# Searches for direct pair production of third generation squarks with the ATLAS detector

John Anders
University of Liverpool
on behalf of The ATLAS collaboration

4th International Conference on New Frontiers in Physics
23-30th August

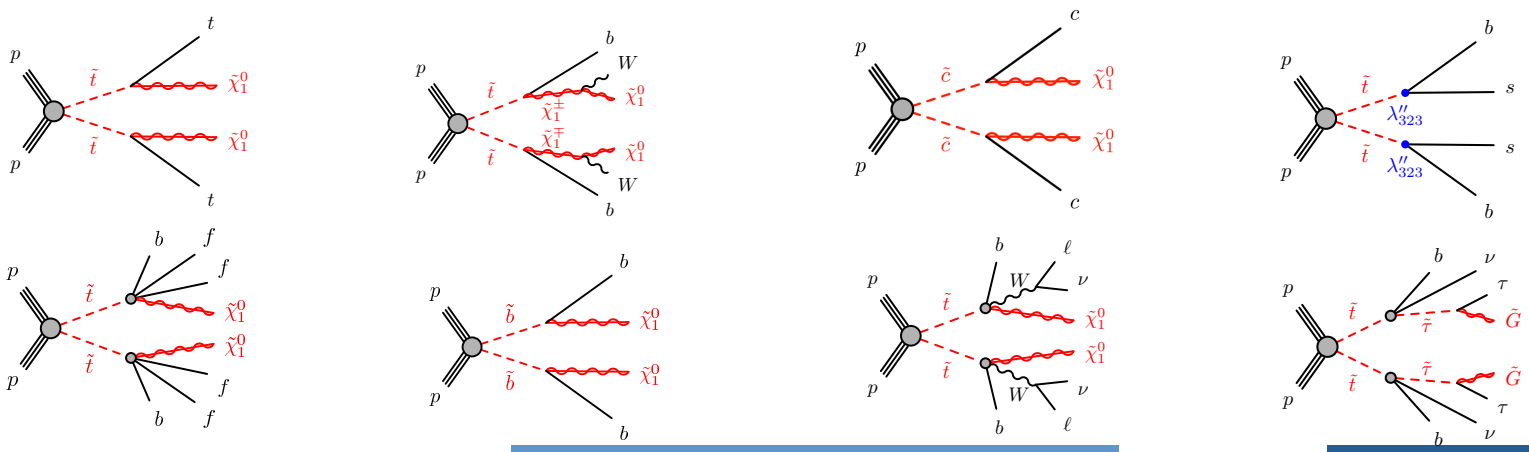
# Outline

- Introduction
- Recent Run I analyses:
  - Search for charm squark pair production
  - Search for top squark pair production via tau slepton decays
  - RPV Searches for top squark pair production (2x2 jets)
- Fully exploiting Run I results:
  - Third generation summary paper
- Outlook and prospects for Run II
- Summary

# Introduction

## Third Generation Overview

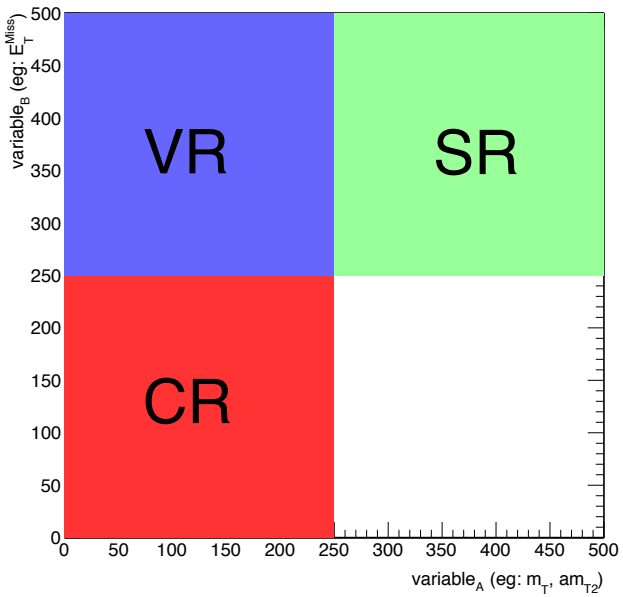
- Supersymmetry is one of the theories of beyond the standard model physics which provides solutions to unanswered questions, such as the hierarchy problem and offers a candidate for dark matter.
  - The hierarchy problem may be solved if third generation sparticles are at the TeV scale.
  - Third generation squarks may be produced at a high rate at the LHC
- This talk focuses on searches for direct top/bottom/charm squark production.
  - R-parity conserving models (RPC), the lightest SUSY particle (LSP) is stable and a dark matter candidate, the main signature of these models is large amount of missing energy $E_T^{Miss}$ in the detector
  - R-parity violating models (RPV), where the final products of the sparticle decays are SM particles. The main signature of these models is a high object multiplicity



# Introduction

## General Search Strategy

- Define Signal Regions (SRs) targeting a specific model & SUSY mass parameter set
  - Optimise by attempting to maximise the discovery or exclusion significance for a model
- Define multiple Control Regions (CRs) to constrain the main SM background processes in the SR
  - Kinematically close to the SRs, however designed such that they are orthogonal to the SR
  - Designed to contain events with only the specific background process considered (where possible)
  - The number of events in the CRs is used to produce normalisation parameters for the backgrounds in the SRs
- The normalisation parameters are validated in Validation Regions (VRs)
  - Kinematically close to the SR, however orthogonal to both the SR and the CR
- After validation the observed yields in the SRs are compared to the prediction
  - If no significant excesses are seen, limits are placed on the signal models under consideration



# Recent Run I Analyses

Search for charm squark pair production (arXiv:1501.01325)
Search for top squark pair production via tau slepton decays
RPV Searches for top squark pair production (2x2 jets)

Third Generation Public Results page:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

# Search for charm squark pair production arXiv:1501.01325

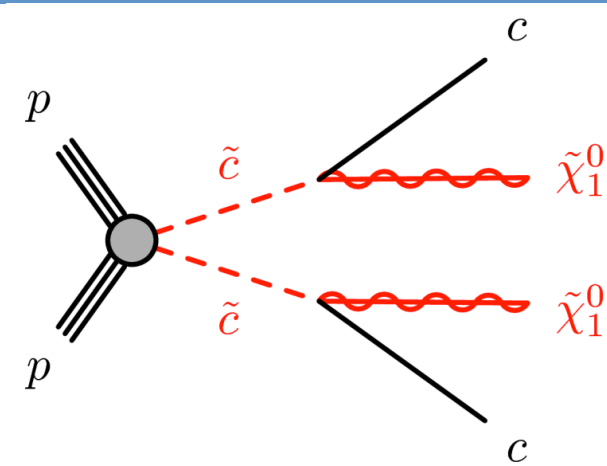
## Signal Models and Selection

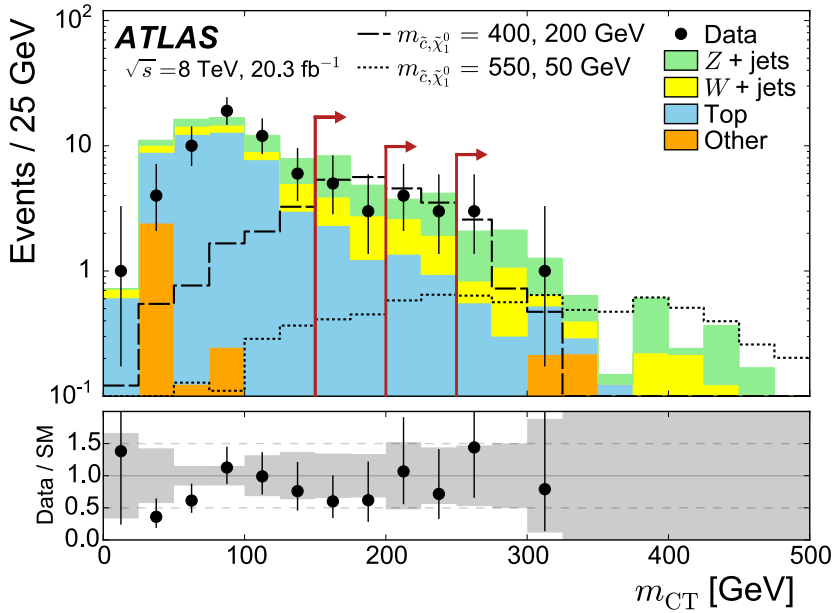
- Targeting final states with 2 c-tagged jets.
- Searching for direct scharm production (treating scharms as non-degenerate)

  $\tilde{c}\tilde{c} \rightarrow c\tilde{\chi}_1^0 c\tilde{\chi}_1^0$
- $m_{CT}$ is the main discriminating variable:

$$m_{CT}^{\max} = \frac{m^2(\tilde{c}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{c})}$$

- 3 overlapping SRs with different $m_{CT}$ selections
- c-jets are identified with specific charm tagging algorithms (efficiency O(20%))



