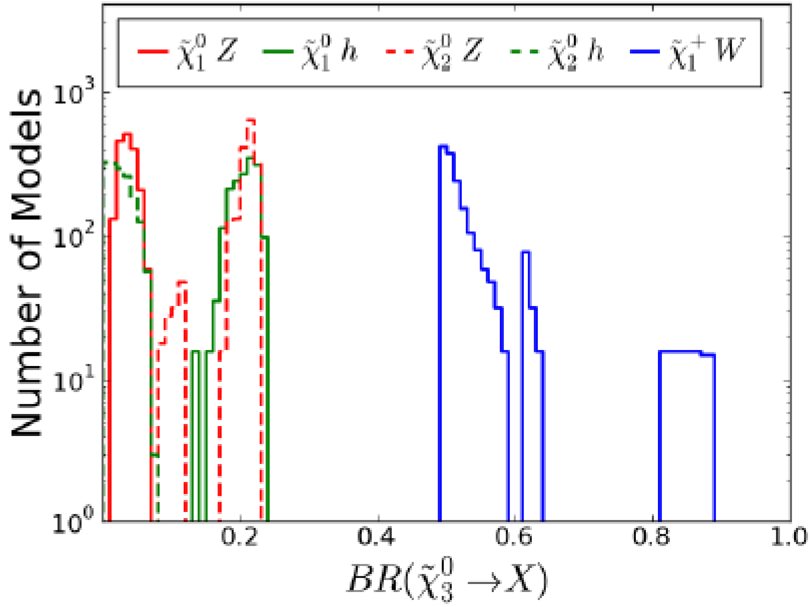
Number of Z + MET events, m(Q_L) = 500 GeV
Number of Z + MET events, m(Q_L) = 600 GeV
Number of Z + MET events, m(Q_L) = 700 GeV
Number of Z + MET events, m(u_R) = 450 GeV
Number of Z + MET events, m(u_R) = 500 GeV
Number of Z + MET events, m(d_R) = 450 GeV
m(χ3) − m(χ1), GeV
m(χ1), GeV
5
10

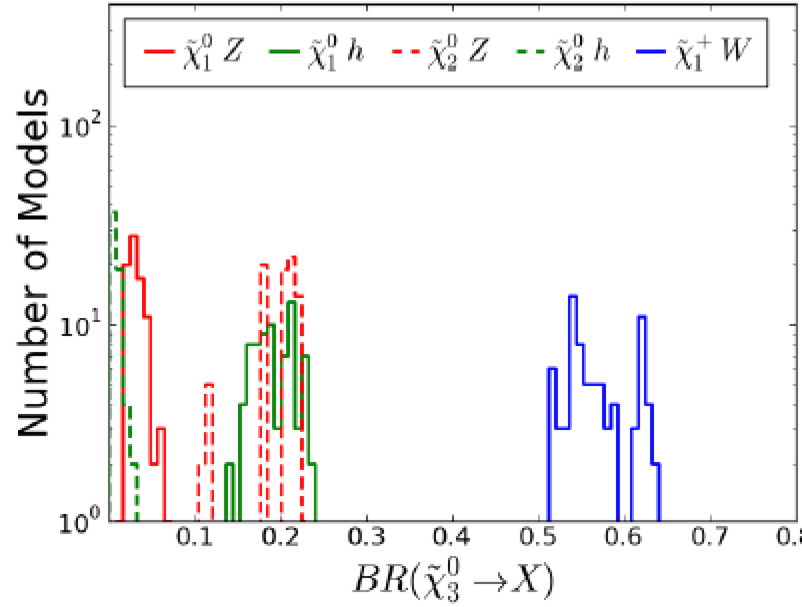
Summary & Conclusions

- ATLAS has observed an excess in the Z+MET channel in both 8 & 13 TeV data
- The 8 TeV CMS analysis is different enough that their null result can be compatible with ATLAS
- But CMS has an ATLAS-like null analysis at 13 TeV?
- The types of SUSY models that can explain this are quite interesting and have important implications elsewhere
- As usual we must be patient & wait another ~5 months

