New Results on Electroweak Baryogenesis

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Based on following recent works:

C. Balazs, M. Carena and C.W.; Phys. Rev. D70:015007, 2004.
A. Menon, D. Morrissey and C.W.; Phys. Rev. D70:035005, 2004.
M. Carena, A. Megevand, M. Quiros and C.W., hep-ph/0410352
C. Balazs, M. Carena, A. Menon, C. Morrissey and C.W., hep-ph/0412264

Aspen Winter Conference, Aspen, February 17, 2005

Baryon-Antibaryon asymmetry

- Baryon Number abundance is only a tiny fraction of other relativistic species

$$\frac{n_B}{n_\gamma} \approx 6\ 10^{-10}$$

- But in early universe baryons, antibaryons and photons were equally abundant. What explains the above ratio ?

- No net baryon number if B would be conserved at all times.

- What generated the small observed baryon-antibaryon asymmetry ?

Baryogenesis in the Standard Model

- 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.

Baryogenesis at the Weak Scale

- Weak scale spectrum and processes to be tested in the near future.

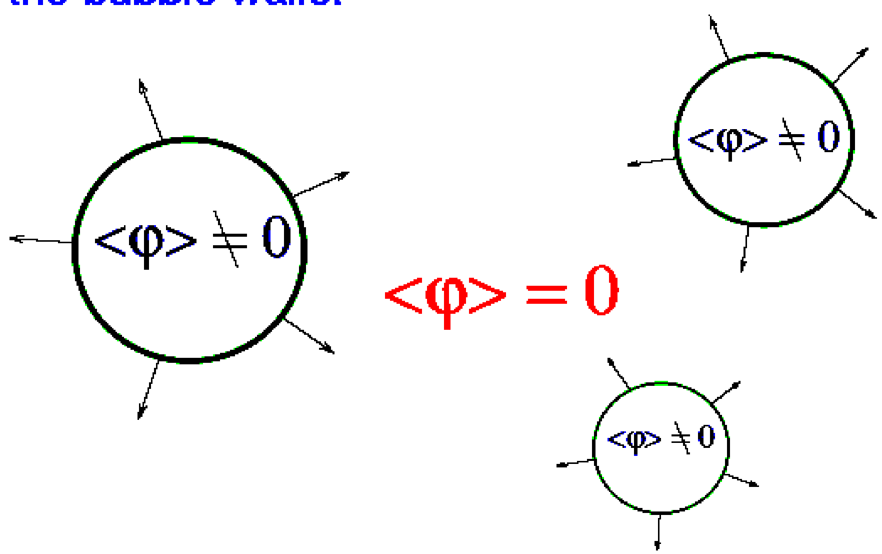
- Baryogenesis from out of eq. weak scale mass particle decay: Difficult, since non-equilibrium condition is satisfied for small couplings, for which CP-violating effects become small (example: resonant leptogenesis).

  Pilaftsis,Underwood, hep-ph/0309342

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

  Cohen, Kaplan and Nelson, hep-ph/9302210; A. Riotto, M. Trodden, hep-ph/9901362

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



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.

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

$$\Gamma(\Delta B \neq 0) \propto A\,T \exp\left(-\frac{E_{sph}}{T}\right) \qquad \mathbf{E_{sph}} \propto \frac{8\pi\,\mathbf{v}}{\mathbf{g}}$$

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

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

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

Kuzmin, Rubakov and Shaposhnikov, '85—'87

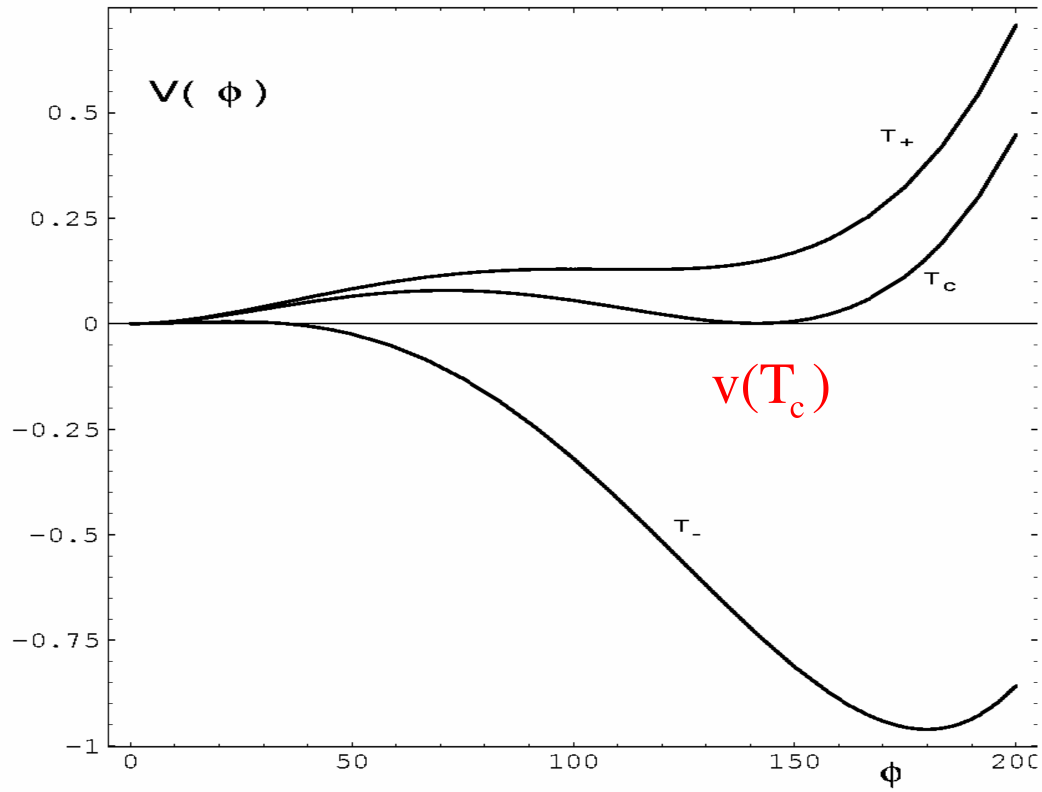
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

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

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

Electroweak Phase Transition

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



Finite Temperature Higgs Potential

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

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

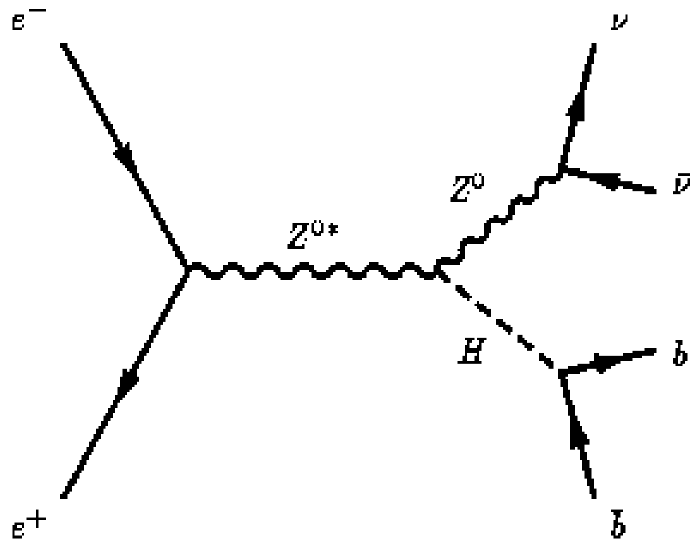
E receives contributions proportional to the sum of the cube of all light boson particle couplings

