Towards Model Independent Limits on Light Stops

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A. Belyaev, V. Sanz, MT (*arXiv:1510.07688*)

Program on Particle Physics at the Dawn of the LHC13 **26/11/2015**

Plan

- **Background**
  - SUSY, light stops.
  - Light stops effects on Higgs properties.
  - Stop mediated EWBG.
  - Status current stop searches.

- **Results**
  - Reproduce and extend ATLAS analyses where $m_{\tilde{t}} - m_{\tilde{\chi}} \approx M_W$.
  - Exclude light stop EWBG given certain branching ratio assumptions.
  - Show in more model independent case where BR ≠ 100% exclusion limits are **severely weakened.**

- **Conclusion**

What is SUSY?

Symmetries of Lagrangian

- **Spacetime (Poincare)**
  - Translational
  - Lorentz
- **Internal**
  - $U(1)_Y$
  - $SU(2)_L$
  - $SU(3)_C$

The Coleman-Mandula No-Go Theorem

No non-trivial extensions of the Poincare group

↓

$$\mathbf{Poincare} \otimes \mathbf{Internal}$$

What is SUSY?

Symmetries of Lagrangian

- **Spacetime (Poincare)**
  - Translational
  - Lorentz
  - **SUSY**
- **Internal**
  - $U(1)_Y$
  - $SU(2)_L$
  - $SU(3)_C$

The Coleman-Mandula No-Go Theorem

No non-trivial extensions of the Poincare group

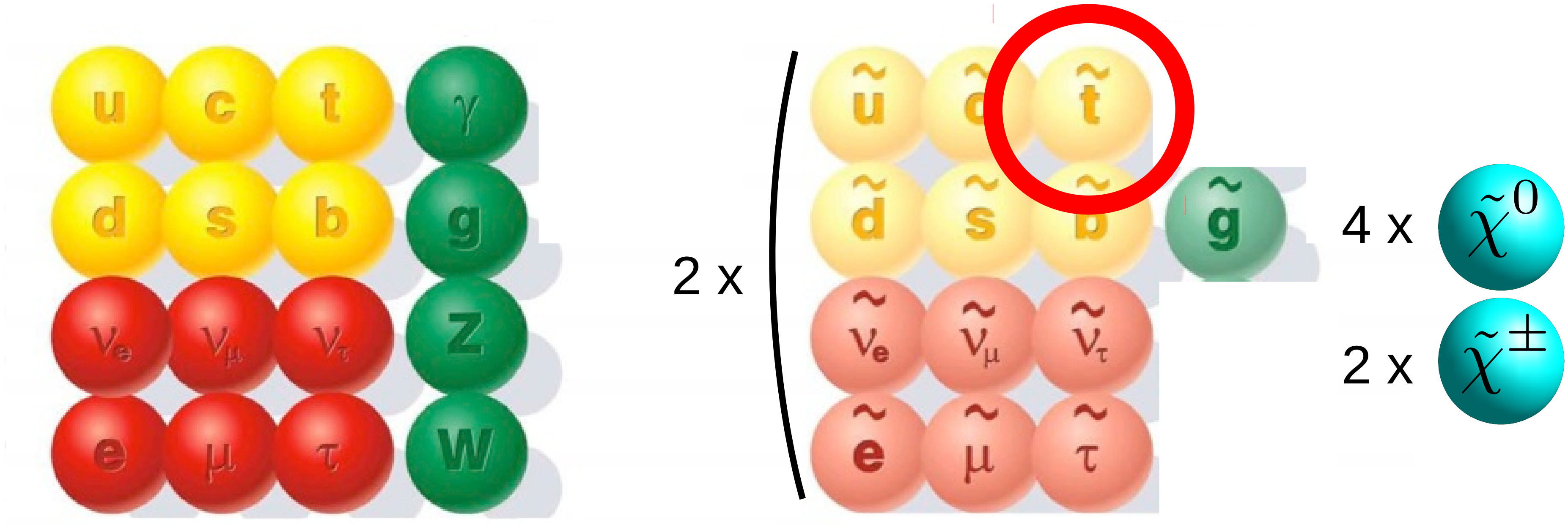
Haag-Lopuszanski-Sohnius (*Do-Go*) Theorem

Poincare group ***can*** be extended if we allow fermionic (anticommuting) generators

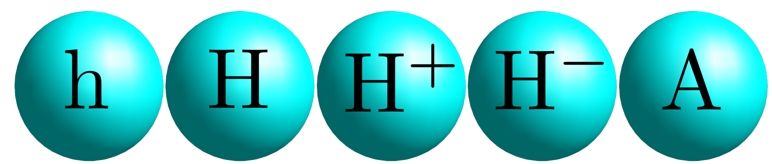
$$
\begin{aligned}
Q|\mathbf{Fermion}> &= |\mathbf{Boson}> \\
Q|\mathbf{Boson}> &= |\mathbf{Fermion}>
\end{aligned}
$$

The MSSM

(Minimal Supersymmetric Standard Model)



2 Higgs Doublets → 5 x Higgs

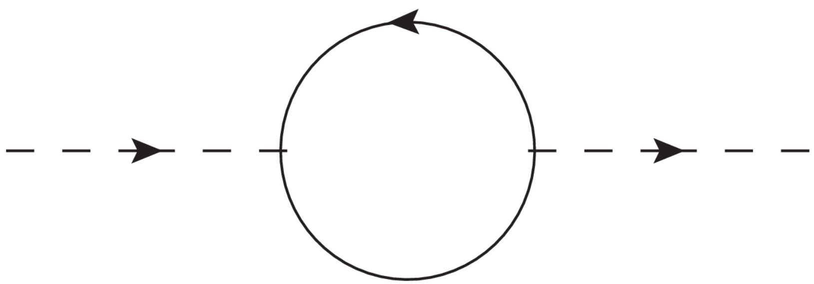


- **Minimal** supersymmetric extension of standard model.
- Supersymmetric partner to each standard model particle
- **Stop** is top quark partner.

The gauge hierarchy problem

Standard Model

$$-\lambda_f H \bar{f} f$$



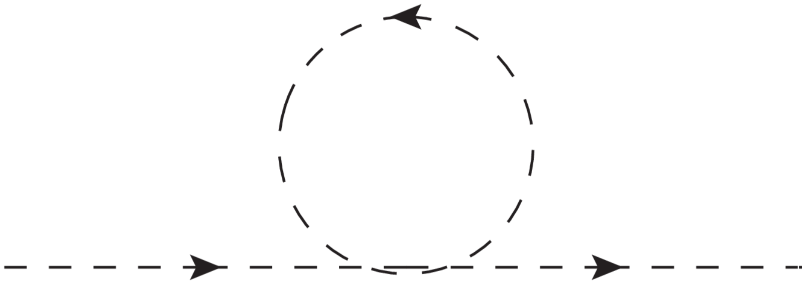
$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

Quadratic divergence in cutoff

+

Supersymmetry

$$-\lambda_S |H|^2 |S|^2$$



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{\rm UV}^2 + \ldots$$

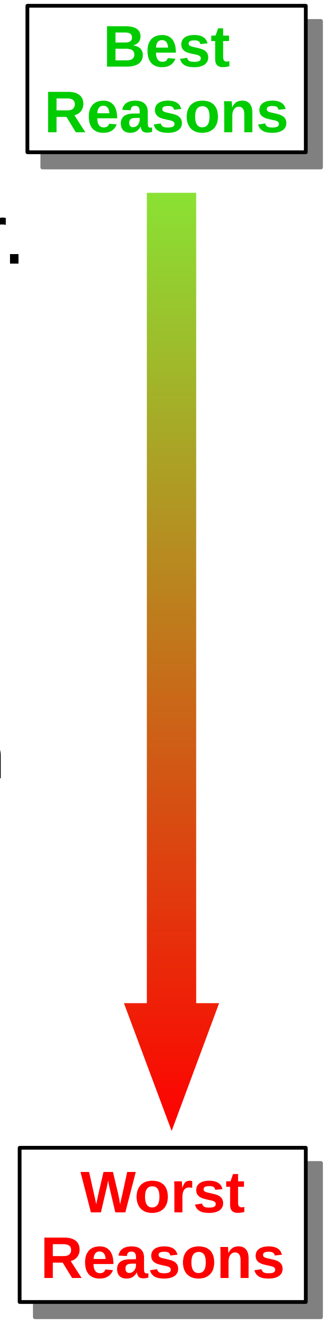
Cancels quadratic divergence

Conditions

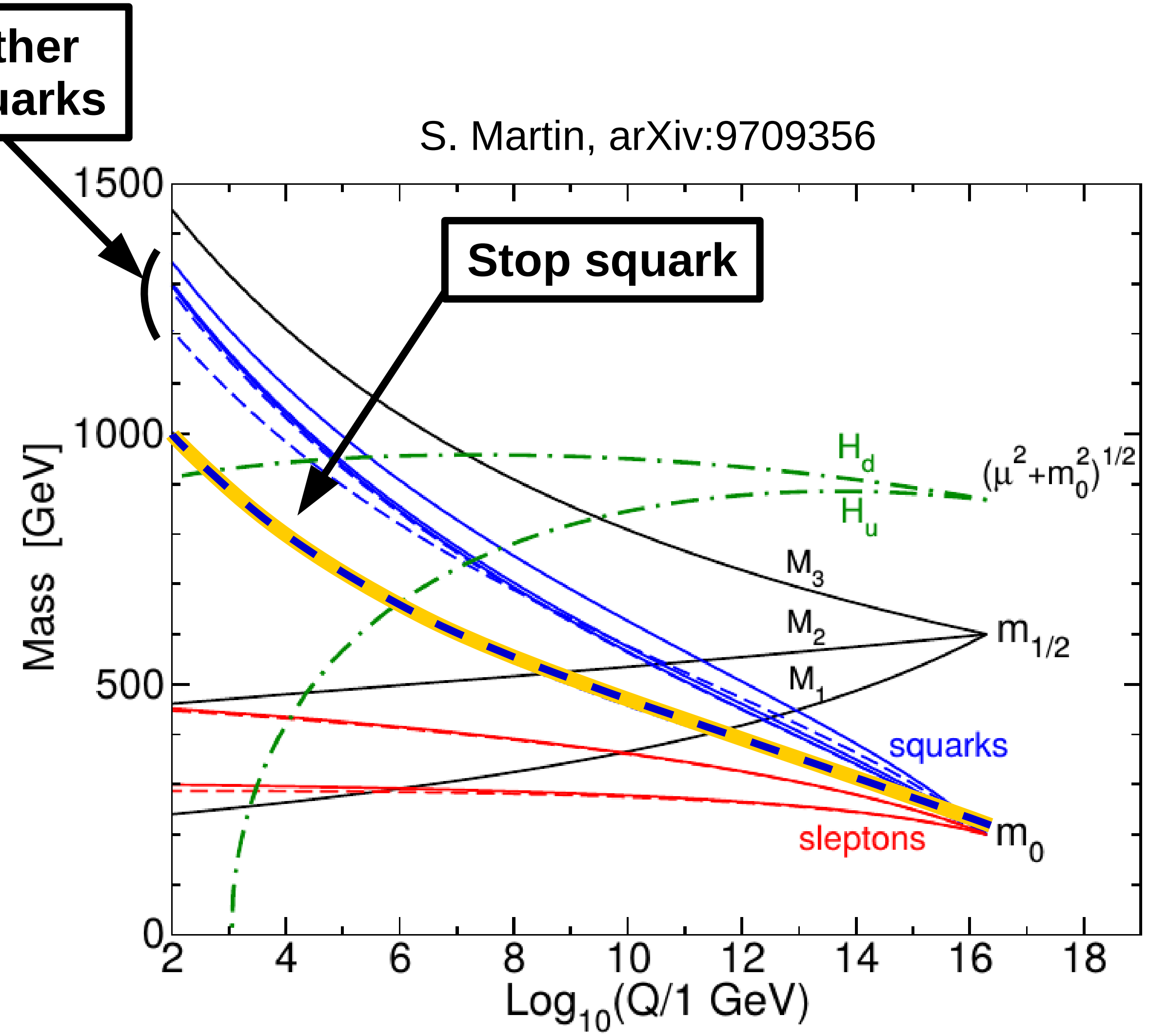
- Two scalars for each fermion ✓
- $\lambda_S = |\lambda_f|^2$ ✓

Why do we like SUSY?

- Solves the gauge hierarchy problem.
- Contains natural candidates for dark matter.
- Allows grand unification.
- When gauged you get a graviton.
- Required by string theory.
- MSSM "*predicts*" a Higgs mass less than 135 GeV.
- Can explain current 3.6σ deviation from SM seen in muon (g-2) anomaly.
- Can have spontaneous electroweak symmetry breaking.
- Can allow electroweak baryogenesis.
- Because all the other spacetime symmetries are realised.
- Allows vacuum stability.
- *"Can explain inflation".*



Light stop scenario



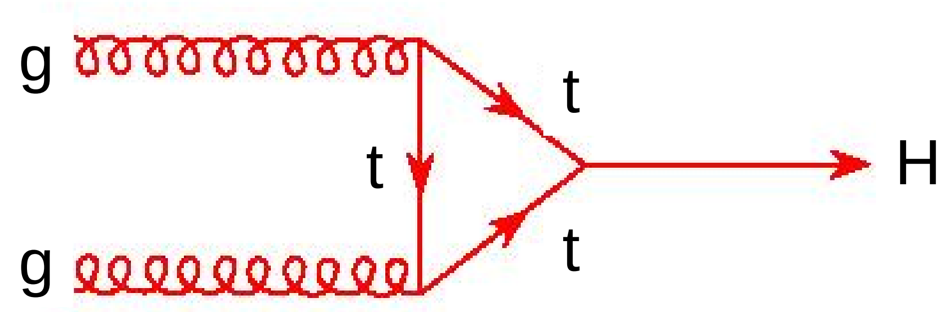
- Stops are naturally lighter.
  - Large top Yukawa enters RGE.
  - Keeps the stop lighter than the other squarks.
- Light stops help keep fine tuning low.

$$\Delta m_h^2 \sim \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

- Light stops allow electroweak baryogenesis.
- Can have important observable effects on Higgs production and decay.

Altered Higgs Production

- **Gluon Fusion**
  - Top loop dominant
  - New contribution from stop loops



$$\Gamma(h \to gg) = \frac{\alpha_s^2 m_h^3}{512\pi^3} \left| \frac{2\hat{g}_{ht\bar{t}}}{m_t} F_{1/2}(x_t) + \frac{\hat{g}_{h\tilde{t}\tilde{t}}}{m_{\tilde{t}}^2} F_0(x_{\tilde{t}}) \right|^2$$

Extra factor for coloured SUSY scalars

Top quark - $F_{1/2}(x_f) \simeq 1.4$

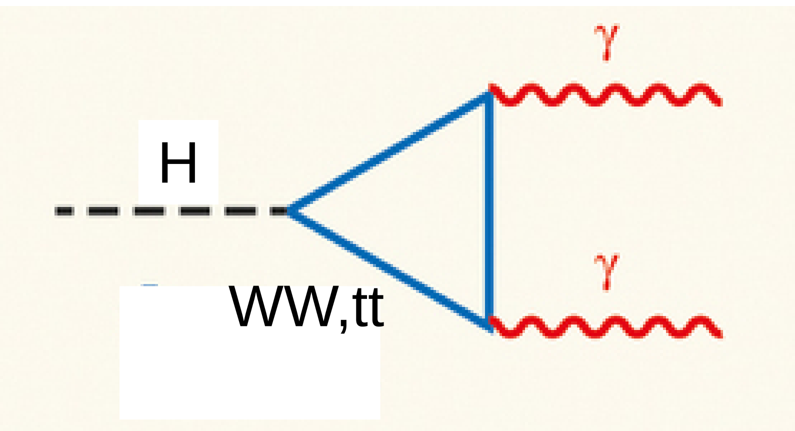
SUSY scalar - $F_0(x_S) \simeq 0.4$ $\quad M_S \sim \mathcal{O}(100 \text{ GeV})$

- Substantial effects possible for very light stops or large couplings

Higgs decay to photons

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{1024\pi^3} \left| \frac{g_{hVV}}{m_V^2} Q_V^2 F_1(x_V) + \frac{2g_{hf\bar{f}}}{m_f} N_{c,f} Q_f^2 F_{1/2}(x_f) + \frac{g_{hSS}}{m_S^2} N_{c,S} Q_S^2 F_0(x_S) \right|^2$$

Extra factor for charged SUSY scalars



- W/Z bosons large dominant contribution
- SUSY effect smaller than ggF
- Opposite sign of W and top contribution
  - **If scalar increases diphoton decay will reduce gluon fusion, and vice versa**

