Connection to Cosmology

The electroweak phase transition and the flavour puzzle

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Higgs tasting workshop - Benasque, 19 May 2016

Electroweak baryogenesis - an exciting link between the Higgs and cosmology.

- Small review of electroweak baryogenesis
- Some new ideas on the flavour puzzle and its possible role in electroweak baryogenesis

Electroweak baryogenesis - basic picture

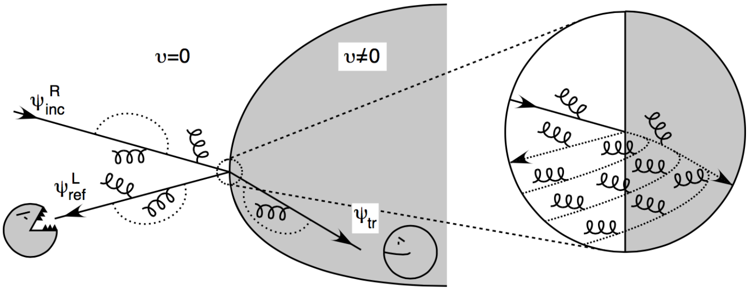
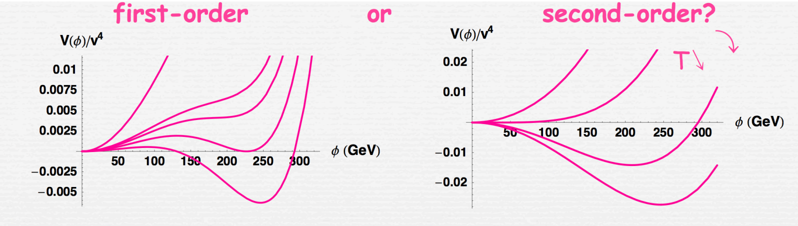


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- 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
- Sufficient CP violation

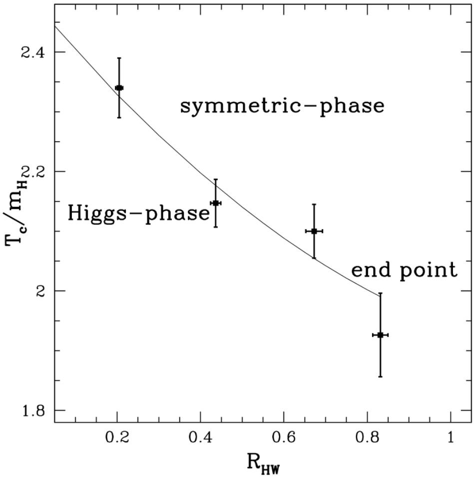
However in the SM:

- 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.



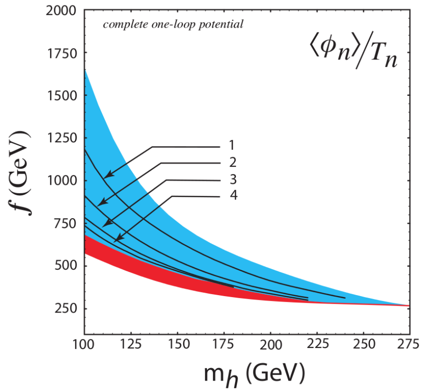
- Csikor, Fodor, Heitger, Phys. Rev. Lett. 82, 21 (1999)

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

Endpoint at:

$m_H \approx 67$ GeV

Require a modification of the Higgs potential



- Delaunay, Grojean, Wells [0711.2511]

$V(H) =$
$m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6$

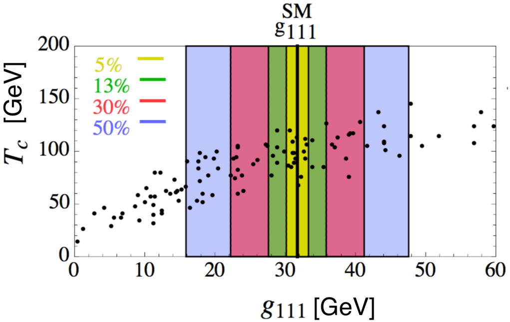
Other options:

- Singlet models/tree level barriers
- Thermal barriers from bosonic loops
- Multi-step transitions

Successful electroweak baryogenesis requires:

$$\Gamma_{\rm sph} \sim 10^{1\div 4}\left(\frac{\alpha_W T}{4\pi}\right)^4 \left(\frac{2M_W(\phi)}{\alpha_W T}\right)^7 \mathrm{Exp}\left[-\frac{3.2 M_W(\phi)}{\alpha_W T}\right] \lesssim H \;\Rightarrow\; \frac{\phi_c}{T_c} \gtrsim 1$$

Collider signatures - example

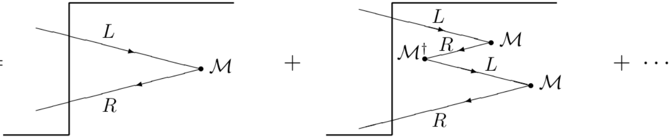


Correlation between T_c and triple Higgs couplings $g_{111}h^3$ in a singlet model. - Profumo, Ramsey-Musolf, Wainwright, Winslow [1407.5342]

- Example of how the Higgs potential can be probed by experiment.
- This would also constrain the parameter f in the previous example.
- Other signals can also be found in the literature e.g. $h \to \gamma\gamma$ in inert 2HDM models. - Blinov, Profumo, Stefaniak [1504.05949]

Baryogenesis from charge transport with SM CP violation

$R_{LR} =$



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

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

SM quark masses are too small!

EDMs

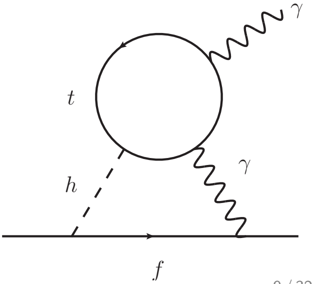
Additional CP violation

$$\mathcal{L} \supset y_{ij}\overline{Q_i}\Phi u_j + x_{ij}\frac{(\Phi^\dagger\Phi)}{\Lambda_{\rm CP}^2}\overline{Q_i}\Phi u_j$$

- Huber, Pospelov, Ritz [hep-ph/0610003], Konstandin [1302.6713]

Neutron EDM: $|d_n| < 3 \times 10^{-26} e\ \mathrm{cm}$

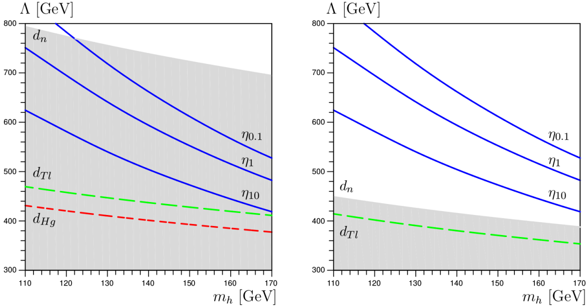
- Such operators are constrained from EDMs and FCNCs.
- Constraint from neutron EDM: $\Lambda_{\rm CP} \gtrsim \sqrt{\mathrm{Im}[x_{33}]} \times 750$ GeV.
- Small $\Lambda_{\rm CP}$ possible with $x_{ij} \sim y_{ij}$.



EDMs

Additional CP violation

$$\mathcal{L} \supset y_{ij} \overline{Q_i} \Phi u_j + x_{ij} \frac{(\Phi^\dagger \Phi)}{\Lambda_{\rm CP}^2} \overline{Q_i} \Phi u_j$$



Plots for $\Lambda \equiv f = \Lambda_{\rm CP}$. Left: top only ($x_{33}$). Right: MFV.

- Huber, Pospelov, Ritz [hep-ph/0610003]

Common constraint on EWBG!

