Strong EW phase transition from varying Yukawas

Iason Baldes

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Electroweak baryogenesis - basic picture

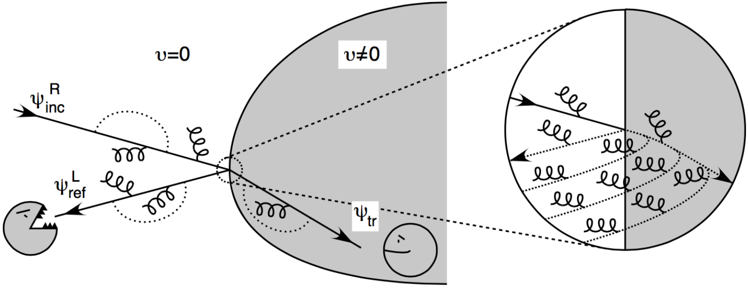
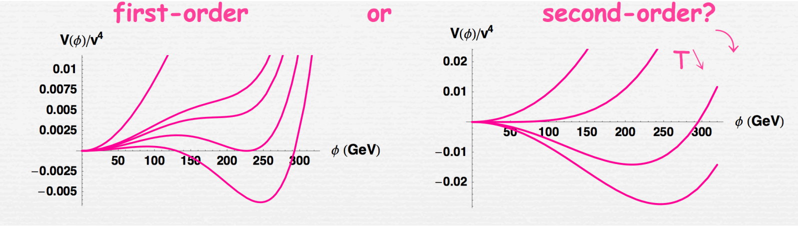


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- CP violating collisions with the bubble walls lead to a chiral asymmetry.
- Sphalerons convert this to a Baryon Asymmetry.
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



Electroweak baryogenesis requires:

- A strong first order phase transition ($\phi_c / T_c \gtrsim 1$)
- Sufficient CP violation

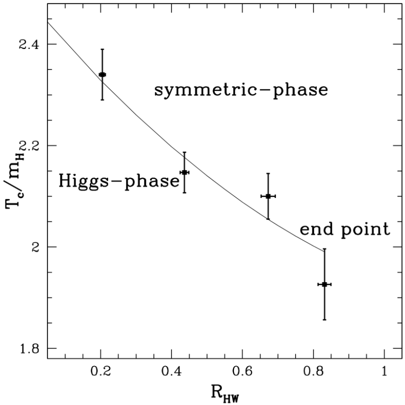
However in the SM:

- The Higgs mass is too large
- Quark masses are too small

We require new (EW-scale) physics!

Electroweak phase transition

Lattice calculations show the SM Higgs mass is too large.



- Csikor, Fodor, Heitger, Phys. Rev. Lett. 82, 21 (1999)

$$R_{HW} \equiv m_H/m_W$$

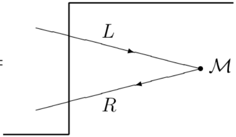
Endpoint at:

$m_H \approx 67$ GeV

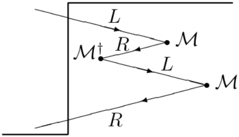
Higgs mass is too large in the SM. The Higgs potential must be modified.

Baryogenesis from charge transport with SM CP violation

$R_{LR} =$



$+$



$+ \cdots$

$$\epsilon_{\rm CP} \sim \frac{1}{M_W^6 T_c^6} \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) J_{\rm CP}$$

- Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289],
- Huet, Sather [hep-ph/9404302].

SM quark masses are too small!

Could the solution be linked to flavour?

