Future Supersymmetry at Colliders

and

New Limits on Light Stops

Sunghoon Jung
KIAS

The 25th Busan Particle Physics Workshop, Dec 2014

Based on collaborations with
G.Barenboim, B.Batell, E.J.Chun, S.Gori, B.S.Kyae, W.I.Park, L.T.Wang, J.D.Wells

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Future SUSY

- Overall heavy.
  => Gauginos and Higgsinos are well-separated in mass and mix minimally, in general.

- Dirac higgsino vs. Majorana gaugino.

- Goldstone Equivalence Theorem applies inherently.

- Gaugino code — primary observable and variable.

- Several disparate mass scales => Resummation.

Perspectives on Light Stops: New Limits and Models

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1412.xxxx, 1412.xxxx, 1312.1802, 1404.2691, 1410.6287

Naturalon

- Light stops soften UV dependences of the EW scale.
- Essential for naturalness

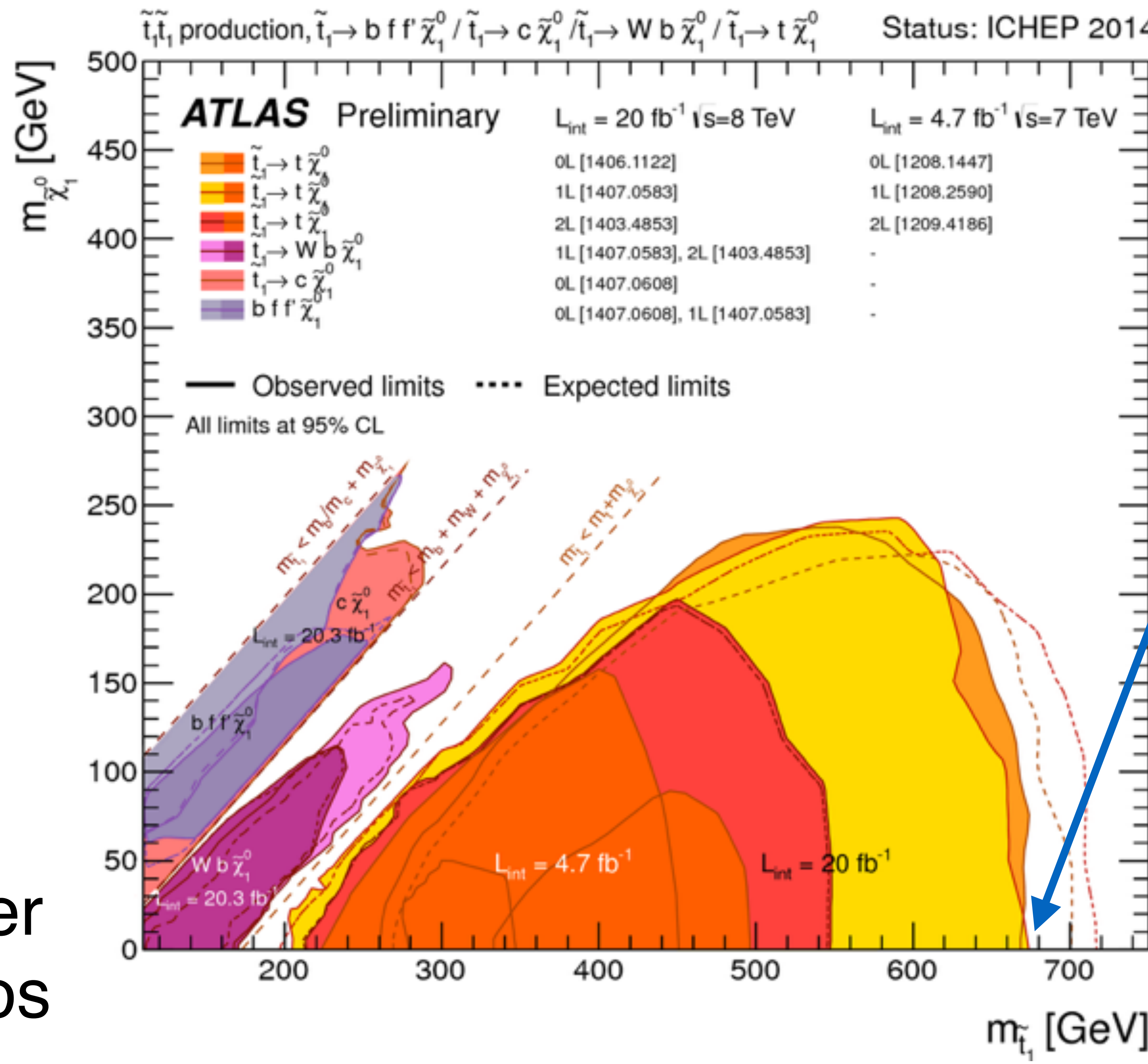
$$\text{tuning} = \frac{\Delta m_{Hu}^2}{M_Z^2} \simeq \frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2 M_Z^2} \ln \frac{\Lambda}{m_{\tilde{t}}}.$$

- 10% tuning ~ 450 GeV stop.
  700 GeV stop already 4.5% tuning.

Three sources of tuning

- LHC lower bounds on the stop mass.
- Stronger LHC bounds on the gluino mass; masses of the gluino and stop are tightly RG-related.
- Heavy Higgs mass ~ 125 GeV needs sizeable quantum corrections (from heavy stops).

Current stop limits



~700 GeV stops are already excluded!

no lighter charginos

Sunghoon Jung, KIAS

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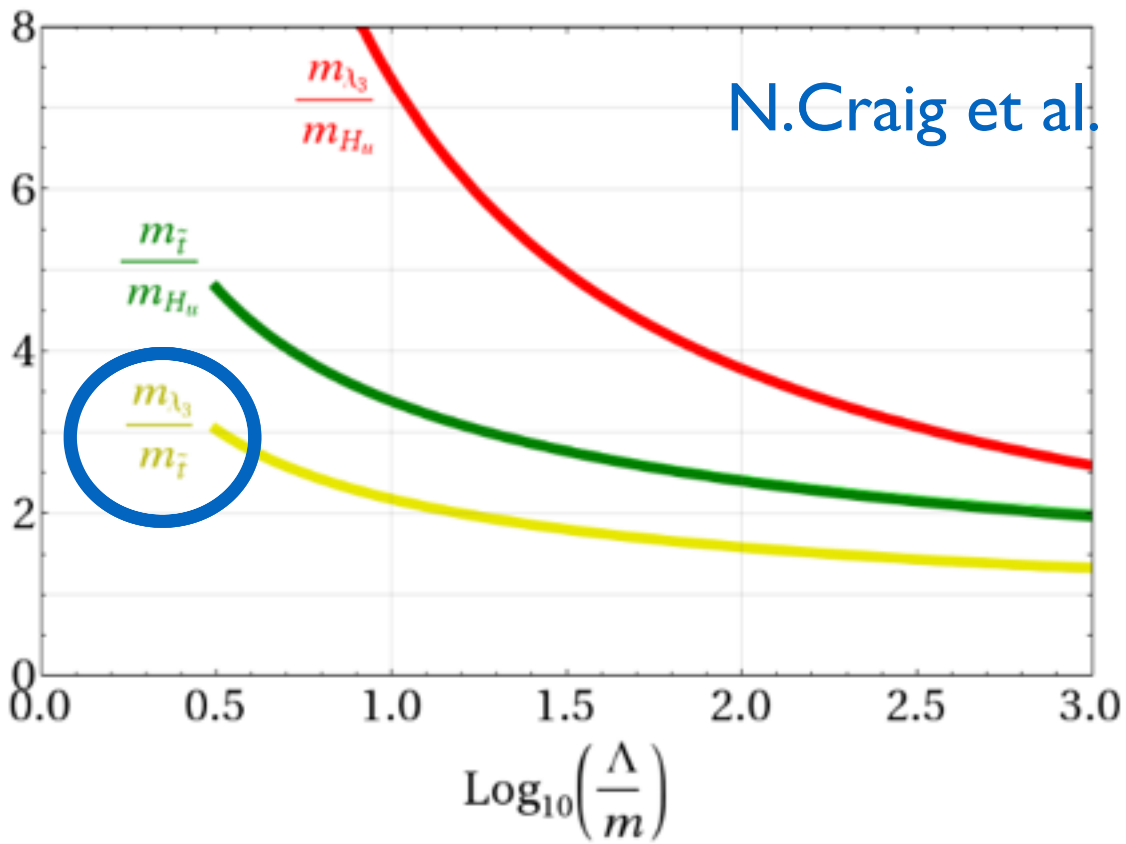
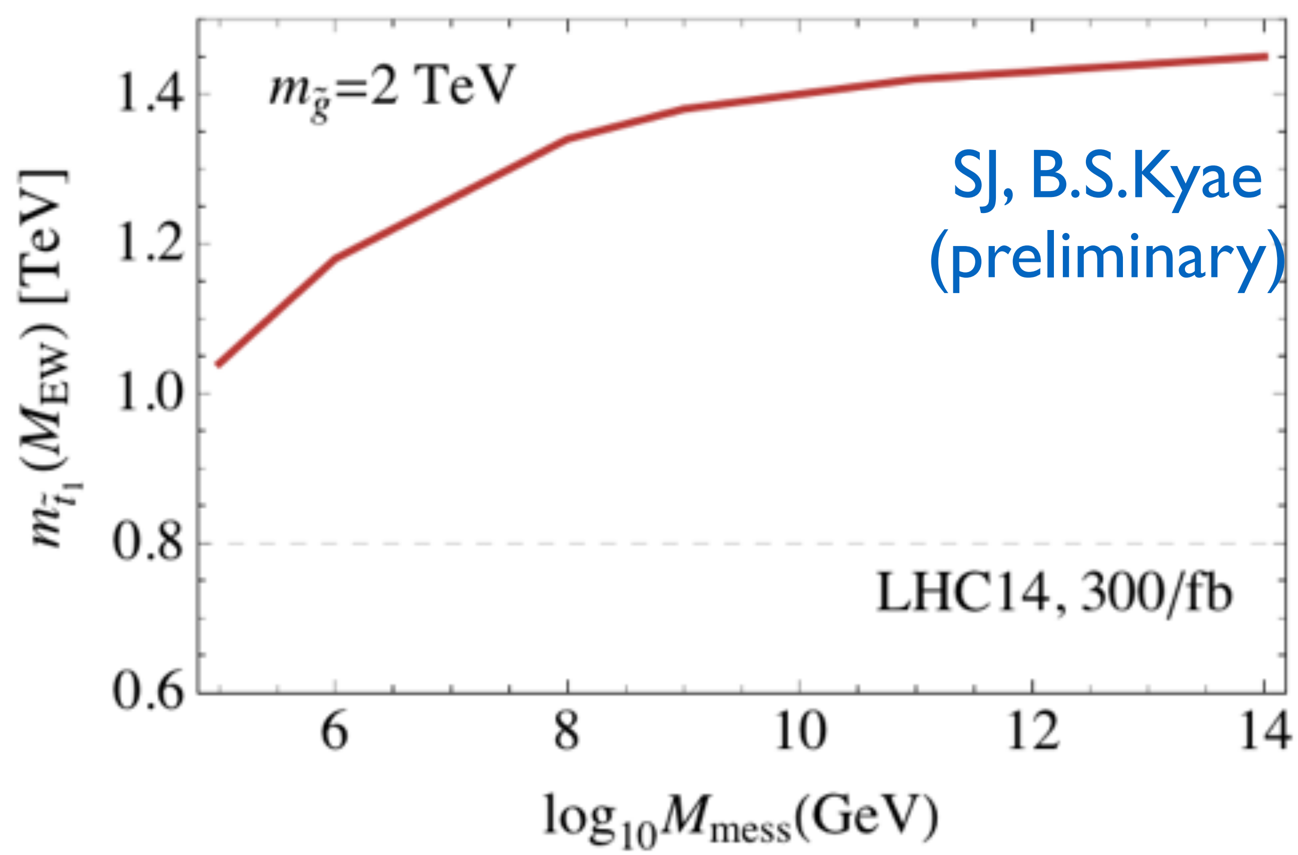
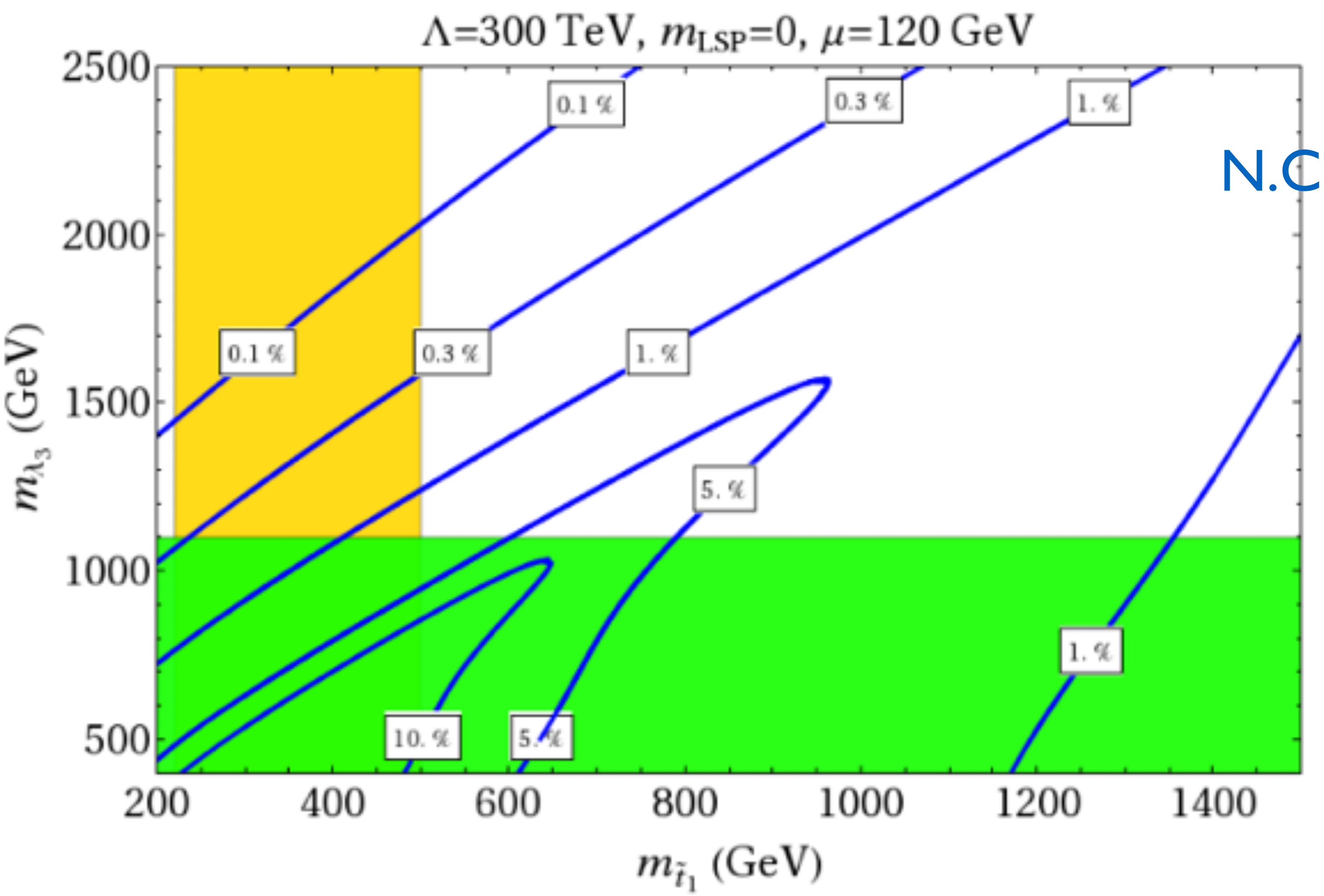
RG related gluino-stop





