Electroweak Baryogenesis

in the Next-to-Minimal Supersymmetric Standard Model

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Contents

01 Model

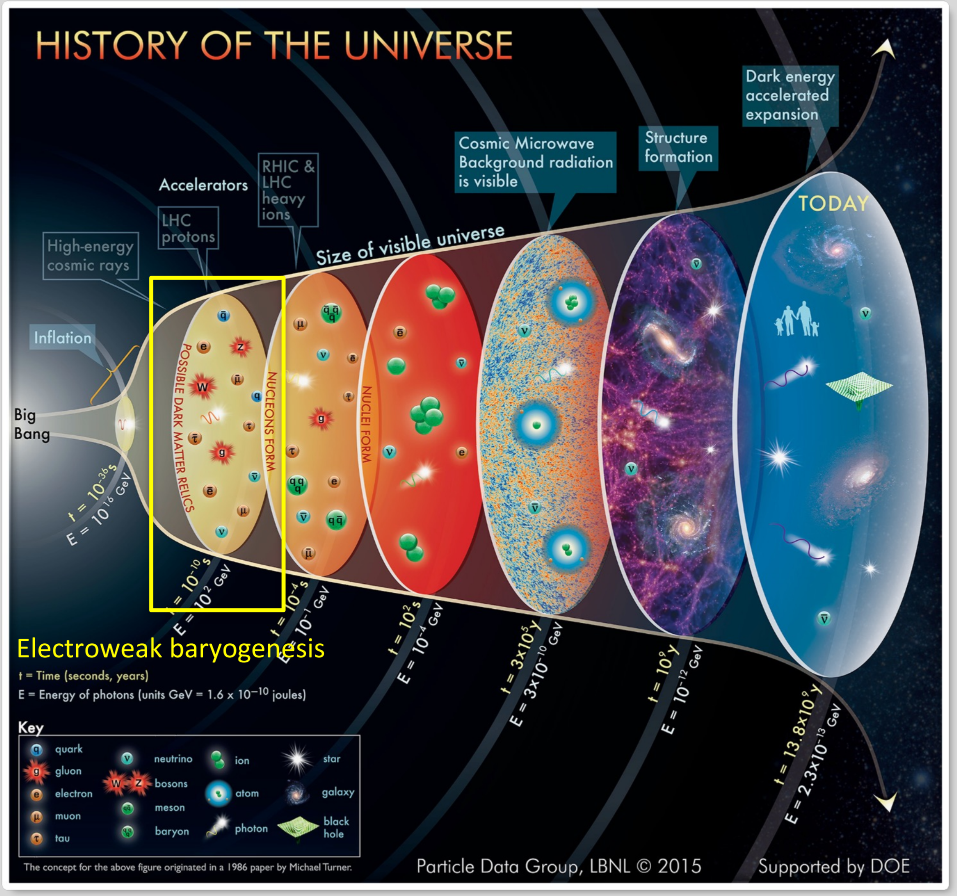
- Next-to-Minimal SUSY
- CP violation

02 Method

- VEV-insertion approximation
- Quantum transport equation

03 Results

- Baryon asymmetry
- Electric dipole moment



Credit: Particle Data Group at Lawrence Berkeley National Lab

Next-to-Minimal SUSY

NMSSM: $W^{\mathrm{NMSSM}} = W^{\mathrm{MSSM}} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \frac{1}{2}\beta S^2 + \alpha S$

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Phase Invariants	
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Electron EDM	
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$\tilde{\chi}^\pm$	$\Phi_1, \phi_0, \phi_2, \phi_9$
γH	$\Phi_{1,3,4}, \phi_0, \phi_0', \phi_{1\cdots 9}$
WW	$\Phi_1, \phi_0, \phi_2, \phi_3, \phi_5, \phi_9$
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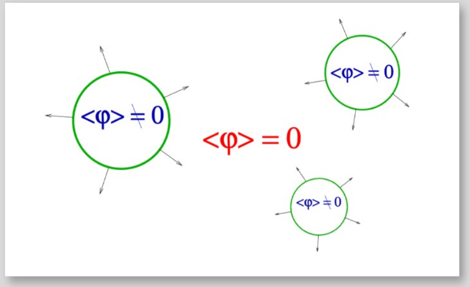
ZH	$\Phi_1, \phi_0, \phi_0', \phi_{2\cdots 9}$

VEV Insertion Approximation



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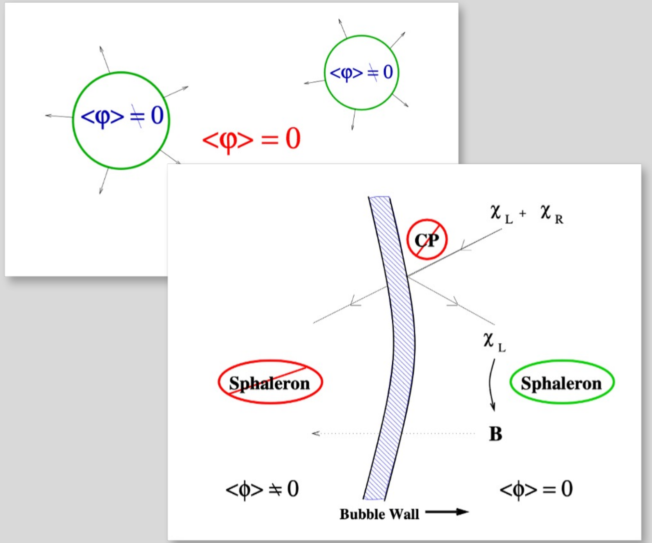

