

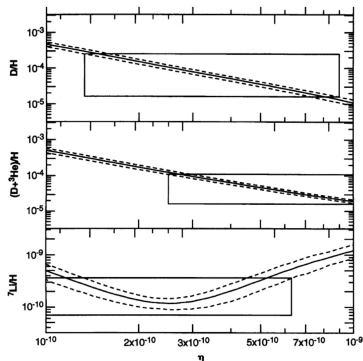
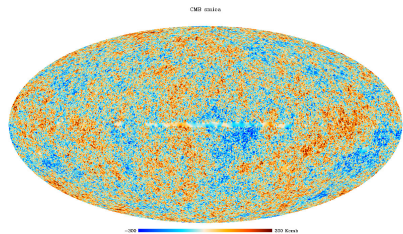
# Update on Electroweak Baryogenesis

Iason Baldes



COSMO'19, Aachen  
3 September 2019

# The matter-antimatter asymmetry



CMB in agreement with BBN:

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

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- 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).

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

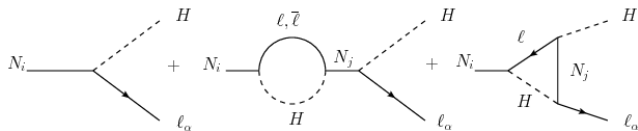
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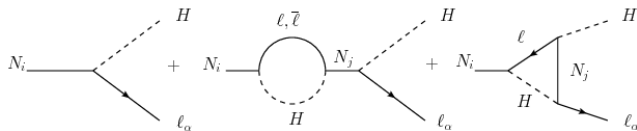
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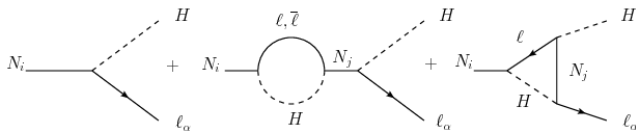
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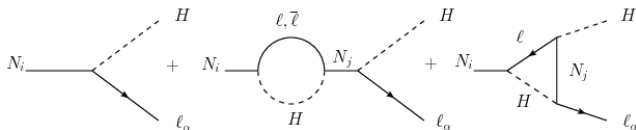


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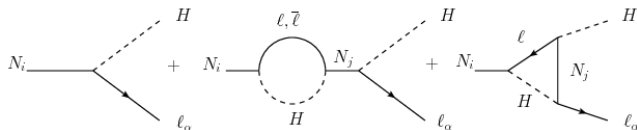


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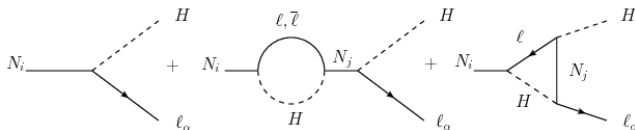


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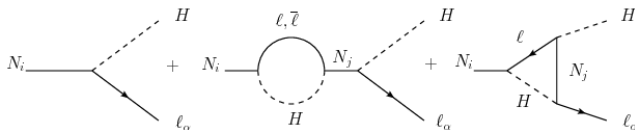


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The scale of EWBG is more closely tied to  $\sim 246$  GeV.

# Electroweak baryogenesis - basic picture

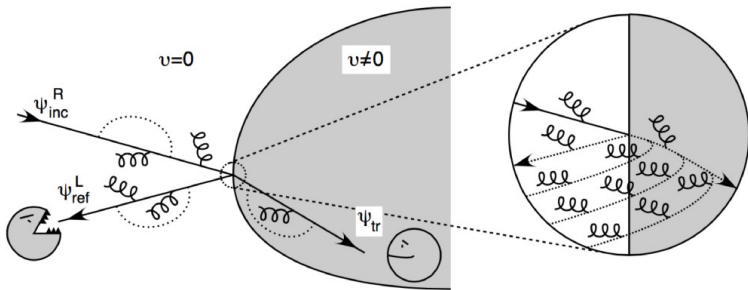


Image from - Gavela, Hernandez, Orloff, Pène, Quimbay [hep-ph/9406289]

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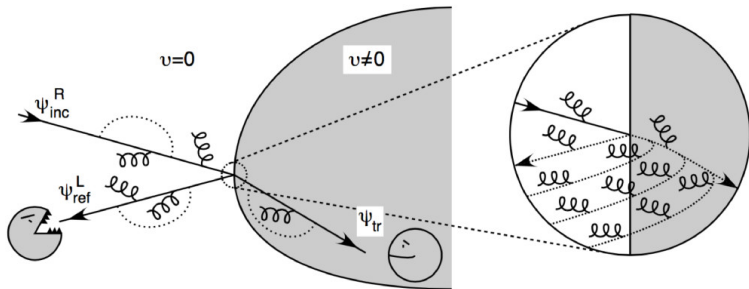