- Masses of gluinos and stops are very likely within a factor 2 whatever the initial stop mass at high-scale is.

Fine-Tuning



N.Craig et al.

- Gluino mass lower bounds do worsen the fine-tuning.

Three sources of tuning

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My talk is about

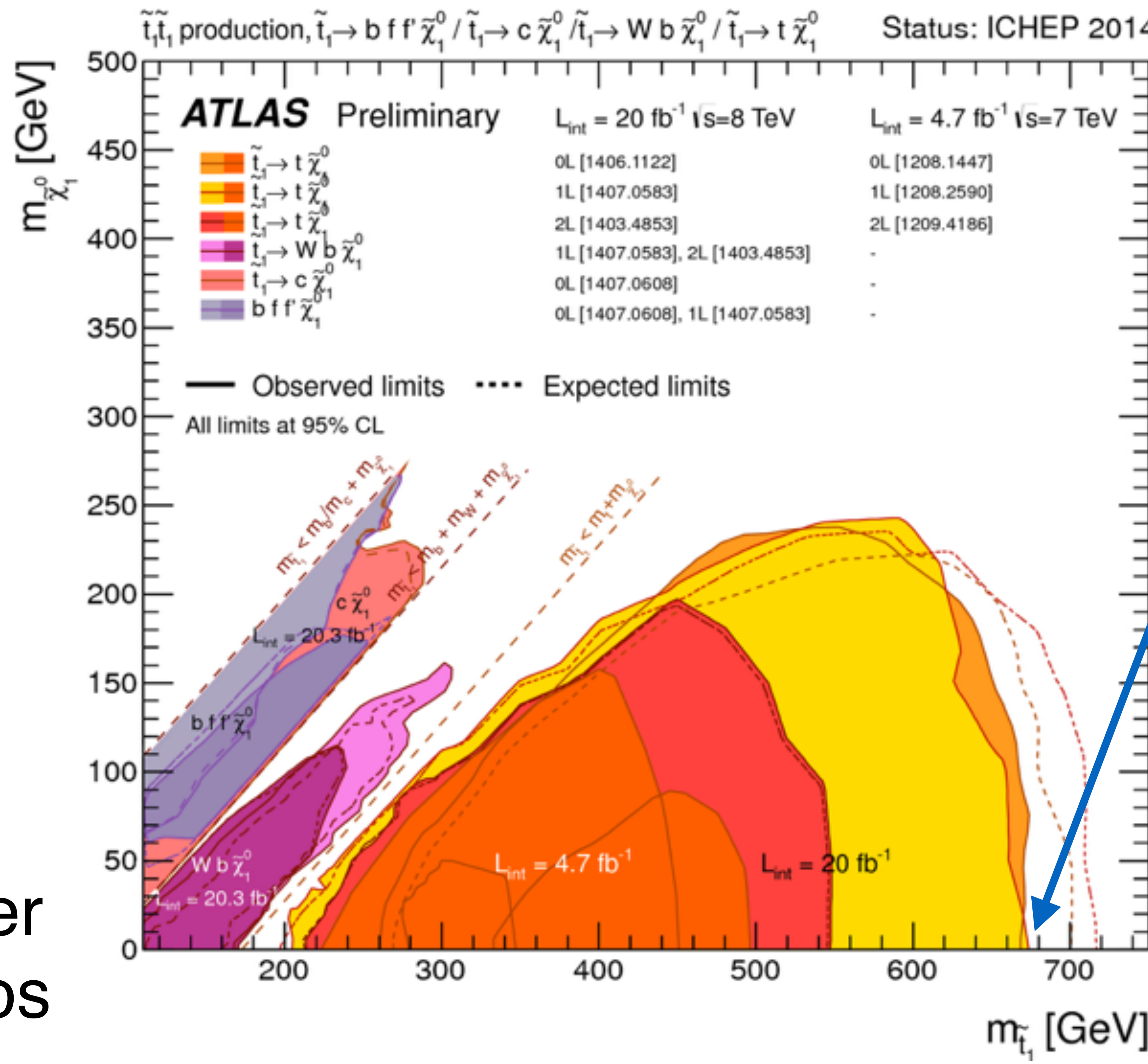
- New Limits on Light Stops (from stoponium).
  => Is all light stop excluded? Important complementary searches are studied.

- Breaking the RG-relation (model building options).
  => Light enough stops with heavy enough gluinos. "Enoughness" is either quantified by tuning or discoverability (our new direction).

1. New limits on light stops from stoponium

B.Batell, SJ
(preliminary)

Current stop limits



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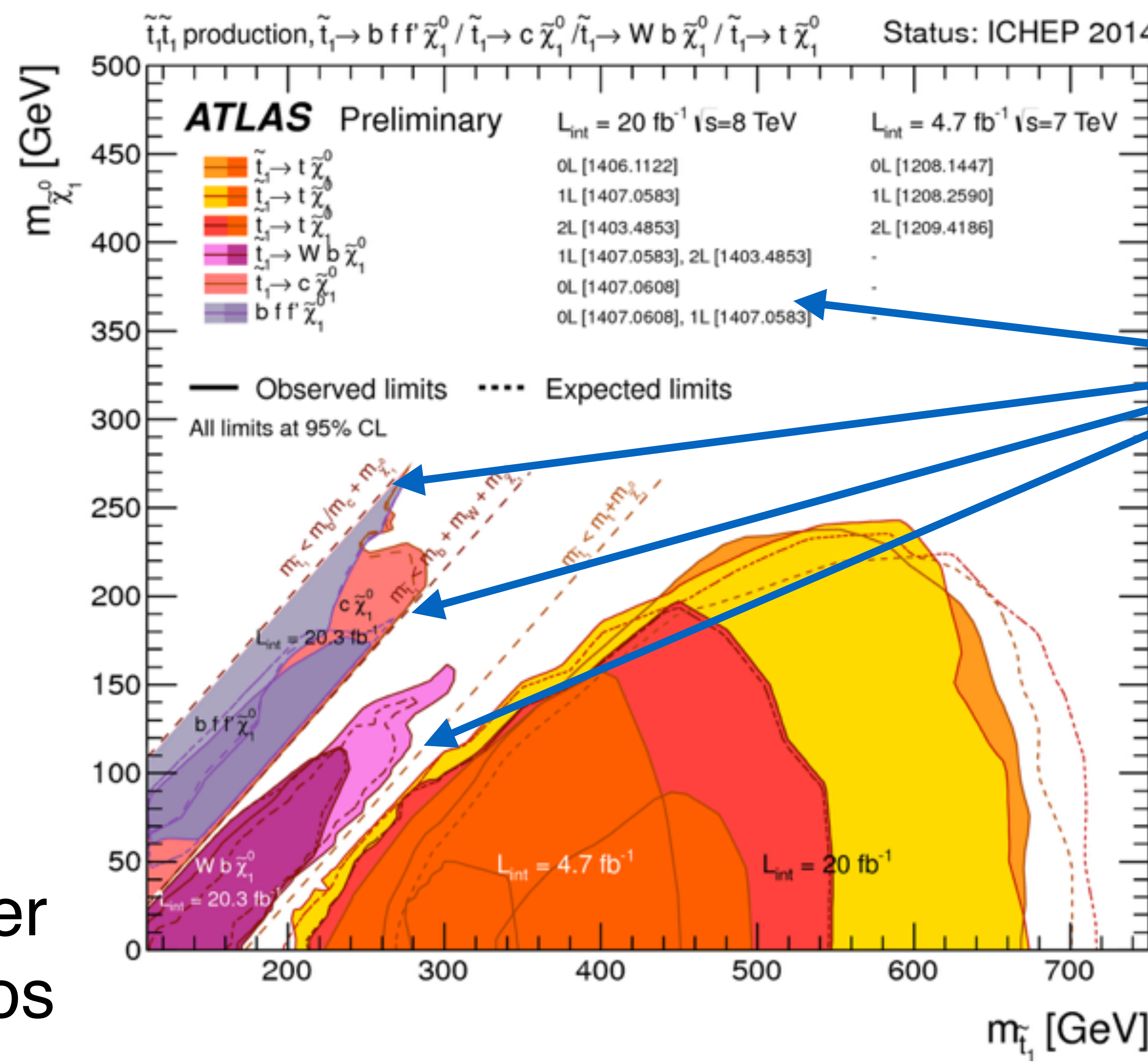
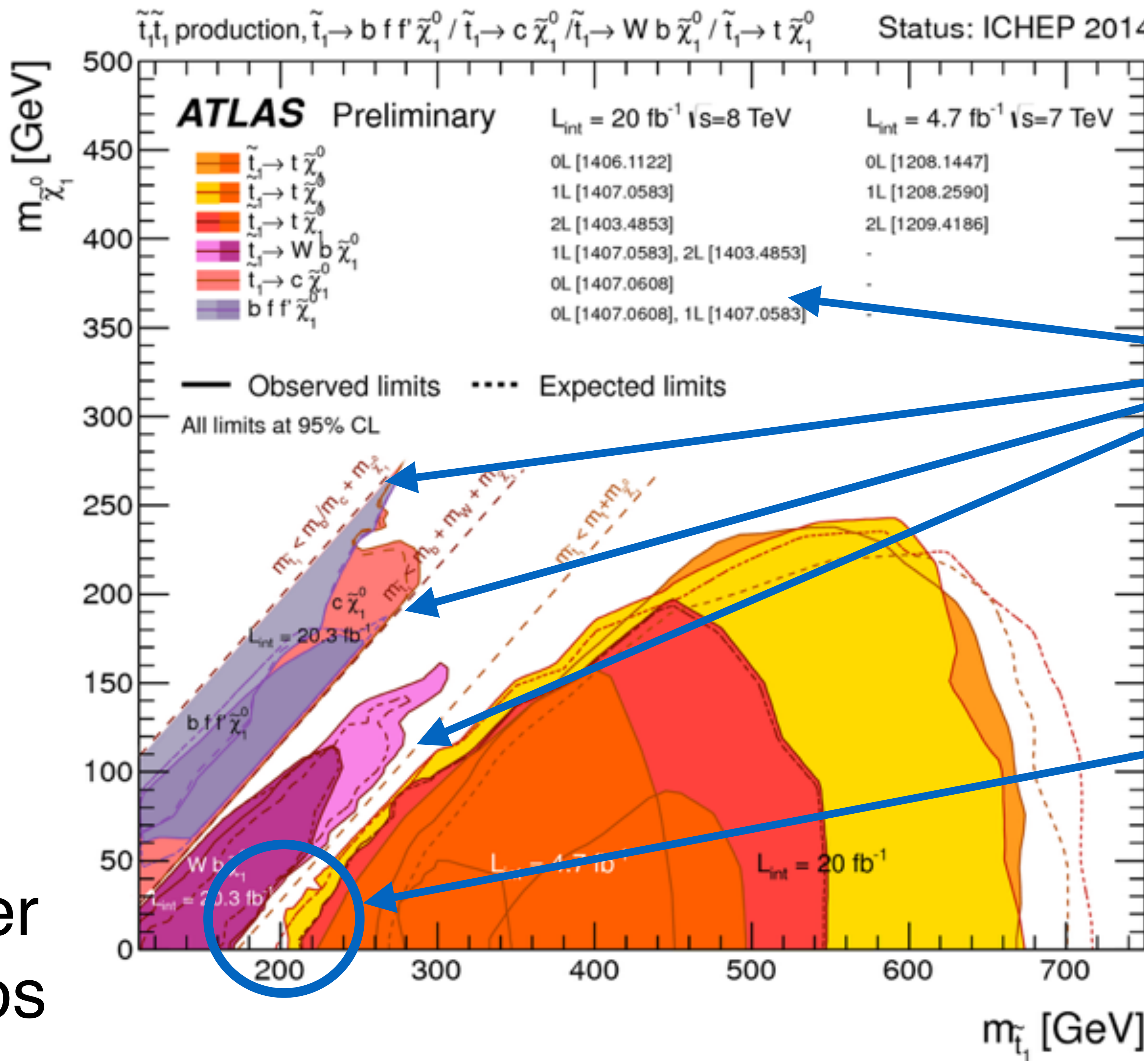


