Electroweak Baryogenesis and Higgs Signatures

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with Aaron Pierce
arXiv:1110.0482
with David Morrissey and Aaron Pierce
arXiv:1203.2924

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Baryogenesis

• It is well established that there is a baryon asymmetry.

\[ \frac{n_b - \bar{n}_b}{n_\gamma} \simeq 6 \times 10^{-10} \quad \text{WMAP7 [arXiv:1001.4538]} \]

• Models which generate this asymmetry must satisfy the Sakharov conditions:
  i) Baryon number violation;
  ii) CP violation;
  iii) Departure from equilibrium.

• Many paradigms for baryogenesis:
  • Leptogenesis - lepton number from right handed neutrino decays;
  • Affleck-Dine - baryon number from the “decay” of flat directions;
  • Dark-o-genesis - simultaneous generation of baryon and dark matter asymmetries;
  • Electroweak Baryogenesis - baryon number generated at the electroweak phase transition.
The Universe is a hot baryon symmetric thermal bath with $\langle H \rangle = 0$. 

For a review see Trodden [arXiv:hep-ph/9803479]
Electroweak Baryogenesis

At the critical temperature $T_C$, bubbles of $\langle H \rangle \neq 0$ begin to percolate.
Electroweak Baryogenesis

Scatterings with the (CP violating) bubble wall lead to non-zero, opposite chemical potentials inside and outside the bubbles.

For a review see Trodden [arXiv:hep-ph/9803479]
Electroweak Baryogenesis

Outside the bubbles: Electroweak sphalerons convert this charge asymmetry to a baryon asymmetry.

For a review see Trodden [arXiv:hep-ph/9803479]

\[ \Gamma_S \sim T^4 \]
Electroweak Baryogenesis

Inside the bubbles: Electroweak sphaleron rates are exponentially suppressed.

\[ \Gamma_S \sim \exp\left(-\phi_C/T_C\right) \]

\[ \Gamma_S \sim T^4 \]
Electroweak Baryogenesis

A net baryon asymmetry is generated outside the bubbles.

\[ \Delta (n_B - \bar{n}_B) = 0 \]

\[ \Delta (n_B - \bar{n}_B) \neq 0 \]

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Electroweak Baryogenesis

The bubbles of broken phase overtake the Universe and the baryon asymmetry is frozen in.

\[ n_B - \bar{n}_B \neq 0 \]
The Electroweak Phase Transition

- A 1st order phase transition is characterized by the existence of a non-zero local minimum for the finite temperature Higgs potential.
- The temperature when this minimum is degenerate with the origin is the critical temperature $T_C$. 

![Diagram of the Higgs potential](image)
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To realize electroweak baryogenesis:

$$\frac{\phi_C}{T_C} \gtrsim 0.9$$
Outline

I. New Colored Scalars
II. Correlating the EWPT with Higgs Signatures
III. Applications to the MSSM
IV. Collider Signatures
V. Conclusions

• Note: this talk will not address the new source of CP violation required for successful electroweak baryogenesis, e.g. in SUSY models, a non-zero
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NEW COLORED Scalars
The Model

• We will study a model where we couple a new scalar, $X$ to the Higgs boson through the “Higgs portal.”

$$\mathcal{L} \supset M_X^2 |X|^2 + \frac{K}{6} |X|^4 + Q |X|^2 |H|^2$$

$$\supset M_X^2 |X|^2 + \frac{K}{6} |X|^4 + \frac{1}{2} Q \left( v^2 + 2 v h + h^2 \right) |X|^2$$

• Then the physical mass of $X$ is given by

$$M_X^{\text{phys}} = \sqrt{M_X^2 + \frac{Q}{2} v^2}$$

• We will usually take $X$ to be a fundamental under $SU(3)$.

• This is similar to the “light stop effective theory” limit of the MSSM. Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]
Charge-color Breaking Vacua

- We will be analyzing models which have negative values of the bare mass for a colored scalar.
- This can be consistent as long as we including thermal corrections for the scalar mass (daisy resummation).
  - The total mass squared must be positive.
- In this region of parameter space, there is the possibility of ending up in a charge color breaking (CCB) vacuum.
- We compute the finite temperature potential in the CCB direction.
- Then we can check that $T^\phi_C > T^X_C$. 
Two Loop Contributions

2-Loops versus 1-Loop

The other parameters are taken to be $K = 1.6$, $m_h = 115$ GeV.

For a detailed description of 2-loop resummed finite temperature calculations, see Arnold and Espinosa [1994]
2-Loops versus 1-Loop

Going to 2-loops can yield an enhancement factor of 3.5!

