# Third generation SUSY searches at the LHC

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on behalf of the ATLAS and CMS collaborations

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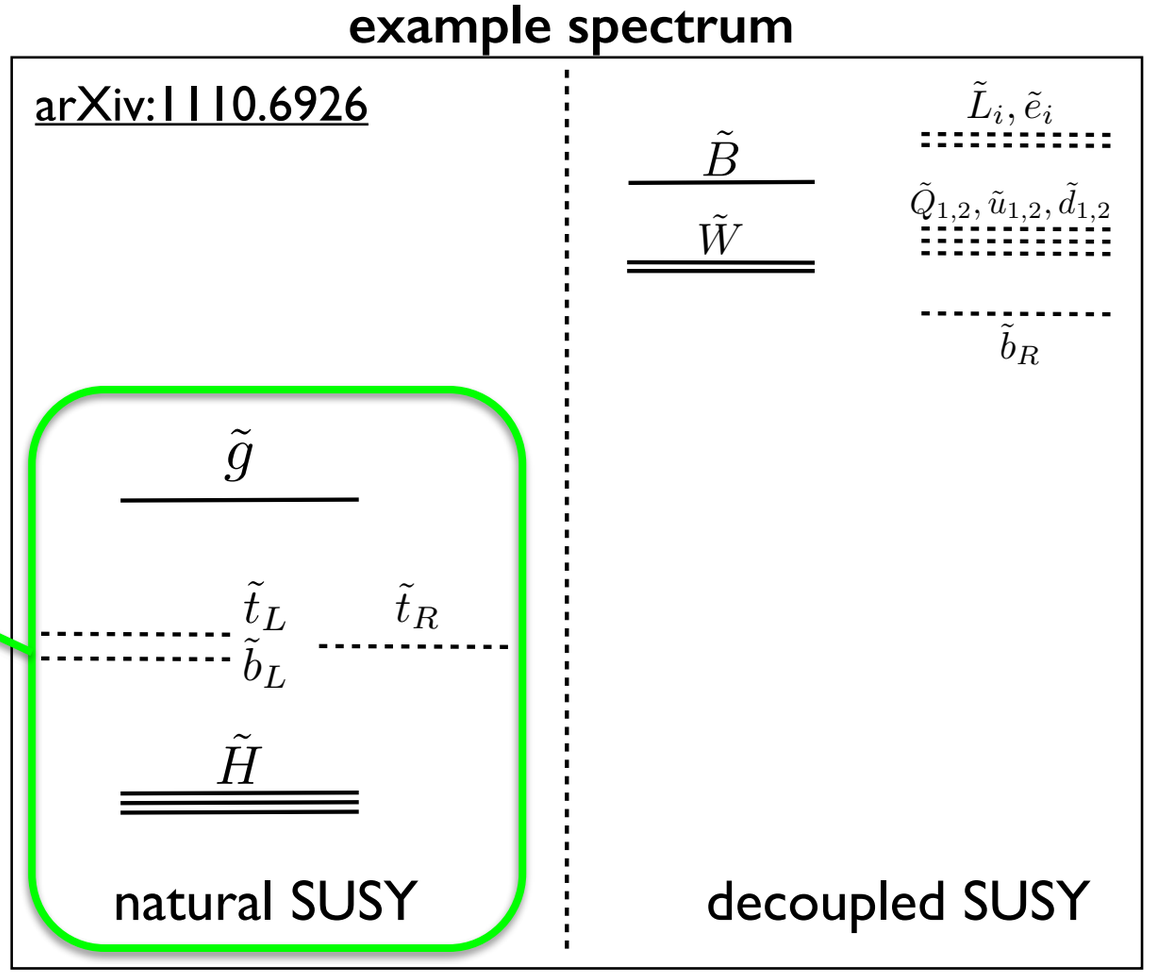
# Motivation

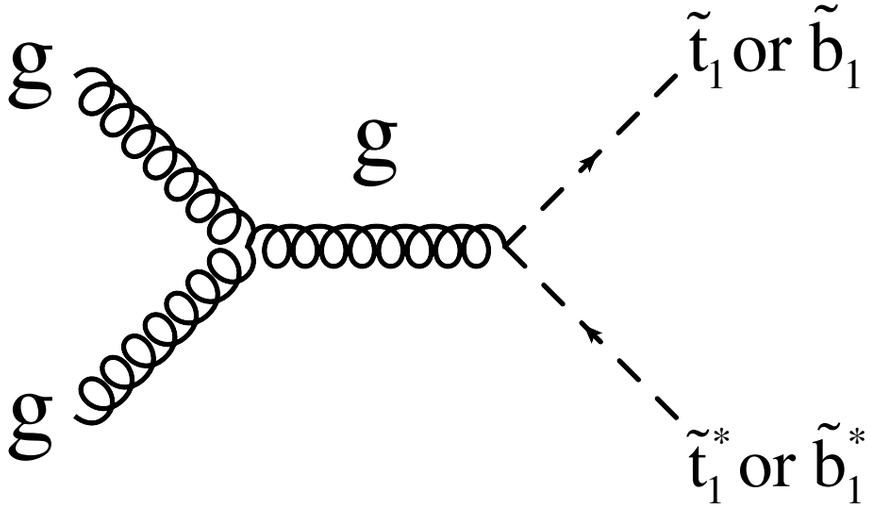
- Third generation particles play special role in electroweak symmetry breaking
  - Higgs boson has been discovered with mass $m_H$=126 GeV
  - Top quark loop gives largest divergent contribution to $m_H$
  - A top partner can cancel divergence

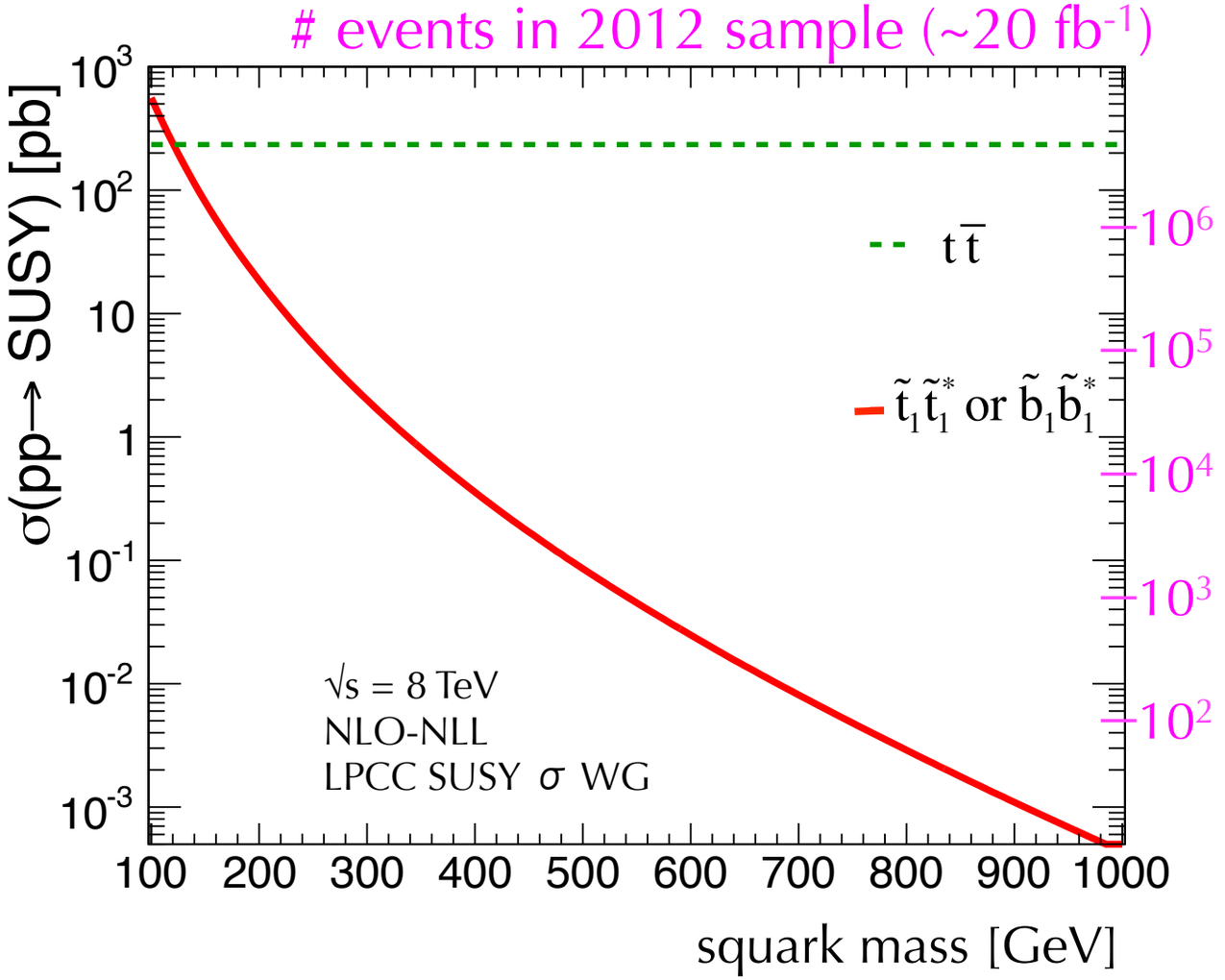
- In SUSY, natural EWSB constrains part of the spectrum to be relatively light (~$m_t$)
  - 3rd generation squarks may be accessible at LHC



# Production mechanisms

- Direct squark pair production by gg fusion or $q\bar{q}$ annihilation



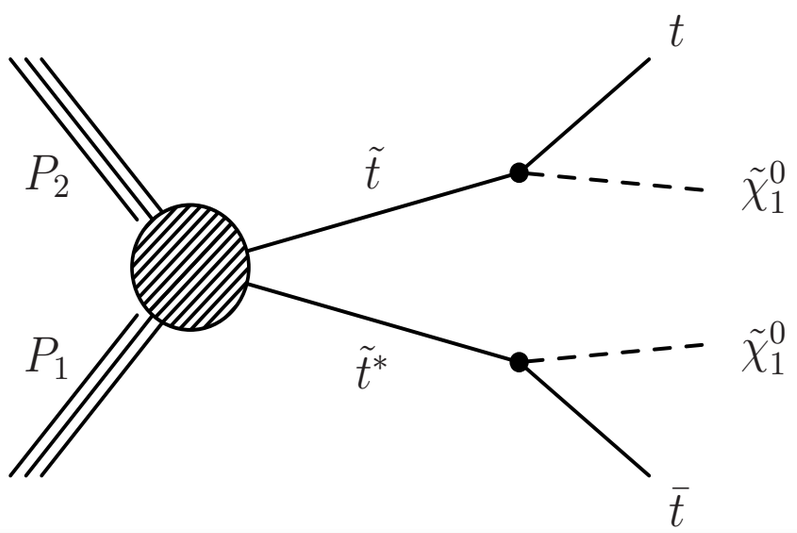

- Cross-section rapidly falls with mass
  - ~100 events expected in 8 TeV dataset for 700 GeV squarks
- Cross-section ~1/6 of quark pairs with same mass (e.g. $t\bar{t}$)

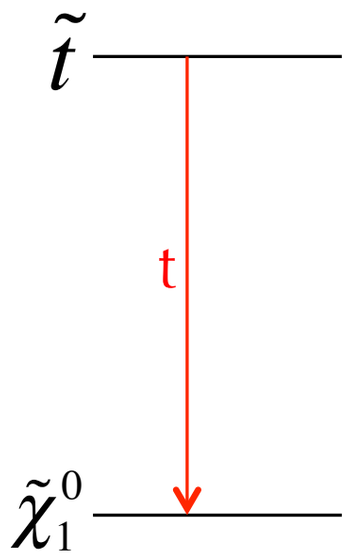
# Decay signatures

- When R-parity is conserved, the number of SUSY particles must be preserved in the decay (assumed in this talk)
  - Lightest supersymmetric particle (LSP) cannot decay
    - Provides nice dark matter candidate
    - In this talk, the LSP is always the lightest neutralino ($\tilde{\chi}_1^0$)
- Simplest squark decay signature: direct decay of squark to quark + LSP

**Focus first on stops:**

$$\tilde{t}\tilde{t}^* \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$




mass of sparticle

# Decay signatures

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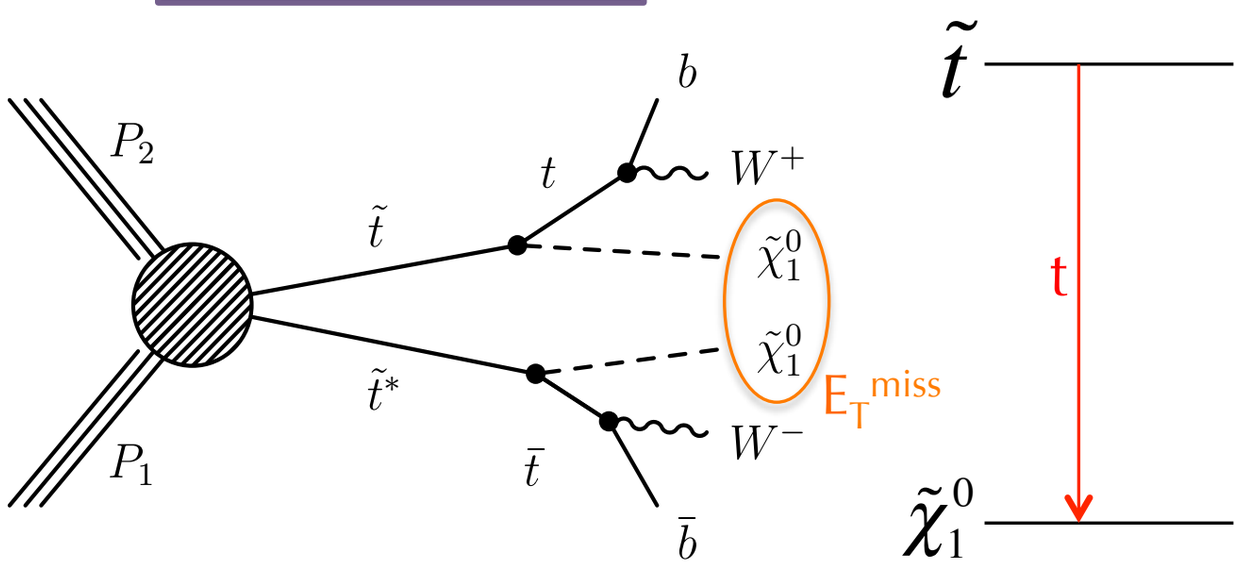
**"$t\bar{t}$ + MET"**

$$\tilde{t}\tilde{t}^* \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

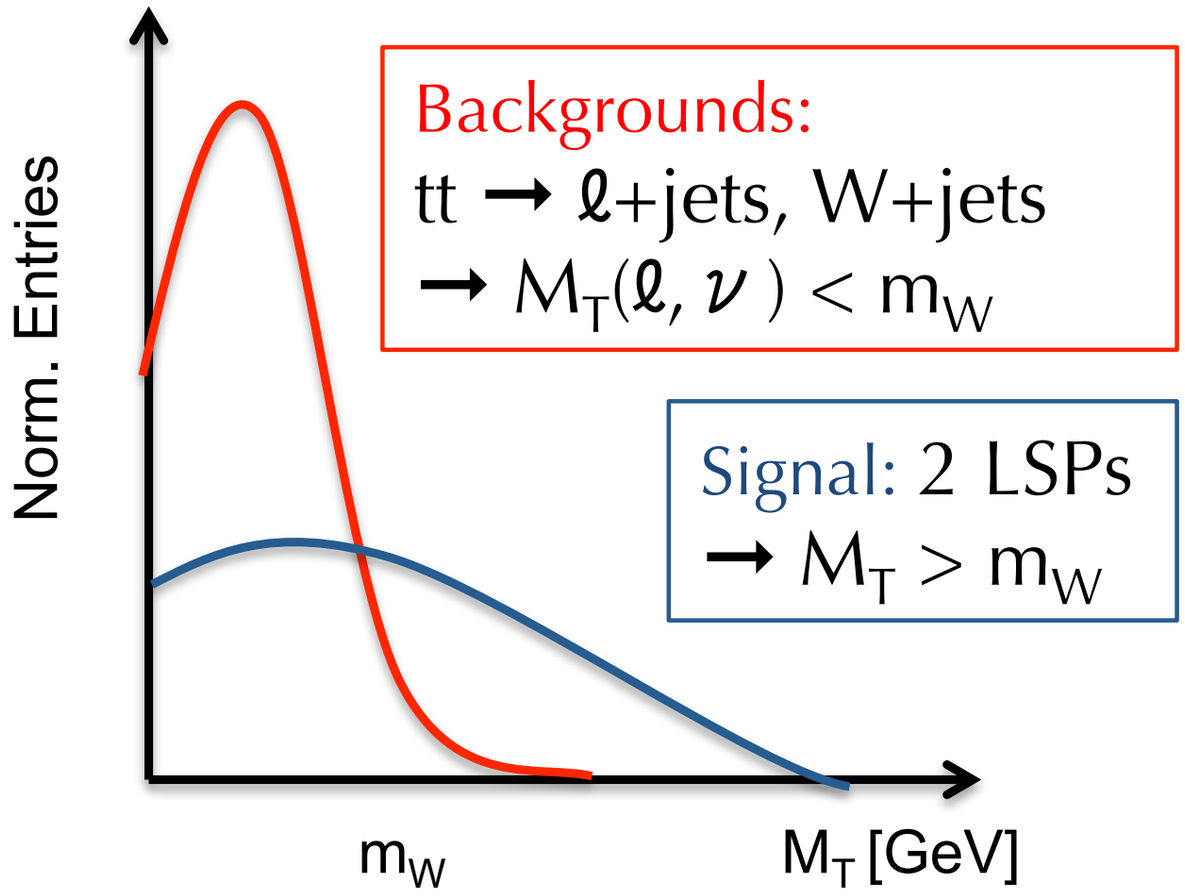



- W decay subcategories:
  - all hadronic (more bkg, large BR)
  - lepton+jets (clean, moderate BR)
  - dilepton (cleanest, low BR)

