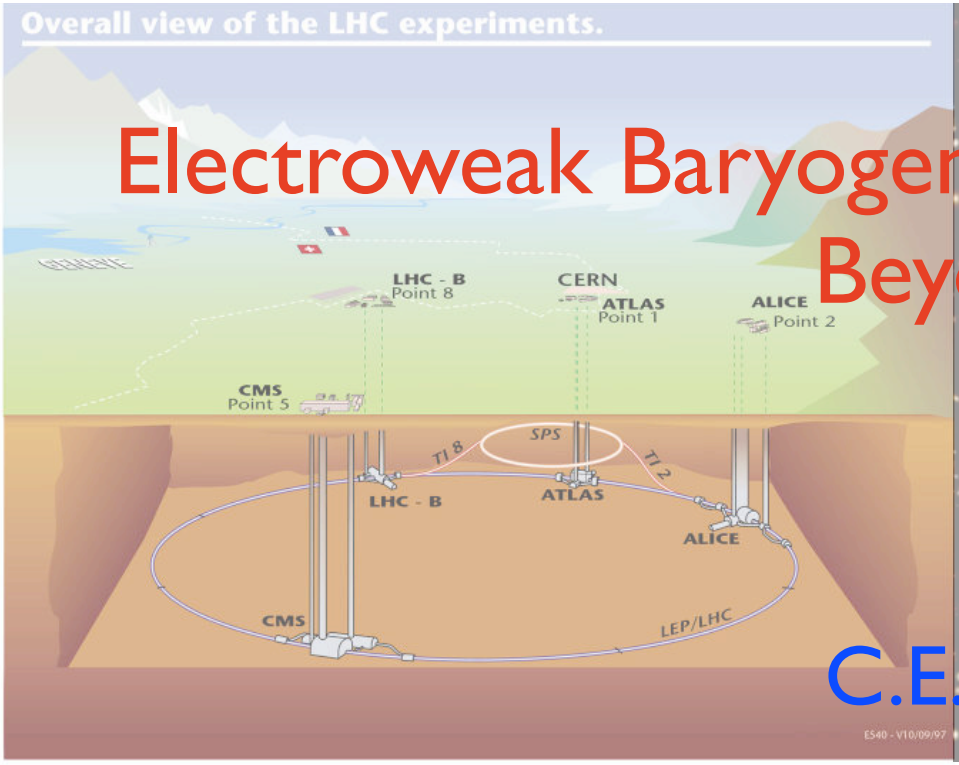
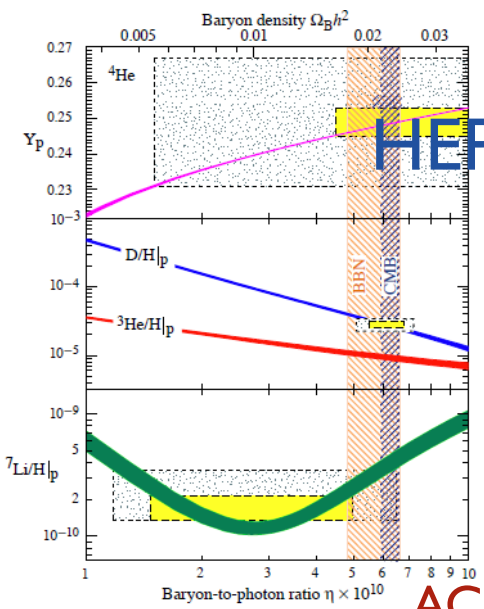
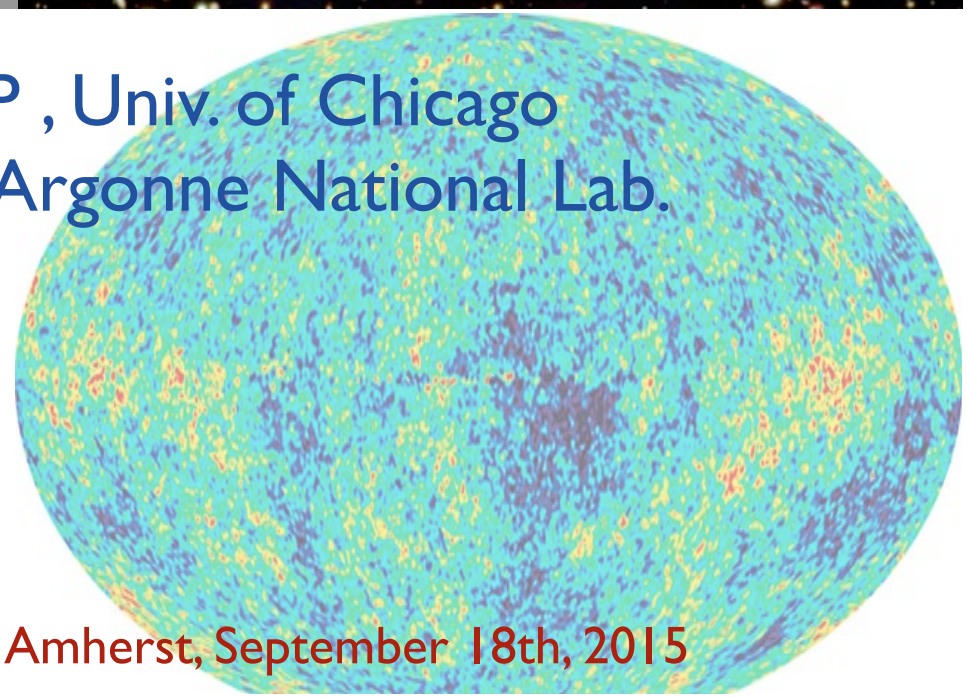


Electroweak Baryogenesis in the MSSM and Beyond

C.E.M. Wagner

EFI & KICP , Univ. of Chicago
HEP Division, Argonne National Lab.





ACFI Workshop , Amherst, September 18th, 2015

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is composed of matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

$$\frac{n_{\bar{P}}}{n_P} \approx 10^{-4}$$

Conditions for Baryogenesis

- Under natural assumptions, there are three conditions, enunciated by Sakharov, that need to be fulfilled for baryogenesis. The SM fulfills them :
- Baryon number violation: Anomalous Processes
- C and CP violation: Quark CKM mixing
- Non-equilibrium: Possible at the electroweak phase transition.

Baryon Number Violation at finite T

- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

$$S_{inst} = \frac{2\pi}{\alpha_W} \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst}\, 2)$$

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

$T<T_{EW}$ $$\frac{\Gamma_{B+L}}{V} = k\frac{M_W^7}{(\alpha T)^3} e^{-\beta E_{ph}(T)} \sim e^{\frac{-4M_W}{\alpha k T}}$$

$T>T_{EW}$ $$\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1} T^4$$

Klinkhamer and Manton ’85, Arnold and Mc Lerran ’88

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\mathrm{GeV})} \exp\left(-\frac{E_{sph}(T_c)}{T_c} \right) \right)$$

Kuzmin, Rubakov and Shaposhnikov, '85—'87

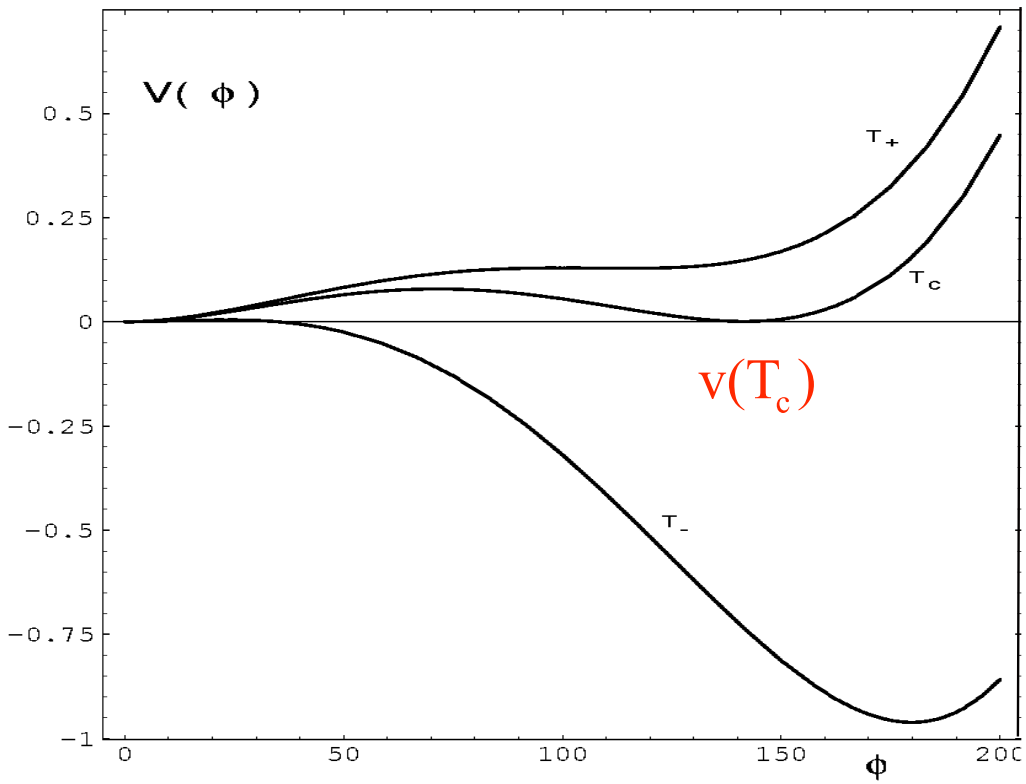
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase. $E_{sph} \propto \frac{8\pi\, v}{g}$

Therefore, to preserve the baryon asymmetry, a strongly first order phase transition is necessary:

$$\frac{v(T_c)}{T_c} > 1$$

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order Phase Transition



Finite Temperature Higgs Potential in the SM

$$V(T) \quad = \quad D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

E receives contributions proportional to the sum of the cube of all light boson particle couplings

$$\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda} \quad , \quad \text{with} \quad \lambda \propto \frac{m_H^2}{v^2}$$

Since in the SM the only bosons are the gauge bosons, and the quartic coupling is proportional to the square of the Higgs mass,

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H \quad < 40 \text{ GeV}.$$

CP-Violation sources

- Another problem for the realization of the SM electroweak baryogenesis scenario:

- Absence of sufficiently strong CP-violating sources

- Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitues lower than required

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}}\frac{\alpha_W T}{32\sqrt{\alpha_s}}\right]^3 J\,\frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\,\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

$$J \equiv \pm Im[K_{li}K_{lj}^*K_{l'j}K_{l'i}^*] = c_1c_2c_3s_1^2s_2s_3s_\delta$$

γ : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94

Preservation of the Baryon Asymmetry

- EW Baryogenesis would be possible in the presence of new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario. Huet, Nelson '91; Giudice '91, Espinosa, Quiros,Zwirner '93.

- Relevant SUSY particle: Superpartner of the top

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\, E_{SM}$$

M. Carena, M. Quiros, C.W. '96, '98

- Since $\frac{v(T_c)}{T_c} \approx \frac{E}{\lambda}$, with $\lambda \propto \frac{m_H^2}{v^2}$

Higgs masses up to 120 GeV may be accomodated

Comments

- Stop particles have explicit soft mass terms and acquire temperature dependent masses at high T
- The effective coupling is reduced due to the presence of mixing. For left-handed stops much heavier than the right handed ones $(m_Q \gg m_U)$

$$m_{\tilde{t}_1}^2 \simeq m_U^2 + \frac{4g_3^2}{9}T^2 + .. + h_t^2\phi^2\left(1 - \frac{A_t^2}{m_Q^2}\right)$$

- This is the object entering in the cubic term
- In order to strengthen the phase transision the mixing must be small and the right-handed stop mass parameter must be negative. One stop is lighter than the top !
- But mixing and stop masses controls the Higgs mass !

Comments II

- No mixing and a light stop imply that the heaviest stop must be far away from the LHC reach.
- One loop effective potential leads to a weak first order phase transition for the observed Higgs masses. Two loop effects are important, and bring a dependence on the strong gauge coupling

$$V_2(\phi, T) \simeq \frac{\phi^2 T^2}{32\pi^2}\left[\frac{51}{16}g^2 - 3\left[h_t^2 \sin\beta^2\left(1 - \frac{\widetilde{A}_t^2}{m_Q^2}\right)\right]^2 + 8g_s^2 h_t^2 \sin^2\beta\left(1 - \frac{\widetilde{A}_t^2}{m_Q^2}\right)\right]\log\left(\frac{\Lambda_H}{\phi}\right)$$

- Negative stop masses also bring potential color breaking problems

Right-handed Stop Potential

A negative stop mass can induce color breaking minima

$$V_0(U) + V_1(U,T) = \left(-\widetilde{m}_U^2 + \gamma_U T^2\right) U^2 - T E_U U^3 + \frac{\lambda_U}{2} U^4,$$

where

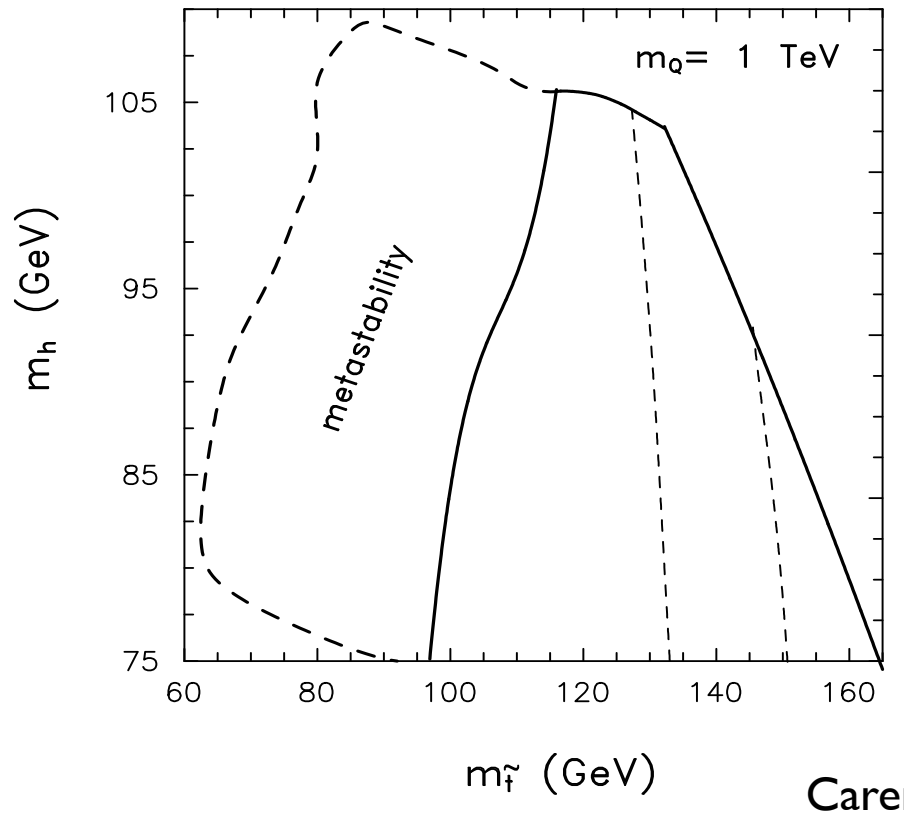
$$\begin{aligned}
\gamma_U &\equiv \frac{\Pi_{\widetilde{t}_R}(T)}{T^2} \simeq \frac{4g_s^2}{9} + \frac{h_t^2}{6}\left[1 + \sin^2\beta(1 - \widetilde{A}_t^2/m_Q^2)\right]; \quad \lambda_U \simeq \frac{g_s^2}{3} \\
E_U &\simeq \left[\frac{\sqrt{2}g_s^2}{6\pi}\left(1 + \frac{2}{3\sqrt{3}}\right)\right]^{3/2} \\
&+ \left\{\frac{g_s^3}{12\pi}\left(\frac{5}{3\sqrt{3}} + 1\right) + \frac{h_t^3 \sin^3\beta(1 - \widetilde{A}_t^2/m_Q^2)^{3/2}}{3\pi}\right\}.
\end{aligned}$$

$$V_2(U,T) = \frac{U^2T^2}{16\pi^2}\left[\frac{100}{9}g_s^4 - 2h_t^2\sin^2\beta\left(1 - \frac{\widetilde{A}_t^2}{m_Q^2}\right)\right]\log\left(\frac{\Lambda_U}{U}\right)$$