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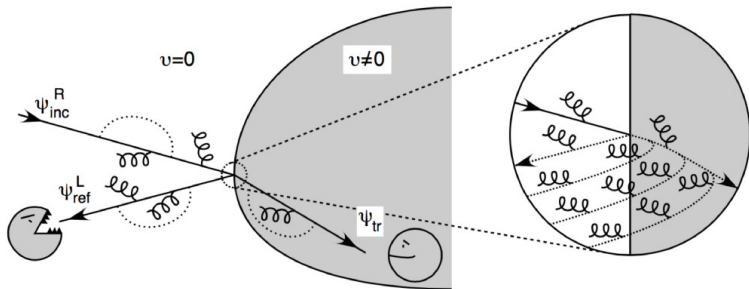


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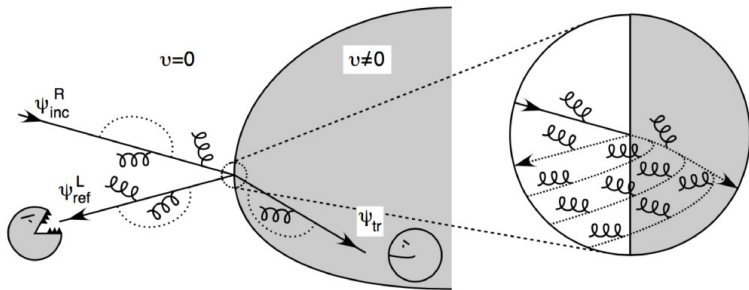
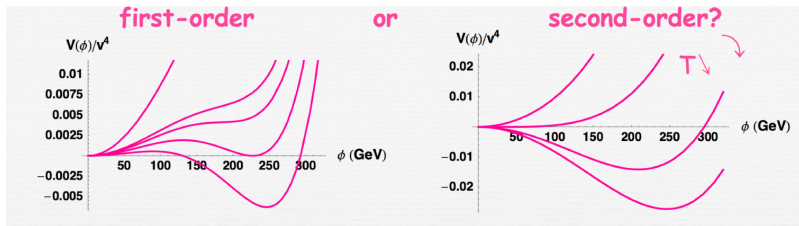


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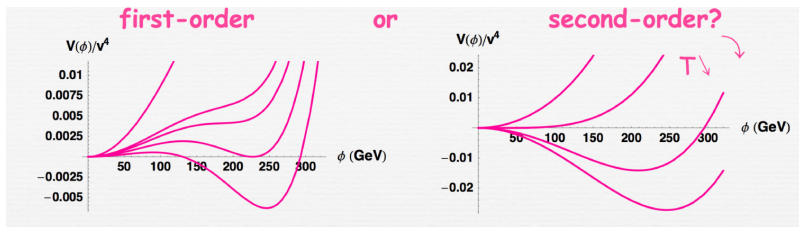
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- This is swept into the expanding bubble where sphalerons are suppressed.

# Electroweak baryogenesis - Requirements



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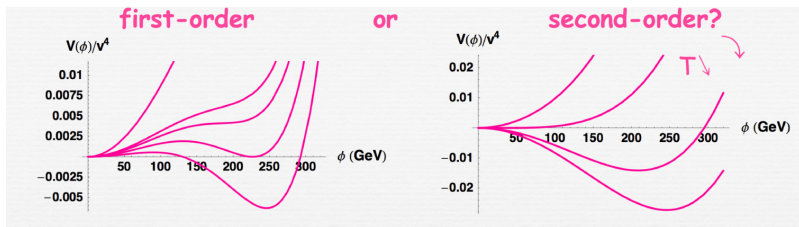
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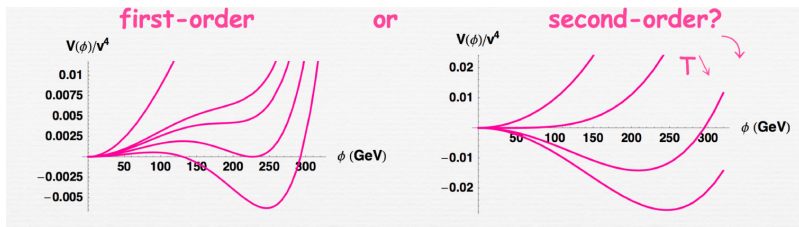


