Constraining Electroweak Baryogenesis at Colliders

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Based on work done in collaboration with N. Bell[1] , M. Dolan[1], M. Ramsey-Musolf[2,3,4], and R. Volkas[1]

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and arXiv:1912.XXXX

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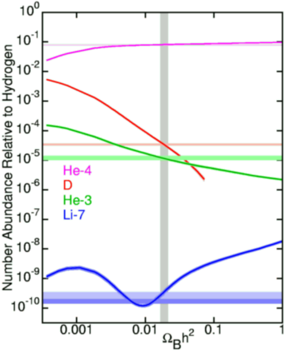
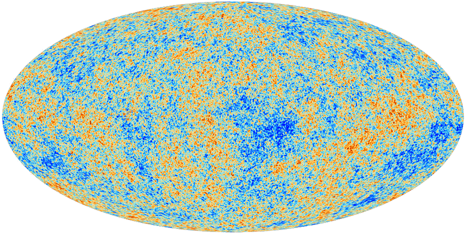
Introduction - Baryon Asymmetry

- The universe has a non-zero baryon asymmetry, $\frac{n_B}{s} \sim 10^{-10}$.
- The standard model has no means of generating this asymmetry.
- We need some BSM baryogenesis mechanism.





Introduction - Sakharov Conditions

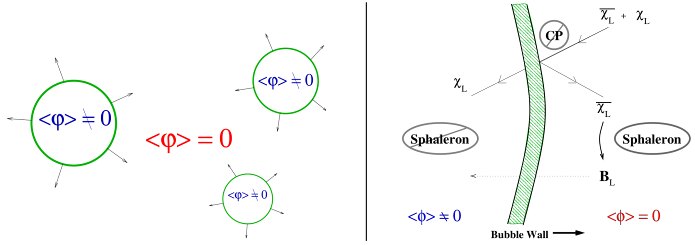
A baryogenesis mechanism must satisfy the three Sakharov conditions:

1. There must be a B number violating processes $\implies \Delta B \neq 0$
2. It must involve C and CP violation $\implies \Gamma(X \to Y) \neq \Gamma(\bar{X} \to \bar{Y})$
3. And it has to occur out of equilibrium $\implies \Gamma(X \to Y) \neq \Gamma(Y \to X)$

Baryon number can be violated in the SM via electroweak sphalerons, the other two conditions require BSM physics.

Introduction - Electroweak Baryogenesis

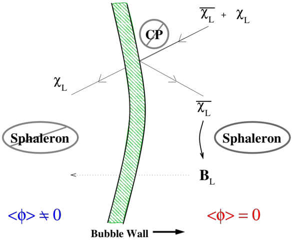
One possible mechanism is electroweak baryogenesis (EWBG). In Electroweak baryogenesis the asymmetry is generated during a strongly first order elctroweak phase transition.



[Image credit: D. Morrissey and M. Ramsey-Musolf, arXiv:1206.2942]

Introduction - Electroweak Baryogenesis

- CPV interactions set up asymmetry in χ_L & $\bar{\chi}_L$.
- Sphalerons inside bubble are suppressed due to the SU(2) breaking VEV.
- Outside of the bubble sphalerons act on this asymmetry to generate net B.



[Image credit: D. Morrissey and M. Ramsey-Musolf, arXiv:1206.2942]

Introduction - EWBG Phenomenology

What do we need for EWBG to work?

- New “light” particles that couple to the SM Higgs ($m < 1$ TeV).
  - Particles are producible at current colliders.
- New CPV interactions wih the SM Higgs (or with new scalars).
  - Strongly constrained by electron electric dipole moments measurements.

Introduction - EWBG Models

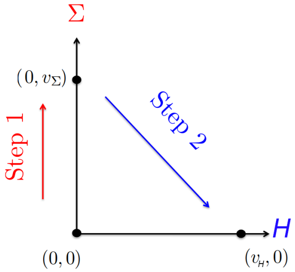
Some common features of models that are capable of generating a first order phase transition include:

- 2HDM models.
    - See (N)MSSM studies.
- Adding exotic scalars charged under SU(2) or SU(3).
- Adding gauge singlet scalars.

