Confronting Supersymmetric Electroweak Baryogenesis with Precision and Collider Constraints

Jonathan Kozaczuk

Cosmology at Colliders Workshop

TRIUMF, 12/10/2013

TRIUMF

Outline

1. Overview: Baryogenesis in supersymmetry
2. Computing the Baryon Asymmetry
3. Current Constraints on MSSM EWB
4. Beyond the MSSM
5. Summary and Conclusions

Baryogenesis in SUSY

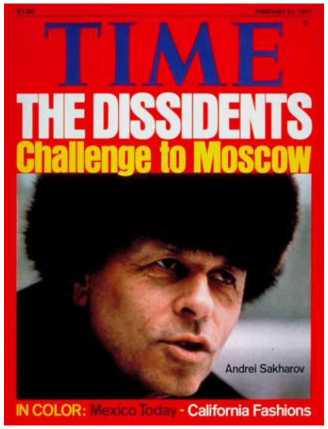
-Observed baryon asymmetry: $Y_B \equiv \frac{n_q - n_{\bar{q}}}{3s} \sim 10^{-10}$

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

1. $B-$violation

2. $C-$ and $CP-$violation

3. "Arrow of time"



-Several possibilities at different scales...

Baryogenesis in SUSY

- Planck scale: $M_P \sim 10^{19}$ GeV
- Affleck-Dine: $M_{inflation} \sim ?$
- GUT scale: $M_{GUT} \sim 10^{16}$ GeV
- Leptogenesis: $M_{seesaw} \sim 10^{15}$ GeV
- Electroweak baryogenesis: $M_{EW} \sim 100$ GeV

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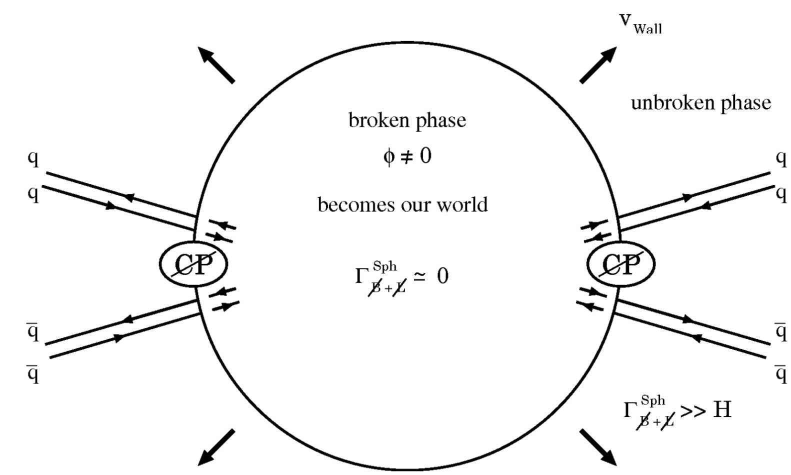

Bernreuther, 0205279

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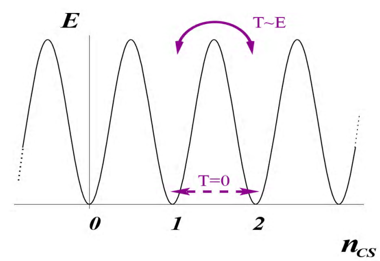
EWB in the SM:

Dine+Kusenko, 0303065



$$\Delta(B+L) = \Delta N_{CS}$$
$$\Gamma_{ws}(T \gg M_W) \propto (\alpha_W T)^4$$

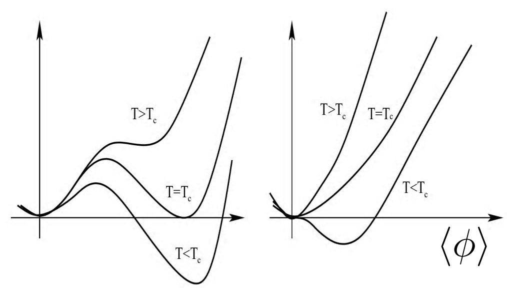
- ☐ *B*-violation from *SU(2)* sphalerons

- ☐ CPV from CKM matrix

$$\Delta_{CPV} = J \times (m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2)(m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2)$$
$$J = s_{12}s_{13}s_{23}c_{12}c_{13}^2c_{23}\sin\delta_{13}$$

- ☐ Departure from equilibrium at the EWPT

Dine+Kusenko, 0303065



First order → Second order

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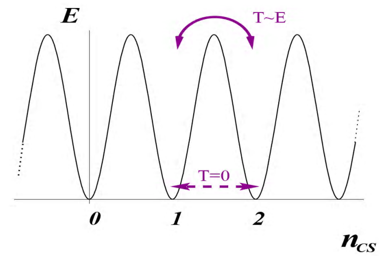


$$\Delta(B+L) = \Delta N_{CS}$$
$$\Gamma_{ws}(T \gg M_W) \propto (\alpha_W T)^4$$

EWB in the SM: almost...

☑ *B*-violation from *SU(2)* sphalerons

☐ CPV from CKM matrix

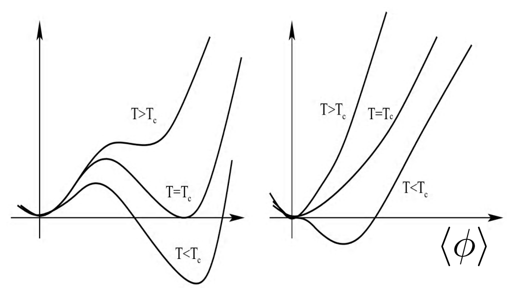
$$\Delta_{CPV} = J \times (m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2)(m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2)$$

$$J = s_{12}s_{13}s_{23}c_{12}c_{13}^2c_{23}\sin\delta_{13} \quad \rightarrow Y_B \sim 10^{-20}$$

☐ Departure from equilibrium at the EWPT

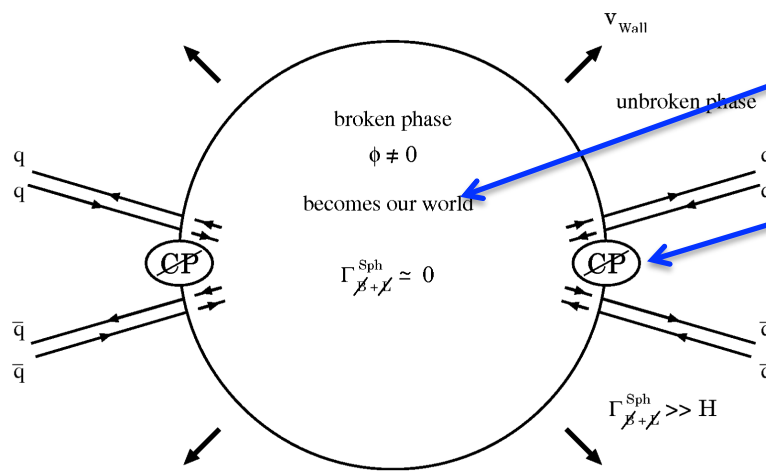
No first order phase transition

Dine+Kusenko, 0303065



First order → Second order

Baryogenesis in SUSY



Bernreuther, 0205279

Mechanism for strongly 1st order EWPT?

Sources of CP-violation?

Need to go beyond the Standard Model…

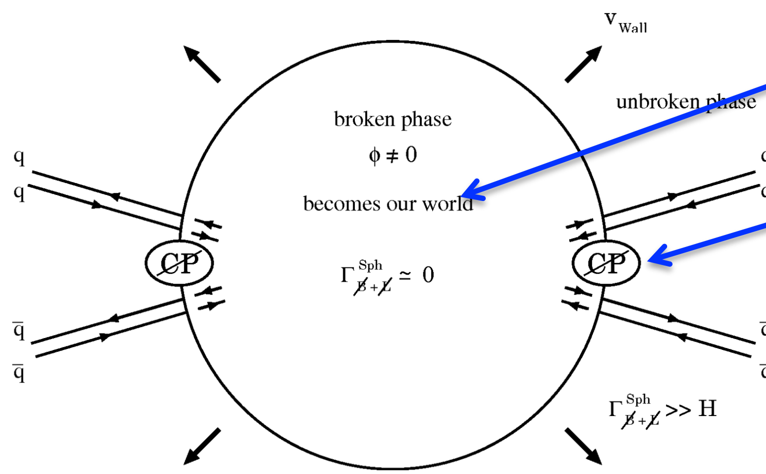
<u>Other issues with SM:</u>

-Higgs mass put in by hand (quartic coupling). Extremely sensitive to loop corrections (Hierarchy problem)

-No Dark Matter candidate

Supersymmetry can provide a solution. What about EWB?

Baryogenesis in SUSY



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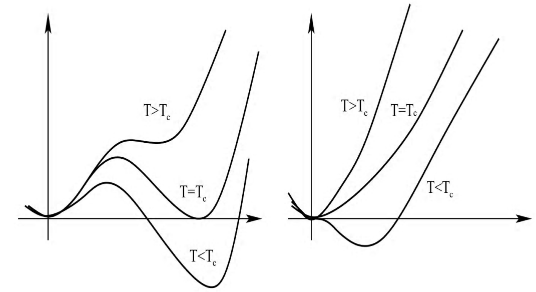


First order → Second order

Increasing m_h →

← additional scalars (new cubic terms)

Supersymmetry can also provide new sources of CP-violation and a first order EWPT

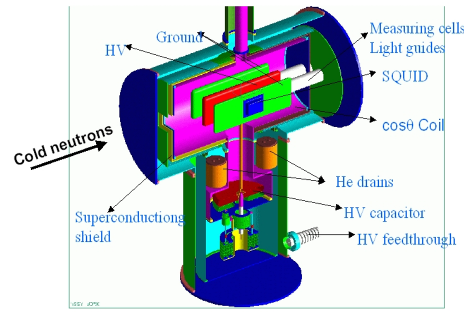
-MSSM has 40 new CP-violating phases (SUSY-breaking masses, couplings, etc)

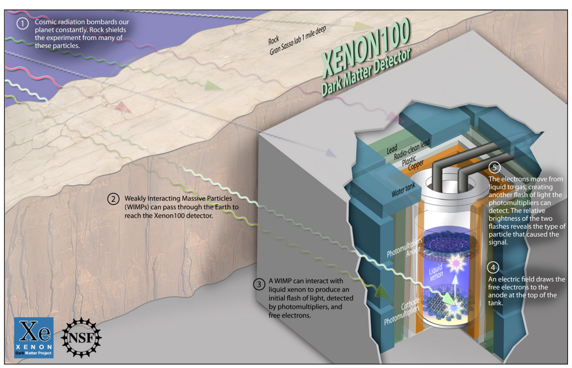
-Bosons contribute a cubic term to the finite temperature effective potential

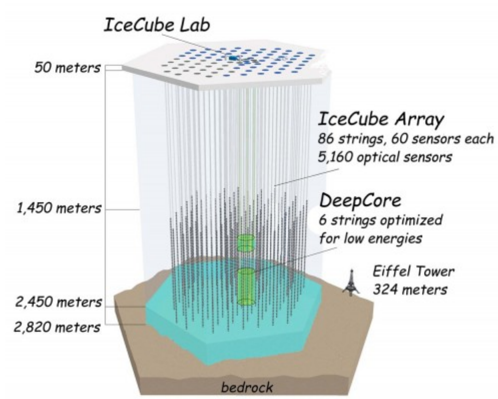
Baryogenesis in SUSY

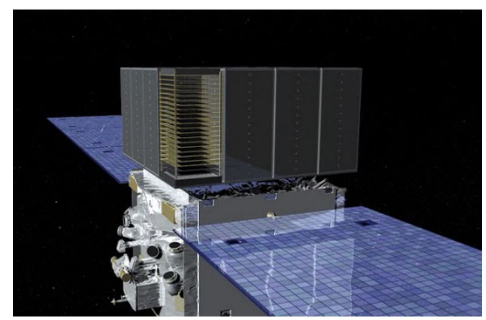
See e.g. Balasz et al, 0412264

SUSY EWB is **testable** today...