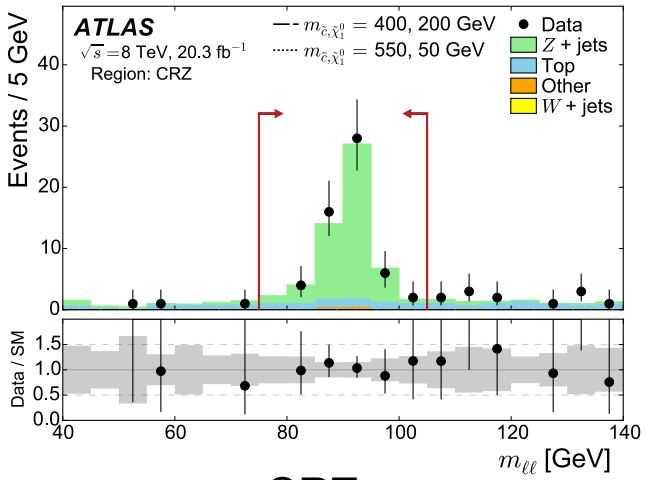




$m_{CT}$

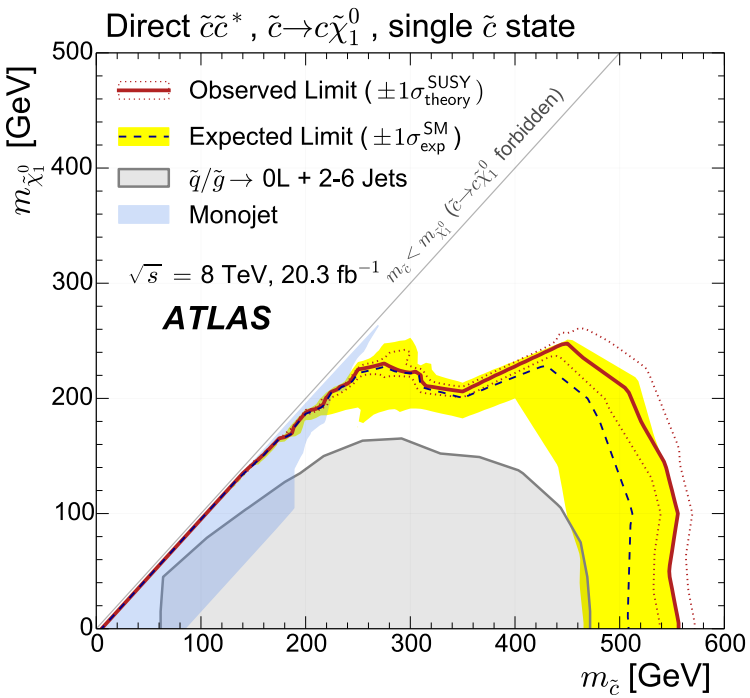
# Search for charm squark pair production arXiv:1501.01325

## Background Estimation & Limits

- The three main backgrounds are Z+Jets, W+Jets and $t\bar{t}$. One or two lepton control regions are defined for each of these three main backgrounds, with each region also requiring 2 c-tagged jets.
  - Z+jets – 2 lepton CR with SF (ee or μμ), OS leptons in the Z-mass window
  - W+jets – 1 lepton CR with $E_T^{Miss}$ > 100 GeV
  - $t\bar{t}$ - 2 lepton CR with DF(eμ), OS leptons




CRZ - $m_{ll}$

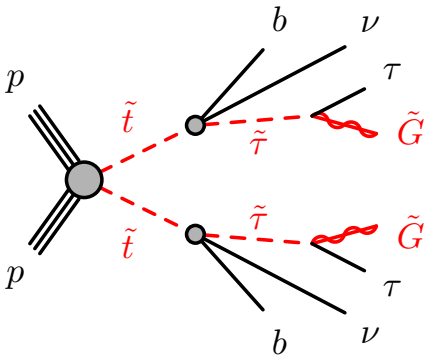


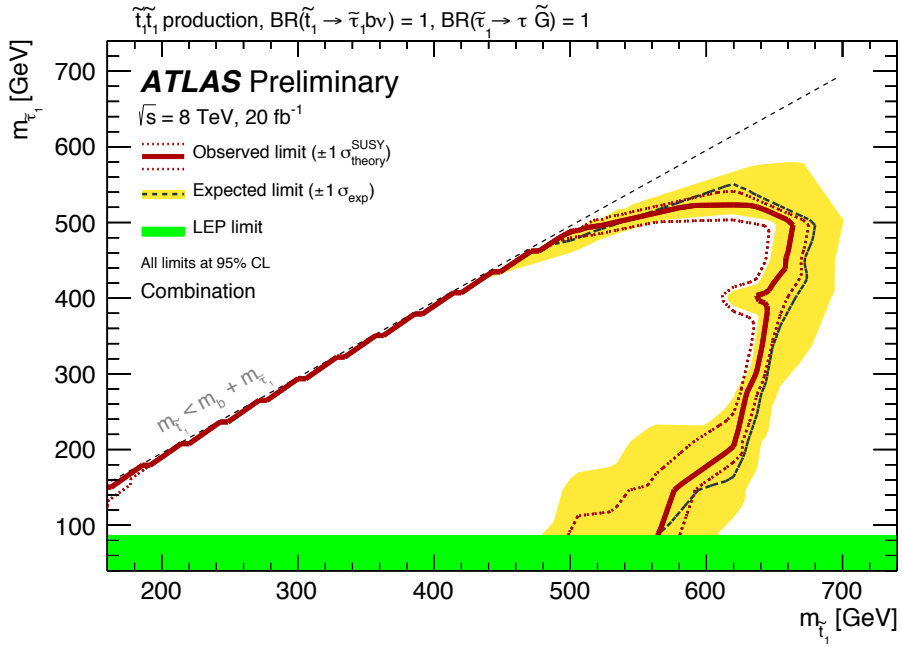

- No excesses seen
- Extends the general exclusion for non degenerate squarks set by the ATLAS Strong production 0L + 2-6 jets analysis.

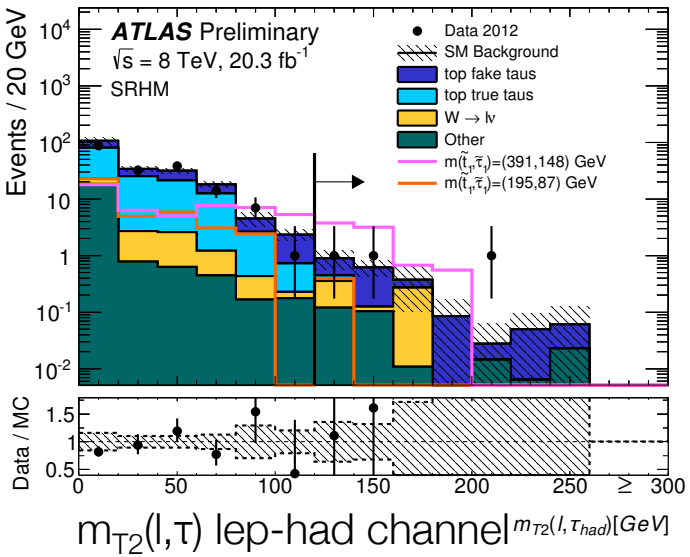
# Search for top squark pair production via tau slepton decays

## Overview

- Stop pair production investigated assuming gauge-mediated symmetry breaking (Gravitino LSP)
- $\tilde{t}\tilde{t} \rightarrow \tilde{\tau}\tilde{\tau}bb\nu\nu$ (via a virtual chargino), subsequently: $\tilde{\tau} \rightarrow \tau\tilde{G}$
- Three channels investigated, depending on the tau decay:
  - Lep-Lep Channel, Lep-Had Channel, Had-Had Channel
  - Dedicated SRs for each channel, targeted at difference regions of phase space



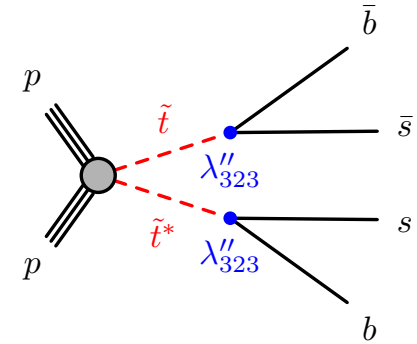



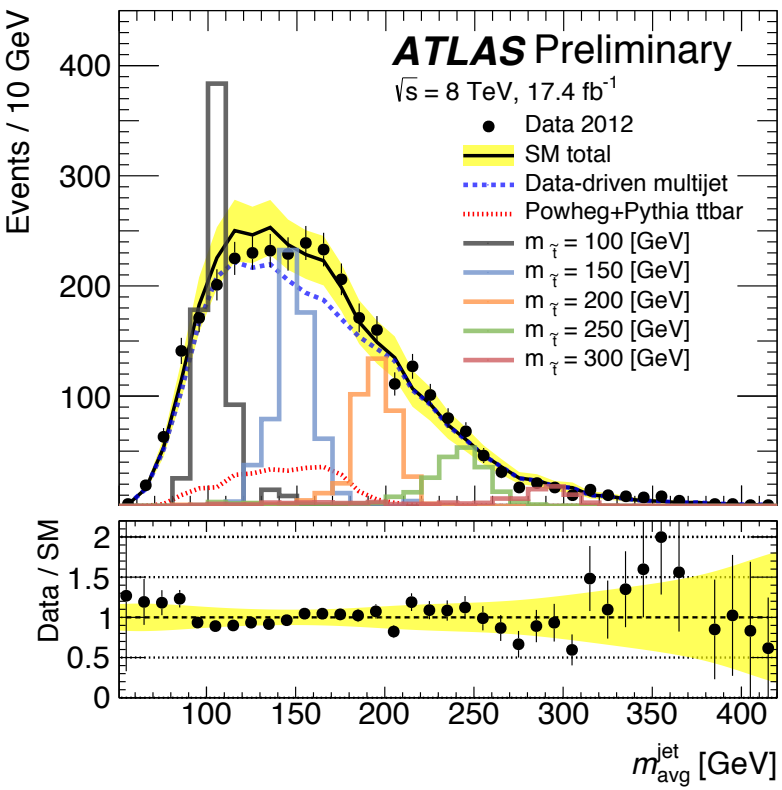

- All SRs, from each channel, are combined to place limits on the stop, stau phase space

