LHC Signals of Electroweak Baryogenesis

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Physics in LHC and Beyond

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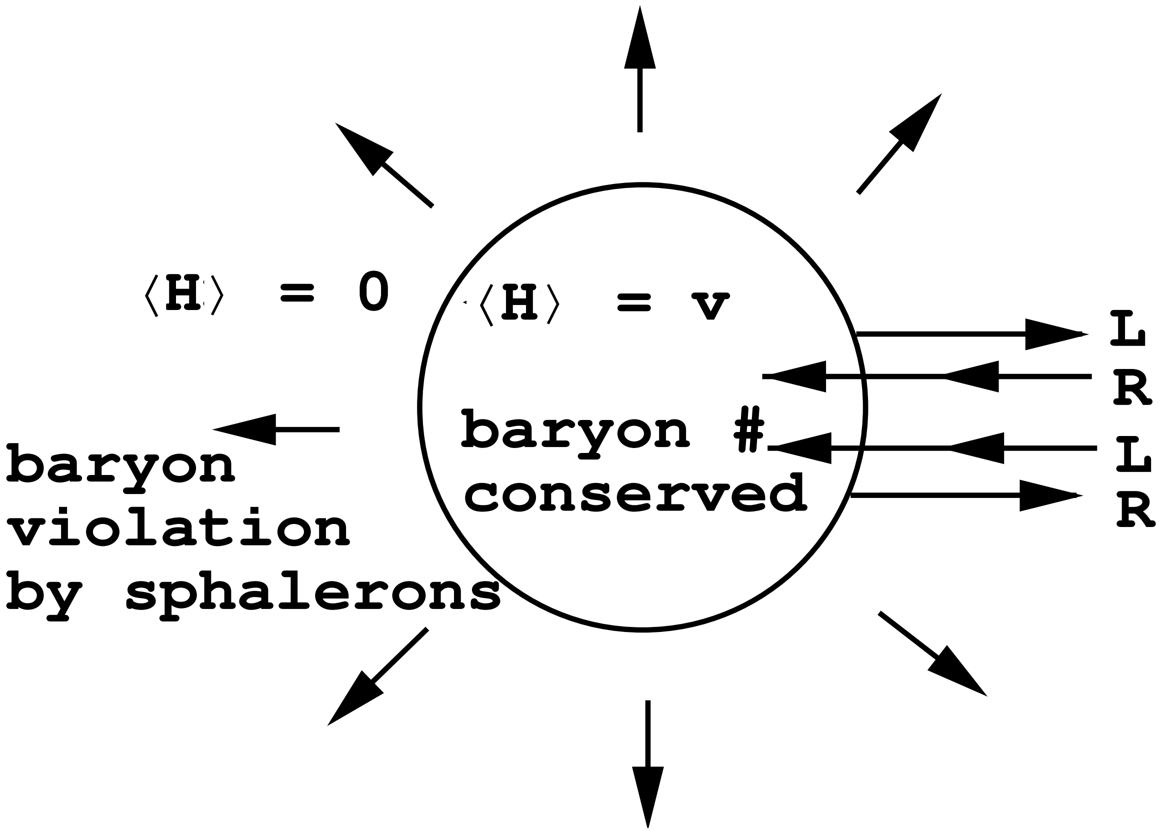
Outline

- Electroweak baryogenesis review
- New physics for the phase transition
- New physics for CP violation
- Theoretical caveats for EWBG predictions

I. Electroweak Baryogenesis

EWBG relies on a strongly 1st order electroweak phase transition, and CP violating interactions of fermions at the bubble walls,



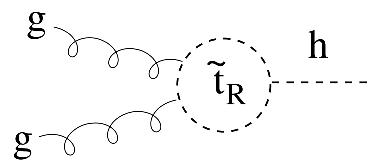
Needs new physics at the electroweak scale to get both ingredients.

A highly testable model of baryogenesis. In some scenarios it is already ruled out.

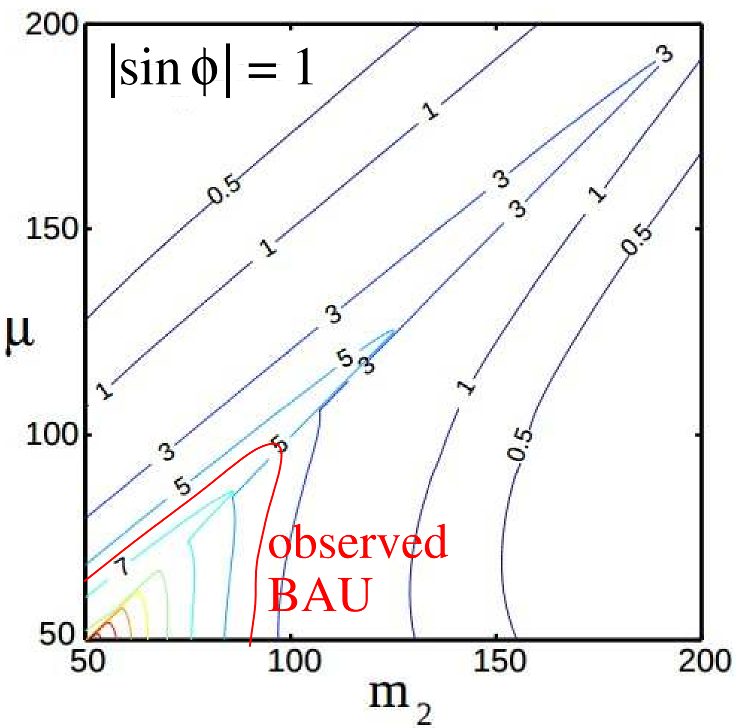
EWBG in the MSSM

Strong EWPT (with $m_h = 125\,\mathrm{GeV}$) needs light right-handed stop, $m_{\tilde{t}_R} \lesssim m_h$ and heavy left-handed stop, $m_{\tilde{t}_L} \gtrsim 100\,\mathrm{TeV}$

Such a light stop increases hgg fusion production; essentially ruled out



Getting large enough baryon asymmetry requires too much CP violation and too light charginos/neutralinos:



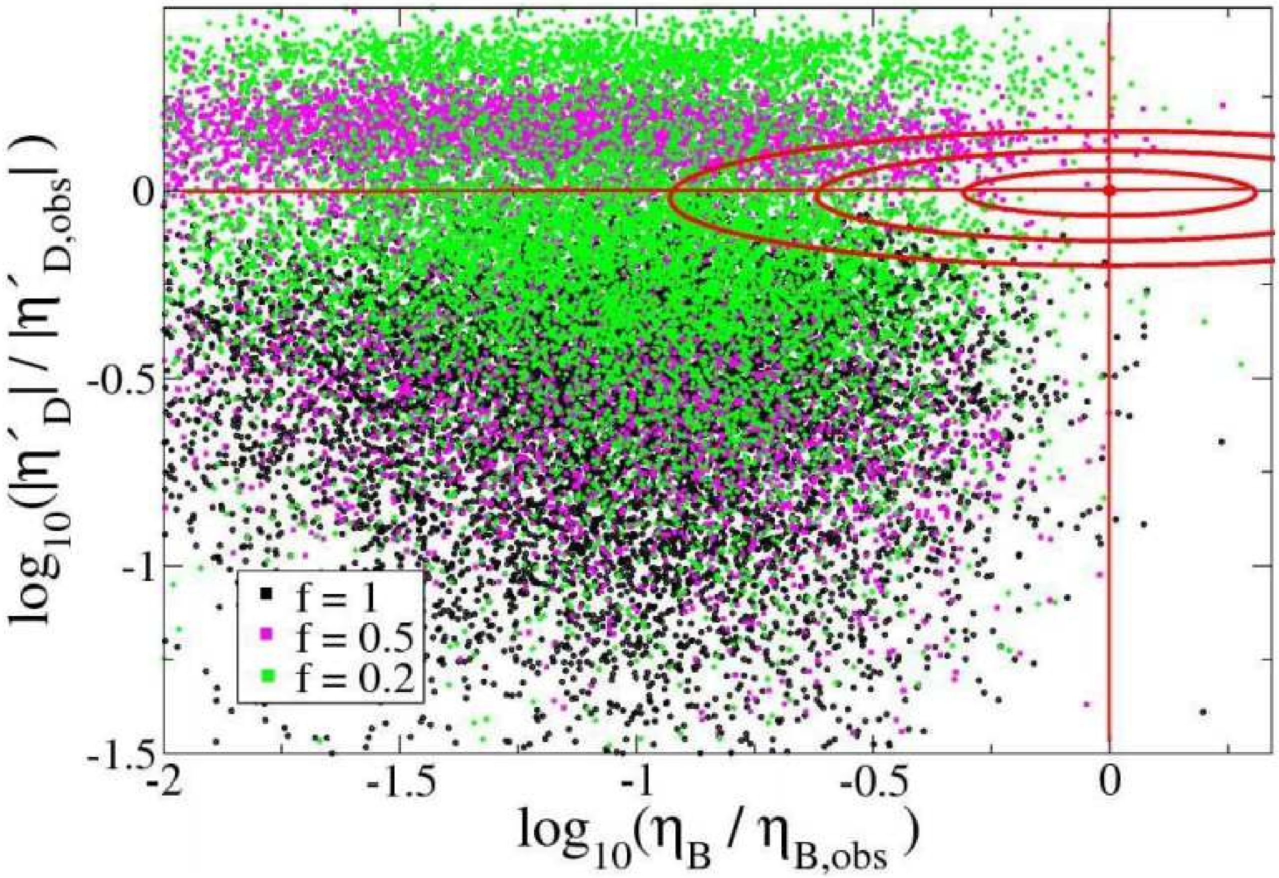
Cline & Kainulainen, PRL 85 (2000) 5519 (hep–ph/000272)

maximal CP phase ruled out by neutron EDM, need even lighter sparticles

EWBG in two Higgs doublet models

MSSM is a two Higgs doublet model. More general 2HDMs have the needed ingredients for EWBG. But the parameter space that works is extremely small.

Results from MCMC scan of 10,000 models (JC, Kainulainen, Trott, 1107.3559). Only a handful give big enough asymmetry.

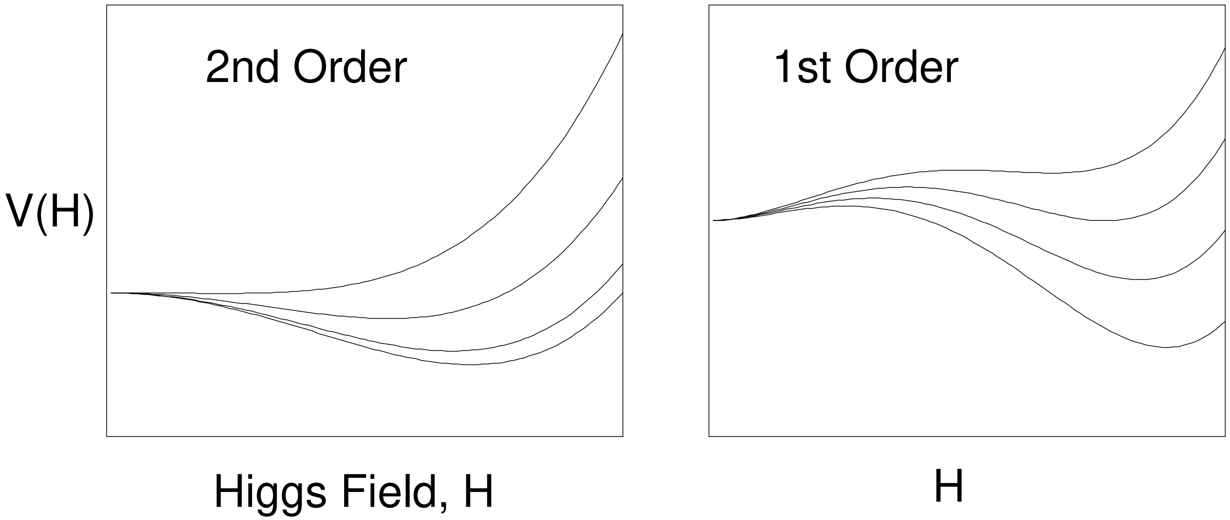


For a contrasting view, see Dorsch, Huber, Konstandin, No, 1611.05874

Requires very large couplings, low Landau poles

Challenge for strong phase transition

First order phase transition requires potential barrier,



Traditionally, the barrier came from finite-temperature cubic correction to potential,

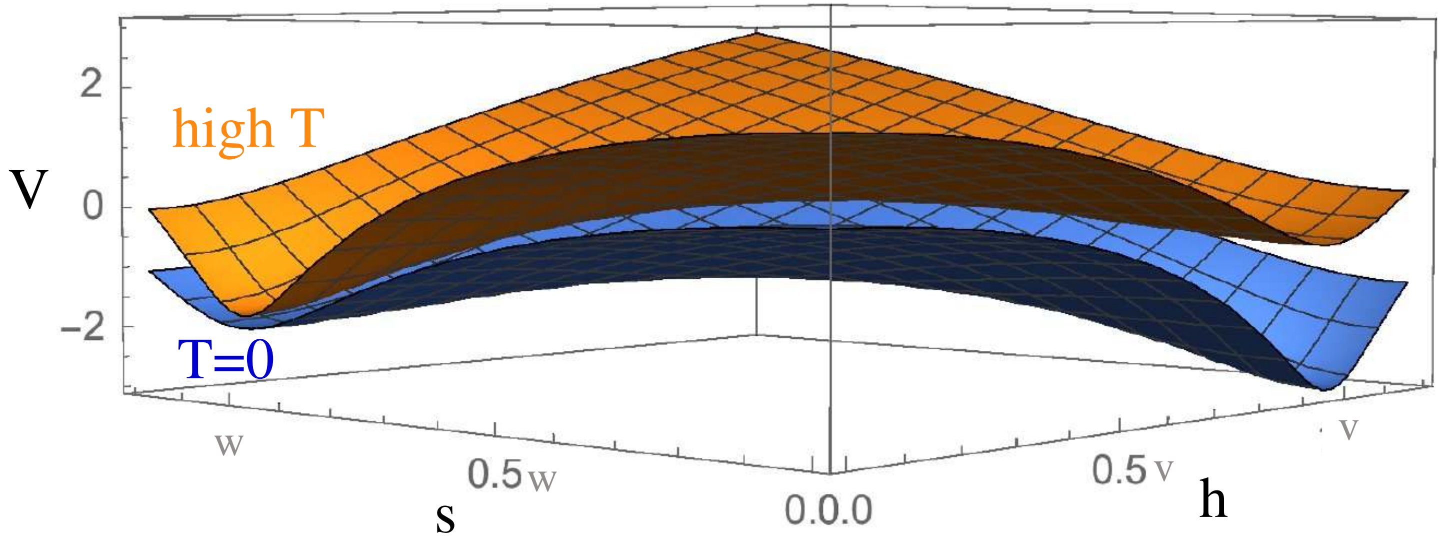
$$\Delta V = -\frac{T}{12\pi}\sum_i (m_i^2(h))^{3/2} = -\frac{T}{12\pi}\sum_i (m_{i,0}^2 + g_i^2 h^2 + c_i T^2)^{3/2}$$