...What do we know, and what will we learn?

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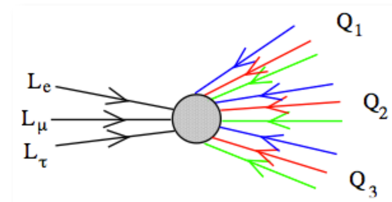
Computing the Baryon Asymmetry

-*SU(2)* sphalerons convert LH density n_L → baryon density

$$n_B = \frac{-3\Gamma_{ws}}{v_w}\int_{-\infty}^{0} dz\; n_L(z) e^{\frac{15\Gamma_{ws}}{4v_w}z}$$

Stongly1[st] order EWPT → sphalerons quenched in broken phase



Cline, 0609145

- n_L determined by coupled quantum Boltzmann equations for chemical potentials, accounting for all particle-number changing interactions:

$$n_i = \frac{T^2}{6} k_i \mu_i + \mathcal{O}\left(\frac{\mu_i}{T}\right)^3$$

Define common density H for both Higgses and Higgsinos (superequilibrium); sfermions decoupled

$$\longrightarrow \quad n_L = \sum_{i=1}^{3} \frac{k_{q_i}}{k_{Q_i}} Q_i + \sum_{i=1}^{3} \frac{k_{l_i}}{k_{L_i}} L_i$$

-Schwinger-Dyson → diffusion equations for all relevant particle species:

$$\partial_\mu j_i^\mu(x) = S_i(x, \{n_i\})$$

Computing the Baryon Asymmetry

Current density depends on all active particle-number changing processes

$$\partial_\mu J_i^\mu = S_i^{CP} + S_i^{CPV} + S_i^{\text{sph}}$$

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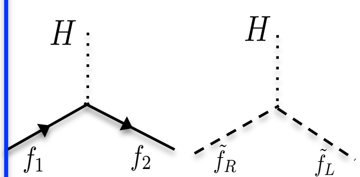
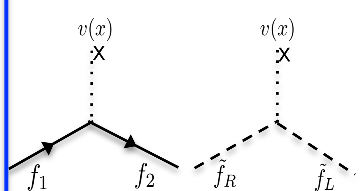
<u>CP-conserving</u>:

Yukawa and triscalar interactions



Chiral relaxation terms



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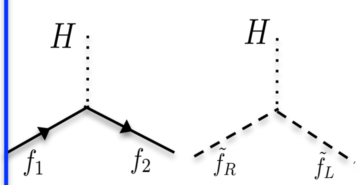

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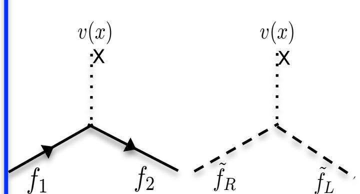
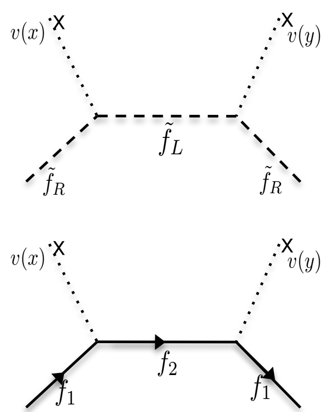


CP-violating:

Interactions with spacetime varying Higgs vevs



Compute via perturbative "vev-insertion" scheme, neglecting flavor effects (results in resonant sources and relaxation rates)

Resummed sources: Carena et al, 0011055, 0208043
Prokopec et al, 0312110, 0406140
Flavor effects: Cirigliano et al, 0912.3523, 1106.0747

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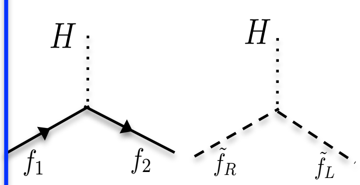

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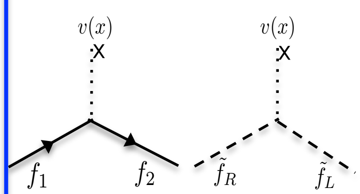

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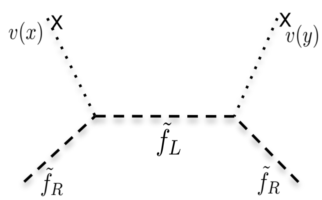

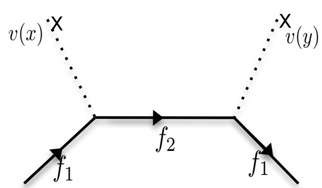

<u>Sphalerons</u>:

SU(3) sphalerons convert quark densities between generations

Non-perturbative quantity; lattice estimation

$$\Gamma_{ss} = 6\kappa' \frac{8}{3}\alpha_s^4 T$$

$$\kappa' \sim \mathcal{O}(1)$$

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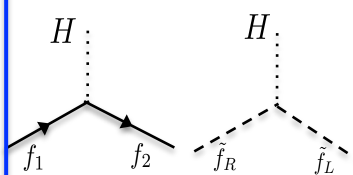

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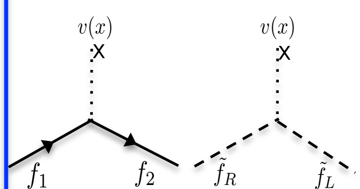

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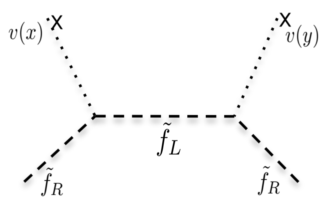

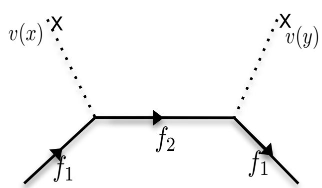

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$$\begin{aligned}
\partial_\mu Q^\mu =& -\Gamma_{yt}\left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) - \Gamma_{yb}\left(\frac{Q}{k_Q} + \frac{T+Q}{k_B} - \frac{H}{k_H}\right) \\
& - \Gamma_{mt}\left(\frac{Q}{k_Q} - \frac{T}{k_T}\right) - \Gamma_{mb}\left(\frac{Q}{k_Q} + \frac{T+Q}{k_B}\right) - S_{\tilde{t}}^{CPV} - S_{\tilde{b}}^{CPV} \\
& - 2\Gamma_{ss}\left(2\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{Q+T}{k_B} + \frac{1}{2}\sum_{i=1}^{2}\left[4\frac{1}{k_{Q_i}} + \frac{1}{k_{U_i}} + \frac{1}{k_{D_i}}\right] Q_1\right)
\end{aligned}$$

$$\begin{aligned}
\partial_\mu T^\mu =& \Gamma_{yt}\left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) + \Gamma_{mt}\left(\frac{Q}{k_Q} - \frac{T}{k_T}\right) + S_{\tilde{t}}^{CPV} \\
& + \Gamma_{ss}\left(2\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{Q+T}{k_B} + \frac{1}{2}\sum_{i=1}^{2}\left[4\frac{1}{k_{Q_i}} + \frac{1}{k_{U_i}} + \frac{1}{k_{D_i}}\right] Q_1\right)
\end{aligned}$$

$$\partial_\mu Q_1^\mu = -2\Gamma_{ss}\left(2\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{Q+T}{k_B} + \frac{1}{2}\sum_{i=1}^{2}\left[4\frac{1}{k_{Q_i}} + \frac{1}{k_{U_i}} + \frac{1}{k_{D_i}}\right] Q_1\right)$$

$$\begin{aligned}
\partial_\mu H^\mu =& -\Gamma_{yt}\left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) + \Gamma_{yb}\left(\frac{Q}{k_Q} + \frac{T+Q}{k_B} - \frac{H}{k_H}\right) \\
& + \Gamma_{y\tau}\left(\frac{L}{k_L} - \frac{R}{k_R} - \frac{H}{k_H}\right) - \Gamma_h \frac{H}{k_H} + S_{\tilde{H}}^{CPV}
\end{aligned}$$

$$\partial_\mu L^\mu = -\Gamma_{y\tau}\left(\frac{L}{k_L} - \frac{R}{k_R} - \frac{H}{k_H}\right) - \Gamma_{m\tau}\left(\frac{L}{k_L} - \frac{R}{k_R}\right) - S_\tau^{CPV}$$

$$\partial_\mu R^\mu = \Gamma_{y\tau}\left(\frac{L}{k_L} - \frac{R}{k_R} - \frac{H}{k_H}\right) + \Gamma_{m\tau}\left(\frac{L}{k_L} - \frac{R}{k_R}\right) + S_\tau^{CPV}$$

Relevant QBEs in the MSSM

Compute via perturbative "vev-insertion" scheme, neglecting flavor effects (results in resonant sources and relaxation rates)

