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Particles, Strings, and the Early Universe
Collaborative Research Center SFB 676

MSSM electroweak baryogenesis dead or alive?

based on arXiv:1512.09172
with Stefano Profumo and Tim Stefaniak

IPA
Interplay between Particle and Astroparticle Physics
LAL - Orsay, September 05 - 09, 2016

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HELMHOLTZ | GEMEINSCHAFT

Outline

1. Electroweak baryogenesis
2. Indirect constraints on MSSM EWBG from Higgs rates
3. χ^2 compatibility of MSSM EWBG with experimental data
4. Conclusions

Outline

Asymmetry between matter and antimatter (from CMB - WMAP, Planck):

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim (6.2 \pm 0.2) \cdot 10^{-10}$$

Mechanism to generate baryon asymmetry needs to fullfill the Sakharov conditions: [A. D. Sakharov 1967]

- ✓ C- and CP-violation
- ✓ Baryon number B violation
- ✓ Departure from thermal equilibrium

Two categories:

- ✓ Baryogenesis
- ✓ Leptogenesis (transfer to B through sphalerons)

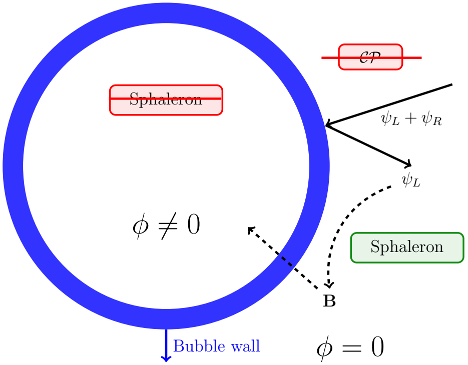
Focus of this talk:
MSSM electroweak baryogenesis (EWBG) [Review Morrissey Ramsey-Musolf '12]
$\longleftrightarrow$ Light particles testable at colliders

EWBG happens at temperatures $T \lesssim 100$ GeV,
i.e. when EW symmetry breaking occurs $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{em}}$.
It needs: First-order electroweak phase transition (expanding bubbles).
$\to$ Along the walls sphaleron processes can provide baryon asymmetry.

Main ingredients:
1. We need sufficient CP violation!
2. We need to ensure a first-order phase transition.

Problem: SM presumably does not provide enough CP violation and a first-order phase transition only occurs for $m_H \lesssim 70$ GeV.

Needed: Physics beyond the SM.



First-order phase transition:
Perturbative and non-perturbative (lattice) calculations
Issues of perturbative description:

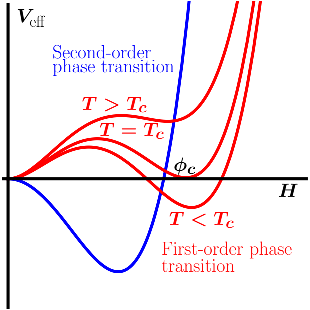
- ✗ fails at large g^2T^2/m^2 (daisy resummation of thermal corrections)
- ✗ problems with gauge dependence

Finite-temperature effective potential in short:
(high temperature expansion)

$$V_{\text{eff}}(H,T) \sim D(T^2 - T_0^2)H^2 - ETH^3 + \frac{\overline{\lambda}}{4}H^4$$

Degeneracy of minima at $T = T_c$.
Transition characterized by ϕ_c/T_c.

Strong first-order phase transition $\phi_c/T_c \geq 1$ to avoid washout of baryon asymmetry through sphalerons.



