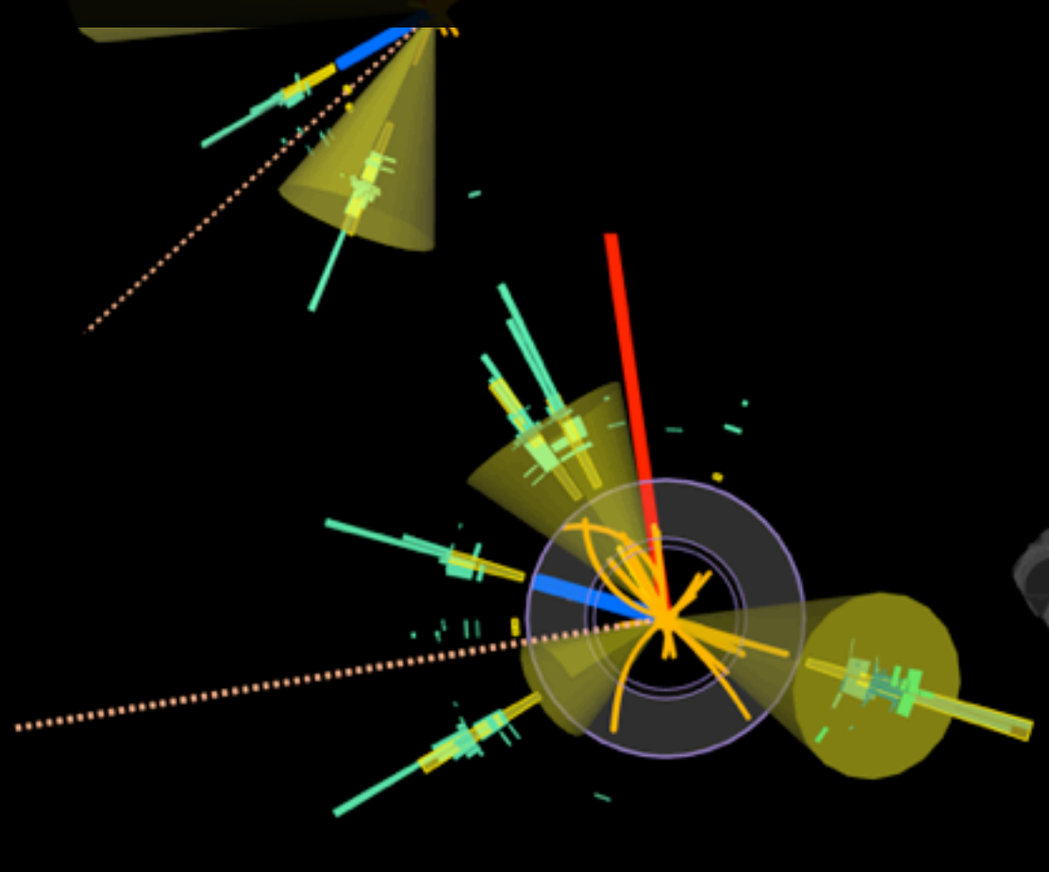
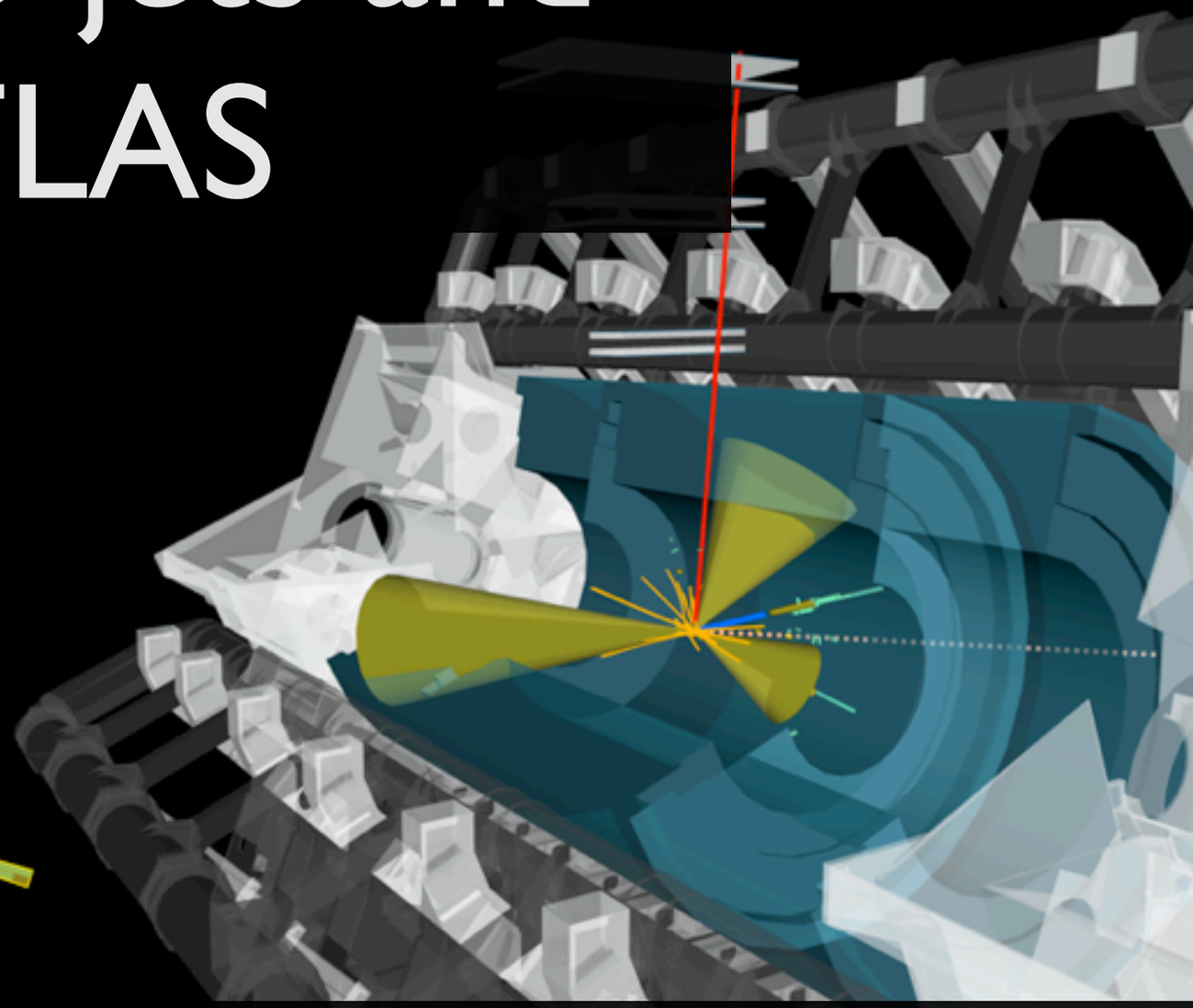
# Searches for gluino, stop and sbottom production in channels with b-jets and MET in ATLAS





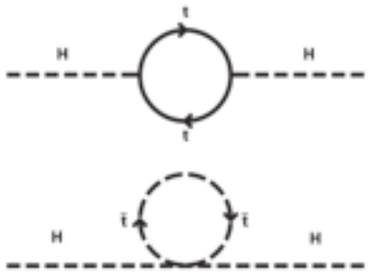
Maria Fiascaris (University of Chicago)

SUSY 2014 - 21/07/2014

# Supersymmetry and 3rd generation

Supersymmetry adds a new fundamental symmetry relating fermions and bosons → more than doubles the particle spectrum w.r.t. the Standard Model

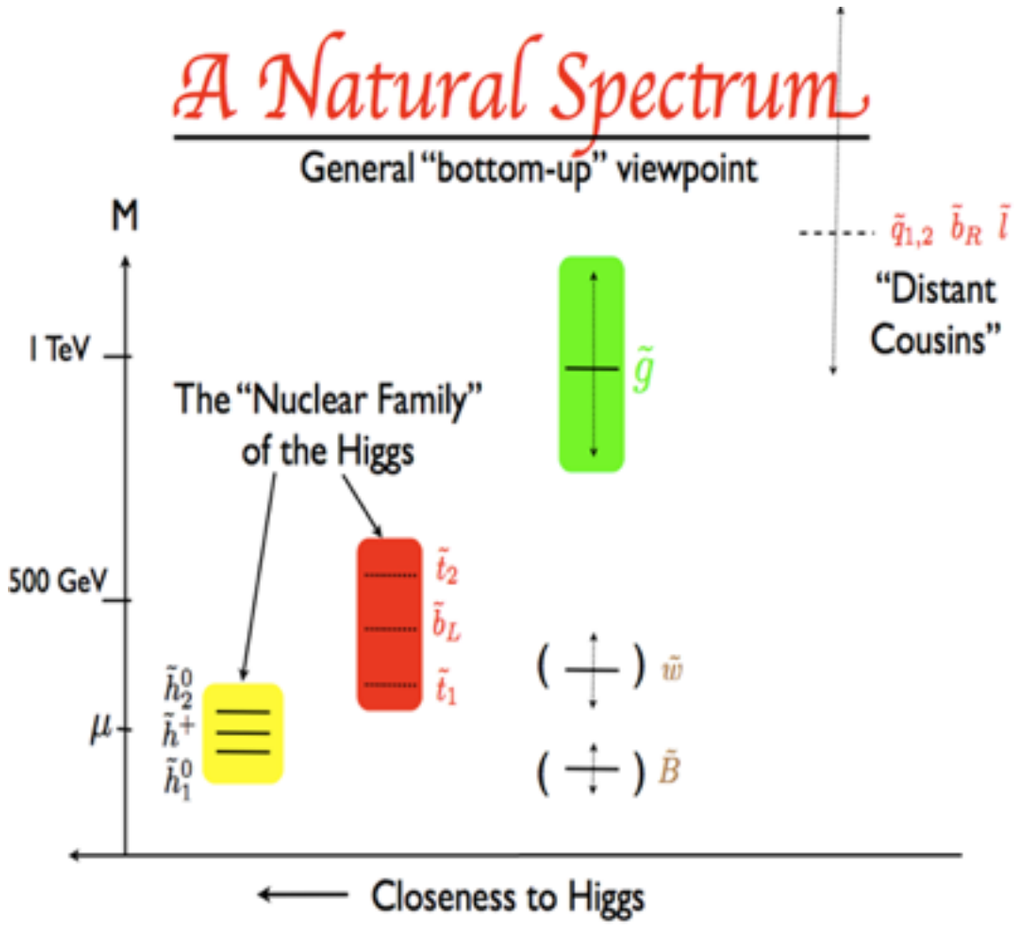
## SUSY and the Gauge hierarchy problem




fermions and boson loops contribute with different signs to the Higgs radiative corrections

For **natural SUSY** (low level of fine-tuning):

- light higgsinos
- light stop and sbottoms (< 1 TeV)
- light gluinos (< 1-2 TeV)




➡ Strong physics case for **third generation squarks**

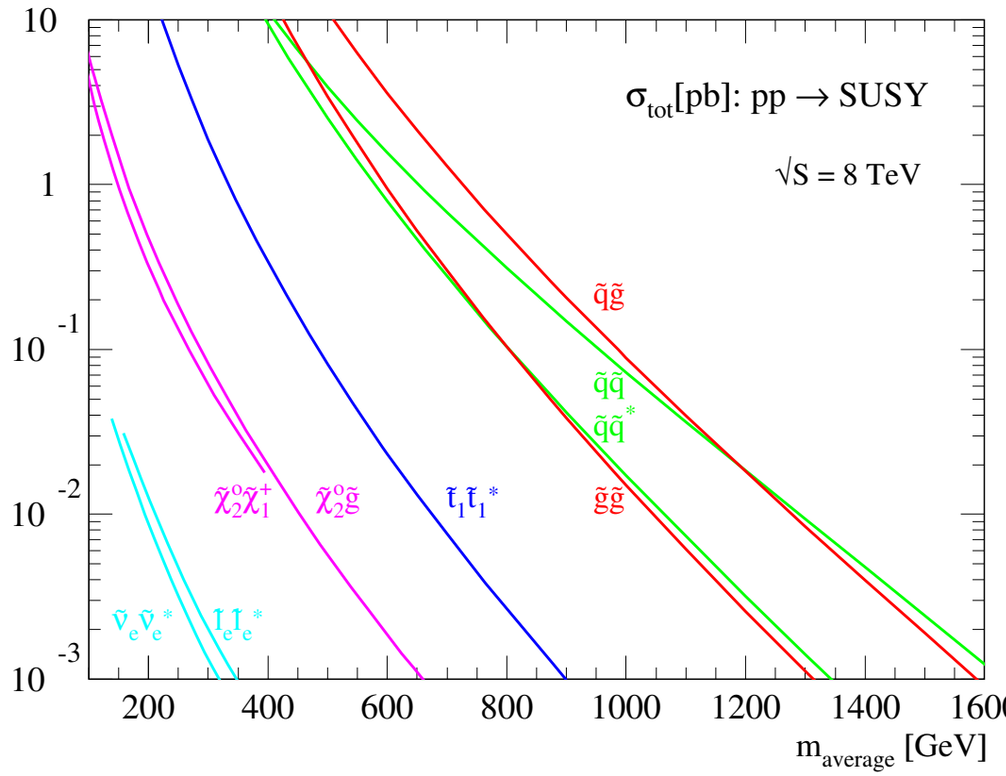
# Supersymmetry and 3rd generation

Top and bottom squarks (assuming RPC) can be produced at the LHC via:

- **gluino-mediated production**
  ($\tilde{g}\tilde{g}$ followed by $\tilde{g} \to b_1 b$ or $\tilde{g} \to \tilde{t}_1$ )
- **directly in pairs**

In ATLAS several searches to cover different production and decay modes and regions of the phase space.

Interpretation in the context of simplified models, assuming typically 100% BR for given decay mode.




**Direct sbottom and/or gluino-mediated production:**

- 0L: ***JHEP10(2013)189***
- 0L + ≥ 7- 10 jets : ***JHEP10(2013)130***
- → 0/1L + 3 b-jets: ***arXiv 1407.0600***
- → 2SS/3L: ***JHEP 06 (2014) 035***

**Direct stop searches:**

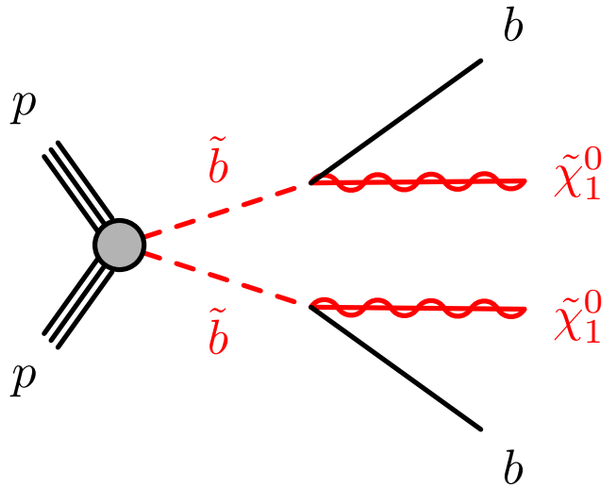
- → 0L: ***arXiv:1406.1122***
- → 1L: ***arXiv 1407.0583***
- 2L: ***JHEP 06 (2014) 124***
- Z search: ***Eur. Phys. J. C (2014) 74:2883***
- stau search: ***ATLAS-CONF-2014-014***
- → c search: ***arXiv 1407.0608***

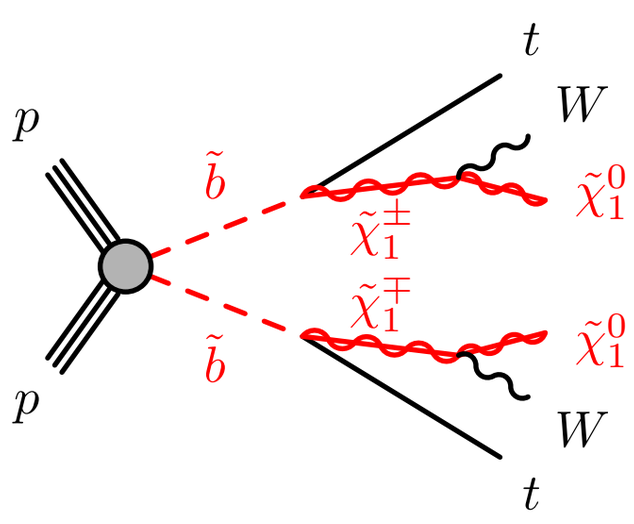
→ **Most recent results presented in this talk**

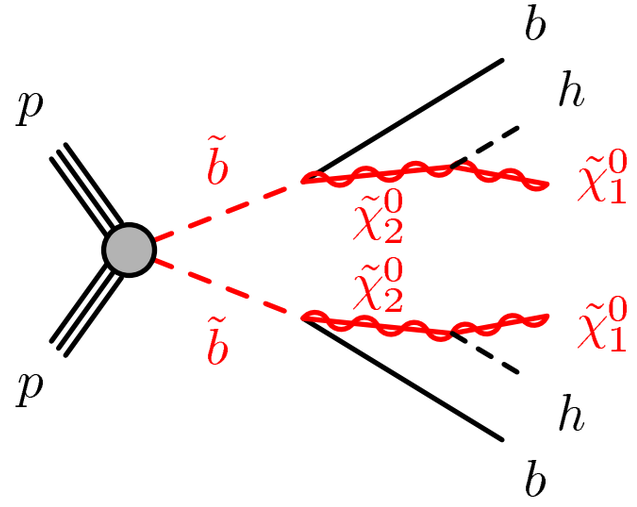
# Direct sbottom and gluino-mediated stop/sbottom