Credit: David E. Morrissey1, Michael J. Ramsey-Musolf, hep-ph/1206.2942

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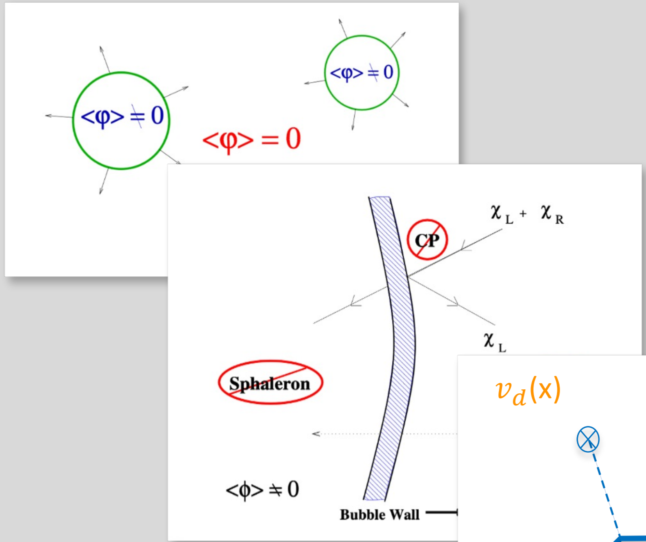
$$\mathcal{L} = -\frac{|\lambda|}{\sqrt{2}}\bar{\psi}_{\tilde{H}}\left(v_d e^{i\theta_R}\hat{P}_R - v_u e^{i\theta_L}\hat{P}_L\right)\psi_{\tilde{S}} + \text{h.c.}$$



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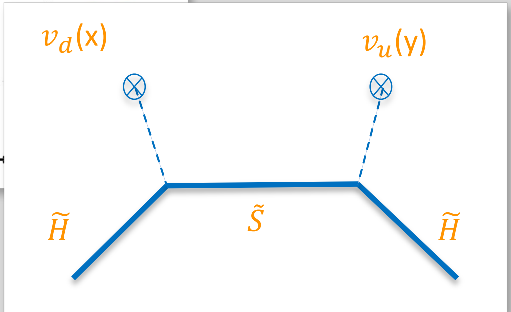

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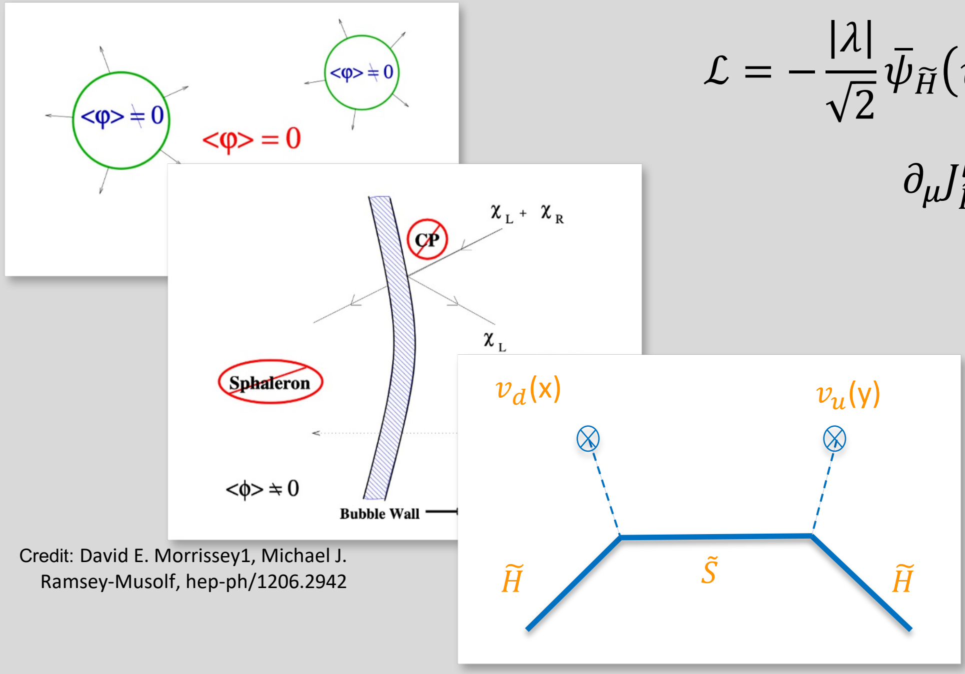

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$\Gamma^\pm$ relaxation rates

$\mu_{\tilde{H}}, \mu_{\tilde{S}}$ chemical potentials ($n_i = \frac{k_i T^2}{6}\mu_i$)

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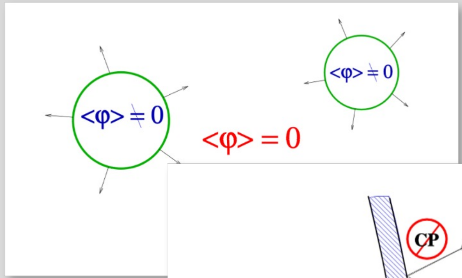

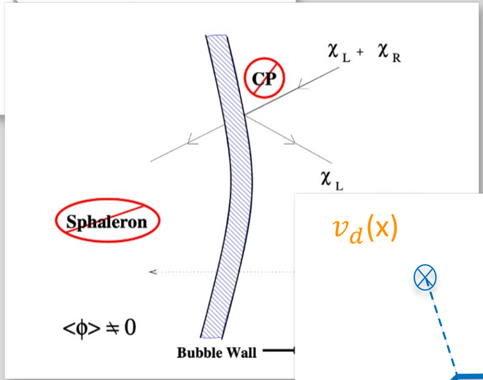

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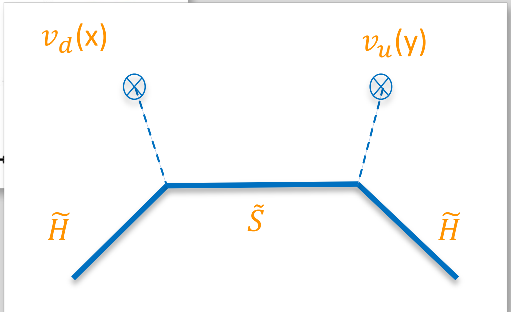