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EWPT with Singlet Scalars

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• For 6 singlet scalars:

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For 6 singlet scalars:

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The Punchline

• Two-loop corrections to $\phi_C/T_C$ can be very important.


• Colored scalars are “better” than singlet scalars:
  i) Automatically get 6 degrees of freedom;
  ii) Larger 2-loop enhancements due to loops involving gluons;
  iii) These models make observable predictions!
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• Models with
  • a single vacuum expectation value;
  • a coupling to colored scalars via the Higgs portal;

  can result in a strong enough EWPT for electroweak baryogenesis.

• (Note that this is not the only way to get a strong EWPT.)

• The rest of this talk will be devoted to the resultant phenomenology of this model.
CORRELATING THE EWPT WITH HIGGS SIGNATURES
Gluon Fusion and Di-photon Decays

- We will take ratios of our production and decay rates to the Standard Model values.
- NLO effects mostly cancel for $m_i > m_h/2$ since the relevant vertex is approximately point like.
  - Gluon fusion: $h G_{\mu\nu}^a G^{a,\mu\nu}$
  - Di-photon decay: $h F_{\mu\nu} F^{\mu\nu}$
- Therefore, we will only consider leading order effects.

Djouadi, Spira [arXiv:hep-ph/9912476];
Anastasiou, Beerli, Daleo [arXiv:0803.3065]
Gluon Fusion and Di-photon Decays

• Gluon fusion is dominated by the top. For $Q > 0$ there is constructive interference between the top and the $X$.

$$\Gamma_{gg} = \frac{\alpha_s^2}{128\pi^3} \frac{m_h^3}{m_W^2} \left| \sum_i g_i T^i_2 F_{s_i}(\tau_i) \right|^2$$

$$gx = \frac{2}{g} \left( \frac{m_W}{m_{\phi_i}} \right)^2 Q$$

• Di-photon decay is dominated by the $W^\pm$ loop. For $qX \lesssim 1$ there will be destructive interference between the $W^\pm$ and the $X$.

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2}{1024\pi^3} \frac{m_h^3}{m_W^2} \left| \sum_i g_i q_i^2 d_i F_{s_i}(\tau_i) \right|^2$$

$$\tau_i = 4m_i^2/m_h^2$$

$$F_0(\tau) = \tau [1 - \tau f(\tau)]$$

$$F_{1/2}(\tau) = -2\tau [1 + (1 - \tau) f(\tau)]$$

$$F_1(\tau) = 2 + 3\tau + 3\tau(2 - \tau) f(\tau)$$

$$f(\tau) = \begin{cases} 
\sin^{-1}(\sqrt{1/\tau})^2 & ; \tau \geq 1 \\
-\frac{1}{4} \left[ \ln \frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi \right]^2 & ; \tau < 1 
\end{cases}$$

Gunion, Haber, Kane, Dawson [The Higgs Hunter’s Guide]
Combined Results

- The other parameters are taken to be $K = 1.6$, $m_h = 125$ GeV.

\[ \frac{\phi_C}{T_C} \]

\[
- \frac{\text{sgn} (M_x^2) \sqrt{M_x^2}}{M_x^2}
\]

\[
\frac{\sigma_{gg}}{(\sigma_{gg})_{\text{SM}}}
\]

\[
\frac{\sigma_{gg} \times \text{BR}_{\gamma\gamma}}{(\sigma_{gg} \times \text{BR}_{\gamma\gamma})_{\text{SM}}}
\]
APPLICATIONS TO THE MSSM
MSSM-like Model

• In order to map onto the MSSM, we must include the Higgsino state and a Yukawa coupling $Y_t \tilde{H}_u Q_L^3 X^*$.

• We will take a typical value $Y_t = 0.8$.  
  Carena, Nardini, Quiros, Wagner [arXiv:0806.4297]

• We will scan over a range of values for $Q$.

• Note that in the MSSM, $Q \lesssim 0.9$ for $M_X^2 = -(80 \text{ GeV})^2$, $\tan \beta = 10$, and $m_{Q_3} = 1000 \text{ TeV}$.  
  Morrissey, Menon [arXiv:0903.3038]

• Non-zero $a$-terms for the stop reduce the value of $Q$.

The electroweak phase transition for the MSSM has been studied by e.g., Giudice [1992]; Anderson, Hall [1992]; Carena, Quiros, Wagner [arXiv:hep-ph/9603420]
MSSM-like Results

$m_h = 115$ GeV

$m_h = 125$ GeV

Red, dashed contours show $\frac{\sigma_{gg} \times BR_{\gamma\gamma}}{(\sigma_{gg} \times BR_{\gamma\gamma})_{SM}}$. 
MSSM-like Results

\( M_{\text{stop}} \approx 140 \text{ GeV} \)

The MSSM region

\( m_h = 115 \text{ GeV} \)

\( m_h = 125 \text{ GeV} \)

Red, dashed contours show \( \frac{\sigma_{gg} \times \text{BR}_{\gamma\gamma}}{(\sigma_{gg} \times \text{BR}_{\gamma\gamma})_{\text{SM}}} \).
COLLIDER SIGNATURES
Measuring Higgs Properties

• First, we need to establish the discovery of a Higgs boson.
• There are the current CMS and ATLAS searches/hints.