It is typically not very cubic, and not big enough. Tends to give only a 2nd order or weak 1st order phase transition, $v/T < 1$, unless $m_{i,0}$ is small or g_i is large.

Tree-level barrier with extra scalar

Another way is to let an extra scalar S get VEV during EWPT.

Choi & Volkas, hep-ph/9308234; Espinosa, Konstandin, Riva, 1107.5441; Kozaczuk, Ramsey-Musolf, Shelton, 1911.10210; Carena, Liu, Wang, 1911.10206; Bell *et al*,, 2001.05335



At $T = 0$, EWSB vacuum is deepest, but at higher T, the $h = 0$, $S \neq 0$ vacuum is lower energy.

The transition is controlled by the leading $T^2\phi_i^2$ corrections in the finite-T potential.

Phase transition can easily be very strong (with some parameter tuning).

II. New physics for phase transition

Can couple Higgs to various BSM particles:

- Singlet scalars
- Triplet or other EW-interacting scalars
- TeV-scale fermions

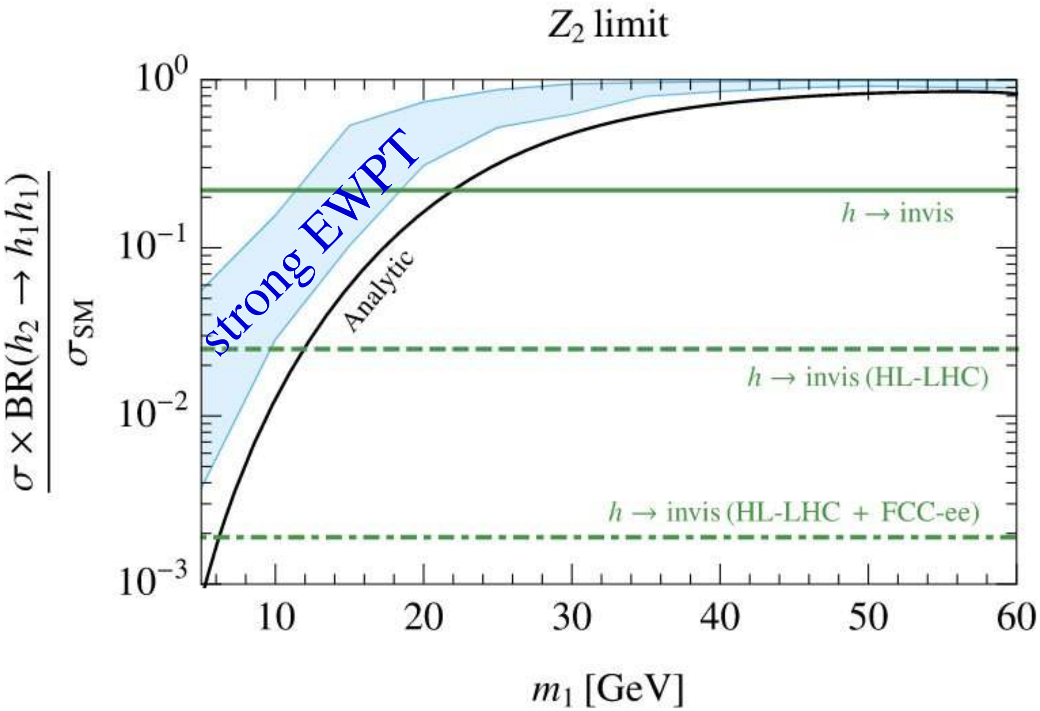
N.B. Criterion for strong enough phase transition is relatively simple,

$$\frac{v}{T} \gtrsim 1$$

while question of enough CP violation (baryon production) is more controversial; see part IV.

Light singlet collider signals

Light singlet $m_s < m_h/2$ is constrained by $h \to 2s$ invisible decays.