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

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

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

If the Higgs Boson is created , it will decay rapidly into other particles



At LEP energies mainly into pairs of b quarks

One detects the decay products of the Higgs and the Z bosons

LEP Run is over

- **No Higgs seen with a mass below 114 GeV**
- **But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach)**

Electroweak Baryogenesis in the SM is ruled out

Electroweak Baryogenesis

and

New Physics at the Weak Scale

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires 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

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

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

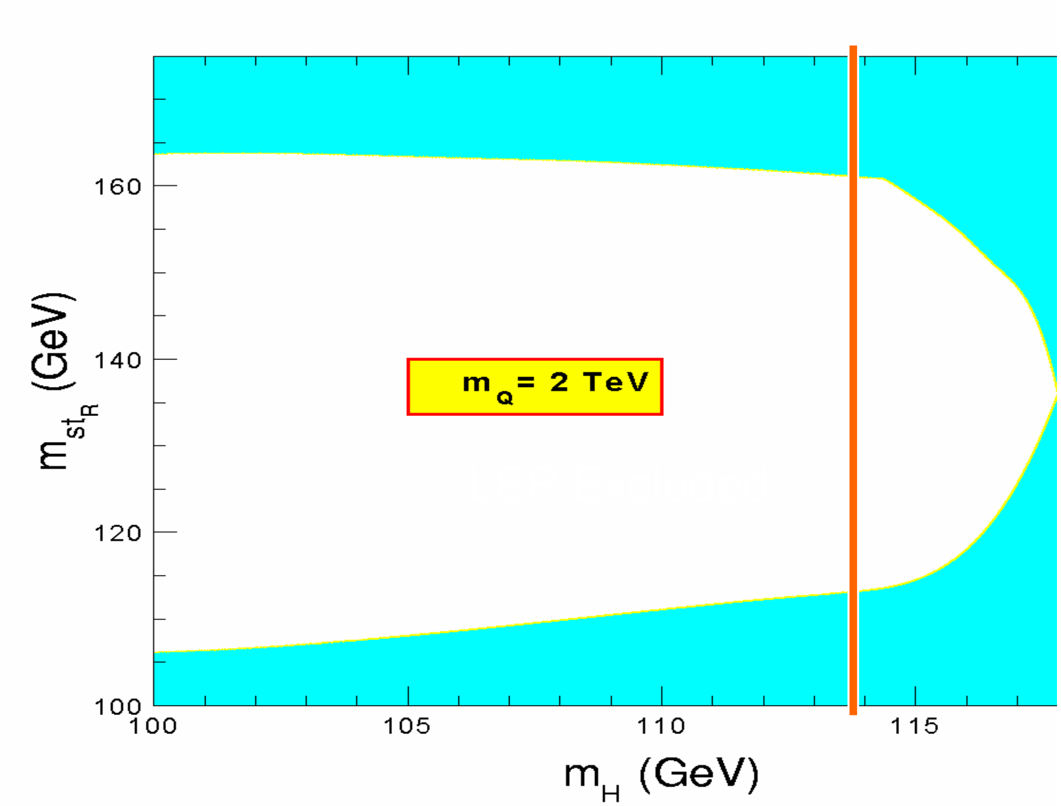
Higgs masses up to 120 GeV may be accomodated

MSSM: Limits on the Stop and Higgs Masses to preserve the baryon asymmetry

Suficciently strong first order phase transition to preserve generated baryon asymmetry:

• Higgs masses up to 120 GeV

• The lightest stop must have a mass below the top quark mass.



- Moderate values of $\tan\beta$, $\tan\beta \geq 5$ preferred in order to raise the Higgs boson mass.

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

Experimental Tests of Electroweak Baryogenesis in the MSSM

Experimental Tests of
Electroweak Baryogenesis and Dark Matter

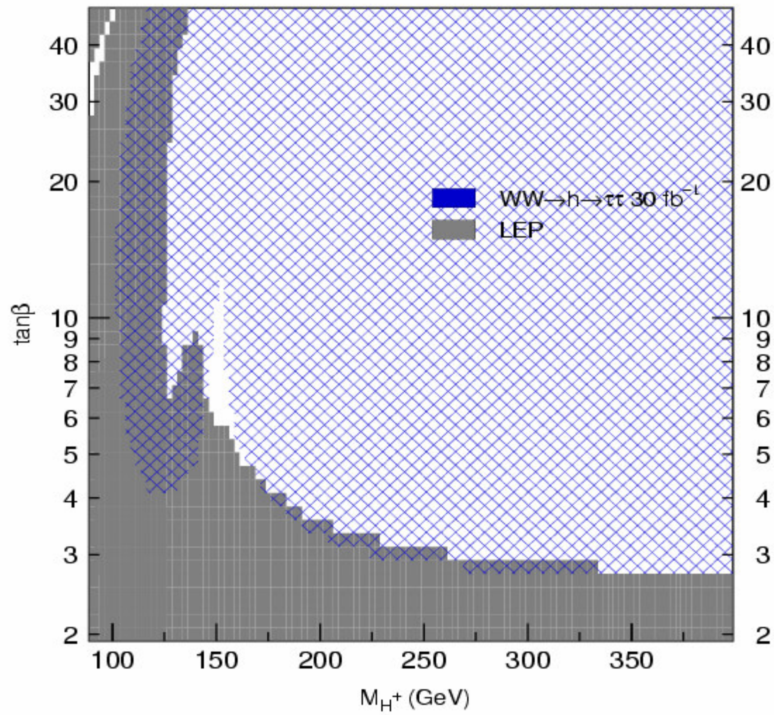
- Higgs searches beyond LEP:

1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

Discovery quite challenging, detecting a signal will mean that the Higgs has relevant strong (SM-like) couplings to W and Z

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

$$qq \to qqV^*V^* \to qqh$$
$$\text{with } h \to \tau^+\tau^-$$



Tevatron Stop Reach when two body decay channel is dominant

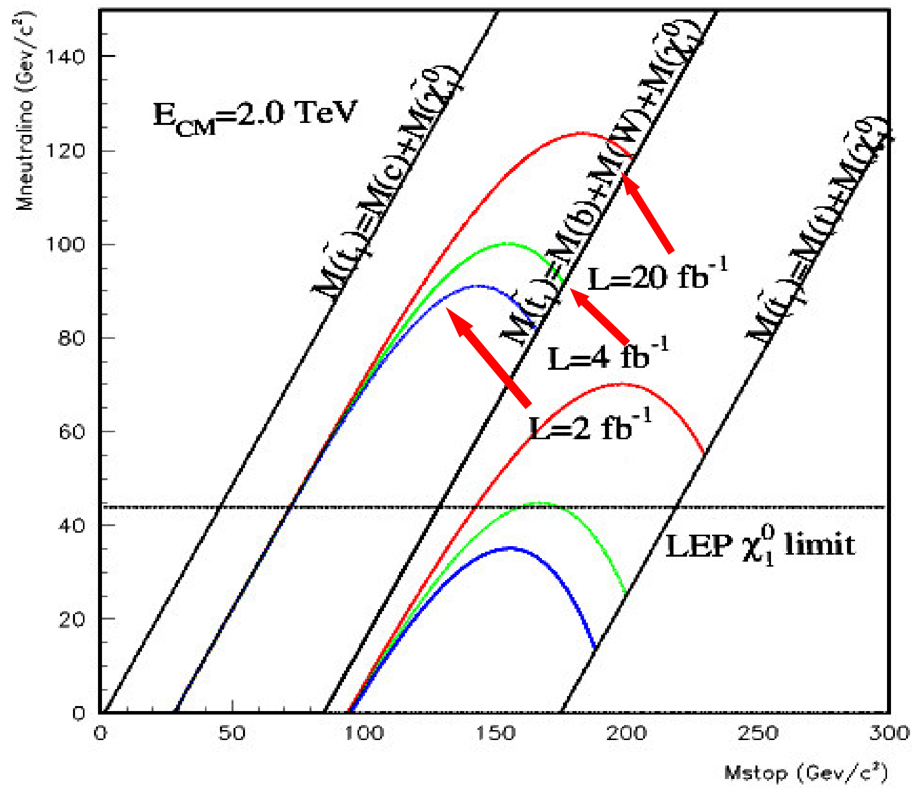
Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15\,\mathrm{GeV}$