I will discuss the collider phenomenology of two models that fall into the latter two categories.

Triplet Model - Introduction

- We examine a model where the SM is extended by adding a real scalar field Σ transforming as $(1,3,0)$ under the $SU(3)\times SU(2)\times U(1)_Y$ SM gauge group.
- In particular we are interested in the region of parameter-space where the triplet gains a VEV in the early universe.
- The phase transitions of this model have been previously examined by H. Patel and M. Ramsey-Musolf (arXiv:1212.5652).



Triplet Model - Parameters

$$\mathcal{L} \supset -\frac{1}{2}\mu_\Sigma^2 \mathrm{Tr}(\Sigma^2) + \frac{1}{2} a_2 \mathrm{Tr}(\Sigma^2) H^\dagger H + \frac{1}{\sqrt{2}} a_1 H^\dagger \Sigma H \, ,$$

$$\Sigma = \begin{bmatrix} \frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) \end{bmatrix} , \quad H = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_H + H^0 + iA^0) \end{bmatrix} .$$

- In order to gain a VEV in the early universe, the triplet's quadratic term should be negative ($\mu_\Sigma^2 > 0$).
- The Triplet-Higgs coupling generates a positive mass via the Higgs VEV.
- $m_{\Sigma^0}^2 \approx -\mu_\Sigma^2 + \frac{1}{2} a_2 v_H^2$.

Triplet Model - Upper Bound on Mass

$$\mathcal{L} \supset -\frac{1}{2}\mu_\Sigma^2 \mathrm{Tr}(\Sigma^2) + \frac{1}{2}a_2 \mathrm{Tr}(\Sigma^2)H^\dagger H + \frac{1}{\sqrt{2}}a_1 H^\dagger \Sigma H\,,$$

$$\Sigma = \begin{bmatrix} \frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) \end{bmatrix}, \quad H = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_H + H^0 + iA^0) \end{bmatrix}.$$

- $m_{\Sigma^0}^2 \approx -\mu_\Sigma^2 + \frac{1}{2}a_2 v_H^2$.
- Large $m_{\Sigma^0} \implies$ large a_2.
- Require that couplings satisfy tree-level vacuum stability and perturbative unitarity.
- Upper bound on $a_2 \implies$ upper bound on m_{Σ^0}
- If $\mu_\Sigma^2 = 0$, $m_{\Sigma^0} \lesssim 700$ GeV.

Triplet Model - Cubic Term

$$\mathcal{L} \supset -\frac{1}{2}\mu_\Sigma^2 \mathrm{Tr}(\Sigma^2) + \frac{1}{2}a_2 \mathrm{Tr}(\Sigma^2) H^\dagger H + \frac{1}{\sqrt{2}} a_1 H^\dagger \Sigma H \,,$$

$$\Sigma = \begin{bmatrix} \frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) \end{bmatrix}, \quad H = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_H + H^0 + iA^0) \end{bmatrix}.$$

- The cubic term induces a non-zero VEV.
- The triplet's VEV gives mass to the W-boson but not to the Z-boson.
- From electroweak precision measurements we know triplet's VEV has to be small at zero temperature.
- $v_\Sigma \lesssim 3$ GeV

Triplet Model - Stable Scenario

$$\mathcal{L} \supset -\frac{1}{2}\mu_\Sigma^2 \mathrm{Tr}(\Sigma^2) + \frac{1}{2}a_2 \mathrm{Tr}(\Sigma^2) H^\dagger H + \frac{1}{\sqrt{2}} a_1 H^\dagger \Sigma H \,,$$

$$\Sigma = \begin{bmatrix} \frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\left(\Sigma^0 + v_\Sigma\right) \end{bmatrix}, \quad H = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(v_H + H^0 + iA^0) \end{bmatrix}.$$

Consider $a_1 = 0 \implies v_\Sigma = 0$:

- Lagrangian has a $\mathbb{Z}_2$ symmetry, invariant under $\Sigma \to -\Sigma$.
- There exists a small radiative mass splitting $m_{\Sigma^\pm} - m_{\Sigma^0} \approx 160$ MeV.
- Neutral component of triplet is stable, will contribute to dark matter density.
- Charged components can decay into neutral component and a low energy pion or lepton and neutrino pair $\implies$ results in disappearing tracks.
- Triplet with $\mu_\Sigma^2 > 0$ is excluded by disappearing track searches and dark matter direct detection constraints.