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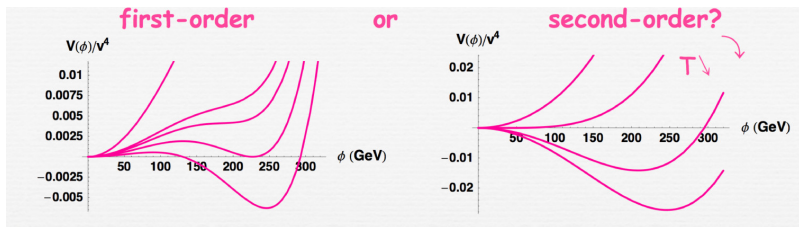
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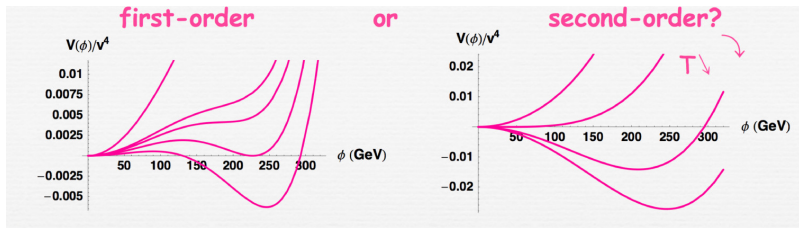
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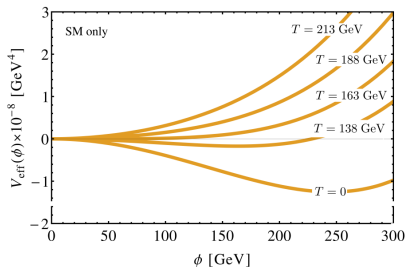
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We require new EW-scale physics!

# EW Crossover in the SM



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

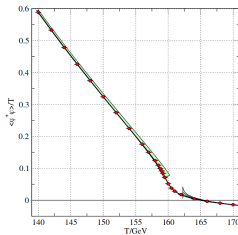
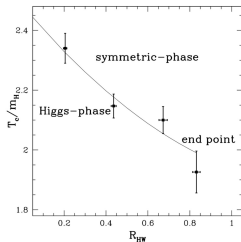
All the parameters are known:

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

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

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

# Electroweak phase transition - Lattice Studies

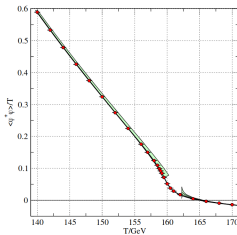
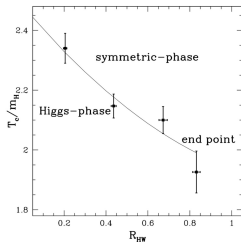


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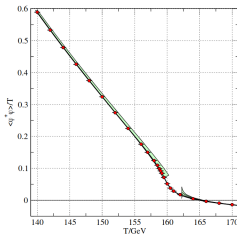
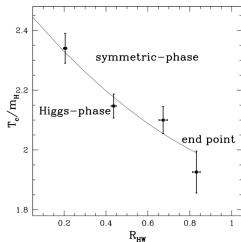
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The Higgs potential must be modified.

## Require a modification of the Higgs potential

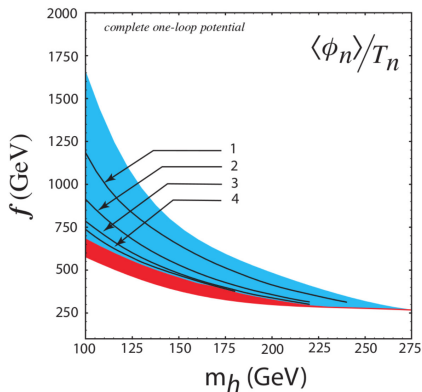
Successful electroweak baryogenesis requires suppressed washout:

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

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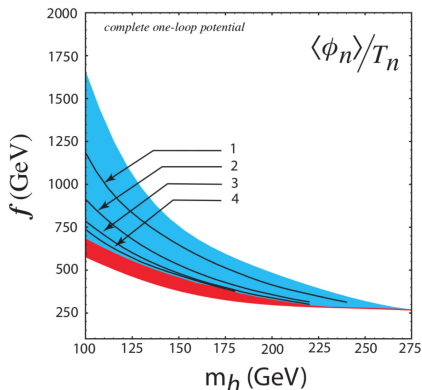
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- Delaunay, Grojean, Wells [0711.2511]

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## Other options:

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

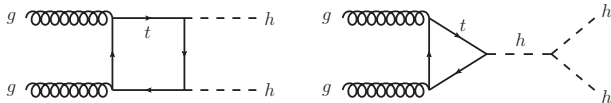
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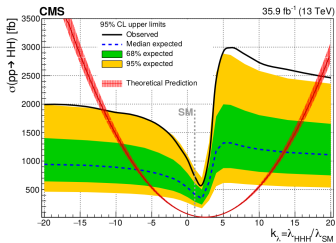
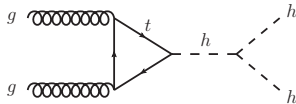
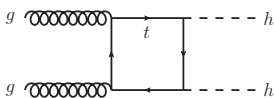
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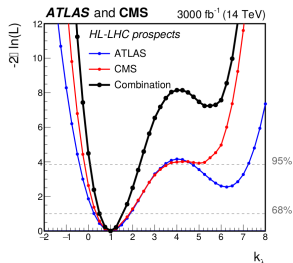