# Target models

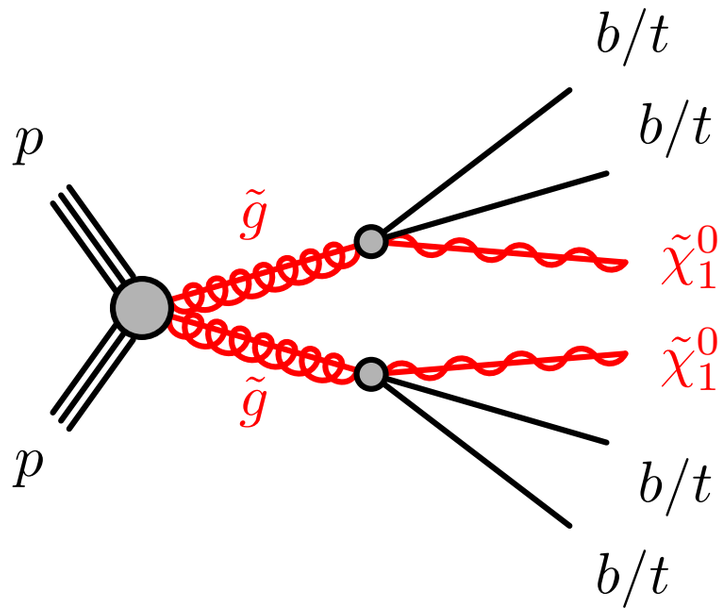
## Direct sbottom

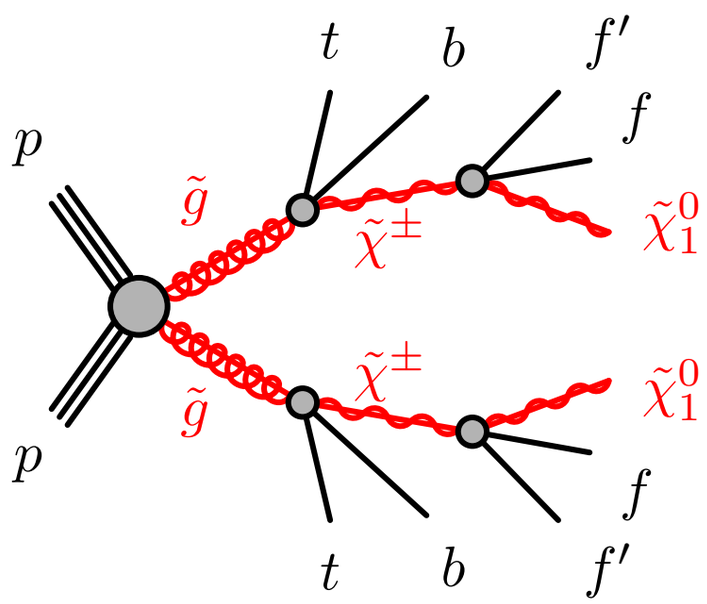



## Gluino-mediated stop / sbottom



# 0/1 lepton + 3 b-jets

NEW

arXiv 1407.0600

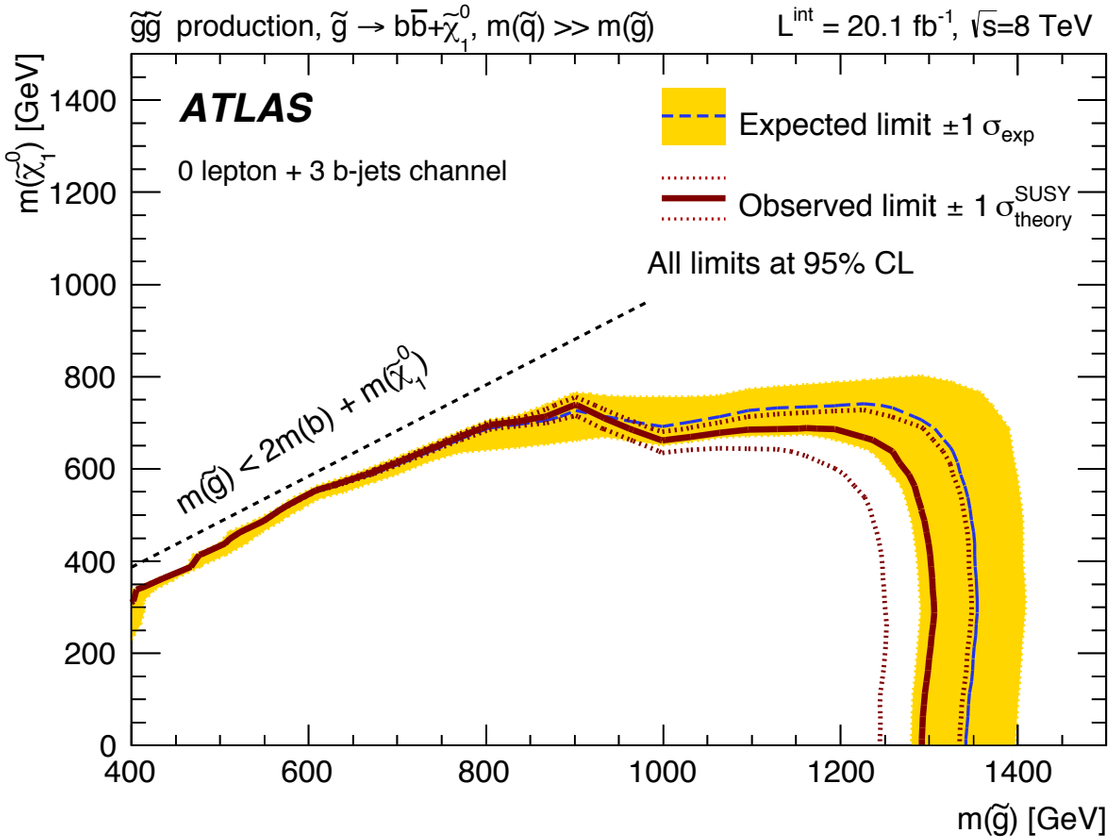
**0/1 lepton, ≥ 3 b-jets, 4-7 jets, MET**

3 sets of SRs:

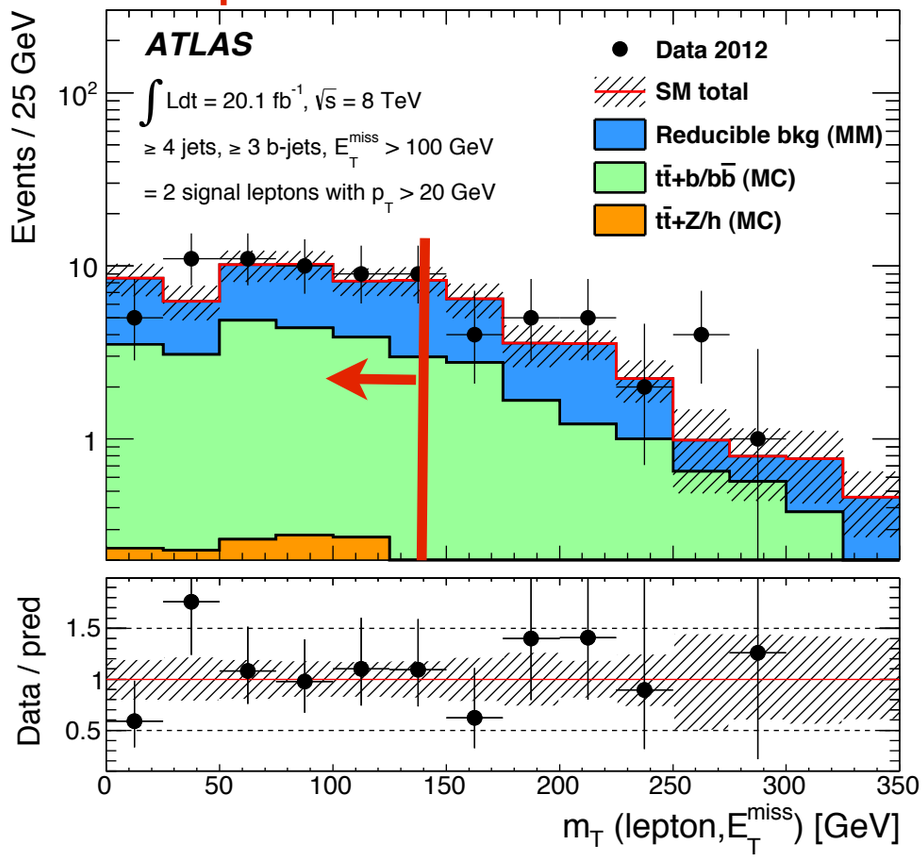
- 0L + ≥ 4 jets: sbottom models
- 0L + ≥ 7 jets, 1L + ≥ 6 jets: models with tops

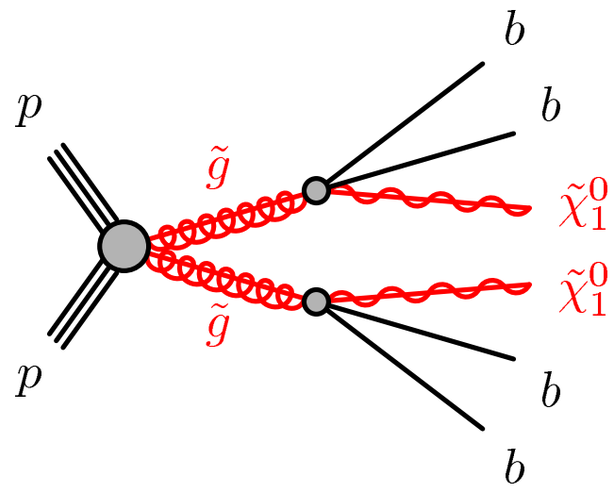
Backgrounds:

- fake b-jets (mainly ttbar)→ Matrix Method
- processes with 3 real b-jets: ttbar + b/bbbar (using 2 lep. CR), ttbar + Z/h(→ bbbar) (from MC)




2 lepton CR

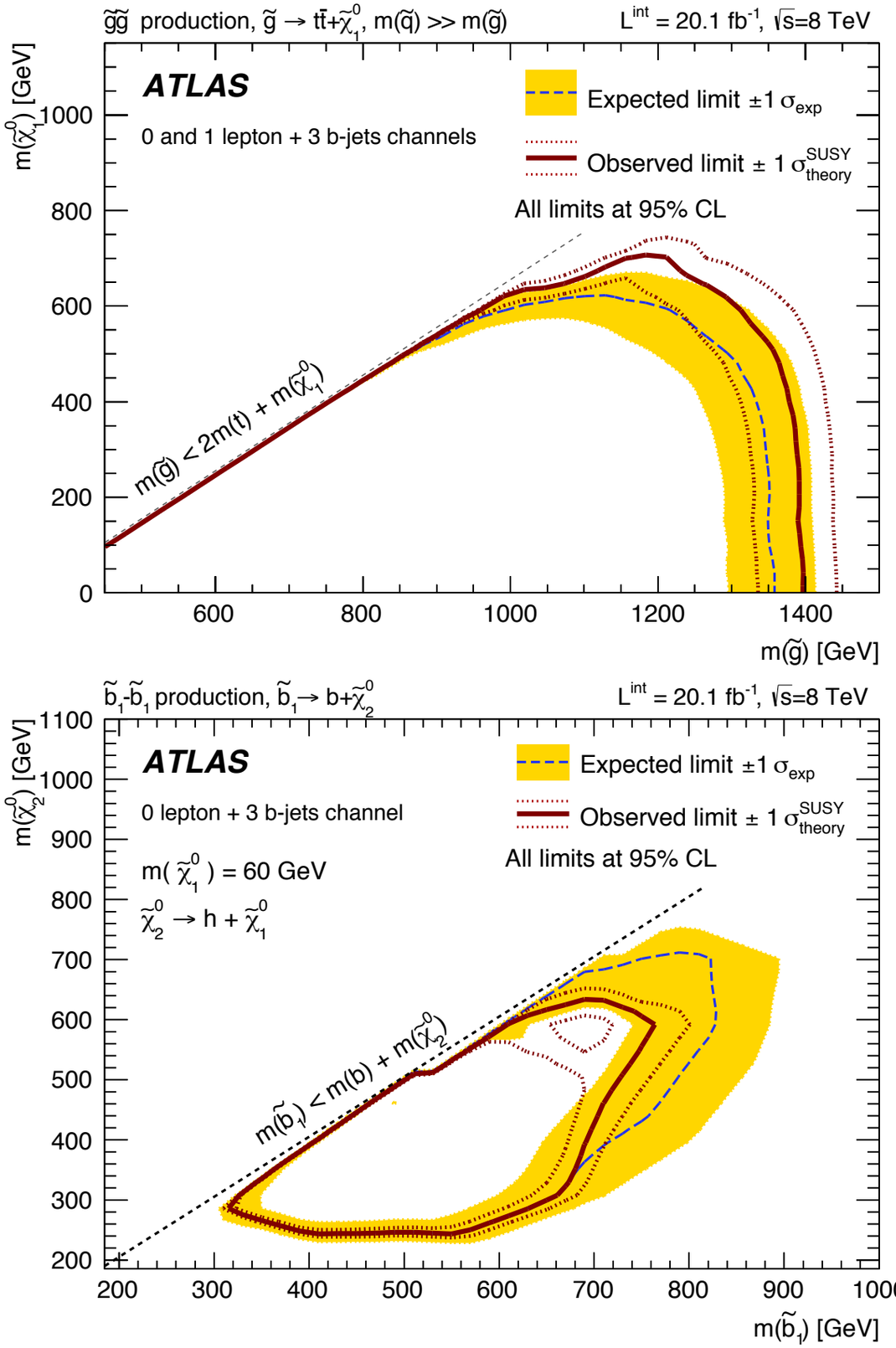


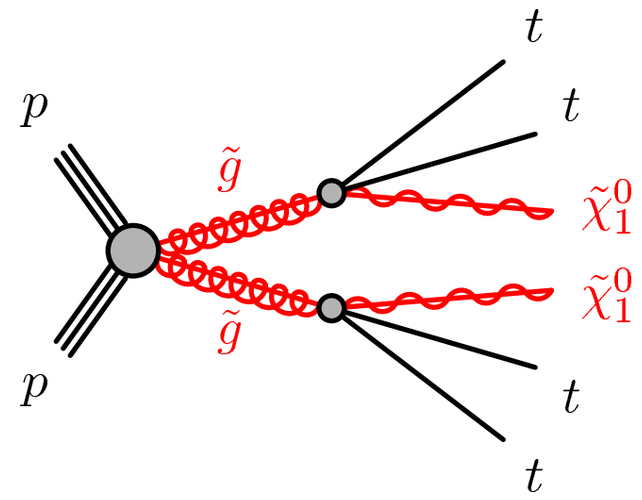




Gluino-mediated sbottom

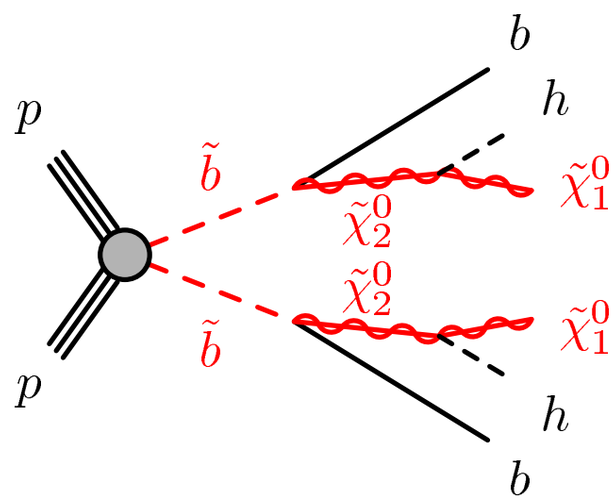
# 0/1 lepton + 3 b-jets

NEW




Gluino-mediated stop




Direct sbottom

# 2SS / 3L + jets

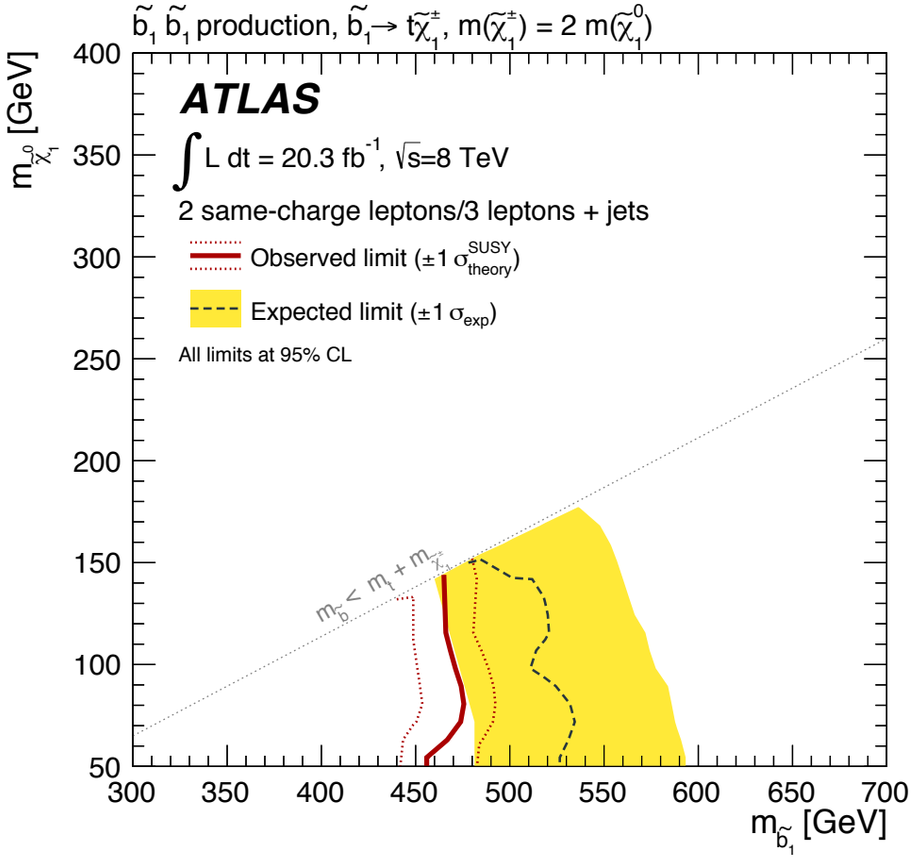
**2 same-sign or 3 leptons, jets, MET**

arXiv 1404.2500, JHEP 06 (2014) 035

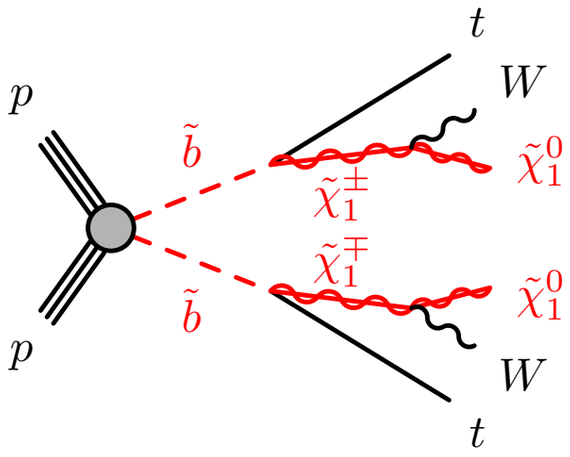
| Variable | SR3b | SR1b | SR0b | SR3L$_{low}$ | SR3L$_{high}$ |
|---|---|---|---|---|---|
| **Leptons** | SS or 3L | SS | SS | 3L | 3L |
| **$N_{b\text{-jets}}$** | ≥3 | ≥1 | 0 | - | - |
| **$N_{jets}$** | ≥5 | ≥3 | ≥3 | ≥4 | ≥4 |
| **$E_T^{miss}$** | - | > 150 | > 150 | 50 - 150 | > 150 |
| **$m_{Eff}$** | > 350 | > 700 | > 400 | > 400 | > 400 |

Backgrounds:

- fake leptons → Matrix Method
- charge mis-identification: data-driven (likelihood method)
- processes with prompt leptons (dibosons, ttbar +V): from MC, cross-checked in validation regions