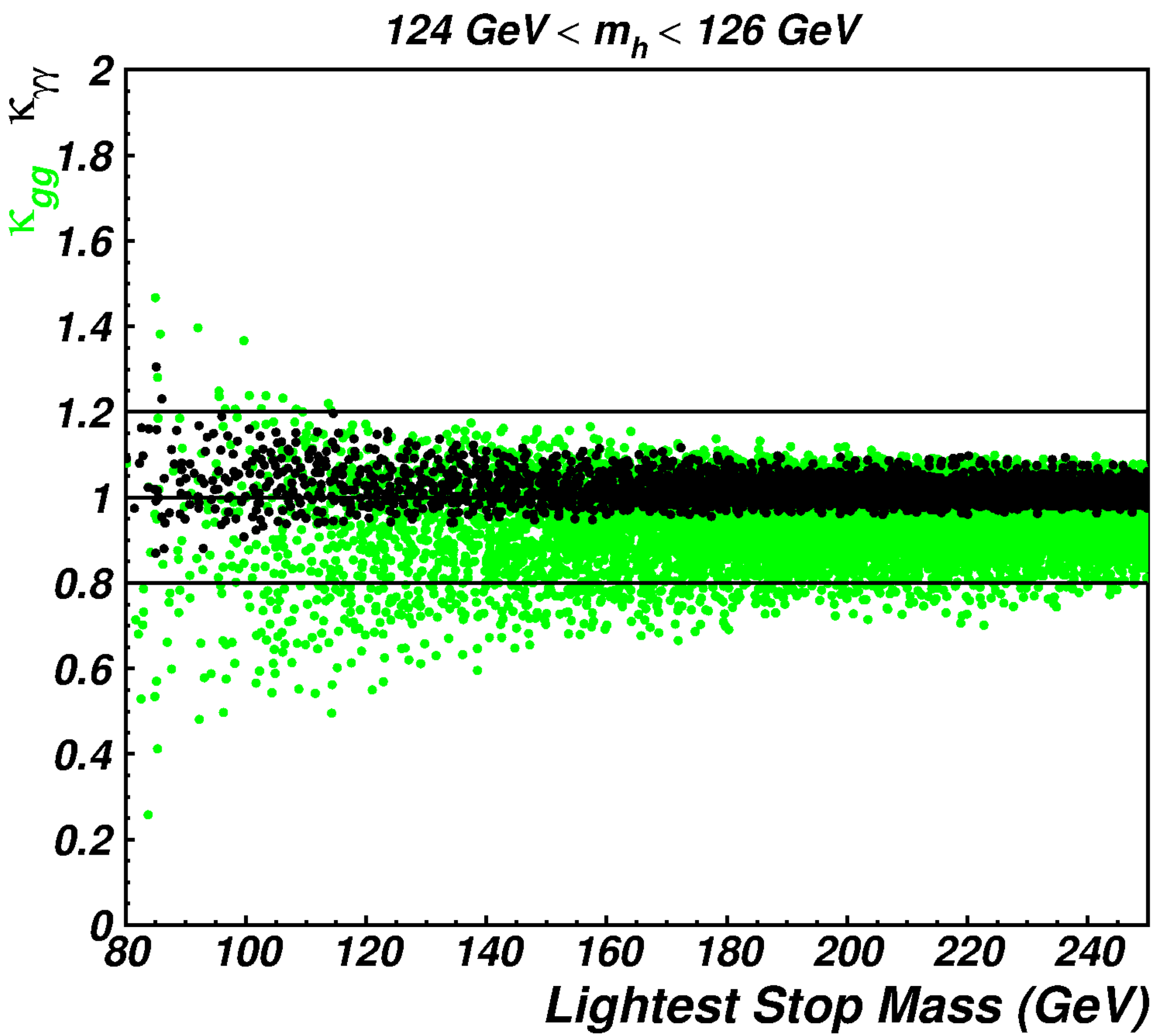
W boson - $F_1(x_W) \simeq -8.3$

Top quark - $N_{c,f} Q_f^2 F_{1/2}(x_f) \simeq 1.8$

Charged scalar - $F_0(x_S) \simeq 0.4$ $M_S \sim \mathcal{O}(100 \text{ GeV})$

W : Top : Scalar
5 : 1 : 1/5

Stops effect on Higgs properties



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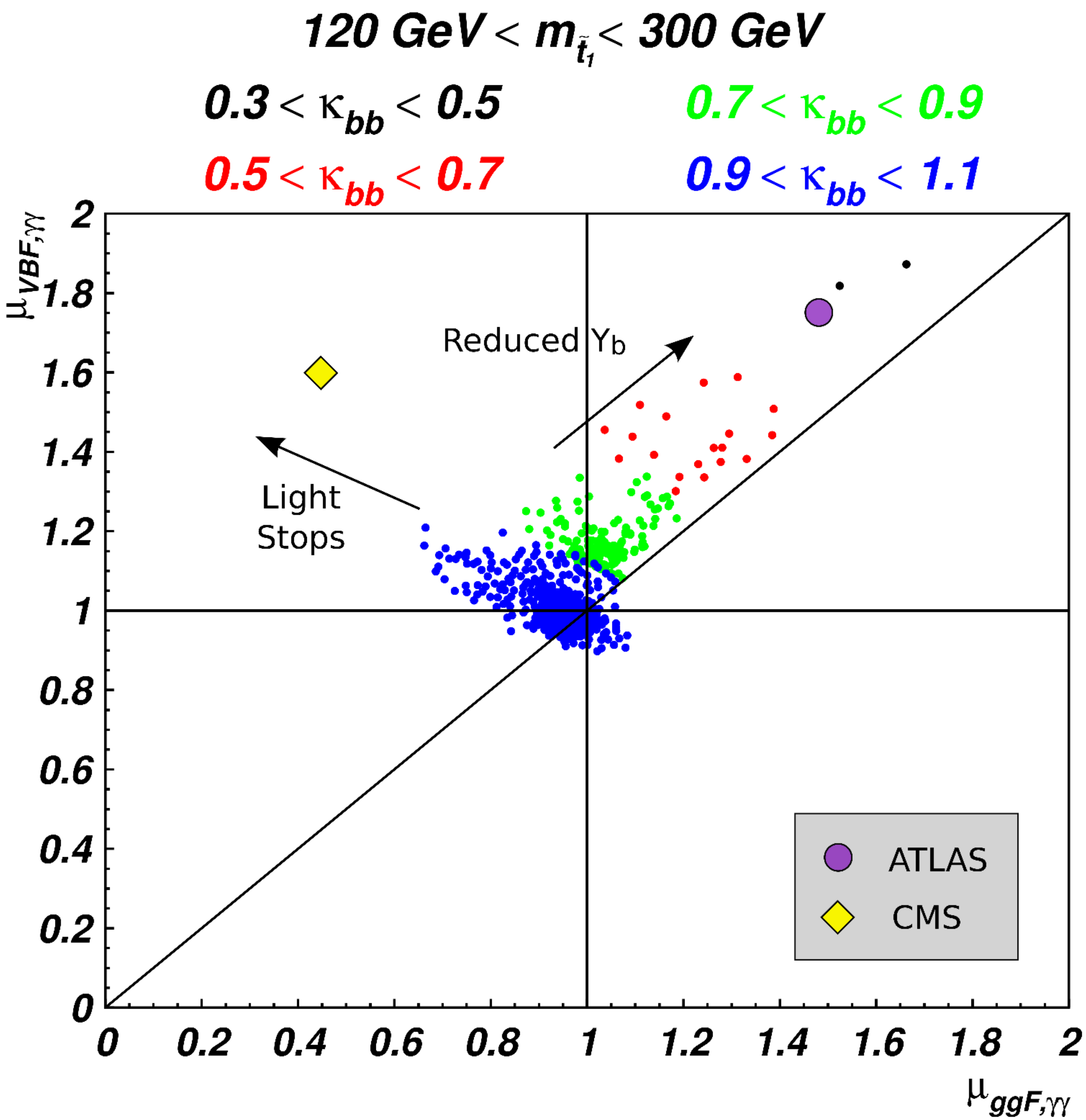
- κ_{gg}
- $\kappa_{\gamma\gamma}$

} Scaling relative to SM

- Effects on production larger than diphoton decay.
- Can increase or decrease channel.
- Larger effects for lighter stops.

Stops effects on signal strengths



- Non-universality of production channels occurs.
- $\mu_{ggF,\gamma\gamma} \approx 1$ with $\mu_{VBF,\gamma\gamma} \approx 1.3$ can occur in light stop scenario with reduced Y_b
- **Limiting stop masses would limits the possible deviation from the SM.**

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Electroweak Baryogenesis

The light stop scenario

- **Sakharov conditions**
  - 1) Departure from thermodynamic equilibrium.
  - 2) Baryon number violation (via sphaleron transitions).
  - 3) C and CP-violation.

- **All occur in the SM**
  - Unfortunately not enough to explain baryogenesis!

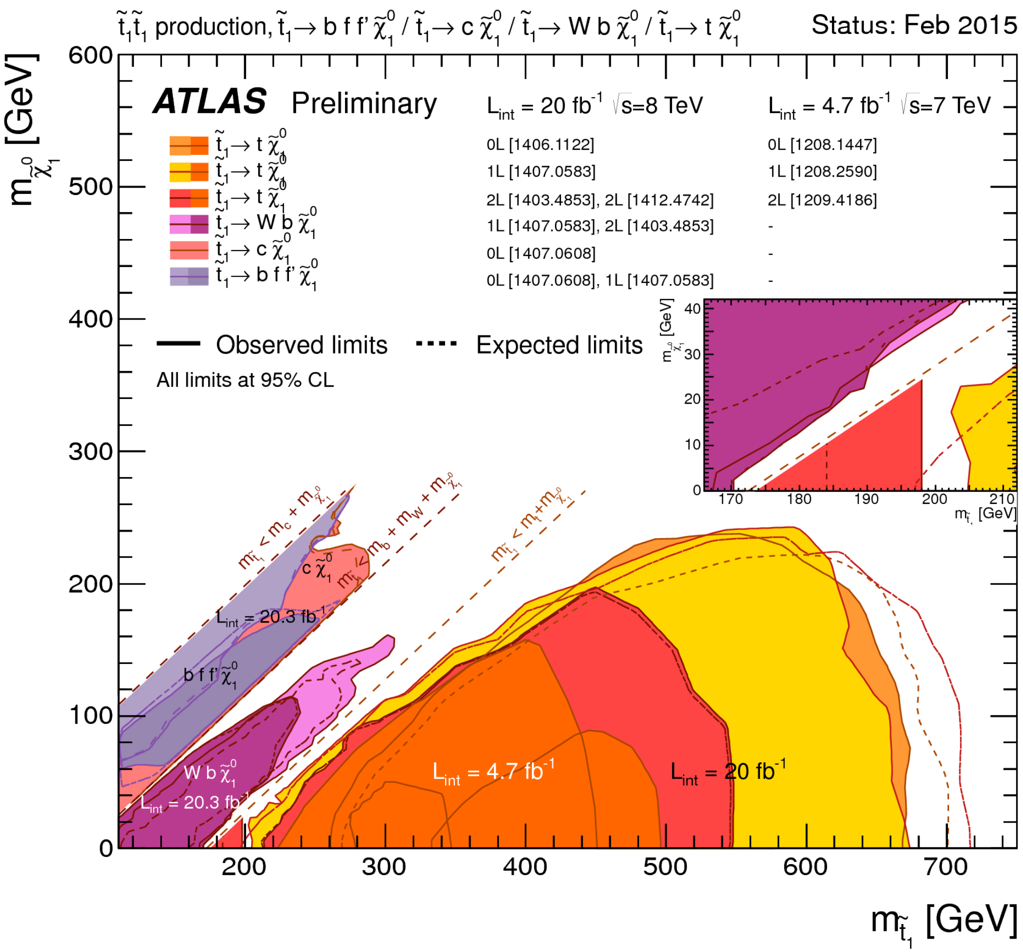
- **Light right handed stops enable a first-order phase transition**
  - light large enough departure from thermodynamic equilibrium to explain baryogenesis.
  - Requires $m_{\tilde{t}} \lesssim m_t$

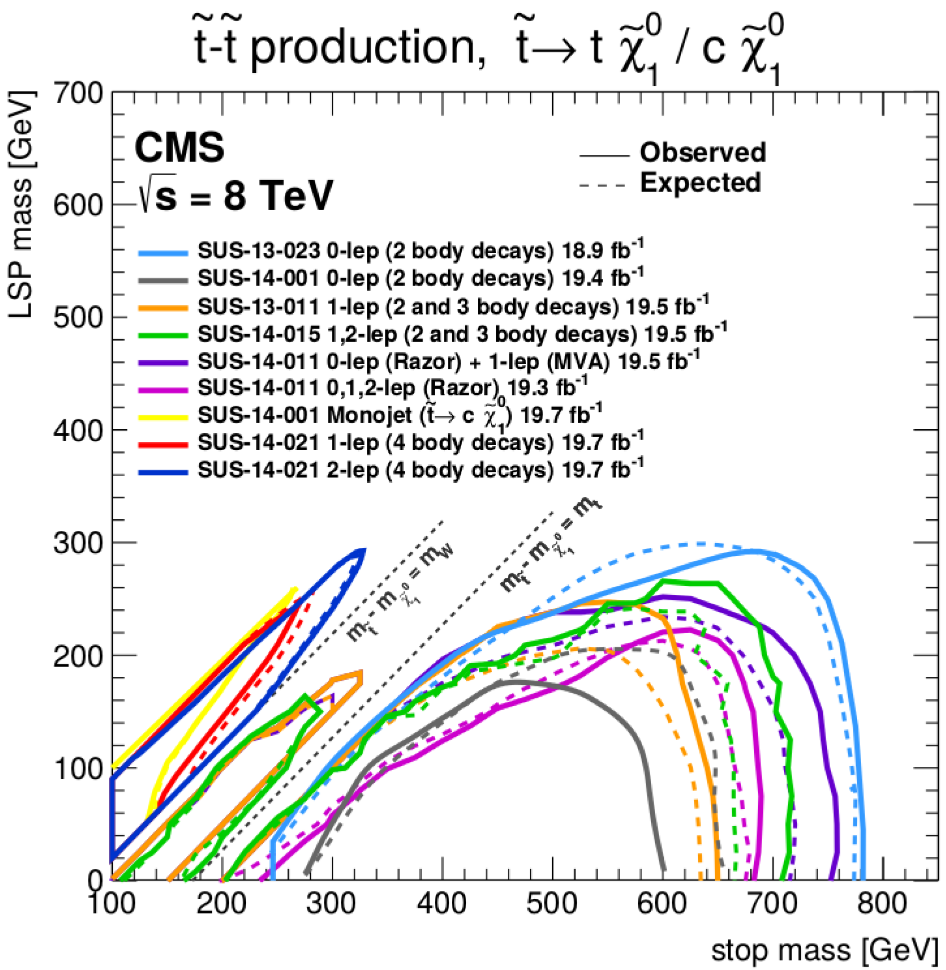
Electroweak Baryogenesis

The light stop scenario

- **Is it already ruled out?**
  - Papers claim to have ruled out light stop EWBG using Higgs data.(e.g. Curtin, et. al. JHEP **08** (2012) 005)
  - Others claim their limits are too optimistic, and also find loopholes.
    - Large Higgs decay to invisible.(Carena et. al. JHEP **1302** (2013) 001)
    - "funnel region" - both stops contributions to Higgs properties cancel each other. (Espinosa et. al. JHEP **1212** 077)
  - **Straightforward exclusion of EWBG by showing** $m_{\tilde{t}} > m_t$ **would be free of these loopholes.**

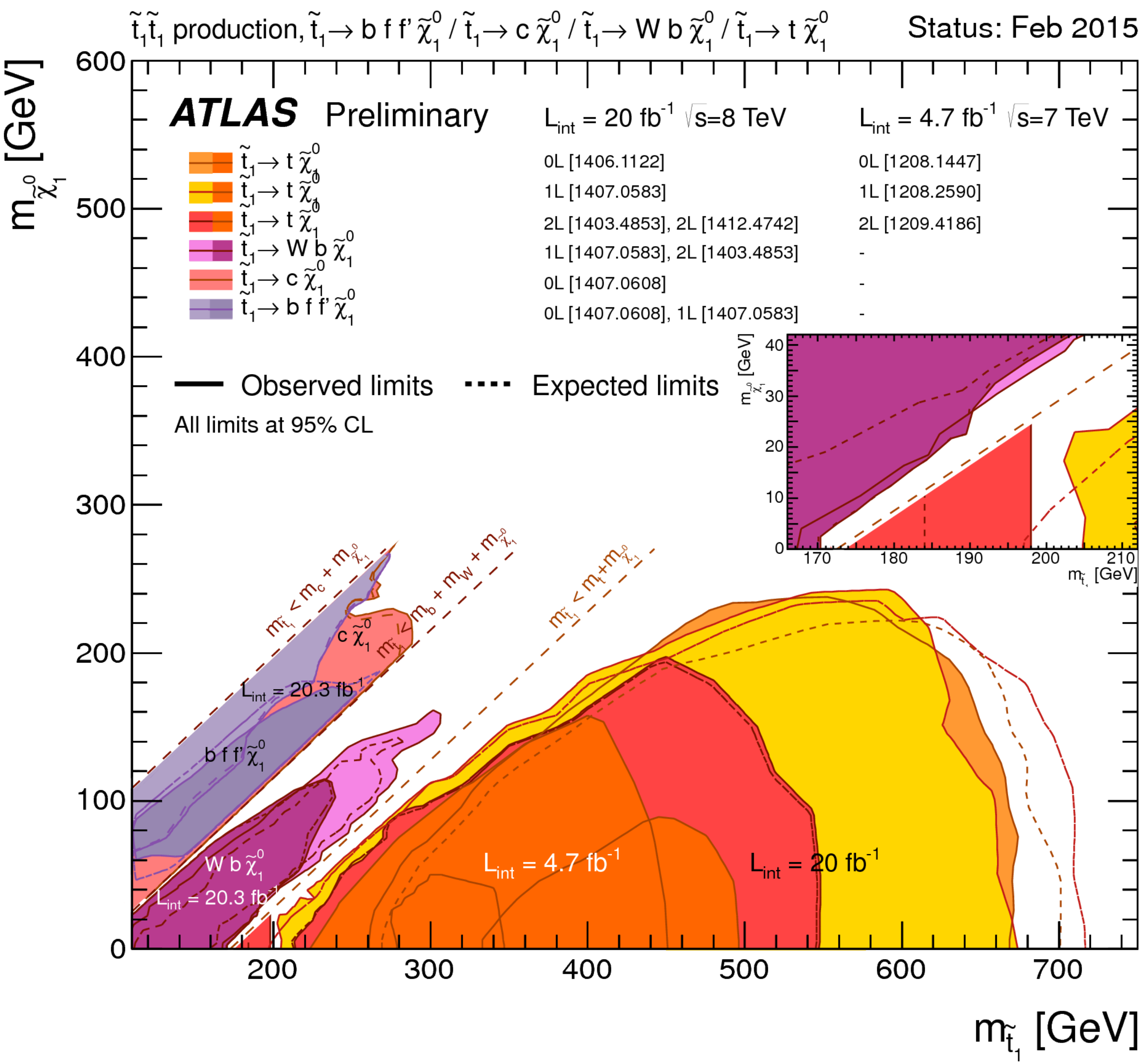
Current status of stop searches





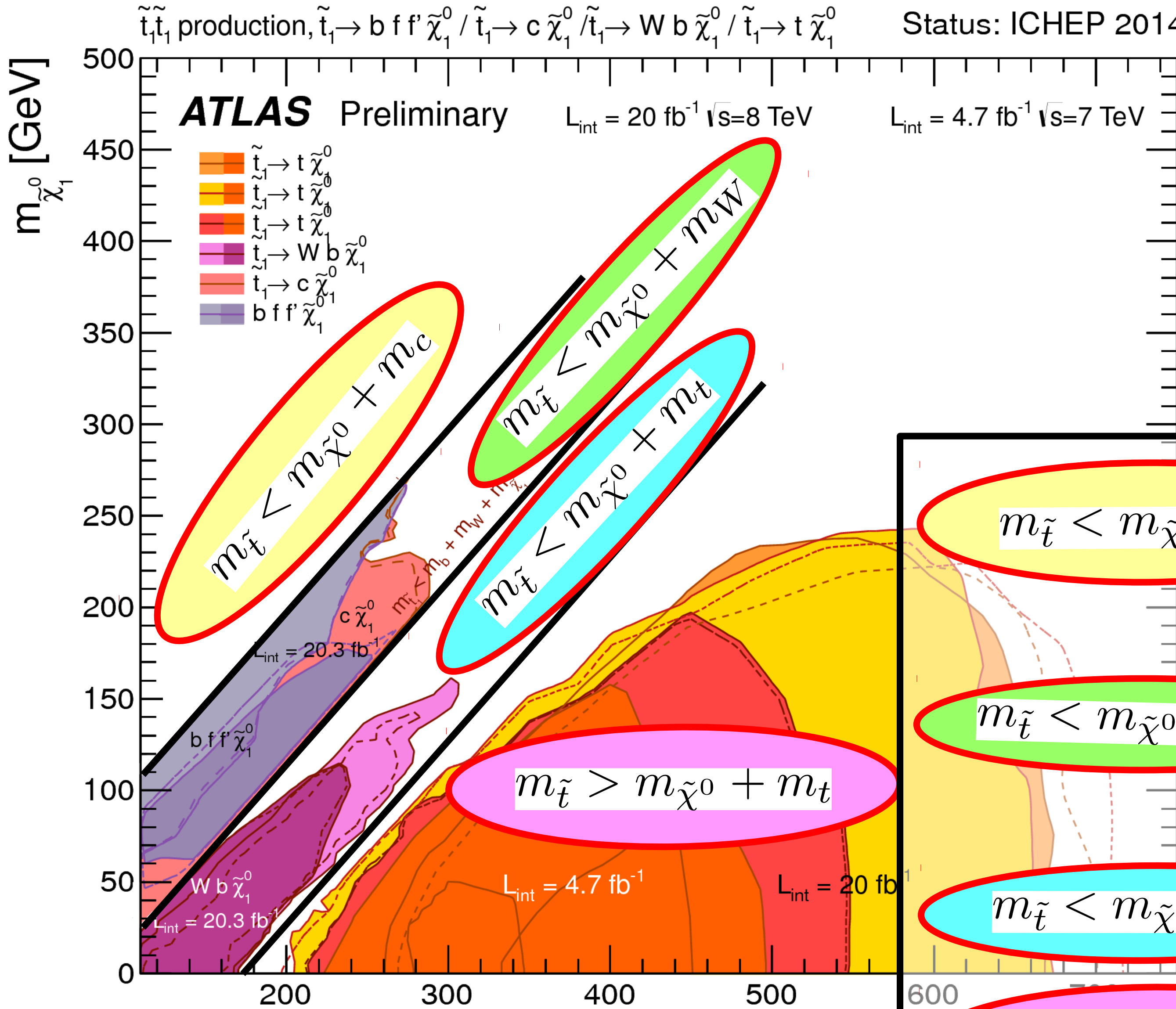
- Similar summary plots and analyses from CMS and ATLAS.
- Scope for extending some of the ATLAS analyses.