Triplet Model - Unstable Scenario

Given that stable with triplets with $\mu_\Sigma^2 > 0$ are excluded, let us instead consider the scenario where $a_1 \neq 0 \implies v_\Sigma \neq 0$:

- $\mathbb{Z}_2$ symmetry is broken, neutral triplet component will decay.
- Triplet and SM Higgs components will mix,

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_N & -\sin\theta_N \\ \sin\theta_N & \cos\theta_N \end{pmatrix} \begin{pmatrix} H^0 \\ \Sigma^0 \end{pmatrix},$$

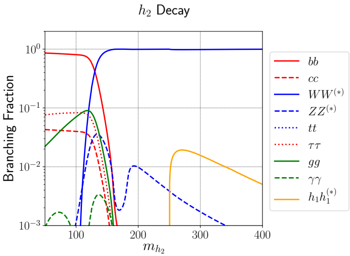
$$\begin{pmatrix} G^+ \\ h^+ \end{pmatrix} = \begin{pmatrix} \cos\theta_C & -\sin\theta_C \\ \sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} H^+ \\ \Sigma^+ \end{pmatrix},$$

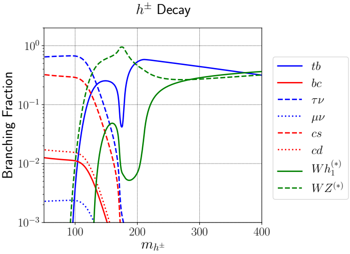
$$\theta_C, \theta_N \propto \frac{v_\Sigma}{v_H} \ll 1\,.$$

Triplet Model - Decay Channels

From this mixing,

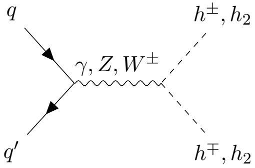
- Neutral triplet inherits SM-higgs type decays.
- Charged triplet inherits decays similar to the charged scalar in 2HDM models.
- Unless $v_\Sigma \lesssim 10^{-4}$ GeV, We have no more disappearing tracks.



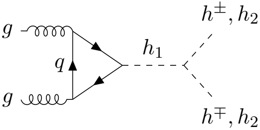


Triplet Model - Production Processes

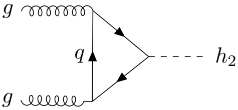
- Triplets are primarily pair produced via Drell-Yan procceses,



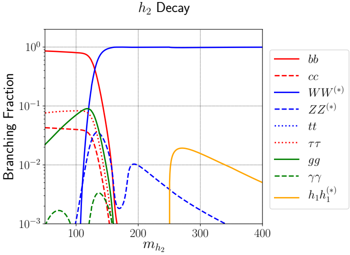
- If a_2 is large, production can also occur via an off-shell intermediate h_1,

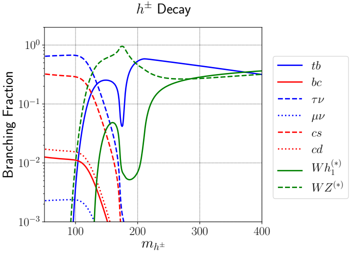


- Production of a single neutral-triplet like scalar is suppressed by the mixing angles $\theta_{N,C} \ll 1$,