# Background and discriminating variables

- Use kinematics to distinguish between signal and background
- Look for increased MET from the LSPs
  - also use the direction of the MET

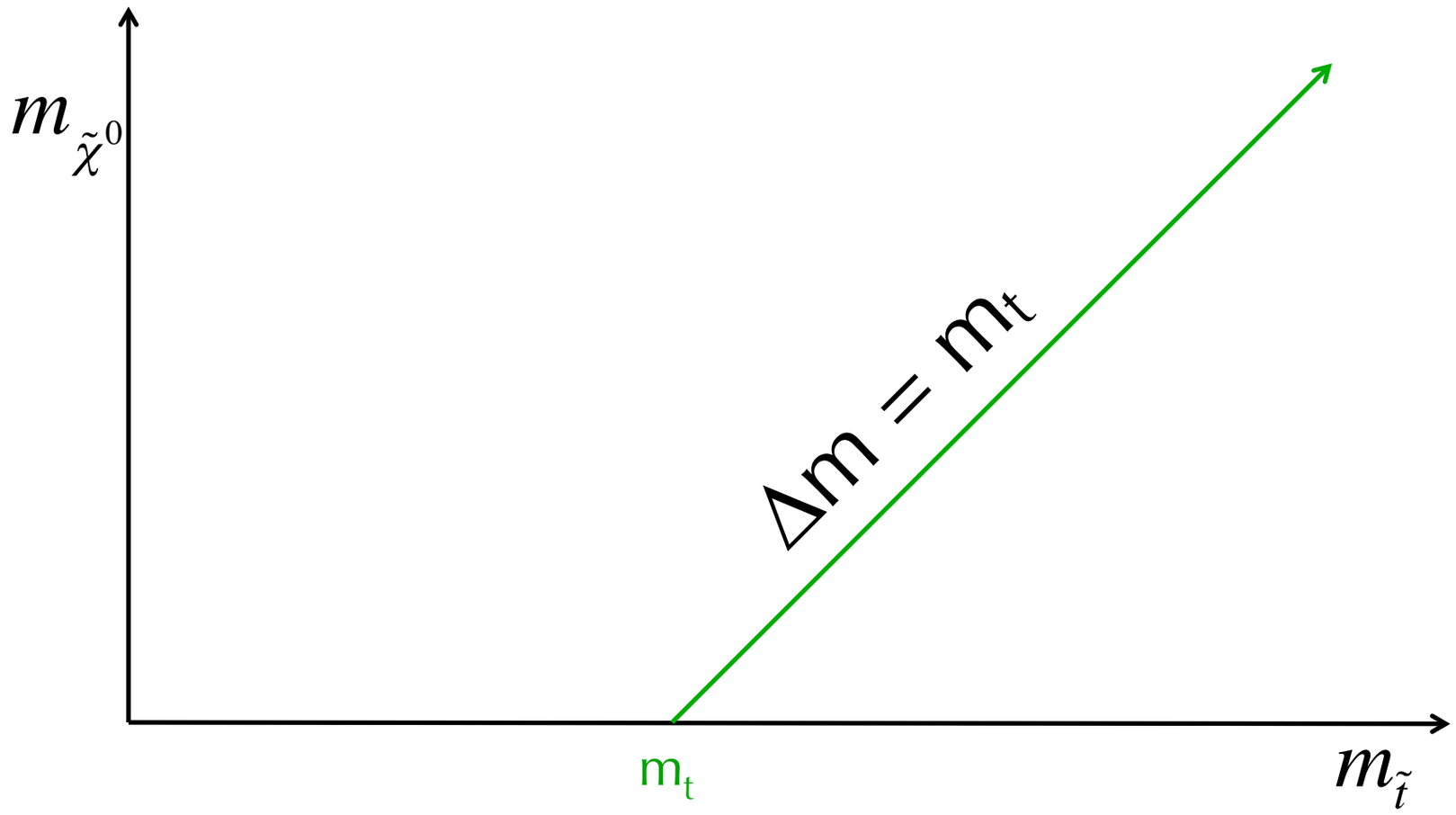
- Use variables with end-point at $m_t$ in top backgrounds
  - MT2-like variables
- Use W-mass end-point for single-lepton W backgrounds
  - signal can have $M_T(\ell, \nu) > m_W$



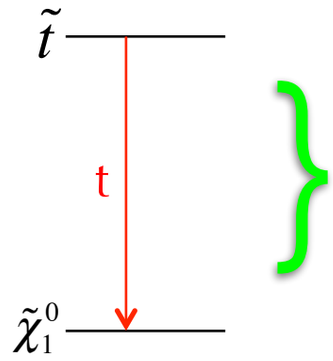

- Sensitivity to SUSY reliant on good modelling of SM background: predict based on control regions (CR) in data

# Parameter space ($m_{stop}$, $m_{LSP}$)

- Relevant SUSY parameter space defined by stop and LSP masses




- A given mass splitting (Δm) is represented by a line




$$\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

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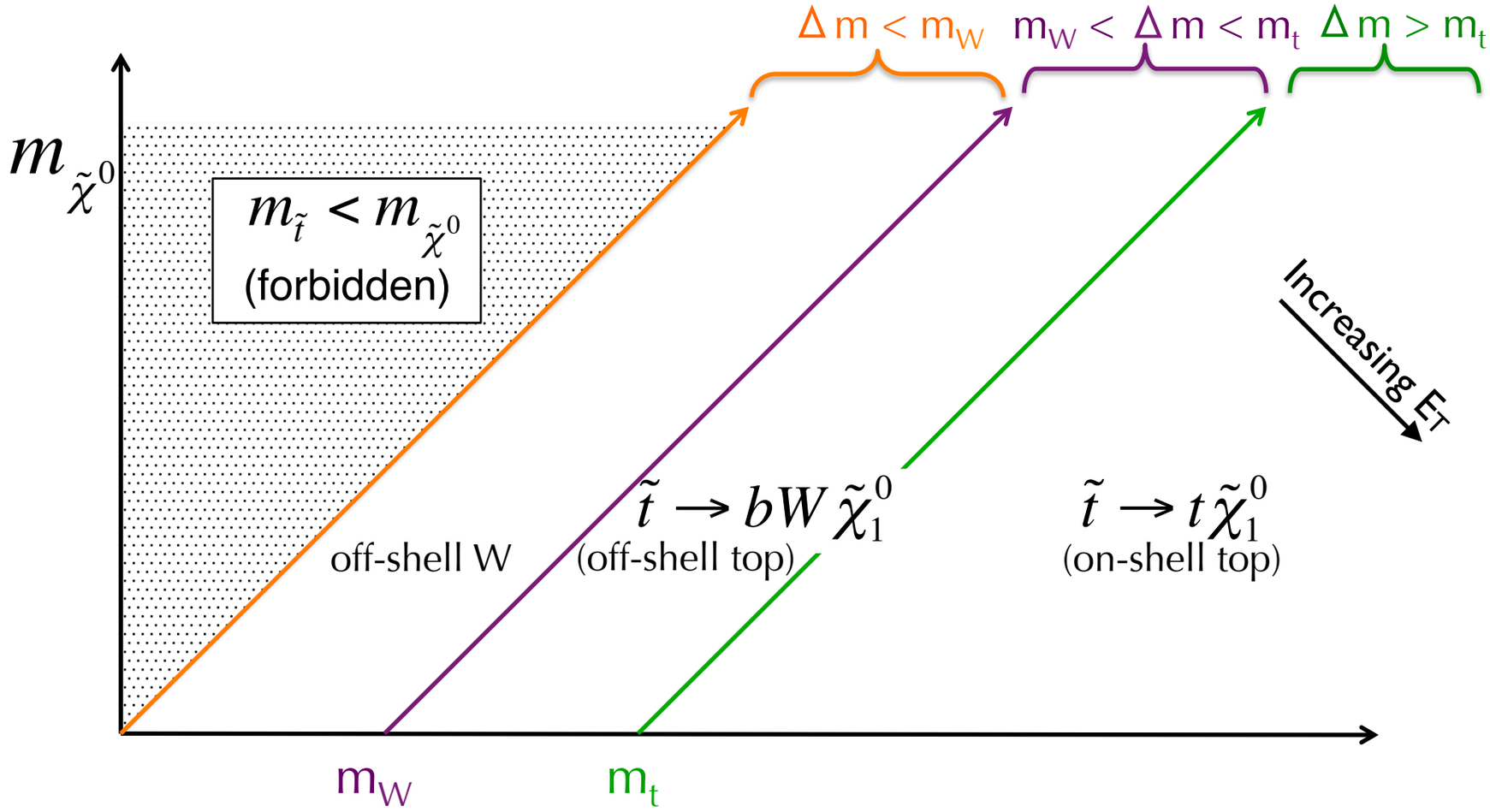
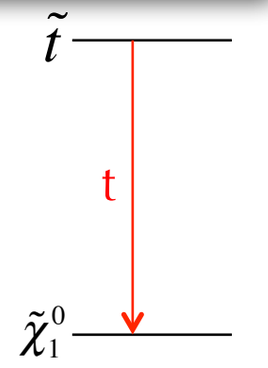
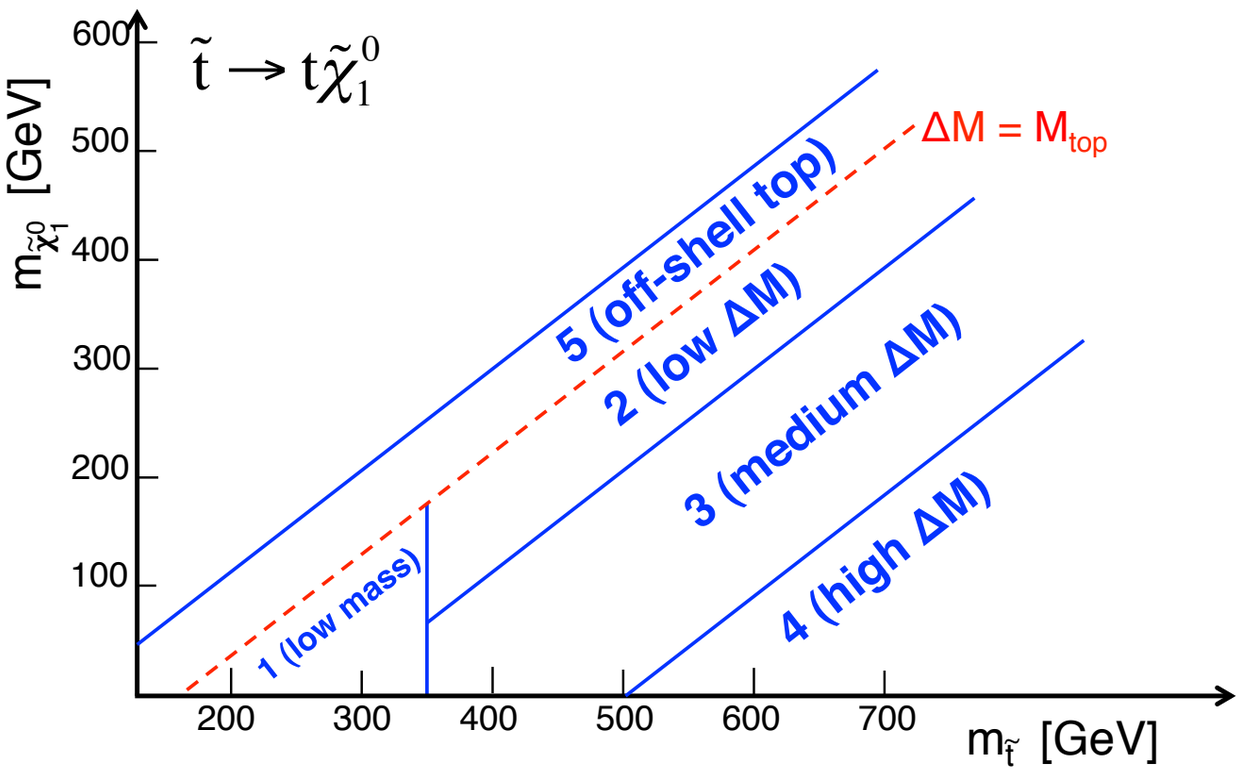


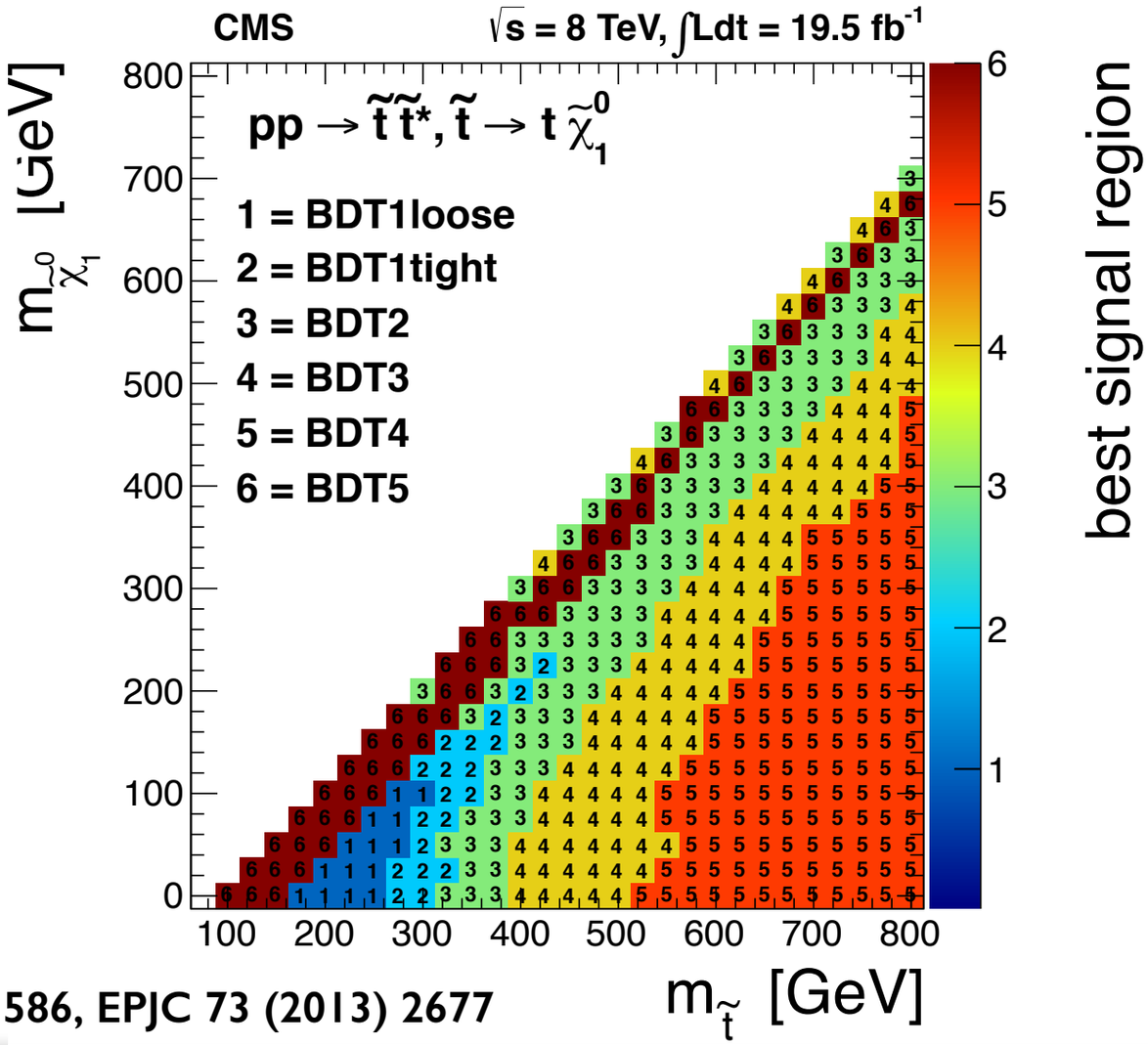

- Δm lines important dividers of phase space
  - regions of different kinematically allowed decays
  - defines amount of energy for decay products

# Example $\tilde{t} \rightarrow t$ LSP search (CMS, 1 lepton)

- General strategy: multiple signal regions (SRs) sensitive to different regions of $m_{stop}$,$m_{LSP}$ parameter space
- 1 lepton channel: $M_T$ an excellent discriminator between signal and ttbar
  - require $M_T$>120 GeV for all SRs, with $M_T$<120 GeV used for normalisation
  - SRs then defined using BDTs optimised for different $\Delta m$ regions
  - SR with best expected xsec limit chosen for each point of parameter space




SUS-13-011, arXiv:1308.1586, EPJC 73 (2013) 2677

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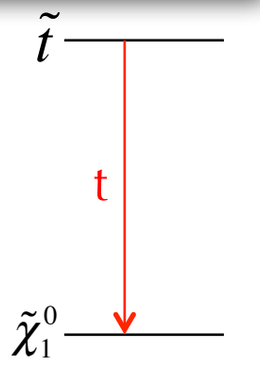