However, several blind spots exist. (final states are soft)

no lighter charginos

Current stop limits



However, several blind spots exist. (final states are soft)

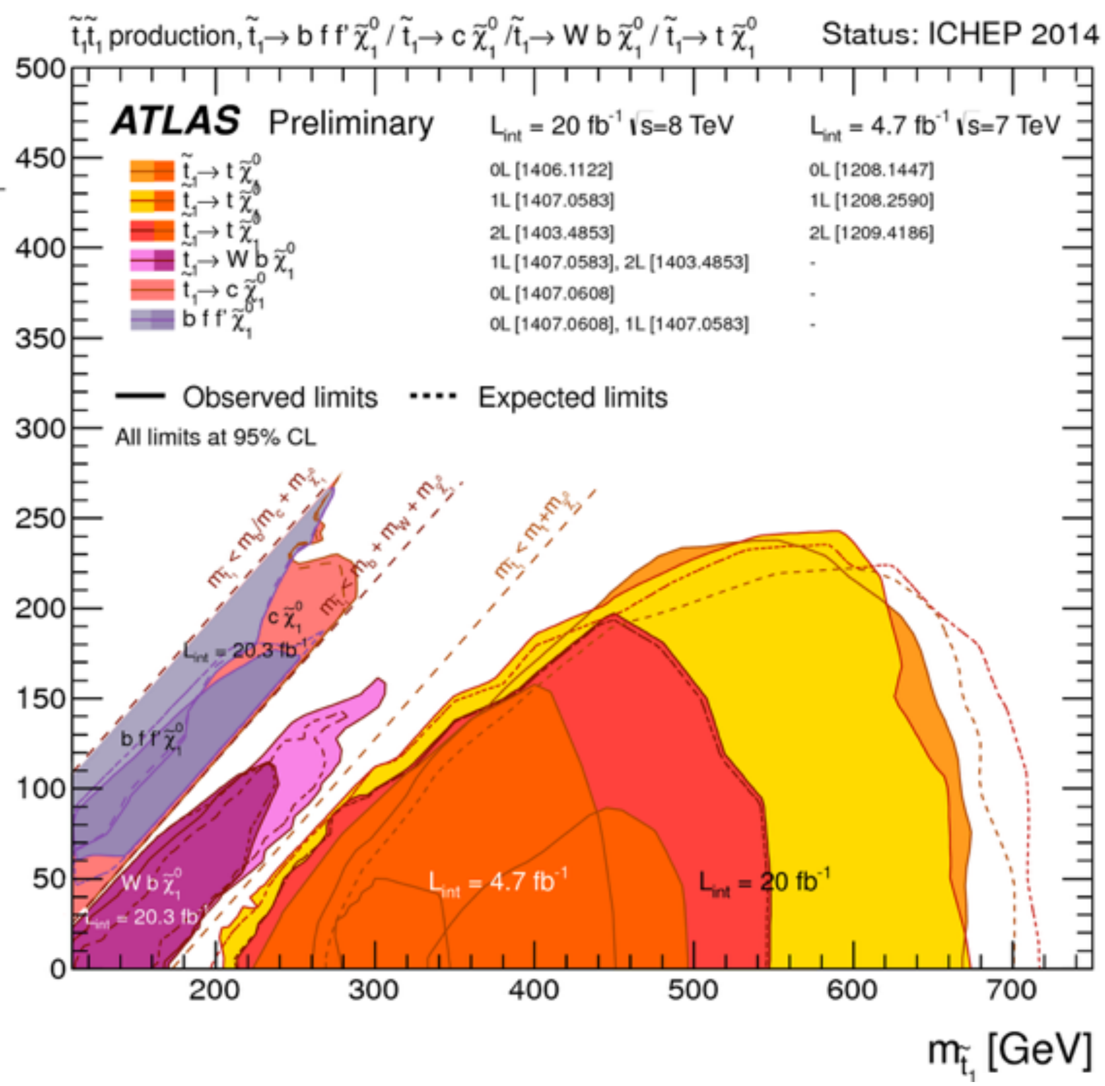
a.k.a the stealth stop (stops look like tops)

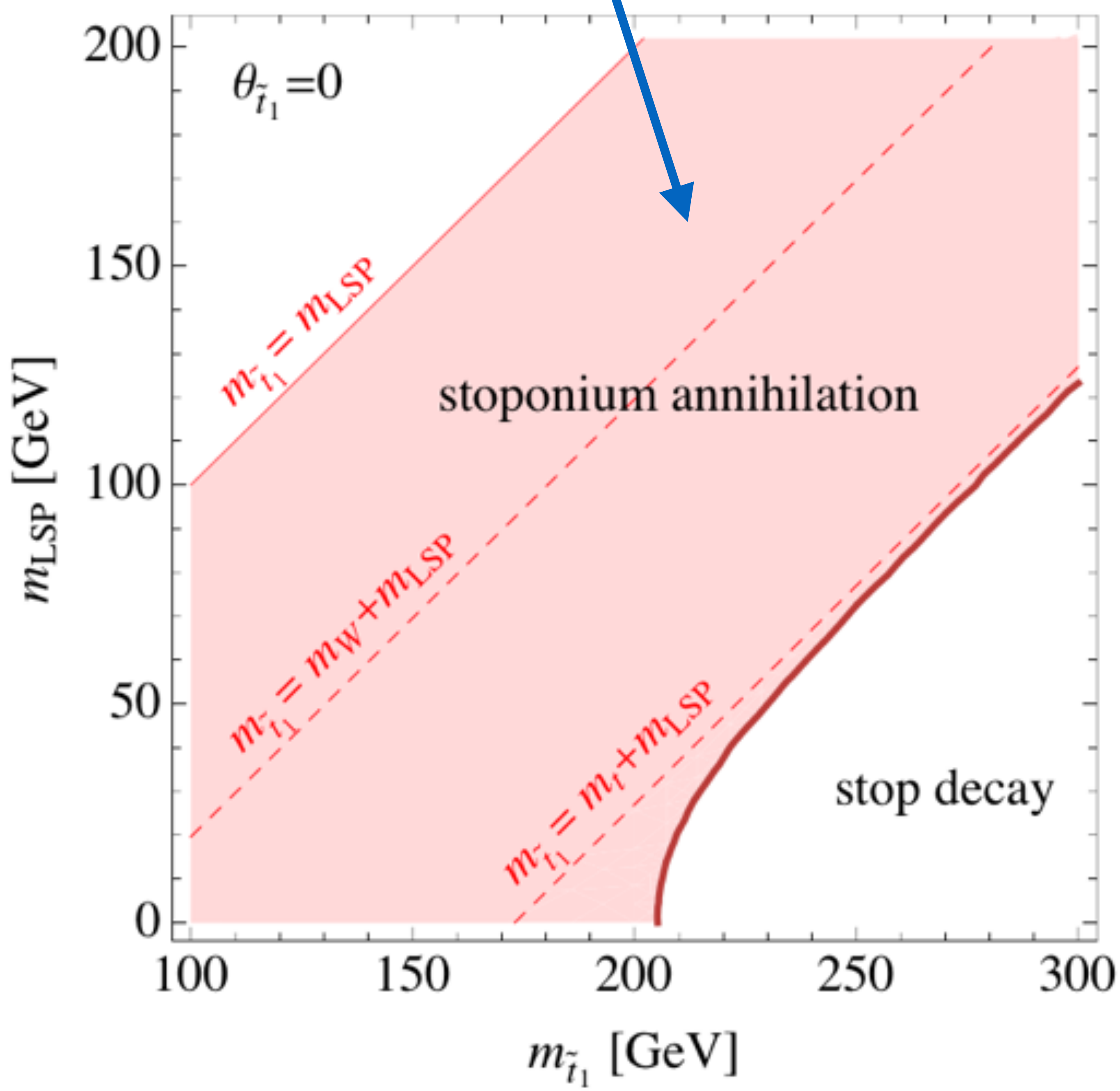
no lighter charginos

Sunghoon Jung, KIAS

Stoponium can potentially cover

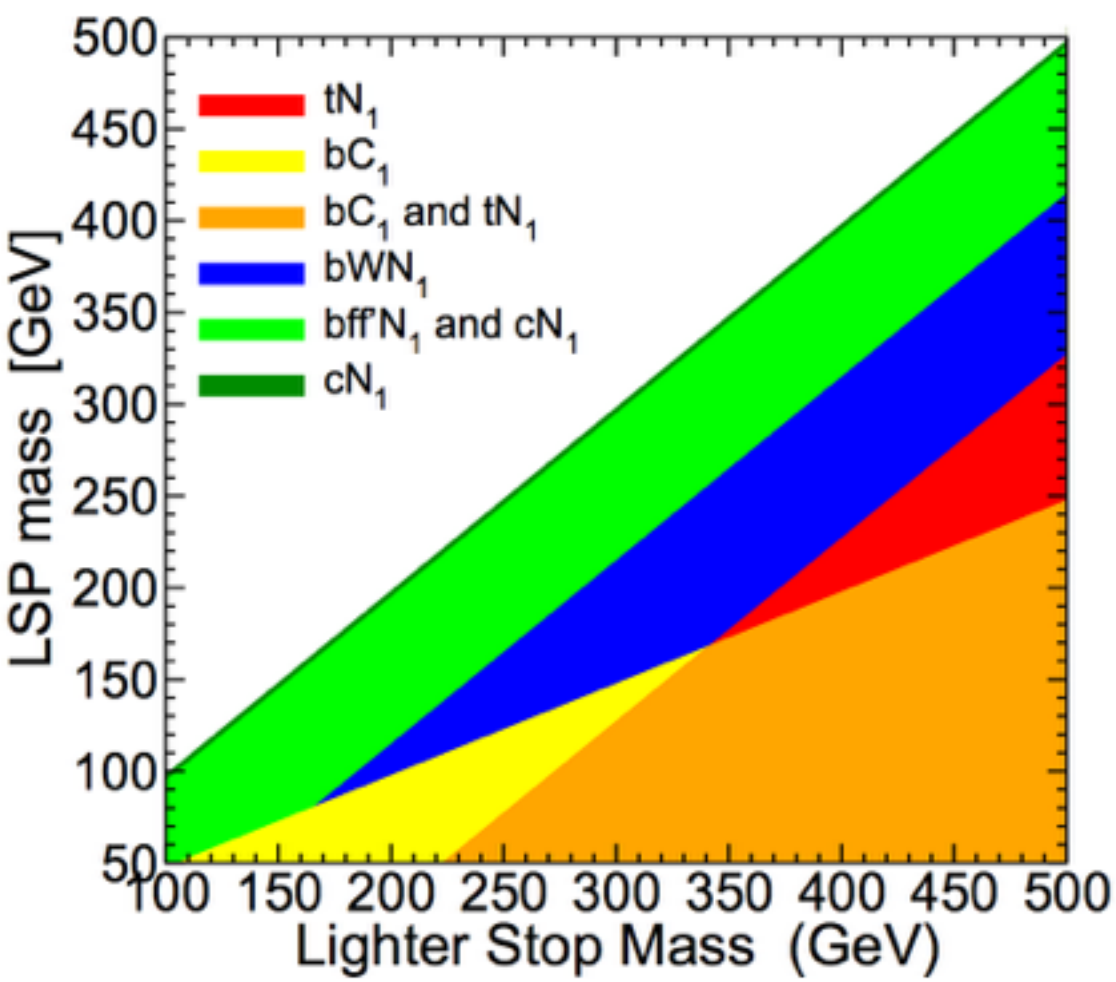
B.Batell, SJ (preliminary)





Current best, common sensical knowledge

In green and blue regions, the top squark hadronizes before it decays.



