SUSY, Naturalness and the Electroweak Phase Transition

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Probing the EWPT with a Next Generation PP Collider
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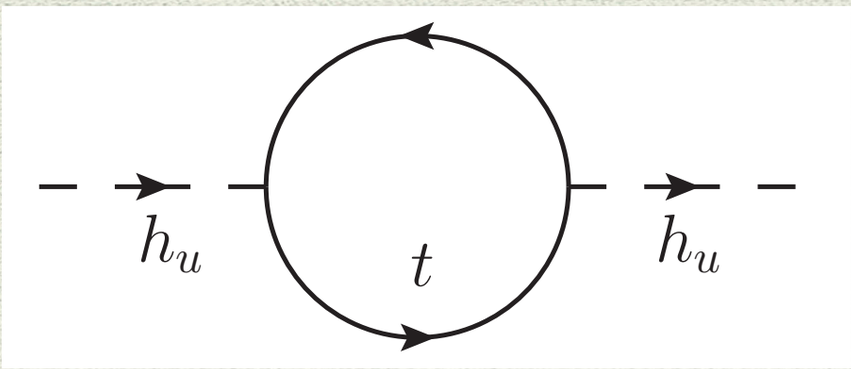
EWPT Beyond the Standard Model

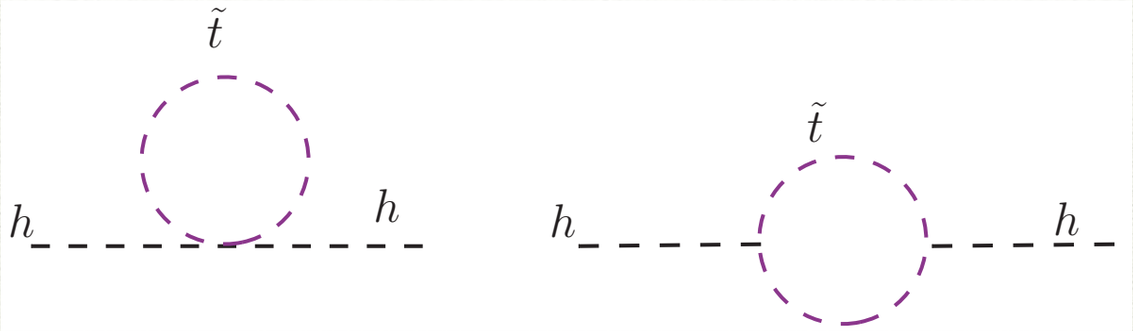
Sakharov Conditions:		**EW Theory**
Baryon Number Violation	✔	*Does not happen in the SM with $m_h > 80$ GeV. The transition from the EW unbroken to the broken phase is cross-over. Need new particles which couple to the Higgs strongly to get strong 1st order PT*
CP violation	✗	
Departure from thermal equilibrium	✗	

(Un)-Naturalness

Basic problem — top contributions to the high scale sensitivity

SM





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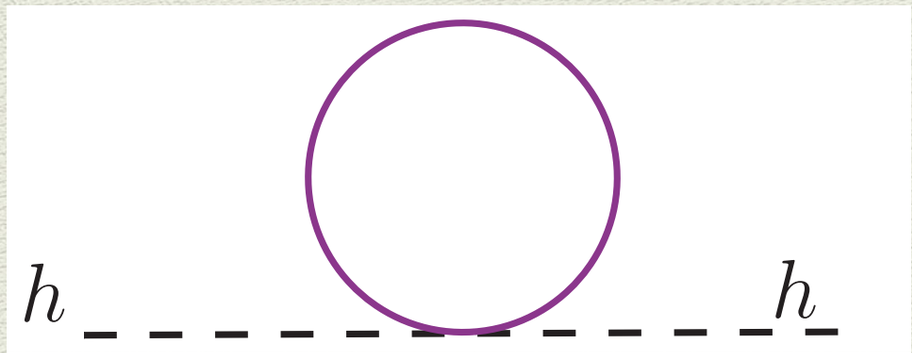


We need relatively light top-partners both in SUSY-like models and pNGB-higgs models

EWPT Meets Naturalness

Because the naturalness problem is tightly connected to the Higgs physics, we would expect that lots of models, motivated by naturalness will have an impact on the EWPT.

- SUSY
- folded SUSY
- partial compositeness
- twin Higgs

- **light stops**
- **2HDM - extra Higgses**
- **singlets in nMSSM**

No obvious candidate.
Top partners?

1st order PT from 1-Loop Thermal Potential

High-T approximation:

$$V_T = \frac{gm^2(h)T^2}{24} - \frac{gm^3(h)T}{12\pi} + \ldots$$

$m^2(h) \propto h^2$

potentially new quadratic term in h

potentially new cubic term in h

Cubic is often enough to trigger 1st order PT, but needed:

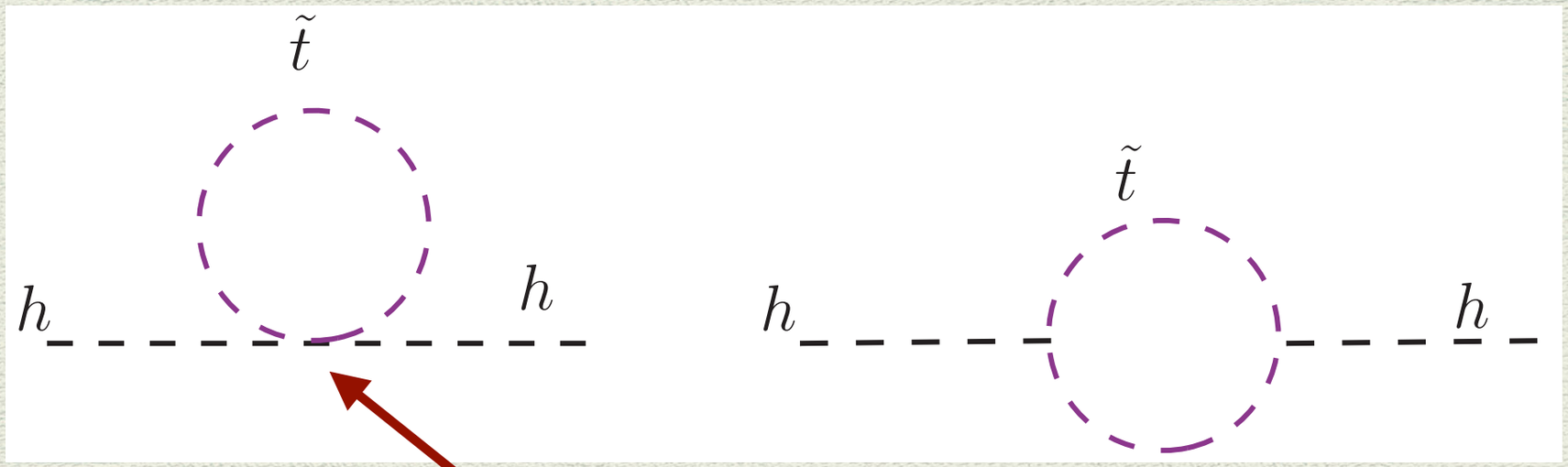
- New particle with O(1) coupling to the higgs
- The particle should be very light