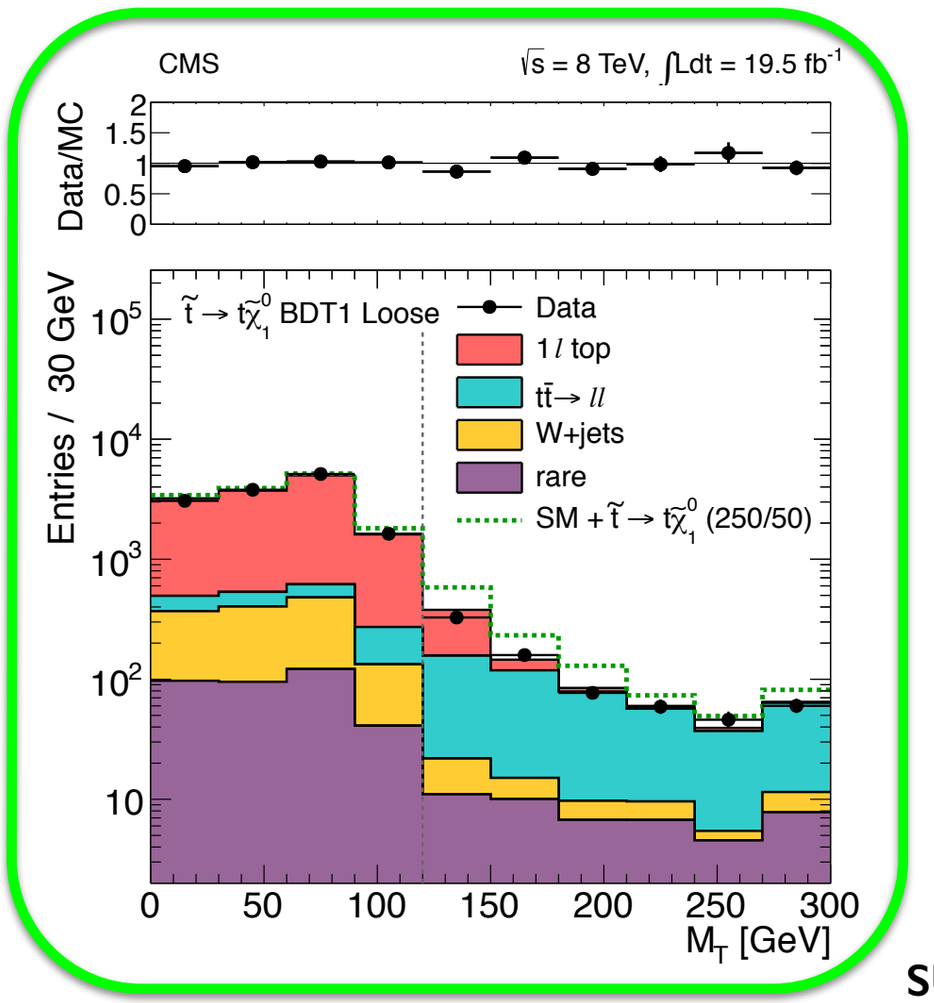


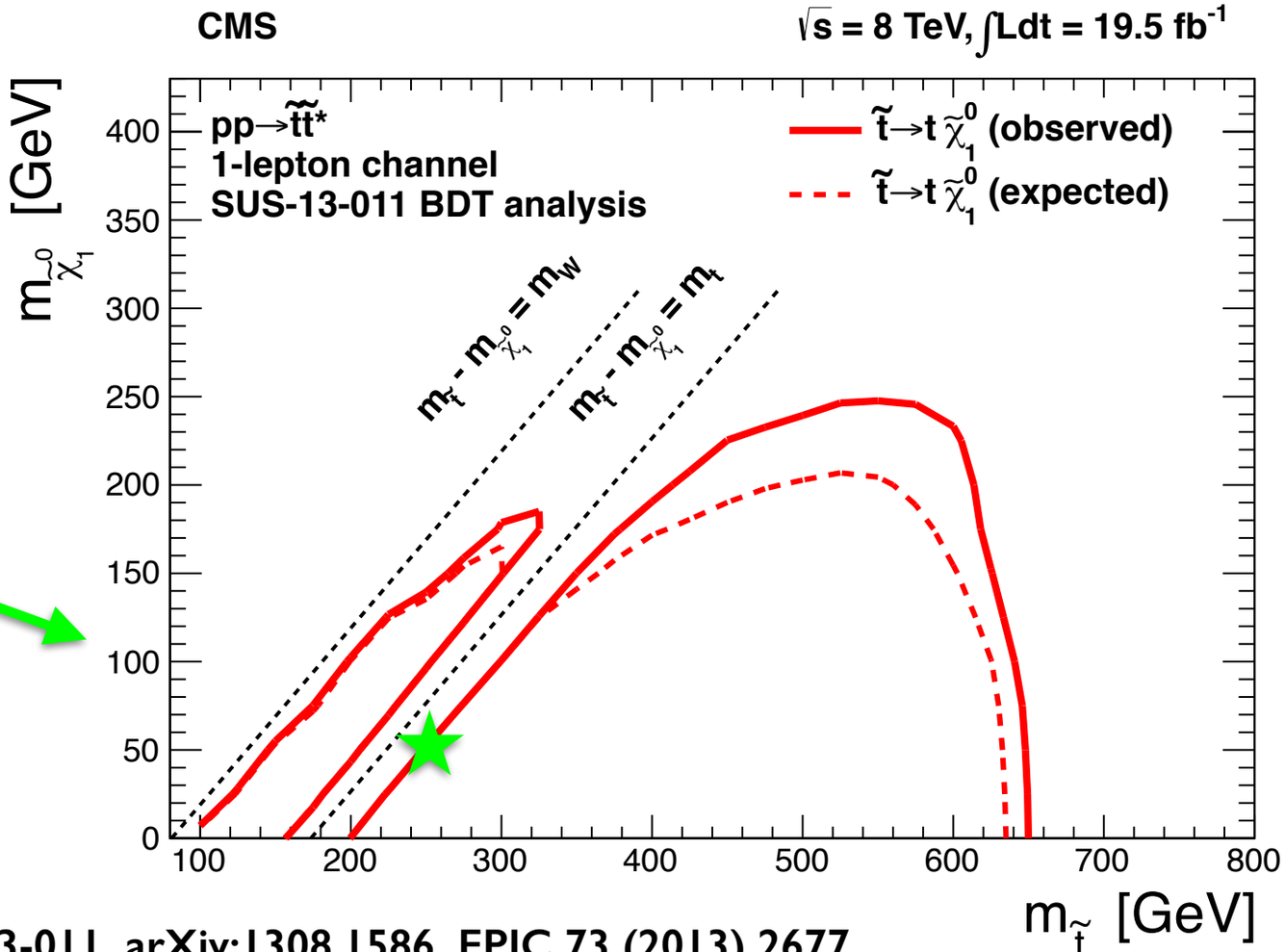


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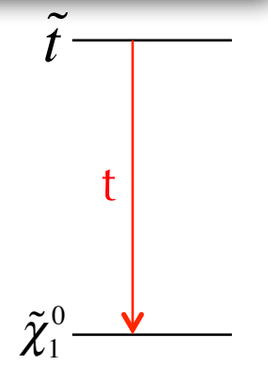
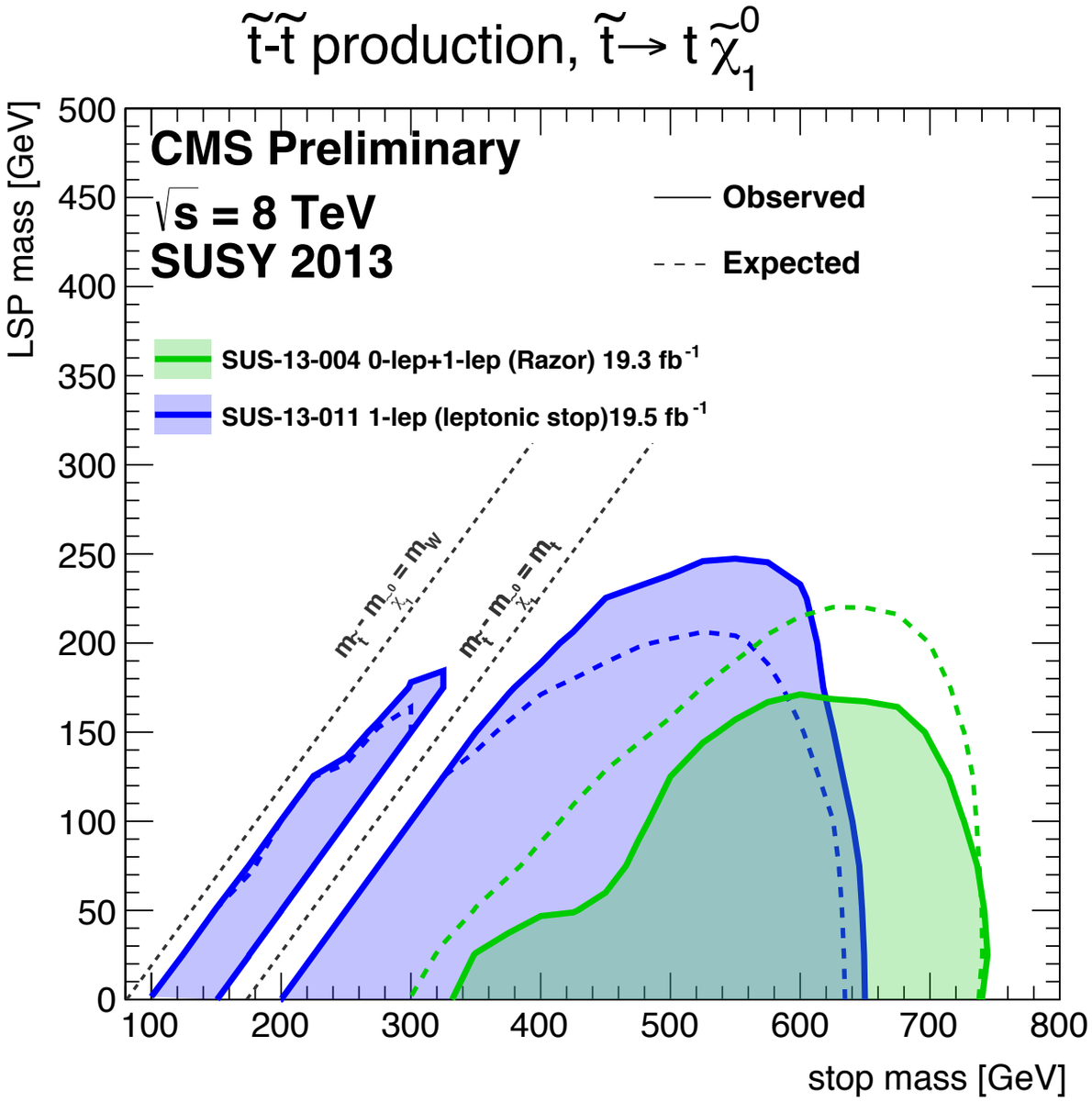
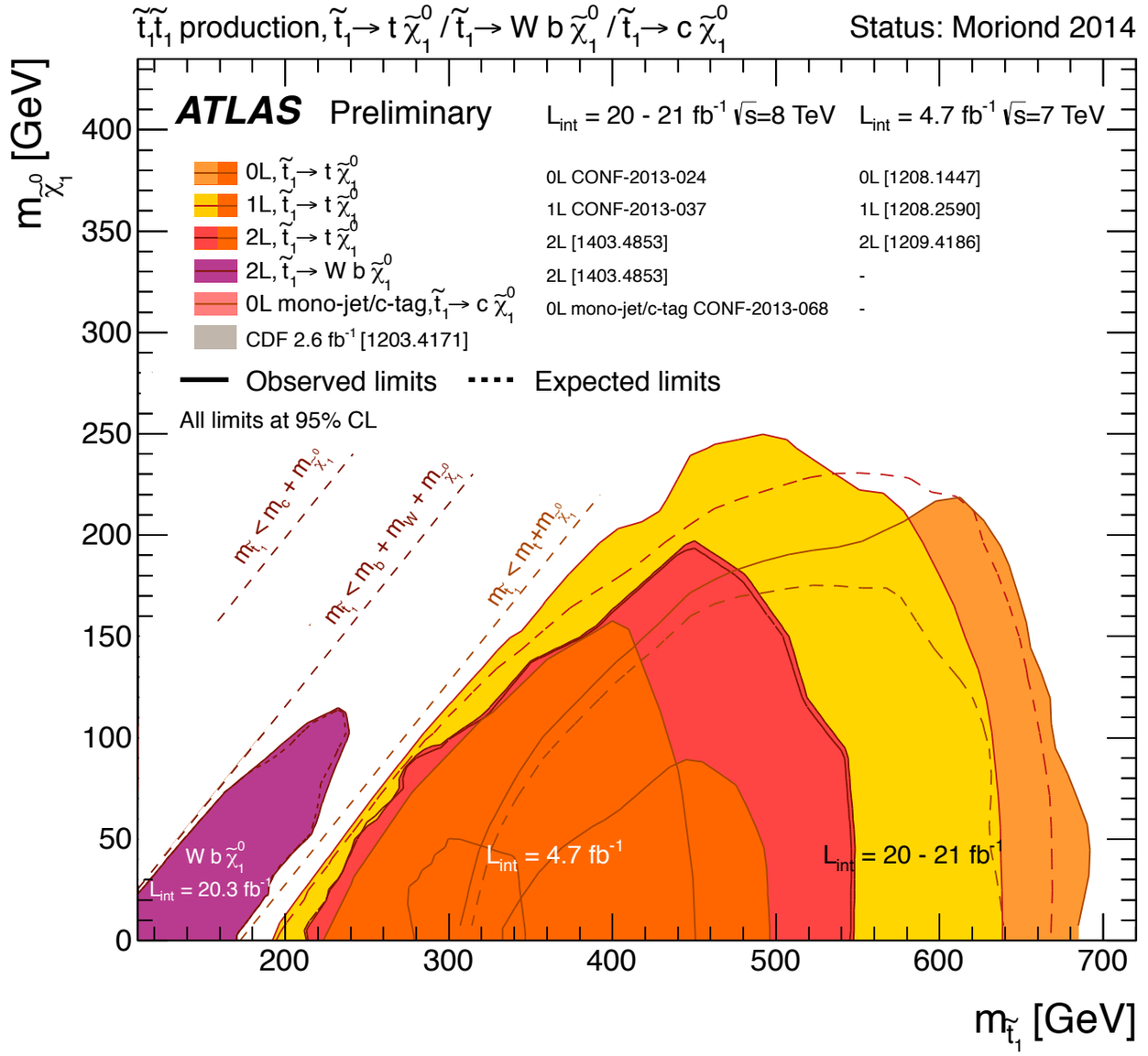
# LHC $\tilde{t} \rightarrow t$ LSP summary

- Combining channels: $m_{stop} < 700$ GeV exclusion for light LSP
- Note gap in exclusion for $\Delta m = m_t$ (stop "on top" of top)
- No exclusion for $\Delta m < m_W$ from these non-targeted searches