Red, yellow, orange = 2-body

Blue = 3-body

Green = competition between

2-body flavor violating,

4-body decays

from S.Martin's slide

Stoponium can potentially cover

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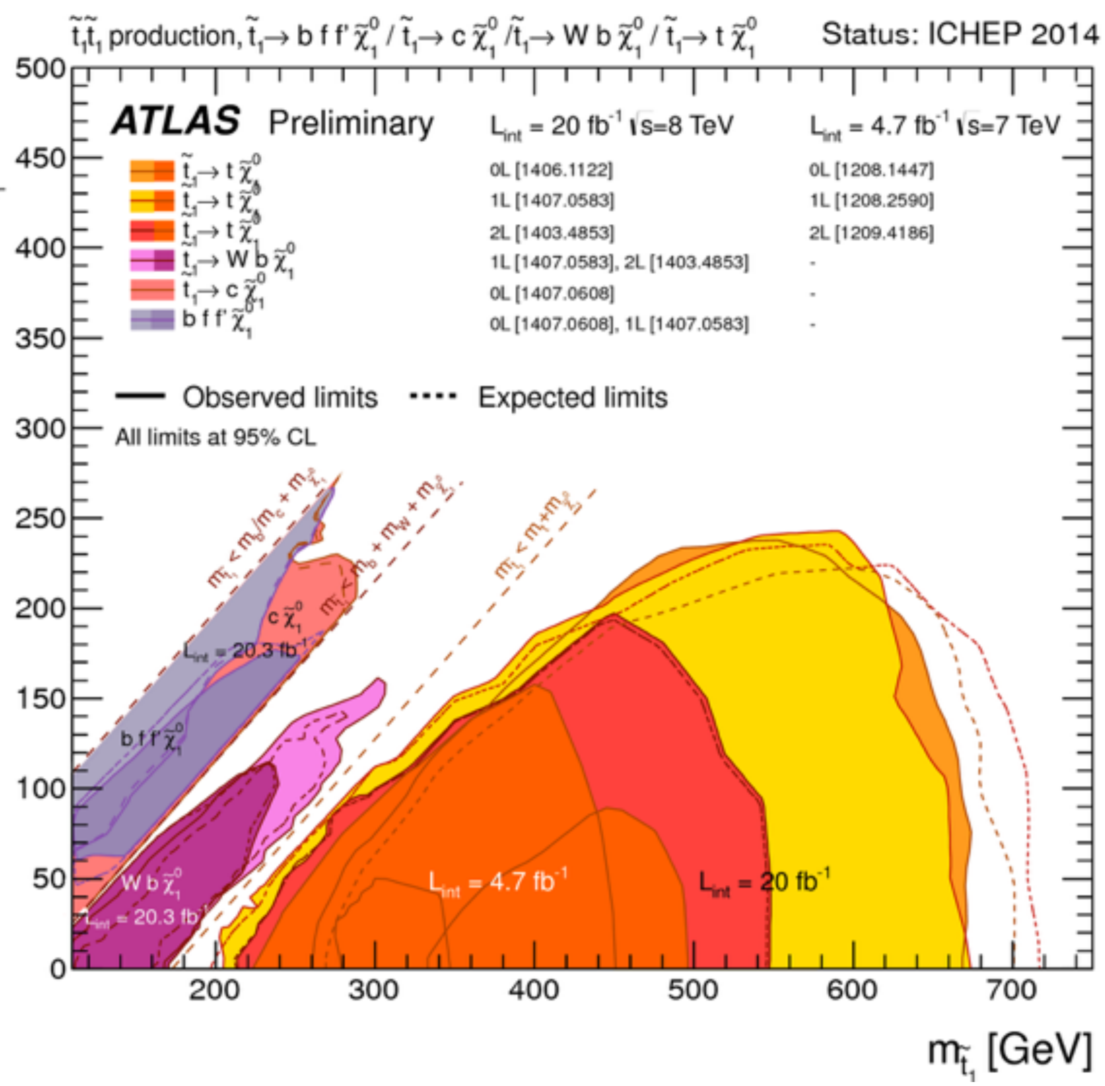

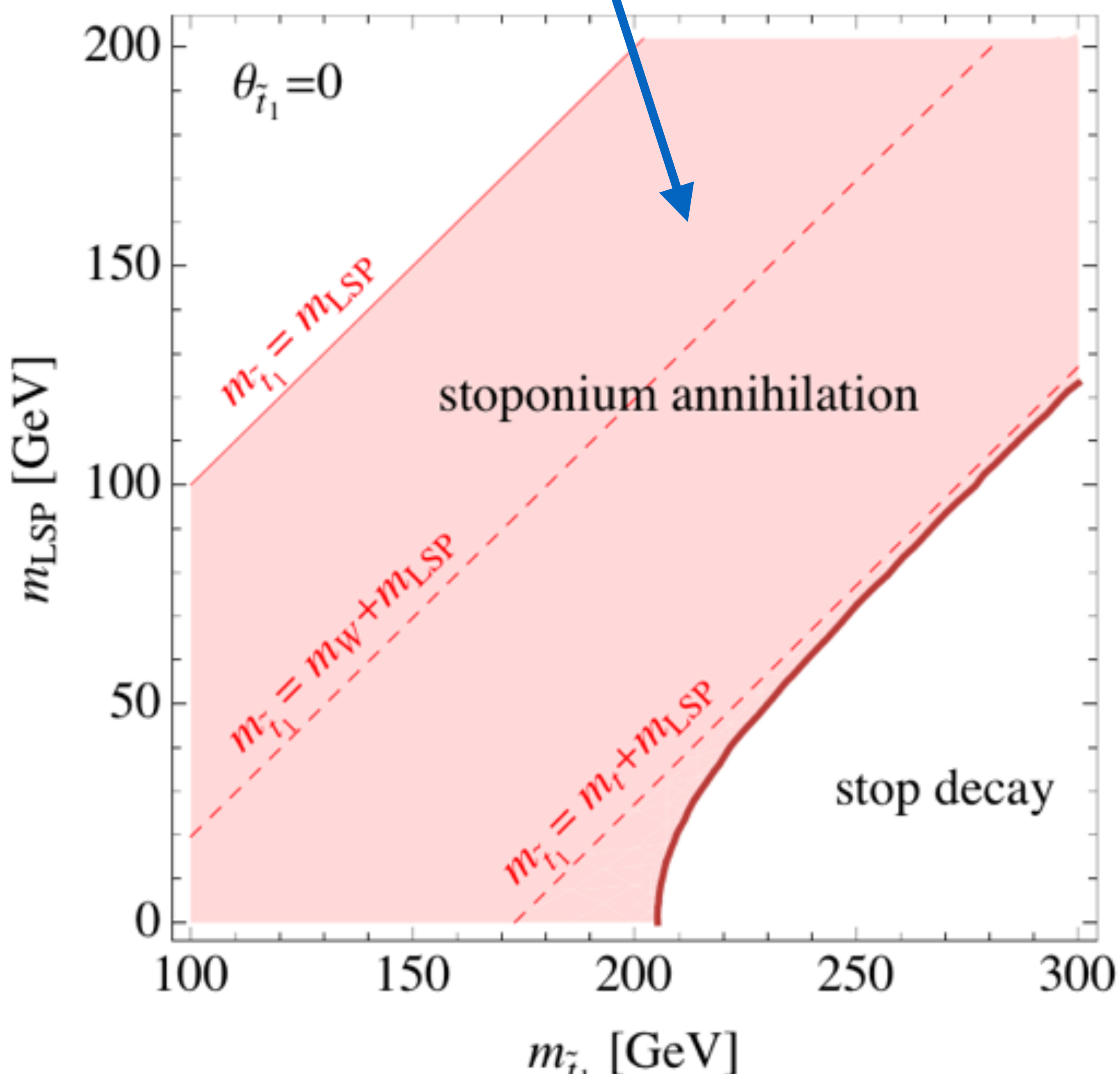

Sunghoon Jung, KIAS

M.Drees, M.Nojiri
S.Martin et al.
V.Barger et al.
C.Kim, T.Mehen et al.
Y.Kats et al.

Stoponium

- It's a bound state of a stop and an anti-stop bonded by QCD Coulomb potential.

- It is spin-0, CP-even, color singlet (same as Higgs).

M.Drees, M.Nojiri
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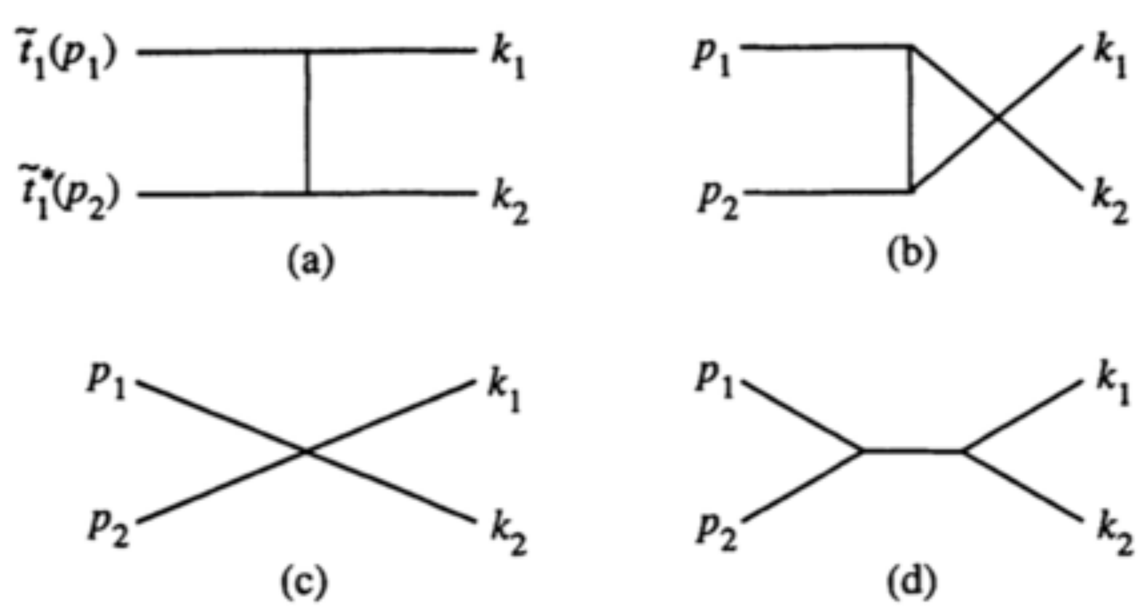
Stoponium

- It's a bound state of a stop and an anti-stop bonded by QCD Coulomb potential.

