High Scale Electroweak Baryogenesis

Iason Baldes
In collaboration with Géraldine Servant

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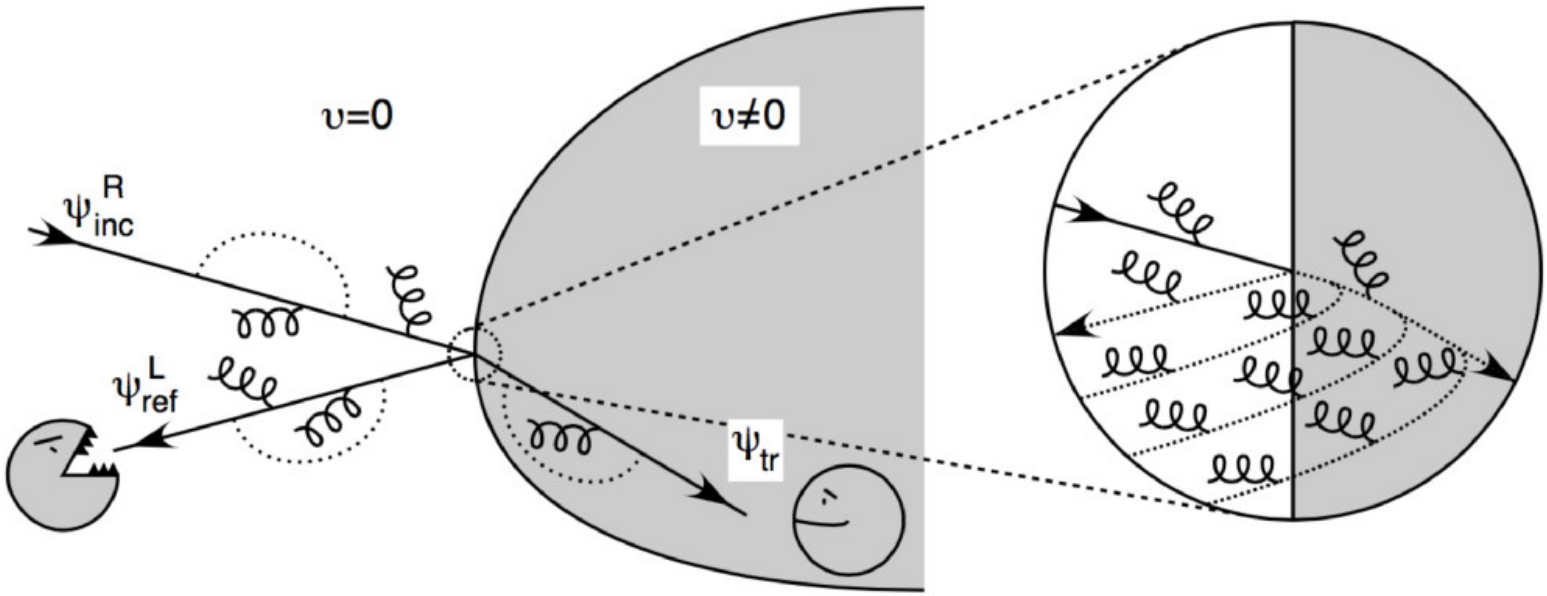
BLV2019, Madrid
22 October 2019

Electroweak baryogenesis - basic picture



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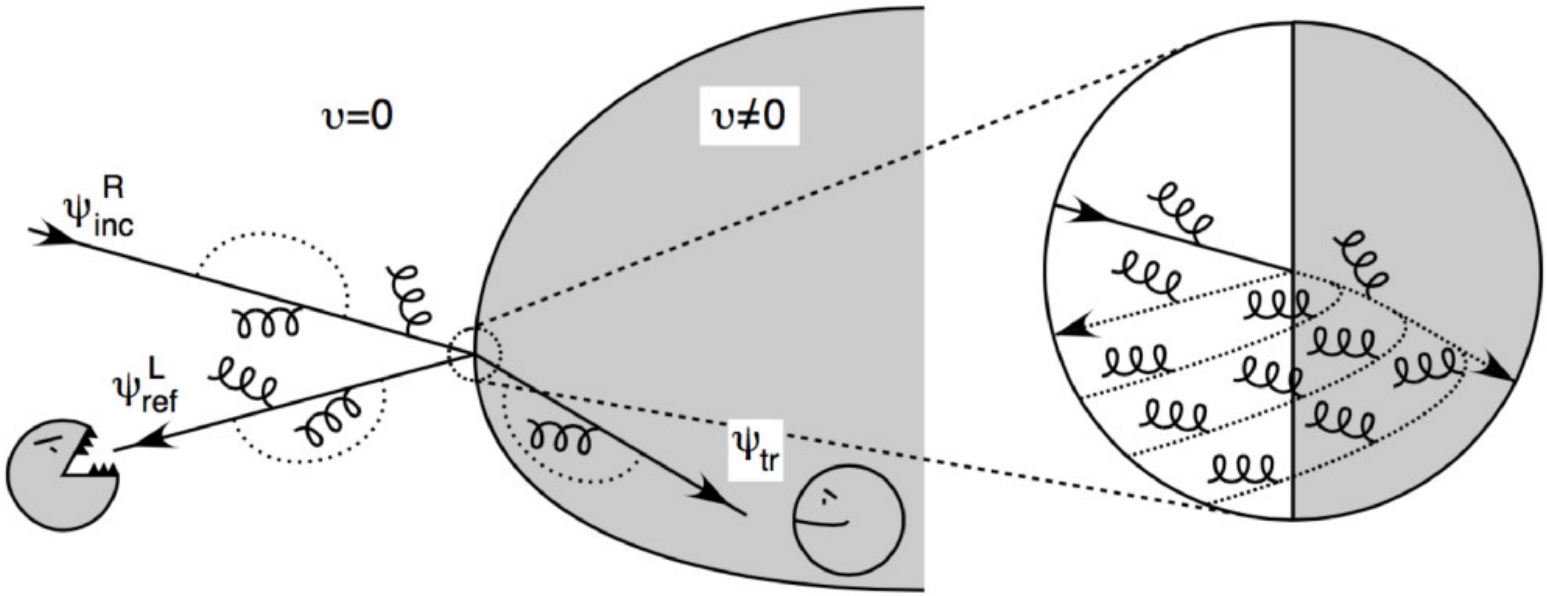

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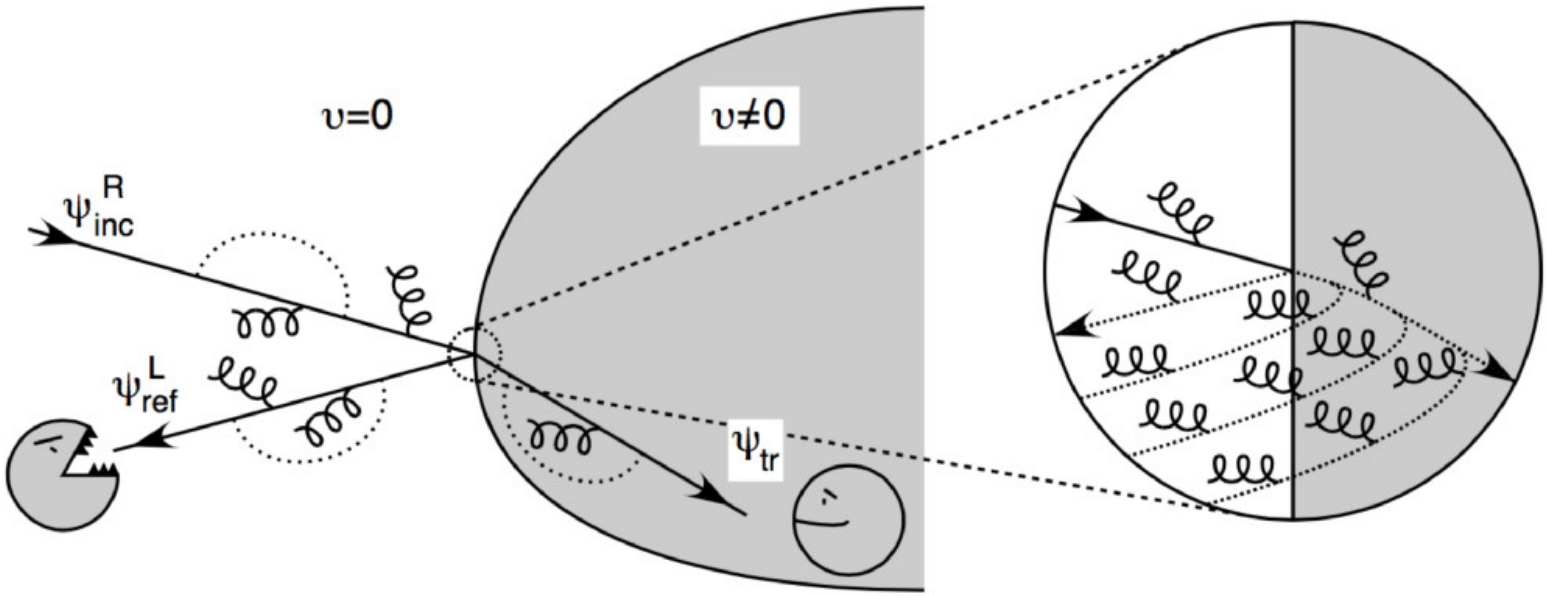

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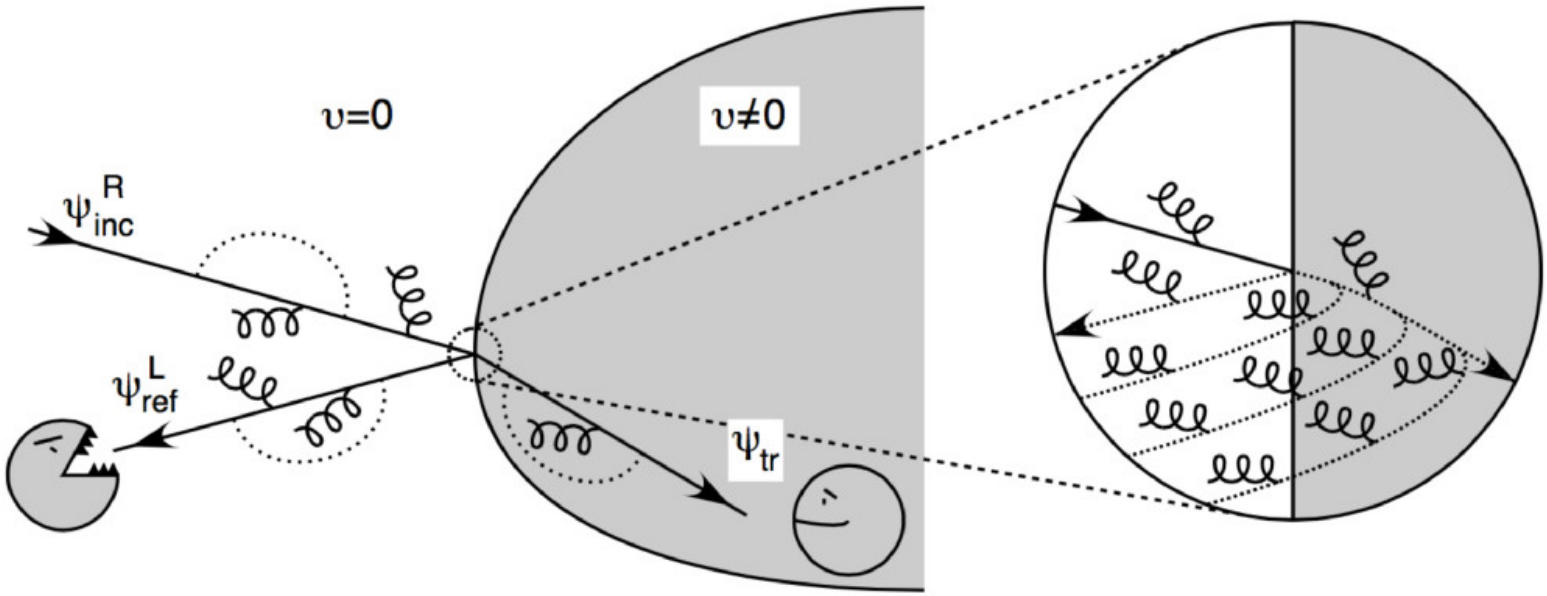

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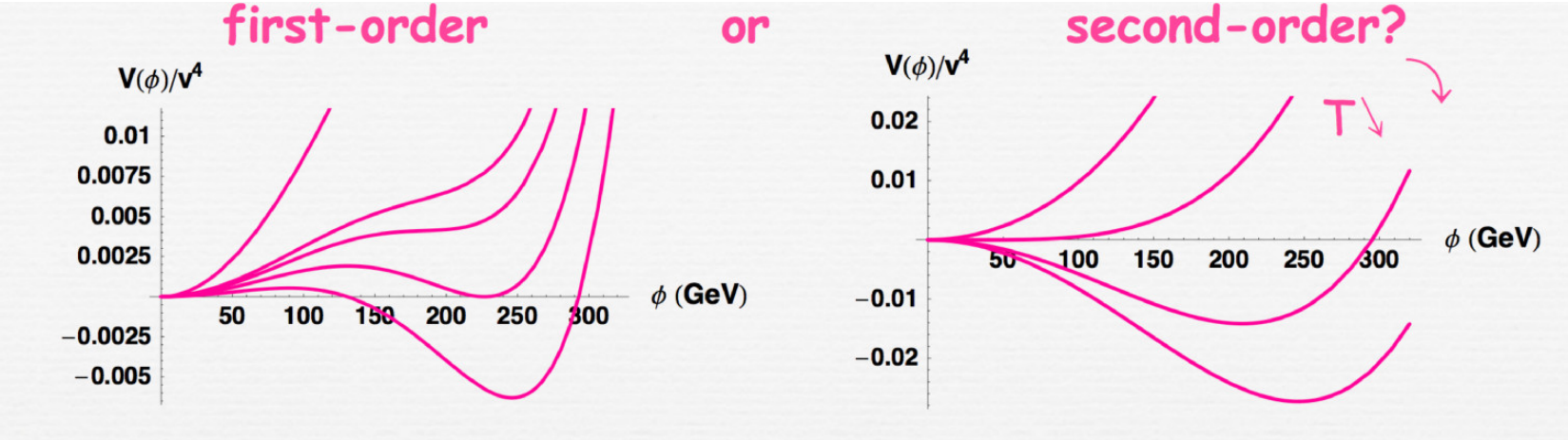
- This is swept into the expanding bubble where sphalerons are suppressed.

Electroweak baryogenesis - Requirements



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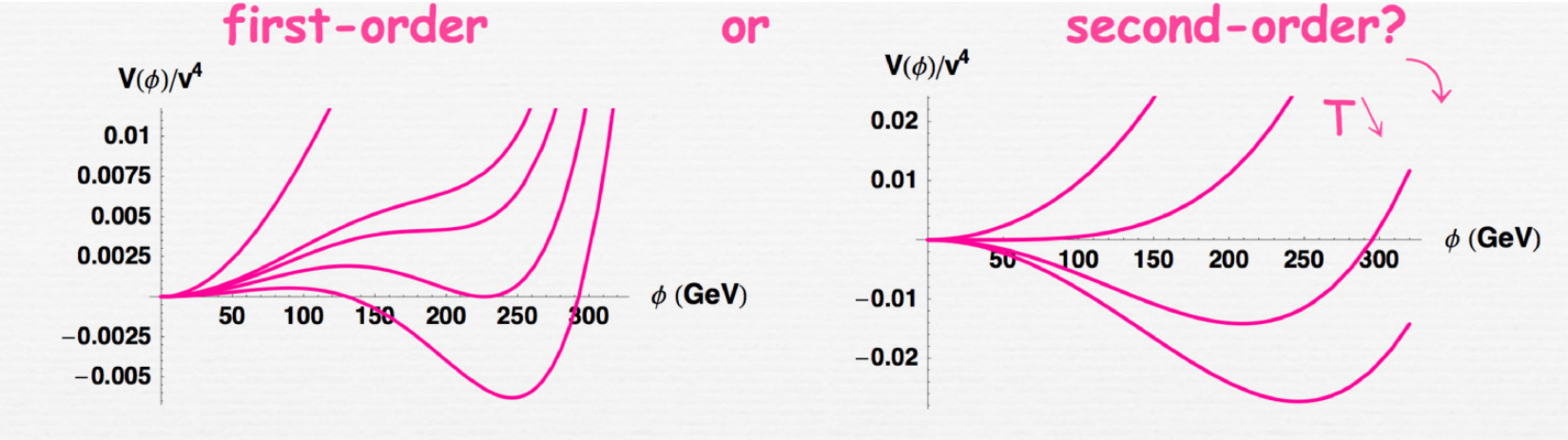

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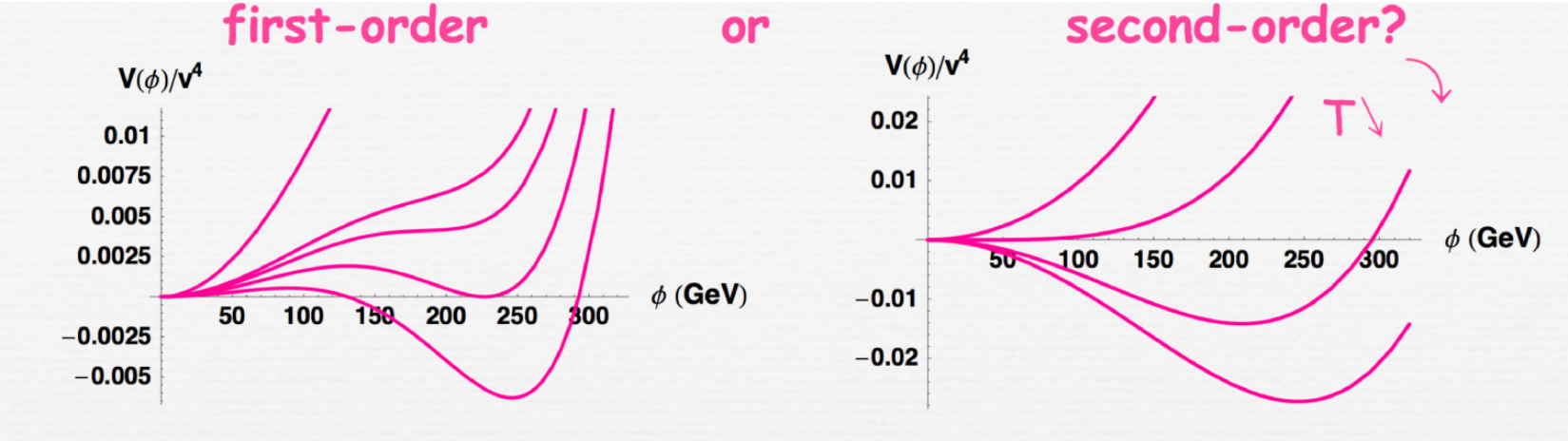

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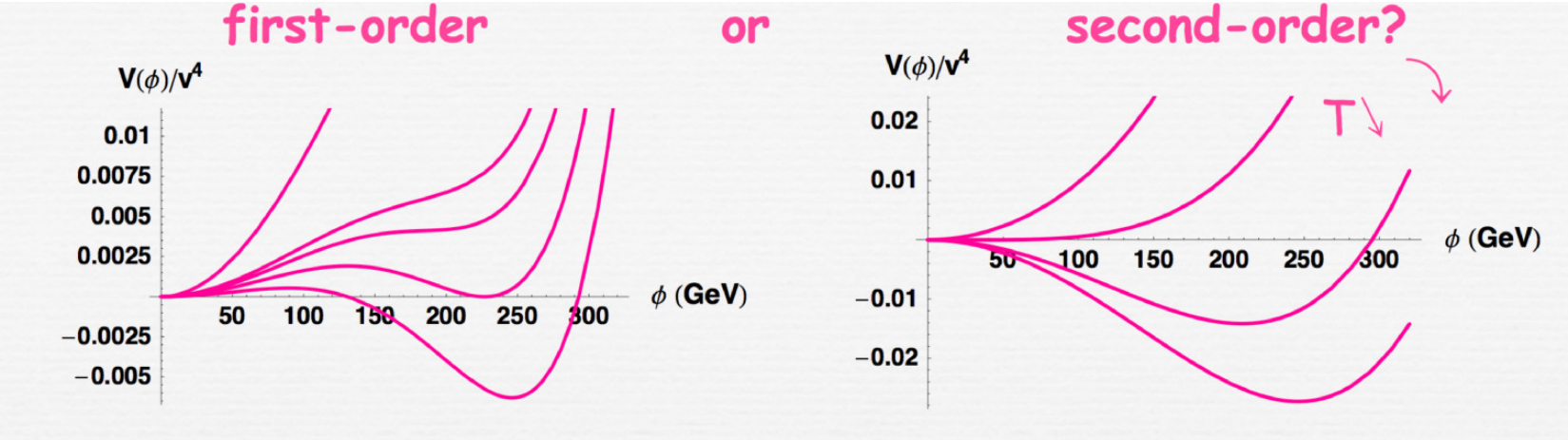

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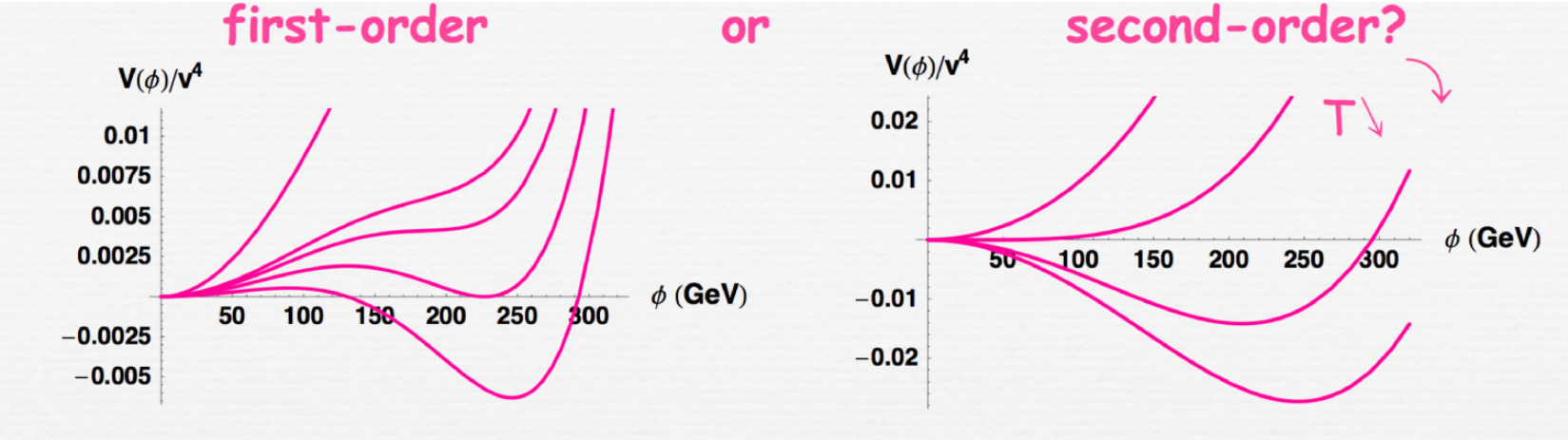

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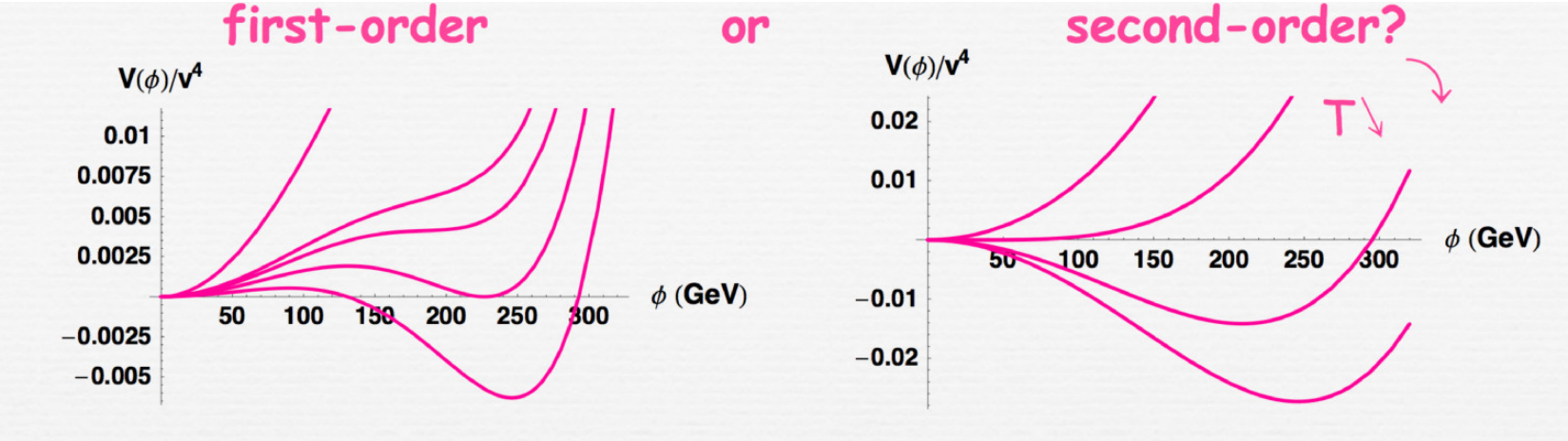

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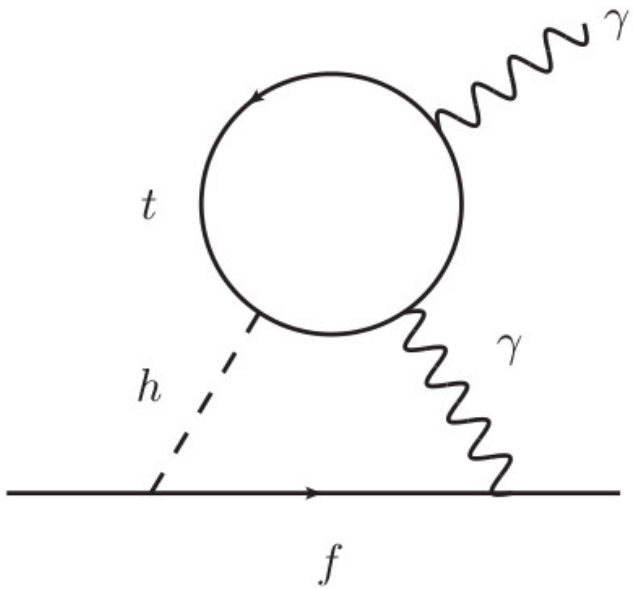
We require new EW-scale physics!

Electron EDM constraint



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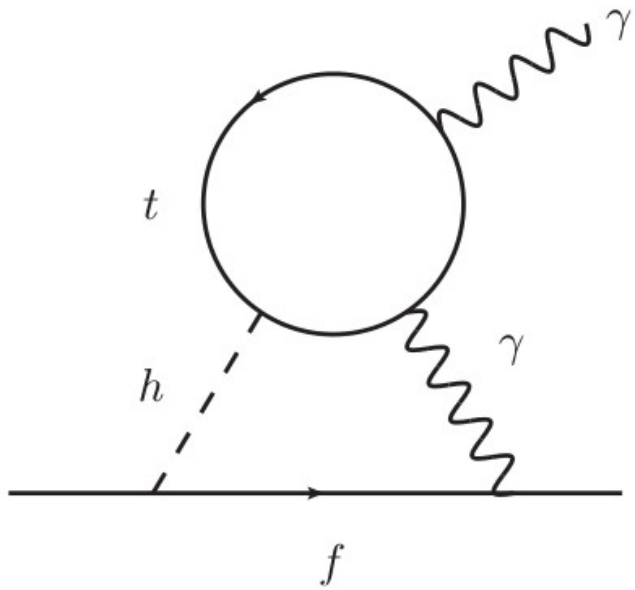

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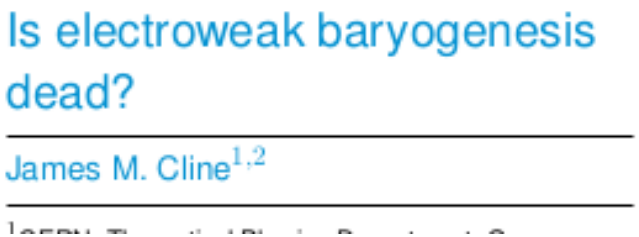
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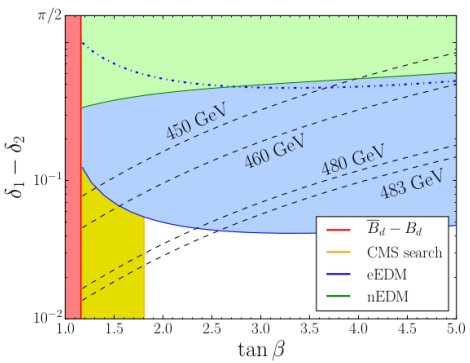

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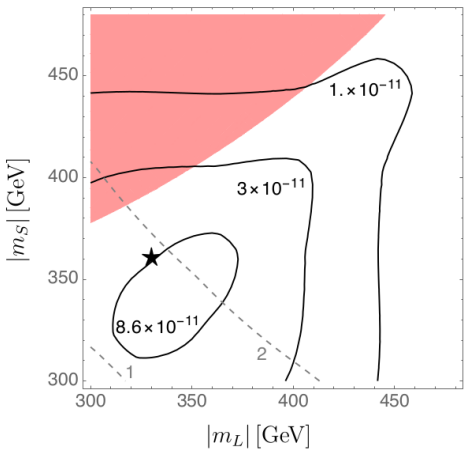

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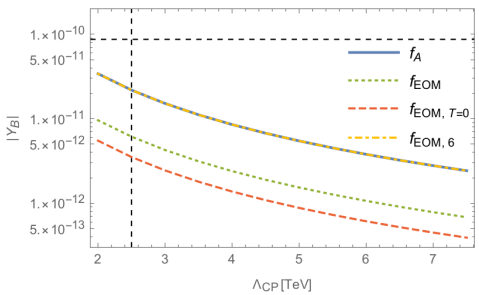

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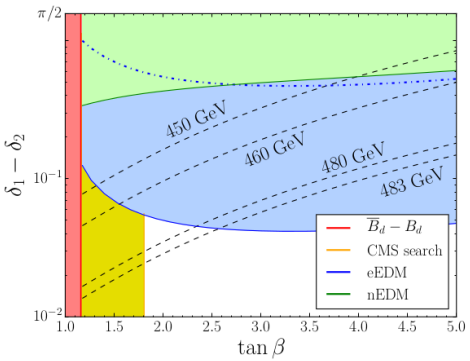

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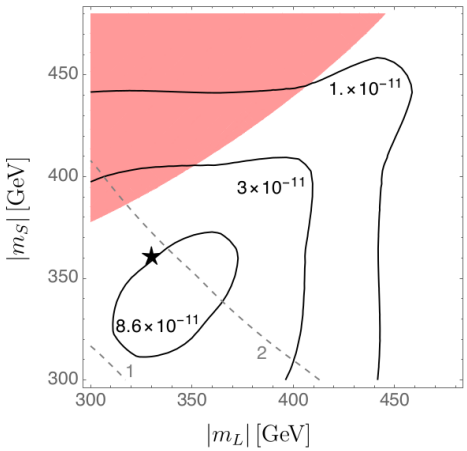

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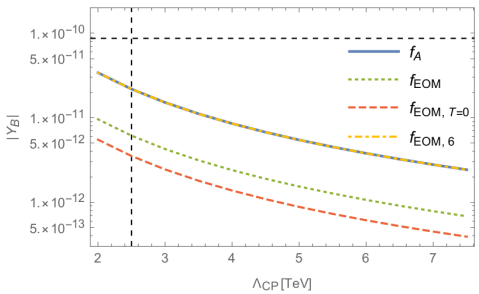

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Severe constraint on EWBG!

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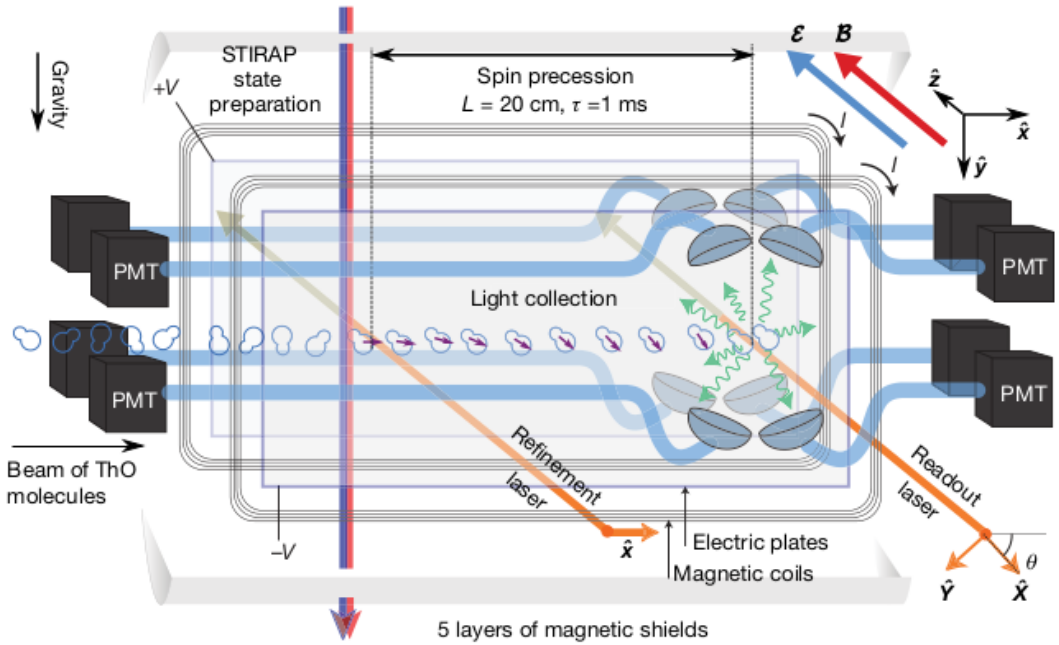

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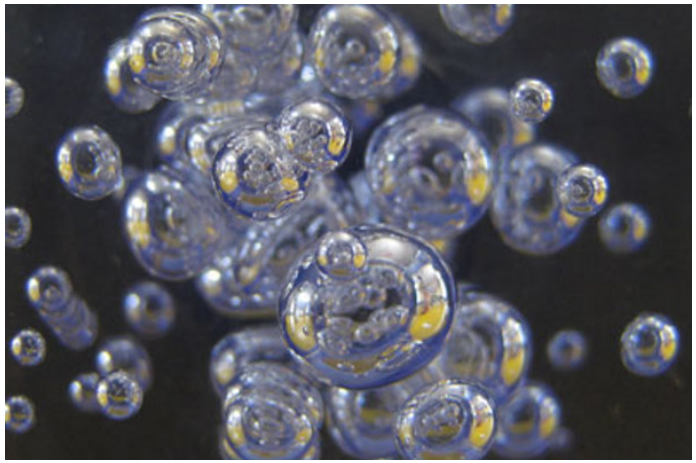
2. Push the EWPT to some large Λ.

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.
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Warning: large N ahead.

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

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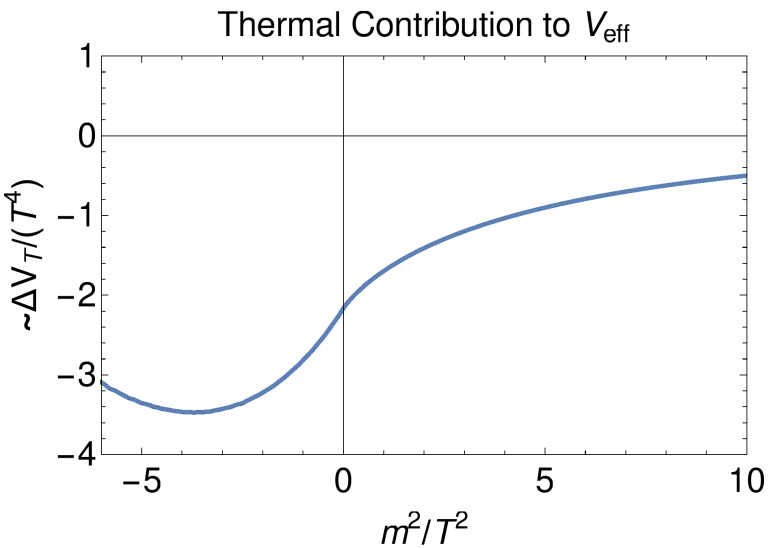

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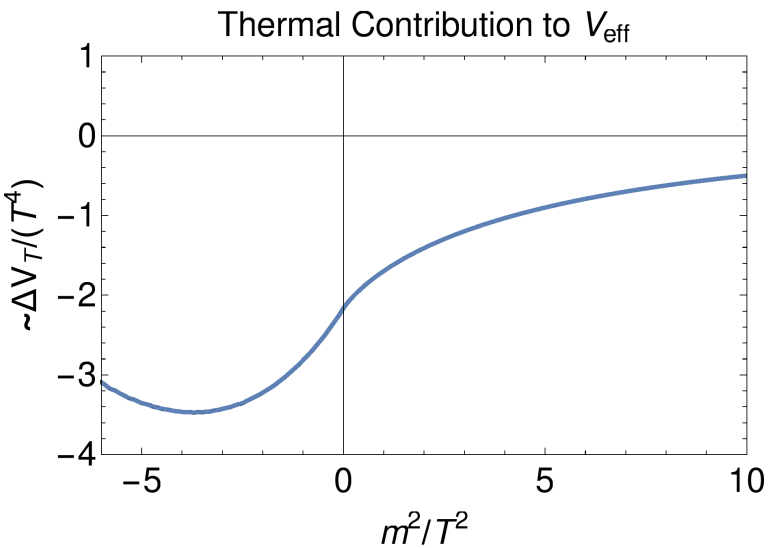

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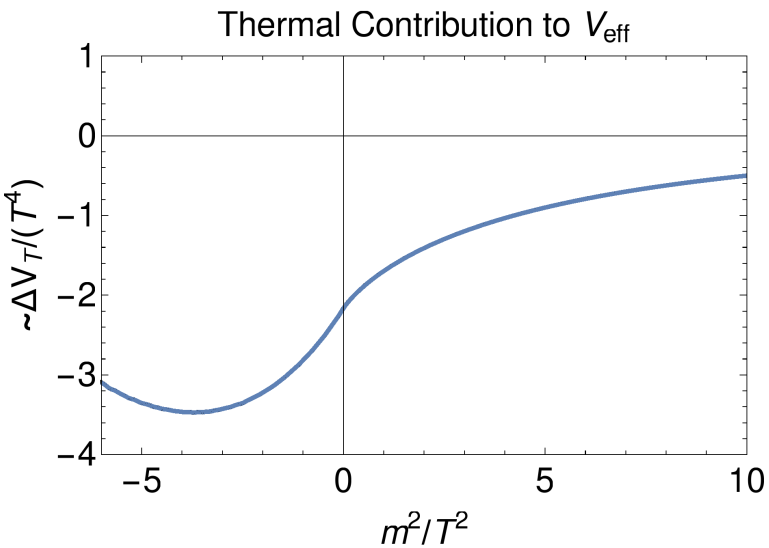

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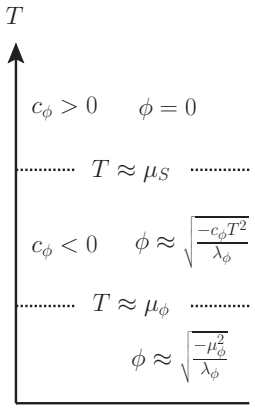
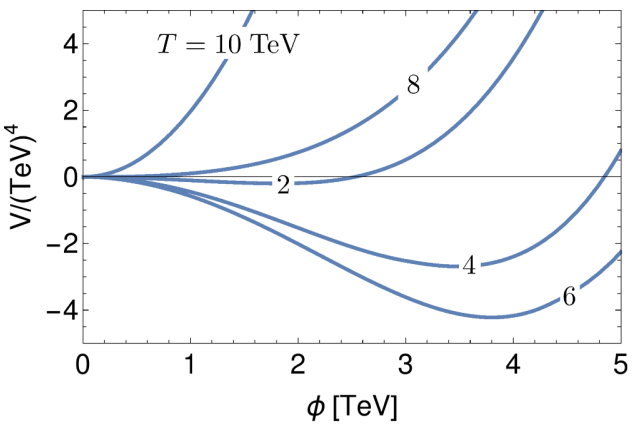
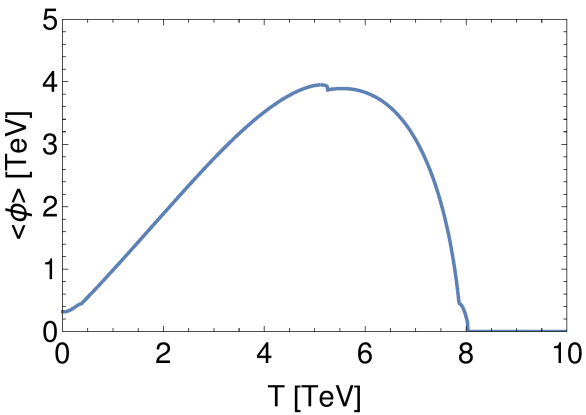
$$V(\phi) = (m_\phi^2 + c_\phi T^2)\phi^2 + \lambda_\phi\phi^4 \implies \langle\phi\rangle = \sqrt{-\frac{c_\phi}{\lambda_\phi}}\,T!$$

Toy Example - Numerical analysis



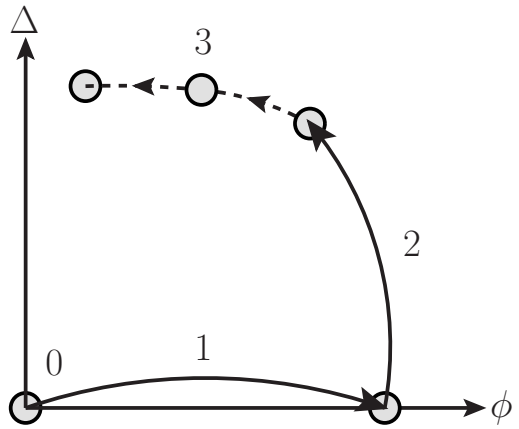
An additional threshold switches the thermal mass from +ve to -ve.





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

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

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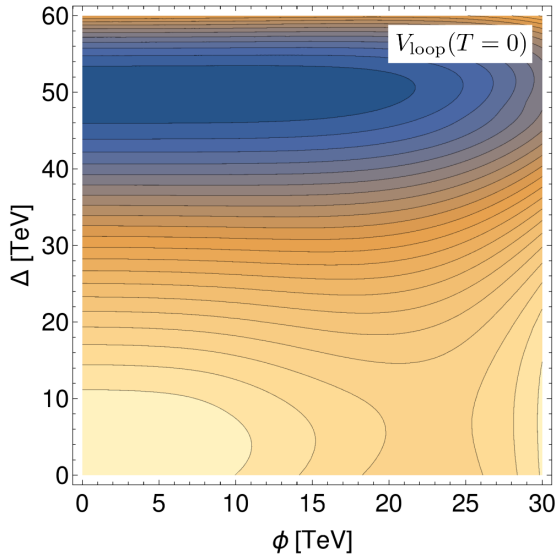
In our analysis we consider the UV flavour picture - details suppressed here.

The Scalar Potential



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

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

Symmetry Non-restoring sector

We add a few extra scalar degrees of freedom.

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

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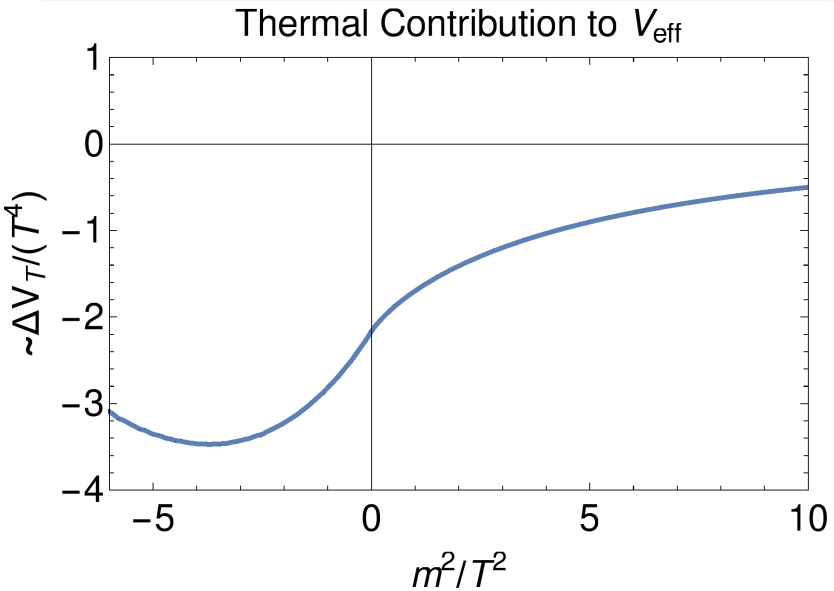

(i) $c_{\chi i} \approx \frac{\lambda_\chi}{4} + \frac{\lambda_{\phi\chi}}{6} \ll 1$

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

(iii) $c_\phi \approx \frac{\lambda_\phi}{2} + 3\frac{g_2^2}{16} + \frac{g_Y^2}{16} + \frac{\lambda_{\phi\Delta}}{24}$

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

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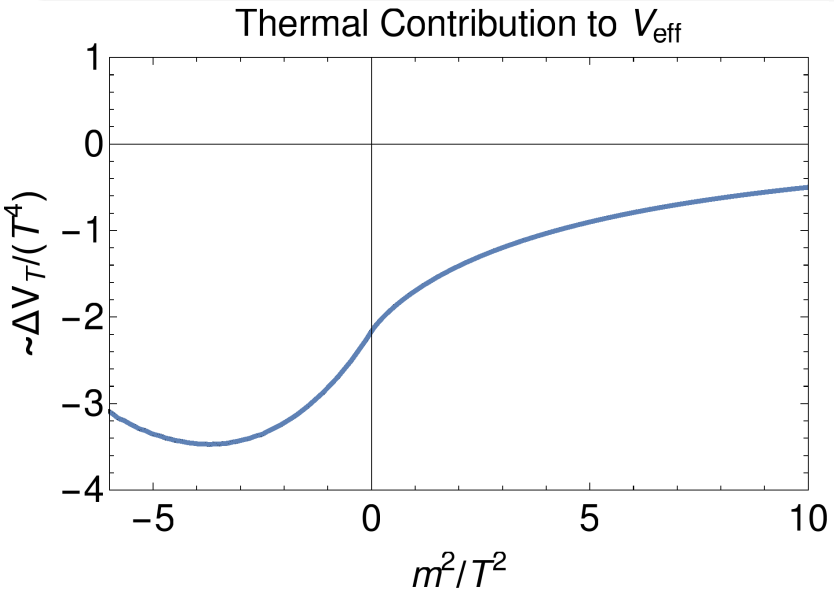

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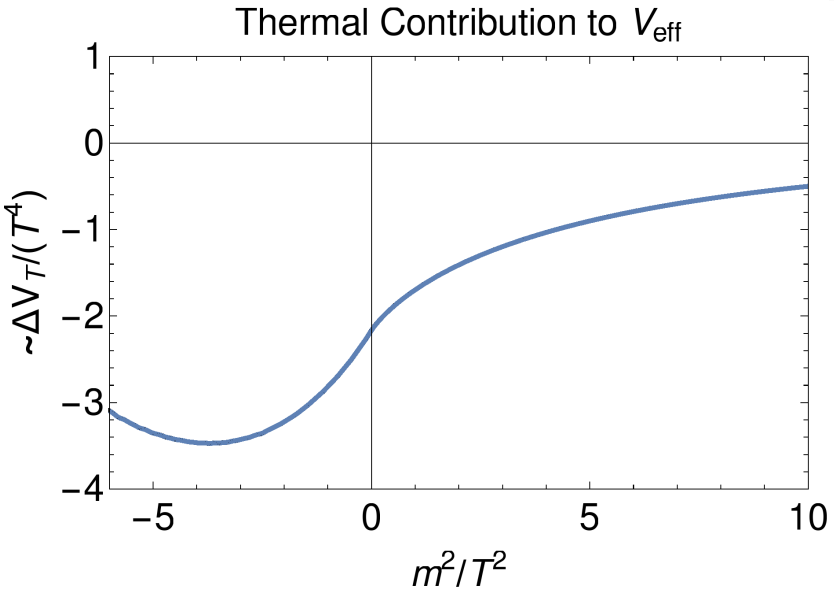

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$N_{\rm Gen}=2000,\qquad N_{\chi i}=1,\qquad \lambda_\chi=0.7,\qquad \lambda_{\phi\chi}=-0.012.$

The EWPT

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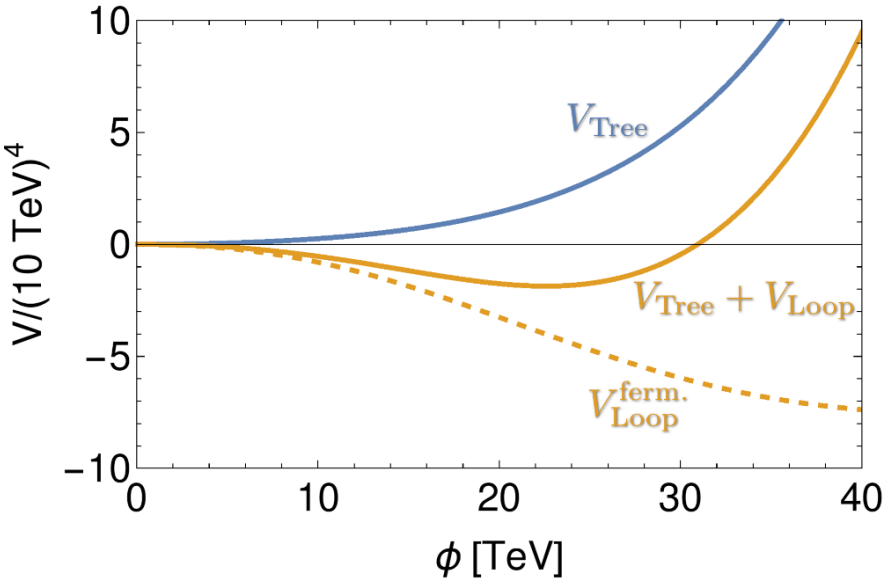
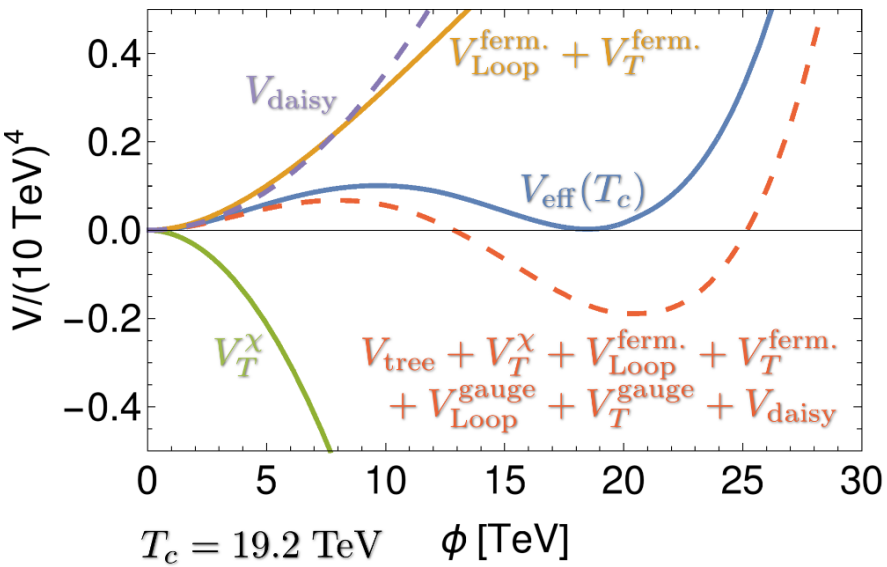
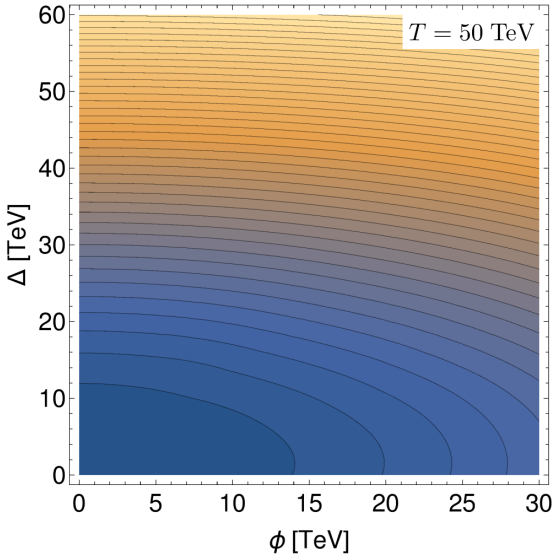




Achieve $\frac{\phi_n}{T_n} \gtrsim 1$.

Thermal Evolution



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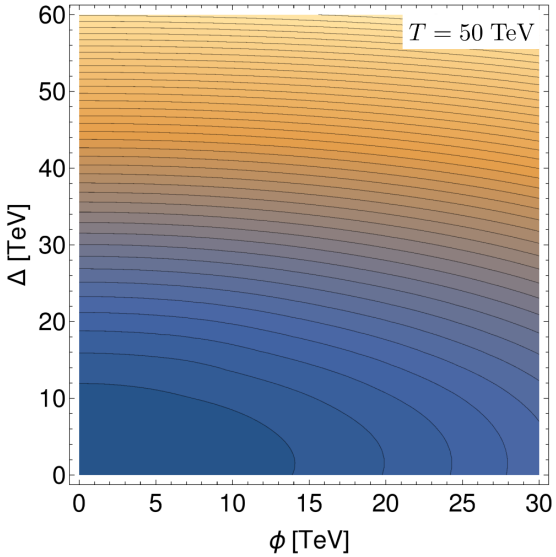

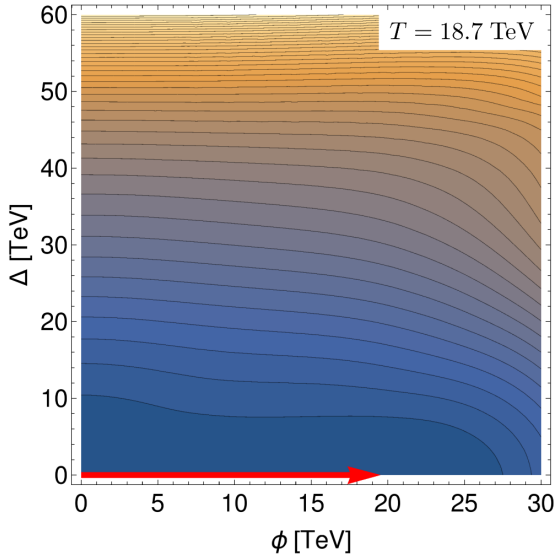

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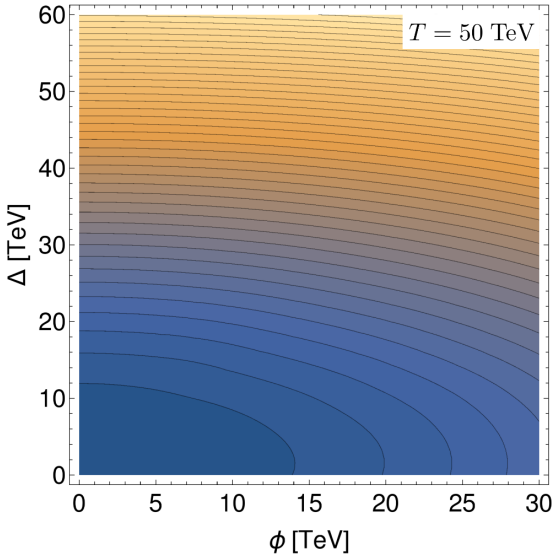

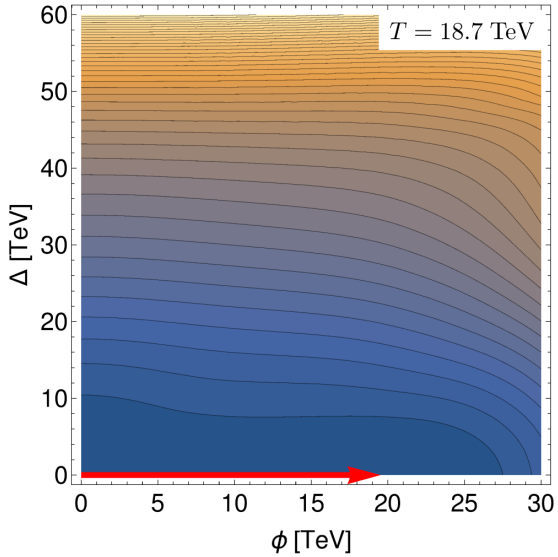

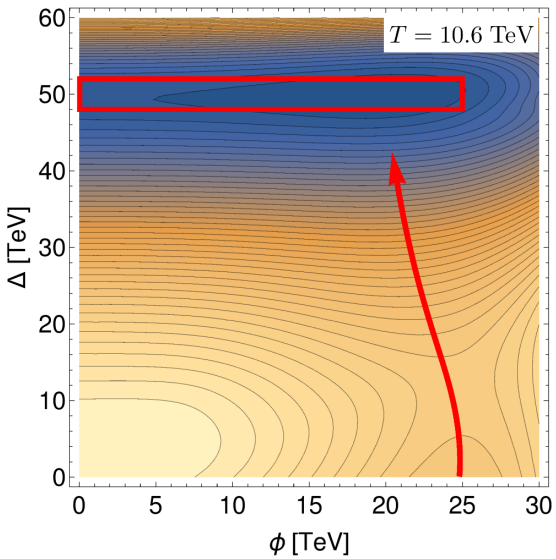

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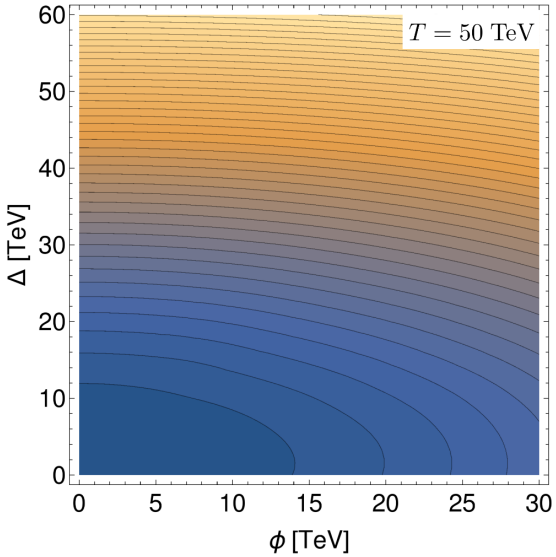
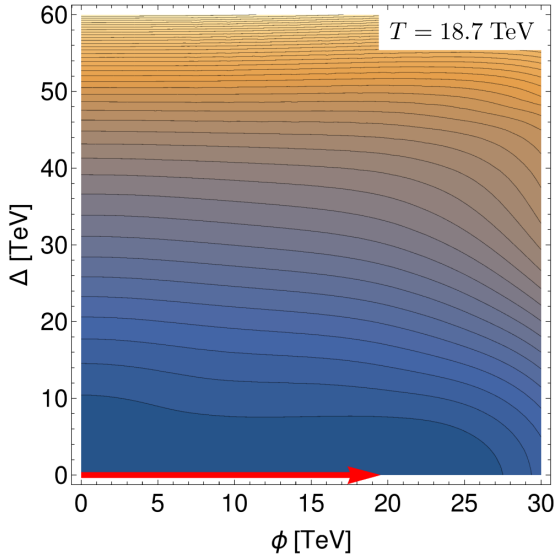
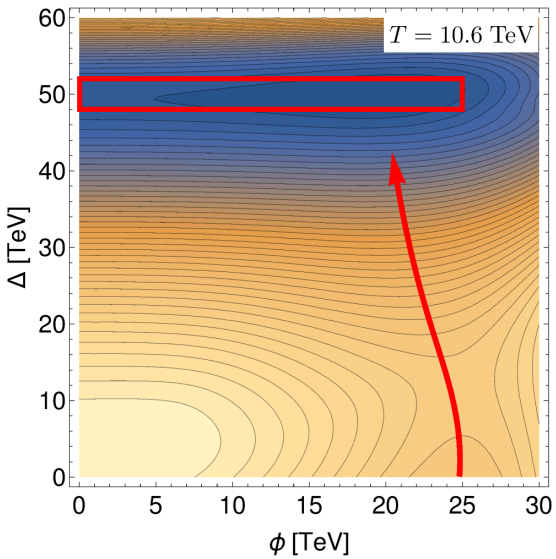
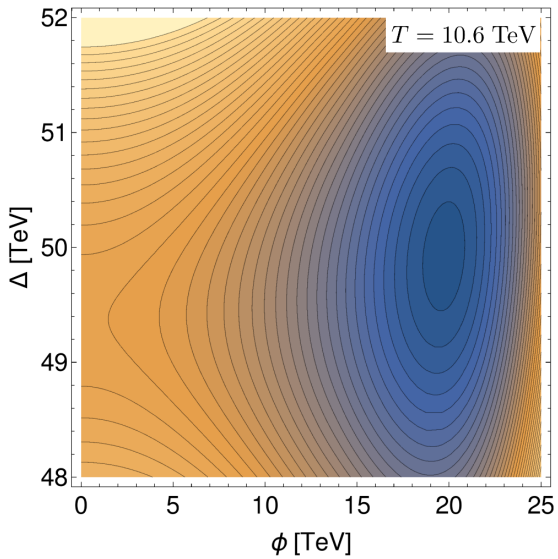
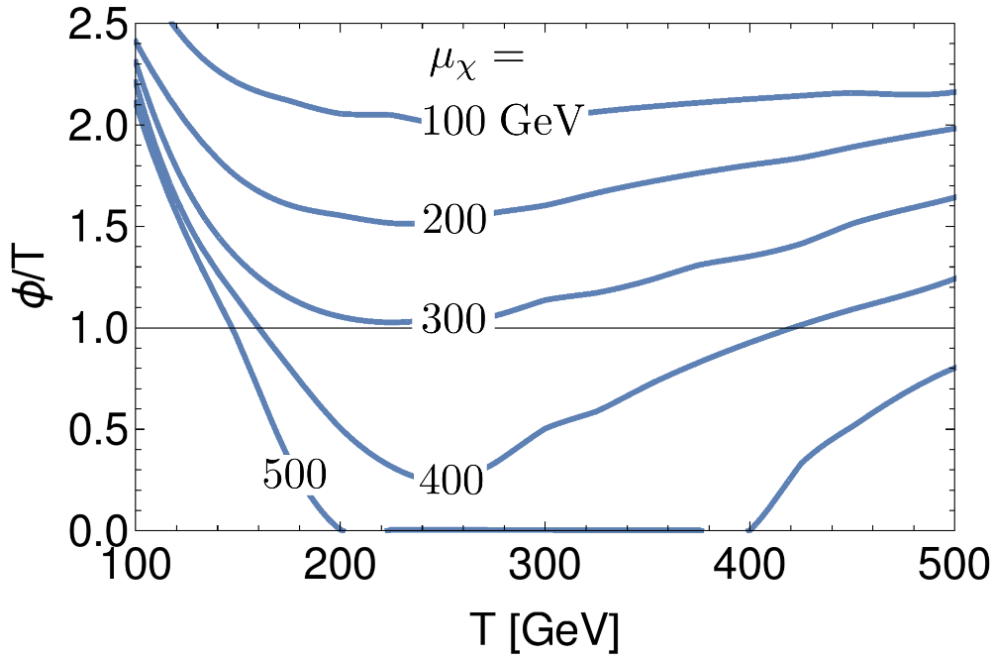








Scalar Sector in the IR



Spectrum of states with masses

$$m_{\chi_i}^2 \sim \mathcal{O}(\mu_\chi^2 + \lambda_{\phi\chi} v_\phi^2/2)$$

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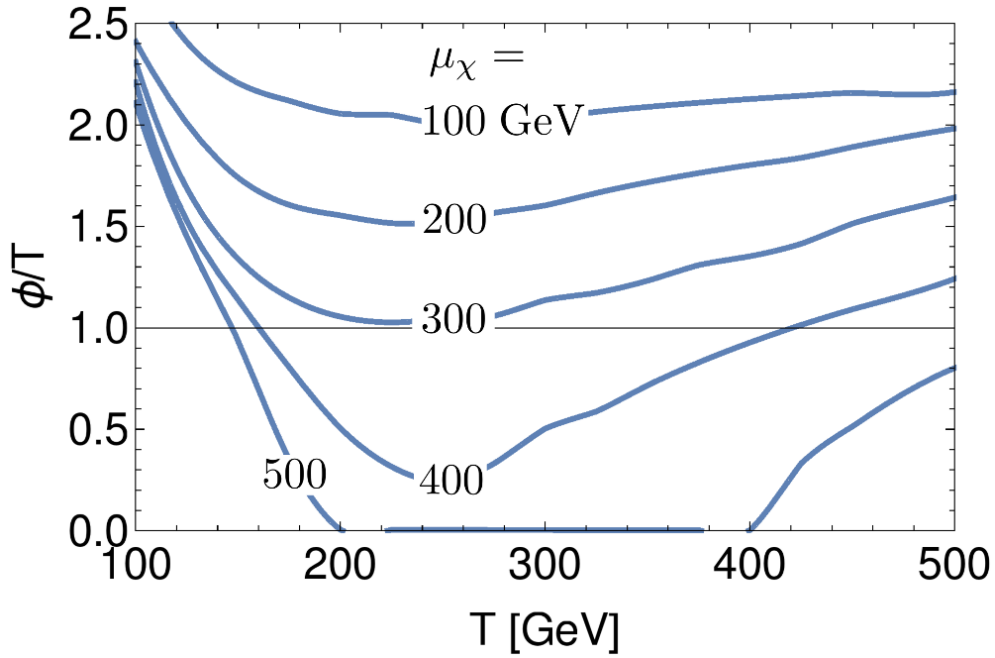

Spectrum of states with masses

$$m_{\chi_i}^2 \sim \mathcal{O}(\mu_\chi^2 + \lambda_{\phi\chi} v_\phi^2/2)$$

Constraints:

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

Conclusions

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Thanks

The terms of the one-loop effective potential

Effective Potential

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

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

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

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

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.

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

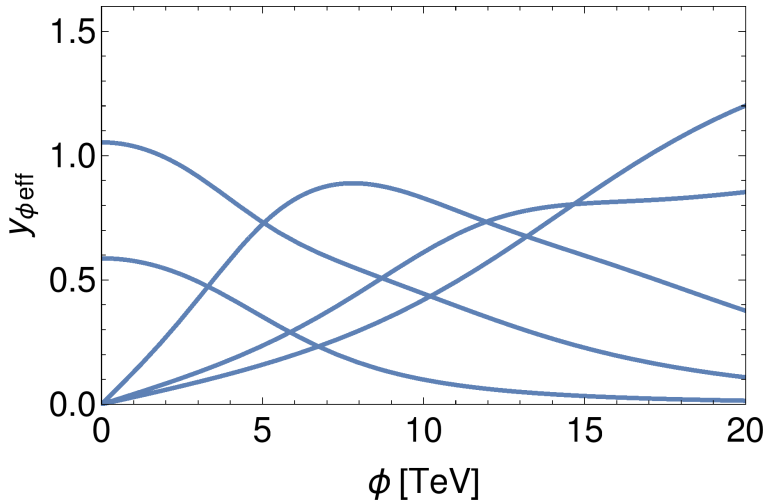
Δ is another scalar which (partially) controls the FN quark mass

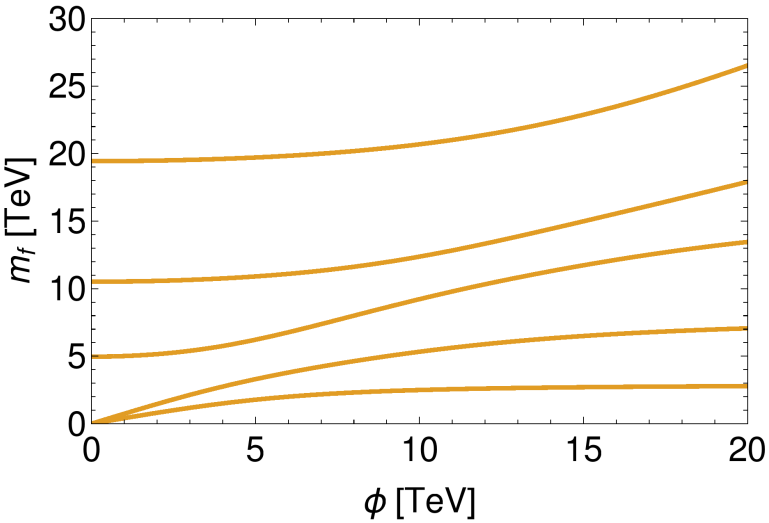
$$\mathcal{L} \supset (M + \Delta)\bar{G}^i_R G^i_L. \qquad \text{We take } M \sim a_s.$$

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

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

Effective Yukawa Couplings





Effective Yukawa couplings

$$y_{f\phi}^{\text{eff}} = \sqrt{2}\frac{\partial m_f}{\partial \phi}, \qquad y_{f\Delta}^{\text{eff}} = \sqrt{2}\frac{\partial m_f}{\partial \Delta}.$$

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.

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

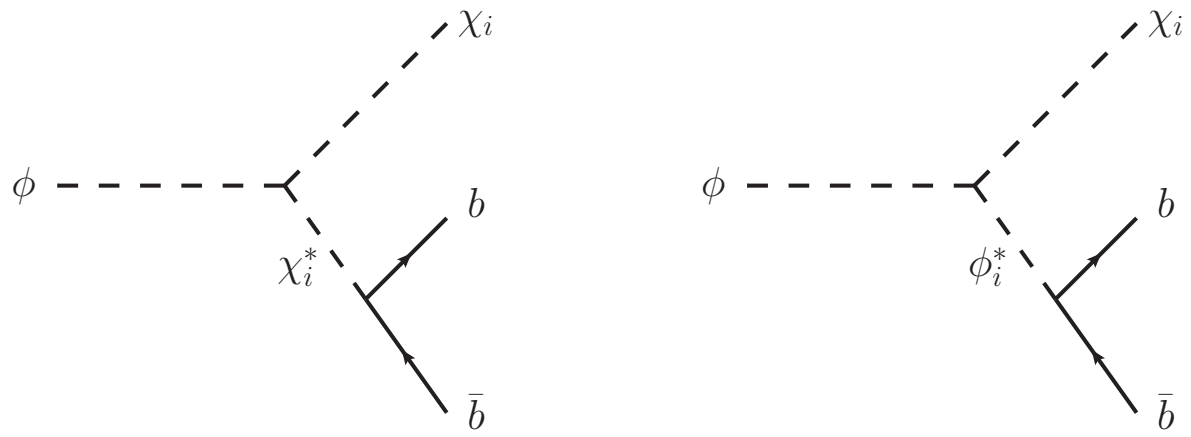
$$\text{Mixing:} \qquad \theta_i \approx \frac{\lambda_{\phi\chi} v_\phi v_{\chi_i}}{m_{\chi_i}^2 - m_\phi^2}.$$

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

Bounded by BBN and the Higgs signal strength.

Exotic EW Higgs Decays

More decay channels open for the EW Higgs

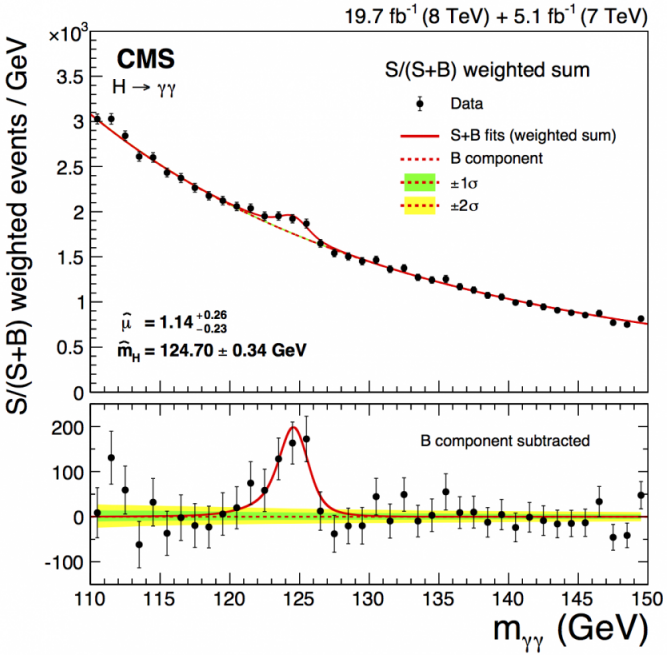


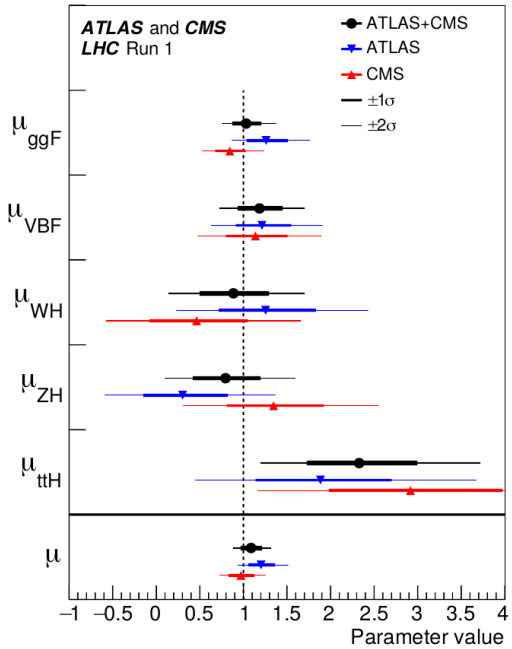
But these are negligible

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

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

LHC constraints - Limit on Mixing

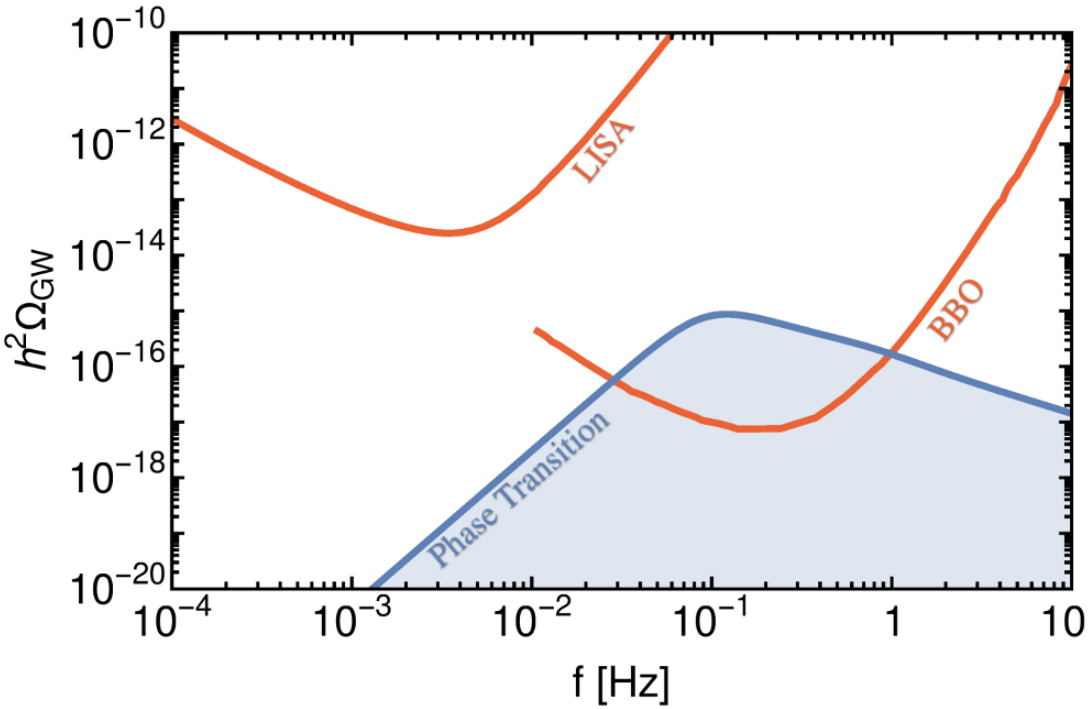


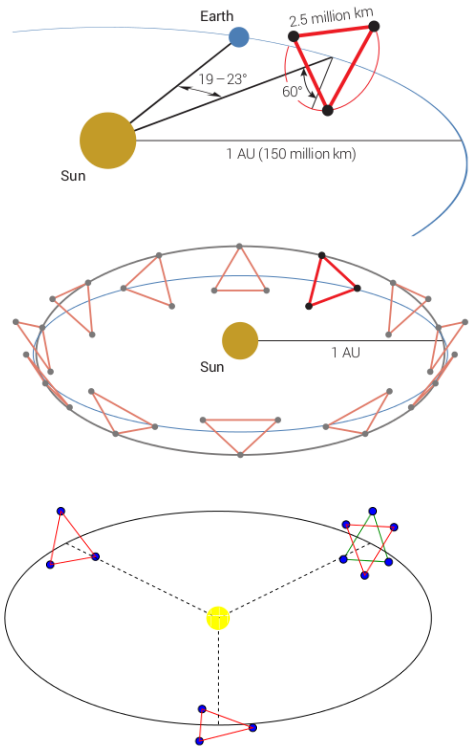


$\mu = 1.09 \pm 0.11$	LHC Run 1	7 + 8 TeV	1606.02266
$\mu = 1.10 \pm 0.06$	LHC Run 2	13 TeV	1810.02521

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

Gravitational wave signal





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

EDMs - Situation in 2006

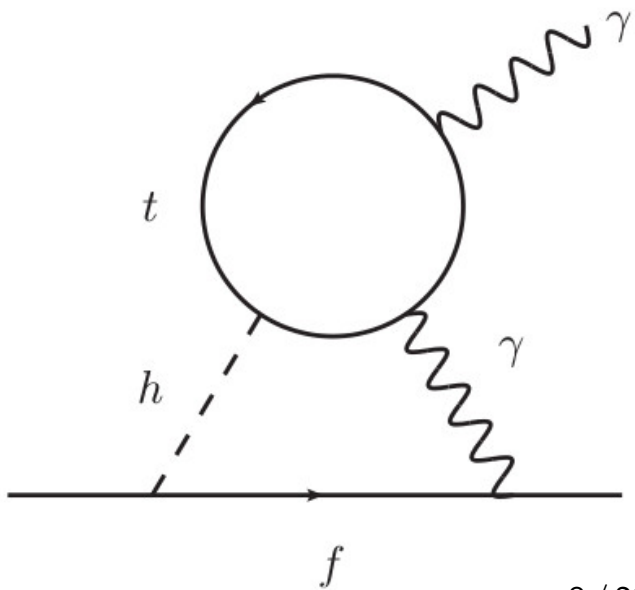
Additional CP violation

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

- 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 $x_{ij} \sim y_{ij}$.



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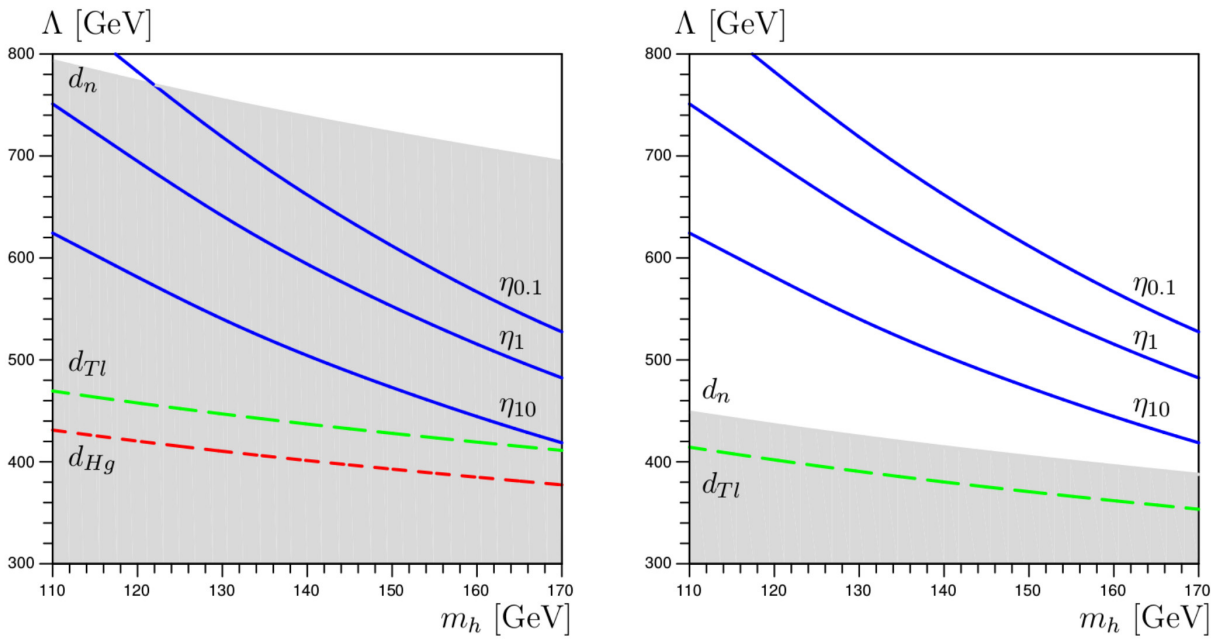


Plots for $\Lambda \equiv f = \Lambda_{\rm CP}$. Left: top only ($x_{33}$). Right: MFV.

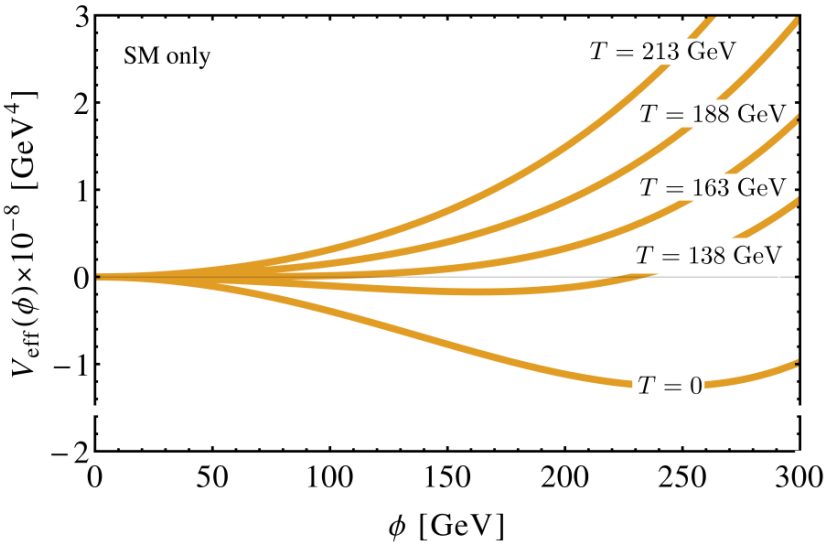
- Huber, Pospelov, Ritz [hep-ph/0610003]

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

EW Crossover in the SM



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

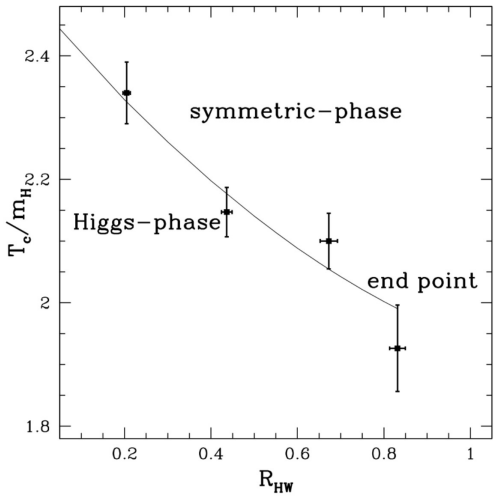
All the parameters are known:

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

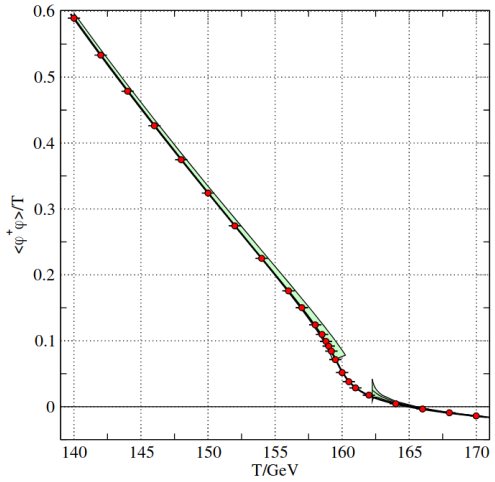
$$v_{\rm EW} = \sqrt{\frac{2m_h^2}{\lambda}} = 246 \text{ GeV}$$

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

Electroweak phase transition - Lattice Studies



- Csikor, Fodor, Heitger, hep-ph/9809291,



D'Onofrio, Rummukainen 1508.07161

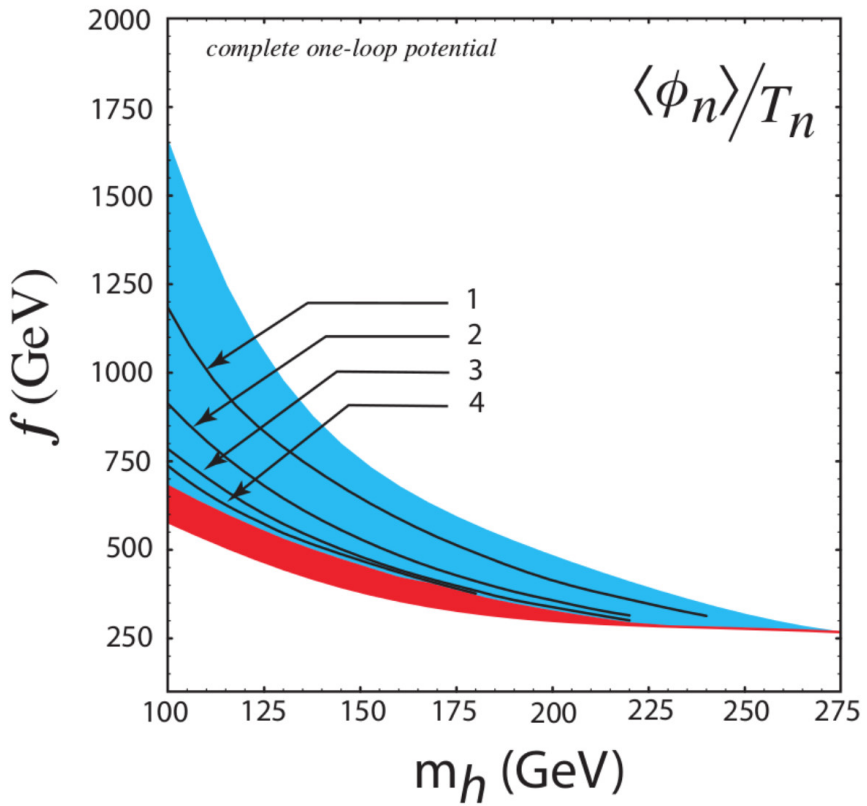
SM with $m_h = 125$ GeV predicts a crossover.
Nevertheless, only the minimum (VEV) of the potential, and the 2nd derivative there (m_h), is known if we allow for BSM physics.