Solutions to the flavour puzzle

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

Previous work on flavour cosmology and EWBG

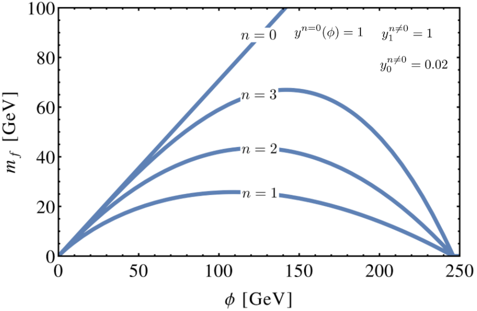
1. Baryogenesis from the Kobayashi-Maskawa phase
   - Berkooz, Nir, Volansky - Phys. Rev. Lett. 93 (2004) 051301
   - Froggatt-Nielsen scenario.
   - Pointed out that CP violation could be unsuppressed before EWPT.
   - No EDM signal.
   - Ignored phase transition strength.
2. Split fermions baryogenesis from the Kobayashi-Maskawa phase
   - Perez, Volansky - Phys. Rev. D 72 (2005) 103522
   - Baryogenesis from the localiser phase transition.
   - CP violation unsuppressed before localiser phase transtion.
   - Non-standard EWBG: unsuppressed $B - L$ violating operators play the role of sphalerons.

However:

Varying Yukawas can themselves change the nature of the EWPT.

Varying Yukawas

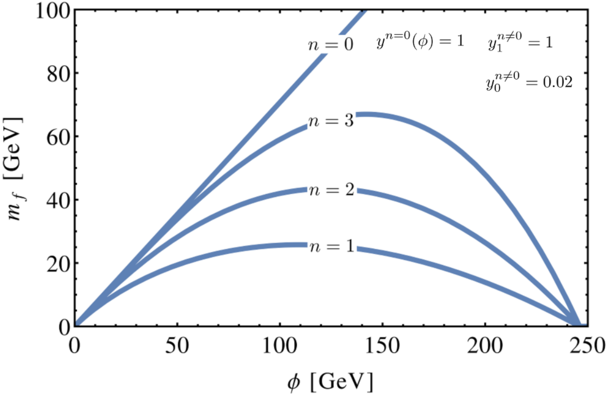
Study the strength of the EWPT with varying Yukawas in a model independent way. - IB, Konstandin, Servant (1604.04526)