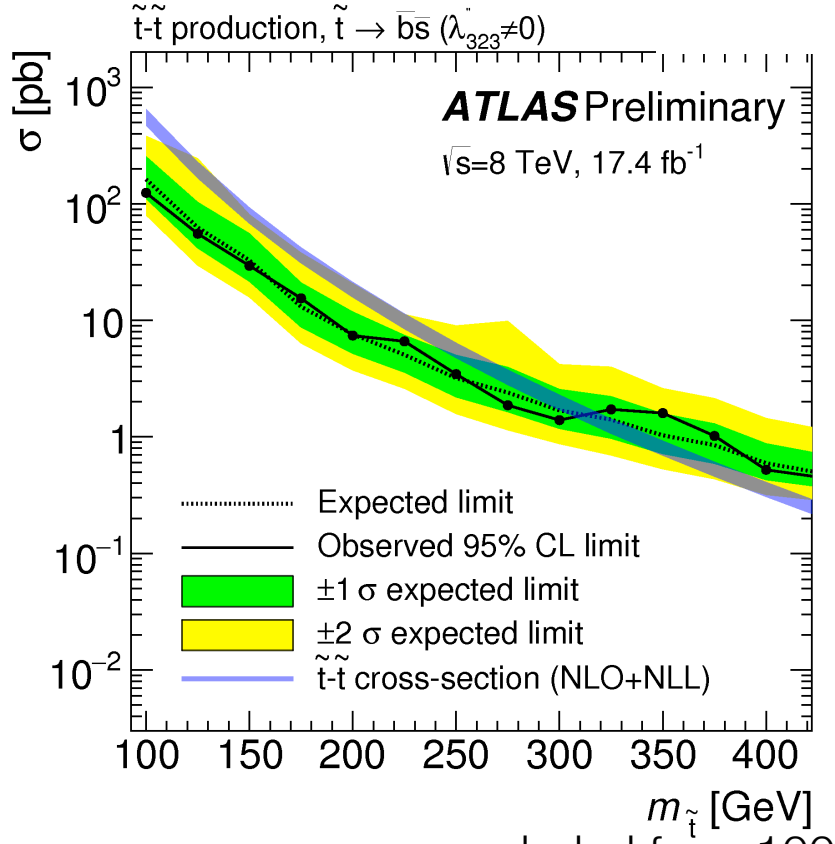
# RPV Scenarios: Searches for top squark pair production (2x2 jets)

## Overview

- Search for RPV top squark decays $\tilde{t} \rightarrow bs$
- Limits from LEP and CDF: < 100 GeV
- Search exploits merging of stop decay products with a radius $\Delta R = m_{stop}/p_T$ (initial stop $p_T$)
  - ➔ Large R jets with $m_{Jet} \sim m_{stop}$




- $m_{Stop}$ excluded from 100 to 310 GeV

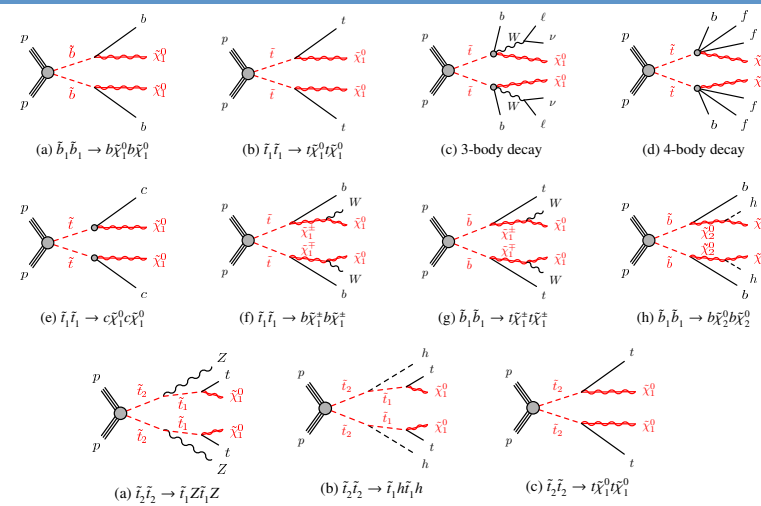
# Fully Exploiting Run I Results

## Third Generation Summary Paper

# Third Generation Summary Paper arXiv:1506.08616

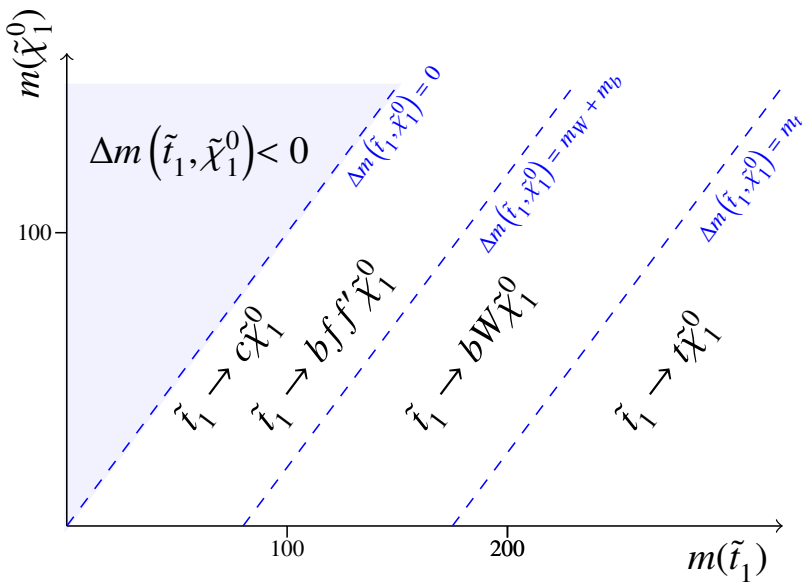
## Introduction

- Many channels covered by analyses in Run I, with many signatures (various jet, b-jet and lepton multiplicities) place limits on the SUSY parameter space.




- The parameter space can be restricted further by:
  - Reinterpreting existing analyses
  - Investigating additional decay modes
  - Combining existing analyses
  - Investigating compressed or “sneaky” scenarios ($m_{top} \approx m_{stop}$)

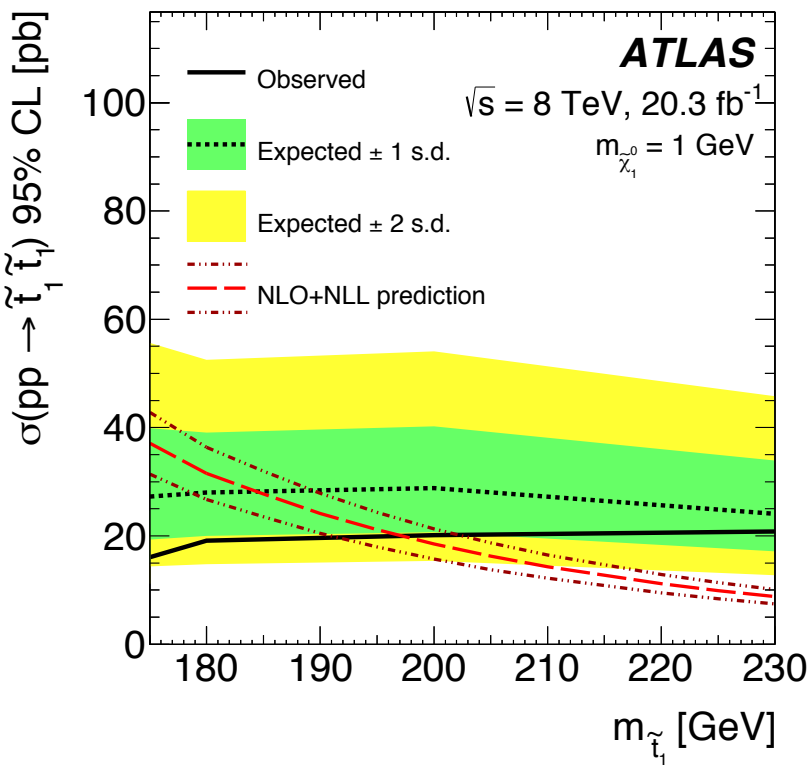
- All approaches are included in the third generation summary paper

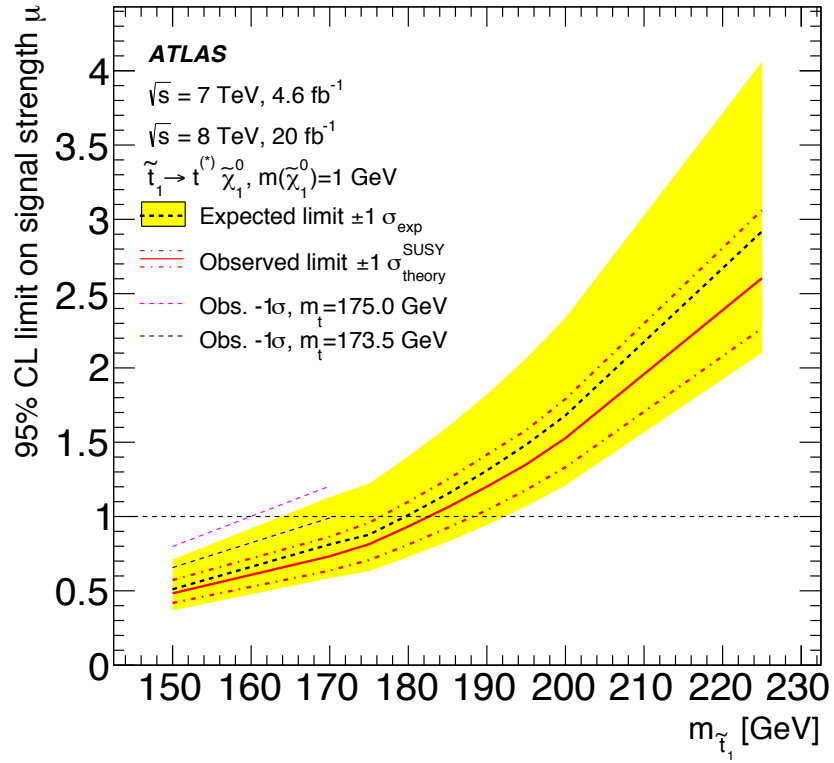


# Reinterpreting Existing Analyses arXiv:1506.08616

## Search for top squark production: Spin Correlations & $\sigma_{tt}$ Reinterpretation

- Interpretations of the SM measurements such as spin correlations ($\Delta\phi$ ($l^+$,$l^-$) ) or $\sigma_{tt}$ in the hypothesis of a top squark with mass close to the top quark.