• At face value, the overall rates are high (deficit in $WW^*$).
• When looking at the best fit cross sections for ATLAS and CMS, these measurements do not constrain our model:

  $\frac{\sigma_{gg}}{(\sigma_{gg})_{SM}} \lesssim 1.7 \quad \text{[ATLAS]}$  
  $\frac{\sigma_{gg}}{(\sigma_{gg})_{SM}} \lesssim 1.6 \quad \text{[CMS]}$

• This appears in tension with theorist's more sophisticated studies.
Measuring Higgs Properties

- Dominate uncertainty in measuring the gluon fusion rate will be systematics limited by theory and PDFs at O(20%).
- Dominate uncertainty in measuring di-photon BR will be systematics limited by experimental effects. Maybe eventually measure the $q_X = 2/3, 4/3$ cases?
- We expect that this will be enough to “discover”/exclude the region of parameter space consistent with electroweak baryogenesis.
- Note: doing a global fit to the Higgs couplings, maybe we can measure various ratios to 10-40%?

Decay Mode: $X \rightarrow c \chi$

- $\chi$ is a new neutral state (may be a remnant of the CP violating sector).
- Multi-jet and Monojet use Atlas and CMS $1 \text{ fb}^{-1}$ results.
Decay Mode: $X \to q\ q$

- The search is more difficult.
- There was an early ATLAS result using $34\ \text{pb}^{-1}$, looking for scalar octets. Zhu [Talk at SUSY 2011]
  - No bound applies for $SU(3)_c$ fundamental scalars.
- Extending this analysis for the larger data set is challenging due to harder trigger level cuts.
- There is an open window for this decay mode.
- We are not sure if/when it will close.
  - Most likely this will require a new search strategy.
CONCLUSIONS
Conclusions

• We are interested in simple extensions of the standard model Higgs sector with a strong enough phase transition for viable electroweak baryogenesis.
• We studied the model with new colored scalars which couple via the Higgs portal.
• We demonstrated that 2-loop corrections are vital for accurate computations of the strength of the EWPT.
• The viable regions of parameter space lead to changes in the Higgs gluon fusion rate and branching ratio to di-photons of $O(50\%)$ or more with respect the standard model values.
• This statement applies to the MSSM in the baryogenesis window.
• These modification to the Higgs properties can potentially be observed at the LHC with this year’s upcoming data.
• Depending on the decay mode, the new scalars can also be searched for directly at the LHC.
BACKUP SLIDES
Resummation at 2-Loops

• The trick for making computations tractable is to separate out zero modes from non-zero modes:

\[
\frac{1}{k^2 + m^2(\phi)} \quad \longrightarrow \quad \frac{1}{k^2 + m^2(\phi, T)}
\]

\[
\frac{1}{(2n\pi T)^2 + k^2 + m^2(\phi)} \quad \longrightarrow \quad \frac{1}{(2n\pi T)^2 + k^2 + m^2(\phi)} \quad (n \neq 0)
\]

• This procedure introduces temperature dependent counterterms which must be included for consistency.
• All longitudinal gauge boson zero modes must also be resummed.
• Derivative couplings to the longitudinal gauge boson zero modes vanish since \(\partial^0 \sim n = 0\) for zero modes.
Other electric charges

\[ (\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}} \]

- For \( q_x = 1/3, N_{\text{scalars}} = 1 \)
- For \( q_x = 4/3, N_{\text{scalars}} = 1 \)
Two Colored Scalars

\[ \frac{\sigma}{\sigma_{SM}} \]

\( N_{\text{scalars}} = 2 \)

\( \frac{\sigma \times BR}{(\sigma \times BR)_{SM}} \)

\( q_x = 2/3, N_{\text{scalars}} = 2 \)
X-onium

- Requires the new colored state to be long lived so it can hadronize.
- Recently there has been theoretical progress in computing the properties for stoponium. Martin [arXiv:0801.0237]
- An analysis using LHC data shows bounds on the order of $m_X \lesssim 100 \text{ GeV}$. Barger, Ishida, Keung [arXiv:1110.2147]
- If the X-onium decays to the Higgs it will be even harder to find. Barger, Keung [1988]