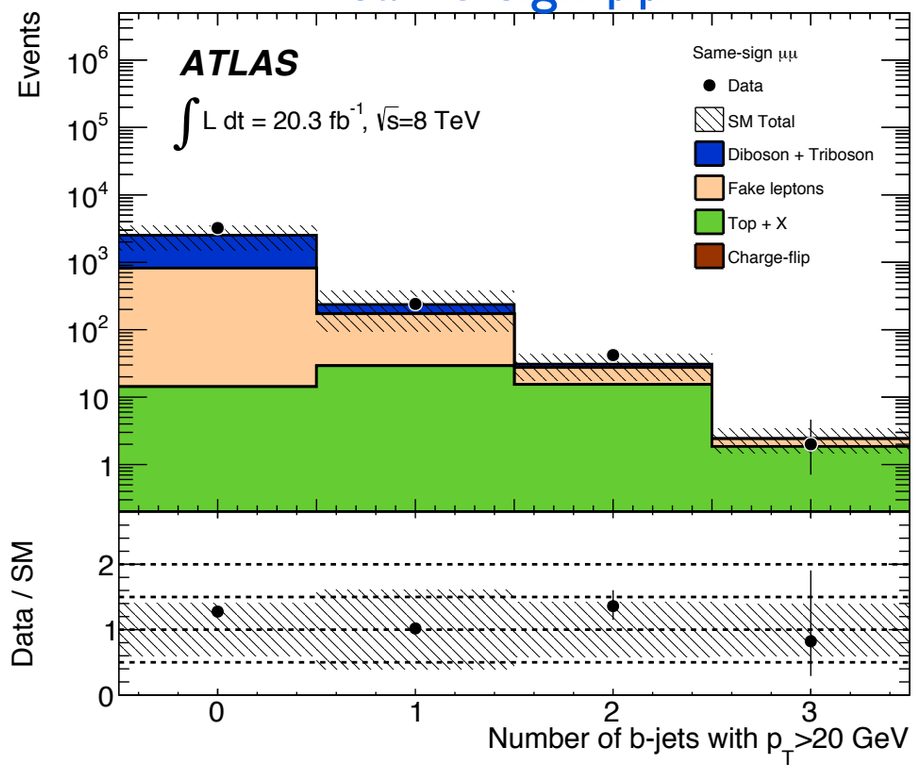



Direct sbottom → top chargino




dominated by SR1b, SR3Llow, SR3Lhigh

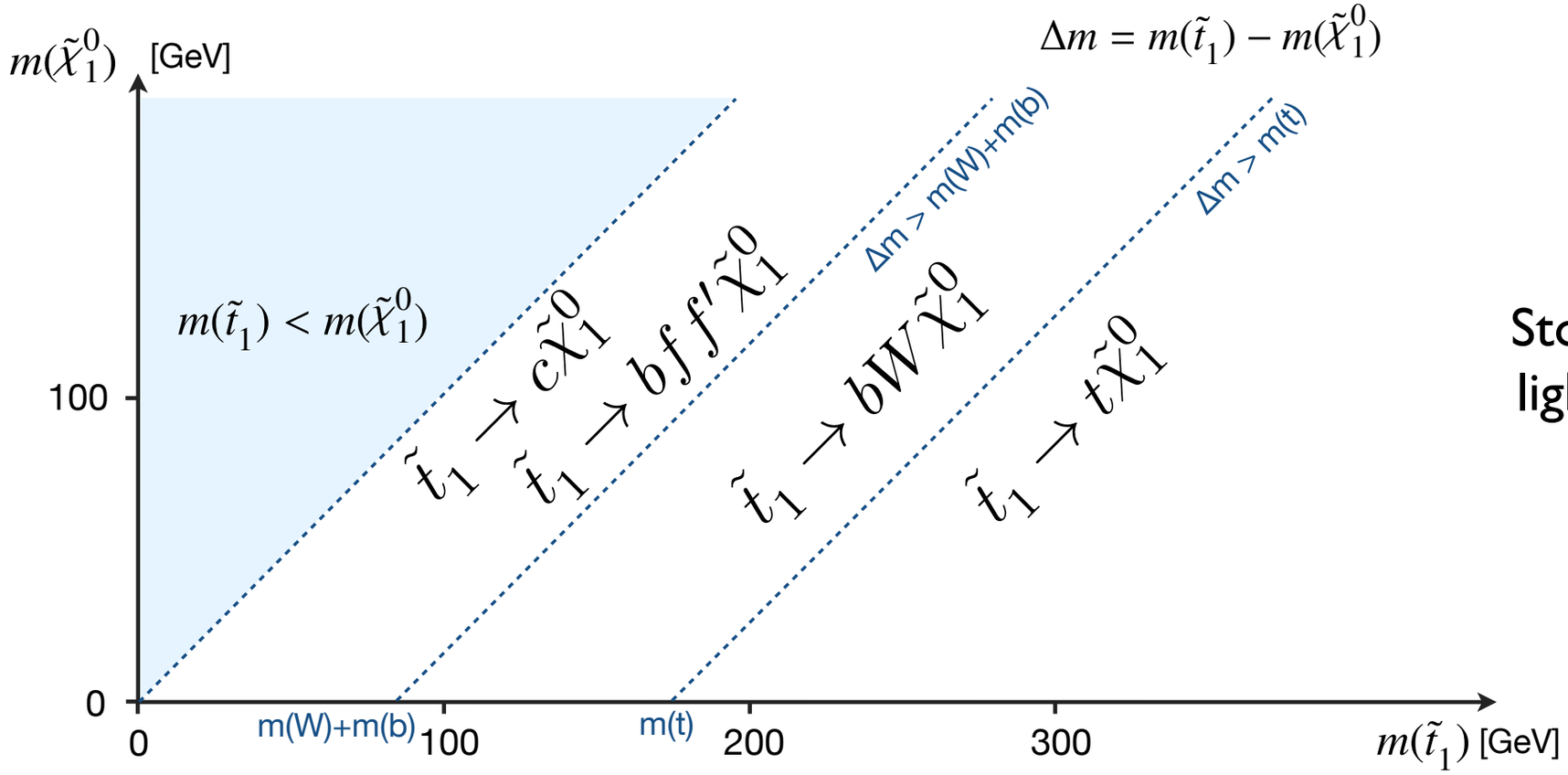
Same-sign μμ



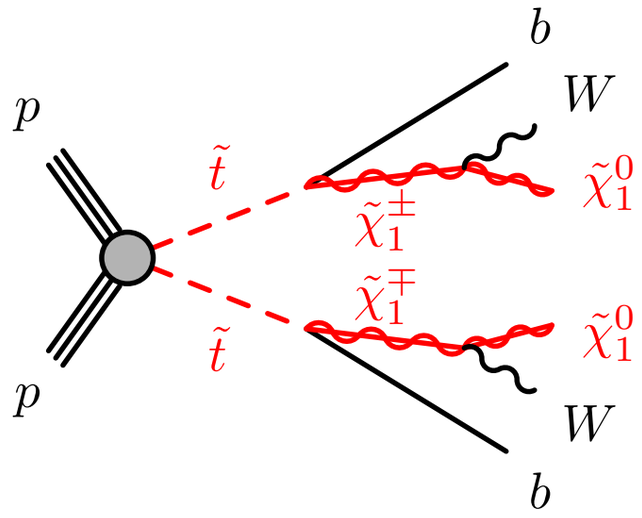
# Direct stop

# Stop decay modes

The stop can decay to a variety of final states, depending also on the mass hierarchy of the lightest stop, chargino and neutralino




Stop decays to the lightest neutralino




Stop decays via the lightest chargino also possible.

# All hadronic final states

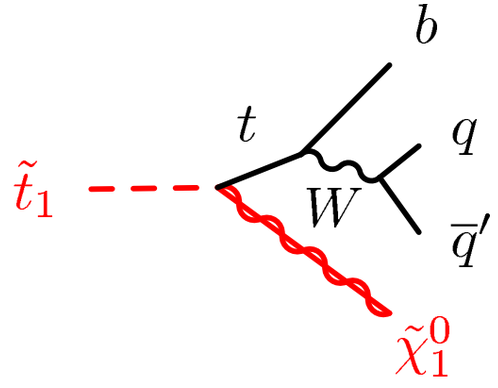
Target 2 possible stop decay modes (100% BR for each decay mode and a mix of the two)

**0 leptons, ≥ 2 b-jets, MET**

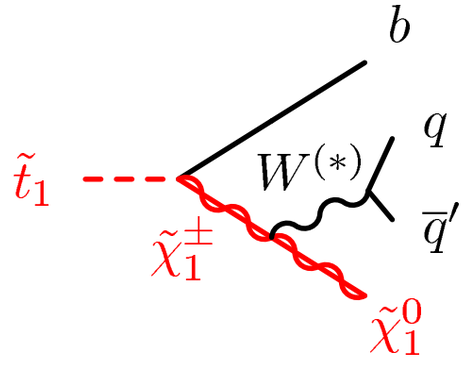
arXiv:1406.1122

Three sets of signal regions:

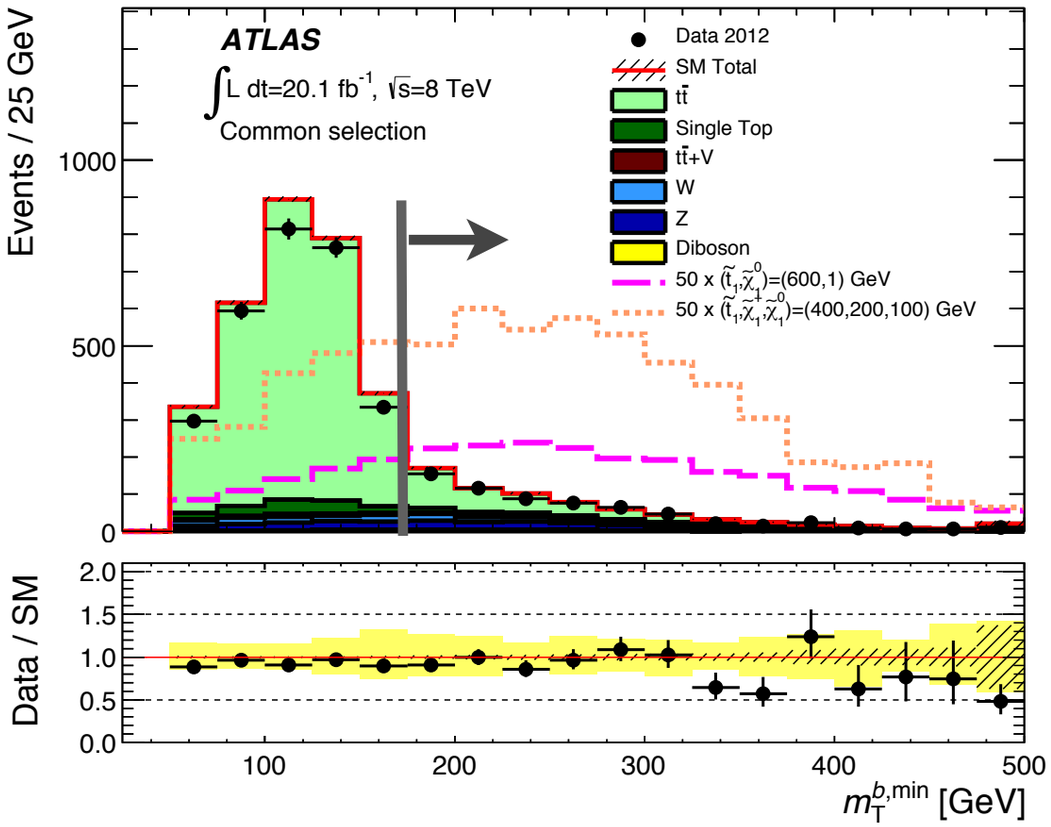
- SRA, "fully resolved": 6 distinct jets from stop-stop decay (in A, B)
- SRB, "partially resolved": 4 or 5 jets due to boosted top in A (high stop mass)
- SRC: 5 jets, one below threshold due to small mass splitting $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ in B




mode A




mode B




Discriminating variables

- min Δφ (MET, jet): reject events with fake MET
- $m_T$ from MET and b-jet closest in φ to MET vector: reject ttbar

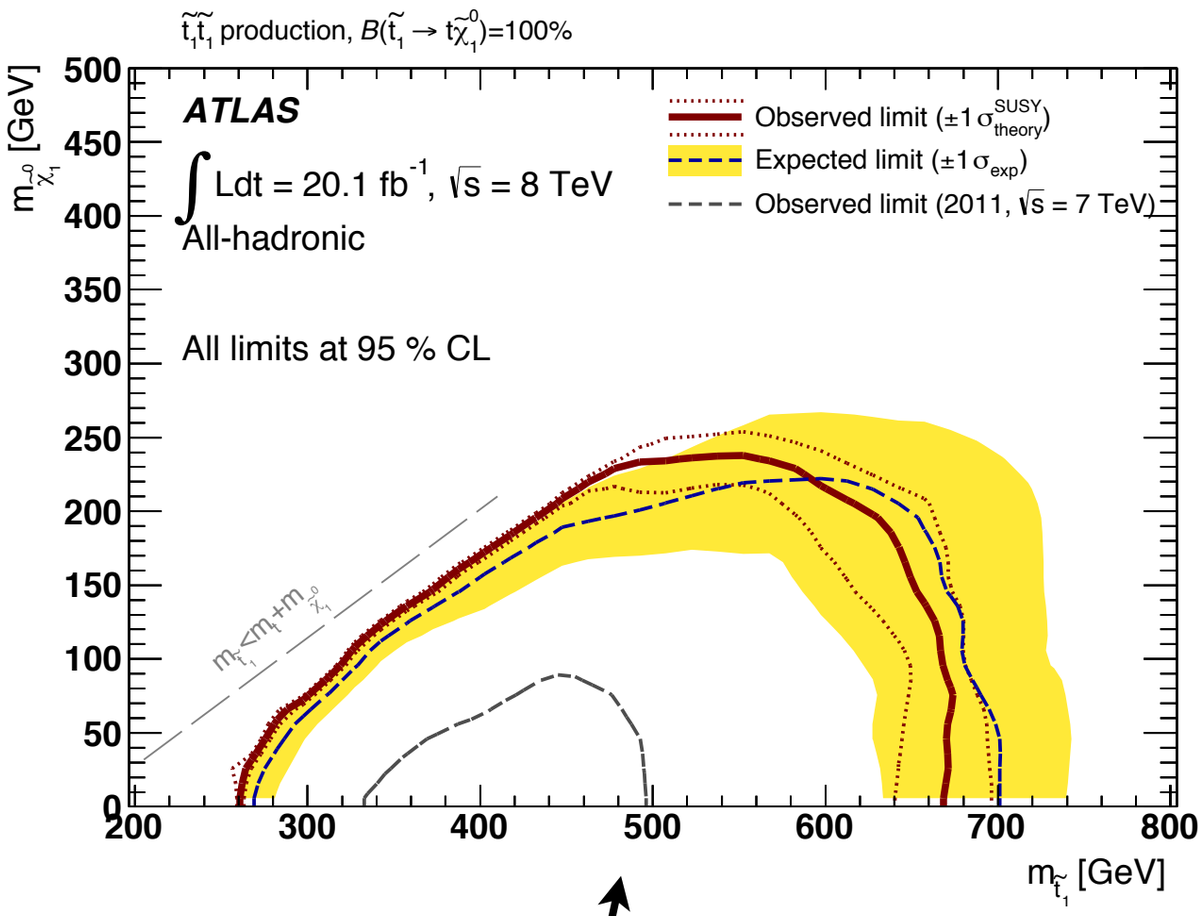
Main Backgrounds:

- Multi-jets: jet smearing method
- Semileptonic ttbar and Z(νν) + HF jets: from CRs

1 lepton CR, treat lepton as jet

2 lepton CR, add lepton $p_T$ to MET

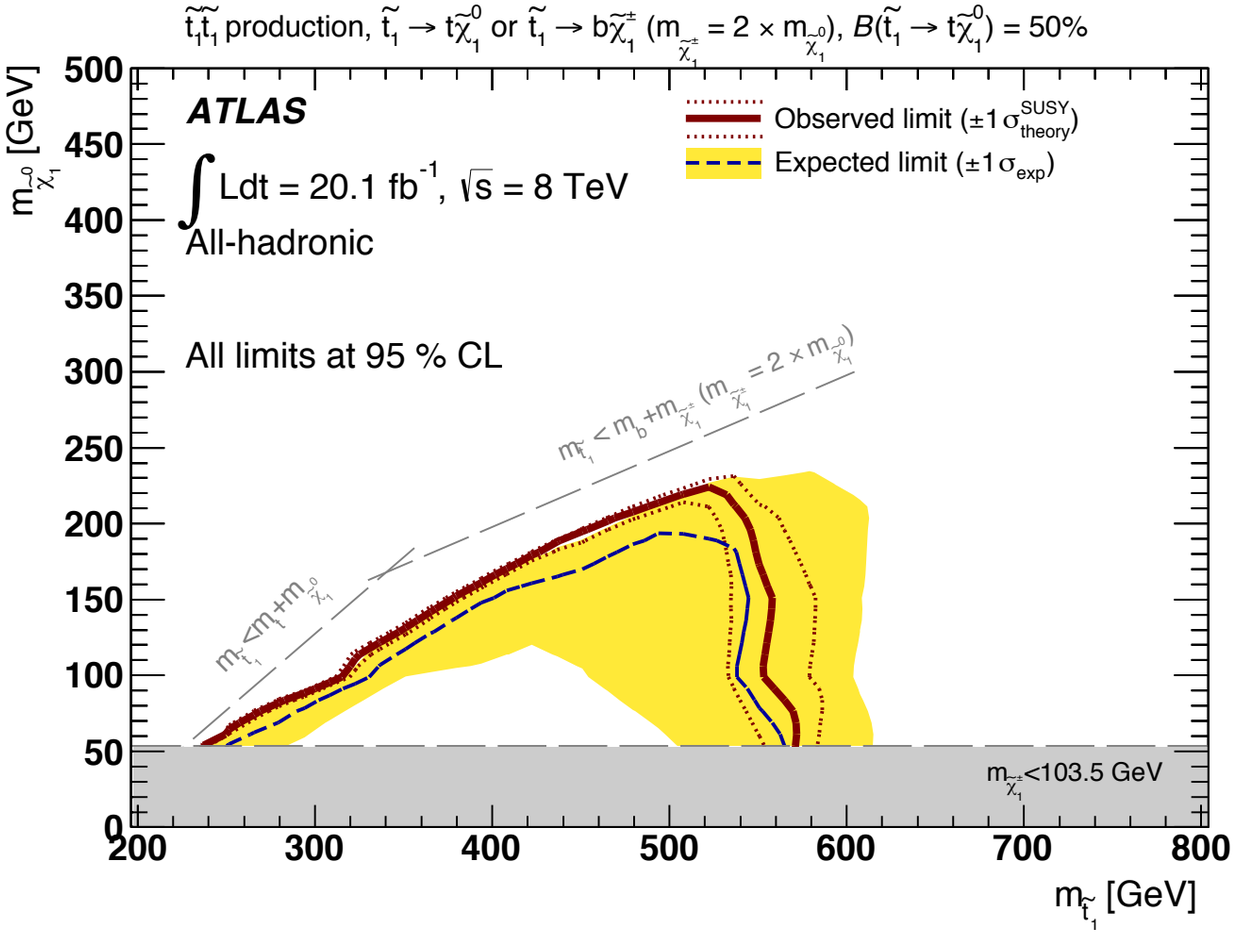
# All hadronic final states: limits




Combination of SRA and SRC regions most sensitive for small Δm (stop-neutralino)

Combination of SRA and SRB regions most sensitive for large Δm (stop-neutralino)

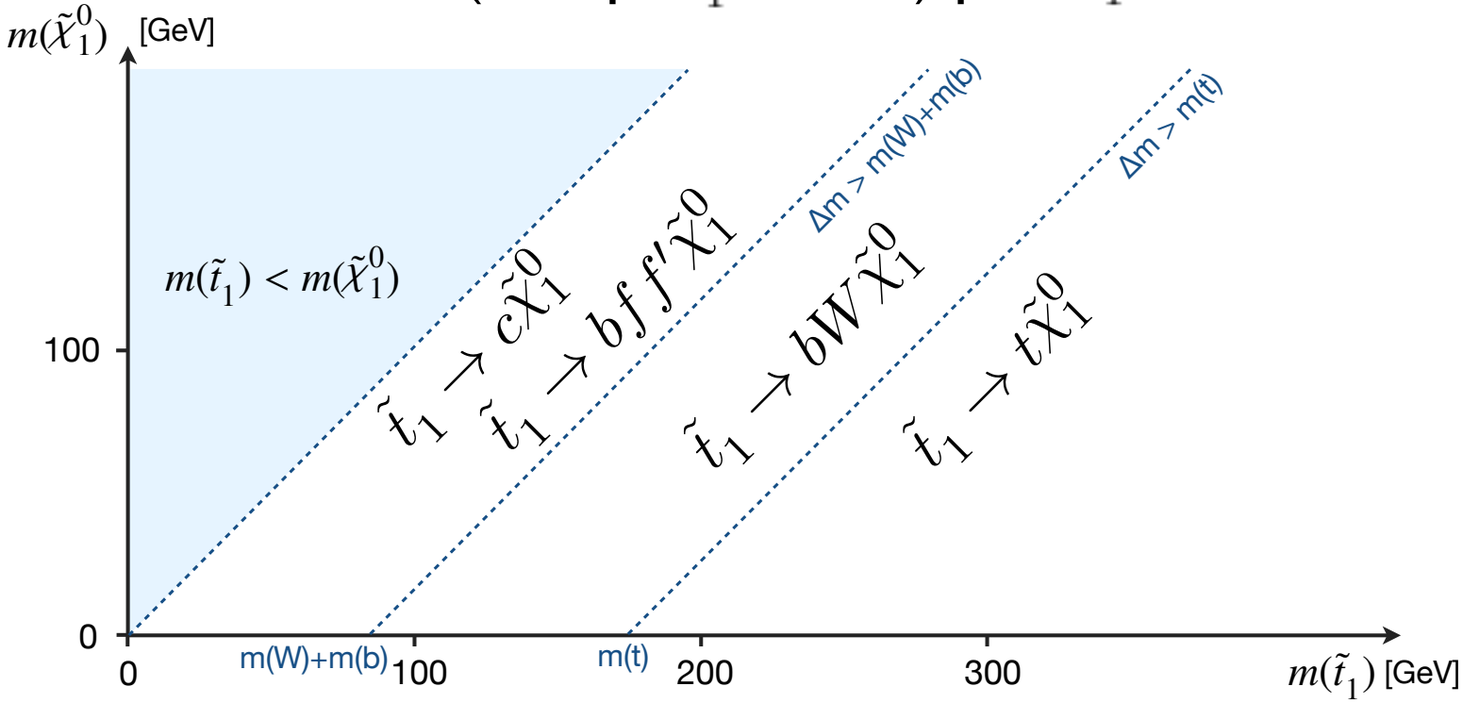
Exclusion limits as for a mix of the two stop decay modes