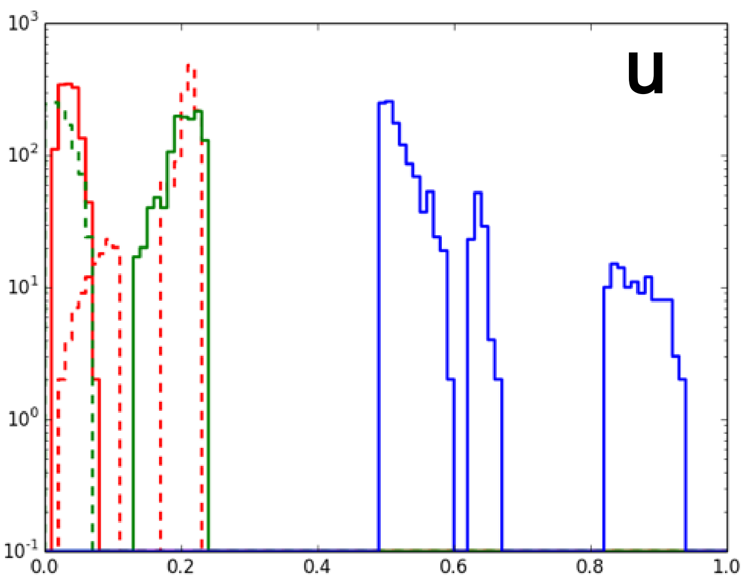
Backups

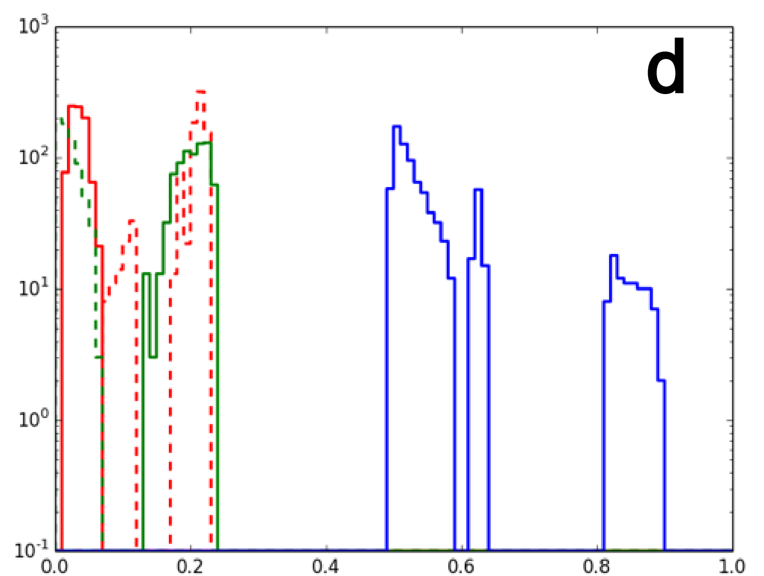
Q





Branching Fractions





LSP type

Analysis	All LSPs	Bino-like	Wino-like	Higgsino-like
0-lepton + 2–6 jets + E_T^{miss}	32.1%	35.8%	29.7%	33.5%
0-lepton + 7–10 jets + E_T^{miss}	7.8%	5.5%	7.6%	8.0%
0/1-lepton + 3b-jets + E_T^{miss}	8.8%	5.4%	7.1%	10.1%
1-lepton + jets + E_T^{miss}	8.0%	5.4%	7.5%	8.4%
Monojet	9.9%	16.7%	9.1%	10.1%
SS/3-leptons + jets + E_T^{miss}	2.4%	1.6%	2.4%	2.5%
$\tau(\tau/\ell)$ + jets + E_T^{miss}	3.0%	1.3%	2.9%	3.1%
0-lepton stop	9.4%	7.8%	8.2%	10.2%
1-lepton stop	6.2%	2.9%	5.4%	6.8%
2b-jets + E_T^{miss}	3.1%	3.3%	2.3%	3.6%
2-leptons stop	0.8%	1.1%	0.8%	0.7%
Monojet stop	3.5%	11.3%	2.8%	3.6%
Stop with Z boson	0.4%	1.0%	0.4%	0.5%
tb+E_T^{miss}, stop	4.2%	1.9%	3.1%	5.0%
ℓh, electroweak	0	0	0	0
2-leptons, electroweak	1.3%	2.2%	0.7%	1.6%
2-τ, electroweak	0.2%	0.3%	0.2%	0.2%
3-leptons, electroweak	0.8%	3.8%	1.1%	0.6%
4-leptons	0.5%	1.1%	0.6%	0.5%
Disappearing Track	11.4%	0.4%	29.9%	0.1%
Long-lived particle	0.1%	0.1%	0.0%	0.1%
$H/A \to \tau^+\tau^-$	1.8%	2.2%	0.9%	2.4%
Total	40.9%	40.2%	45.4%	38.1%