Current status of stop searches

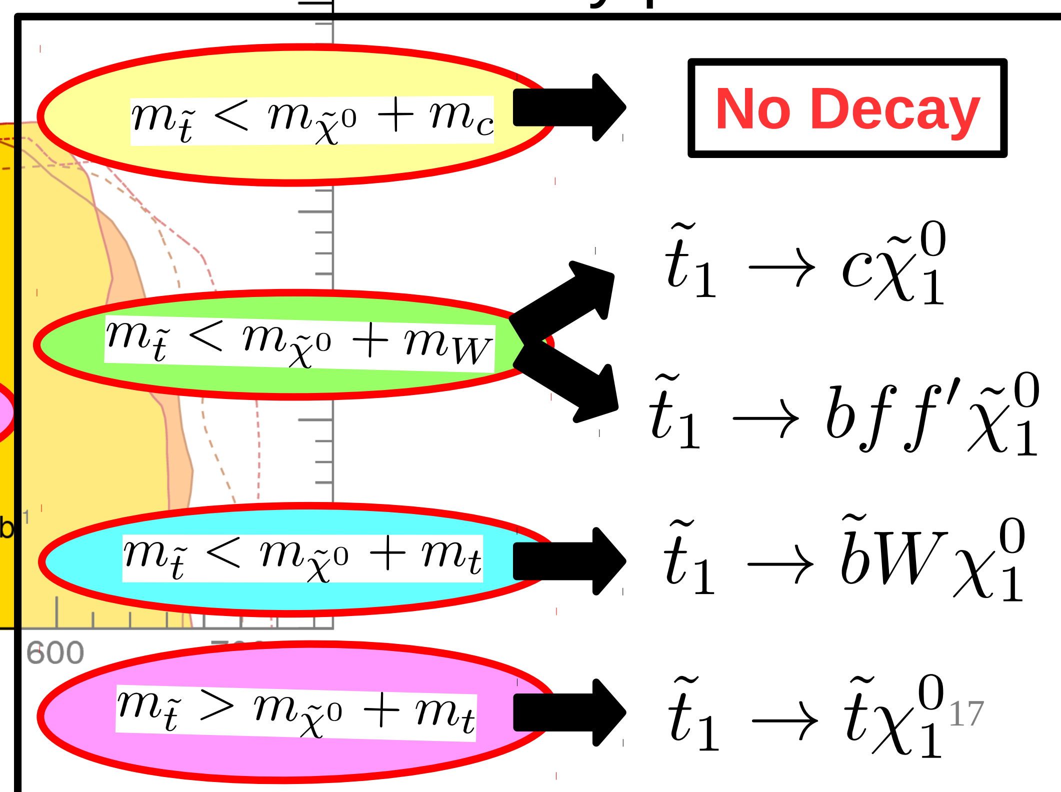


- Multiple search channels.
- **Generally assume 100% branching ratios.**
- Claim that stops ruled out up to 670 GeV only true for $M_{LSP} \sim 0$.
- If $M_{LSP} > 250$ GeV then only limit is $M_{stop} < M_{LSP}$

Current status of stop searches



- Separated into regions depending on relationship between stop mass and masses of decay products.



Current status of stop searches

- Different search criteria depending on area of parameter space targeted.

Monojet search + charm tag search

$\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$

Monojet + 1 lepton

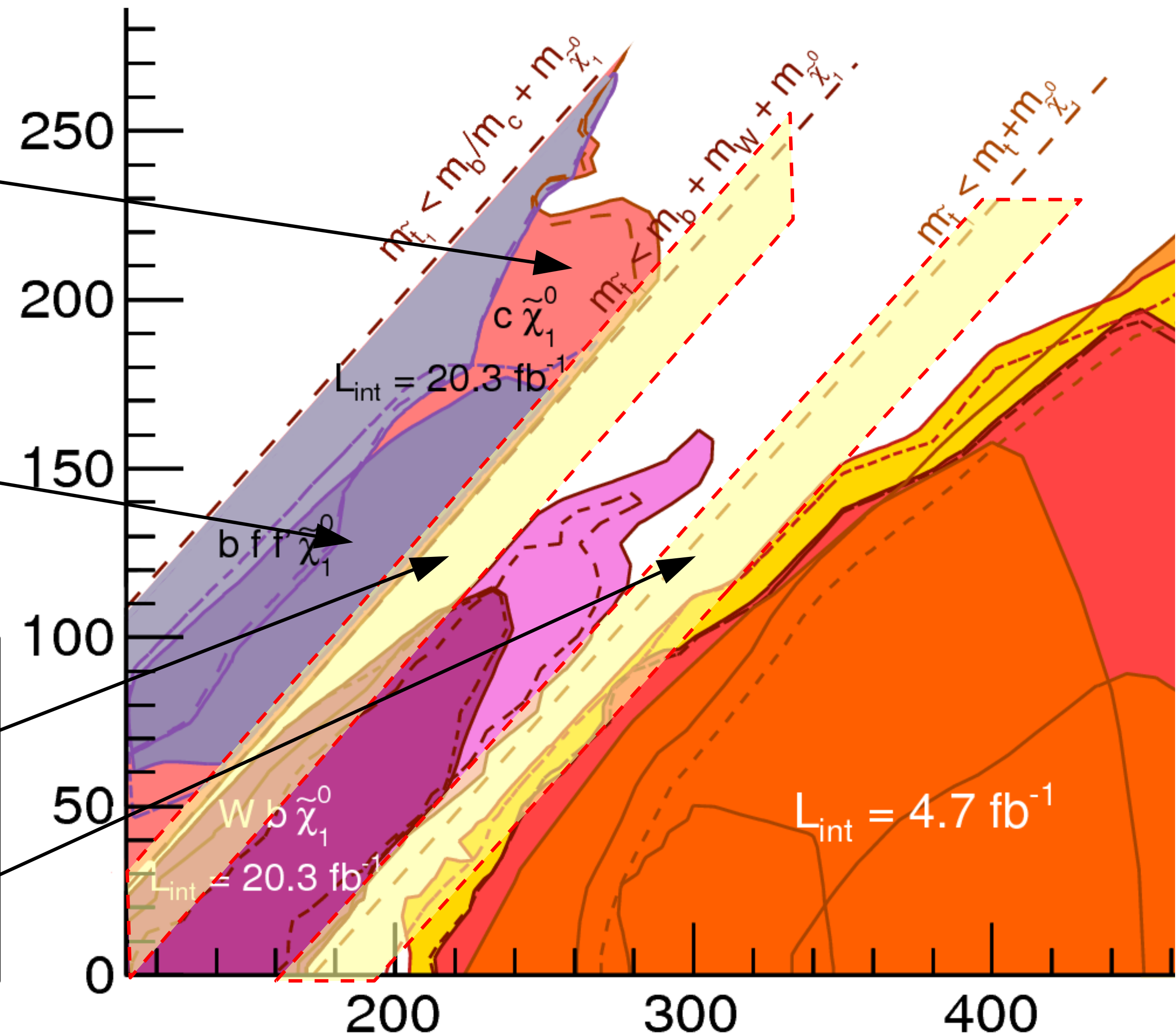
$\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$

Difficult regions where

$m_{\tilde{t}} \sim m_{\tilde{\chi}^0} + M_W$

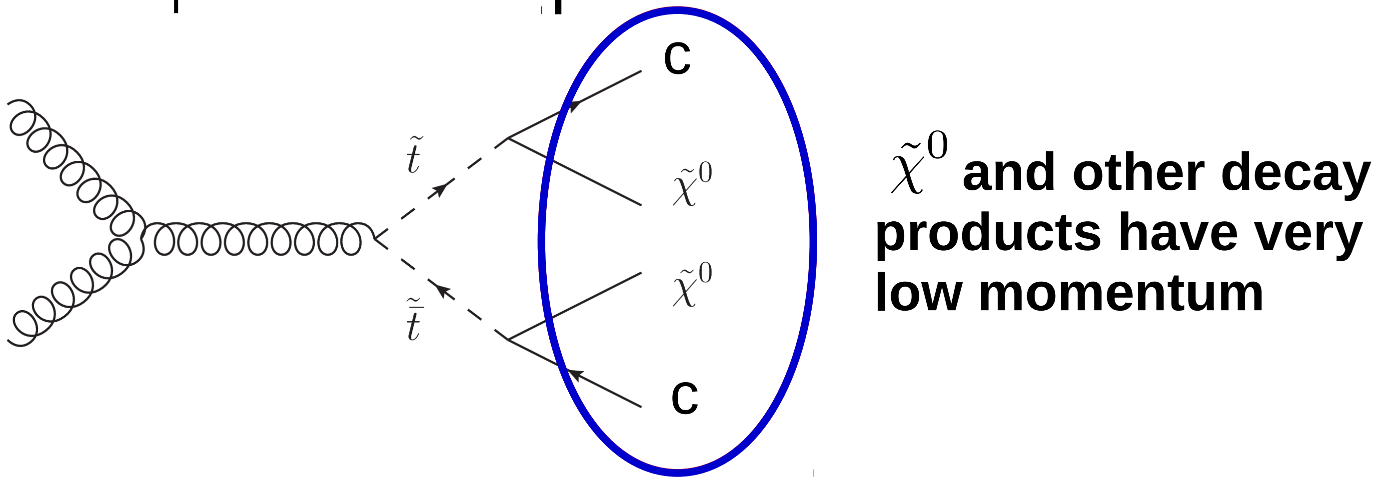
or

$m_{\tilde{t}} \sim m_{\tilde{\chi}^0} + m_t$

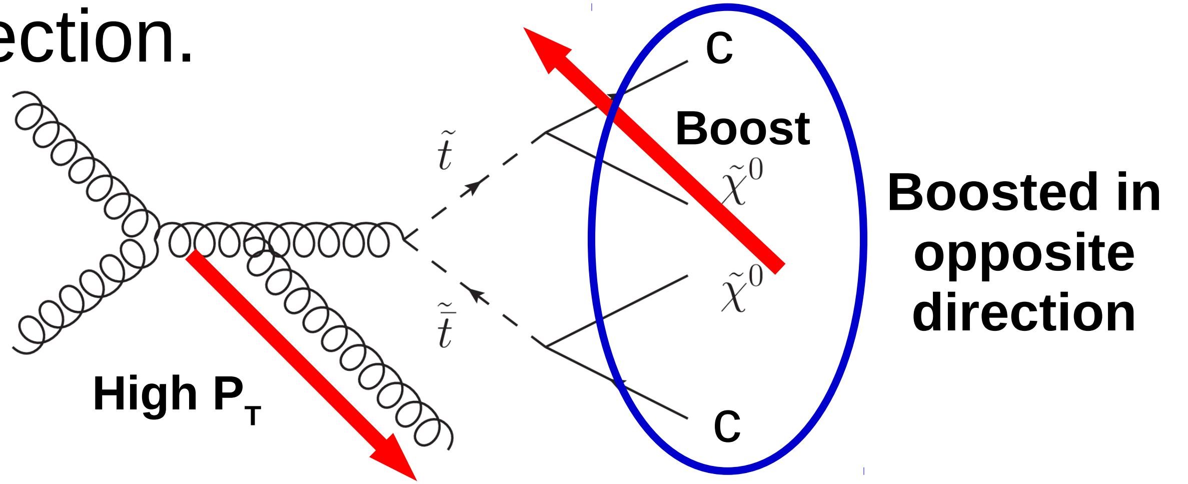


Monojet searches

- If $m_{\tilde{t}} \sim m_{\tilde{\chi}^0}$ then no missing transverse momentum (E_T^{miss}), and jets P_T too low to pass cuts.



- **With monojet** added, decaying particles boosted in opposite direction.



- Can be recognised in detector.

Charm Tagging

- First time charm tagging used at LHC.
- Multivariate techniques
  - Impact parameters of displaced vertices
  - Topological properties of 2nd, 3rd decay vertices reconstructed within a jet
- 2 operating points used in analysis:

"***medium***"
- c-tag efficiency 20%
- Rejection factors
  - b-jet: 5
  - Light-jet: 140
  - Tau-jet: 10

"***loose***"
- c-tag efficiency 95%
- Rejection factors
  - b-jet: 2
  - light/tau jets: no rejection

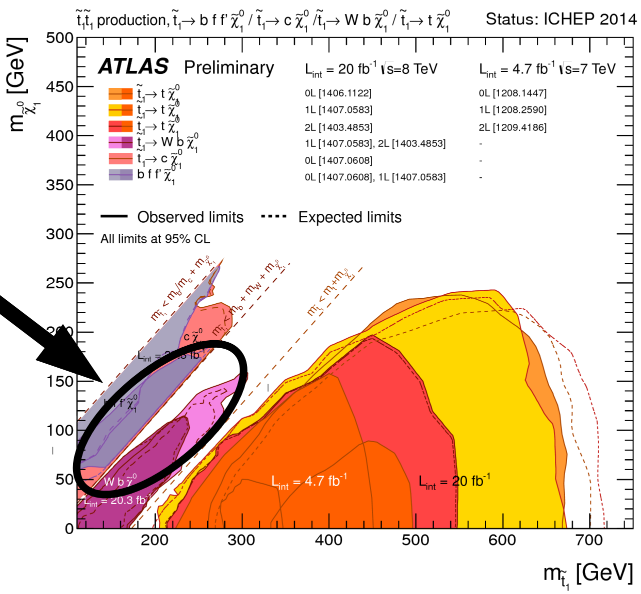
Summary points of stop searches

1) Always assume 100% BRs.

- Is this realistic?
- What are the limits if we relax this assumption?
- Relaxing this assumption is more model independent.

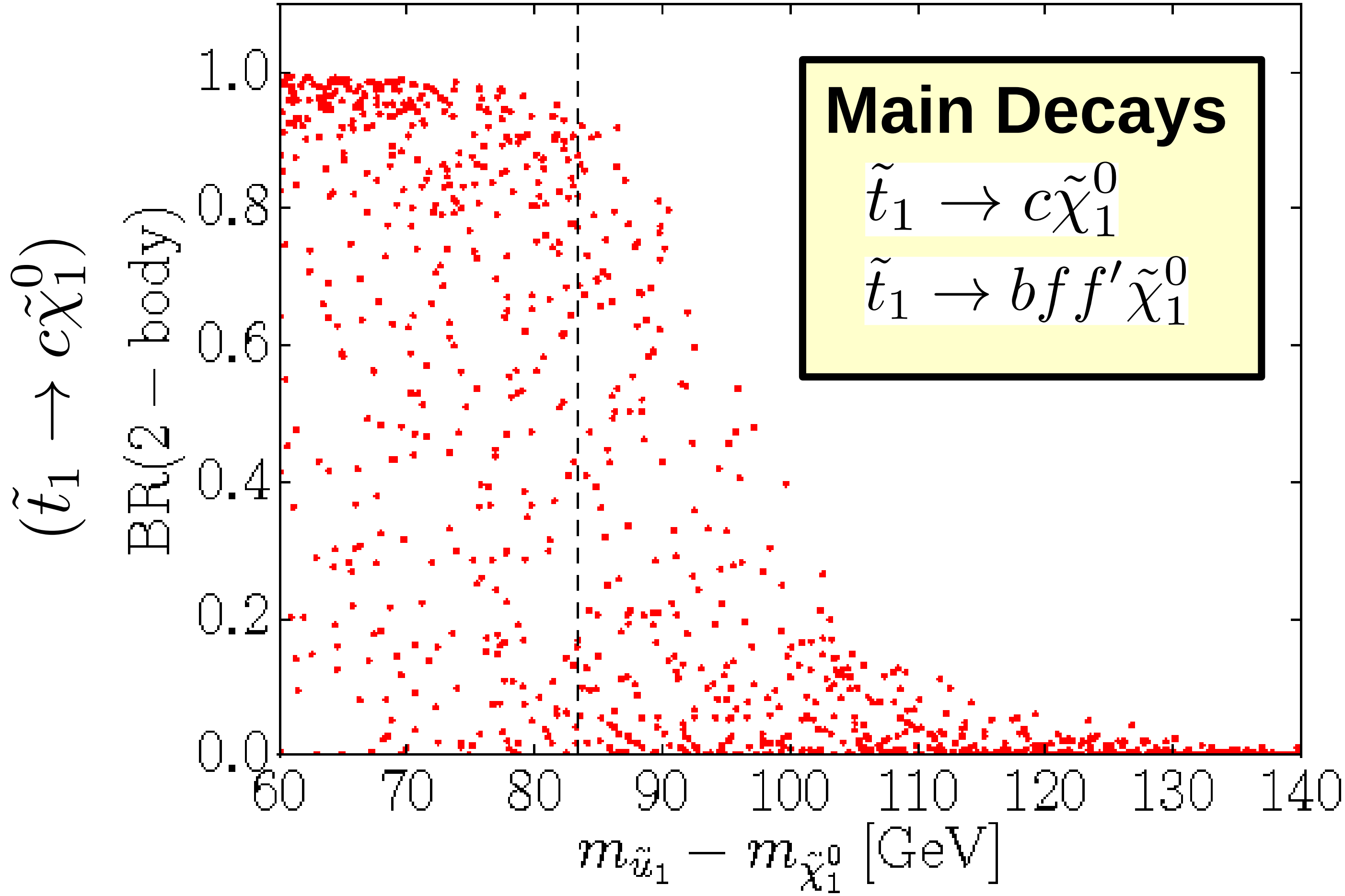
2) Important gaps in low mass region.

- Can we fill them?



Is a 100% BR realistic? NO!