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$$S^{\text{CPV}} \propto |\lambda|^2 v^2 \Delta\beta \sin\phi_{\text{CPV}} \times F(M_{\tilde{H}}, M_{\tilde{S}})$$

$\beta \equiv \tan(v_u/v_d)$

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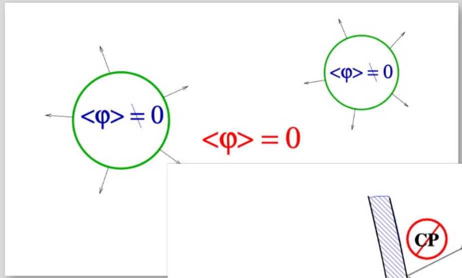

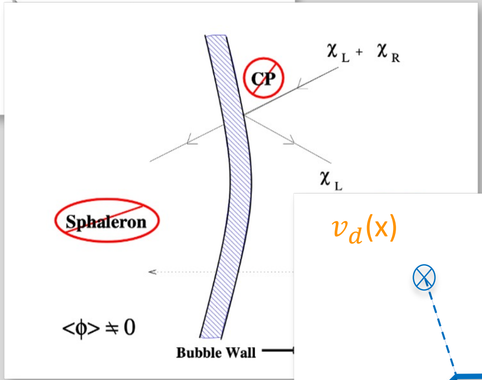

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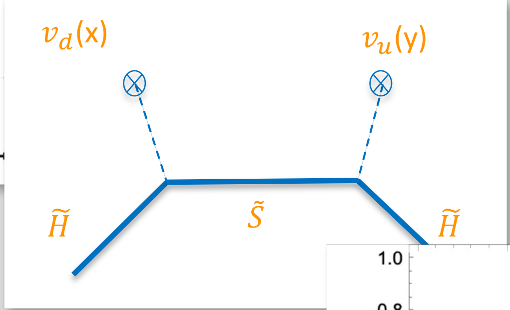

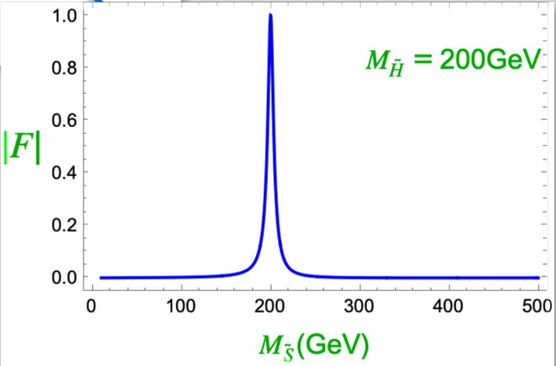

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Resonance behavior near mass degeneracy

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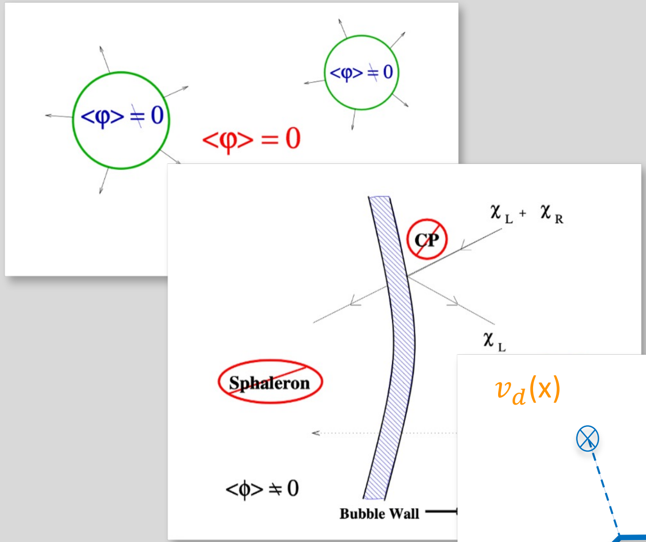

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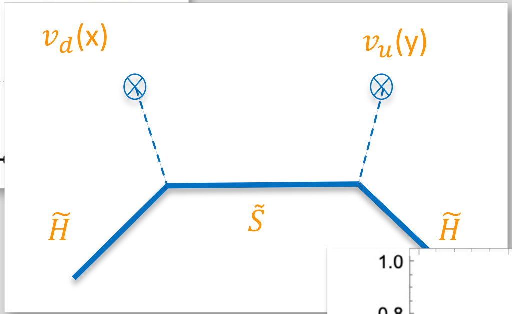

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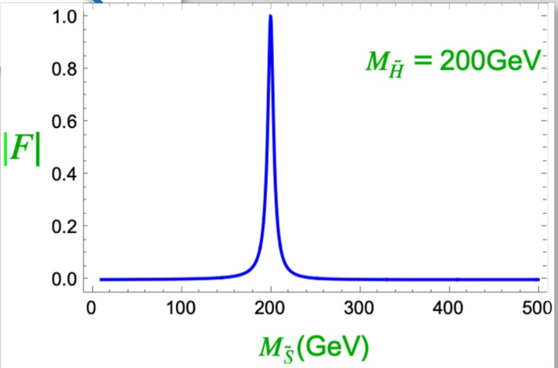
$\phi_{\text{CPV}} = \theta_R - \theta_L = \phi_9 - \phi_2 - \phi_5$

Higgsino is massless in unbroken space!

