ELECTROWEAK BARYOGENESIS
and the LHC

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OUTLINE

- Introduction
- Standard Model results
- Standard Model+singlet(s)
  - Electroweak breaking
  - Electroweak phase transition
- The MSSM
  - The baryogenesis window
  - Analysis of metastability region
  - BAU
- Conclusions

Introduction

Conditions for baryogenesis were stated by Sakharov in 1967 [a]

- B-violation

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[a] A.D. Sakharov, JETPL 91B (1967) 24

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- B-violation
- C and CP violation
- Departure from thermal equilibrium
- Kuzmin, Rubakov and Shaposhnikov considered in 1985 the possibility of baryogenesis at the electroweak phase transition (EWPT)

A.D. Sakharov, JETPL 91B (1967) 24

Introduction

The question that created lot of excitement in the physics community

CAN THE SM PRODUCE BARYONS?

provided a POSITIVE ANSWER!

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- Baryon number is non-perturbatively violated in the SM: sphalerons at finite temperature
- C and CP violating (CKM) phases are present in the SM
- The out-of-equilibrium conditions are present in the bubble wall in a FIRST ORDER PHASE TRANSITION

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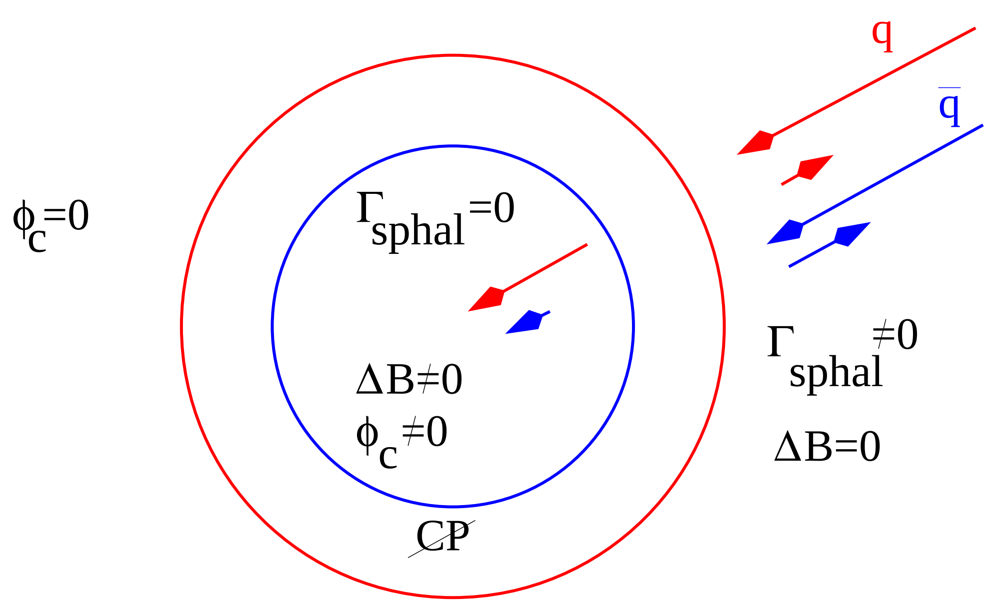

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> If the phase transition is not strongly enough first order any previously generated BAU is erased by sphalerons in the symmetric phase $\Rightarrow \dfrac{\phi_c}{T_c} \geq 1$

Standard Model results

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• The CP violation provided by the CKM phase is too small to generate the required BAU

• The phase transition is not strong enough. Would a BAU be generated it would be erased by weak sphalerons in the broken phase. In fact the strength of the phase transition strongly depends on the Higgs mass and for present experimental limits it is extremely weak. A one-loop (improved by hard thermal loops) result is plotted

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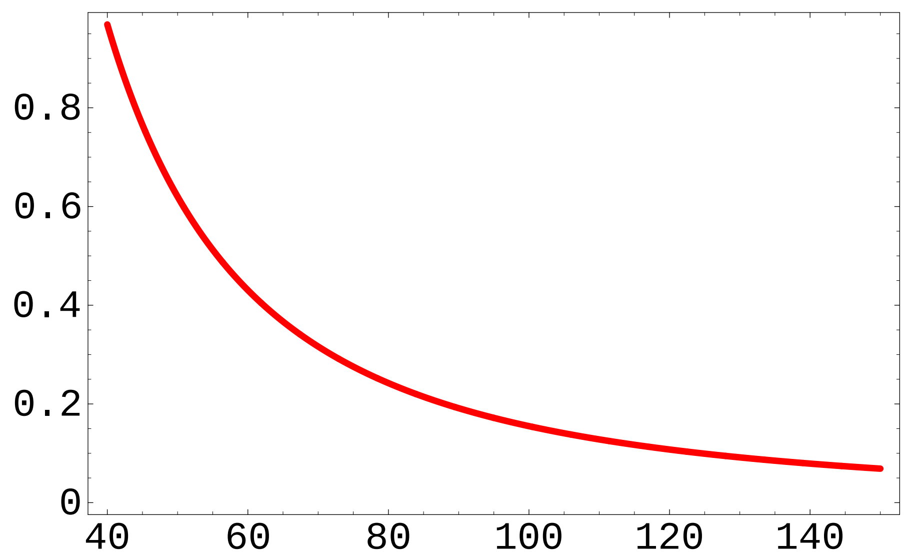

$v(T_c)/T_c$ as a function of m_H (in GeV) [one-loop]

Standard Model results

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  BOSONS STRONGLY COUPLED TO THE HIGGS SECTOR

- Bosons have $n = 0$ Matsubara modes and thus they contribute to the cubic terms in the finite-temperature potential and to create a first order phase transition
- Bosons can be singlets (from some HIDDEN sector) or appear in supersymmetric extensions of the SM: in particular STOPS

SM+singlets

- Many SM extensions, e.g. string theory, contain hidden sectors with a matter content transforming non-trivially under a hidden sector gauge group, singlet under the SM
- The SM Higgs field H plays a very special role with respect to such hidden sectors since it can provide a window (a portal) into it through the renormalizable interaction $|H|^2 \ldots$
- We will assume that the hidden sector is "singlet" under the SM gauge group

SM+singlets

- We will consider interactions between the hidden sector fields S_i and the SM Higgs as $|H|^2 S_i^2$
- The SM Lagrangian is extended minimally to

$$\mathcal{L} = \mathcal{L}_{SM} - \zeta^2 |H|^2 S_i^2$$

- Such a simple term can dramatically change the patterns of electroweak breaking and the strength of the electroweak phase transition

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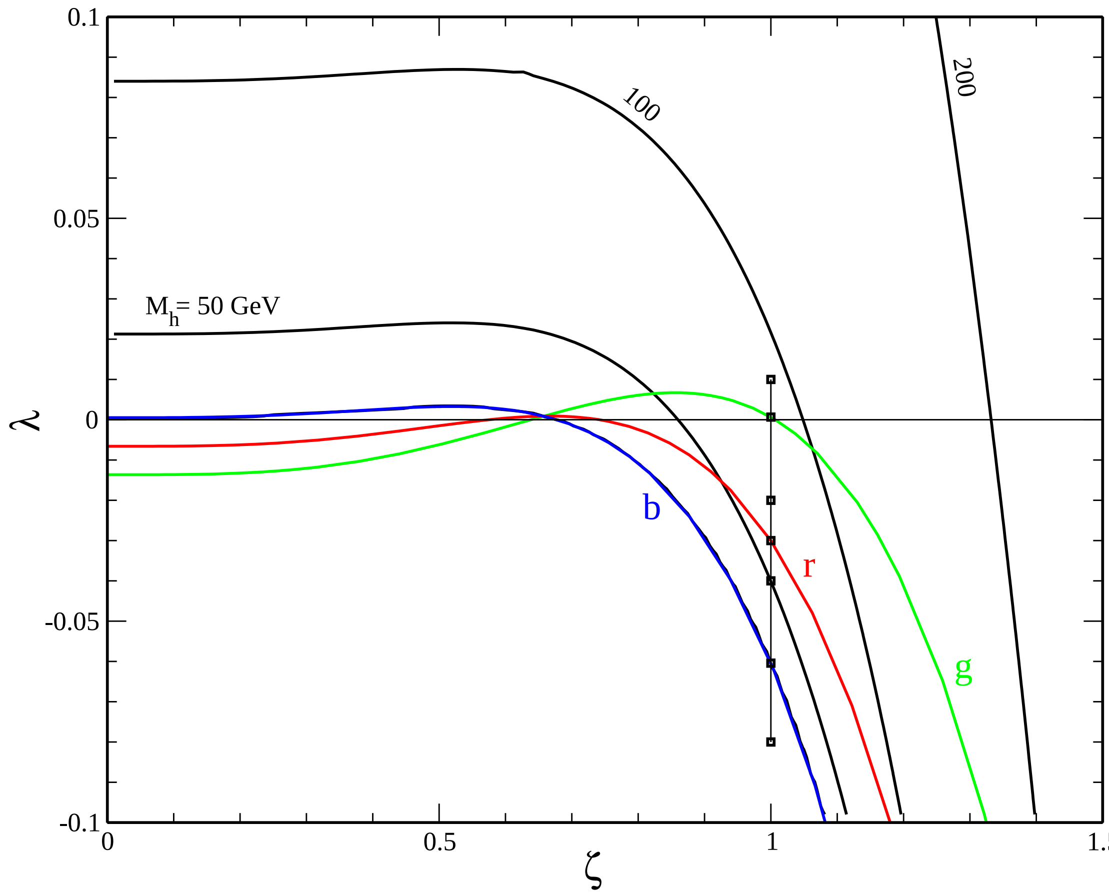
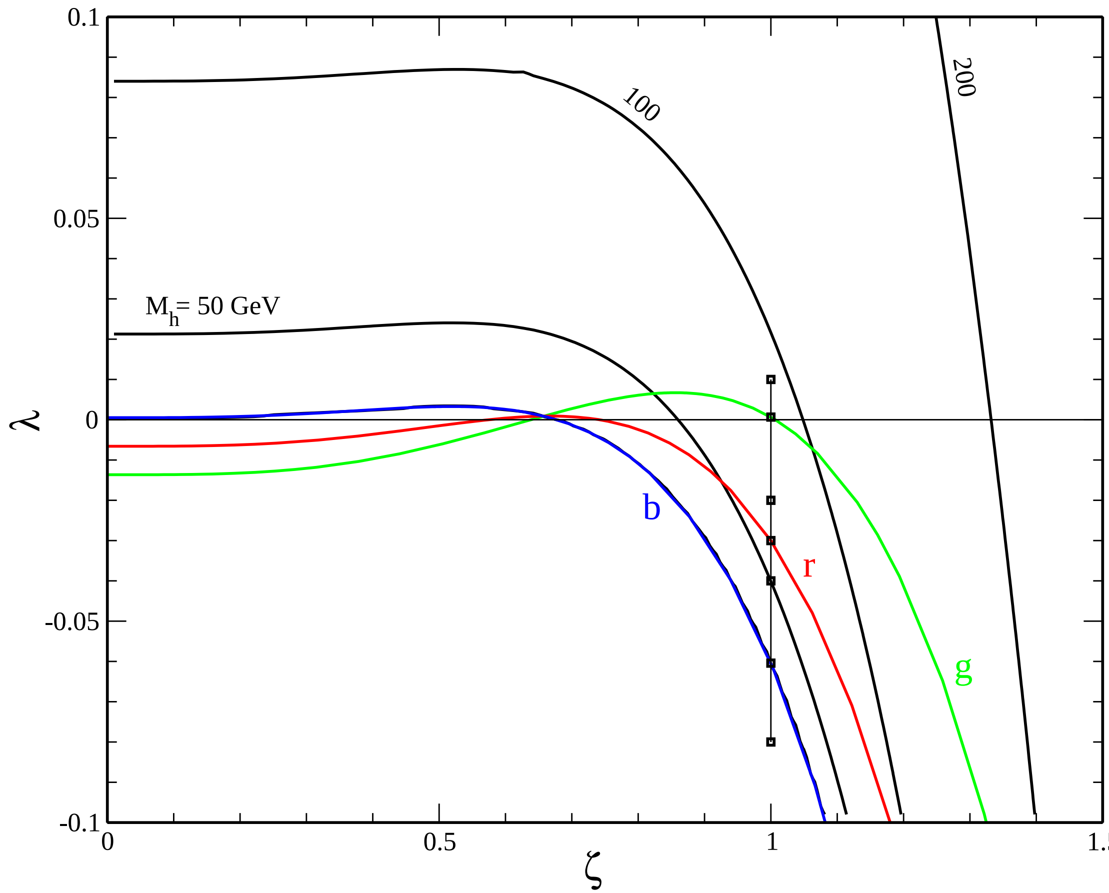
J.R. Espinosa and M. Quiros, PRD 76 (2007) 076004

