Experience from Run-1 ATLAS SUSY searches:

Overview of techniques and approach

G. Redlinger, BNL

Experimental Challenges for the LHC Run II

KITP Santa Barbara

Outline

- Signal cross section and uncertainties
- Signal Monte Carlo
- Background estimation
- Search strategy and signal models

Outline

- Signal cross section and uncertainties
- Signal Monte Carlo
- Background estimation
- Search strategy and signal models

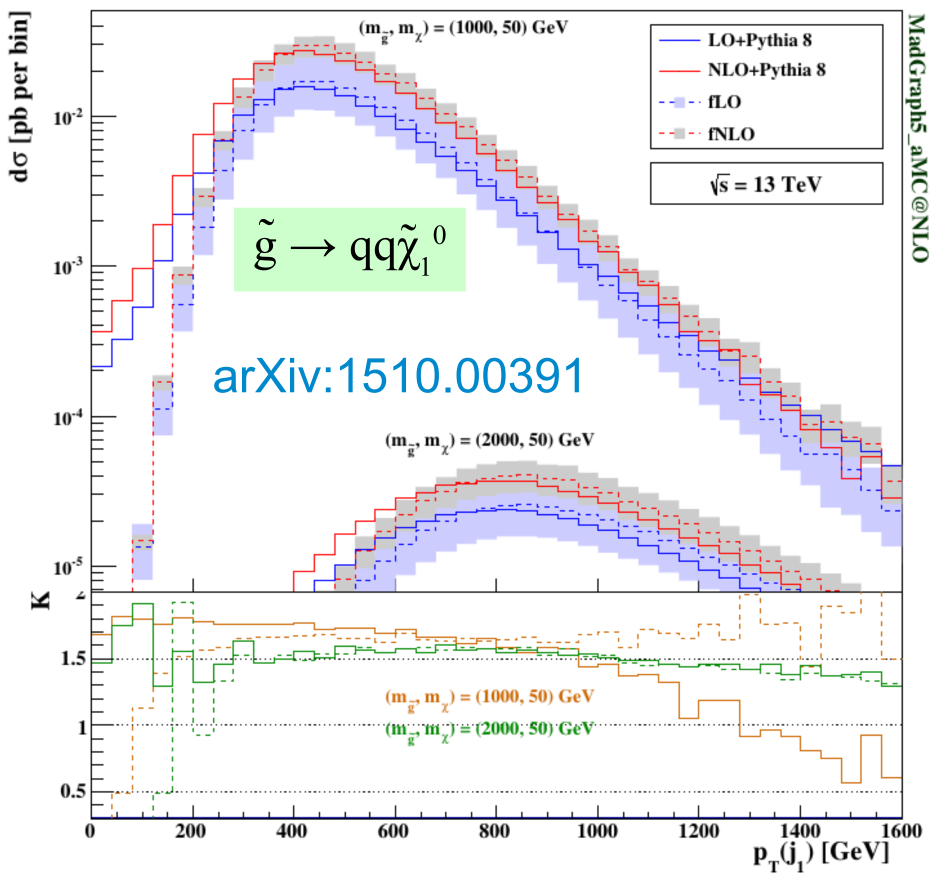
Rather than describing the techniques in detail, I will try to highlight some of the areas that are possibly less well under control

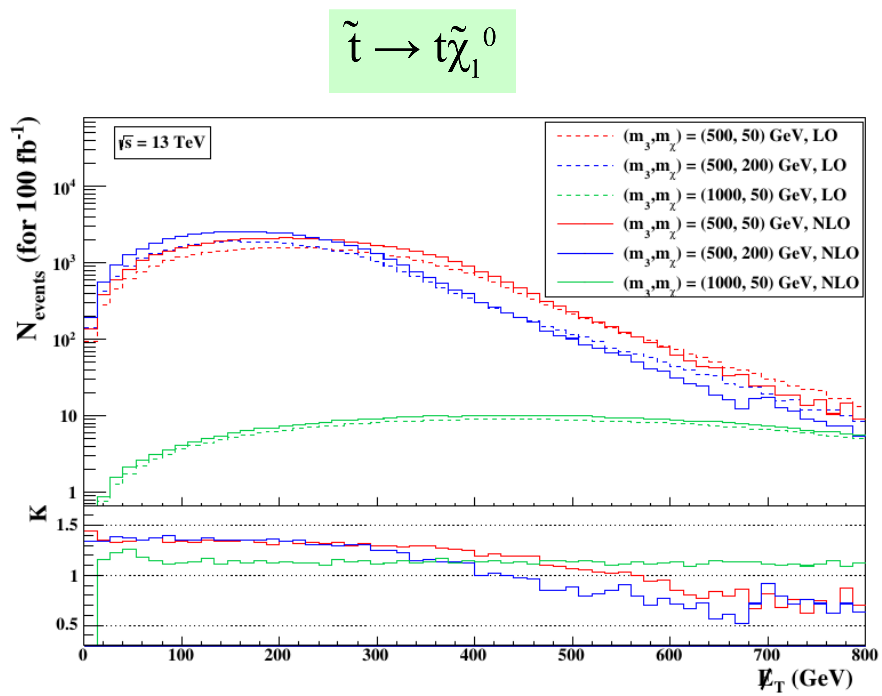
Signal cross section

- Cross section calculations follow state-of-the-art prescriptions of the LHC SUSY Cross Section Working group: link
- Squark/gluino cross sections via NLL-fast (also estimates scale, PDF and α_S uncertainties)
- For EWK processes, PROSPINO2 is used. Cross sections are re-calculated for a range of scale, PDF and α_S variations.

Signal Modeling

- A mix of Herwig++ and MadGraph+Pythia6 in Run1. MadGraph samples generated with up to one extra parton in the matrix element. (Run2 samples are almost all in MadGraph with 2 extra partons).
- NLO models implemented in FeynRules for aMC@NLO are becoming available: link Also in POWHEG: here and here