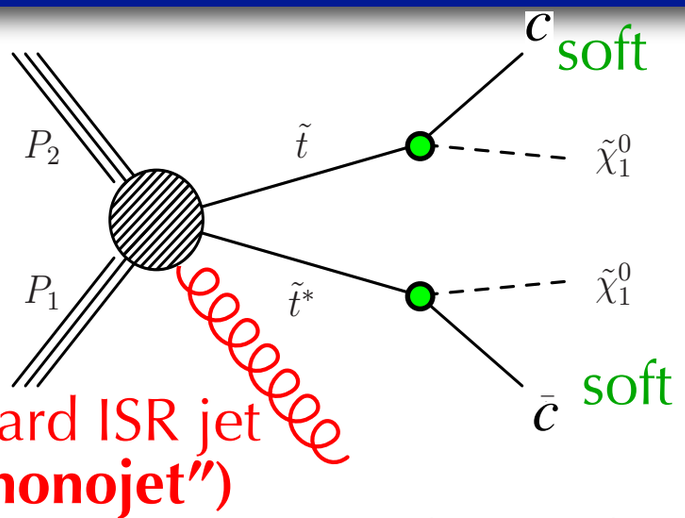


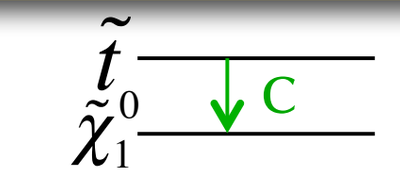



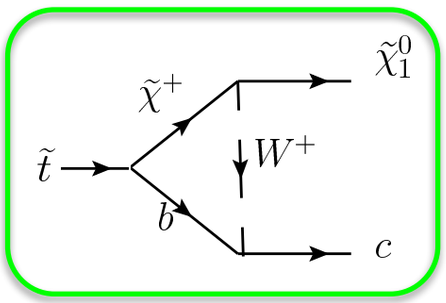



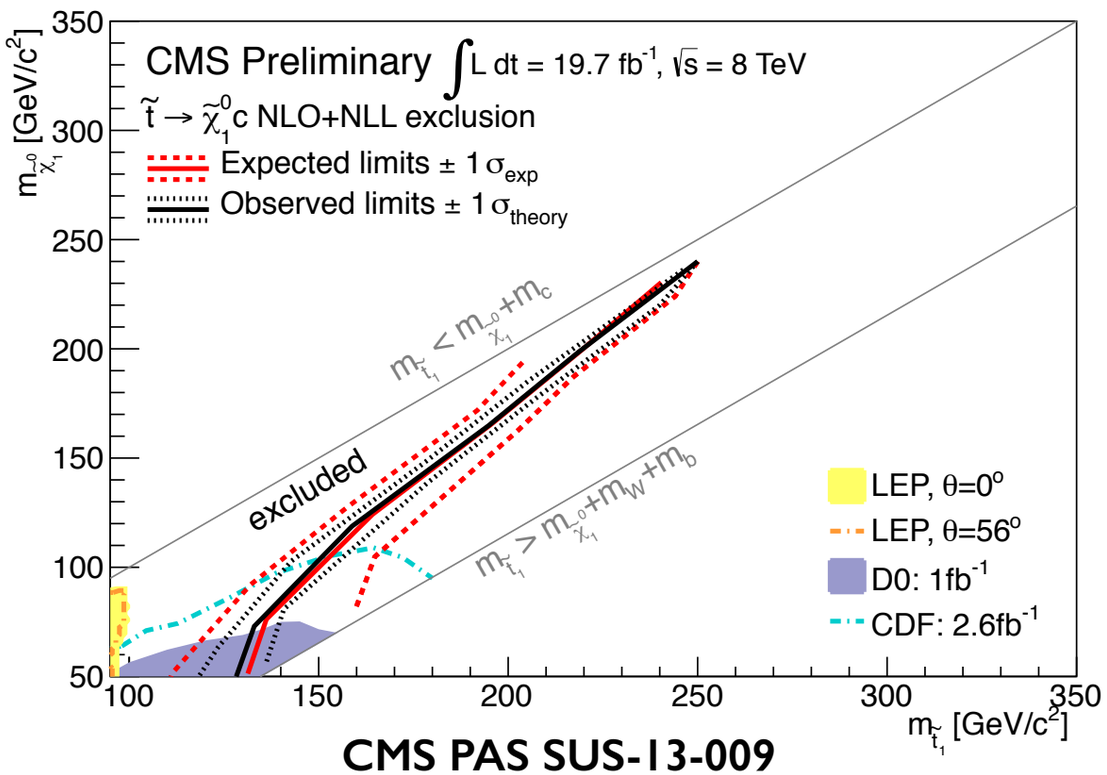
# Monojet search

- For $\Delta m < m_W$, $\tilde{t}_1 \to bW^+\tilde{\chi}_1^0$ not possible
- Instead, search for $\tilde{t}_1 \to c\tilde{\chi}_1^0$
  - allowed when $\Delta m > m_c$
- Charm jets very soft and LSPs ~back-to-back, so require hard ISR jet recoiling against MET from the LSPs
  - also use charm tagging to target $\Delta m$ closer to $m_W$ (ATLAS)

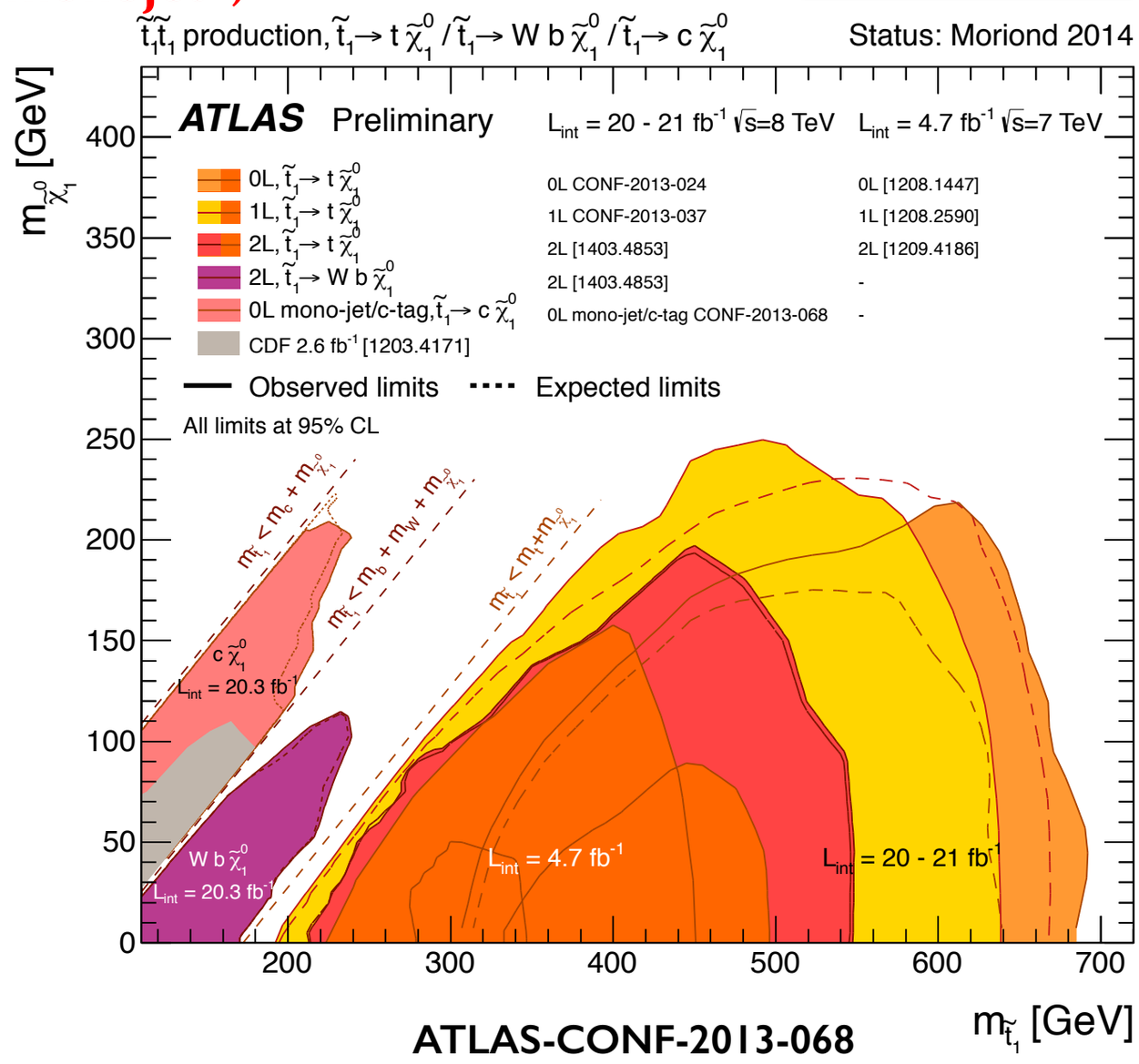



CMS PAS SUS-13-009

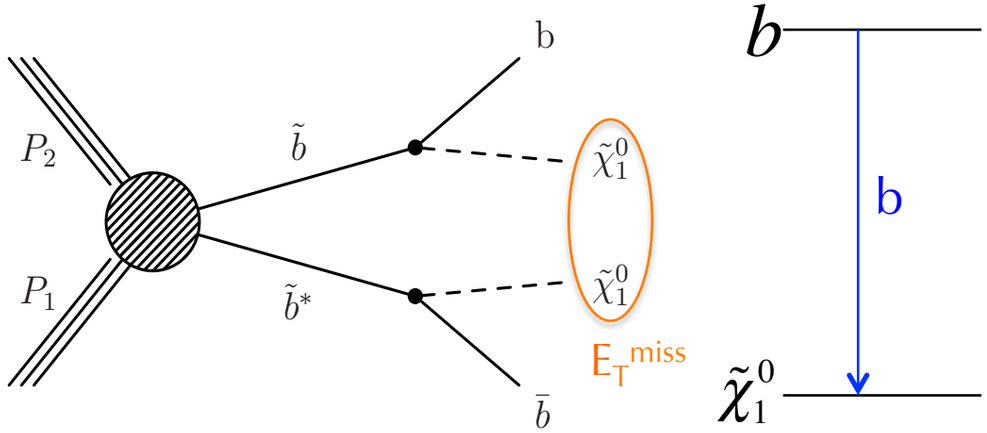



ATLAS-CONF-2013-068

# $\tilde{b} \rightarrow b$ LSP

- Simplest signature for sbottoms: direct decay of squark to quark + LSP

$\tilde{b}\tilde{b}^* \rightarrow b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0$



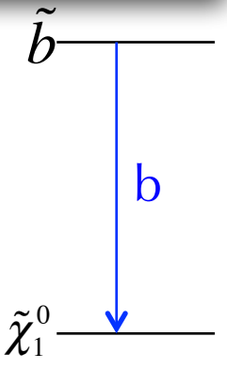




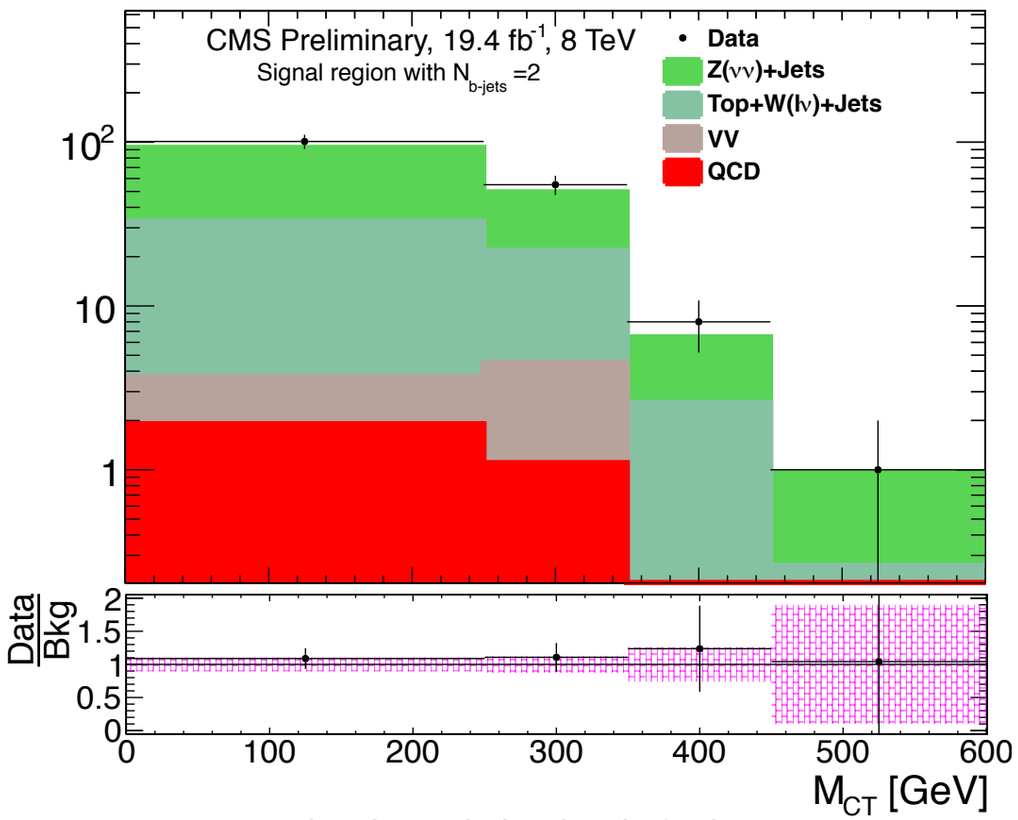
$$\Delta m \equiv m_{\tilde{b}} - m_{\tilde{\chi}^0}$$

- Looks like $b\bar{b}$ + MET
  - always all hadronic
- $\Delta m$ lines still good way to group regions of parameter space
  - $\Delta m$ defines amount of energy for decay products

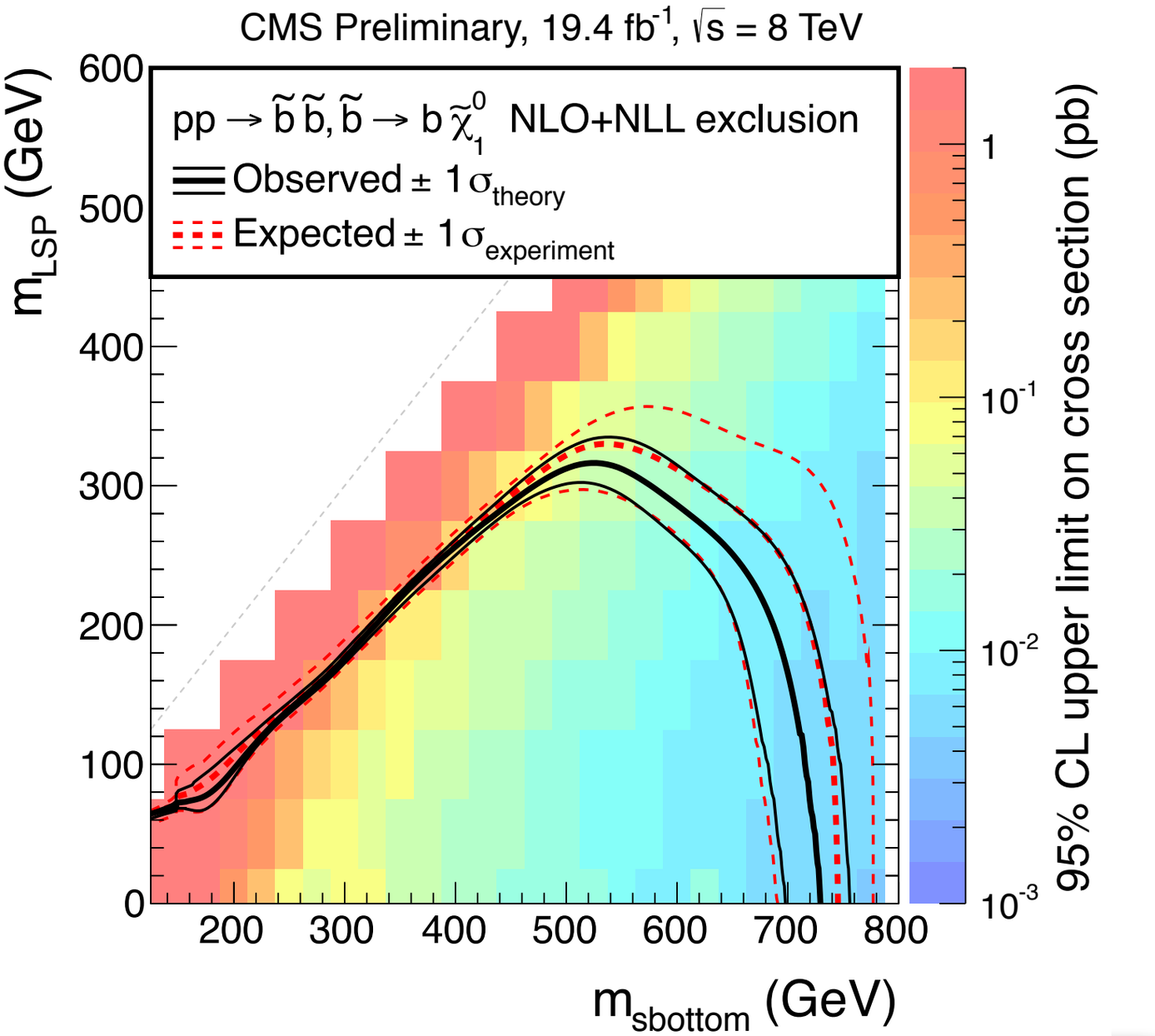
# $\tilde{b} \rightarrow b$ LSP search (CMS)




- Use contransverse mass of bs: $M_{CT}^2(J_1, J_2) = 2p_T(J_1)p_T(J_2)(1 + \cos\Delta\phi(J_1, J_2))$
  - like $M_T$ but invariant under *contra-linear* boosts of the bs
- End-point in signal: $m_{\mathrm{CT}}^{\mathrm{max}} = \dfrac{m^2(\tilde{b}) - m^2(\tilde{\chi}_1^0)}{m(\tilde{b})}$ in $t\bar{t}$: $M_{CT}^{max} = 135$ GeV
- SRs in bins of increasing $M_{CT}$, targeting regions of increasing $\Delta m$