Obvious Consequences of the 1st order PT

New light particle which couples strongly to the Higgs ⇒ Higgs couplings (BR, production X-section) might change:

- If the new particles are EM-charged, they modify the effective coupling of the higgs to di-photons
- If the new particles are colored, they modify the effective coupling to the gluons — dominant production mode
- Even if they are completely sterile, they can modify the higgs wavefunction at the 1-loop level and trigger O(1%) corrections in the higgs to di-Z coupling — reasonable target for future colliders

Stop-Catalyzed 1st order PT



Y_t^2 coupling (neglecting tri-linear terms)

Needed for the 1st order PT:

- Very light stop below 120 GeV
- Large tan β ≳ 10
- Mixing between the stops not too large

Carena, Quiros, Wagner, 1996

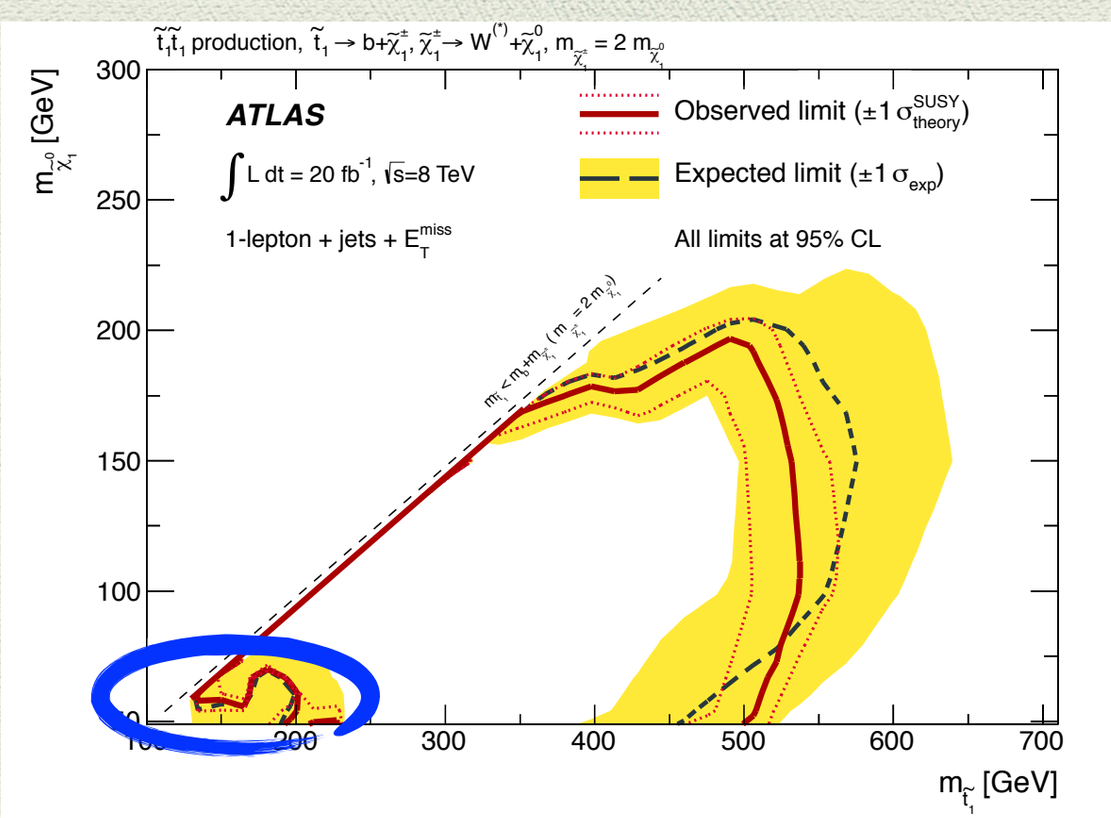
Stop-Catalyzed Baryogenesis and the LHC — Light Stops

How can the light stop (≲ 120 GeV) decay?

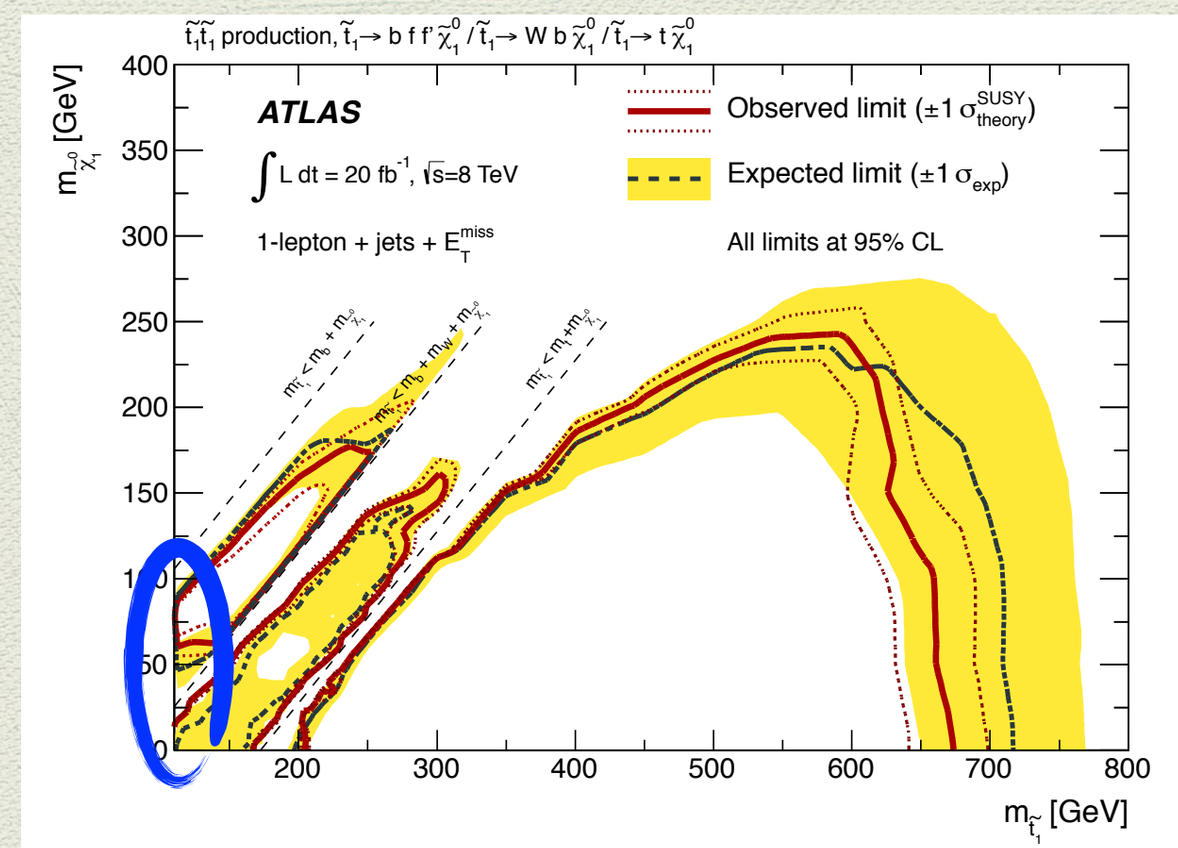
- 3-body into b, W and neutralino
- 4-body: b, 2 quarks (lepton + neutrino) and neutralino
- charm + neutralino
- di-jets (RPV scenario)