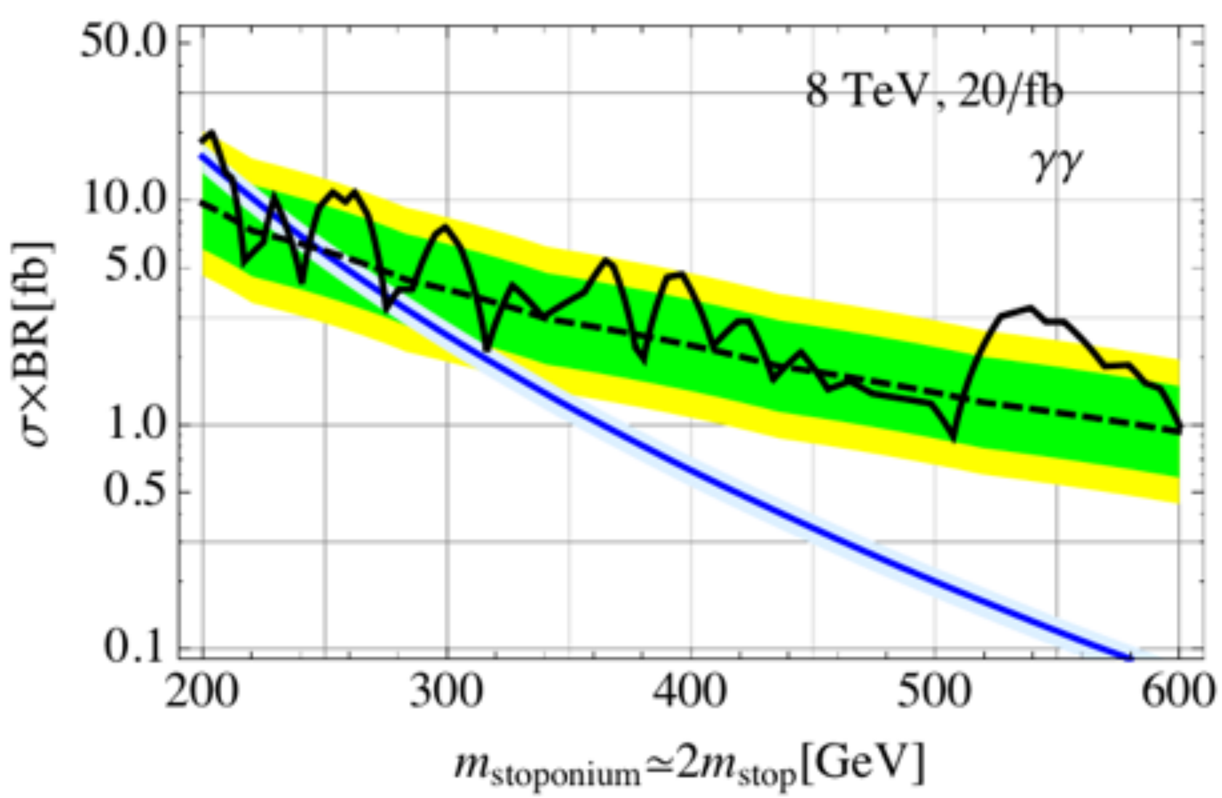
- It is spin-0, CP-even, color singlet (same as Higgs).

- Once formed, they can pair annihilate into gg, diphoton, WW, ZZ, hh, LSP LSP… similar to Higgs but different BRs.



Stoponium discovery

- Any heavy Higgs resonance searches in diphoton, WW, ZZ, hh can also search for stoponium annihilation.
- When the stop mixing is small, BR(gg)~100%, BR(diphoton)~0.35%. => Diphoton search is best.



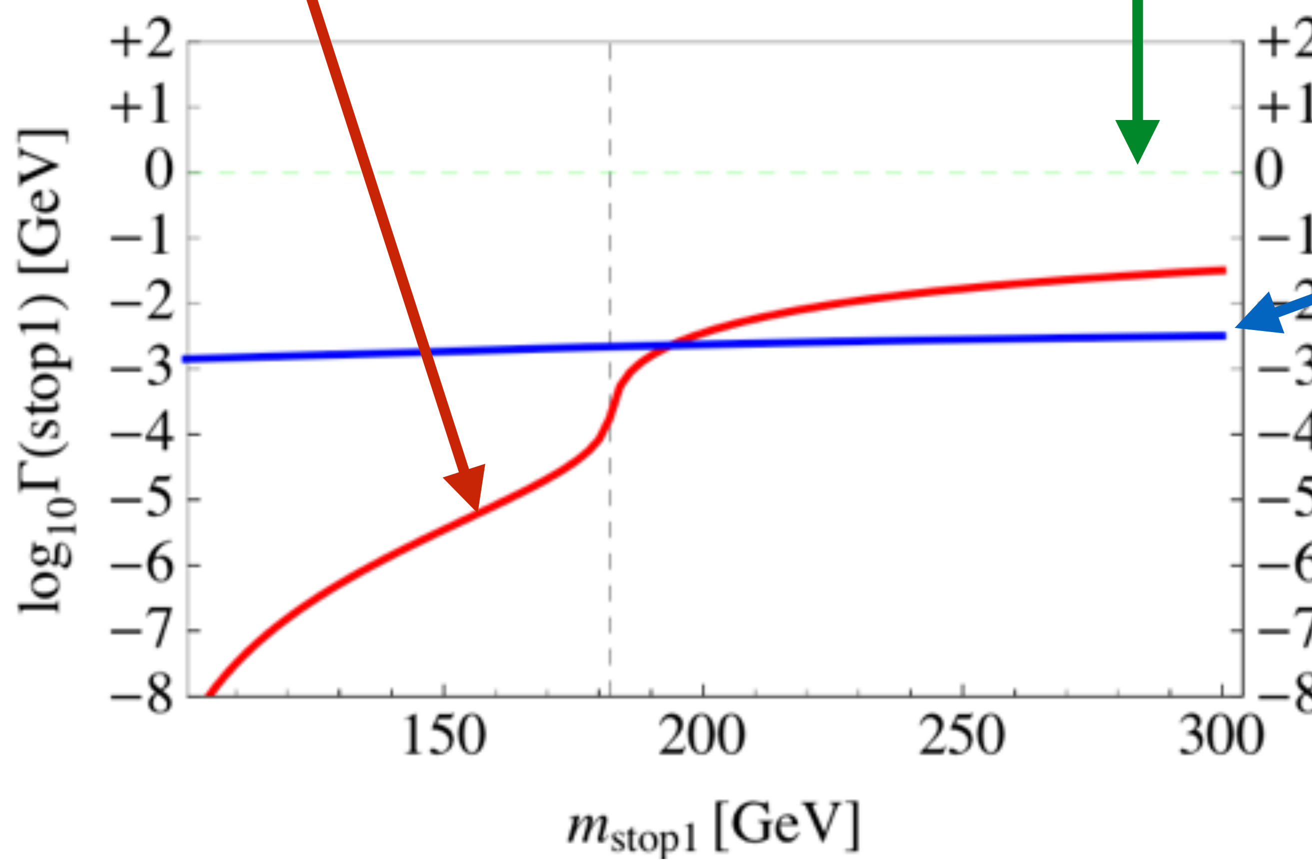
B.Batell, SJ (preliminary)

Sunghoon Jung, KIAS

Stoponium formation conditions

- When the stop and anti-stop are produced with a small relative velocity: only near stop pair threshold.
- When the stop decay is slowly enough. Binding energy ~ 1 GeV: almost always true!

(NB: the toponium has not been observed!)

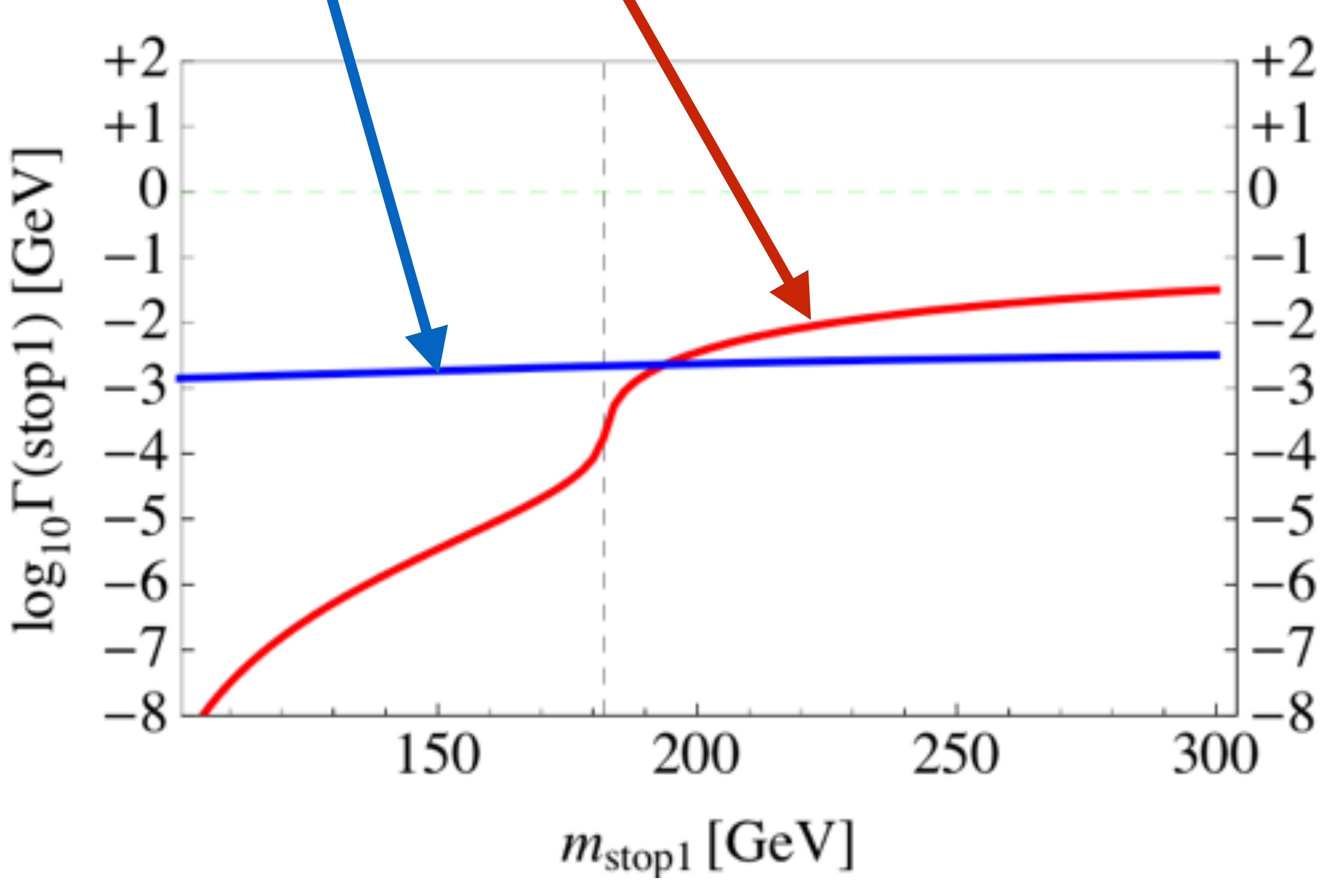


B.Batell, SJ (preliminary)