Add another term to $\mathcal{L}^{\text{NMSSM}}_{\text{soft}}$: $-\mu' \tilde{H}_u \tilde{H}_d$



Resonance behavior near mass degeneracy

Quantum Transport Equation

16 coupled equations for 16 distinct species of particles!

$$t, b, q, u, d, q_{1,2}, \tilde{t}, \tilde{b}, \tilde{q}, \tilde{u}, \tilde{d}, \tilde{q}_{1,2}, H_u, H_d, \widetilde{H}, S$$

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$$\begin{aligned}\partial_\mu J^\mu_{\widetilde{H}} = &-(\Gamma_{\widetilde{H}\widetilde{W}} + \Gamma_{\widetilde{H}\widetilde{B}} + \Gamma_{\widetilde{H}\tilde{S}})\mu_{\widetilde{H}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\widetilde{\mathrm{W}}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\widetilde{\mathrm{B}}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\tilde{\mathrm{S}}} \\ &-(\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}H_u} + \Gamma_{\widetilde{\mathrm{H}}\tilde{\mathrm{S}}\mathrm{H_u}})(\mu_{\widetilde{H}} - \mu_{H_u}) - (\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}\mathrm{H_d}} + \Gamma_{\widetilde{\mathrm{H}}\tilde{\mathrm{S}}\mathrm{H_d}})(\mu_{\widetilde{H}} + \mu_{H_d}) \\ &-\Gamma^Y_{t\tilde{\mathrm{q}}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_{\tilde{\mathrm{q}}} - \mu_t) - \Gamma^Y_{\tilde{\mathrm{t}}\mathrm{q}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_q - \mu_{\tilde{\mathrm{t}}})\end{aligned}$$

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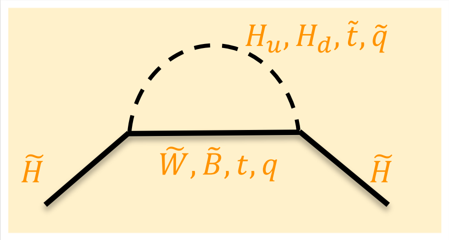
$$-(\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}H_u} + \Gamma_{\widetilde{\mathrm{H}}\tilde{\mathrm{S}}\mathrm{H_u}})(\mu_{\widetilde{H}} - \mu_{H_u}) - (\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}\mathrm{H_d}} + \Gamma_{\widetilde{\mathrm{H}}\tilde{\mathrm{S}}\mathrm{H_d}})(\mu_{\widetilde{H}} + \mu_{H_d})$$
$$-\Gamma^Y_{t\tilde{\mathrm{q}}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_{\tilde{\mathrm{q}}} - \mu_t) - \Gamma^Y_{\tilde{\mathrm{t}}\mathrm{q}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_q - \mu_{\tilde{\mathrm{t}}})$$



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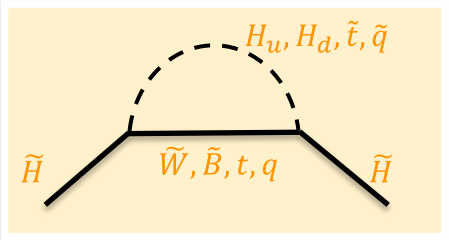
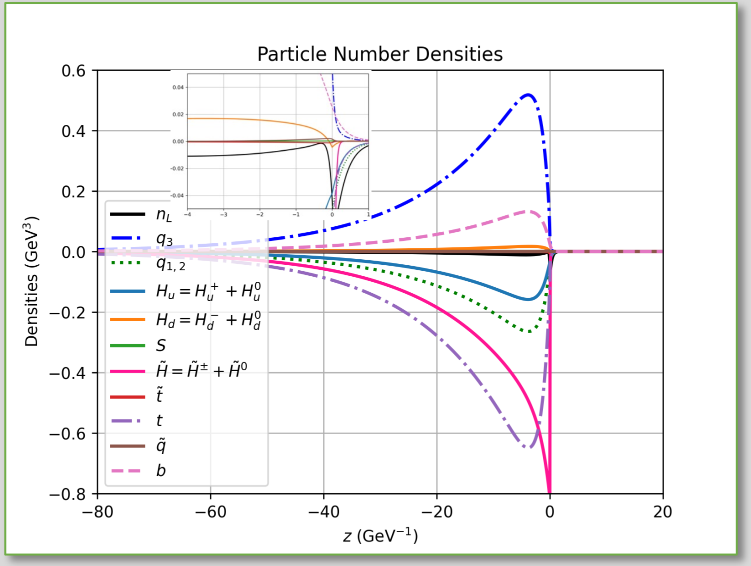
$$\begin{aligned}\partial_\mu J^\mu_{\widetilde{H}} = &-(\Gamma_{\widetilde{H}\widetilde{W}} + \Gamma_{\widetilde{H}\widetilde{B}} + \Gamma_{\widetilde{H}\widetilde{S}})\mu_{\widetilde{H}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\widetilde{\mathrm{W}}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\widetilde{\mathrm{B}}} + S^{\mathrm{CPV}}_{\widetilde{\mathrm{H}}\widetilde{\mathrm{S}}} \\ &-(\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}H_u} + \Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{S}}\mathrm{H_u}})(\mu_{\widetilde{H}} - \mu_{H_u}) - (\Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{V}}\mathrm{H_d}} + \Gamma_{\widetilde{\mathrm{H}}\widetilde{\mathrm{S}}\mathrm{H_d}})(\mu_{\widetilde{H}} + \mu_{H_d}) \\ &-\Gamma^Y_{t\tilde{\mathrm{q}}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_{\tilde{\mathrm{q}}} - \mu_t) - \Gamma^Y_{\tilde{\mathrm{t}}\mathrm{q}\widetilde{\mathrm{H}}}(\mu_{\widetilde{H}} + \mu_q - \mu_{\tilde{\mathrm{t}}})\end{aligned}$$





Quantum Transport Equation

16 coupled equations for 16 distinct species of particles!