Wagner, Carena, Quiros'96 &'98

Contribution of longitudinal gluons ignored

The upper bound on the Higgs comes from the impossibility of obtaining larger Higgs masses for the chosen parameters



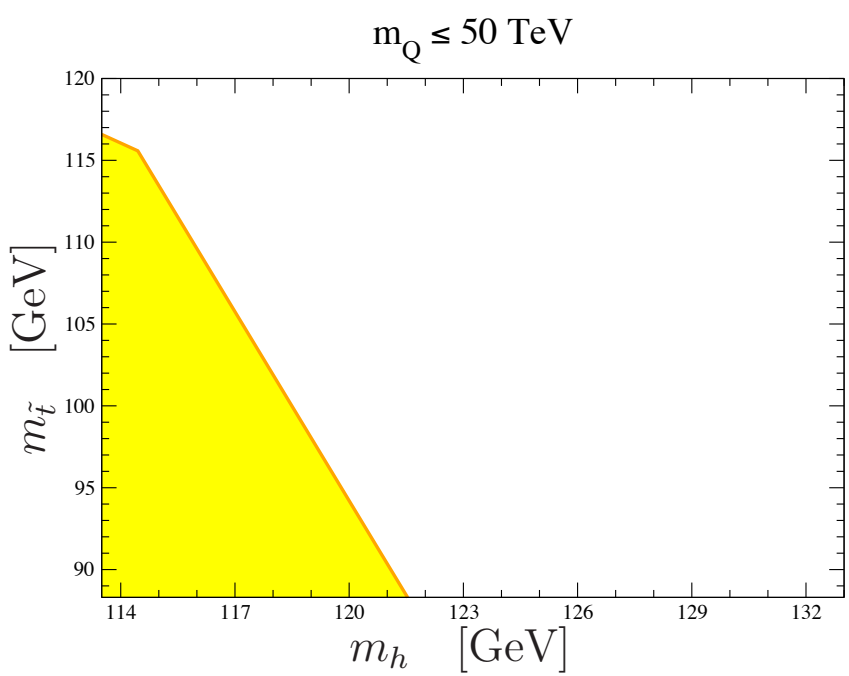
Carena, Quiros, C.W.'98

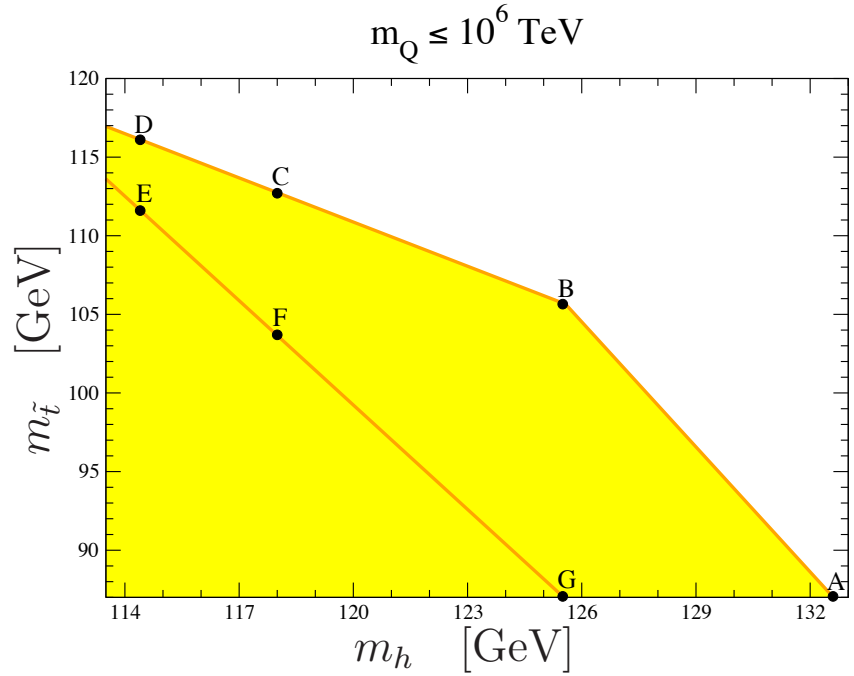
But phase transition can still be strong, if one includes the metastable regions.

For larger values of mQ, however, large logarithmic contributions must be resummed.

Final Results
(Meta)stability of Color Breaking Minima assumed

Point	A	B	C	D	E	F	G
$\lvert A_t/m_Q \rvert$	0.5	0	0	0	0.3	0.4	0.7
$\tan\beta$	15	15	2.0	1.5	1.0	1.0	1.0

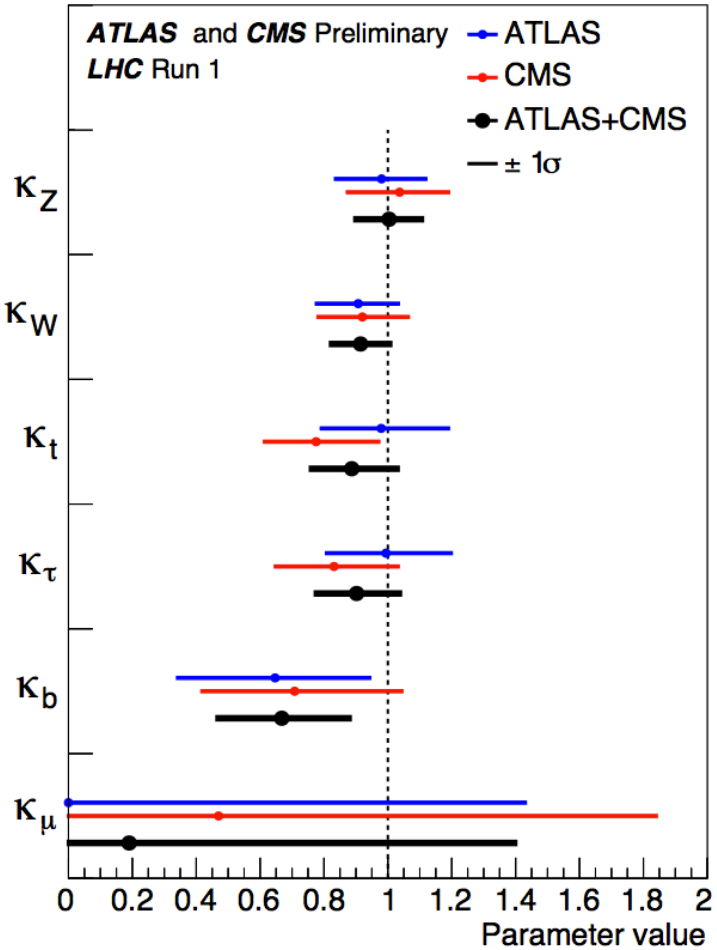


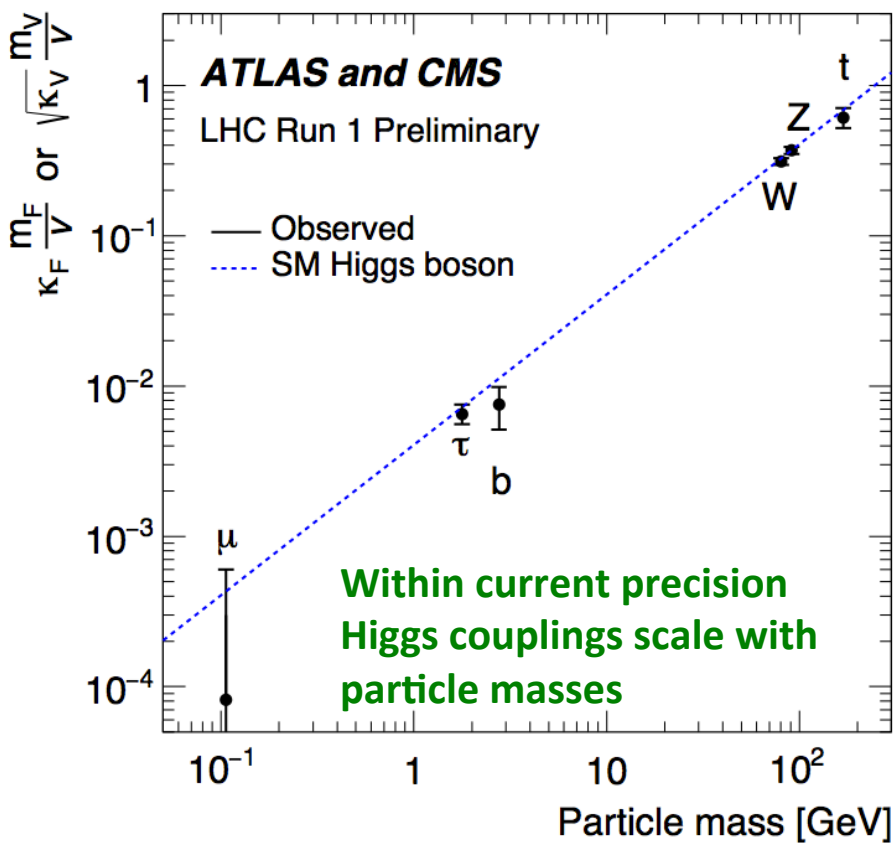


M. Carena, G. Nardini, M. Quiros, C.W.'13

LHC Higgs Physics

Combining all channels the LHC experiments found a best fit to the Higgs production rate consistent with that one of a SM Higgs of mass close to 125 GeV





Higgs Physics Constraints

Chung, Long, Wang'12

Light Stop Contribution to Higgs Loop Processes

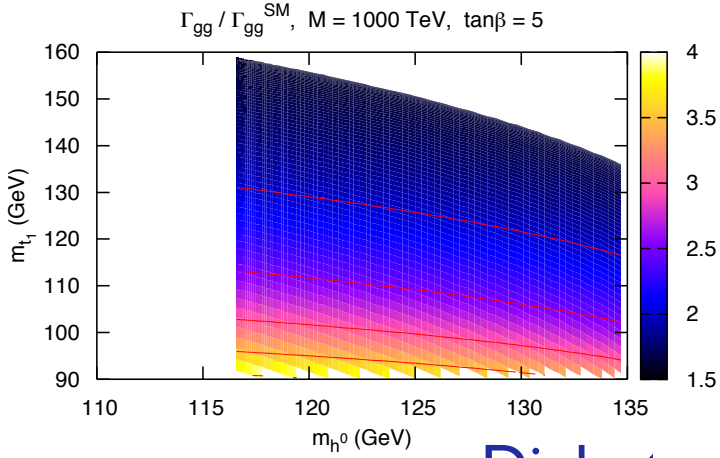
- In a normalization in which the stops contribute a factor 4 to the amplitude, the stops contribute like

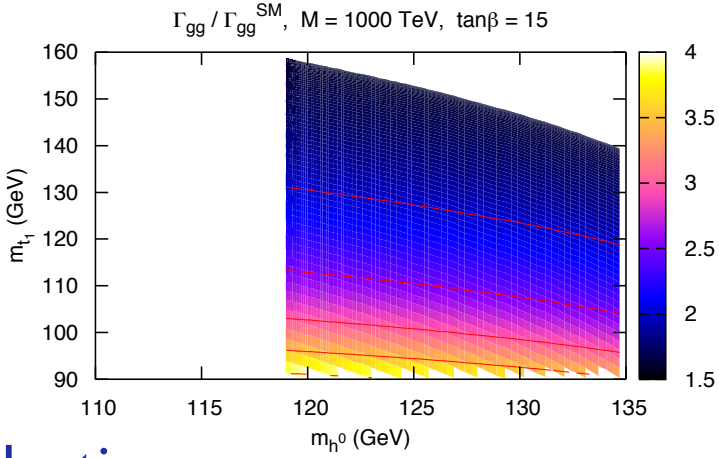
$$\delta A^{\tilde{t}}_{\gamma\gamma,gg} \propto \frac{m_t^2}{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}} \left(m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2} - X_t^2\right) .$$

- For the diphoton rate, the SM contribution to the amplitude would be approximately (-15) and governed by W contributions.
- In the limit of light stops we are considering, one can see the appearance of the light stop coupling we discuss before.
- This contribution grows for light stops and small mixing, and can cause important enhancement of the gluon fusion process rate.
- The diphoton decay branching ratio will be affected in a negative way.