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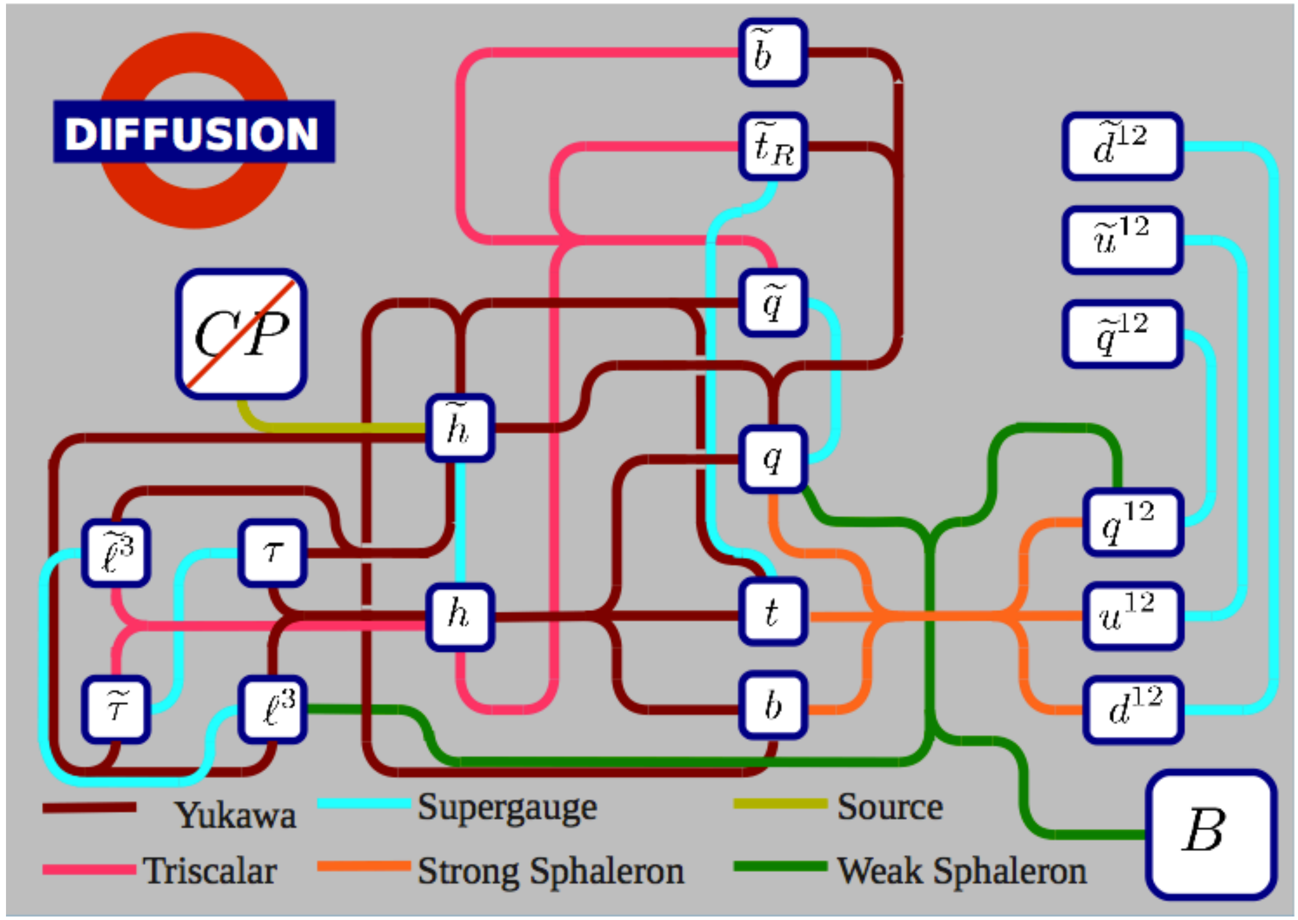
Computing the Baryon Asymmetry

- Up to $\mathcal{O}(10)$ uncertainties in CPV sources

- VEV insertion approximation is the most optimistic



B. Garbrecht

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Constraints on MSSM EWB

Both the EWPT and CP-violating sources are highly constrained in the MSSM

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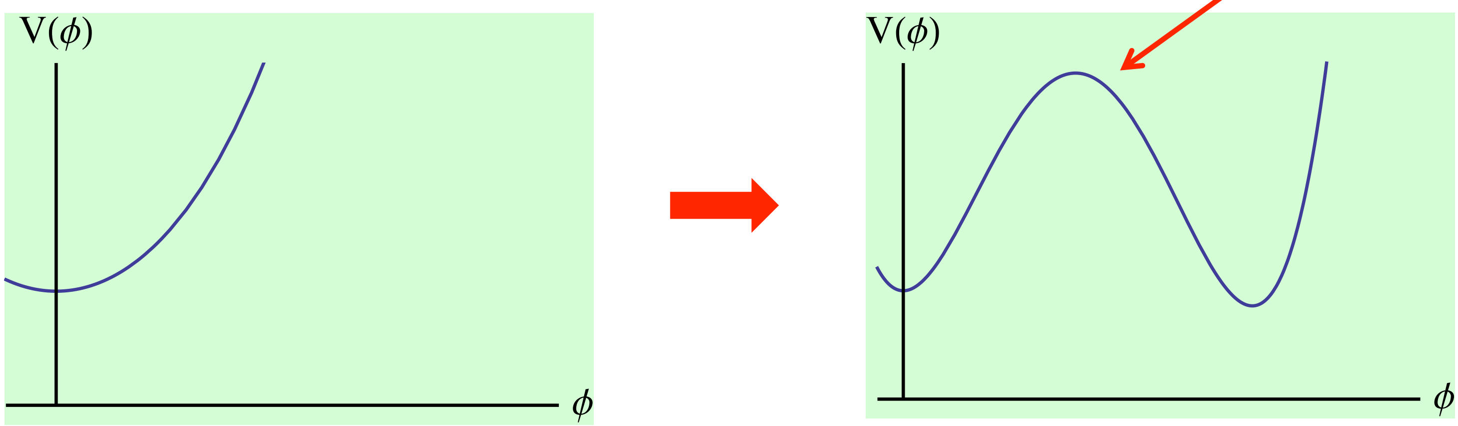
MSSM: light stops contribute cubic term to finite-T effective potential

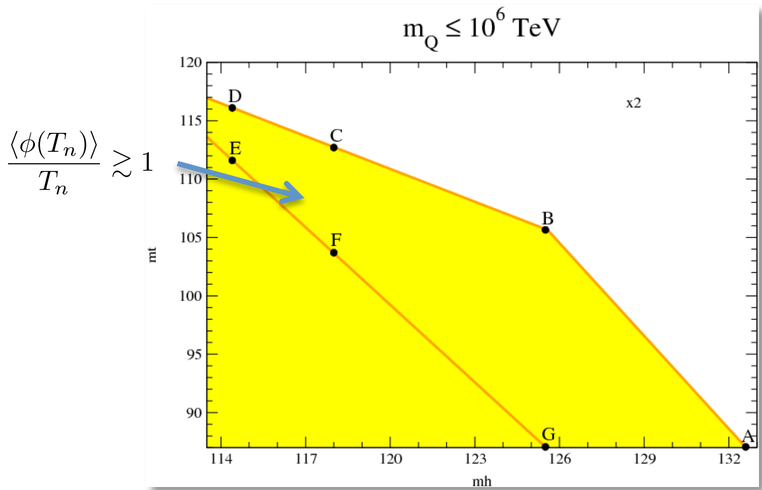
$$V_1(T>0) = V_1(T=0) + \frac{T^2}{2\pi^2}\sum_i n_i J_\pm\left(\frac{m_i^2}{T^2}\right)$$

$$J_\pm(x^2) \equiv \pm\int_0^\infty dy\, y^2 \log\left(1 \mp e^{-\sqrt{y^2+x^2}}\right) \underset{\text{High-T expansion for bosons}}{\rightarrow} \simeq -\frac{\pi^4}{45} + \frac{\pi^2 m^2}{12T^2} - \frac{\pi}{6}\left(\frac{m^2}{T^2}\right)^{3/2} + \cdots$$

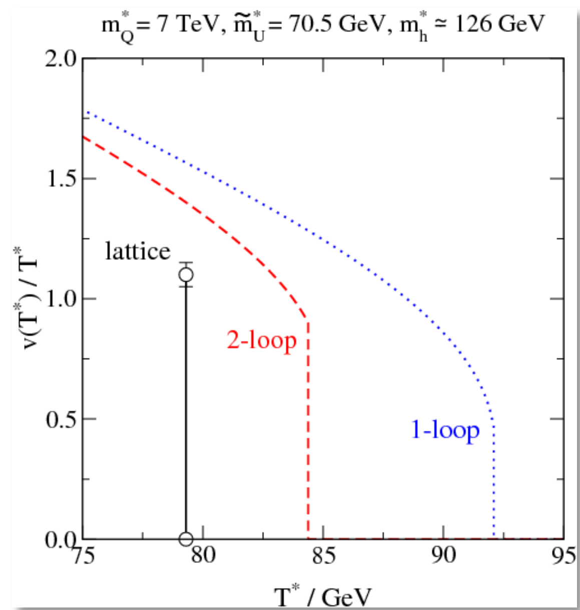


Constraints on MSSM EWB

Strongly first order EWPT in MSSM from light stop:



Carena et al, 1207.6330



Laine et al, 1211.7344

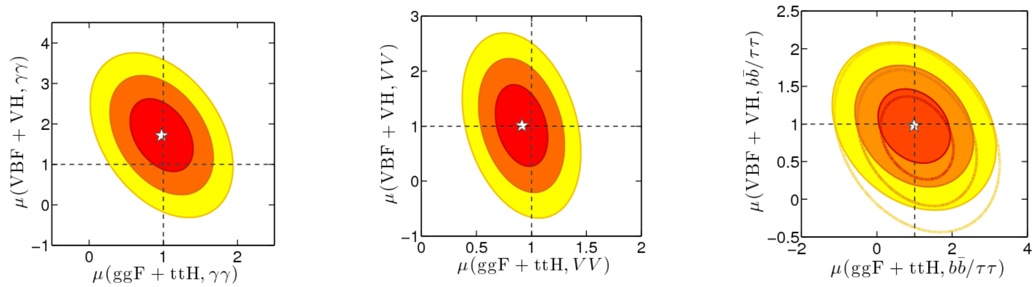
Recent results from lattice simulations suggest the window might be slightly larger than from 2-loop results.