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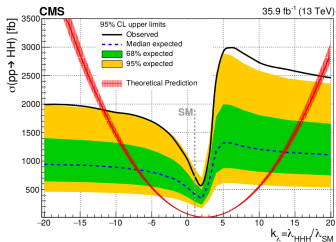
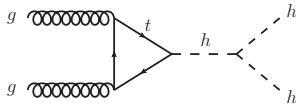
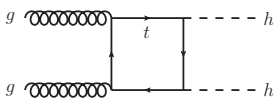
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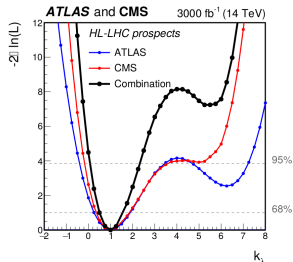
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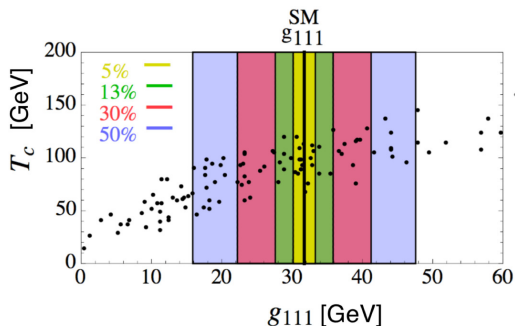


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Measuring the cubic term is long term challenge.

# 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

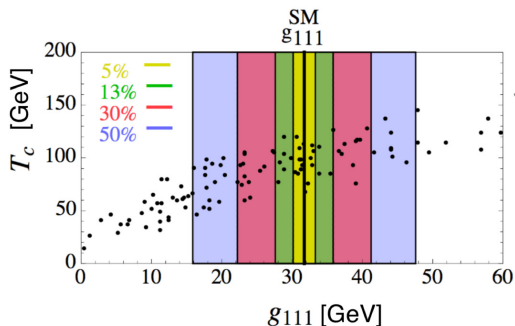
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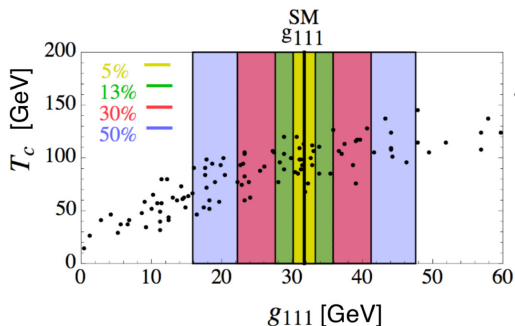
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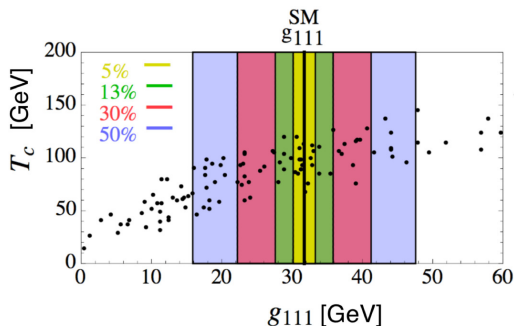
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- Example of how the Higgs potential can be probed by experiment.
- In comparison: light stop scenario ruled out (thermal barrier).
- Another possibility: mixing reducing the signal strength.

Currently LHC:  $\theta \lesssim \mathcal{O}(0.1)$  compatible with singlet models of EWBG.

# CPV and The Baryonic Yield

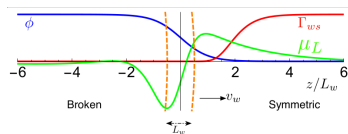


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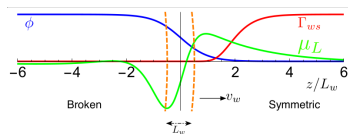


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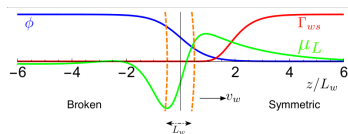


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# CPV and The Baryonic Yield

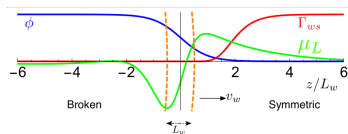


Image from 1706.08534 - Bruggisser, Konstandin, Servant

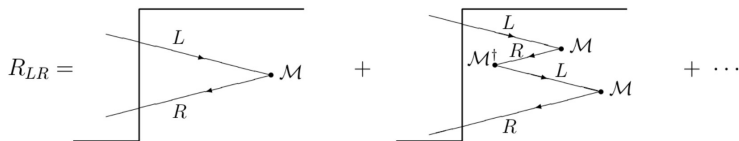
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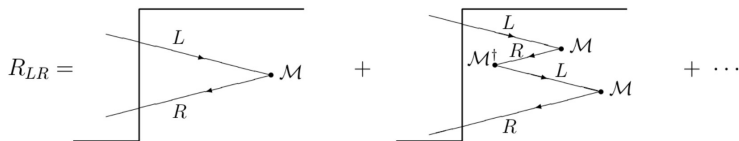
# Baryogenesis from charge transport with SM CP violation