Muhlleitner et. al. Phys.Lett. B747 (2015) 144-151



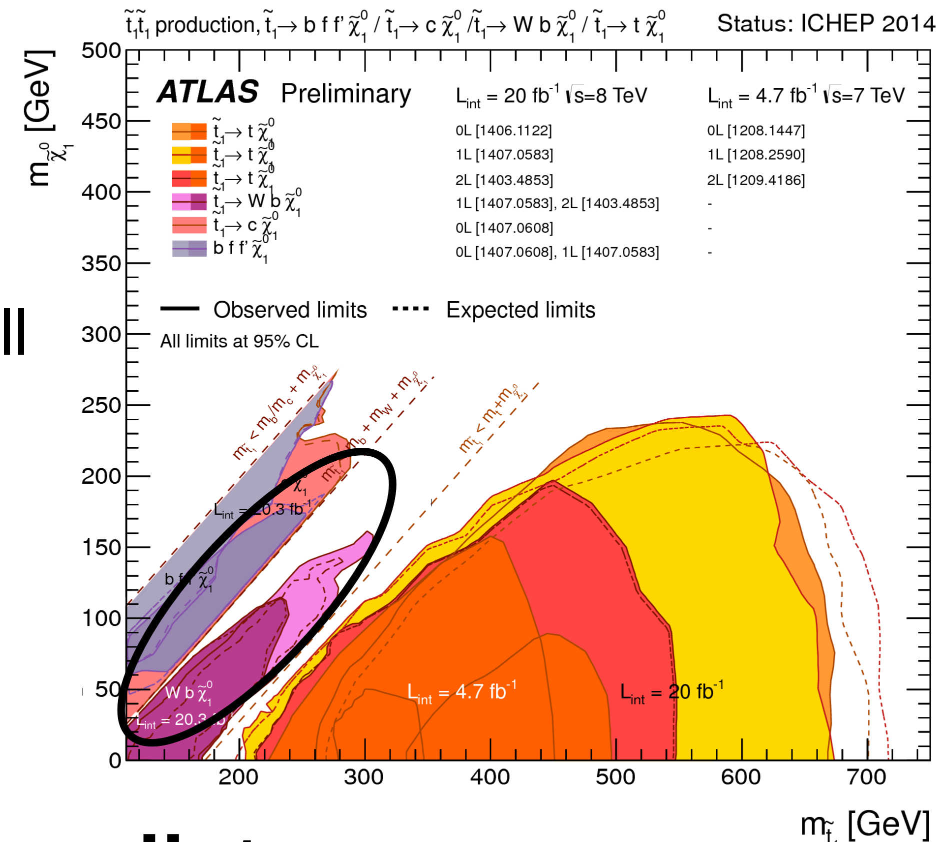
- Flavour changing currents within experimental constraints can still give a large $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0)$ for $m_{\tilde{t}} - m_{\tilde{\chi}^0} \sim 100$ GeV
- **We need to understand the limits when BR ≠ 100%**

Our goals

Extend to cover area missed by ATLAS

1) **Redo and extend ALTAS analyses**

- Due to difficulties in SUSY signal event generation and analysis, ATLAS unable to cross the line where $m_{\tilde{t}} \sim m_{\tilde{\chi}^0} + m_W$
- Aim to overcome limitations and fill this gap as much as possible.



- Important region for **stop baryogenesis** and **naturalness**.

2) **Study effects of intermediate branching ratios for $\tilde{t}_1 \to c\tilde{\chi}_1^0$ and $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$**

- More model independent scenario.

What we did

- Reproduced and extended 3 different ATLAS analysis regions near $m_{\tilde{t}} \sim m_{\tilde{\chi}^0} + m_W$ line
  - Monojet
  - Monojet + charm-tag
  - Monojet + 1 lepton

- Produce full matrix element events using MadGraph5.
  - Computationally difficult for $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$
  - **Overcomes limitation of ATLAS analysis,** which used Pythia (computationally easy but not valid in on-shell region).
  - Delphes for detector level simulation.

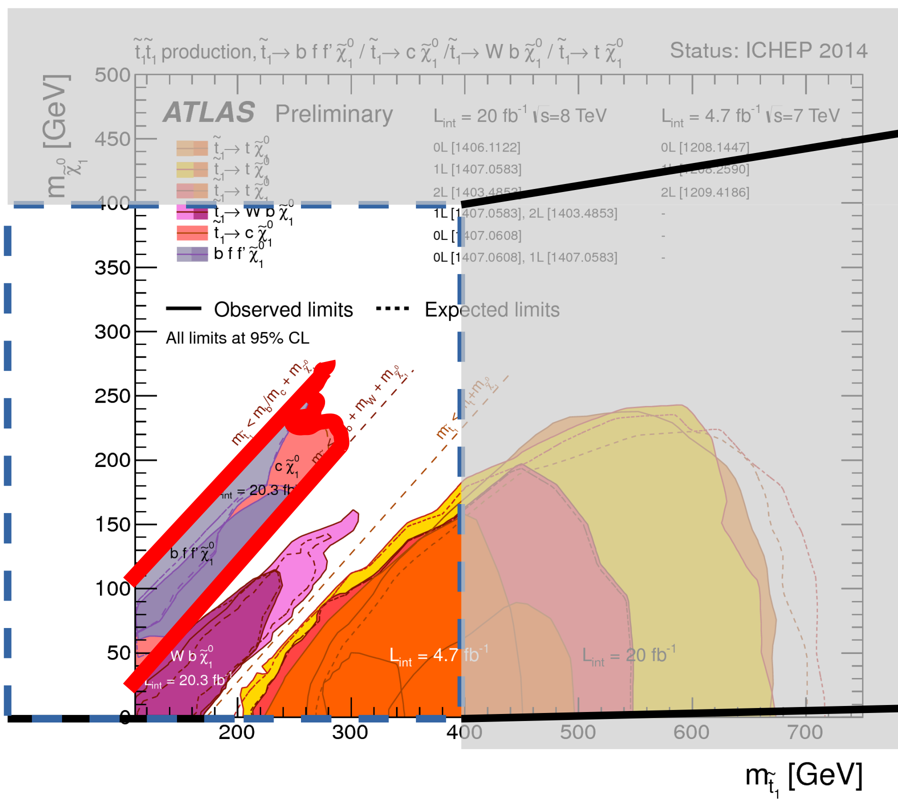
- Use published data to calculate excluded region at 95% CL.
- Study how the limits change when BR ≠ 100%

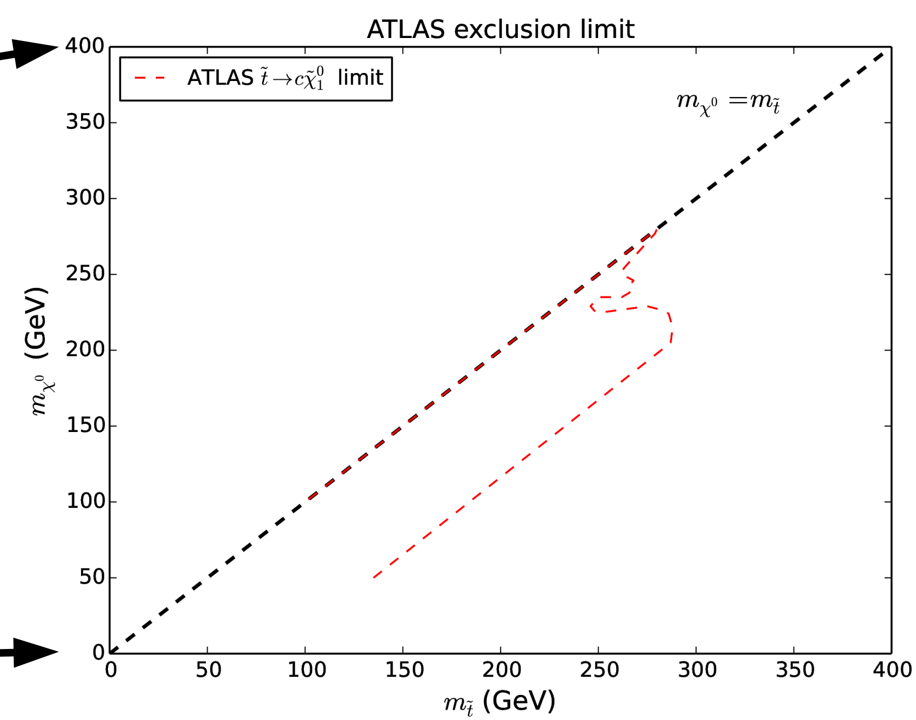
Results $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$

Monojet and Monojet + charm tag regions

Monojet Cuts
(3 subregions)
Leading Jet P_T > 280-450 GeV
Minimum E_T^{miss} > 220-450 GeV
+ other cuts

Monojet + charm tag
(2 subregions)
Charm tag on subleading jet
+
Leading Jet P_T > 290 GeV
Minimum E_T^{miss} > 250-350 GeV
+ other cuts





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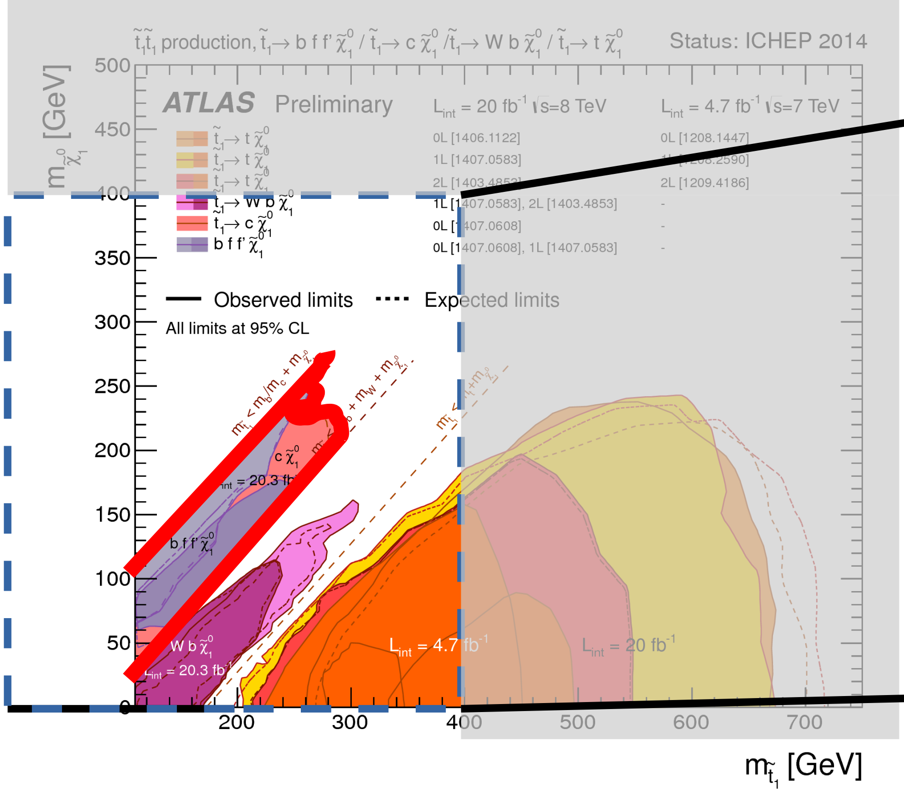

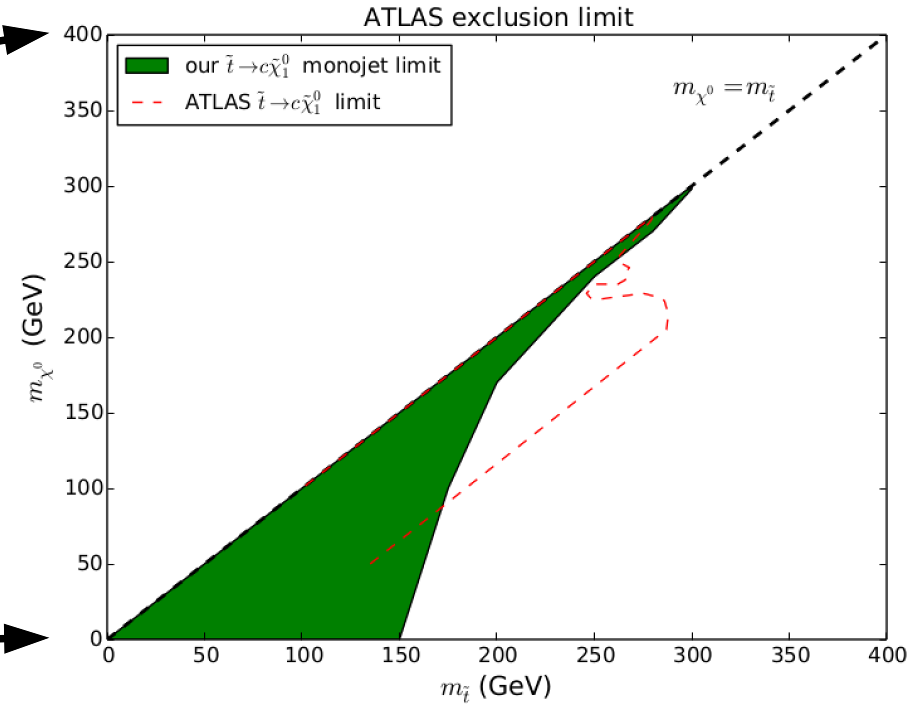

Results $\tilde{t}_1 \to c\tilde{\chi}^0_1$

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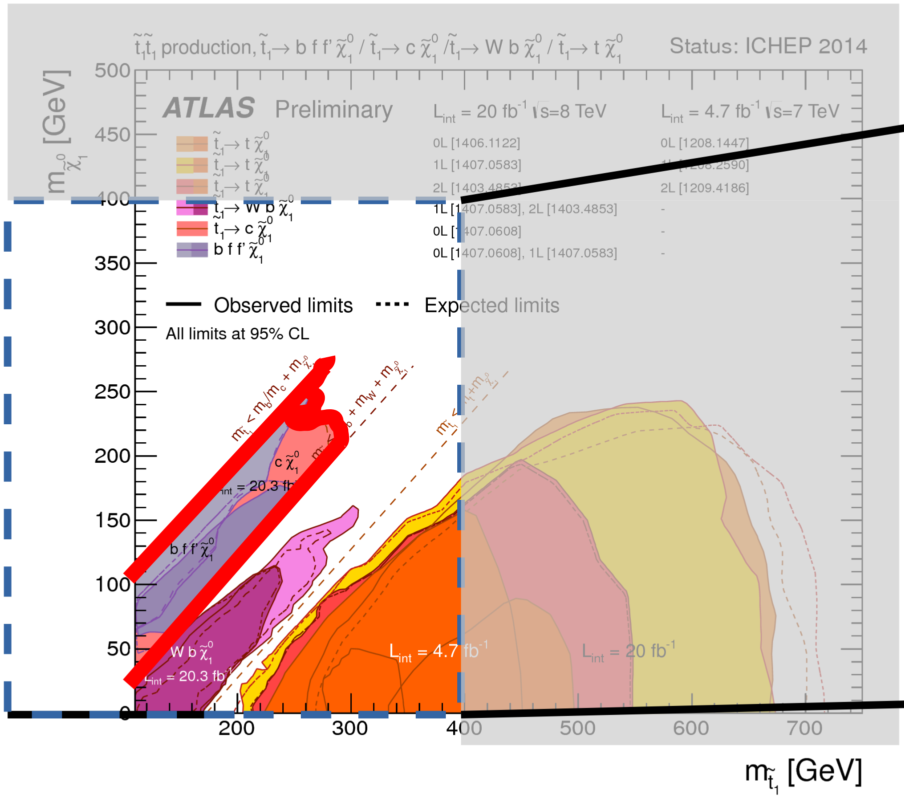
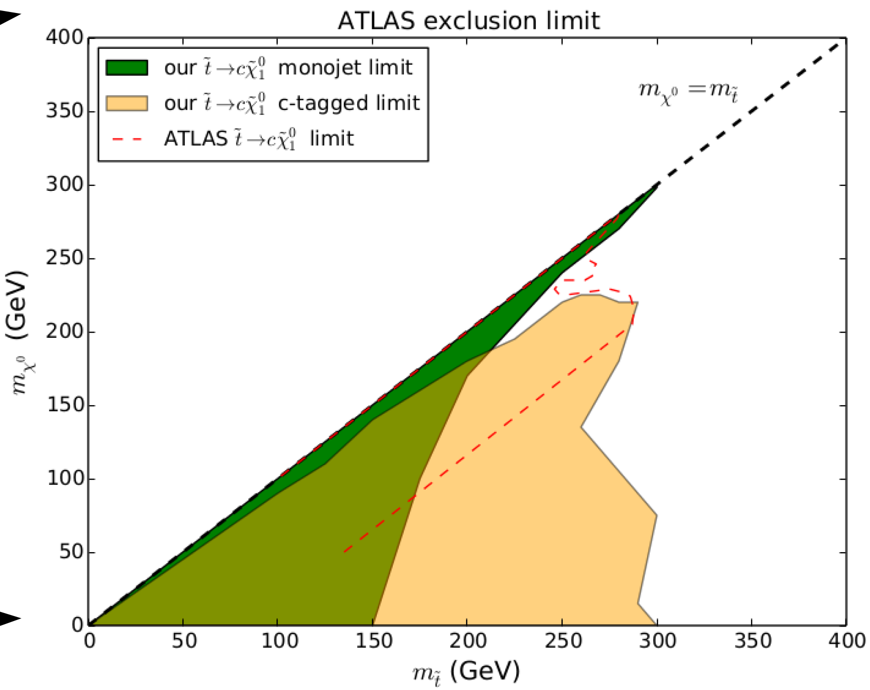




Results $\tilde{t}_1 \to b f f' \tilde{\chi}_1^0$

Monojet + 1 lepton

Monojet + 1 lepton

(2 subregions)