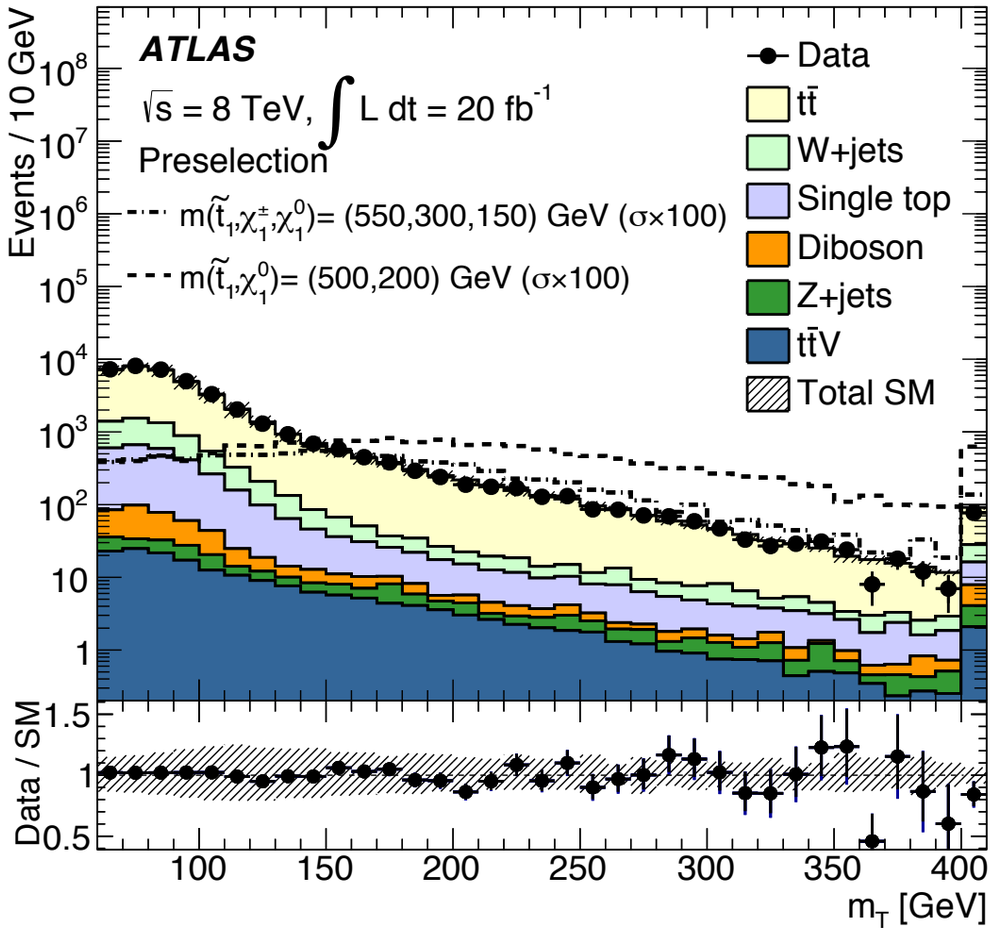
# 1 lepton + jets + MET

NEW

This search targets all decay modes to LSP (except $\tilde{t}_1 \to c\tilde{\chi}_1^0$) plus $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$



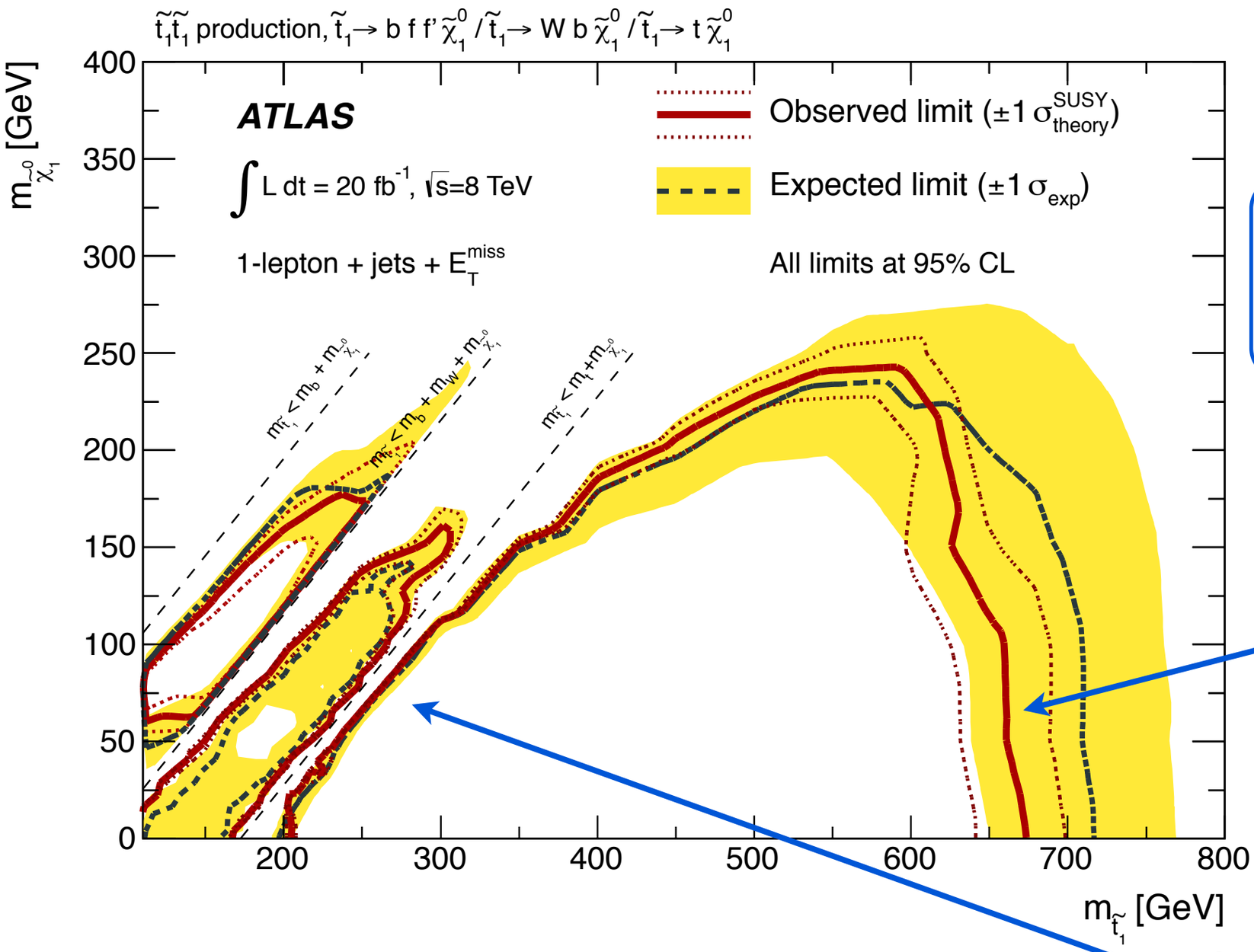

arXiv 1407.0583




- Preselection: **1 lepton, ≥ 2-4 jets, MET**
- 15 SRs for different decay modes and parts of the mass plane
- Main background di-leptonic ttbar, discriminating variables: $m_T$ and $m_{T2}$ variables, topness, hadronic top mass, etc.
- W+jets and ttbar background normalized in CRs (selected using $m_T$ )
- Hypothesis testing using cut-and-count or shape-fit

# 1 lepton + jets + MET

NEW




$\tilde{t}_1 \to t\tilde{\chi}_1^0$

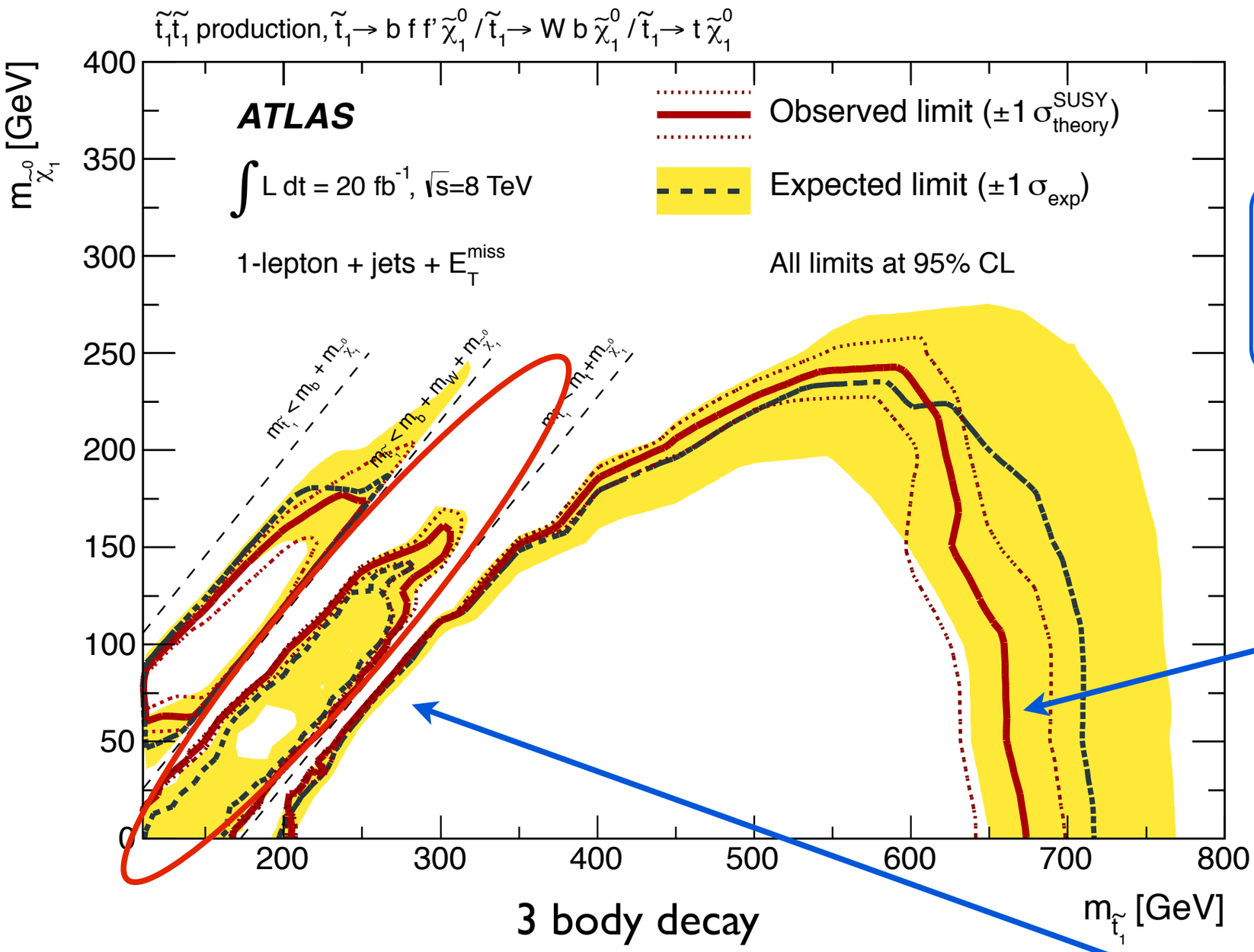
1 lepton ($p_T$ > 25 GeV)
≥ 4 jets, ≥ 1 b-jet
large MET

Take advantage of boosted topology of heavy stop decay: large R-jets

Shape fit to improve sensitivity on the diagonal in MET and $m_T$

# 1 lepton + jets + MET

NEW




$\tilde{t}_1 \to t\tilde{\chi}_1^0$

1 lepton ($p_T$ > 25 GeV)
≥ 4 jets, ≥ 1 b-jet
large MET

Take advantage of boosted topology of heavy stop decay: large R-jets

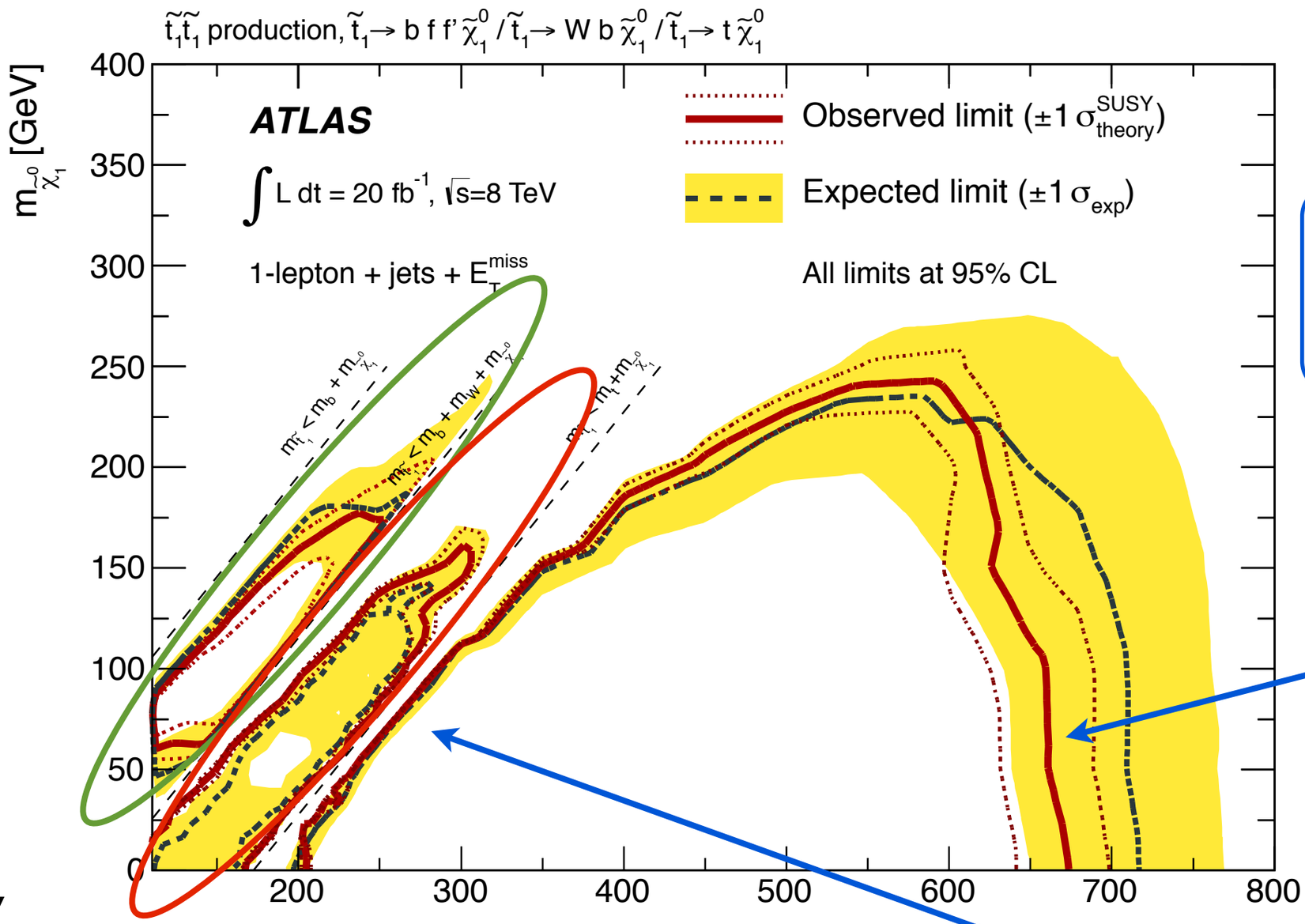
3 body decay

1 lepton ($p_T$ > 25 GeV)
≥ 4 jets, ≥ 1 b-jet, MET
softer thresholds
2D shape fit in $m_T$ and $m_{T2}$

Shape fit to improve sensitivity on the diagonal in MET and $m_T$

# 1 lepton + jets + MET

NEW




$\tilde{t}_1 \to t\tilde{\chi}_1^0$

1 lepton ($p_T$ > 25 GeV)
≥ 4 jets, ≥ 1 b-jet
large MET

Take advantage of boosted topology of heavy stop decay: large R-jets

Shape fit to improve sensitivity on the diagonal in MET and $m_T$

4 body decay

uses ISR jet recoiling against stop decay products
1 soft lepton ($p_T$ > 6/7 GeV)
hard leading jet anti b-tagged
≥ 1 b-jet, MET

3 body decay

1 lepton ($p_T$ > 25 GeV)
≥ 4 jets, ≥ 1 b-jet, MET
softer thresholds
2D shape fit in $m_T$ and $m_{T2}$

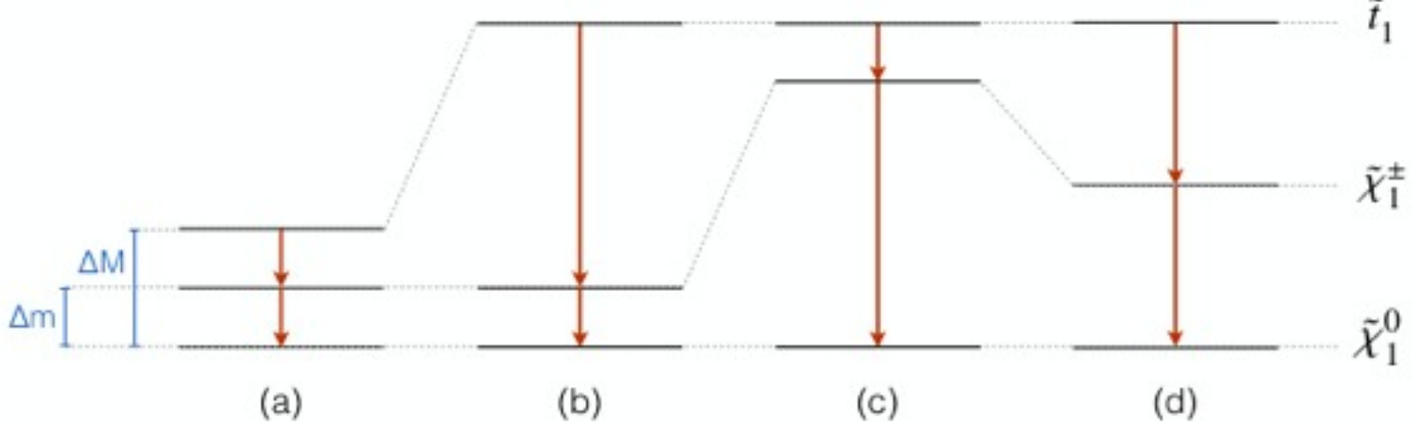
# 1 lepton + jets + MET

NEW

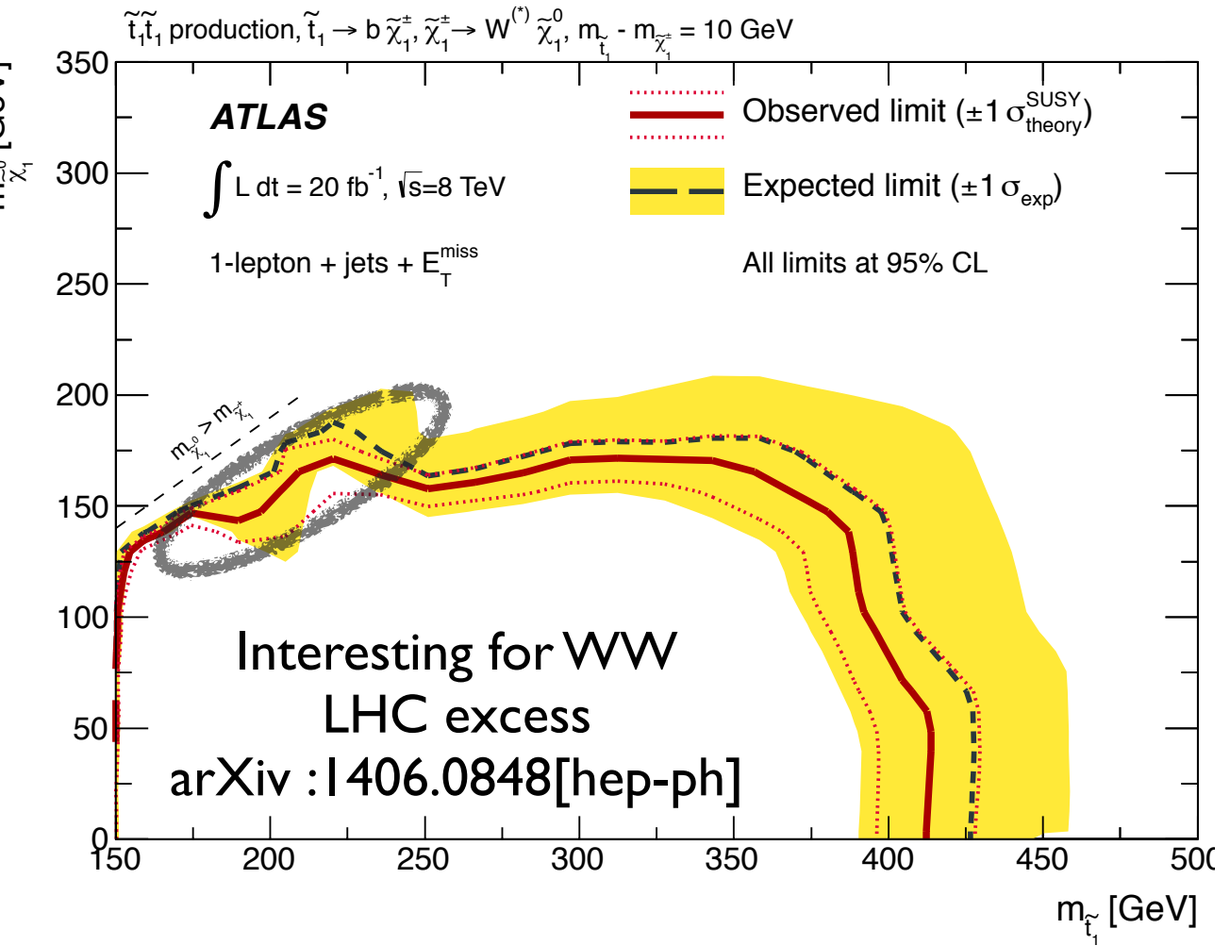
$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$