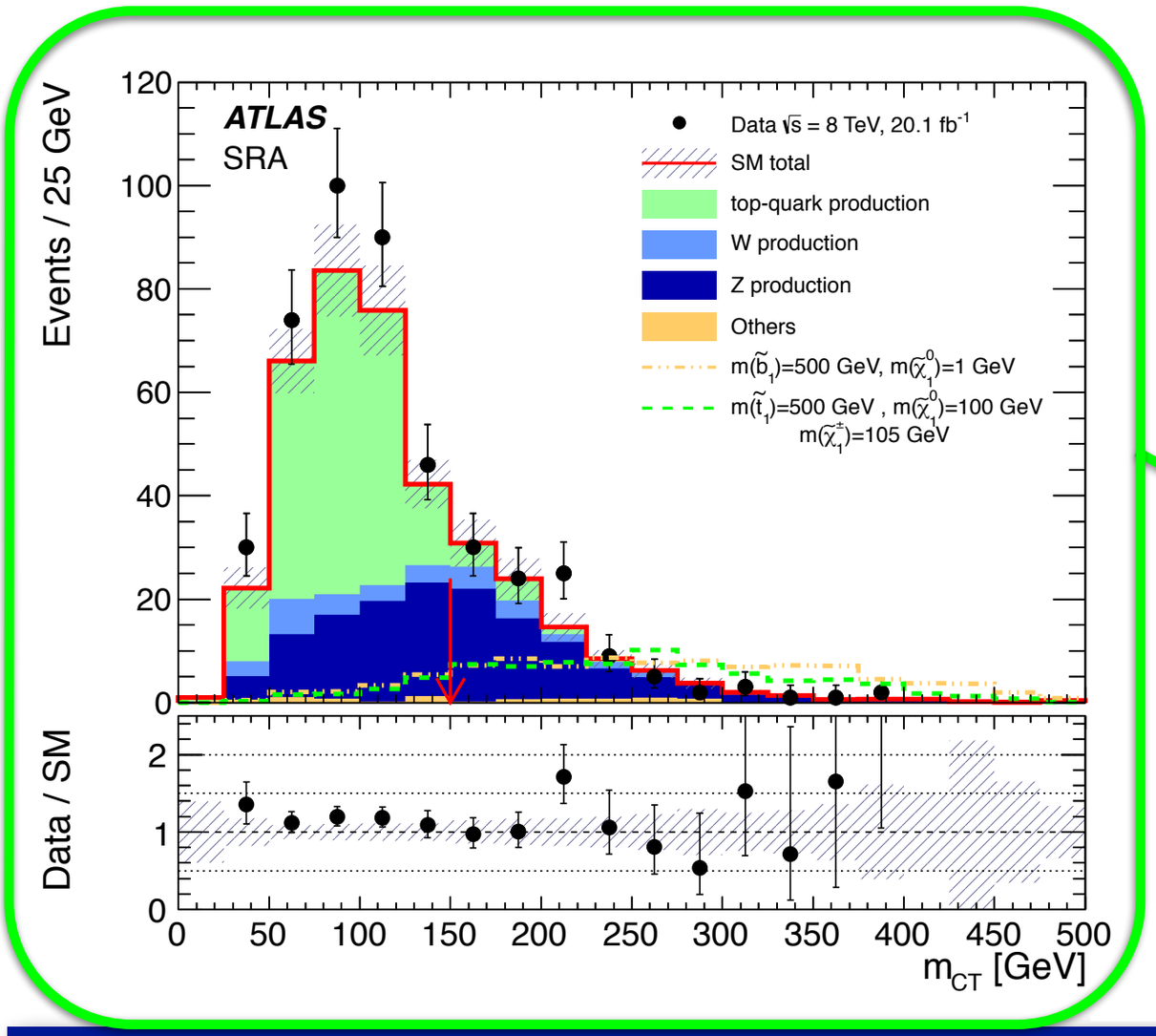


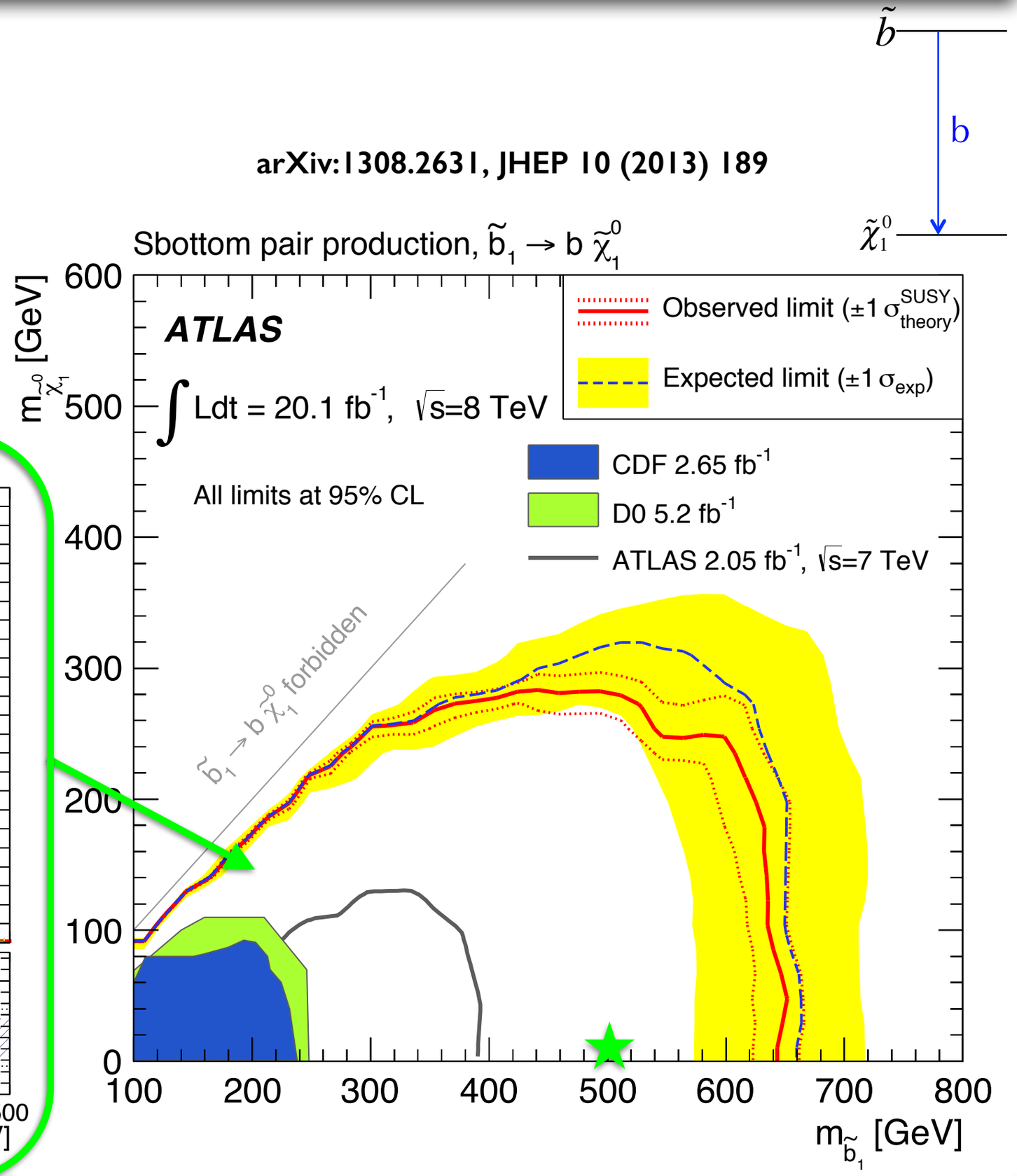

CMS PAS SUS-13-018



# $\tilde{b} \rightarrow b$ LSP search (ATLAS)

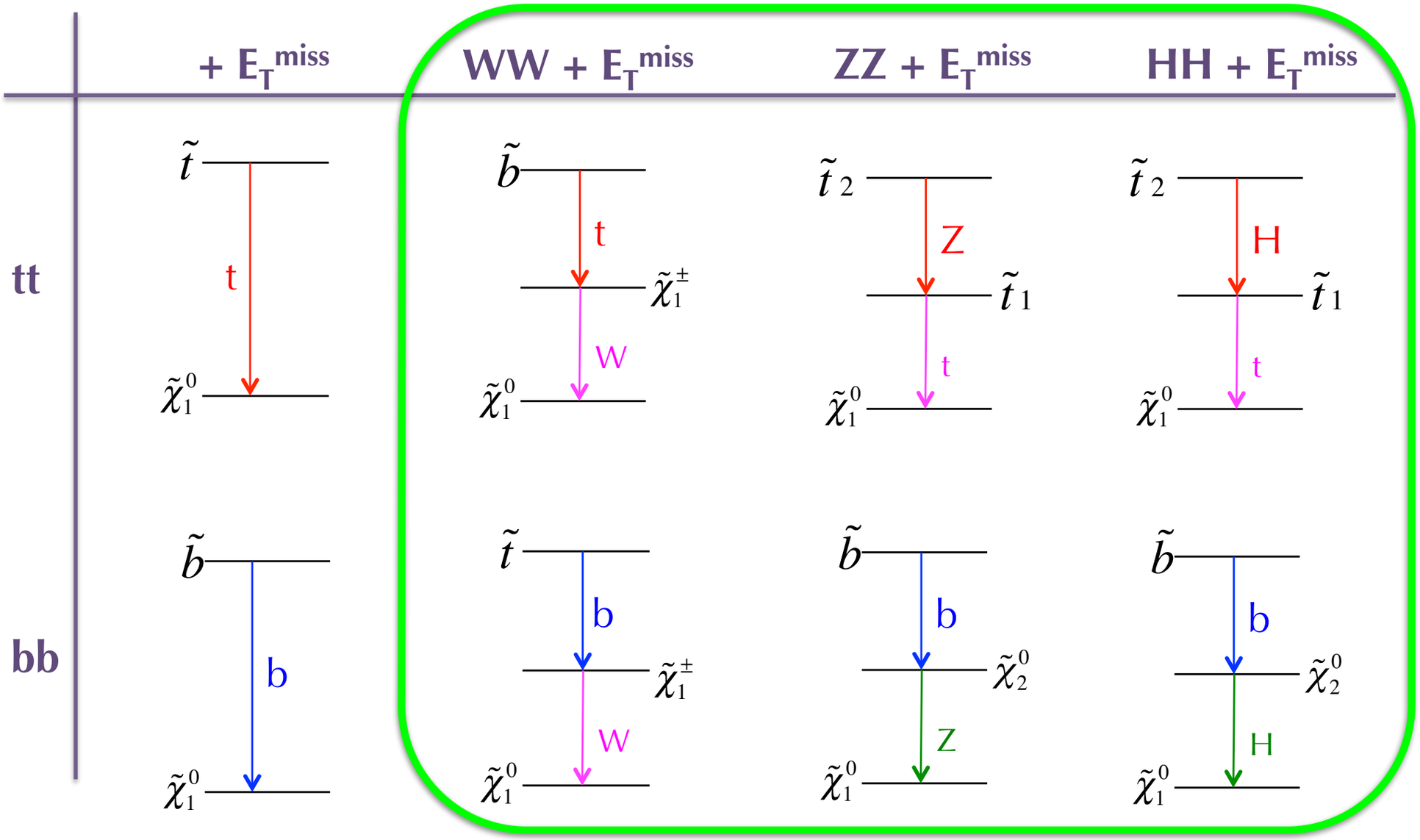
- Similar analysis using $M_{CT}$ at ATLAS
- Separate selection with ISR jet to target low $\Delta m$ region



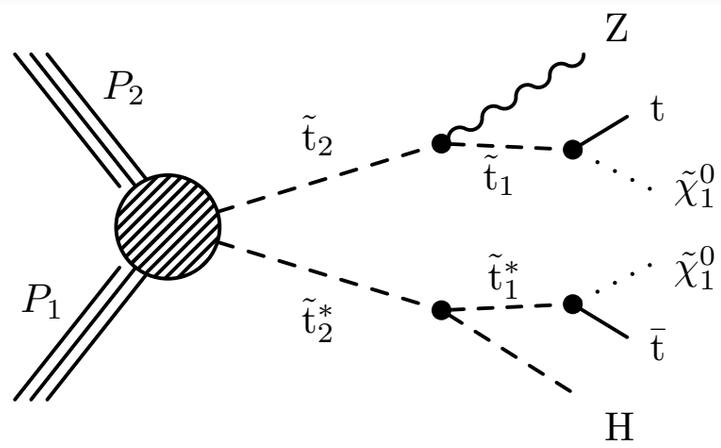
# Cascade signatures

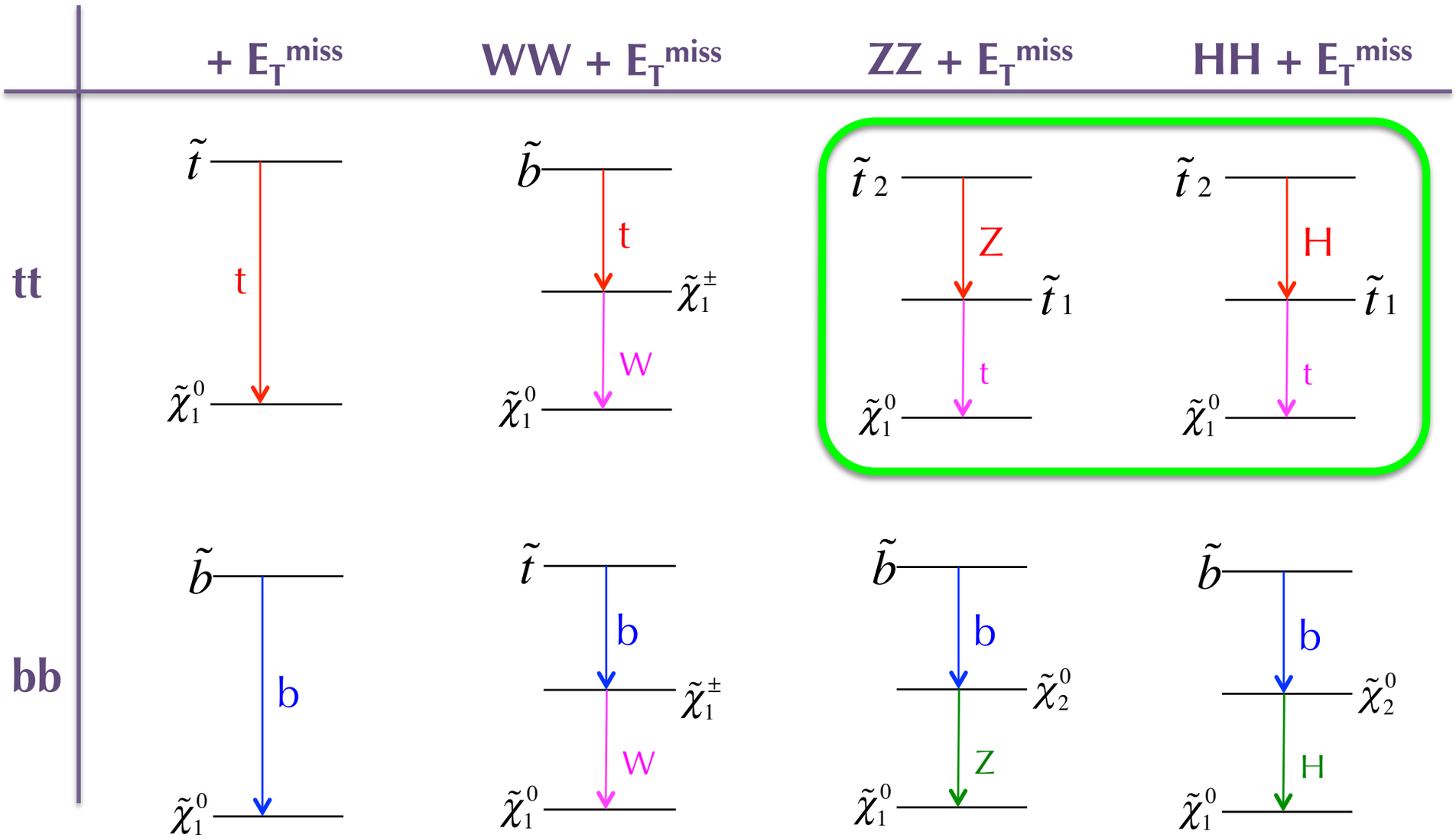
- Light $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$, $\tilde{t}_2$ all well motivated in natural SUSY
- Allows intermediate states, resulting in "cascade" decays
  - signatures with additional W, Z, or H bosons in addition to simple $t\bar{t}/b\bar{b}$ + MET
- Signal regions typically defined by number of leptons (from W/Z) and bs (from t/H)



# $\tilde{t}_2 \rightarrow \tilde{t}_1$ Z/H LSP

- What if we can't see $\tilde{t}_1$ because $\Delta m \sim m_t$ ?
- Look for relatively light $\tilde{t}_2$ that decays to $\tilde{t}_1$
  - same final state as $\tilde{t} \rightarrow t$ LSP, but with multiple additional leptons (from Z) and/or bs (from H)

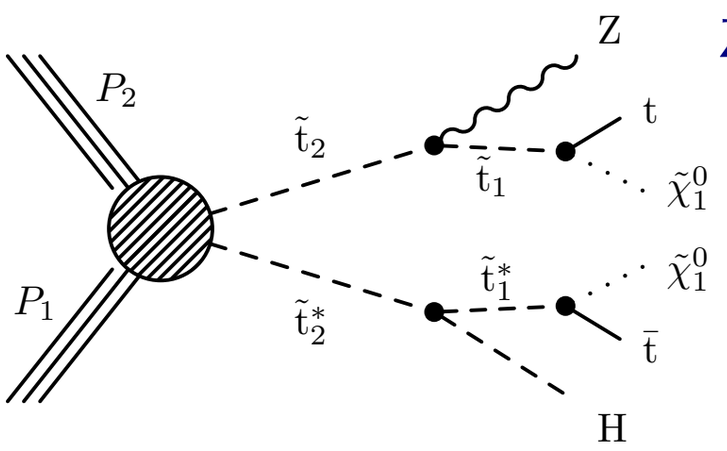



using Higgs to tag SUSY signatures!