Triplet Model - Signal Events





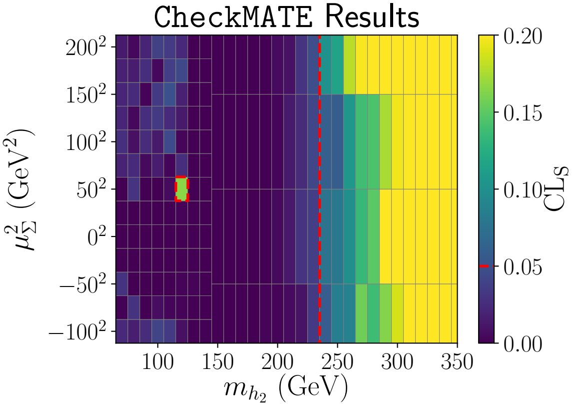
- If the triplet-like scalars are light, then pair production can lead to events featuring many tau-leptons, i.e., $qq' \to h_2 h^+ \to \tau^+\tau^-\tau^+\nu_\tau$.
- If they are heavy, they will instead decay via weak-gauge or SM-higgs bosons. This too can result in final states with many leptons.
- Therefore, ATLAS and CMS analyses featuring multipleton signal regions can be used to constrain the unstable triplet scenario.

Triplet Model - Collider Phenomenology Tools

- We use `MadGraph`, `Pythia`, `Delphes` to generate monte-carlo events.
- The events are then analysed using `CheckMATE`, which implements a range of ATLAS and CMS analyses.
- Currently implemented analyses include searches with 36fb^{-1} of data at 13 TeV.
- Recently released Run 3 analyses with up to 139fb^{-1} are not yet implemented.

Triplet Model - Collider Phenomenology Results

- We find that the unstable triplet is largely excluded at 95% confidence for masses less than $m_{h_2} \sim 230$.
- There is a small region of parameterspace that is still allowed near $m_\Sigma = 120$ GeV, $\mu_\Sigma^2 = 50^2$ GeV^2 .
- Inclusion of 139 fb^{-1} analyses will likely exclude this points and move the lower bound up.



Triplet Model - Implications

- The triplet cannot be stable and have a negative quadratic term.
- Current collider searches require $m_\Sigma \gtrsim 230$ GeV, and this limit will get more stringent with run-3 LHC data.
- This limit is already larger than the masses considered in papers that have investigated multi-step electroweak phase transitions featuring SU(2) Triplets .
  - Note that sucesfull EWBG requires some additional particles, which may significantly modify the decays of the Triplets.
  - However, we expect they will be similarly constrained.

Intermission - EWBG Models

- 2HDM type models.
  - See (N)MSSM Studies.
- Adding exotic scalars charged under SU(2) or SU(3).
  - Minimal SU(2) tripelts are getting too heavy for EWBG
  - Other SU(2) multiplets are similarly constrained
  - Scalars charged under SU(3) have larger production cross sections, but the signal events are not as clean.
- Adding gauge singlet scalars.

Singlet+ψ Model - Introduction

Consider the SM extended with;

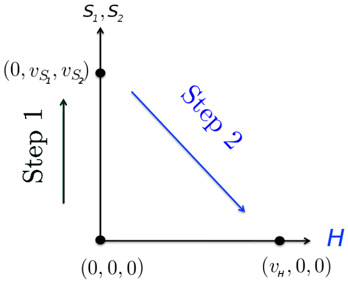
- Two real gauge singlet scalars $S_1, S_2 \sim (1, 1, 0)$.
- One vector-like (VL) lepton doublet $\psi \sim \left(1, 2, -\frac{1}{2}\right)$.
- We restrict VL leptons to couple only to third generation SM leptons.

$$S_i = s_i + v_{S_i}\,, \qquad \psi = \begin{bmatrix} N \\ E^- \end{bmatrix}$$

Singlet+ψ Model - EWBG Outline

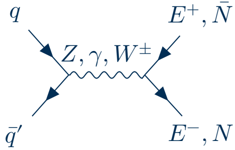
- The singlet scalars S_i enable a SFO EWPT.
- The singlets can have changing VEVs during the electroweak phase transition.
- CPV Interactions between the singlet scalars, VL leptons (ψ), and SM lepton doublet (L) generate the asymmetry.

$$\mathcal{L} \supset \lambda_{\psi i} S_i \bar{L}_L \psi_R + \text{h.c.}$$



Singlet+ψ Model - Collider Production

- Minimal gauge singlet scalar models are difficult to search for at colliders as they only couple to SM Higgs.
- On the other hand, VL leptons can be directly produced via electroweak processes,



