Quantum transport and electroweak baryogenesis

Thomas Konstandin

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Outline

Introduction

MSSM

Composite Higgs
Baryogenesis

[Sakharov '69]

Baryogenesis aims at explaining the observed asymmetry between matter and antimatter abundances.

\[ \eta = \frac{n_B - n_{\bar{B}}}{n_{\gamma}} \simeq 10^{-10} \]

The main ingredients for viable baryogenesis are stated by the celebrated Sakharov conditions:

- B-number violation (baryon-number)
- C and CP violation (charge/parity)
- out-of-equilibrium
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\[
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\]
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\[
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\text{+} & \text{+} & \text{+} & \text{+} \\
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\text{+} & \text{+} & \text{+} & \text{+}
\end{array} - \begin{array}{cccc}
\text{-} & \text{-} & \text{-} & \text{-} \\
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\[ n = n(m/T) \]
\[ m = \bar{m} \]
\[ n_B = n_{\bar{B}} \]
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[Sakharov '69]
First-order phase transition

The free energy (as a function of the Higgs vev) decides the nature of the phase transition:

- Second-order crossover
- First-order
First-order phase transitions

- First-order phase transitions proceed by bubble nucleations.

- In case of the electroweak phase transition, the "Higgs bubble wall" separates the symmetric from the broken phase.

- This is a violent process \( v_b = O(1) \) that drives the plasma out-of-equilibrium.

- Bosons that are strongly coupled to the Higgs tend to make the phase transition stronger.
Electroweak baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]
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avoid washout: $\langle \phi \rangle \gtrsim T$
Hierarchical problem

This indicates that there is some kind of new physics around the corner that did not appear in collider experiments yet.

$m_{Higgs}$

small hierarchy problem

$\Lambda_{new} \sim 1 - 10 \text{ TeV}$

SUSY?
(warped) extra-dimensions
strong coupling / technicolor?

$\text{CP}$

$\text{eq}$
Why is this interesting?

- The hierarchy problem indicates that there is some BSM physics at EW scales.
- Electroweak baryogenesis involves only physics at the electroweak scale that is accessible to collider experiments.
- Electroweak baryogenesis leads naturally to the observed baryon asymmetry.

\[ \eta_B \sim \frac{\Gamma_{ws}}{l_w T^2} \delta_{CP} e^{-m_x/T} \sim 10^{-11} - 10^{-9} \]
What are the challenges?

[Kuzmin, Rubakov, Shaposhnikov '85]
[Cohen, Kaplan, Nelson '93]
Many particles change their mass when passing into the Higgs bubble:

\[ m > 0 \quad \Rightarrow \quad \tilde{p}^2 = m^2 \]
\[ m = 0 \quad \Rightarrow \quad p^2 = 0 \]

wall frame \[ \tilde{E} = E \]

and \[ \tilde{p}_z^2 = p_z^2 - m^2 \]

reflected when \( p_z < m \)
Transport equations

In case of a statistical system with particle distribution function

\[ f(p_z, x, t) \]

the change in momentum

\[ \tilde{E} = E \quad \text{and} \quad \tilde{p}_z^2 = p_z^2 - m^2 \]

translates into

\[ f(p_z, left t) = f(\sqrt{p_z^2 - m^2}, right) \]

or

\[ p_z \partial_z f + \frac{1}{2} \partial_z m(z)^2 \partial_{p_z} f = 0 \]

flow term force

transport equation of Boltzmann type
In order to quantify electroweak baryogenesis one needs a formalism that includes quantum effects (CP violation) as well as statistical effects (diffusion/transport).