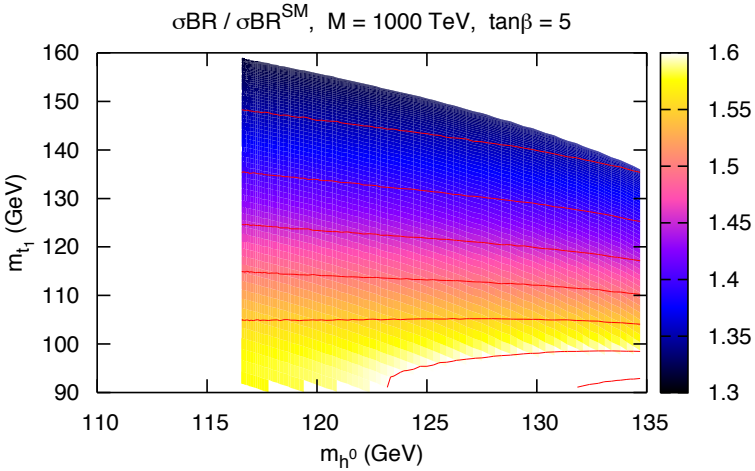
Higgs Signatures put a strong constraint on this scenario

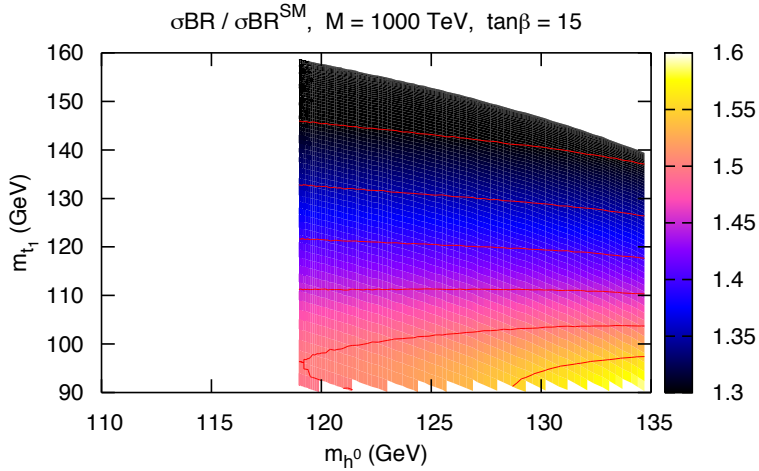
A. Menon and D. Morrisey'09





Diphoton Production



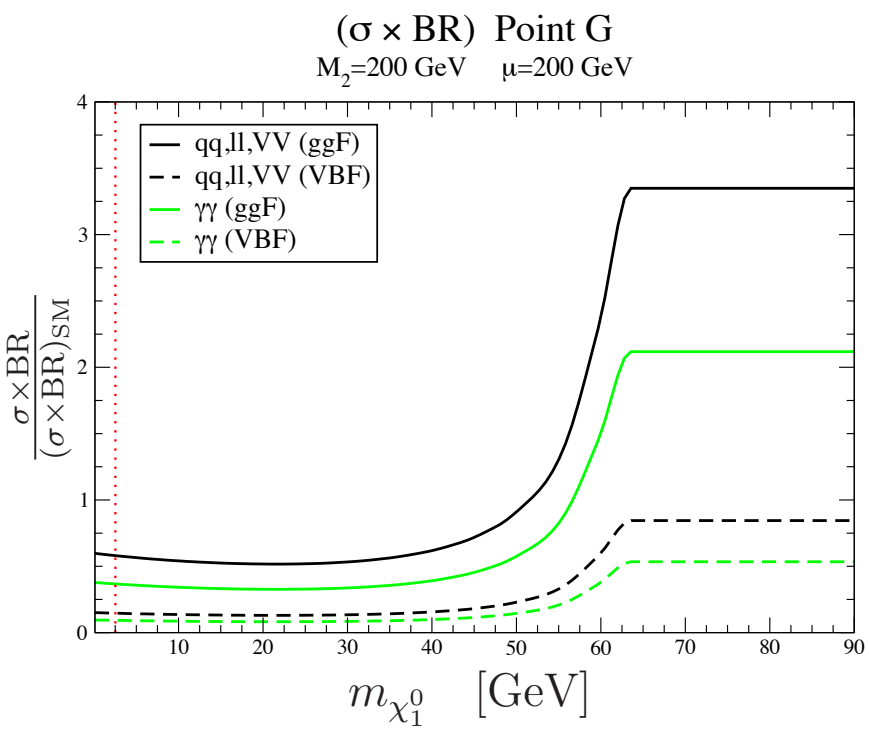


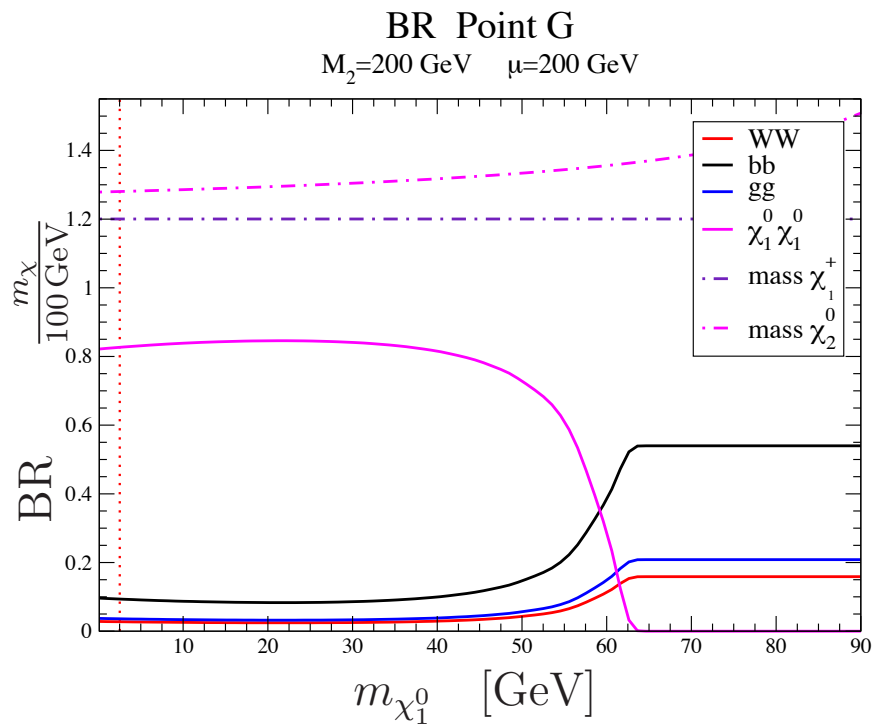
Similar results, by Cohen, Morrissey and Pierce'12 showed
Higgs physics testability of this model at the LHC
Moreover, other authors found these results to be inconsistent with LHC data

[Curtin, Jaiswal, Meade '12; Katz + Perelstein '14]

Alternative : Increase Higgs Invisible Width

M. Carena, G. Nardini, M.Quiros, C.W., **JHEP 1302 (2013) 001**



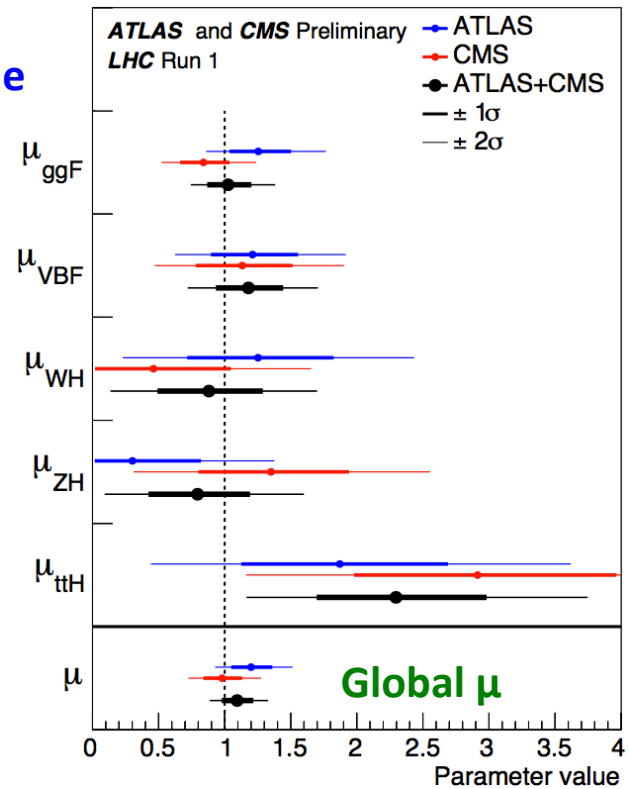


LHC Data put strong constraints on this possibility.
Only a narrow band, of neutralino masses close to threshold would be allowed in this case
The invisible width would be of order 50 percent and then, again, could be tested.
Weak Boson Fusion processes would be suppressed. This model is in agony.

No Evidence of VBF Suppression

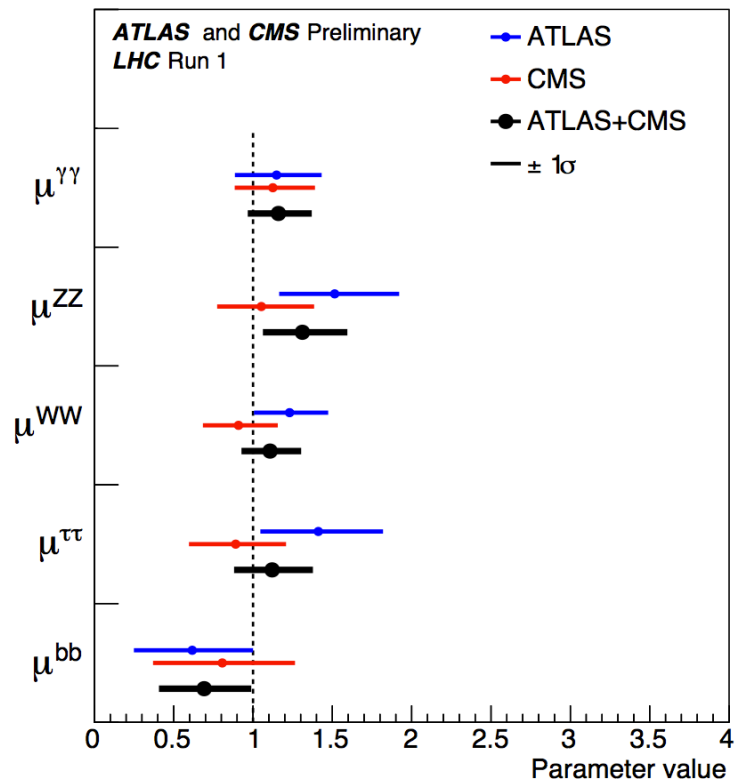
SM BRs assumed

SM p-value 25%



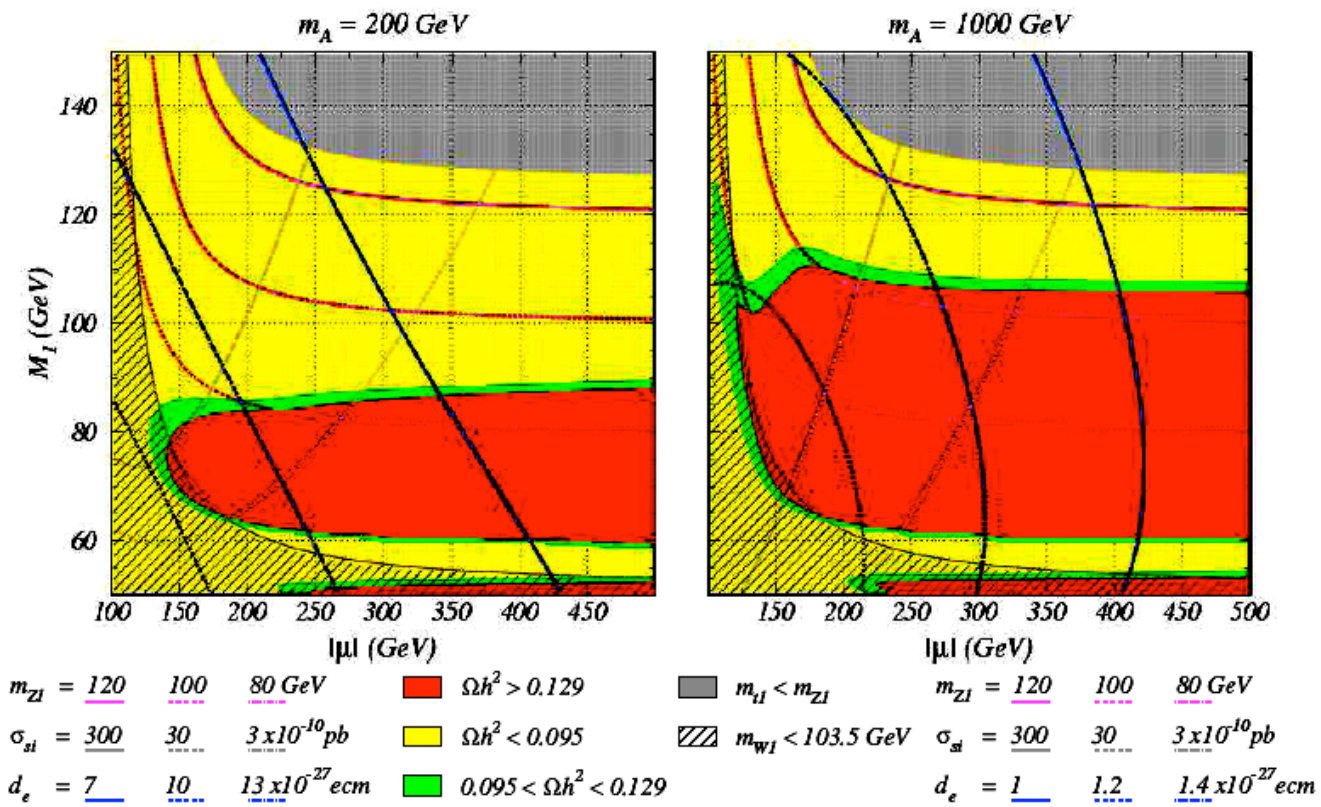
SM production σ assumed

SM p-value 60%



Light Stop and Relic Density Constraints

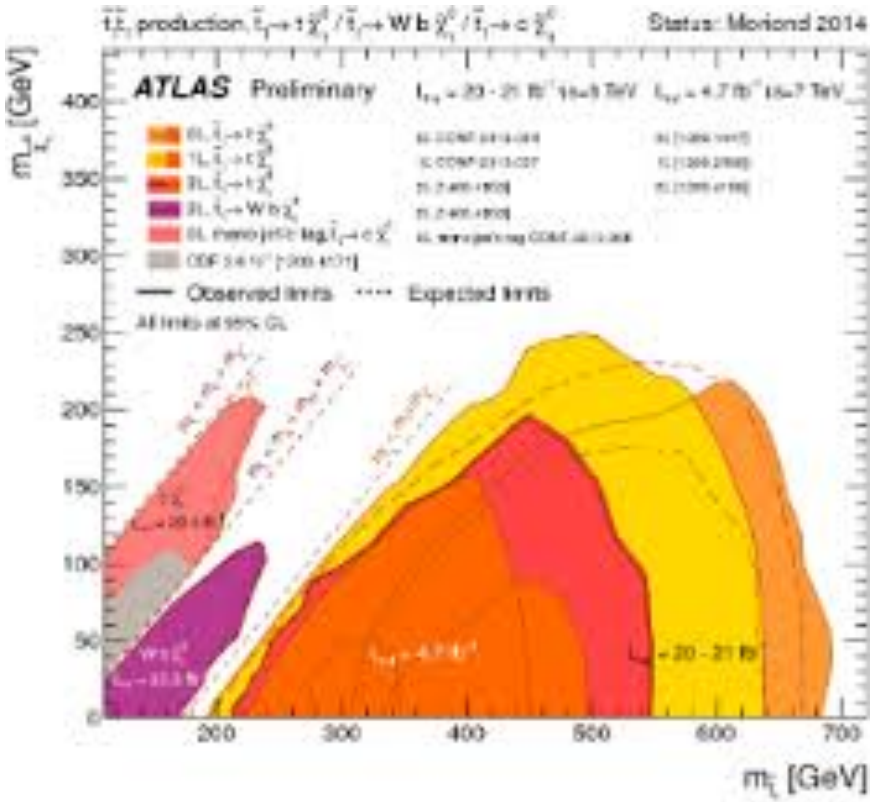
In the presence of a light stop, the most relevant annihilation channel is the coannihilation between the stop and the neutralino at small mass differences. Relic density may be naturally of the observed size in this region of parameters. Light Higgs resonant annihilation may be relevant (here Higgs mass is about 115 GeV)