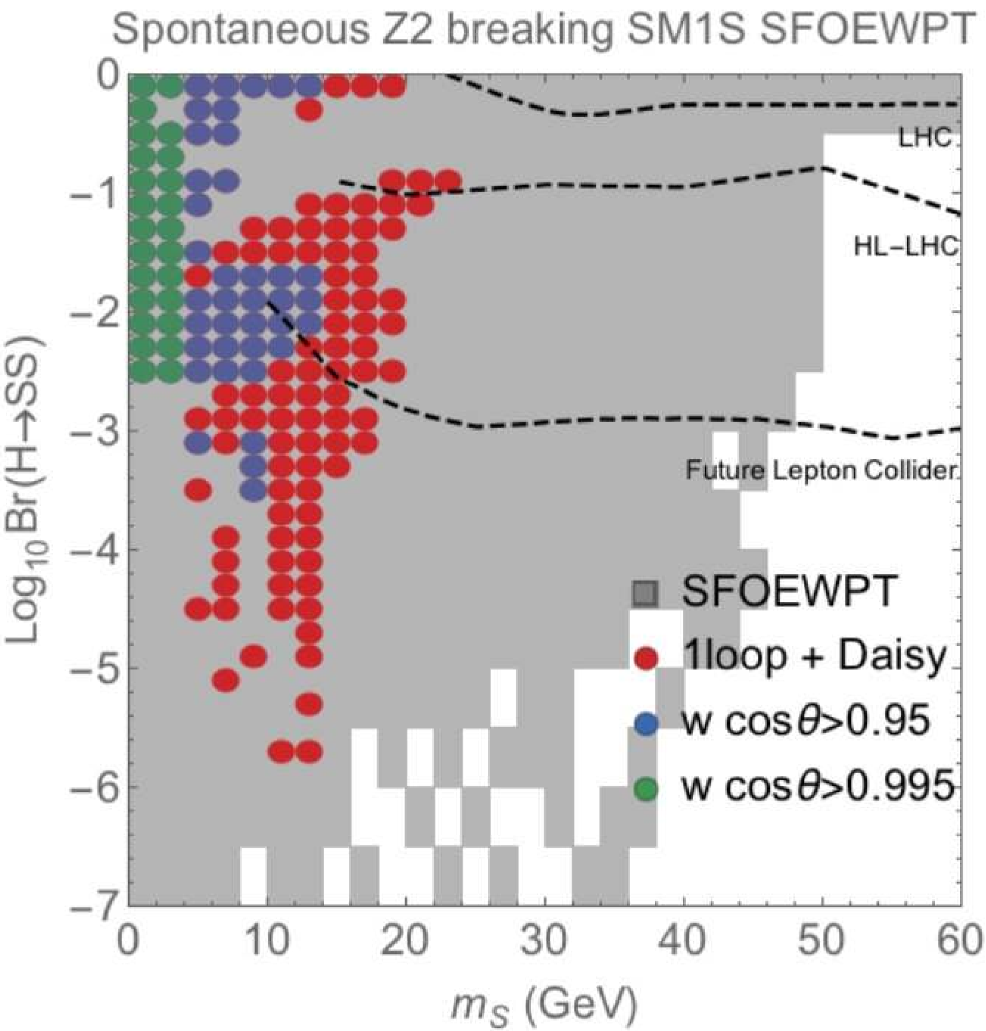


E.g., Z_2-symmetric singlet. Must have $m_s \lesssim 20\,\mathrm{GeV}$) to satisfy current LHC constraint. Kozaczuk, Ramsey-Musolf, Shelton 1911.10210

However $m_s > m_h/2$ evade this constraint and can also give strong EWPT.

Light singlet collider signals

If s gets VEV at $T = 0$, its mixing with Higgs is constrained. Higgs self-coupling is modified. $h \to 2s \to f f \bar{f} \bar{f}$ can become visible.



E.g., spontaneously broken Z_2-symmetric singlet. Must be light ($\lesssim 20\,\mathrm{GeV}$) to give strong phase transition. Barely within reach of HL-LHC. Carena, Liu, Wang, 1911.10206

These kind of signals tend to be small, requiring precision measurements.

Light singlet collider signals

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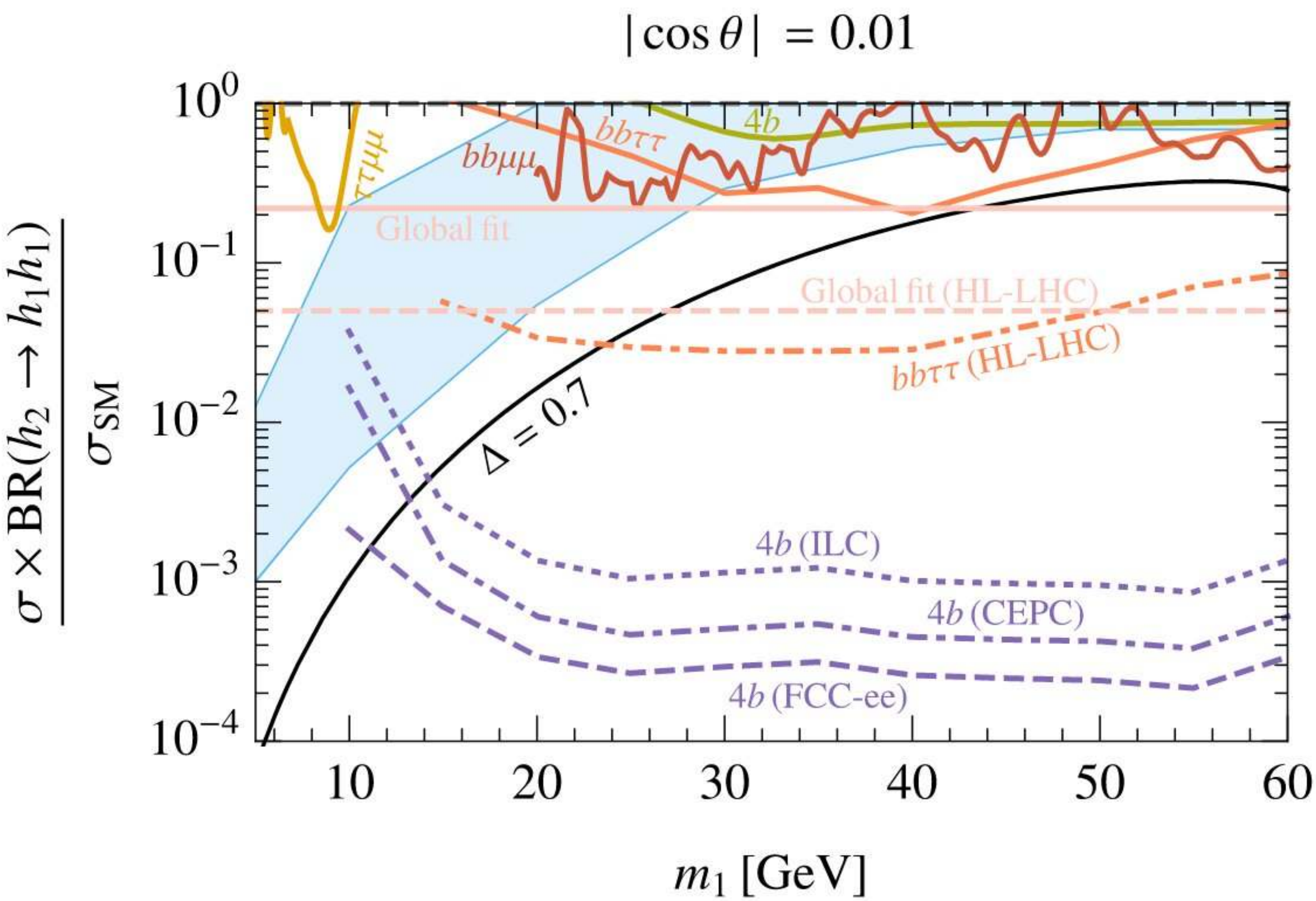


Singlet without Z_2 symmetry.

Kozaczuk, Ramsey-Musolf, Shelton 1911.10210

NMSSM signals

The next-to-minimal supersymmetric standard model needs light singlet $m_S \gtrsim 70\,\mathrm{GeV}$ and extra Higgs H could be $m_H \gtrsim 200\,\mathrm{GeV}$

