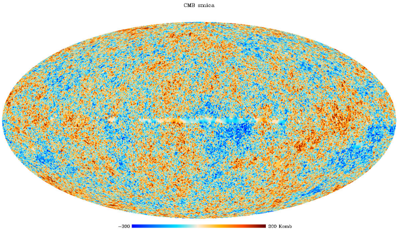
Update on Electroweak Baryogenesis

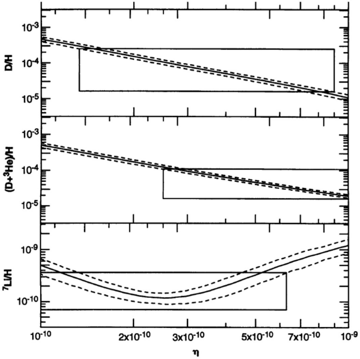
Iason Baldes

UNIVERSITÉ
LIBRE
DE BRUXELLES

COSMO'19, Aachen
3 September 2019

The matter-antimatter asymmetry





CMB in agreement with BBN:

$$Y_B \equiv \frac{n_b - n_{\bar{b}}}{s} = (0.86 \pm 0.02) \times 10^{-10}$$

Baryogenesis

Sakharov Conditions

1. B violation
2. C and CP violation
3. Departure from thermal equilibrium (or spontaneously broken CPT)

SM + FLRW

1. (B+L) violation present in symmetric phase at $T \gtrsim 100$ GeV from non-perturbative EW sphaleron process.
2. CP violation observed in quark sector (but not strong enough).
3. Can be driven by expansion (but SM EW phase transition is a crossover).

Baryogenesis Mechanisms

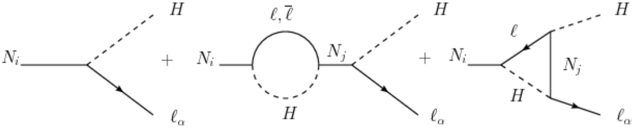
Baryogenesis Mechanisms

1. Leptogenesis — Related to the Seesaw mechanism.
2. Electroweak Baryogenesis — Related to the Higgs mechanism.
3. Affleck Dine, Spontaneous, Cold EWBG ...

Focus here is on EWBG. But first a few words on leptogenesis.

A Few Words on Leptogenesis

$$m_\nu \sim \frac{y_\nu^2 v_{\mathrm{EW}}^2}{M_N} \sim 0.1\ \mathrm{eV}$$



Leptogenesis

- Very minimal. Tied to $M_N \gtrsim 10^9$ GeV in the vanilla scenario.
- This introduces a calculable hierarchy problem.
- Only indirect tests: m_ν and $0\nu\beta\beta$.
- Scale can be lowered, while remaining rather minimal.
  Price: degeneracies or other complications.

The scale of EWBG is more closely tied to ~ 246 GeV.

Electroweak baryogenesis - basic picture

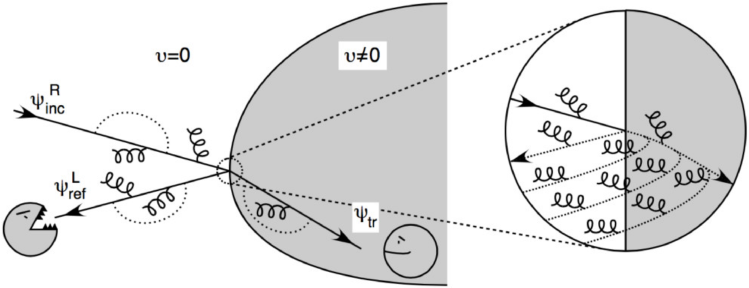
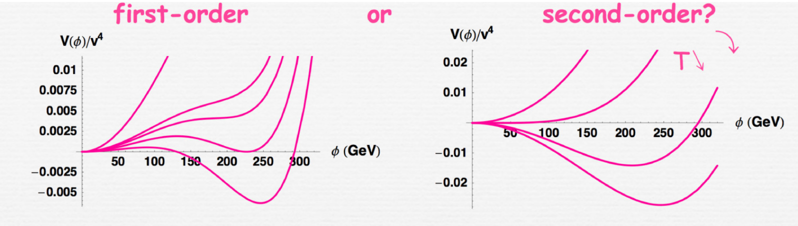


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

- 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:

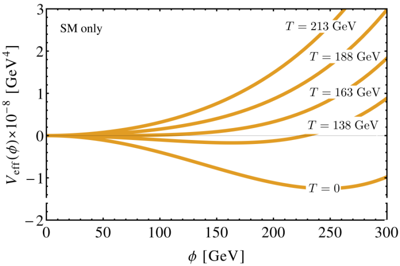
- A strong first order phase transition ($\phi_n/T_n \gtrsim 1$)
- Sufficient CP violation

However in the SM:

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

We require new EW-scale physics!

EW Crossover in the SM



$$V(\phi) \approx -\frac{1}{2}\mu_\phi^2\phi^2 + \frac{1}{4}\lambda_\phi\phi^4 + \frac{1}{2}c_\phi T^2\phi^2$$

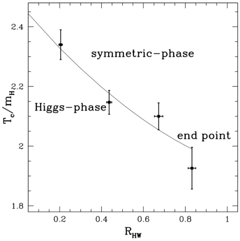
All the parameters are known:

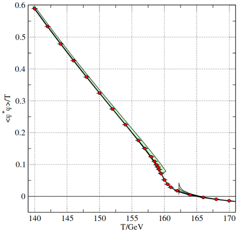
$$\sqrt{2}\mu_\phi = m_h = 125 \text{ GeV}$$

$$v_{\text{EW}} = \sqrt{\frac{2m_h^2}{\lambda}} = 246 \text{ GeV}$$

$$c_\phi \approx \left(\frac{\lambda_\phi}{2} + \frac{3g_2^2}{16} + \frac{g_Y^2}{16} + \frac{1}{4}y_t^2\right) \approx 0.4$$

Electroweak phase transition - Lattice Studies





- Csikor, Fodor, Heitger, hep-ph/9809291, D'Onofrio, Rummukainen 1508.07161

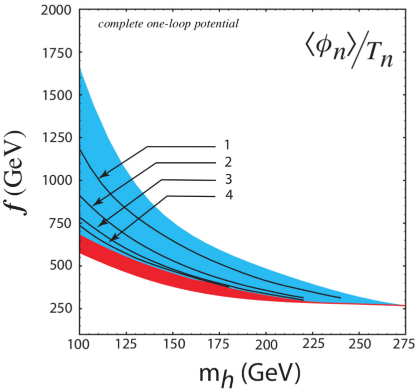
SM with $m_h = 125$ GeV predicts a crossover.
Nevertheless, only the minimum (VEV) of the potential, and the 2nd derivative there (m_h), is known if we allow for BSM physics.

The Higgs potential must be modified.

Require a modification of the Higgs potential

Successful electroweak baryogenesis requires suppressed washout:

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



- Delaunay, Grojean, Wells [0711.2511]

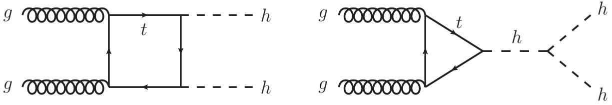
$$V(\Phi) = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6$$

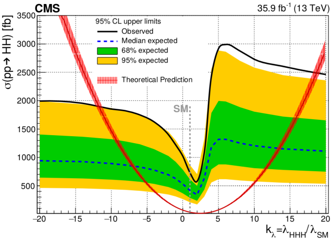
Other options:

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

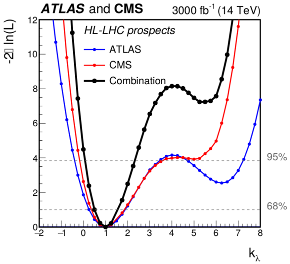
Collider signatures - Triple Higgs coupling

SM: $V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v_{\rm EW} h^3 + \frac{1}{4}\lambda h^4$ with $v_{\rm EW} = \sqrt{\frac{2m_h^2}{\lambda}} = 246$ GeV.





- 1811.09689

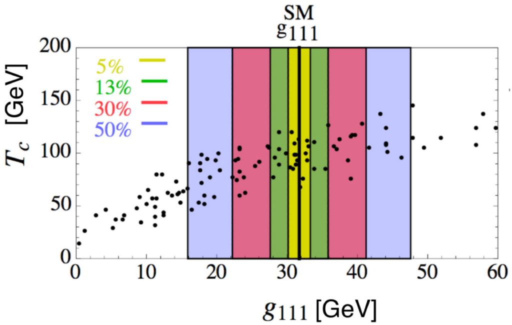


- 1902.00134

Measuring the cubic term is long term challenge.

Collider signatures - Singlet models difficult to detect

First order EW Phase Transition from a singlet - Choi, Volkas '93 + ...



Somewhat optimistically:

$\sim 30 - 50\%$ HL-LHC or TLEP

$\sim 13\%$ ILC

$\sim 3 - 8\%$ 100 TeV pp

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.
- In comparison: light stop scenario ruled out (thermal barrier).
- Another possibility: mixing reducing the signal strength.
  Currently LHC: $\theta \lesssim \mathcal{O}(0.1)$ compatible with singlet models of EWBG.

CPV and The Baryonic Yield

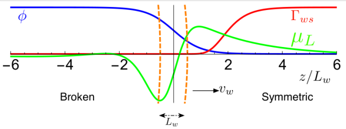


Image from 1706.08534 - Bruggisser, Konstandin, Servant

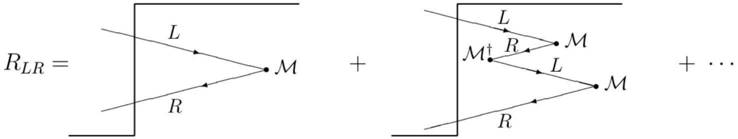
Diffusion equation

$$\partial_z\, n_B = \frac{3}{2} v_w^{-1} \Gamma_{ws} \left(N_c \mu_L T^2 - \mathcal{A}\; n_B \right) , \qquad \Gamma_{ws} = 10^{-6}\; T\; \exp(-a\phi(z)/T)$$

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\;\; N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} dz\; \Gamma_{ws}\;\, \mu_L\;\, e^{-\frac{3}{2}\mathcal{A}\frac{1}{v_w}\int_{-\infty}^{z} dz_0 \Gamma_{ws}}$$

$$\eta_B \sim \frac{\Gamma_{ws} \mu_L L_w}{g_* T} \sim \frac{10^{-8} \mu_L}{T} \quad \text{for} \quad L_w \sim \frac{1}{T}$$

Baryogenesis from charge transport with SM CP violation

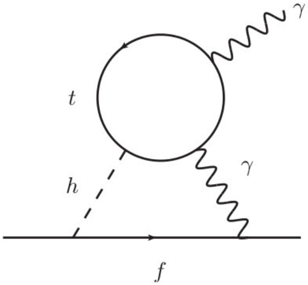


$$\epsilon_{\mathrm{CP}} \sim \frac{1}{M_W^6 T_c^6} \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) J_{\mathrm{CP}} \sim 10^{-19}$$

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

SM quark masses are too small!

electron EDM constraint



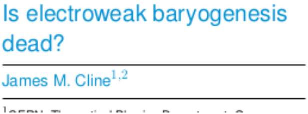
Rough estimate of the EDM - Glioti, Rattazzi, Vecchi, 1811.11740.

$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}}\left(\frac{50\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 1-\mathrm{loop}$$

$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}}\left(\frac{2.5\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 2-\mathrm{loop}$$

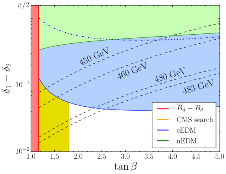
EDMs - Situation 2013-2018

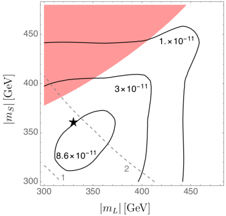
ACME: $|d_e| < 8.7 \times 10^{-29}\ e\,\mathrm{cm}$ (2013) $|d_e| < 9.4 \times 10^{-29}\ e\,\mathrm{cm}$ (2017)

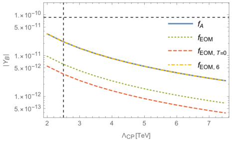


Is electroweak baryogenesis dead?

James M. Cline[1,2]

1.


2.


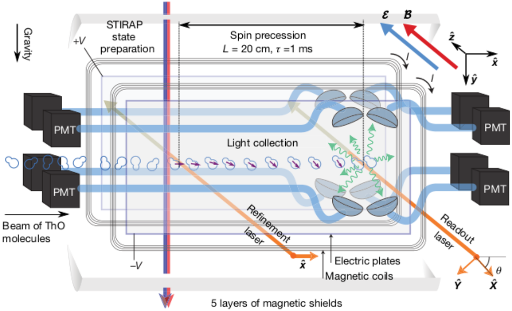
3.


1. 1611.05874 - Dorsch, Huber, Konstandin, No
2. 1707.02306 - Egana-Ugrinovic
3. 1710.04061 - de Vries, Postma, van de Vis, White

Severe constraint on EWBG!

EDMs - Situation after 18.10.2018

$$\text{ACMEII: } |d_e| < 1.1 \times 10^{-29}\ e\,\mathrm{cm}.$$



Extremely severe constraint on EWBG!

Circumventing the EDM constraint

Rough estimate of the EDM - Glioti, Rattazzi, Vecchi, 1811.11740.

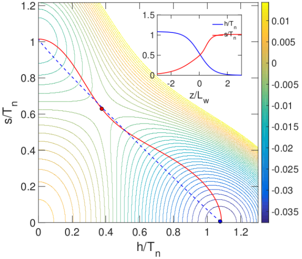
$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{50\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 1-\mathrm{loop}$$

$$|d_e| \sim 10^{-29}\ e\,\mathrm{cm}\,\theta_{\mathrm{CP}} \left(\frac{2.5\ \mathrm{TeV}}{\Lambda}\right)^2 \qquad 2-\mathrm{loop}$$

To overcome this

1. Hide CP violation through additional loops.
2. Push the EWPT to some large Λ.

1. Additional Loops



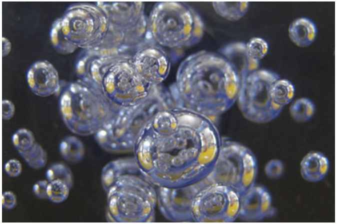
$\mathcal{L} \supset \frac{1}{2}\bar{\chi}\left((\eta P_R + \eta^* P_L)S + m_\chi\right)\chi + y\bar{L}_\tau\phi_2 P_R\chi + \mathrm{h.c.}$ - from (1) below.

One idea is to hide the CP violation in the dark sector

1. "Electroweak baryogenesis from a dark sector", Cline, Kainulainen, Tucker-Smith, 1702.08909.
2. "Electroweak Baryogenesis From Dark CP Violation," Carena, Quirós, Zhang, 1811.09719 and 1908.04818.

- eEDM at 3 or 4-loops.

2. Increase Λ - High Scale EWBG



Bold approach here:

- Lift **electroweak** baryogenesis from the **electroweak** scale.

Based on: IB, Servant, 1807.08770

Also see:

- Meade and Ramanim, 1807.07578.
- Glioti, Rattazzi, Vecchi, 1811.11740.

High scale EWBG

We will now take a novel approach and push the EWBG scale up to the flavour scale.

1. EWPT and EWBG at the flavour scale.
   (For EWBG/flavour connection overview see: Servant 1807.11507)
2. Source of CP violation at the flavour scale (suppress EDM signature and also flavour constraints.)
3. Need the Higgs VEV to eventually get to 246 GeV and protect from washout.

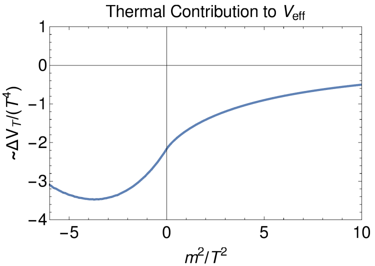
Warning: large N ahead.

We will see (3) requires new, but different, physics at the EW scale.

High scale EWBG - Symmetry non-restoration

Need to switch off the sphalerons, $\phi/T \gtrsim 1$, to avoid washout after baryogenesis.

Use symmetry non-restoration! Weinberg '74, ...



New scalar field with mass

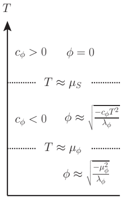
$$m_\chi^2 = \mu_\chi^2 + \frac{1}{2}\lambda_{\phi\chi}\phi^2 + 3\lambda_\chi\chi^2.$$

Take $\lambda_{\phi\chi} < 0$.

$$c_\phi T^2 \approx \left(\frac{\lambda_\phi}{2} + \frac{3g_2^2}{16} + \frac{g_Y^2}{16} + \frac{1}{4}y_t^2 + N_{\rm dof}\frac{\lambda_{\phi\chi}}{24}\right)T^2 < 0$$

$$V(\phi) = (m_\phi^2 + c_\phi T^2)\phi^2 + \lambda_\phi\phi^4 \implies \langle\phi\rangle = \sqrt{-\frac{c_\phi}{\lambda_\phi}}T!$$

Toy Example - Numerical analysis



$c_\phi > 0 \quad \phi = 0$

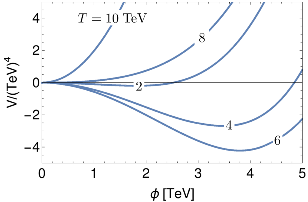
$T \approx \mu_S$

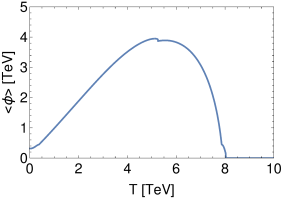
$c_\phi < 0 \quad \phi \approx \sqrt{\frac{-c_\phi T^2}{\lambda_\phi}}$

$T \approx \mu_\phi$

$\phi \approx \sqrt{\frac{-\mu_\phi^2}{\lambda_\phi}}$

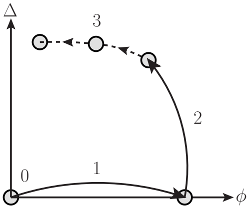
An additional threshold switches the thermal mass from +ve to -ve.





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

Complete Model



The Ingredients

1. flavour sector (new fermions + scalar)
2. scalar potential with higher dimensional operators
3. symmetry non-restoring scalars

The analysis

- Phase Transitions
- Pheno
- IR sector + Constraints

Flavour sector

Flavour sector

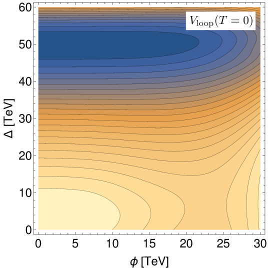
- The idea is to have large/varying Yukawa couplings during the EWPT.
- These then reach their SM values when flavour sector scalar VEVs have reached their present values.
- Froggatt-Nielsen Mechanism for top/charm used as an example here.
- We introduce a global $U(1)_{\mathrm{FN}}$.

$$\frac{\phi}{\sqrt{2}} \begin{pmatrix} \bar{t_R} \\ \bar{c_R} \end{pmatrix}^T \begin{pmatrix} 1 & \epsilon^2 \\ \epsilon & \epsilon^3 \end{pmatrix} \begin{pmatrix} t_L \\ c_L \end{pmatrix} \qquad \epsilon \equiv a_s/\Lambda_{\mathrm{FN}} \sim 0.2$$

Flavour constraints ($K - \bar{K}$) imply $\Lambda_{\mathrm{FN}} \gtrsim 10$ TeV.
Soft breaking terms give mass to the Goldstone boson.

In our analysis we consider the UV flavour picture - details suppressed here.

The Scalar Potential



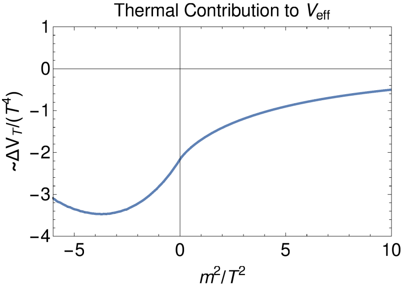
$$V(\phi,\Delta)=\frac{\mu_\phi^2}{2}\phi^2+\frac{\lambda_\phi}{4}\phi^4+\frac{\lambda_{\phi\Delta}}{4}\phi^2\Delta^2+\frac{\mu_\Delta^2}{2}\Delta^2+\frac{\lambda_\Delta}{4}\Delta^4 \\ +\frac{1}{8\Lambda_a^2}\Delta^6+\frac{1}{8\Lambda_b^2}\phi^2\Delta^4+\frac{1}{8\Lambda_c^2}\phi^4\Delta^2+\frac{1}{8\Lambda_d^2}\phi^6.$$

$$v_\Delta=50\ \mathrm{TeV},\qquad \lambda_{\phi\Delta}=-0.05,\qquad \lambda_\Delta=-0.23,$$
$$\Lambda_a=\Lambda_d=100\ \mathrm{TeV},\qquad \Lambda_b=\Lambda_c=300\ \mathrm{TeV}.$$

Symmetry Non-restoring sector

We add a few extra scalar degrees of freedom.

$$V(\phi,\chi) = \frac{\lambda_{\phi\chi}}{4}\phi^2 \sum_{i=1}^{N_{\rm Gen}} \chi_i^2 + \frac{\mu_\chi^2}{2} \sum_{i=1}^{N_{\rm Gen}} \chi_i^2 + \frac{\lambda_\chi}{4} \sum_{i=1}^{N_{\rm Gen}} \chi_i^4$$



(i) $c_{\chi i} \approx \frac{\lambda_\chi}{4} + \frac{\lambda_{\phi\chi}}{6} \ll 1$

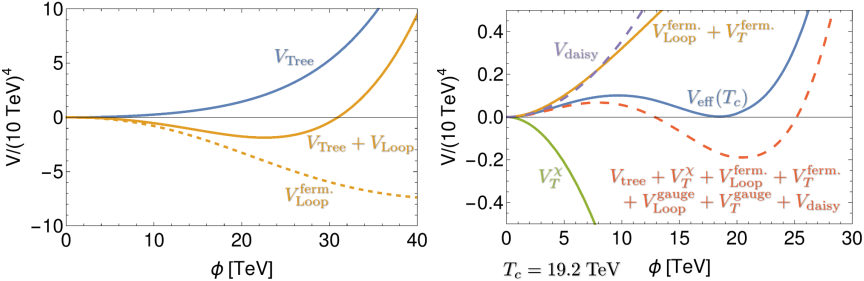
(ii) Stability: $\lambda_{\phi\chi} > -2\sqrt{\frac{\lambda_\phi \lambda_\chi}{N_{\rm Gen}}}$

(iii) $c_\phi \approx \frac{\lambda_\phi}{2} + 3\frac{g_2^2}{16} + \frac{g_Y^2}{16} + \frac{\lambda_{\phi\Delta}}{24}$
$+N_{\rm Gen}\frac{\lambda_{\phi\chi}}{24} + \frac{1}{4}\sum_f \left[y_{f\phi}^{\rm eff}(\phi,\Delta)\right]^2 < 0$

Large $N_{\rm dof}$ needed: (i) keep χ thermal mass small,
(ii) keep potential stabilized, (iii) obtain $c_\phi < 0$.

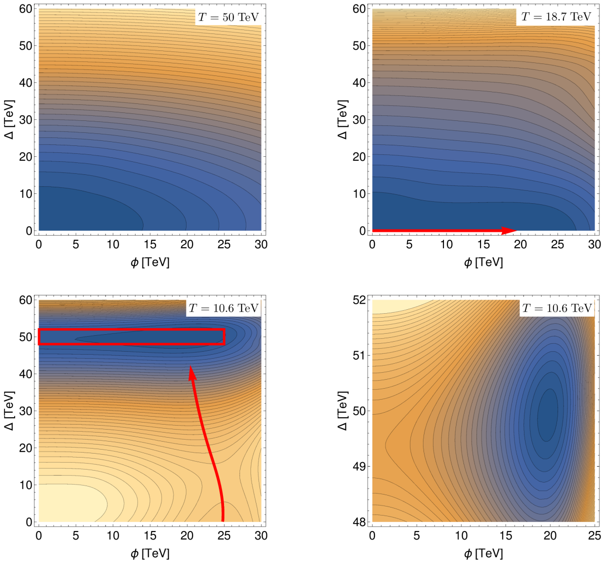
$N_{\rm Gen} = 2000, \qquad N_{\chi i} = 1, \qquad \lambda_\chi = 0.7, \qquad \lambda_{\phi\chi} = -0.012.$

The EWPT

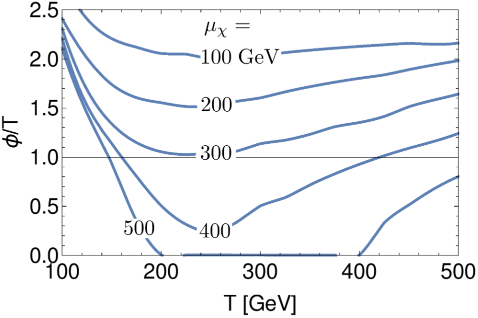


Achieve $\frac{\phi_n}{T_n} \gtrsim 1$.

Thermal Evolution



Scalar Sector in the IR



Spectrum of states with masses

$$m^2_{\chi_i} \sim \mathcal{O}(\mu^2_\chi + \lambda_{\phi\chi} v^2_\phi/2)$$

Constraints:

$$63\ \mathrm{GeV} \lesssim m_{\chi_i} \lesssim 300\ \mathrm{GeV}$$

Conclusions

Summary

- EWBG is a testable – already constrained – model of baryogenesis.
- Severe EDM constraints:
  (i) need to hide CP violation with additional loops.
  (ii) lift EWBG from the EW scale.
- The latter allows us to tie EWBG to flavour physics → source of CPV.
- Signal is a large number of light scalars with a small coupling to the Higgs.

Thanks

The terms of the one-loop effective potential

Effective Potential

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

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

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

$$V_{\mathrm{Daisy}}^{\phi}(\phi, T) = \frac{T}{12\pi}\left\{m_\phi^3(\phi) - \left[m_\phi^2(\phi) + \Pi_\phi(\phi, T)\right]^{3/2}\right\}$$

Flavour sector - UV picture

In the UV completion add vector-like quarks

These transform as u_R under the SM gauge group. Superscript gives FN charge.

$$G^0_{L,R} \qquad G^1_{L,R} \qquad G^2_{L,R}$$

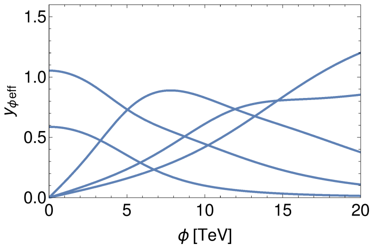
Δ is another scalar which (partially) controls the FN quark mass

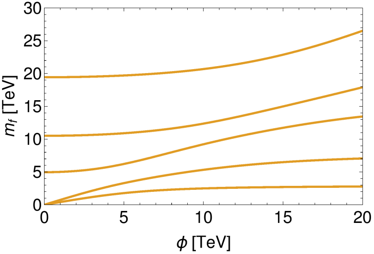
$$\mathcal{L} \supset (M + \Delta)\bar{G}^i_R G^i_L. \qquad \text{We take } M \sim a_s.$$

$$\frac{1}{\sqrt{2}} \begin{pmatrix} \bar{G}^0_R \\ \bar{G}^1_R \\ \bar{G}^2_R \\ \bar{t}_R \\ \bar{c}_R \end{pmatrix}^T \begin{pmatrix} a_s + \Delta & a_s & 0 & \phi & 0 \\ a_s & a_s + \Delta & a_s & 0 & 0 \\ 0 & a_s & a_s + \Delta & 0 & \phi \\ a_s + \Delta & a_s & 0 & \phi & 0 \\ a_s & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} G^0_L \\ G^1_L \\ G^2_L \\ t_L \\ c_L \end{pmatrix}$$

$$\epsilon \approx a_s / v_\Delta \approx 1/5$$

Effective Yukawa Couplings





Effective Yukawa couplings

$$y^{\mathrm{eff}}_{f\phi} = \sqrt{2}\frac{\partial m_f}{\partial \phi}, \qquad y^{\mathrm{eff}}_{f\Delta} = \sqrt{2}\frac{\partial m_f}{\partial \Delta}.$$

For $v_\Delta \lesssim a_s$ the Yukawa couplings are large.

Avoiding χ_i overabundance

Options

1. The χ_i annihilate into hidden sector.
2. The χ_i decay into lighter states.

Option 2. The χ_i decay into light SM dof.

$$V \supset -\sum_i a_{\chi_i}^3 \chi_i \implies v_{\chi_i} \sim \frac{a_{\chi_i}^3}{m_{\chi_i}^2}$$

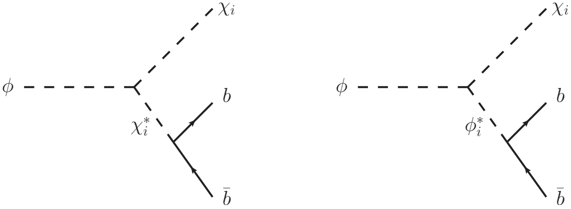
$$\text{Mixing:} \qquad \theta_i \approx \frac{\lambda_{\phi\chi} v_\phi v_{\chi_i}}{m_{\chi_i}^2 - m_\phi^2}.$$

$$10^{-6} \lesssim |\theta_i| \lesssim 10^{-4} \left(\frac{2000}{N_{\mathrm{Gen}}}\right).$$

Bounded by BBN and the Higgs signal strength.