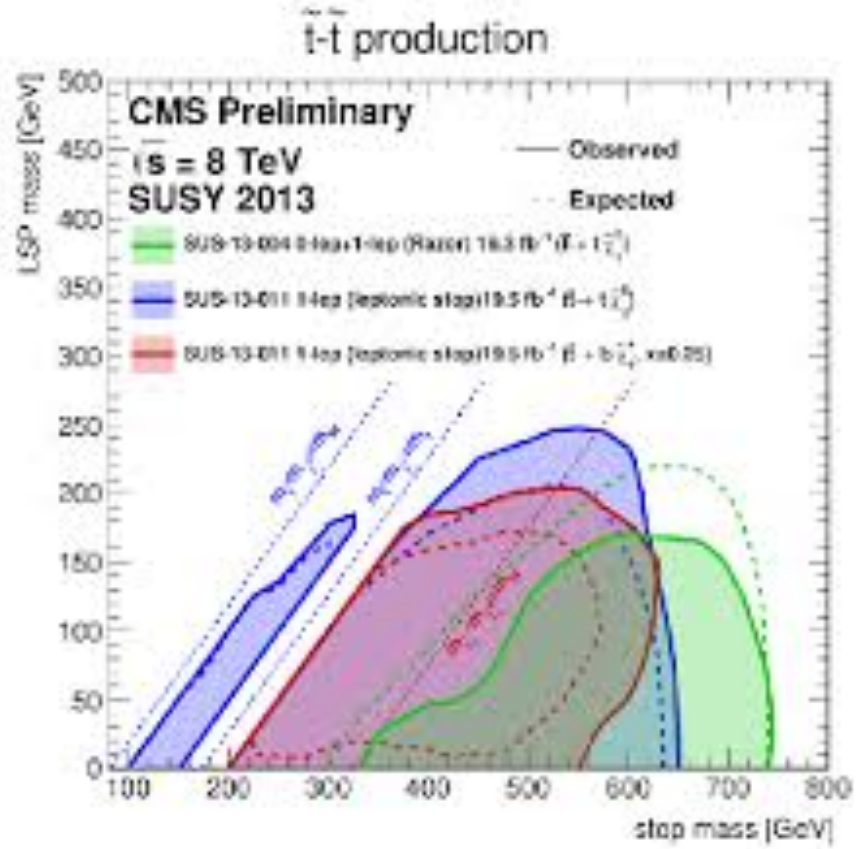


$\tan\beta = 7$

C. Balazs, M. Carena, A. Menon, D. Morrissey, C.W. 05
Cirigliano, Profumo, Ramsey-Musolf 07, Martin'06--'07

Stop Bounds



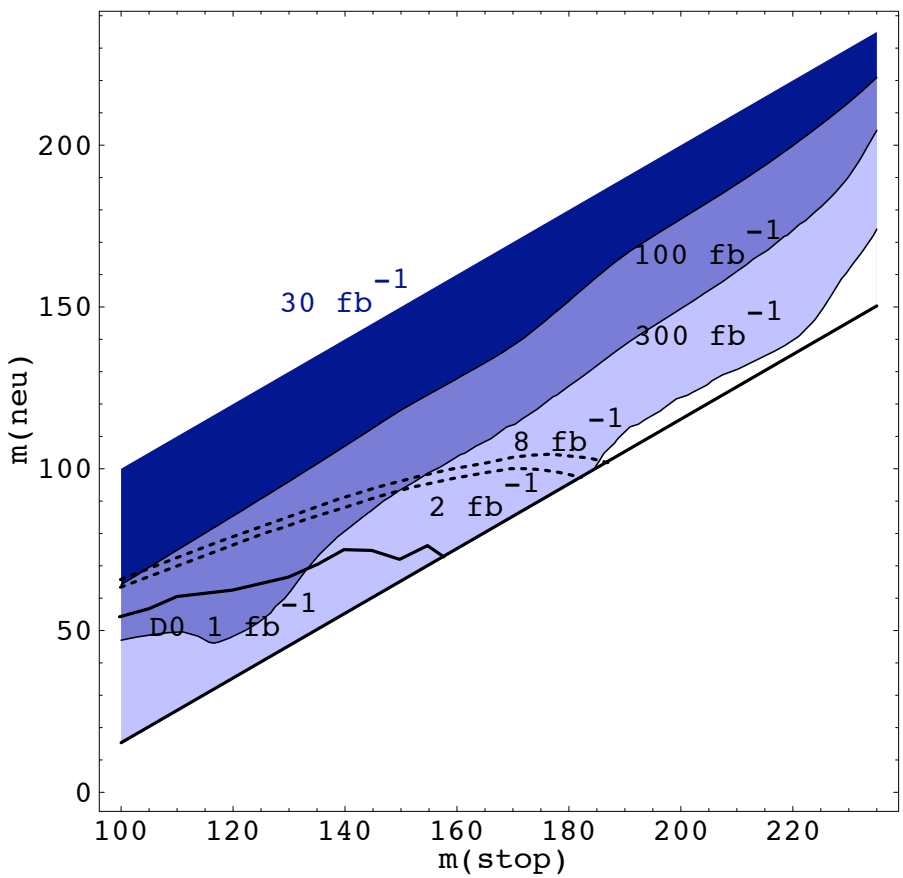


In the region of parameters of interest, they may be avoided when different decays become competitive or if there are, for instance, light staus or tau sneutrinos. Another challenge for this scenario.

Alternative Channel at the LHC

- When the stops and neutralino mass difference is small, the jets will be soft.
- One can look for the production of stops in association with jets or photons. Signature: Jets (or photons) plus missing energy

M. Carena, A. Freitas, C.W. '08



Excellent reach until masses of the order of 220 GeV and larger.

Full region consistent with EWBG will be probed by combining the LHC with the Tevatron searches.

Baryon Number Generation

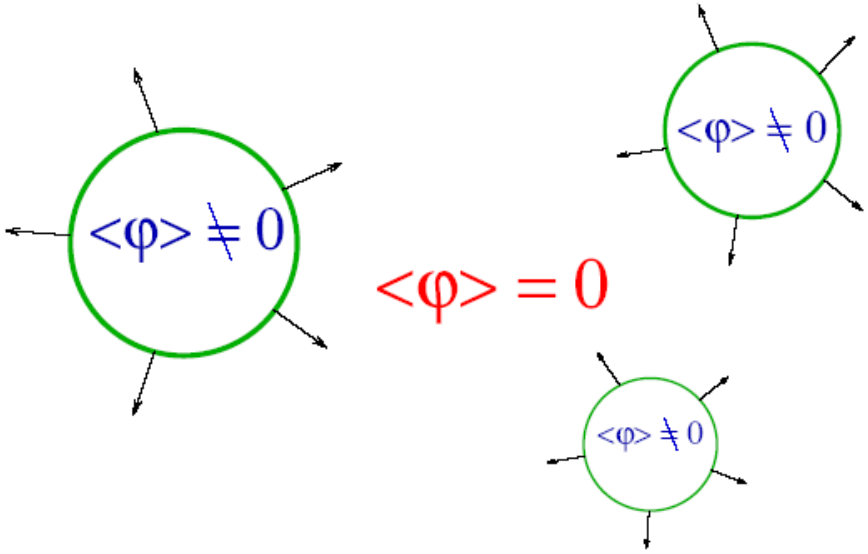
- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order.

Cohen, Kaplan and Nelson, hep-ph/9302210; A. Riotto, M. Trodden, hep-ph/9901362; Carena, Quiros, Riotto, Moreno, Vilja, Seco, C.W.'97--'03,

Konstantin, Huber, Schmidt,Prokopec'00--'06

Cirigliano, Profumo, Ramsey-Musolf'05--06

Baryon number is generated by reactions in and around the bubble walls.



The diffusion equations for the evaluation of the baryon density takes into account the interaction rates and sources

$$v_\omega n'_Q = D_q n''_Q - \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$-6\Gamma_{ss}\left[2\,\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\,\frac{n_Q + n_T}{k_B}\right] + \tilde{\gamma}_Q$$

$$v_\omega n'_T = D_q n''_T + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] + \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$+3\Gamma_{ss}\left[2\,\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\,\frac{n_Q + n_T}{k_B}\right] - \tilde{\gamma}_Q$$

$$v_\omega n'_H = D_h n''_H + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_h\,\frac{n_H}{k_H} + \tilde{\gamma}_{\tilde{H}_+}$$
$$v_\omega n'_h = D_h n''_h + \rho\,\Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h/\rho}{k_H}\right] - (\Gamma_h + 4\,\Gamma_\mu)\,\frac{n_h}{k_H} + \tilde{\gamma}_{\tilde{H}_-}$$

No Baryon number violation:
Chiral charges generated from CP-violating sources (gamma's)

Here the ki's are statistical factors relating the densities to chemical potentials and the Gammas are rates per unit volume. In particular,

$$\Gamma_{ws} = 6\,\kappa_{ws}\,\alpha_w^5 T, \quad \Gamma_{ss} = 6\,\kappa_{ss}\,\frac{8}{3}\,\alpha_s^4 T \qquad \Gamma_X = \frac{6\,\gamma_X}{T^3}$$

Once the chiral charge is obtained, we can compute the baryon number generation via sphaleron effects

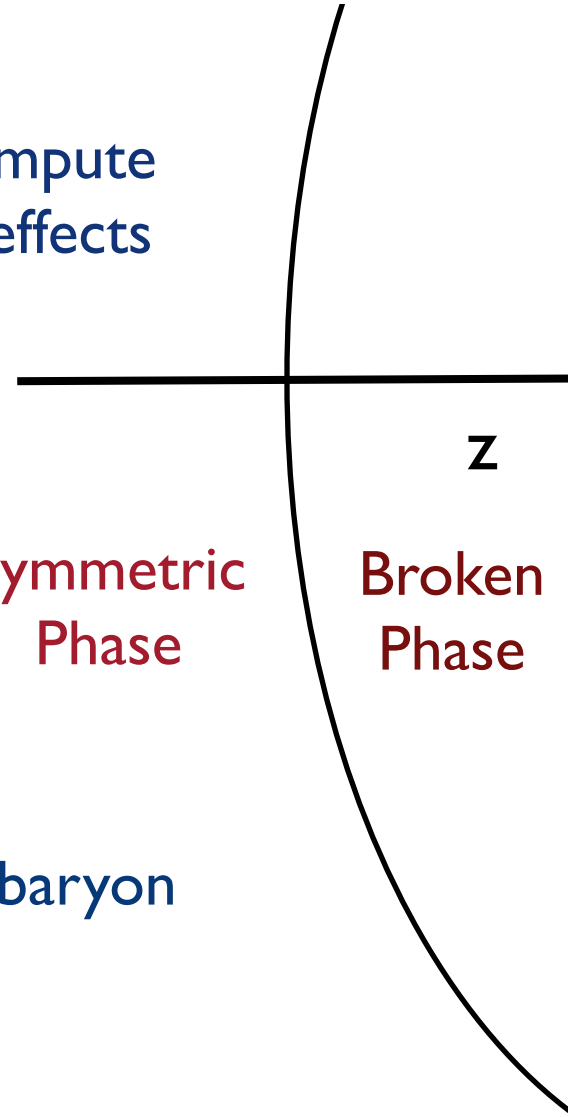
$$v_\omega n_B'(z) = -\theta(-z)\left[n_F \Gamma_{ws} n_L(z) + \mathcal{R} n_B(z)\right]$$