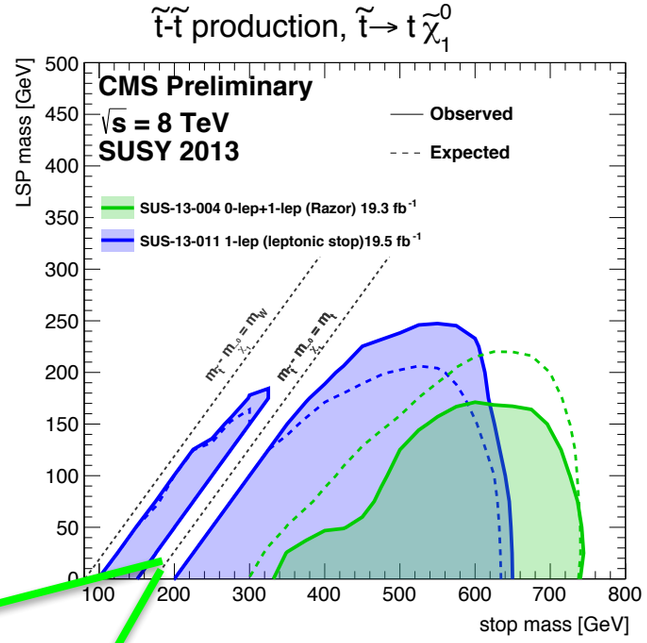
# $\tilde{t}_2 \rightarrow \tilde{t}_1$ Z/H LSP

- Probe gap in $\tilde{t}_1 \rightarrow$ t LSP coverage by looking for cascade decay of heavier $\tilde{t}_2$, with $\Delta m(\tilde{t}_1, \mathrm{LSP}) = m_t$

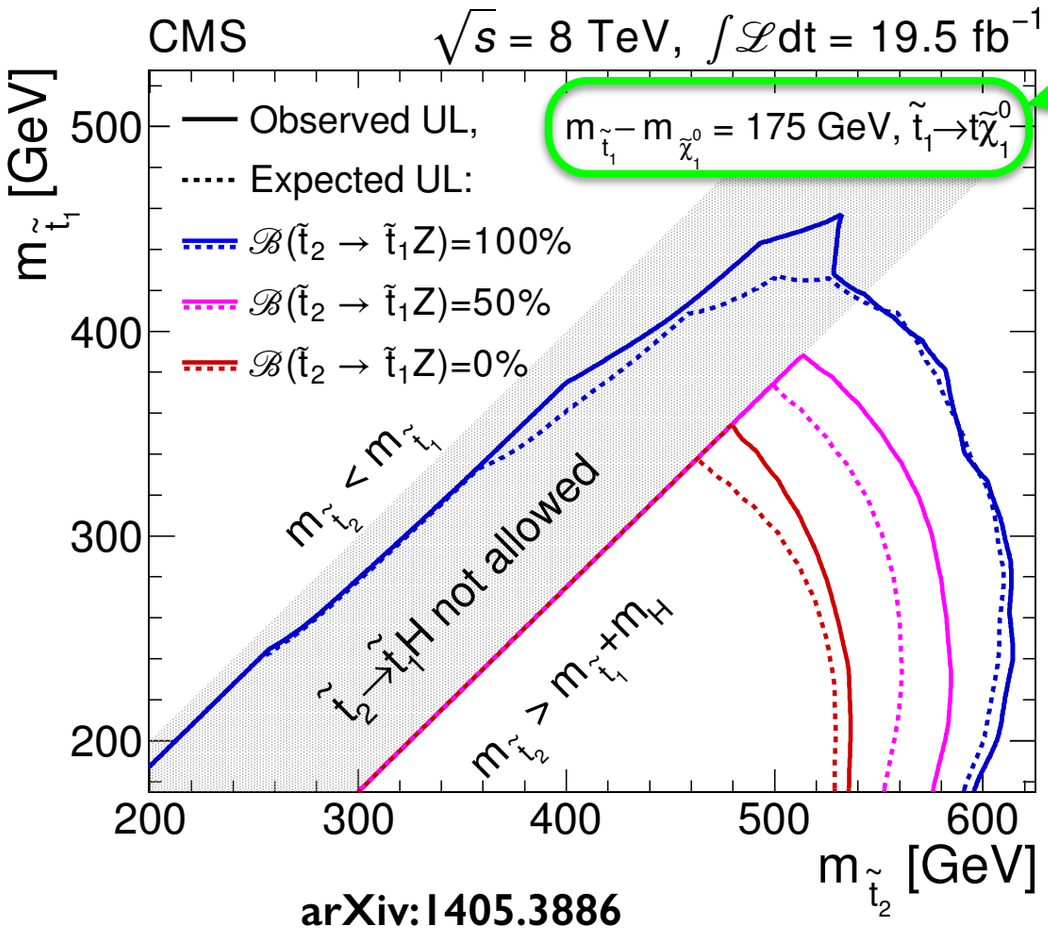



Z → dileptons signature

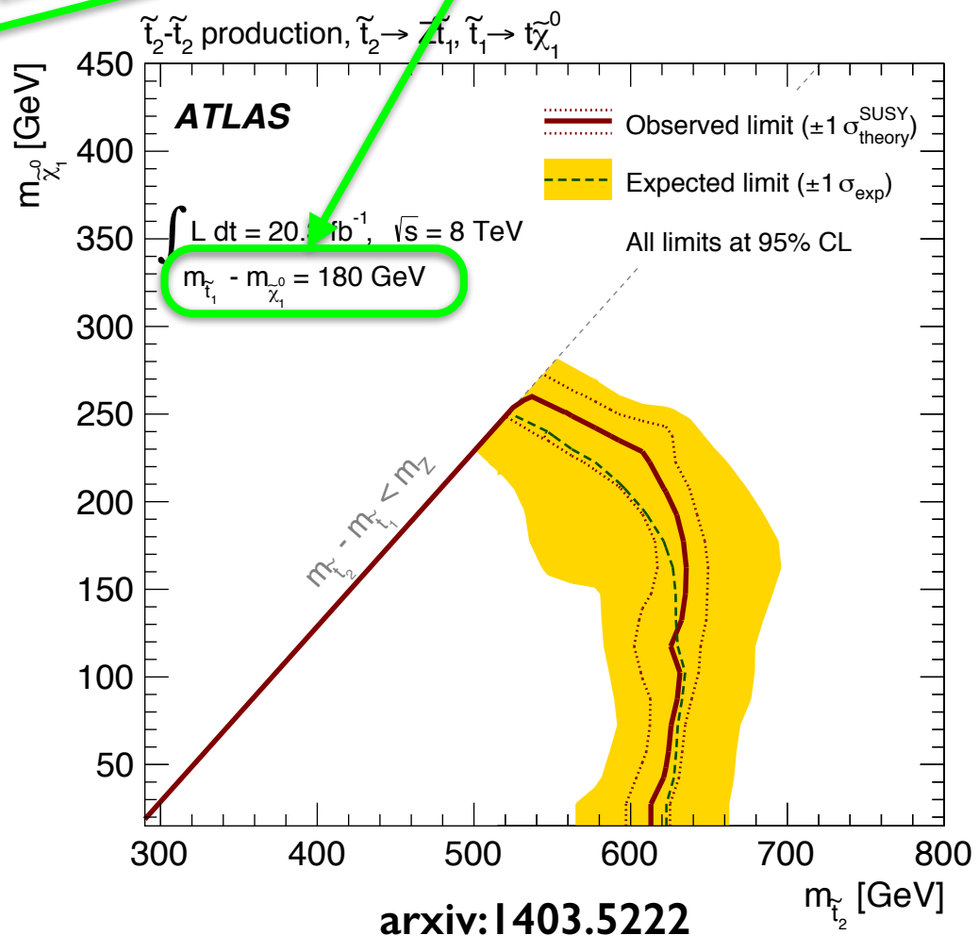
H → $b\bar{b}$ signature




set $\Delta m = m_t$




arXiv:1405.3886




arxiv:1403.5222

# Summary

- Presented results of LHC searches for direct production of 3rd generation squarks

- Searches cover a comprehensive spectrum of final states and exclude large regions of squark and LSP masses
  - recent progress in exploring increasingly difficult regions of parameter space
  - lots of progress understanding SM background

- Now need 13 TeV data to probe higher squark mass regions

- Exciting prospects for discovery at 13 TeV!

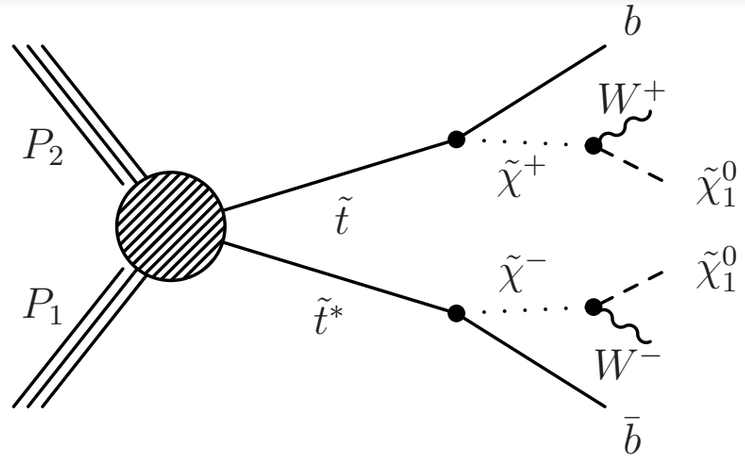
# Backup

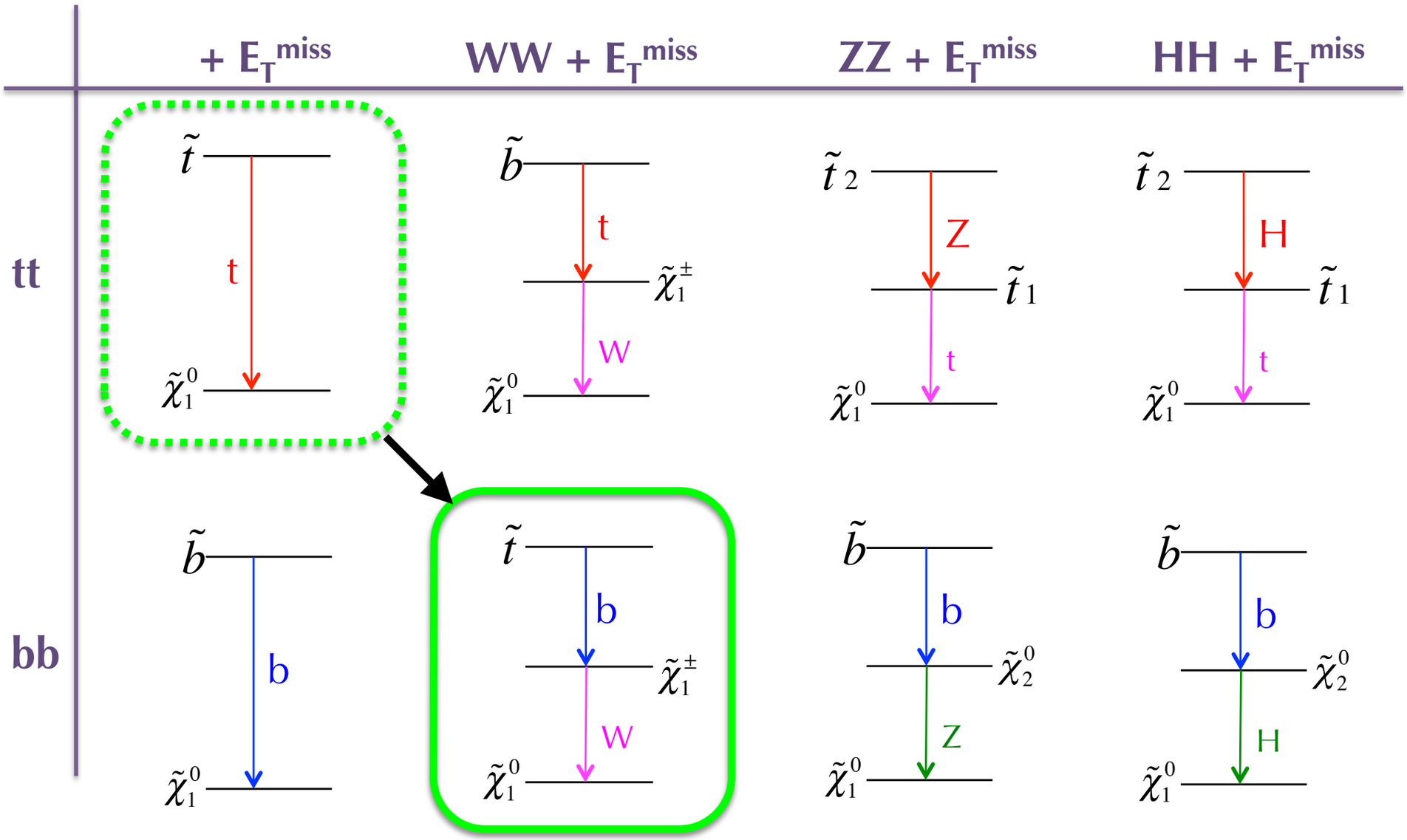
# Public results

- ATLAS:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
- CMS:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

# $\tilde{t} \rightarrow bW$ LSP

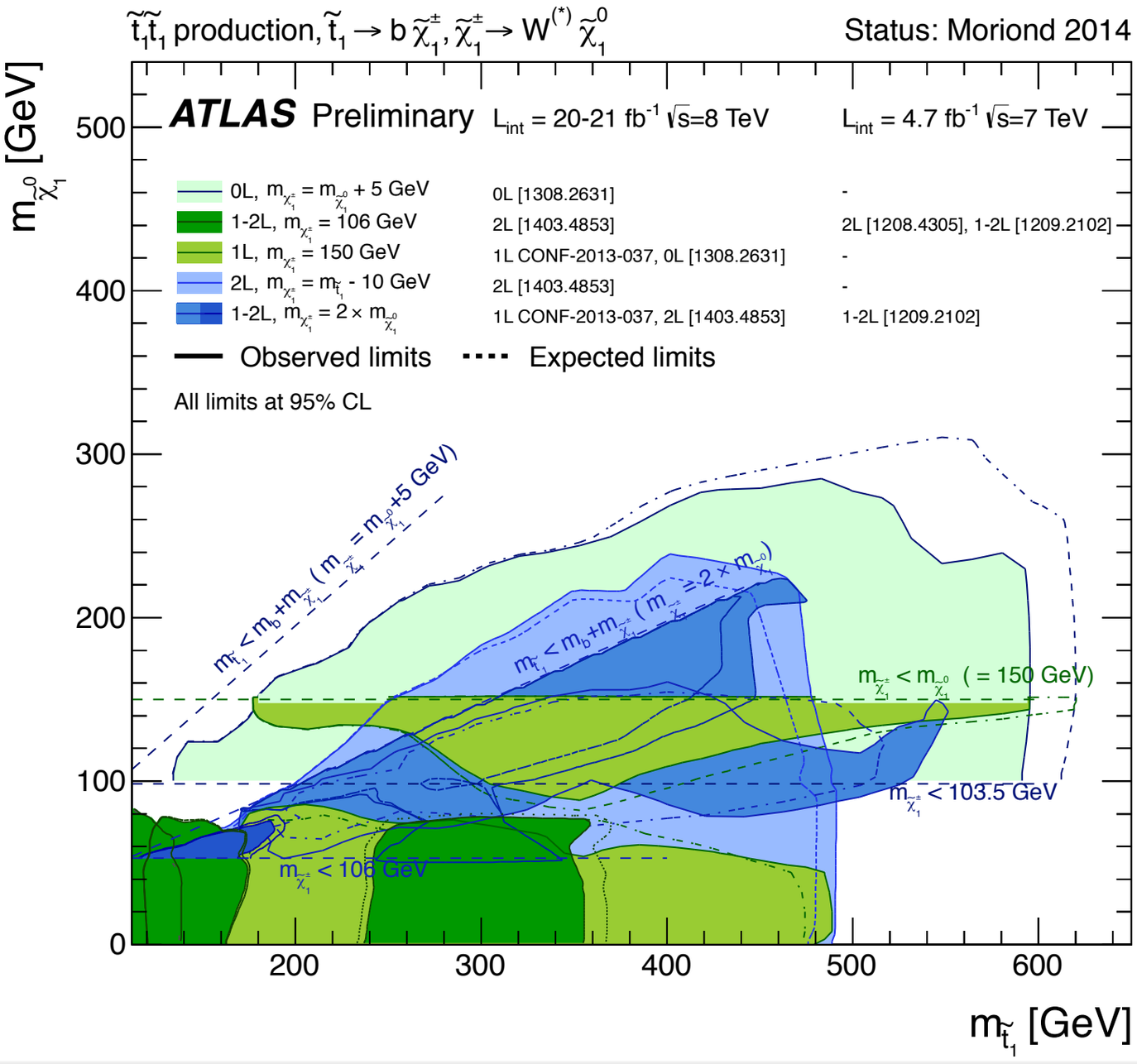
- Light $\tilde{\chi}_1^{\pm}$ opens up $\tilde{t} \rightarrow b\,\tilde{\chi}_1^{\pm}$
  - same final state as $\tilde{t} \rightarrow t$ LSP