Ansatz

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

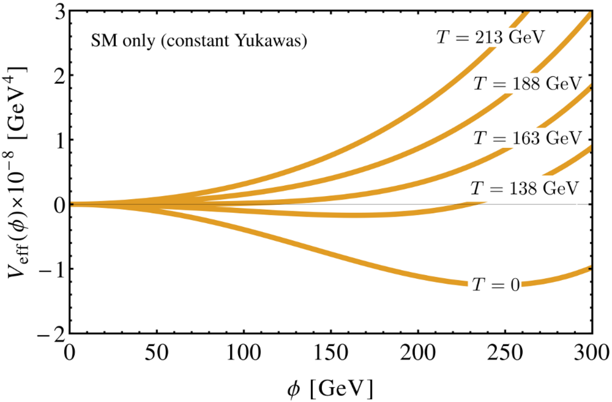
Effective Potential



Thermal correction

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

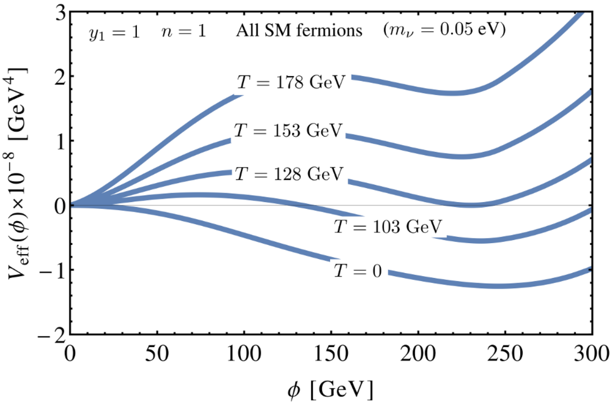
Effective Potential - SM case



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

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

Effective Potential - Varying Yukawas



Strong first order phase transition

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

Effective Potential - $T = 0$ terms

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

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

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

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

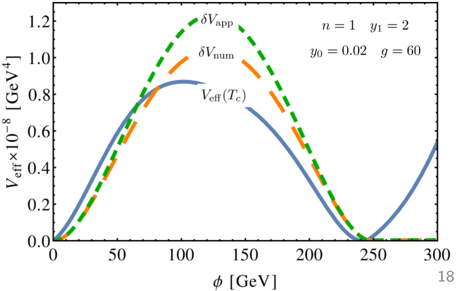
$$V_1^T(\phi, T) = \sum_i \frac{g_i(-1)^F T^4}{2\pi^2} \times \int_0^\infty y^2 \mathrm{Log}\left(1 - (-1)^F e^{-\sqrt{y^2 + m_i^2(\phi)/T^2}}\right) \mathrm{d}y$$

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

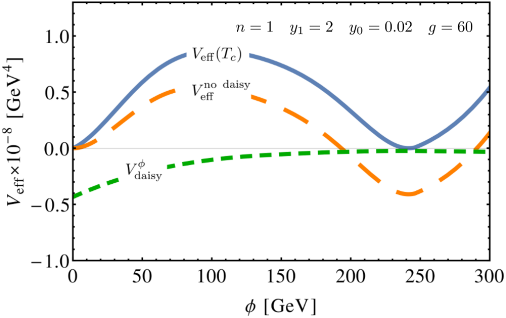
$$J_f\left(\frac{m_f(\phi)^2}{T^2}\right) \approx \frac{7\pi^4}{360} - \frac{\pi^2}{24}\left(\frac{m}{T}\right)^2 - \frac{1}{32}\left(\frac{m}{T}\right)^4 \mathrm{Log}\left[\frac{m^2}{13.9\, T^2}\right], \quad \text{for } \frac{m^2}{T^2} \ll 1,$$

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

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



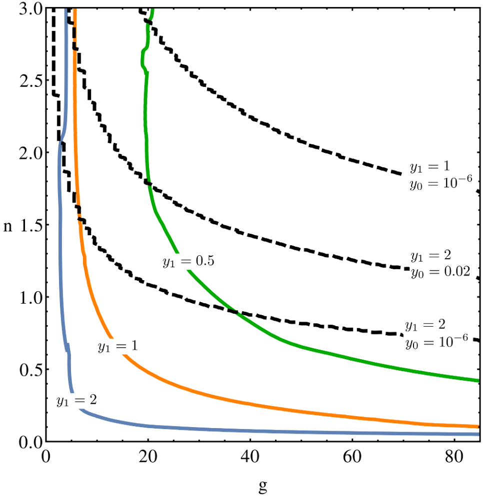
Effective Potential - daisy correction



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

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

Overall strength



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

Introducing the Flavon — An illustrative example

We now introduce the flavon dof - IB, Konstandin, Servant [16mm.xxxxx]

Froggatt-Nielsen

$$\mathcal{L} = \tilde{y_{ij}} \left(\frac{S}{\Lambda_s}\right)^{n_{ij}} \overline{U}_i \tilde{\Phi} Q_j + y_{ij} \left(\frac{S}{\Lambda_s}\right)^{m_{ij}} \overline{D}_i \Phi Q_j$$
$$+ \tilde{f_{ij}} \left(\frac{X}{\Lambda_\chi}\right)^{2n_{ij}} \overline{U}_i \tilde{\Phi} Q_j + f_{ij} \left(\frac{X}{\Lambda_\chi}\right)^{2m_{ij}} \overline{D}_i \Phi Q_j + H.c.$$

Under $U(1)_{\mathrm{FN}}$: S (-1) and X $(-1/2)$. Define $\epsilon_s \equiv \langle S \rangle / \Lambda_s$, $\epsilon_\chi \equiv \langle X \rangle / \Lambda_\chi$.

Charges and resulting Yukawas and mixings

$$\begin{array}{cccccc} Q_3\ (0), & Q_2\ (+2), & Q_1\ (+3), & y_t \sim 1, & y_c \sim \epsilon_s^3, & y_u \sim \epsilon_s^7, \\ \overline{U}_3\ (0), & \overline{U}_2\ (+1), & \overline{U}_1\ (+4), & y_b \sim \epsilon_s^2, & y_s \sim \epsilon_s^4, & y_d \sim \epsilon_s^6, \\ \overline{D}_3\ (+2), & \overline{D}_2\ (+2), & \overline{D}_1\ (+3). & s_{12} \sim \epsilon_s, & s_{23} \sim \epsilon_s^2, & s_{13} \sim \epsilon_s^3. \end{array}$$

Introducing the Flavon — An illustrative example

Froggatt-Nielsen

$$\mathcal{L} = \tilde{y}_{ij} \left(\frac{S}{\Lambda_s} \right)^{n_{ij}} \overline{U}_i \tilde{\Phi} Q_j + y_{ij} \left(\frac{S}{\Lambda_s} \right)^{m_{ij}} \overline{D}_i \Phi Q_j$$
$$+ \tilde{f}_{ij} \left(\frac{X}{\Lambda_\chi} \right)^{2n_{ij}} \overline{U}_i \tilde{\Phi} Q_j + f_{ij} \left(\frac{X}{\Lambda_\chi} \right)^{2m_{ij}} \overline{D}_i \Phi Q_j + H.c.$$

What if Froggatt-Nielsen dynamics takes place close to the EW scale?
This can lead to variation of Yukawa couplings during the EWPT.

Symmetry breaking

$$\Phi \to \frac{1}{\sqrt{2}}\begin{pmatrix} G_1 + iG_2 \\ v_\phi + \phi + iG_3 \end{pmatrix}, \qquad S \to \frac{v_s + \sigma + i\rho}{\sqrt{2}}, \qquad X \to \frac{v_\chi + \chi + i\eta}{\sqrt{2}}.$$

Long range forces must be suppressed by introducing explicit breaking of $U(1)_{\mathrm{FN}}$.

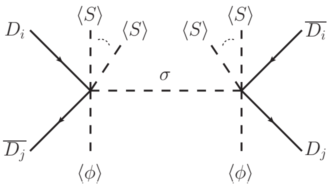
$$V(S) \supset -\mu_s^2 S^\dagger S + \lambda_s (S^\dagger S)^2 - A^2(SS + S^\dagger S^\dagger)$$

Minimisation of the potential gives the relations

$$m_\sigma^2 = 2\mu_s^2 + 4A^2 = 2\lambda_s v_s^2, \quad m_\rho^2 = 4A^2.$$

We will take $m_\rho > m_\sigma$ below.

Constraints on S



$$\mathcal{H} = C_2^{sd}(\bar{s}Ld)^2 + \tilde{C}_2^{sd}(\bar{s}Rd)^2 + C_4^{sd}(\bar{s}Ld)(\bar{s}Rd) + H.c.$$

$$C_2^{sd} = \left(\frac{5\epsilon_s^4 v_\phi y_{21}}{2\Lambda_s m_\sigma}\right)^2$$

$$\tilde{C}_2^{sd} = \left(\frac{5\epsilon_s^4 v_\phi y_{12}^*}{2\Lambda_s m_\sigma}\right)^2$$

$$C_4^{sd} = y_{12}y_{21}^*\left(\frac{5\epsilon_s^4 v_\phi}{2\Lambda_s m_\sigma}\right)^2$$

$$\sqrt{\Lambda_s m_\sigma} \gtrsim |\mathrm{Im}[y_{12}y_{21}^*]|^{1/4} \times 15 \text{ TeV}$$

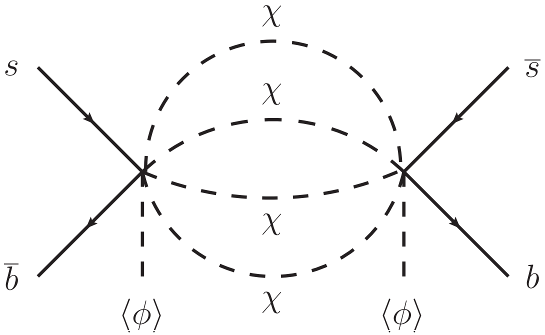
$$\sqrt{\Lambda_s m_\sigma} \gtrsim |\mathrm{Re}[y_{12}y_{21}^*]|^{1/4} \times 4.8 \text{ TeV}$$

$$\sqrt{\Lambda_s m_\sigma} \gtrsim |\mathrm{Im}[y_{21}y_{21}|^{1/4} \times 10 \text{ TeV}$$

$$\sqrt{\Lambda_s m_\sigma} \gtrsim |\mathrm{Re}[y_{21}y_{21}|^{1/4} \times 2.7 \text{ TeV}$$

$\Rightarrow \sqrt{\Lambda_s m_\sigma} \gtrsim$ few $\times$ TeV. For Yukawa variation we need $m_\sigma \sim v_\phi^2/\Lambda_s$.

Constraints on X



We assume $\langle\chi\rangle = 0$ today.

$$|C_2^{bs}| \approx \left(\frac{|f_{23}|v_\phi}{2\Lambda_\chi^4}\right)^2 \left\{\frac{1}{(8\pi)^3}\Lambda_\chi^4\right\}$$

$$\Lambda_\chi \gtrsim \sqrt{|f_{23}|} \times 360\ \mathrm{GeV}$$

VEV variation *to* Yukawa variation

We want the VEV of χ to move from:

$$\langle \chi \rangle = v_\chi \sim \Lambda_\chi$$

to:

$$\langle \chi \rangle = 0.$$

during the EWPT.

- Choice of FN charge $-1/2$ for X gives a Z_2 symmetry and allows us to have $\langle \chi \rangle = 0$ in a consistent manner.
- FN charge -1 would allow, e.g. $S^\dagger S^\dagger S X$ term in the potential.

$$y_i = f_i \left(\frac{\chi}{\sqrt{2}\Lambda_\chi} \right)^{2n_i} + y_i^{\mathrm{SM}}$$

Yukawa variation at tree level - renormalisable potential

$$V = \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \frac{\mu_\chi^2}{2}\chi^2 + \frac{\lambda_\chi}{4}\chi^4 + \frac{\lambda_{\phi\chi}}{4}\phi^2\chi^2.$$

VEV conditions

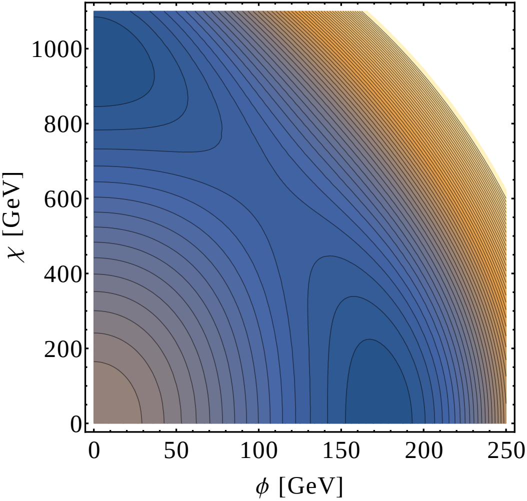
$$\mu_\chi^2 + \lambda_\chi v_\chi^2 = 0,$$
$$\mu_\phi^2 + \lambda_\phi v_\phi^2 = 0.$$

Constraints

$$m_\chi^2 = \mu_\chi^2 + \frac{\lambda_{\phi\chi} v_\phi^2}{2} = -\lambda_\chi v_\chi^2 + \frac{\lambda_{\phi\chi} v_\phi^2}{2} > 0$$

$$\lambda_\chi < \lambda_\phi \left(\frac{v_\phi}{v_\chi}\right)^4 = 4.7 \times 10^{-4} \left(\frac{1 \text{ TeV}}{v_\chi}\right)^4$$