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

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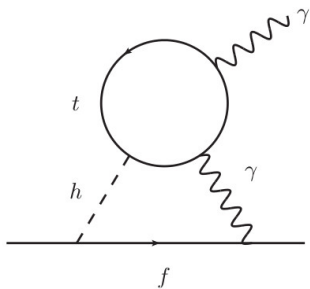


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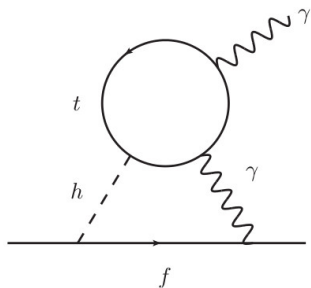
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SM quark masses are too small!

# electron EDM constraint



# electron EDM constraint



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

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

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

Is electroweak baryogenesis  
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James M. Cline<sup>1,2</sup>

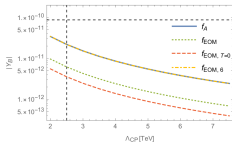
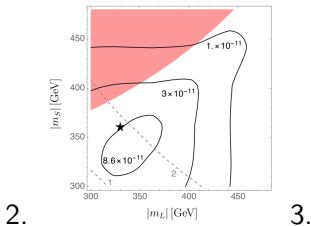
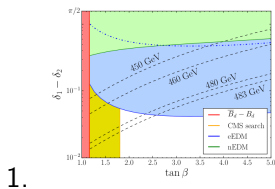
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# EDMs - Situation 2013-2018

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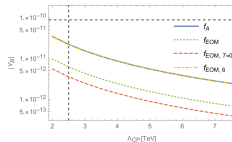
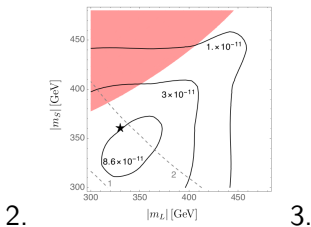
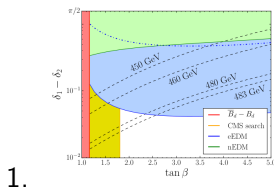
- 1611.05874 - Dorsch, Huber, Konstandin, No
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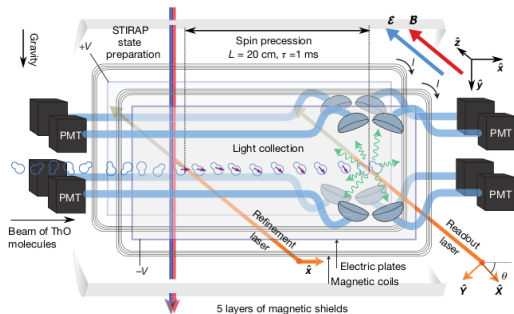


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Severe constraint on EWBG!

# EDMs - Situation after 18.10.2018

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



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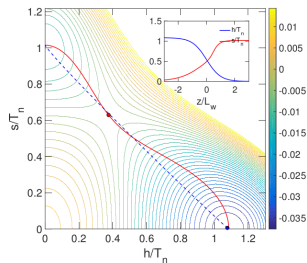
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To overcome this

- 1 Hide CP violation through additional loops.
- 2 Push the EWPT to some large  $\Lambda$ .

# 1. Additional Loops



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

## 2. Increase $\Lambda$ - 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.

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**Warning: large  $N$  ahead.**

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

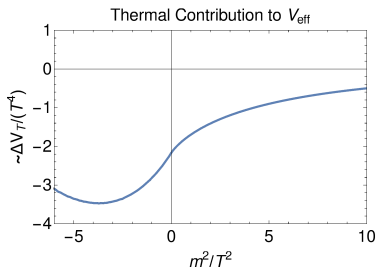
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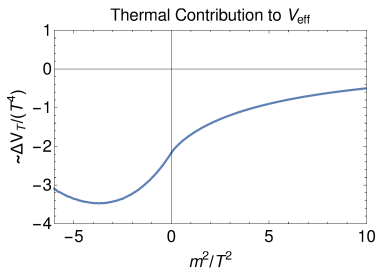
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Take  $\lambda_{\phi\chi} < 0$ .