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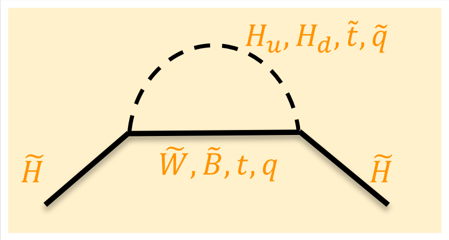
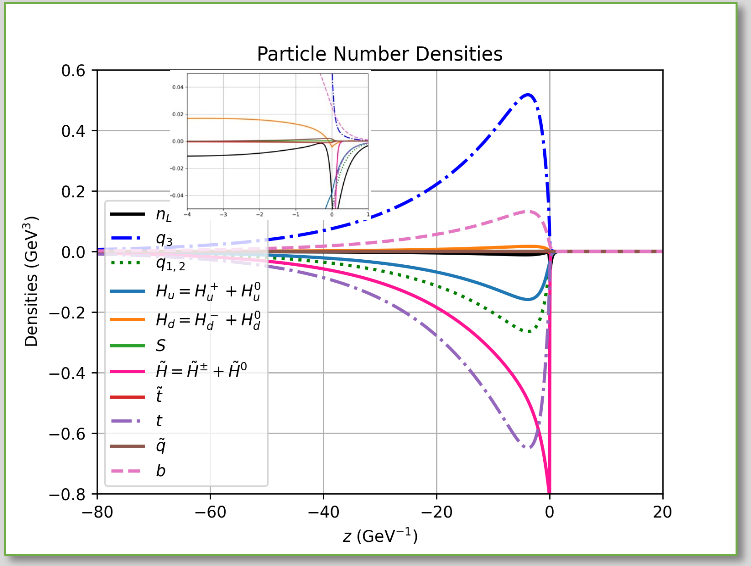
$$\partial_\mu J^\mu_{\tilde{H}} = -(\Gamma_{\tilde{H}\tilde{W}} + \Gamma_{\tilde{H}\tilde{B}} + \Gamma_{\tilde{H}\tilde{S}})\mu_{\tilde{H}} + S^{\mathrm{CPV}}_{\tilde{H}\tilde{W}} + S^{\mathrm{CPV}}_{\tilde{H}\tilde{B}} + S^{\mathrm{CPV}}_{\tilde{H}\tilde{S}}$$
$$-(\Gamma_{\tilde{H}\tilde{V}H_u} + \Gamma_{\tilde{H}\tilde{S}H_u})(\mu_{\tilde{H}} - \mu_{H_u}) - (\Gamma_{\tilde{H}\tilde{V}H_d} + \Gamma_{\tilde{H}\tilde{S}H_d})(\mu_{\tilde{H}} + \mu_{H_d})$$
$$-\Gamma^Y_{t\tilde{q}\tilde{H}}(\mu_{\tilde{H}} + \mu_{\tilde{q}} - \mu_t) - \Gamma^Y_{\tilde{t}q\tilde{H}}(\mu_{\tilde{H}} + \mu_q - \mu_{\tilde{t}})$$





The baryon asymmetry:

$$n_B = -3\frac{\Gamma_{\mathrm{ws}}}{v_{\mathrm{w}}}\int_{-\infty}^{0} dz\ n_{\mathrm{left}} e^{\frac{15}{4}\frac{\Gamma_{\mathrm{ws}}}{v_{\mathrm{w}}} z}$$

- v_{w}: wall velocity
- Γ_{ws}: weak sphaleron rate
- $n_{\mathrm{left}} = q + q_1 + q_2$

Electric Dipole Moment

EDM is the most powerful probe to CP violation! It puts stringent limit on every phase that is relevant.

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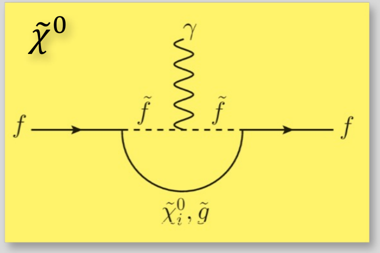

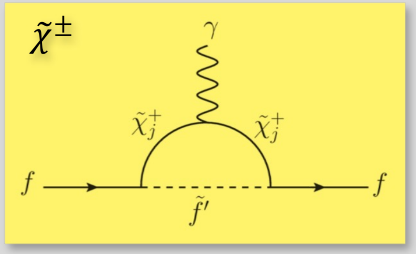

Normally suppressed by heavy sfermions.