Selection depends on mass splittings between stop, chargino and neutralino

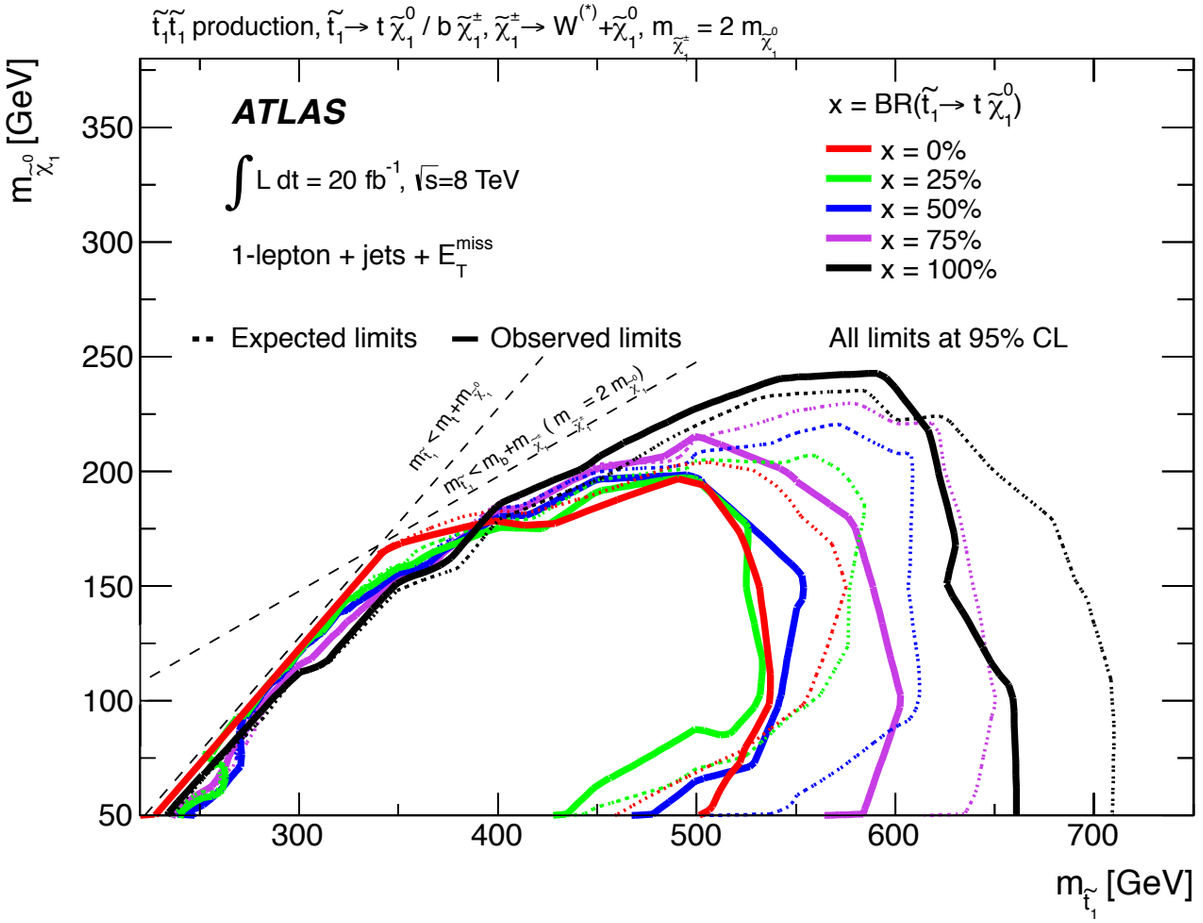
Dedicated selection to cover all scenarios: here showing two examples




## Scenario a and c (ΔM=10 GeV)




## Exclusion limits as for a mix of the two stop decay modes: contours as a function of $\tilde{t}_1 \to t\tilde{\chi}_1^0$ BR



# Stop charm search

NEW

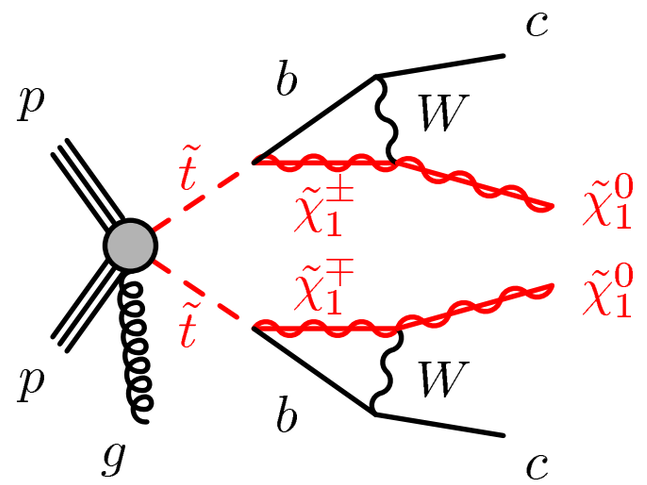
arXiv 1407.0608

Two possible stop decay modes for $\Delta m < m_W + m_b$
(where $\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$)

- $\tilde{t}_1 \to c + \tilde{\chi}_1^0$
- four-body decay

Signature:
- two charm jets with relatively low $p_T$
- small MET

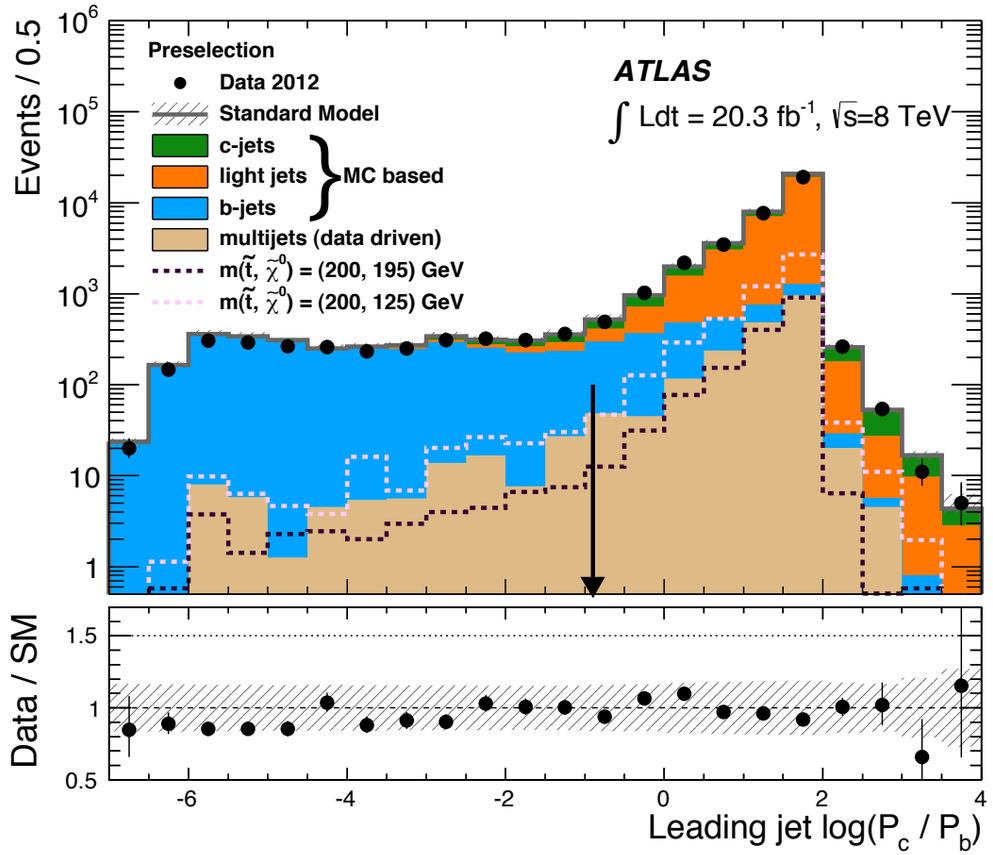
→ Require ISR to boost the stop system




Discriminator against b-jets
(using multi-variate algorithm)

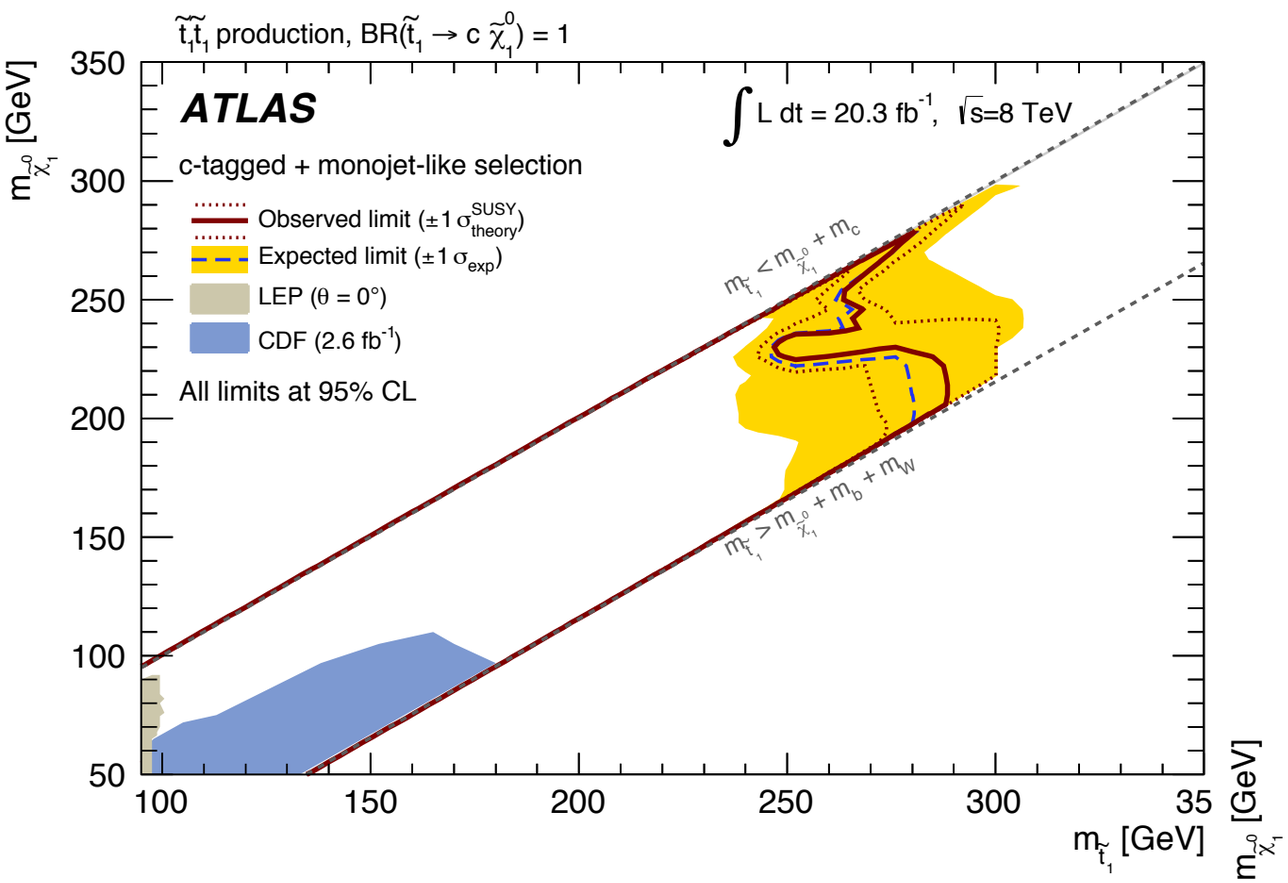
Two different approaches:
- small Δm (< 20 GeV): c-jets with low $p_T$
  - ➡ mono-jet like approach:
    ≤ 3 jets, high $p_T$ leading jet, large MET
- large Δm (> 20 GeV): c-jets reconstructed
  - ➡ charm tagging
    ≥ 4 jets, ≥ 1 c-tagged jet, high $p_T$
    untagged leading jet, large MET

Main backgrounds (W/Z+jets and ttbar)
normalized to data in CRs

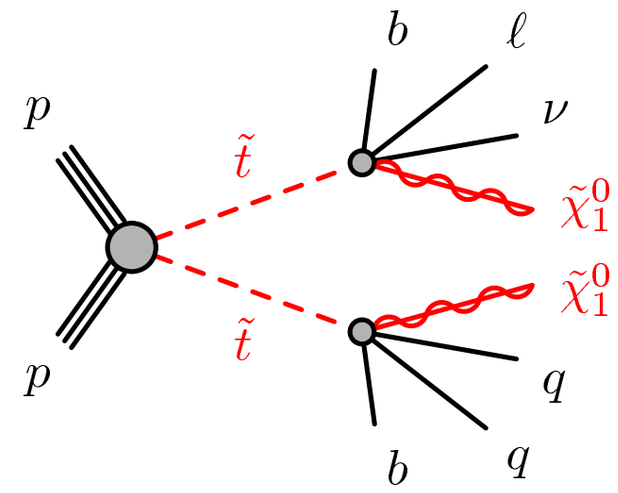


# Stop charm search: limits

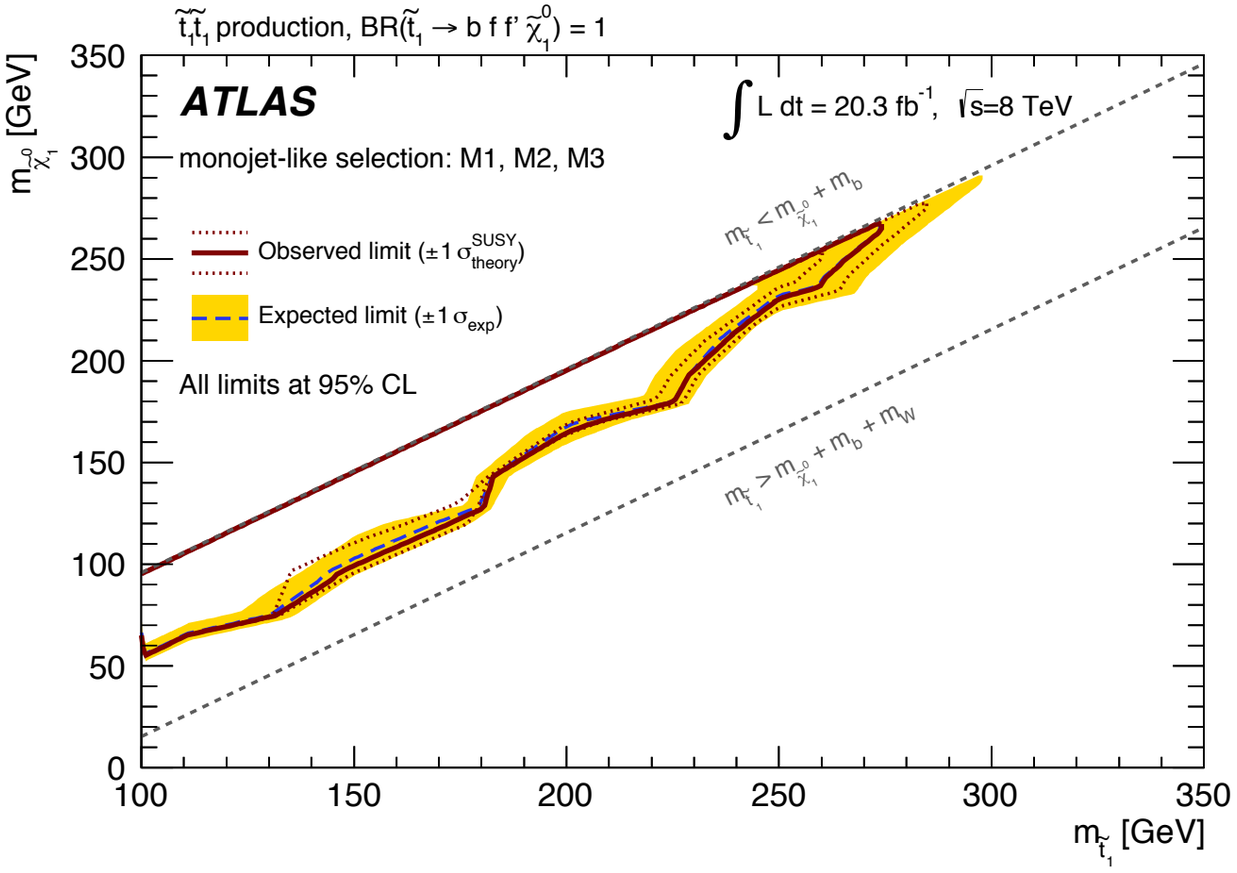
NEW




Mono-jet like search drives the sensitivity at very low Δm (along the diagonal)
c-tagged selection everywhere else



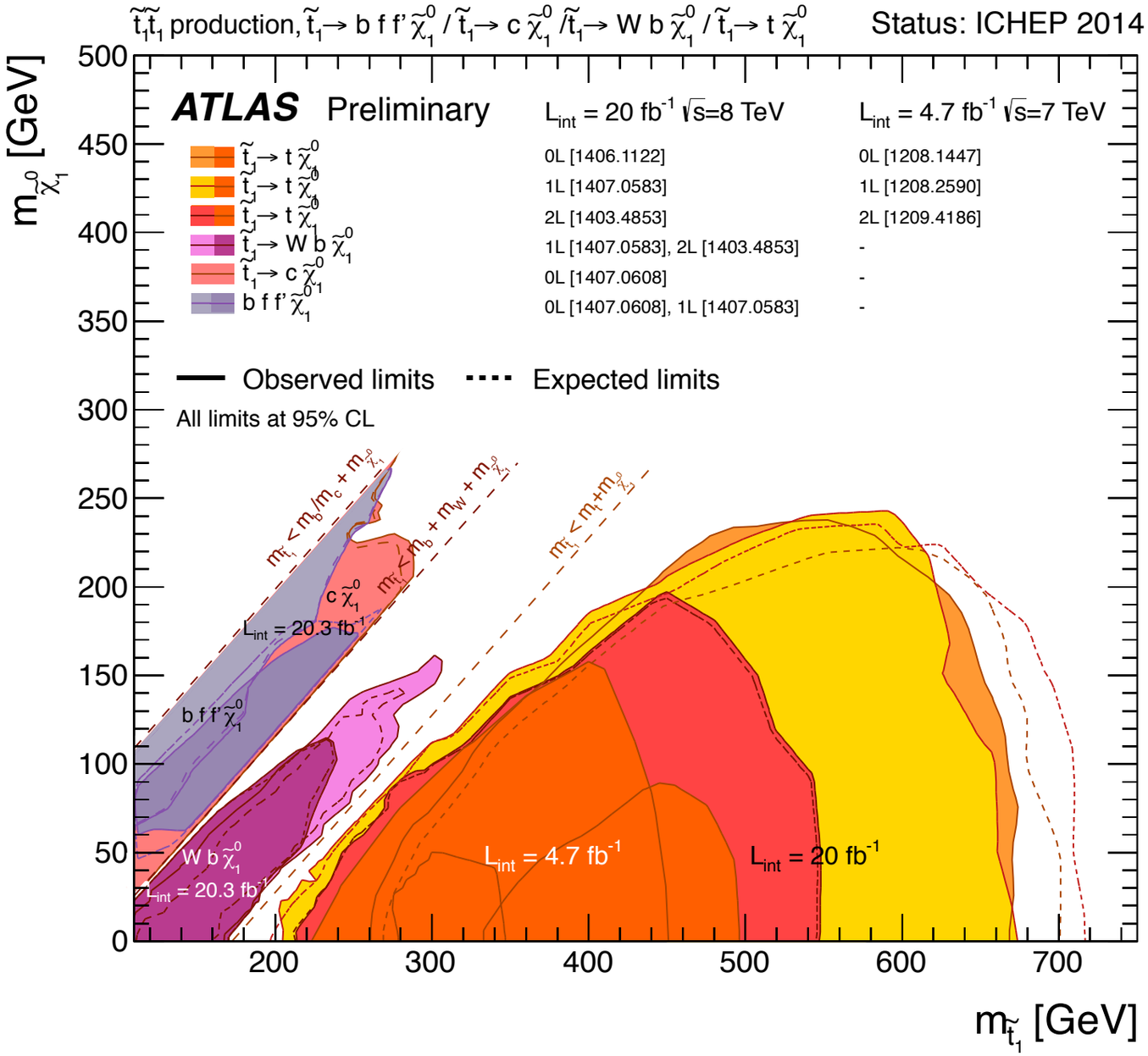

Interpretation also provided for stop four-body decay



# Summary

ATLAS has a strong search program for third generation squarks.
No excess found in Run1, stringent exclusion limits were set.