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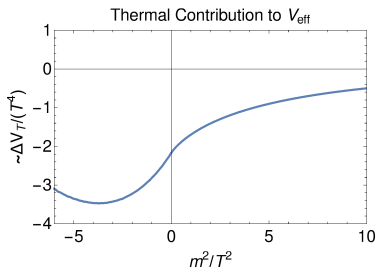
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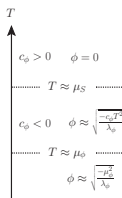
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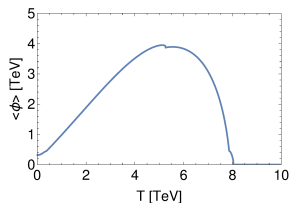
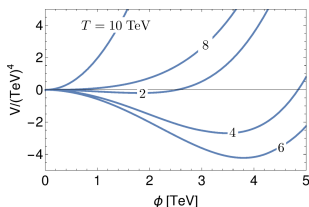
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$$V(\phi) = (m_\phi^2 + c_\phi T^2)\phi^2 + \lambda_\phi\phi^4 \implies \langle \phi \rangle = \sqrt{-\frac{c_\phi}{\lambda_\phi}} T!$$

# Toy Example - Numerical analysis

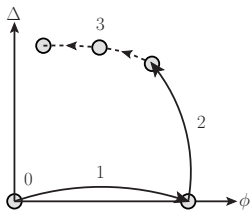


An additional threshold switches the thermal mass from +ve to -ve.



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

# 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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$$\frac{\phi}{\sqrt{2}} \begin{pmatrix} \bar{t}_R \\ \bar{c}_R \end{pmatrix}^T \begin{pmatrix} 1 & \epsilon^2 \\ \epsilon & \epsilon^3 \end{pmatrix} \begin{pmatrix} t_L \\ c_L \end{pmatrix} \quad \epsilon \equiv a_s/\Lambda_{\text{FN}} \sim 0.2$$

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Soft breaking terms give mass to the Goldstone boson.

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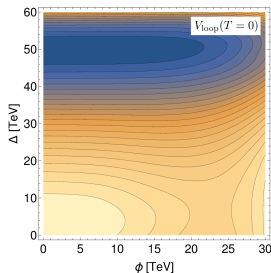
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In our analysis we consider the UV flavour picture - details suppressed here.

# The Scalar Potential



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

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

## Symmetry Non-restoring sector

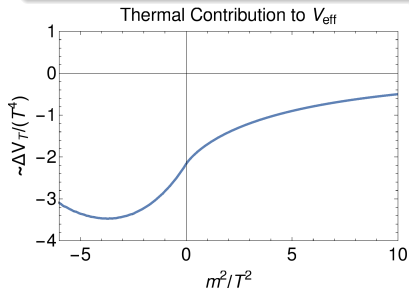
We add a few extra scalar degrees of freedom.

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

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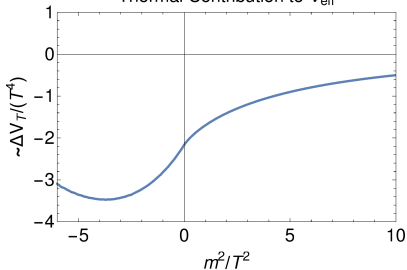
- (i)  $c_{\chi i} \approx \frac{\lambda_\chi}{4} + \frac{\lambda_{\phi\chi}}{6} \ll 1$
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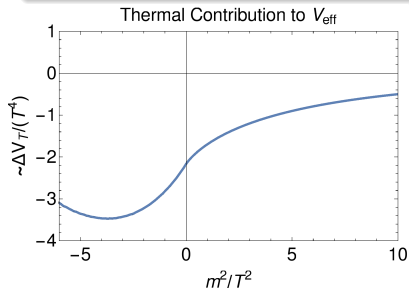
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Large  $N_{\text{dof}}$  needed: (i) keep  $\chi$  thermal mass small,  
(ii) keep potential stabilized, (iii) obtain  $c_\phi < 0$ .

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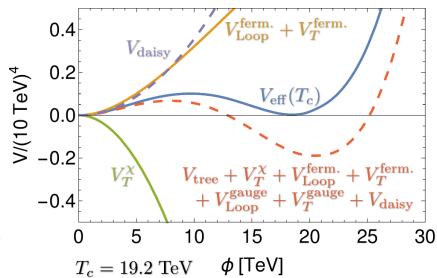
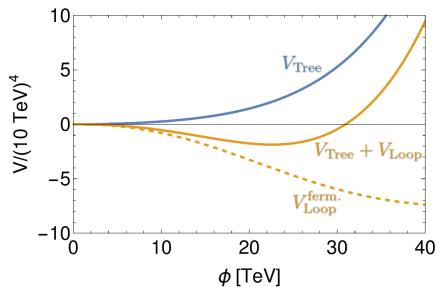
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- (iii)  $c_\phi \approx \frac{\lambda_\phi}{2} + 3\frac{g_2^2}{16} + \frac{g_Y^2}{16} + \frac{\lambda_{\phi\Delta}}{24} + N_{\text{Gen}} \frac{\lambda_{\phi\chi}}{24} + \frac{1}{4} \sum_f \left[ y_{f\phi}^{\text{eff}}(\phi, \Delta) \right]^2 < 0$