Light Stops in 3- and 4-Body Decays

Decays into chargino co-LSP

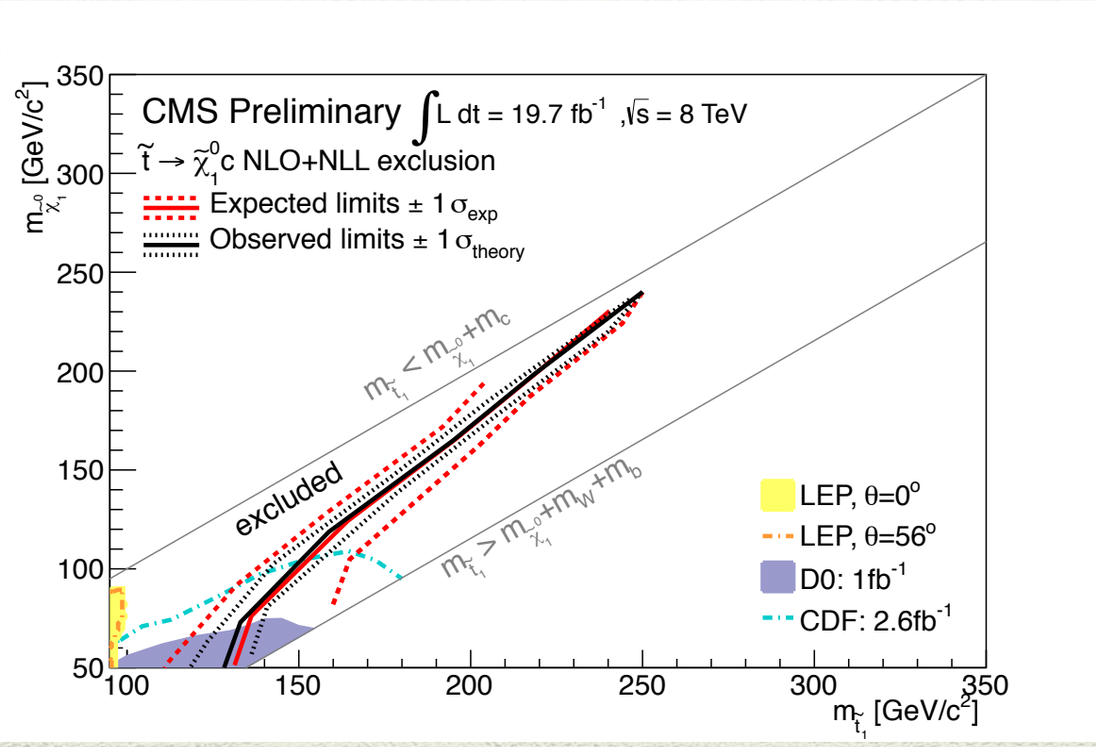


Decays into neutralino LSP

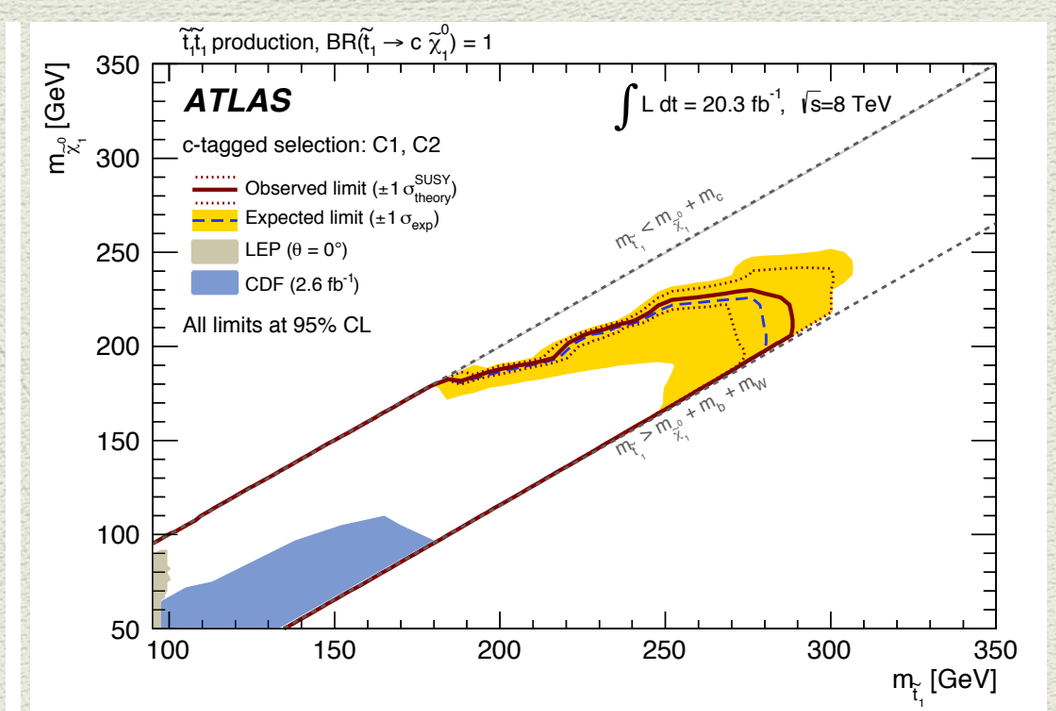


"Cracks" which are compatible w/ 1st order PT

Light Stops: Charm + Neutralino



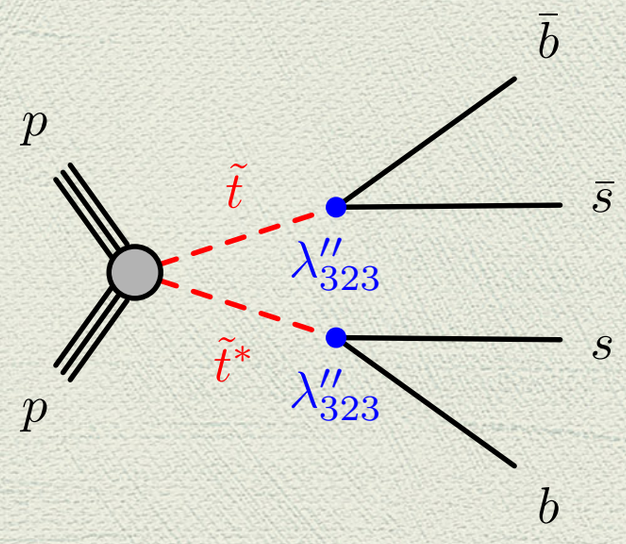
monojets



c-tagging

Generally c-tagging selection performs better than monojets. The exclusion is not by orders of magnitude. Relaxing the assumption BR(stop→c + neutralino) = 1 might open more room

Light Stops and RPV

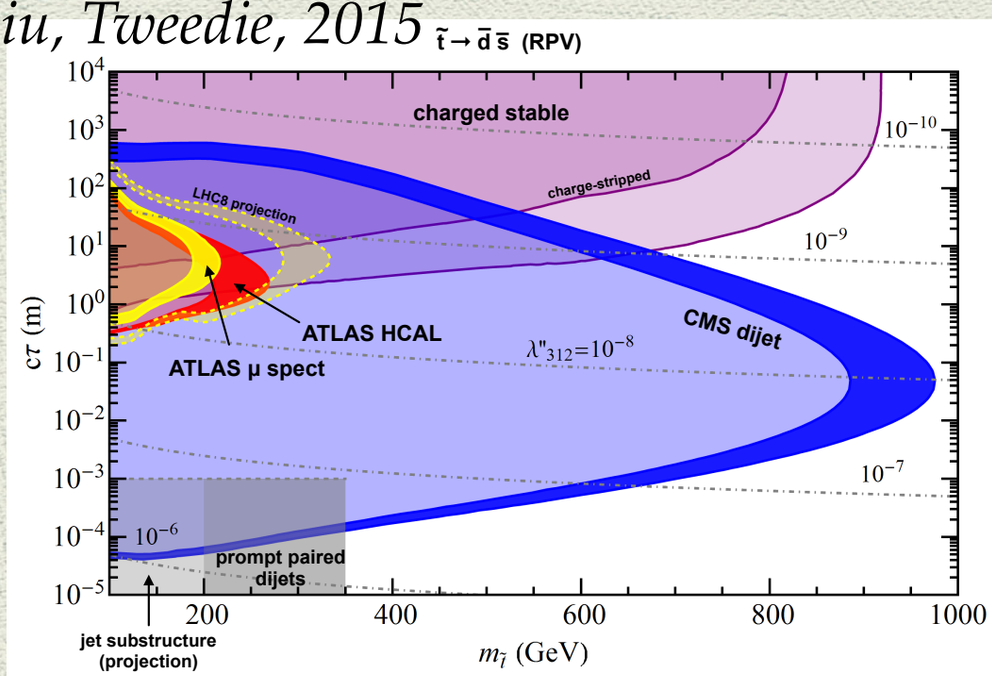


This kind of stop poses a severe danger to baryon asymmetry: BNV might simply wash the asymmetry out

(Dimopoulos, Hall, 1984; Barry, Graham, Rajendran, 2014).

Cosmological safety → small couplings → displaced vertices

Liu, Tweedie, 2015