Missing $E_T > 35\,\mathrm{GeV}$

$\bar{t}_1 \to c + \bar{\chi}_1^0$ or $\bar{t}_1 \to b\,W\,\bar{\chi}_1^0$



Demina, Lykken, Matchev,Nomerotsky ‘99

Stop-Neutralino Mass Difference: Information from the Cosmos

M. Carena, C. Balazs, C.W., PRD70:015007, 2004

- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

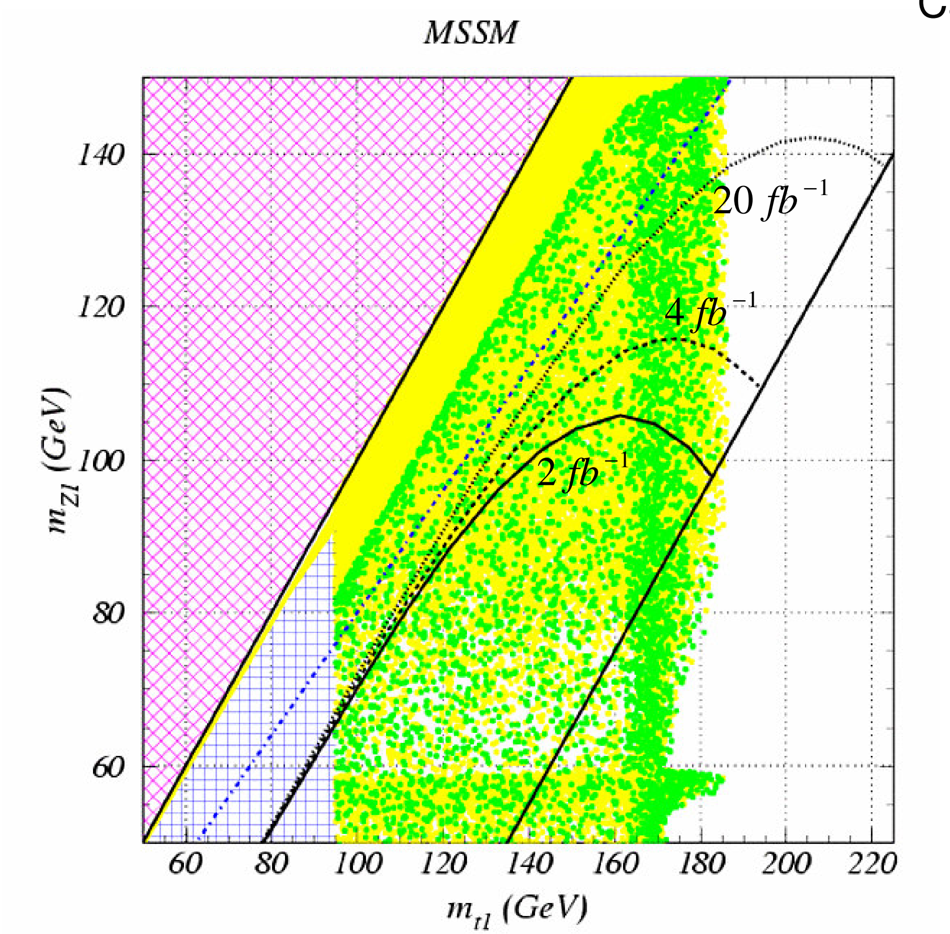
- Relic density is inversely proportional to the neutralino annihilation cross section.

If only stops, charginos and neutralinos are light, there are three main annihilation channels:

1. Coannihilation of neutralino with light stop or charginos: Small mass differences.
2. s-channel annihilation via Z or light CP-even Higgs boson
3. s-channel annihilation via heavy CP-even Higgs boson and CP-odd Higgs boson

Tevatron stop searches and dark matter constraints

Carena, Balazs and C.W. '04



Green: Relic density consistent with WMAP measurements.

Searches for light stops difficult in stop-neutralino coannihilarion region.

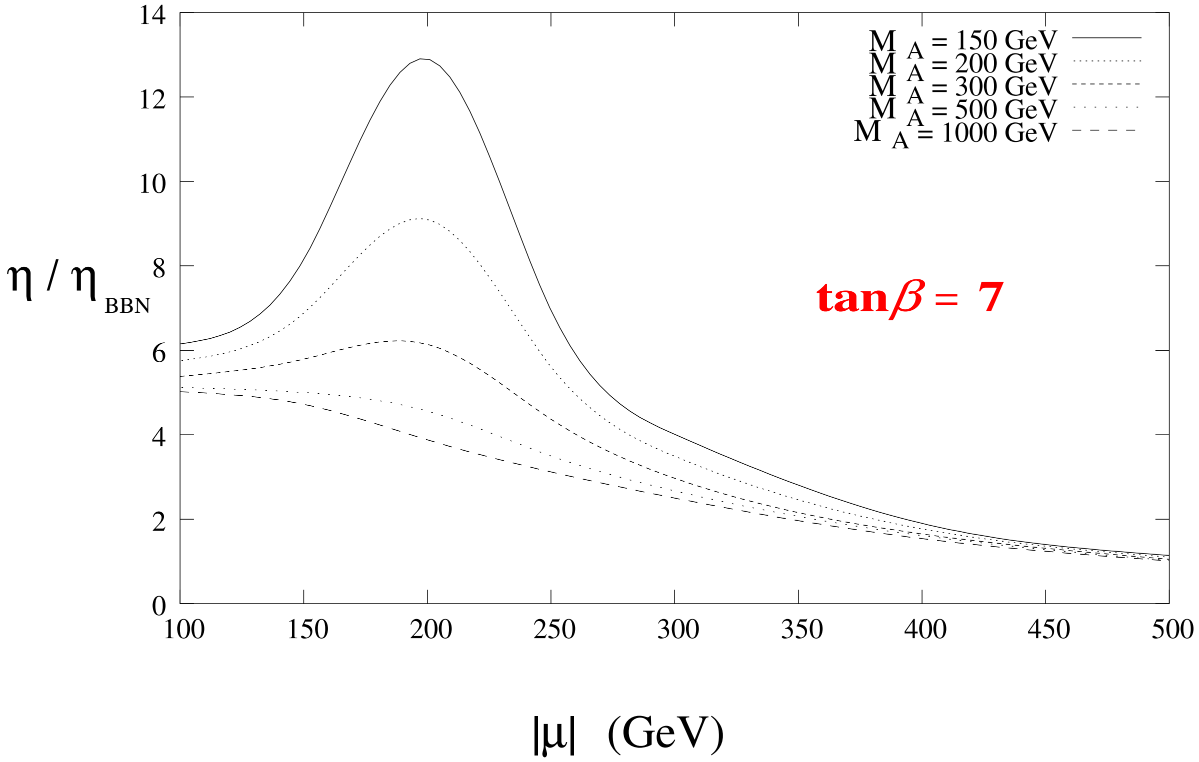
LHC will have equal difficulties. Searches become easier at a Linear Collider !