Electroweak breaking



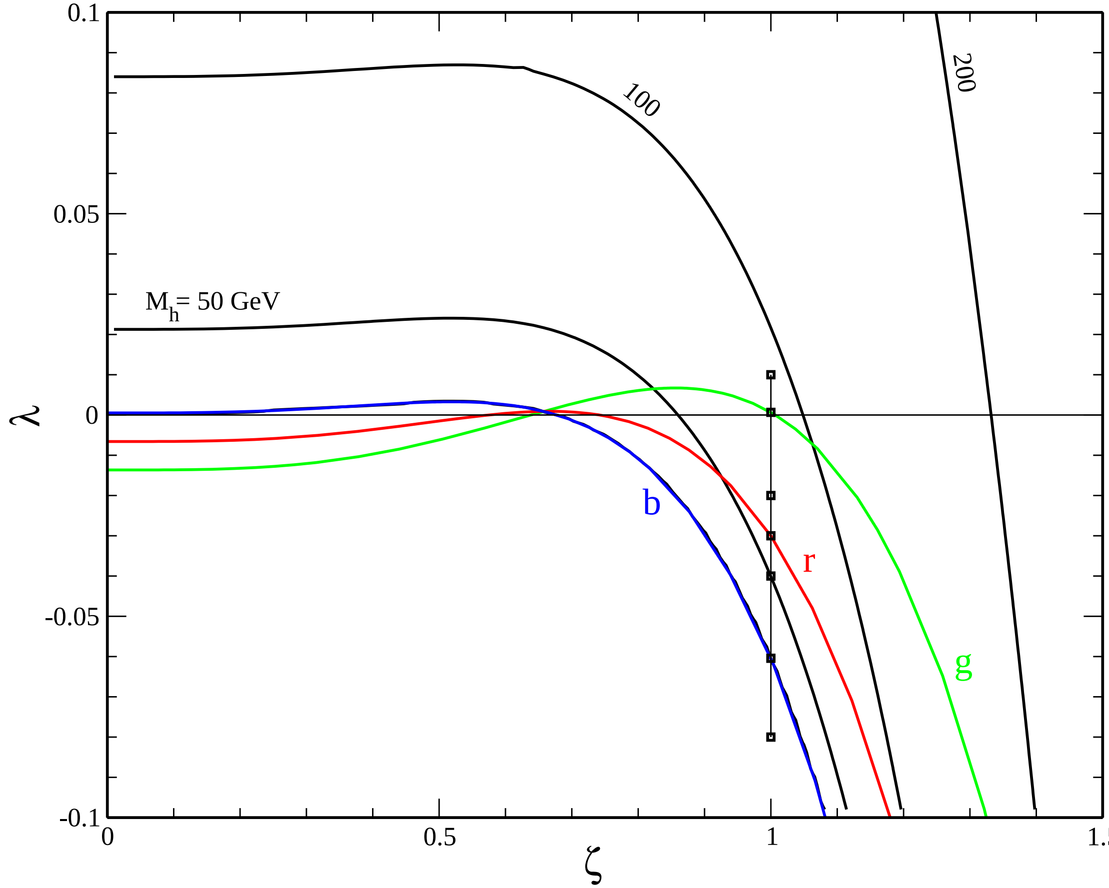
The region below the blue line is forbidden: there $M_h^2 < 0$.

Electroweak breaking



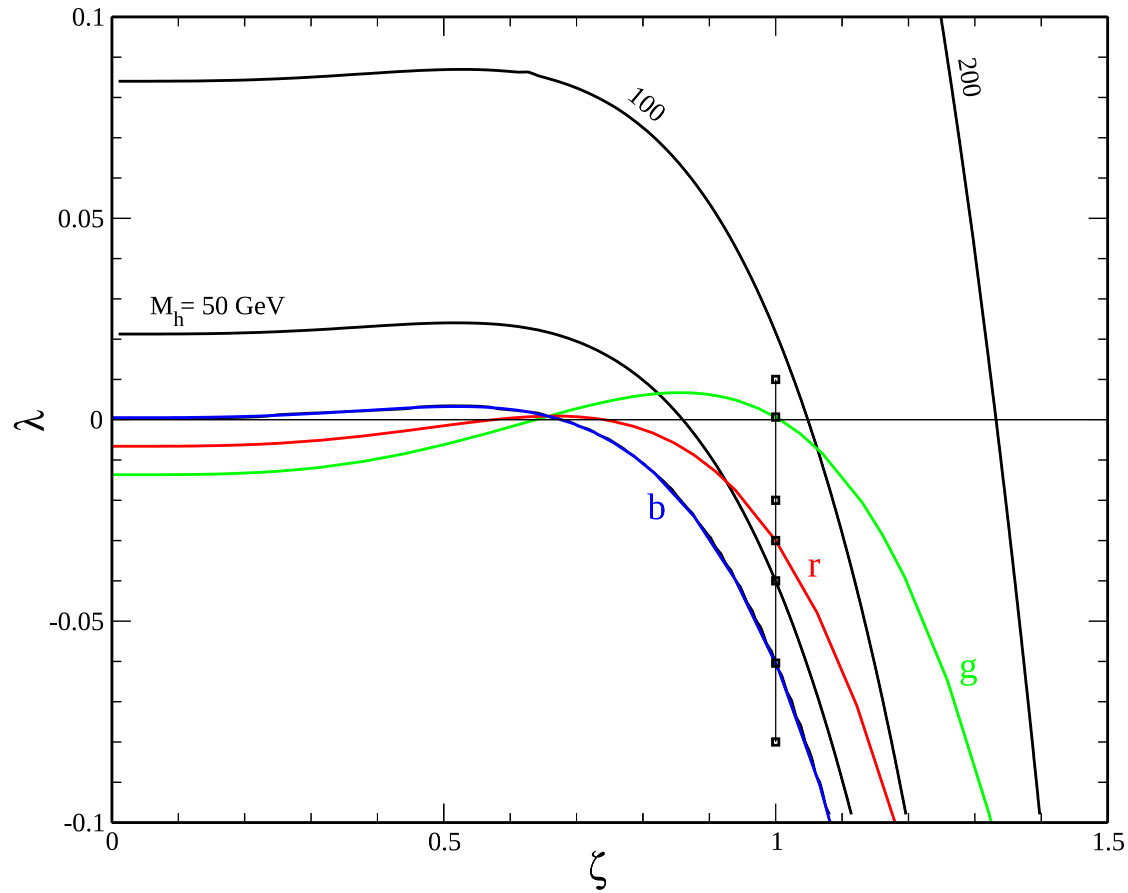
In the region between the blue and the red line ($m^2 > 0$) there is a false electroweak minimum

Electroweak breaking



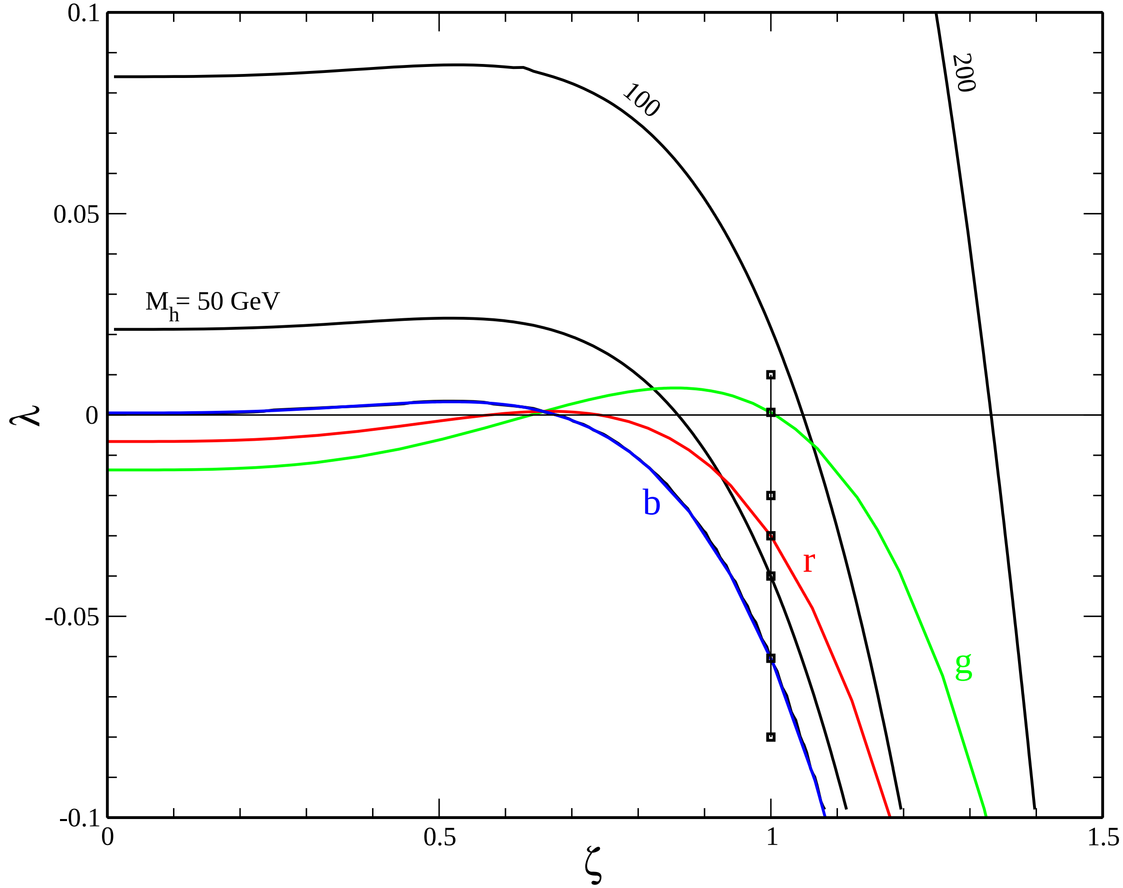
In red line the minima at the origin and at v are degenerate

Electroweak breaking



Between the red and green line [defined by $V''(0) = 0$] the electroweak minimum is stable