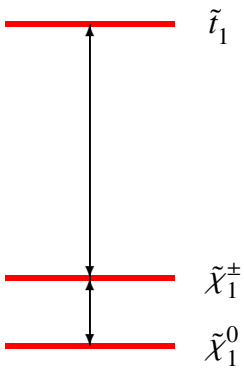

- $m_{stop}$ excluded between 150 and 191 GeV, for $m_{Neutralino}$ = 1GeV

# Investigating additional Decay Modes

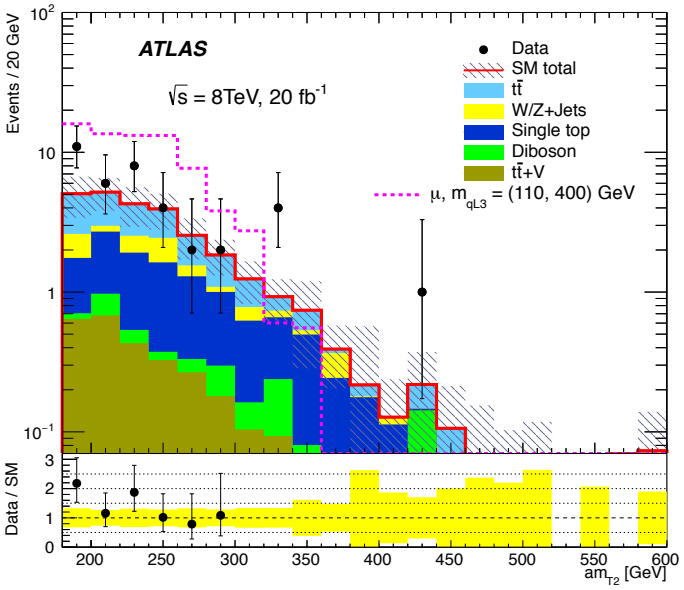
arXiv:1506.08616

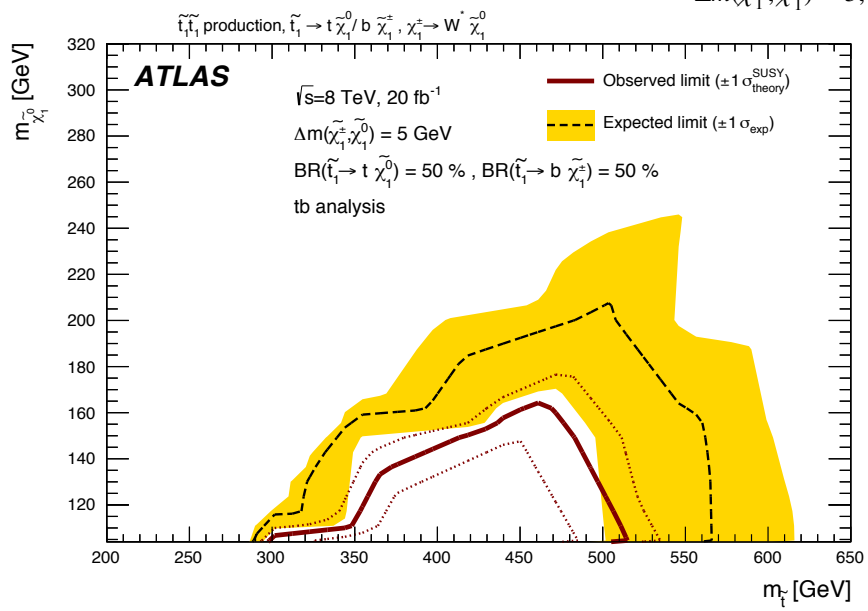
## Search for top squark production: t+b+$E_T^{Miss}$ Final State

- New analysis targeted at models with mixed stop decay modes
  - Both $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$ decay modes are available
  - $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ are nearly degenerate in mass
  - Various possible branching ratios for the two decays are investigated
  - Optimised for the 1L+2b + $E_T^{Miss}$ final state (soft W* from $\tilde{\chi}_1^{\pm}$ decay)
  - 4 SRs defined for different regions of the parameter space
  - Main backgrounds, W+Jets & top




$\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 5, 20$ GeV




Limits placed on various BRs for the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay mode (50% shown)

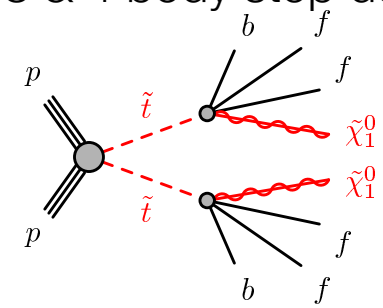
# Investigating additional Decay Modes

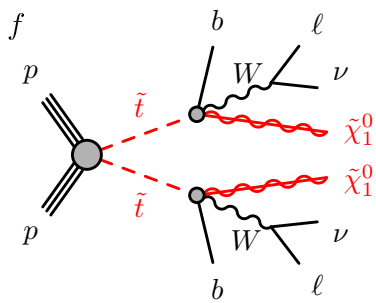
arXiv:1506.08616

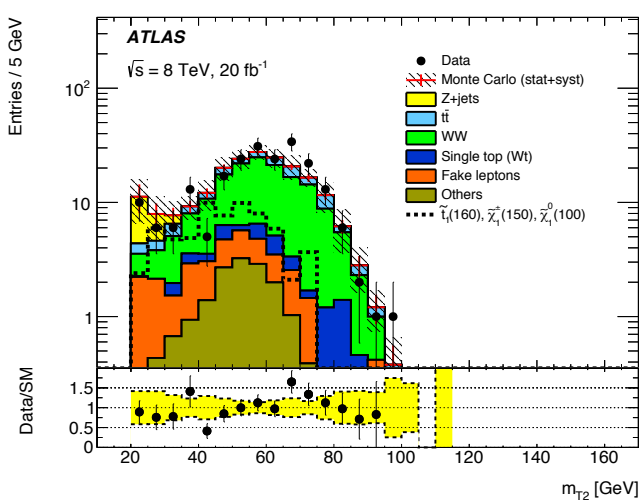
## Search for top squark production: WW-Like decay

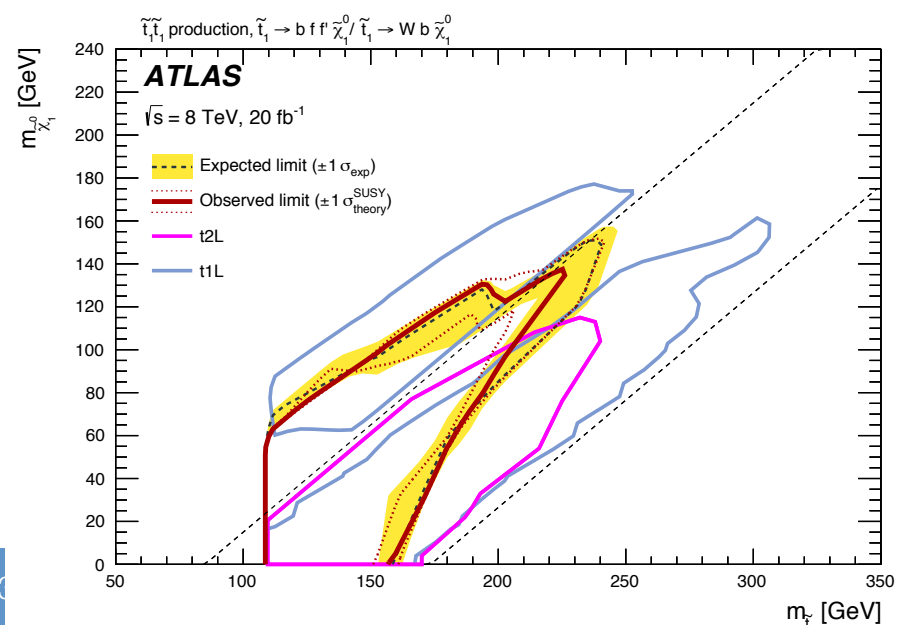
- Discrepancy in $\sigma_{WW}$ from both ATLAS and CMS in Run I, could have a SUSY explanation?
  - Analysis targeted at light stops
    - $m_{stop} - m_{LSP} < m_W$
    - $m_W < m_{stop} - m_{LSP} < m_{top}$
  - Optimised for 2 DF (eμ) OS leptons final state
  - 7 SRs with $m_{T2}(l,l)$ the main discriminating variable
  - Main background is WW production