Prompt stops: excluded by Atlas up to 350 GeV if decay into one b-jet (boosted analysis). CMS excludes stops between 200 GeV and 350 GeV. There are still cracks…

Stop-Catalyzed Baryogenesis and the LHC — Precision Measurements

In order to trigger 1st order EWPT the lightest stop mass was supposed to be lighter than 120 GeV (*Carena, Quiros, Wagner; 1996*). If we add an input m_h = 125 GeV, we should demand stop below 110 GeV.

MSSM:

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3y_t^2}{4\pi^2}\cos^2\alpha\, m_t^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + f(X_t)$$

Higgs at 125 GeV + 1st order EWPT ➞ the heavy stop is above 100 TeV or the stops are heavily mixed

Corrections to the couplings to gluons and photons:

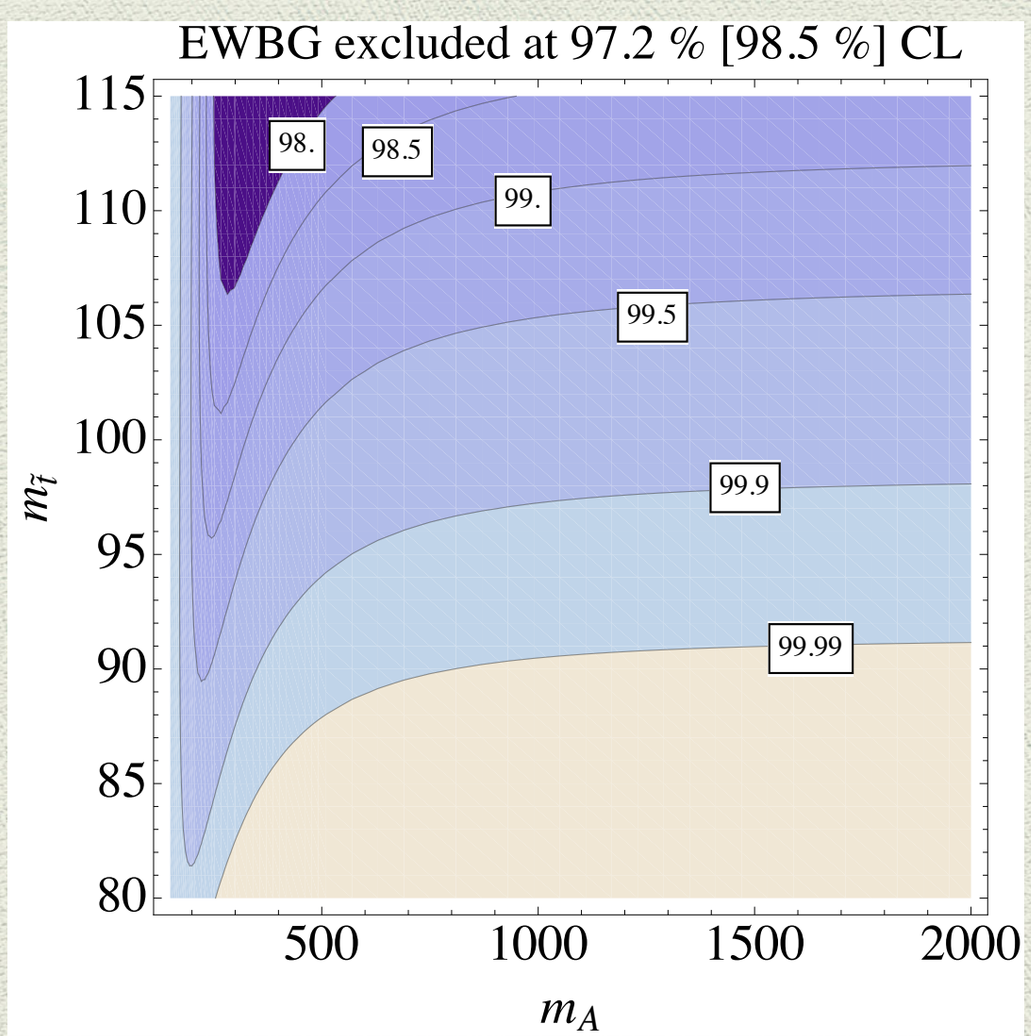
$$g_{hgg}/g_{hgg}^{SM} - 1 \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}\right).$$