Electroweak breaking



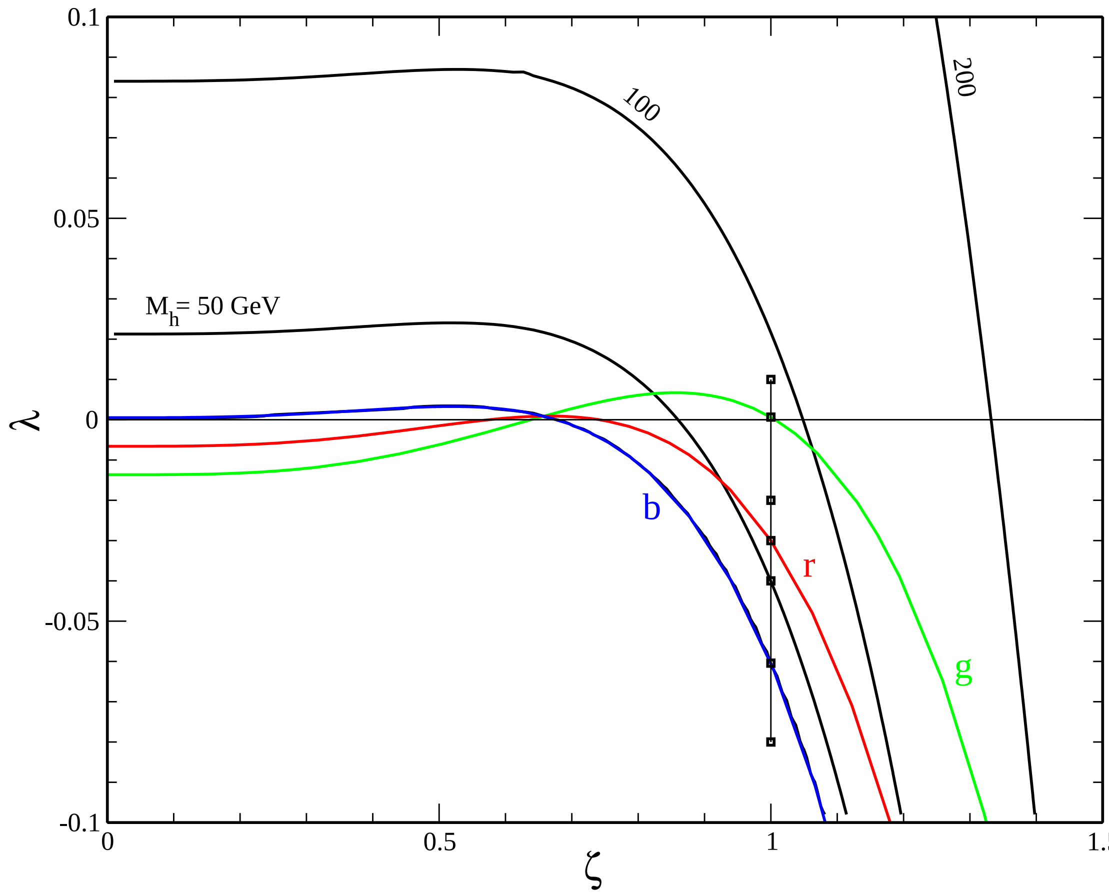
and there is a barrier separating the false minimum at the origin from the electroweak minimum

Electroweak breaking

This region is very interesting for two reasons

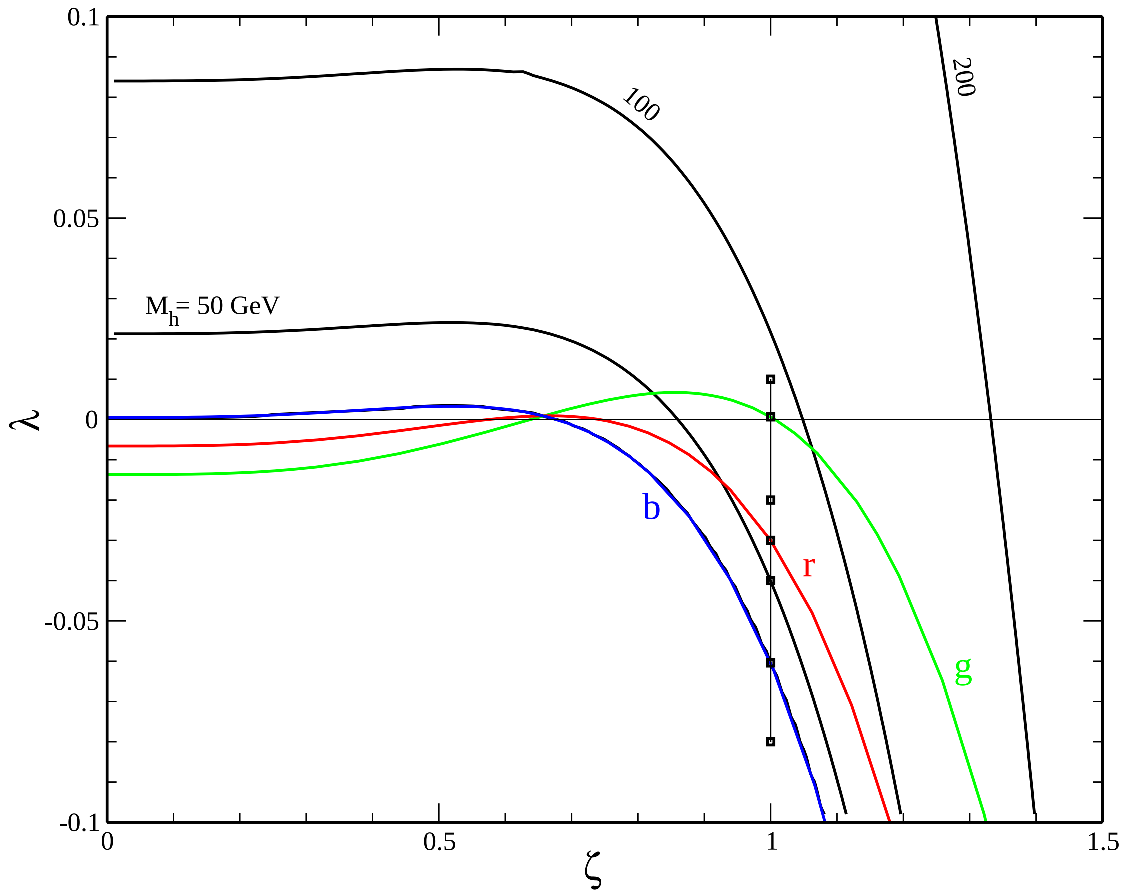
- The barrier between both minima (at zero temperature) will produce an overcooling of the Higgs field at the origin at finite temperature, strengthening the first order phase transition (see below).
- Electroweak symmetry breaking is not associated with the presence of a tachyonic mass at the origin, as in the SM. Instead it is triggered by radiative corrections via the mechanism of dimensional transmutation.

Electroweak breaking



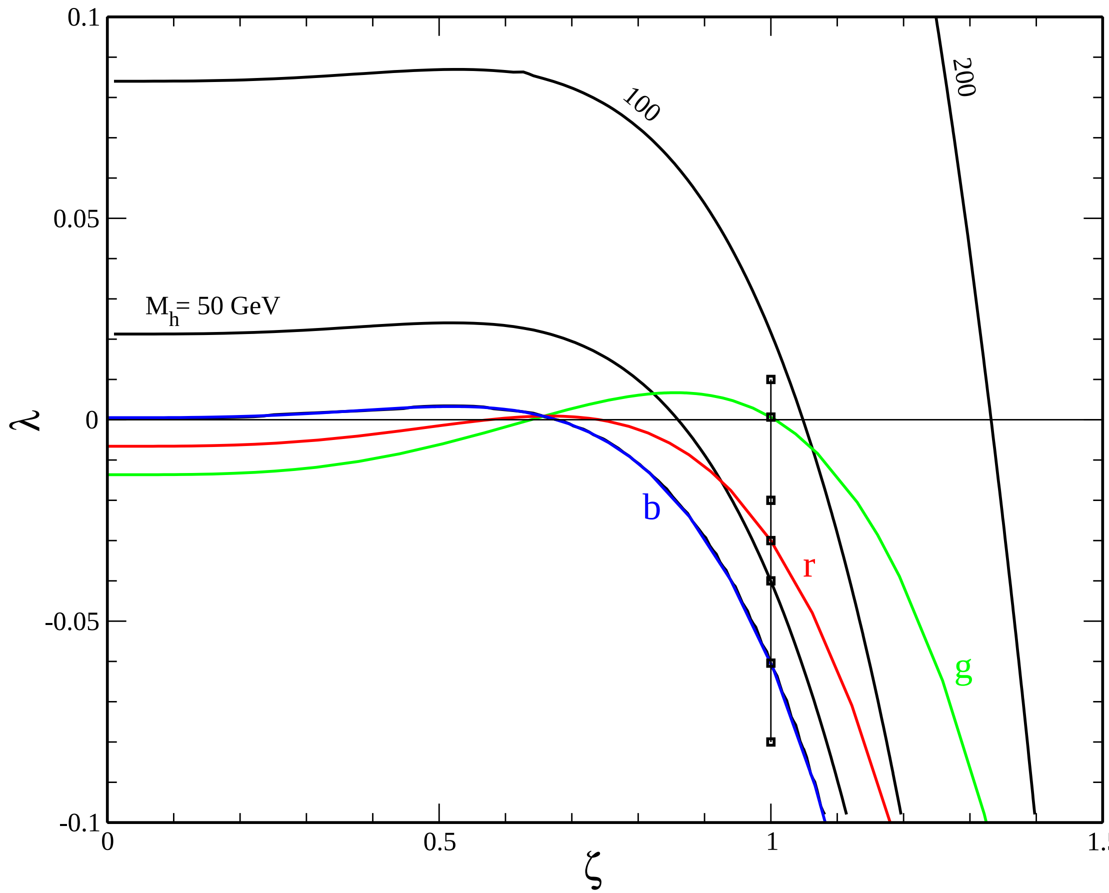
Green line corresponds to the conformal case where $m^2 = 0$

Electroweak breaking



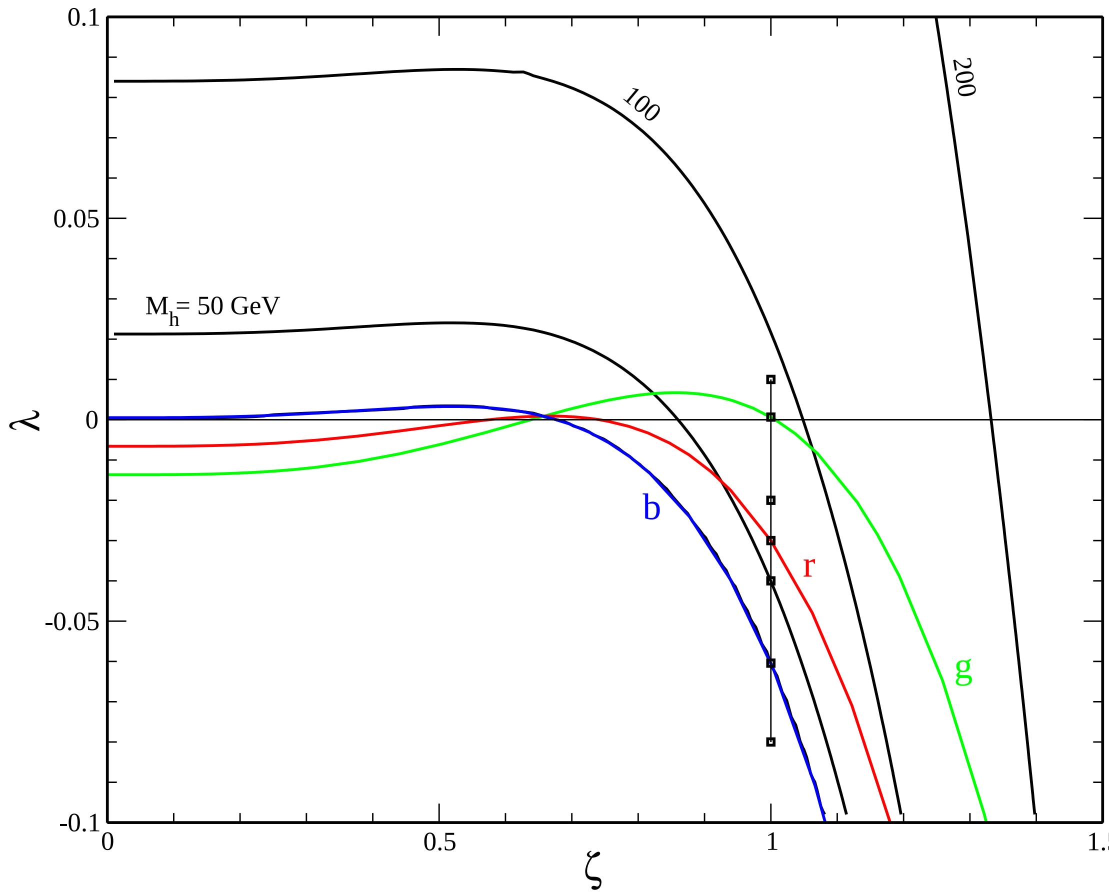
and electroweak breaking proceeds by dimensional transmutation