Sensitive to the region where the the 3 & 4 body stop decay overlap



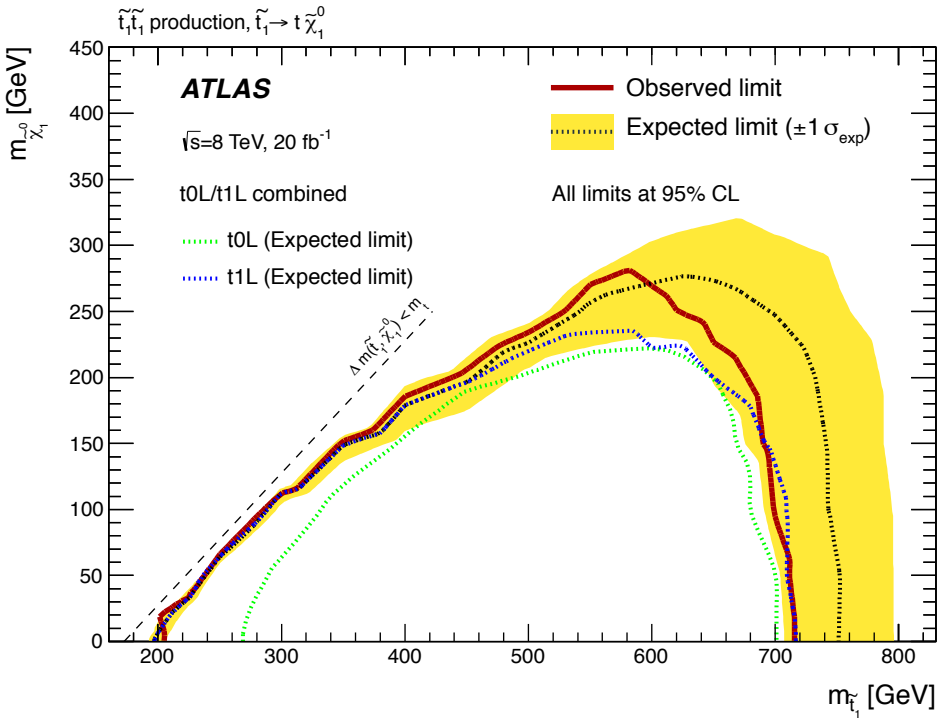



# Combining Existing Analyses

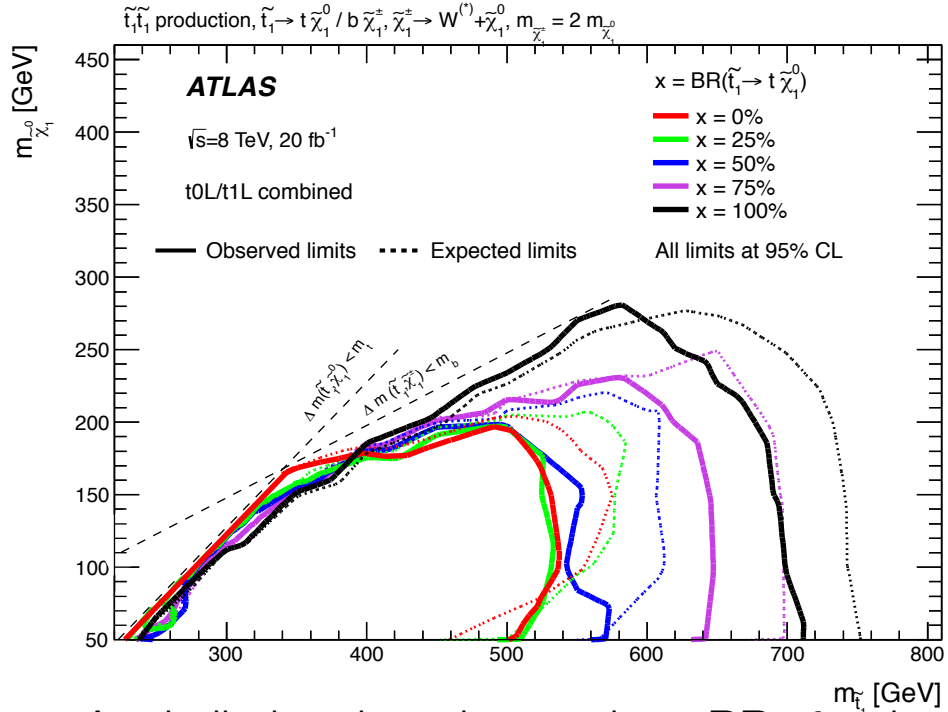
arXiv:1506.08616

## Stop 0L, 1L Combination

- A combination of the stop 0L & 1L analyses was performed, with a combined fit to all control regions and signal regions




Required recalculation of systematics and normalisation parameters

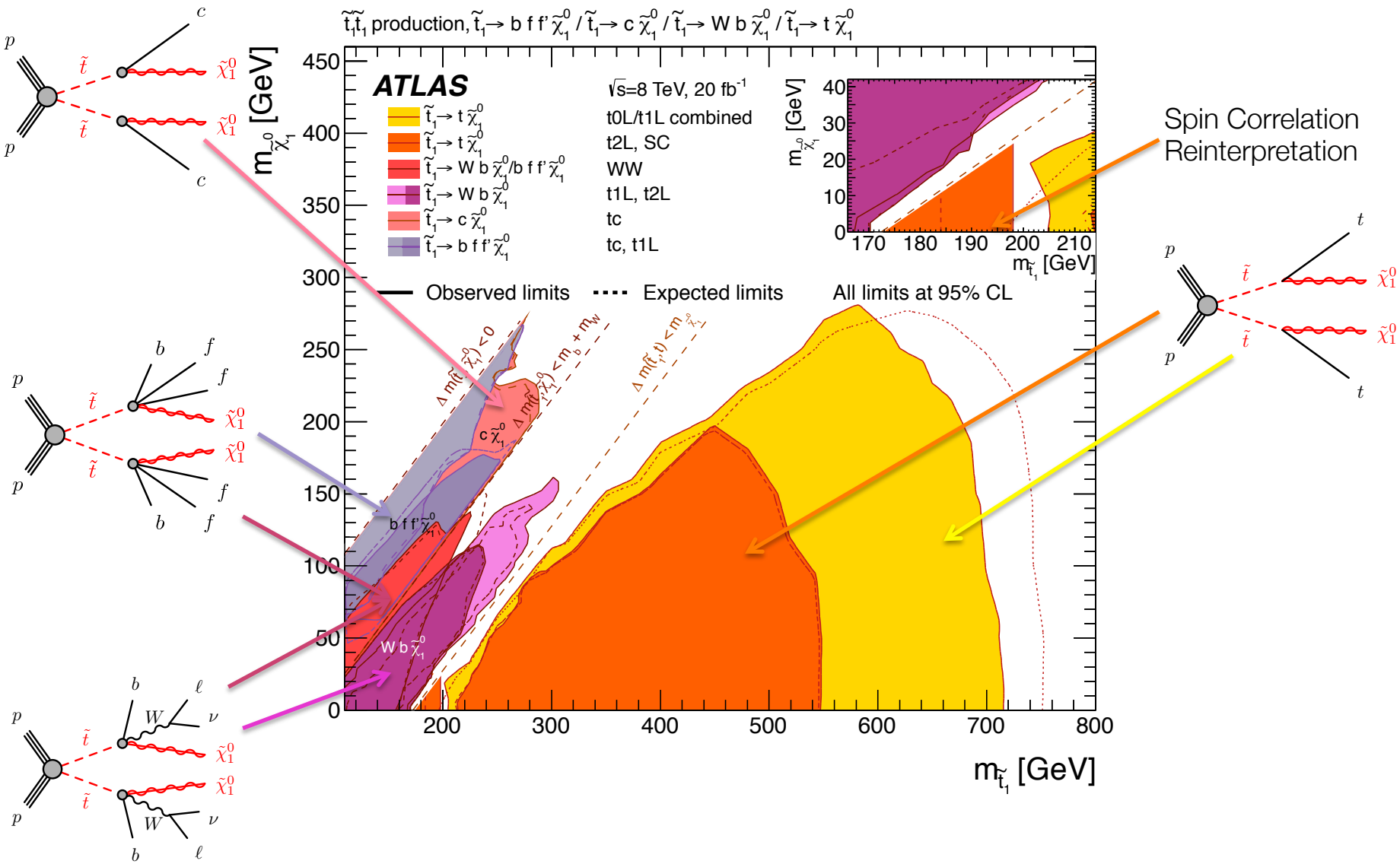



Again limits placed on various BRs for the $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$ decay mode assuming:

$$m(\tilde{\chi}_1^{\pm}) = 2m(\tilde{\chi}_1^0)$$

# Third Generation Summary Paper arXiv:1506.08616

## Stop Decays Overview

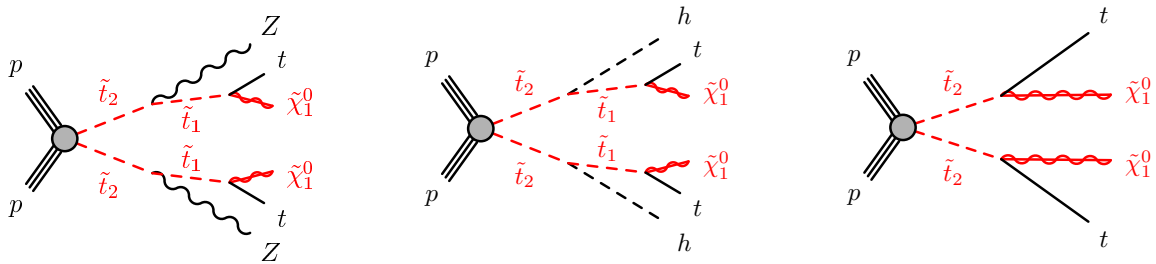



(Assuming BR = 100% for the decay under consideration)