Light stops are highly constrained by LHC…

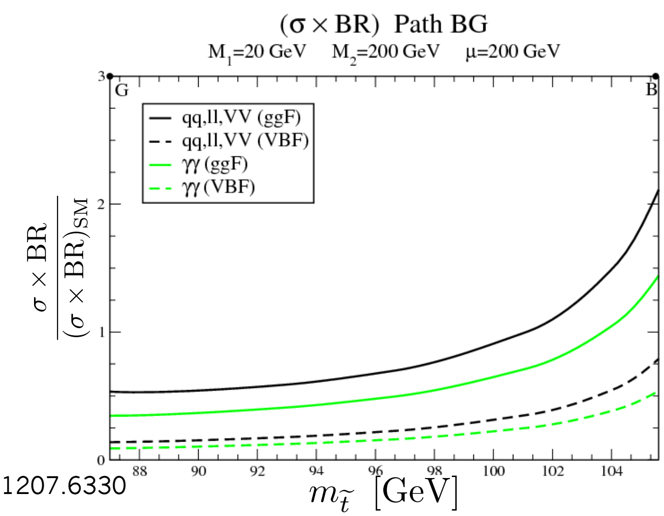
Constraints on MSSM EWB

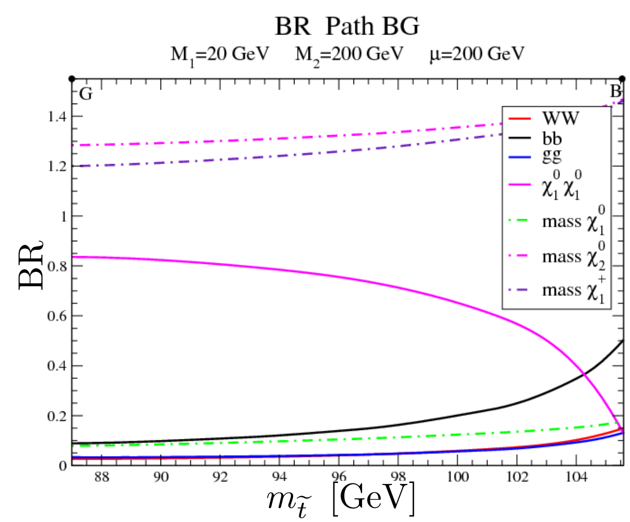
Light stops lead to e.g. increase in gluon-gluon fusion Higgs production cross section (Menon +Morrissey 0903.3038)

Can be ameliorated with a light neutralino, but tenuous



Global fit by Belanger et al,1306.2941





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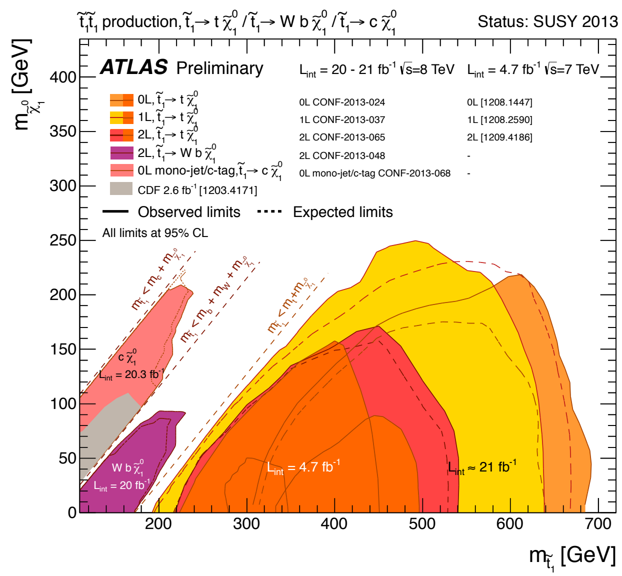
Constraints on MSSM EWB

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

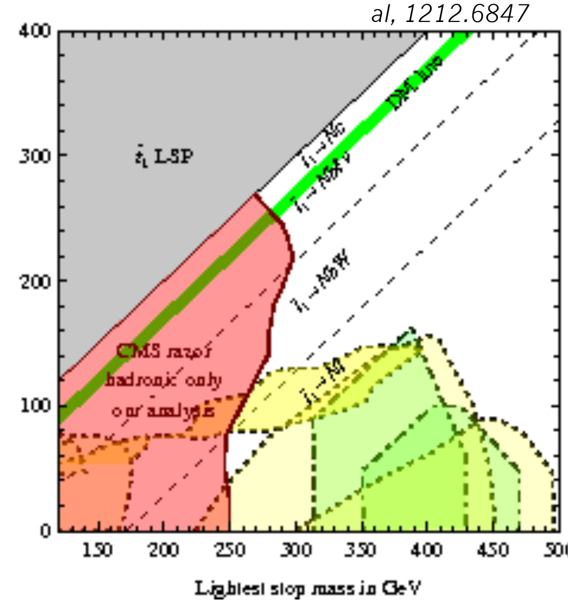
For $m_{\widetilde{t}} < m_t + m_{\chi_1^0}$ relevant decay channels are e.g. $\widetilde{t} \to \chi_1^0 b W^+$, $\widetilde{t} \to \chi_1^0 c$, $\widetilde{t} \to \chi_1^0 b \ell \nu$

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 $\widetilde{t} \to \widetilde{\tau}^+ \nu b$ (Carena et al, 1303.4414)

Constraints on MSSM EWB

So...

The light stop scenario in the MSSM is barely holding on

What about CP-violating sources?

Constraints on MSSM EWB

CP-violation either in 3rd generation sfermion sector

See e.g.
Huet + Nelson, 9506477
JK et al, 1206.4100
…

$$\mathcal{L} \supset \; y_t \tilde{t}_L \tilde{t}_R^* (A_t H_u^0 - \mu^* H_d^{0*}) + y_b \tilde{b}_L \tilde{b}_R^* (A_b H_d^0 - \mu^* H_u^{0*}) + y_\tau \tilde{\tau}_L \tilde{\tau}_R^* (A_\tau H_d^0 - \mu^* H_u^{0*}) - b H_u^0 H_d^0 + h.c.,$$

Thermal suppression

$$S_{\tilde{t}}^{CPV}(x) = \frac{N_C y_t^2}{2\pi^2} \mathrm{Im}(\mu A_t) v^2(x) \dot{\beta}(x) \int_0^\infty \frac{dk k^2}{\omega_R \omega_L} \mathrm{Im}\left[\frac{n_B(\mathcal{E}_R^*) - n_B(\mathcal{E}_L)}{(\mathcal{E}_L - \mathcal{E}_R^*)^2} + \frac{n_B(\mathcal{E}_R) + n_B(\mathcal{E}_L)}{(\mathcal{E}_L + \mathcal{E}_R)^2} \right]$$

Resonance

Or Higgsinos + Gauginos:

$$\mathcal{L} \supset -\frac{g_1}{\sqrt{2}} \bar{\Psi}_{\tilde{H}^0} (H_d^{0*} P_L - e^{i\phi_1} H_u^0 P_R) \Psi_{\tilde{B}} + h.c.$$ (+ wino interactions)

See e.g.
Huet + Nelson, 9506477
Carena et al, 9702409
Cline et al, 0006119
…

$$S_{\tilde{H}^\pm}^{CPV}(x) = \frac{g_2^2}{\pi^2} v(x)^2 \dot{\beta}(x) M_2 |\mu| \sin\phi_2 \int_0^\infty \frac{dk k^2}{\omega_{\tilde{H}} \omega_{\tilde{W}}} \mathrm{Im}\left[\frac{n_F(\mathcal{E}_{\tilde{W}}) - n_F(\mathcal{E}_{\tilde{H}}^*)}{(\mathcal{E}_{\tilde{W}} - \mathcal{E}_{\tilde{H}}^*)^2} - \frac{n_F(\mathcal{E}_{\tilde{W}}) - n_F(\mathcal{E}_{\tilde{H}})}{(\mathcal{E}_{\tilde{W}} + \mathcal{E}_{\tilde{H}})^2} \right]$$

Both possibilities have important phenomenological consequences

Constraints on MSSM EWB

Intensity frontier:

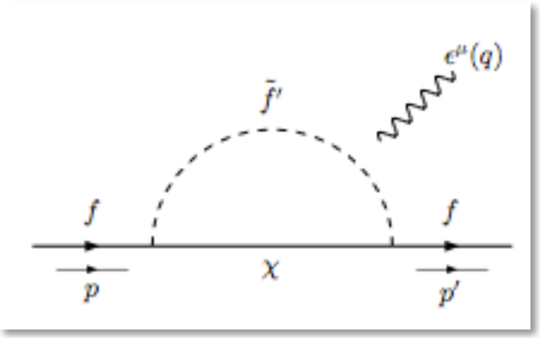
-Electric Dipole Moments sensitive to CP-violation

$$H = -\mu_f^B \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d_f^E \mathbf{E} \cdot \frac{\mathbf{S}}{S} \longrightarrow \mathcal{L} = -d_f^E \frac{i}{2} \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu}$$

P-odd, *T*-odd (*CP*-odd)

$$\mathcal{L}_{(C)EDM} = -\frac{i}{2} d_f^E F^{\mu\nu} \bar{f} \sigma_{\mu\nu} \gamma_5 f - \frac{i}{2} d_q^C G^{a\mu\nu} \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q$$

(Chromo-EDM)



-EDM can be induced at one-loop and beyond. With heavy sfermions, two-loop contributions can still be sizable

Energy frontier:

-Collider searches constrain new SUSY degrees of freedom which must be light (*O* (100 GeV)) to avoid thermal suppression near the EWPT

-Predictions for mass and properties of observed 126 GeV Higgs affected by new particles

Cosmic Frontier:

-Light gauginos for CPV sources have implications for dark matter

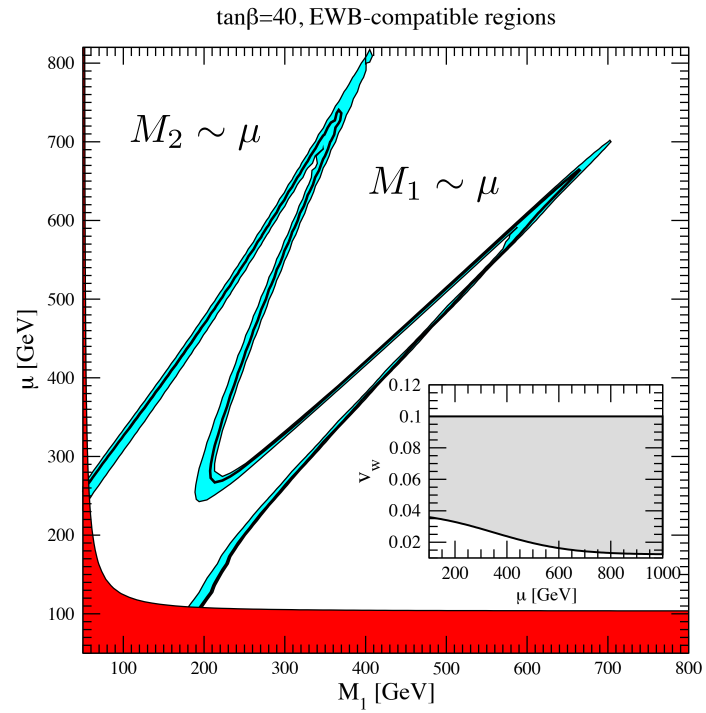
Constraints on MSSM EWB

Higgsino-gaugino sources

·Relatively light neutralinos/charginos to avoid thermal suppression

·Resonant structure in VEV-insertion scheme

·Optimistic estimate of baryon asymmetry (keep factor of 10 in mind)