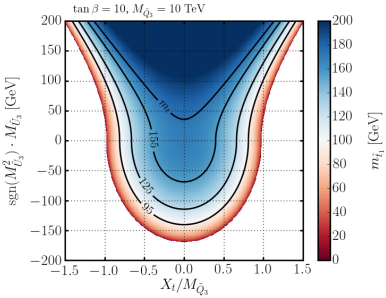
Assume scalar X modifiying Higgs potential:

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

$$\Delta V_{\text{eff}}(H,T) \supset -\frac{n_X T}{12\pi}\left[\Pi_X(T) + M_X^2 + \frac{Q}{2}H^2\right]^{3/2} \sim -ETH^3$$

Cubic term enhanced for $\mathrm{SU}(3)_C$ triplets with $Q \gtrsim 1$ and $M_X^2 \lesssim 0$.
Problem: $M_X^2 < 0$ can induce a VEV for X and thus charge-breaking minima!
Simple candidates: ✓Gauge singlet (e.g. NMSSM)
✓MSSM with right-handed stop $Q \sim Y_t^2$, $K \sim 4\pi\alpha_s$, $M_X^2 \sim M_{\tilde{U}_3}^2$.

MSSM EWBG:
Right-handed stop with $M_{\tilde{U}_3}^2 \lesssim 0$ and heavy left-handed stop with $M_{\tilde{Q}} \gg$ TeV to obtain $m_h \sim 125\,$GeV.
Resummation of large logarithms.
Stop mixing $X_t = 0$ to lower influence of heavy SUSY on EDM's and due to small effects for $X_t \leq \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.



MSSM EWBG only works for:
perturbative calculations $m_{\tilde{t}_1} \lesssim 105\,\mathrm{GeV}$ [Carena Nardini Quiros Wagner '08 '12]
non-perturbative calculations $m_{\tilde{t}_1} \lesssim 155\,\mathrm{GeV}$ [Laine Nardini Rummukainen '12]

We probably need CP violation in addition to the SM CKM (PMNS).
Three possiblities in the MSSM:

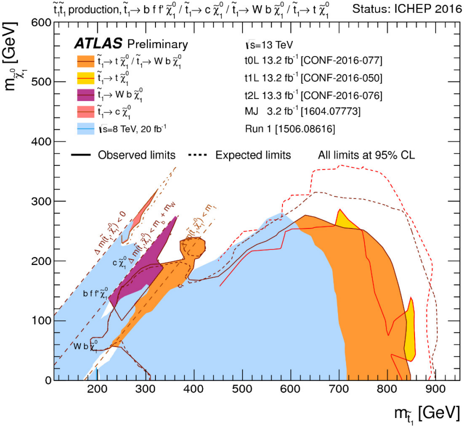
- Resonant fermion sources $m_{\tilde{f}_L} \simeq m_{\tilde{f}_R}$
  stops: clearly impossible
  sbottoms: constraints from chromo-electric dipole moments
  staus: ✓ $\rightarrow m_{\tilde{\tau}}$ below one TeV and large $\tan\beta$
- Soft-breaking bino and wino masses
  $\rightarrow$ at least one light chargino
- Heavy Higgs sector at low masses
  $\rightarrow$ Low value of pseudoscalar mass m_A

These three options motivate the three scenarios **B** to **D** in our later study.

How can EWBG be tested? [Review by Morrissey Ramsey-Musolf arXiv:1206.2942]

- ▷ The intensity frontier: Searches for electric dipole moments of electron, neutron, neutral atoms. $\rightarrow$ Bounds on CP-violating parameters
- ▷ The cosmological frontier: Strongly first-order phase transition can trigger gravitational waves [e.g. 1605.08663, 1607.08057, 1608.00583]. Dark matter.
- ▷ The high-energy frontier: Direct searches for light particles at colliders!
  ✗depend on $\tilde{t}_1$ decay
  ✗not valid for R-parity violation
  [Ferretti Franceschini Petersson Torre '15] [ATLAS CMS Eifert '14]

  Complementary approach:
  Indirect searches through effects on Higgs rates!
  [Carena Nardini Quiros Wagner '12] [Curtin Jaiswal Meade '12]



Outline

Observable effects in Higgs rates: Two dominant effects:

▷Contribution to $gg \to h$ ($h \to gg$): Partonic XS expanded in $1/m_{\tilde{t}_1}^2$:

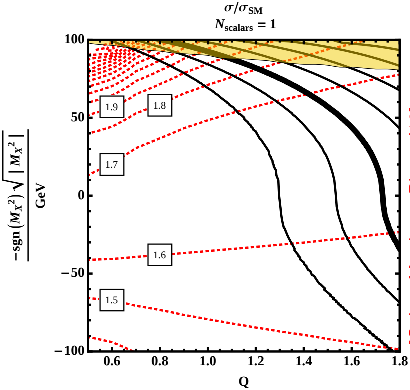
$$\sigma(gg \to h) = \frac{G_F \alpha_s(\mu_R)}{288\sqrt{2}\pi} |\mathcal{A}_{SM}^{LO} + \mathcal{A}_{\tilde{t}_1}^{LO}|^2$$

$$\mathcal{A}_{\tilde{t}_1}^{LO} = \left[2 + \frac{m_Z^2}{m_t^2}\left(1 - \frac{4}{3}s_W^2\right)\cos 2\beta\right] \frac{m_t^2}{m_{\tilde{t}_1}^2} \left[\frac{1}{8} + \frac{m_h^2}{m_{\tilde{t}_1}^2} + \ldots\right]$$

$\to$ Enhancement of $\sigma(gg \to h)$.
$\to$ Suppression with $1/m_{\tilde{t}_1}^2$.

▷Contribution to $h \to \gamma\gamma$:
$\to$ Negative interference with W loop.
$\to$ Suppression with $1/m_{\tilde{t}_1}^2$.

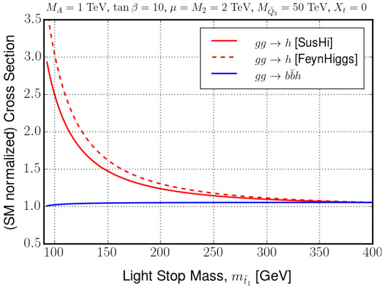
Further effects on $\Gamma(h \to \gamma\gamma)$:
$\tilde{\tau}_1$: Enhancement (for large $\tan\beta$)
$\tilde{\chi}_1^{\pm}$: Enhancement (for low $\tan\beta$)

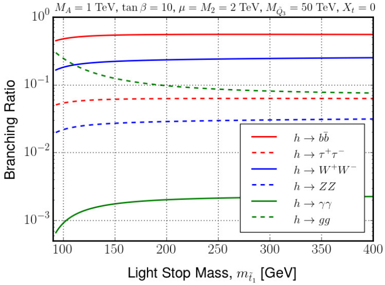


[Cohen Morrissey Pierce '12]

Setup for our analysis: To calculate precise cross section and branching ratios to be compared with experimental data, we use

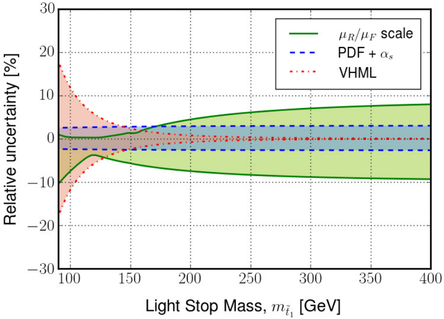
- ✓ `FeynHiggs 2.11.0` [Frank Hahn Heinemeyer Hollik Rzehak Weiglein]:
  Calculation of m_h (w resummation), VBF, VH (w/o stops) and BR's of h
  NLO QCD corrections to top and stop contribution in $h \to \gamma\gamma/gg$
- ✓ `SusHi 1.4.1` [Harlander Liebler Mantler]: Calculation of $gg \to h$
  Electroweak and NLO QCD corrections to top, bottom and stop contribution (stops in the EFT of light Higgs – VHML)
  NNLO QCD corrections to top and stop (both in the EFT of light Higgs – VHML, approximation for stop)





Careful treatment of theoretical uncertainties for $gg \to h$:

- ✓ PDF+α_s uncertainties as provided by LHC Higgs Cross Section Working Group (LHCHXSWG) $^{+7.5\%}_{-6.9\%}$ for $m_h \sim 125\,$GeV.
- ✓ Nine-point variation of renormalization and factorization scales μ_R and μ_F around central scales $\mu_\mathrm{R} = \mu_\mathrm{F} = m_h/2$.
- ✓ Two-loop and approximate three-loop stop contributions are based on light Higgs mass $4m^2_{\tilde{t}_1}/m^2_h \gg 1$. Uncertainty from multiplication of difference from expanded LO amplitude to exact LO amplitude to higher orders. Also applied to $\Gamma(h \to gg)$!