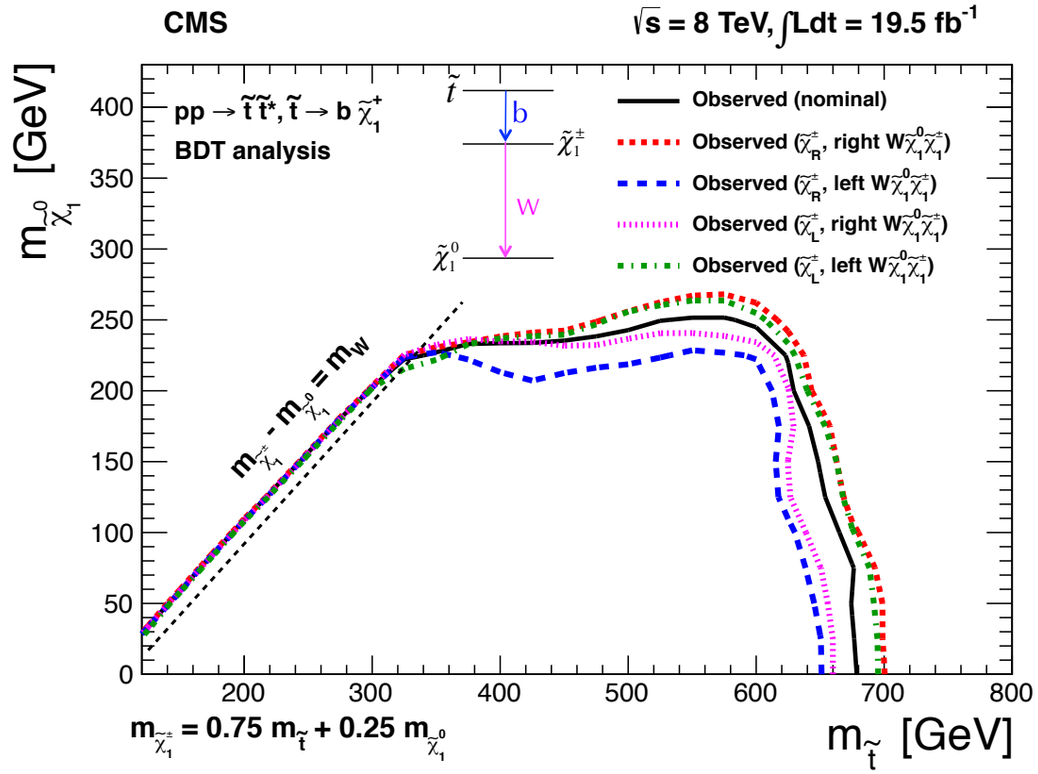


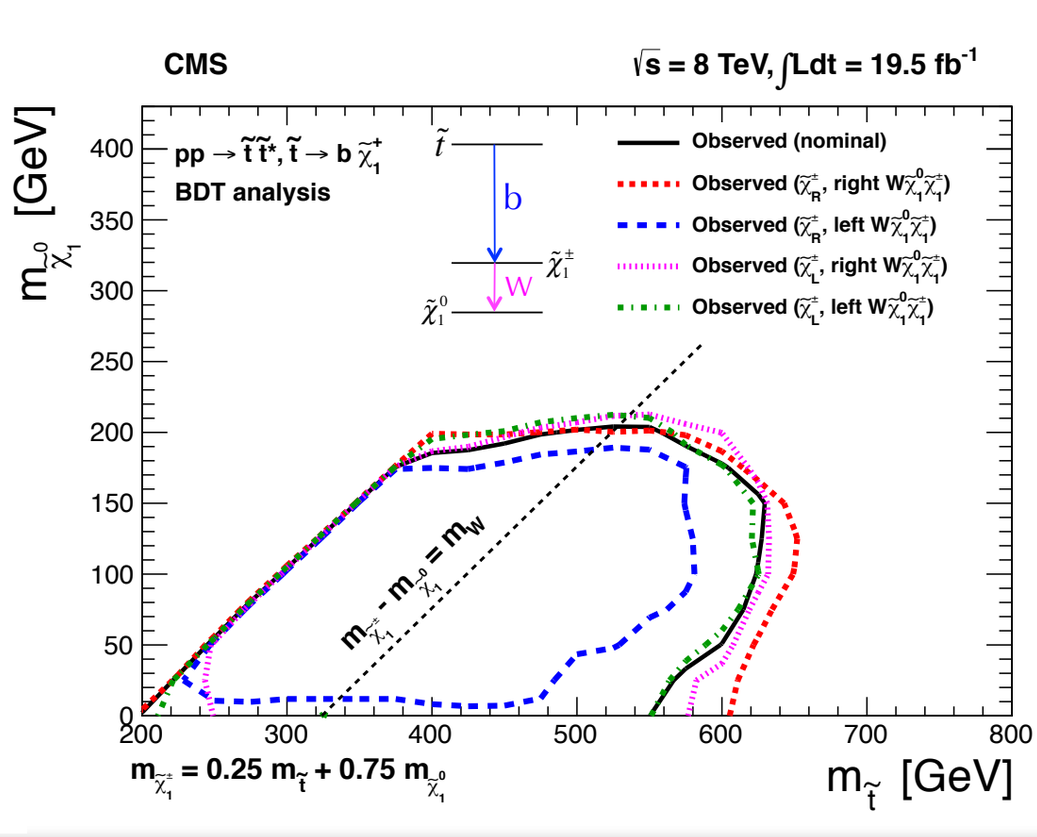



# $\tilde{t} \rightarrow bW$ LSP

- Limits strongly dependent on chargino mass
  - CMS: fractional position between stop and LSP
  - ATLAS: various parameterisations

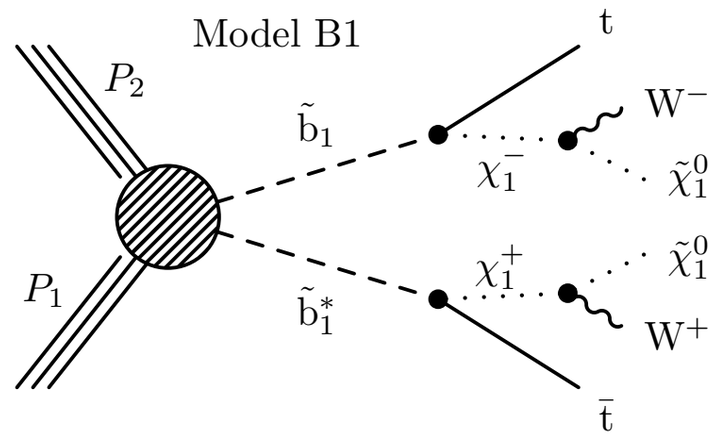


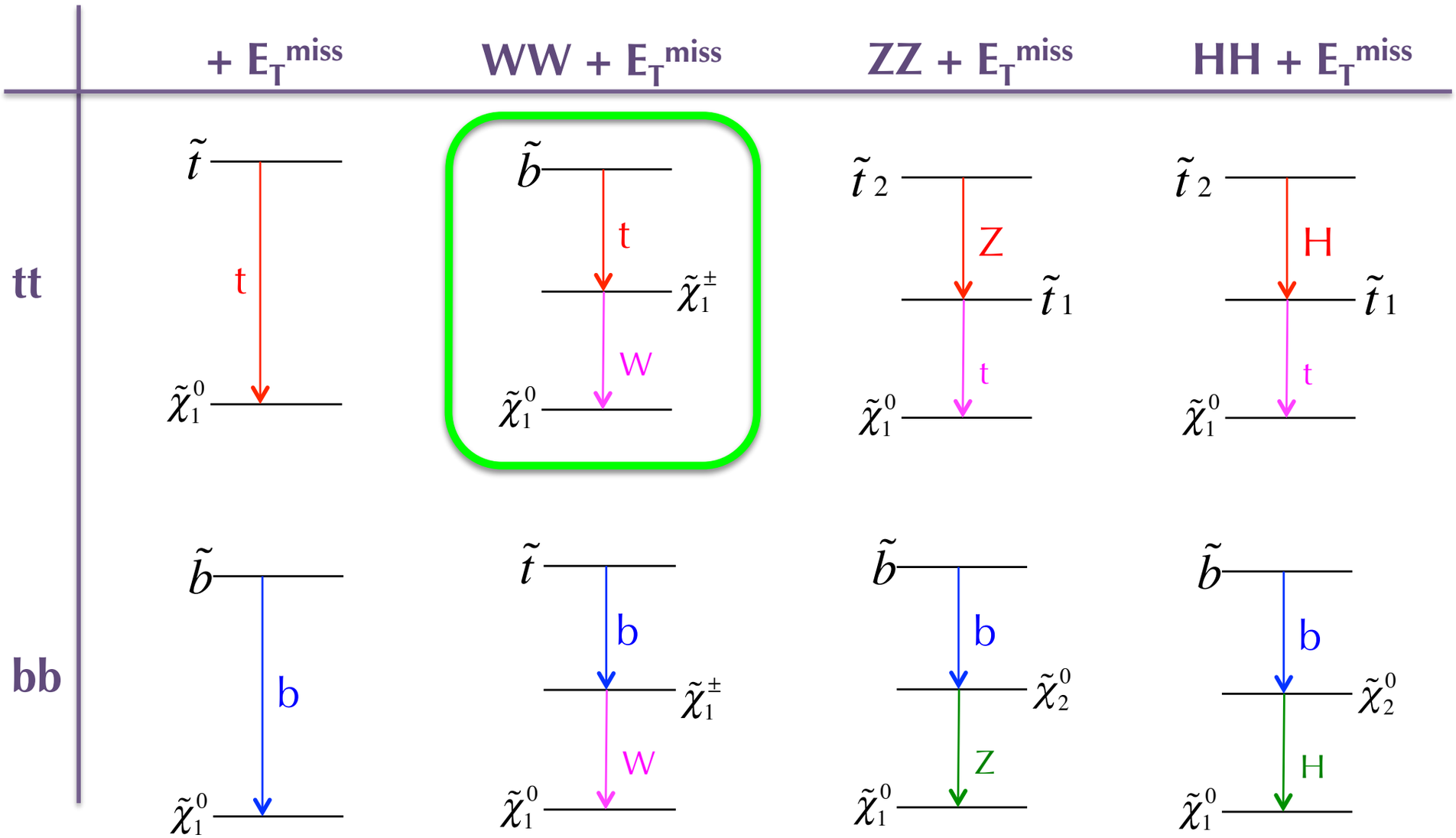



# $\tilde{b} \rightarrow tW$ LSP

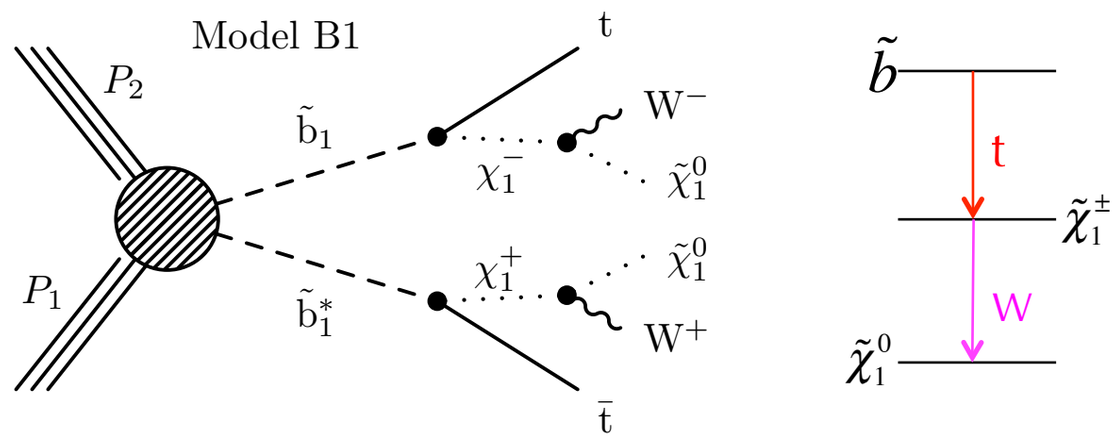
- Light $\tilde{\chi}_1^{\pm}$ opens up $\tilde{b} \rightarrow t\,\tilde{\chi}_1^{\pm}$
- Same final state as $\tilde{t} \rightarrow t$ LSP, but 2 additional W bosons in the final state

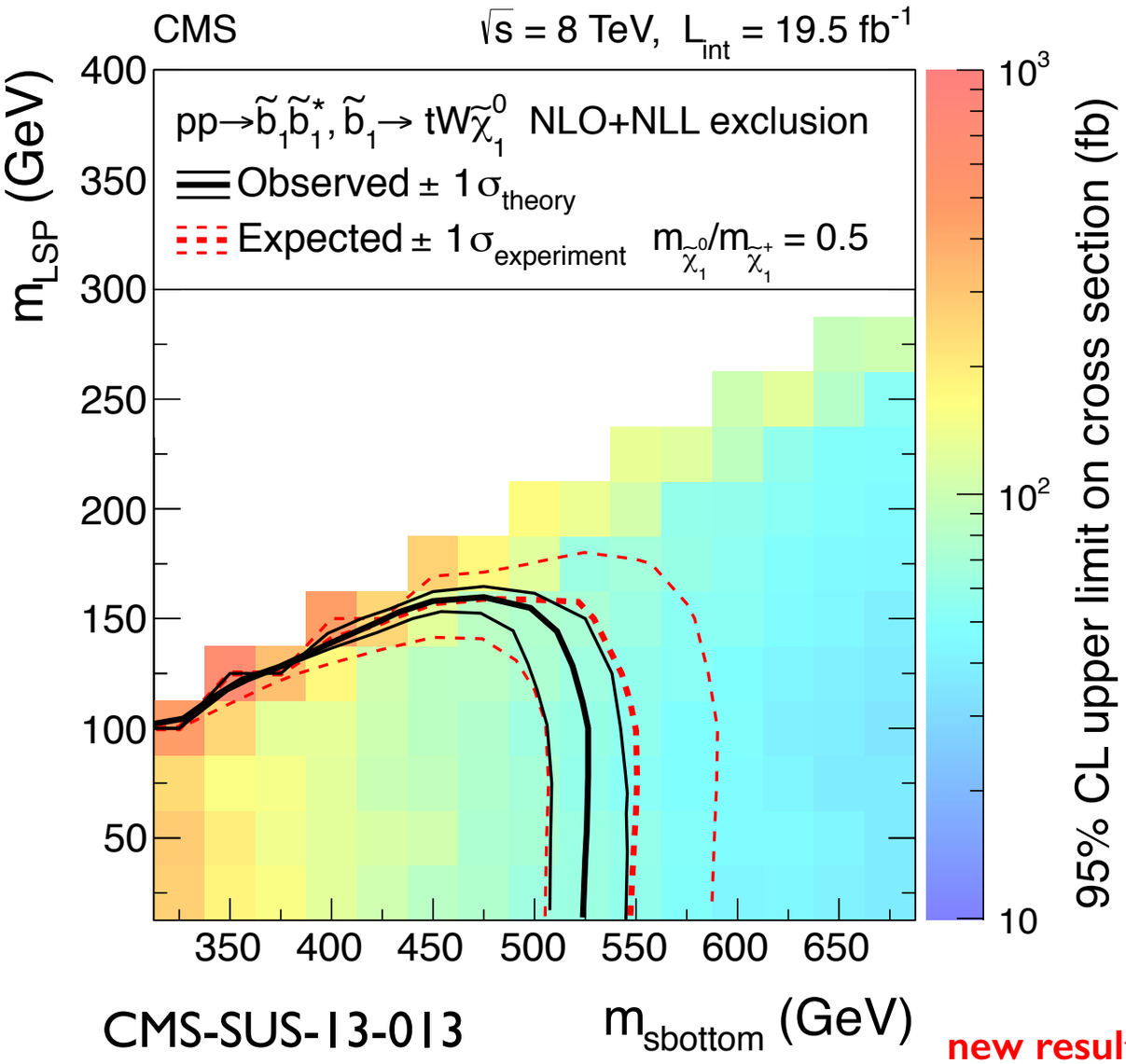


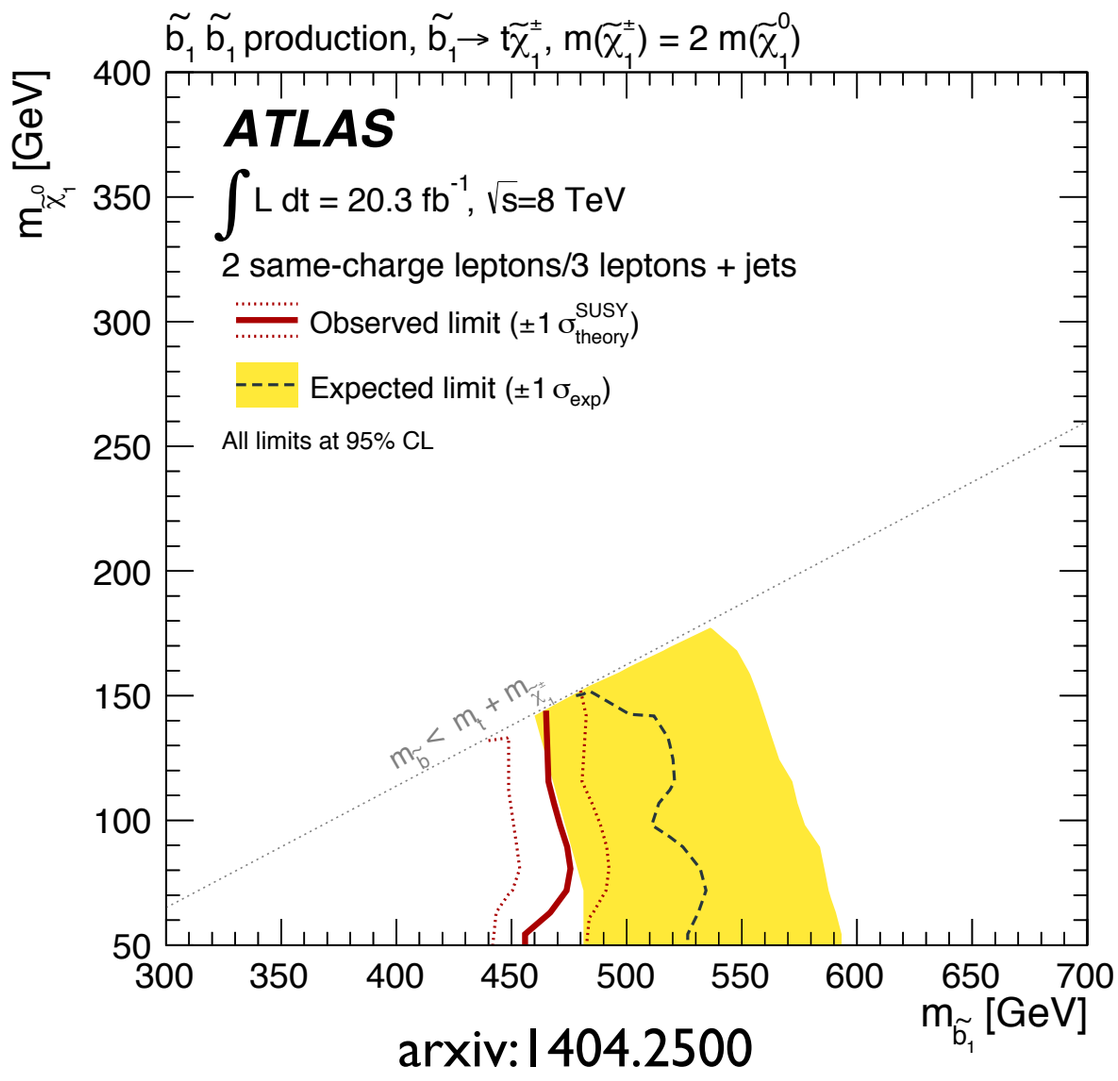



# $\tilde{b} \rightarrow tW$ LSP

- 4 W bosons in the final state
  - Target same-sign leptons
  - Also require 1-2 b-tags, and large MET and $H_T$