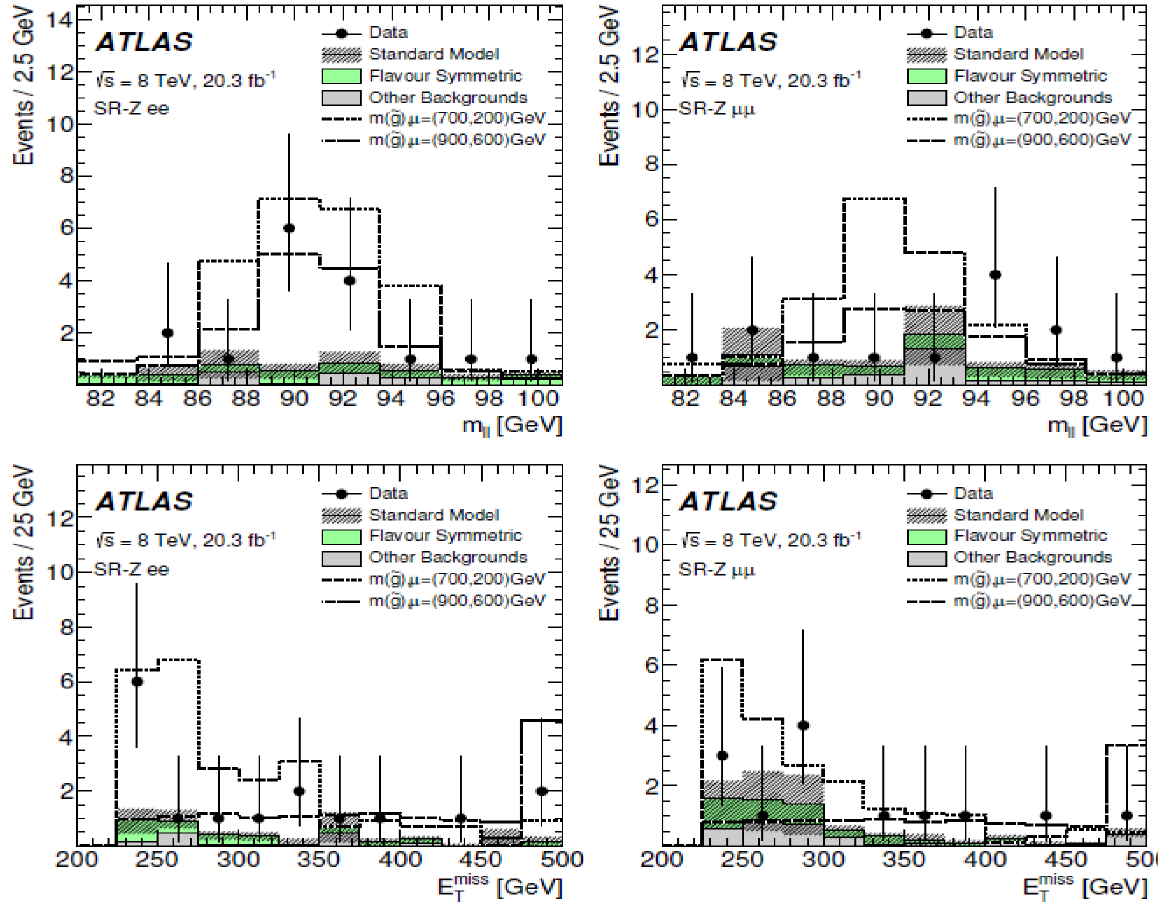
ATLAS Analyses

Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-033	21.2%	17.4%	36.5%
multijets	ATLAS-CONF-2012-037	1.6%	2.1%	10.6%
1-lepton	ATLAS-CONF-2012-041	3.2%	5.3%	18.7%
HSCP	1205.0272	4.0%	17.4%	<0.1%
Disappearing Track	ATLAS-CONF-2012-111	2.6%	1.2%	<0.1%
Muon + Displaced Vertex	1210.7451	-	0.5%	-
Displaced Dilepton	1211.2472	-	1.1%	-
Gluino $\rightarrow$ Stop/Sbottom	1207.4686	4.9%	3.5%	21.2%
Very Light Stop	ATLAS-CONF-2012-059	<0.1%	<0.1%	0.1%
Medium Stop	ATLAS-CONF-2012-071	0.3%	5.1%	2.1%
Heavy Stop (0l)	1208.1447	3.7%	3.0%	17.0%
Heavy Stop (1l)	1208.2590	2.0%	2.2%	12.6%
GMSB Direct Stop	1204.6736	<0.1%	<0.1%	0.7%
Direct Sbottom	ATLAS-CONF-2012-106	2.5%	2.3%	5.1%
3 leptons	ATLAS-CONF-2012-108	1.1%	6.1%	17.6%
1-2 leptons	1208.4688	4.1%	8.2%	21.0%
Direct slepton/gaugino (2l)	1208.2884	0.1%	1.2%	0.8%
Direct gaugino (3l)	1208.3144	0.4%	5.4%	7.5%
4 leptons	1210.4457	0.7%	6.3%	14.8%
1 lepton + many jets	ATLAS-CONF-2012-140	1.3%	2.0%	11.7%
1 lepton + γ	ATLAS-CONF-2012-144	<0.1%	1.6%	<0.1%
γ + b	1211.1167	<0.1%	2.3%	<0.1%
$\gamma\gamma$ + MET	1209.0753	<0.1%	5.4%	<0.1%
$B_s \rightarrow \mu\mu$	1211.2674	0.8%	3.1%	*
$A/H \rightarrow \tau\tau$	CMS-PAS-HIG-12-050	1.6%	<0.1%	*

Search	Reference	Neutralino	Gravitino	Low-FT
2-6 jets	ATLAS-CONF-2012-109	26.7%	21.6%	44.9%
multijets	ATLAS-CONF-2012-103	3.3%	3.8%	20.9%
1-lepton	ATLAS-CONF-2012-104	3.3%	6.0%	20.9%
SS dileptons	ATLAS-CONF-2012-105	4.9%	12.4%	35.5%
Medium Stop (2l)	ATLAS-CONF-2012-167	0.6%	8.1%	4.9%
Medium/Heavy Stop (1l)	ATLAS-CONF-2012-166	3.8%	4.5%	21.0%
Direct Sbottom (2b)	ATLAS-CONF-2012-165	6.2%	5.1%	12.1%
3rd Generation Squarks (3b)	ATLAS-CONF-2012-145	10.8%	9.9%	40.8%
3rd Generation Squarks (3l)	ATLAS-CONF-2012-151	1.9%	9.2%	26.5%
3 leptons	ATLAS-CONF-2012-154	1.4%	8.8%	32.3%
4 leptons	ATLAS-CONF-2012-153	3.0%	13.2%	46.9%
Z + jets + MET	ATLAS-CONF-2012-152	0.3%	1.4%	6.8%

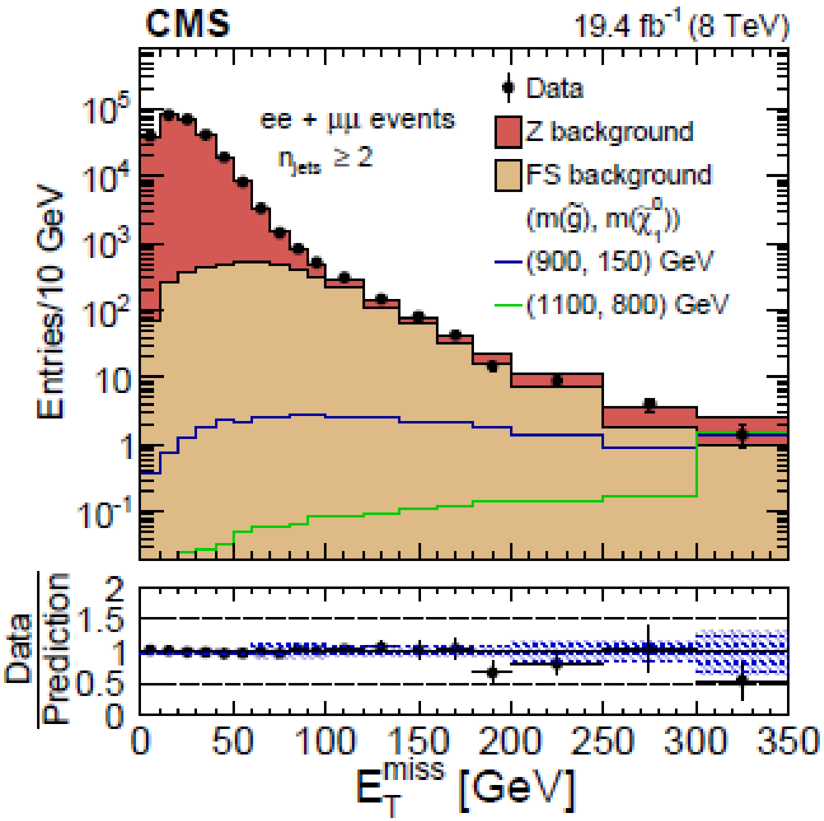
Our Analyses

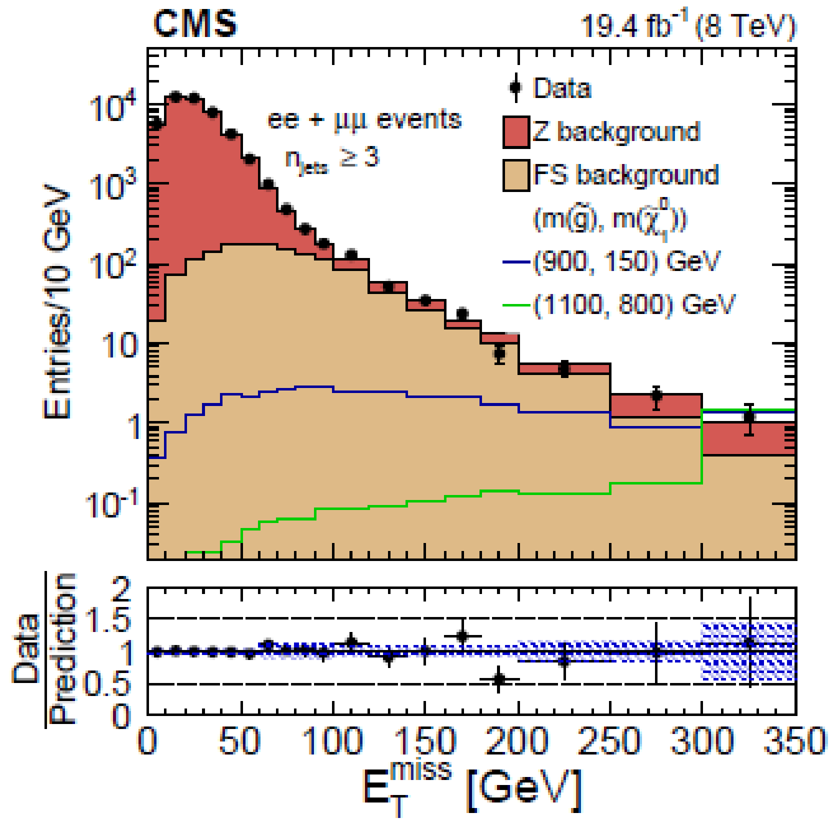
ATLAS @ 8 TeV



Signal region	Channel	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_B	$p(s=0)$	Gaussian significance
SR-Z	$ee+\mu\mu$	1.46	29.6	12^{+5}_{-2}	0.998	0.0013	3.0
	ee	1.00	20.2	8^{+4}_{-2}	0.998	0.0013	3.0
	$\mu\mu$	0.72	14.7	9^{+4}_{-2}	0.951	0.0430	1.7