Yukawa interactions:

$$y_{ij}\overline{f}^i_L\Phi^{(c)}f^j_R$$

Possible solutions

- Froggatt-Nielsen
- Composite Higgs
- Randall-Sundrum Scenario

Froggatt-Nielsen Yukawas:

$$y_{ij} \sim \left(\frac{\langle\chi\rangle}{\Lambda}\right)^{-q_i+q_j+q_H}$$

Some previous work: Baryogenesis from the Kobayashi-Maskawa phase

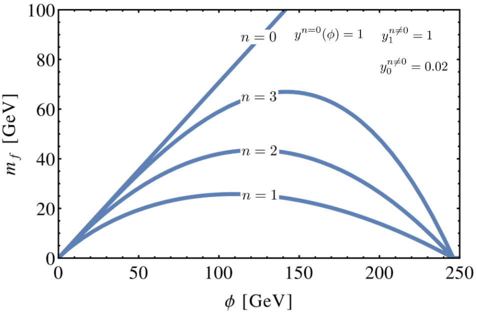
- Berkooz, Nir, Volansky - Phys. Rev. Lett. 93 (2004) 051301

Split fermions baryogenesis from the Kobayashi-Maskawa phase

- Perez, Volansky - Phys. Rev. D 72 (2005) 103522

We postulate varying Yukawas

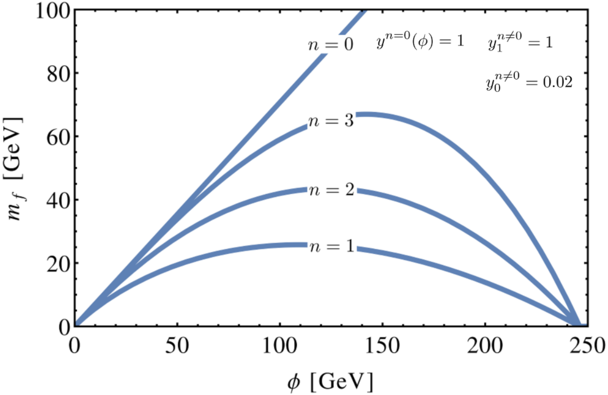
Study the strength of the EWPT with varying Yukawas in a model independent way. - IB, Konstandin, Servant (1604.04526)



Ansatz

$$y(\phi) = \begin{cases} y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 & \text{for} \quad \phi \leq v, \\ y_0 & \text{for} \quad \phi \geq v. \end{cases}$$

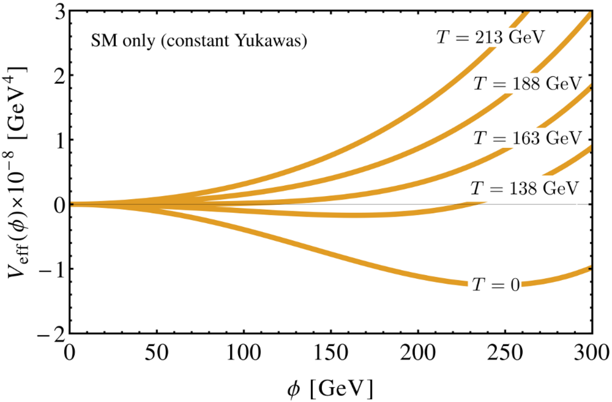
Effective Potential



Thermal correction

$$V_{\text{eff}} \supset -\frac{g_* \pi^2}{90} T^4$$

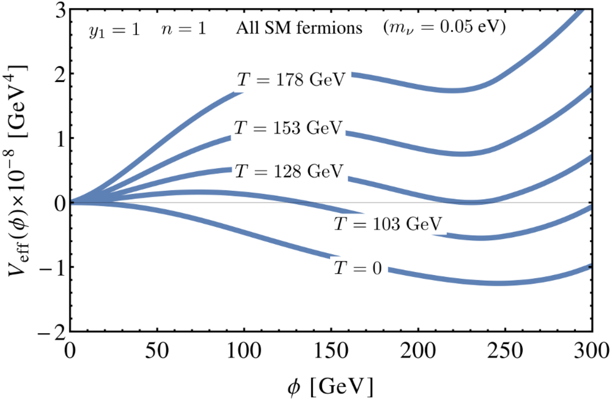
Effective Potential - SM case



Second order phase transition $T_c = 163\ \mathrm{GeV}$.

$$V_{\rm eff} = V_{\rm tree}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\rm Daisy}(\phi, T)$$

Effective Potential - Varying Yukawas

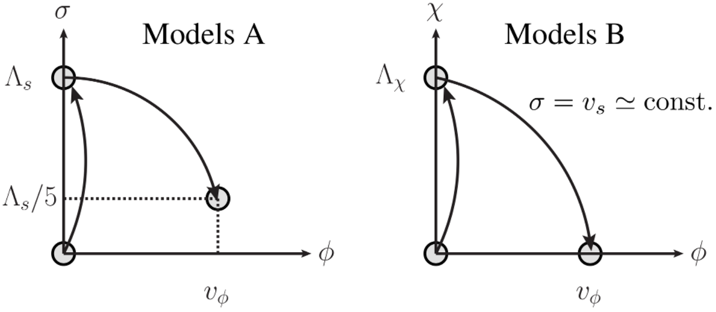


Strong first order phase transition

$$\phi_c = 230 \text{ GeV}, \qquad T_c = 128 \text{ GeV}, \qquad \phi_c/T_c = 1.8$$

Including the flavon

Flavor Cosmology: Dynamical Yukawas in the Froggatt-Nielsen Mechanism
- IB, Konstandin, Servant (1608.03254)

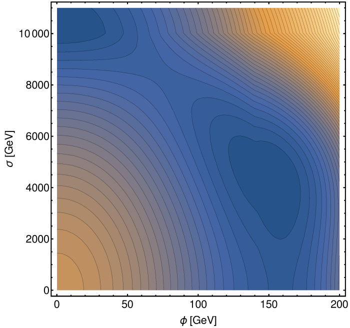


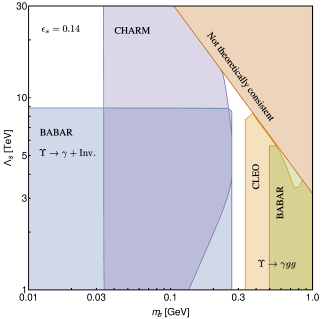
- Have to take into account from flavour physics.
- Flavon dof also affects ϕ_c/T_c.
- Generic prediction: light flavon with mass below the EW scale.

We have implemented this idea in some non-standard Froggatt-Nielsen scenarios.

Expermental signatures - Model A-2

Couple a flavon to each mass eigenstate - Knapen, Robinson (1507.00009).
Here we assume a simple polynomial scalar potential up to dimension four + FN style coupling to b's.



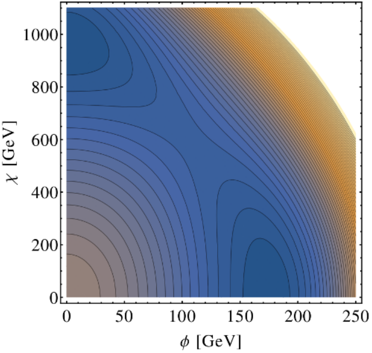


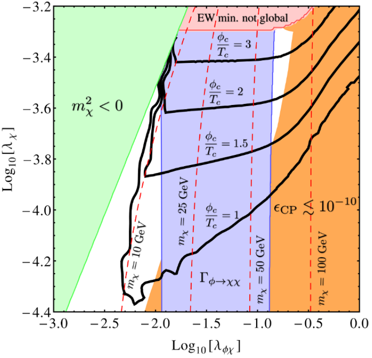
$m_\sigma = 0.13$ GeV, $\phi_c/T_c = 1.1$, $\epsilon_s \equiv v_s/\sqrt{2}\Lambda_s = 0.12$, $\lambda_{s\phi} = 10^{-5}$.

$$\mathcal{L} \supset \frac{y_b}{\sqrt{2}}\left(\frac{\sigma}{\sqrt{2}\Lambda_s}\right)^2 \phi\bar{b}b \qquad \mathrm{Br}(\phi \to \bar{b}b\sigma) = 1.1\% \left(\frac{0.1}{\epsilon_s}\right)^2 \left(\frac{1\ \mathrm{TeV}}{\Lambda_s}\right)^2$$

Model B-1: $Q_{\rm FN}(X) = -1/2$ - phase transition strength

Here we assume a simple polynomial scalar potential up to dimension four + the Yukawa sector.





$\Lambda_\chi = 1$ TeV, $\lambda_\chi = 10^{-4}$, $\lambda_{\phi\chi} = 10^{-2}$, $m_\chi = 14$ GeV

$$\Gamma(\chi \to \bar{c}c) \approx 10^{-12}\ \mathrm{GeV} \left(\frac{m_\chi}{10\ \mathrm{GeV}}\right) \left(\frac{v_\chi^{\rm today}}{1\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{\Lambda_\chi}\right)^4$$

Conclusions

Electroweak baryogenesis and flavour physics may be closely related.

Yukawa variation may allow us to address:

- The lack of a strong first order phase transition in the SM
- The insufficient CP violation for EW baryogenesis. See next talk!
  - Bruggisser, Konstandin, Servant (in preperation)
- The related limits on EDMs (this approach leads to a lack of EDM signals)

This offers additional motivation to consider low scale flavour models and their cosmology.

Other models of flavour are worth looking at too (not just Froggatt-Nielsen). e.g. RS1 - von Harling, Servant (in preperation)
New experimental signatures should then be accessible as we further probe the Higgs potential!

Effective Potential - $T = 0$ terms

$$V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T)$$

$$V_{\text{tree}}(\phi) = -\frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4$$

$$V_1^0(\phi) = \sum_i \frac{g_i(-1)^F}{64\pi^2}\left\{ m_i^4(\phi)\left(\text{Log}\left[\frac{m_i^2(\phi)}{m_i^2(v)}\right] - \frac{3}{2}\right) + 2m_i^2(\phi)m_i^2(v)\right\}$$

Gives a large negative contribution to the ϕ^4 term.

- Can lead to a new minimum between $\phi = 0$ and $\phi = 246$ GeV.
- Not an issue for previous $y_1 = 1$, $n = 1$ example.
- Can make phase transition weaker.

Effective Potential - one-loop $T \neq 0$ correction

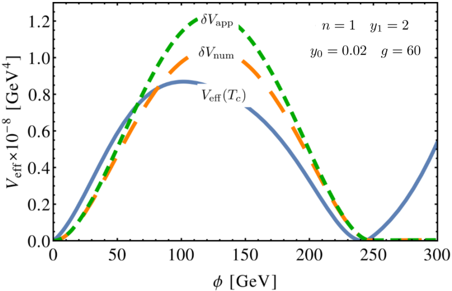
$$V_1^T(\phi, T) = \sum_i \frac{g_i(-1)^F T^4}{2\pi^2} \times \int_0^\infty y^2 \mathrm{Log}\left(1-(-1)^F e^{-\sqrt{y^2+m_i^2(\phi)/T^2}}\right) \mathrm{d}y$$

$$V_f^T(\phi, T) = -\frac{gT^4}{2\pi^2} J_f\left(\frac{m_f(\phi)^2}{T^2}\right)$$

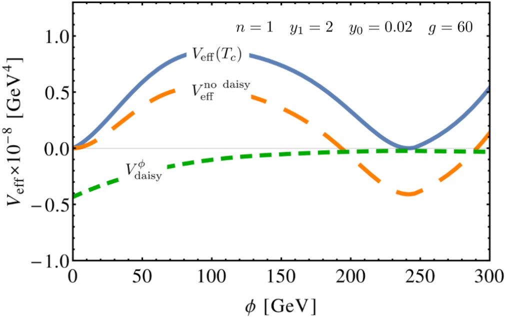
$$J_f\left(\frac{m_f(\phi)^2}{T^2}\right) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}\left(\frac{m}{T}\right)^2 - \frac{1}{32}\left(\frac{m}{T}\right)^4 \mathrm{Log}\left[\frac{m^2}{13.9T^2}\right], \quad \text{for } \frac{m^2}{T^2} \ll 1,$$

$$\delta V \equiv V_f^T(\phi, T) - V_f^T(0, T)$$

$$\approx \frac{gT^2\phi^2[y(\phi)]^2}{96}$$



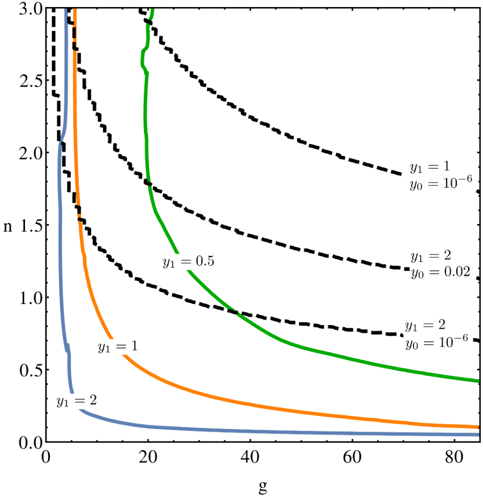
Effective Potential - daisy correction



$$V^{\phi}_{\text{Daisy}}(\phi, T) = \frac{T}{12\pi}\left\{ m^3_{\phi}(\phi) - \left[m^2_{\phi}(\phi) + \Pi_{\phi}(\phi, T) \right]^{3/2} \right\}$$

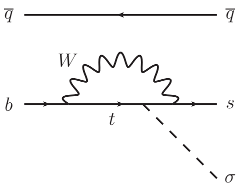
$$\Pi_{\phi}(\phi, T) = \left(\frac{3}{16} g_2^2 + \frac{1}{16} g_Y^2 + \frac{\lambda}{2} + \frac{y_t^2}{4} + \frac{g y(\phi)^2}{48} \right) T^2$$

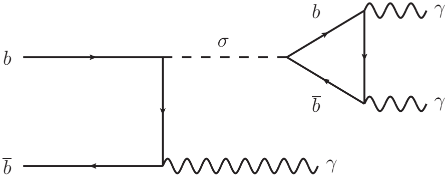
Strength of the phase transition with varying Yukawas



$$y(\phi) = y_1 \left(1 - \left[\frac{\phi}{v}\right]^n\right) + y_0 \quad \text{for} \quad \phi \leq v$$

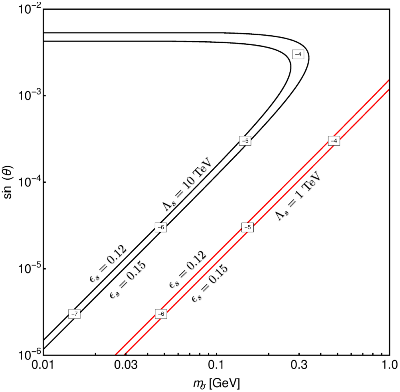
Upsilon and B decays





$$\epsilon_s \equiv \frac{\langle\sigma\rangle}{\sqrt{2}\Lambda_s} \qquad \mathcal{L} \supset \frac{y_b}{\sqrt{2}}\left(\frac{\sigma}{\sqrt{2}\Lambda_s}\right)^2 \phi\bar{b}b$$

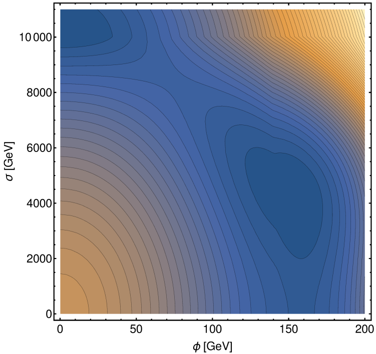
Parameter curves

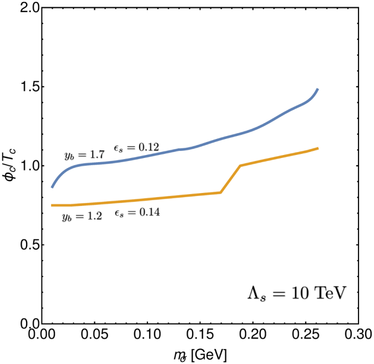


$$\epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2}\Lambda_s} \qquad \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left(\frac{\sigma}{\sqrt{2}\Lambda_s} \right)^2 \phi \bar{b} b$$