Singlet+ψ Model - Decay

- Minimal VL lepton models decay via SM Higgs induced mixing with SM leptons.

$$\mathcal{L} \supset y_\psi \bar{\psi}_L H \tau_R \implies \begin{cases} E^- & \to & Z\tau^- \\ E^- & \to & h\tau^- \\ N & \to & W^+\tau^- \end{cases}$$

- With the addition of light singlet scalars ($m_{s_i} < m_\psi$), VL leptons can instead decay through the new couplings,

$$\mathcal{L} \supset \lambda_{\psi i} S_i \bar{L}_L \psi_R \implies \begin{cases} E^- & \to & s_i\tau^- \\ N & \to & s_i\nu_\tau \end{cases}$$

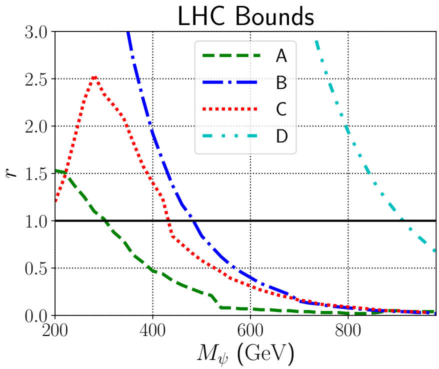
- If the singlets mix with the SM Higgs, they inherit the SM higgs decays ($s_i \to b\bar{b}$, $\tau^+\tau^-$, etc).

Singlet+ψ Model - Collider Searches

- Similar to the SU(2) Triplet model, this will result in events with many leptons in the final state.
- i.e., $q\bar{q} \rightarrow E^+E^- \rightarrow \tau^+\tau^- s_i s_i \rightarrow \tau^+\tau^-\tau^+\tau^- b\bar{b}\,.$
- This model is similarly constrained by multilepton searches at the LHC.

Singlet+ψ - Collider Constraints

- Lower bound on the mass of the VL Lepton doublet is strongly dependent on singlet masses.
- Singlet masses come from scalar potential, which must yield the desired phase transition.
- i.e., $m_{s_1},\ m_{s_2} = 136,\ 158$ GeV or $m_{s_1},\ m_{s_2} = 127,\ 205$ GeV
- Lower bound on m_ψ can range from ~ 300 to ~ 900 GeV.



Singlet+ψ Model - Summary

- The Singlet + VL Lepton model is strongly constrained by existing LHC searches.
- The model can just barely generate sufficient asymmetry.
- The model is likely not capable of doing so with the inclusion of 139fb^{-1} analyses.

Conclusion - EWBG Models

- 2HDM type models.
    - See (N)MSSM Studies.
- Adding exotic scalars charged under SU(2) or SU(3).
    - The lower bounnd on charged exotic scalars are starting to get too large for EWBG.
- Adding gauge singlet scalars.
    - Minimal gauge singlet scalar models (which only couple to SM Higgs) are hard to rule out
    - However, need more BSM to generate an asymmetry.
    - If scalar singlets couple to this new physics they can significantly change the phenomenology.

Conclusion

- Electroweak barogenesis must introduce new electroweak-scale physics.
- EWBG is therefore often described as appealing due to its testability.
- Current and future collider searches are doing a very good job of testing it.

END

Appendix - Vacuum Stability and Perturbative Unitarity

$$\lambda_H > 0,\ \ b_4 > 0,\ \ a_2 \geq -2\sqrt{\lambda_H b_4}\,, \tag{1}$$

$$0 \leq \lambda_H \leq \frac{4}{3}\pi\,, \tag{2a}$$

$$0 \leq b_4 \leq \frac{8}{5}\pi\,, \tag{2b}$$

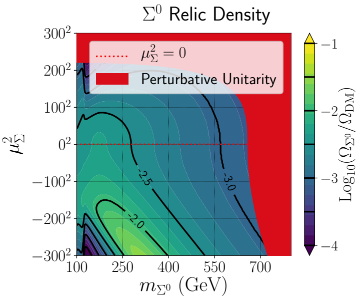
$$|a_2| \leq \sqrt{10\left(\lambda_H - \frac{4}{3}\pi\right)\left(b_4 - \frac{8}{5}\pi\right)} \lesssim 4.54\pi\,. \tag{2c}$$