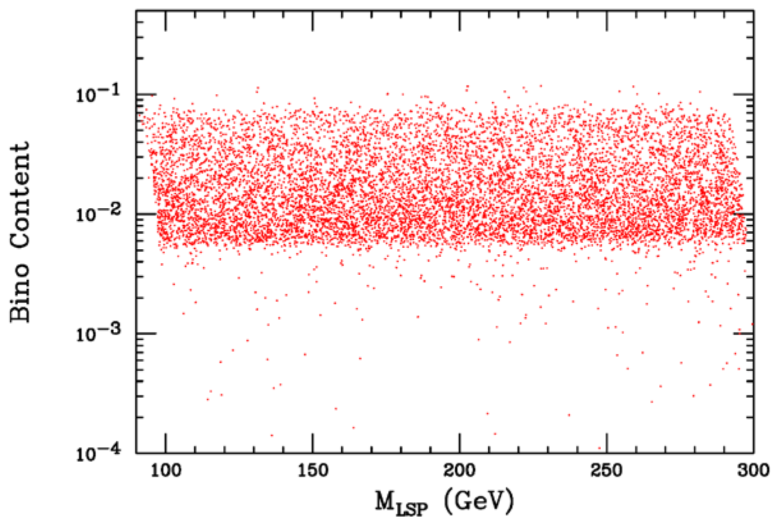
The CMS distributions all look ‘normal’…





A Bit More Detailed Look

LSP Bino Content

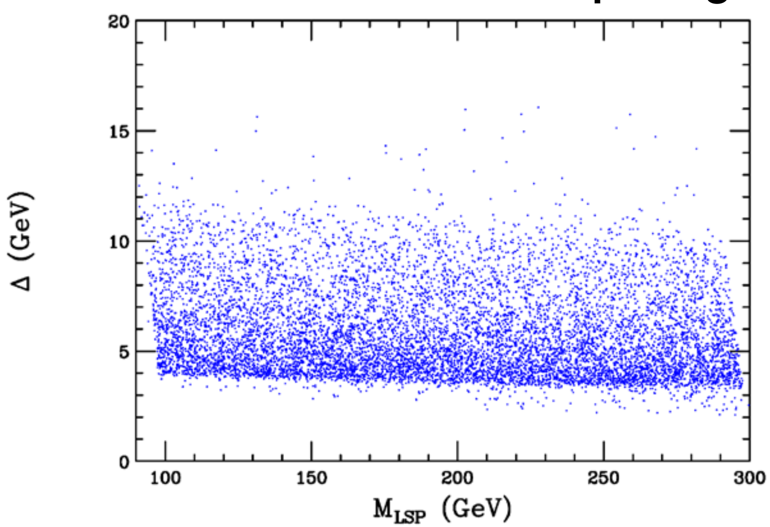


Bino-Higgsino mixing generates the appropriate couplings & decays of $l \rightarrow \chi(Z, h)$ etc

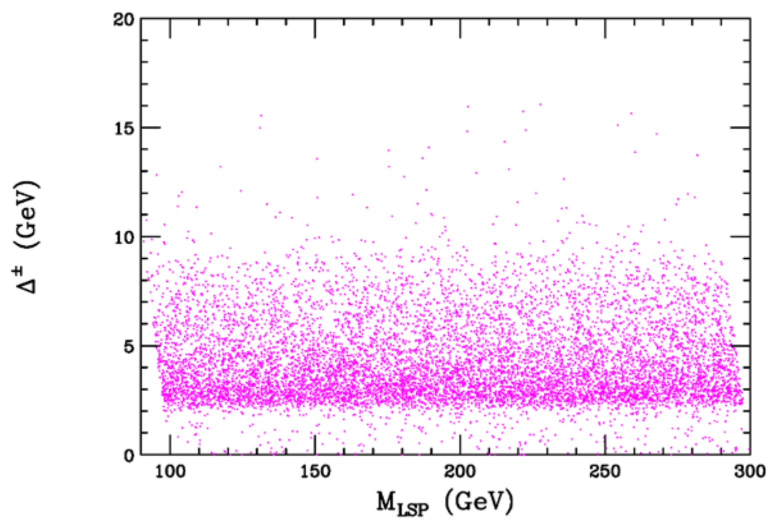
The LSP Bino content is ~ few %

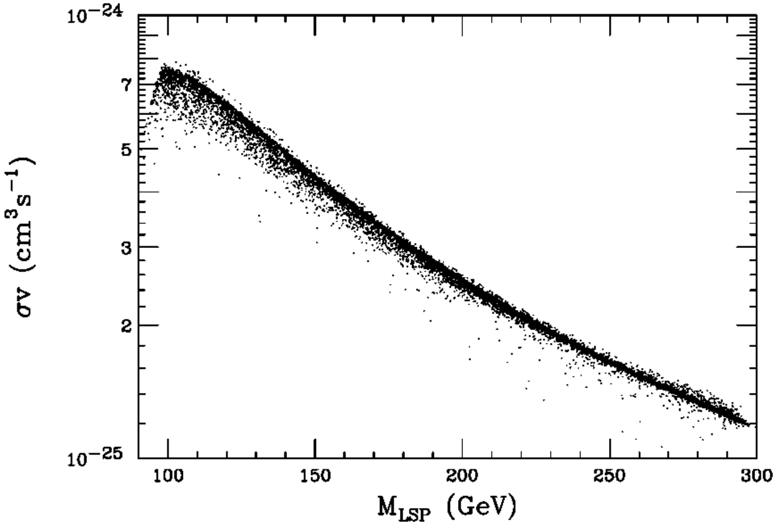
Splittings interesting for e+e- !