Electroweak breaking



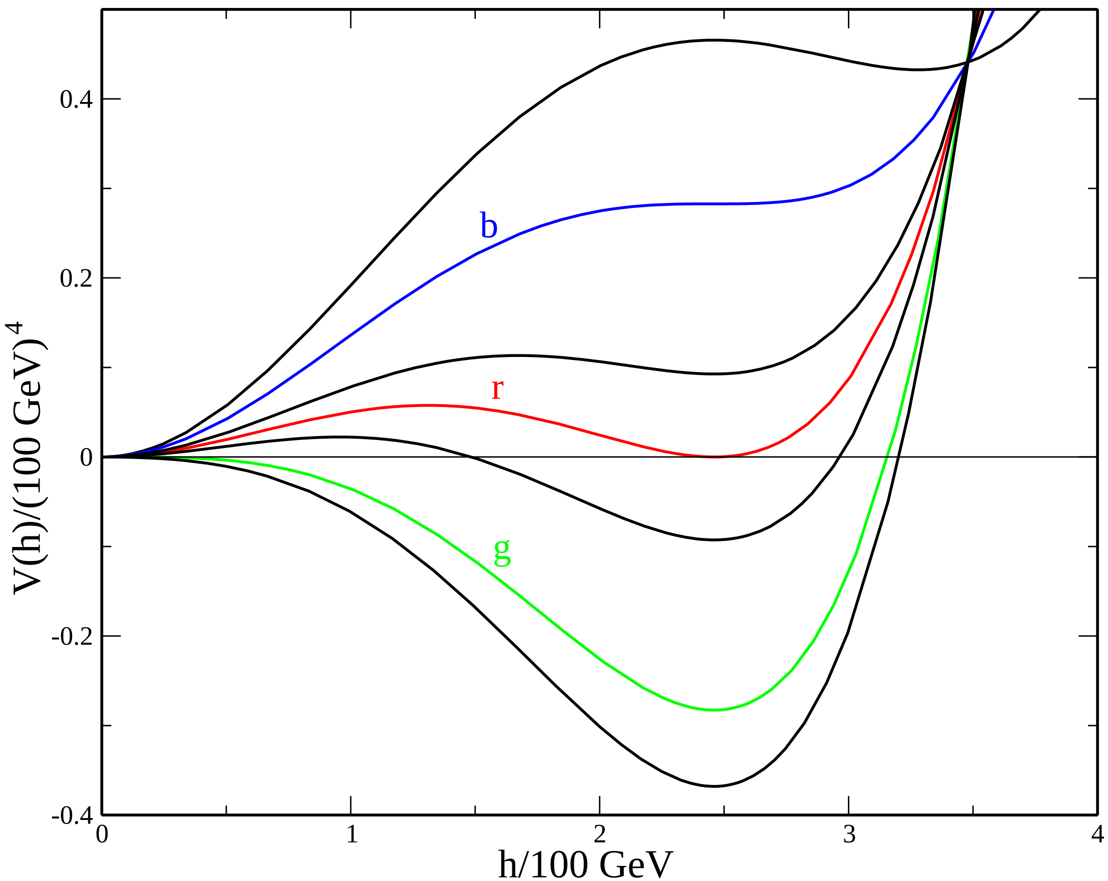
In the region above the green line the origin is a maximum as in the SM, with $m^2 < 0$

Electroweak breaking



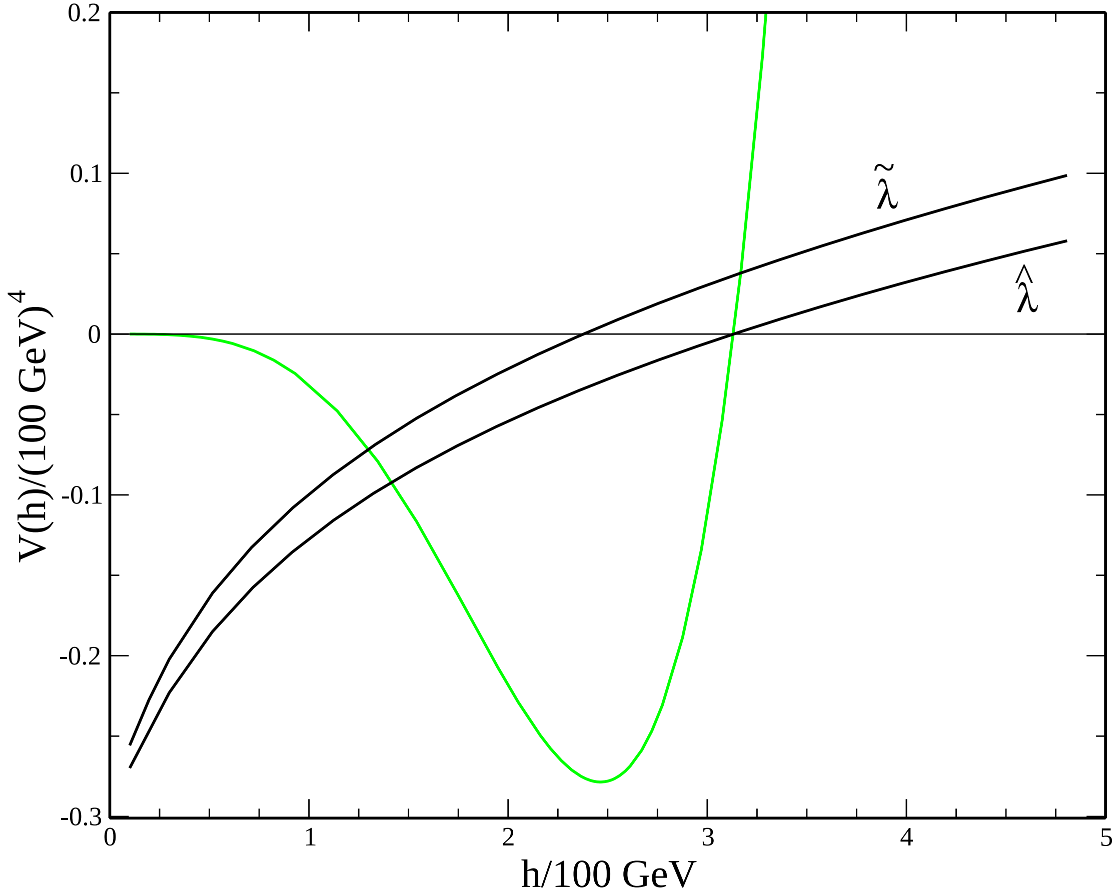
The potential for the spots in the above figure

Electroweak breaking



The different effective potentials

Electroweak breaking



The conformal case with λ running

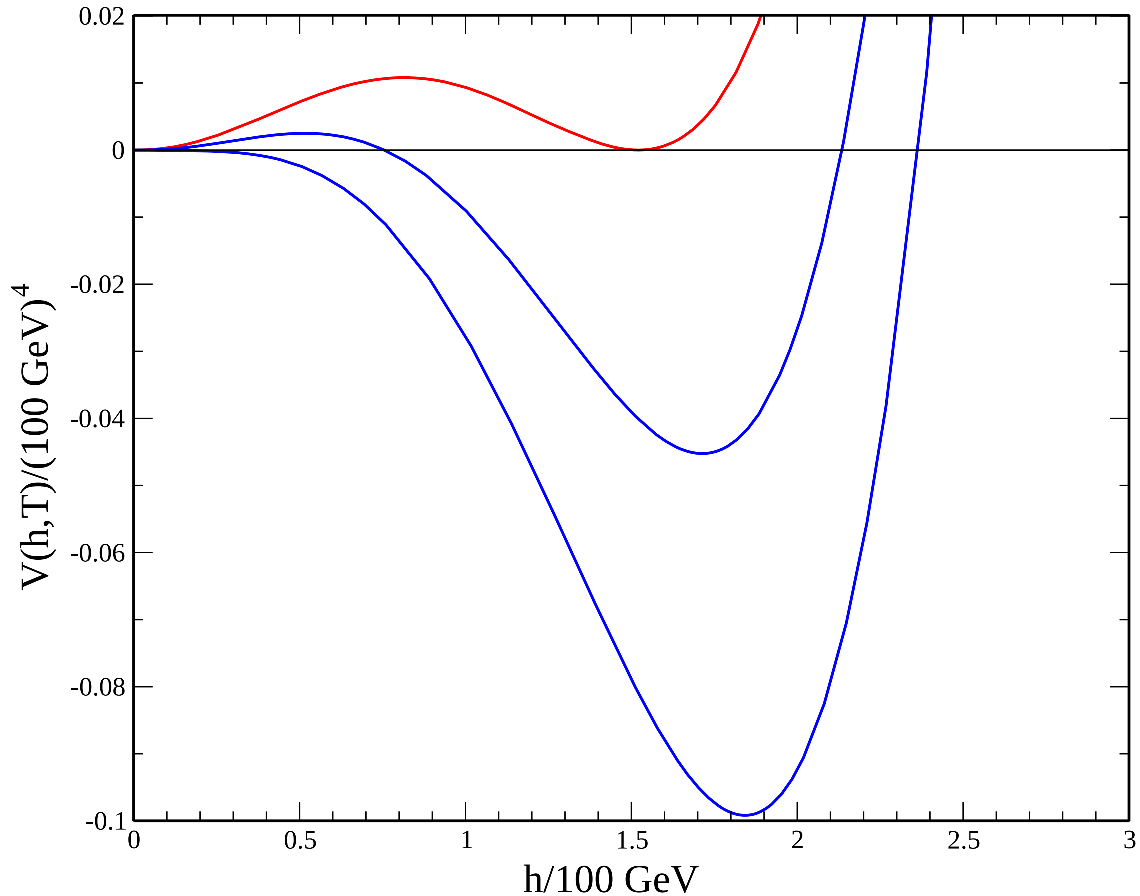
Electroweak phase transition

In the presence of hidden sector fields S_i coupled to the SM Higgs the electroweak phase transition is strengthened by:

- The thermal contribution from S_i, if ζ is large enough. "This fact was already known"
- The fact that, in part of the (ζ, λ)-plane, there is a barrier separating the origin (energetically favored at high temperature) and the electroweak minimum at zero temperature. "This effect is new"