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]

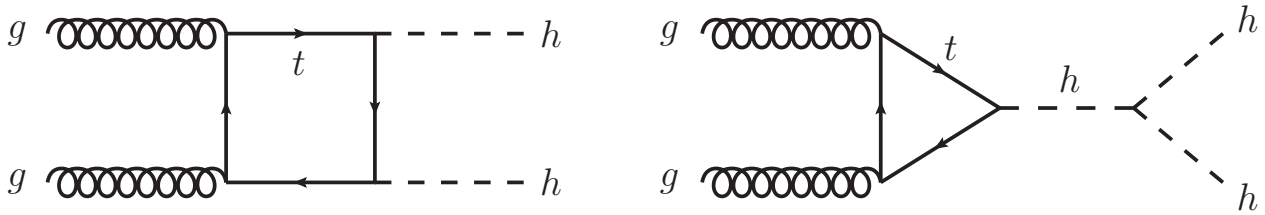
$$V(\Phi) = m^2|\Phi|^2 + \lambda|\Phi|^4 + \frac{1}{f^2}|\Phi|^6$$

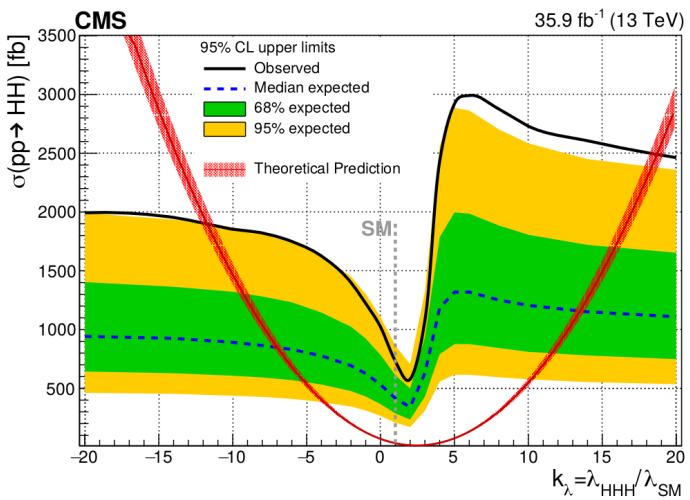
Other options:

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

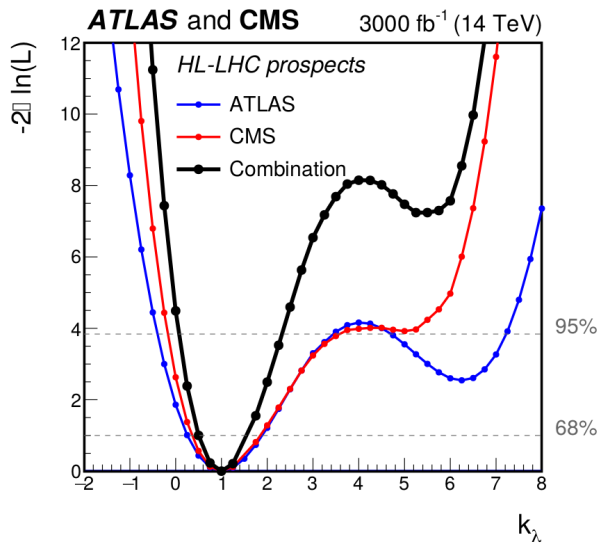
Collider signatures - Triple Higgs coupling

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





- 1811.09689

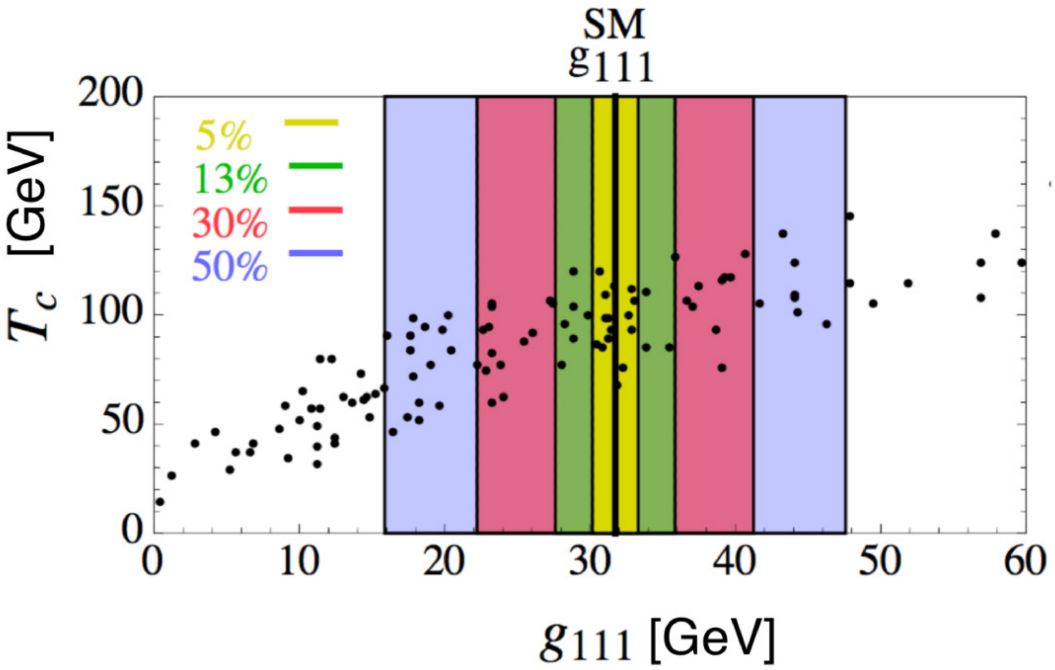


- 1902.00134

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

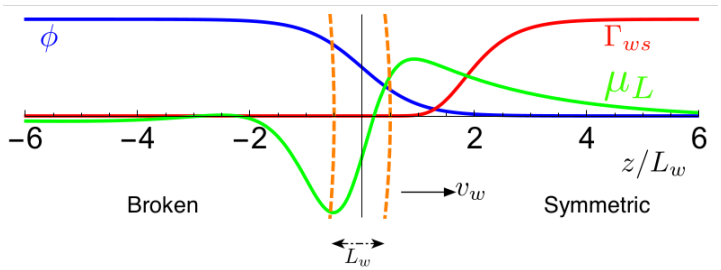


Image from 1706.08534 - Bruggisser, Konstandin, Servant

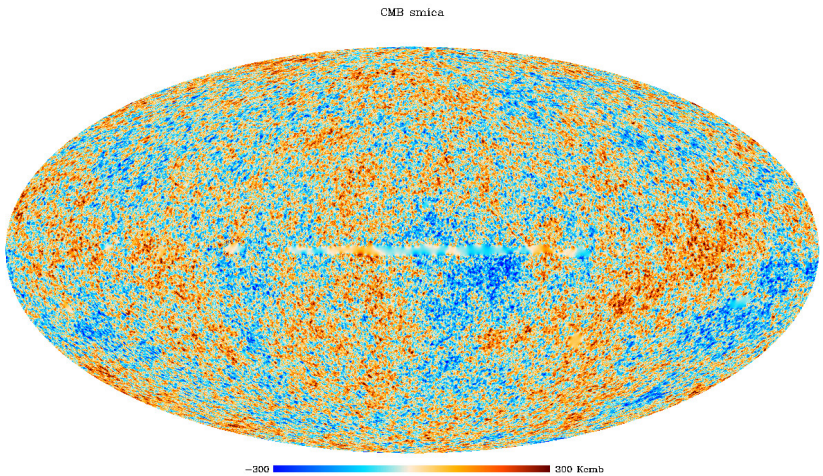
Diffusion equation

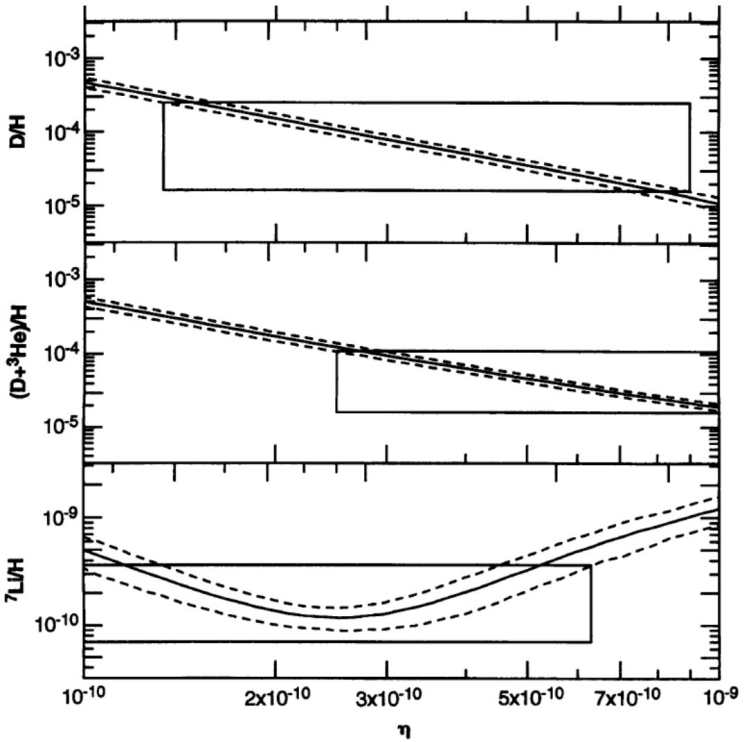
$$\partial_z n_B = \frac{3}{2} v_w^{-1} \Gamma_{ws} \left(N_c \mu_L T^2 - \mathcal{A}\, n_B \right), \qquad \Gamma_{ws} = 10^{-6}\, T\, \exp(-a\phi(z)/T)$$

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

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

The matter-antimatter asymmetry

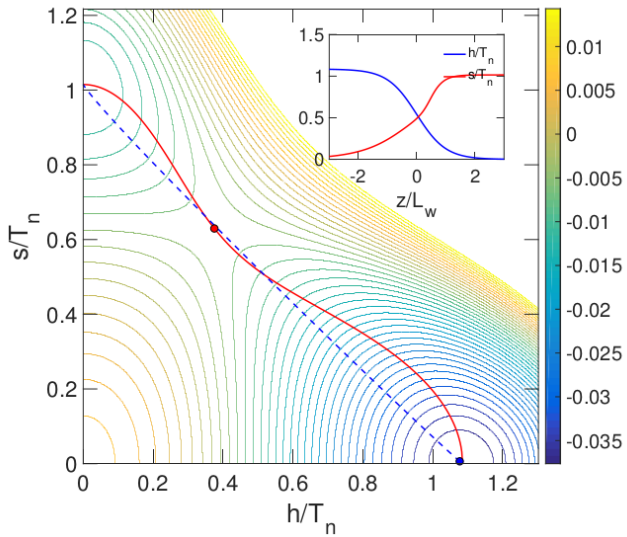




CMB in agreement with BBN:

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

1. Additional Loops



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

Baryogenesis

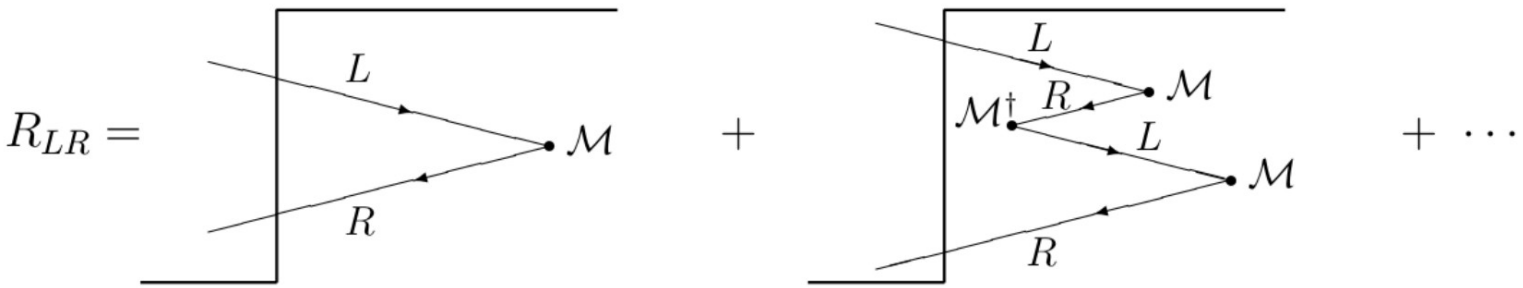
Sakharov Conditions

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 from charge transport with SM CP violation



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

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

SM quark masses are too small!

Baryogenesis Mechanisms

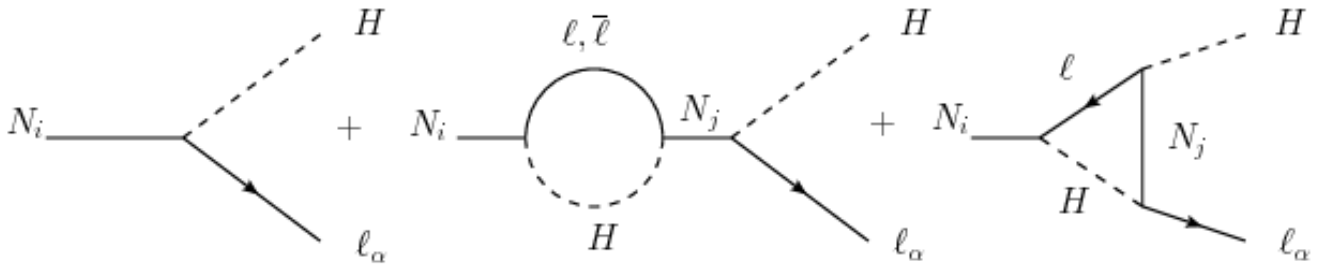
Baryogenesis Mechanisms

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.