Subdominant effects:

- ✓ Uncertainty due to approximation of NNLO stop contributions, $\pm 1\%$.
- ✓ Left: Logarithmic dependence on heavy stop and gluino mass.

Outline

We discussed **four scenarios** (inspired by the CP violating frameworks), for which we compared XS's and BR's in scans over a vast of SUSY parameters to experimental data (85 **channels** from Tevatron and Run I of LHC).
χ^2 compatibility checked with
`HiggsSignals 1.4.0` [Bechtle Heinemeyer Stål Stefaniak Weiglein]:
$\chi^2 - \chi^2_{\text{BF}} \leq 2.30$: 68% C.L. region, $\chi^2 - \chi^2_{\text{BF}} \leq 5.99$: 95% C.L. region

- We allow for decays to new physics BR($h \to$ NP) from 0% to 50% in steps of 0.5% $\leftrightarrow$ This lowers all branching ratios.
  Note: BR($h \to$ inv.)$\leq 28/36\%$ from ATLAS/CMS Run I
- Scan point has to provide Higgs mass within $124\,\text{GeV} \leq m_h \leq 126\,\text{GeV}$. M_{SUSY} is chosen to be 50 and $300\,$TeV to fit the light Higgs mass!

$$M_{\tilde{L}_j} = M_{\tilde{E}_j} = M_{\tilde{U}_j} = M_{\tilde{D}_j} = M_{\tilde{Q}_j} = M_{\text{SUSY}} \quad j = 1, 2$$
$$\{M_{\tilde{D}_3}, M_{\tilde{Q}_3}, M_3\} \in [0.8, 1.5] M_{\text{SUSY}}$$

  M_{SUSY} only fixes the Higgs mass, collider pheno hardly depends on it!
- Described uncertainties are included in two covariance matrices for production and decay modes.

Scenario **A**: Decoupling Limit with light stop

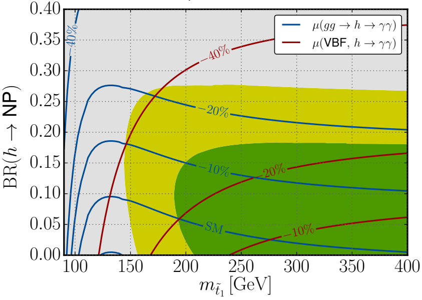
$M_A = 1$ TeV, $\mu = M_2 = 1$ TeV, $\tan\beta = 10$, $A_t = A_b = A_\tau = 100$ GeV ($X_t = 0$)

Scan: $M_{\tilde{U}_3} \in [-150, 500]$ GeV, BR($h \to$NP)

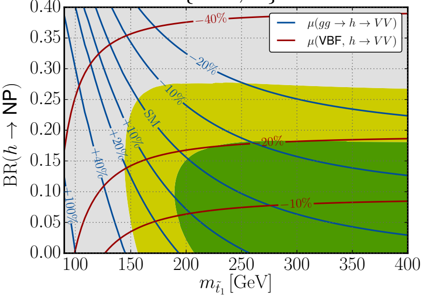
$$\mu = \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}}$$

BF:($m_{\tilde{t}_1}$, BR($h \to$ NP)) = (527GeV, 3.0%)

68% C.L., 95% C.L.



