Baryogenesis via mesino oscillations

AKSHAY GHALSASI, DAVE MCKEEN, ANN NELSON

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The one minute summary

- Mesino a bound state of colored scalar and quark
- Model analogous to Kaon system
- Mesinos form after the QCD hadronization temp
- Oscillations analogous to Kaon system give CP violation
- Baryon violating decays give baryogenesis
Outline

- Introduction and Motivation
- The Model
- Oscillations and CP Asymmetry
- Experimental Constraints
- Cosmology
- Conclusion
Introduction and Motivation
Evidence for baryogenesis

- Universe is made up of baryons $\eta_B = 8.6 \times 10^{-11}$
No baryogenesis in SM

- Sakharov conditions
  - Baryon number violation ✓ (sphalerons)
  - C and CP Violation ✗ (CKM phase not enough)
  - Departure from thermal equilibrium ✗ (no first order PT)

- Models of baryogenesis require high reheating temperature
Reheating temperature can be low

- No evidence of high reheating temperature

- Many reasonable theories favor a low reheating scale
  - Gravitino production in SUSY extensions of SM \(^{(Moroi \text{ et al } '83)}\)
  - Isocurvature perturbations \(^{(Fox \text{ et al } '04)}\)

- There do exist low scale baryogenesis models \(^{(Claudson \text{ et al } '84, \text{ Dimopolous et al } '87)}\)
The Model
Particle content

\[ \mathcal{L} \supset y_{ij} \phi \bar{d}_i N_j - \frac{1}{2} m_{N_{ij}} N_i N_j + \alpha_{ij} \phi^* \bar{d}_i \bar{u}_j + \text{c.c.} \]
Complex phases

Oscillations and CP violation

all 9 phases remain

real and diagonal

two complex phases remain

B violation

\[ \mathcal{L} \supset y_{ij} \phi \bar{d}_i N_j - \frac{1}{2} m_{N_{ij}} N_i N_j + \alpha_{ij} \phi^* \bar{d}_i \bar{u}_j + \text{c.c.} \]
Decay Modes

\[ \Phi_s \rightarrow \phi^* \rightarrow d_i \rightarrow u_j \text{ Baryon + mesons} \]

\[ \Phi_s \rightarrow \phi^* \rightarrow s \rightarrow u^*_j \text{ Antibaryon + mesons} \]

\[ \Phi_s \rightarrow \phi^* \rightarrow N_1 \rightarrow d_i \text{ + mesons} \]

\[ \Phi_s \rightarrow \phi^* \rightarrow s \rightarrow N_1 \text{ + mesons} \]
Oscillations and CP Asymmetry
On-shell and off-shell oscillations

Off shell diagrams

On shell diagrams via common final states
Off-shell contribution

- Off shell oscillations $M_{12}$:

$$M_{12} = \sum_i M_{12} (N_i) = \frac{2 f_{\Phi q}^2}{3} \sum_i \frac{y_{qi}^2 m_{N_i}}{m_{N_i}^2 - m_{\Phi q}^2}$$

Form factor $f_{\Phi s} \approx 21.5$ MeV $\sqrt{\frac{650 \text{ GeV}}{m_\phi}}$

$$|M_{12} (N_i)| \approx 2.4 \times 10^{-4} \text{ GeV} |y_{si}|^2 \times \left( \frac{1 \text{ TeV}}{m_\phi} \right) \left( \frac{1 \text{ GeV}}{\Delta m_{\Phi N_i}} \right)$$

Berger et al '13
On-shell contribution

Contributions to $\Gamma_{12}$:

We want to be in the squeezed limit $\Delta m_{\Phi N_1} = 1 \text{ GeV}$

In squeezed limit one can show

$$\Gamma_{12} = \Gamma_{\Phi \rightarrow N_1 \eta} \approx 9 \times 10^{-6} \text{ GeV} |y_{s1}|^2 \times \left( \frac{1 \text{ TeV}}{m_\phi} \right) \left( \frac{1 \text{ GeV}}{\Delta m_{\Phi N_i}} \right)$$

$$|M_{12}(N_i)| \approx 2.4 \times 10^{-4} \text{ GeV} |y_{si}|^2 \times \left( \frac{1 \text{ TeV}}{m_\phi} \right) \left( \frac{1 \text{ GeV}}{\Delta m_{\Phi N_i}} \right)$$
Hamiltonian is not diagonal

- Hamiltonian without oscillations

\[
H = \begin{pmatrix}
  M - i \frac{\Gamma}{2} & 0 \\
  0 & M - i \frac{\Gamma}{2}
\end{pmatrix}
\]

With oscillations we get off diagonal terms

\[
H = \begin{pmatrix}
  M - i \frac{\Gamma}{2} & M_{12} - i \frac{\Gamma_{12}}{2} \\
  M_{12}^{*} - i \frac{\Gamma_{12}^{*}}{2} & M - i \frac{\Gamma}{2}
\end{pmatrix}
\]
Diagonalizing the Hamiltonian