Here R is the relaxation coefficient

$$\mathcal{R} = \frac{5}{4} n_F \Gamma_{ws}$$

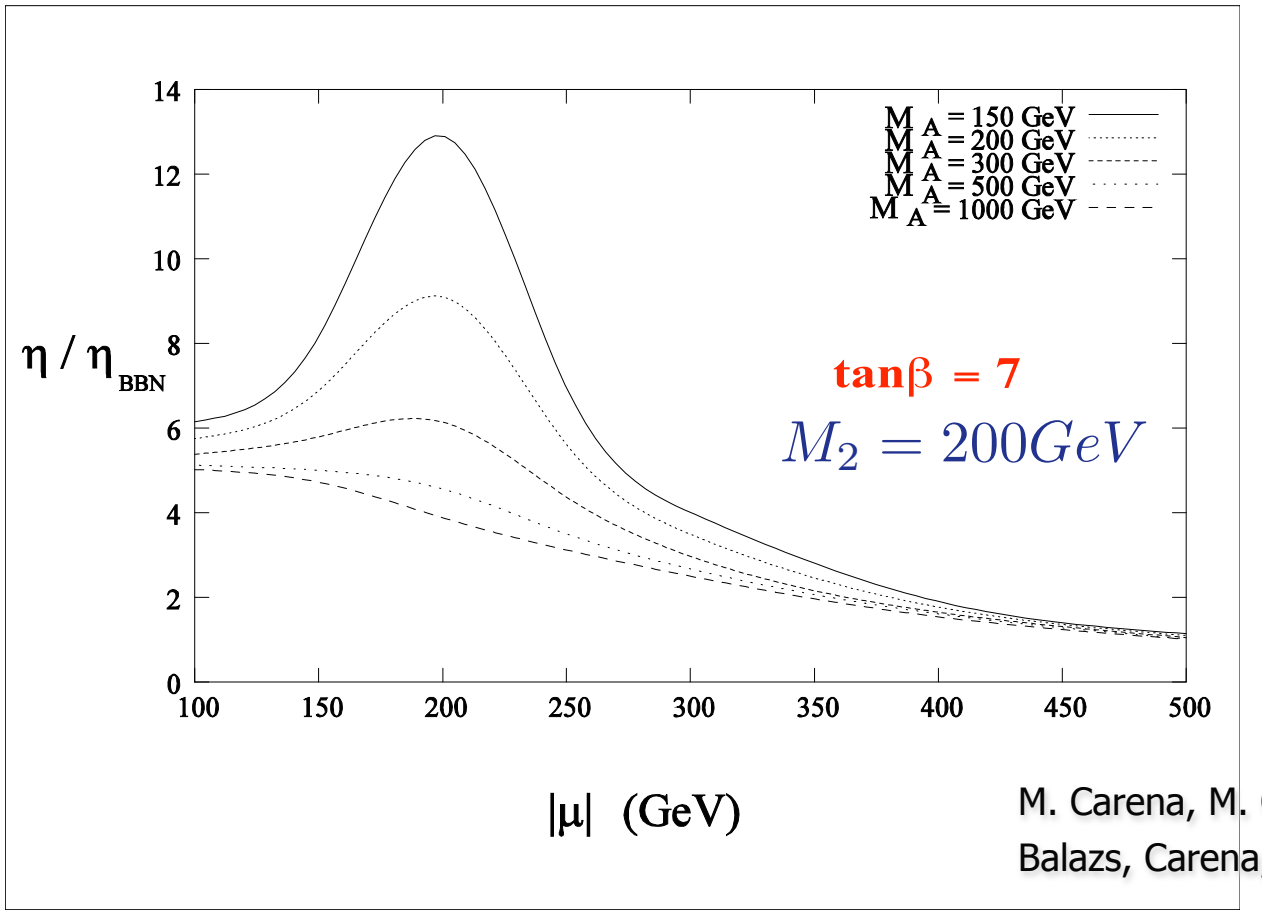
The solution to this equation gives the final baryon number density in the broken phase, namely

$$n_B = -\frac{n_F \Gamma_{ws}}{v_\omega} \int_{-\infty}^{0} dz\, n_L(z)\, e^{z\mathcal{R}/v_\omega}$$

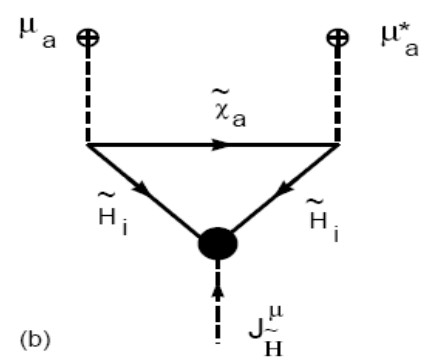


Generation of Baryon Asymmetry

- Here the Wino mass has been fixed to 200 GeV, while the phase of the parameter μ has been set to its maximal value. Necessary phase given by the inverse of the displayed ratio. Baryon asymmetry linearly decreases for large $\tan\beta$



Carena,Quiros,Seco,C.W.'02



M. Carena, M. Quiros, M. Seco, C.W. '02
Balazs, Carena, Menon, Morrissey, C.W.'05

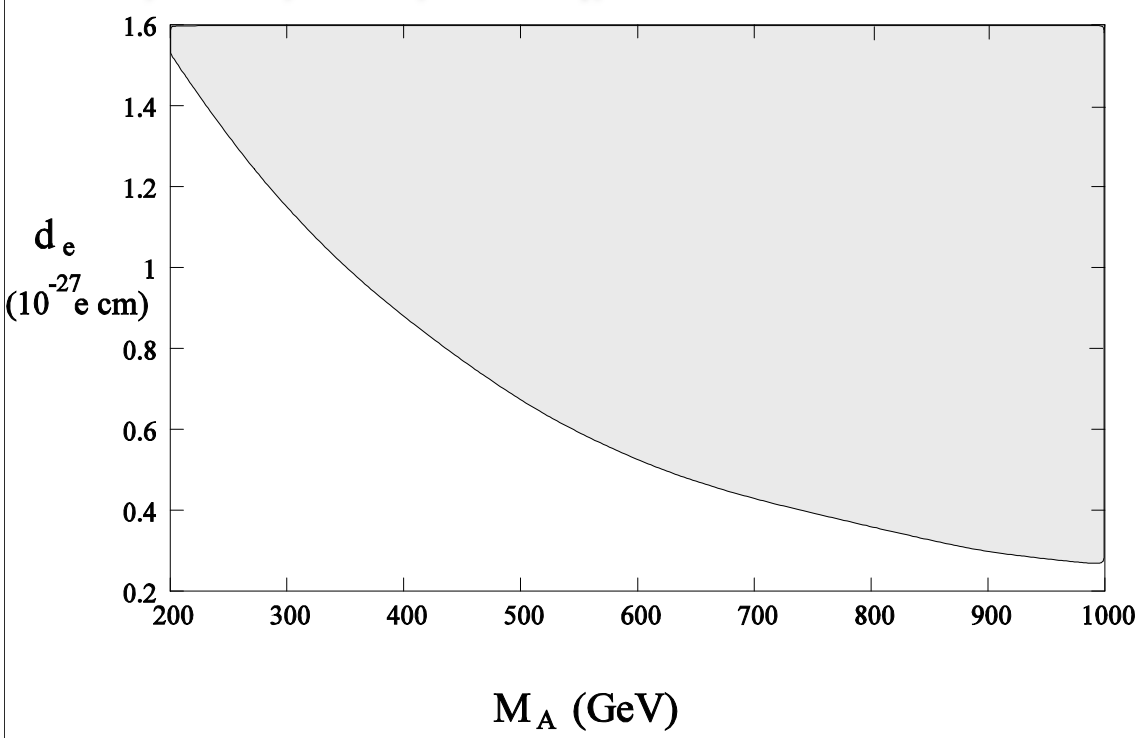
Electron electric dipole moment

- Asssuming that sfermions are sufficiently heavy, dominant contribution comes from two-loop effects, which depend on the same phases necessary to generate the baryon asymmetry.

- Chargino mass parameters scanned over their allowed values. The electric dipole moment is constrained to be smaller than

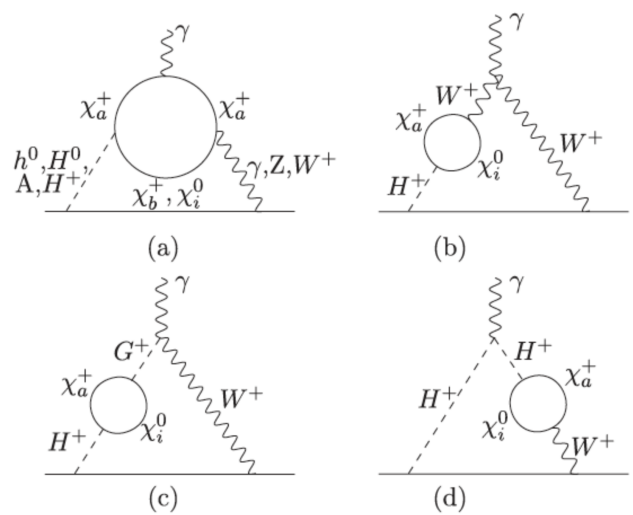
$$d_e < 8.7 \times 10^{-29}\ \mathrm{e\ cm}$$

Balazs, Carena, Menon, Morrissey, C.W.'05



- Two loop:

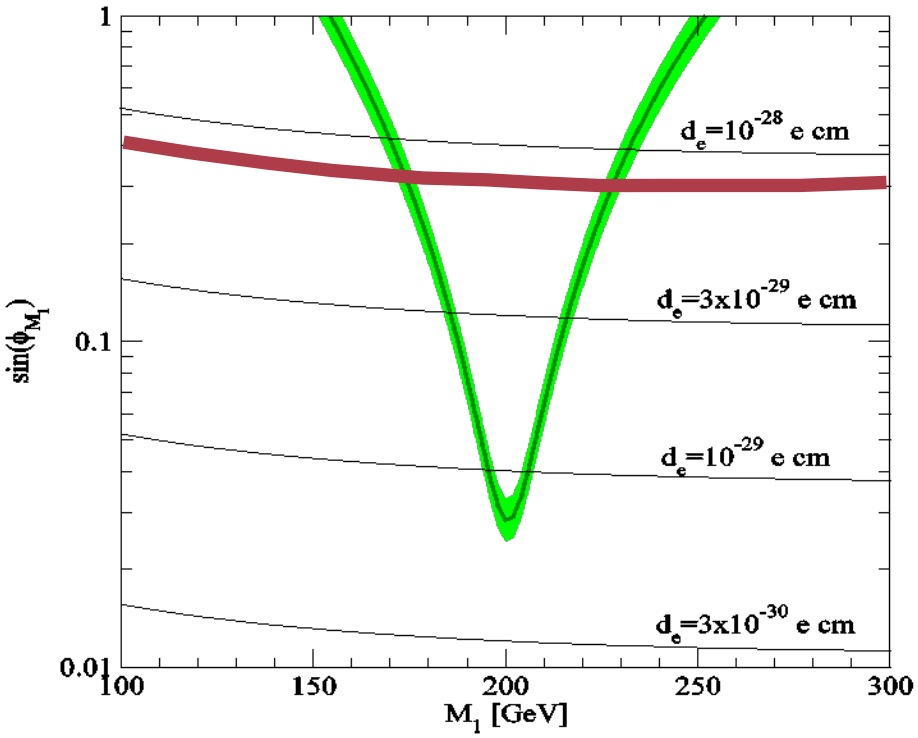
[Chang, Keung, Pilaftsis '98; ...]

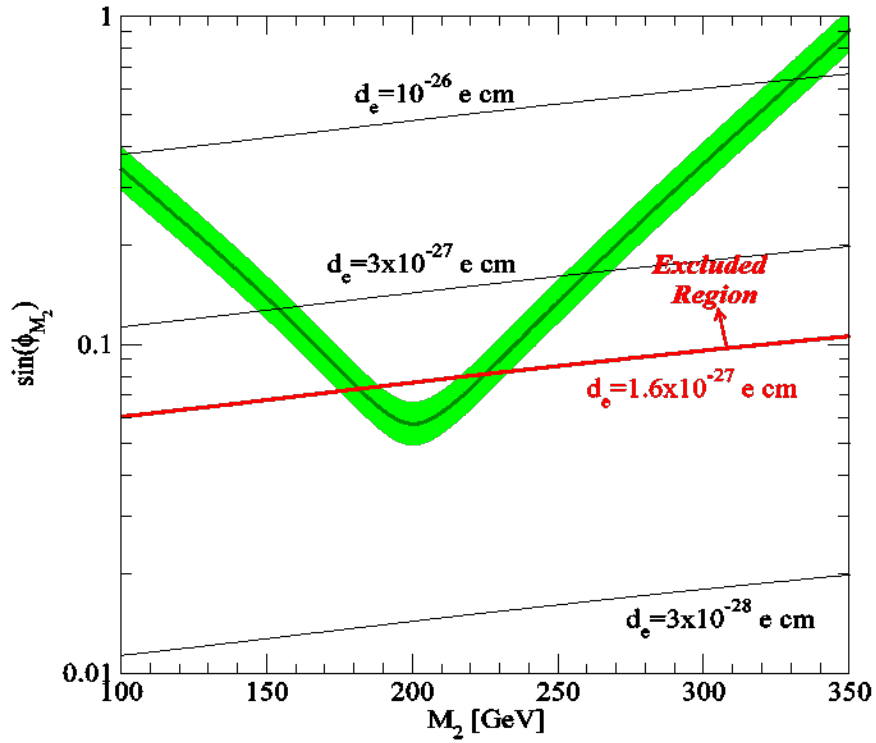


Chang, Chang, Keung '00, Pilaftsis '02

Comparing bino- and wino-driven EWB

- Electron EDM: $d_e < 8.7 \times 10^{-29}$ e cm





Ref. point: $M_1 = 95\text{GeV}, M_2 = 190\text{GeV}, |\mu| = 200\text{GeV}, \tan\beta = 10, m_{A^0} = 300\text{GeV}$

Cirigliano, Profumo, Ramsey-Musolf'06

YL, S. Profumo, M. Ramsey-Musolf, arXiv:0811.1987

Baryogenesis beyond the MSSM

[Pietroni '92; Davies *et al.* '96; Huber+Schmidt '00; Menon *et al.* '04; .

- {N}MSSM = MSSM + singlet (S):

$$W \supset \lambda S H_u \cdot H_d + \ldots$$

- Singlet VEV: $\mu_{eff} = \lambda \langle S \rangle$
- The singlet can induce a strongly first-order EWPT driven partly by tree-level effects with: [Carena, Shah, C.W.'12]

[Huang *et al.* '14; Kozaczuk *et al.* '14]

  - $m_h \simeq 125\,\mathrm{GeV}$.
  - Higgs rate corrections consistent with data.
  - Viable Bino-Singlino dark matter.
- Higgs rate corrections are still expected.