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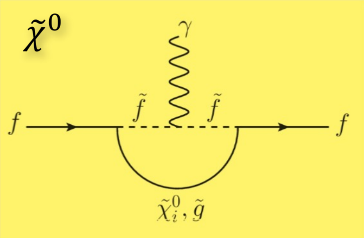

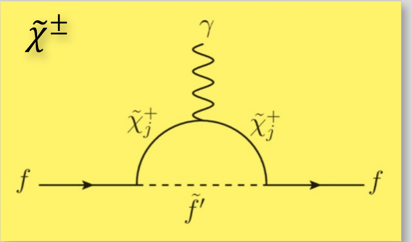

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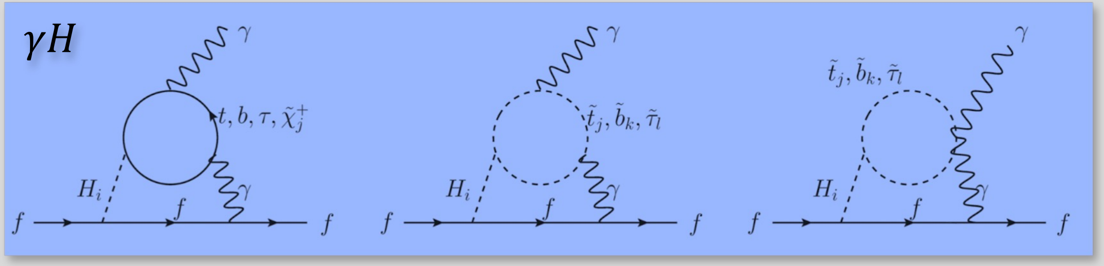

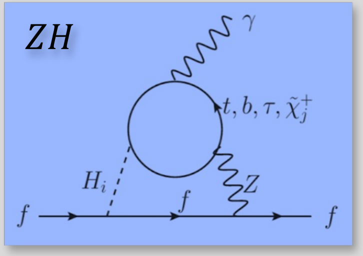

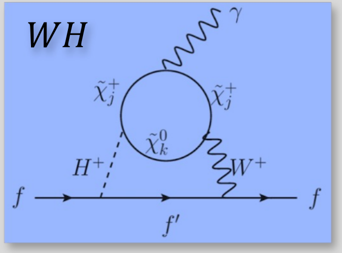

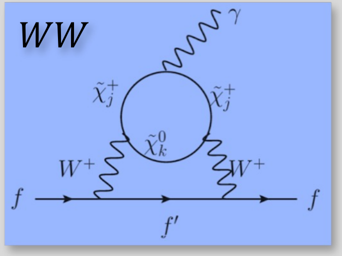

Barr-Zee diagram, comparable to or even dominant over one-loop contributions.

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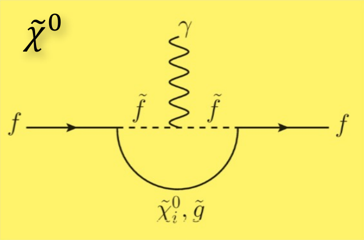
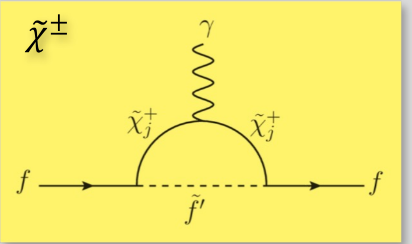
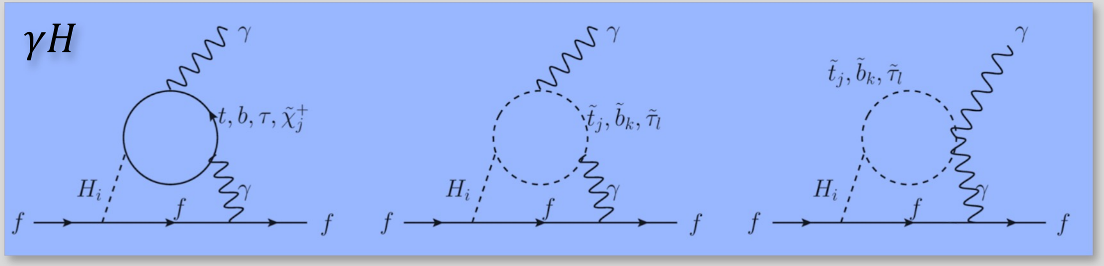
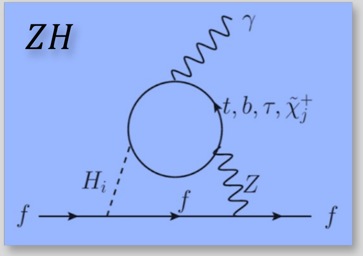


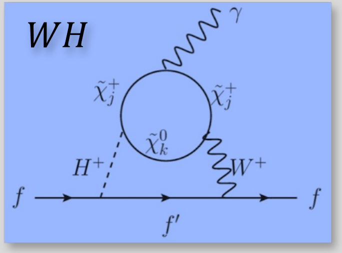


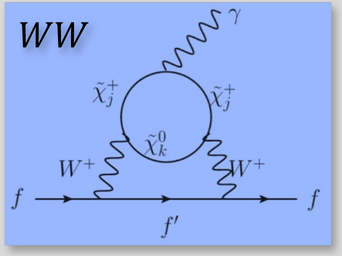
Normally suppressed by heavy sfermions.

CP violating phase invariants enter at vertices of each diagram.









Barr-Zee diagram, comparable to or even dominant over one-loop contributions.

Preliminary Results

EWBG Driven by	Singlino($\tilde{H} - \tilde{S}$)
$M_{\tilde{H}^0}, M_{\tilde{H}^\pm}$	200
$M_{\tilde{S}}$	200
$(M_{\tilde{B}}, M_{\tilde{W}})$	(400, 800)
(M_{H_u}, M_{H_d}, M_S)	(341,535,455)
$(m_{h^0}, m_{A^0}, m_{H^+})$	(110, 569, 663)
$(m_{\tilde{\chi}^0}, m_{\tilde{\chi}^\pm})$	(45, 311)
Single phase EWBG & EDM	
$\|\sin(\Phi_1, \Phi_3, \Phi_4)\|$	$> (\varnothing, \varnothing, \varnothing)$
$\|\sin(\Phi_1, \Phi_3, \Phi_4)\|$	$< (0.002, 1, 1)$
$\|\sin(\phi_0, \phi_0', \phi_1)\|$	$> (\varnothing, \varnothing, \varnothing)$
$\|\sin(\phi_0, \phi_0', \phi_1)\|$	$< (0.002, 0.094, 1)$
$\|\sin(\phi_2, \phi_3, \phi_4)\|$	$> (0.004, \varnothing, 0.374)$
$\|\sin(\phi_2, \phi_3, \phi_4)\|$	$< (0.005, 0.044, 0.021)$
$\|\sin(\phi_5, \phi_6, \phi_9)\|$	$> (0.004, \varnothing, 0.004)$
$\|\sin(\phi_5, \phi_6, \phi_9)\|$	$< (0.023, 0.086, 0.003)$