Baum, Carena, Shah, Wagner, Wang, 2009.10743

Discovery at LHC via

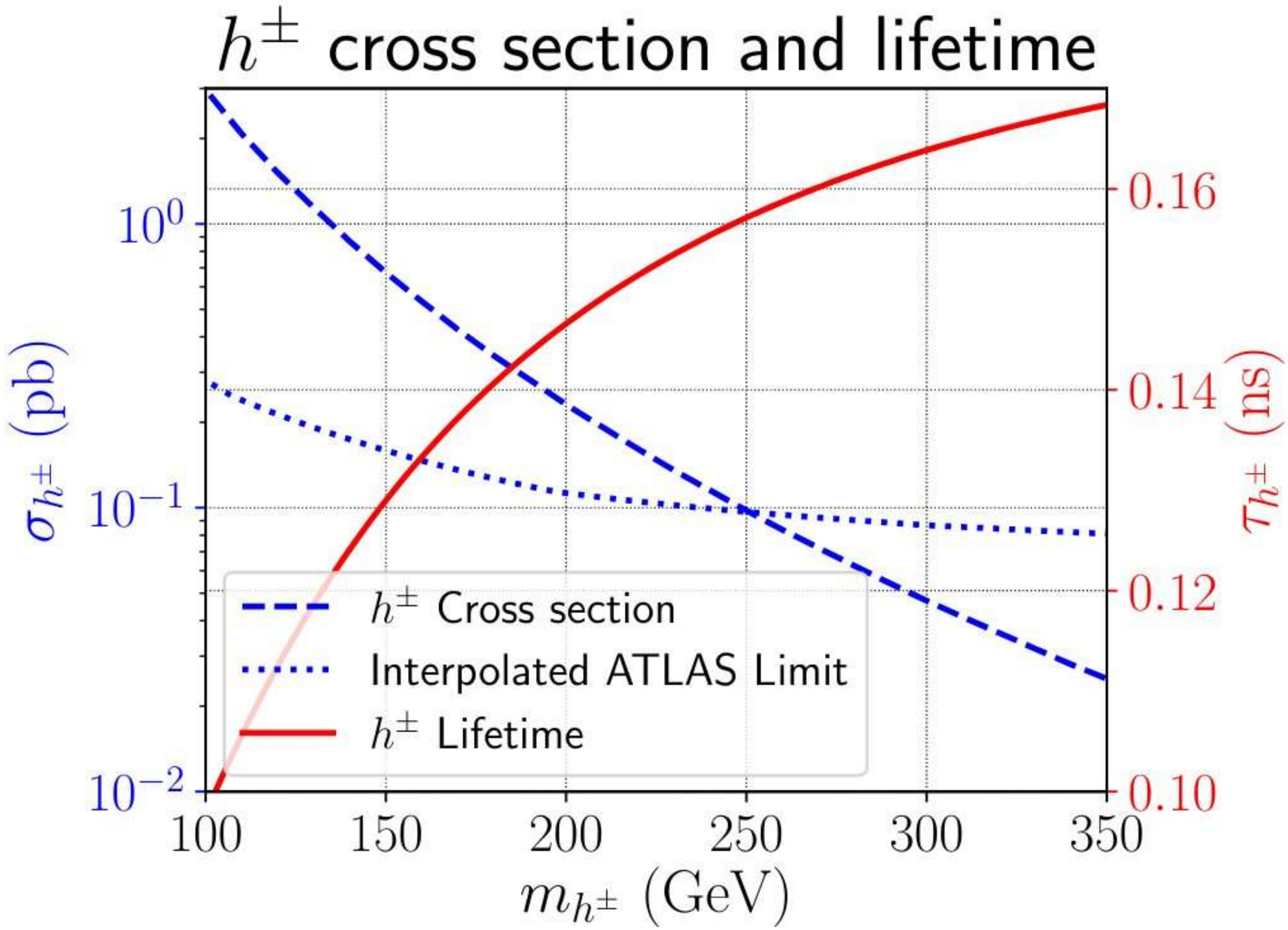
$$H \to t\bar{t},\ \tau^+\tau^-$$

is difficult due to small $\tan\beta \sim 3$. Singlet-like production is suppressed.

No systematic collider study so far.

Triplet collider signals

Electroweak triplet (h^+, h^0, h^-) could have stable DM candidate h^0;
Decays $h^\pm \to h^0 \ell^\pm \nu$ or $h^0 \pi^\pm \pi^0$ leave disappearing charged track.



ATLAS constrains $m_{h^\pm} > 250\,\mathrm{GeV}$.

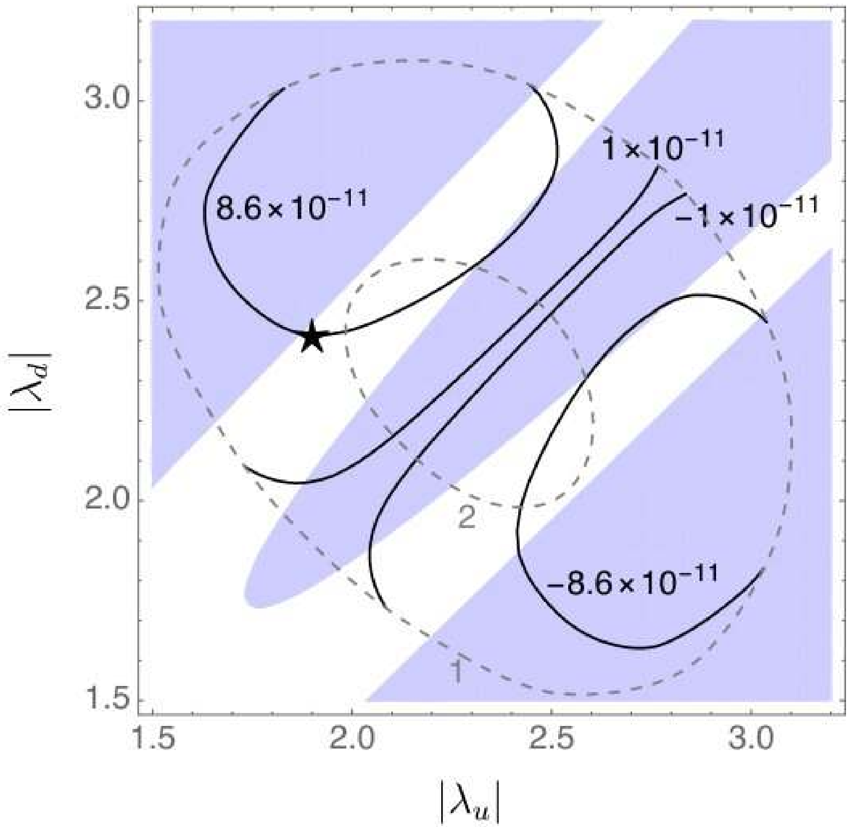
Bell, Dolan, Friedrich, Ramsey-Musolf, Volkas, 2001.05335

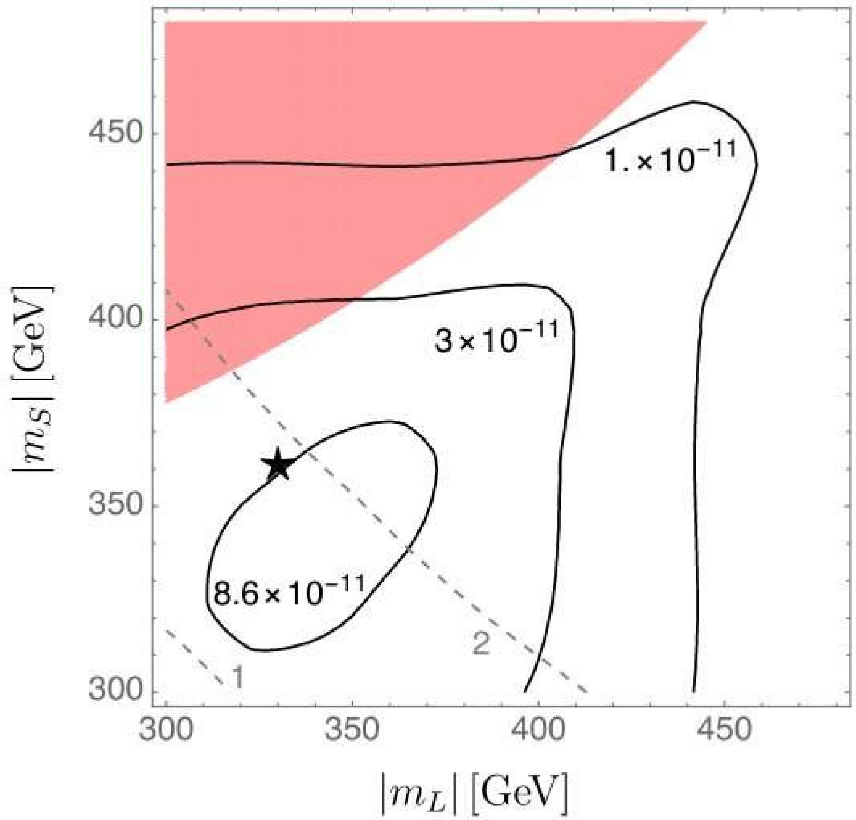
(2-step EWPT enabled by triplet)

Similar limit for model with unstable h^0.