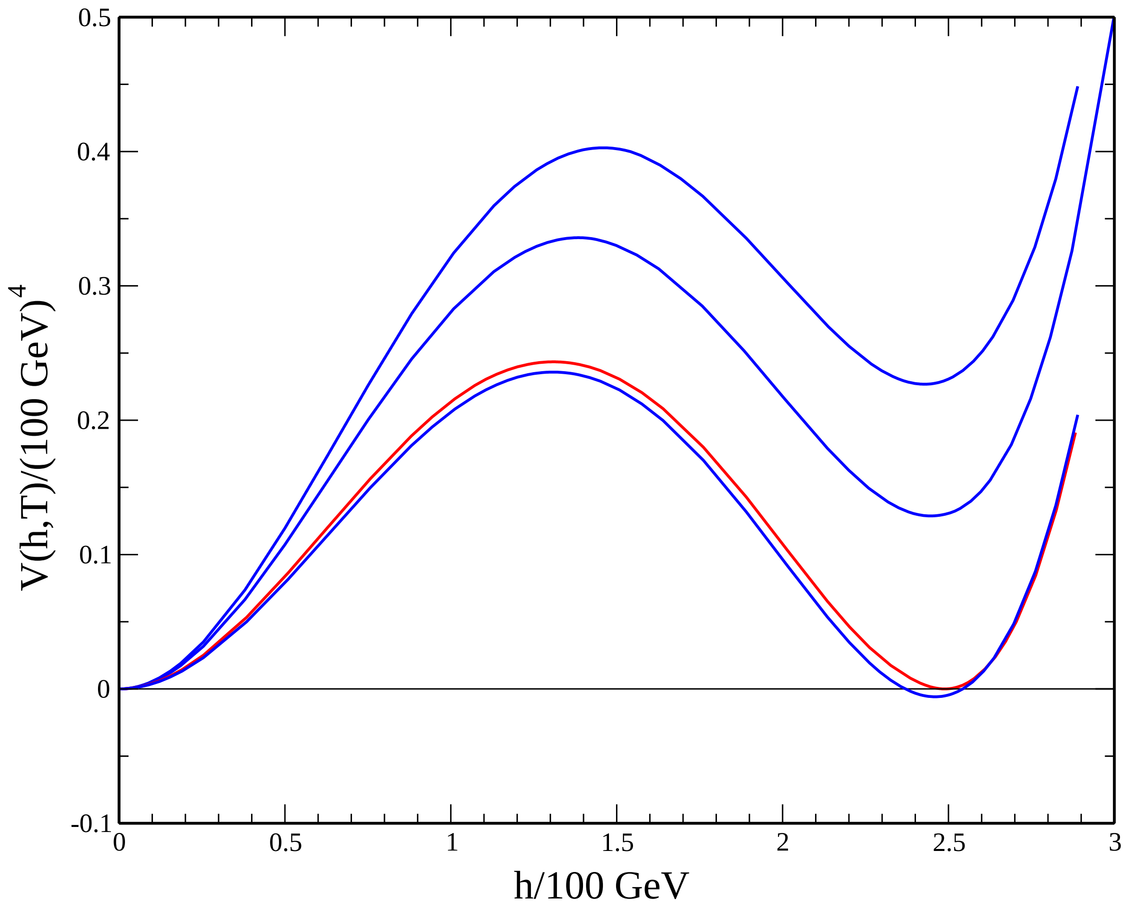
We have studied the effective potential at finite temperature for $N = 12$ and the bounce action

Electroweak phase transition

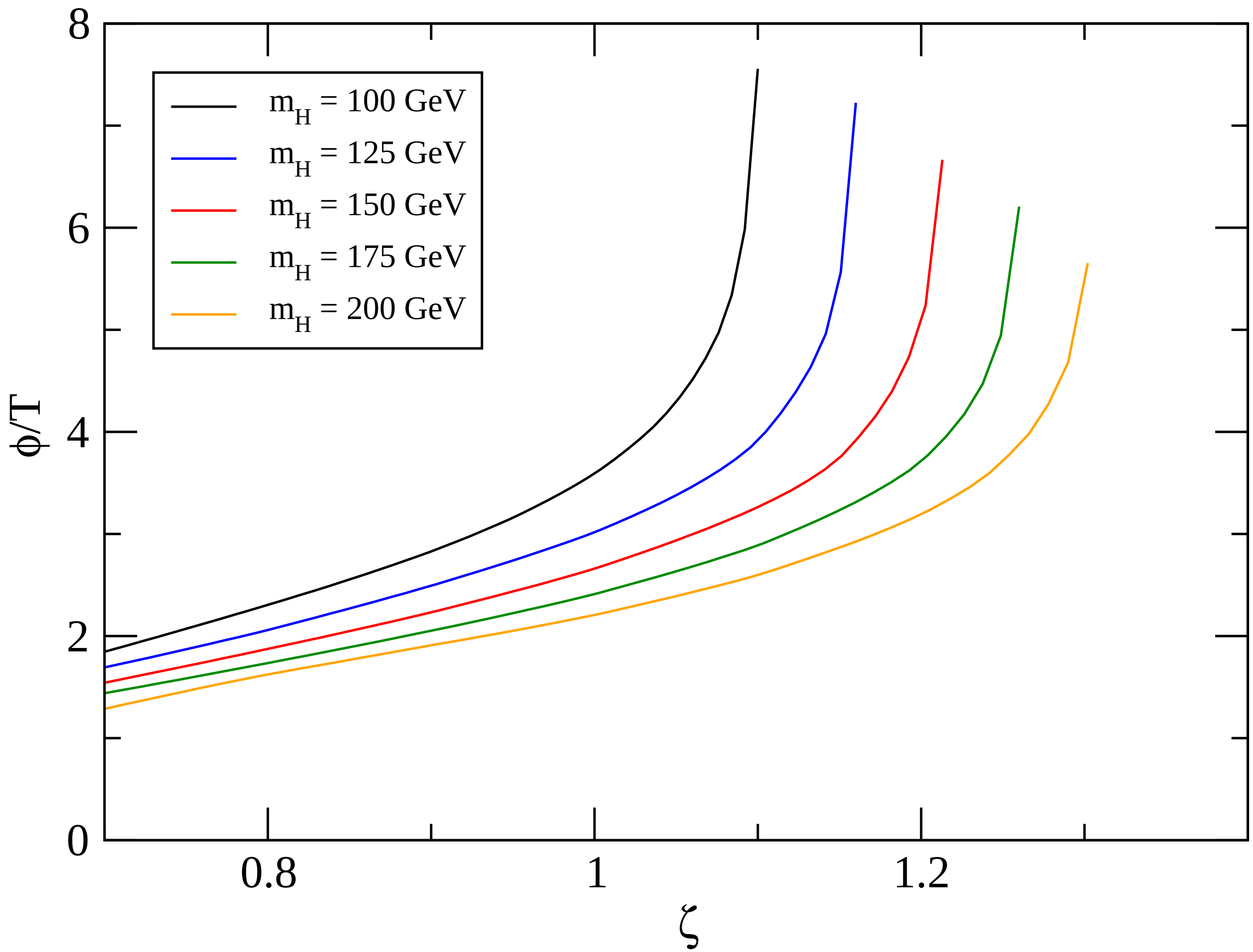


$M_h = 125$ GeV $\zeta = 0.8$ and $T = 110.85$, 108 and 105 GeV

Electroweak phase transition



$M_h = 125$ GeV $\zeta = 1.365$ and $T = 50$, 40 and 30 GeV



Plot of $\langle h \rangle / T_c$

with J.R. Espinosa, J. No and T. Konstandin, arXiv:0809.3215 [hep-ph]

CP violation and BAU

- To generate enough CP violation we would need to go beyond the present model

[a] Dine-Huet-Singleton-Susskind, PLB 257 (1991) 351

CP violation and BAU

- To generate enough CP violation we would need to go beyond the present model
- An interesting possibility from the LE point of view is the appearance of effective operators as e.g.

$$\frac{g^2}{32\pi^2\Lambda^2}|H|^2 F\tilde{F}$$

that generates

$$n_B/s \sim 10^{-9}(T_c/\Lambda)^2$$

Dine-Huet-Singleton-Susskind, PLB 257 (1991) 351

The MSSM

- In the MSSM there is the so-called [a] light stop window where BAU is produced by fermions: charginos and neutralinos
- BAU is barely consistent with WMAP results for $\mathcal{O}(1)$ phases and light charginos and neutralinos
- The lightest neutralino is a candidate to Dark Matter

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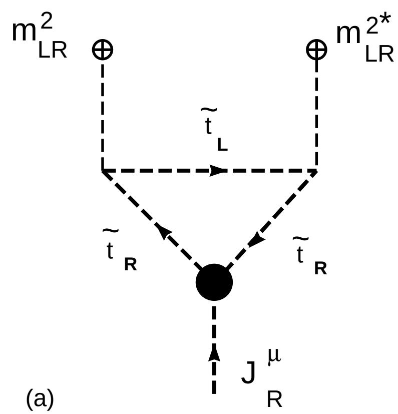
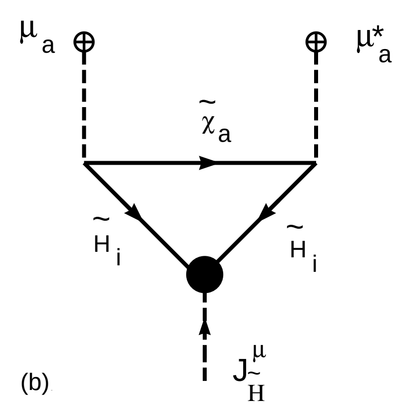
[a] M. Carena, M. Quiros, C.E.M. Wagner, PLB380 (1996) 81

The MSSM

Diagrams contributing to the CPV currents from $\varphi(A_t)$ and $\varphi(\mu)$





MSSM

* References 20th century

- Cohen-Kaplan-Nelson, PLB **336**, 41 (1994)
- Riotto, PRD **53**, 5834 (1996); NPB **518**, 339 (1998)
- Huet-Nelson, PRD **53**, 4578 (1996)
- Carena-Quiros-Riotto-Vilja-Wagner, NPB **503**, 387 (1997)
- Joyce, PRD **55**, 1875 (1997)
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- Rius-Sanz, NPB **570**, 155 (2000)
- Cline-Joyce-Kainulainen, JHEP **0007**, 018 (2000)
- Cline-Kainulainen, PRL **85**, 5519 (2000)

MSSM

* References 21st century

- Carena-Moreno-Quiros-Seco-Wagner, NPB **599**, 158 (2001)
- Carena-Quiros-Seco-Wagner, NPB **650**, 24 (2003)
- Kainulainen-Prokopec-Schmidt-Weinstock, JHEP **0106**, 031 (2001)
- Kainulainen-Prokopec-Schmidt-Weinstock, PRD **66**, 043502 (2002)
- Prokopec-Schmidt-Weinstock, AP **314**, 208 (2004)
- Konstandin-Prokopec-Schmidt-Seco, NPB **738**, 1 (2006)

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  - All other sfermions are much heavier with (common) mass $\tilde{m}$ to avoid EDM bounds ($\tan\beta < 10$)
  - Charginos and neutralinos are light to generate BAU and DM

MSSM

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$$m_U^2 \sim -\Pi_R(T)$$

- Generating two minima $(h, \tilde{t}) = (v, 0)$ and $(h, \tilde{t}) = (0, u)$

MSSM

There are four possible cosmological scenarios

INSTABILITY REGION

When $T_U^n > T_H^n$ and $\langle V_H \rangle > \langle V_U \rangle$ the transition to the color breaking minimum happens first and since the latter is deeper than the electroweak minimum, the system will stay in the color breaking minimum forever. This region, that we call "instability region", is of course non-realistic

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TWO STEP PHASE TRANSITION

When $T_U^n > T_H^n$ and $\langle V_H \rangle < \langle V_U \rangle$ the transition to the color breaking minimum also happens first but since the electroweak vacuum is deeper than the color breaking one the system becomes metastable at a given temperature.
It was proven that the phase transition from the color breaking to the electroweak minimum never happens which makes this region non-realistic too.