$M_2=2M_1$

JK+Profumo, 1108.0393

How do these sources fare with the new ACME e-EDM bound? $|d_e| \leq 8.7 \times 10^{-29} e$ cm

Constraints on MSSM EWB

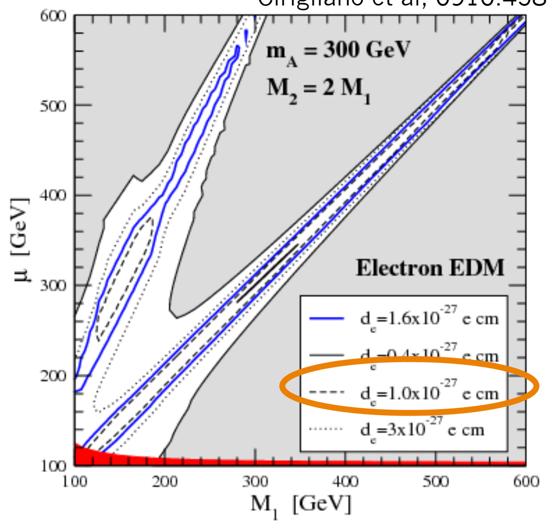
<u>Higgsino-gaugino sources</u>

Wino-driven EWB and EWB with universal phases (tentatively) excluded by ACME EDM limits alone!

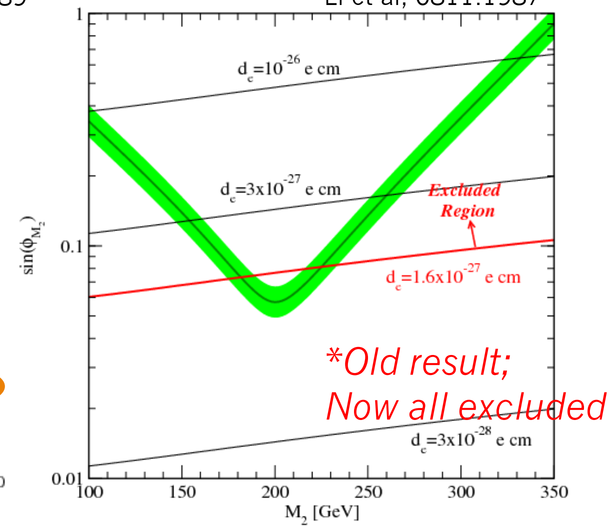
Independent of phase transition, collider searches, etc. Also true beyond MSSM

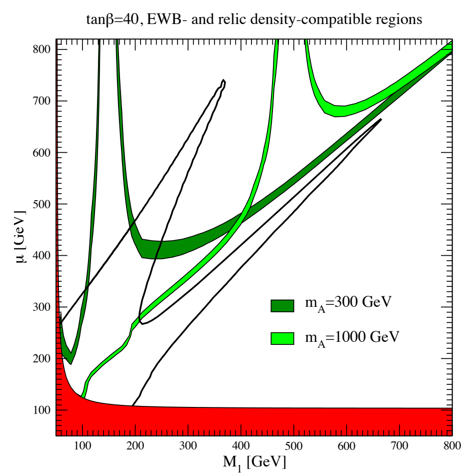
*Implies that Higgsino-gaugino driven EWB is in tension with a good neutralino DM candidate

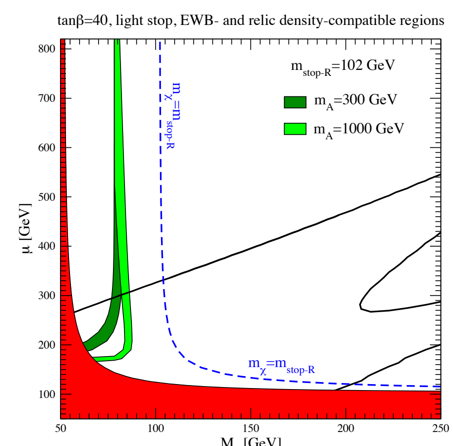
Cirigliano et al, 0910.4589



Li et al, 0811.1987







JK+Profumo, 1108.0393

Constraints on MSSM EWB

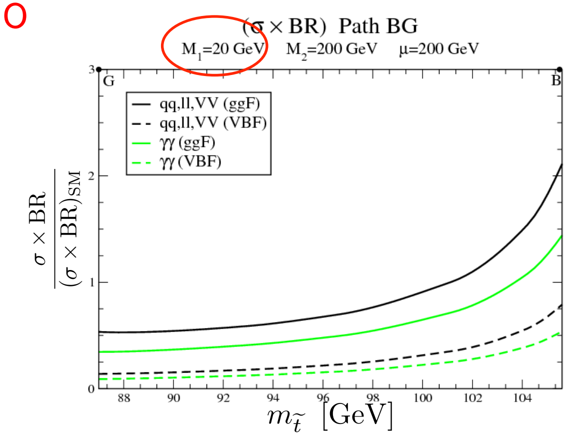
<u>**Higgsino-gaugino sources**</u>

Bino-driven EWB slightly more subtle

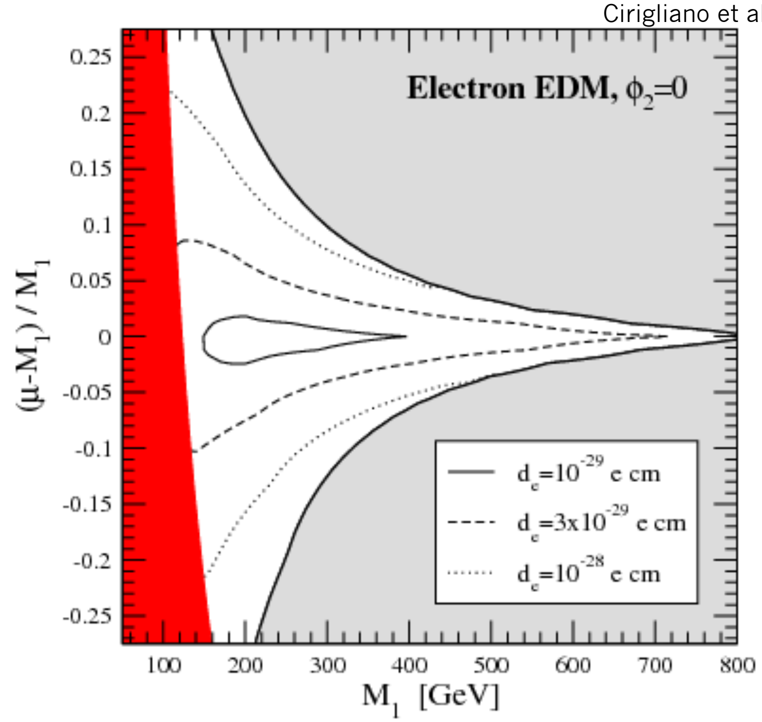
☑ EDMs suppressed in this case

☐ Incompatible with strongly first order EWPT via light stop scenario

Recall:



Cirigliano et al, 0910.4589

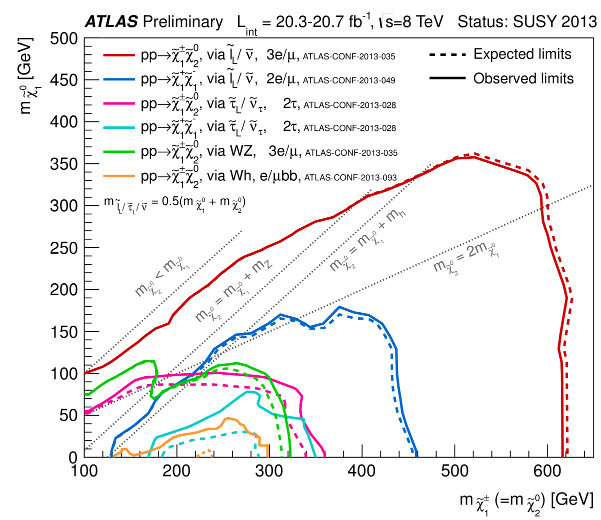


MSSM Bino-driven EWB now excluded by stop searches, Higgs production rates, and EDMs

Constraints on MSSM EWB

Higgsino-gaugino sources

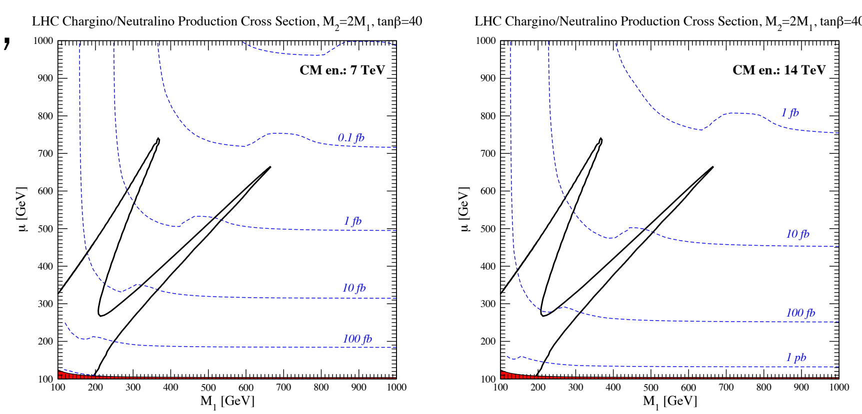
What about beyond the light stop scenario?