Sunghoon Jung, KIAS

Stoponium annihilation conditions

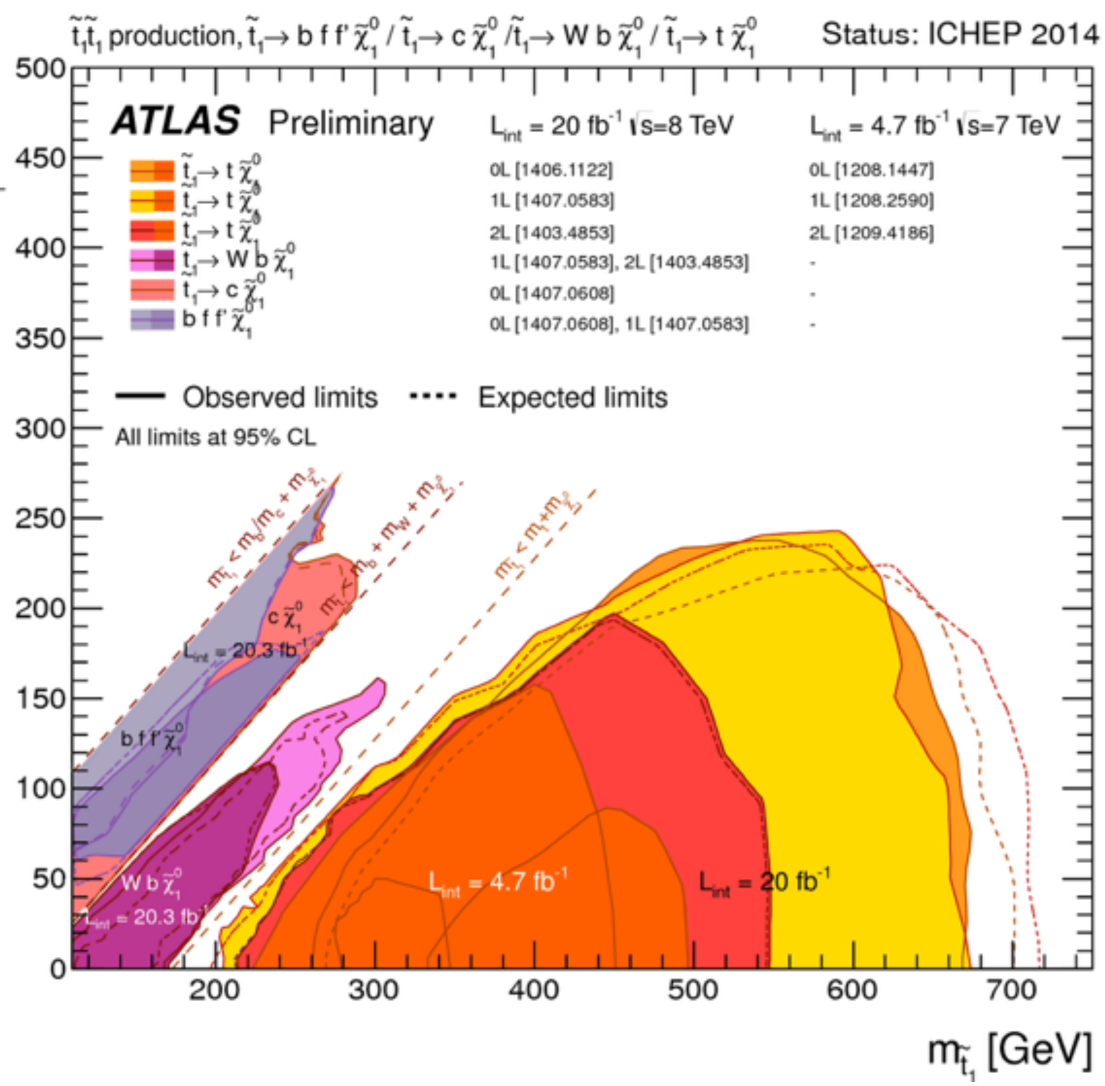
- Annihilation is what makes it look like a resonance.
- Individual stop decay should be slower than stoponium annihilation. Crucial condition for stoponium pheno.

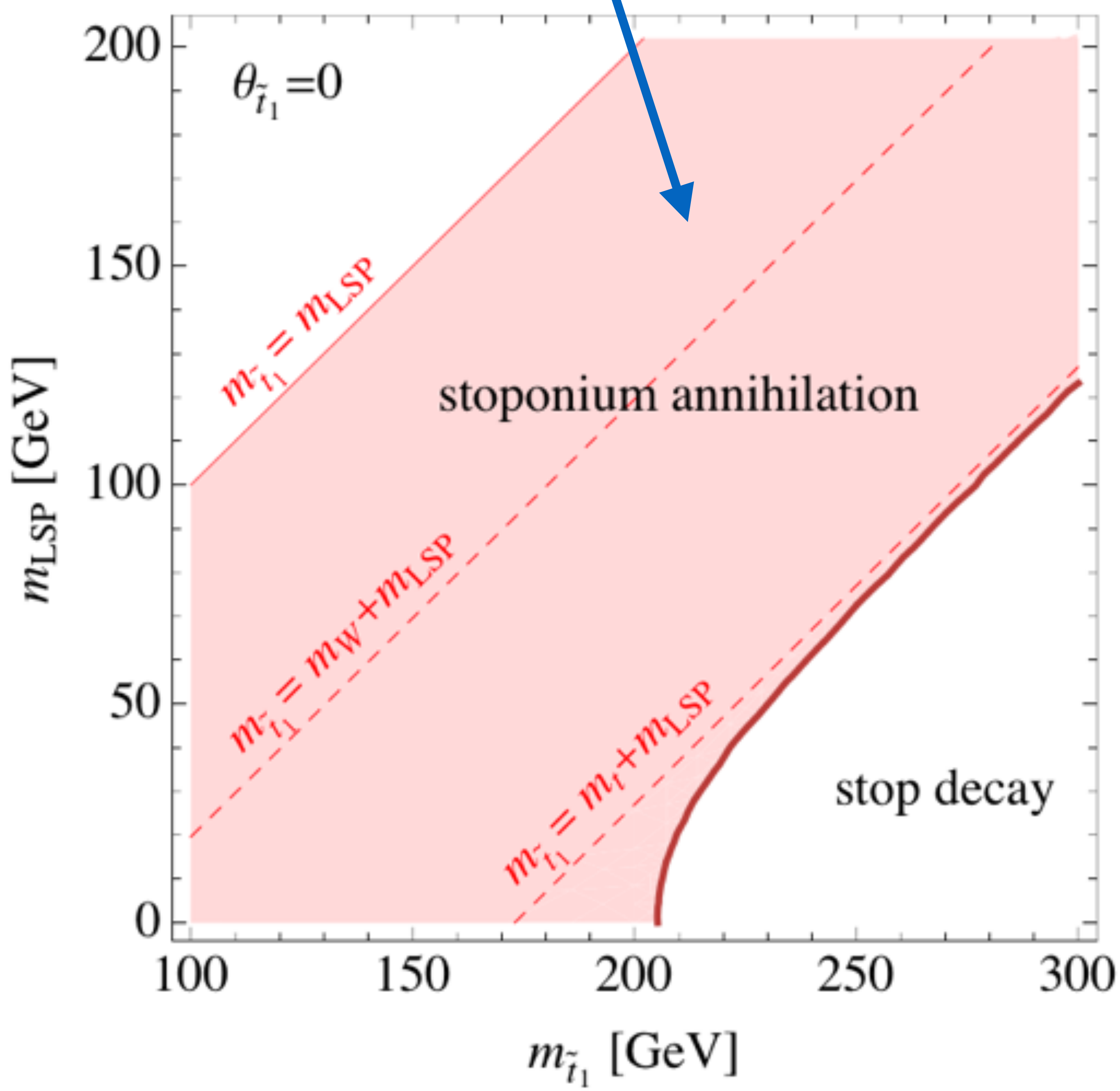


B.Batell, SJ (preliminary)

Stoponium can potentially cover

B.Batell, SJ (preliminary)





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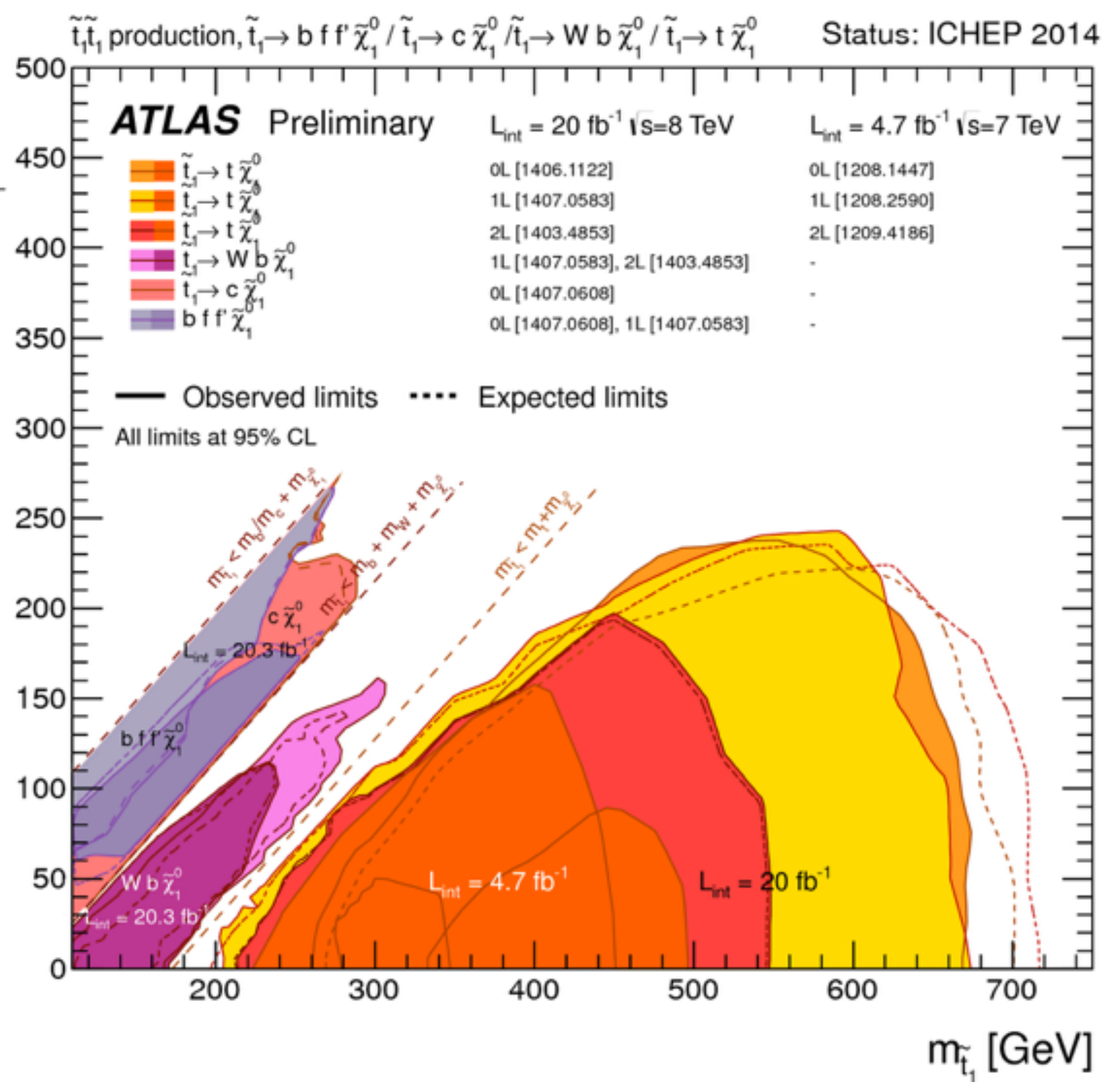
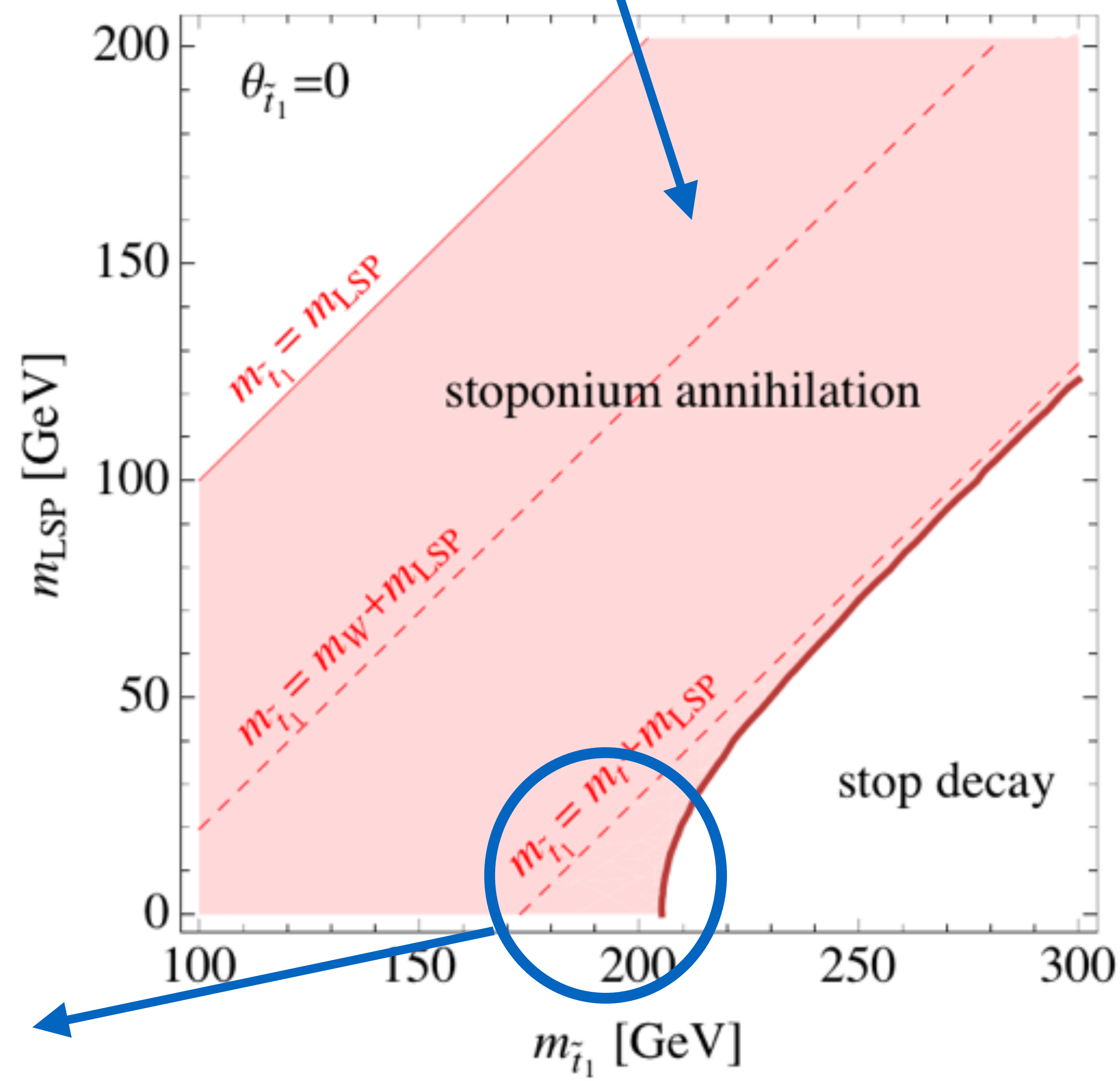
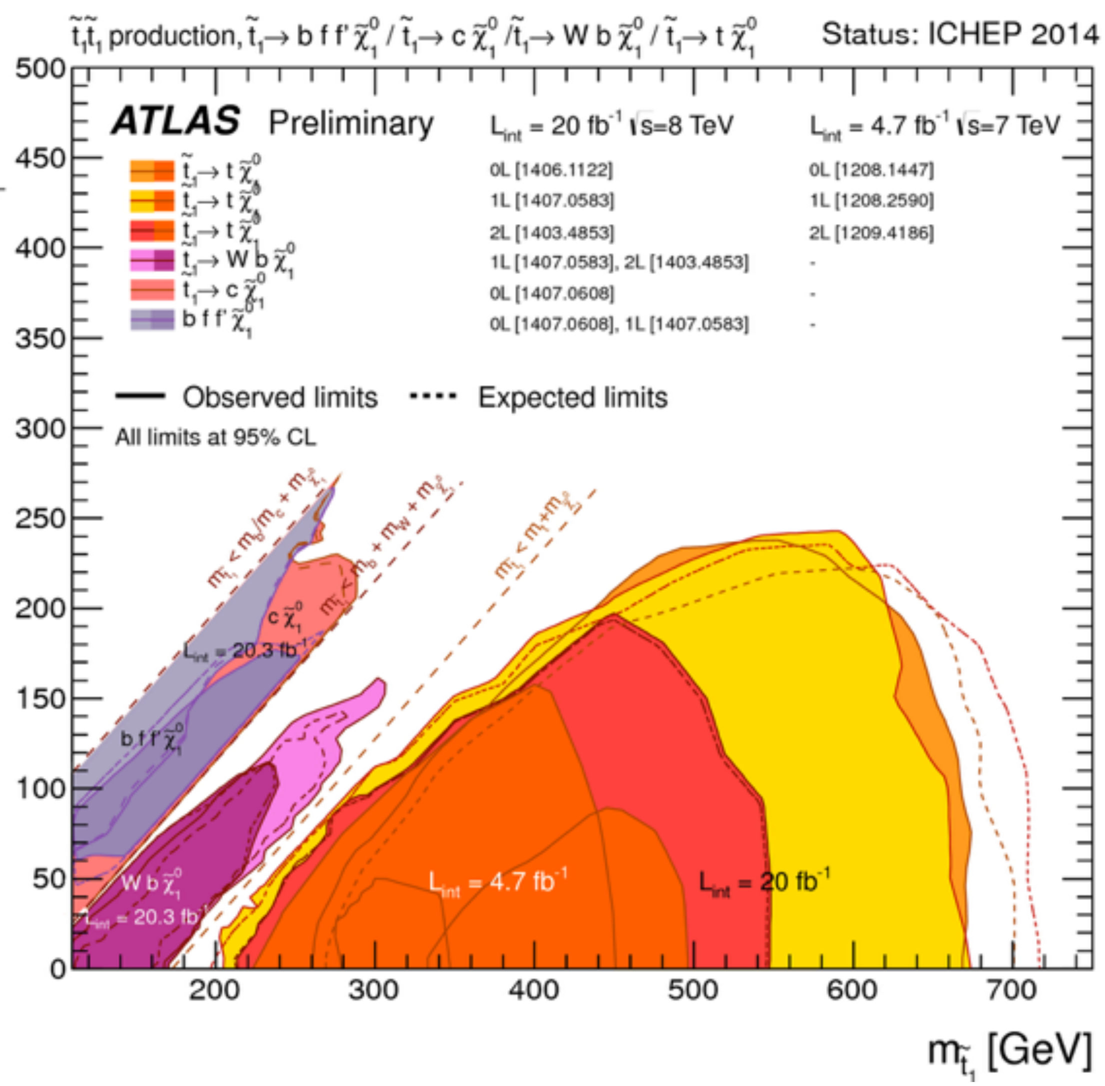