LSP – 2nd Neutralino Splitting



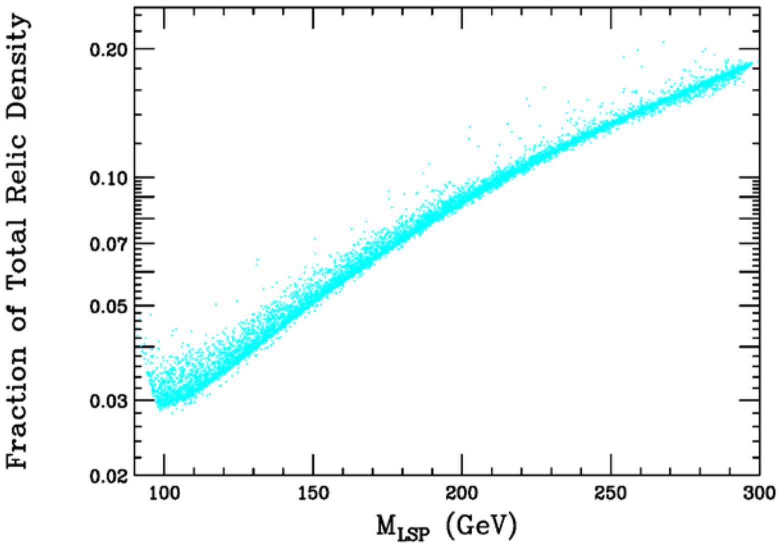
LSP-Chargino Splitting

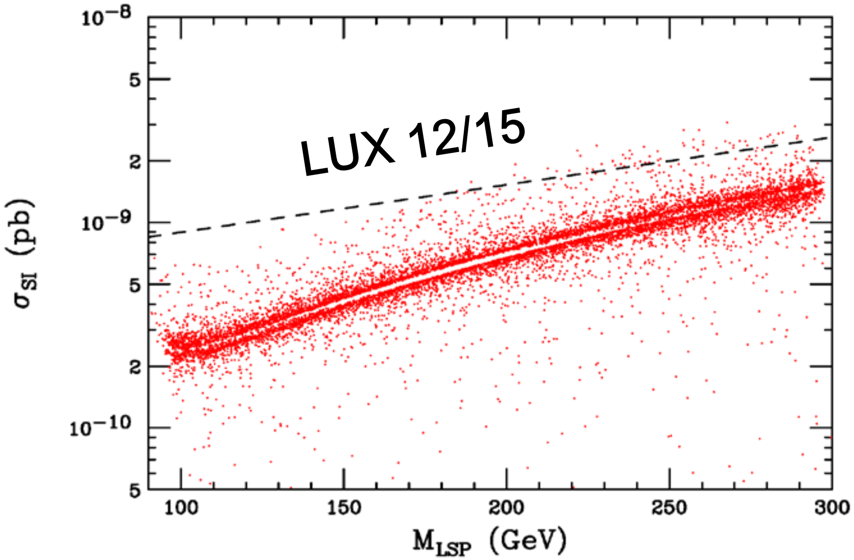


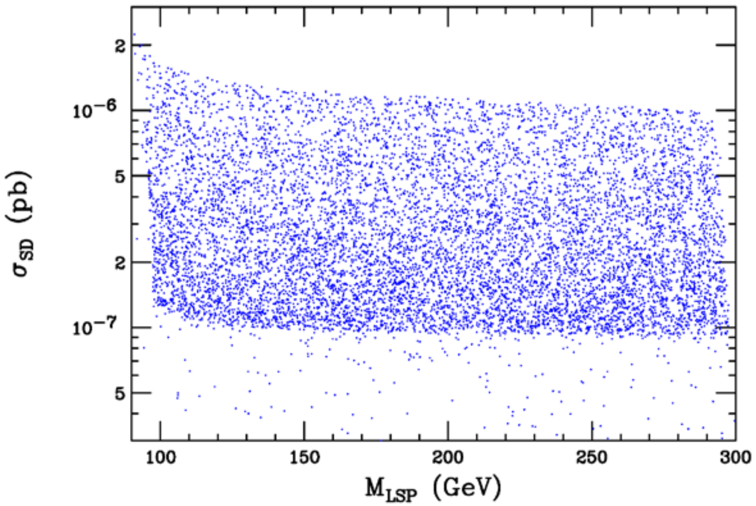


Given the LSP masses & couplings we can ask how it might contribute to thermal DM.. ~3-10%

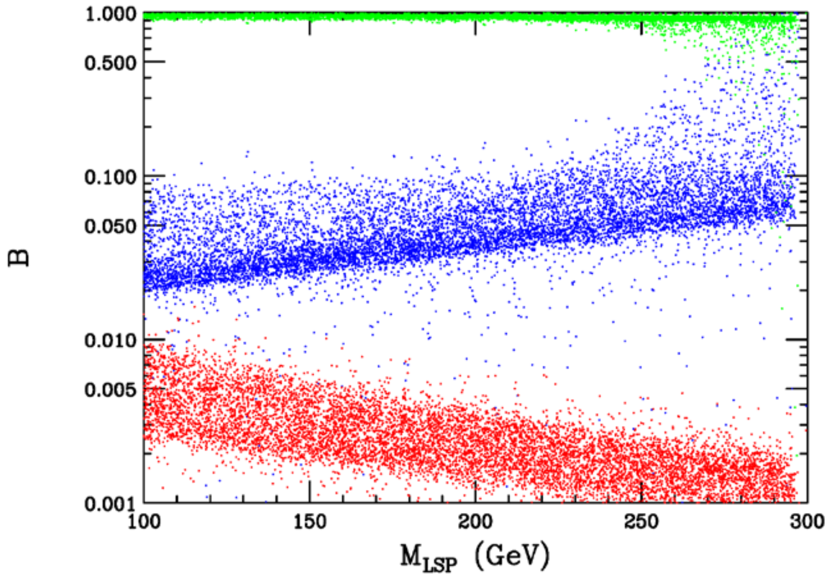
Even with this low value these models will soon be accessed by SI DD experiments







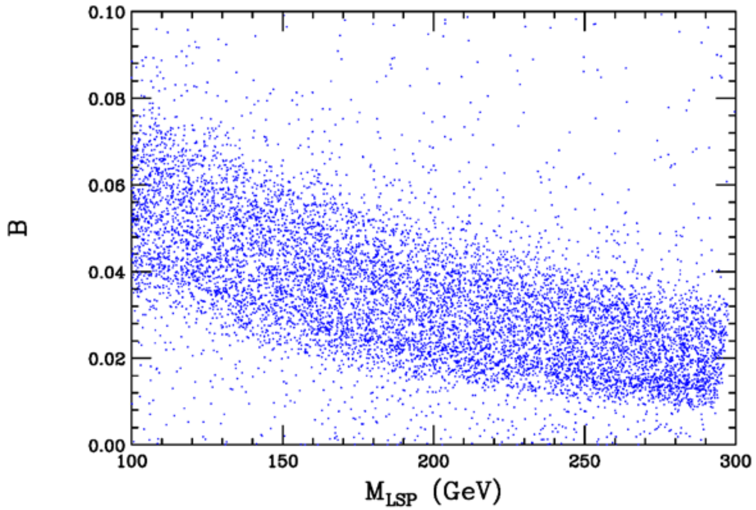
SD direct detection is not (yet) sensitive for any of these models