Looking forward to Run2 with increased centre of mass energy and luminosity!



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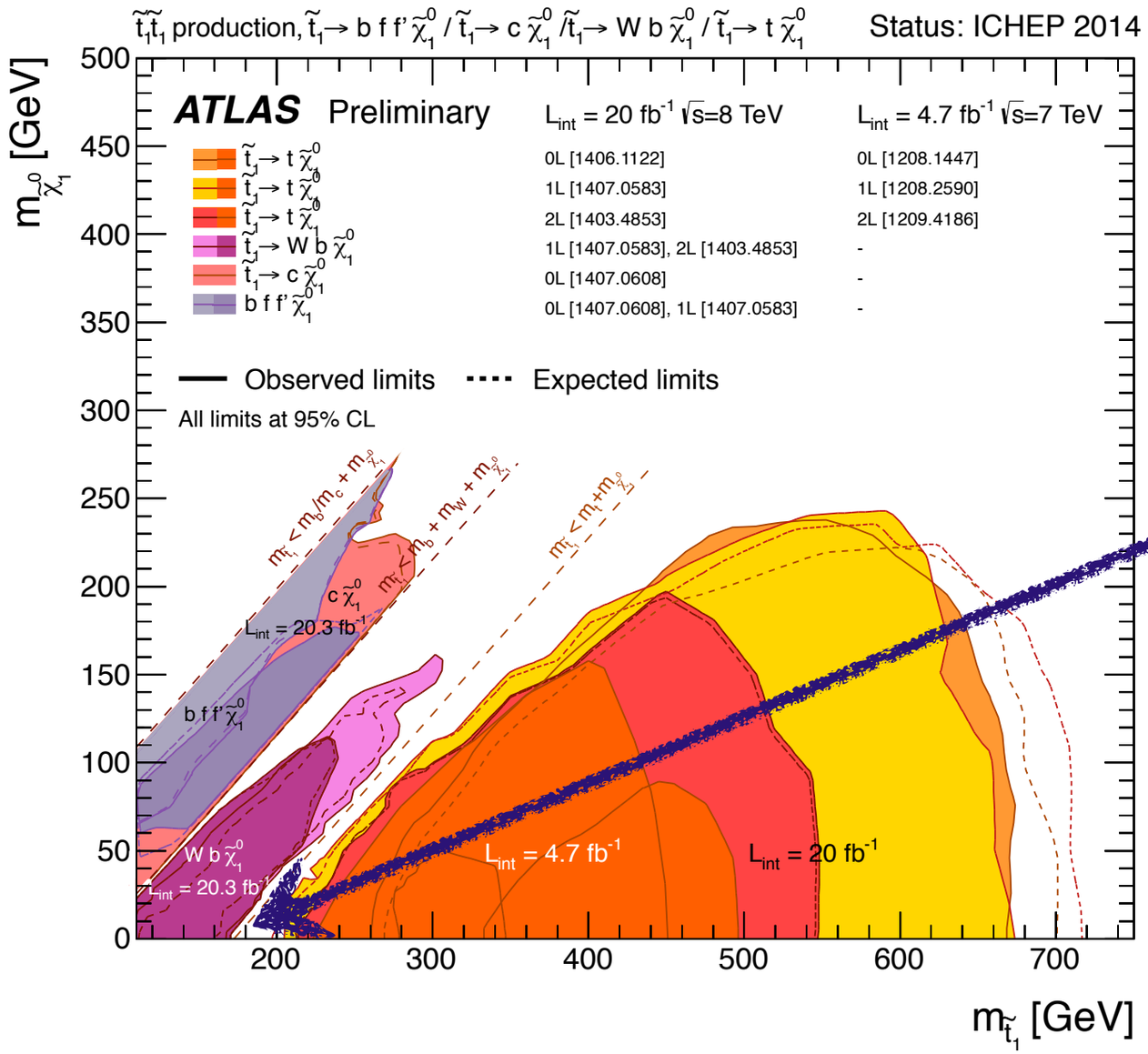
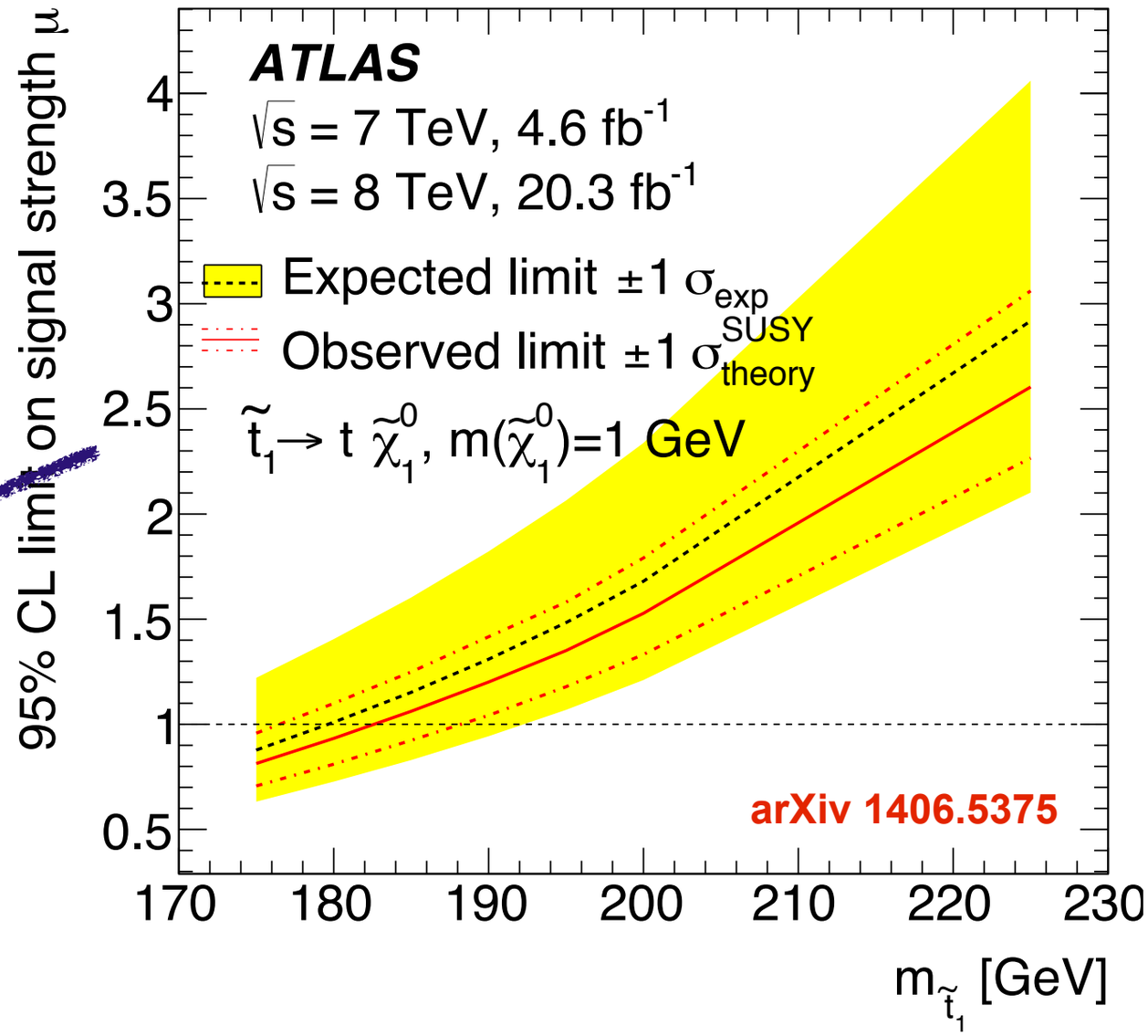



Limits on stop pair production from the ttbar cross-section measurement



# EXTRAS

# Searching for SUSY at the LHC

**SM Backgrounds:**
ttbar, multijets,
V, VV, VVV, Higgs
and combinations of these

**Reducible (fake) Backgrounds:**

Data driven
Method analysis dependent

**Irreducible Backgrounds:**

Dominant sources: normalize MC predictions in CRs and extrapolate to SRs

Sub-dominant sources: from MC

**Validation Regions:**

to cross-check the background predictions

**Signal Regions:**

look for excess

**Combined fit** of control and signal regions (exp. and theor. systematic uncertainties as nuisance parameters)

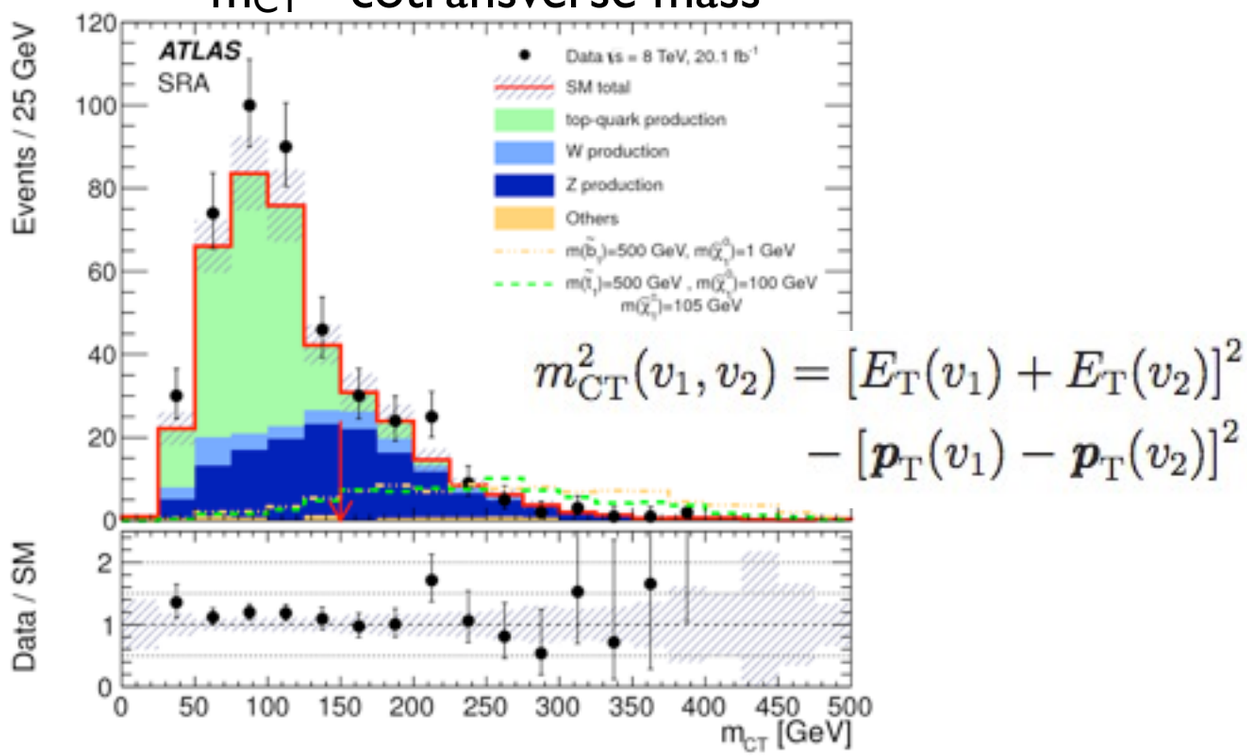
# 0 lepton + 2 b-jets + MET

**0 leptons, ≥ 2 b-jets, MET**

*JHEP10(2013)189*

SRA: large Δm(squark, neutralino)
- two leading jets b-tagged, veto third jet
- $m_{bb}$ > 200 GeV, $m_{CT}$ > [150, 350] GeV

$m_{CT}$ - cotransverse mass

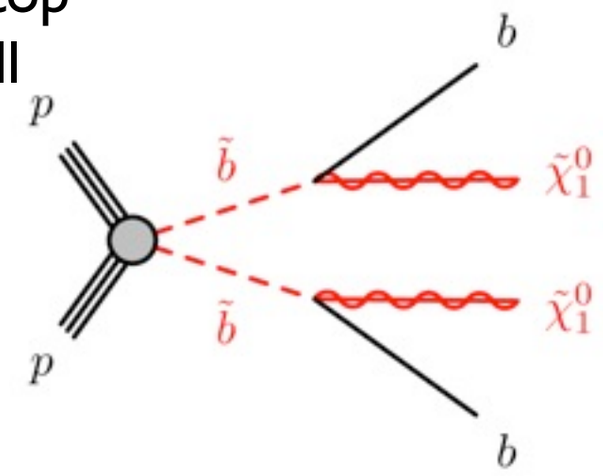


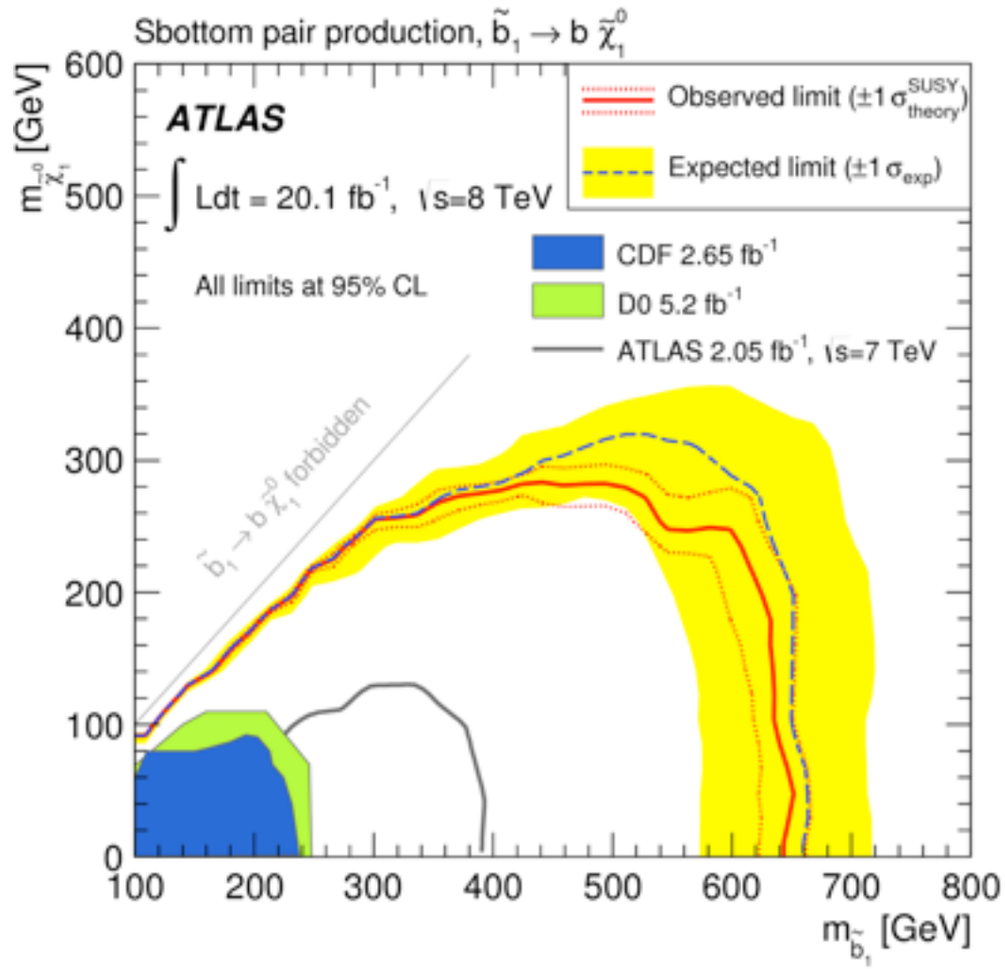

$$m^2_{\mathrm{CT}}(v_1, v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\boldsymbol{p}_{\mathrm{T}}(v_1) - \boldsymbol{p}_{\mathrm{T}}(v_2)]^2$$

SRB: small Δm(squark, neutralino) - exploit ISR
- 1st jet: high $p_T$, anti b-tagged
- 2nd and 3rd jets b-tagged, small $H_{T,3}$, large MET

