Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Baryogenesis from a CP violating Higgs Sector II

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Work in progress with Satoru Inoue and Michael Ramsey-Musolf

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The CP Nature of the Higgs Boson, Amherst, MA

Outline

- Motivation
- The model
- Electron/Neutron EDM bounds
- Generation of the baryon asymmetry
- Conclusions

Motivation

Sakharov's conditions:

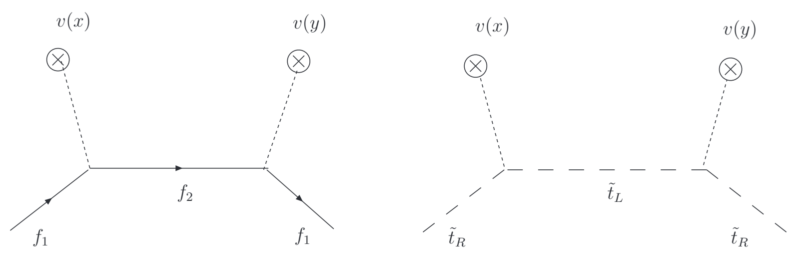
1. B violation
2. First order EW phase transition
3. C and CP violation

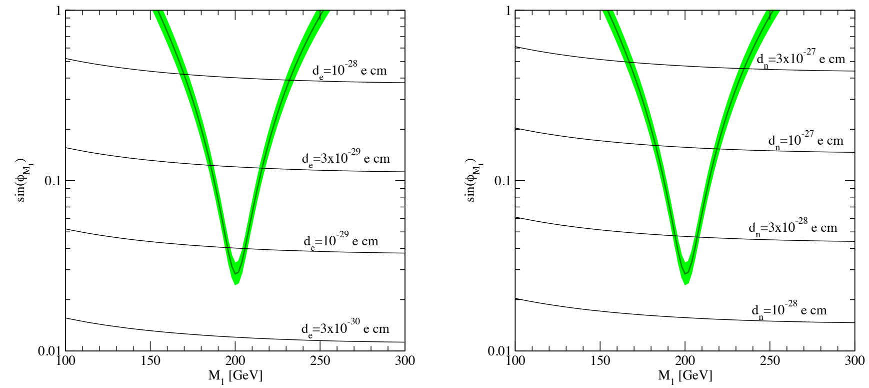
- Standard Model is a very successful effective theory
- Plenty of motivation to go beyond (Dark Matter, hierarchy problem, …)
- Standard Model is not sufficient to describe Baryon Asymmetry of the Universe (BAU)

Examples of successful EW Baryogenesis

Li,Profumo, Ramesy-Musolf, 2008-2010

- MSSM

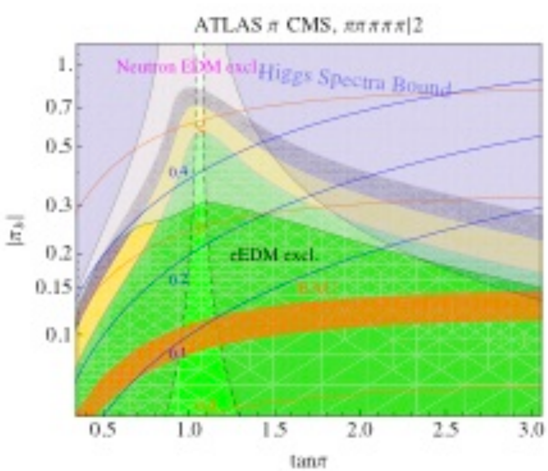




Bian, Liu, Shu, 2014

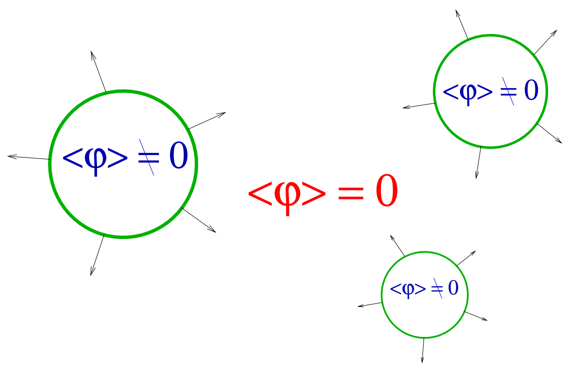
- 2HDM

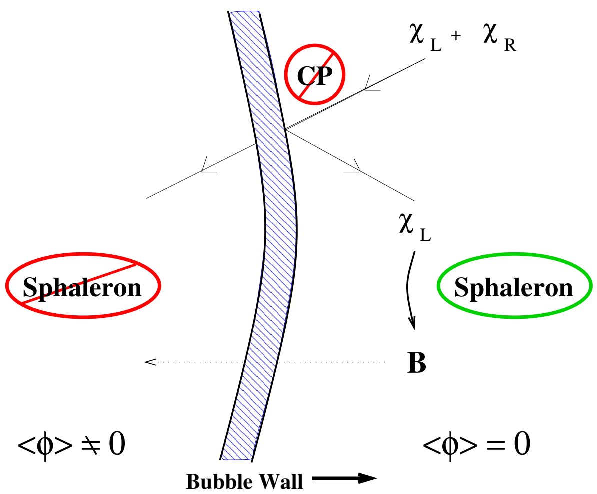
$$\tan\theta_t = -\frac{\cos\beta}{\cos\alpha}\ \tan\alpha_b$$



Electroweak baryogenesis

Morrissey, Ramsey-Musolf, 2012





- At the boundary of two phases the particle-antiparticle asymmetry is generated
- It diffuses into the symmetric phase and EW sphalerons transfer the left handed quark asymmetry into the net baryon asymmetry

$$n_B = -3\frac{\Gamma_{\rm ws}}{v_{\rm w}}\int_{-\infty}^{0} {\rm d}z\, n_{\rm left}(z)\, {\rm e}^{\frac{15}{4}\frac{\Gamma_{\rm ws}z}{v_{\rm w}}}$$

Huet, Nelson, 1995

Extended Higgs sectors

- With the discovery of the Higgs boson, it is plausible that the new physics is hiding in the extended Higgs sector
- Adding a real singlet to Standard Model modifies the SM scalar potential so that the 1st order PT can be achieved without upsetting existing collider bounds

Profumo, Ramsey-Musolf, Wainwright, Winslow, 2014

- Adding a real triplet to Standard Model provides a stable DM candidate, possibility for a two step phase transition

Perez, Patel, Ramsey-Musolf, 2008

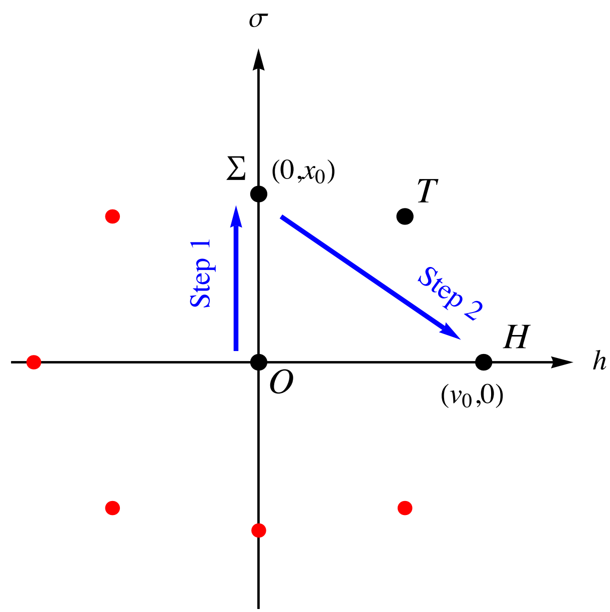
Patel, Ramsey-Musolf, 2012

Blinov, Kozaczuk, Morrissey, Tamarit, 2015

Phase transition in two steps?

- The first step of the phase transition is driven by the triplet acquiring VEV. Easy to obtain 1st order PT condition with heavier SM Higgs mass
- In the first step because the triplet carries $SU(2)_L$ charge the B+L violating monopole interactions inside the $\Sigma-$ bubbles are suppressed
- In the second step the net baryon asymmetry generated during the first step survives due to (sufficiently) strong 1st order PT

Patel, Ramsey-Musolf, 2012



Open question: explicit model realization with CPV and BAU evaluation during the first step

Our Goal

- Our goal is to perform an explicit calculation of the BAU generated during the first step of a 2-step phase transition
- The choice for the model is 2HDM+real triplet+real singlet
- Can we get BAU consistent with the EDMs?

$$\Delta V(H_1, H_2, \Sigma) = -\frac{\mu_\Sigma^2}{2}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{b_4}{4}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right)^2 + \left[\frac{1}{2}\, a_{2\Sigma}\, H_1^\dagger H_2 \left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{1}{2} a_{2S} H_1^\dagger H_2 S^2 + \mathrm{h.c.}\right]$$

$a_{2\Sigma}, a_{2S}$ are complex

The Model

$$V(H_1,H_2) = \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2$$
$$+\lambda_3\left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4\left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right)$$
$$+\frac{1}{2}\left[\lambda_5\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] - \frac{1}{2}\Big\{m_{11}^2\left(H_1^\dagger H_1\right)$$
$$+\left[m_{12}^2\left(H_1^\dagger H_2\right) + \text{h.c.}\right] + m_{22}^2\left(H_2^\dagger H_2\right)\Big\}.$$

$$H_i = \begin{pmatrix} H_i^+ \\ \frac{v_i + H_i^0 + iA_i^0}{\sqrt{2}} \end{pmatrix}, \qquad \text{where} \quad i = 1, 2\,.$$

$$\tan\beta \equiv v_2/v_1$$

$$\Delta V(H_1,H_2,\Sigma) = -\frac{\mu_\Sigma^2}{2}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{b_4}{4}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right)^2$$
$$+\left[\frac{1}{2}\,a_{2\Sigma}\,H_1^\dagger H_2\left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{1}{2}a_{2S}H_1^\dagger H_2 S^2 + \text{h.c.}\right]$$

Rephasing invariant CPV phases:

$$\delta_1 = \arg\left[\lambda_5^*\,\left(m_{12}^2\right)^2\right],$$
$$\delta_2 = \arg\left[\lambda_5^*\left(m_{12}^2\right)v_1 v_2^*\right],$$
$$\delta_3 = \arg\left[\lambda_5^*\,\left(a_{2\Sigma}\right)^2\right],$$
$$\delta_4 = \arg\left[\lambda_5^*\,\left(a_{2S}\right)^2\right].$$

We have two additional complex phases compared to 2HDM
We assume at zero temperature the VEVs of triplet and singlet are zero
Vacuum stability conditions are identical to the 2HDM case (relate first two phases)

Mass spectrum

Charged Higgses

$$\phi_1^+ = -s_\beta H_1^+ + c_\beta H_2^+ ,$$
$$\phi_2^+ = \Sigma^+ ,$$

$$M^2_{\phi_i} = \begin{bmatrix} m^2_{H^+} & 0 \\ 0 & m^2_{\Sigma^+} \end{bmatrix}$$

$$m^2_{H^+} = \frac{1}{2}\left(2\nu - \lambda_4 - \mathrm{Re}\,\lambda_5\right) v^2 , \quad \text{where} \quad \nu \equiv \frac{\mathrm{Re}\, m^2_{12}}{2 v^2 c_\beta s_\beta}$$
$$m^2_{\Sigma^+} = -\mu^2_\Sigma + \mathrm{Re}\, a_2\, v^2\, c_\beta s_\beta \,. \qquad (13)$$

Neutral Higgses

$$H_1^0, H_2^0, (A^0 \equiv -\sin\beta A_1^0 + \cos\beta A_2^0), \Sigma^0 \qquad m_{\Sigma^0} \equiv m_{\Sigma^+}$$

$$M^2_{\text{neutral}} = v^2 \begin{pmatrix} \lambda_1 c_\beta^2 + \nu s_\beta^2 & (\lambda_{345} - \nu) s_\beta c_\beta & -\frac{1}{2} s_\beta\, \mathrm{Im}\,\lambda_5 & 0 \\ (\lambda_{345} - \nu) s_\beta c_\beta & \lambda_2 s_\beta^2 + \nu c_\beta^2 & -\frac{1}{2} c_\beta\, \mathrm{Im}\,\lambda_5 & 0 \\ -\frac{1}{2} s_\beta \mathrm{Im}\,\lambda_5 & -\frac{1}{2}\, c_\beta \mathrm{Im}\,\lambda_5 & \nu - \mathrm{Re}\,\lambda_5 & 0 \\ 0 & 0 & 0 & \frac{m^2_{\Sigma^0}}{v^2} \end{pmatrix} ,$$

No mixing among the new scalars (triplet and singlet) and the 2 Higgs doublets

Mass matrices block diagonal, the top 3x3 block of the neutral matrix identical to 2HDM

Inoue, Ramsey-Musolf, Zhang, 2014

Parameters in the potential vs phenomenological parameters

Parameters in the potential	Phenomenological parameters
$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \mathrm{Re}\lambda_5, \mathrm{Im}\lambda_5$	$v, x_0, \xi, \tan\beta, \nu, \mathrm{Re}\, a_{2\Sigma}, \mathrm{Re}\, a_{2S}$
$m_{11}^2, m_{22}^2, \mathrm{Re}m_{12}^2, \mathrm{Im}m_{12}^2$	$\alpha, \alpha_b, \delta_\Sigma, \delta_S$
$\mathrm{Re}a_{2\Sigma}, \mathrm{Im}a_{2\Sigma}, \mu_\Sigma, b_4, \mathrm{Re}a_{2S}, \mathrm{Im}a_{2S}$	$m_{H^+}, m_{h_1}, m_{h_2}, m_{h_3}, m_\Sigma, b_4$

$$\delta_\Sigma = \arg\left[a_{2\Sigma}^*\, v_1 v_2^*\right] = \delta_2 - \frac{\delta_1 + \delta_3}{2},$$

$$\delta_S = \arg\left[a_{2S}^*\, v_1 v_2^*\right] = \delta_2 - \frac{\delta_1 + \delta_4}{2}.$$

Compared to the 2HDM model two additional CPV phases appear

Technical simplification for BAU analysis

Cirigliano, Lee, Ramsey-Musolf, Tulin, 2006

- When the $m_{12}^2 \neq 0$ coupling is present it leads to flavor oscillations when the triplet and singlet undergo phase transition in the early universe
- To avoid this technical difficulty we set

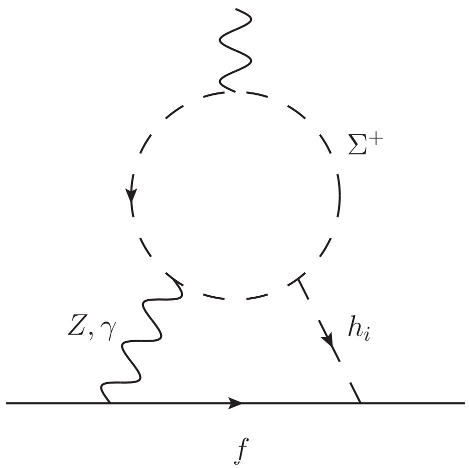
$m_{12}^2 = 0$ which removes CPV from the 2HDM sector $(\alpha_b = \alpha_c = 0)$ and the only two possible phases are δ_Σ, δ_S

Thus, we work in the exact Z_2 symmetry limit of 2HDM

We also will assume everywhere the alignment limit $\alpha = \beta - \pi/2$

Electron EDM bound

Bar-Zee graph



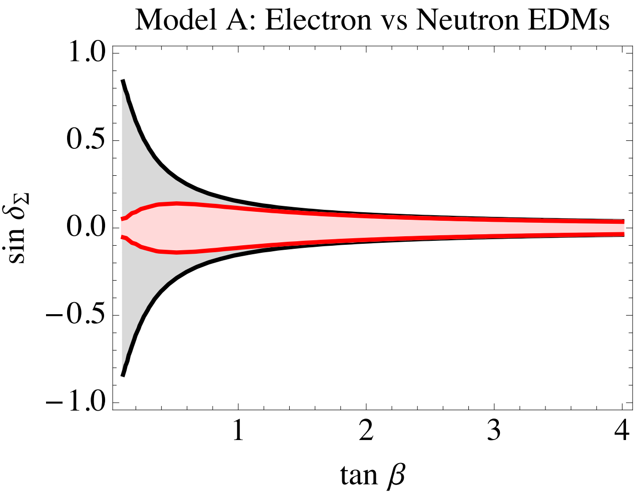
$$\delta_f \equiv -\frac{d_f}{2m_f e}$$ (dimensionless EDM)

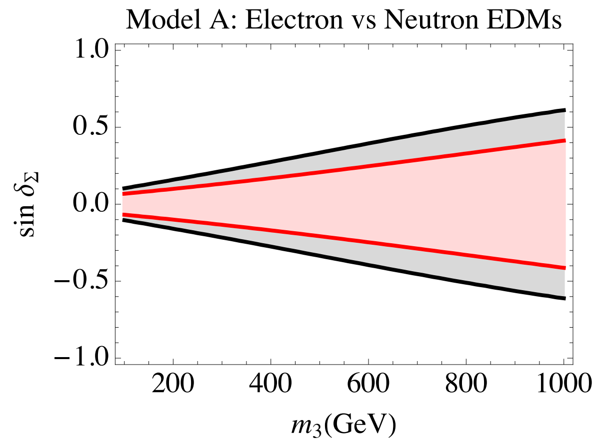
$$\delta_e = \sin\delta_\Sigma \tan\beta\, F(m_\Sigma, m_{h_3})$$

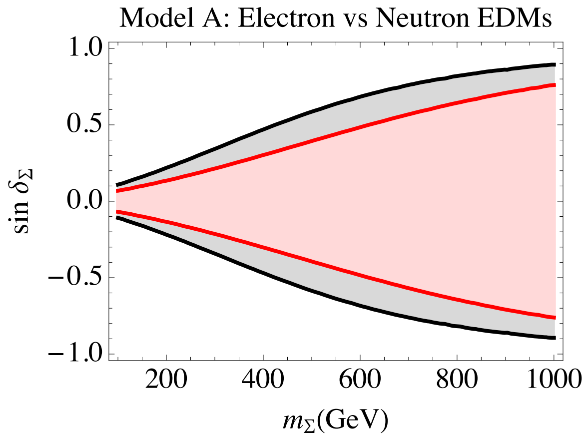
$$|d_e| < 8.7 \times 10^{-29}\,\mathrm{ecm}$$ at 90% confidence level

- In the exact Z_2 limit of our theory EDM is sensitive only to the phase δ_Σ and not δ_S
- Amount of BAU as you will see depends on the combination $\delta_\Sigma - \delta_S$

EDM exclusion results







Parameter dependence of electron EDM in the exact Z_2 limit

$$\delta_e = \sin\delta_\Sigma \tan\beta\, F(m_\Sigma, m_{h_3})$$

- Electron EDM bound $|d_e| < 8.7 \times 10^{-29}\,\mathrm{ecm}$
- Neutron EDM bound (100xcurrent sensitivity) $|d_n| < 2.9 \times 10^{-28}\,\mathrm{ecm}$

Generation of the baryon asymmetry

Theoretical framework

- We assume relying on previous studies that the 1st order phase transition condition is satisfied Patel, Ramsey-Musolf, 2012 Blinov, Kozaczuk, Morrissey, Tamarit, 2015
- We use closed time path integral (CTP) approach to derive transport equations that describe the dynamics of the bubble nucleation during the EW phase transition
- For CPV source terms we use the VEV insertion approximation

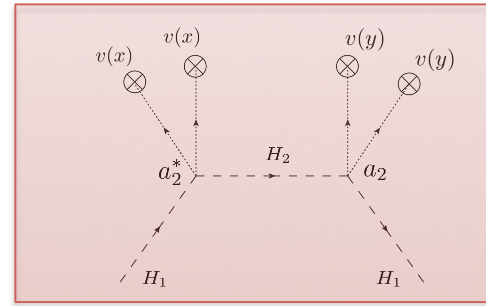
Coupled Boltzmann eqns

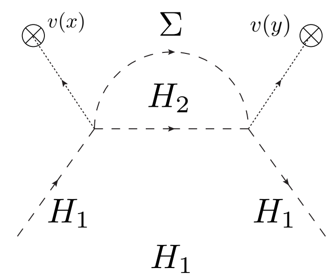
$$T = n_{t_R}$$

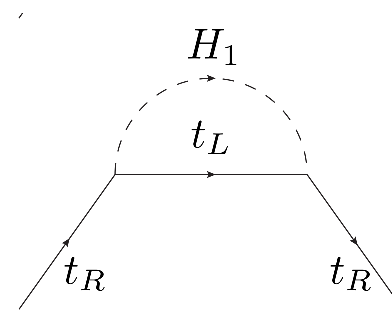
$$Q = n_{t_L} + n_{b_L}$$

$$H = n_{H_1^+} + n_{H_1^0} - n_{H_2^+} - n_{H_2^0}$$

$$h = n_{H_1^+} + n_{H_1^0} + n_{H_2^+} + n_{H_2^0}$$







$$\partial^\mu T_\mu = -\Gamma_Y\left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right) + \Gamma_Y\frac{h}{k_h} + \Gamma_{ss}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right),$$

$$\partial^\mu Q_\mu = -\Gamma_Y\left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) - \Gamma_Y\frac{h}{k_h} - 2\Gamma_{ss}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right),$$

$$\partial^\mu H_\mu = \Gamma_M^+\frac{h}{k_h} - \Gamma_M^-\frac{H}{k_H} - \Gamma_H\frac{H}{k_H} - \Gamma_Y\left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) - \Gamma_Y\frac{h}{k_h} + S_H^{CPV},$$

$$\partial^\mu h_\mu = -\Gamma_Y\left(\frac{H}{k_H} + \frac{Q}{k_Q} - \frac{T}{k_T}\right) - \Gamma_Y\frac{h}{k_h}.$$

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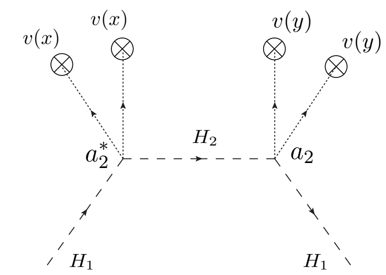
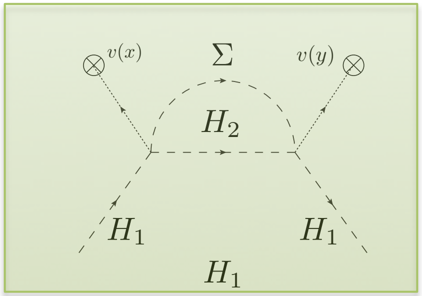
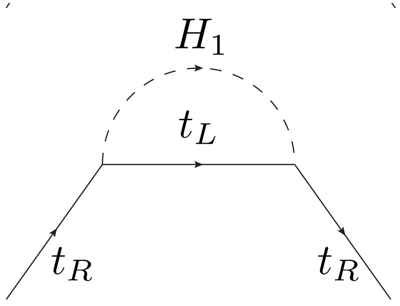
$$h = n_{H_1^+} + n_{H_1^0} + n_{H_2^+} + n_{H_2^0}$$

$$\Gamma_H \sim v(x)^2$$

$$\Delta V(H_1, H_2, \Sigma) = a_2 v\, H_1^\dagger H_2\, \sigma^0$$







$$\partial^\mu T_\mu = -\Gamma_Y \left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right) + \Gamma_Y \frac{h}{k_h} + \Gamma_{ss}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right),$$

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$$\partial^\mu H_\mu = \Gamma_M^+ \frac{h}{k_h} - \Gamma_M^- \frac{H}{k_H} - \Gamma_H \frac{H}{k_H} - \Gamma_Y \left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) - \Gamma_Y \frac{h}{k_h} + S_H^{CPV},$$

$$\partial^\mu h_\mu = -\Gamma_Y \left(\frac{H}{k_H} + \frac{Q}{k_Q} - \frac{T}{k_T}\right) - \Gamma_Y \frac{h}{k_h}.$$

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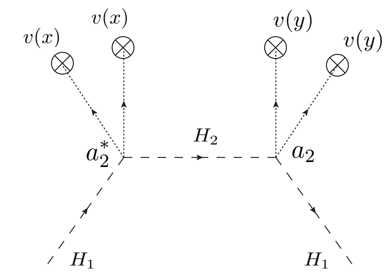

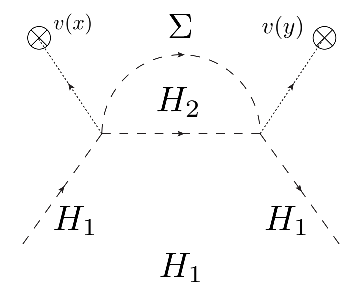

$$\partial^\mu T_\mu = -\Gamma_Y \left(\frac{T}{k_T} - \frac{Q}{k_Q} - \frac{H}{k_H}\right) + \Gamma_Y \frac{h}{k_h} + \Gamma_{ss}\left(\frac{2Q}{k_Q} - \frac{T}{k_T} + \frac{9(Q+T)}{k_B}\right),$$

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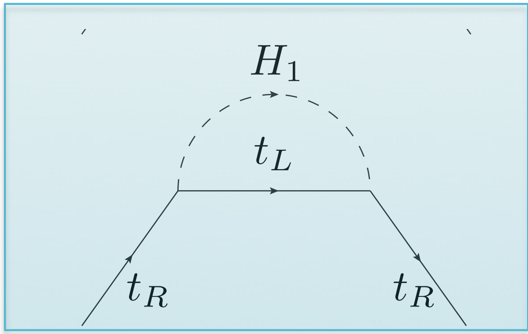
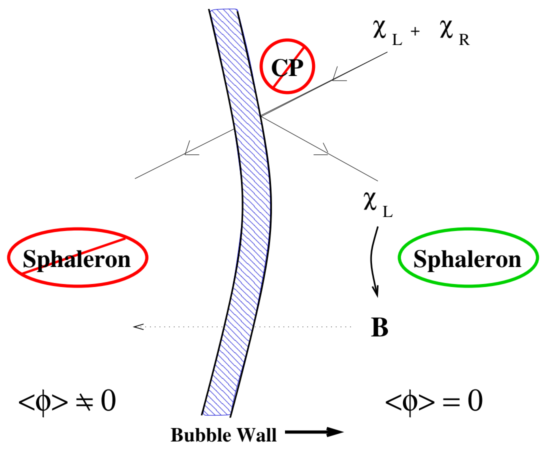
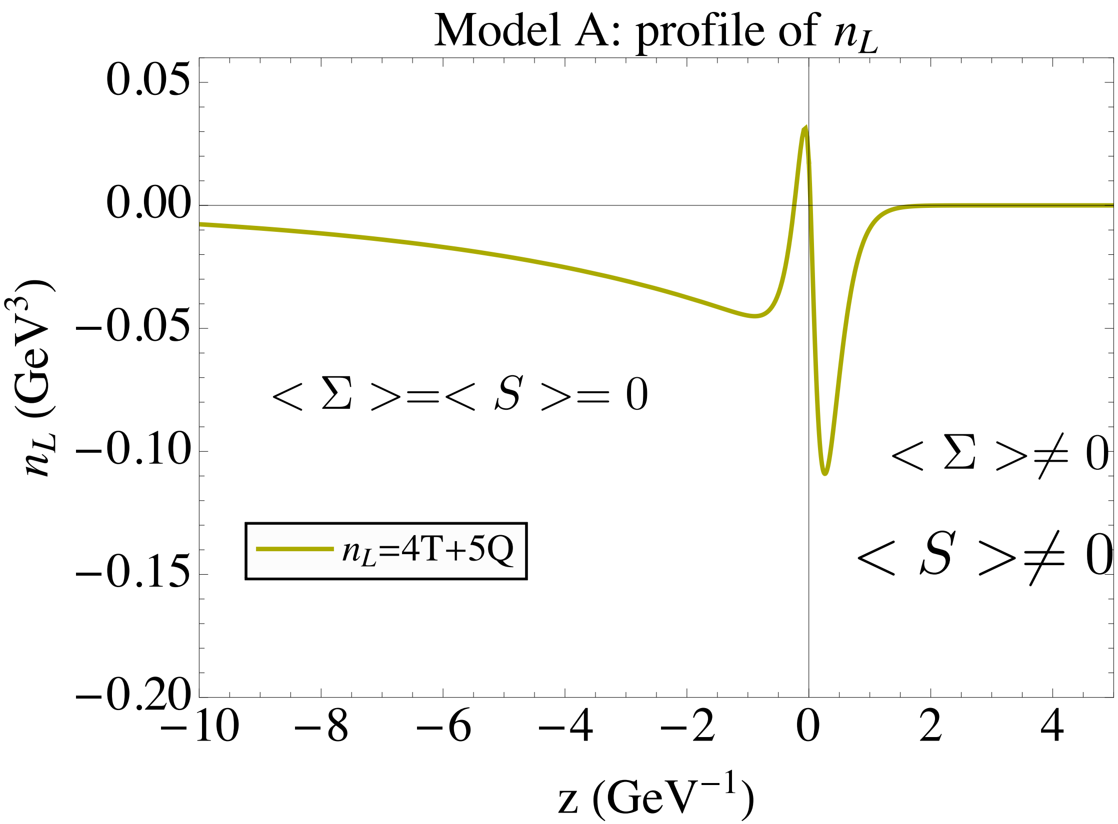
$$\partial^\mu H_\mu = \Gamma_M^+ \frac{h}{k_h} - \Gamma_M^- \frac{H}{k_H} - \Gamma_H \frac{H}{k_H} + \Gamma_Y \left(\frac{Q}{k_Q} - \frac{T}{k_T} + \frac{H}{k_H}\right) - \Gamma_Y \frac{h}{k_h} + S_H^{CPV},$$

$$\partial^\mu h_\mu = -\Gamma_Y \left(\frac{H}{k_H} + \frac{Q}{k_Q} - \frac{T}{k_T}\right) - \Gamma_Y \frac{h}{k_h}.$$



Left handed quark density profile





$$n_B = -3\frac{\Gamma_{\rm ws}}{v_{\rm w}}\int_{-\infty}^{0} {\rm d}z\, n_{\rm left}(z)\, {\rm e}^{\frac{15}{4}\frac{\Gamma_{\rm ws} z}{v_{\rm w}}}$$

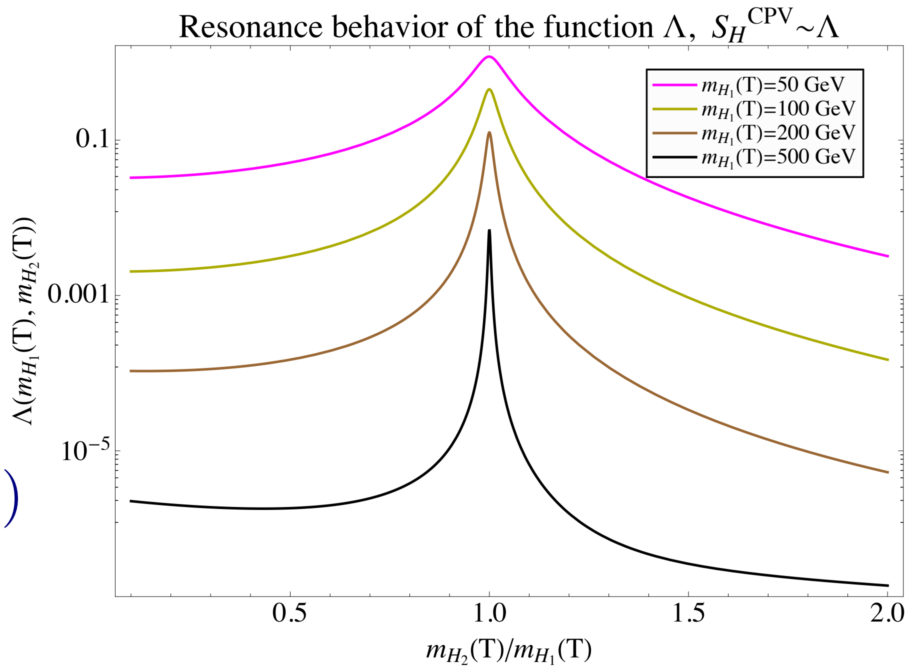
Resonant relaxation

CPV source

$$S_H^{\rm CPV}(x) = \frac{|a_{2\Sigma}a_{2S}|\sin(\delta_S-\delta_\Sigma)}{\pi^2}v_S(x)v_\Sigma(x) \times \left[v_S(x)\dot{v}_\Sigma(x)-\dot{v}_S(x)v_\Sigma(x)\right]\Lambda,$$

$$\Lambda = \int \frac{k^2{\rm d}k}{\omega_1\omega_2}{\rm Im}\left(\frac{n_B(\epsilon_1^*)-n_B(\epsilon_2)}{(\epsilon_1^*-\epsilon_2)^2}+\frac{n_B(\epsilon_1)+n_B(\epsilon_2)+1}{(\epsilon_2+\epsilon_1)^2}\right)$$

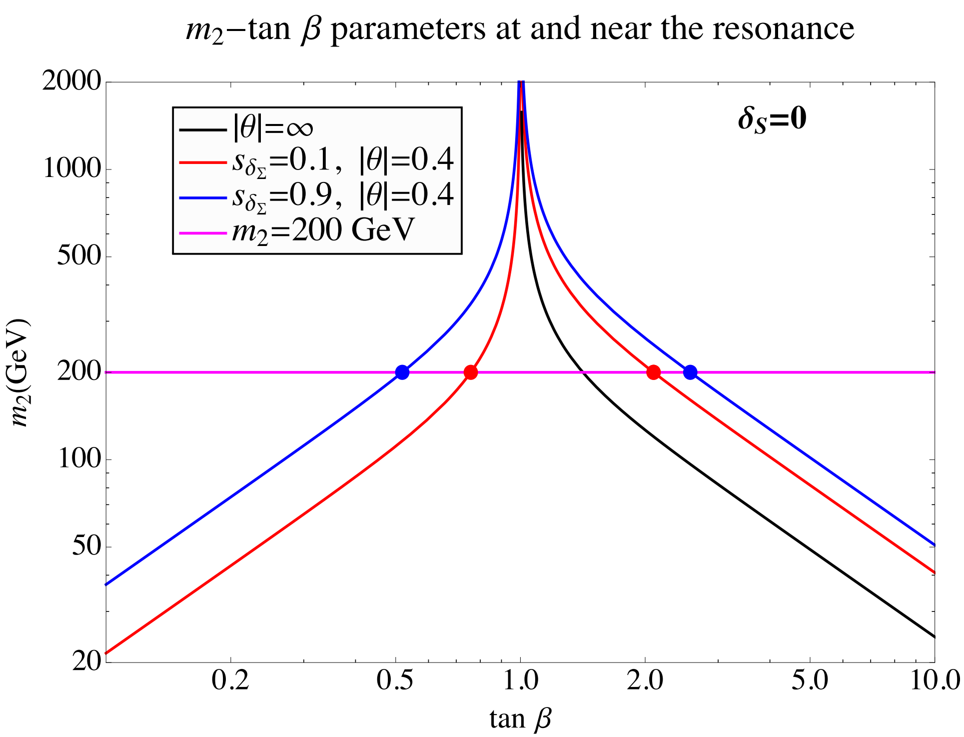
$$S_H \sim \sin(\delta_\Sigma-\delta_S)\,\Lambda(m_{H_1}(T),m_{H_2}(T))$$

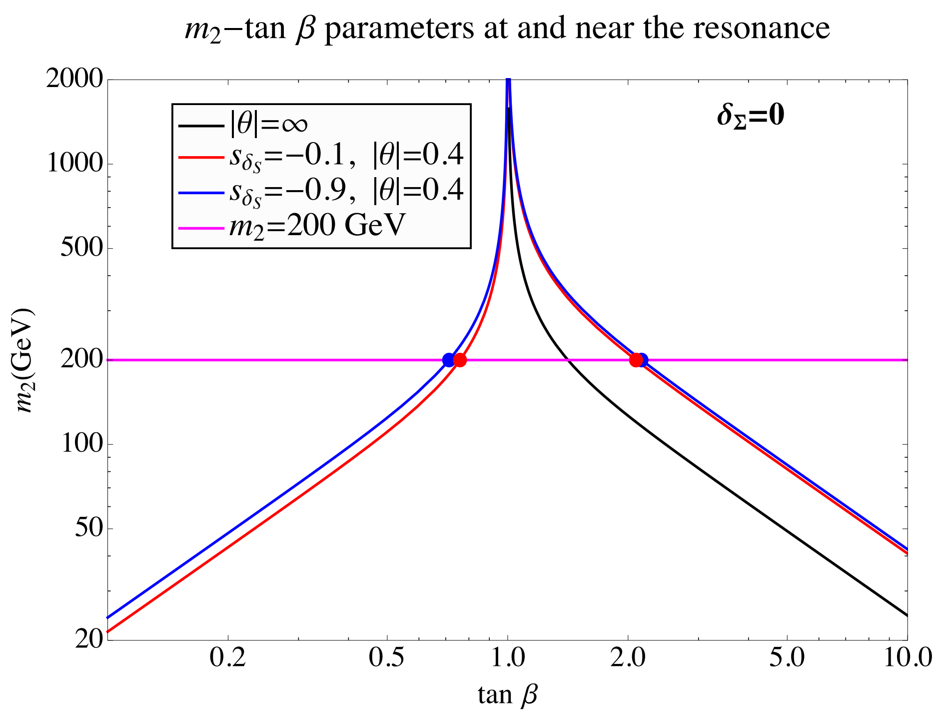


$$m^2_{H_1}(T)-m^2_{H_2}(T) = f(y_b,y_t,m_2,\tan\beta)$$

Expect strong parameter dependence of the BAU on the CP even (heavy) Higgs mass m_2 and $\tan\beta$

Flavor oscillations at finite temperature

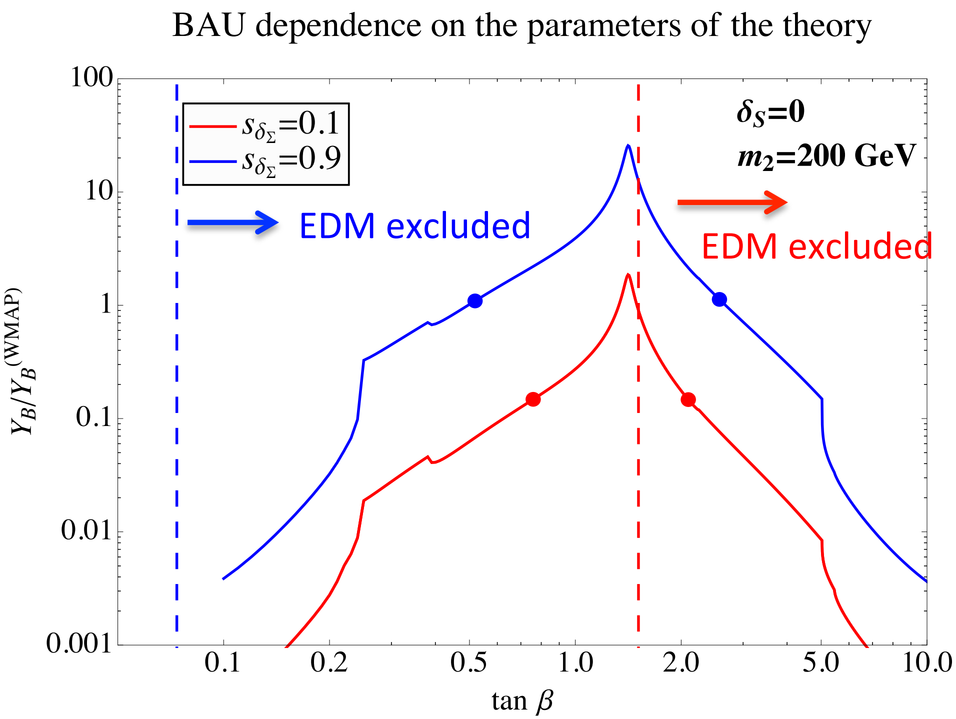


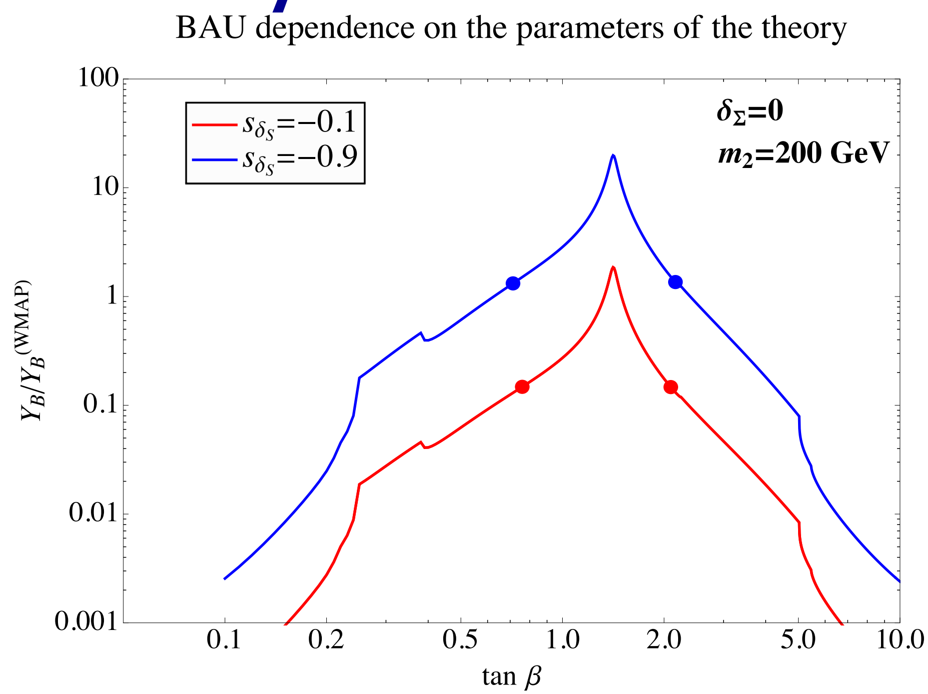


1. Black line corresponds to the precise resonant relaxation $m^2_{H_1}(T) = m^2_{H_2}(T)$
2. Red and Blue lines correspond to being away from the resonant relaxation so that $|\theta| = 0.4$ and different CPV angle $\delta_\Sigma - \delta_S = 0.1, 0.9$
3. The solid circles tell us which parameters ($\tan\beta, m_2$) give maximum amount of BAU with the flavor oscillations of the order of 0.4*0.4=16%

$$P_{\rm osc} \sim |\theta|^2$$

BAU anatomy





- For a representative case m_2=200 GeV we scan through $\sin\delta_\Sigma = 0.1$, 0.9 (left plot with $\delta_S = 0$) and $\sin\delta_S = -0.1$, -0.9 (right plot with $\delta_\Sigma = 0$) and show the dependence of BAU on $\tan\beta$.
- In the $\delta_S = 0$ case the electron EDM is excluding the BAU bounds (except for the red curve near resonance where the flavor oscillations are non-negligible)

BAU anatomy

- The result of the comprehensive analysis of the BAU anatomy plots (more in the backup) is that in order to generate the observed BAU and avoid large flavor oscillations and EDM bounds, need large phase δ_S

$$\delta_S >\sim -0.5,\ \delta_\Sigma\ \text{small or zero}$$

we also assumed m_2>50 GeV, otherwise exists possibility with

$$m_2 \sim 45\,\text{GeV},\ \delta_S = 0, \delta_\Sigma \sim 0.6,\ \tan\beta \sim 0.2,$$

Parameter dependence of bounds

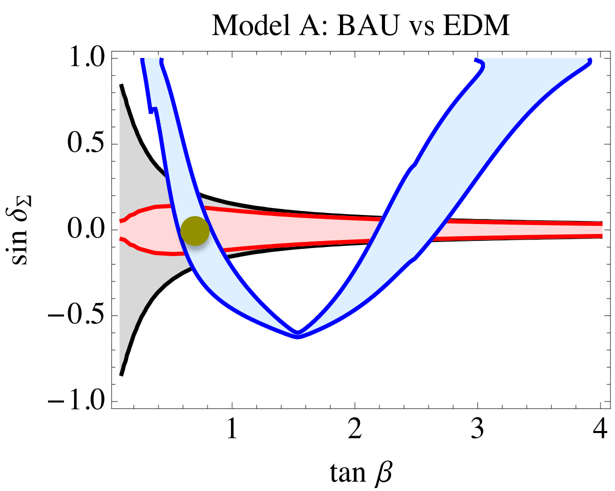
Electron EDM

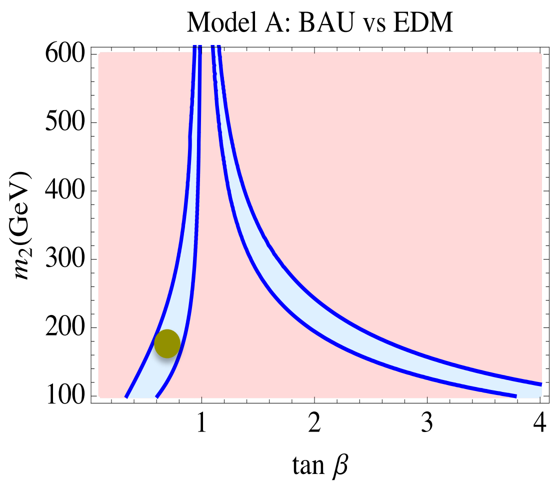
$$\delta_e = \sin\delta_\Sigma \tan\beta\, F(m_\Sigma, m_{h_3})$$