$V \in \{W^\pm, Z\}$



Bound on the light stop: $m_{\tilde{t}_1} \geq 144$ GeV

Scenario **B**: Decoupling Limit with light stop and a light stau

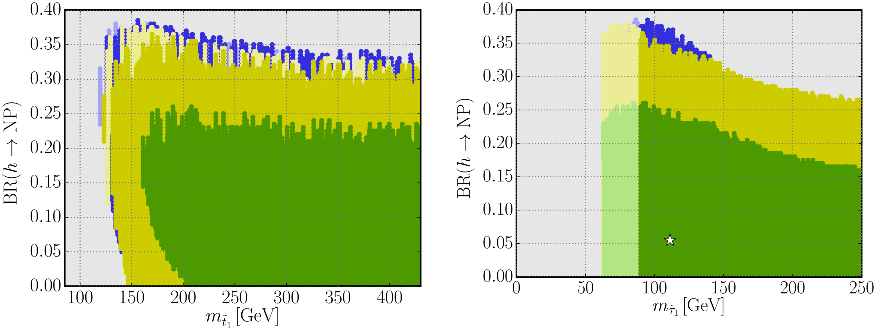
$M_A = 1$ TeV, $\mu = M_2 = 1$ TeV, $X_t = X_b = 0$, $A_\tau = 1$ TeV

Scan:

$M_{\tilde{U}_3} \in [-150, 500]$ GeV, $M_{\tilde{L}_3} = M_{\tilde{E}_3} \in [70, 300]$ GeV, $\tan\beta \in [5, 60]$, BR($h \to$NP)

BF:$(m_{\tilde{t}_1}, m_{\tilde{\tau}_1}, \text{BR}(h \to \text{NP})) = (526\text{GeV}, 111\text{GeV}, 5.5\%)$

68% C.L., 95% C.L., charge-breaking minima, pale: $m_{\tilde{\tau}_1} \leq 90$ GeV (✗LEP)



Bound on the light stop: $m_{\tilde{t}_1} \geq 123$ GeV ($\tilde{\tau}_1$ enhances $h \to \gamma\gamma$)

Scenario **C**: Decoupling Limit with light stop and a light chargino

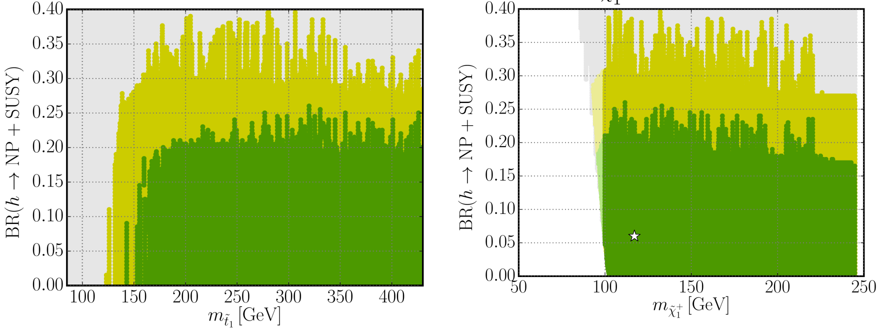
$M_A = 1$ TeV, $M_1 = 1$ TeV, $X_t = 0$

Scan:

$M_{\tilde{U}_3} \in [-150, 500]$ GeV, $\mu = M_2 \in [50, 300]$ GeV, $\tan\beta \in [1, 20]$, BR($h \to$NP)

BF:$(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, \text{BR}(h \to \text{NP})) = (523\text{GeV}, 117\text{GeV}, 6.0\%)$

68% C.L., 95% C.L., charge-breaking minima, pale: $m_{\tilde{\chi}_1^\pm} \leq 103.5$ GeV (✗LEP)



Bound on the light stop: $m_{\tilde{t}_1} \geq 123$ GeV (BR($h \to$SUSY)$\leq 30\%$)