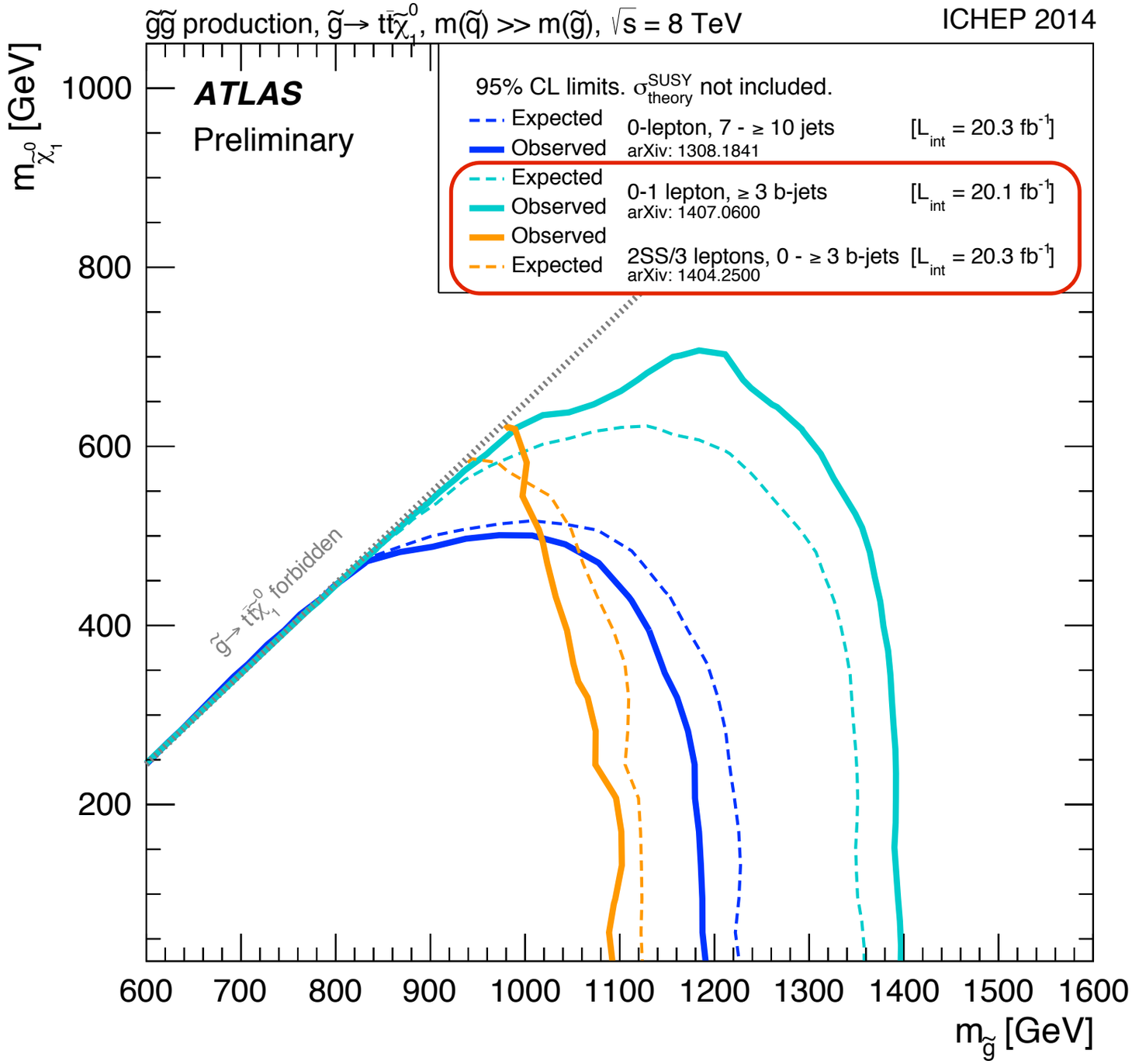
Main backgrounds:
- Z(νν) + HF jets: 2-lepton CRs (SFOS $m_{ll}$ close to Z mass)
- Top and W + HF jets: 1-lepton CRs or 2-lep with DFOS

Target direct sbottom
Also sensitive to direct stop with $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ and small $\Delta m \equiv m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$



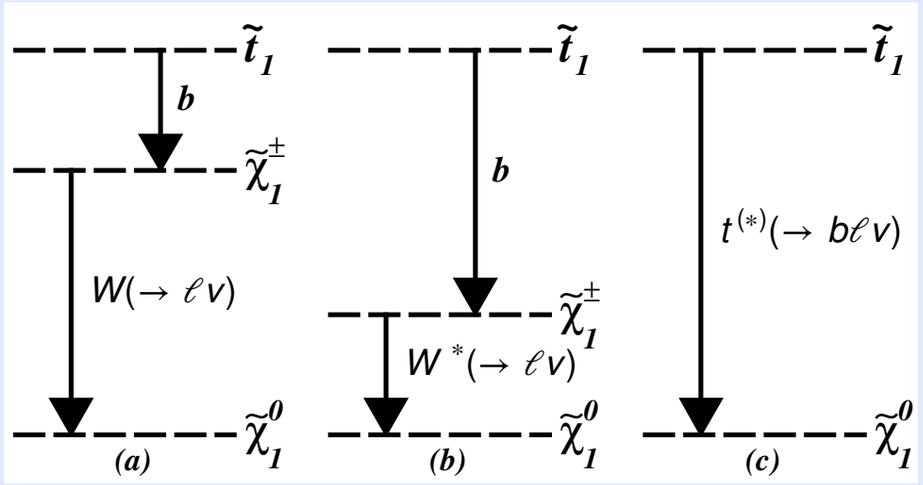



# Gluino-mediated stop summary



# stop 2 lepton searches

**= 2 leptons of opposite charge**



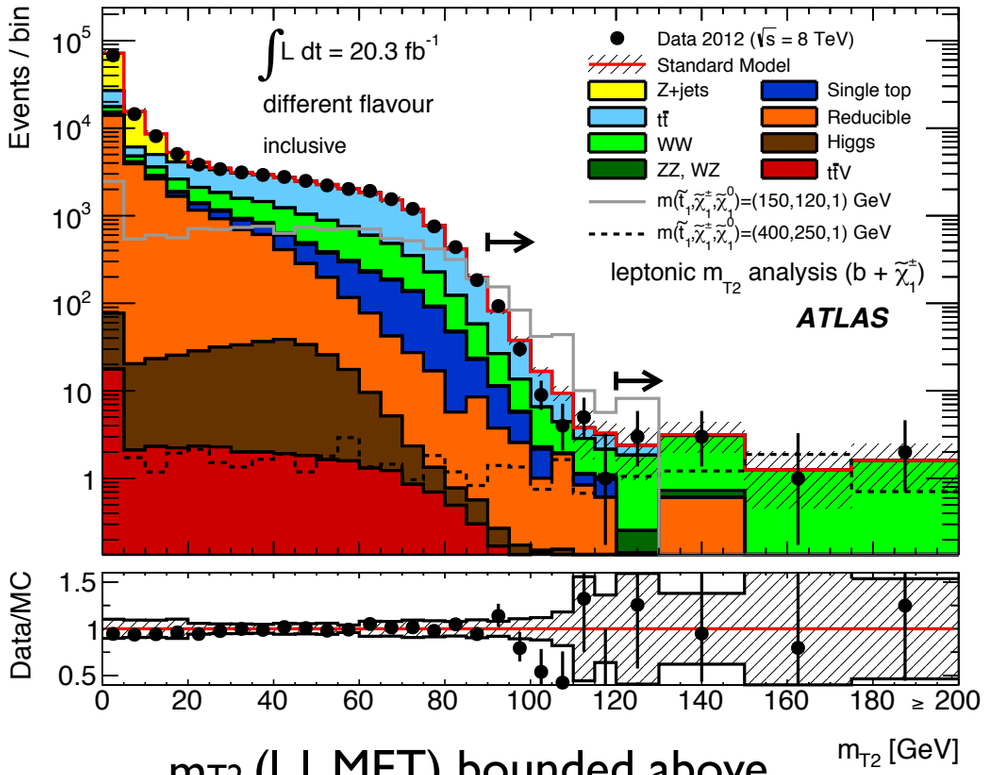

Three different analysis strategies: *JHEP 06 (2014) 124*

**leptonic $m_{T2}$:** targets (a) (large Δm) and 3 body-decay
- require large $m_{T2}$

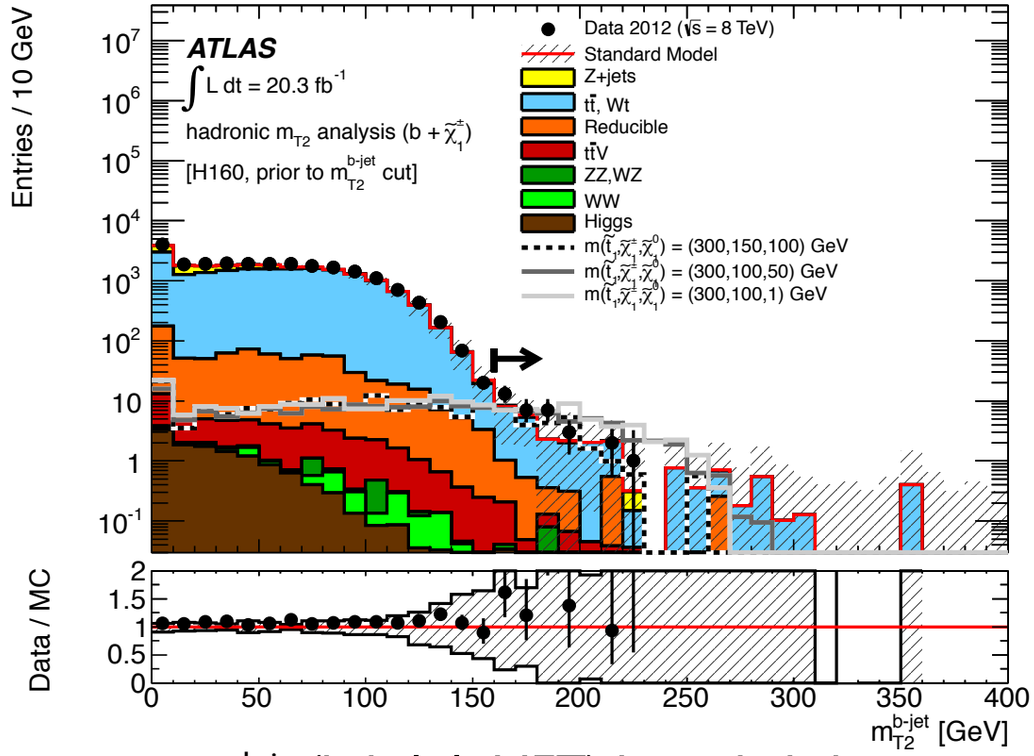
**hadronic $m_{T2}$:** targets (b) (small Δm)
- require 2 b-jets, large $m_{T2}^{\text{b-jet}}$

**multivariate:** targets (c) with on-shell top
- ≥ 2 jets, large MET, large $m_{Eff}$, train BDT using MET, $m_{ll}$, $m_{T2}$, Δφ(l,l), Δφ(MET,l), Δφ(MET,jet)

Stransverse mass ($m_{T2}$): $$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{q}_T) = \min_{\mathbf{q}_{T,1}+\mathbf{q}_{T,2}=\mathbf{q}_T} \{\max[\, m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})\,]\}$$

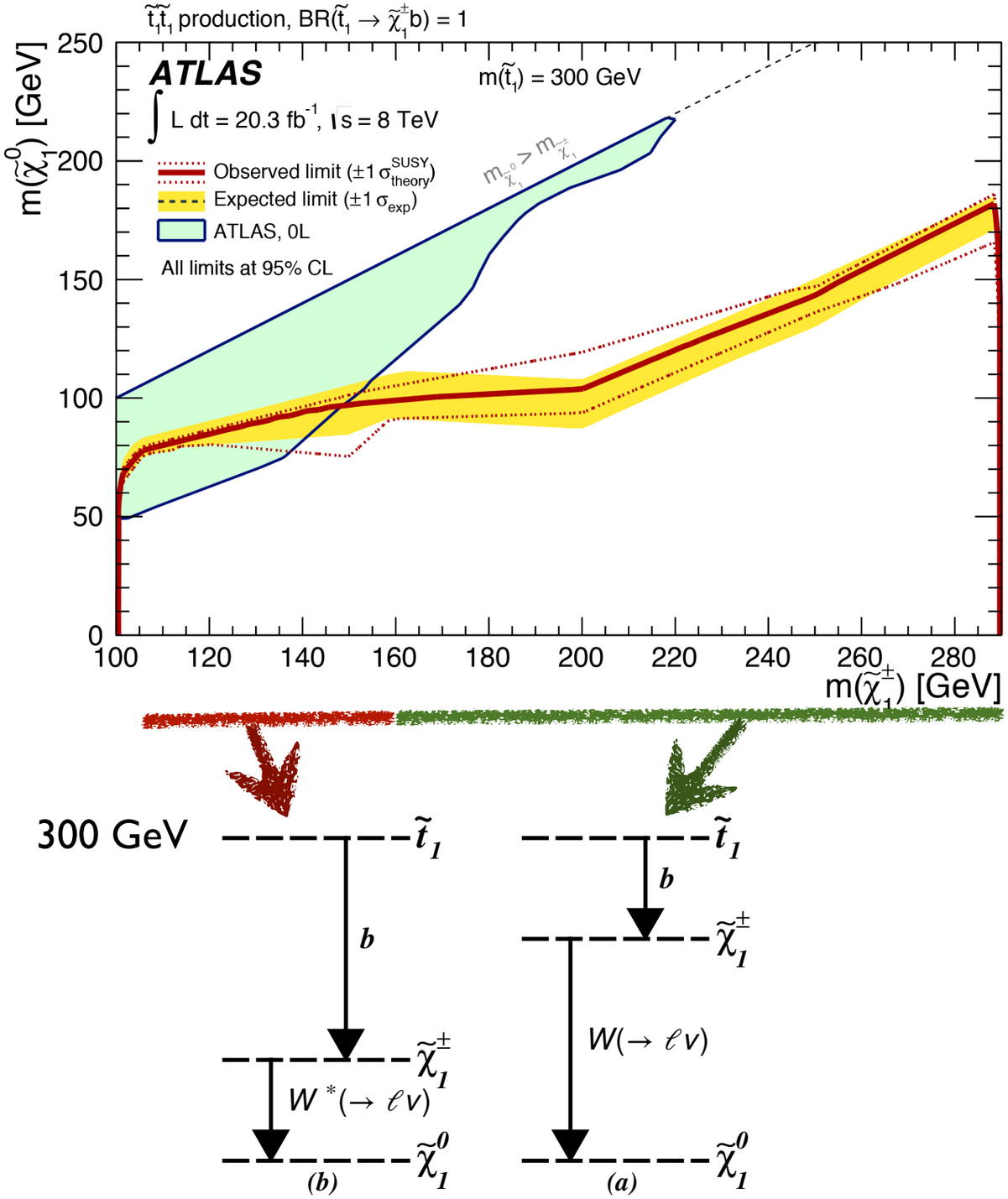


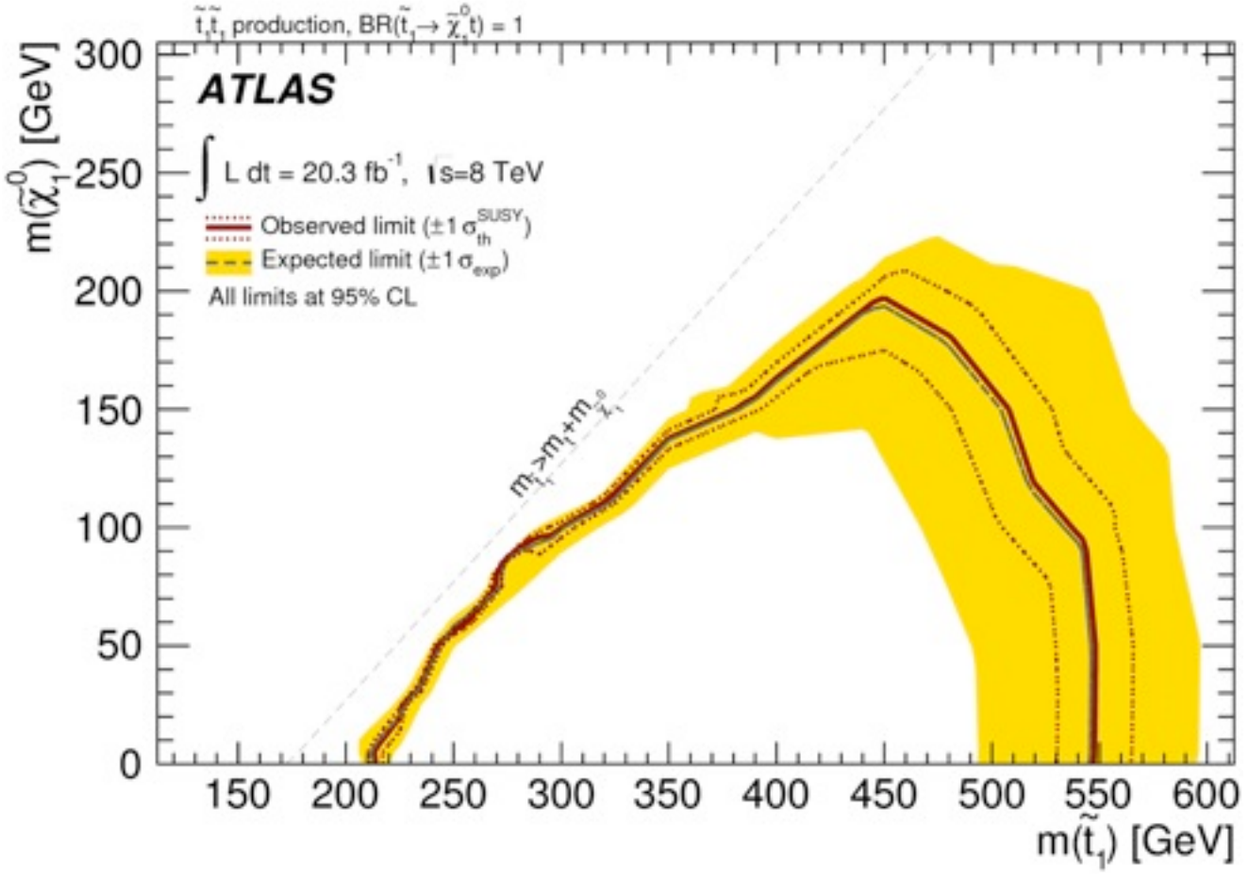

$m_{T2}$ (l, l, MET) bounded above by the W mass for WW and ttbar

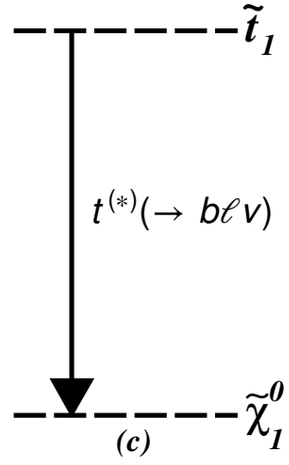



$m_{T2}^{\text{b-jet}}$(b, b, l+l+MET) bounded above by the top mass for ttbar

# stop 2 lepton searches



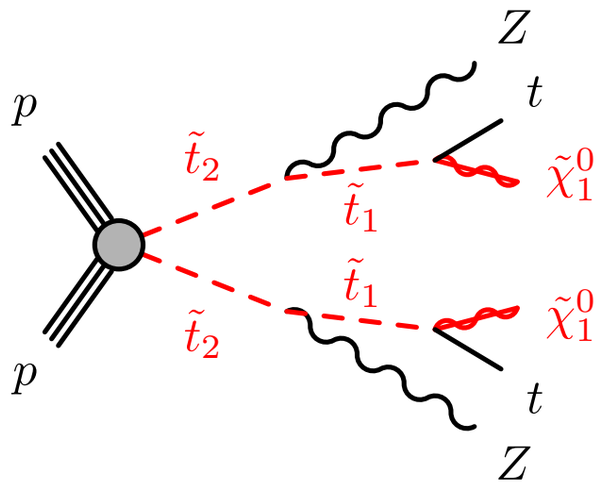
# stop Z search

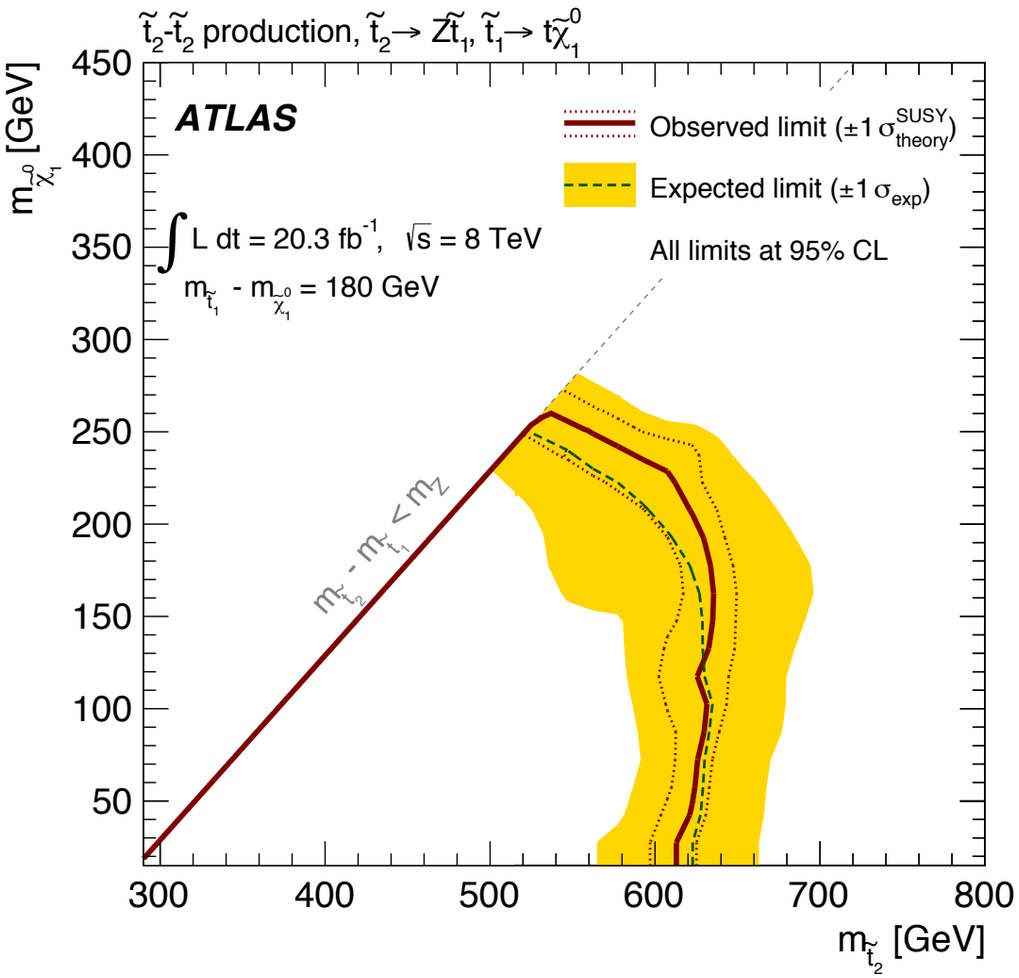
arXiv 1403.5222, accepted by EPJC

For $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and m(stop1) ≈ m(top) + m(LSP) signature very similar to ttbar

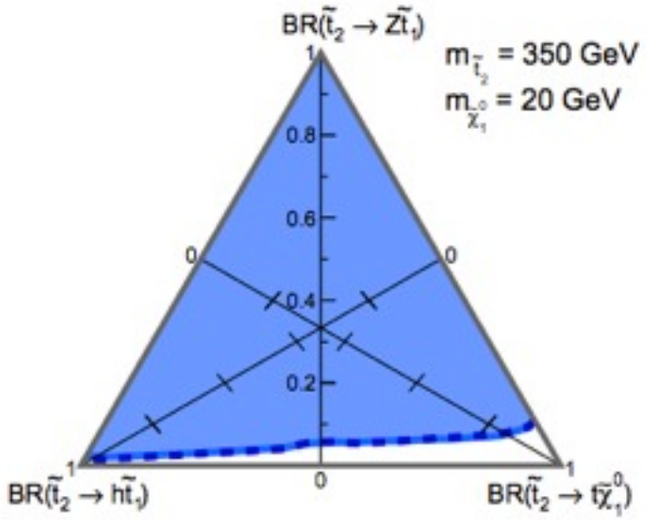
Use $\tilde{t}_2 \to Z\tilde{t}_1$ to discriminate against ttbar

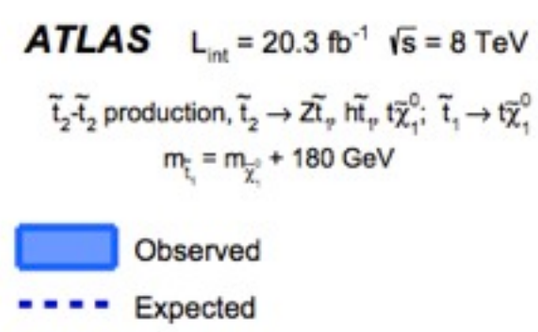
Signature:
Z→ $l^+l^-$ (l), 3-5 jets, ≥ 1 b-jets, MET



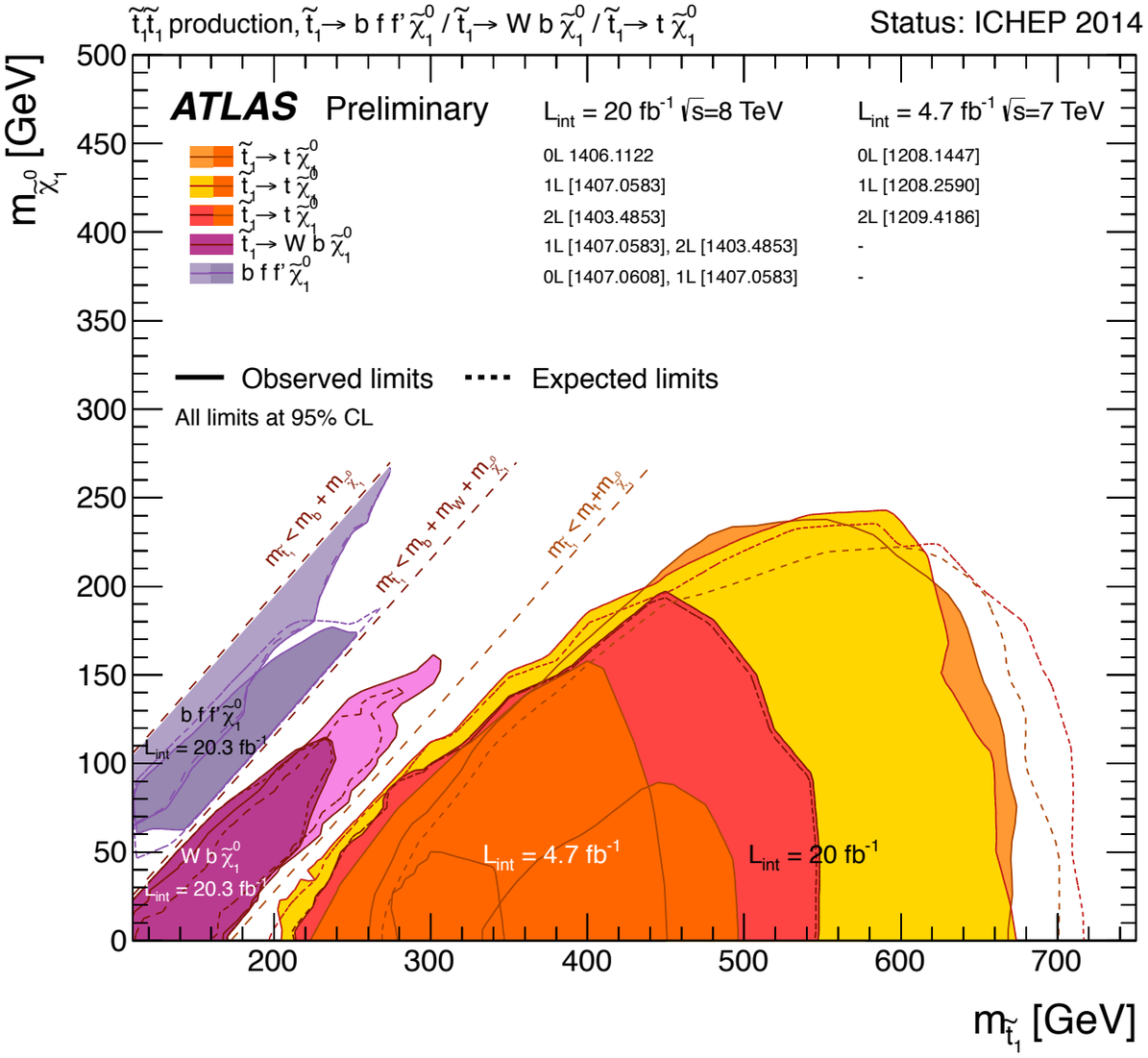



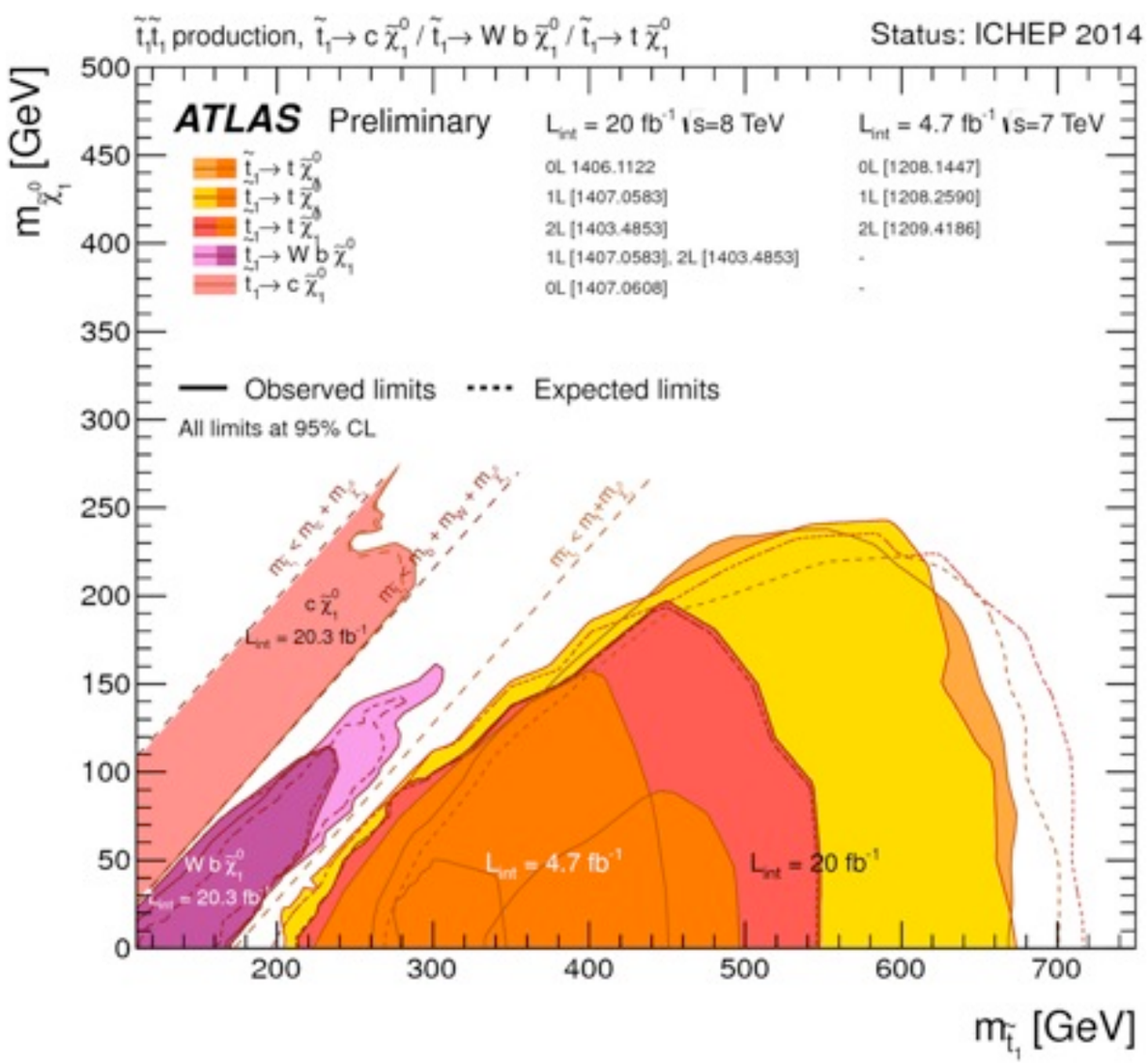

Relaxing the assumption of BR( $\tilde{t}_2 \to Z\tilde{t}_1$ )=100%, including the decay modes $\tilde{t}_2 \to t\tilde{\chi}_1^0$ and $\tilde{t}_2 \to h\tilde{t}_1$ → interpret the results as limits on the decay branching ratios



# Summary


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b\,f\,f'\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
Status: ICHEP 2014
ATLAS Preliminary
$L_{int}$ = 20 fb$^{-1}$ $\sqrt{s}$=8 TeV
$L_{int}$ = 4.7 fb$^{-1}$ $\sqrt{s}$=7 TeV
$\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_2^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_3^0$
$\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$
$b\,f\,f'\,\tilde{\chi}_1^0$
0L 1406.1122
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608], 1L [1407.0583]
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
-
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$b\,f\,f'\,\tilde{\chi}_1^0$ $L_{int}$ = 20.3 fb$^{-1}$
$W\,b\,\tilde{\chi}_1^0$ $L_{int}$ = 20.3 fb$^{-1}$
$L_{int}$ = 4.7 fb$^{-1}$
$L_{int}$ = 20 fb$^{-1}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]


$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$ / $\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
Status: ICHEP 2014
ATLAS Preliminary
$L_{int}$ = 20 fb$^{-1}$ $\sqrt{s}$=8 TeV
$L_{int}$ = 4.7 fb$^{-1}$ $\sqrt{s}$=7 TeV
$\tilde{t}_1 \to t\,\tilde{\chi}_1^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_2^0$
$\tilde{t}_1 \to t\,\tilde{\chi}_3^0$
$\tilde{t}_1 \to W\,b\,\tilde{\chi}_1^0$
$\tilde{t}_1 \to c\,\tilde{\chi}_1^0$
0L 1406.1122
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
-
Observed limits
Expected limits
All limits at 95% CL
$c\,\tilde{\chi}_1^0$ $L_{int}$ = 20.3 fb$^{-1}$
$W\,b\,\tilde{\chi}_1^0$ $L_{int}$ = 20.3 fb$^{-1}$
$L_{int}$ = 4.7 fb$^{-1}$
$L_{int}$ = 20 fb$^{-1}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

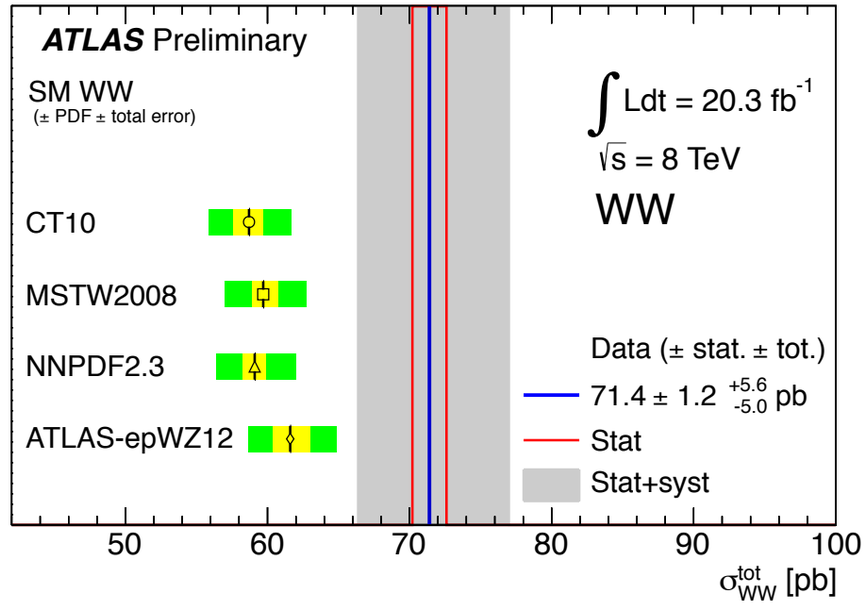
# Excess in WW production?

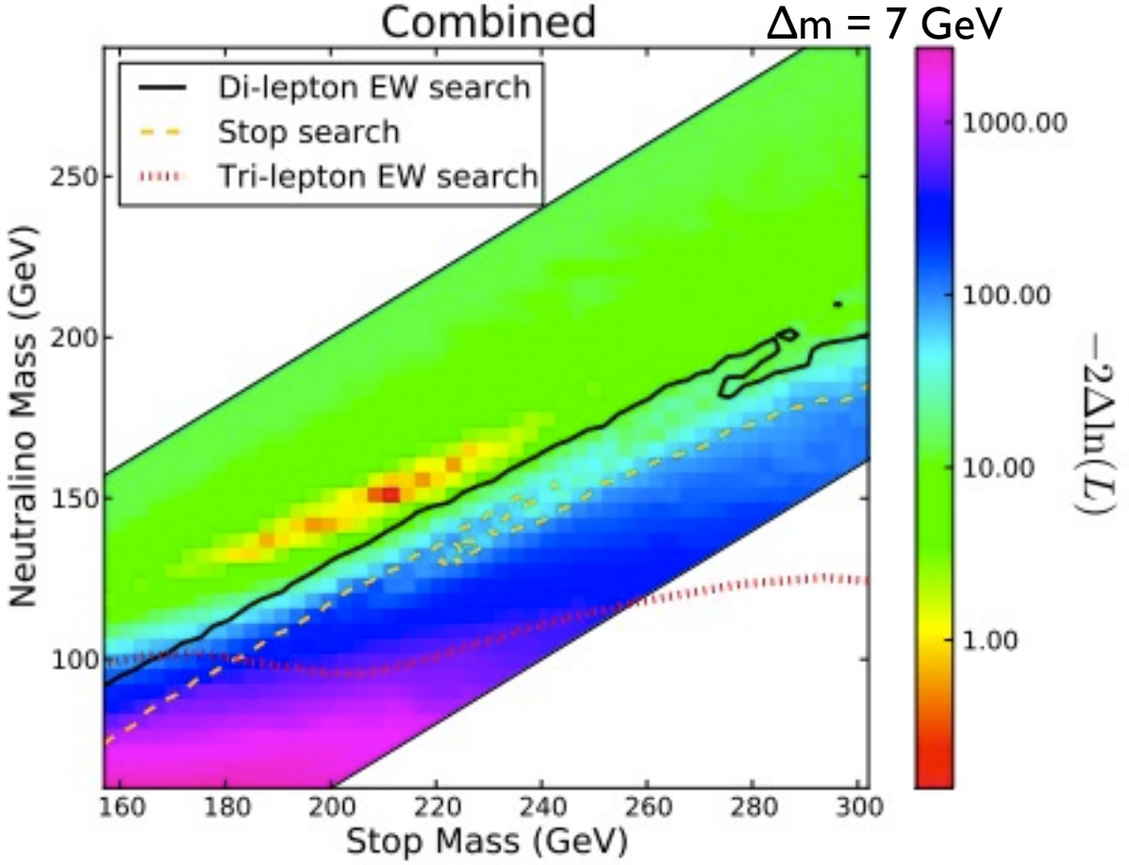
Measurements of WW cross-section at 8 TeV

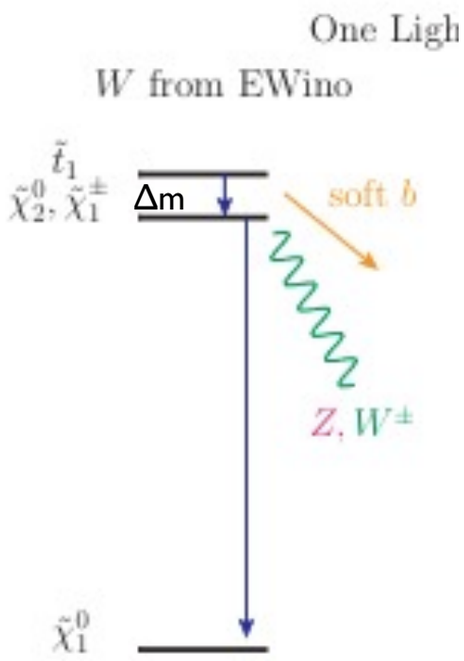
Phys. Lett. B 721 (2013) 190–211

CMS: 69.9 ± 2.8 (stat) ± 5.6 (syst) ± 3.1 (lumi) pb
TH: 57.3 + 2.3 - 1.6 pb

ATLAS-CONF-2014-033




arXiv :1406.0848[hep-ph]
arXiv :1406.0858[hep-ph]

# Run 2 and beyond

ATLAS-PHYS-PUB-2013-011