# Reinterpreting Existing Analyses arXiv:1506.08616

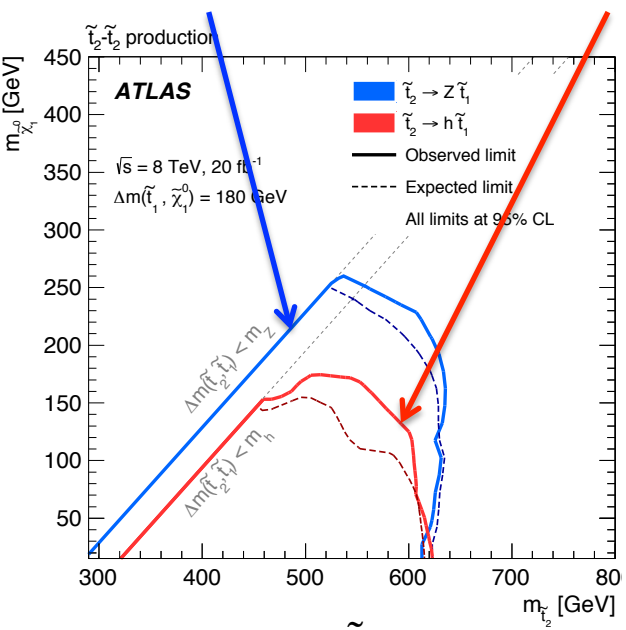
## Limits on pair production of the heavier stop eigenstate

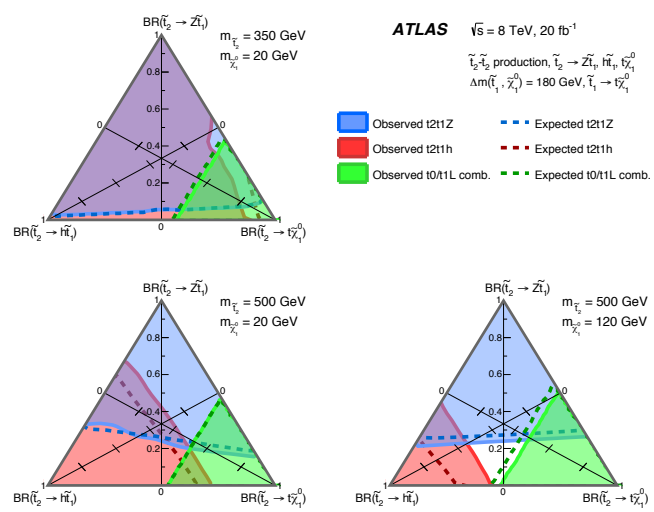
- While $\sigma_{\tilde{t}_1\tilde{t}_1}$ is by definition larger than $\sigma_{\tilde{t}_2\tilde{t}_2}$, in difficult regions of the phase space it is convenient to search for $\tilde{t}_2$ pair production (as sensitivity to $\tilde{t}_1$ is limited)




(a) $\tilde{t}_2\tilde{t}_2 \to \tilde{t}_1 Z \tilde{t}_1 Z$ (b) $\tilde{t}_2\tilde{t}_2 \to \tilde{t}_1 h \tilde{t}_1 h$ (c) $\tilde{t}_2\tilde{t}_2 \to t\tilde{\chi}_1^0 t\tilde{\chi}_1^0$

- Useful to target the region where $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \approx m_{top}$ (difficult to distinguish between SM and $\tilde{t}_1$ decays)
- Is assumed that the $\tilde{t}_1$ decay proceeds via $\tilde{t}_1 \to t\tilde{\chi}_1^0$



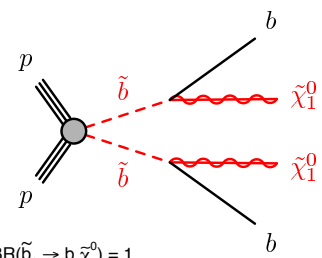



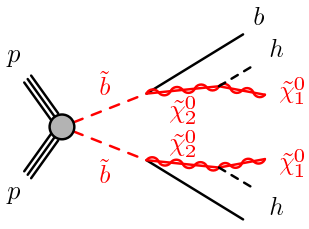

Stop 0 & 1L combination is rescaled to produce limits as a function of the BR for three decays considered

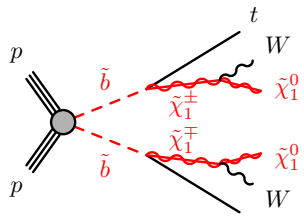
Exclusion limits on $\tilde{t}_2$ pair production assuming BR = 100% for the decays considered

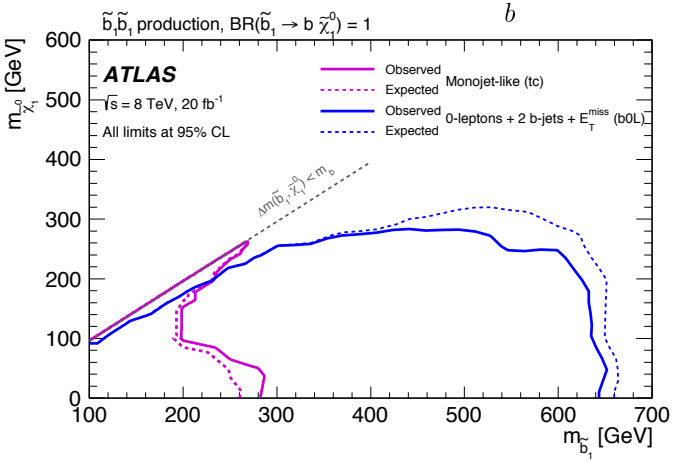
## Sbottom Decays Overview

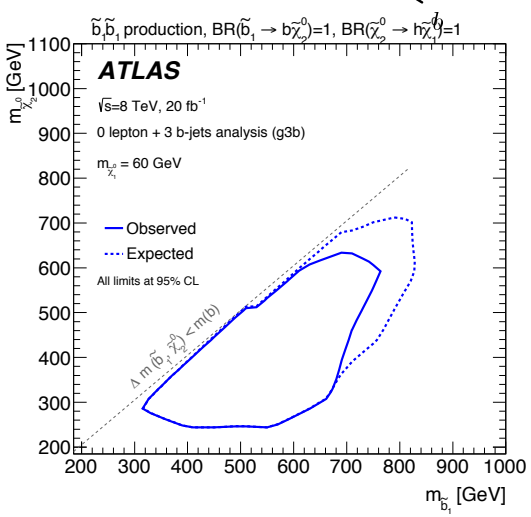
- Sbottom decay modes are also explored with dedicated searches & reinterpretations:
  - bb+$E_T^{Miss}$
    (dedicated search for $\tilde{b} \rightarrow b\tilde{\chi}_1^0$)
  - Monojet+$E_T^{Miss}$
    (reinterpretation of $\tilde{t} \rightarrow c\tilde{\chi}_1^0$)
  - Final states with 3b-jets
    (reinterpretation of a strong production analysis, targeting $\tilde{b} \rightarrow b\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$)
  - Strongly produced final states with 2 same sign leptons or 3 leptons
    (targeting $\tilde{b} \rightarrow t\tilde{\chi}_1^{\pm} \rightarrow W^{(*)}\tilde{\chi}_1^0$)

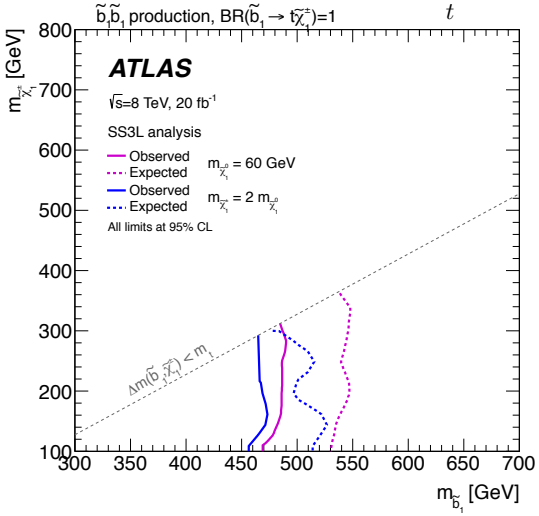


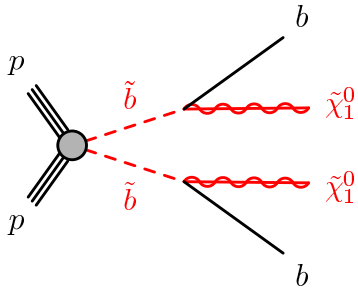



# Outlook & Preparation for Run II

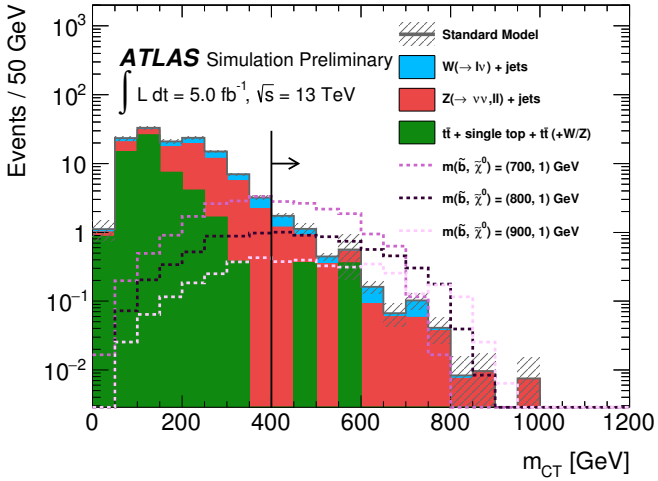
# Preparation for Run II

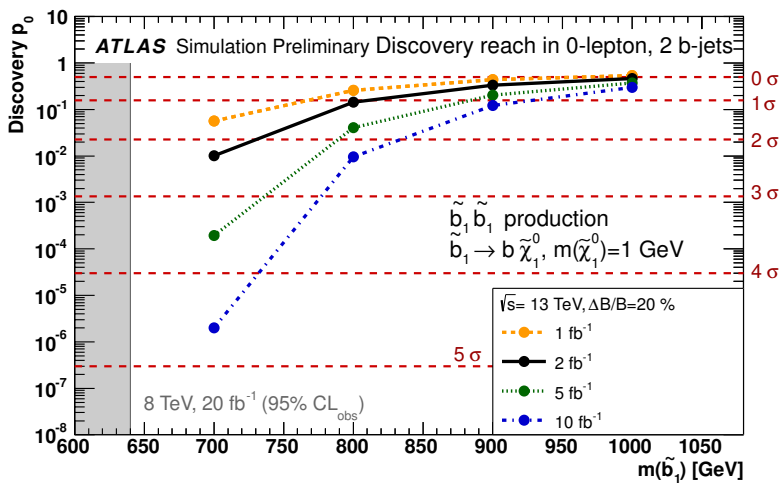
## Sbottom Analysis

- Third generation searches targeting early Run II data. One example of which is the sbottom analysis $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ with a similar analysis strategy to Run I
- Targeting final states with 2 b-jets and a large amount of missing transverse momentum




- As in the Run I analysis the main discriminating variable is $m_{CT}$



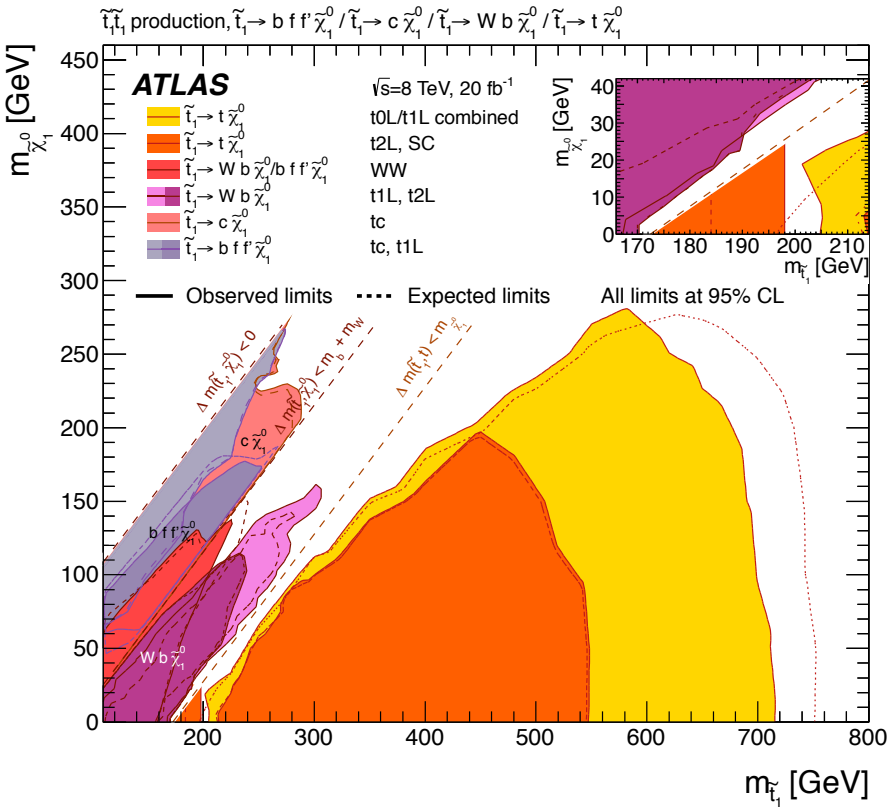



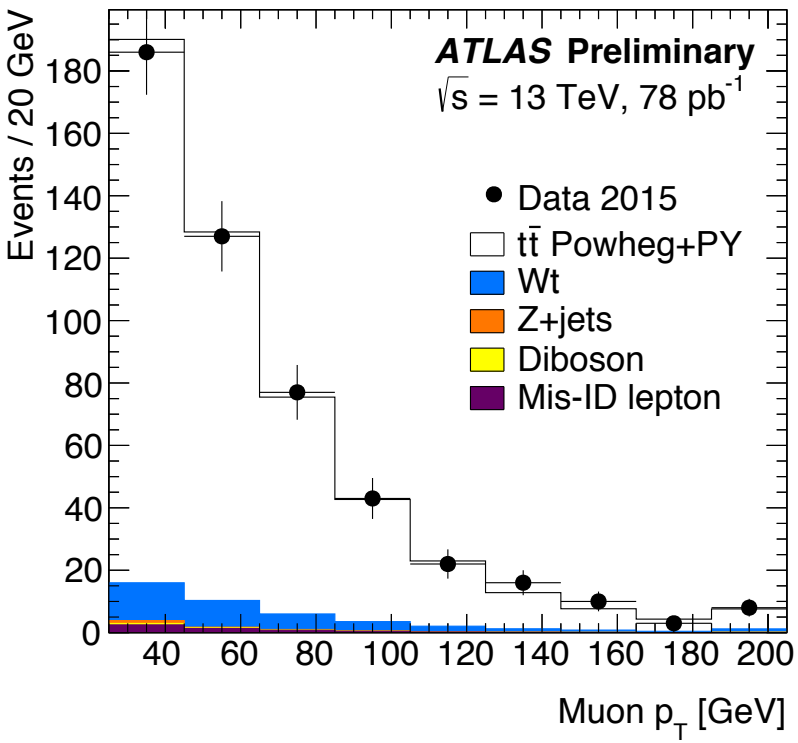

- With a 20% uncertainty and an integrated luminosity of 10fb-1, 3σ evidence can be obtained for a sbottom with mass ≈ 800 GeV

# Summary

# Summary

- Dedicated program of searches for 3rd generation squarks in Run I.
- Run I program almost complete, remaining analyses are finalising results etc.
- Run II preparation well underway for all analysis groups, discovery potential with between 5-10fb$^{-1}$, but first we need to "rediscover" the SM



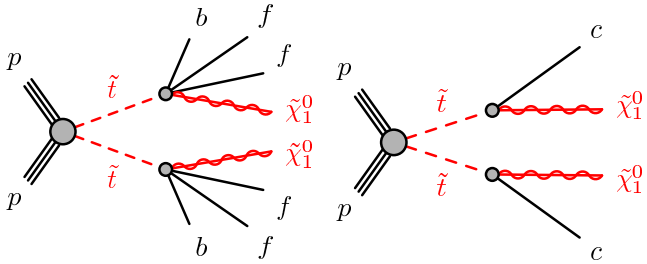



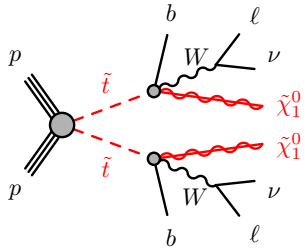
# Appendix

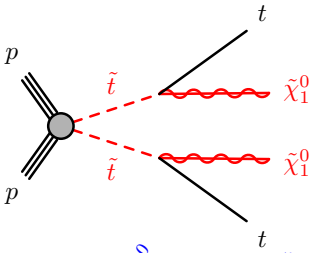
# Third Generation Summary Paper arXiv:1506.08616

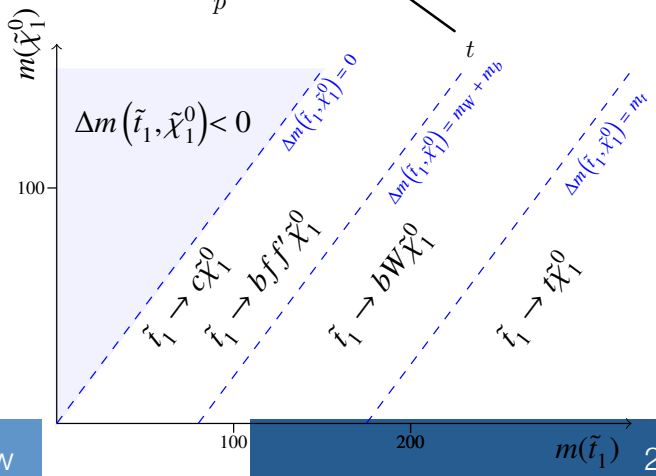
## Stop Decays without Charginos in the Decay Chain

- The only SUSY particles produced are the stop and the neutralino (neutralino is the LSP)
  - Stop decay modes are defined by $\Delta m(\tilde{t},\tilde{\chi}_1^0)$ leading to 4 kinematic regions:
- $\Delta m(\tilde{t},\tilde{\chi}_1^0) < m_W + m_b$
  - Two competing decays ($\tilde{t} \rightarrow bff\tilde{\chi}_1^0, \tilde{t} \rightarrow c\tilde{\chi}_1^0$) the dominant of which is dependent upon the mass separation and the amount of flavour violation allowed in the model.
- $m_W + m_b < \Delta m(\tilde{t},\tilde{\chi}_1^0) < m_{top}$
  - The $\tilde{t} \rightarrow bW\tilde{\chi}_1^0$ three body decay is dominant
- $\Delta m(\tilde{t},\tilde{\chi}_1^0) \approx m_{top}$
  - Almost degenerate stop and top, kinematics are similar to that of SM top pair production. Limits obtained by performing precision SM measurements ($t\bar{t}$ spin correlation analysis)
- $\Delta m(\tilde{t},\tilde{\chi}_1^0) > m_{top}$
  - $\tilde{t} \rightarrow t + \tilde{\chi}_1^0$ is the dominant decay mode. Results are obtained by performing a statistical combination of the stop 0 & 1 Lepton analyses.
  - Lepton selection makes SR selections mutually exclusive