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

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

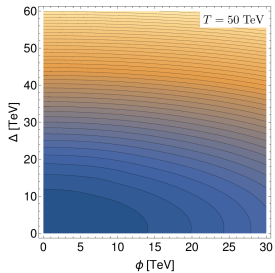
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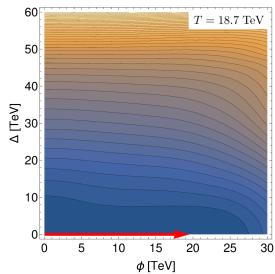
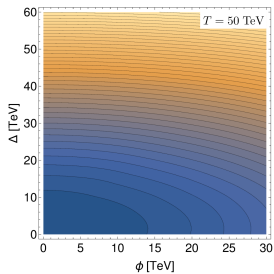


Achieve  $\frac{\phi_n}{T_n} \gtrsim 1$ .

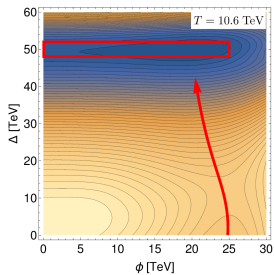
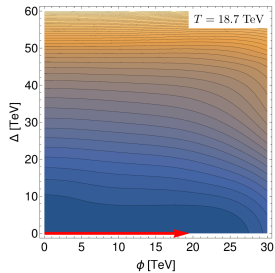
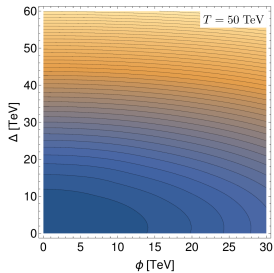
# Thermal Evolution



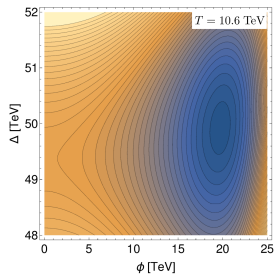
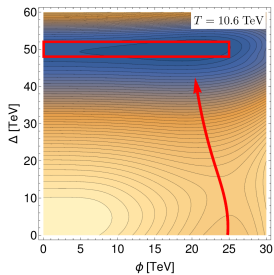
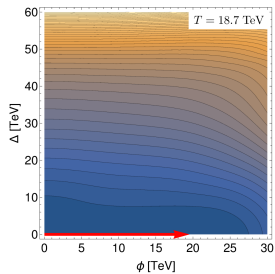
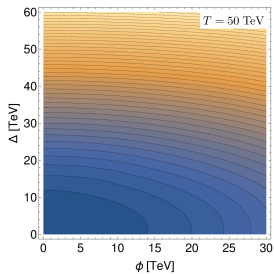
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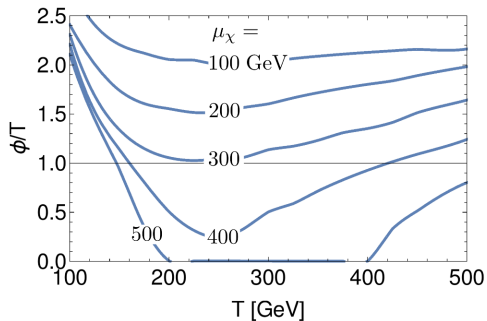
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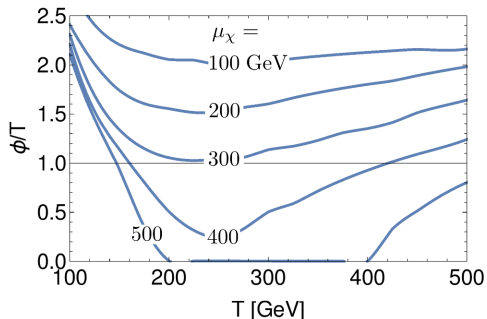
# Scalar Sector in the IR



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

Constraints:

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

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Thanks

# The terms of the one-loop effective potential

## Effective Potential

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

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

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

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

# 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.

$$G_{L,R}^0 \quad G_{L,R}^1 \quad G_{L,R}^2$$

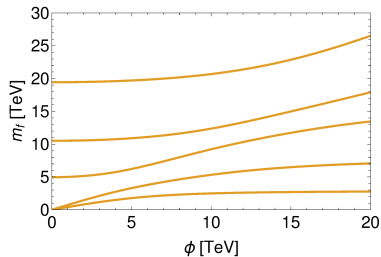
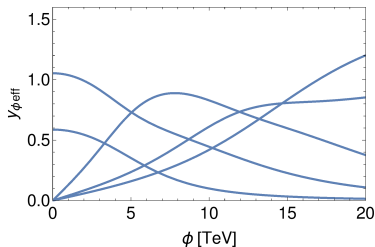
$\Delta$  is another scalar which (partially) controls the FN quark mass

$$\mathcal{L} \supset (M + \Delta) \bar{G}_R^i G_L^i. \quad \text{We take } M \sim a_s.$$

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

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

# Effective Yukawa Couplings



## Effective Yukawa couplings

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

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

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

# Avoiding $\chi_i$ overabundance

## Options

- 1 The  $\chi_i$  annihilate into hidden sector.
- 2 The  $\chi_i$  decay into lighter states.