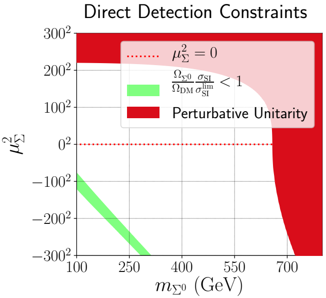
$$\mu_\Sigma^2 \ \lesssim\ 221^2\ \mathrm{GeV}^2\,. \tag{3}$$

$$m_{\Sigma^0}^2 \leq -\mu_\Sigma^2 + \frac{1}{2}v_H^2\sqrt{10\left(\lambda_H - \frac{4}{3}\pi\right)\left(\frac{\mu_\Sigma^4\lambda_H}{\mu_H^4} - \frac{8}{5}\pi\right)} \lesssim 700^2\mathrm{GeV}^2 \tag{4}$$

Triplet Model - Stable Triplet Dark Matter

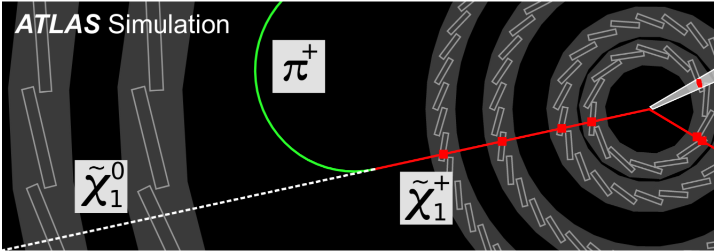
- $m_{\Sigma^0}^2 = -\mu_\Sigma^2 + \frac{1}{2} a_2 v_H^2$.
- Large triplet mass $\implies$ large coupling to SM higgs $\implies$ large direct detection cross section.
- A triplet with $\mu_\Sigma^2 > 0$ and $m_{\Sigma^0} > 100$ GeV is ruled out by direct detection constraints.





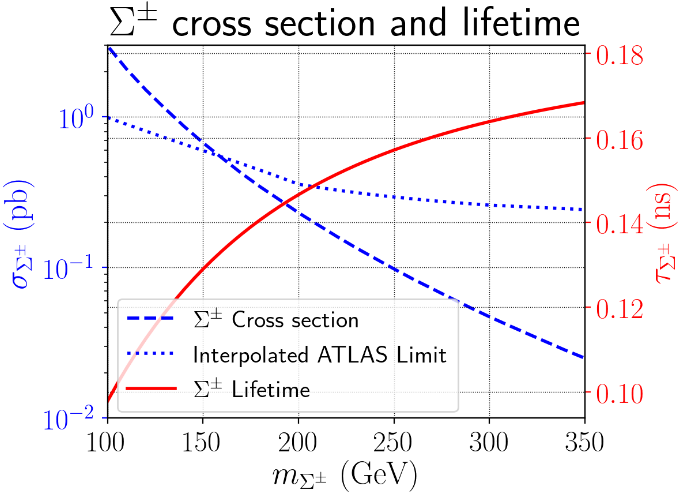
Triplet Model - Stable Triplets at Colliders

- Neutral triplets produced will escape the detector and leave missing energy $\implies$ standard DM searches, weakly constrained.
- Charged triplets will decay into neutral triplets and low energy pions or leptons $\implies$ disappearing tracks! Requires $m_{\Sigma^0} \gtrsim 120$ GeV.