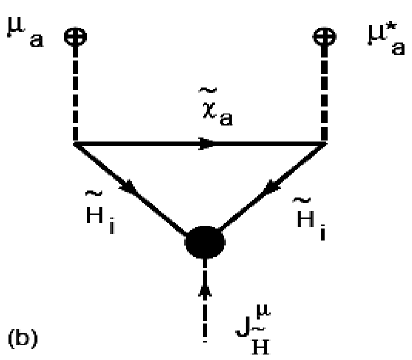
Carena,Freitas et. al.,'05, to appear

Baryon Asymmetry

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

Balazs, Carena, Menon, Morrissey, C.W.'04



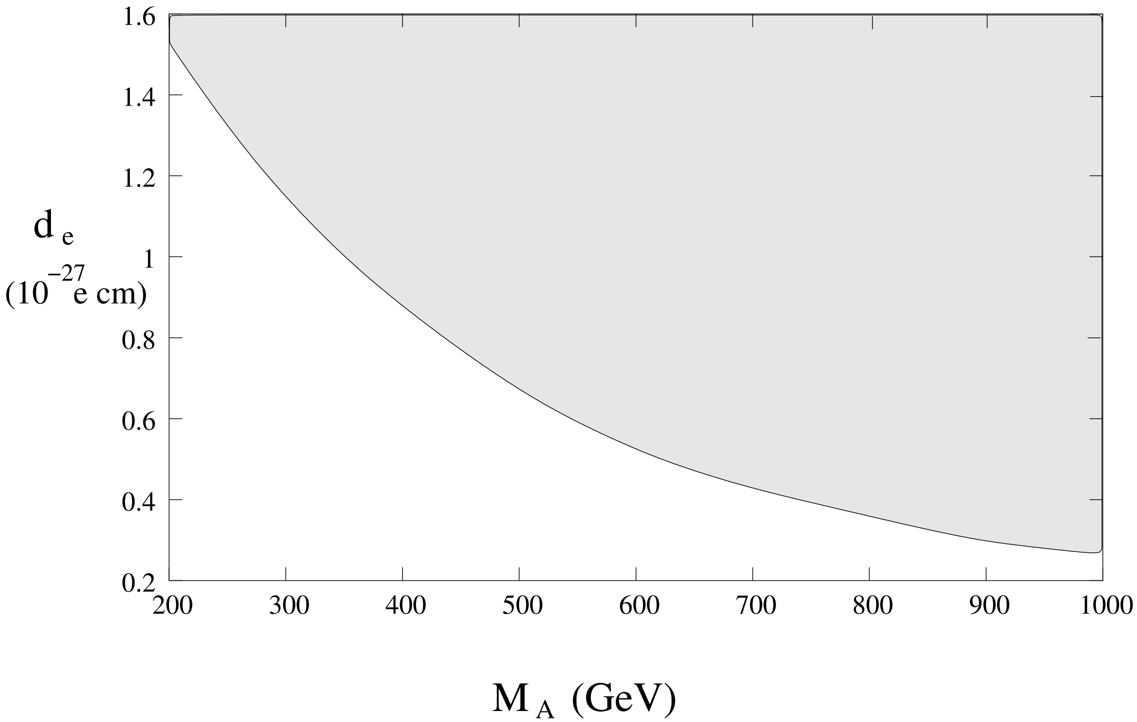


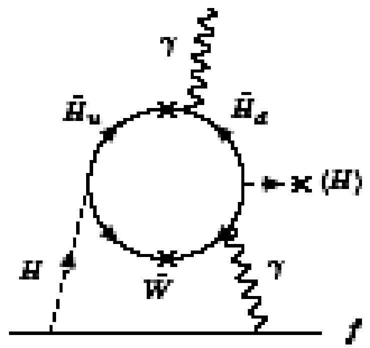
Electron electric dipole moment

- 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

$$\mathbf{d_e < 1.6\ 10^{-27}\ e\ cm}$$

Balazs, Carena, Menon, Morrissey, C.W.'04

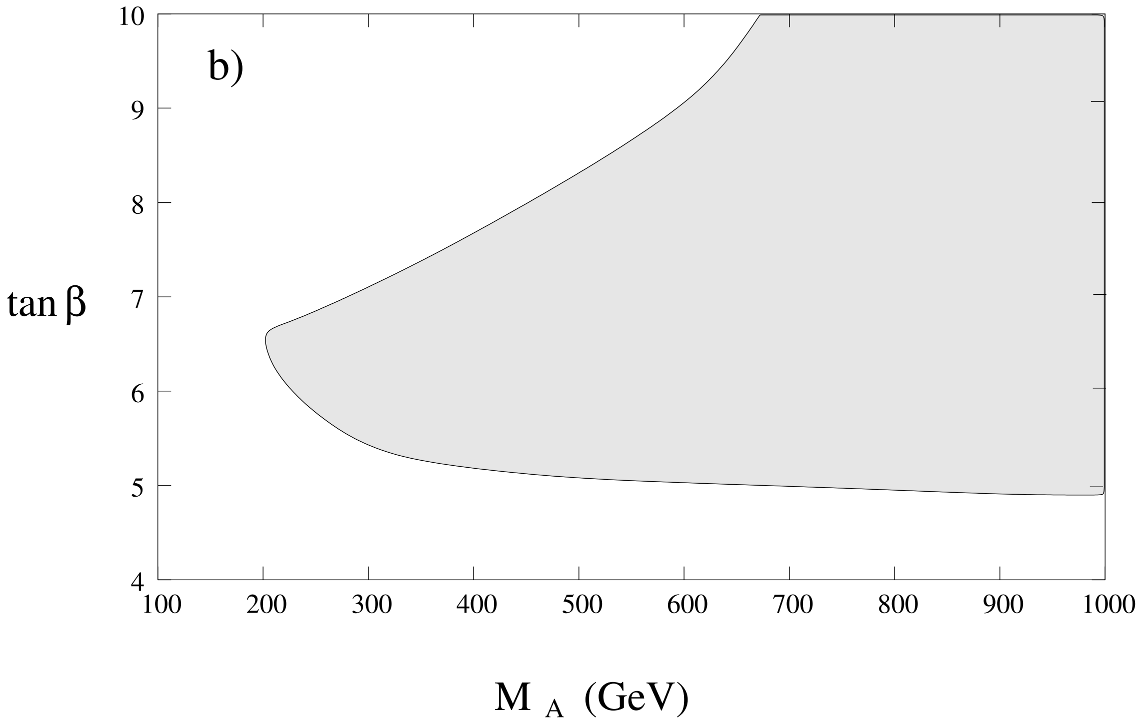




Allowed region of parameters

- After constrains from the electric dipole moment, the baryon asymmetry and the dark matter constraints are included, there is a limited region of $\tan\beta$ consistent with electroweak baryogenesis.