This is achieved by the Kadanoff-Baym equations that are a statistical generalisation of the Schwinger-Dyson equations of QFT (Schwinger-Keldysh formalism).

\[(\Box + m^2 + \Sigma)G(x, y) = \delta(x - y)\]

Formally the equation looks like SD, but:

- The 2-point function depends on x and y seperately → X and p in Fourier (Wigner) space
- There is an additional 2x2 structure from the in-in-formalism
Kadanoff-Baym equations

In Wigner space this leads to the Moyal star product

\[(p^2 - m(X)^2 - \Sigma) e^{i\diamond} G(X, p) = 1\]

With \(\diamond = \overleftarrow{\partial_X} \overrightarrow{\partial_p} - \overleftarrow{\partial_p} \overrightarrow{\partial_X}\)

\[X = \frac{x + y}{2}\]

One of the Green functions (Wightman function) encodes the particle distribution function and is in equilibrium given by

\[G^\leq_e (X, p) = 2\pi i \ f^e q(p, X) \ \delta(p^2 - m^2)\]

and

\[f^e q = \frac{1}{e^{p_0/T} \pm 1}\]
For one fermion flavor with a space-time dependent mass, the Kadanoff-Baym equation reads

\[(\not{\tau} - m P_L - m^* P_R - \Sigma^R) e^{i\diamond} G^< = \text{collisions}\]

In order to do progress analytically, one typically uses several approximations/techniques:

1) Neglect most interactions: \[\Sigma^R \rightarrow 0\]

2) Planar approximation (z): \[\hat{S} \propto (p_0 \gamma_0 - p_\perp \cdot \gamma) \gamma_3 \gamma_5\]

3) Gradient expansion: \[\diamond \sim \partial_x \partial_p \sim (LT)^{-1} \ll 1\]

[Kainulainen, Prokopec, Schmidt, Weinstock '02]
One fermion flavor

For one fermion flavor with a space-time dependent mass, an expansion in gradients leads to the equations

\[(p^2 - m^2 + \cdots)G^< = 0\]

and with \[m(z) = |m(z)|e^{i\theta(z)}\] and spins s

\[
\left(p \cdot \partial_X + \frac{1}{2}(m^2)' \partial_p + \frac{s}{2p_z} (m^2 \theta')' \partial_p \right)f_s = \text{collisions}
\]

\[m(\partial_t + \vec{v} \cdot \nabla)\]

forces

decays
scatterings

[Cline, Joyce, Kainulainen '00]
[Kainulainen, Prokopec, Schmidt, Weinstock '02]
Technical details
Ingredients

1. Strong first-order electroweak phase transition \( \phi > T \)

2. Some fermion species that changes its mass in a CP violating way during the electroweak phase transition (and preferably charged under \( SU(2)_L \))
\[
\left( p \cdot \partial_X + \frac{1}{2} (m^2)' \partial_p + \frac{s}{2p_z} (m^2 \theta')' \partial_p \right) f_s = \text{collisions}
\]

\[
m = |m(X)| e^{i \theta(X)}
\]
Outline

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MSSM

Composite Higgs
In the minimal supersymmetric standard model, the leading \( \text{CP} \) violation comes from the mass matrix of the charginos

\[
m = \begin{pmatrix} M_2 & g v_1(X) \\ g v_2(X) & \mu c e^{i\varphi} \end{pmatrix} \quad \varphi \neq 0
\]

The strength of the electroweak phase transition

- is reduced by larger Higgs masses
- is enhanced by bosonic degrees of freedom that couple strongly to the Higgs - stops important

\[
m_{\text{stop}} \lesssim m_{\text{top}}
\]
Several flavours

In the most prominent case (MSSM), CP violation results from mixing effects between different flavors.