These are the (Q,u,d) BFs into χ_3 (green), χ_1 (blue) & χ_2 (red)

They are all (Q,u,d) the same in the complete decoupling limit & thus there are no decays to the charginos here

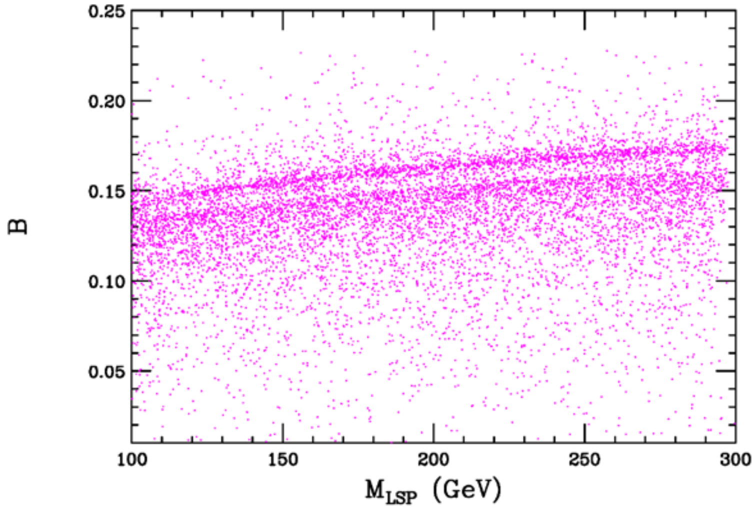
$\chi_3 \to Z\, \chi_1$



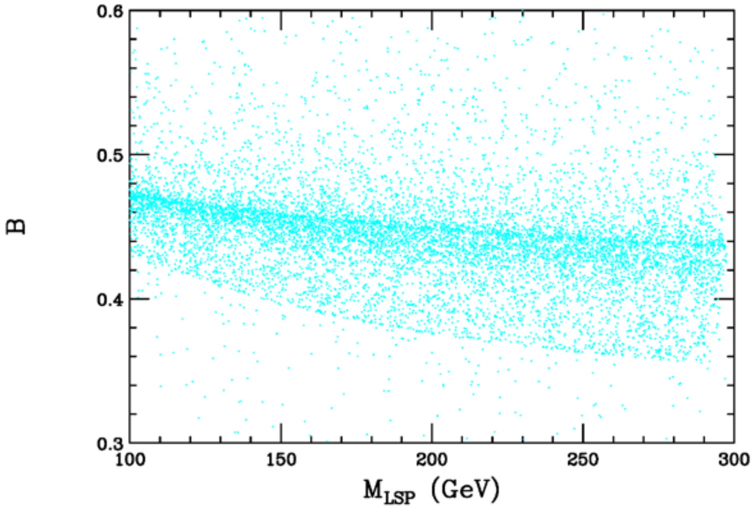
Decays directly to the LSP via either Z or h are somewhat suppressed

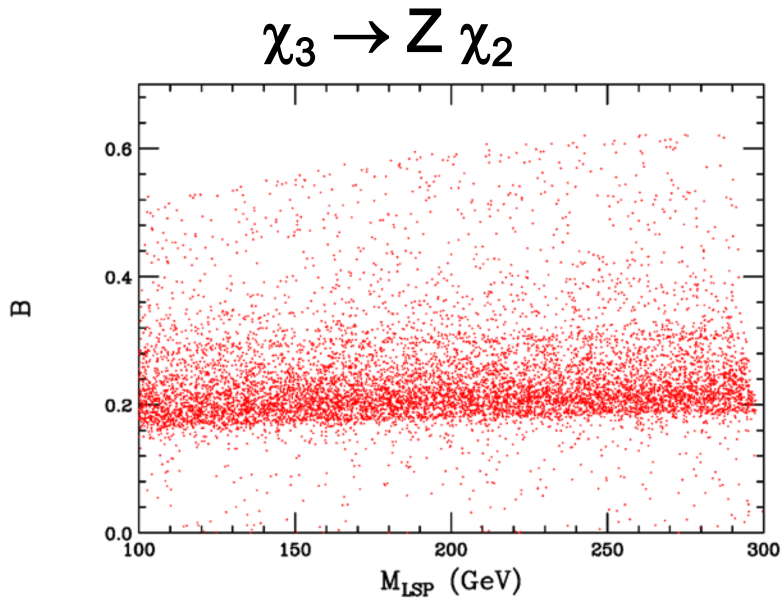
Those to the chargino are more significant.. charginos are common decay products

$\chi_3 \to h\, \chi_1$

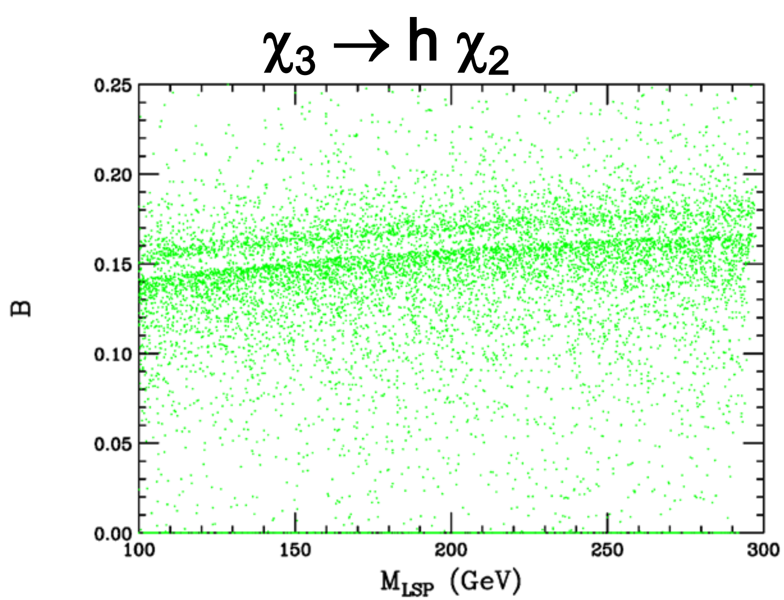


$\chi_3 \to W^\pm\, \chi_1^\pm$





Most of the Z's actually arise from this decay process & not from those to the LSP