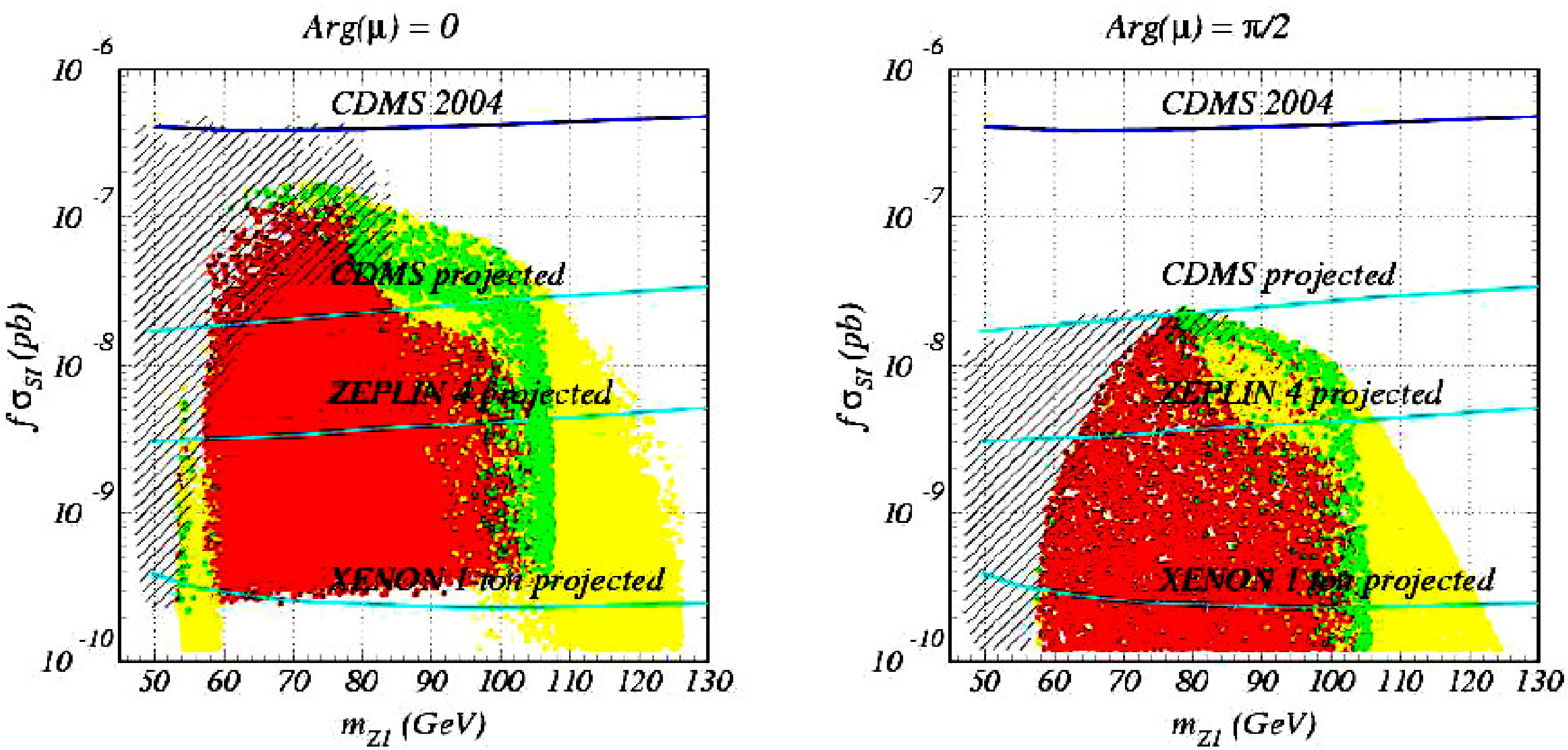
Balazs, Carena, Menon, Morrissey, C.W.'04



Direct Dark Matter Detection

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei
- Hatched region: Excluded by LEP2 chargino searches

Balazs, Carena, Menon, Morrissey, C.W.'04



Electroweak Baryogenesis in the nMSSM

A. Menon, D. Morrissey and C.W., PRD70:035005, 2004

(See also Kang, Langacker, Li and Liu, hep-ph/0402086)

Minimal Extension of the MSSM

Dedes et al. , Panagiotakopoulos, Pilaftsis'01

- Superpotential restricted by Z_5^R or Z_7^R symmetries

$$W = \lambda S H_1 H_2 + \frac{m_{12}^2}{\lambda} S + y_t Q H_2 U$$

- No cubic term. Tadpole of order cube of the weak scale, instead
- Discrete symmetries broken by tadpole term, induced at the sixth loop level. Scale stability preserved
- Similar superpotential appears in Fat-Higgs models at low energies

Harnik et al. '03, G. Kribs' talk

$$V_{soft} = m_1^2 H_1^2 + m_2^2 H_2^2 + m_S^2 S^2 + \left(t_s S + h.c. \right)$$
$$+ \left(a_\lambda S H_1 H_2 + h.c. \right)$$

Electroweak Phase Transition

Defining $\phi^2 = \mathbf{H}_1^2 + \mathbf{H}_2^2$, $\tan\beta = \frac{\mathbf{v}_1}{\mathbf{v}_2}$

- 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

$$V_{eff} = (-m^2 + A\,T^2)\phi^2 - \left(\frac{t_s + \tilde{a}\,\phi^2}{m_s^2 + \lambda^2\phi^2}\right) + \tilde{\lambda}^2\phi^4.$$

Non-renormalizable potential controlled by m_s. Strong first order phase transition induced for small values of m_s.

Similar phenomenon discussed by Grojean, Servant and Wells, hep-ph/0407019.

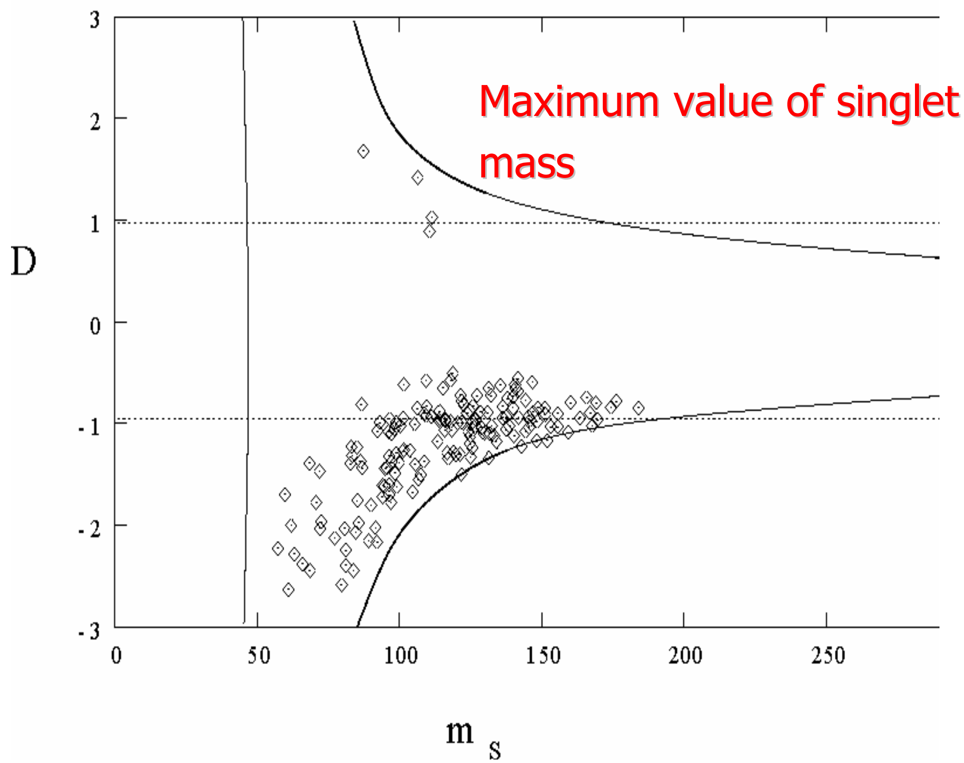
Parameters with strongly first order transition