Leading Jet P_T > 180 GeV

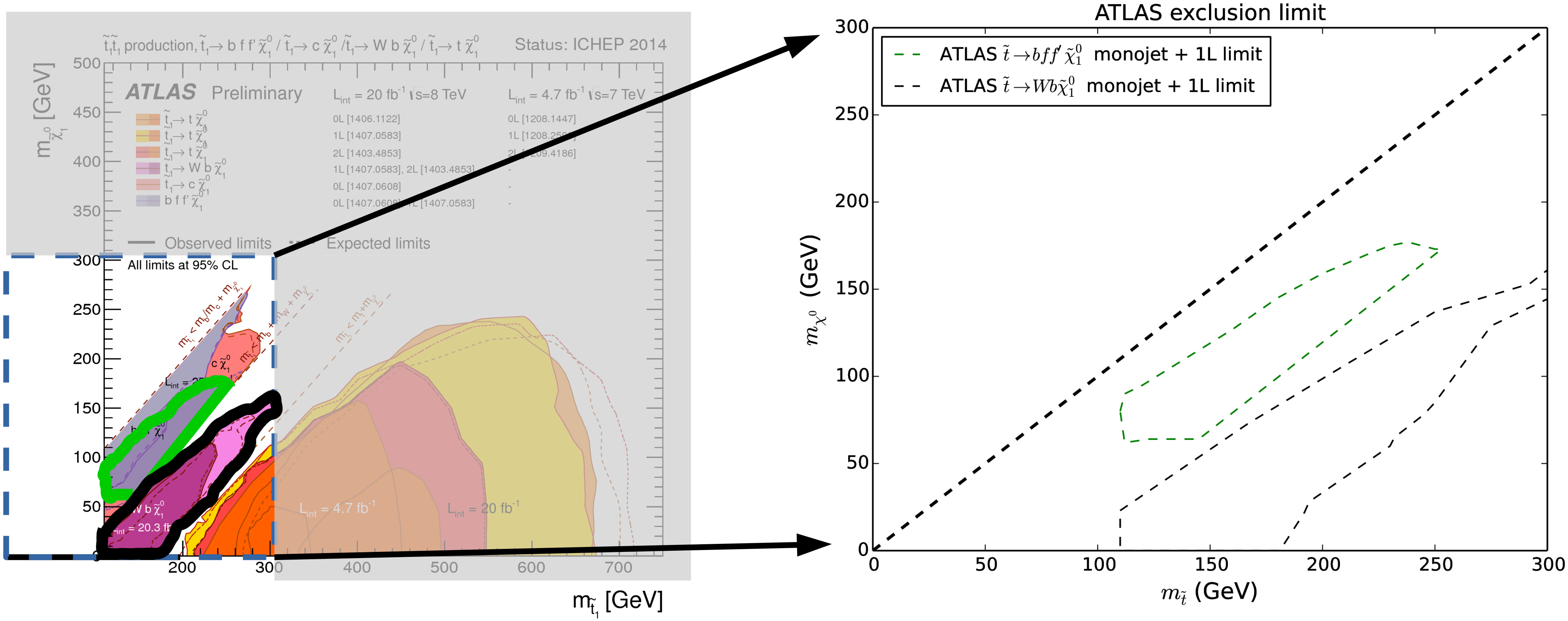
Second (Third) Jet P_T > 25 GeV

Minimum E_T^{miss} > 300-370 GeV

1[st] Jet *not* b-tagged

6 (7) GeV < 1 Lepton < 25 GeV

+ other cuts



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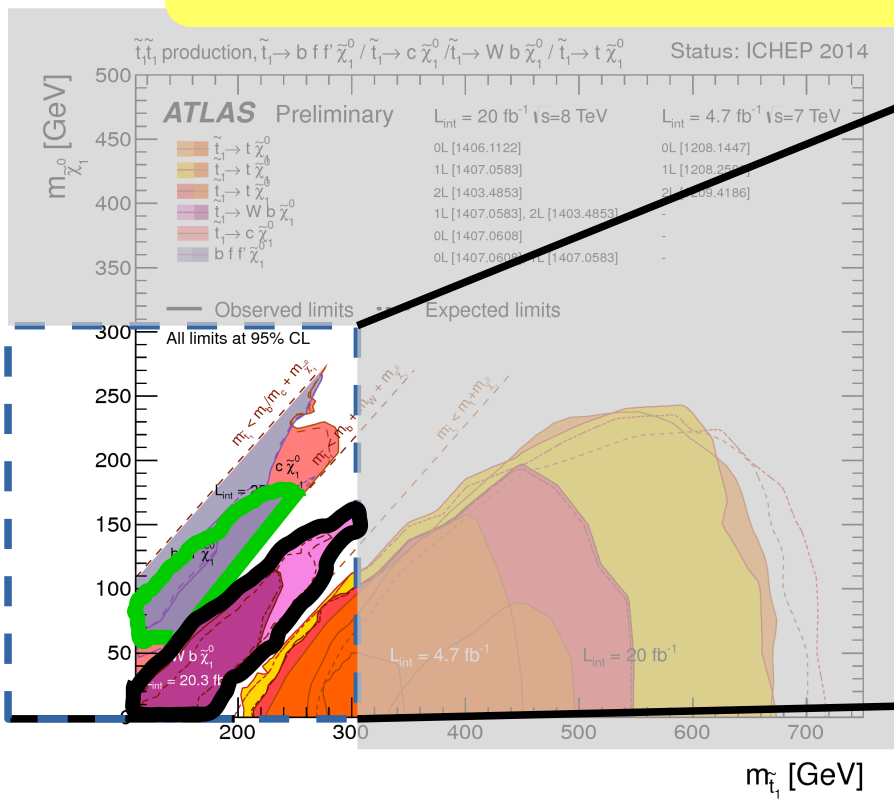
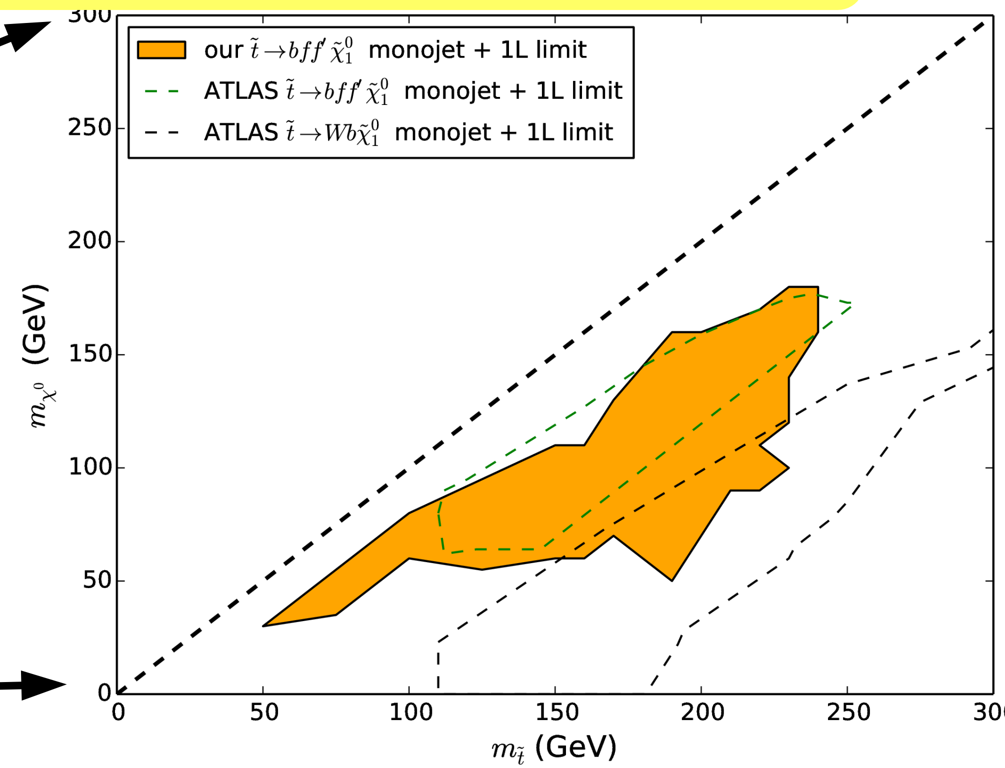
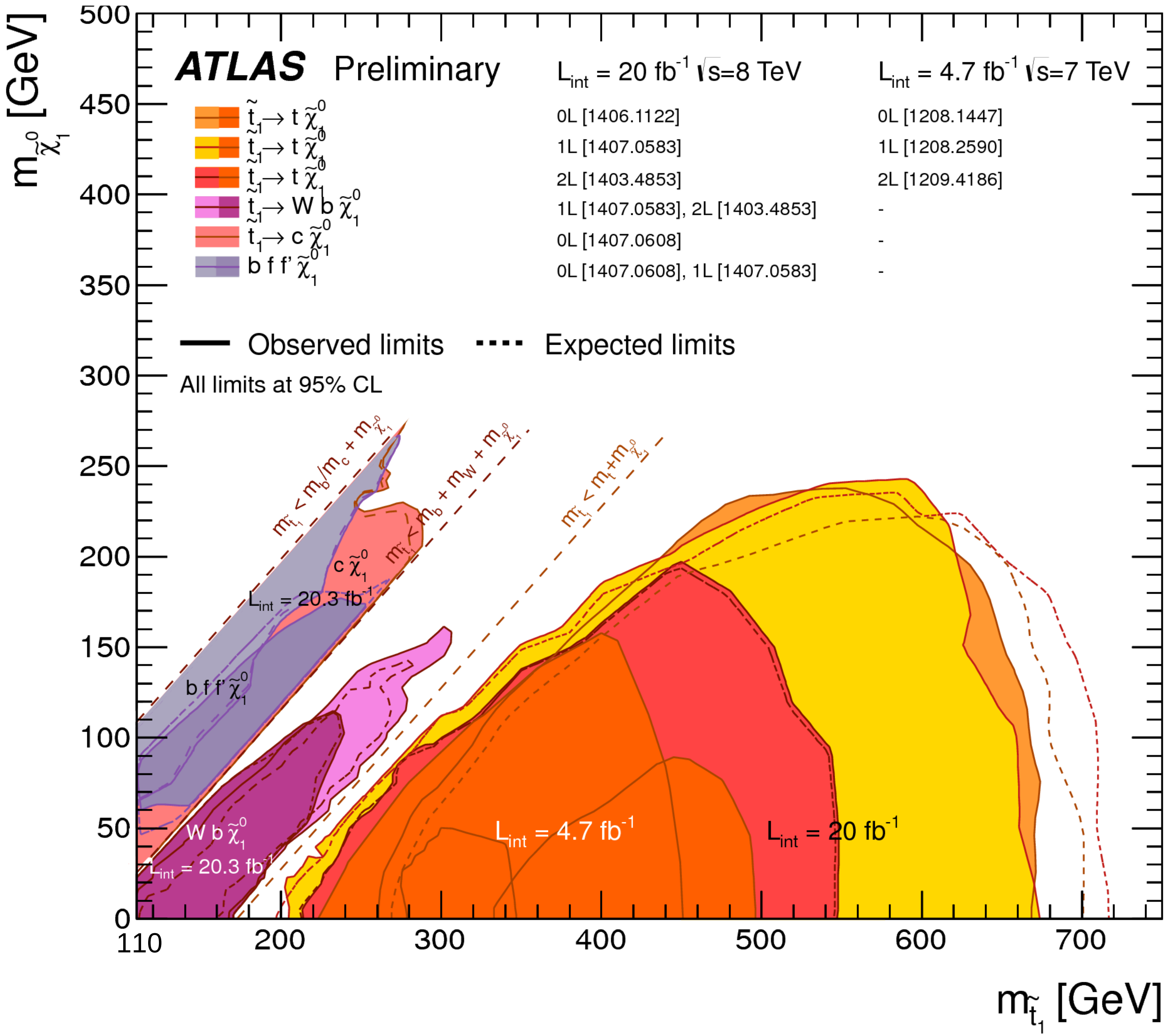




Superimposed results on ATLAS plot



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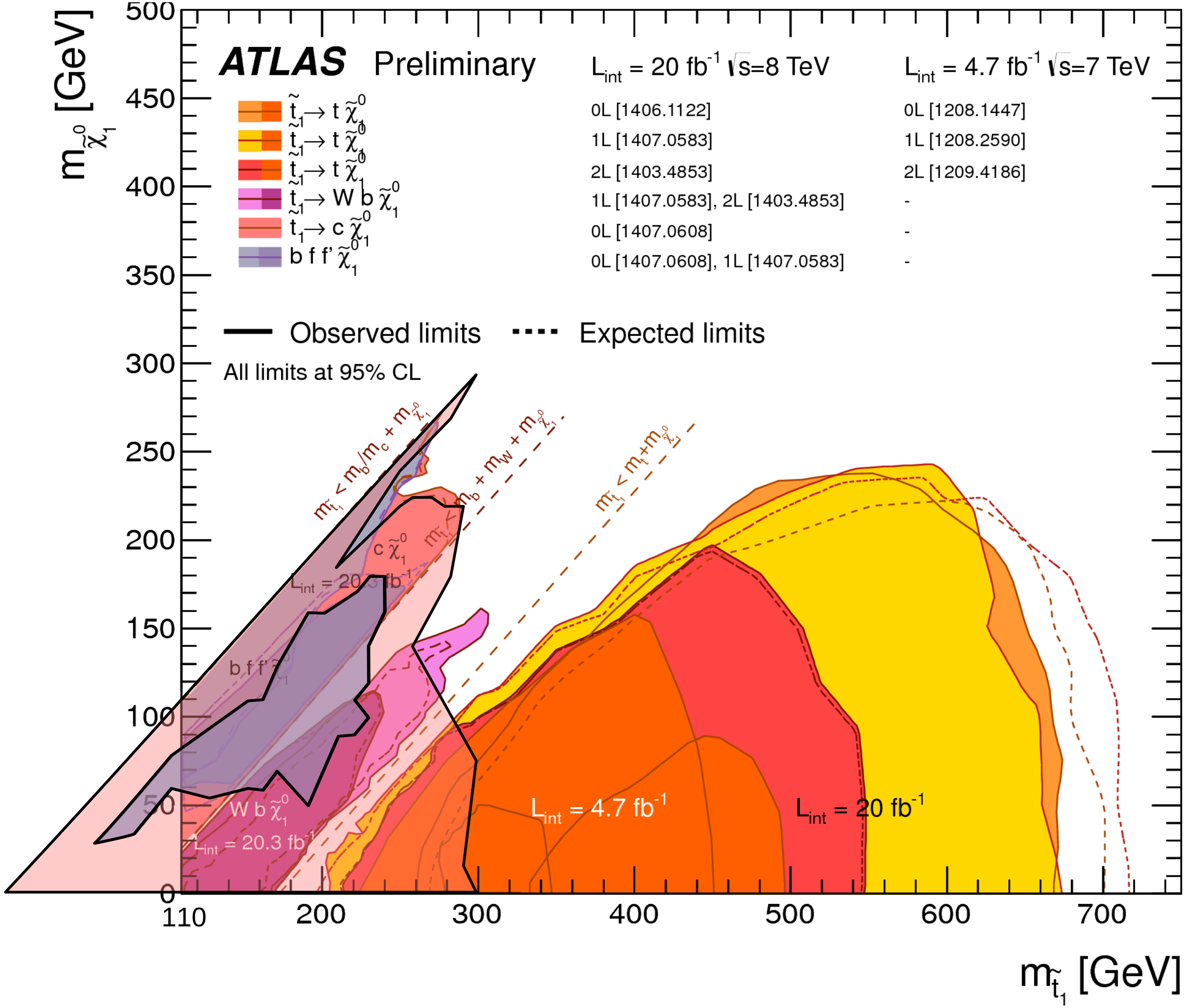

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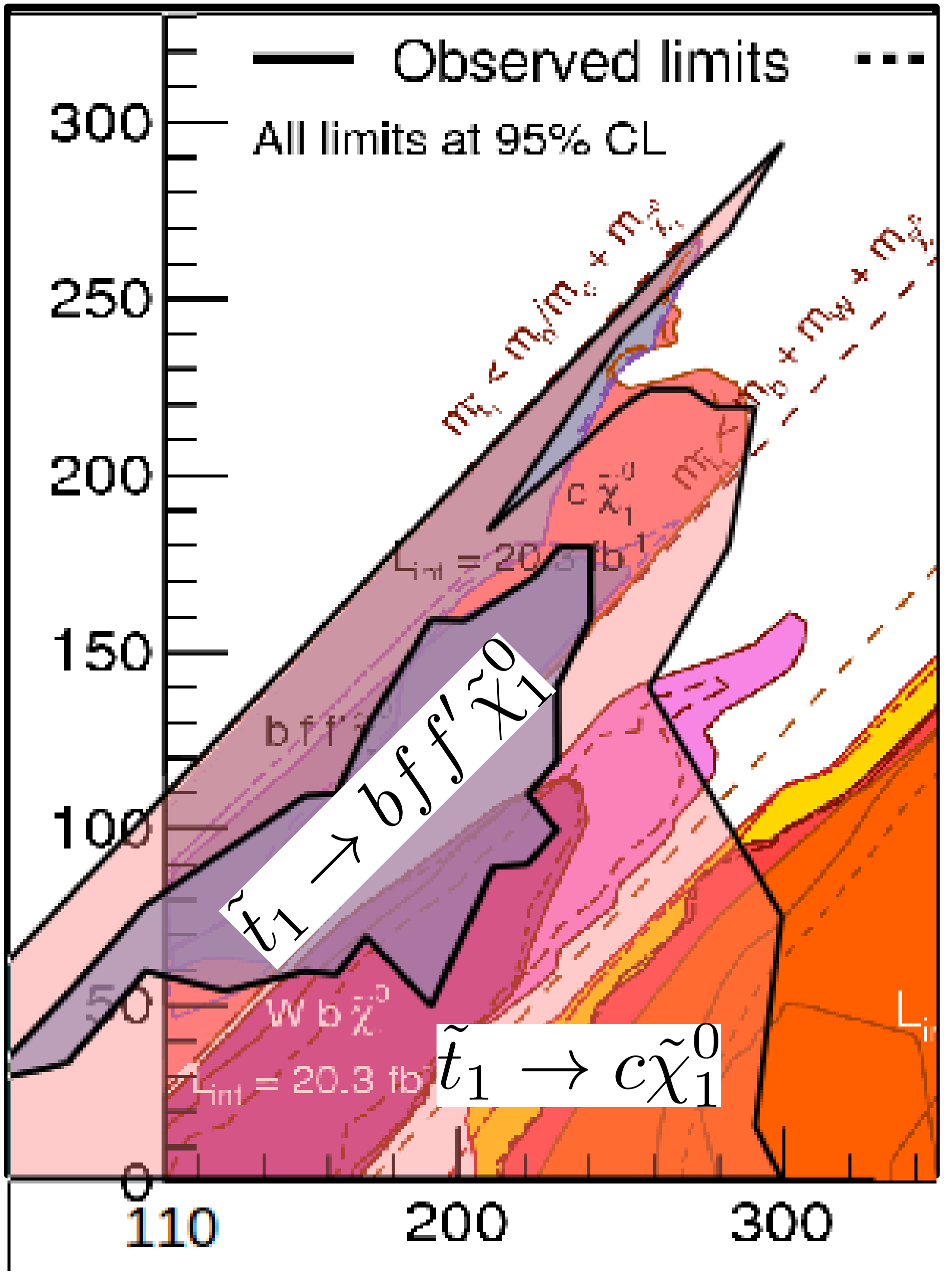
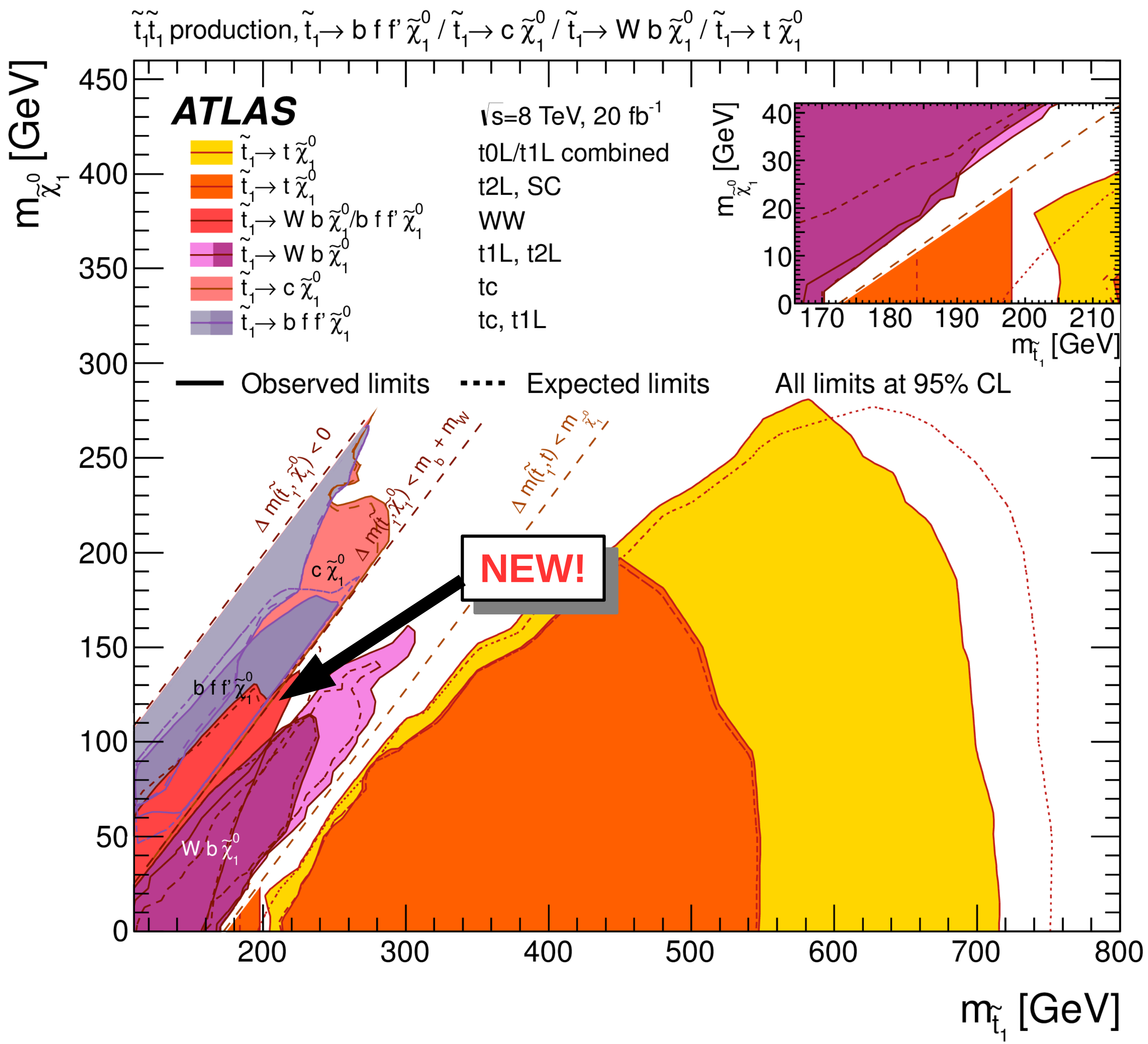


