The Electroweak Phase Transition in the NMSSM

Jonathan Kozaczuk (**TRIUMF**)

ACFI EWPT Workshop, 9/18/15

- **JK**, Profumo, Stephenson-Haskins, Wainwright, *1407.4134*
- **JK**, *1506.04741*

Outline

1. Why not the MSSM?

2. The NMSSM Parameter Space

3. The EWPT and electroweak baryogenesis in the NMSSM

4. A challenge for singlet-driven EWB: fast bubble walls

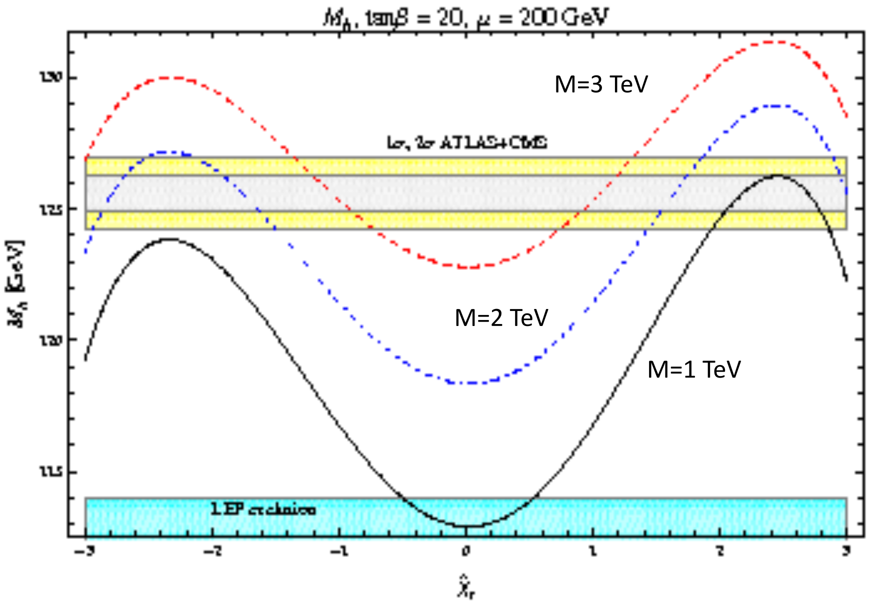
5. Testing the EWPT in the NMSSM

6. Conclusions

Why not the MSSM?

Why not the MSSM?

The Higgs wants to be light



$$m_h^{\text{tree}} \leq m_Z \left|\cos 2\beta\right|$$

Draper, Lee, Wagner, 1312.5743

Require large radiative contributions with heavy sfermions and/or large mixing (bad for naturalness, vacuum stability)

See e.g. Blinov and Morrissey, 1310.4174

Why not the MSSM?

There's a μ problem

$$m_Z^2 = \frac{\left|m_{H_d}^2 - m_{H_u}^2\right|}{\sqrt{1 - \sin^2 2\beta}} - \underset{\uparrow}{m_{H_u}^2} - \underset{\nearrow}{m_{H_d}^2} - 2\,\underset{\uparrow}{|\mu|^2}$$

SUSY breaking SUSY conserving

Could invoke e.g. Giudice-Masiero ($\mu = \langle F \rangle / M_{\mathrm{Pl}}$) , but the μ - term is not a priori connected with SUSY breaking

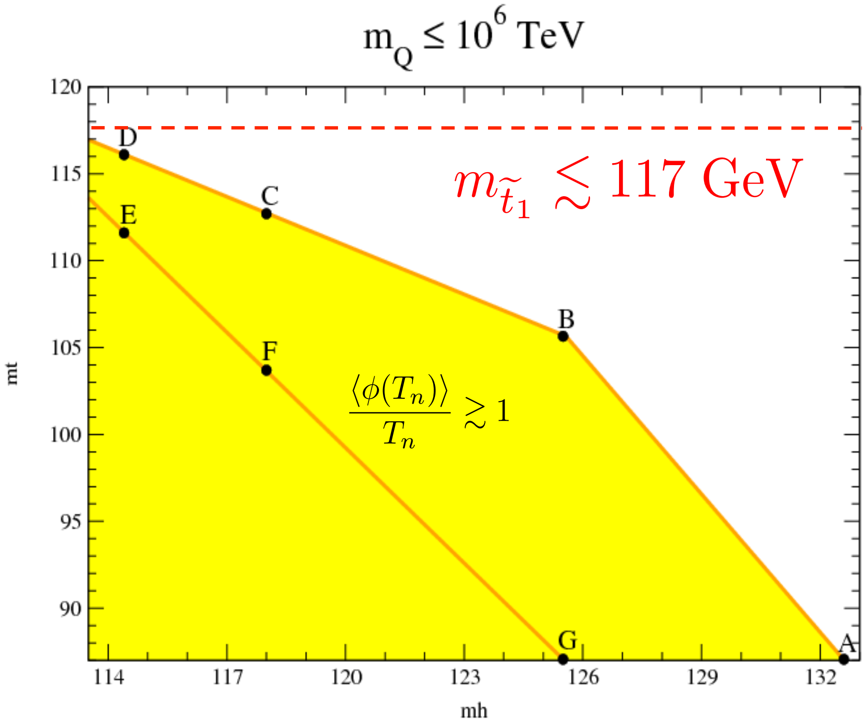
Why not the MSSM?

Stops aren't light

$$V^T(\phi, T) = \frac{T^4}{2\pi^2}\left[\sum_i \pm N_i J_\pm\left(\frac{m_i^2(\phi)}{T^2}\right)\right]$$