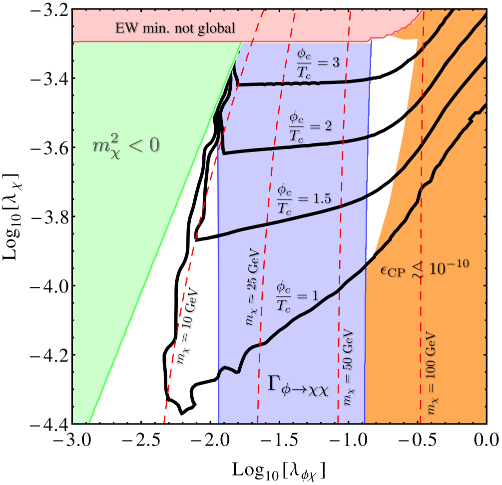
The finite T potential



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

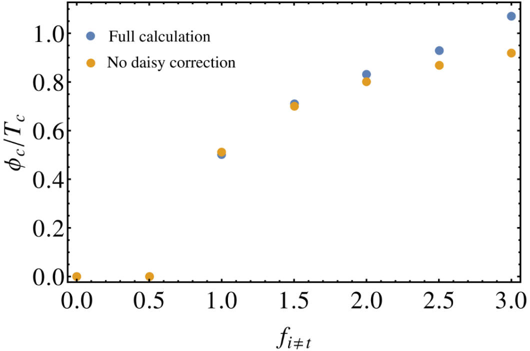
$$T_c = 133 \text{ GeV}, \qquad \phi_c = 174 \text{ GeV}, \qquad \phi_c/T_c = 1.3.$$

Parameter scan with $f_i = 1$, $v_\chi = \Lambda_\chi = 1$ TeV



Tree level barrier for: $\lambda_{\phi\chi} \geq -2\frac{\mu_\phi^2}{v_\chi^2} = 1.56 \times 10^{-2} \left(\frac{\mathrm{TeV}}{v_\chi}\right)^2$

The effect of the Yukawas

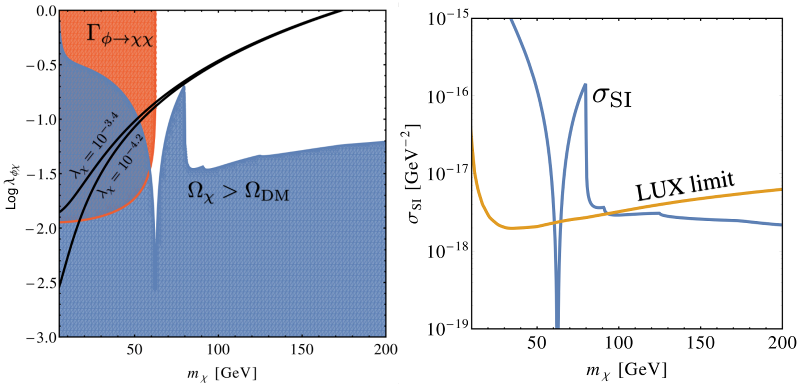


$v_\chi = 1$ TeV
$\Lambda_\chi = 1$ TeV
$\lambda_\chi = 10^{-4}$
$\lambda_{\phi\chi} = 10^{-2.4}$
$m_\chi = 14$ GeV.

We find the varying Yukawas can change the nature of the phase transition near the $\phi_c/T_c = 1$ contour.

$$y_b = f_b \left(\frac{\chi}{\sqrt{2}\Lambda_\chi} \right)^4 + y_b^{\mathrm{SM}}$$

Relic Abundance



The Z_2 symmetry may be softly broken, allowing χ to decay.
(Alternatively new annihilation channels may also be present.)

e.g. $\frac{X^\dagger X \overline{N^c} N}{\Lambda}$

Conclusions

The Higgs may have links to cosmology with experimentally accessible signatures.

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,
- 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).
New experimental signatures should then be accessible as we further probe the Higgs potential!