Instead of analyzing the potential of a specific model, one can try to analyze the generic potential with non-renormallizable operators

$$V_{\rm eff} = (-m^2 + AT^2)\phi^2 + \lambda\phi^4 + \gamma\phi^6 + \kappa\phi^8 + \eta\phi^{10} + \ldots$$

Perelstein, Grojean et al

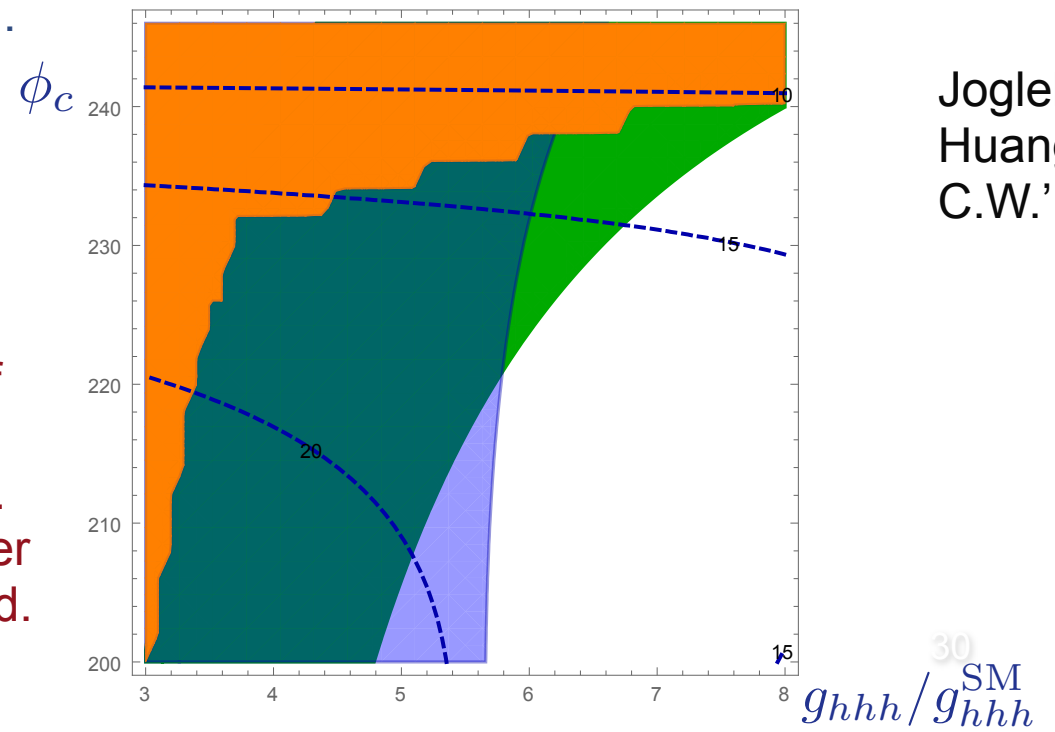
Here, $\gamma \propto 1/\Lambda^2$, $\kappa \propto 1/\Lambda^4$ and $\eta \propto 1/\Lambda^6$.

One of the relevant characteristics of this model is that the self interactions of the Higgs are drastically modified.

For instance, the trilinear coupling of the Higgs, coming from the third derivative of the Higgs potential at the minimum can be enhanced with respect to the SM.

Dashed line :
Critical temperture

Green and dark blue regions lead to a first order P.T. with a cutoff larger than 400 and 500 GeV, respectively. Enhancements of order 5 to 8 may be obtained.



Joglekar, Huang, Li, C.W.'15

Low Energy Effective Potential Analysis

$$V(\phi, T) = \frac{k_2 + a_0 T^2}{2}\left(\phi^\dagger\phi\right) + \frac{k_4}{4}\left(\phi^\dagger\phi\right)^2 + \sum_{n=3}^{\infty} \frac{c_{2n}}{2^n \Lambda^{2(n-2)}}\left(\phi^\dagger\phi\right)^n,$$

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{8v^2}{3m_h^2}\sum_{n=3}^{\infty}\frac{n(n-1)(n-2)c_{2n}v^{2(n-2)}}{2^n\Lambda^{2(n-2)}}\right).$$

The trilinear coupling is hence modified by

$$\delta = \frac{\lambda_3}{\lambda_3^{SM}} - 1 = \frac{8v^2}{3m_h^2}\sum_{n=3}^{\infty}\frac{n(n-1)(n-2)c_{2n}v^{2(n-2)}}{2^n\Lambda^{2(n-2)}}$$

This expression is generic and must be complemented by the requirement of the physical vacuum being the global minimum of the theory at least at scales of the order of the weak scale we are working with.

Also, in general a first order phase transition will take place for a subset of these potentials, which depart significantly from the SM one.

Minimal Modification of SM Potential

Grojean, Servant, Wells '05

$$V(\phi,T) = \frac{k_2 + a_0 T^2}{2}\left(\phi^\dagger\phi\right) + \frac{k_4}{4}\left(\phi^\dagger\phi\right)^2 + \frac{k_6}{6}\left(\phi^\dagger\phi\right)^3$$

$$\lambda_3 = \frac{3m_h^2}{v}\left(1 + \frac{8k_6 v^4}{3m_h^2}\right)$$

We define the critical temperature as the one in which a second non-trivial minimum, degenerate with the origin, appears in the theory, namely

$$\left(\phi_c^\dagger\phi_c\right) = v_c^2 = -\frac{3k_4}{4k_6} \qquad\qquad 3k_4^2 = 16k_{2_{T_c}}k_6$$

It is easy to show from here that, at zero temperature

$$k_4 + 2k_6 v^2 = \frac{m_h^2}{2v^2}$$

From the above expressions, it is easy to obtain relations between the potential coefficients, the Higgs mass and the scalar VEV's

$$k_6 = \frac{m_h^2}{4v^2\left(v^2 - \frac{2}{3}v_c^2\right)}$$

$$T_c^2 = \frac{k_6}{a}\left(v^2 - v_c^2\right)\left(v^2 - \frac{v_c^2}{3}\right)$$

From the requirement of positivity of the critical temperature, k6 and the square of the VEV's, it follows that vc should be smaller than v and

$$k_6 < \frac{3m_h^2}{4v^4}$$

and

$$k_6 > \frac{m_h^2}{4v^4}$$

Hence, one obtains that a first order phase transition can take place only for certain values of the coefficients, which determine the modifications of the triple gauge coupling.

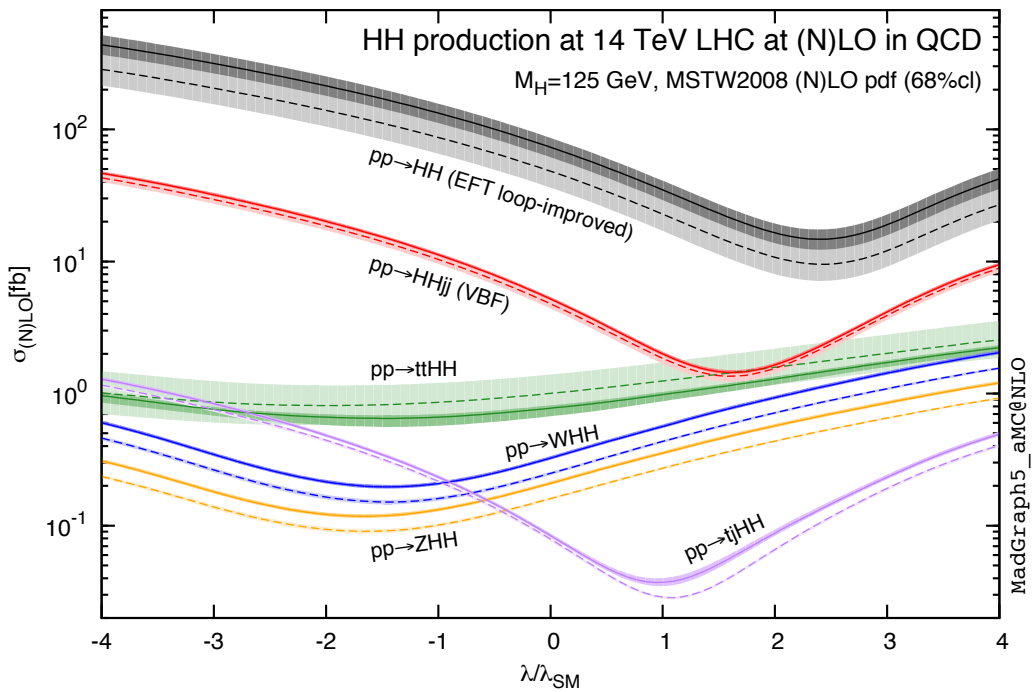
$$\frac{2}{3} \leq \delta \leq 2$$

$$488 \text{ GeV} \lesssim \Lambda \lesssim 838 \text{ GeV}$$

Here the effective cutoff was defined with c6 = 1 in our original definition.

Unfortunately, the test of this possibility is hard at the LHC.

Frederix et al'14

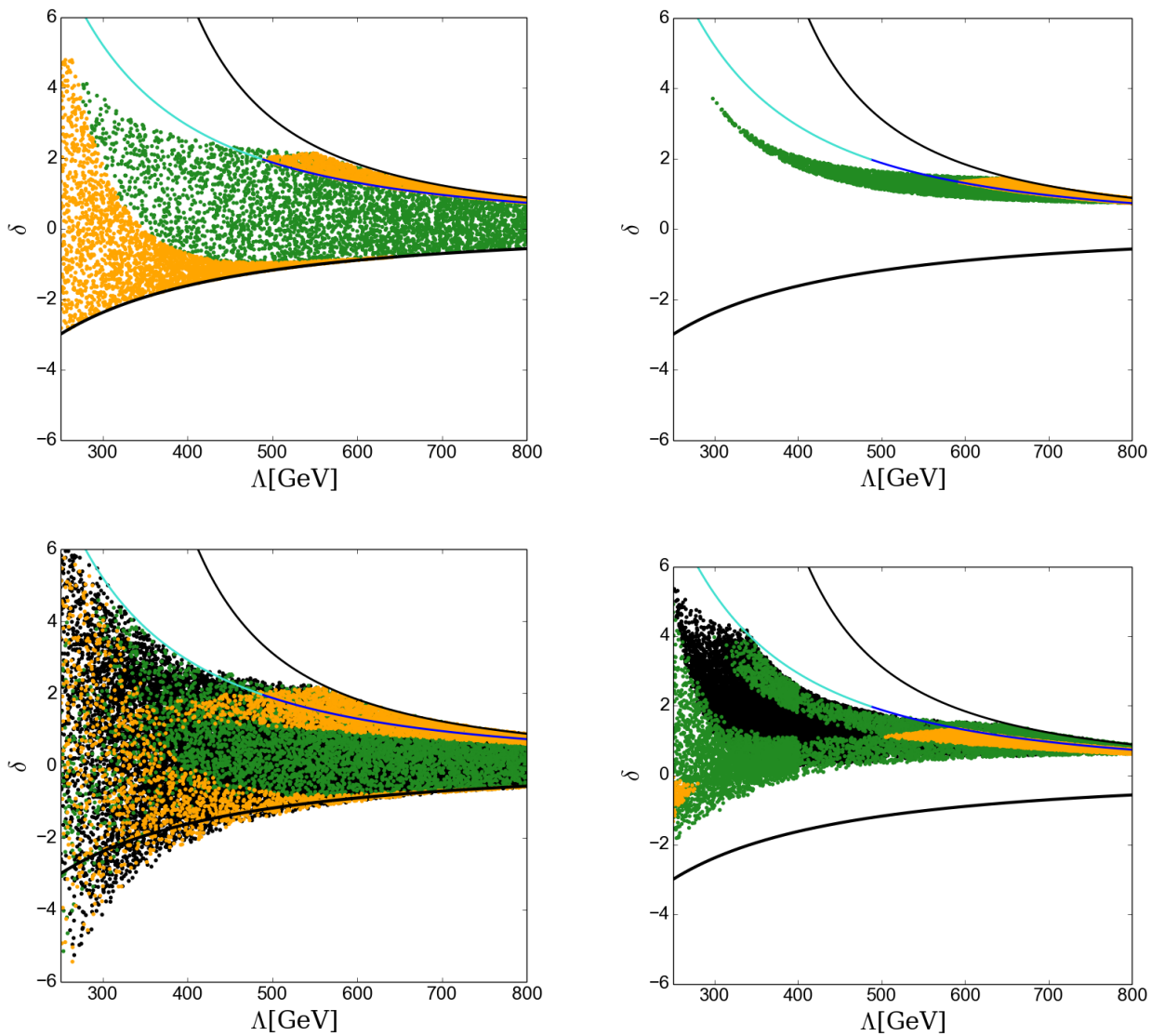


Very few events in the SM case after cuts are implemented. The number of events does not improve dramatically in gluon fusion processes even for enhancements of order 5. In addition, gain is in region of parameters where acceptance is low.

Higher Order Corrections to the Potential may lead to a different regime of δ's

Joglekar, Huang, Li, C.W. '15

Blue Lines : Sixth order terms discussed before



Right Panels :
First order PT

Left Panels :
General Result

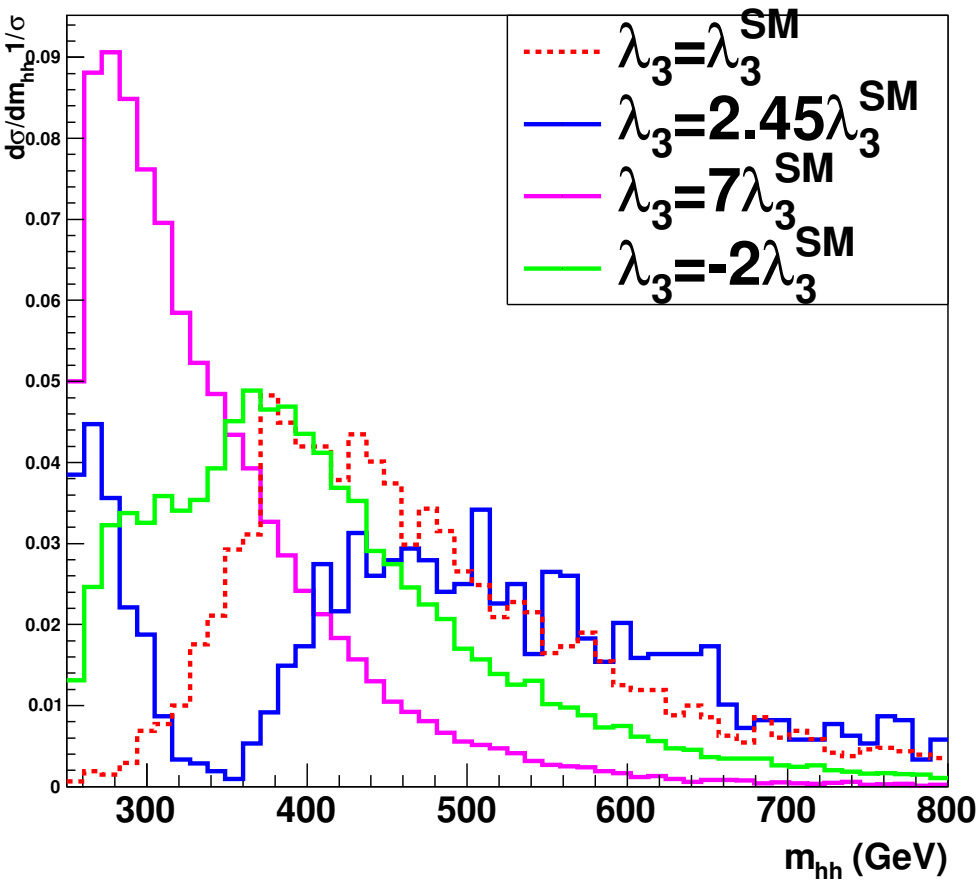
Upper Panels
Eighth order term additions

Lower Panesls
Tenth order terms added

Color code denote different hierarchy between coefficients

In general First Order PT correlated with positive enhancements of triple Higgs Couplings, but in general negative enhancements possible.