Exotic EW Higgs Decays

More decay channels open for the EW Higgs

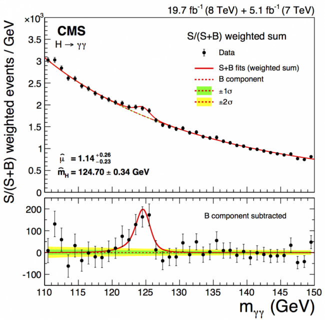


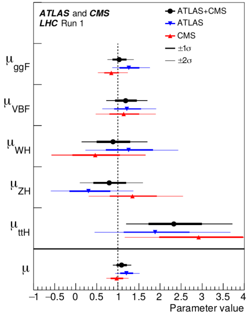
But these are negligible

$$\sum_i \Gamma(\phi \to \chi_i^* \chi_i \to \bar{b} b \chi_i) \sim \frac{3 N_{\mathrm{Gen}} \lambda_{\phi\chi}^2 \theta_i^2 m_b^2}{128\pi^3 m_\phi} \sim 10^{-10}\ \mathrm{MeV}$$

$$\sum_i \Gamma(\phi \to \phi^* \chi_i \to \bar{b} b \chi_i) \sim \frac{3 N_{\mathrm{Gen}} \lambda_{\phi\chi}^2 v_{\chi_i}^2 m_b^2}{128\pi^3 v_\phi^2 m_\phi} \sim 10^{-7}\ \mathrm{MeV}$$

LHC constraints - Limit on Mixing

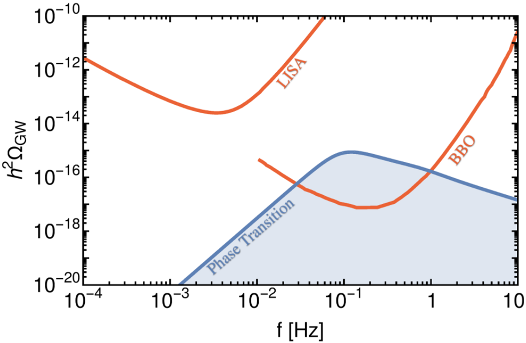


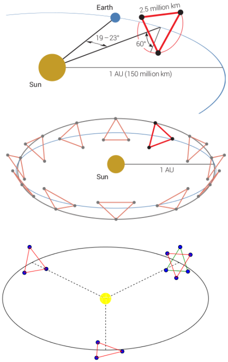


$\mu = 1.09 \pm 0.11$	LHC Run 1	7 + 8 TeV	1606.02266
$\mu = 1.10 \pm 0.06$	LHC Run 2	13 TeV	1810.02521

$$\theta \lesssim \mathcal{O}(0.1)$$

Gravitational wave signal





$$\frac{\beta}{H} \equiv T_n \frac{d}{dT}\left(\frac{S_3}{T}\right)\Bigg|_{T_n} \approx 180 \qquad \alpha \equiv \frac{\rho_{\mathrm{vac}}(\mathrm{false}) - \rho_{\mathrm{vac}}(\mathrm{true})}{\rho_{\mathrm{rad}}} \approx 8 \times 10^{-3}$$

EDMs - Situation in 2006

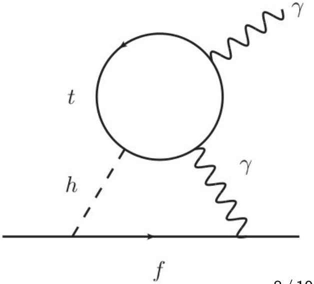
Additional CP violation

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

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

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

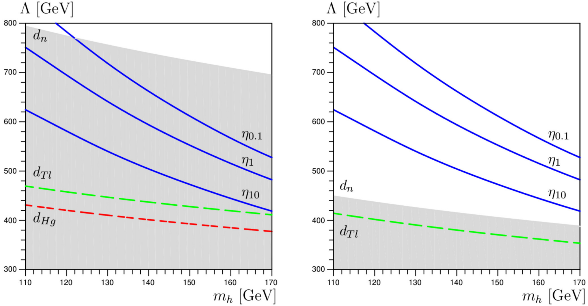
- Such operators are constrained from EDMs and FCNCs.
- Constraint from neutron EDM: $\Lambda_{\mathrm{CP}} \gtrsim \sqrt{\mathrm{Im}[x_{33}]} \times 750$ GeV.
- Small Λ_{CP} possible with $x_{ij} \sim y_{ij}$.



EDMs - Situation in 2006

Additional CP violation

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



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

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

The matter-antimatter asymmetry

Textbook Argument for Baryogenesis

- In a symmetric universe $n_b/s = n_{\bar{b}}/s \approx 10^{-20}$
- The post-inflation causal volume is too small for baryons/antibaryons to be sufficiently separated
- $n_b/s = n_{\bar{b}}/s \approx 10^{-10}$ would be reached at $T \approx 40$ MeV when $M_{H^{-3}} \approx 10^{-7} M_\odot$
- Need a mechanism to generate the asymmetry