OK with current LHC constraints on EWinos

Bino-driven EWB requires $M_1 \sim \mu$ → compressed χ^0_1, $\chi^{\pm,0}_{1,2}$ spectrum = difficult, but not impossible for future searches (see e.g. Gori et al, 1307.5952)

LSP under-abundant, so tough to get at with DM constraints

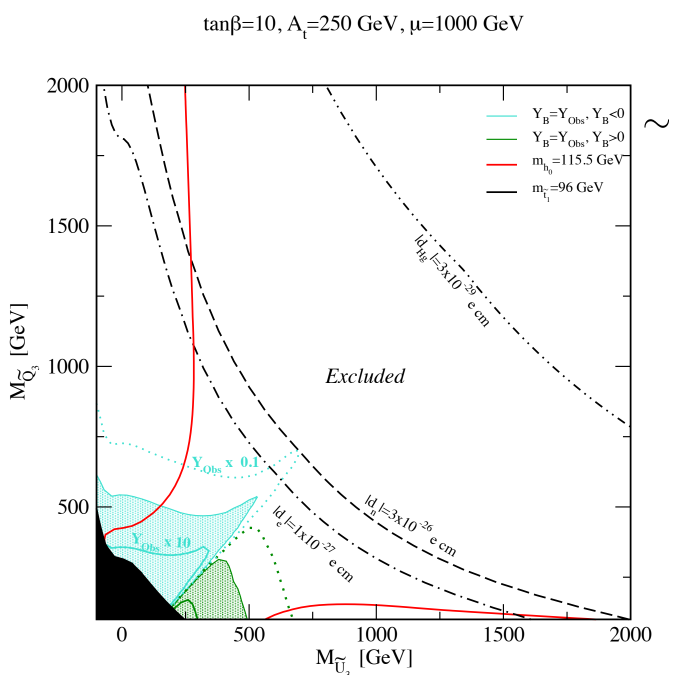


JK+Profumo, 1108.0393

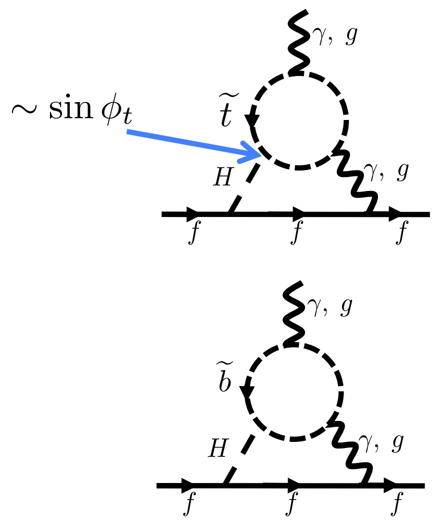
Constraints on MSSM EWB

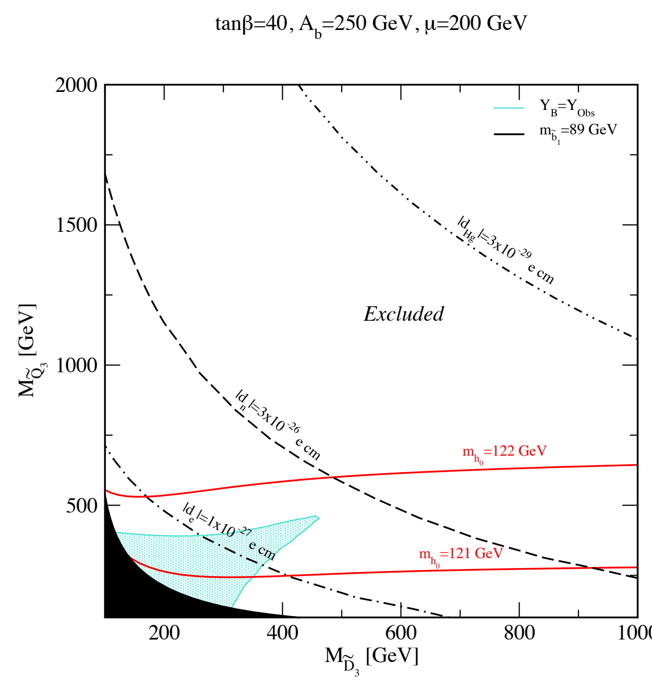
Scalar sources

Stops and sbottoms **excluded** by EDM constraints even *before* the new ACME limit



JK et al, 1206.4100

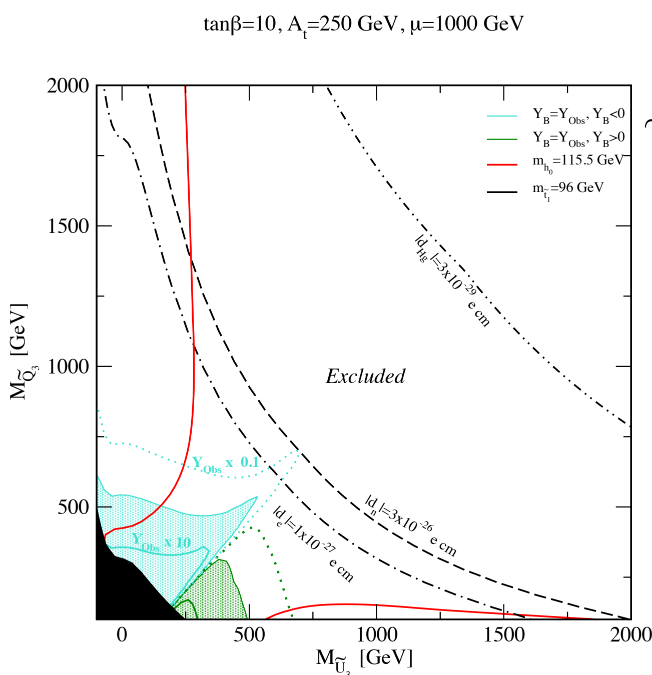




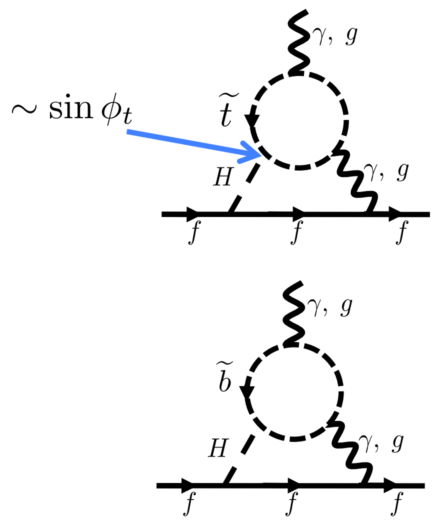
Constraints on MSSM EWB

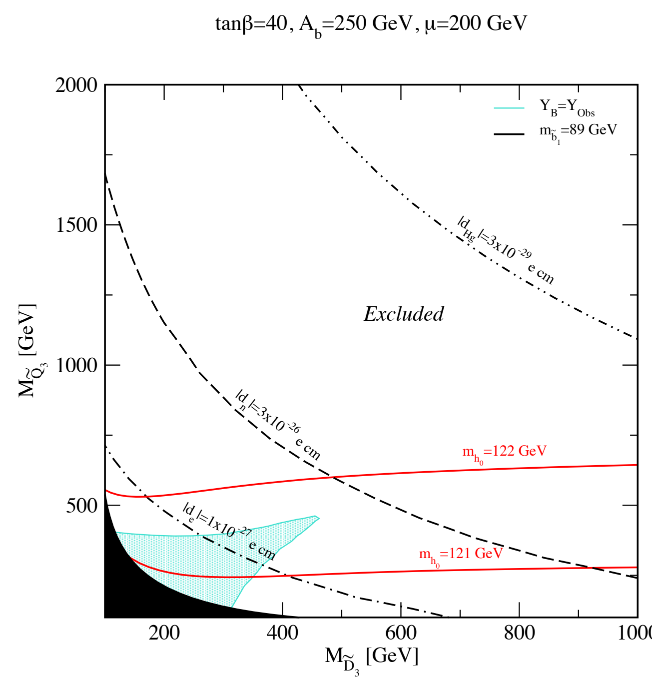
<u>Scalar sources</u>

Stops and sbottoms **excluded** by EDM constraints even *before* the new ACME limit



JK et al, 1206.4100





Large hadronic uncertainties now replaced by e-EDM bound

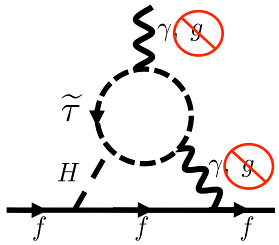
Nuclear Schiff moment   πNN vertices

$$d_{\rm Hg} = \boxed{(1.8\times10^{-3}\ {\rm GeV}^{-1})}\, e\, \boxed{\bar{g}^{(1)}_{\pi NN}} + 10^{-2} d_e^E + (3.5\times10^{-3}{\rm GeV})\, e\, C_S + (4\times10^{-4}\ {\rm GeV})\, e\left[C_P + \left(\frac{Z-N}{A}\right)_{\rm Hg} C_P'\right],$$

Atomic physics

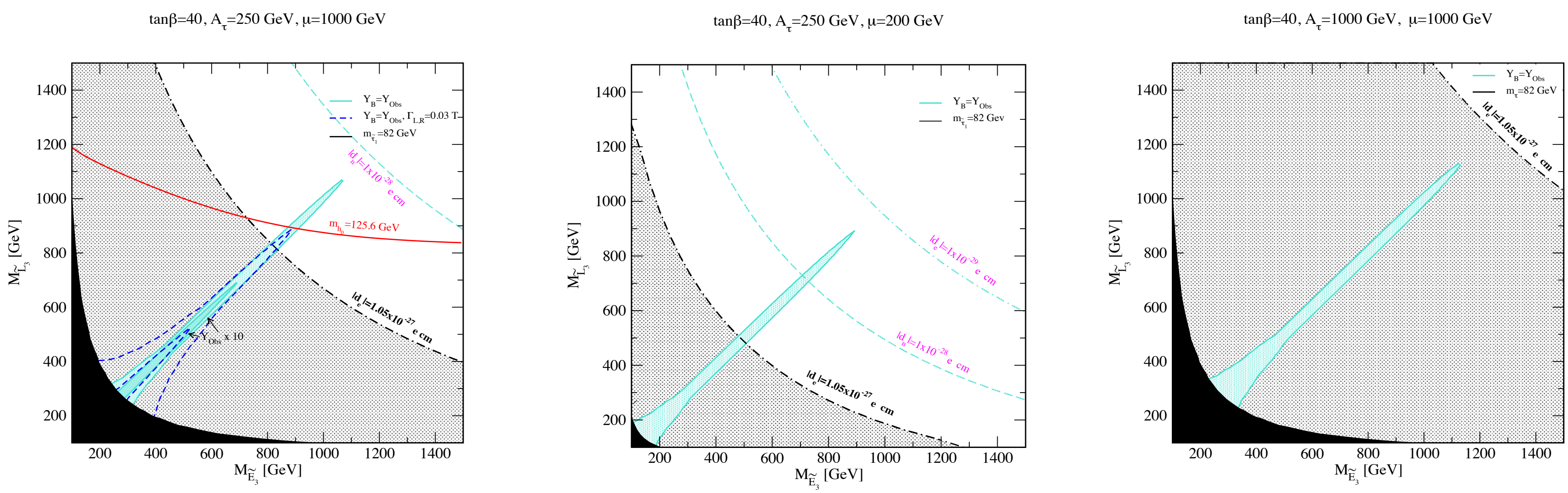
Scalar Sources

Scalar Sources



No CEDM;
Smaller uncertainties

New EDM limit now kills stau sources in the MSSM



JK et al, 1206.4100

EDM bounds require staus too heavy to allow $\tilde{t} \to \tilde{\tau}^{+} \nu b$

Constraints on MSSM EWB

So…

- *All potential CPV sources in the MSSM now appear to be ruled out by EDM + collider constraints required for strongly 1st order PT even in the most optimistic estimates of the baryon asymmetry**

- *Bino- or stau-driven EWB potentially still an option beyond the MSSM light stop scenario*

*Possible caveats: cancellations between various EDM contributions, non-resonant contribution to CPV source

Outline

1. Overview: Baryogenesis in supersymmetry
2. Computing the Baryon Asymmetry
3. Current Constraints on MSSM EWB
4. Beyond the MSSM
5. Summary and Conclusions

EWB Beyond the MSSM

Scenarios beyond the MSSM can provide a strongly first order EWPT and more available parameter space for CP-violating sources

Most obvious choice: the NMSSM

$$W = W_{\mathrm{MSSM}}|_{\mu=0} + \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\widehat{S}^3$$ ← New fermion+complex *scalar*

$$-\mathcal{L}^{soft} = -\mathcal{L}^{soft}_{\mathrm{MSSM}} + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3\right) + \mathrm{h.c.}$$

Already has several nice features:

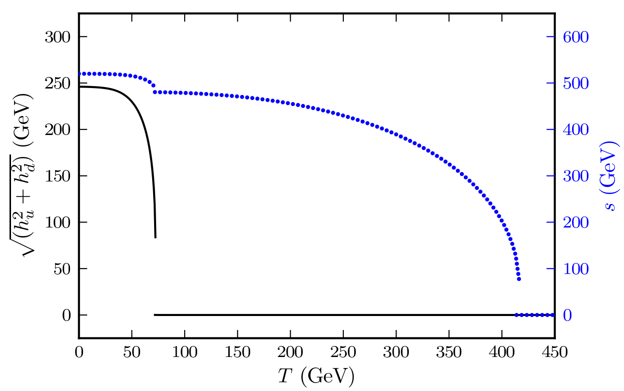
$$m_{h_1}^2 \leq \left(\cos^2 2\beta + \frac{2\lambda^2 \sin^2 2\beta}{g_1^2 + g_2^2}\right) m_Z^2.$$ Tree-level Higgs mass enhancement

$$\mu = \lambda v_s$$ Potentially no μ problem

EWB Beyond the MSSM

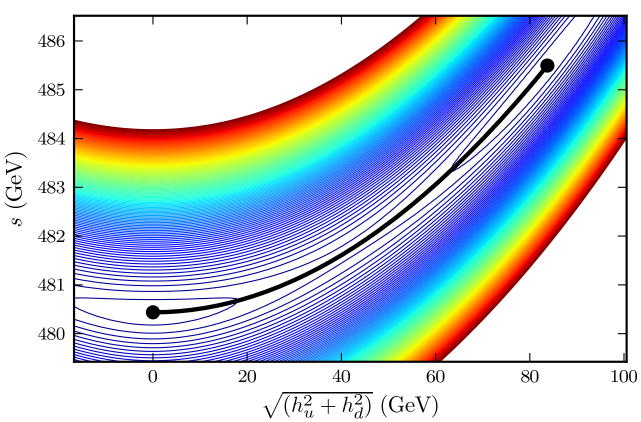
The NMSSM can support a strongly first order EWPT without a light stop

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



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

One loop, finite T: $$V_1(T\!>\!0)=V_1(T\!=\!0)+\frac{T^2}{2\pi^2}\sum_i n_iJ_\pm\left(\frac{m_i^2}{T^2}\right)$$



-Larger λ, A_λ strengthen cubic terms

λ	0.75	m_{A_1} [GeV]	261.26
κ	0.45	$m_{\chi_1^0}$ [GeV]	130.72
$\tan\beta$	1.7	$\langle\sigma v\rangle_{b\bar{b}}$ $[cm^3/s]$	3.07×10^{-26}
A_λ [GeV]	545.0	$\langle\sigma v\rangle_{\gamma\gamma}$ $[cm^3/s]$	1.54×10^{-27}
A_κ [GeV]	-88. 0	$\sigma_P^{\rm SI}$ [pb]	2.8×10^{-9}
μ [GeV]	275.8	$\sigma_P^{\rm SD}$ [pb]	1.4×10^{-6}
M_1 [GeV]	143.5	EWPT Properties:	
M_2 [GeV]	635.5	T_c [GeV]	72.3
m_{h_1} [GeV]	126.4	$\varphi(T_c)/T_c$	1.14

JK et al, 1302.4781

EWB Beyond the MSSM

Variety of symmetry breaking patterns across parameter space consistent with current LHC data

	BM 1	BM 2	BM 3	BM 4
λ	0.65	0.63	0.65	0.72
κ	0.20	0.14	0.15	0.37
A_λ [GeV]	380	250	300	385
A_κ [GeV]	-95	-120	-33	20
$\tan\beta$	1.5	1.5	1.7	1.5
μ [GeV]	220	130	150	195
M_1 [GeV]	-84	145	-93	-161
$M_{\widetilde{Q}_3} = M_{\widetilde{U}_3}$ [TeV]	1	1	1	0.8
$A_t = A_b$ [GeV]	700	700	700	1500
$m_{h_{SM}}, m_{h_s}$ [GeV]	125.7, 146.5	126.3 , 93.1	126.3, 107.2	125.6, 231.4
m_{a_s} [GeV]	179.5	134.2	112.1	145.2
$\Delta\chi^2_{\gamma\gamma}$, , $\Delta\chi^2_{ff}$	3.3	1.2	1.2	5.8
$m_{\widetilde{\chi}_1^0}$ [GeV]	88.6	78.6	98.1	162.9
$\widetilde{\chi}_1^0$ composition	Bino	Higgsino–Singlino	Bino	Bino
Ωh^2	0.12	0.10	0.11	0.12
σ_{SI} [cm^2]	1.3×10^{-45}	2.1×10^{-45}	2.2×10^{-45}	8.8×10^{-46}
$\langle\sigma v\rangle$ [cm$^3/s$]	1.1×10^{-29}	$6.94{\times}10^{-28}$	1.24×10^{-28}	4.7×10^{-28}

JK, Profumo, Stephenson-Haskins, Wainwright, *in prep*

EWB Beyond the MSSM

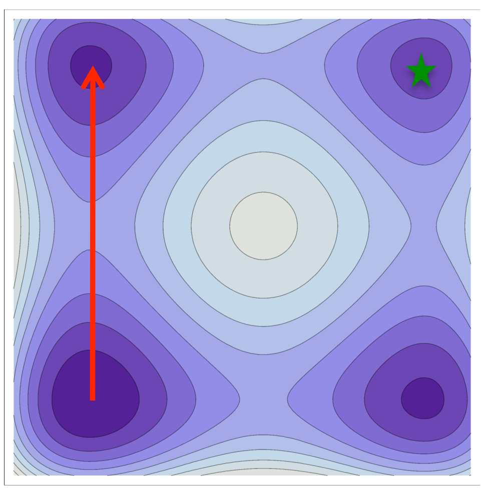
Variety of symmetry breaking patterns across parameter space consistent with current LHC data

<u>BM 1:</u>

SYM → s

$$\frac{\Delta\phi}{T_n} = 1.3$$

T_n=195 GeV



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JK, Profumo, Stephenson-Haskins, Wainwright, *in prep*

EWB Beyond the MSSM

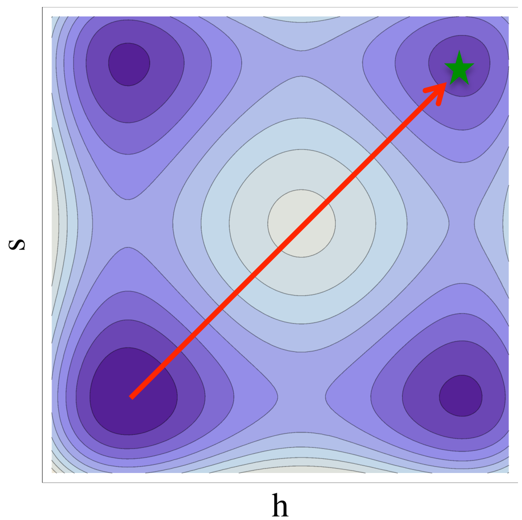
Variety of symmetry breaking patterns across parameter space consistent with current LHC data

BM 2:

SYM → s+h

$$\frac{\Delta\phi}{T_n} = 6.6$$

T_n=58.2 GeV



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JK, Profumo, Stephenson-Haskins, Wainwright, *in prep*

EWB Beyond the MSSM

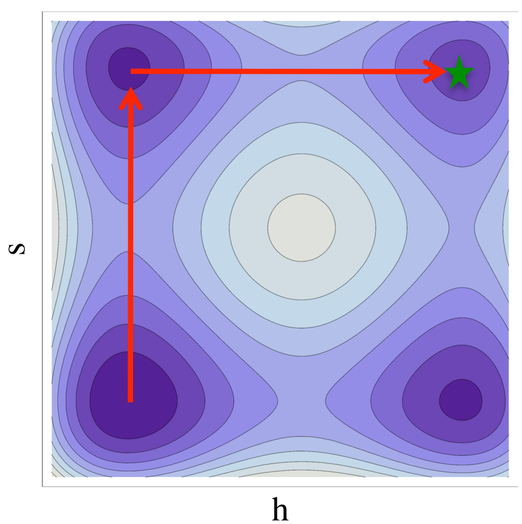
Variety of symmetry breaking patterns across parameter space consistent with current LHC data

BM 3:

SYM → s → h

$$\frac{\Delta\phi}{T_n} = 1.1,\ 2.12$$

T_n=112 GeV, 110 GeV



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JK, Profumo, Stephenson-Haskins, Wainwright, *in prep*

EWB Beyond the MSSM

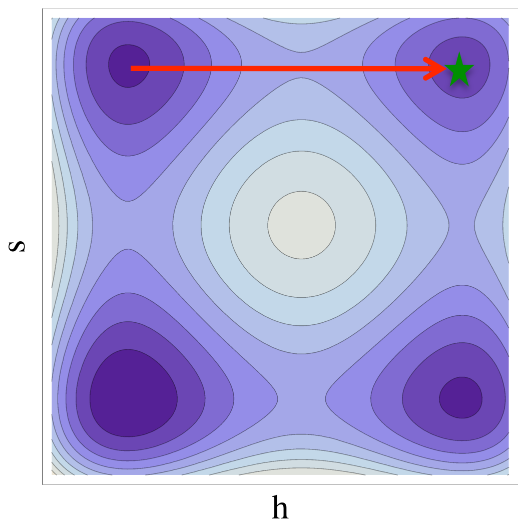
Variety of symmetry breaking patterns across parameter space consistent with current LHC data