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

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

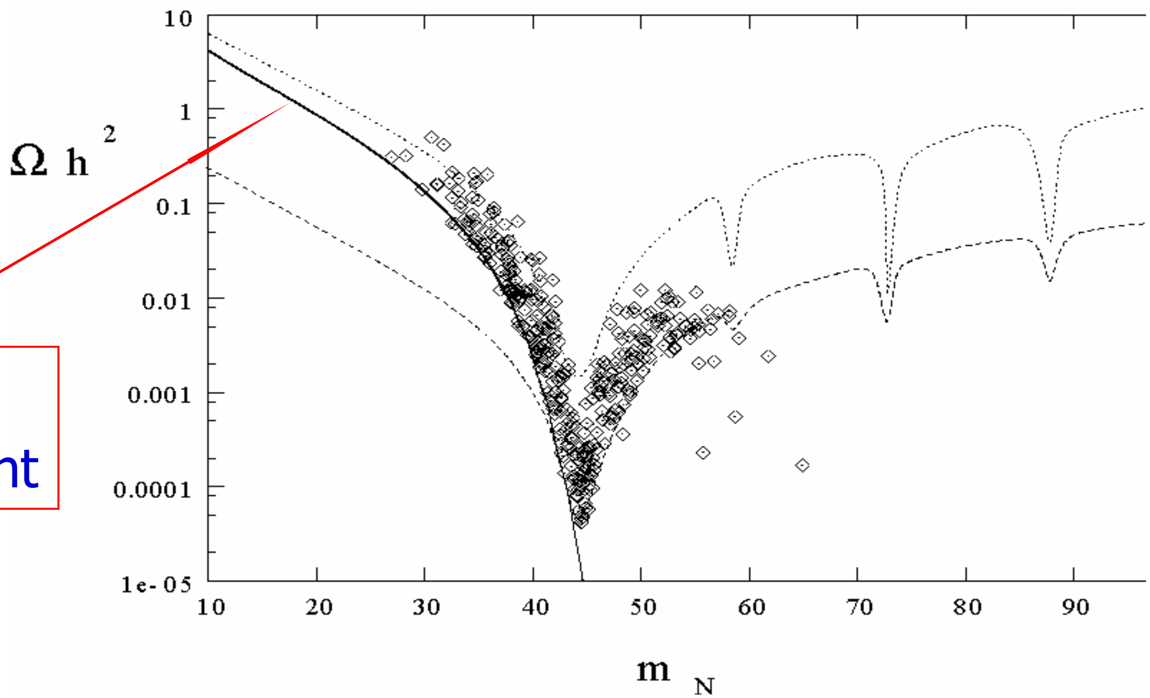
Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



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.



Z-width constraint

Menon,Morrissey,C.W.'04

Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controled by $\mathbf{m_S^2}$)
- They mix with standard CP-even and CP-odd states in a way proportional to λ **and** $\mathbf{a}_\lambda$
- Values of λ restricted to be lower than 0.8 in order to avoid Landau-pole at energies below the GUT scale.
- As in the NMSSM, upper bound on Higgs that couples to weak bosons
- Extra tree-level term helps in avoiding LEP bounds.

$$\mathbf{m_h^2 \leq M_Z^2 \cos^2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loop corrections}}$$

Espinosa,Quiros;Kane et al.

Higgs Searches

- Invisibly decaying Higgs may be searched for at the LHC in the Weak Boson Fusion production channel.
- Defining

$$\eta = \mathbf{BR(H \to inv.)} \frac{\boldsymbol{\sigma}\mathbf{(WBF)}}{\boldsymbol{\sigma}\mathbf{(WBF)_{SM}}}$$

- The value of η varies between 0.5 and 0.9 for the lightest CP-even Higgs boson.
- Minimal luminosity required to exclude (discover) such a Higgs boson, with mass lower than 130 GeV:

Higgs Working Group, Les Houches'01

$$L_{95\%} = \frac{\mathbf{1.2\ fb^{-1}}}{\eta^2} \quad , \quad L_{5\sigma} = \frac{\mathbf{8\ fb^{-1}}}{\eta^2}$$

(see also Davoudiasl,Han,Logan, hep-ph/0412269)

- Lightest CP-odd and heavier CP-even has much larger singlet component. More difficult to detect.

Electroweak Baryogenesis and

New Fermions at the TeV scale

M. Carena, A. Megevand and M. Quiros, hep-ph/0410352

Fermions Strongly Coupled to the Higgs Boson

- The finite T corrections to the effective potential presented before were computed in high temperature expansion, valid for masses smaller than T .

- When finite T expansion not valid, one should keep the whole contribution:

$$\mathcal{F}(\phi,T) = \mathcal{F}_{\rm SM}(\phi,T) \pm \sum_i g_i V_i(m_i(\phi)) + T^4 \sum_i g_i I_{\mp}\left[m_i(\phi)/T\right]/2\pi^2$$

with

$$I_{\mp}(x) = \pm \int_0^\infty dy\, y^2 \log\left(1 \mp e^{-\sqrt{y^2+x^2}}\right)$$

+:Fermions, - :Bosons

for $\mathbf{m}^2(\phi) = \mathbf{h}^2 \phi^2 + \mu^2$,

$$V_i(m_i(\phi)) = \frac{1}{64\pi^2}\left[m_i^4(\phi)\log\left(\frac{m_i^2(\phi)}{m_i^2(v)}\right) - 1.5\, m_i^4(\phi) + 2\, m_i^2(\phi) m_i^2(v)\right]$$

- Particles with masses much larger than the temperature give no finite T contribution to the free energy, while for m = 0,

$$\mathbf{I}_+(\mathbf{0}) = -\frac{7\pi^4}{360} \qquad \mathbf{I}_-(\mathbf{0}) = -\frac{\pi^4}{45}$$

Potential Stability

- Just like in the case of the top quark in the Standard Model, heavy fermions, strongly coupled to the Higgs induce instabilities (Higgs dependent quartic coupling becomes negative).

- We shall assume the presence of stabilizing bosonic fields, and we shall take for them the largest explicit mass consistent with vacuum stability (finite T effects of bosons minimized).

- We shall further assume no CP-violating sources associated with the stabilizing fields.

- What if a particle, strongly coupled to the Higgs has a mass much larger than T in the broken phase ?

- Its contribution to the effective potential for Higgs fields close to the minimum would vanish, while in the symmetric phase it still would give a contribution to the free-energy.

- The critical temperature would then be modified by the presence of this particle. If the dispersion relation is linear in Higgs field,

$$V_{SM}(\phi(T_c, T_c) = -\frac{\pi^2}{90}\Delta g_* T_c^4$$

- This happenes at a lower temperature and larger values of the Higgs v.e.v. The condition of baryon asymmetry preservation is given by

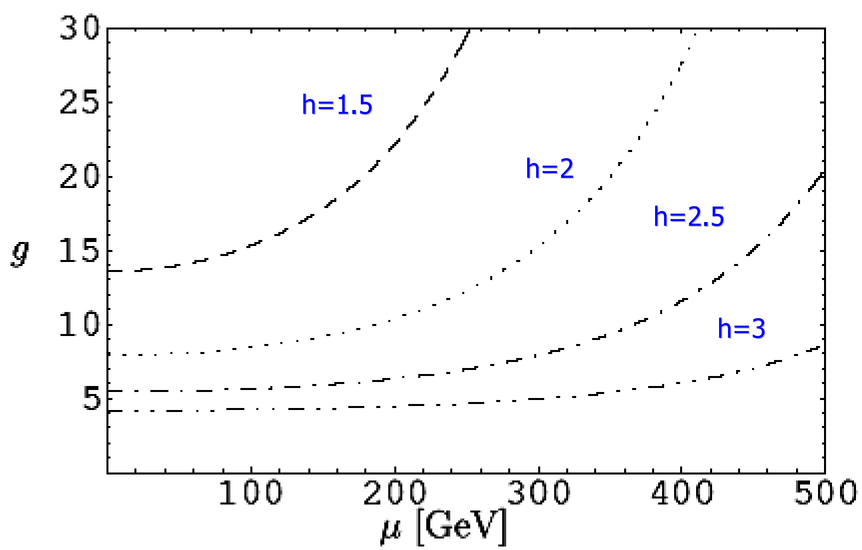
$$\boxed{(m_H/v)^2 < 4E + 4\pi^2 \Delta g_*/45.}$$

- Only a few degrees of freedom need to satisfy this condition for Higgs boson masses above the experimental bound.