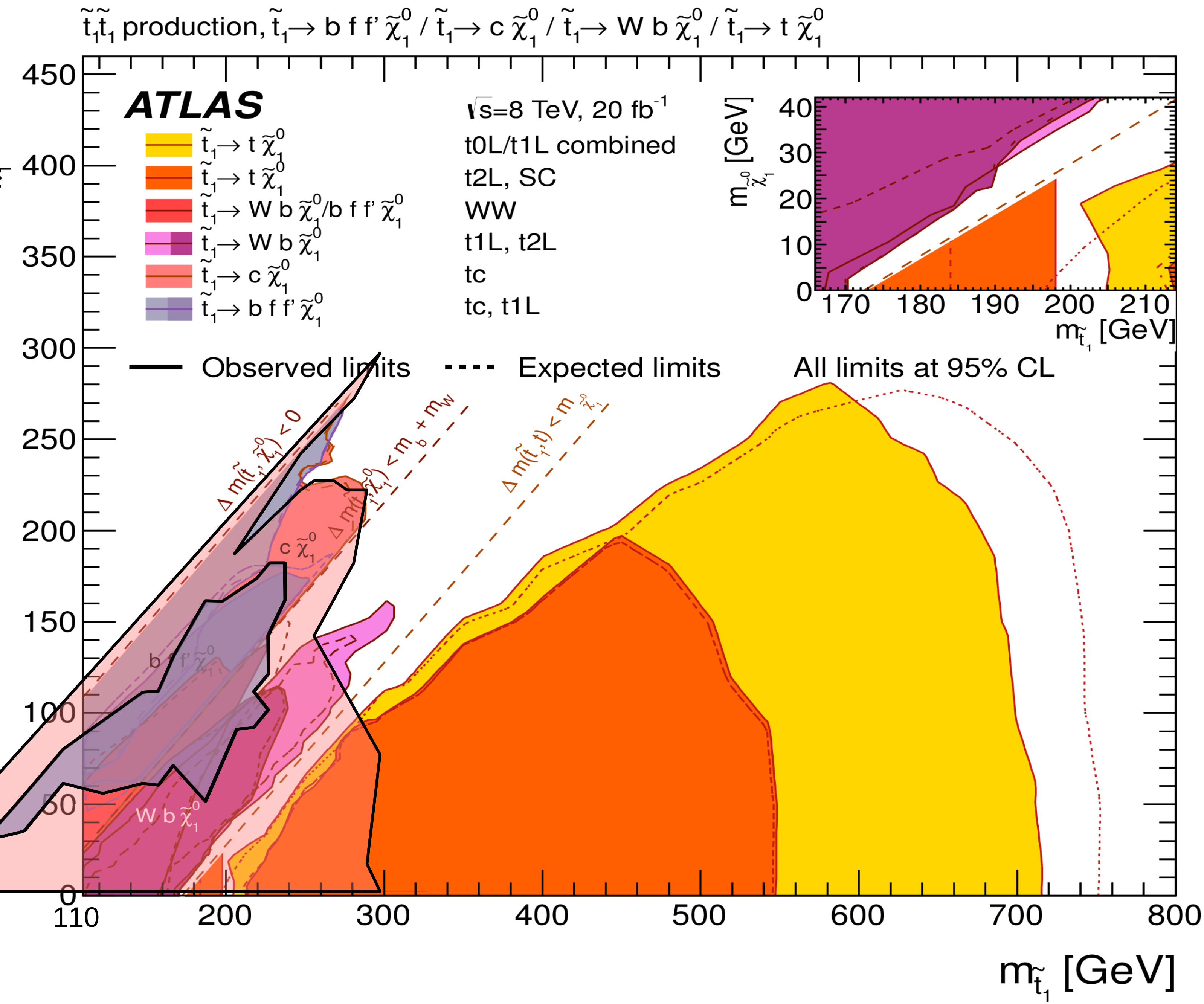
- Good agreement with ATLAS in region where both overlap.
- Successfully extended analysis beyond $m_{\tilde{t}} \sim m_{\tilde{\chi}^0} + m_W$ line.
- "Ruled out" $m_{\tilde{t}} < m_t$ (assuming 100% branching ratio to 2-body decay).

New ATLAS results!



- Recent additional ATLAS analysis.
- Uses M_{T2} variable and 2-lepton signal to look for WW from two $\tilde{t}_1 \to \tilde{b} W \chi_1^0$ decays.

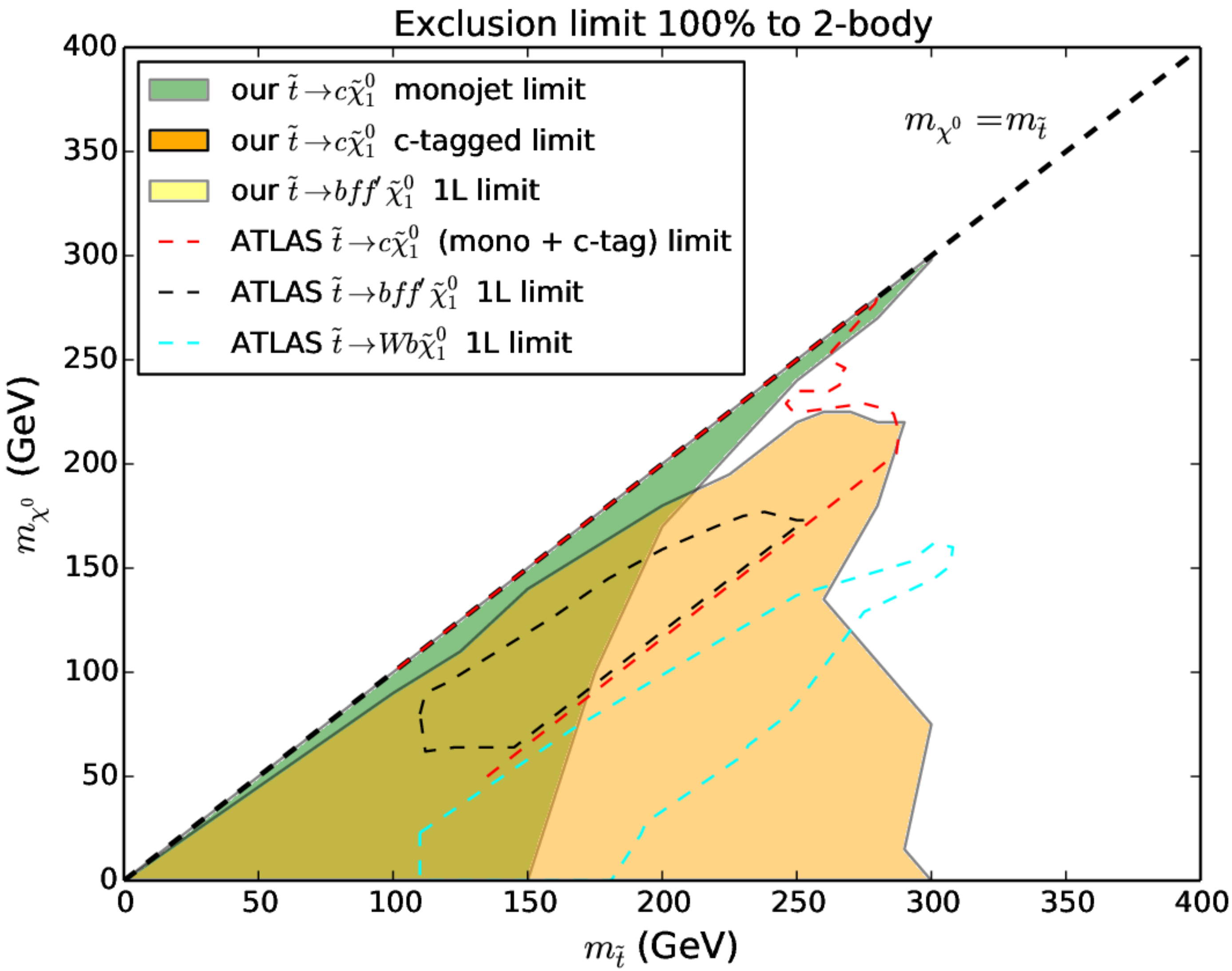
New ATLAS results!



- Our results are slightly better for $\tilde{t}_1 \to b f f' \tilde{\chi}_1^0$
- Does not improve limits for $\tilde{t}_1 \to c\tilde{\chi}_1^0$ (which we do)

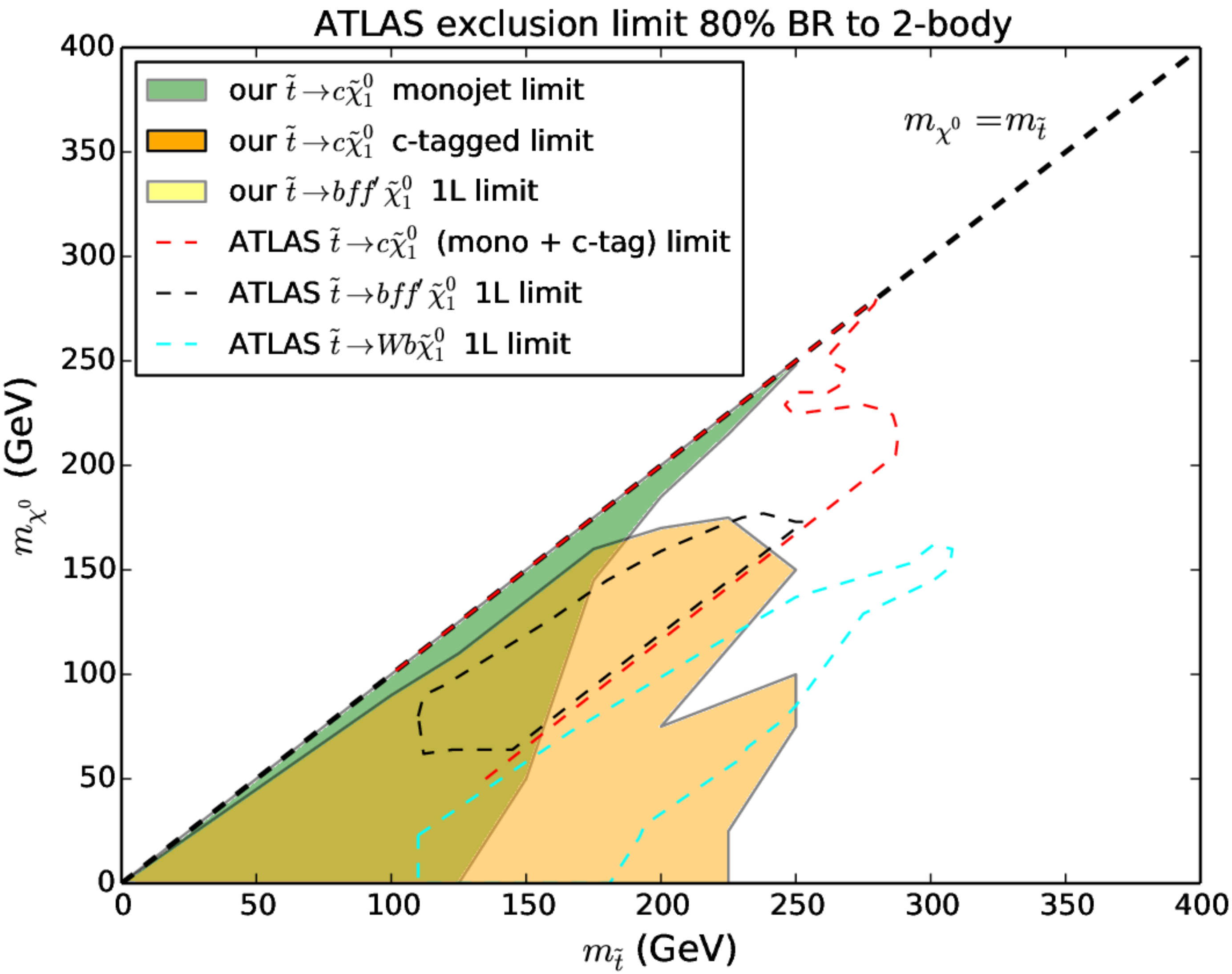
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	100%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	0%



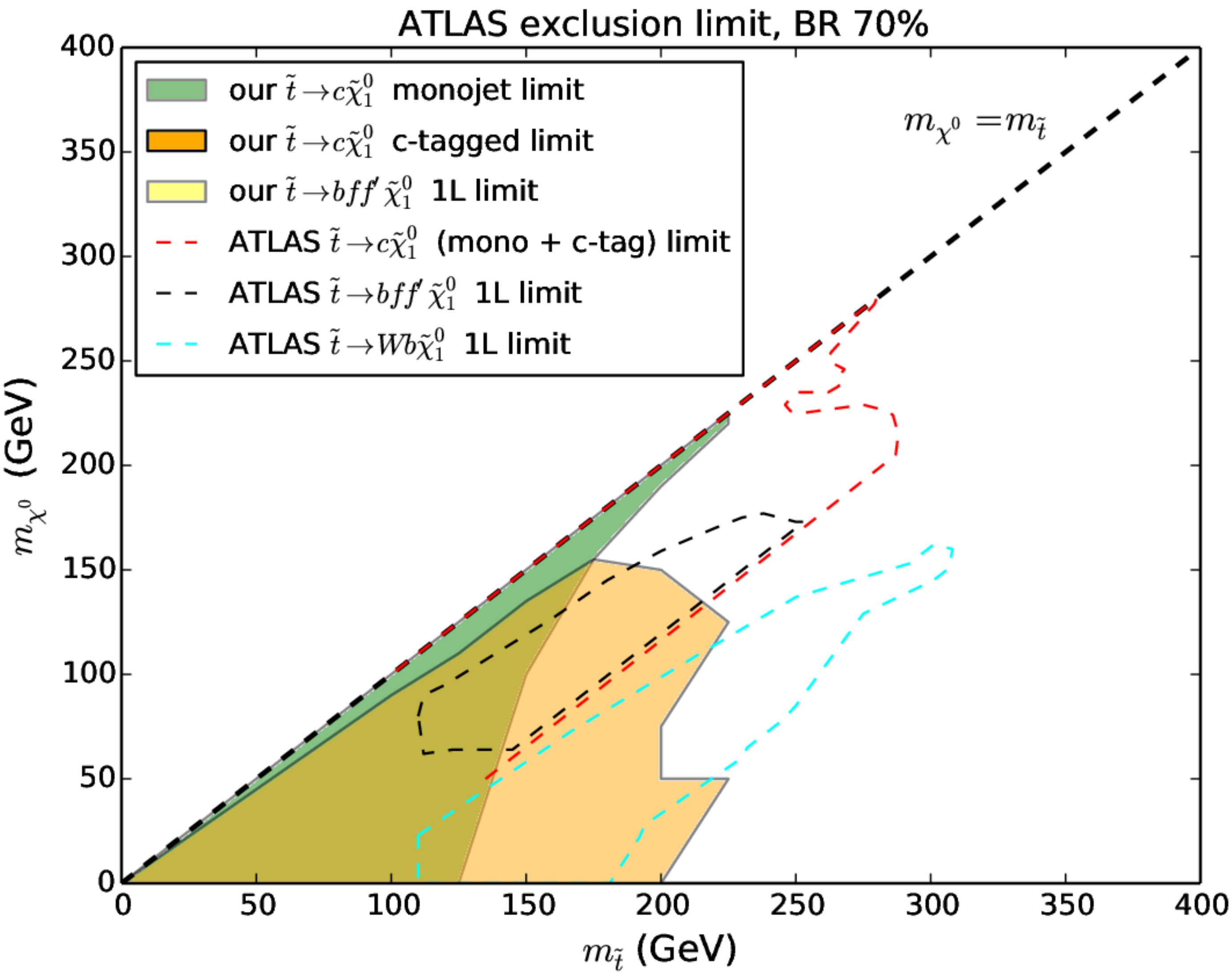
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	80%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	20%