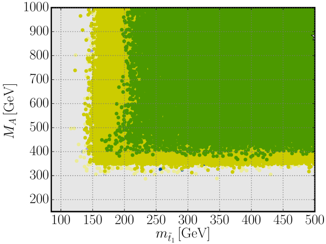
Scenario **D**: Non-decoupling effects

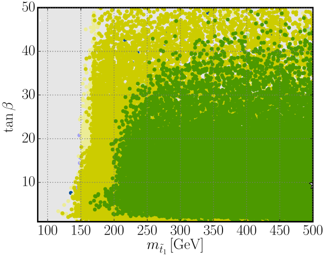
$M_1 = M_2 = 1$ TeV, $X_t = 0$

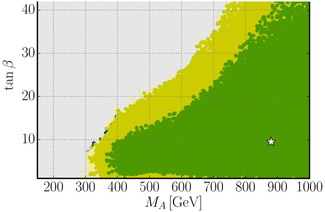
Scan: $M_{\tilde{U}_3} \in [-150, 500]$ GeV, $M_{\tilde{L}_3} = M_{\tilde{E}_3} \in [70, 300]$ GeV, $\tan\beta \in [1, 50]$, $M_A \in [150, 1000]$ GeV, $\mu \in [-5, 5]$ TeV, $H, A, H^\pm$ bounds from HiggsBounds

BF:$(m_{\tilde{t}_1}, m_{\tilde{\tau}_1}, M_A, \mu, \tan\beta) =$
$(501\text{GeV}, 145\text{GeV}, 880\text{GeV}, 3.5\text{TeV}, 9.5)$

68% C.L., 95% C.L.







Bound on the light stop:

$m_{\tilde{t}_1} \geq 122$ GeV

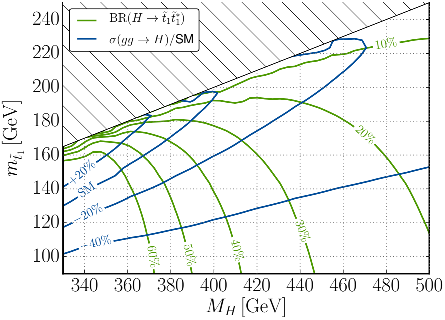
($\tilde{\tau}_1$ effects, non-decoupled Y_b)

Summary of lower $\mathbf{95}\%$ C.L. stop mass limit from Higgs rate measurements:

Stop mass limit	(i) BR(h →NP) free		(ii) BR(h →NP)$\equiv 0$	
Scenario: Scan over $M_{\tilde{U}_3}$ and	all constraints	no constraints	all constraints	no constraints
A:	144 GeV	N/A	154 GeV	N/A
B: $t_\beta, M_{\tilde{L}_3}, M_{\tilde{E}_3}$	123 GeV	119 GeV	146 GeV	146 GeV
C: t_β, μ, M_2	123 GeV	123 GeV	123 GeV	123 GeV
D: $t_\beta, M_A, \mu, M_{\tilde{L}_3}, M_{\tilde{E}_3}$	N/A	N/A	122 GeV	116 GeV

Fit quality for BF points:
χ^2/ndf $\sim 67 - 69/81 - 83$
SM $\sim 68.3/85$

An interesting search topology in MSSM EWBG is $H \to \tilde{t}_1\tilde{t}_1$:
Benchmark scenario in our paper



Outline

Conclusions:

First-order phase transition: $m_{\tilde{t}_1} \lesssim 155\,$GeV

Higgs rate measurements: $m_{\tilde{t}_1} \gtrsim 116\,$GeV

$\rightarrow$ MSSM EWBG is still alive (from Higgs rate measurements)!

With higher statistical precision in the Higgs rates (assuming they agree with SM prediction), the bounds at the end of Run II will likely rule out the remaining space. Search for light stops can also focus on heavy Higgs decays into $\tilde{t}_1\tilde{t}_1$.

Check [1512.09172] for many more plots showing correlations between various SUSY parameters.

Thank you for your attention.

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First-order phase transition: $m_{\tilde{t}_1} \lesssim 155\,\text{GeV}$

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χ^2 dependence with and without VHML uncertainty for scenario **A**: