Cosmological Phase Transitions and their Properties in the NMSSM

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In Prep (Out soon)

TRIUMF

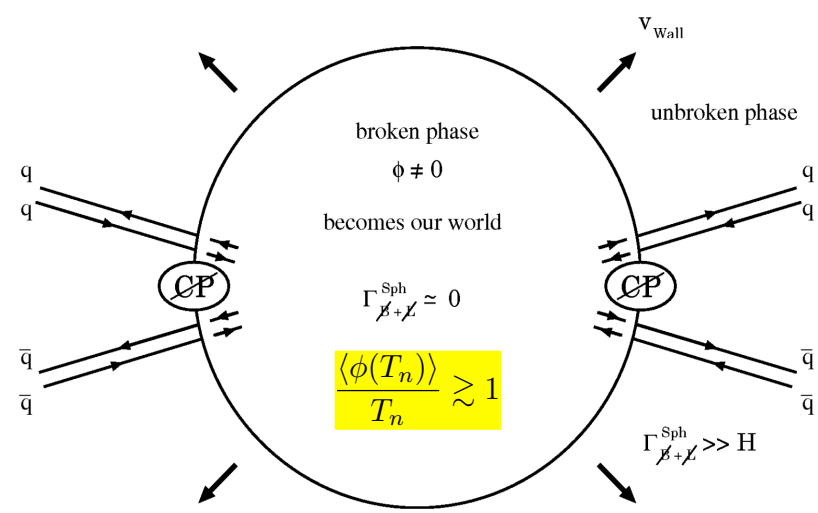
Explaining the Baryon Asymmetry

-Observed baryon asymmetry: $Y_B \equiv \frac{n_q - n_{\bar{q}}}{3s} \sim 10^{-10}$

-Microphysical mechanism for generation of the asymmetry must satisfy the "Sakharov conditions":

1. *B* – violation
2. *C*– and *CP*–violation
3. "Arrow of time"

-Possible at the electroweak phase transition:



Bernreuther, 0205279

Requires physics BSM

Electroweak Baryogenesis in SUSY

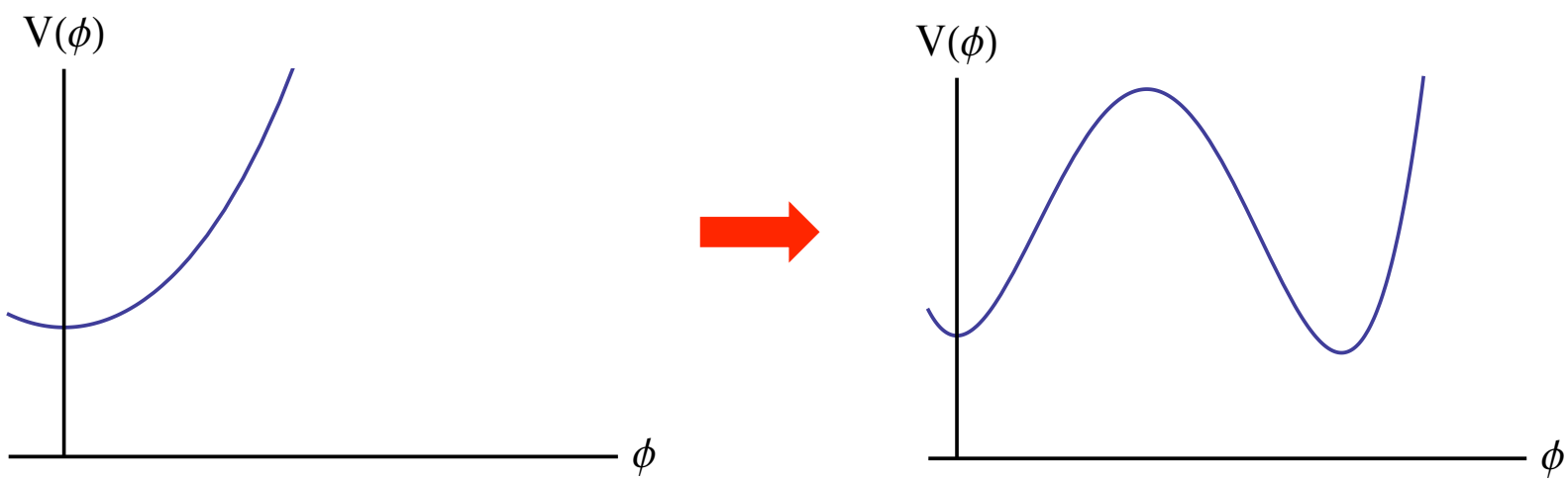
SUSY can help…

New scalars contribute cubic terms to effective potential

$$V_1(T>0) = V_1(T=0) + \frac{T^2}{2\pi^2}\sum_i n_i J_\pm\left(\frac{m_i^2}{T^2}\right)$$

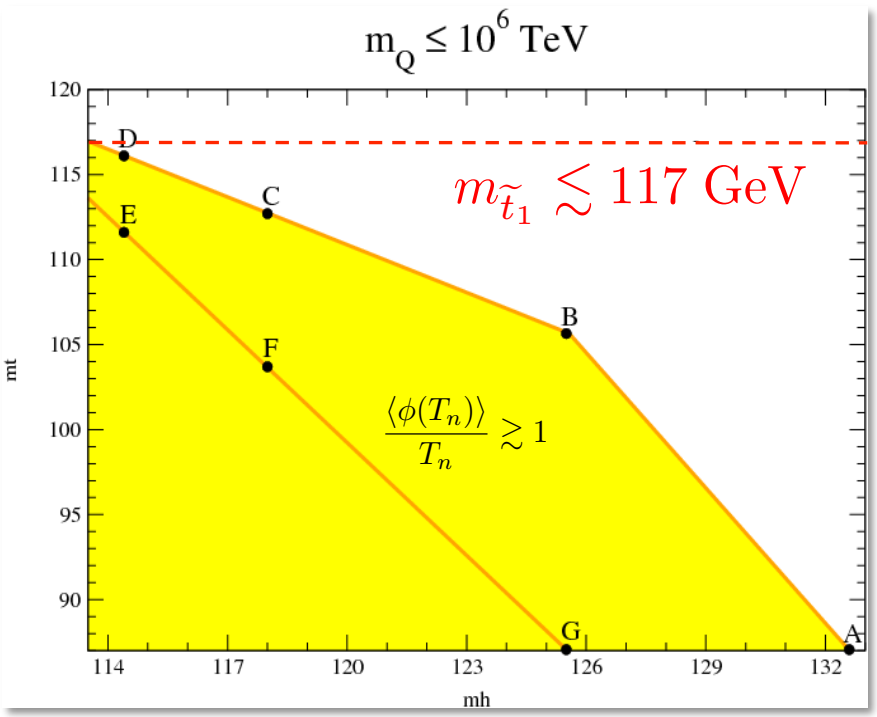
High-T expansion for bosons

$$\simeq -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \ldots$$



Electroweak Baryogenesis in SUSY

...but the MSSM is in trouble



Carena et al, 1207.6330

- Light stops increase gluon-gluon fusion Higgs production cross-section

  Menon +Morrissey, 0903.3038; however, see 1207.6330 for a possible work-around

- Highly constrained by direct searches

  Krizka et al, 1212.4856, Delgado et al, 1212.6847; however, see 1303.4414 for a possible work-around

Baryogenesis in the NMSSM

How about the NMSSM? $W = W_{\rm MSSM}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$

☑ Tree-level Higgs mass enhancement: $m_{h_1}^2 \leq \left(\cos^2 2\beta + \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2}\right) m_Z^2.$

☑ No mu problem: $\mu = \lambda v_s$

☑ New singlet fermion + complex scalar

$$V_0(h_u, h_d, s) = \frac{1}{32}(g_1^2 + g_2^2)\left(h_u^2 - h_d^2\right)^2 + \frac{1}{4}\kappa^2 s^4 - \frac{1}{2}\lambda\kappa s^2 h_u h_d + \frac{1}{4}\lambda^2\left(h_d^2 h_u^2 + s^2\left(h_d^2 + h_u^2\right)\right)$$
$$+ \frac{\sqrt{2}}{6}\underline{\kappa A_\kappa s^3} - \frac{\sqrt{2}}{2}\underline{\lambda A_\lambda s h_u h_d} + \frac{1}{2}m_d^2 h_d^2 + \frac{1}{2}m_u^2 h_u^2 + \frac{1}{2}m_s^2 s^2.$$

→Cubic terms at **tree-level**

→Potentially rich phase transition phenomenology

Baryogenesis in the NMSSM

What are the properties of the PT in viable regions of parameter space?

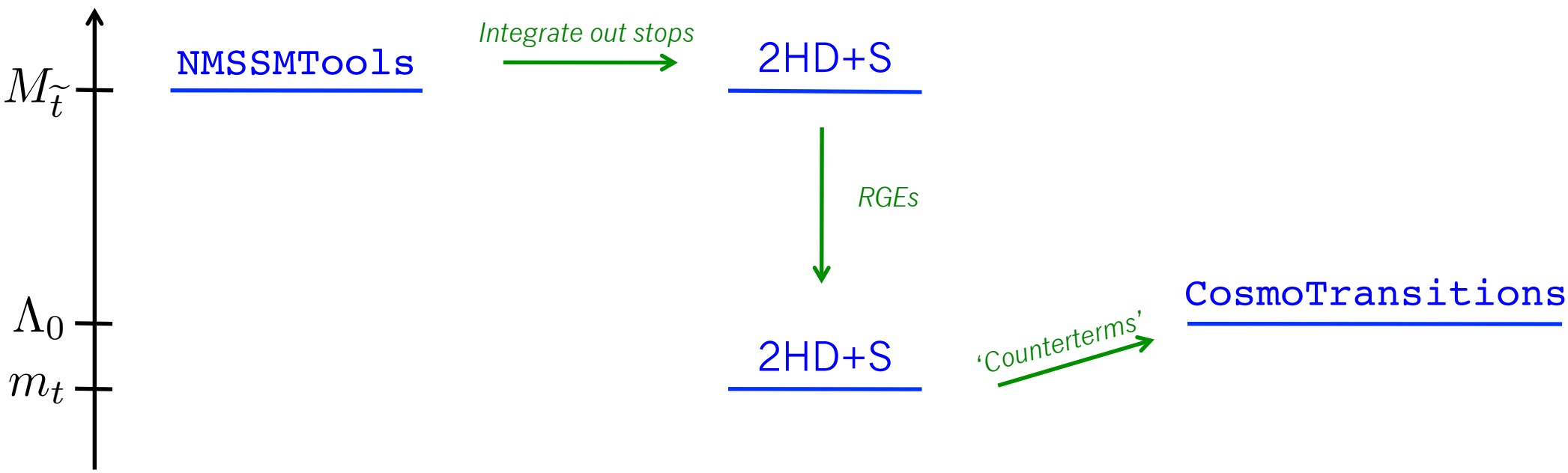
Baryogenesis? Implications for cosmology? Observable signatures?

Focus on regions with: moderately heavy (~1 – 2 TeV) stops, ~125 GeV SM-like Higgs, viable DM, spectrum OK w/LHC

Our method: Effective Field Theory approach

$$V_1(T=0) = \sum_i \frac{\pm n_i}{64\pi^2} m_i^4 \left[\log\left(\frac{m_i^2}{\Lambda^2}\right) - c \right]$$

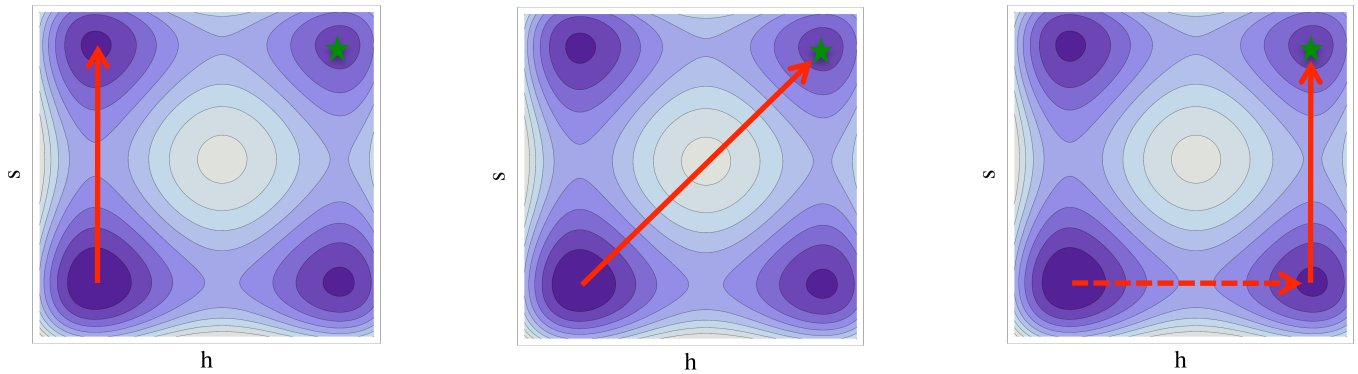
Heavy stops → large logs



Baryogenesis in the NMSSM

What we've found:

Variety of symmetry breaking patterns possible



-Strong 1st order singlet transitions common. Occur at higher temperatures

-Found several points with strong 1st order 1-step EWPT. Typically large λ, A_λ, small $\tan\beta$, moderate μ (see e.g. 1309.5091 for other possibilities)

Baryogenesis in the NMSSM

What we've found:

Electroweak baryogenesis can be realized across this region of parameter space

Sample point:

λ	0.64
κ	0.12
A_λ [GeV]	330
A_κ [GeV]	-60.5
$\tan\beta$	1.5
μ [GeV]	180
M_1 [GeV]	-100
$M_{\widetilde{Q}_3}$ [TeV]	1.0
$M_{\widetilde{U}_3}$ [TeV]	1.0
$A_t = A_b$ [GeV]	380

m_h [GeV]	126.4
m_{h_s} [GeV]	112.0
m_{a_s} [GeV]	120.9
$m_{\widetilde{\chi}_1^0}$ [GeV]	104.8
$\widetilde{\chi}_1^0$ composition	B
Ωh^2	0.13
$\sigma_{\rm SI}$ [cm^2]	1.2×10^{-46}

Transition type	1
Direction	s+h
$T_{\rm n}$	144.8
$\Delta\phi/T_{\rm n}$	1.2

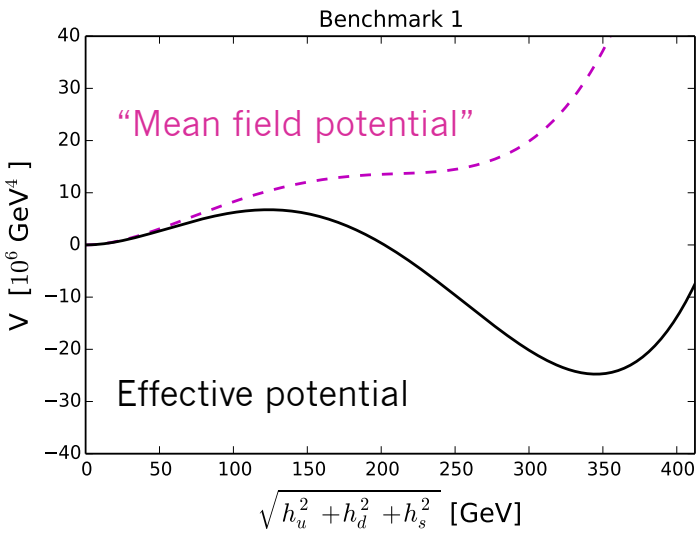
-General feature: new light states (singlet-like scalar/ pseudoscalar; fermions) potentially accessible by LHC 14 and DM experiments

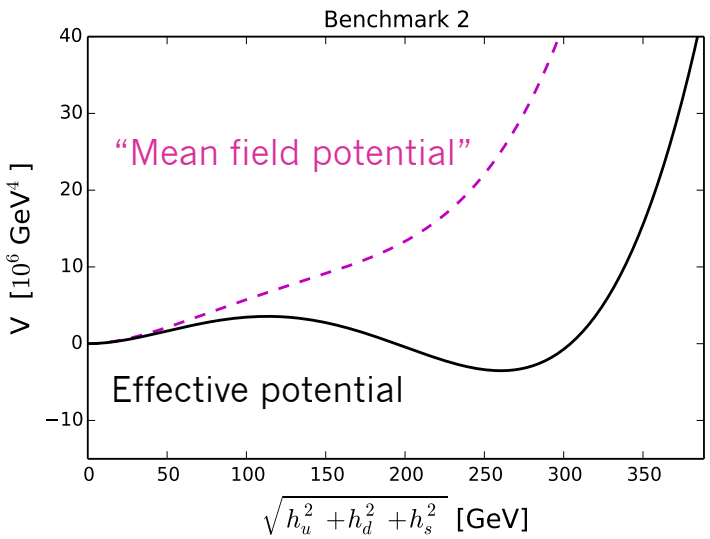
Baryogenesis in the NMSSM

What we've found:

Bubble walls tend not to run away

Broken phase vanishes in mean field potential → no runaway solution *(Bodeker+Moore, 0903.4099)*





→Gravity waves typically not detectable for points we considered

→ <u>EWB looks promising!</u>

Summary and Conclusions

- NMSSM regions with a SM-like 125 GeV Higgs, moderately heavy stops, and viable DM can feature strongly 1st order phase transitions

- Singlet transitions common – may open the door for alternative baryogenesis scenarios

- Bubble walls tend not to run away. Also, other parameters relevant for EWB look promising

- Much of the interesting parameter space of this scenario will be probed soon!

Backup Slides

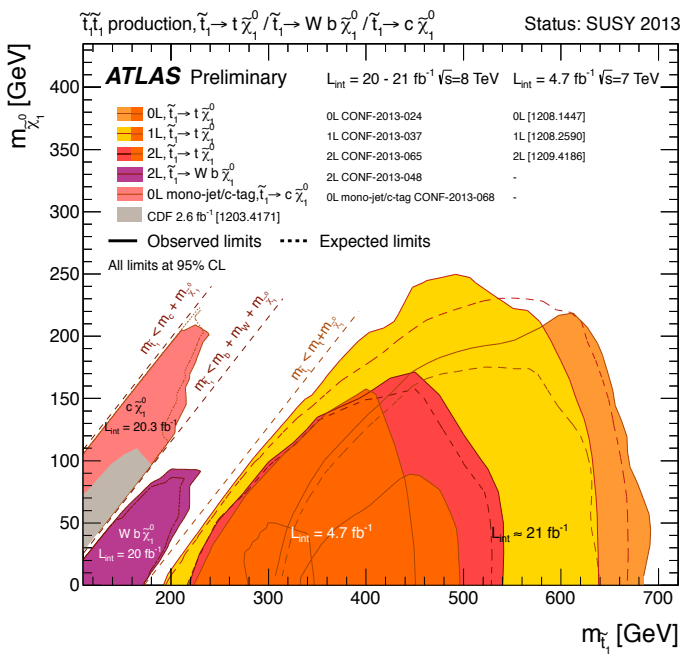
Constraints on Light Stops

Light stops constrained by LHC searches (Krizka et al, 1212.4856, Delgado et al, 1212.6847)

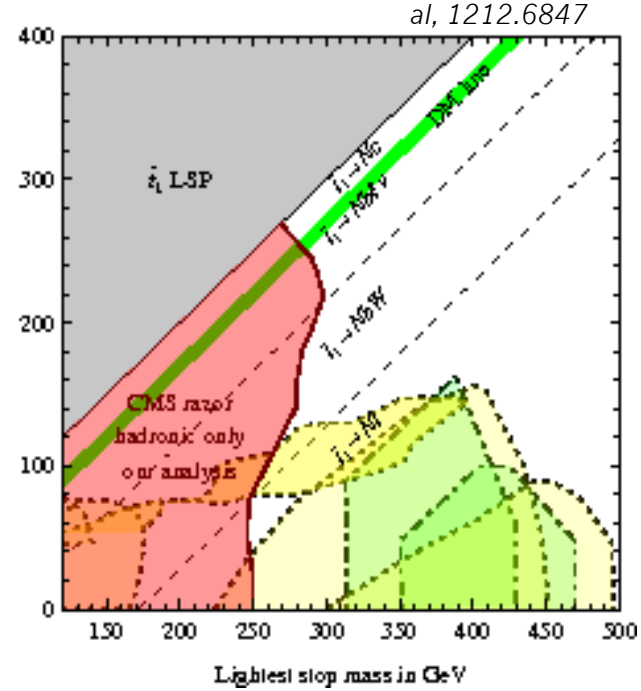
For $m_{\tilde{t}} < m_t + m_{\chi_1^0}$ relevant decay channels are e.g. $\tilde{t} \to \chi_1^0 b W^+$, $\tilde{t} \to \chi_1^0 c$, $\tilde{t} \to \chi_1^0 b \ell \nu$

Razor searches in particular (unofficially) rule out the light stop scenario

Pending official analysis



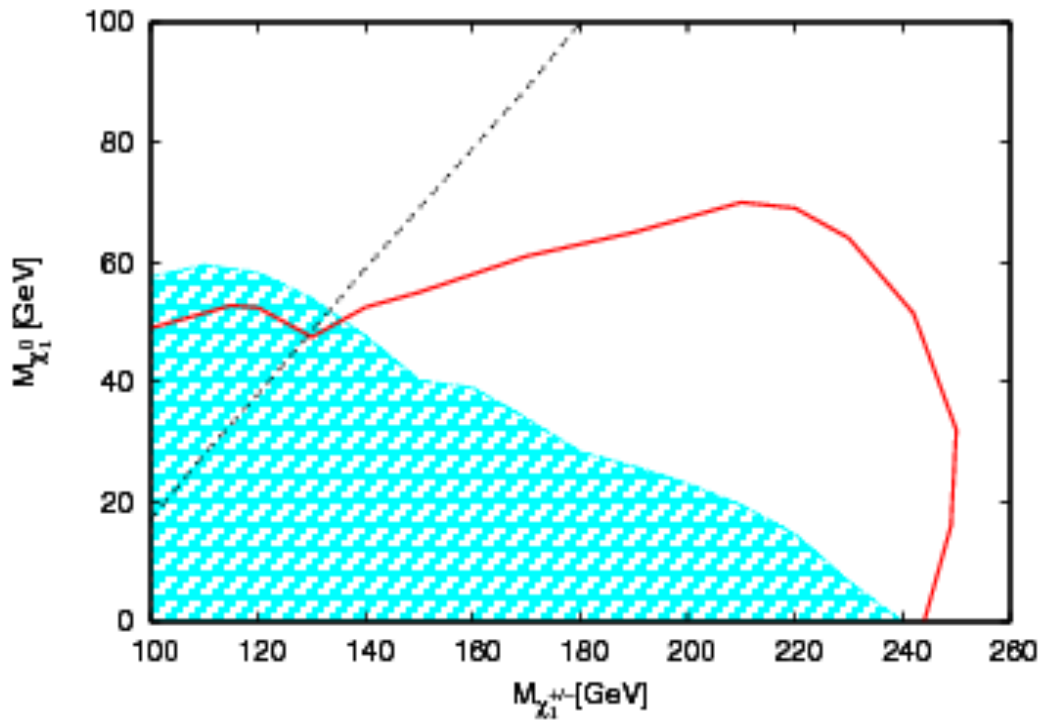
Delgado et al, 1212.6847



May be a small window between 120 GeV and 140 GeV if a light stau allows $\tilde{t} \to \tilde{\tau}^+ \nu b$ (Carena et al, 1303.4414)

Higgsinos/Singlinos at the LHC

Trilepton constraints on Higgsino-singlino scenario are substantially weaker than usual wino-bino case



From Ellwanger,1309.1665