# The Supersymmetric Origin of Matter
## (Both the obscure and the bright)


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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, Nucl. Phys. B , in press
C. Balazs, M. Carena, A. Menon, C. Morrissey and C.W., hep-ph/0412264, Phys. Rev. D, in press

Linear Collider Workshop, Stanford, March 20, 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.

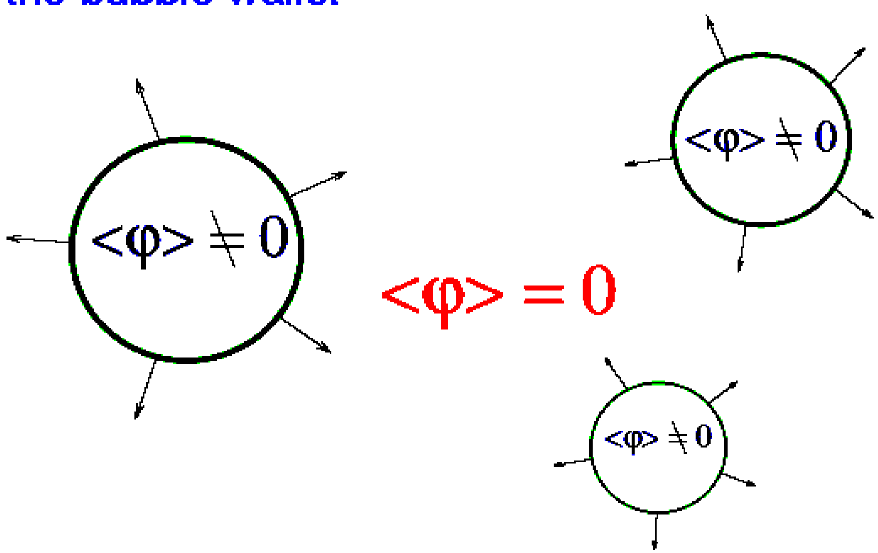
- Baryogenesis from out of eq. weak scale mass particle decay: Difficult, since non-equilibrium condition is satisfied for small couplings, for which CP-violating effects become small (example: resonant leptogenesis).

  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

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

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

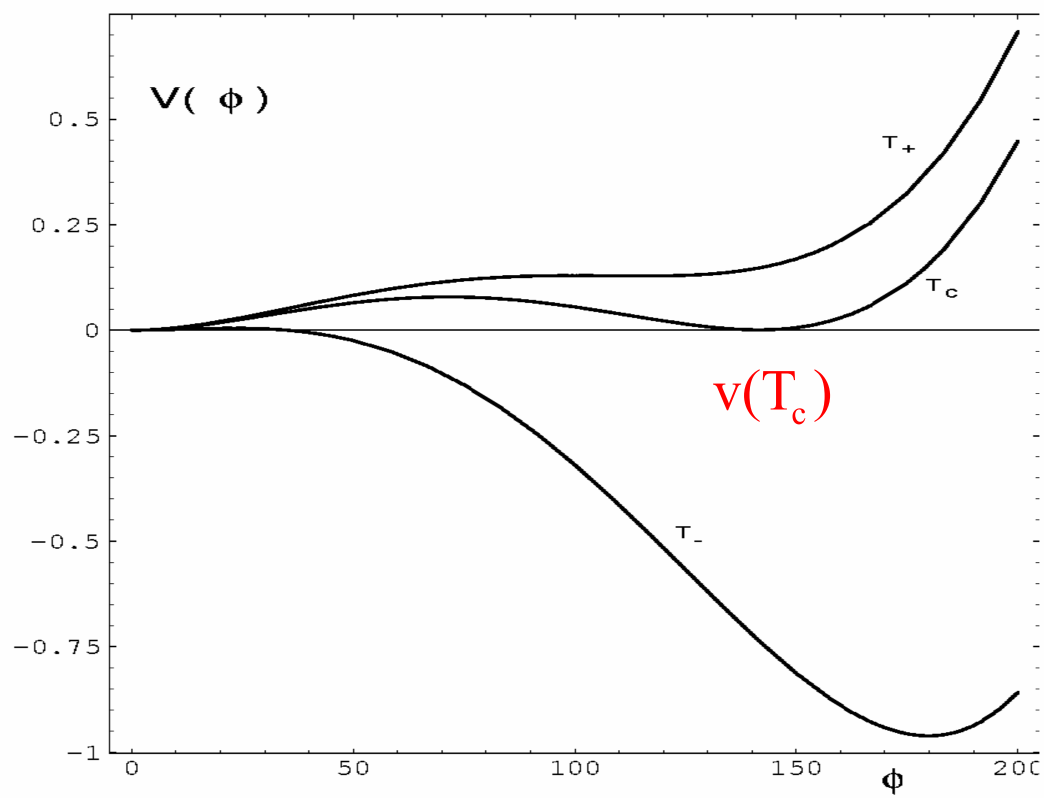
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