- Decoupling of particles only possible for large Yukawa couplings.

- In general, number of degrees of freedom necessary to make the phase transition strongly first order would depend on dispersion relation. For fermions with

$$\mathbf{m}^2(\phi) = \mathbf{h}^2\,\phi^2 + \mu^2\,, \qquad\qquad < \phi(T=0) > \, = 246\;GeV$$



Interesting Example: Model with Charginos and Neutralinos

$$\boxed{\begin{aligned}\mathcal{L} &= H^\dagger\left(h_2\,\sigma_a\tilde{W}^a + h_2'\,\tilde{B}\right)\tilde{H}_2 + H^T\epsilon\left(-h_1\,\sigma_a\tilde{W}^a + h_1'\,\tilde{B}\right)\tilde{H}_1 \\ &+ \frac{M_2}{2}\,\tilde{W}^a\tilde{W}^a + \frac{M_1}{2}\,\tilde{B}\tilde{B} + \mu\,\tilde{H}_2^T\epsilon\tilde{H}_1 + h.c.\end{aligned}}$$

- The same low energy Lagrangian as for gauginos and Higgsinos as in the supersymmetric case, but with arbitrary Yukawa couplings. In the particular case of the MSSM, $h_2 = g\sin\beta/\sqrt{2}$, $h_1 = g\cos\beta/\sqrt{2}$

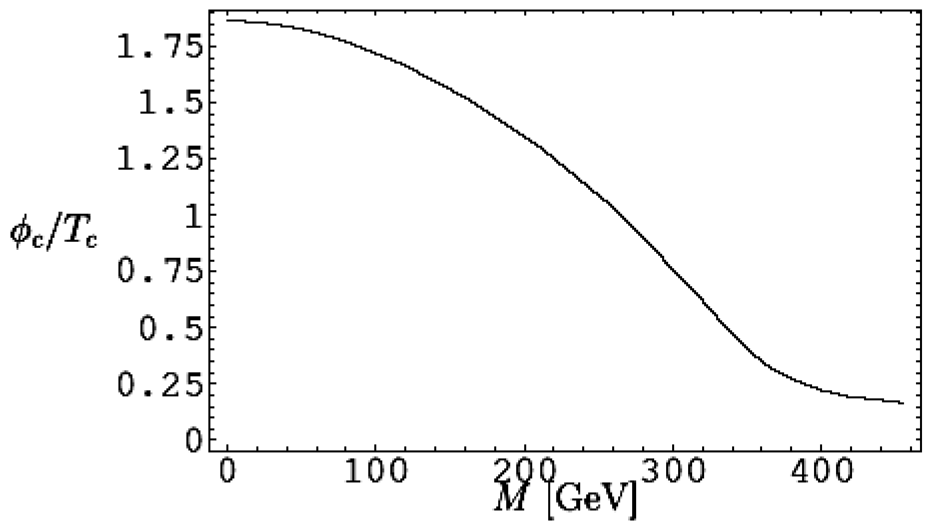
- In the MSSM, the couplings are too weak to influence the electroweak phase transition. Larger values of these couplings necessary. Let's call

$$h_+ = \frac{h_1 + h_2}{2} \qquad\qquad h_- = \frac{h_1 - h_2}{2}$$

Phase Transition strength

- Particular case, $\mathbf{h}' = \mathbf{0}$, 12 degrees of freedom (two Dirac particles and two Majorana, with similar masses coupled to the Higgs)

$$\mu = -\mathbf{M}_2, \quad \mathbf{M}_2 = \mathbf{M}, \qquad \mathbf{h}_+ = \mathbf{2}, \quad \mathbf{h}_- = \mathbf{0}$$

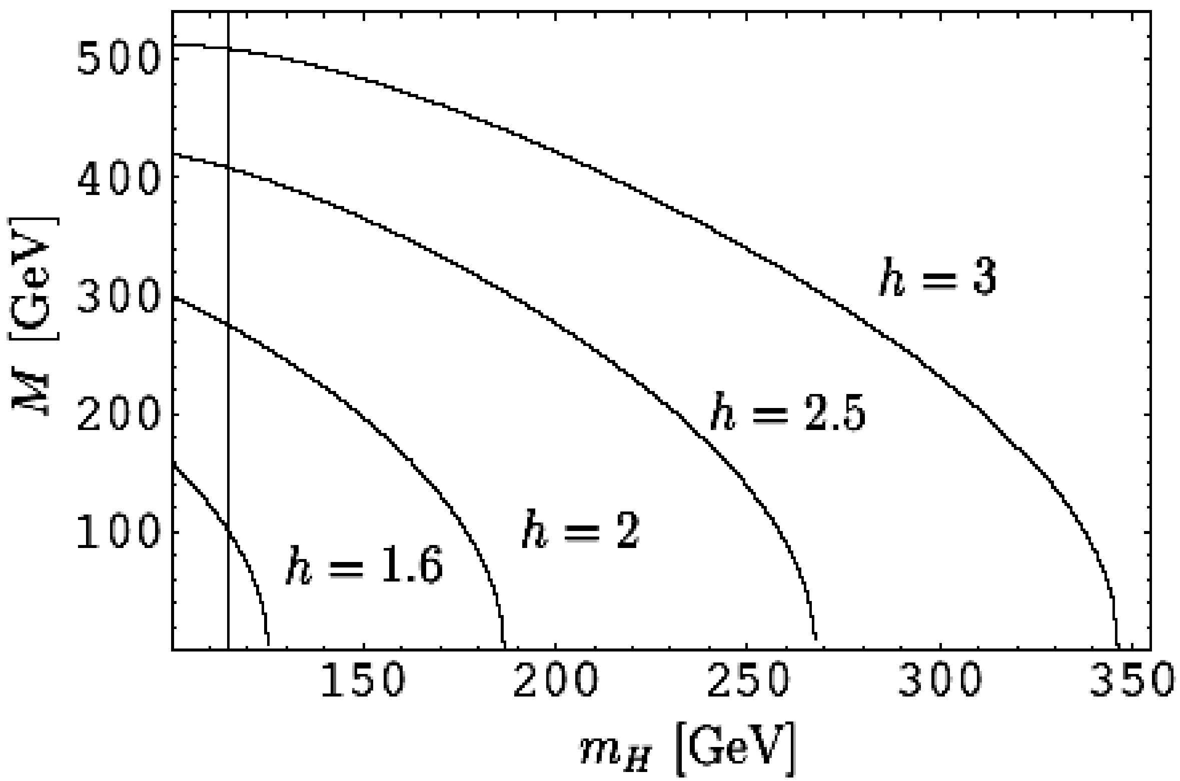


$\mathbf{m_H = 120\ GeV}$

Preservation of Baryon Number

- Phase transition strength diminishes for large values of the Higgs mass. Here both Yukawas take values equal to h, and M is as before.