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

$$+ \dots$$

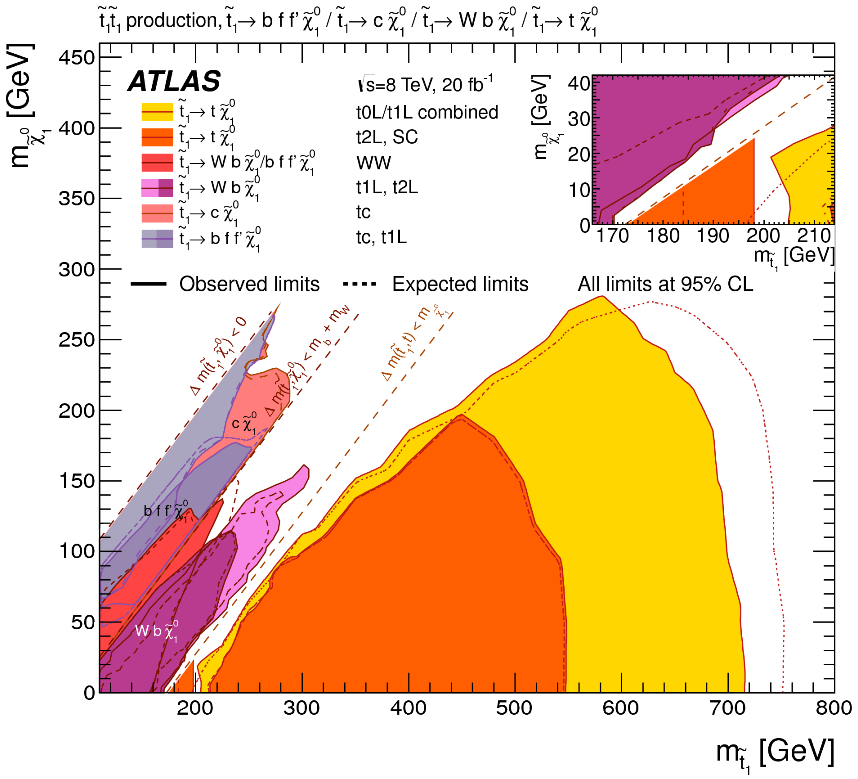


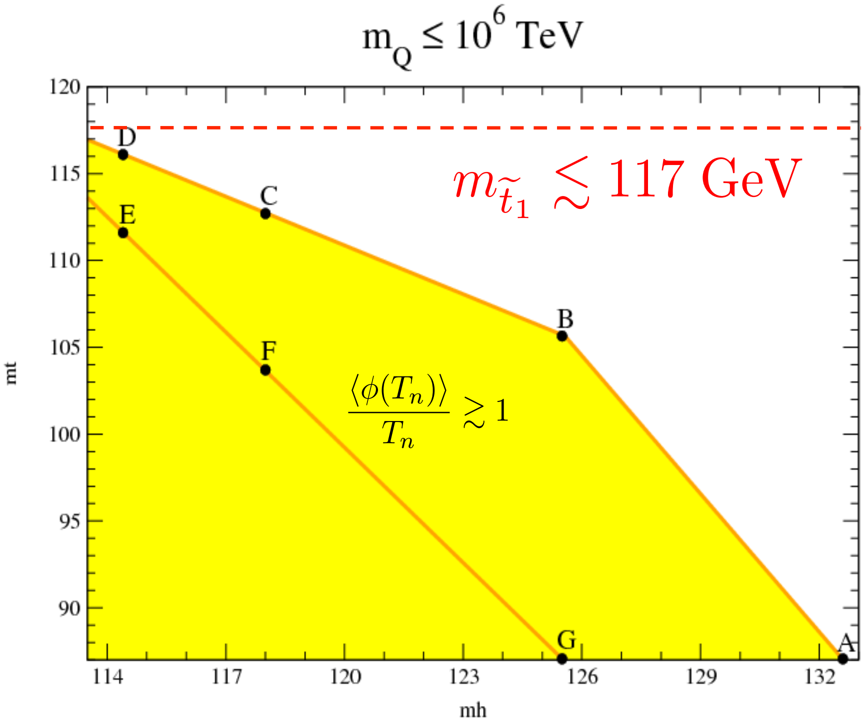
Carena et al, 1207.6330

Large thermal contributions from light stop required for strongly first order PT

Why not the MSSM?

Stops aren’t light





Carena et al, 1207.6330

Strong 1st order PT in MSSM is essentially ruled out (caveats?)

See e.g. Curtin et al, 1203.2932; Cohen et al 1203.2924; Krizka et al, 1212.4856; Delgado et al, 1212.6847; Katz et al, 1509.02934; Andrey’s talk

Why not the MSSM?

We haven't seen a permanent EDM

Bino-Higgsino (Cirigliano et al, 0910.4589) or stau (JK et al, 1206.4100) sources still a possibility, though highly constrained

Likely need beyond-MSSM CP-violation

Next-to-Minimal SUSY

$$W = W_{\rm MSSM}\big|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

Next-to-Minimal SUSY

$$W = W_{\mathrm{MSSM}}\big|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u \cdot \widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$

No μ-term

Larger m_h at tree-level

$$m_h^{\mathrm{tree}} \leq m_Z \cos 2\beta + \frac{\lambda v^2}{2}\sin^2 2\beta$$

New tree-level terms in the potential
(light stops not required)

Not in this talk: also accommodates new CPV sources (Cheung et al, 1201.3781; JK et al, 1302.4781; work in progress with Nikita Blinov, Wei Chao, Martin Gonzalez-Alonso, and Michael R-M)

Long history of PT studies (see e.g. Pietroni, hep-ph/9207227; Davies et al, hep-ph/9603388; Huber and Schmidt, hep-ph/0003122; Funakubo et al, hep-ph/0501052; Huber et al, hep-ph/0608017; Carena et al, 1110.4378; JK et al, 1302.4781; Huang et al, 1405.1152; JK et al, 1407.4134, …)

What do we want to know?

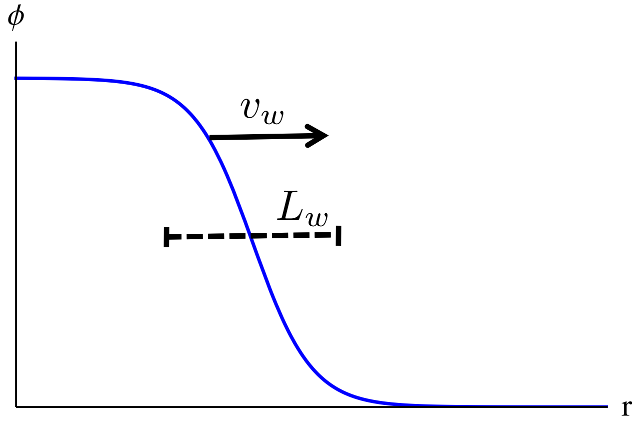
*Phase transition strength in viable parameter space

*Bubble wall profile (input into CPV sources)

*Bubble wall velocity (input into CPV sources and diffusion eqns)

Strength of CPV sources $\propto d\beta/dt \simeq \Delta\beta v_w/L_w$

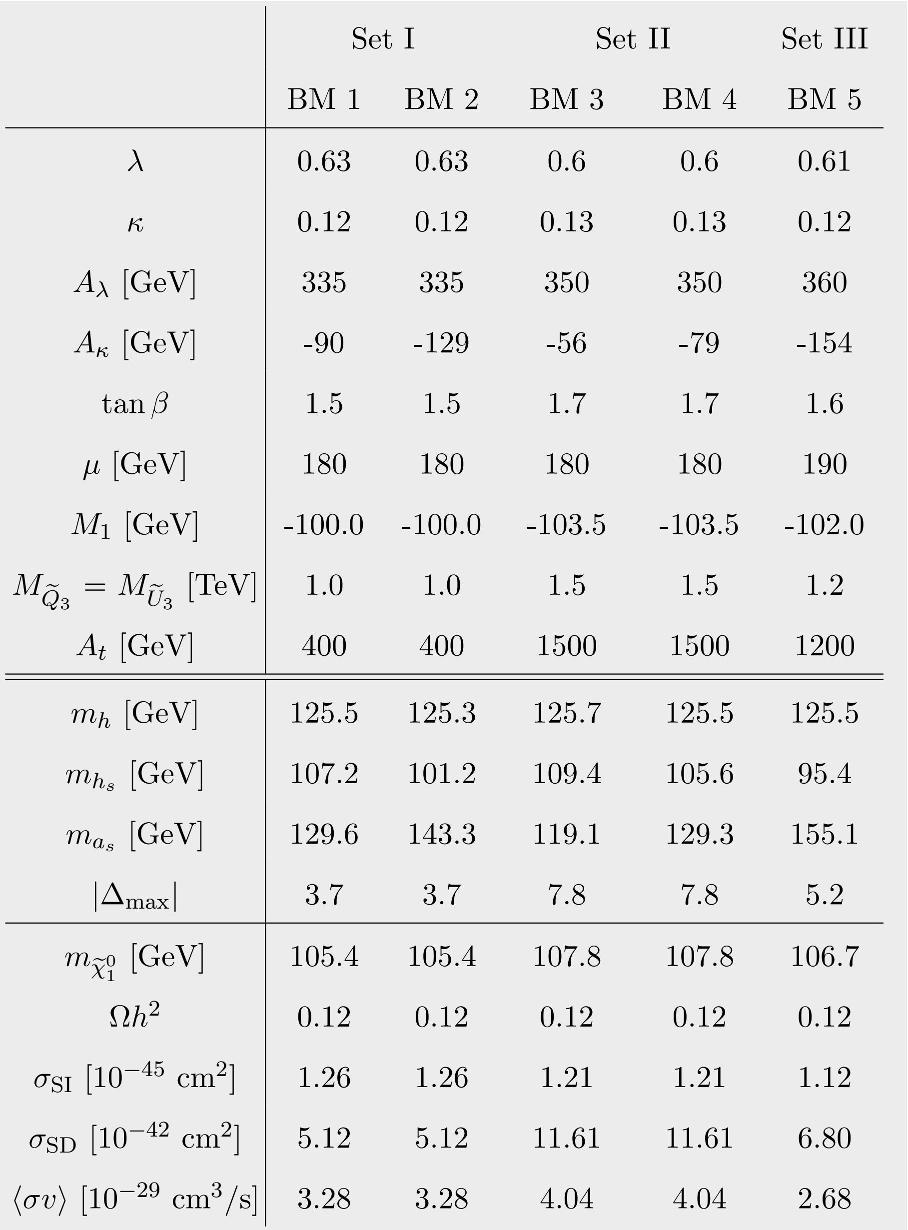
Baryon density $\rho_B = -\frac{n_F\Gamma_{ws}}{2v_w}\int_{-\infty}^{0} n_L(x)e^{x\mathcal{R}/v_w}dx$



NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)



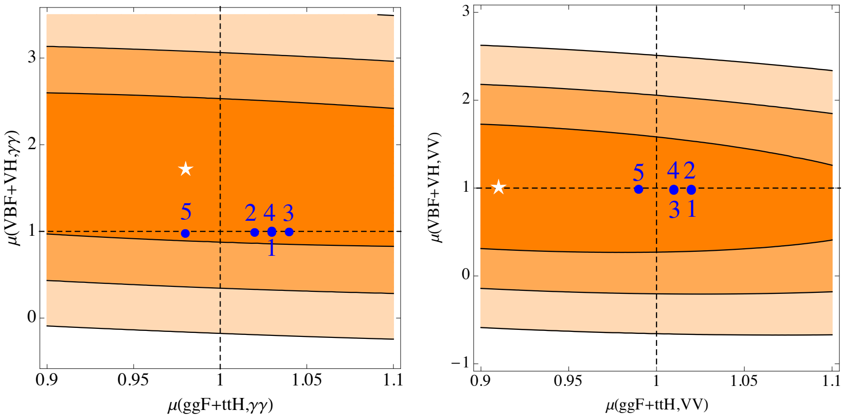
	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\rm max}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\widetilde{\chi}_1^0}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
$\sigma_{\rm SI}$ [10^{-45} cm^2]	1.26	1.26	1.21	1.21	1.12
$\sigma_{\rm SD}$ [10^{-42} cm^2]	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ [10^{-29} cm^3/s]	3.28	3.28	4.04	4.04	2.68

NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)

Based on global fit from 1306.2941



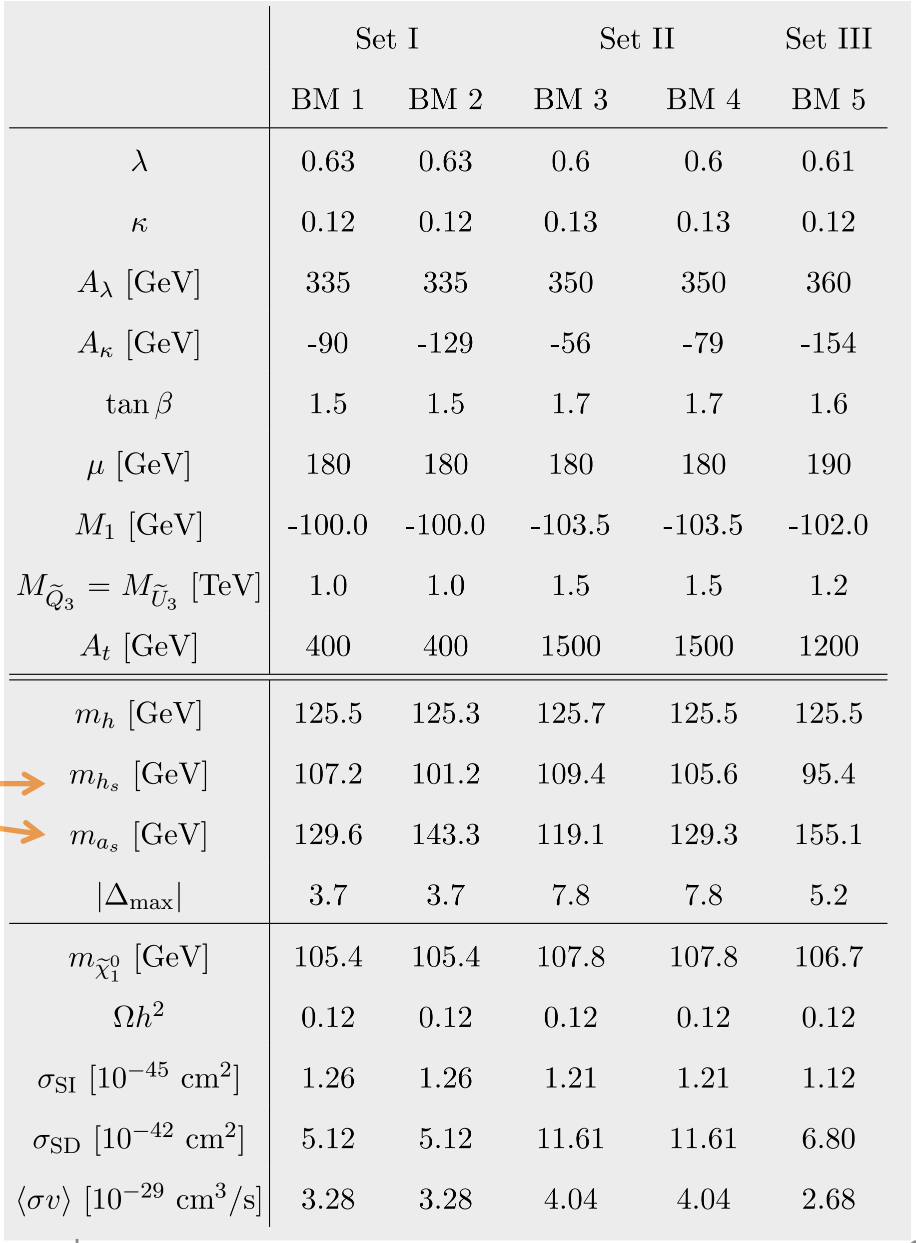
Standard Model-like Higgs →

	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\max}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\widetilde{\chi}_1^0}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
$\sigma_{\rm SI}$ [10^{-45} cm^2]	1.26	1.26	1.21	1.21	1.12
$\sigma_{\rm SD}$ [10^{-42} cm^2]	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ [10^{-29} cm^3/s]	3.28	3.28	4.04	4.04	2.68

NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)



	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\rm max}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\widetilde{\chi}^0_1}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
$\sigma_{\rm SI}$ [10^{-45} cm^2]	1.26	1.26	1.21	1.21	1.12
$\sigma_{\rm SD}$ [10^{-42} cm^2]	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ [10^{-29} cm^3/s]	3.28	3.28	4.04	4.04	2.68

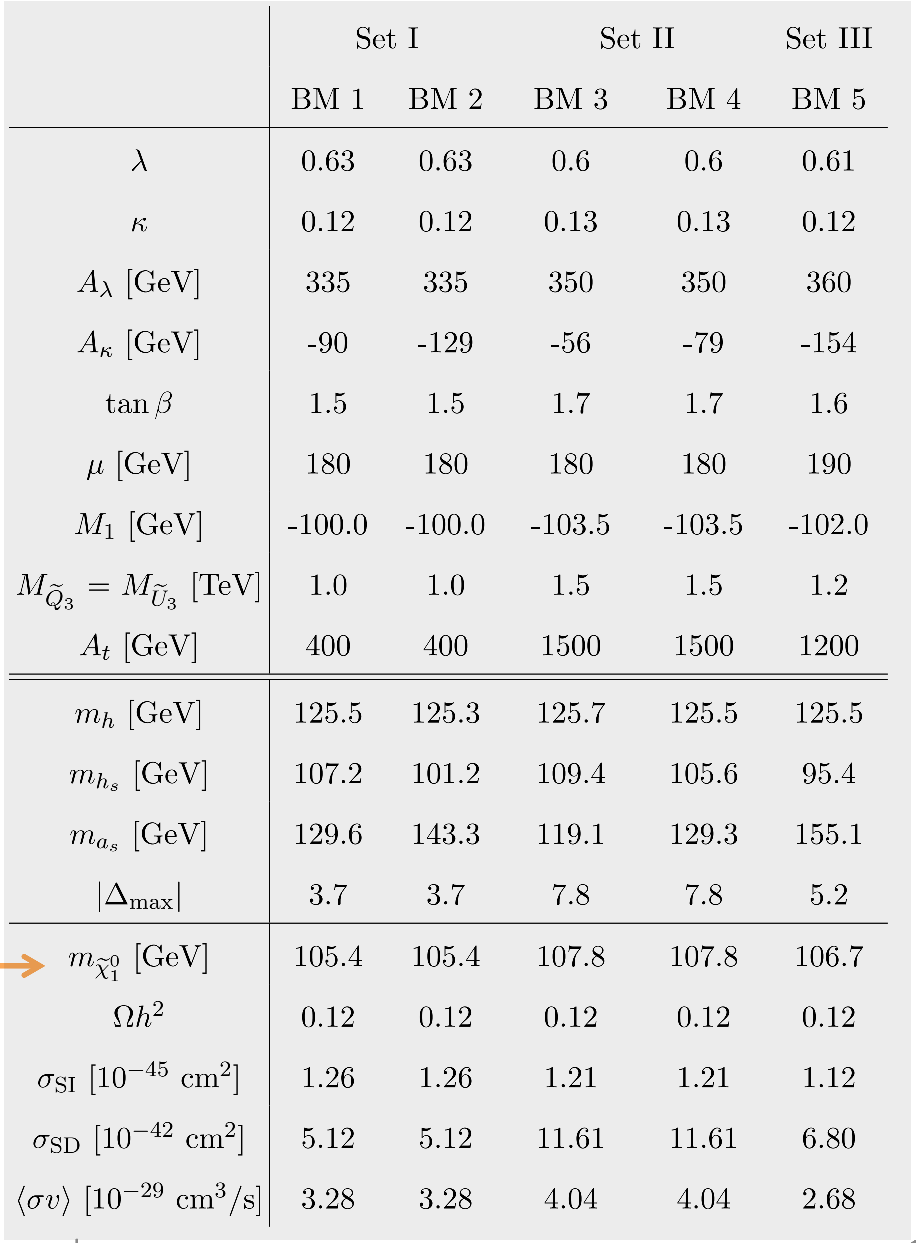
Light singlet-like states
(checked by HiggsBounds
and HiggsSignals)

NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)

Viable neutralino DM candidate

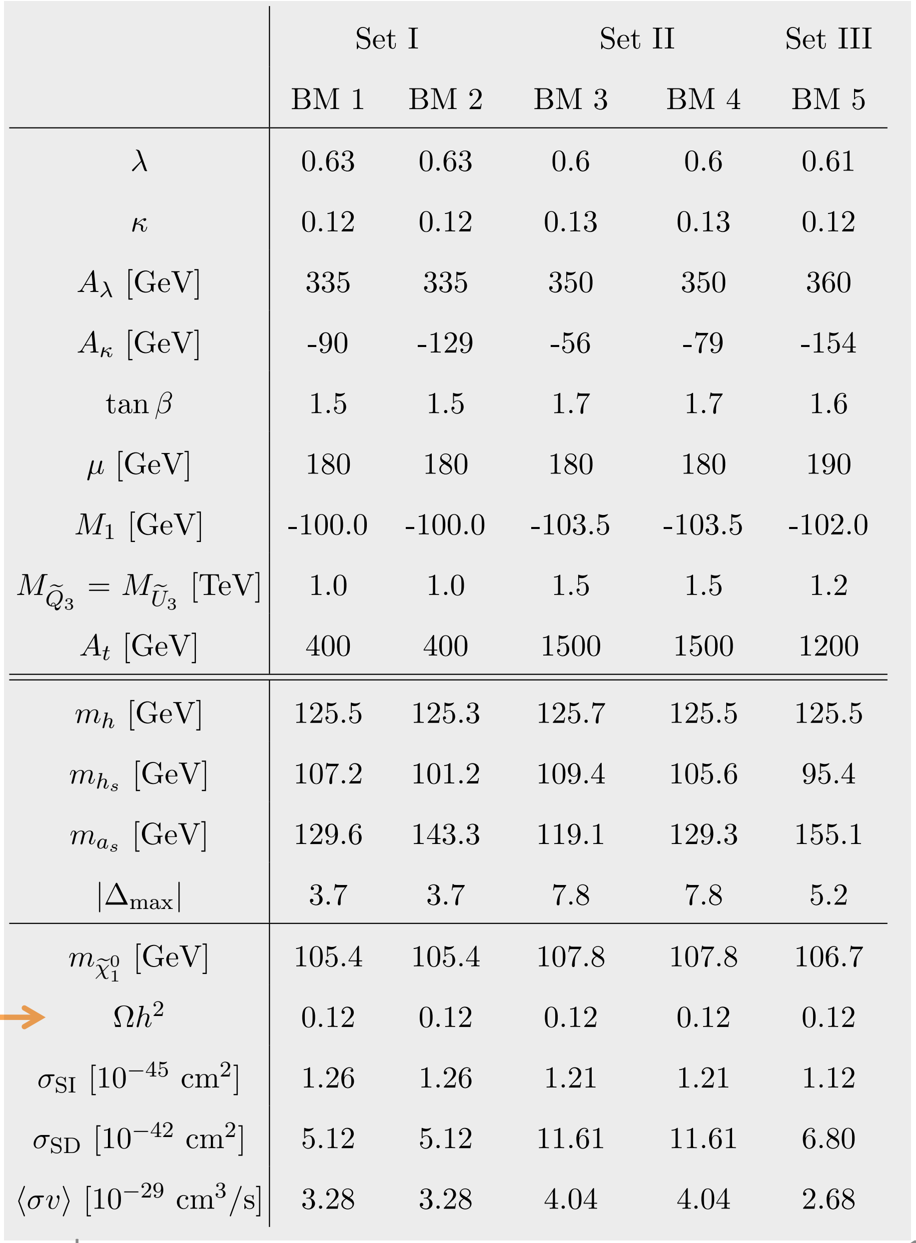


	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\max}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\widetilde{\chi}_1^0}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
$\sigma_{\rm SI}$ [10^{-45} cm^2]	1.26	1.26	1.21	1.21	1.12
$\sigma_{\rm SD}$ [10^{-42} cm^2]	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ [10^{-29} cm^3/s]	3.28	3.28	4.04	4.04	2.68

NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)



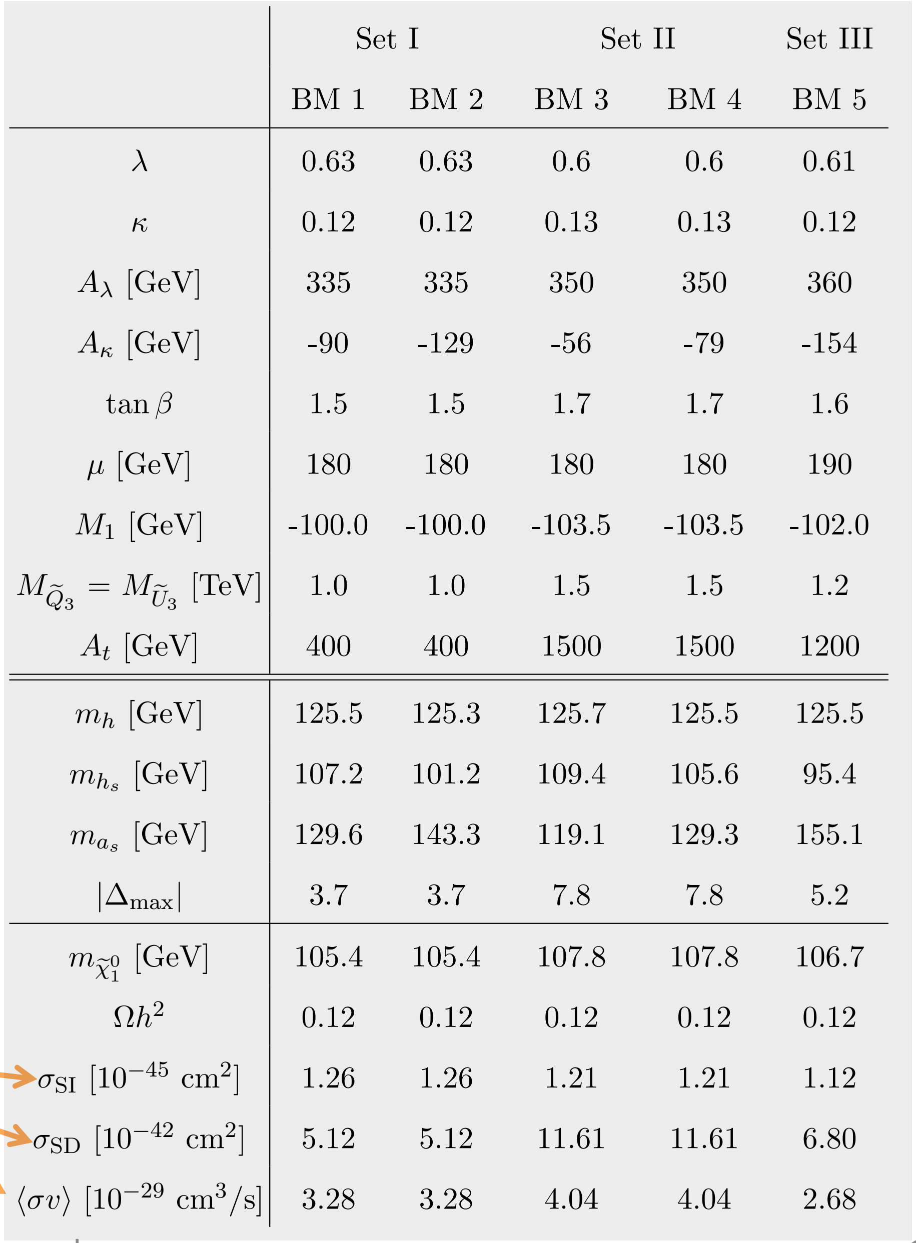
	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\max}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\tilde{\chi}_1^0}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
$\sigma_{\rm SI}$ $[10^{-45}\ {\rm cm}^2]$	1.26	1.26	1.21	1.21	1.12
$\sigma_{\rm SD}$ $[10^{-42}\ {\rm cm}^2]$	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ $[10^{-29}\ {\rm cm}^3/{\rm s}]$	3.28	3.28	4.04	4.04	2.68

Relic density driven down by co-annihilation with singlino-like NLSP →

NMSSM Parameter Space

Example points:

(JK et al, *1407.4134*)



	Set I		Set II		Set III
	BM 1	BM 2	BM 3	BM 4	BM 5
λ	0.63	0.63	0.6	0.6	0.61
κ	0.12	0.12	0.13	0.13	0.12
A_λ [GeV]	335	335	350	350	360
A_κ [GeV]	-90	-129	-56	-79	-154
$\tan\beta$	1.5	1.5	1.7	1.7	1.6
μ [GeV]	180	180	180	180	190
M_1 [GeV]	-100.0	-100.0	-103.5	-103.5	-102.0
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1.0	1.0	1.5	1.5	1.2
A_t [GeV]	400	400	1500	1500	1200
m_h [GeV]	125.5	125.3	125.7	125.5	125.5
m_{h_s} [GeV]	107.2	101.2	109.4	105.6	95.4
m_{a_s} [GeV]	129.6	143.3	119.1	129.3	155.1
$\lvert\Delta_{\text{max}}\rvert$	3.7	3.7	7.8	7.8	5.2
$m_{\widetilde{\chi}_1^0}$ [GeV]	105.4	105.4	107.8	107.8	106.7
Ωh^2	0.12	0.12	0.12	0.12	0.12
σ_{SI} [10^{-45} cm^2]	1.26	1.26	1.21	1.21	1.12
σ_{SD} [10^{-42} cm^2]	5.12	5.12	11.61	11.61	6.80
$\langle\sigma v\rangle$ [10^{-29} cm^3/s]	3.28	3.28	4.04	4.04	2.68

Below current limits from LUX, XENON100, IceCube, Fermi, etc

Phase Transitions in the NMSSM

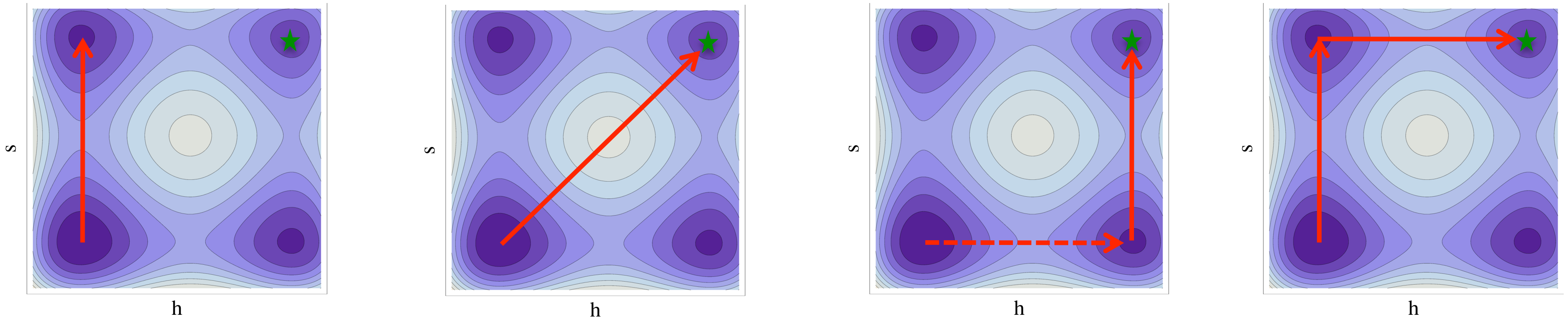
What we found:

(JK et al, 1407.4134; See also Huang et al, 1405.1152 for similar conclusions)

Phase Transitions in the NMSSM

What we found:

(JK et al, 1407.4134; See also Huang et al, 1405.1152 for similar conclusions)



*One- or two-step transitions in the singlet and/or SU(2) directions

Phase Transitions in the NMSSM

What we found:

(JK et al, 1407.4134)

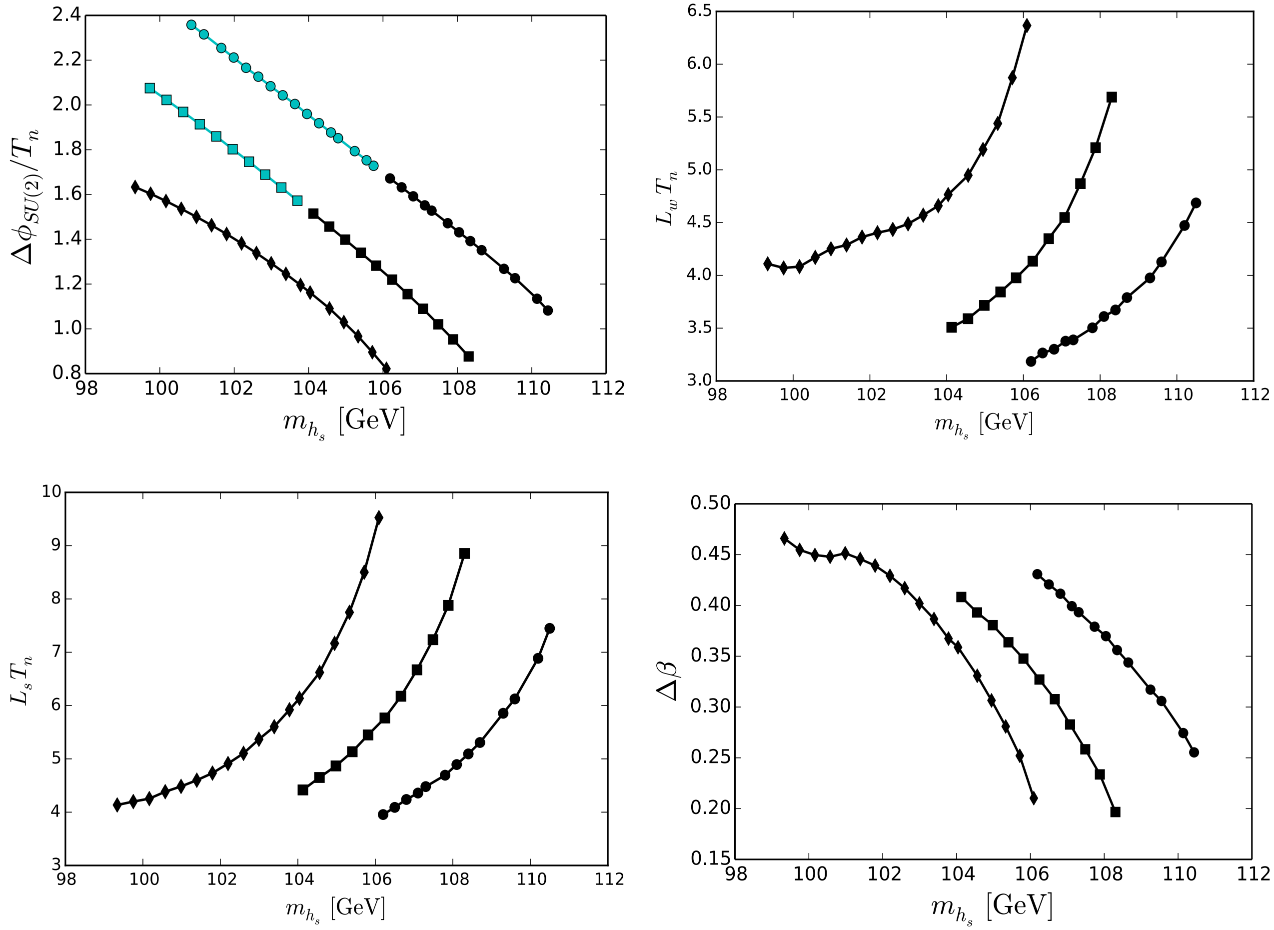
*Phenomenologically viable points w/strong first order EWPT

*Narrow walls

*Large Δβ

Strength of CPV sources

$$\propto d\beta/dt \simeq \Delta\beta v_w/L_w$$

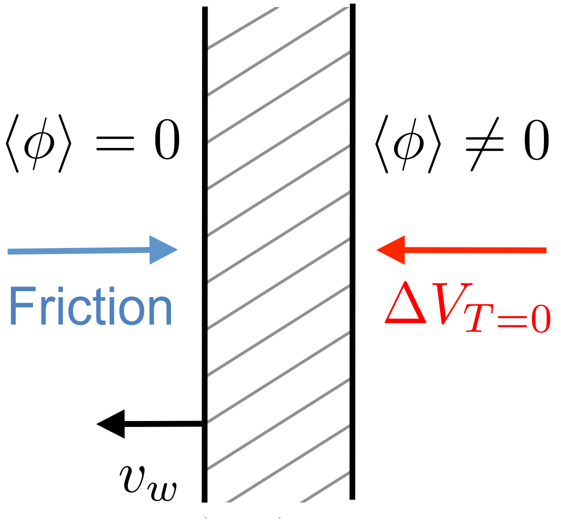


Looking promising for EWB!

A Challenge for Singlet-driven EWB

Generic consequence of additional singlet field directions: **fast bubble walls** *Bodeker + Moore, 0903.4099; JK, 1506.04741*

$$\Box\phi_i + \frac{\partial V(\phi_i)}{\partial\phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial\phi_i}\int\frac{d^3p}{(2\pi)^3 2E_j} f_j(p,z) = 0$$

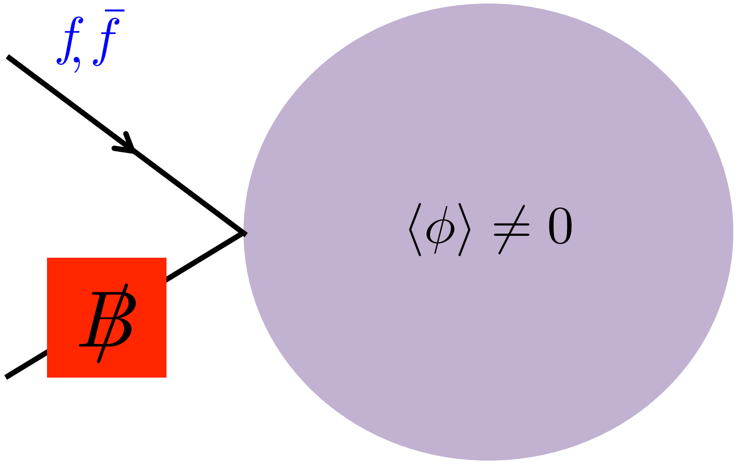


-Terminal velocity reached when friction from plasma balances the vacuum energy difference

-Additional singlet field with changing VEV contributes to ΔV, but doesn't experience much friction

A Challenge for Singlet-driven EWB

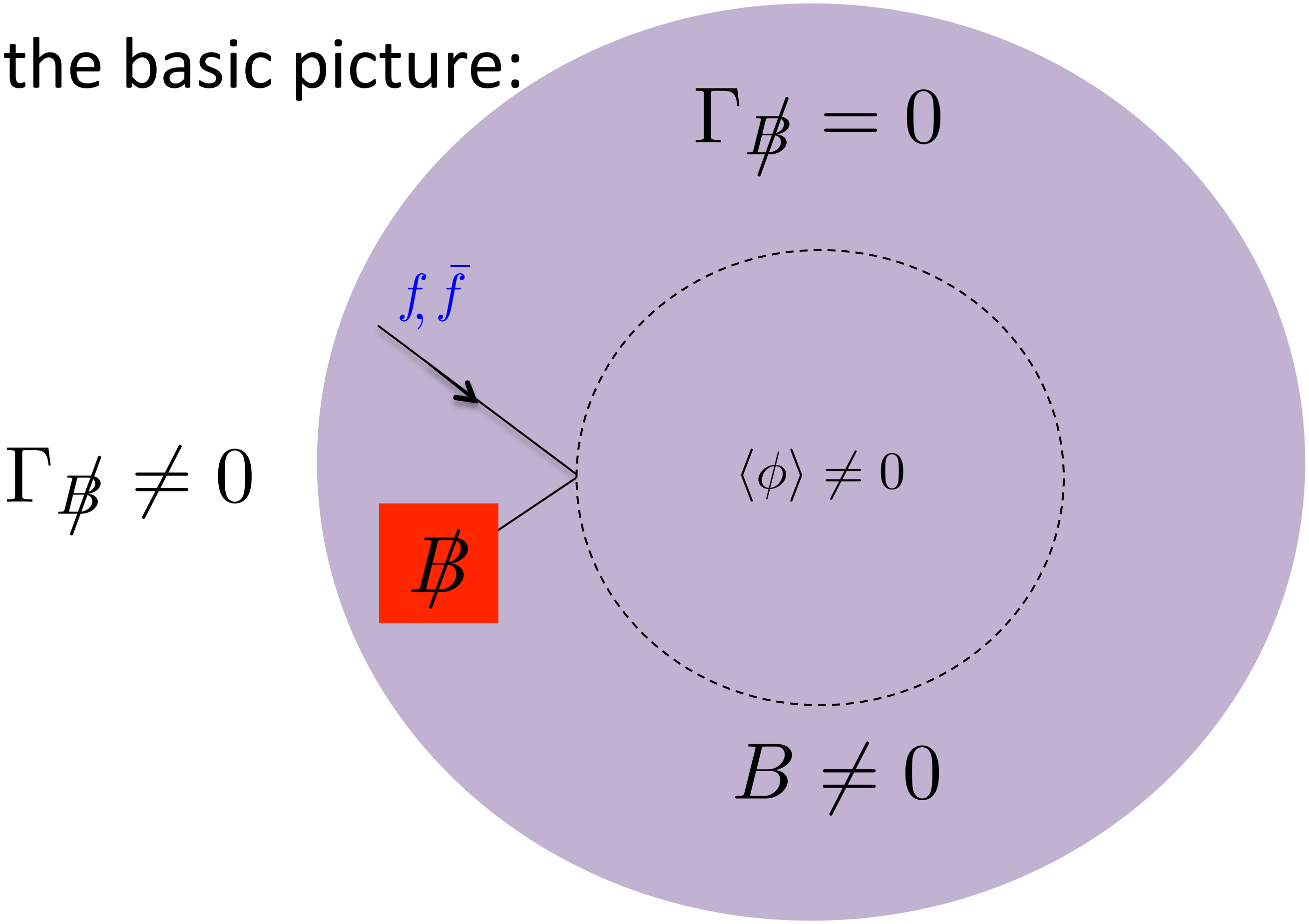
Recall the basic picture:



B-violation acts on the chiral current diffusing in front of the bubble

A Challenge for Singlet-driven EWB

Recall the basic picture:



Bubble wall catches up with diffusing current, freezing in the asymmetry

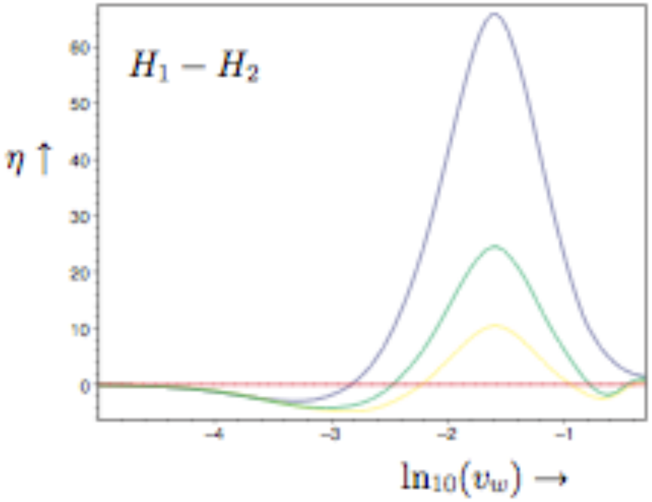
A Challenge for Singlet-driven EWB

Efficient diffusion requires slowly moving, subsonic bubble walls

(for an exception, see *Caprini + No, 1111.1726*)

$$\tau_{\text{capture}} > \tau_{\text{conversion}}$$

$$\Rightarrow v_w < \frac{1}{N}\frac{D}{L_w} \sim \frac{1}{N} \times (0.1 - 0.3) \quad [\text{SM}]$$



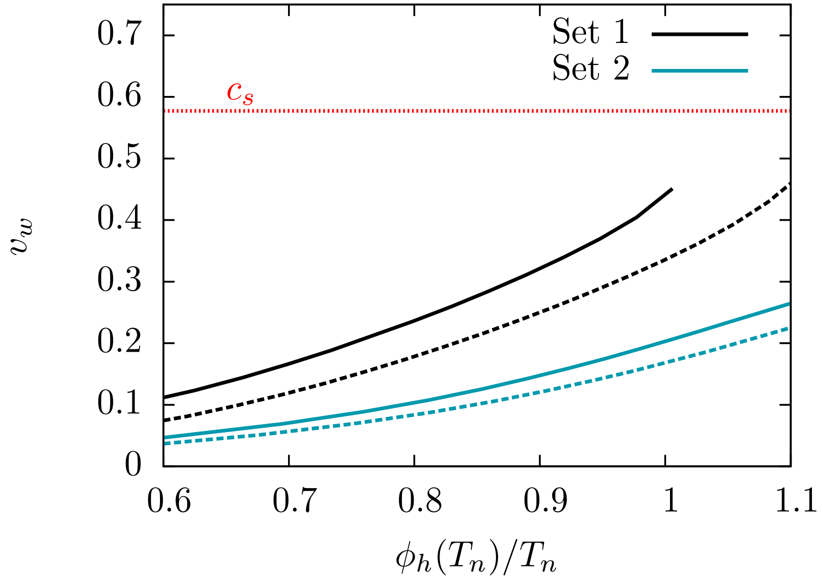
Huber et al, hep-ph/0101249

How fast do we expect walls to move in the NMSSM, or other singlet models?

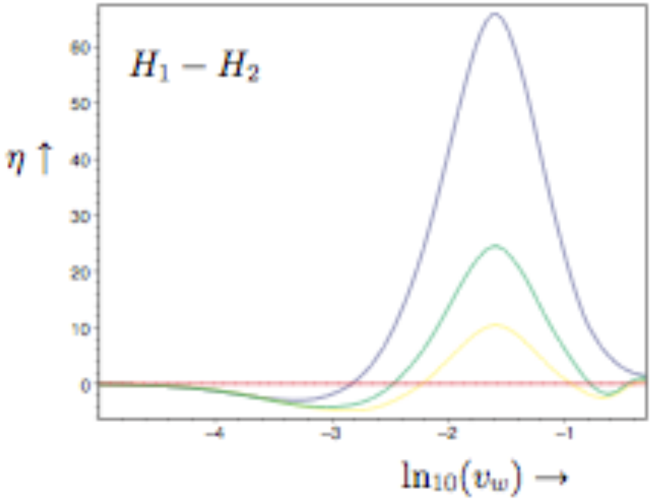
A Challenge for Singlet-driven EWB

Generic consequence of additional singlet field directions: **fast bubble walls**

JK, 1506.04741



Huber et al, hep-ph/0101249



Can be challenging for electroweak baryogenesis

NMSSM analysis still needs to be done (include Higgsino effects, additional scalars)

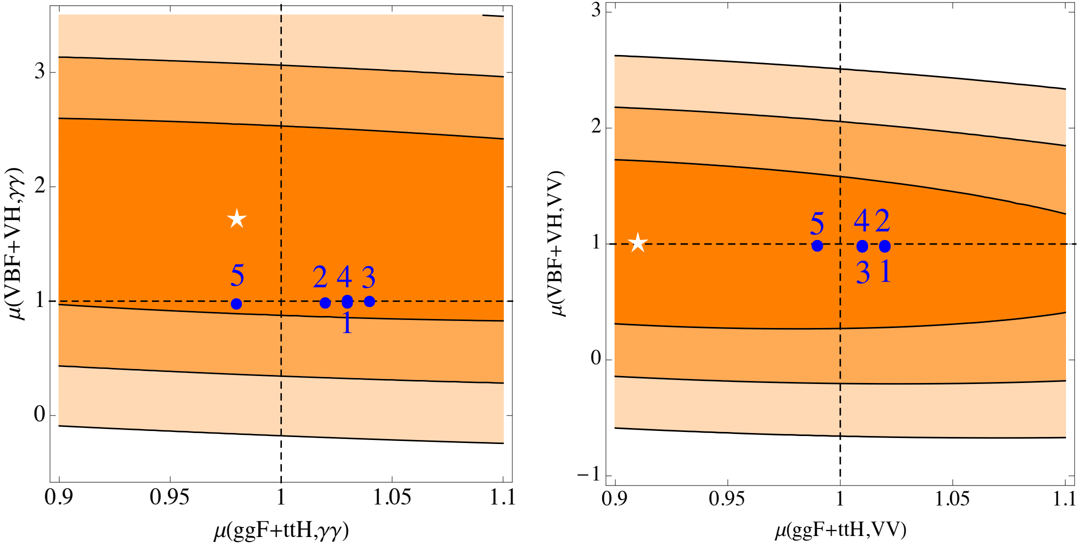
How do we test this scenario?

How do we test this scenario?

Higgs couplings can provide an indirect test, but may take awhile

Expected ILC sensitivity ~ 1%

Based on global fit from 1306.2941

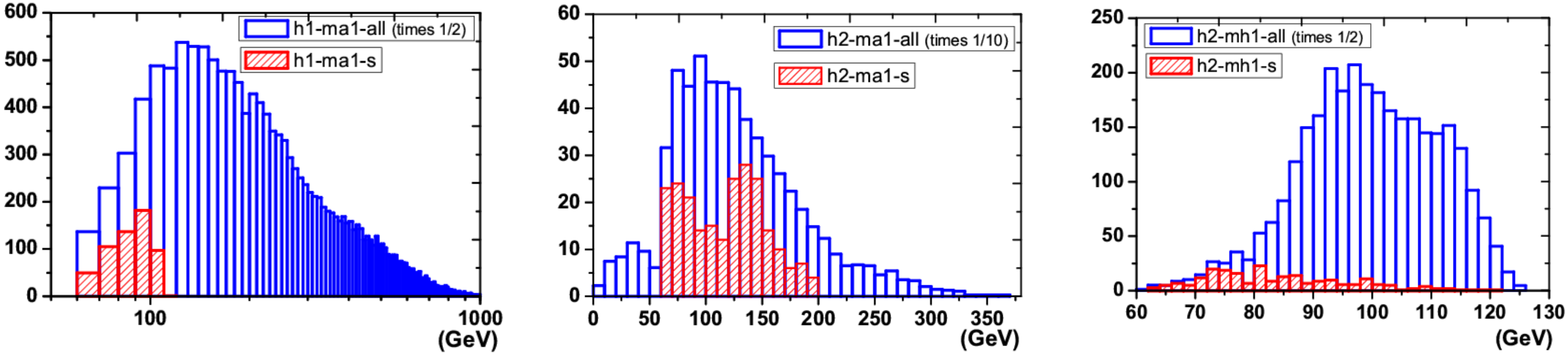


See e.g. Profumo et al, 1407.5342 for similar conclusions in the real singlet extension of the SM

How do we test this scenario?

Another handle: generically expect light singlet-like states

From Huang et al, 1405.1152

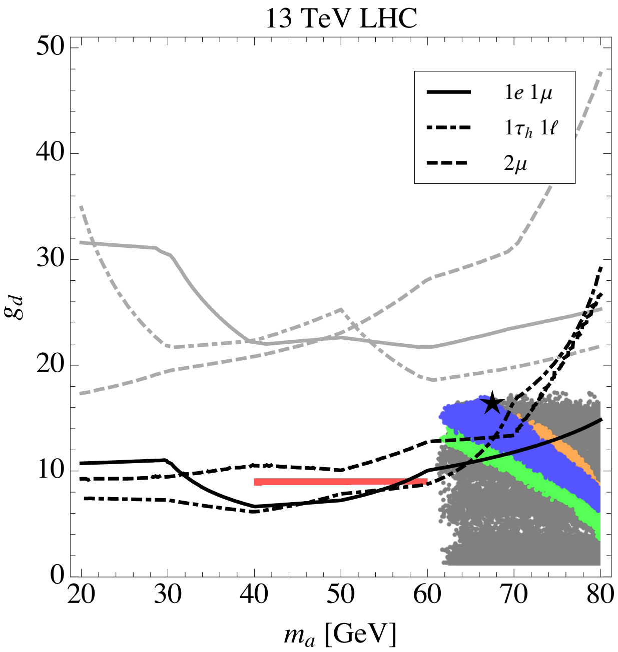


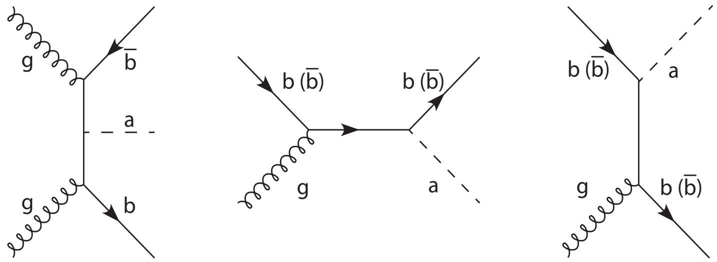
Look for these! Often difficult, but some exceptions

How do we test this scenario?

Look for these states… and don’t leave any gaps!

E.g. light pseudoscalars may have evaded LEP but could be found at the LHC and/or 100 TeV pp collider (if couplings aren’t that suppressed)!





JK and Martin, 1501.07275

See also Casolino et al, 1507.07004; …

100 TeV reach?

How do we test this scenario?

A more direct test: multi-Higgs production at the LHC and future colliders (see e.g. Curtin et al, 1409.0005; Craig et al, 1412.0258)

Various scalar self-couplings can be correlated with the strength of the EWPT in singlet models

May be possible to conclusively test a significant portion of the parameter space at 100 TeV collider (work in progress with Chien-Yi Chen and Ian Lewis – stay tuned!)

Takeaways

-Strong electroweak phase transitions are possible in the NMSSM parameter space allowed by current constraints

-Bubble profiles look promising for electroweak baryogenesis

-Bubble walls may expand too quickly for efficient electroweak baryogenesis in some cases. This is a generic problem in singlet extended scenarios

-Combination of precision Higgs studies and searches for (multi-) scalar production at future colliders can probe much of this scenario

Backup

How fast does the wall move?

Determine steady-state expansion velocity by finding solutions to the condensate equations of motion

Moore + Prokopec, hep-ph/9506475

$$-(1-v_w^2)\phi_i'' + \frac{\partial V(\phi_i, T)}{\partial \phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i} \int \frac{d^3p}{(2\pi)^3 2E_j} \delta f_j(p,x) = 0$$

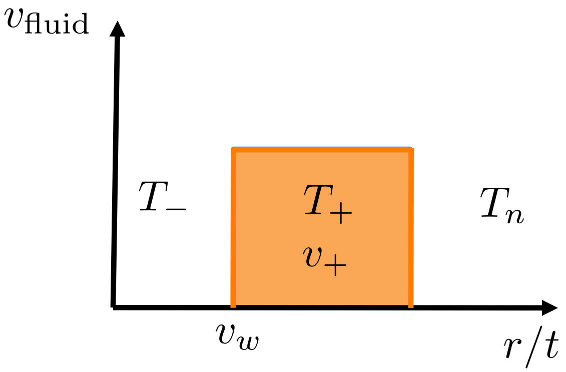
How fast does the wall move?

Determine steady-state expansion velocity by finding solutions to the condensate equations of motion

Moore + Prokopec, hep-ph/9506475

$$-(1-v_w^2)\phi_i'' + \underset{\uparrow}{\frac{\partial V(\phi_i,T)}{\partial \phi_i}} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i} \int \frac{d^3p}{(2\pi)^3 2E_j} \delta f_j(p,x) = 0$$

Solve hydrodynamic equations to determine the temperature profile



$$\partial_\mu T^{\mu\nu} = \partial_\mu T^{\mu\nu}_{\rm condensate} + \partial_\mu T^{\mu\nu}_{\rm plasma} = 0$$

See e.g. *Ignatius et al, astro-ph/9309059; Espinosa et al, 1004.4187*

Look for (subsonic) deflagration solutions for a given profile and value of v_w

How fast does the wall move?

Determine steady-state expansion velocity by finding solutions to the condensate equations of motion

Moore + Prokopec, hep-ph/9506475

$$-(1-v_w^2)\phi_i'' + \frac{\partial V(\phi_i,T)}{\partial \phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i}\int \frac{d^3p}{(2\pi)^3 2E_j}\underset{\uparrow}{\delta f_j(p,x)} = 0$$

Compute quasiparticle inetraction rates and solve Boltzmann equations for the deviations from equilibrium

$$\frac{d}{dt}f_i \equiv \left(\frac{\partial}{\partial t} + \dot{z}\frac{\partial}{\partial z} + \dot{p_z}\frac{\partial}{\partial p_z}\right) f_i = -C[f]_i$$

Compute in effective kinetic theory framework

See e.g. *Arnold et al, hep-ph/0209353, hep-ph/0010177, hep-ph/0302165*

Relevant states are top quarks, gauge, Higgs and singlet bosons

How fast does the wall move?

Determine steady-state expansion velocity by finding solutions to the condensate equations of motion

Moore + Prokopec, hep-ph/9506475

$$-(1-v_w^2)\phi_i'' + \frac{\partial V(\phi_i,T)}{\partial \phi_i} + \sum_j \frac{\partial m_j^2(\phi_i)}{\partial \phi_i} \int \frac{d^3p}{(2\pi)^3 2E_j} \delta f_j(p,x) = 0$$

Scan over profile parameters and v_w. Impose constraints to obtain approximate steady-state solutions

$$\int dx \; (\text{E.O.M.}) \cdot \frac{d\vec{\phi}}{dx} = 0$$

$$\int dx \; (\text{E.O.M.}) \cdot \frac{d^2\vec{\phi}}{dx^2} = 0$$

See e.g. *Konstandin, 1407.3132*