Invariant Mass Distribution of Pairs of Higgs for Different values of the triple Higgs Coupling



Calculated at NLO (MCFM)

Barger et al'14

Joglekar, Huang, Li, C.W. '15

It is clear that for large triple Higgs couplings the acceptance increases for smaller invariant masses

Double Higgs Production at LHC 13 (3000 fb^{-1})

Standard Cuts

$$p_t(b) > 30 \text{ GeV}, \; p_t(\gamma) > 30 \text{ GeV}$$

$$112.5 \text{ GeV} < m_{bb} < 137.5 \text{ GeV}, \; 120 \text{ GeV} < m_{\gamma\gamma} < 130 \text{ GeV}. \quad (22)$$

	x-sec	Eq (22) + Eq (23)	Eq (22) + Eq (24)
hh ($\lambda_3 = \lambda_3^{SM}$)	0.15	1.0×10^{-2}	-
hh ($\lambda_3 = 5\lambda_3^{SM}$)	0.26	-	1.12×10^{-2}
hh ($\lambda_3 = 7\ \lambda_3^{SM}$)	0.71	-	3.3×10^{-2}
hh ($\lambda_3 = 9\ \lambda_3^{SM}$)	1.43	-	6.08×10^{-2}
hh ($\lambda_3 = 0$)	0.29	1.33×10^{-2}	-
hh ($\lambda_3 = -\lambda_3^{SM}$)	0.50	2.26×10^{-2}	-
hh ($\lambda_3 = -2\lambda_3^{SM}$)	0.77	2.94×10^{-2}	-
$b\bar{b}\gamma\gamma$	5.05×10^{3}	1.34×10^{-2}	4.0×10^{-2}
$c\bar{c}\gamma\gamma$	6.55×10^{3}	4.19×10^{-3}	2.68×10^{-2}
$b\bar{b}\gamma j$	9.66×10^{6}	4.60×10^{-3}	1.38×10^{-2}
$jj\gamma\gamma$	7.82×10^{5}	2.38×10^{-3}	5.26×10^{-3}
$t\bar{t}h$	1.39	1.40×10^{-3}	2.33×10^{-3}
zh	0.33	6.86×10^{-4}	9.01×10^{-4}
$b\bar{b}jj$	7.51×10^{9}	5.34×10^{-4}	6.47×10^{-4}

λ_3	λ_3^{SM}	$5\lambda_3^{SM}$	$7\lambda_3^{SM}$	$9\lambda_3^{SM}$	0	$-\lambda_3^{SM}$	$-2\ \lambda_3^{SM}$
$S/\sqrt{B}$	3.3	2.1	6.0	11	4.4	7.5	9.8

$$m_{hh} > 350 \text{ GeV} \quad (23)$$

$$\lambda_3 > 3\ \lambda_3^{SM}$$

$$250 \text{ GeV} < m_{hh} < 350 \text{ GeV} \quad (24)$$

This cut improves the acceptance at high values of the triple Higgs coupling

Double Higgs Production at a 100 TeV collider
Similar cuts as at the LHC employed

	x-sec	Eq (22) + Eq (23)	Eq (22) + Eq (24)
$\mathrm{hh}(\lambda_3 = \lambda_3^{SM})$	3.4	0.11	-
$\mathrm{hh}(\lambda_3 = 3\lambda_3^{SM})$	1.48	0.042	-
$\mathrm{hh}(\lambda_3 = 5\lambda_3^{SM})$	4.45	-	0.10
$b\bar{b}\gamma\gamma$	1.7×10^{6}	0.129	0.52
$c\bar{c}\gamma\gamma$	1.0×10^{5}	$6.45\ \times10^{-2}$	0.42
$b\bar{b}\gamma j$	1.19×10^{5}	1.68×10^{-2}	6.72×10^{-2}
$jj\gamma\gamma$	2.73×10^{6}	1.92×10^{-2}	7.3×10^{-2}
$t\bar{t}h$	86.41	2.72×10^{-2}	2.53×10^{-2}
zh	0.88	1.76×10^{-3}	1.4×10^{-3}
$b\bar{b}jj$	4.07×10^{10}	2×10^{-3}	$4.7\ \times10^{-3}$

λ_3	λ_3^{SM}	$3\ \lambda_3^{SM}$	$5\ \lambda_3^{SM}$
$S/\sqrt{B}$	11	4.5	5.3

100 TeV collider may lead to a full test of this possibility

(

Electroweak Phase Transition in the nMSSM

Defining $\phi^2 = H_1^2 + H_2^2$, $\tan\beta = \frac{v_1}{v_2}$

- In the nMSSM, the potential has the approximate form:

(*i.e.* tree-level + dominant one-loop high-T terms)

$$V_{eff} \simeq (-m^2 + A\,T^2)\phi^2 + \tilde{\lambda}^2\phi^4 + 2t_s\phi_s + 2\tilde{a}\,\phi_s\phi^2 + \lambda^2\phi^2\phi_s^2$$

with $\tilde{a} = \frac{1}{2}\,a_\lambda\,\sin 2\beta$, $\tilde{\lambda}^2 = \frac{\lambda^2}{4}\sin^2 2\beta + \frac{\bar{g}^2}{2}\cos^2 2\beta$.

- Along the trajectory $\frac{\partial V}{\partial \phi_s} = 0$, the potential reduces to

$$V_{\rm eff} = (-m^2 + AT^2)\phi^2 - \frac{(t_s + \tilde{a}\phi^2)^2}{m_s^2 + \lambda^2\phi^2} + \tilde{\lambda}^2\phi^2$$

Non-renormalizable potential controlled by m_s. Strong first order phase transition induced for small values of m_s. Contrary to the MSSM case, this is induced at tree level.

Menon, Morrisey, C.W. '04; Carena, Shah, C.W. '11; J. Shu'14

Performing a similar analysis as before, one can show that

$$\phi_c^2 = \frac{1}{\lambda^2}\left(-m_s^2 + \frac{1}{\tilde{\lambda}}|m_s\,\tilde{a} - \frac{\lambda^2\,t_s}{m_s}|\right)$$

$$T_c^2 = 8\left(F(\phi_c^2) - F(v^2)\right)\Big/\left(g^2 + \frac{\bar{g}^2}{2} + 2y_t^2\sin^2\beta\right)$$ with $$F(\phi) = -\frac{V'(\phi,0)}{2\phi}$$

The phase transition remains first order provided the critical field and temperatures are positive. These conditions cease to be fulfilled at

$$m_s^6\tilde{\lambda}^2 = (am_s^2 - t_s\lambda^2)^2$$

$$m_s^2\tilde{\lambda}^2\left(m_s^2 + \phi_c^2\lambda^2\right)^2 = (am_s^2 - t_s\lambda^2)^2$$

Scalar Mixing and the modification of the trilinear Coupling

$$V(\phi_h, \phi_s, T) = \frac{m_0^2 + a_0 T^2}{2}\phi_h^2 + \frac{\lambda_h}{4}\phi_h^4 + a_{hs}\phi_s\phi_h^2 + \frac{\lambda_{hs}}{2}\phi_s^2\phi_h^2 + t_s\phi_s + \frac{m_s^2}{2}\phi_s^2 + \frac{a_s}{3}\phi_s^3 + \frac{\lambda_s}{4}\phi_s^4$$

The mass matrix reads

$$\mathcal{M}^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{21}^2 & m_{22}^2 \end{pmatrix} = \begin{pmatrix} 2\lambda_h v_h^2 & 2\left(a_{hs} + \lambda_{hs} v_s\right) v \\ 2\left(a_{hs} + \lambda_{hs} v_s\right) v & m_s^2 + \lambda_{hs} v_h^2 \end{pmatrix}$$

$$\tan\, 2\theta = \frac{4v(a_{hs} + \lambda_{hs} v_s)}{2\lambda_h v_h^2 - m_s^2 - \lambda_{hs} v_h^2} = \frac{4v(a_{hs} m_s^2 - t_s \lambda_{hs})}{(2\lambda_h v_h^2 - m_s^2 - \lambda_{hs} v_h^2)(m_s^2 + \lambda_{hs} v_h^2)}$$

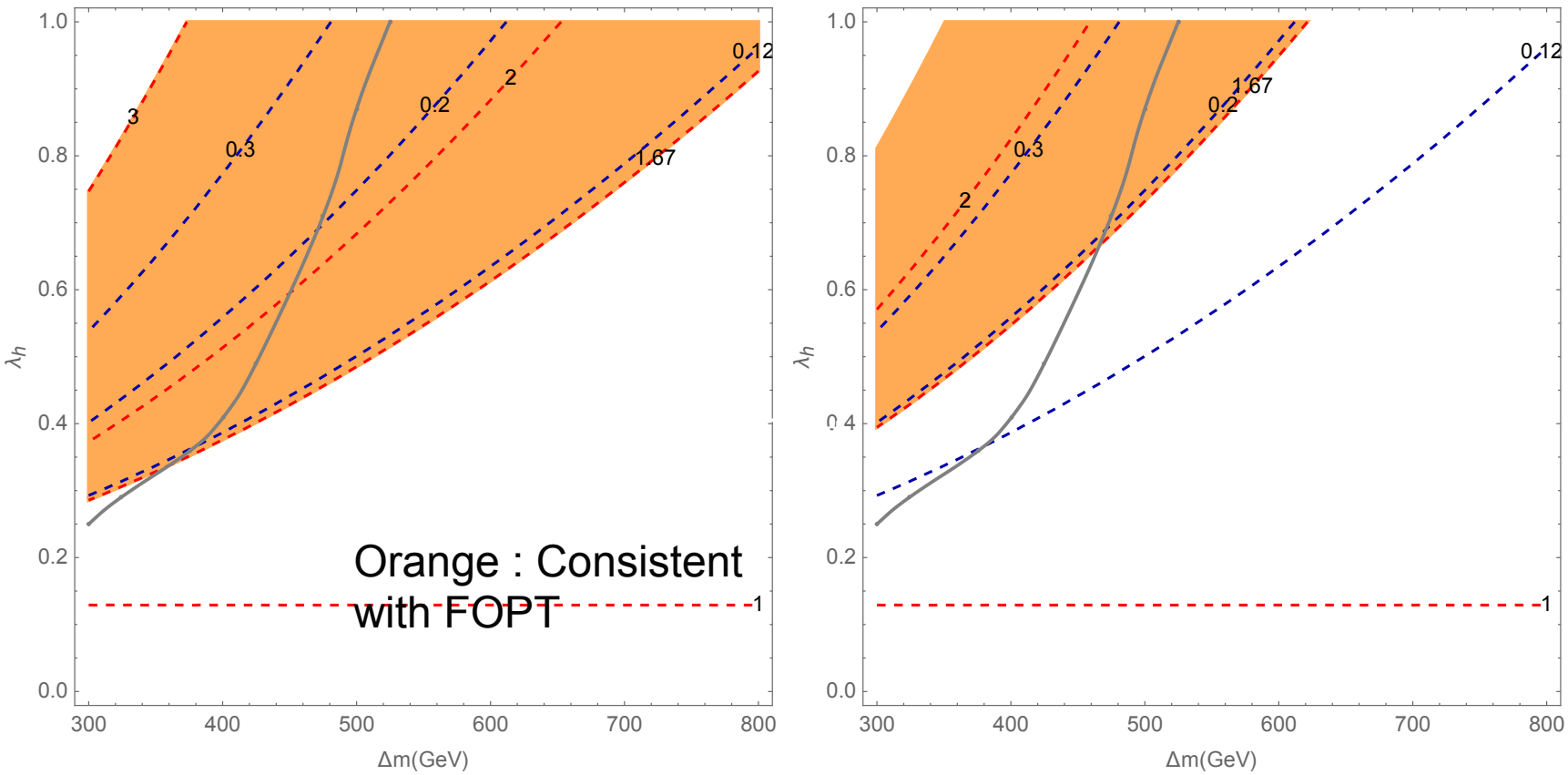
From here, it is easy to obtain the modified triple Higgs coupling, namely

$$\lambda_3 = 6\lambda_h v_h \cos^3\theta \left[1 + \left(\frac{\lambda_{hs} v_s + a_{hs}}{\lambda_h v_h}\right)\tan\theta + \frac{\lambda_{hs}}{\lambda_h}\tan^2\theta\right].$$

Combination of parameters affecting mixing and trilinear coupling are the same as affecting the order of the PT

Modification of the trilinear coupling and first order phase transition in the singlet extended theory

Joglekar, Huang, Li, C.W. ’15



Blue lines : Square of the sign of the mixing, restricted by precision Higgs couplings. Black line : Excluded by search for resonances decaying into vector boson pairs. Precisioin measurement constraints weak.

Conclusions

- LHC Higgs data rules out the realization of electroweak baryogenesis in the MSSM
- Extensions with singlets, like the NMSSM, still alive and providing an attractive alternative
- Effective Potential analysis reveals the possibility of sizable or negative enhancements of the triple gauge couplings
- Acceptance in LHC analysis of double Higgs production depends strongly on invariant mass of the Higgs and optimized set of cuts should be used

Conclusions

- The origin of the matter-antimatter asymmetry is one of the fundamental open questions in particle physics and cosmology
- Several proposals exist for its dynamical generation, and lead to very different physical phenomena
- The resolution of this question will involve experiments in the high energy, intensity and cosmic frontiers.
- Of particular relevance are the Majorana nature of neutrinos and the presence of CP-violation, as well as the search for electric dipole moments, for instance, of the electron and the neutron.
- Collider physics is already constraining some scenarios.
- The relation between the baryon and Dark Matter contributions to the Universe energy budget may be a clue towards the resolution of this puzzle.