Heavy vectorlike fermions

Heavy fermions that also couple to Higgs can make the EWPT strongly first order Carena, Megevand, Quirós, Wagner, hep-ph/0410352. Minimal model has singlet + doublet fermions Egana-Ugrinovic, 1707.02306. Doublet is pair-produced and decays to $\not{E}_T$, leptons, jets.





$\sim 100\times$ below LHC sensitivity; may be testable at HL-LHC.

III. New physics for CP violation

Need new CP-violating interactions in the bubble wall to create the baryon asymmetry.

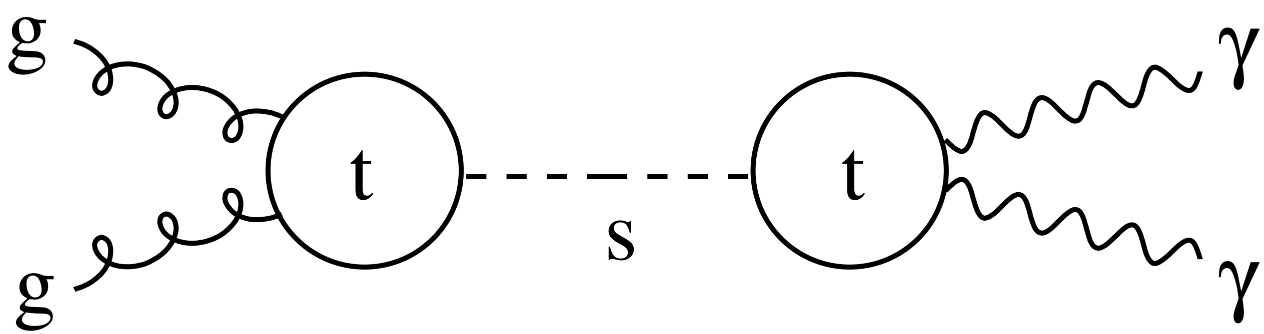
Example: top quark mass term gets $\not{C}\!\!\not{P}$ contribution in the wall from a singlet field S:

$$\bar{t}_L\, H(z) \left(y_t + \frac{i}{\Lambda} S(z) \right) t_R$$

Can be induced by integrating out heavy vectorlike top partner T

Laurent, Cline, Friedlander, He, Kainulainen, Tucker-Smith, 2102.12490

Can be constrained by resonant diphoton searches,



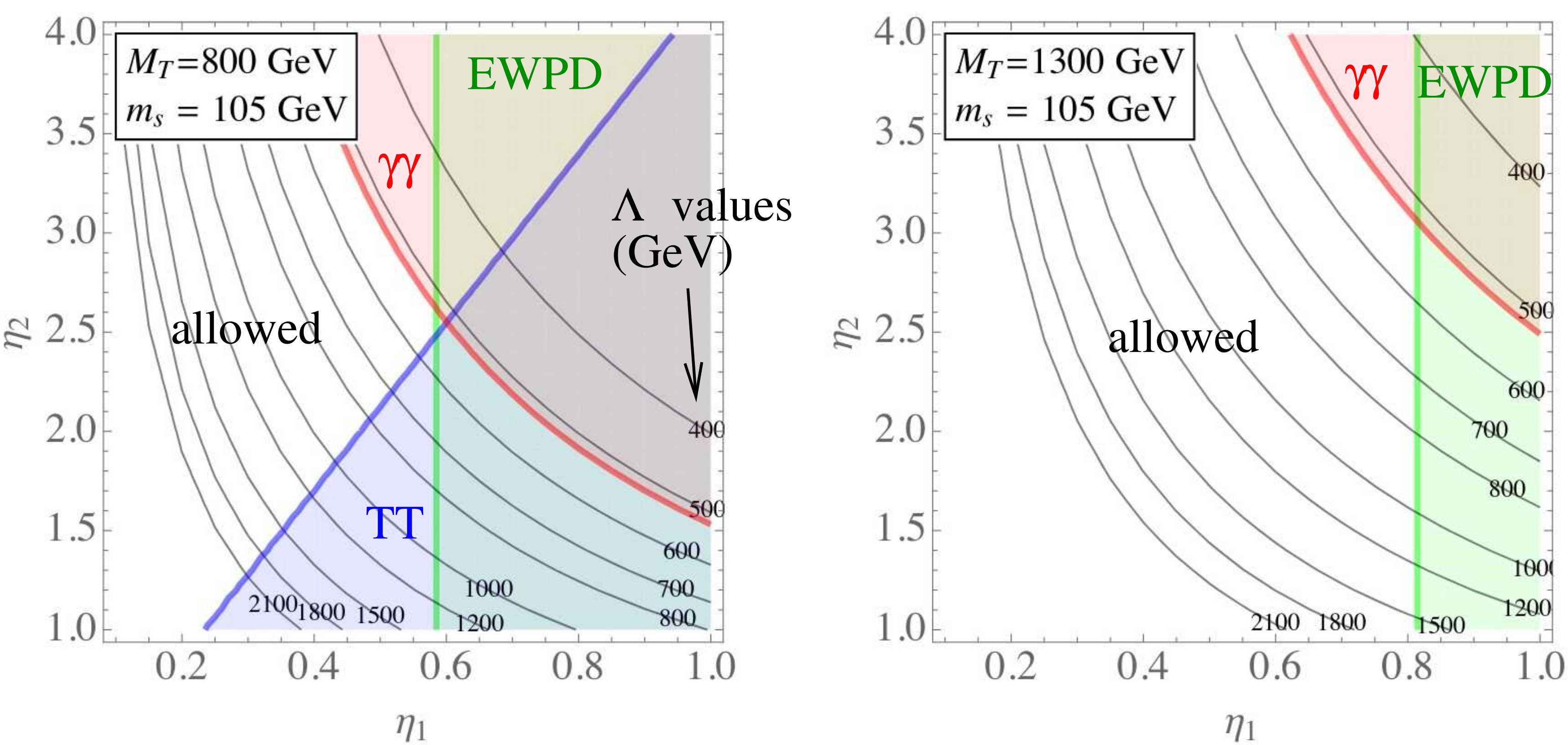
Also by searches for pair-produced top partners . . .