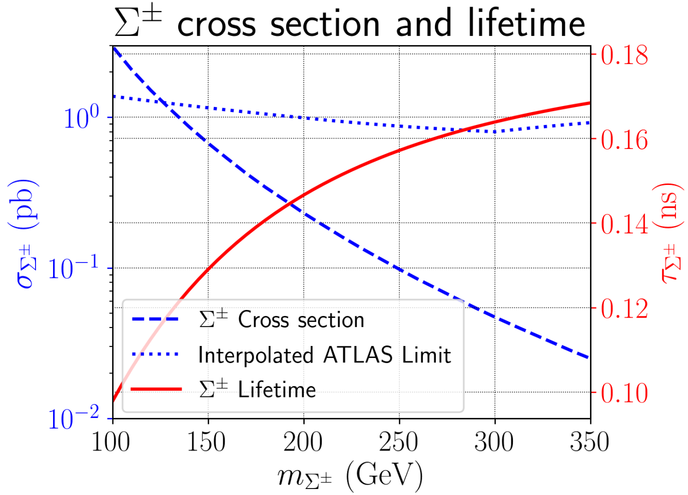


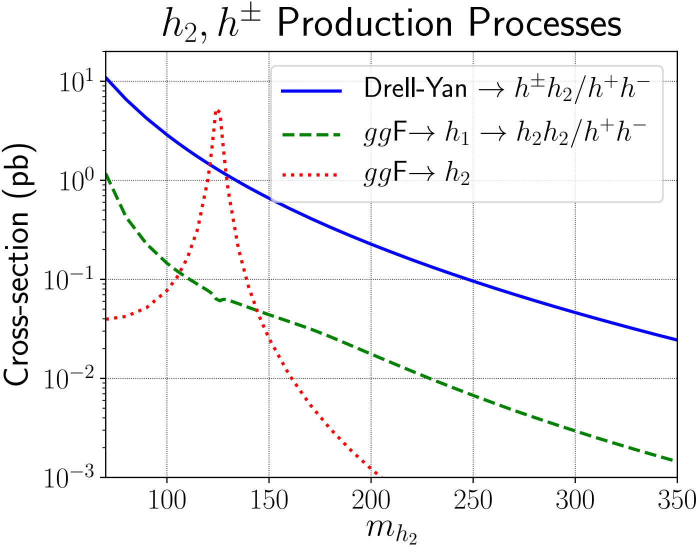
[Image credit: ATLAS Collaboration, arXiv:1712.02118]

Appendix Disappearing Track Constraints (exponential interpolation)

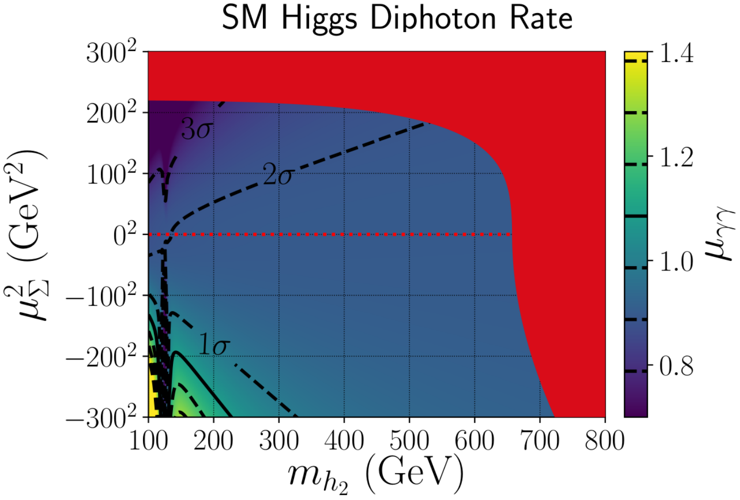


Appendix - Disappearing Track Constraints (linear interpolation)




$h_2, h^{\pm}$ Production Processes
Drell-Yan $\rightarrow h^{\pm}h_2/h^+h^-$
ggF$\rightarrow h_1 \rightarrow h_2h_2/h^+h^-$
ggF$\rightarrow h_2$
Cross-section (pb)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
100
150
200
250
300
350
m_{h_2}

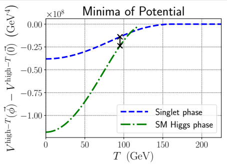
Appendix - SM Higgs Diphoton Rate

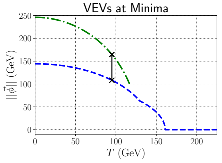


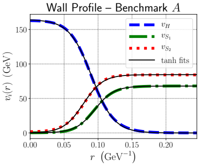
Singlet Model - Electroweak Phase Transition

We evaluate the dynamics of the electroweak phase transition using the Cosmotransitions Package.