[Careno, Moreno, Quiros, Seco, Wagner '00]

In this case, new CP-violating sources occur

\[ \text{forces} \ni -\frac{1}{4} \{ m^{2'}, \partial_p \} + \frac{i}{16} [ m^{2''}, \partial^2_p ] \]

but also additional complications arise due to flavor oscillations

\[ \left( p \cdot \partial_X + \frac{i}{2} [ m^2, . ] + \text{forces} \right) f_s = \text{collisions} \]

\[ e^{i \frac{\Delta m^2}{p} z} \]

[TK, Prokopec, Schmidt '05]
Assuming a strong first-order phase transition, the baryon asymmetry depends mostly on the chargino mass and the CP violation in the chargino sector.

\[
m = \begin{pmatrix}
M_2 & g v_1(X) \\
g v_2(X) & \mu_c e^{i\varphi}
\end{pmatrix}
\]

\[
\varphi = \frac{\pi}{2}
\]

\[
\frac{\eta_{\text{max}}}{\eta_{\text{observed}}} \approx 5
\]

[TK, Prokopec, Schmidt, Seco '05]
In the minimal supersymmetric standard model, the leading CP violation comes from the mass matrix of the charginos

\[ m = \begin{pmatrix} M_2 & g v_1(X) \\ g v_2(X) & \mu_c e^{i\varphi} \end{pmatrix} \]

Flavor mixing?  
Resonances?  
Higgs resummation?  
Flavor oscillations?  
Higgs transport?  

\[ \frac{\eta_{\text{max}}}{\eta_{\text{observed}}} \text{ for maximal CPV} \]

\[ 00/01 \quad 00/06 \quad 02/08 \quad 04/12 \quad 05/05 \quad 08/11 \]
Even if all sfermions are heavy, there are two-loop (Barr-Zee) contributions from the **chargino** to the EDM of the electron and the neutron.

[Chang, Chang, Keung '02]
EDMs

Even if all sfermions are heavy, there are two-loop (Barr-Zee) contributions from the chargino to the EDM of the electron and the neutron

\[
\sin \varphi \ < \ ?
\]

[Hudson et al. '11]

\[ d_e < 1.05 \times 10^{-27} \, e \, \text{cm} \]

[Chang, Chang, Keung '02]
The EDM constraints translate into

\[ \frac{\eta_{\text{max}}}{\eta_{\text{observed}}} \gtrsim 23 \]

\[ \text{[Hudson et al. '11]} \]
Chargino driven MSSM baryogenesis ruled out

The EDM constraints translate into

\[ \frac{\eta_{\text{max}}}{\eta_{\text{observed}}} \gtrsim 250 \]

[Baron et al. '13]

Caveat: EDM bounds avoided by using binos

[Li, Profumo, Ramsey-Musolf '08]
MSSM phase transition after LEP:
very heavy left-handed stop required

\[ m_{\text{stop, L}} \sim 500 \text{ TeV} \]

\[ \frac{\phi_c}{T_c} > 1.0 \]

\[ m_{\text{stop, R}} \lesssim 110 \text{ GeV} \]

\[ m_{\text{stop, L}} \gtrsim 30 \text{ TeV} \]

[Carena, Nardini, Quiros, Wagner '08]
MSSM phase transition after LEP: very heavy left-handed stop required

\[ \frac{\phi_c}{T_c} > 1.0 \]

\[ m_{\text{stop},R} \]

\[ m_H \]

\[ m_{\text{stop},L} \gtrsim 10^6 \text{ TeV} \]

[Carena, Nardini, Quiros, Wagner '08]

and hide right-handed stop from LHC
Electroweak baryogenesis in SUSY models is technically not ruled out yet, but with current experimental constraints it is a rather contrived scheme.

- Light (< 200 GeV) and almost mass degenerate charginos or binos
- CP violation for charginos that in the most optimistic cases is at the verge of being seen in EDM experiments (caveat: binos)
- Very specific spectrum required for a strong first-order phase transition (or extended Higgs sector?)
Outline

Introduction

MSSM

Composite Higgs
Composite Higgs models

The Higgs could be a Pseudo-Goldstone boson of a broken global symmetry

\[
\begin{align*}
\text{QCD:} & \quad \frac{SU(2)_L \times SU(2)_R}{SU(2)_V} \rightarrow 3\pi \\
\text{The broken symmetry will determine the light degrees of freedom and their quantum numbers} & \quad \frac{SO(5)}{SO(4)} \rightarrow H \\
\text{but also} & \quad \frac{SO(6)}{SO(5)} \rightarrow H + S \\
& \quad \frac{SO(6)}{SO(4) \times SO(2)} \rightarrow 2H
\end{align*}
\]

[Kaplan, Georgi '84]
Holographic techniques in composite Higgs models

Lately, this old idea underwent a renaissance due to holographic models to determine some quantity of the strongly coupled theory (like the Higgs potential) in a 5D setup.