$\mu = -\mathbf{M}_2, \quad \mathbf{M}_2 = \mathbf{M}$



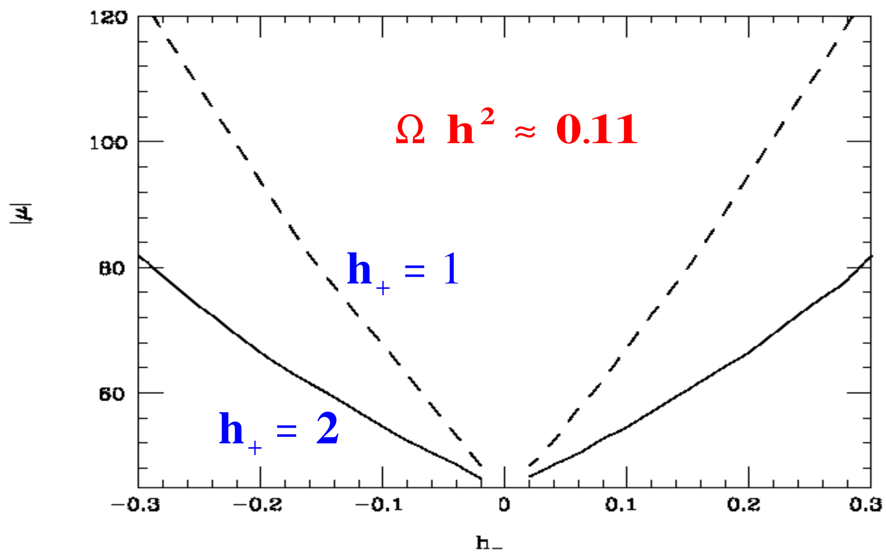
Dark Matter

- In the limit under analysis, the Bino decoupled and one of the neutralinos decouple from the Higgs boson. It is a pure Higgsino state with mass $|\mu|$.

- Relevant cross section is induced by s-channel Z diagram. Relevant coupling vanish for equal values of the Yukawa couplings:

$$\boxed{\tilde{\chi} \simeq \frac{h_1}{\sqrt{h_1^2+h_2^2}}\tilde{H}_2 + \frac{h_2}{\sqrt{h_1^2+h_2^2}}\tilde{H}_1}$$

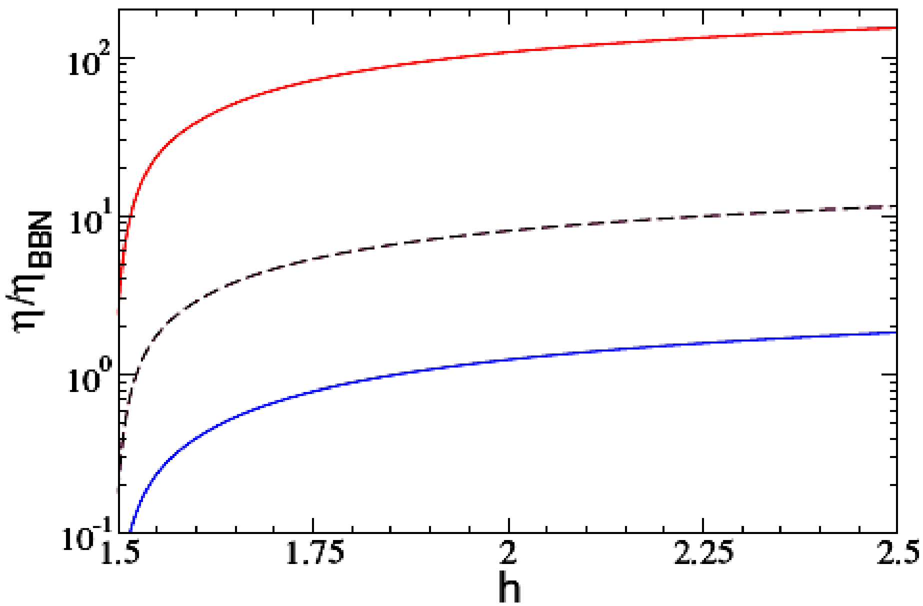
$$\boxed{g_{\tilde{\chi}Z} \propto \frac{h_1^2-h_2^2}{h_1^2+h_2^2}}$$



Dark matter imposes an interesting correlation between its mass and the difference of Yukawa couplings.

Baryon asymmetry generation

- Ratio of the baryon asymmetry to the one determined by WMAP, for maximal values of the CP-violating phase, for equal values of the Yukawa couplings, for M = 100 GeV.

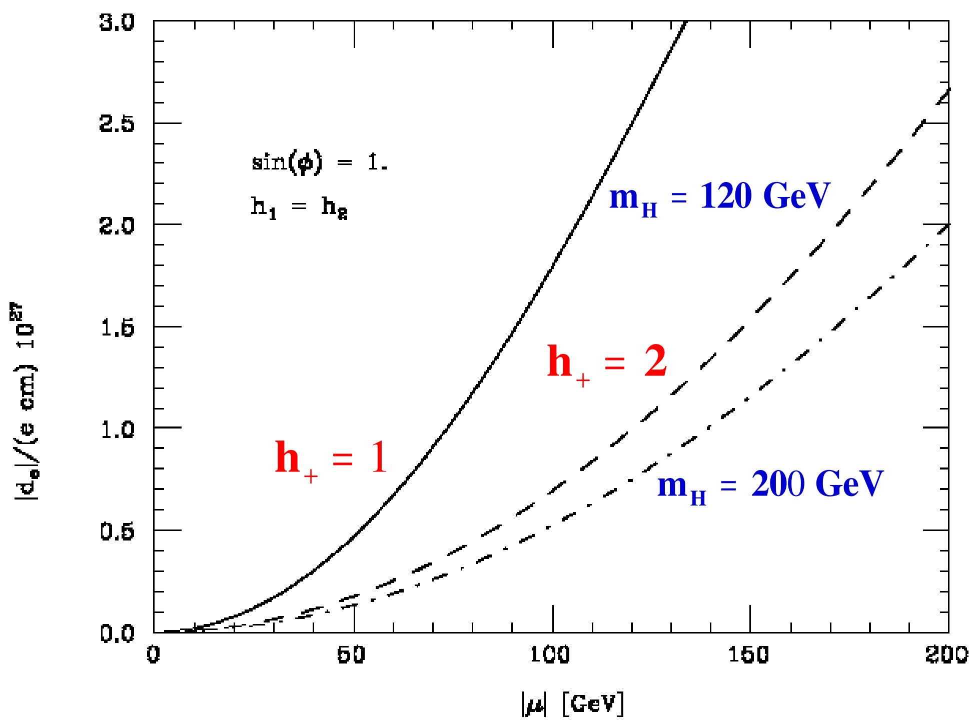


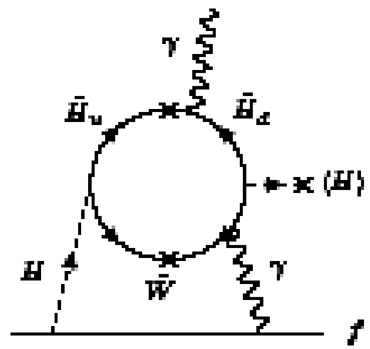
From below, results are shown for the case of no light sfermions, a 500 GeV squark and a light squark

- Phases of order one necessary to generate baryon asymmetry.

Electron electric dipole moment

- For heavy sfermions, e.d.m. induced at two loops





Present bound, of order 1.6, does not constrain the model. But the expected improvement of bound by three to five orders of magnitude, sufficient to test model, even for h = 2.

Conclusions

- Electroweak Baryogenesis in the MSSM demands a light Higgs, with mass lower than 120 GeV and a stop lighter than the top-quark.
- Dark Matter : Even lighter neutralinos. If coannihilation channel relevant, searches for stops at hadron colliders difficult.
- To be tested by electron e.d.m. experiments, Tevatron, LHC and LC.
- nMSSM provides an attractive phenomenological scenario.
- New Scenario with TeV fermions, strongly coupled to the Higgs.
- Model with charginos and neutralinos, consistent with baryogenesis, dark matter and precision electroweak data. To be tested soon by LHC and e.d.m. experiments.