Example electroweak phase transition benchmark


Minima of Potential

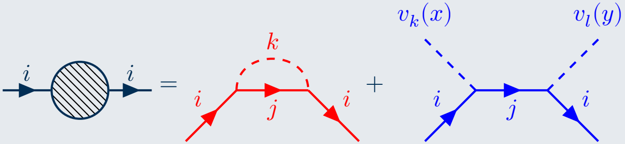

VEVs at Minima


Wall Profile – Benchmark A

Singlet Model - EWBG Methodology 1

- We use the VEV-insertion approximation framework
- System of transport equations arise from self-energy diagrams.
- VEV-insertion diagrams lead lead to CPV source term
- Other diagrams lead to relaxation rates that drive towards equilibrium

Reaction rates



$$\Longrightarrow \; Dn_i''(z) - v_w n_i'(z) \approx \Gamma_{ijk}\left(n_i - n_j \pm n_k\right) + \Gamma(z)_{ij}(n_i \pm n_j) - S_i^{\mathrm{CPV}}(z)$$

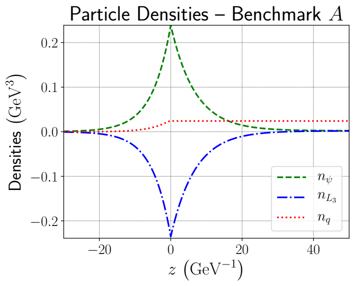
Singlet Model - EWBG Methodology 2

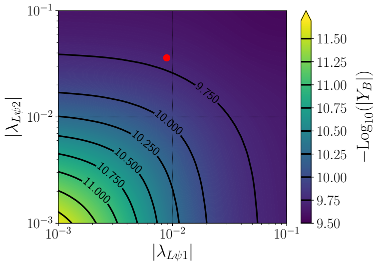
After solving the system of transport equations for the number densities, one can obtain the resulting baryon asymmetry.

$$Dn_j''(z) - v_w n_i'(z) = \Gamma_{ijk}\left(n_i - n_j \pm n_k\right) + \Gamma(z)^{\pm}_{i,j}(n_i \pm n_j) - S_i^{\mathrm{CPV}}(z)$$

$$\to n_i(z) \to n_B \sim -\frac{n_f}{2v_w}\int_0^\infty dz \Gamma_{\mathrm{WS}} \sum_i n_{i,L}(z)$$

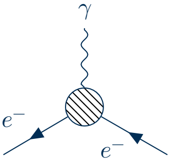
Benchmark Results





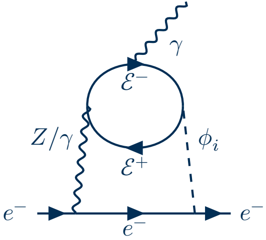
Singlet Model - Phenomenology - EDM 1

- CP violation can lead to electric dipole moments (EDM).
- the SM predicts a very small electron EDM $d_e \sim 10^{-38}\,\mathrm{e}\cdot\mathrm{cm}$
- Experimental observations place an upper bound $|d_e^{\mathrm{expt}}| \sim 10^{-28}\mathrm{e}\cdot\mathrm{cm}$



$$\mathcal{L}_{\mathrm{eff}} \supset i\frac{d_e}{2}\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi F^{\mu\nu} \;\rightarrow\; d_e$$

Singlet Model - Phenomenology - EDM 2



Benchmark	A, B	C
d_e (e · cm)	$3.02 \cdot 10^{-31}$	$1.07 \cdot 10^{-29}$
$\frac{d_e}{d_e^{\text{expt}}}$	0.0275	0.978

Triplet Model - Collider Phenomenology Results 2