[Contino, Nomura, Pomarol '03]
[Agashe, Contino, Pomarol '04]

- 5D GIM mechanism for flavor problems
- Oblique parameters better than in technicolor
- Many parameters and a certain arbitrariness in the scalar sector
Two ingredients of baryogenesis are missing in the Standard Model. These are provided in models that have an additional singlet in the low energy effective description.

\[ \mathcal{L} \supset y_t \overline{\psi}_Q H \psi_t + \frac{\tilde{y}_t}{f} S \overline{\psi}_Q H \psi_t + h.c. \]

\[ \Im(y_t \tilde{y}_t^*) \neq 0 \]

- Strong first-order electroweak phase transition: \[ V(s, h) \]
- CP violation from dimension-five operators
The construction of a potential barrier and hence first-order phase transitions are easily achieved in extended scalar sectors:

\[ V(h, s) = \frac{\lambda}{4} (h^2 - v^2)^2 + m_s^2 s^2 + a_s s^3 + \lambda_s s^4 + a_m s h^2 + \lambda_m s^2 h^2 \]

For example consider deformations of the $\mathbb{Z}_2$ - symmetric "super-Mexican-hat"

\[ V(s, h) = \frac{\lambda}{4} (h^2 + s^2/\alpha^2 - v^2)^2 + \lambda_m h^2 s^2 \]

that has a phase transition

\[ (h, s) = (0, \alpha v) \rightarrow (h, s) = (v, 0) \]
CP violation

\[ \mathcal{L} \supset y_t \bar{\psi}_t H \psi_t + \frac{\tilde{y}_t}{f} S \bar{\psi}_t H \psi_t \]

During the phase transition this leads to a top mass of the form

\[ m_t = |m_t| e^{i\theta_t} = \frac{y_t h}{\sqrt{2}} \left( 1 + \frac{\tilde{y}_t s}{y_t f} \right) \]

So, the complex phase during the phase transition behaves as

\[ \theta_t \sim \frac{\Im(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{s}{f} \]

This is a one flavor system and the BAU can be reliably determined with the semi-classical force approach.
Baryogenesis

strength of the phase transition

$\Delta \theta_t \gtrsim 0.15$

strength of CP violation

$\Delta \theta_t \gtrsim \frac{\mathcal{S}(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{\Delta s}{f}$

$m_s = 130\;\text{GeV}$

$m_s = 80\;\text{GeV}$

$\Delta \theta_t \gtrsim 0.25$

[Espinosa, Gripaios, TK, Riva '11]
Signals

$m_h = 120 \text{ GeV}$

$m_h = 140 \text{ GeV}$

singlet mass

Higgs-singlet mixing

CP violation

$\frac{S(y_t \tilde{y}_t^*)}{y_t y_t^*} \frac{1}{f} = (500 \text{ GeV})^{-1}$

[Espinosa, Gripaios, TK, Riva '11]
Conclusions composite Higgs

Baryogenesis in composite Higgs models is generically possible if the sector of pseudo-Goldstone bosons is non-minimal.

In the case of a scalar extension of the low energy theory, this leads to

- rich phenomenology
- traces of CP violation in terms of EDMs
- no $\mathbb{Z}_2$ (Higgs-singlet mixing; singlet is not DM)
Conclusions

Electroweak baryogenesis is still a compelling framework to explain the observed baryon asymmetry.

Higgs found

No EDMs

No minimal SUSY
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