Constraints on top-partner/singlet

Dimension-5 mass operator is generated from couplings to vectorlike top partner,

$$\eta_1 \bar{q}_R H T_L + i\eta_2 \bar{T}_R S t_R$$

giving $\Lambda = y_T M_T/(\eta_1\eta_2)$.

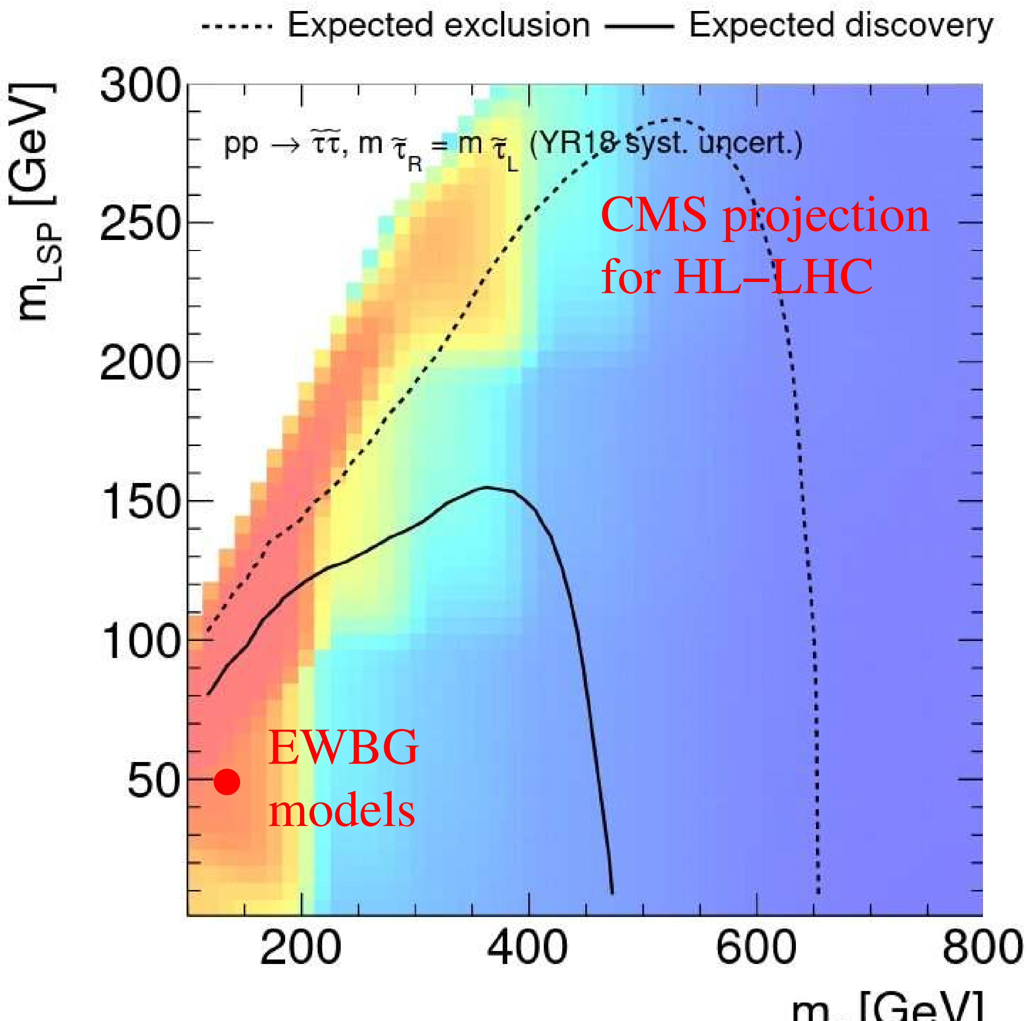


Large couplings are typically needed for successful baryogenesis.

$\not{C}\not{P}$ in a dark sector

Suppose singlet S couples to dark matter χ, and χ couples to τ lepton via inert Higgs doublet ϕ (Cline, Kainulainen, Tucker-Smith, 1702.08909):

$$\tfrac{1}{2}\bar\chi\left((\eta + i\eta'\gamma_5)S + m_\chi\right)\chi + y\bar L_\tau \phi\chi_R$$



Evades EDM bounds on $\not{C}\not{P}$. Can map $\phi \to$ stau, $\chi \to$ LSP, and recast SUSY searches at LHC.

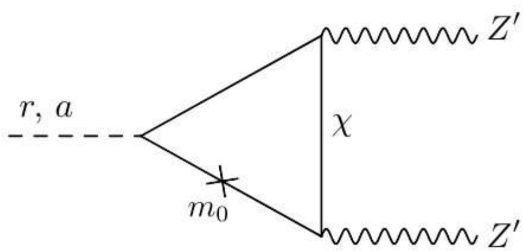
Successful EWBG puts us close to ATLAS run 1 limits (1407.0350), and still below CMS run 2 limits (1807.02048)

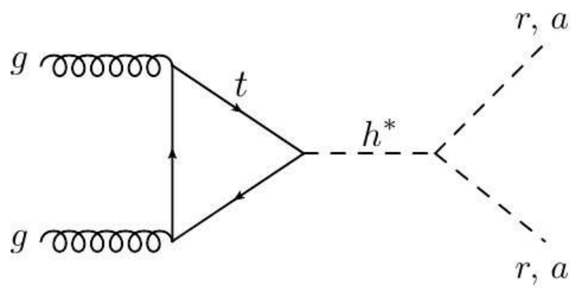
Can be excluded by HL-LHC (CMS PAS FTR-18-010)

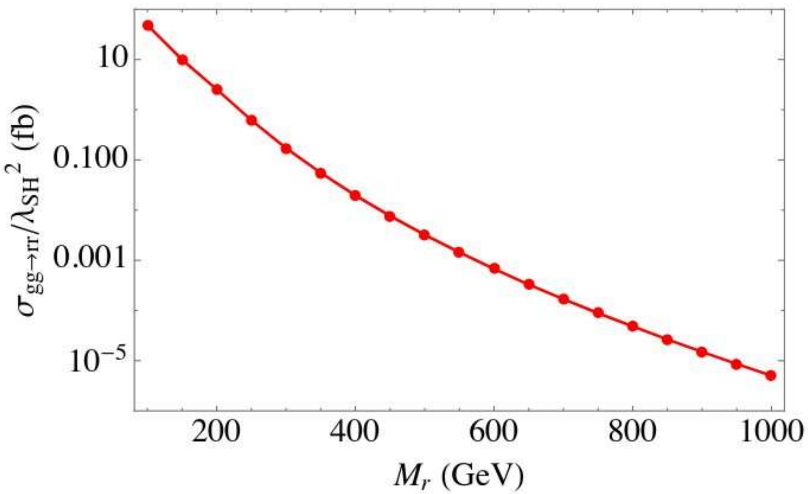
$\not{C}\not{P}$ in a dark sector

Suppose singlet $S = (r + ia)$ couples to dark matter χ, and χ couples to a leptonic Z' (Carena, Quirós, Zhang, 1908.04818):

$$\tfrac{1}{2}\bar\chi\left((\eta + i\eta'\gamma_5)S + m_\chi\right)\chi + g' Z'_\mu\left(\bar\chi\gamma^\mu\chi + \bar L\gamma^\mu L\right)$$