J.M. Cline, G.D. Moore and G. Servant, hep-ph/9902220

MSSM

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STABILITY

When $T_U^n < T_H^n$ and $\langle V_H \rangle < \langle V_U \rangle$ the electroweak phase transition happens first and since the electroweak minimum is the true vacuum of the theory this process gives rise to the usual electroweak phase transition.
Present bounds on the Higgs mass imply that the electroweak phase transition is too weak in this region for the mechanism of electroweak baryogenesis to take place.

MSSM

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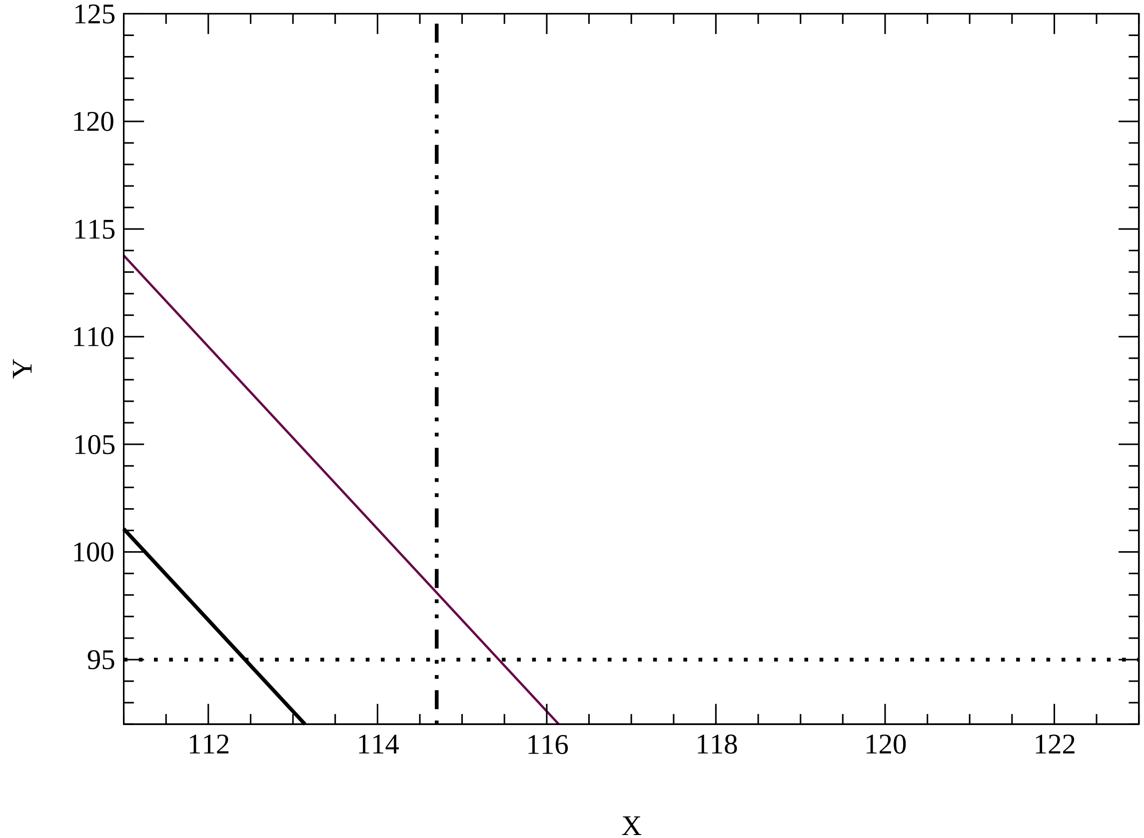
METASTABILITY

When $T_U^n < T_H^n$ and $\langle V_H \rangle > \langle V_U \rangle$ the electroweak phase transition happens first but the color breaking minimum is deeper than the electroweak minimum which makes the system to be in a metastable situation.
This scenario is proven to be viable

M. Carena, G. Nardini, M. Quiros and C.E.M. Wagner, arXiv:0809.3760

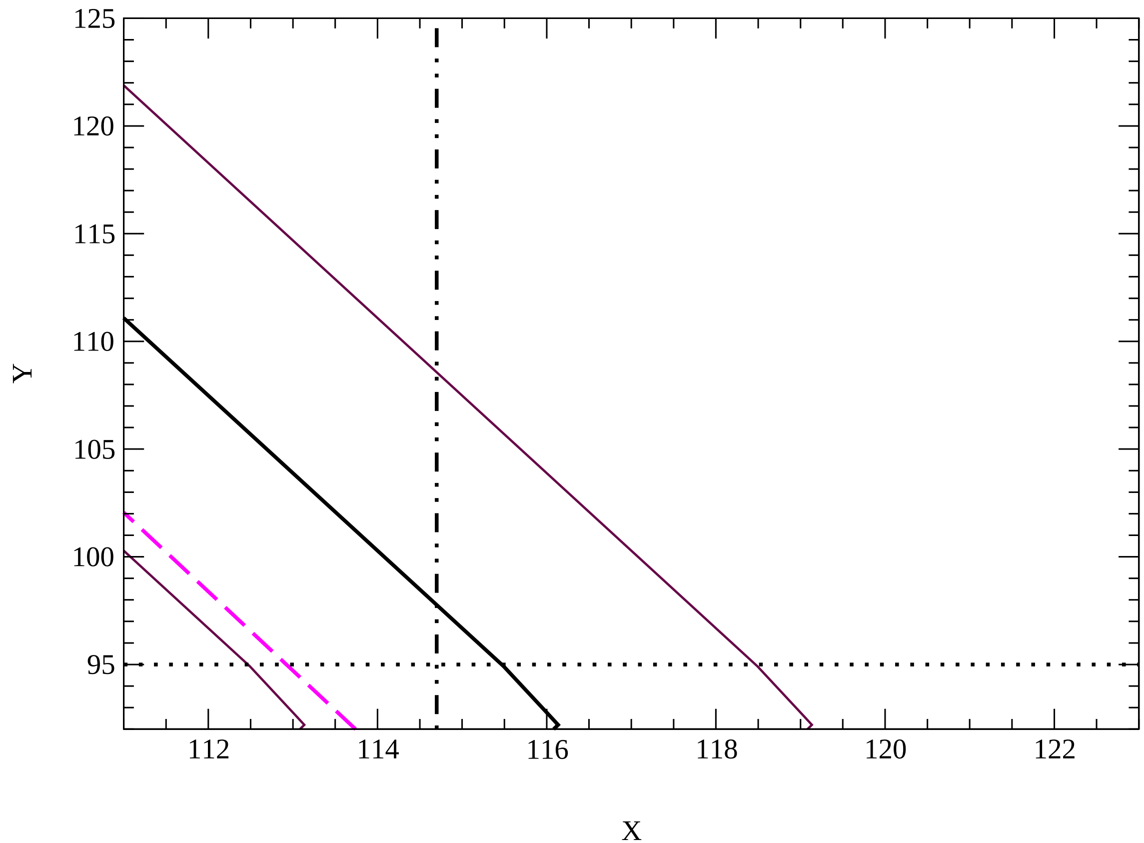
Baryogenesis window



METASTABILITY REGION FOR $\tilde{m}$ =10 TeV [a]
[plane $(y = m_{\tilde{t}_R}, x = m_H)$]

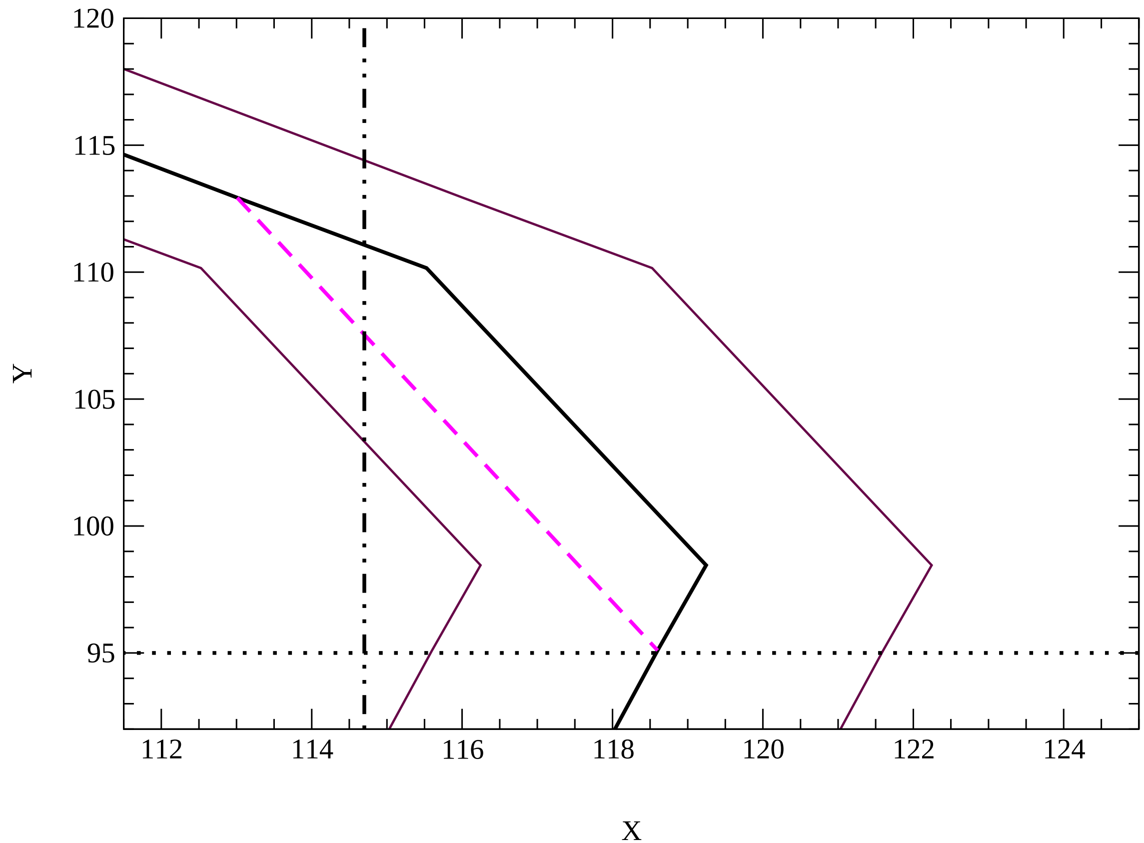
[a] M. Carena, G. Nardini, M. Quiros and C.E.M. Wagner, arXiv:0809.3760