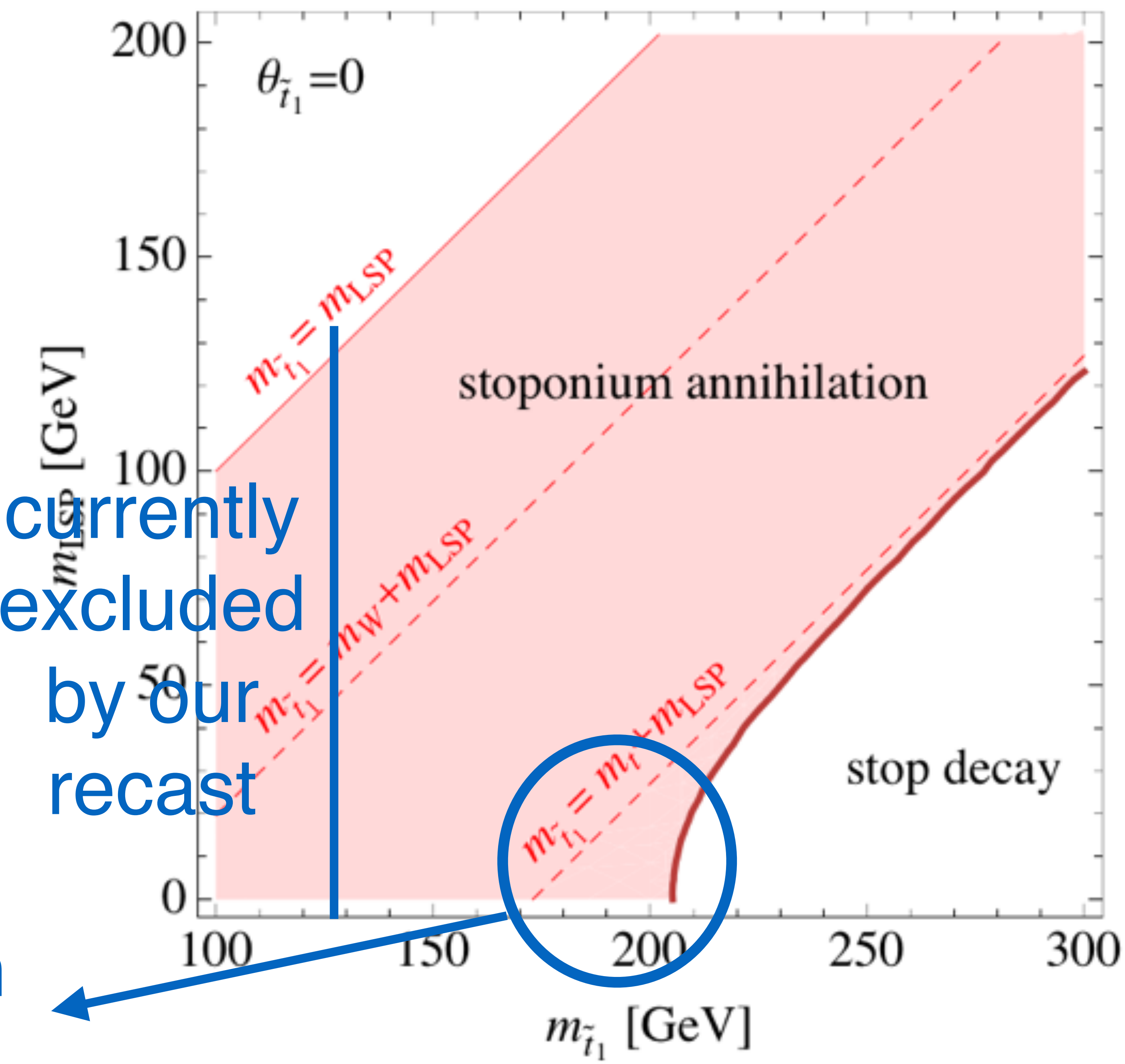


The stealth stop can also be probed!

Current recasted limits

B.Batell, SJ
(preliminary)





currently excluded by our recast

The stealth stop can also be probed soon.

2. Discoverably light stops with undiscoverably heavy gluinos

SJ, B.S.Kyae
(preliminary)

Enoughness 1: tuning

N.Craig et al.
E.Hardy et al.
Arvanitaki et al.
J.M-Russell et al.
J.J.Fan et al.
…

- Light "enough" stops with heavy "enough" gluinos.
- Light stops not to induce significant tuning in the EW scale. Gluinos are heavy enough to avoid collider limits.
- Subjective criteria. Widely studied.

Enoughness 2: discovery

- If gluinos are nearby in mass with other sparticles, the gluino is typically the easiest discovery channel.

- Can a gluino be *undiscoverably* heavy while stops are *discoverably* light?

- More objective quantification.

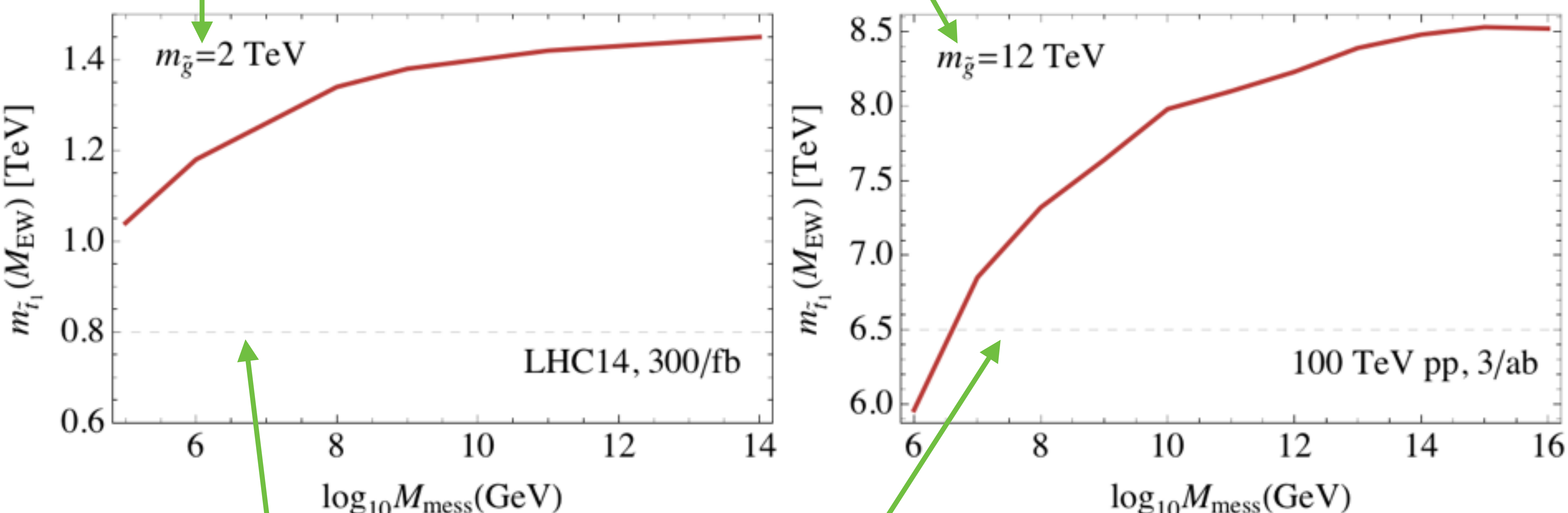
- Less strict than requiring natural light stops. So models do exist. But what are they; any exotic requirements?

Stop vs. gluino

SJ, B.S.Kyae
(preliminary)

In the MSSM:

Undiscoverably heavy gluinos



Discoverably light stops

Heavy squark 2-loop effects

SJ, B.S.Kyae
(preliminary)

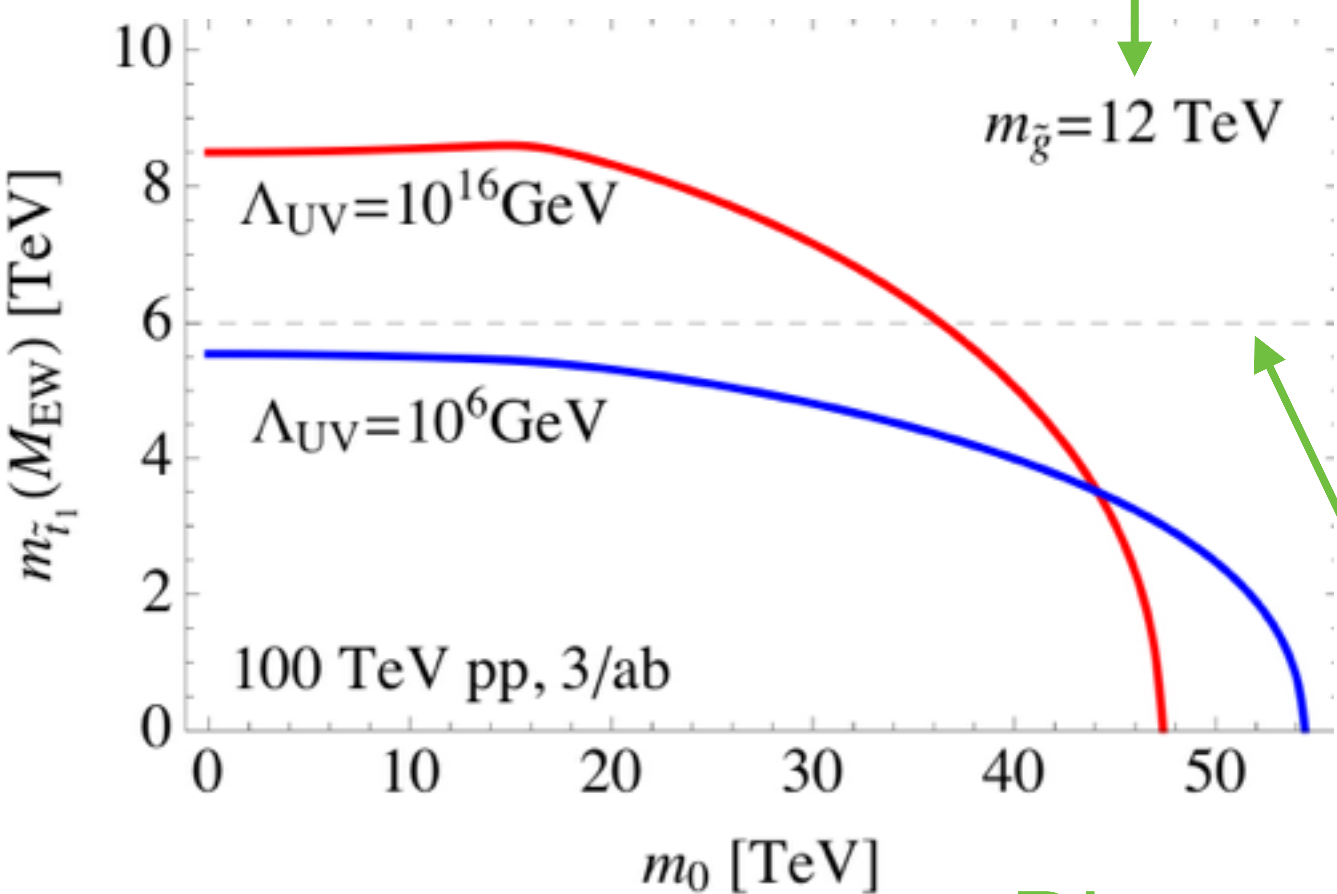
$$\frac{d}{dt} m^2_{\widetilde{Q}_3}$$

$$= 2\widetilde{y}_t^{\,2}(m^2_{H_u} + m^2_{Q_3} + m^2_{u_3}) + 2\widetilde{a}_t^{\,2} - \frac{32}{3}\widetilde{g}_3^{\,2} M_3^2 + \frac{128}{3}\widetilde{g}_3^{\,4} m_0^2.$$

Heavy squark 2-loop effects

SJ, B.S.Kyae (preliminary)

Undiscoverably heavy gluinos



Discoverably light stops

- Squarks ~3-4 times heavier than gluinos can lead to light enough stops. O(1-10) fine-tuning.

Other solutions to study

- Dirac gluinos
- Low-scale gaugino mediations
- Hybrid mediations

- Interestingly, (General) Gauge Mediation never make it.

Summary

- Stoponium resonance search is so easy, useful and complementary to usual collider searches of light stops. The stealth stop can be covered at early 14 TeV.
- Stops can be much lighter than gluinos with much heavier squarks without serious cancellations; so stops can be discoverable earlier.

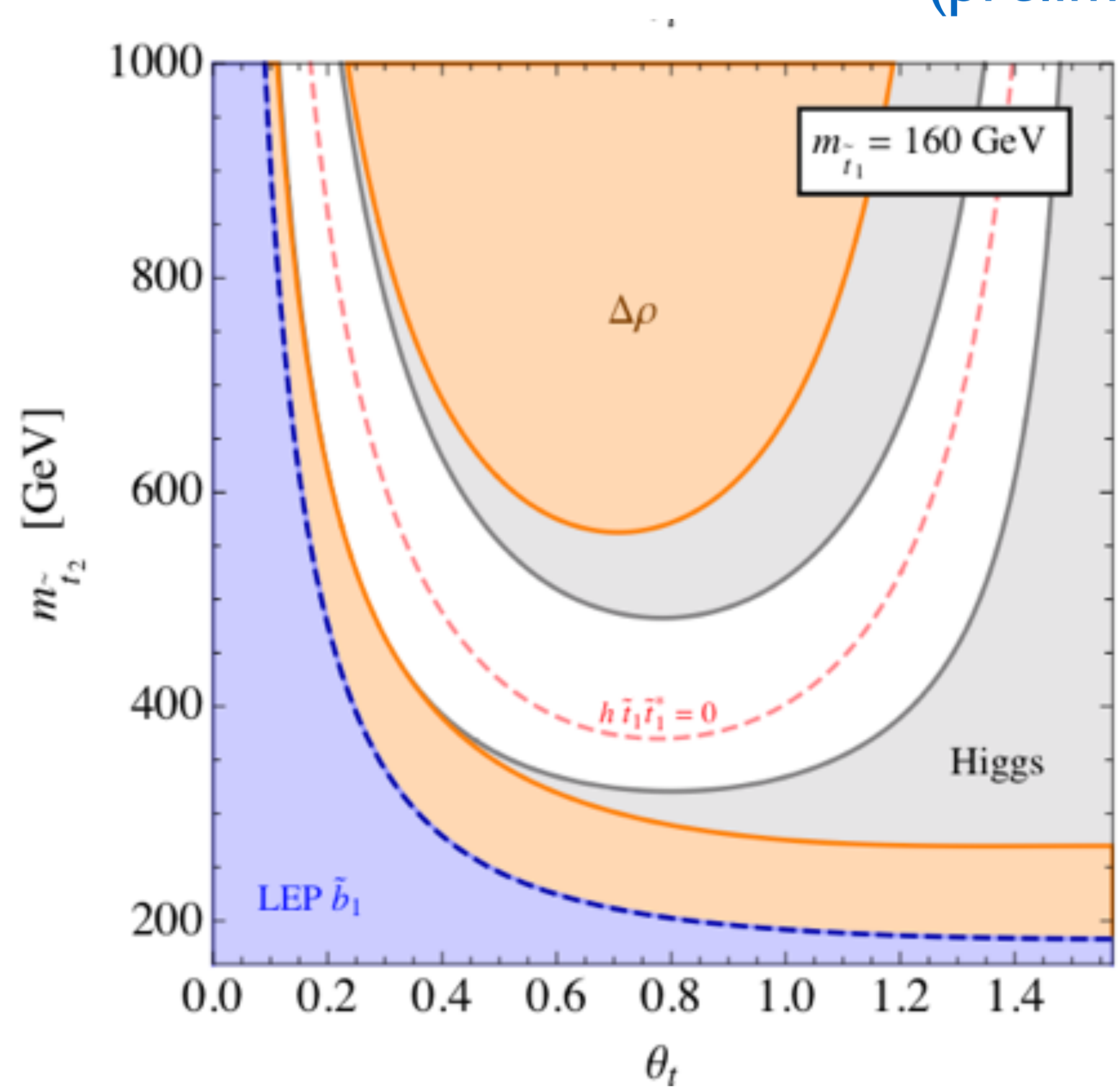
Thank you for your attention and time.

back-up

Stop Constraints

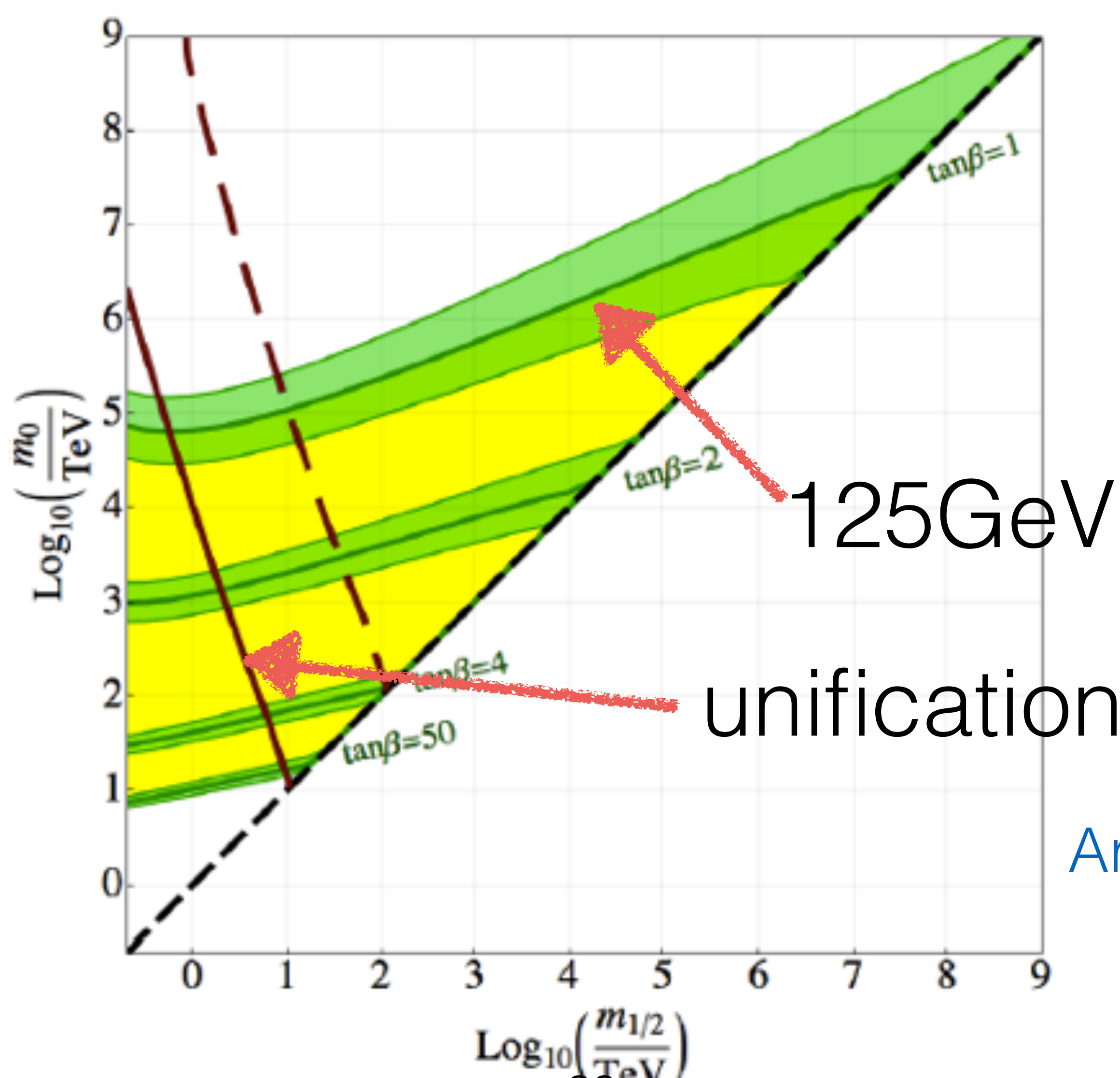
- Sizable stop mixing is strongly constrained by indirect constraints.
- WW and ZZ have only limited complimentary sensitivities.
- hh and other modes hardly help.

B.Batell, SJ
(preliminary)



Unification upper limits

- Best unification is achieved with light gauginos and higgsinos ~O(1)TeV or lighter.



Arvanitaki,Craig, Dimopoulos, Villadoro

Sunghoon Jung, KIAS