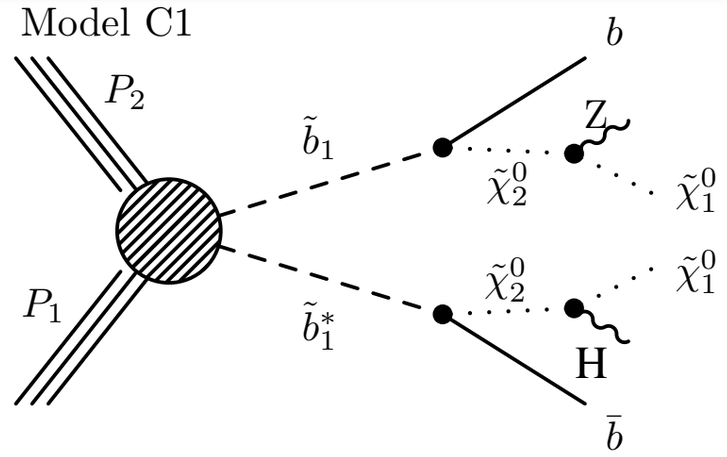



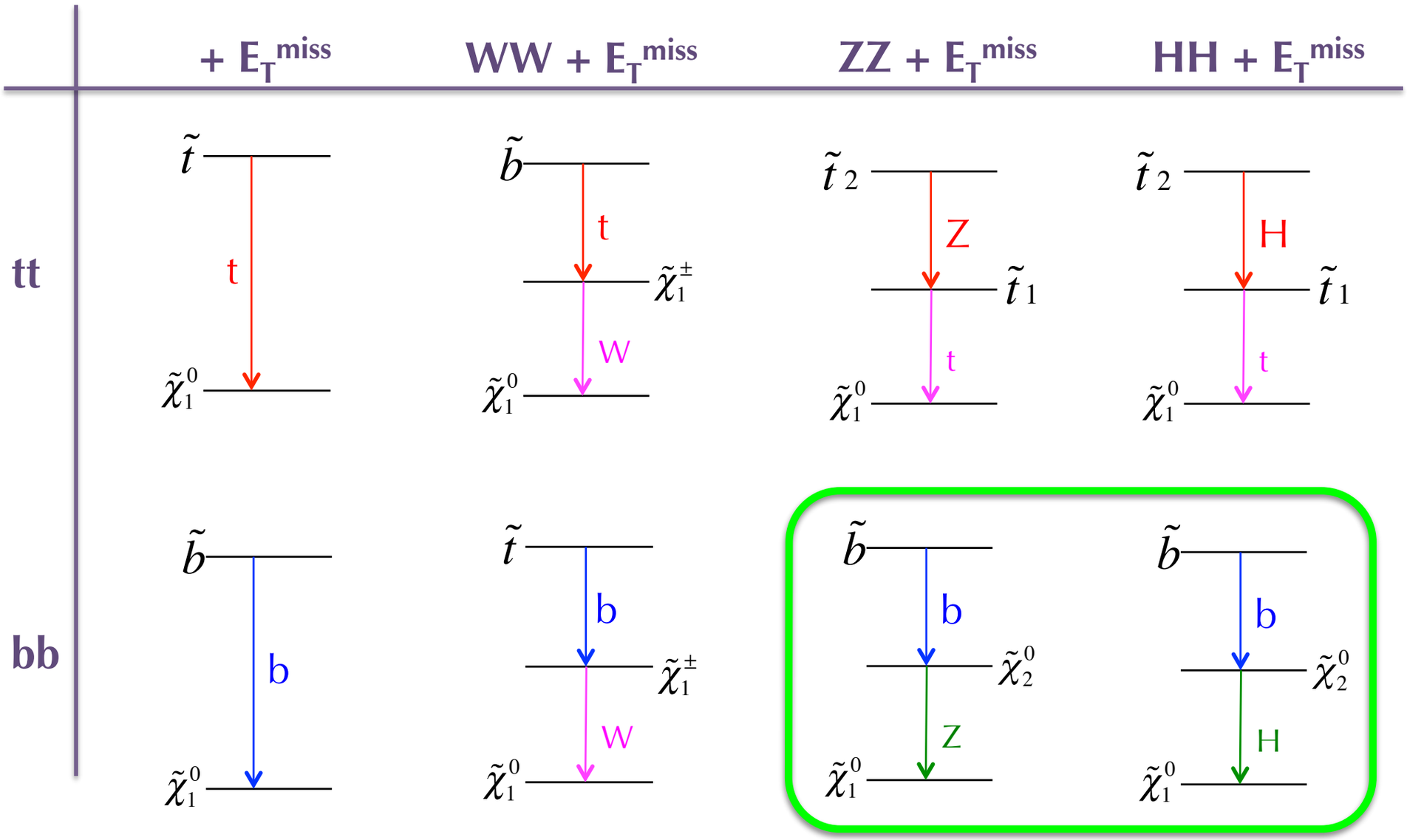




**new results both part of much broader analyses**

# $\tilde{b} \rightarrow b$ Z/H LSP

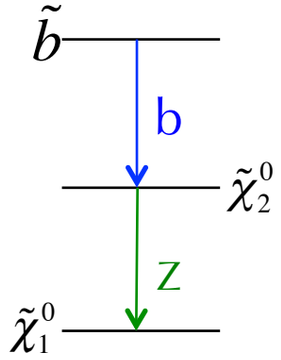
- Same final state as $\tilde{b} \rightarrow b$ LSP, but with multiple additional leptons (from Z) or bs (from H) in the final state



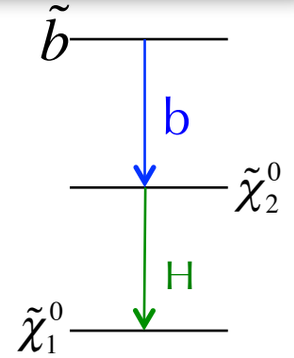



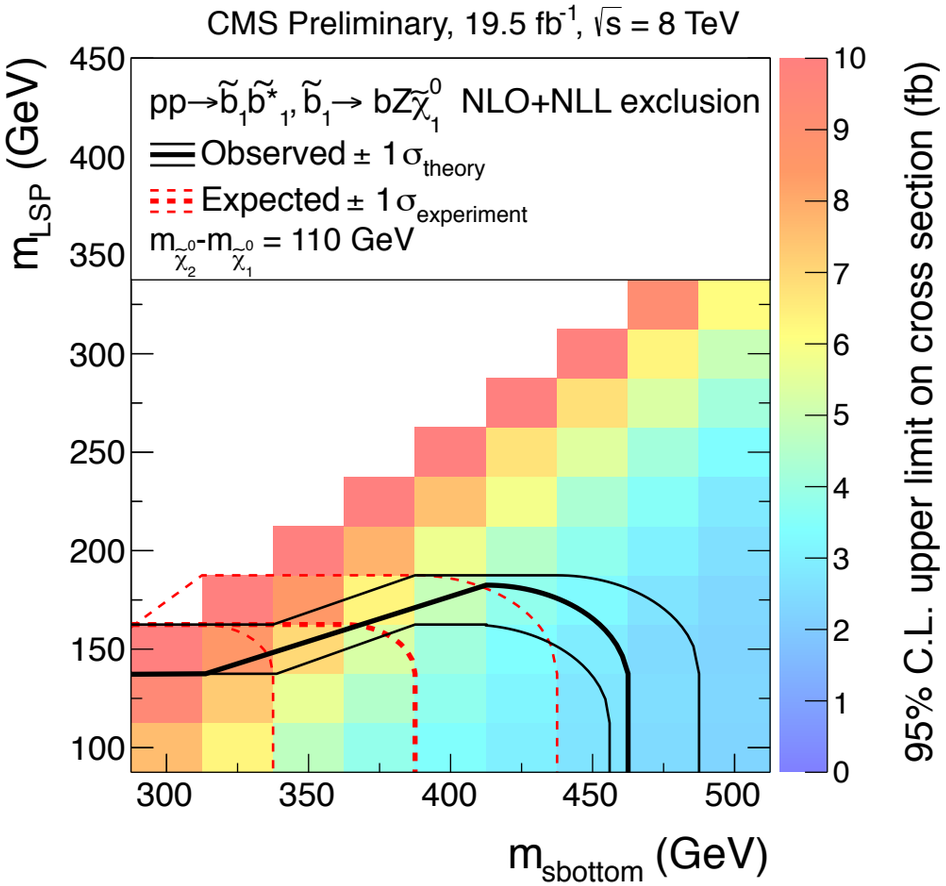
# $\tilde{b} \rightarrow b\ Z/H\ LSP$

- Signal: MET, 2 b-jets, 4 leptons ($Z \rightarrow ll$)
- Require: MET, ≥1 b-jets, ≥3 leptons




- Signal: MET and 6 b-jets ($H \rightarrow bbar$)
- Require: MET and ≥3 b-tags

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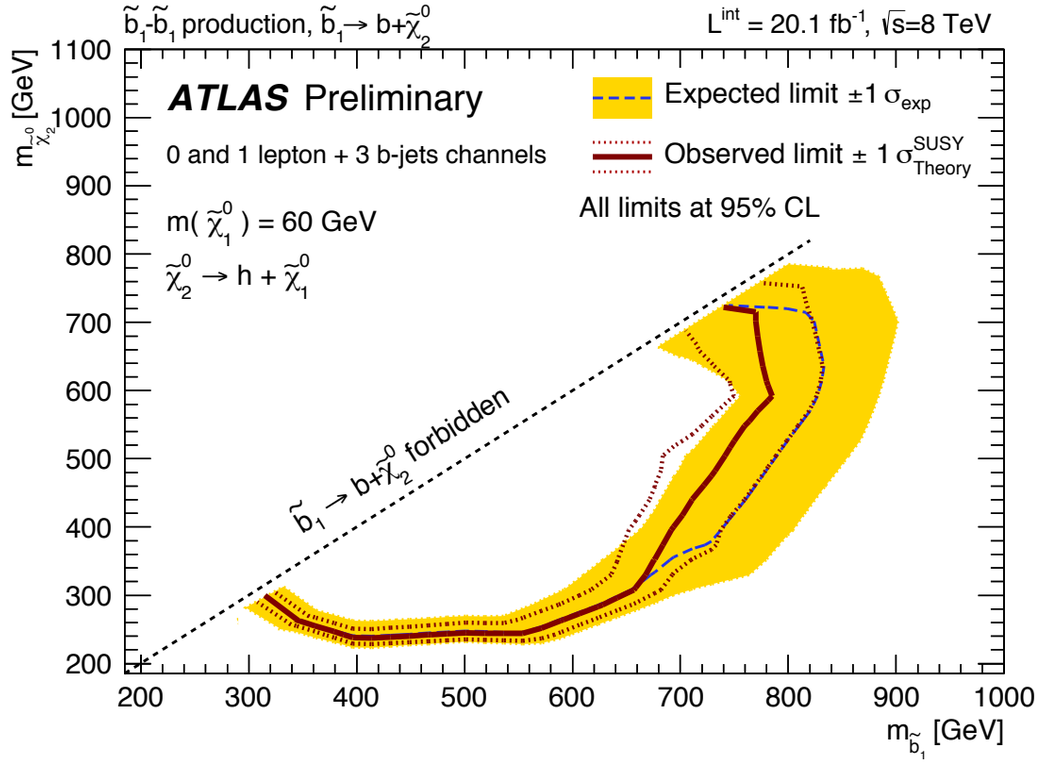
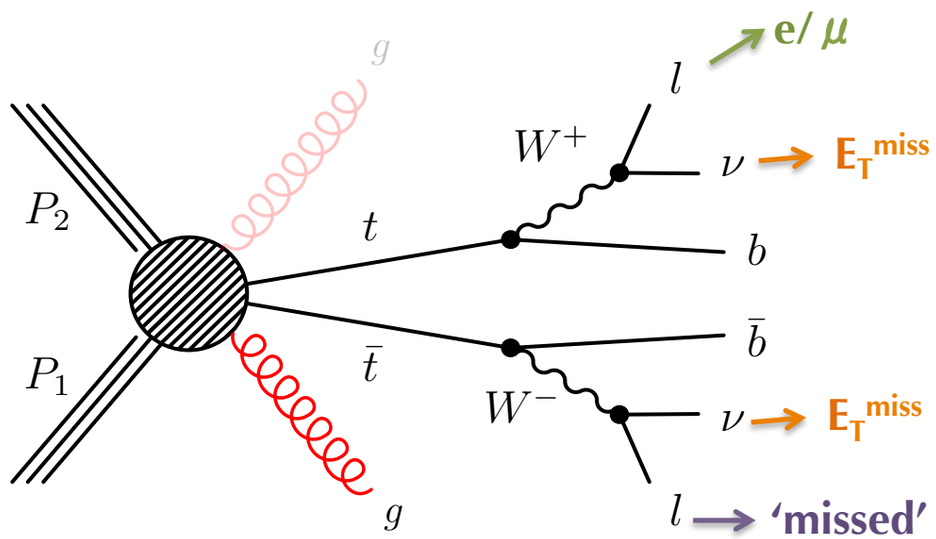



- Low $\tilde{\chi}_2^0$ mass not excluded since it leads to soft b-jets in the final state

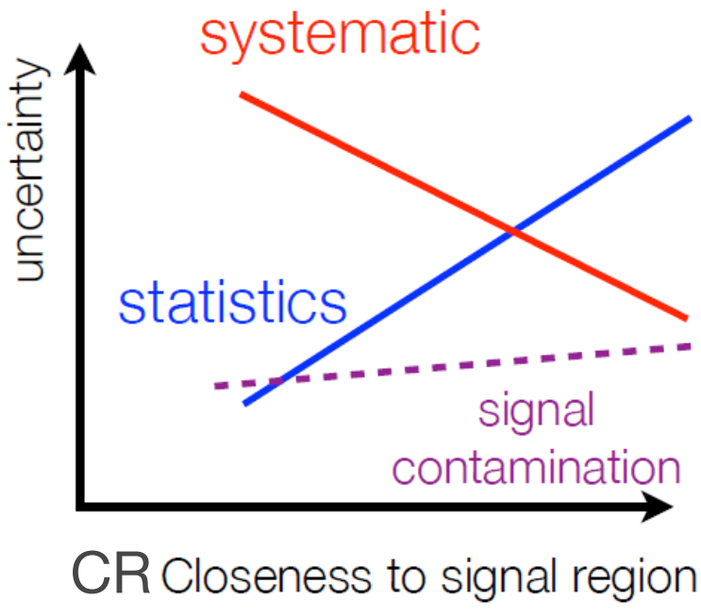
# Backgrounds

- ttbar often main background
  - produces the bs and Ws associated with signal



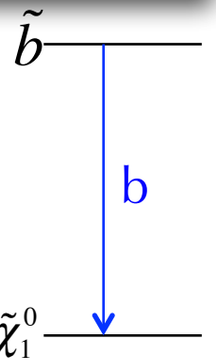

- multijet, single top, V, VV, VVV, can also be significant

- Sensitivity to SUSY reliant on good understanding of SM background
  - Dominant background predictions based on control regions in data



# $\tilde{b} \rightarrow b$ LSP search (ATLAS)

- Similar analysis using $M_{CT}$ at ATLAS
- Separate selection "SRB" with ISR jet to target low $\Delta m$ region
- Other SRs with increasing $M_{CT}$:
  - SRA150
  - SRA200
  - SRA250
  - SRA300
  - SRA350
- SR with best expected xsec limit chosen for each point
  - chosen SRs roughly follow $\Delta m$ lines




arXiv:1308.2631, JHEP 10 (2013) 189