Need $X_t \sim$ heavy stop mass to be in agreement with the higgs measurements

Stop-Catalyzed EWPT in the MSSM

Curtin, Jaiswal, Meade, 2012

Needed for MSSM stop-catalyzed 1st order EWPT: one very light stop (~100 GeV), one very heavy stop (~100 TeV).



Questions to address:

- *The higgs measurements have improved a lot since 2012. Do we still have less robust exclusions in the decoupling limit?*
- *What happens if we relax the condition on the heavy stop mass (beyond MSSM)?*
- *How far away can we go beyond the pure RH stop limit?*

Going Beyond the MSSM

MSSM severely constraints the SM-like higgs mass. We have good motivation to abandon these constraints:

- *New terms in the effective 2-higgs potential are easy to get from new F- or D-terms at the TeV scale. Assume new particles at 1…3 TeV scale — no direct impact on EWPT*
- *These new terms can be parametrize as small hard SUSY breaking terms at 100 GeV scale — strong impact on the SM-higgs mass*
- *Departure from MSSM is strongly motivated by naturalness considerations*

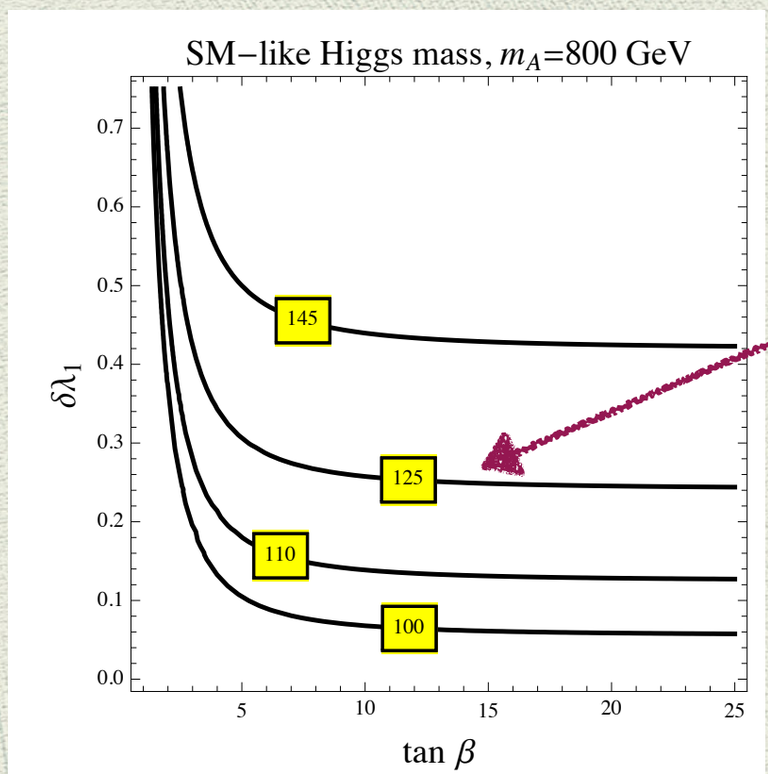
$$
\begin{aligned}
V(H_u,H_d) \;=\; & M_u^2\left|H_u\right|^2 + M_d^2\left|H_d\right|^2 + \left(bH_u\cdot H_d + \text{h.c.}\right) + \frac{1}{2}\lambda_1\left|H_u\right|^4 + \lambda_2 H_u^\dagger H_u\left(H_u\cdot H_d + \text{h.c.}\right) \\
& + \lambda_3\left|H_u\right|^2\left|H_d\right|^2 + \frac{1}{2}\lambda_4\left(H_u\cdot H_d + \text{h.c.}\right)^2 + \lambda_5\left|H_u\cdot H_d\right|^2 \\
& + \lambda_6 H_d^\dagger H_d\left(H_u\cdot H_d + \text{h.c.}\right) + \frac{1}{2}\lambda_7\left|H_d\right|^4 . \qquad (1)
\end{aligned}
$$