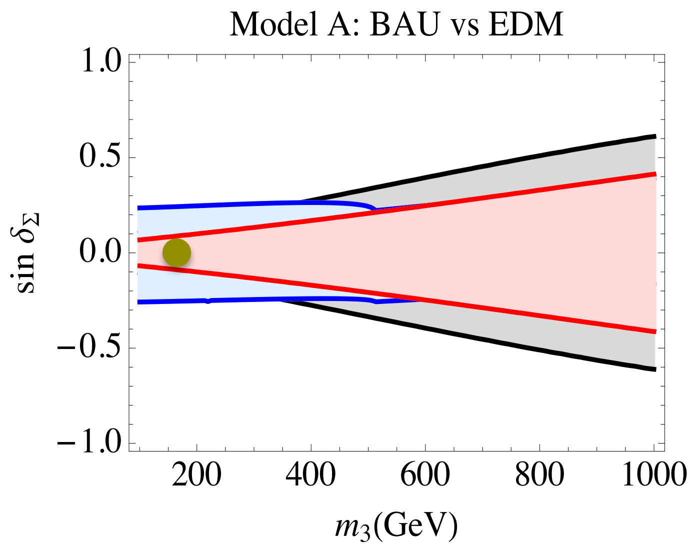
BAU

$$Y_B \approx \sin(\delta_\Sigma - \delta_S)\, G(m_{h_2}, \tan\beta)$$

BAU vs EDM bounds







Blue

$Y_B^{\mathrm{WMAP}} = (7.3 \pm 2.5) \times 10^{-11}$

$$\delta_S = -0.65$$

Gray: electron EDM

Pink(ish): neutron EDM
(x100 sensitivity improvement)

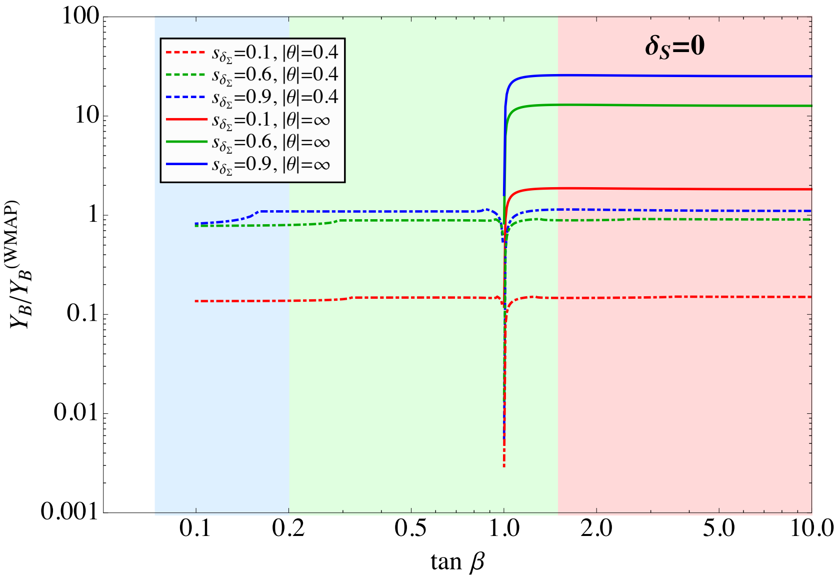
Guided by the anatomy plots we easily find successful benchmark scenarios that satisfy both Baryogenesis and EDM bounds with negligible flavor oscillations

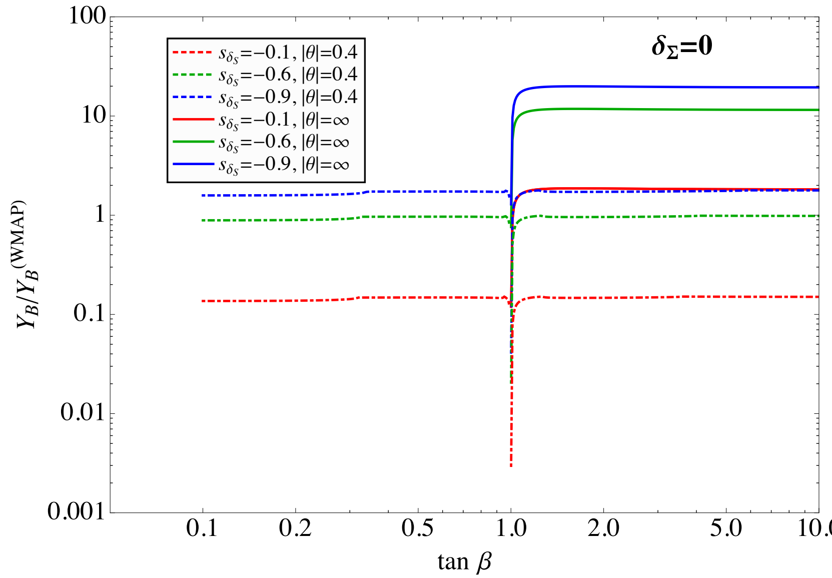
Conclusions

- In an extension of the 2HDM with a real triplet and a real singlet we have computed the BAU from CTP formalism
- We found a range for successful benchmarks consistent with both BAU and EDMs
- We neglected flavor oscillations and checked that the assumption is valid for the benchmark (additional suppression of BAU)
- This work is another step towards a consistent phenomenology of multi-step phase transitions

Backup slides

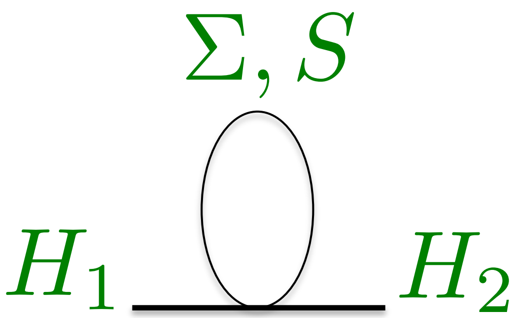
BAU anatomy





- Same as in the last slide, but for a value of m_2 that is a function of so that $\tan\beta$ is a fixed number $|\theta|$
- Solid lines sitting on the resonance (maximum possible BAU)
- Dashed lines moving away from resonance to suppress the flavor oscillation to 16% (maximum possible BAU with fixed magnitude of the flavor oscillations)
- Conclusion from the left plot: $\delta_S = 0$ excluded by the EDM and collider bound m_2>150 GeV. Right plot: need a large phase in the $\delta_S \sim 0.5 - 0.8$

Flavor oscillations at finite temperature



Cirigliano, Lee, Ramsey-Musolf, Tulin, 2006

$$\delta m_{12}^2(T) = \frac{a_{2\Sigma} T^2}{8} + \frac{a_{2S} T^2}{24}$$

$$\theta \sim \frac{\delta m^2(T)}{m_{H_1}^2(T) - m_{H_2}^2(T)}, \; P_{\rm osc} \sim |\theta|^2$$

- We removed the m_{12} coupling in order to avoid “complicated” flavor oscillations
- However at finite temperature we generate such off-diagonal mass term
- Our approach, neglect this mass term and flavor oscillations, however for selected benchmarks check that assumption is reasonable
- Note that at the point of flavor resonant relaxation $\theta = \infty$

Thermal masses formula

$$m_{H_1}^2(T) - m_{H_2}^2(T)$$
$$= \left[y_b^2 - y_t^2 + \frac{m_{h_2}^2}{v^2}\left(\tan^2\beta - \cot^2\beta\right)\right]\frac{T^2}{4}$$