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Baryogenesis is relatively insensitive to the phases involved in interactions of thermally suppressed particles.

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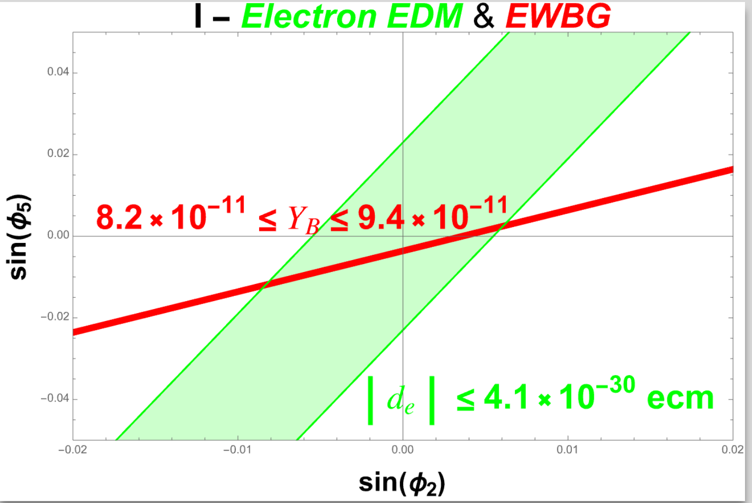

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$\lvert\sin(\phi_0, \phi_0', \phi_1)\rvert$	$> (\varnothing, \varnothing, \varnothing)$
$\lvert\sin(\phi_0, \phi_0', \phi_1)\rvert$	$< (0.002, 0.094, 1)$
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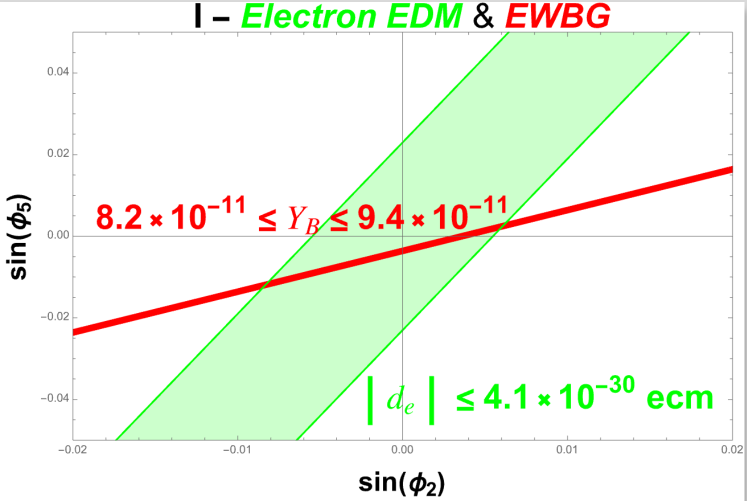

Baryogenesis is relatively insensitive to the phases involved in interactions of thermally suppressed particles.

Electron EDM itself does not preclude EWBG in NMSSM.

Summary

- NMSSM can generate enough CP violation to explain the BAU.
- It can be consistent with the current electron EDM search limit.
- EDMs of other particles(e.g. neutron) will introduce further constraints on the parameter space.

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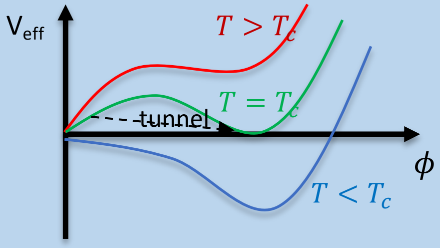
Thanks for listening!

Backup: MSSM

SUSY: $$W^{\mathrm{MSSM}} = \bar{u}\mathbf{y_u}QH_u - \bar{d}\mathbf{y_d}QH_d - \bar{e}\mathbf{y_e}LH_d + \mu H_u H_d$$

First order phase transition not strong enough



μ problem

$$\Delta_\mu = \frac{\partial \ln v^2}{\partial \ln \mu} \sim \frac{2\mu^2}{m_Z^2} > \mathcal{O}(10^2)$$

Backup: VEV Insertion Approximation

Schwinger-Dyson Equation:

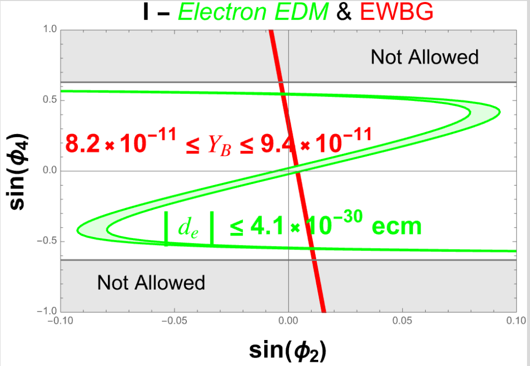
$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z \; \widetilde{G}^0(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}(z,y)$$