Compatible with new F- and D-terms at the TeV scale

The Higgs Mass Beyond the MSSM

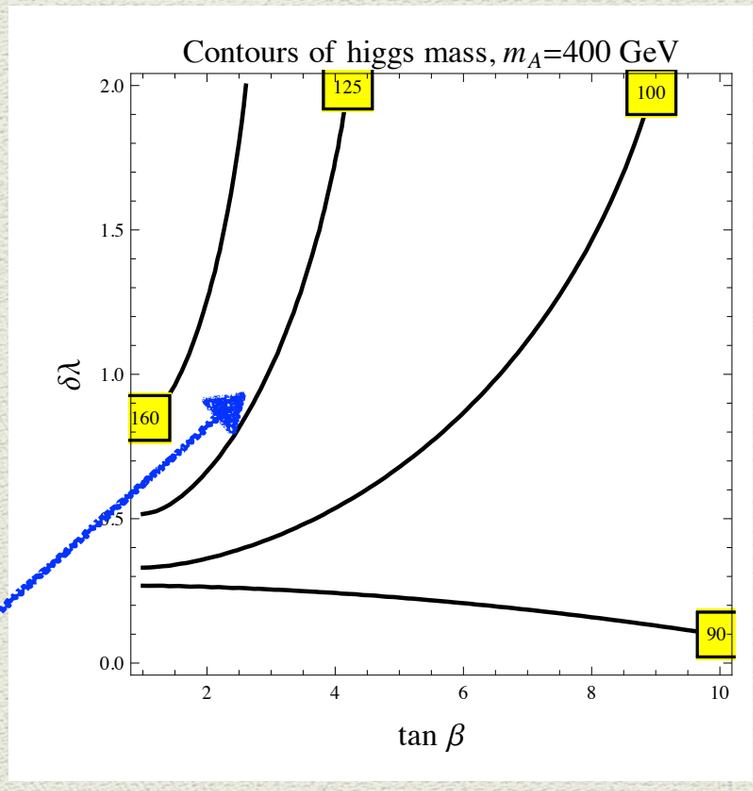
AK, Reece, Sajjad, 2014

$$
\begin{aligned}
V(H_u,H_d) \;=\; & M_u^2\left|H_u\right|^2 + M_d^2\left|H_d\right|^2 + \left(bH_u\cdot H_d + \text{h.c.}\right) + \frac{1}{4}\lambda_1\left|H_u\right|^4 + \lambda_2 H_u^\dagger H_u\left(H_u\cdot H_d + \text{h.c.}\right) \\
& + \lambda_3\left|H_u\right|^2\left|H_d\right|^2 + \frac{1}{2}\lambda_4\left(H_u\cdot H_d + \text{h.c.}\right)^2 + \lambda_5\left|H_u\cdot H_d\right|^2 \\
& + \lambda_6 H_d^\dagger H_d\left(H_u\cdot H_d + \text{h.c.}\right) + \frac{1}{4}\lambda_7\left|H_d\right|^4 . \qquad (1)
\end{aligned}
$$



Relatively small additional coefficient needed

Needed almost NP new term unless tan beta is too small for 1st order EWPT

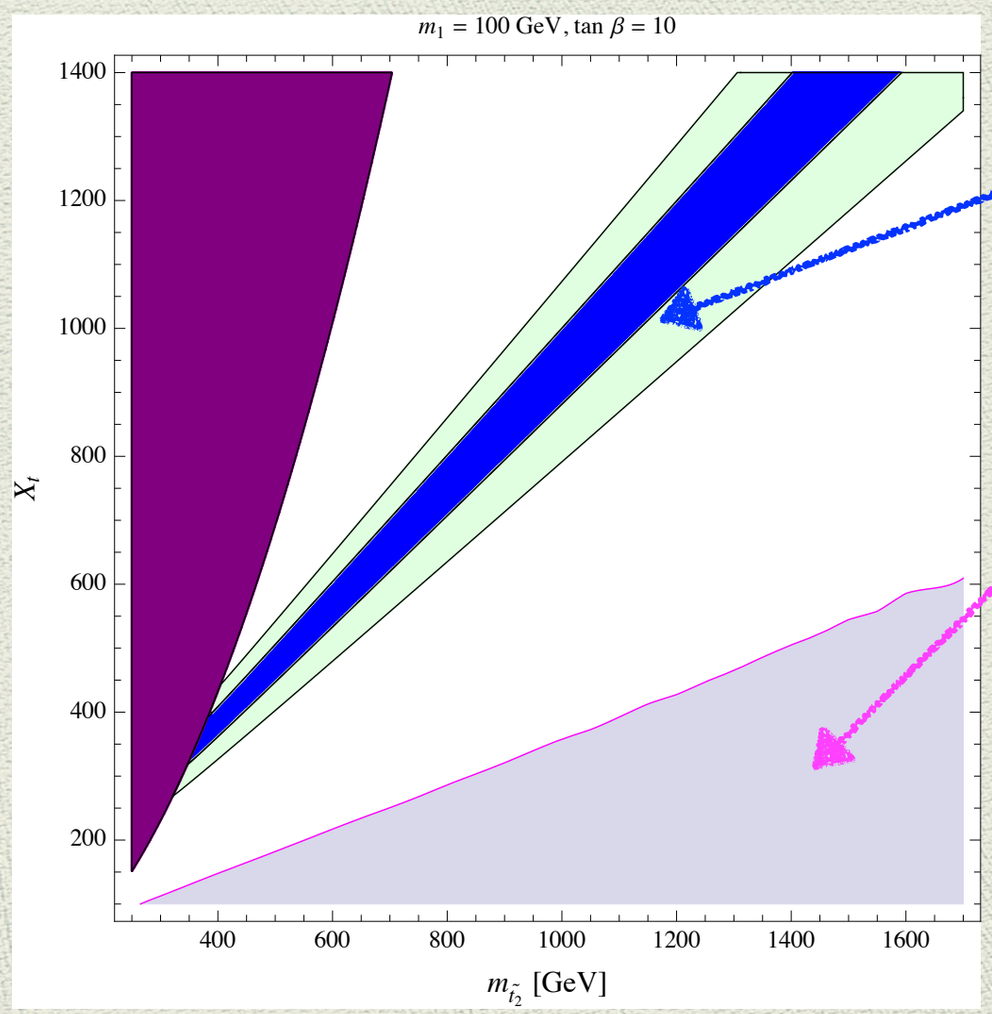


Further consider the first coefficient as the most promising scenario.

Stop-Catalyzed 1st Order EWPT w / o MSSM Constraints

AK, Perelstein, Ramsey-Musolf. Winslow, 2015

In the decoupling limit the constraints are coming from the hgg and hγγ couplings.