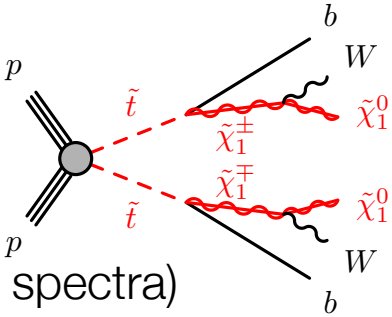



# Third Generation Summary Paper

## Stop Decays with Charginos in the Decay Chain

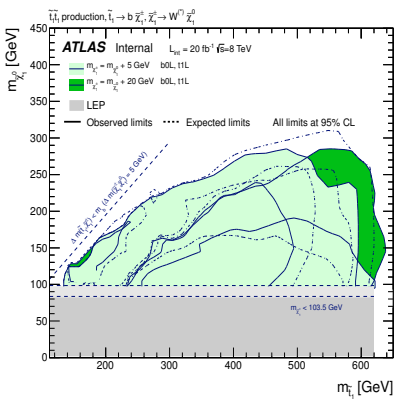
- In the pMSSM the mass difference between the lightest neutralino and chargino is not expected to be too large
  - The mass hierarchy $m_{\tilde{\chi}_1^0} < m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}}$ is well motivated, leading to decay chains:
  - This can lead to complex decay chains with phenomenology that are dependent upon a variety of SUSY parameters (chargino mass, stop mixing & neutralino composition)

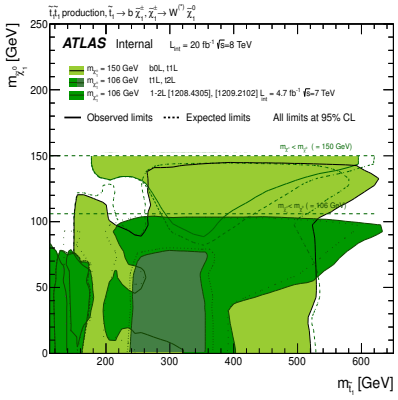



- Limits are placed on a range of scenarios (dependent upon the mass spectra) assuming BR = 100% for both the $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$ decays.

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 5$ GeV

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 20$ GeV

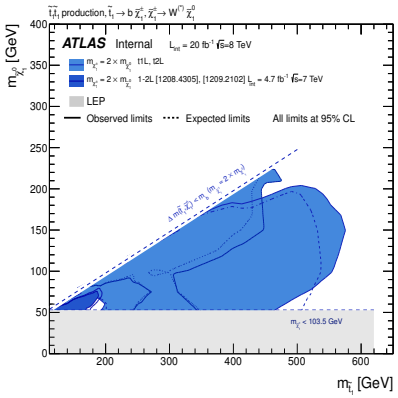


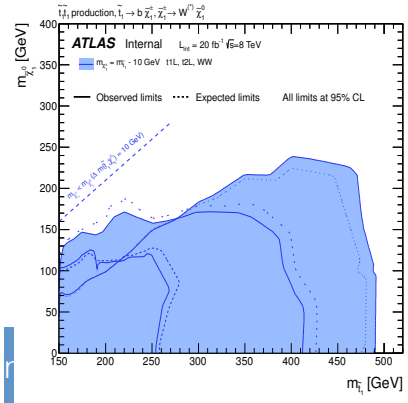




$m(\tilde{\chi}_1^\pm) = 150$ GeV

$m(\tilde{\chi}_1^\pm) = 106$ GeV

$m(\tilde{\chi}_1^\pm) = 2 \times m(\tilde{\chi}_1^0)$




$m(\tilde{\chi}_1^\pm) = m(\tilde{t}) - 10$ GeV

# Third Generation Summary Paper

## Interpretation in terms of pMSSM Models

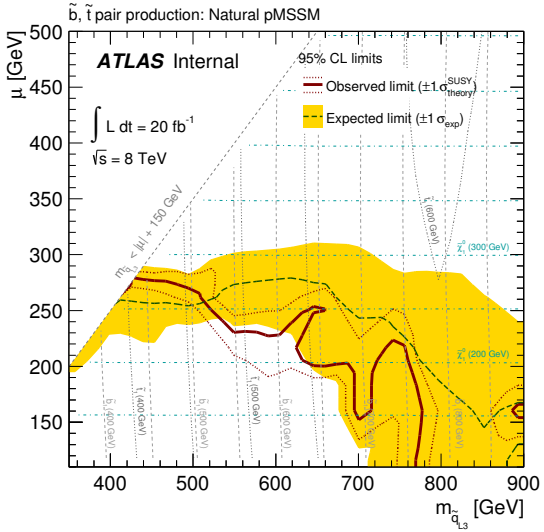
- The 3rd generation analyses are also used to place limits on three, more realistic, pMSSM scenarios.
- Naturalness-inspired pMSSM
  - Requires higgsino mass parameter (μ) in the range of a few hundred GeV
  - Favours stop masses below 1 TeV (also weak constraints on gluino masses)
  - Maximal stop mixing
  - Generated by varying μ and $m_{\tilde{q}L3}$, the left handed squark mass parameter: $100 < \mu < 750$ GeV, $350 < m_{\tilde{q}L3} < 900$ GeV
- Well-tempered neutralino pMSSM
  - Designed to explicitly satisfy dark matter thermal relic density constraints, while keeping fine tuning lower than 1%
  - Higgs mass constraints are satisfied in the same way as the Naturalness-inspired pMSSM
  - Generated by varying $M_1$ (gaugino mass parameter) and $m_{\tilde{q}L3}$, with $\mu = -M_1$
- h/Z Enriched pMSSM
  - Designed such that Higgs and Z bosons are produced abundantly in the SUSY particle decay chains
  - Two sets of models, generated by varying μ and $m_{\tilde{b}R}$ (right-handed sbottom mass parameter); and varying μ and $m_{\tilde{q}L3}$

- A combination of all of the SRs used in the paper is used on a point by point basis on the pMSSM grids, and the SR with the smallest expected $CL_s$ value is chosen.

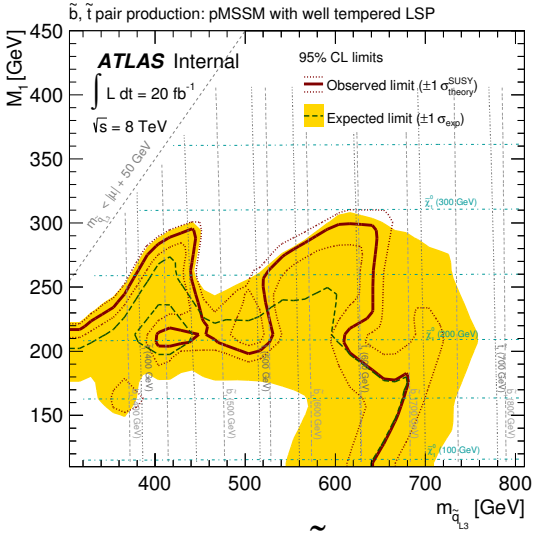
# Third Generation Summary Paper

## Interpretation in terms of pMSSM Models

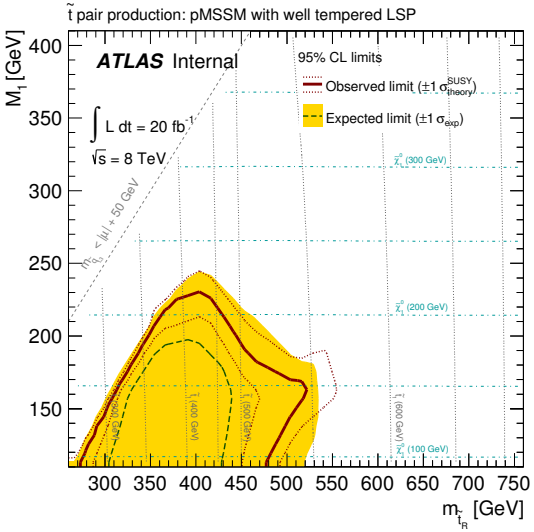
### Natural pMSSM

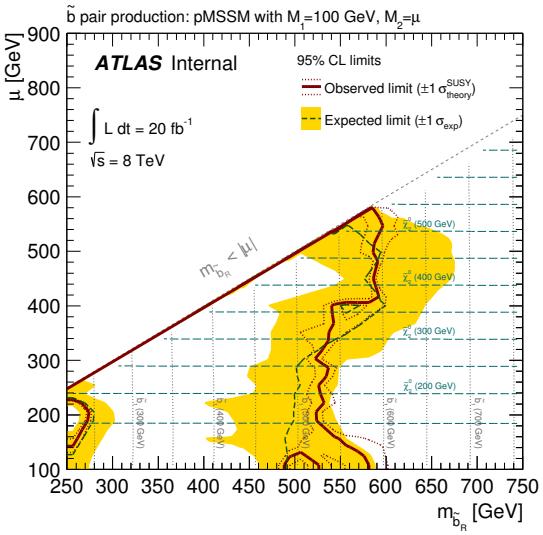
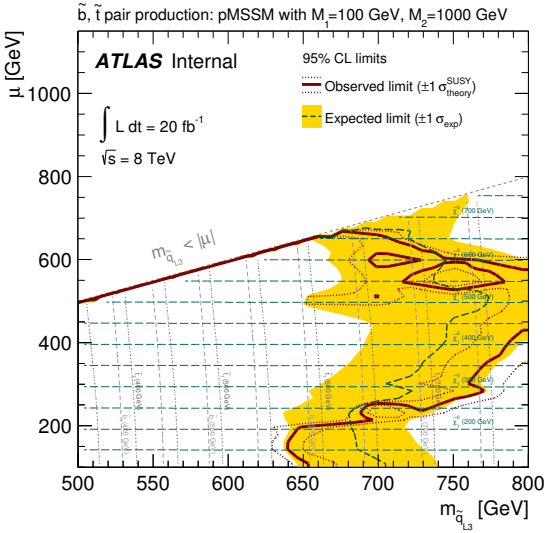



### Well tempered neutralino




### projection onto $\tilde{t}_R$ mass plane




### H/Z enriched