Model A-2: Disentangled hierarchy and mixing mechanism

Couple a flavon to each mass eigenstate - Knapen, Robinson (1507.00009)





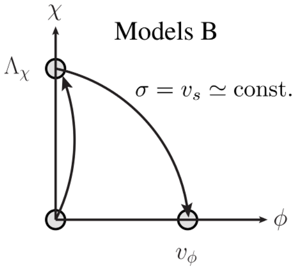
Here we assume a simple polynomial scalar potential up to dimension four augmented with a σ dependent Yukawa term.

$$\epsilon_s \equiv \frac{\langle \sigma \rangle}{\sqrt{2}\Lambda_s} \qquad \mathcal{L} \supset \frac{y_b}{\sqrt{2}} \left(\frac{\sigma}{\sqrt{2}\Lambda_s} \right)^2 \phi \bar{b} b$$

Models B

Two FN fields

$$\mathcal{L} = \tilde{y}_{ij} \left(\frac{S}{\Lambda_s}\right)^{\tilde{n}_{ij}} \overline{Q}_i \tilde{\Phi} U_j + y_{ij} \left(\frac{S}{\Lambda_s}\right)^{n_{ij}} \overline{Q}_i \Phi D_j + \tilde{f}_{ij} \left(\frac{X}{\Lambda_\chi}\right)^{\tilde{m}_{ij}} \overline{Q}_i \tilde{\Phi} U_j + f_{ij} \left(\frac{X}{\Lambda_\chi}\right)^{m_{ij}} \overline{Q}_i \Phi D_j$$



We assume a small VEV for the second FN field today: $\langle X \rangle \simeq 0$.
The VEV $\langle S \rangle$ sets the Yukawas today while $\langle X \rangle$ varies during the EWPT.

Model B-1: $Q_{\mathrm{FN}}(X) = -1/2$

$\Lambda_\chi \gtrsim 700$ GeV ($K - \overline{K}$)

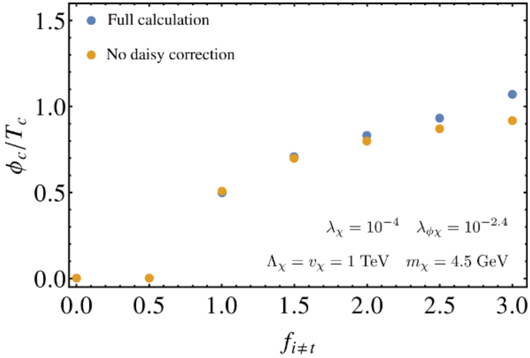
$\Lambda_\chi \gtrsim 250$ GeV ($B_s - \overline{B_s}$)

Model B-2: $Q_{\mathrm{FN}}(X) = -1$

$\Lambda_\chi \gtrsim 2.5$ TeV ($K - \overline{K}$)

$\sqrt{\Lambda_\chi m_\chi} \gtrsim 500$ GeV ($D - \overline{D}$)

Model B-1: $Q_{\mathrm{FN}}(X) = -1/2$ - phase transition strength



Yukawas sector

$$\mathcal{L} \supset \tilde{f}_{ij}\left(\frac{X}{\Lambda_\chi}\right)^{\tilde{m}_{ij}} \overline{Q}_i \tilde{\Phi} U_j + f_{ij}\left(\frac{X}{\Lambda_\chi}\right)^{m_{ij}} \overline{Q}_i \Phi D_j + H.c.$$