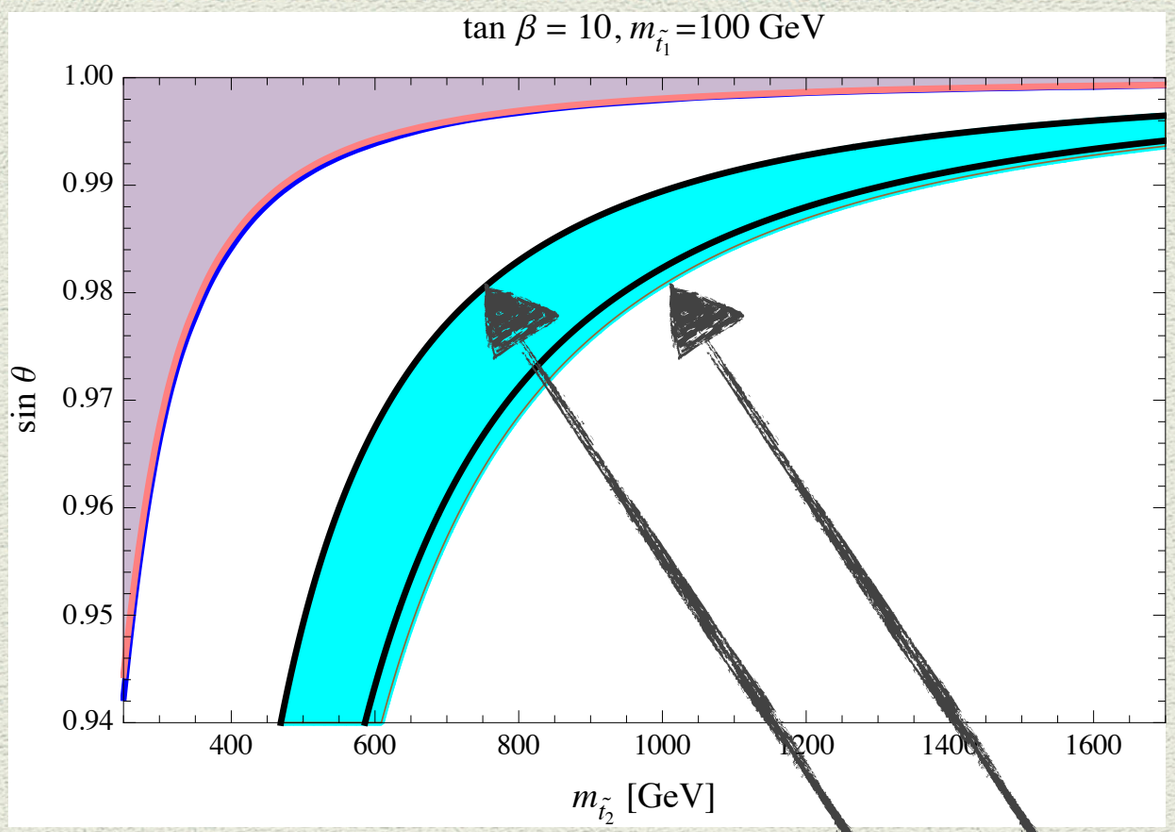
Allowed by higgs precisions

Region with the 1st order PT - also scales linearly with the mixing!

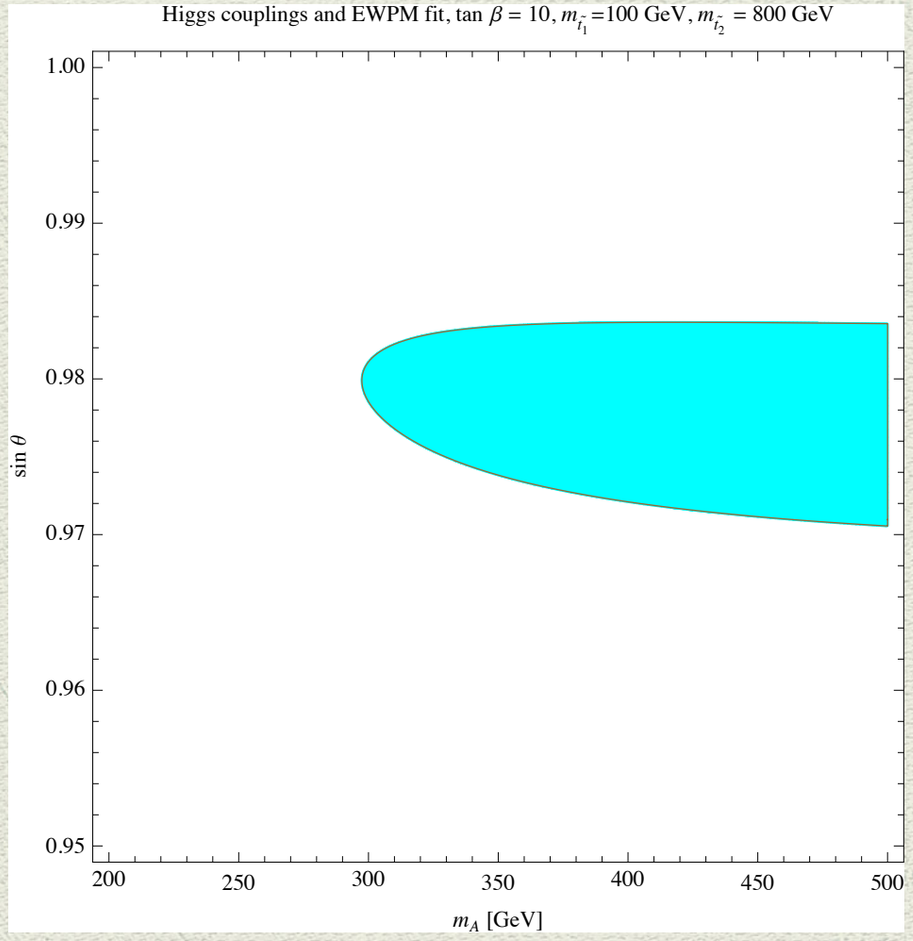
$$M_{\tilde{t}_1}(h,T)^2 \supset y_t^2 h_u^2 \left(1 - \frac{X_t^2}{m_Q^2}\right) + m_U^2 + \Pi_{\tilde{t}_1}(T),$$

Increase of mixing suppresses the effective coupling

Variations: Invisible Rate, Non-Decoupling



2HDM non-decoupling limit suggest deviations in the down type sector. Other couplings are suppressed by 4 powers of m_A



Additional invisible width (e.g. into light neutralinos) alleviates the problem with gg but only makes it worse with di-photons. The overall fit does not get better

Uncolored Stops ("Folded SUSY")

Burdman, Chacko, Harnik, Goh, 2005

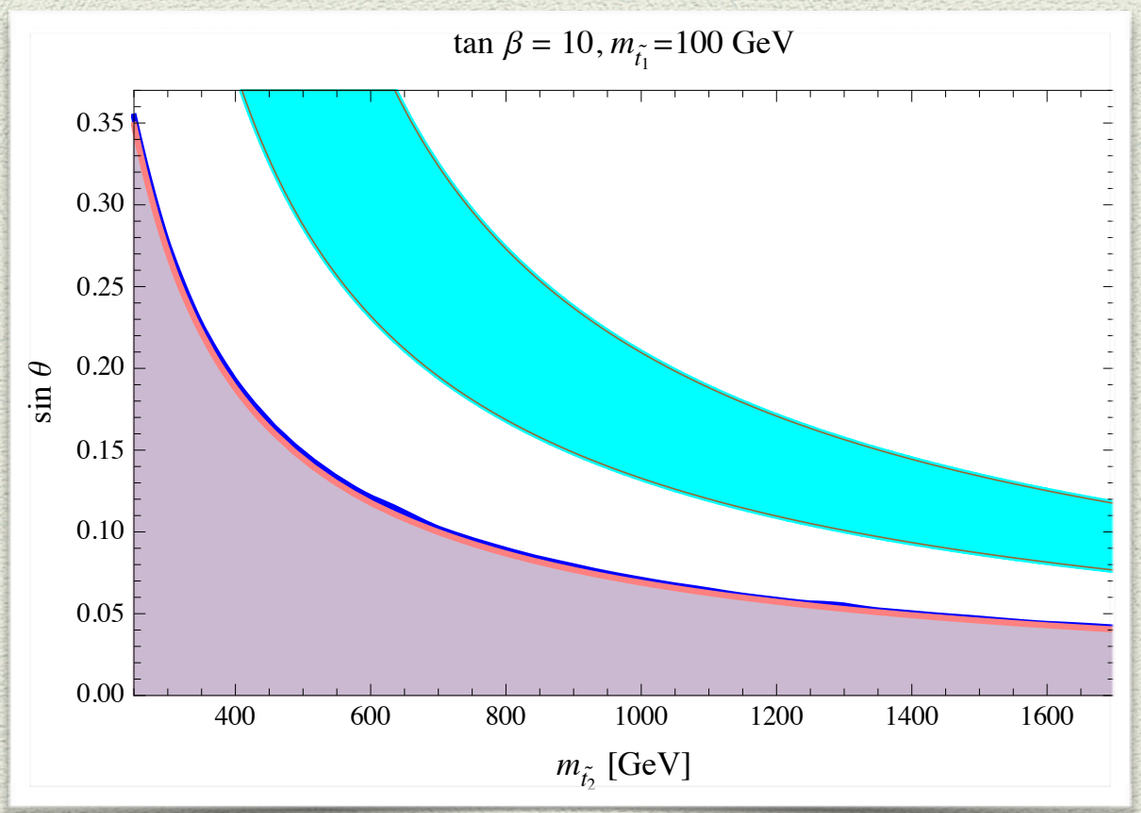
The idea of the 1st order PT here is very similar to the standard SUSY, except that:

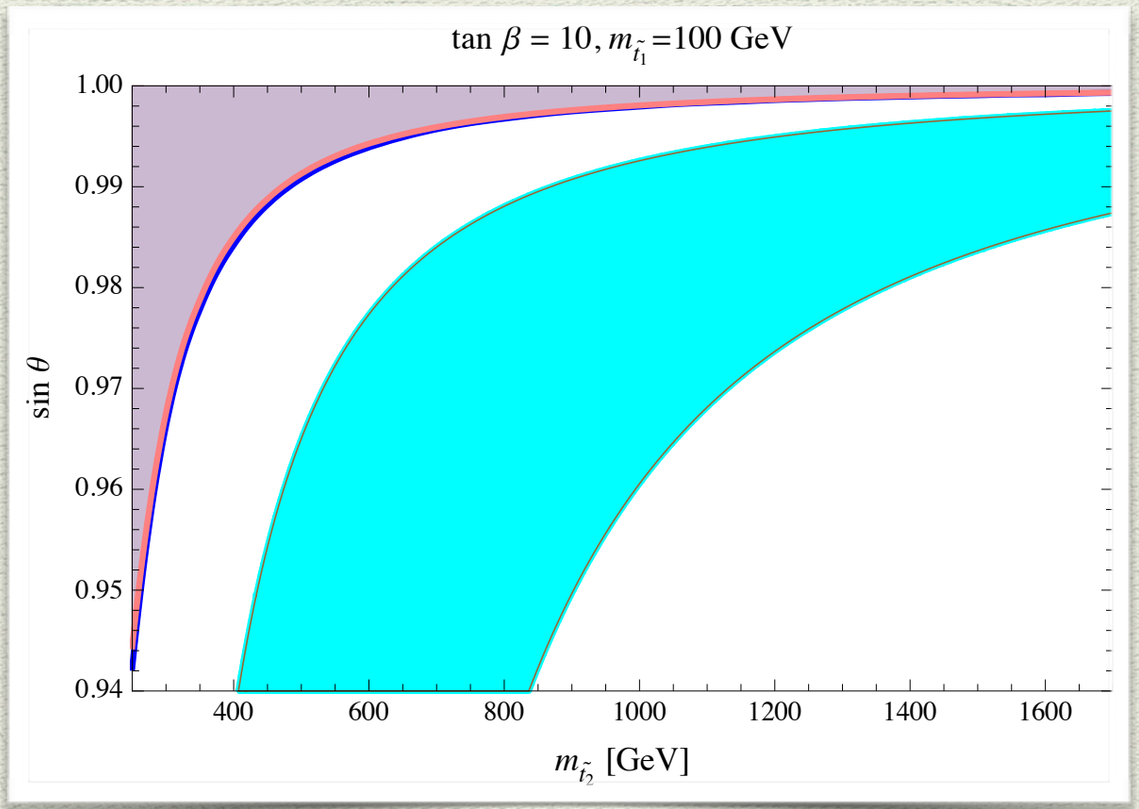
- *Folded stops (and folded quarks in general) are not colored under our SU(3), they are colored under a different, hidden color*
- *Folded stops are charged under EW force, and therefore contribute to hγγ but do not contribute to hgg.*
- *Colored under different group ⇒ uncolored production, quirk constraints apply*

Disclaimer:
"Folded SUSY" in not SUSY. It is a theory where the cancellation between the tops and top-partner loops proceed as in SUSY, but the symmetry is guaranteed by the fact, that the daughter theory on the orbifold inherits the symmetries of the mother theory.

Constraints on Folded-Stops Triggered 1st Order EWPT

AK and Knapen, unpublished





Removing the constraints from the hgg clearly helps, but not enough! For the LH folded stop the EWPM constraints are more important than higgs precisions. Can maybe reconciled in non-decoupling regime or with higgs invisible decays?

Conclusions

- Stop-catalyzed baryogenesis is dead (w/o new light particles)
- Very hard to accommodate 1st order PT on "folded SUSY", but maybe non-minimal scenarios can work
- Scenarios with additional light particles (nMSSM, new triplets) are still wide open, hunt for the 1st order EWPT and Naturalness is ongoing…