- Hamiltonian has off diagonal terms, new eigenstates are

\[ |\Phi_{L,H}\rangle = p|\Phi_s\rangle \pm q|\bar{\Phi}_s\rangle \]

\[ \left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}} \]

- Assuming a state starts as \( \Phi_q (\bar{\Phi}_q) \) at \( t = 0 \) then

\[ \langle \bar{\Phi}_s | \Phi_s (t) \rangle = \frac{q}{p} f(t) \]

\[ \langle \Phi_s | \bar{\Phi}_s (t) \rangle = \frac{p}{q} f(t) \]

- CP violation gives \( \left| \frac{p}{q} \right| \neq 1 \) favoring one state over another
CP asymmetry

- Can show asymmetry per mesino-antimesino pair is given by

\[ \epsilon_B = \frac{2\text{Im}M_{12}^* \Gamma_{12}}{\Gamma^2 + 4|M_{12}|^2} \frac{\Gamma_b}{\Gamma} \]

branching ratio into baryons

- Lets define \( x = \frac{2M_{12}}{\Gamma} \) and \( r \equiv \left| 1 - \frac{M_{12} (N_1)}{M_{12}} \right| \) then we have

\[ \epsilon_B \approx \frac{x r \sin \beta}{1 + x^2} \text{Br}_{\Phi_q \rightarrow B} \text{Br}_{\Phi_q \rightarrow N_1} \]

- We expect generally \( \epsilon_B = O(10^{-3} - 10^{-4}) \)

- Can show \( \max (\epsilon_B) = \frac{1}{8} \)
Experimental Constraints
Experimental Signatures

- Soft quark, no jet
- Usually soft quark, no jet

2 jets

-d_i
-u_j

N_1

-d_i
-u_j

N_1

-d_k

-d_i
-u_j

N_1

-d_i
-u_j

N_1

-d_k

-d_i
-u_j

N_1
Constraints on mass

- Constraints from squarks decaying into b and light quark: $m_\phi > 385$ GeV (CMS)
- Effective constraints from squark decaying to light quarks: $m_\phi > 275$ GeV (CMS)
- Constraints from 3 jet events: $m_\phi > 600$ GeV
- We take $m_\phi = 650$ GeV as our benchmark value
Couplings

\[ \mathcal{L} \supset y_{ij} \phi \bar{d}_i N_j - \frac{1}{2} m_{Nij} N_i N_j + \alpha_{ij} \phi^* \bar{d}_i u_j + \text{c.c.} \]

upper bounds from Kaon oscillations, \( n \bar{n} \) oscillations and diinucleon decays, lower bounds from displaced vertices

upper bounds from \( n \bar{n} \) oscillations and dinucleon decays

upper bound from cosmology

\[
\begin{pmatrix}
y_{d1} & y_{d2} & y_{d3} \\
y_{s1} & y_{s2} & y_{s3} \\
y_{b1} & y_{b2} & y_{b3}
\end{pmatrix}
\]

\[
\begin{pmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix}
\]

\[
\alpha_B^2 \equiv \sum_{i,j} |\alpha_{ij}|^2
\]
Constraints summary

- Totally fine set of couplings for $m_\phi < 1$ TeV:
  \[ y_{s1}, y_{s2} = 1 \quad y_{d1}, y_{d2} = 10^{-2} \quad \alpha_B = 10^{-4} \]
  \[ \epsilon_B \approx 10^{-3} \]

- Constraints only get weaker with increasing mass
Cosmology
Cosmic Story

$T = 200 \text{ MeV}$

$T = 1 \text{ MeV}$

CP Violation

Baryons

Anti Baryons
$N_3$ does not annihilate

- Number density of $N_3$ at hadronization temp $T_c$
  \[ n_{N_3}(t) = n_{N_3}^{\text{relic}} e^{-\Gamma_{N_3} t} \left( \frac{a_{\text{relic}}}{a_t} \right)^3 \]

- For $N_3$ to last until $T_c$ we need
  \[ y_{q3}^2 \lesssim 10^{-15} \left( m_{N_3}/\text{TeV} \right) \]

- Small Yukawa imply $N_3$ annihilations are slower than expansion rate.

- So most of the $N_3$ survives till $T_c$
  \[ n_{N_3}(t_c) = \left( \frac{3}{4} \right) n_\gamma \times e^{-\Gamma t_c} \times (\text{ent dilution}) \]
Exact Solution

We can coevolve the radiation, N_3 and baryons produced from their decay to get the exact solution

\[
\frac{d\rho_{\text{rad}}}{dt} = -4H \rho_{\text{rad}} + \Gamma_{N_3} m_{N_3} n_{N_3}
\]

\[
\frac{d\rho_{N_3}}{dt} = -3H \rho_{N_3} - \Gamma_{N_3} m_{N_3} n_{N_3}
\]

\[
\frac{dn_B}{dt} = -3H n_B + \frac{1}{2} A \Gamma_{N_3} \epsilon_B n_{N_3}
\]
Sudden Decay Approximation

- Baryon to entropy ratio in sudden decay approximation
  \[ \eta_B = \frac{n_{N_3}(t_{\text{dec}})}{s_{\text{rad}}(t_{\text{dec}})} \times \frac{\epsilon_B A}{2} \times (\text{ent dilution}) \]