BM 4:

$s \rightarrow h$

$$\frac{\Delta\phi}{T_n} = 1.1$$

T_n=106 GeV



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$\Delta\chi^2_{\gamma\gamma}$, , $\Delta\chi^2_{ff}$	3.3	1.2	1.2	5.8
$m_{\tilde{\chi}^0_1}$ [GeV]	88.6	78.6	98.1	162.9
$\tilde{\chi}^0_1$ composition	Bino	Higgsino–Singlino	Bino	Bino
Ωh^2	0.12	0.10	0.11	0.12
$\sigma_{\rm SI}$ [cm^2]	1.3×10^{-45}	2.1×10^{-45}	2.2×10^{-45}	8.8×10^{-46}
$\langle\sigma v\rangle$ [cm$^3/s$]	1.1×10^{-29}	$6.94{\times}10^{-28}$	1.24×10^{-28}	4.7×10^{-28}

JK, Profumo, Stephenson-Haskins, Wainwright, *in prep*

EWB Beyond the MSSM

NMSSM also allows for additional sources of CP-violation

Gaugino-Higgsino-, stau-sourced explicit CPV (now with $\mu \rightarrow \mu(x)$)

E.g. JK et al, 1302.4781

"Transitional CPV": CP-violating high-T minimum (no EDM contribution)

Huber et al, 0003122

Spacetime-dependent CP phase

Huber et al, 0606298

Singlino-sourced explicit CPV

Cheung et al, 1201.3781

Rich phenomenology in both EWPT and CPV possibilities worth (re-)exploring

Conclusions

MSSM Electroweak baryogenesis appears to be ruled out.

Pending:

- Incorporating non-resonant CPV sources
- Consideration of potential cancellations in EDM contributions
- More systematic treatment of uncertainties

NMSSM regions compatible with 125 GeV Higgs, LHC, and DM can have a rich phenomenology for EWB.

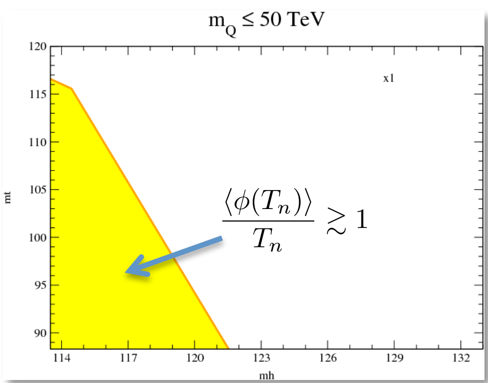
- Strongly 1st order EWPT from singlet without light stop
- New sources of CPV not present in MSSM (worth re-exploring)

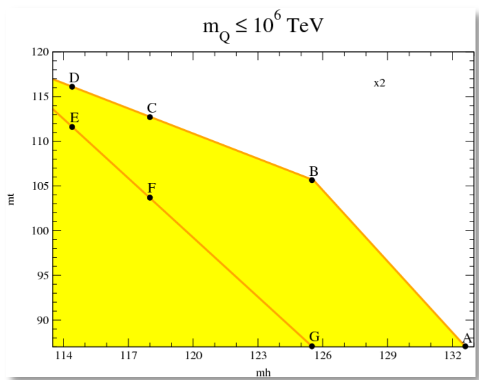
Backup Slides

Constraints on MSSM EWB

Both the EWPT and CP-violating sources are highly constrained in the MSSM

Strongly first order EWPT in MSSM from light stop



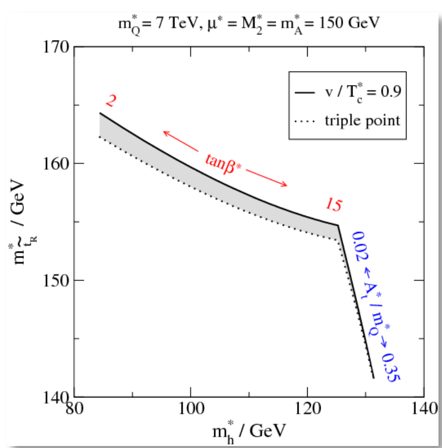


Carena et al, 1207.6330

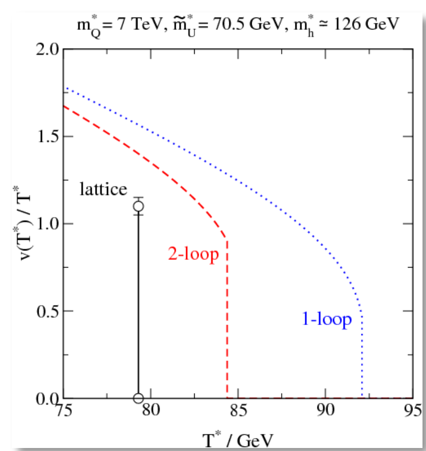
Leads to e.g. increase in gluon-gluon fusion Higgs production cross-section (Menon +Morrissey 0903.3038)

Can be ameliorated with light (~60 GeV) neutralino (Carena et al, 1207.6330)

New results from lattice simulations suggest the window might be slightly larger than from 2-loop results:

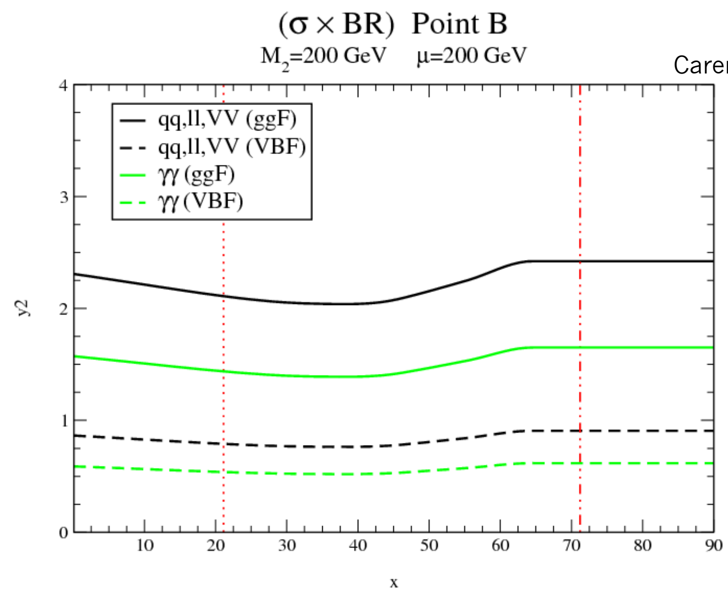


Laine et al, 1211.7344

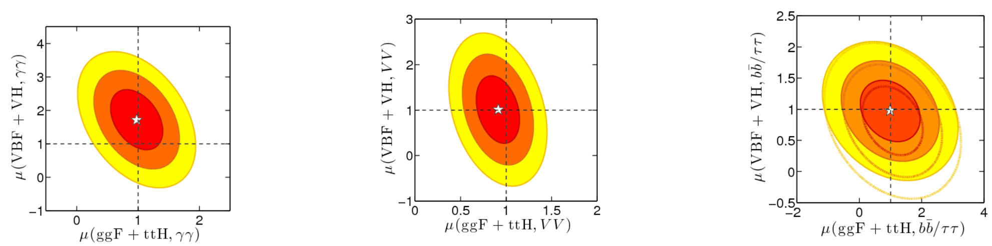


Constraints on MSSM EWB

Light stop → too large ggf production cross-section



Carena et al, 1207.6330

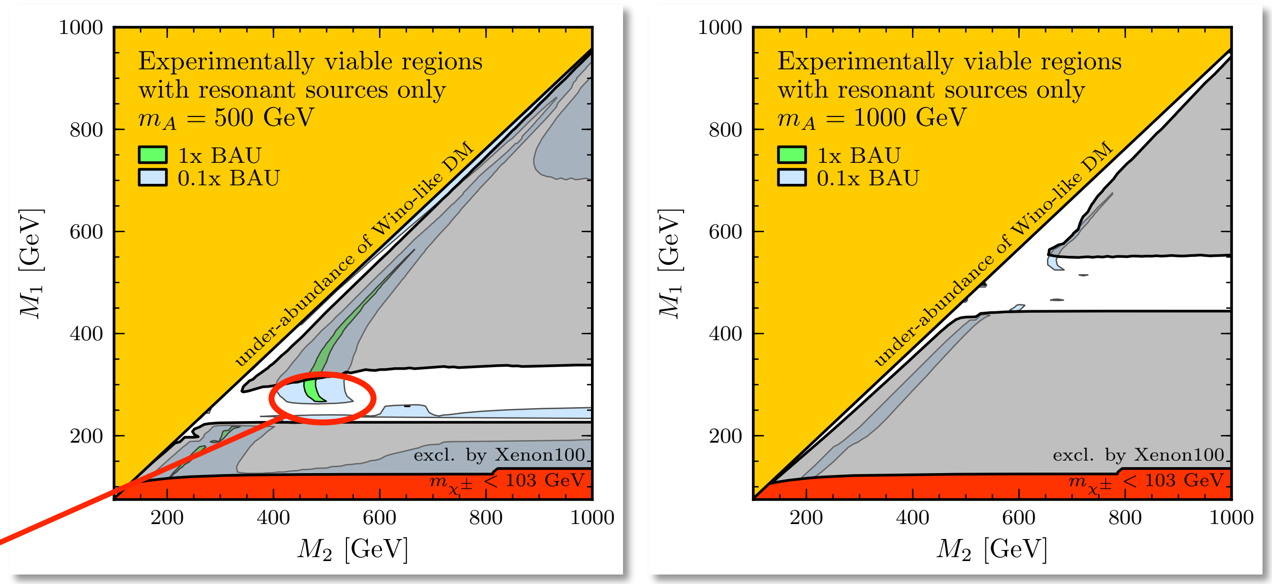


Global fit by Belanger et al,1306.2941

Constraints on MSSM EWB

Putting it all together:

Fix phase to evade EDM constraints (where possible)



successful EWB and a viable DM candidate, as long as:

$$200\text{ GeV} \lesssim m_{\tilde{\chi}_1} \lesssim 500\text{ GeV}$$

$$m_{\tilde{\chi}_1} \simeq m_A/2 \text{ with } m_A \lesssim 700\text{ GeV}$$ (within 20%)

All other neutralinos/charginos within a factor of 2 of $m_{\tilde{\chi}_1}$

*Also verified that non-resonant (resummed) sources do not open up additional parameter space