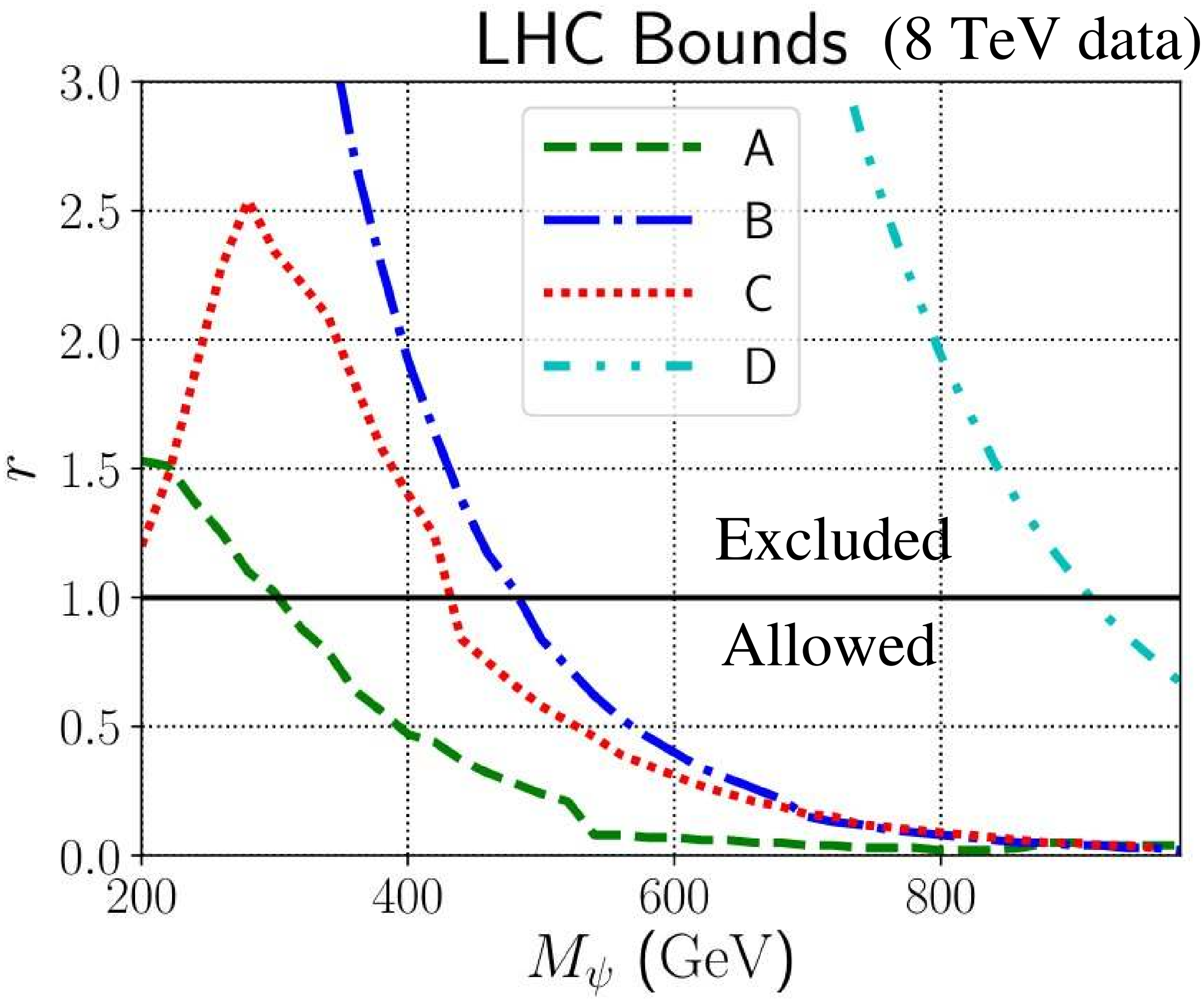


$gg \to rr \to Z'Z'Z'Z' \to 4\,\ell^+\ell^-$ may be constrained by LHC

$\not{CP}$ from vectorlike leptons

Bell, Dolan, Friedrich, Ramsey-Musolf, Volkas, 1903.11255 couple vectorlike doublet leptons ψ to SM L_τ, τ_R and singlets S_i:

$$M_\psi \bar{\psi}_L \psi_R + M_{L\bar{\psi}\tau} \psi_R + \lambda_{1,i} \bar{L}_\tau \psi_R S_i + \lambda_{2,i} \bar{\psi}_L \psi_R S_i + \lambda_3 \bar{\psi}_L \tilde{H} \tau_R$$



$\psi\bar{\psi}$ produced by Drell-Yan.

Exclusion depends on choice of model parameters,

$m_\psi \gtrsim 300 - 900\,\text{GeV}$

IV. Theoretical caveats

How accurate are EWBG predictions?

Two schools of thought have governed calculation of baryon asymmetry:

- WKB (semiclassical) method
- VIA: VEV-insertion approximation

VIA method usually gives larger estimate, often by orders of magnitude Cline, Kainulainen, 2001.00568; Cline, Laurent, 2108.04249
e.g., WKB predicts leptonic $\not{C}\not{P}$ is too small for baryon asymmetry

VIA derivation has been criticized, claiming correct calculation using this method would give *vanishing* contribution! Kainulainen, 2108.08336

My recommendation: use WKB, or at least show predictions of both methods

Bubble wall velocity

Baryogenesis prediction can be sensitive to speed v_w of expanding bubble wall.

Most studies simply assume some value ~ 0.1, favorable to EWBG.

Computation of v_w is difficult, but Laurent, Cline, 2204.13120 find that typically $v_w \sim 1/\sqrt{3}$ (speed of sound), or $v_w \sim 1$.

Formerly it was thought that EWBG is suppressed as $v_w \to 1/\sqrt{3}$, but this need not be the case (Cline, Kainulainen, 2001.00568)

Summary

New physics, $\lesssim$ TeV scale, is typically designed either to strengthen EWPT or to generate the baryon asymmetry.

Selected collider signals of electroweak baryogenesis

new physics	EWPT	$\not{CP}$	collider signals	Expt.	Ref.
scalar singlet s	✓	✗	$h \to 2s\ (\to 4f)$	HL-LHC	1911.10206 1911.10210
scalar singlet + top partner	✓	✓	$s \to 2\gamma$	LHC	2102.12490
scalar triplet	✓	✗	$H^\pm \to \not{E}_T + \dots$	ATLAS	2001.05335
vectorlike doublet ψ $+$ singlet fermions	✓	✓	$\psi \to \not{E}_T + \dots$	HL-LHC	1707.02306*
vectorlike top T	✗	✓	$T \to h/W/Z + t$	LHC	2102.12490
vectorlike leptons L	✗	✓	$L \to h/W/Z + \ell,\ s + \ell$	LHC	1903.11255*
singlet + DM + inert Higgs doublet ϕ	✗	✓	$\phi \to \tau + \not{E}_T$	LHC	1702.08909
singlet + DM +leptonic Z'	✗	✓	$s \to 4Z' \to 8f$	LHC	1908.04818*

* Baryon asymmetry should be re-examined in light of WKB versus VIA controversy.