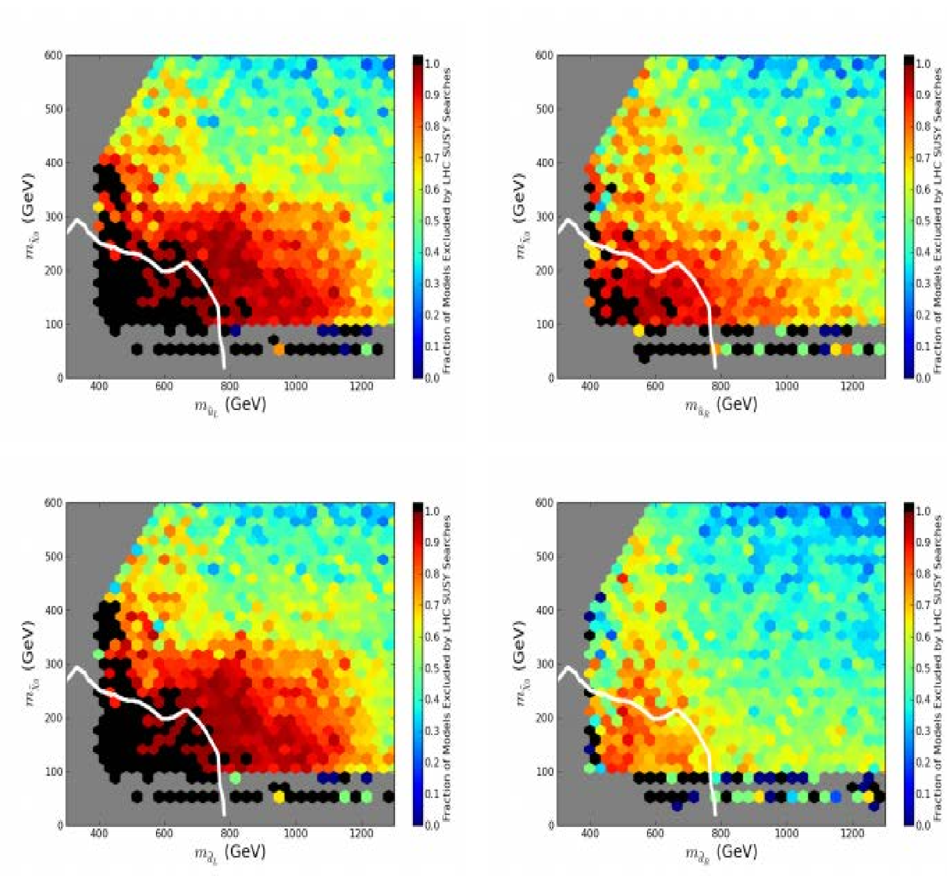


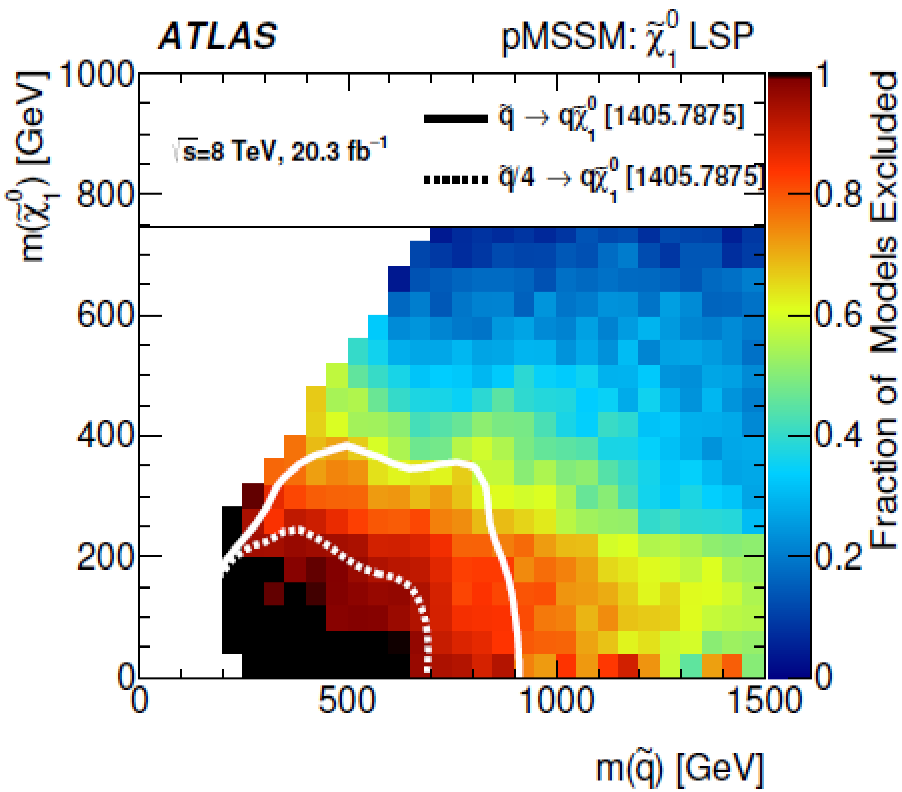
The χ_2 level will be highly populated

The chargino & χ_2 decay via virtual W/Z emission into the LSP with soft by-products

The mass splittings are large enough that these decays are prompt

- After viewing these spectra, one question you might ask is ‘are such light squarks really allowed?’





(b) Lightest (1st/2nd gen) squark / LSP.

Yes !

In principle:

C = Q-, u-, d-squarks , t- or b- squarks or the gluino
I, χ = bino, wino or Higgsinos

BUT (loosely speaking)