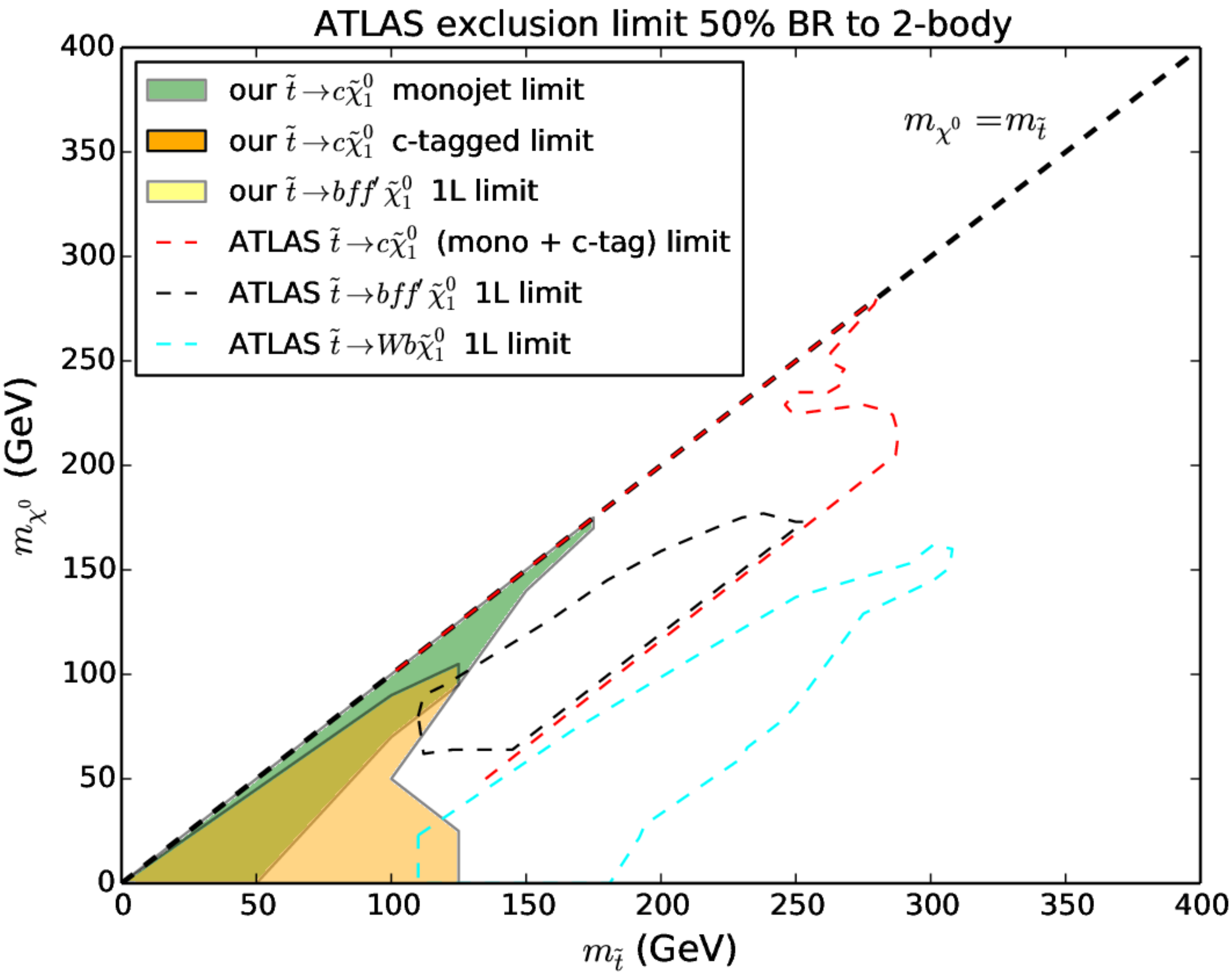
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	70%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	30%



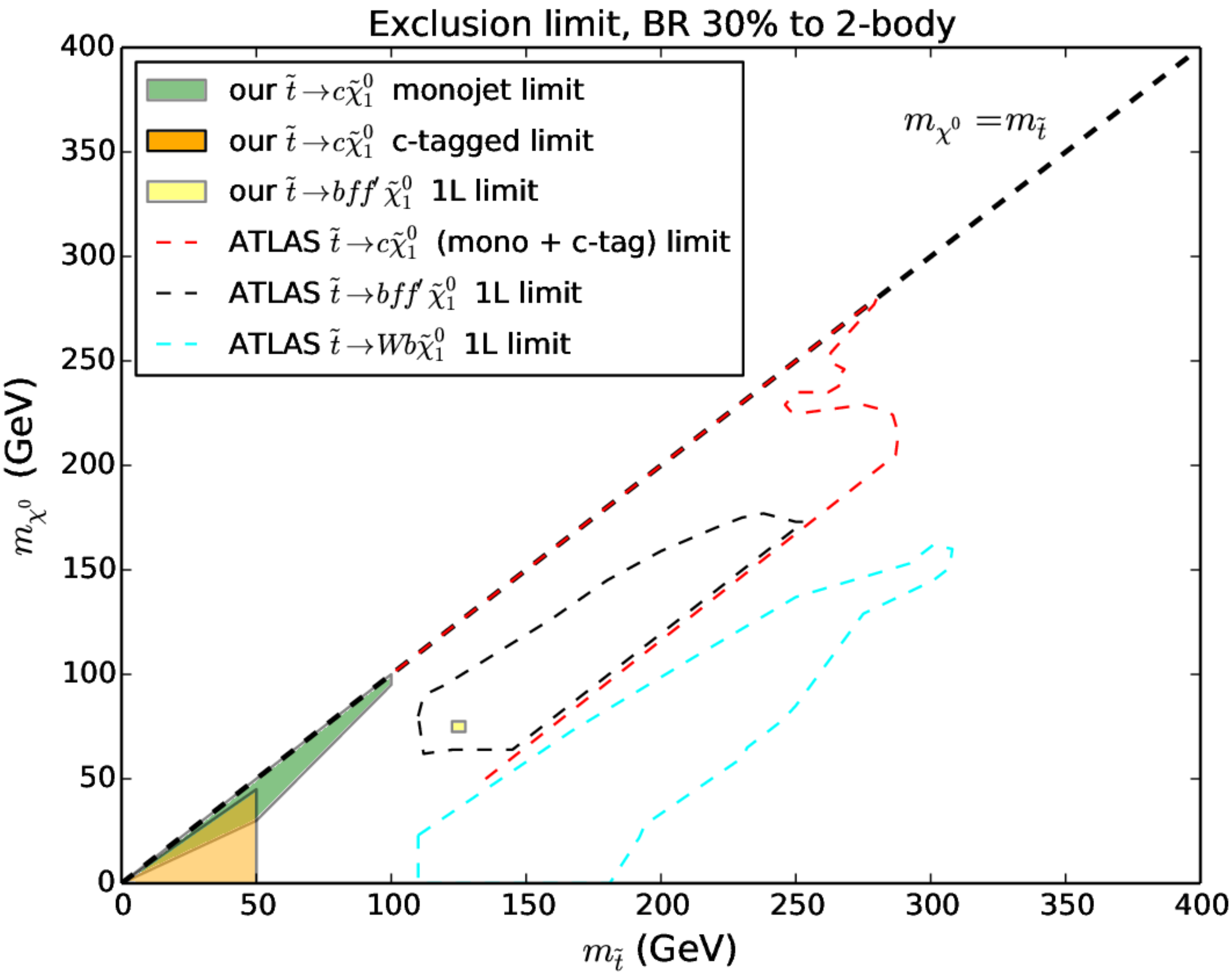
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	50%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	50%



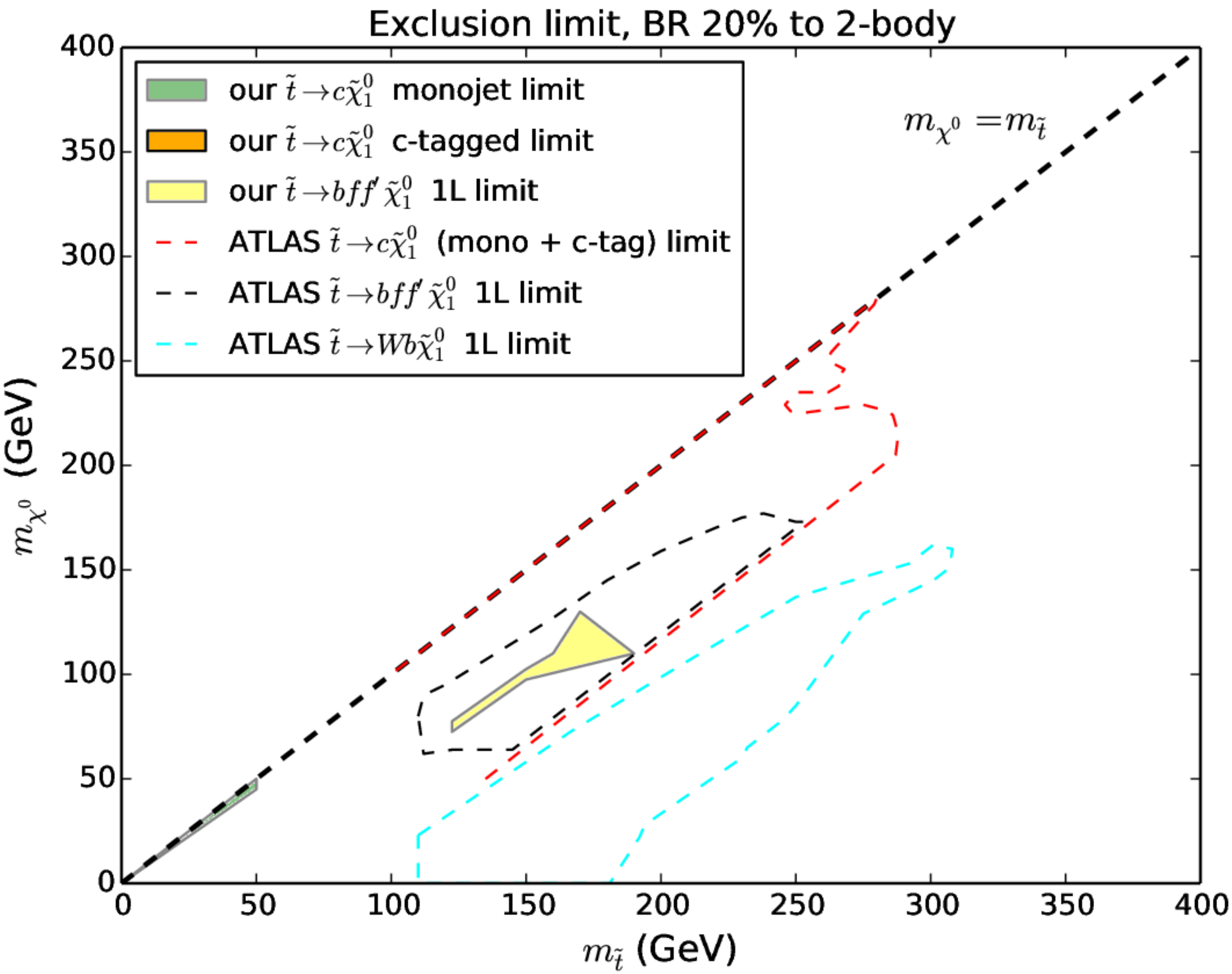
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	30%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	70%



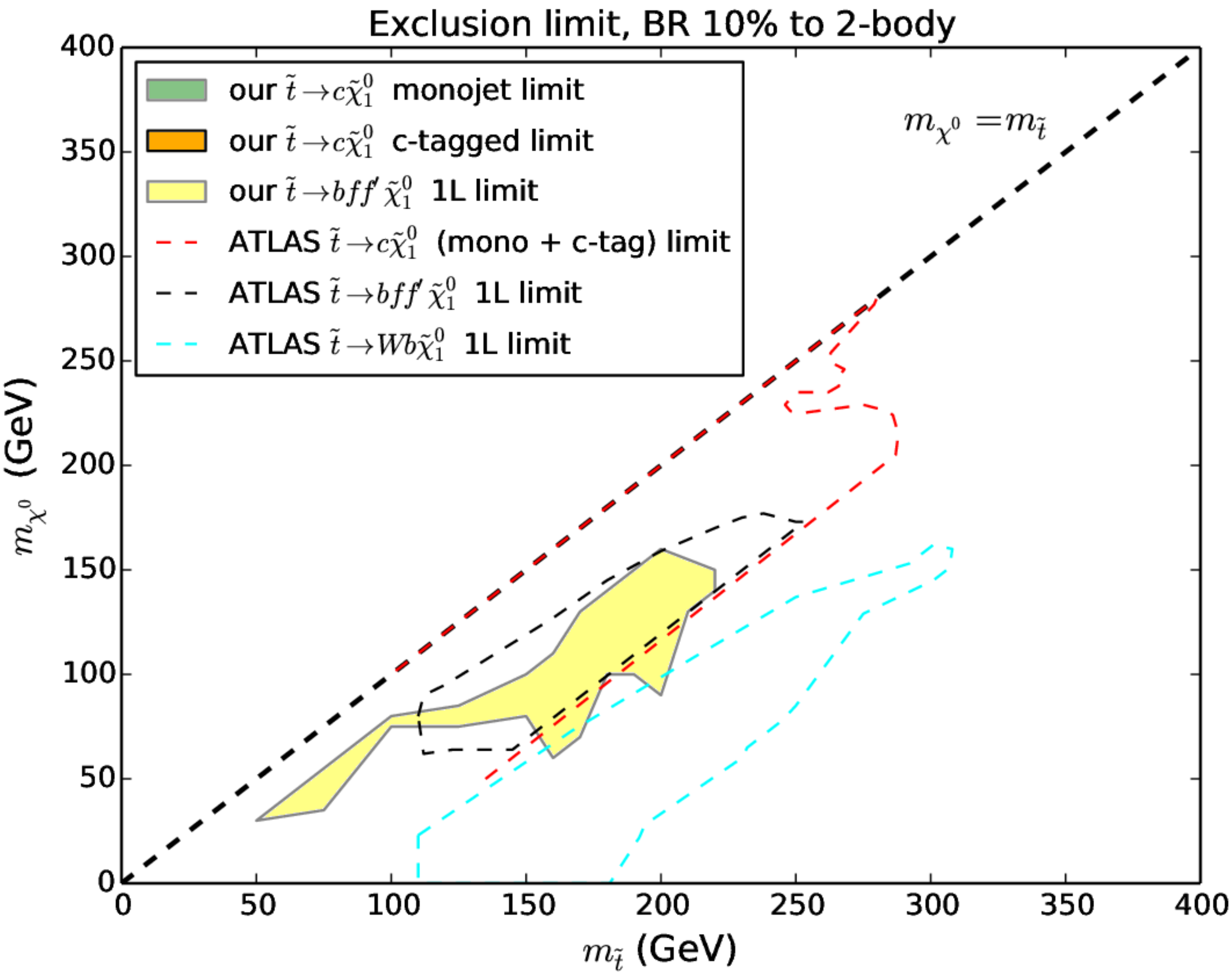
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	20%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	80%



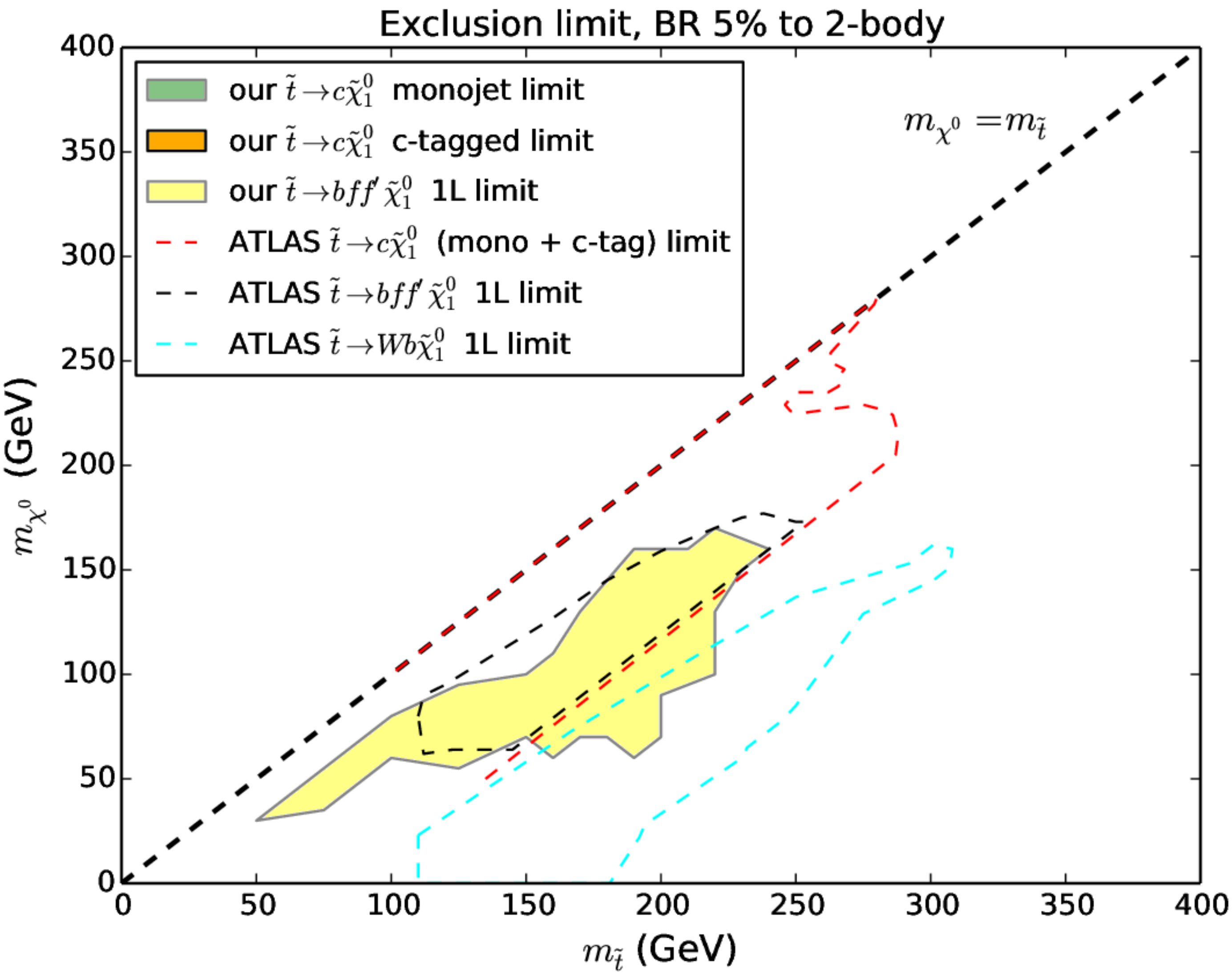
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	10%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	90%