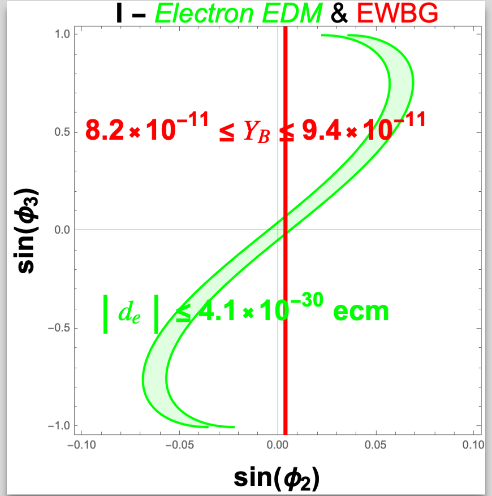
$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z \; \widetilde{G}(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}^0(z,y)$$

Continuity equation for Dirac fermions:

$$\frac{\partial n}{\partial X_0} + \boldsymbol{\nabla}\cdot\mathbf{j}(X) = -\int d^3z \int_{-\infty}^{X_0} dz_0 \; \mathrm{Tr}\Big[\Sigma^{>}(X,z)S^{<}(z,X) - S^{>}(X,z)\Sigma^{<}(z,X) + S^{<}(X,z)\Sigma^{>}(z,X) - \Sigma^{<}(X,z)S^{>}(z,X)\Big]$$

Backup: Preliminary Results





EWBG by	Neutralino$(\tilde{N}^0, \tilde{\chi}^\pm)$		Higgs(H_i)			Both
	Singlino$(\tilde{H}-\tilde{S})$	B&W$(\tilde{H}-\tilde{B}\,\&\,\tilde{H}-\tilde{W})$	Singlet(H_u-S)	Higgs(H_u-H_d)	Scalar(H_u-H_d-S)	All
$M_{\tilde{H}^0}, M_{\tilde{H}^\pm}$	200	200	600	600	600	200
$M_{\tilde{S}}$	200	400	400	400	400	200
$(M_{\tilde{B}}, M_{\tilde{W}})$	(400, 800)	(200, 200)	(400, 800)	(400, 800)	(400, 800)	(200, 200)
(M_{H_u}, M_{H_d}, M_S)	(341,535,455)	(351,549,597)	(189, 324, 204)	(185, 185, 508)	(193, 193, 209)	(201, 201, 208)
$(m_{h^0}, m_{A^0}, m_{H^+})$	(110, 569, 663)	(89, 617, 680)	(94, 317, 421)	(120, 275, 325)	(103, 195, 334)	(108, 169, 343)
$(m_{\tilde{\chi}^0}, m_{\tilde{\chi}^\pm})$	(45, 311)	(154, 163)	(394, 675)	(262, 673)	(394, 673)	(152, 161)
Constraints on CPV phases from EWBG and electron EDM						
$\lvert\sin(\Phi_1,\Phi_3,\Phi_4)\rvert$	$>(\varnothing,\varnothing,\varnothing)$	$>(0.006,\varnothing,\varnothing)$	$>(0.242,\varnothing,\varnothing)$	$>(0.299,\varnothing,\varnothing)$	$>(0.293,\varnothing,\varnothing)$	$>(0.019,\varnothing,\varnothing)$
$\lvert\sin(\Phi_1,\Phi_3,\Phi_4)\rvert$	$<(0.002,1,1)$	$<(0.001,1,1)$	$<(0.002,1,1)$	$<(0.003,1,1)$	$<(0.003,1,1)$	$<(0.001,1,1)$
$\lvert\sin(\phi_0,\phi_0',\phi_1)\rvert$	$>(\varnothing,\varnothing,\varnothing)$	$>(0.005,\varnothing,\varnothing)$	$>(\varnothing,\varnothing,\varnothing)$	$>(0.259,\varnothing,\varnothing)$	$>(\varnothing,\varnothing,\varnothing)$	$>(0.017,\varnothing,\varnothing)$
$\lvert\sin(\phi_0,\phi_0',\phi_1)\rvert$	$<(0.002,0.094,1)$	$<(0.001,0.109,1)$	$<(0.001,0.006,1)$	$<(0.003,0.422,1)$	$<(0.002,0.016,1)$	$<(0.001,0.014,1)$
$\lvert\sin(\phi_2,\phi_3,\phi_4)\rvert$	$>(0.004,\varnothing,0.374)$	$>(\varnothing,\varnothing,0.417)$	$>(\varnothing,0.035,0.003)$	$>(\varnothing,0.100,0.010)$	$>(\varnothing,0.003,0.001)$	$>(0.007,0.040,0.011)$
$\lvert\sin(\phi_2,\phi_3,\phi_4)\rvert$	$<(0.005,0.044,0.021)$	$<(0.003,0.610,0.284)$	$<(0.008,0.008,0.001)$	$<(0.012,0.015,0.003)$	$<(0.011,0.004,0.001)$	$<(0.003,0.006,0.001)$
$\lvert\sin(\phi_5,\phi_6,\phi_9)\rvert$	$>(0.004,\varnothing,0.004)$	$>(0.312,\varnothing,0.005)$	$>(0.010,\varnothing,0.259)$	$>(0.012,\varnothing,0.319)$	$>(0.002,\varnothing,0.314)$	$>(0.006,\varnothing,0.013)$
$\lvert\sin(\phi_5,\phi_6,\phi_9)\rvert$	$<(0.023,0.086,0.003)$	$<(0.203,0.101,0.001)$	$<(0.001,0.006,0.003)$	$<(0.003,0.110,0.004)$	$<(0.001,0.012,0.004)$	$<(0.003,0.014,0.002)$