- Ratio of matter and radiation energy densities for ent. dil.
  \[ \xi = \frac{\rho_{N_3}(t_{\text{dec}})}{\rho_{\text{rad}}(t_{\text{dec}})} \approx 10^{-2} \left( \frac{m_{N_3}^2}{M_{\text{Pl}} \Gamma_{N_3}} \right)^{2/3} \]

- However \( \max(\Gamma_{N_3}) \approx 10^{-19} \text{GeV} \) and \( \min(m_{N_3}) \approx 650 \text{GeV} \) so
  \[ \min(\xi) \approx 150 \quad \text{max}(\eta_B) \approx 10^{-6} \]
Constraints on decay rate

\[ T_{\text{decay}}>200 \text{ MeV} \]

\[ T_{\text{decay}}<1 \text{ MeV} \]

\[ \eta_B=8.6 \times 10^{-11} \]

\[ \epsilon_B=10^{-6} \]

\[ \epsilon_B=10^{-5} \]

\[ \epsilon_B=10^{-4} \]
Asymmetry dependence on $\alpha_B$

$\Delta m_{\Phi N_1} = \Delta m_{\Phi N_2} = 1 \text{ GeV, } \Delta m_{\Phi N_3} = 3 \text{ GeV}$

$\beta = \frac{\pi}{4}, y_{s1} = y_{s2} = 10^{-2} \gg y_{s3}$

$\alpha_B = 10^{-5}$
$\alpha_B = 10^{-6}$
$\alpha_B = 10^{-4}$

$\eta_B = 8.6 \times 10^{-11}$ and $T_d < 200 \text{ MeV}$
not possible
Possible signatures

- Finding colored scalars at LHC (1 TeV at 1000 fb$^{-1}$)
  - final states jets will have third generation quarks
  - mostly 2-jet decays but will have 3-jets sometimes
  - possible displaced vertices signature
  - same sign tops (Berger ‘13)
  - CP violation in same sign tops hard to see at LHC

- Any signature needs to be consistent with neutron-antineutron oscillations and B meson and Kaon oscillations
Conclusions and future work

- If there is a scalar quark it can form mesinos
- CP violation in mesino oscillations can be the source for baryogenesis
- In order to get enough CP violation we need the singlets to be very close in mass with mesinos
THANK YOU!
QUESTIONS?
Constraints on couplings from displaced vertices

- Displaced vertices search give us $c\tau < 1\ mm$
- $\Phi \rightarrow \text{quarks}$: $\alpha_B \gtrsim 10^{-7}\sqrt{650\ \text{GeV}/m_\phi}$
- $\Phi \rightarrow N_1 \rightarrow \text{quarks}$: $(\sum_{i=d,s} |y_{i1}|^2)^{1/2} \gtrsim 10^{-4}$

\[
\alpha_B \gtrsim (\sum_{i} |y_{i1}|^2)^{-1/2} 10^{-6}\sqrt{650\ \text{GeV}/m_\phi}
\]

- These constraints don’t apply if $m_\phi > 1\ \text{TeV}$
- Mass independent constraints from BBN are $O(10^6)$ weaker
Constraints from Rare Processes

- $\Delta B = 2$, neutron-antineutron oscillation: $\sum_k y_{d_k}^2 \alpha_{11}^2 / m_\phi^5 < 2.9 \times 10^{-28}$ GeV$^{-5}$

For $m_\phi = 650$ GeV we get $(y_{d_1}^2 + y_{d_2}^2) \alpha_{11}^2 < \mathcal{O}(10^{-14})$

- Dinucleon to Kaon decay constraints for $m_\phi = 650$ GeV

  $$(y_{s_1}^2 + y_{s_2}^2) \alpha_{11}^2 < \mathcal{O}(10^{-14})$$
  $$ (y_{d_1}^2 + y_{d_2}^2) \alpha_{12}^2 < \mathcal{O}(10^{-14})$$
  $$ (y_{d_1} y_{s_1} + y_{d_2} y_{s_2}) \alpha_{12} \alpha_{11} < \mathcal{O}(10^{-14})$$

- Easily satisfied if $\alpha_{11}, \alpha_{12} \leq 10^{-7}$
Kaon oscillation constraints

Constraints from $K_L$ and $K_S$ mass difference

$$\left( \frac{\text{Re} \sum_{i,j} y_{di}^* y_{dj} y_{si} y_{sj}^*}{\sqrt{\frac{m_\phi}{650 \text{ GeV}}}} \right)^{1/4} < 0.40 \sqrt{\frac{m_\phi}{650 \text{ GeV}}}$$

Constraints from CP violation in Kaon system

$$\left( \frac{\text{Im} \sum_{i,j} y_{di}^* y_{dj} y_{si} y_{sj}^*}{\sqrt{\frac{m_\phi}{650 \text{ GeV}}}} \right)^{1/4} < 0.11 \sqrt{\frac{m_\phi}{650 \text{ GeV}}}$$

B meson oscillations aren’t as constraining