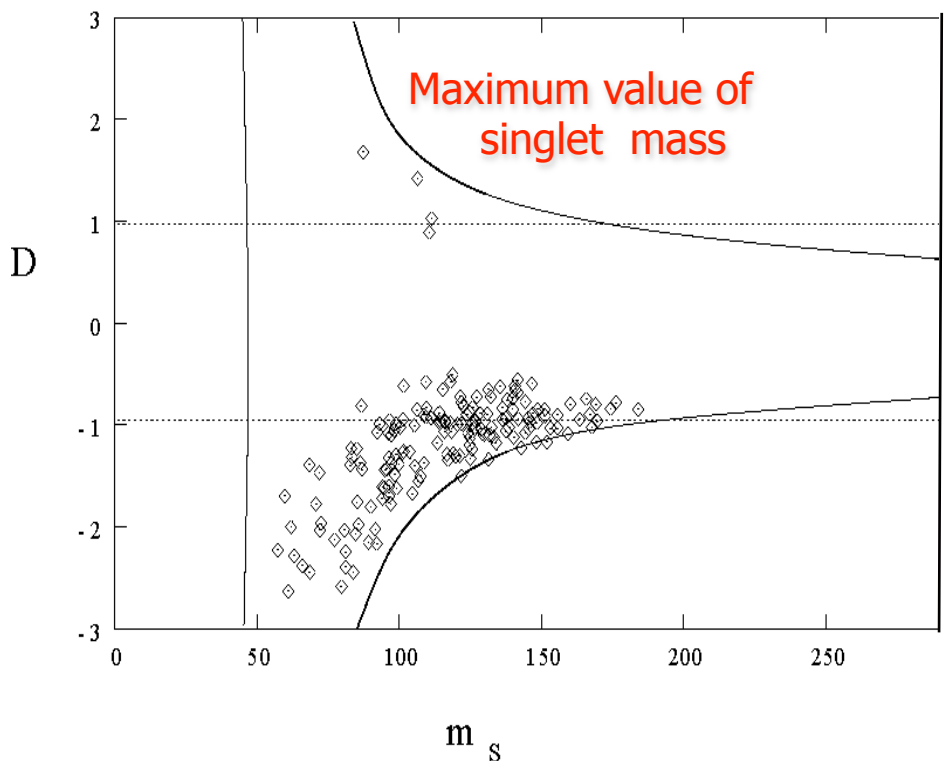
Parameters with strongly first order transition

- All dimensionful parameters varied up to 1 TeV
- Small values of the singlet mass parameter selected

$$D = \frac{1}{\tilde{\lambda}\, m_S^2} \left| \frac{\lambda^2 t_S}{m_S} - m_S\, a_\lambda \cos\beta \sin\beta \right| \geq 1$$

Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



Neutralino Mass Matrix

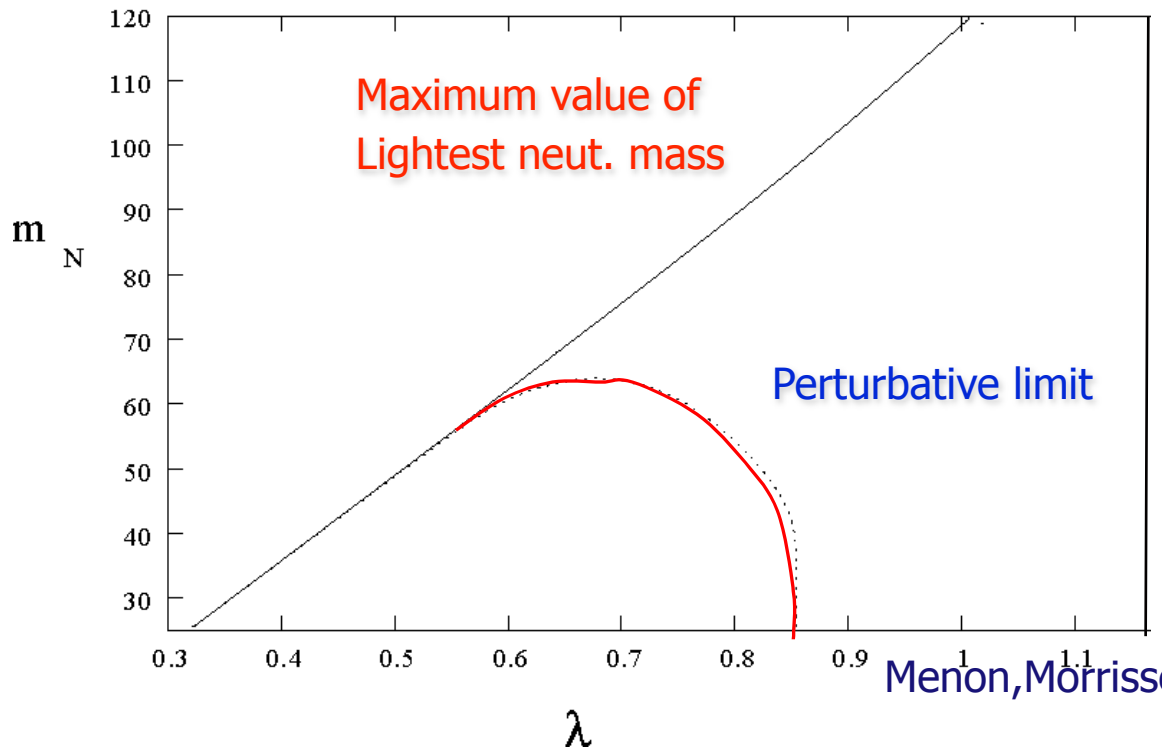
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_{\mathrm{W}} M_{\mathrm{Z}} & s_\beta s_{\mathrm{W}} M_{\mathrm{Z}} & 0 \\ 0 & M_2 & c_\beta c_{\mathrm{W}} M_{\mathrm{Z}} & -s_\beta c_{\mathrm{W}} M_{\mathrm{Z}} & 0 \\ -c_\beta s_{\mathrm{W}} M_{\mathrm{Z}} & c_\beta c_{\mathrm{W}} M_{\mathrm{Z}} & 0 & \lambda v_{\mathrm{s}} & \lambda v_2 \\ s_\beta s_{\mathrm{W}} M_{\mathrm{Z}} & -s_\beta c_{\mathrm{W}} M_{\mathrm{Z}} & \lambda v_{\mathrm{s}} & 0 & \lambda v_1 \\ 0 & 0 & \lambda v_2 & \lambda v_1 & \kappa \end{pmatrix},$$

In the nMSSM, $\kappa = 0$.

Upper bound on Neutralino Masses

$$m_1 = \frac{2\lambda\, v \sin\beta\; x}{(1+\tan^2\beta + x^2)} \qquad \text{with} \quad x = \frac{v_S}{v_1}$$

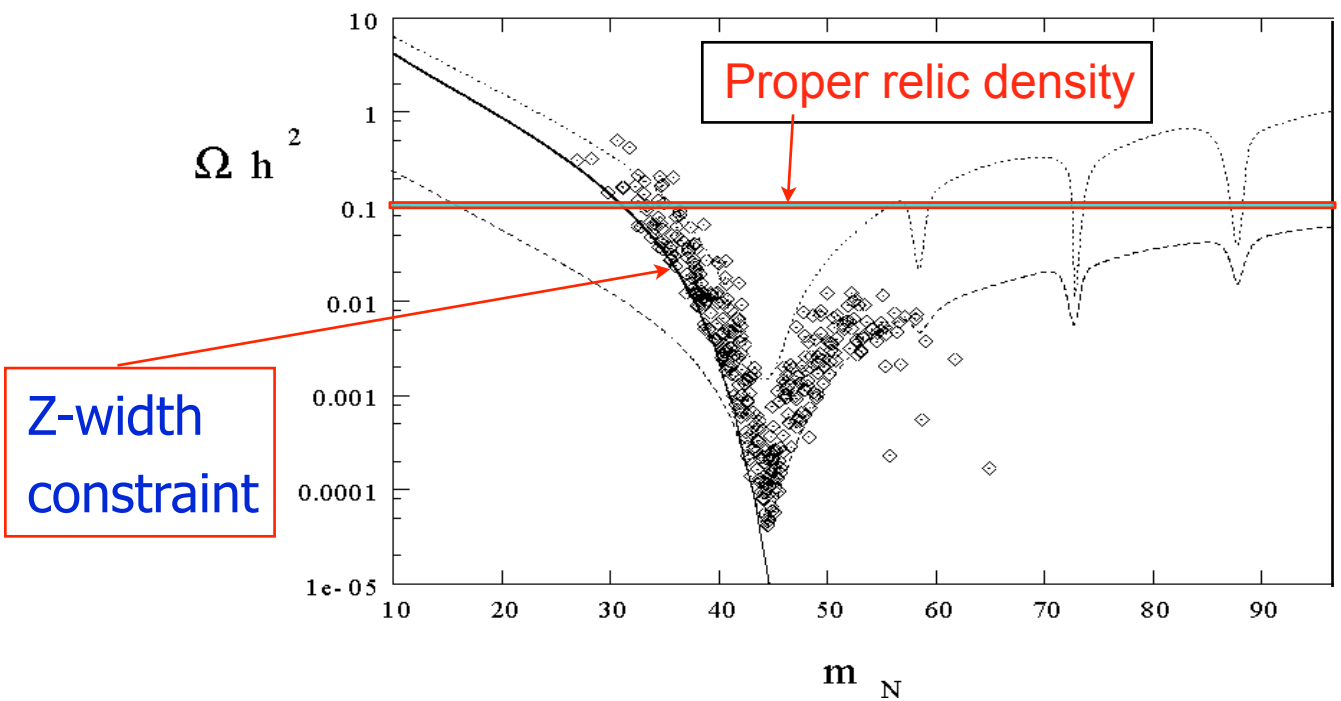
Values of neutralino masses below dotted line consistent with perturbativity constraints.



Menon,Morrissey,C.W.'04

Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are impossed.
Z-boson and Higgs boson contributions shown to guide the eye.
Neutralino masses between 35 GeV and 45 GeV.
Higgs decays affected by presence of light neutralinos. Large invisible decay rate.



Menon,Morrissey,C.W.'04

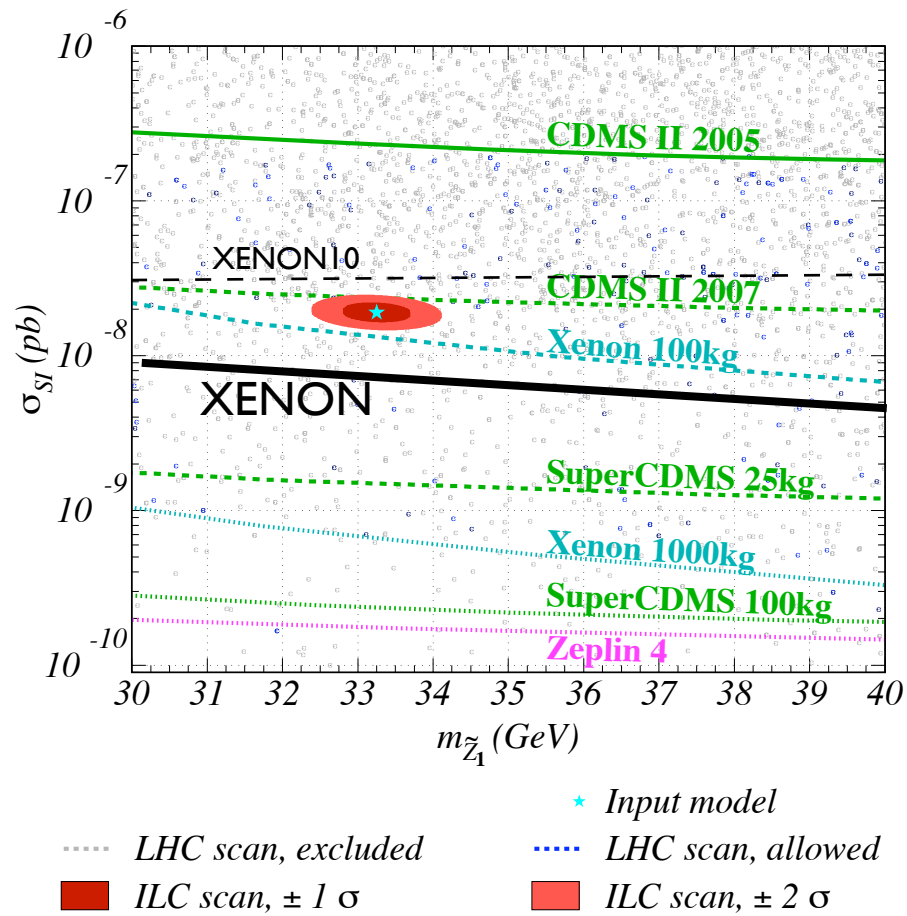
Direct Dark Matter Detection

Since dark matter is mainly a mixing betwen singlinos (dominant) and Higgsinos, neutralino nucleon cross section is governed by the new, λ -induced interactions, which are well defined in the relevant regime of parameters

Recent results from the XENON 100 experiment tends to disfavor this scenario

Balazs, Carena, Freitas, C.W. '07

See also
Barger, Langacker, Lewis, McCaskey, Shaughnessy, Yencho'07



Singlet Mechanism for the generation of μ in the NMSSM

- One could break the symmetry by self interactions of the singlet

$$W = \lambda S H_u H_d - \frac{\kappa}{3} S^3 + h_u Q U H_u + ...$$

- No dimensionful parameter is included. The superpotential is protected by a Z_3 symmetry, $\phi \rightarrow exp(i2\pi/3)\phi$
- This discrete symmetry would be broken by the singlet v.e.v. Discrete symmetries are dangerous since they could lead to the formation of domain walls: Different volumes of the Universe with different v.e.v.'s separated by massive walls. These are ruled out by cosmology observations.
- One could assume a small explicit breakdown of the Z_3 symmetry, by higher order operators, which would lead to the preference of one of the three vacuum states. That would solve the problem without changing the phenomenology of the model.

CP-Violating Phases

The conformal (mass independent) sector of the theory is invariant under an R-symmetry and a PQ-symmetry, with

	$\hat{H}_1$	$\hat{H}_2$	$\hat{S}$	$\hat{Q}$	$\hat{L}$	$\hat{U}^c$	$\hat{D}^c$	$\hat{E}^c$	$\hat{B}$	$\hat{W}$	$\hat{g}$	$W_{\rm nMSSM}$
$\mathrm{U(1)_R}$	0	0	2	1	1	1	1	1	0	0	0	2
$\mathrm{U(1)_{PQ}}$	1	1	-2	-1	-1	0	0	0	0	0	0	0

These symmetries allow to absorve phases into redefinition of fields. The remaining phases may be absorved into the mass parameters. Only physical phases remain, given by

$$\arg(m_{12}^* t_{\rm s} a_\lambda),$$ ← Higgs Sector

$$\arg(m_{12}^* t_{\rm s} M_i), \quad i = 1, 2, 3,$$ ← Chargino-Neutralino Sector

$$\arg(m_{12}^* t_{\rm s} A_{\rm u}), \quad (3 \text{ generations}),$$ ← S-up sector

$$\arg(m_{12}^* t_{\rm s} A_{\rm d}), \quad (3 \text{ generations}),$$ ← S-down sector