arXiv:1412.5589

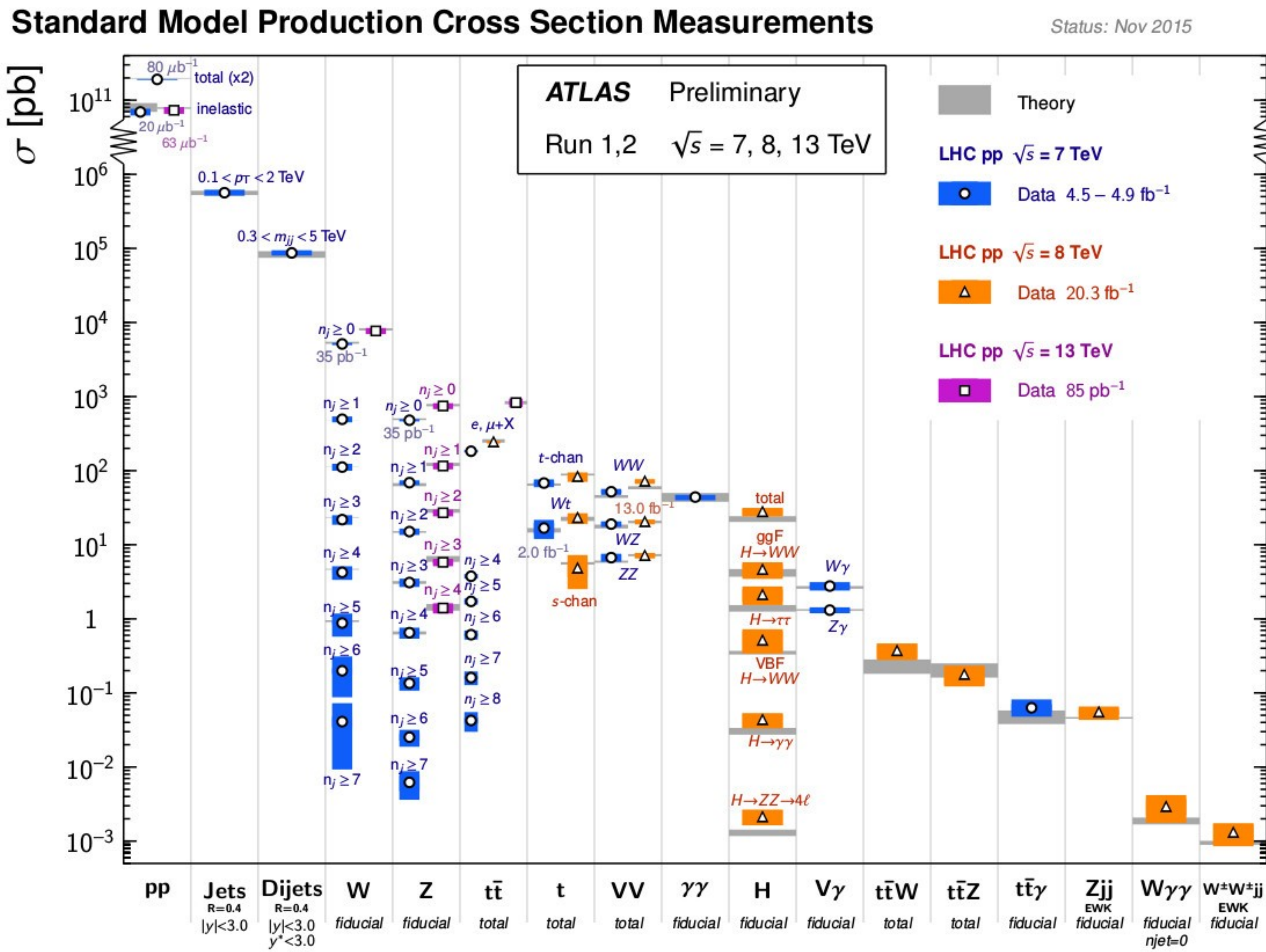
Background estimation

Background estimation methods

- By far, this is the area on which experimentalists spend the most time/effort
- The techniques vary by analysis:
  - Pure MC estimation (usually for small backgrounds)
  - MC estimation, augmented by normalization to data in signal-depleted control regions, and cross-check in validation regions. Probably the most common method in Run1.
  - Analysis-specific methods exploiting particular features of the data with less reliance on the MC. Typically a lack of correlation between two variables is exploited to derive background templates and normalization from the data. Classic examples: fake lepton background, TOF vs dE/dx for slow particle searches

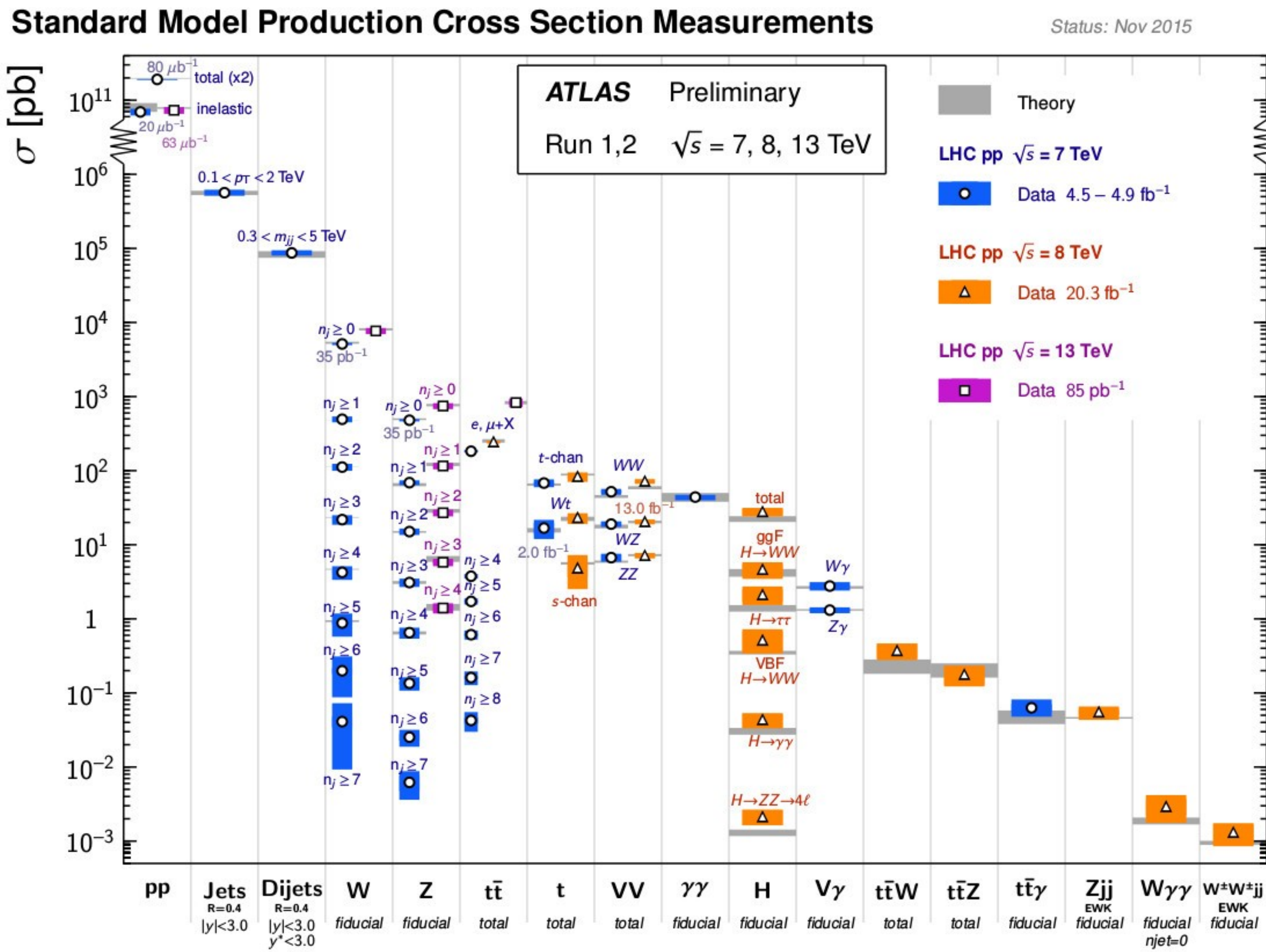
Background estimation

- A little history…
- Long before Run1, ATLAS SUSY group invested considerable effort in developing bkg estimation methods which had less reliance on MC (summarized in the “CSC Book”)
- Early (and very pleasant) surprise of Run1 was just how well the MC does in describing the data



Background estimation

- A little history...
- "data driven" methods rely on MC to verify the technique (e.g. lack of correlations).
- A data-driven method is less "portable", i.e. often specific to a particular background of a particular analysis.
- ATLAS SUSY searches adopt MC-based bkg estimation techniques more generally, though very often in combination with crosschecks against selected data-driven methods.



Standard Model MC samples

Example from Run1 0-lepton 2-6 jets+MET analysis

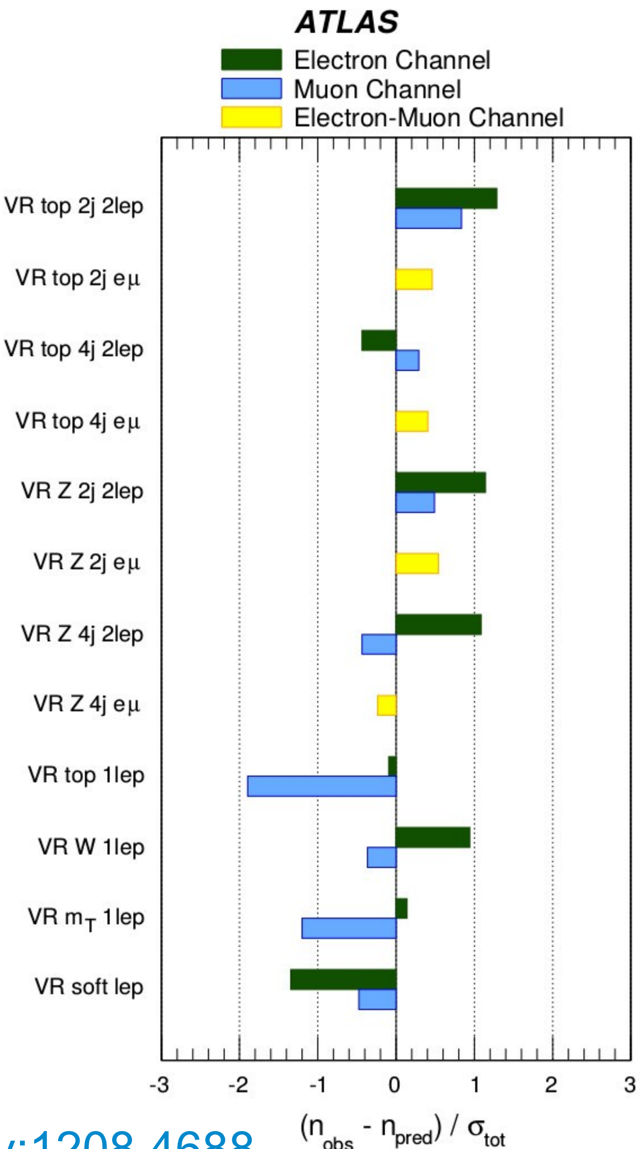
arXiv:1405.7875

Process	Generator + frag./had.	Cross-section order in α_s	Tune	PDF set
W+jets	SHERPA-1.4.0 [28]	NNLO [29]	SHERPA default	CT10 [30]
W+jets (•)	ALPGEN-2.14 [31] + HERWIG-6.520 [34, 35]	NNLO [29]	AUET2B [32]	CTEQ6L1 [33]
Z/γ^*+jets	SHERPA-1.4.0	NNLO [29]	SHERPA default	CT10
Z/γ^*+jets (•)	ALPGEN-2.14 + HERWIG-6.520	NNLO [29]	AUET2B	CTEQ6L1
γ+jets	SHERPA-1.4.0	LO	SHERPA default	CT10
γ+jets (•)	ALPGEN-2.14 + HERWIG-6.520	LO	AUET2B	CTEQ6L1
$t\bar{t}$	POWHEG-BOX-1.0 [36–38] + PYTHIA-6.426 [41]	NNLO+NNLL [39, 40]	PERUGIA2011C [42, 43]	CT10
$t\bar{t}$ (•)	MC@NLO-4.03 [44, 45] + HERWIG-6.520	NNLO+NNLL [39, 40]	AUET2B	CT10
Single top				
t-channel	ACERMC-38 [46] + PYTHIA-6.426	NNLO+NNLL [47]	AUET2B	CTEQ6L1
s-channel, Wt	MC@NLO-4.03 + HERWIG-6.520	NNLO+NNLL [48, 49]	AUET2B	CT10
$t\bar{t}$+EW boson	MADGRAPH-5.0 [50] + PYTHIA-6.426	NLO [51–53]	AUET2B	CTEQ6L1
Dibosons WW, WZ, ZZ, $W\gamma$ and $Z\gamma$	SHERPA-1.4.0	NLO [54, 55]	SHERPA default	CT10

Unified treatment of WWbb missing

Background estimation: bottom line

- Bottom line: Almost all observations have come out consistent with SM expectations
- Too few excesses than one would expect just from statistical fluctuations? Too conservative?
- Many "pull plots" exist. Difficult to interpret the distribution of pulls due to correlations.



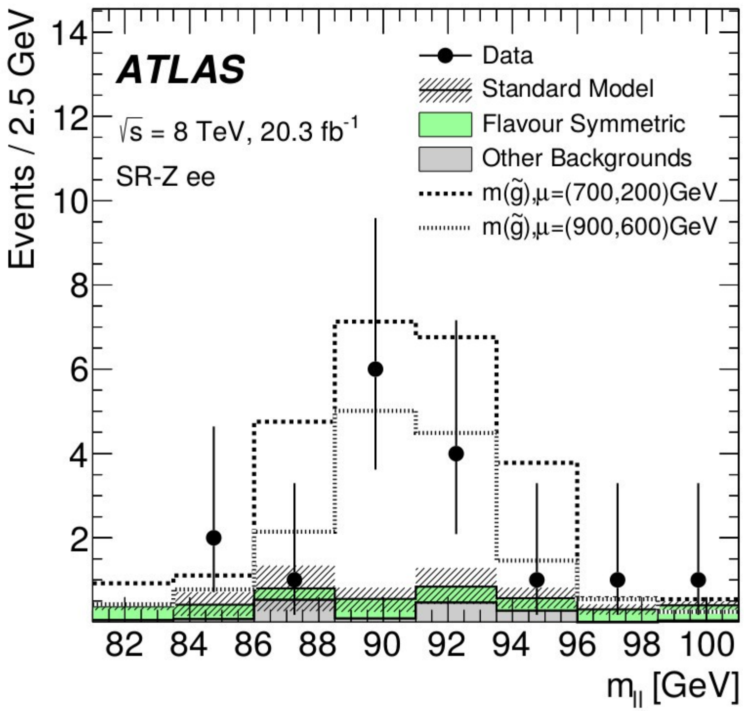
arXiv:1208.4688

Background estimation

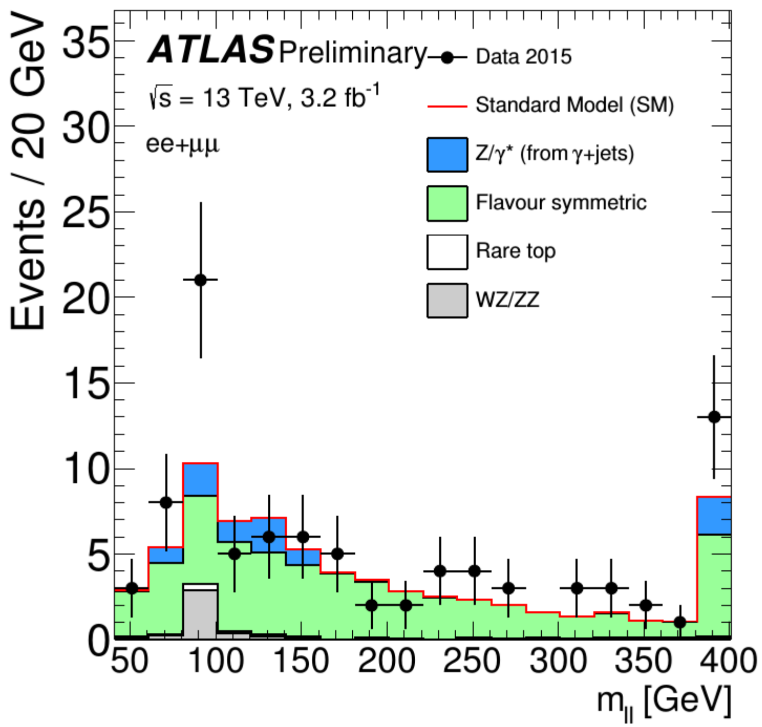
- Opposite extreme: doubts linger about the reliability of MC in far tails of distributions.
  - Recipes for estimating theoretical uncertainties, e.g. scale variations, PS variations, don't seem completely rigorous
  - Experimental uncertainties in extreme phase space are usually not directly estimated and rely on extrapolation
- Would current methods stand up to a “stress test” in the event of an excess?
- Examine test case of the Z+jets+MET excess in ATLAS

ATLAS Z+jets+MET

arXiv:1503.03290



ATLAS-CONF-2015-082



Run1 ATLAS: 3σ excess seen in Z+jets+MET in the ee channel (1.7σ in μμ)

Not confirmed by CMS (cuts were different)

Run2 ATLAS: 2.2σ excess with the same cuts as Run1

Not confirmed by CMS (with the same cuts at ATLAS)

ATLAS Z+jets+MET

Signal region definition

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

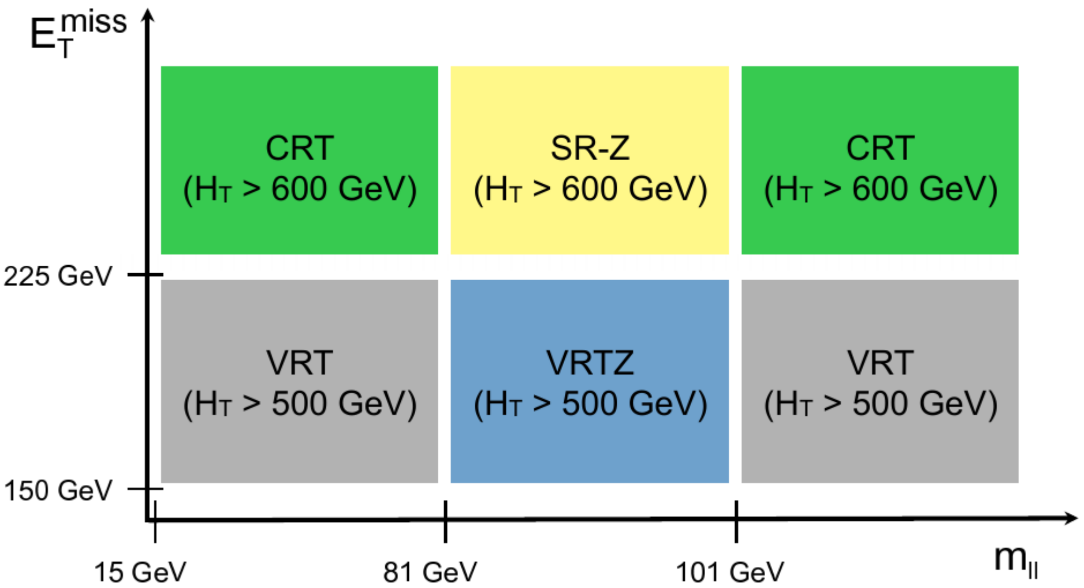
Backgrounds

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	
$Z/\gamma^* +$ 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	from MC
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0	from MC
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$	

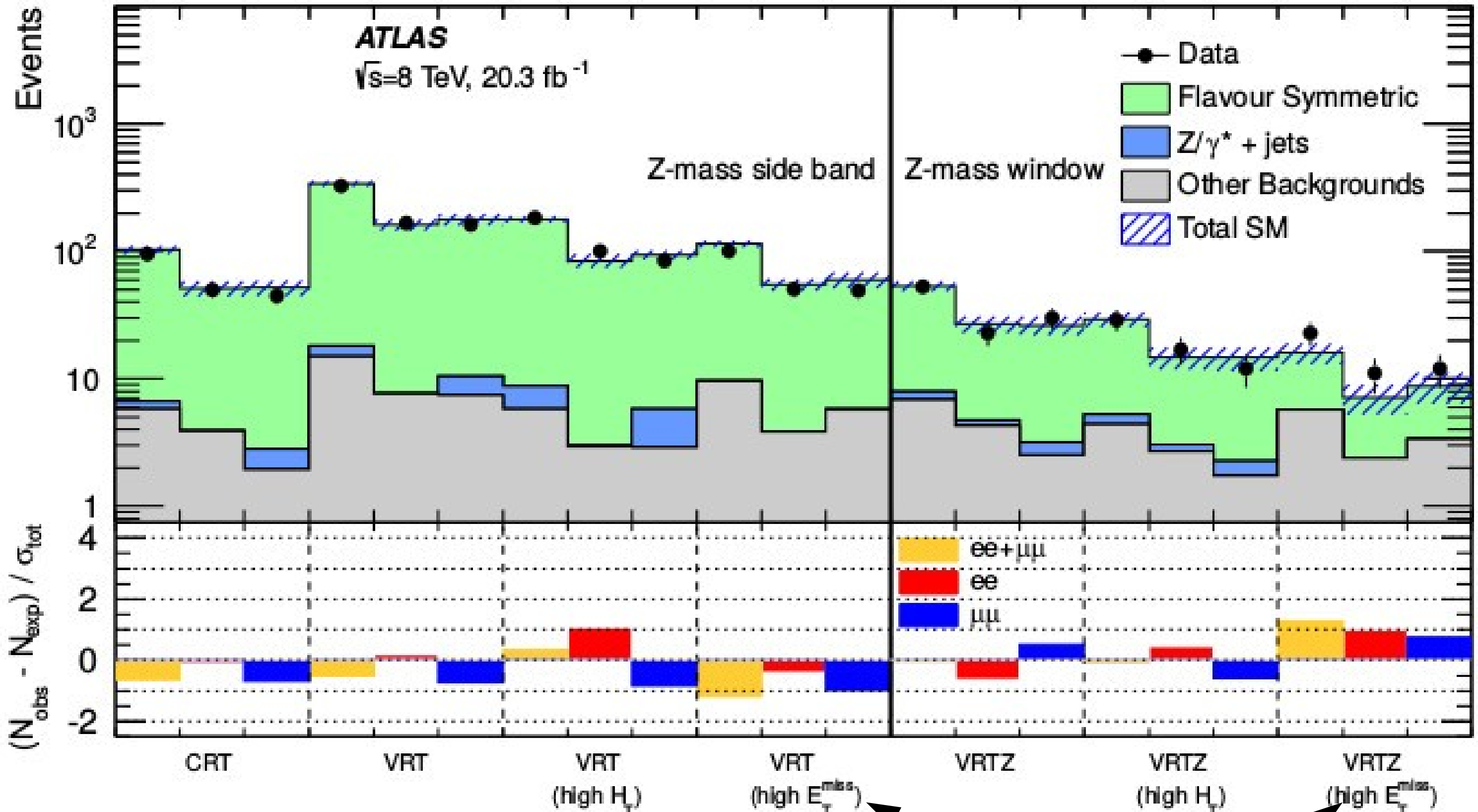
"Flavor symmetric" : mainly ttbar, but also WW, Wt, $Z\rightarrow\tau\tau$

Flavor-symmetric bkg estimation

- eμ control region with exactly the same cuts as the SR except for lepton flavor
  - Subtract fake leptons (matrix method)
  - Subtract other contributions (WZ, ZZ, tZ, ttW, ttZ, ttWW) based on MC
  - Correct for lepton trigger/identification inefficiencies
- Crosscheck using ttbar normalized to data in CRT
  - Norm. factor: 0.52 ± 0.12
- Further validation in VRTZ



Flavor-symmetric bkg estimation



HT>600

HT>600

MET > 225 (same as SR)
HT=[400,600]

Signal region	Flavour-symmetry	Sideband fit
SR-Z *ee*	2.8 ± 1.4	4.9 ± 1.5
SR-Z *μμ*	3.3 ± 1.6	5.3 ± 1.9

Search Strategy

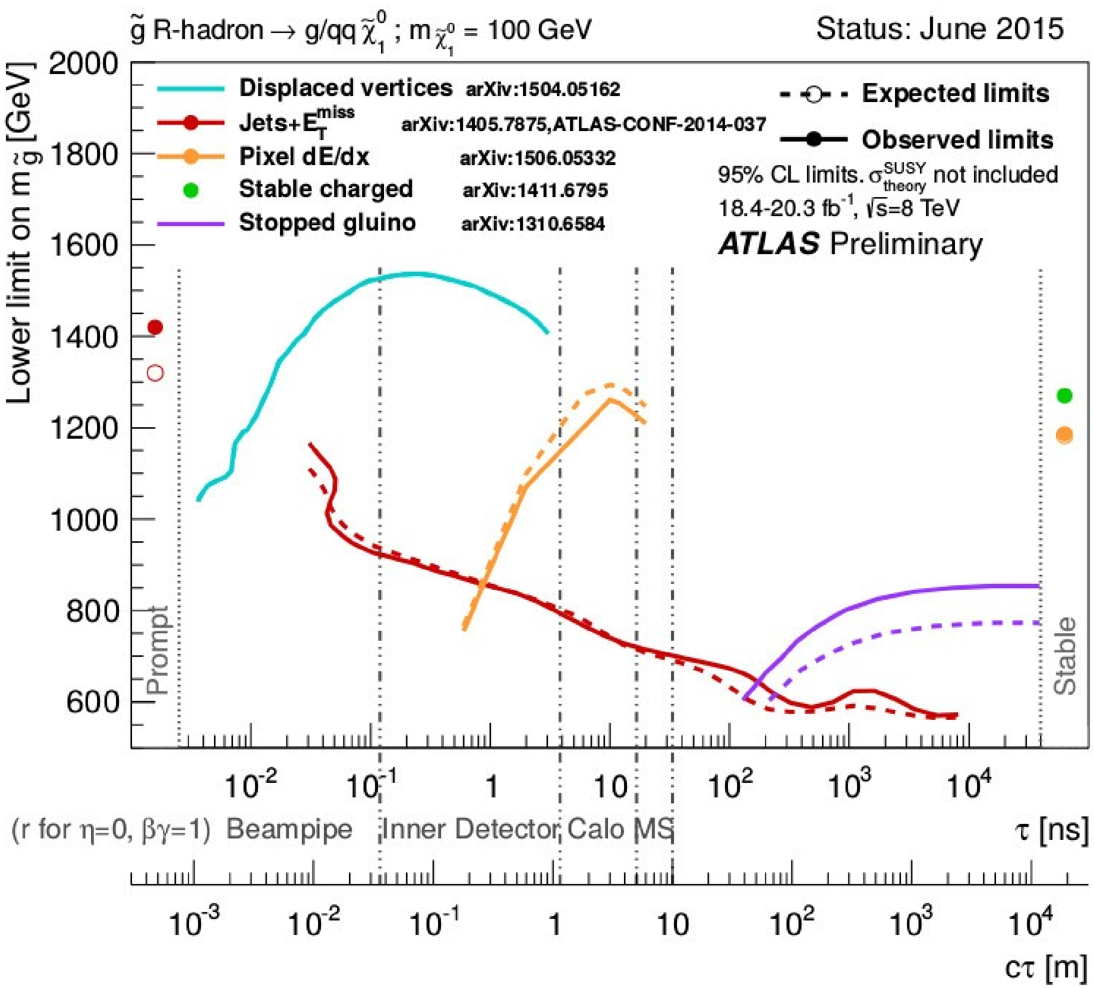
Search strategy

- R-parity conserving
  - Inclusive searches based on jets+MET, with variations on the presence of additional objects (leptons, bjets, …). These are pretty generic, signature-based searches (HT and MET to a large extent), not heavily tuned to SUSY.
  - More specialized searches focusing on particular SUSY final states, optimized using simplified models.
  - Generally focused on prompt signatures
    - But can be sensitive to longer lifetimes, e.g. ATLAS-CONF-2014-037

Search strategy

ATLAS link

- Long-lived signatures (by ATLAS SUSY and Exotics groups)
  - Decaying in tracker:
    - DV+X
    - non-pointing photons
    - disappearing track
  - Decaying in calorimeter:
    - DV+X
  - Detector stable:
    - slow (multi-)charged particle search via pixel dE/dx and/or muon TOF
    - stopped gluino search



Search strategy

$$W_{\not{L}\mathrm{RPV}} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2,$$

$$W_{\not{B}\mathrm{RPV}} = \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k .$$

- Prompt R-parity violating
  - stop → bs (λ''_{323})
  - eμ, eτ, μτ resonance (combination of λ'_{311} with non-zero λ_{132} or λ_{133} or λ_{233})
  - multijets (UDD, λ''_{ijk})
  - 4-lepton (mainly λ_{121} and λ_{122} with sensitivity also to λ_{133} or λ_{233})
  - Reinterpretation of prompt RPC searches (LLE and LQD couplings)
  - Many “exotic” decays are also sensitive (e.g. leptoquark searches) but not explicitly interpreted in RPV SUSY

Strategy assessment

- Coverage of the ATLAS SUSY searches has been examined in a number of pMSSM studies, for example
  - "3"-parameter model for squark production ($m_{\tilde{q}L}$, M_1, M_2) with $M_1 = 60$ GeV and M_2 varied, or $M_2 = ½(M_1 + m_{\tilde{q}L})$
  - "5"-parameter models for stop/sbottom (μ, M_1, M_2) and 2 parameters from ($m_{\tilde{q}L3}$, $m_{\tilde{t}R}$, $m_{\tilde{b}R}$) reduced further by assumptions:
    - "naturalness inspired"
    - well-tempered neutralino
    - h/Z enriched
  - "4"-parameter models for EWK (μ, M_1, M_2, $\tan\beta$) with $M_1 = 50$ GeV and $\tan\beta = 10$
  - the whole shebang: full 19-parameter pMSSM scan (with experimental constraints applied, including Higgs mass and relic density)

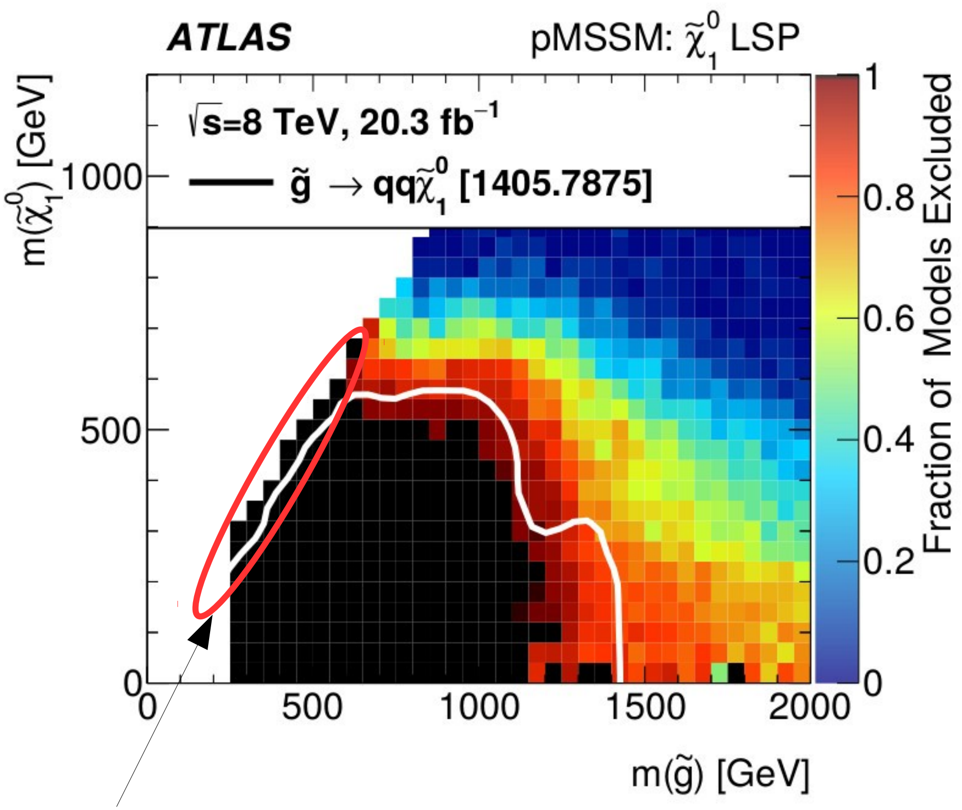
ATLAS searches re-interpreted

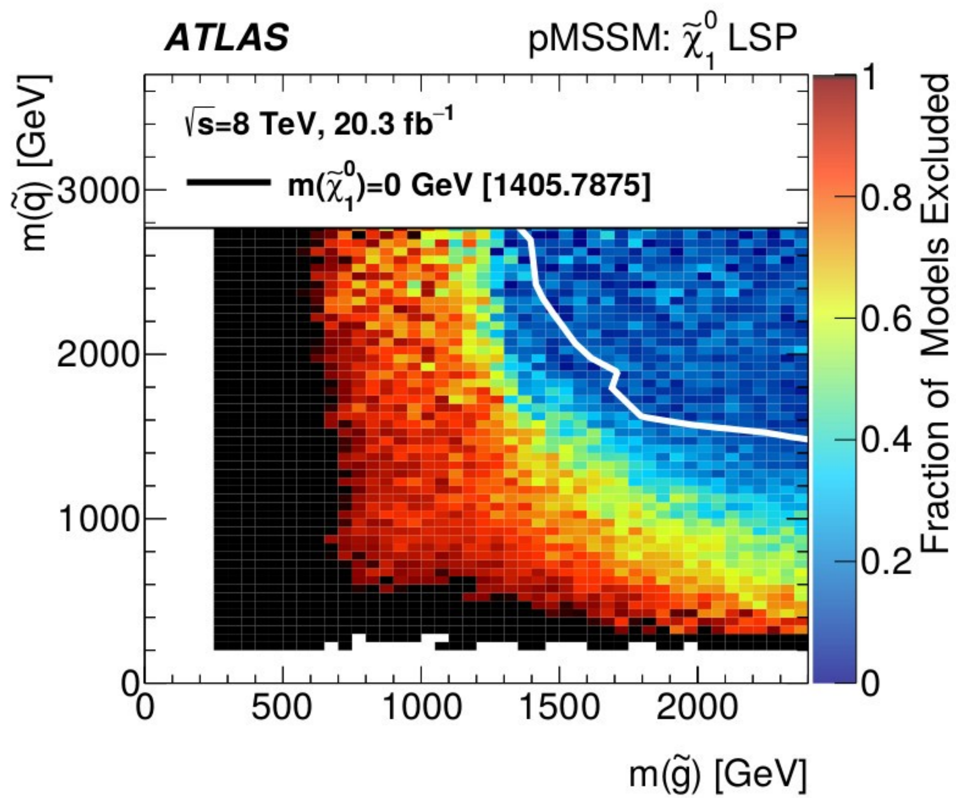
Analysis	Ref.	Category
0-lepton + 2–6 jets + E_T^{miss}	[58]	Inclusive
0-lepton + 7–10 jets + E_T^{miss}	[59]	
1-lepton + jets + E_T^{miss}	[60]	
$\tau(\tau/\ell)$ + jets + E_T^{miss}	[61]	
SS/3-leptons + jets + E_T^{miss}	[62]	
0/1-lepton + 3b-jets + E_T^{miss}	[63]	
Monojet	[64]	
0-lepton stop	[65]	Third generation
1-lepton stop	[56]	
2-leptons stop	[66]	
Monojet stop	[67]	
Stop with Z boson	[68]	
2b-jets + E_T^{miss}	[69]	
tb+E_T^{miss}, stop	[57]	
ℓh	[70]	Electroweak
2-leptons	[54]	
2-τ	[55]	
3-leptons	[53]	
4-leptons	[71]	
Disappearing Track	[72]	
Long-lived particle	[73, 74]	Other
$H/A \to \tau^+\tau^-$	[75]	

arXiv:1508.06608

arXiv:1508.06608

pMSSM-19: gluinos





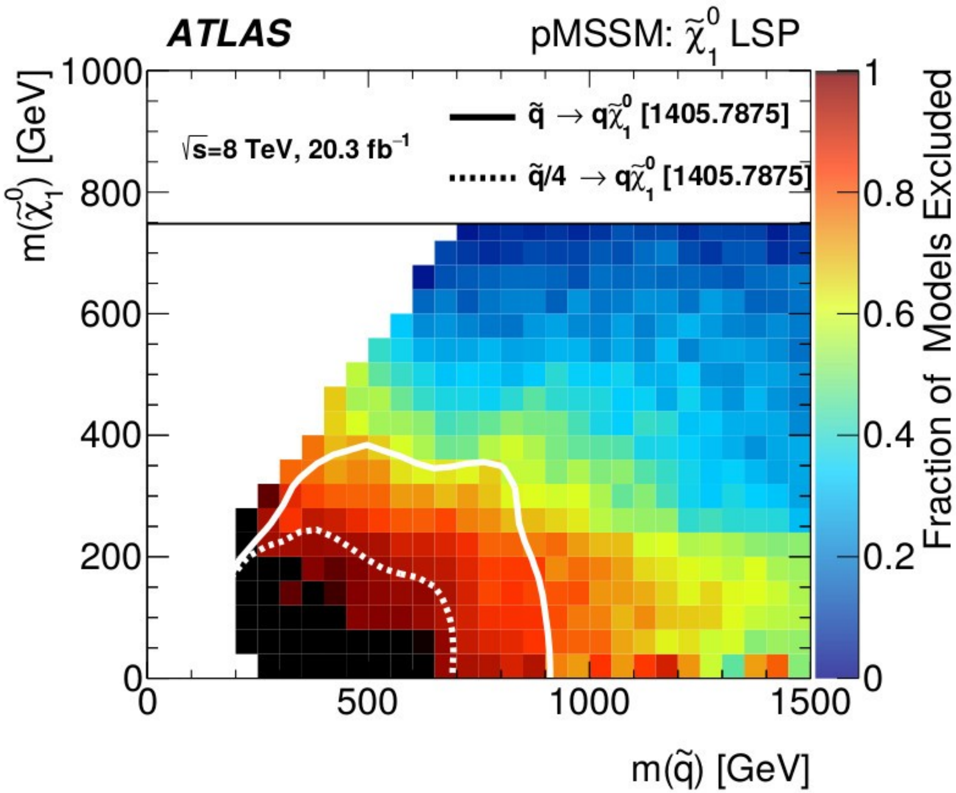
Covered by monojet search

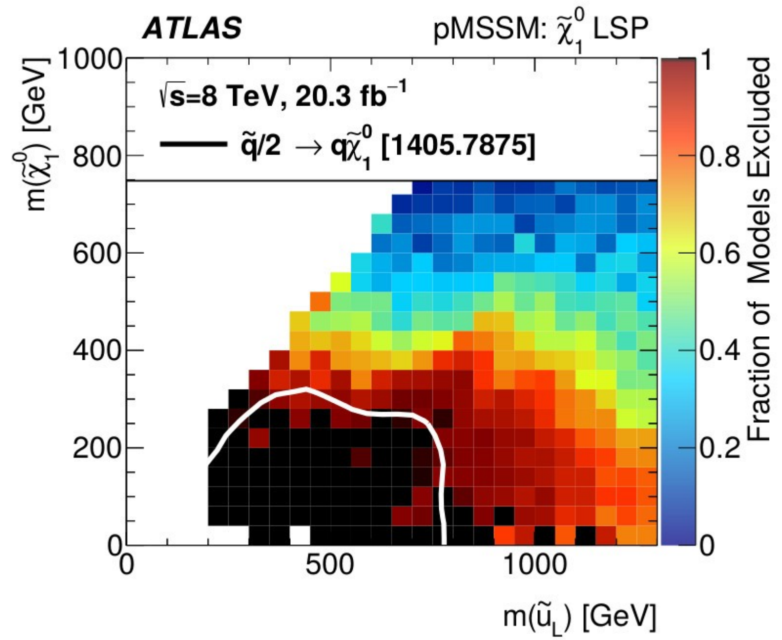
Gluinos are pretty solidly excluded below ~700 GeV.

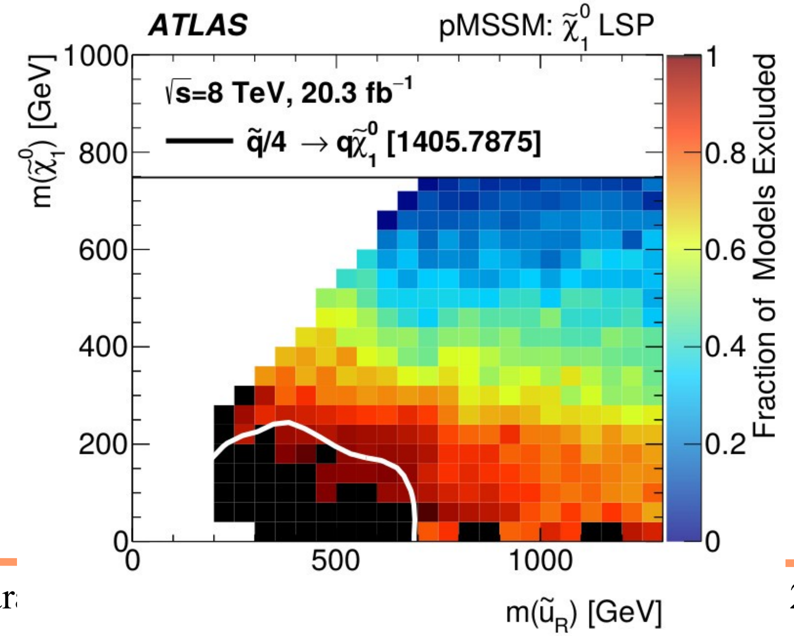
Conclusions from simplified models match pretty well with pMSSM19 scans. Compressed region is an important (and well known) area of difficulty.

arXiv:1508.06608

pMSSM-19: squarks (1st & 2nd gen)







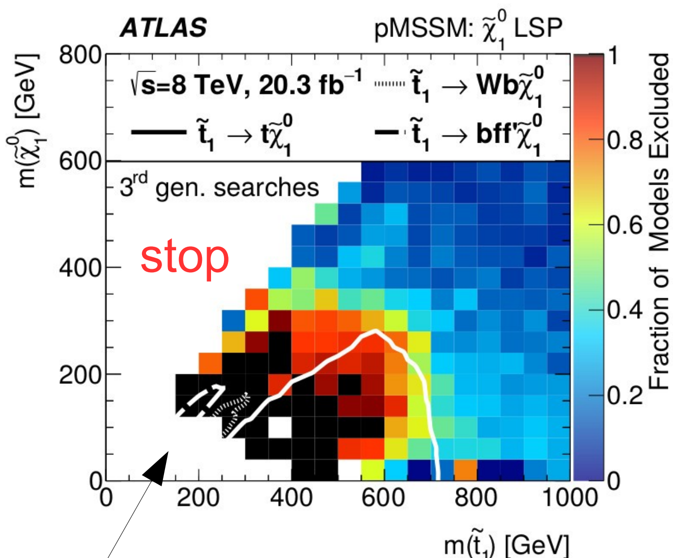
Lower production cross section in pMSSM:

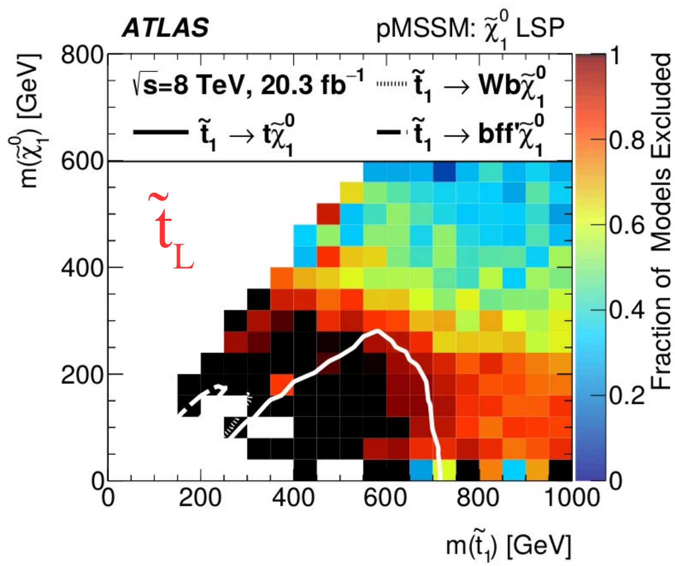
- Break squark mass degeneracy
- d-type squarks suppressed by PDFs
- $\tilde{u}_L$ and $\tilde{d}_L$ form SU(2) doublet, degenerate in mass

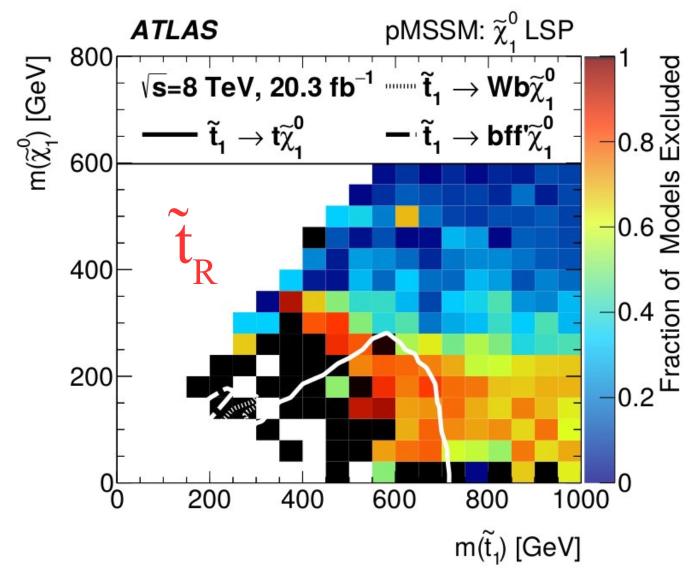
$\tilde{q}_R$ tend to have longer decay chains via EWKino states

arXiv:1508.06608

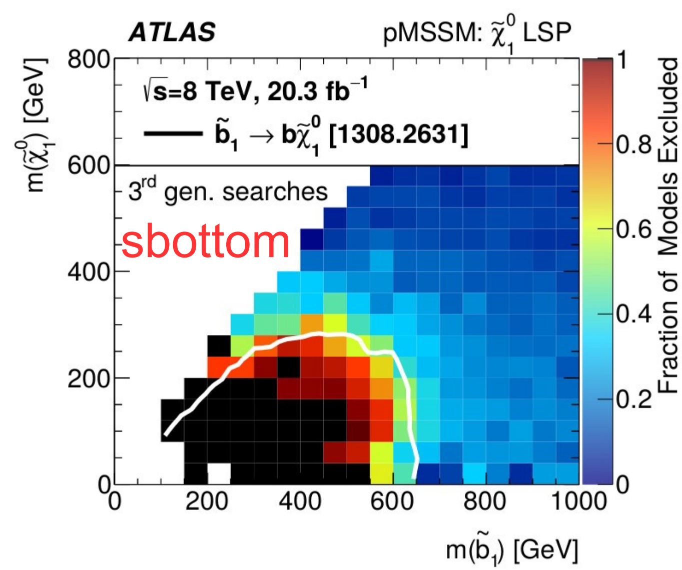
pMSSM-19: stop/sbottom







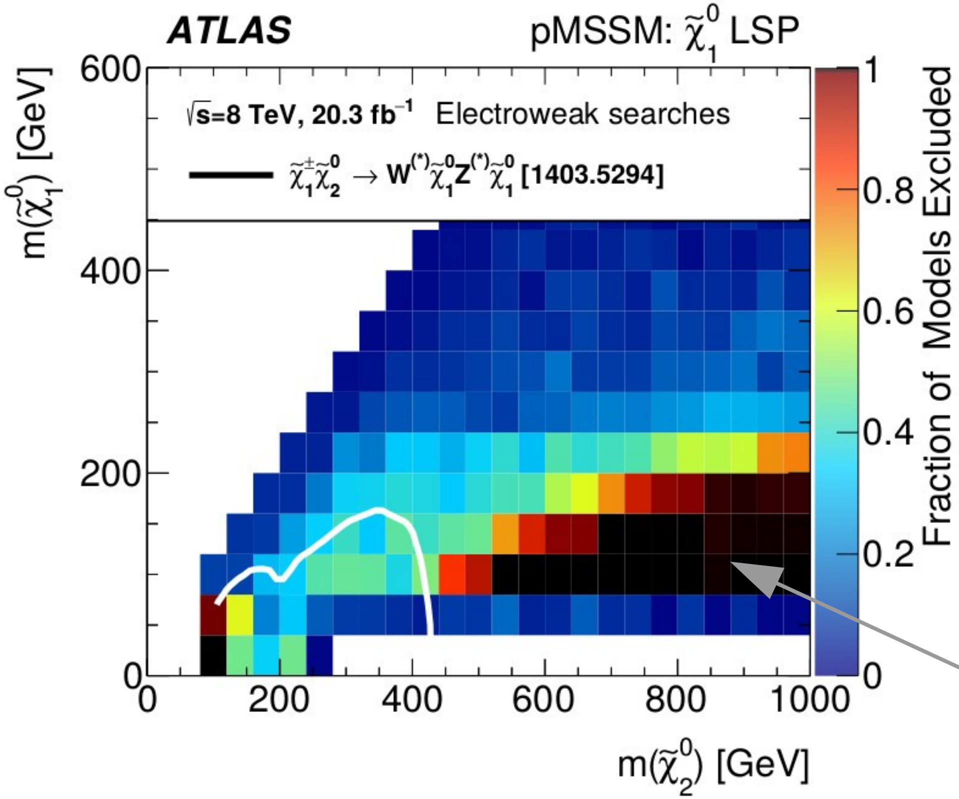
Depletion of sample points at low m(stop) due to Higgs mass constraint.

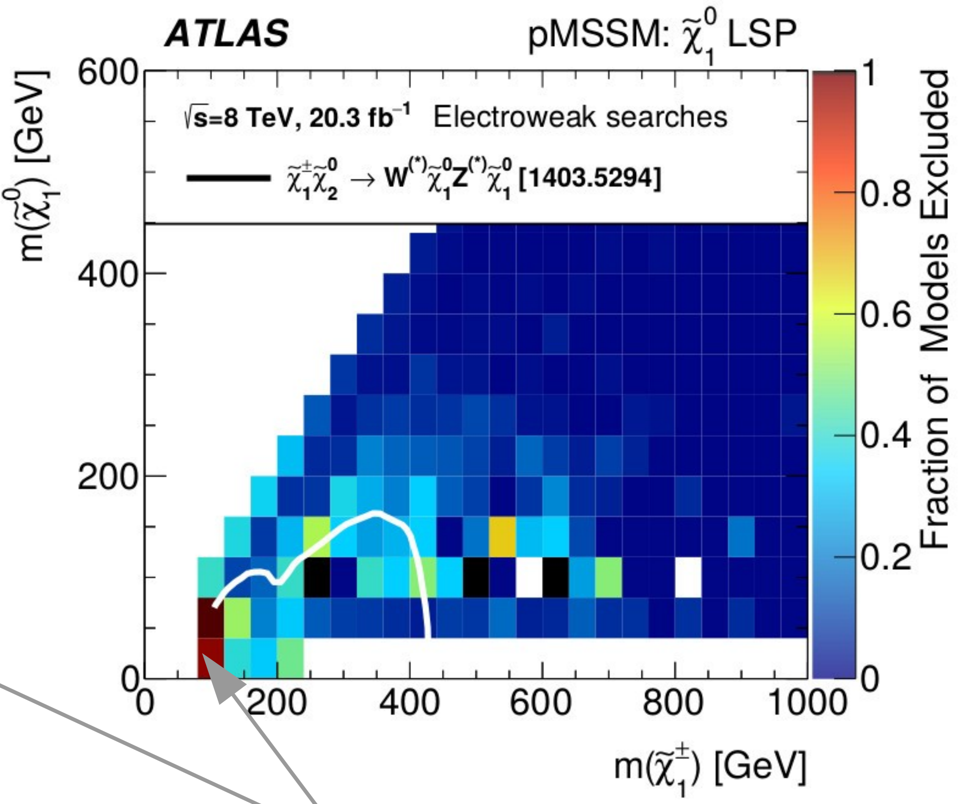


$\tilde{t}_L$ usually comes with a mass-degenerate $\tilde{b}_L$ so that sbottom searches improve the sensitivity

Sensitivity depends on stop decay modes and branching ratios

pMSSM-19: EWK





Significantly lower sensitivity than inferred from simplified models. Reasons include:

- Higgsino-like $\tilde{\chi}_2^0$ reduces production cross section
- Higgsino-like LSP implies small mass gap

Excluded by Disappearing Track analysis

Search strategy conclusion

- More careful scrutiny of low-mass survivors from the pMSSM-19 is ongoing
- Nevertheless, to first approximation, the pMSSM-19 study confirms mechanisms identified in the literature for weak areas in the ATLAS sensitivity:
  - Lower squark cross section by breaking mass degeneracy
  - Lower production cross section for Higgsinos
  - Compressed scenarios
  - Long decay chains (similar to “Stealth”)
  - Multiple decay channels
- Perhaps reassuring that no additional mechanisms have been uncovered so far
  - Higgsino-like EWK sector with a decoupled strong sector remains very challenging
- Coverage as a function of NLSP lifetime seems ok?
- Coverage of RPV: difficult to assess systematically

PRIVATE

BROOKHAVEN NATIONAL LABORATORY
Scientific Staff Appraisal

Employee's Name:	Susie Atlas	**Life Number:**	
Job Title:		**Dept./Division:**	
Manager's Name:		**Period of Appraisal:**	Run1
Author:		**Date Printed:**	

Manager's Evaluation of Employee

Approval: Approved

Section 1 - Scientific Staff Goals

Description/Milestones: Discover SUSY
Metrics :

Rating: Failed
Supervisor Comments: Methods and possible weaknesses have been discussed.

Employee Comments:

Section 6 - Performance Summary and Overall Rating

Overall Rating: 1-Exceeded Expectations
Supervisor Comments:

Looking forward to Run2!

Employee Comments:

Backup material

3rd generation pMSSM models

arXiv:1506.08616

Model name	Parameters scanned	Other parameter settings	Production channels	Typical decays
Naturalness-inspired pMSSM	$350\ \text{GeV} < m_{\tilde{q}L3} < 900\ \text{GeV}$ $100\ \text{GeV} < \mu < m_{\tilde{q}L3} - 150\ \text{GeV}$	$M_2 = 3\mu$ $m_{\tilde{t}_R}$ such that $M_S = 800$ GeV A_t such that $X_t/M_S = \sqrt{6}$	$pp \to \tilde{t}_1\tilde{t}_1$ $pp \to \tilde{b}_1\tilde{b}_1$	For $\mu = 110$ GeV, $m_{\tilde{q}L3} = 400$ GeV $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (33%); $\tilde{t}_1 \to t\tilde{\chi}_2^0$ (36%) $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (26%); $\tilde{b}_1 \to t\tilde{\chi}_1^\pm$ (70%) $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (16%); $\tilde{b}_1 \to b\tilde{\chi}_2^0$ (13%)
Well-tempered neutralino pMSSM	$310\ \text{GeV} < m_{\tilde{q}L3} < 810\ \text{GeV}$ $110\ \text{GeV} < M_1 < m_{\tilde{q}L3} - 50\ \text{GeV}$	$\mu \sim -M_1$ Similar to Naturalness-inspired for A_t, $m_{\tilde{t}_R}$ or $m_{\tilde{q}L3}$, M_3	$pp \to \tilde{t}_1\tilde{t}_1$ $pp \to \tilde{b}_1\tilde{b}_1$	For $M_1 = 110$ GeV, $m_{\tilde{q}L3} = 410$ GeV $\tilde{t}_1 \to t\tilde{\chi}_2^0$ (35%); $\tilde{t}_1 \to t\tilde{\chi}_3^0$ (38%) $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (20%); $\tilde{b}_1 \to t\tilde{\chi}_1^\pm$ (85%) $\tilde{b}_1 \to \tilde{t}_1 W$ (6%); $\tilde{b}_1 \to b\tilde{\chi}_2^0$ (4%)
	$260\ \text{GeV} < m_{\tilde{t}_R} < 760\ \text{GeV}$ $110\ \text{GeV} < M_1 < m_{\tilde{q}L3} - 50\ \text{GeV}$		$pp \to \tilde{t}_1\tilde{t}_1$	For $M_1 = 110$ GeV, $m_{\tilde{t}_R} = 410$ GeV $\tilde{t}_1 \to t\tilde{\chi}_2^0$ (17%); $\tilde{t}_1 \to t\tilde{\chi}_3^0$ (19%) $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (6.7%); $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (57%)
h/Z-enriched pMSSM	$250\ \text{GeV} < m_{\tilde{b}_R} < 750\ \text{GeV}$ $100\ \text{GeV} < \mu < m_{\tilde{b}_R}$	$M_1 = 100$ GeV; $M_2 = \mu$ $m_{\tilde{t}_R} = 1.6$ TeV; $m_{\tilde{q}L3} = 1.2$ TeV A_t fixed by $m_h \sim 125$ GeV	$pp \to \tilde{b}_1\tilde{b}_1$	For $\mu = 300$ GeV, $m_{\tilde{b}_R} = 400$ GeV $\tilde{b}_1 \to b\tilde{\chi}_1^0$ (37%); $\tilde{b}_1 \to b\tilde{\chi}_2^0$ (39%) $\tilde{b}_1 \to b\tilde{\chi}_3^0$ (23%) $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ (29%); $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ (71%) $\tilde{\chi}_3^0 \to Z\tilde{\chi}_1^0$ (85%); $\tilde{\chi}_3^0 \to h\tilde{\chi}_1^0$ (15%)
	$500\ \text{GeV} < m_{\tilde{q}L3} < 800\ \text{GeV}$ $100\ \text{GeV} < M_1 < m_{\tilde{q}L3}$ GeV	$M_1 = 100$ GeV; $M_2 = 1$ TeV $m_{\tilde{b}_R} = 3$ TeV; $m_{\tilde{t}_R} = 2$ TeV A_t fixed by $m_h \sim 125$ GeV	$pp \to \tilde{t}_1\tilde{t}_1$ $pp \to \tilde{b}_1\tilde{b}_1$	For $\mu = 300$ GeV, $m_{\tilde{q}L3} = 600$ GeV $\tilde{t}_1 \to t\tilde{\chi}_2^0$ (46%); $\tilde{t}_1 \to t\tilde{\chi}_3^0$ (39%) $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (11%); $\tilde{b}_1 \to t\tilde{\chi}_1^\pm$ (87%) $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ (24%); $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ (76%) $\tilde{\chi}_3^0 \to Z\tilde{\chi}_1^0$ (88%); $\tilde{\chi}_3^0 \to h\tilde{\chi}_1^0$ (12%)