Baryogenesis window



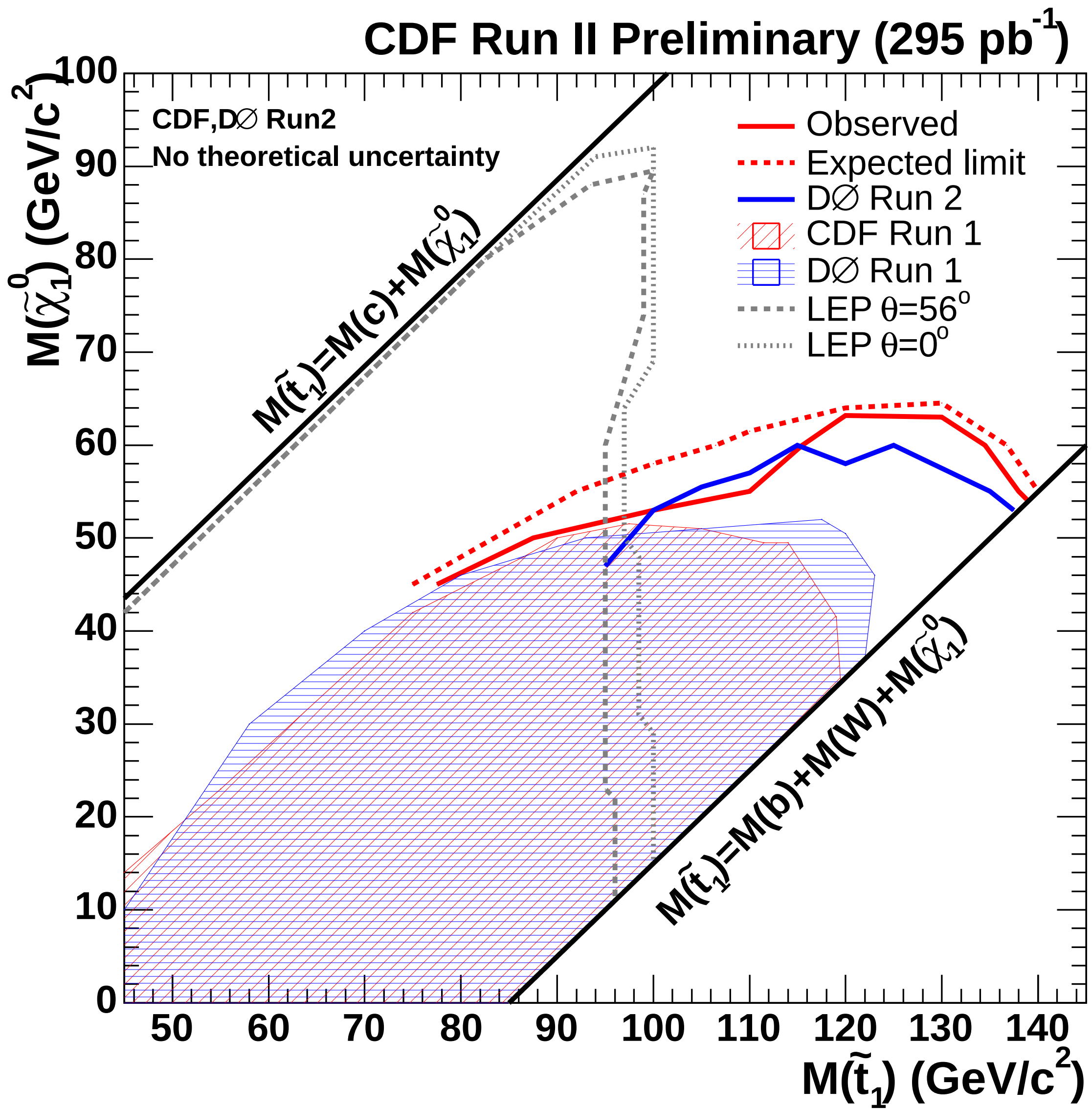
METASTABILITY REGION FOR $\tilde{m} =$30 TeV

Baryogenesis window



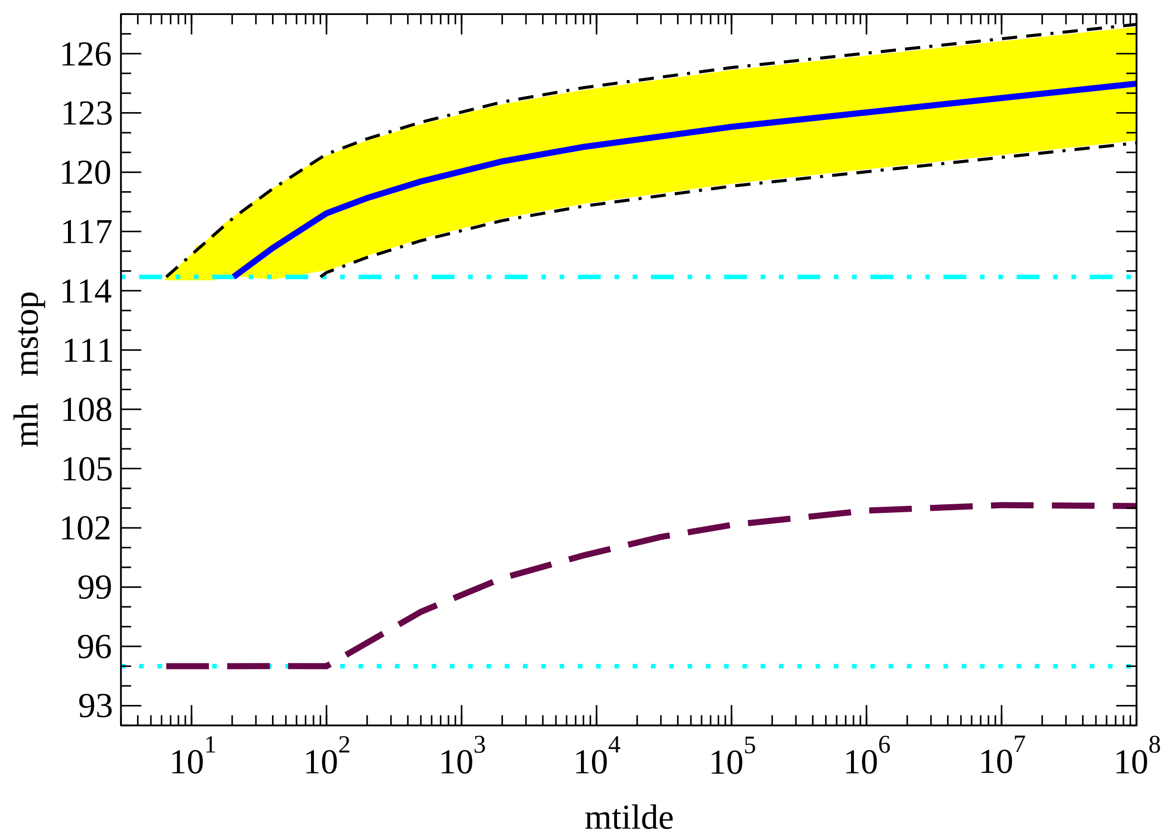
METASTABILITY REGION FOR $\tilde{m} =$500 TeV