## Option 2. The $\chi_i$ decay into light SM dof.

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

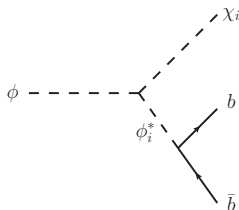
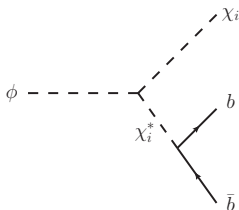
$$\text{Mixing: } \theta_i \approx \frac{\lambda_{\phi\chi} v_\phi v_{\chi_i}}{m_{\chi_i}^2 - m_\phi^2}.$$

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

Bounded by BBN and the Higgs signal strength.

# Exotic EW Higgs Decays

More decay channels open for the EW Higgs

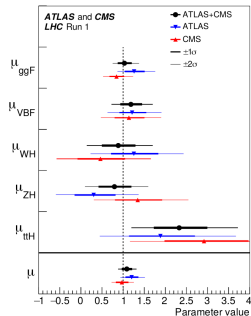
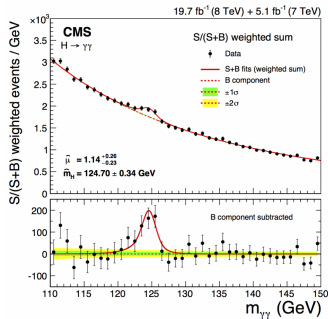


But these are negligible

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

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# LHC constraints - Limit on Mixing



$$\mu = 1.09 \pm 0.11$$

LHC Run 1

7 + 8 TeV

1606.02266

$$\mu = 1.10 \pm 0.06$$

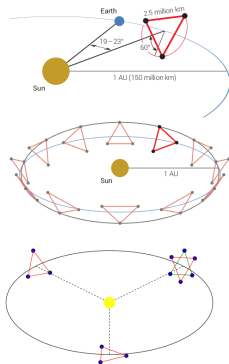
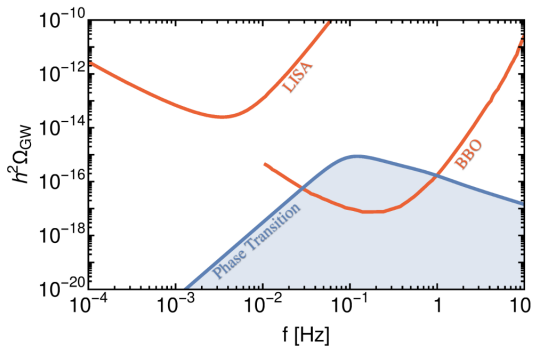
LHC Run 2

13 TeV

1810.02521

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

# Gravitational wave signal



$$\frac{\beta}{H} \equiv T_n \frac{d}{dT} \left( \frac{S_3}{T} \right) \Big|_{T_n} \approx 180$$

$$\alpha \equiv \frac{\rho_{\text{vac}}(\text{false}) - \rho_{\text{vac}}(\text{true})}{\rho_{\text{rad}}} \approx 8 \times 10^{-3}$$

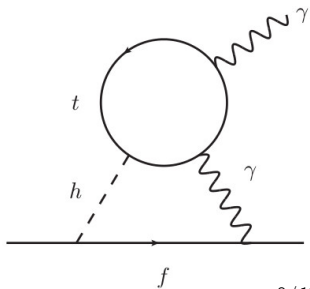
## Additional CP violation

$$\mathcal{L} \supset y_{ij} \bar{Q}_i \Phi u_j + x_{ij} \frac{(\Phi^\dagger \Phi)}{\Lambda_{\text{CP}}^2} \bar{Q}_i \Phi u_j$$

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

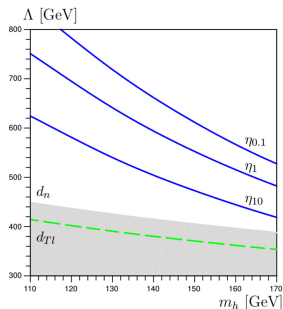
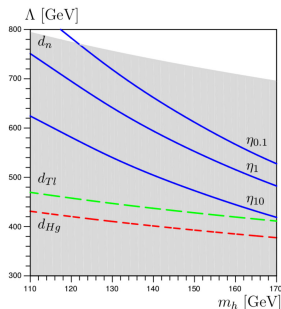
$$\text{Neutron EDM: } |d_n| < 3 \times 10^{-26} \text{ e cm}$$

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



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

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

## 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