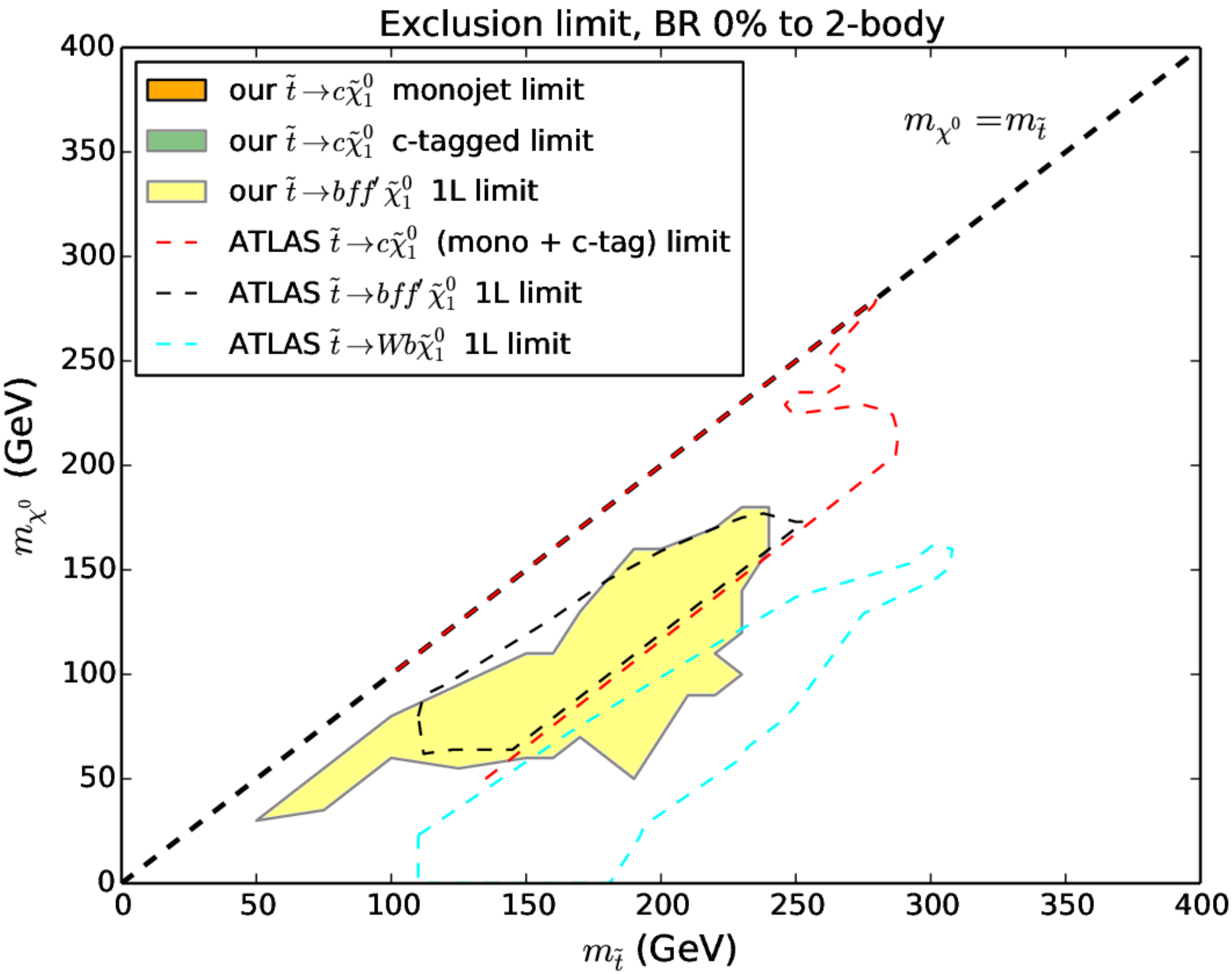
Altering the branching ratios

2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	5%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	95%

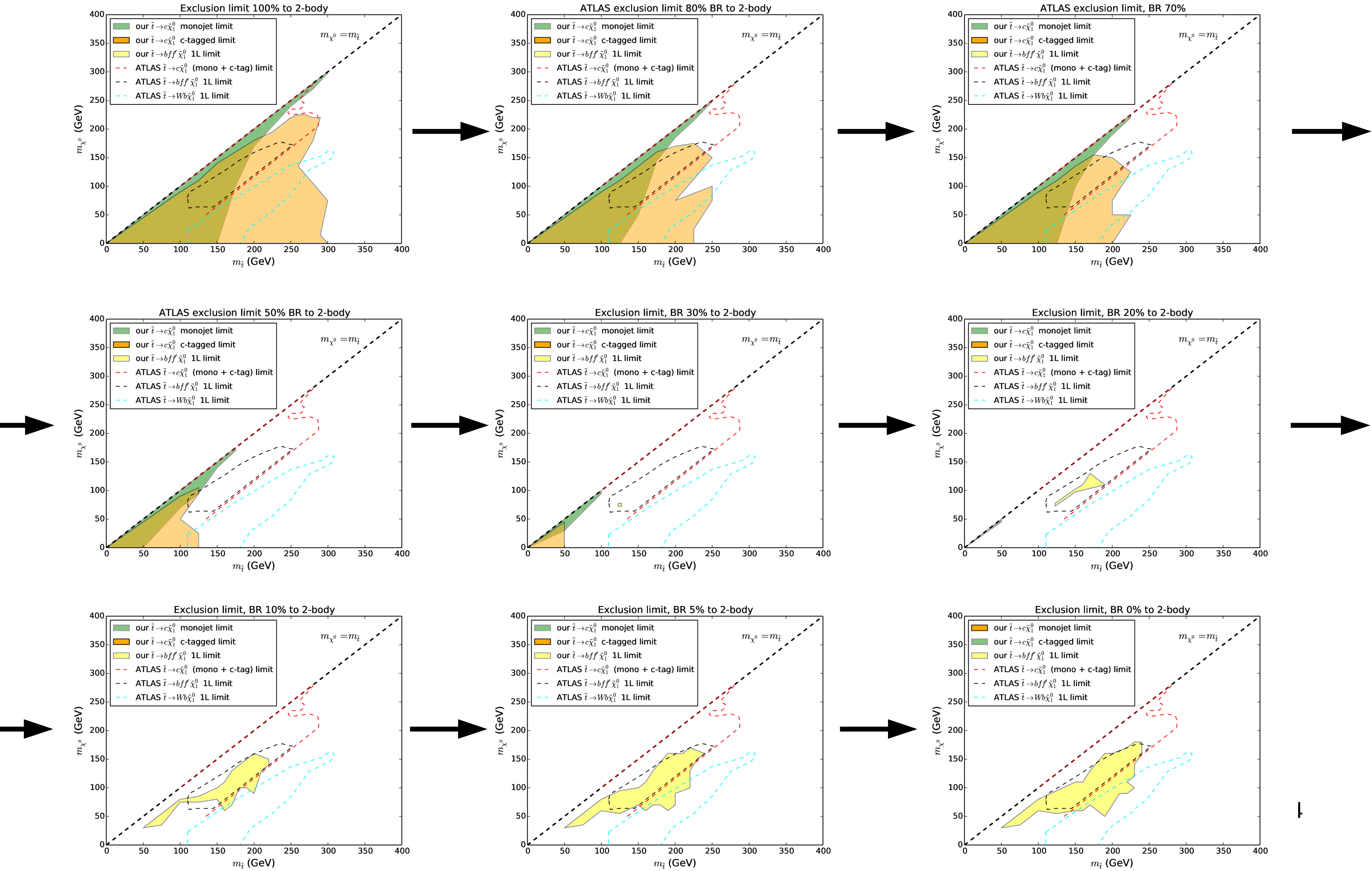


Altering the branching ratios

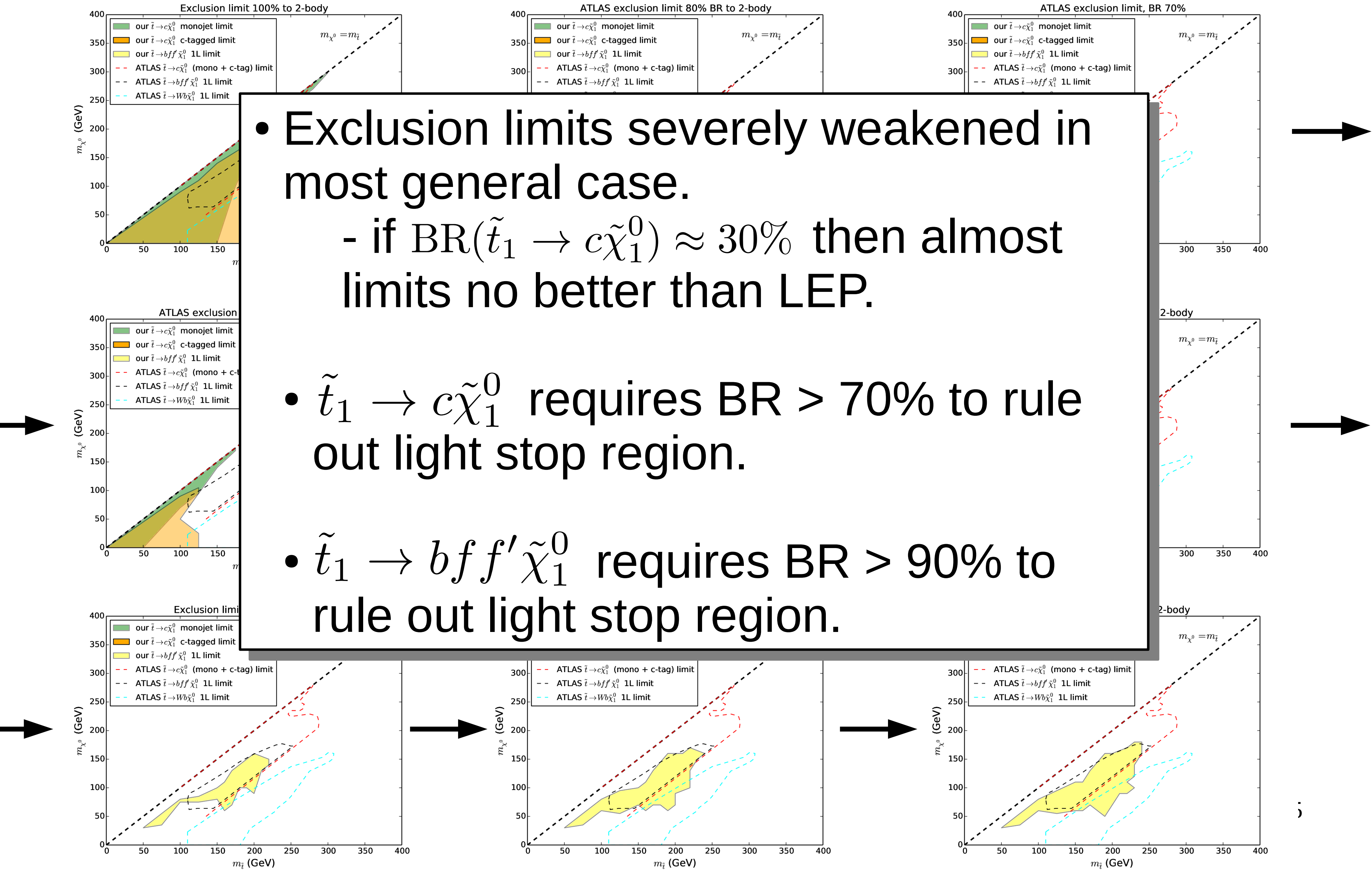
2 body	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	0%
4 body	$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$	100%



Altering the branching ratios



Altering the branching ratios

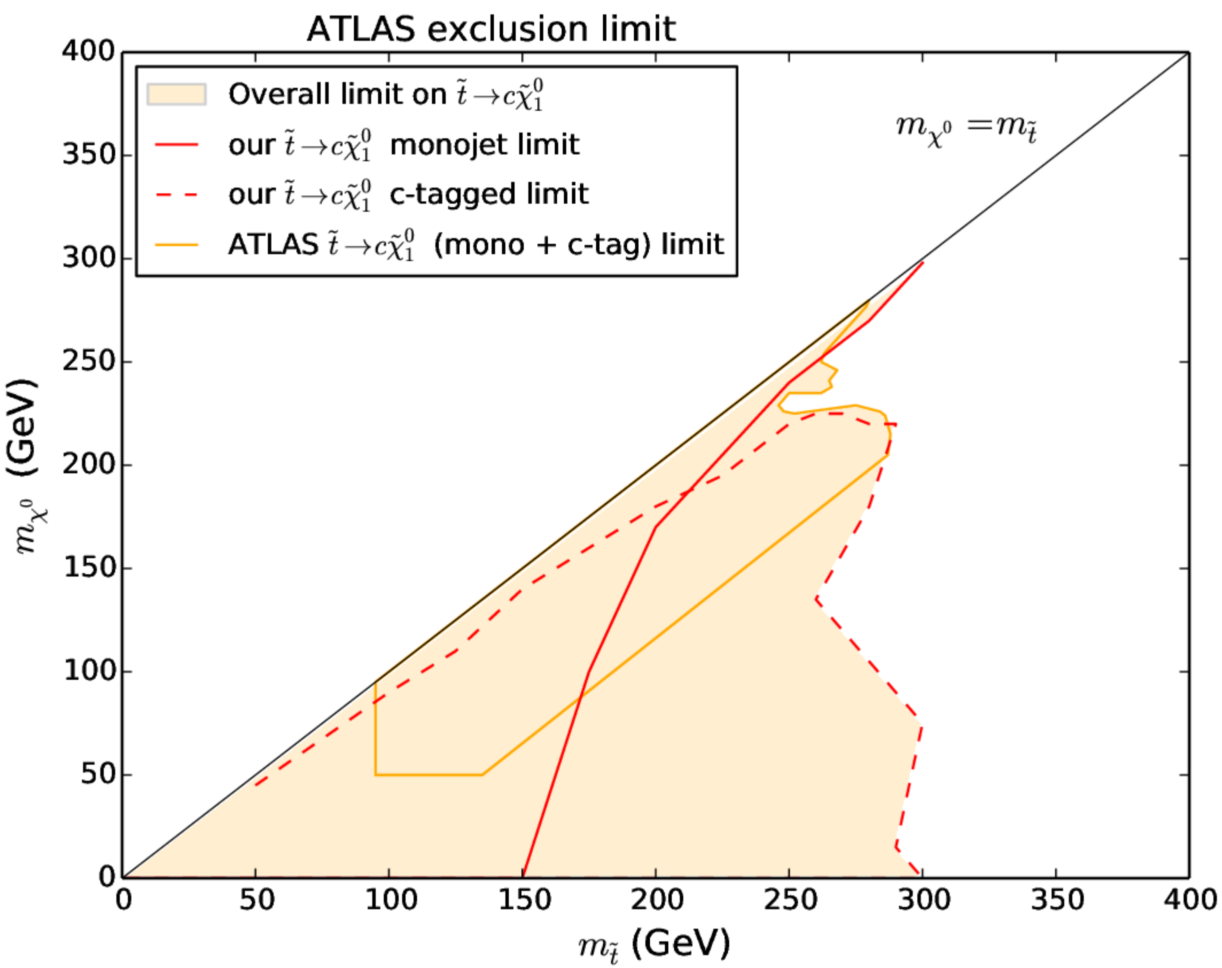


- Exclusion limits severely weakened in most general case.
  - if $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) \approx 30\%$ then almost limits no better than LEP.

- $\tilde{t}_1 \to c\tilde{\chi}_1^0$ requires BR > 70% to rule out light stop region.

- $\tilde{t}_1 \to bff'\tilde{\chi}_1^0$ requires BR > 90% to rule out light stop region.

Combining with ATLAS results



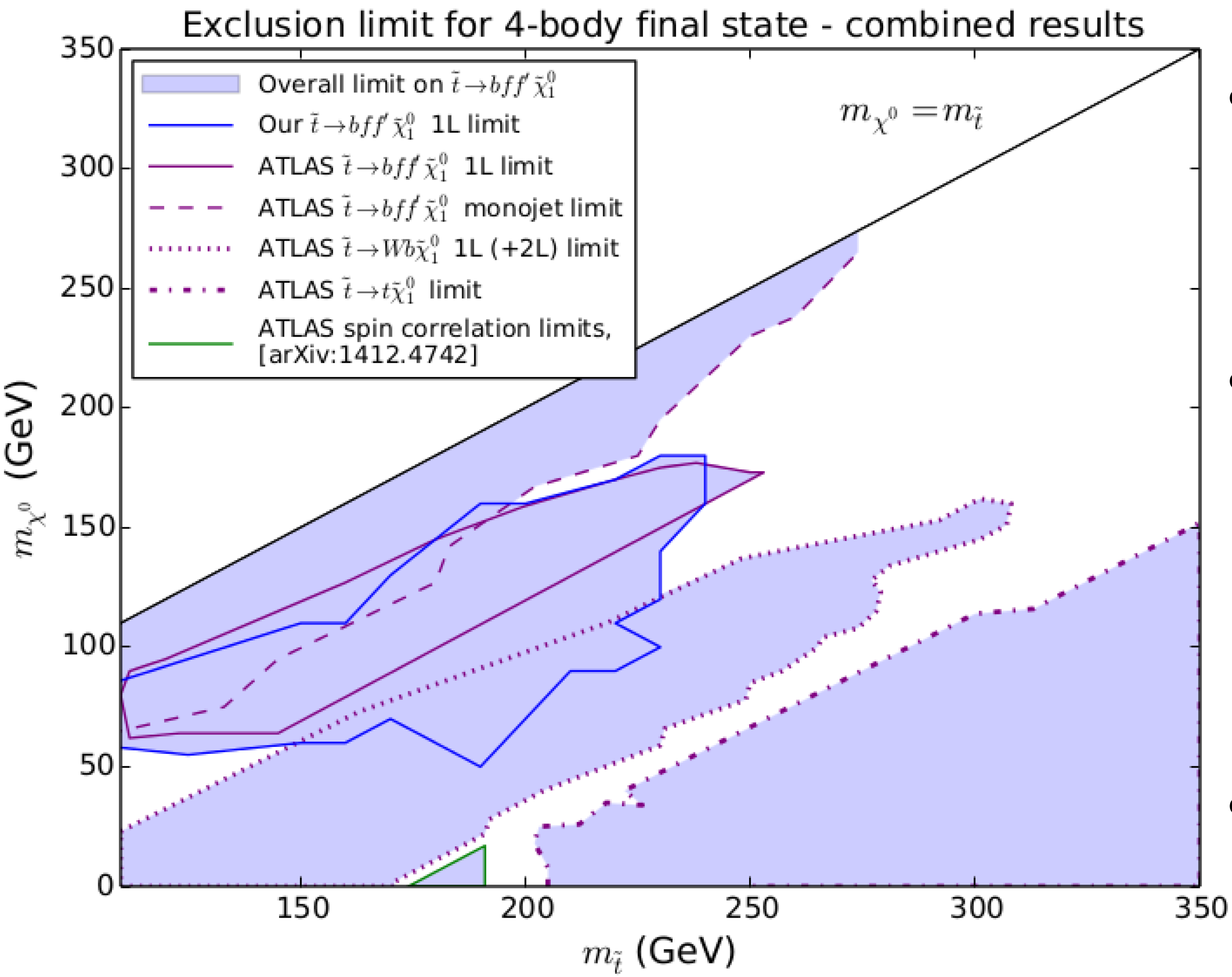
$$\tilde{t}_1 \to c\tilde{\chi}_1^0$$

- Adding ATLAS results rules out small extra region.

- ***If*** $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 100\%$ then:
  - all stops < 250 GeV ruled out at 95% CL.
  - Rules out light stop EWBG

Combining with ATLAS results

$$\tilde{t}_1 \to b f f' \tilde{\chi}_1^0$$



- Adding other ATLAS channels allows large region to be ruled out.
- If $\mathrm{BR}(\tilde{t}_1 \to b f f' \tilde{\chi}_1^0) = 100\%$ then *almost* all stop masses < 175 GeV ruled out at 95% CL.
- Would *almost* entirely rule out light stop scenario of baryogenesis.

Conclusion

- Allowing more realistic branching ratios **severely weaken LHC limits** on stop masses.
  - Important to remember when interpreting summary plots.
  - Setting model independent limits will be very difficult (or at least the limits will be very weak in general)

- Successfully reproduced and extended ATLAS analyses.
  - Ruled out most of remaining region where $m_{\tilde{t}} - m_{\tilde{\chi}^0} \approx 80\ \mathrm{GeV}$

- Rules out light stop EWBG if $\mathrm{BR}(\tilde{t}_1 \to c\tilde{\chi}_1^0) = 100\%$
- (*Almost*) ruled out light stop EWBG if $\mathrm{BR}(\tilde{t}_1 \to bff'\tilde{\chi}_1^0) = 100\%$

END