Baryogenesis window



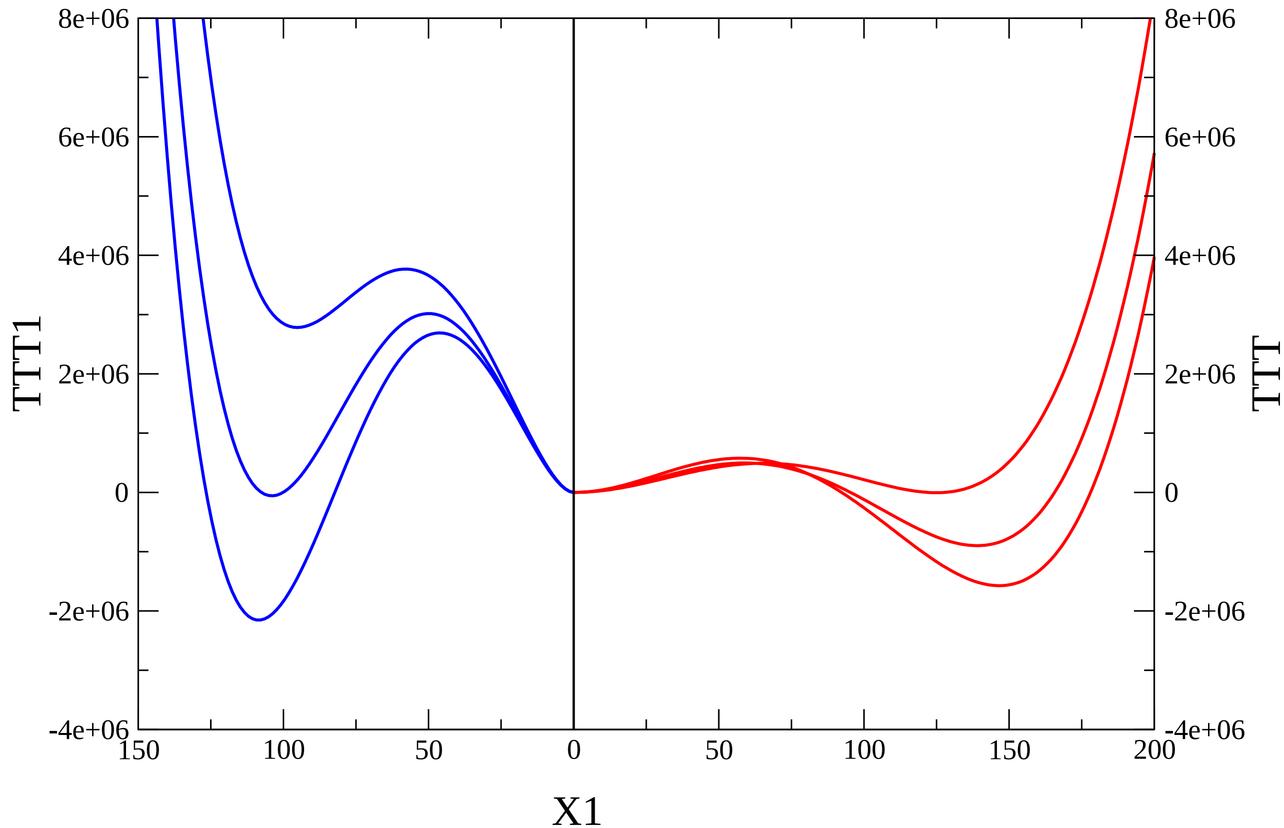
PRESENT EXPERIMENTAL BOUNDS

Baryogenesis window



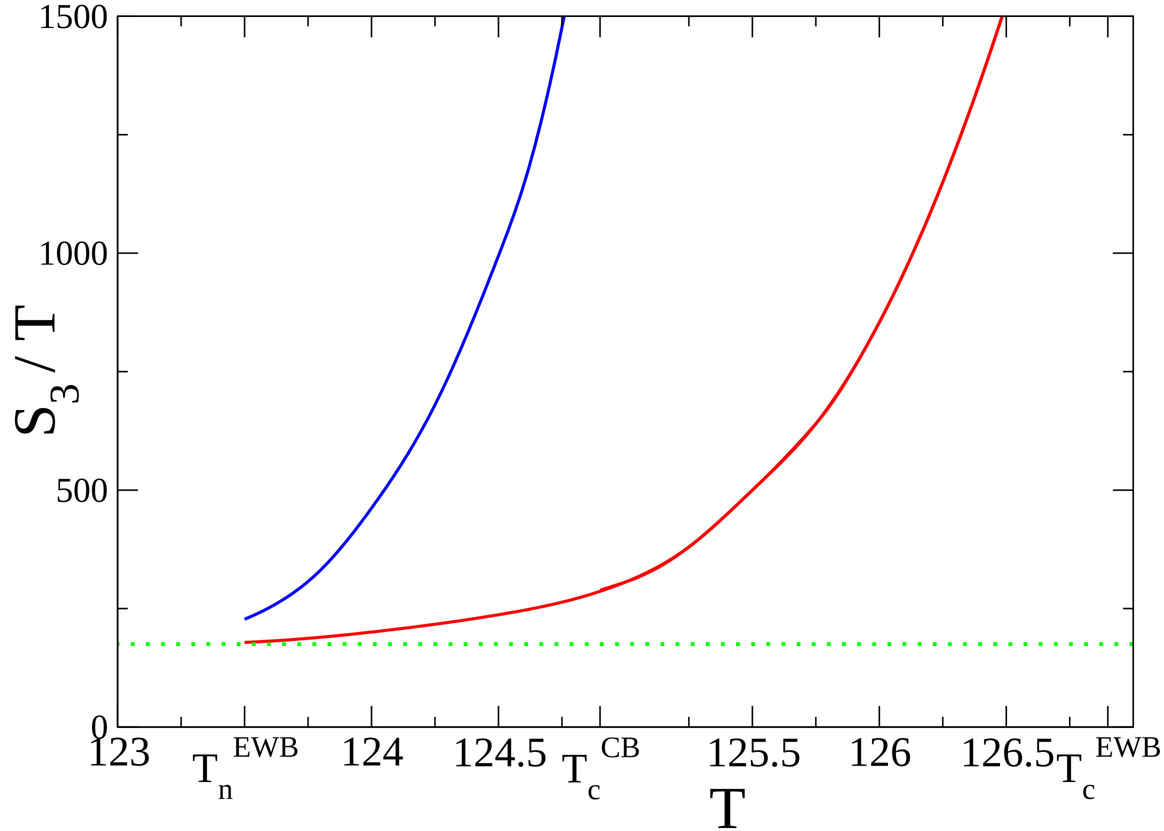
ABSOLUTE UPPER BOUNDS Vs. $\log_{10}(\tilde{m}/GeV)$

Analysis of metastability



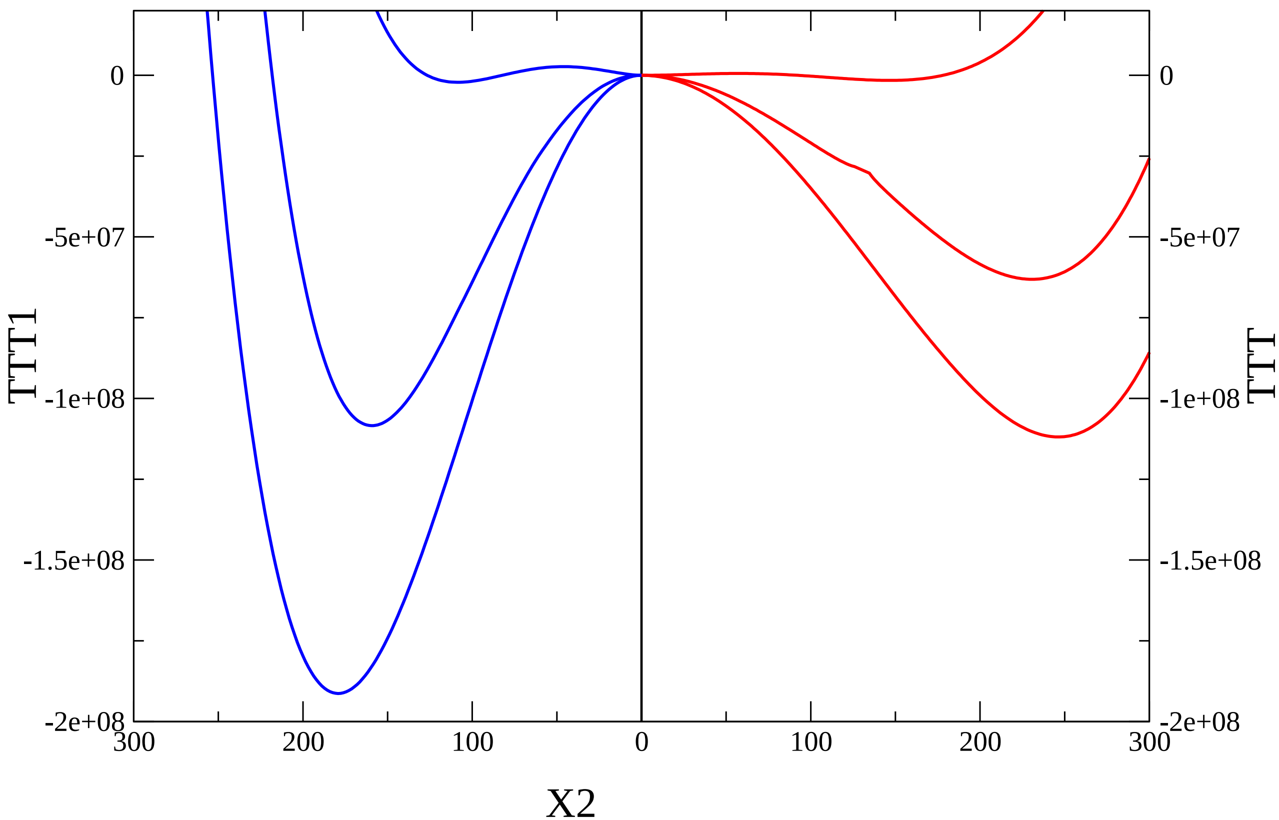
Potential for the stop and Higgs, $\tilde{m} = 10$ TeV and most dangerous point (maximum value of m_H): $T =$126.8, 125, 123.5

Analysis of metastability



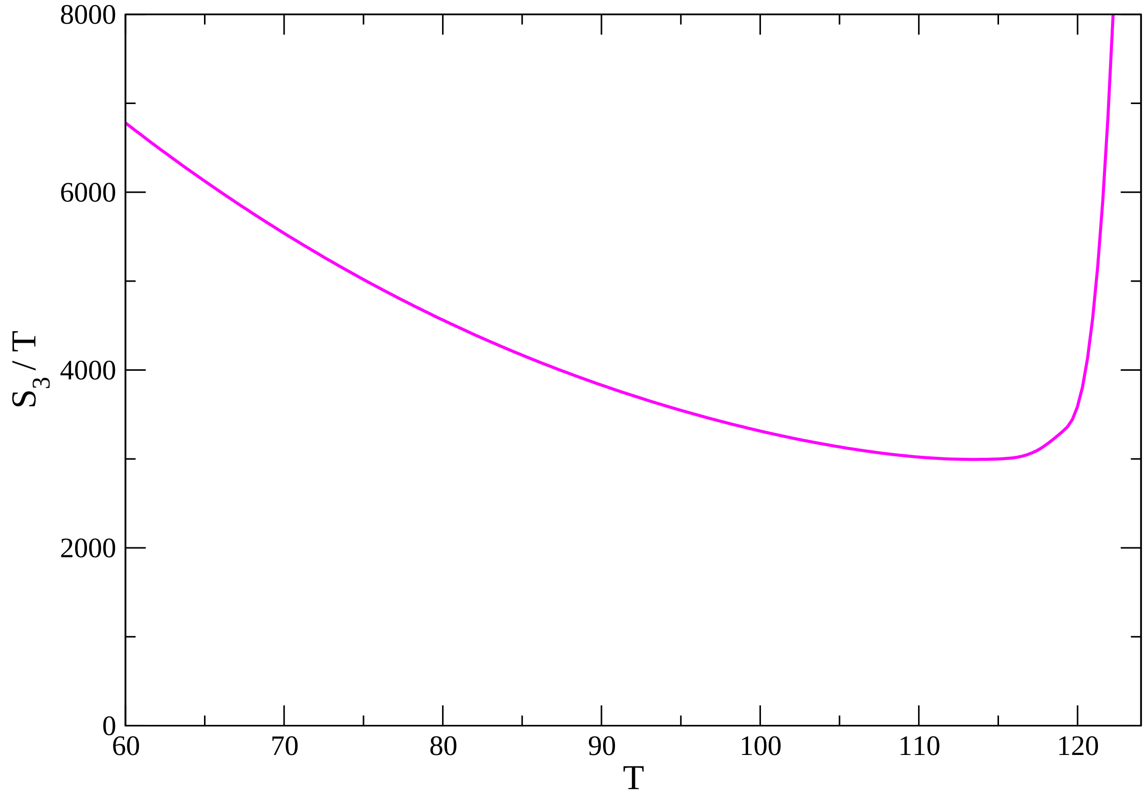
Bounce($0 \to U$) and Bounce($0 \to H$)

Analysis of metastability



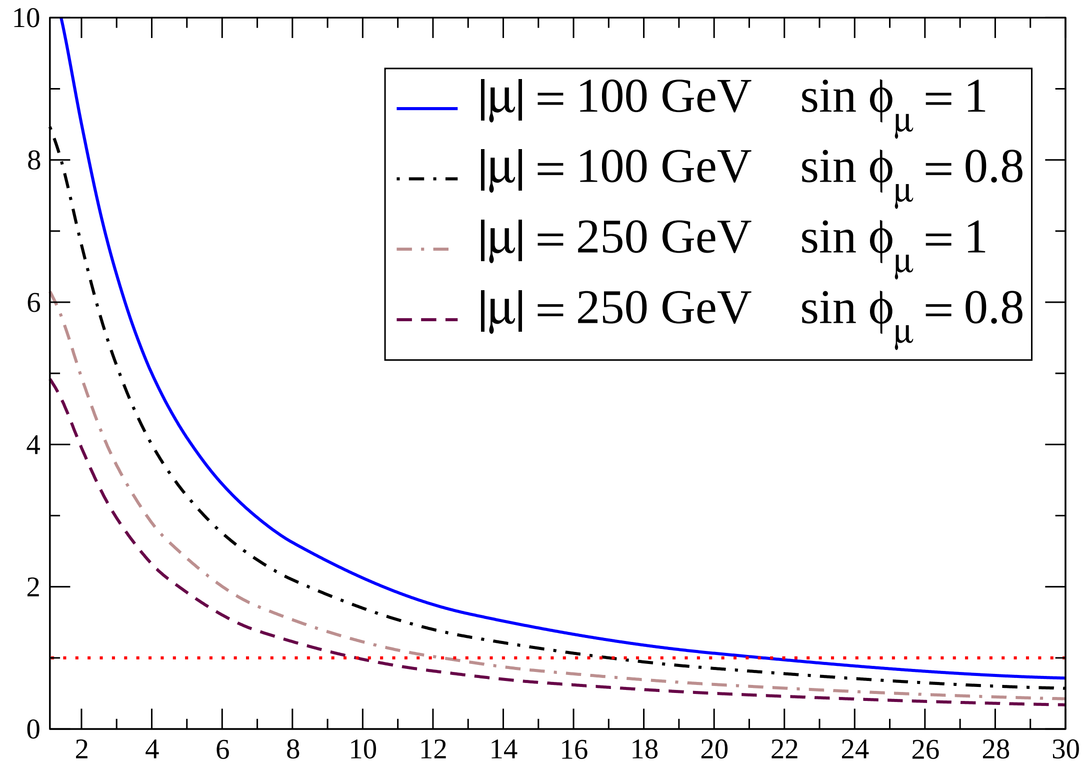
Potential for stop and Higgs for $T =$123.5, 80, 0

Analysis of metastability



Bounce ($H \to U$)

BAU



η/η_{BBN} Vs. $\tan\beta$

M. Carena, G. Nardini, M. Quiros and C.E.M. Wagner, arXiv:0809.3760

Conclusion

EWBG can be tested at LHC that can thus probe the different models

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