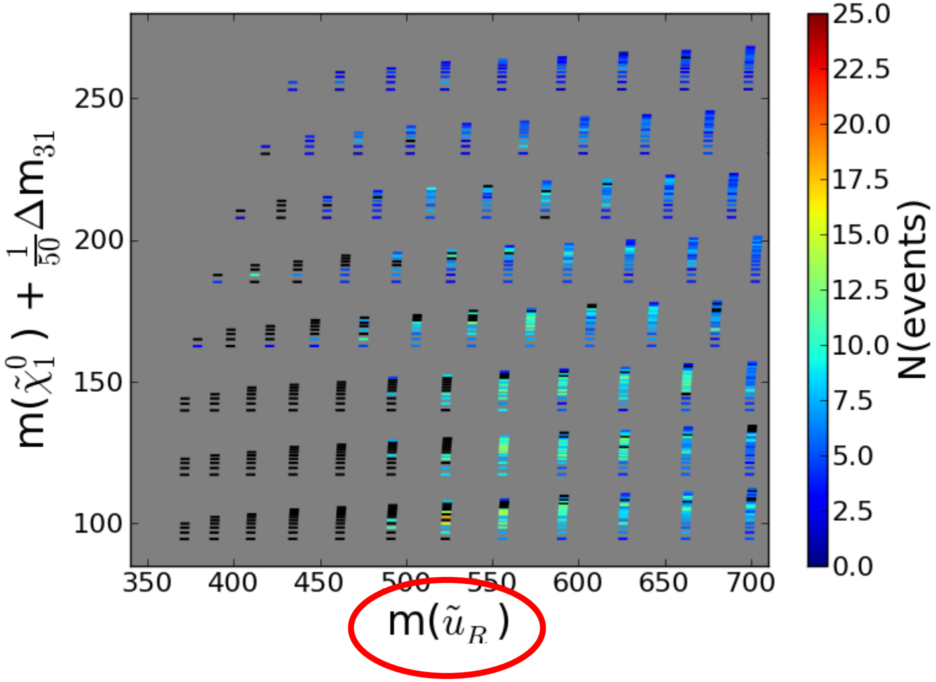
- C can't be gluinos as they don't decay to color singlet I's & their σ's are too large to survive constraints
- (I,χ) cannot be (B,W) or (W,B) as there is no WBZ coupling
- If C = Q,u,d then (I,χ) cannot be (H,W) or (H,B) as their decays will by-pass the intermediate state. If (W,H) then B(W$\rightarrow$ HZ) is too small (mixing suppressed)
- If C = t, b then there is signal dilution & possible 0l+j issues

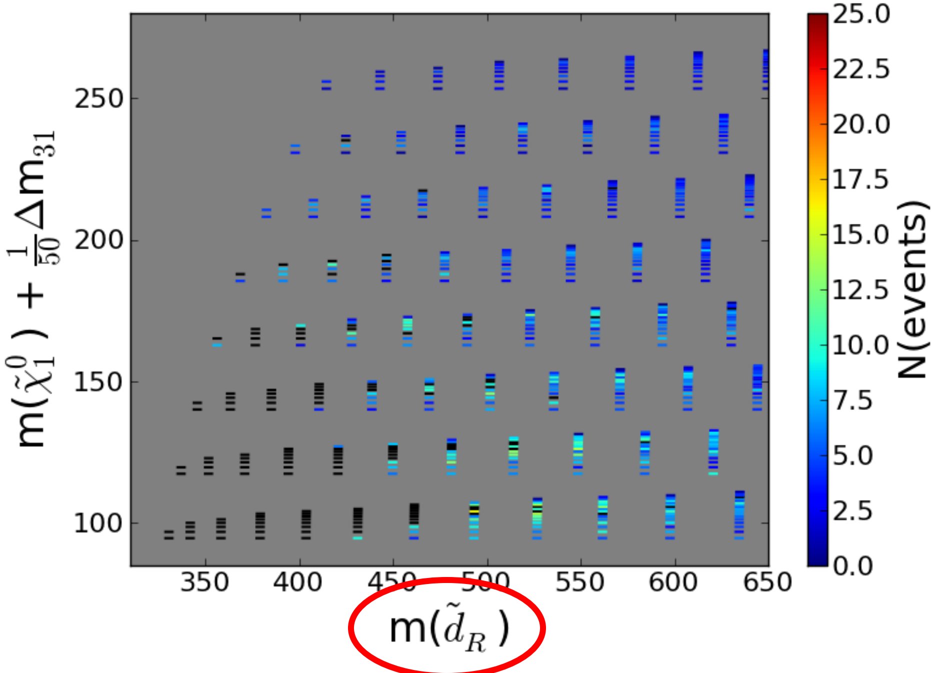
So…rather uniquely

We expect that mostly C = Q,u,d and $(l,\chi) = (B,H)$.

- Increasing Δm_1 lowers the rate & increases the jet p_T
- Modifying Δm_{31} influences the (B,H) mixing, couplings to the Z, the lepton p_T & the amount of MET

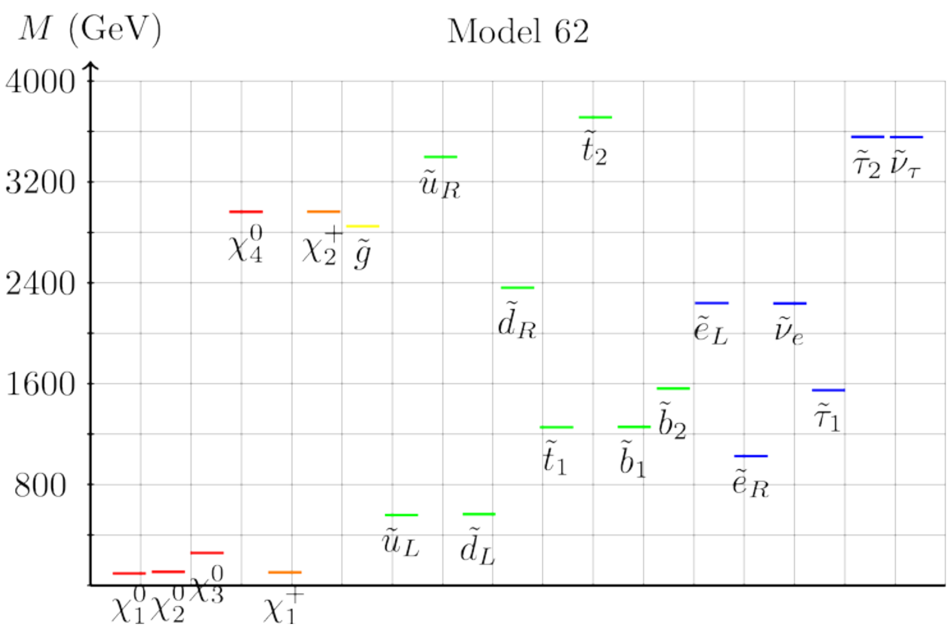
So not only will the sparticle types but also their masses & splittings will be constrained by these many requirements





The u & d preferred regions are somewhat smaller than those for Q & we see that life is somewhat more difficult for the d-type vs u-type models

For d's it's much harder to get the right rate while also satisfying the other analyses


M (GeV)
Model 62
4000
3200
2400
1600
800
χ_1^0
χ_2^0
χ_3^0
χ_4^0
χ_1^+
χ_2^+
$\tilde{g}$
$\tilde{u}_L$
$\tilde{u}_R$
$\tilde{d}_L$
$\tilde{d}_R$
$\tilde{t}_1$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{b}_2$
$\tilde{e}_L$
$\tilde{e}_R$
$\tilde{\nu}_e$
$\tilde{\tau}_1$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$