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

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

***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***

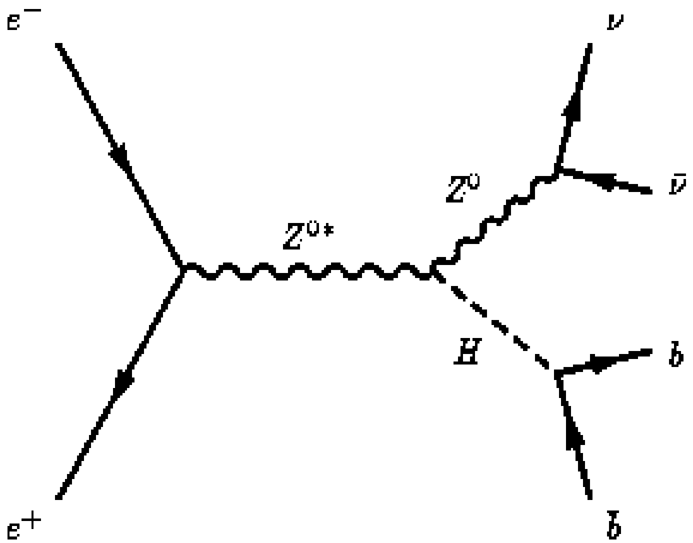
***E receives contributions proportional to the sum of the cube of all light boson particle couplings***

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

***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

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

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

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

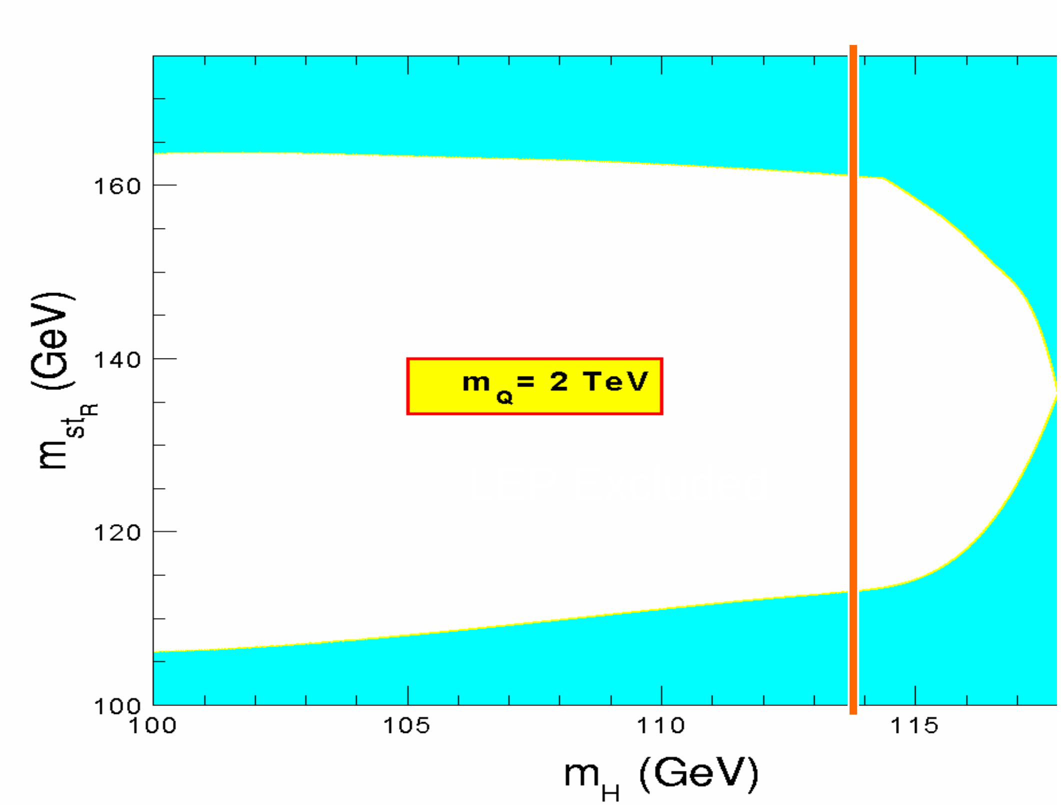
***Higgs masses up to 120 GeV may be accomodated***

# 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

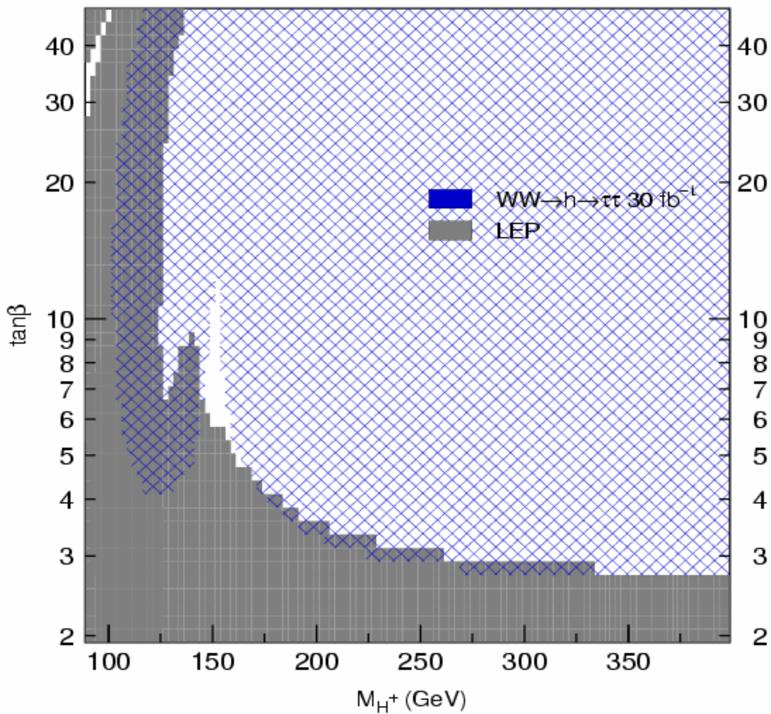
- Higgs searches beyond LEP:

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

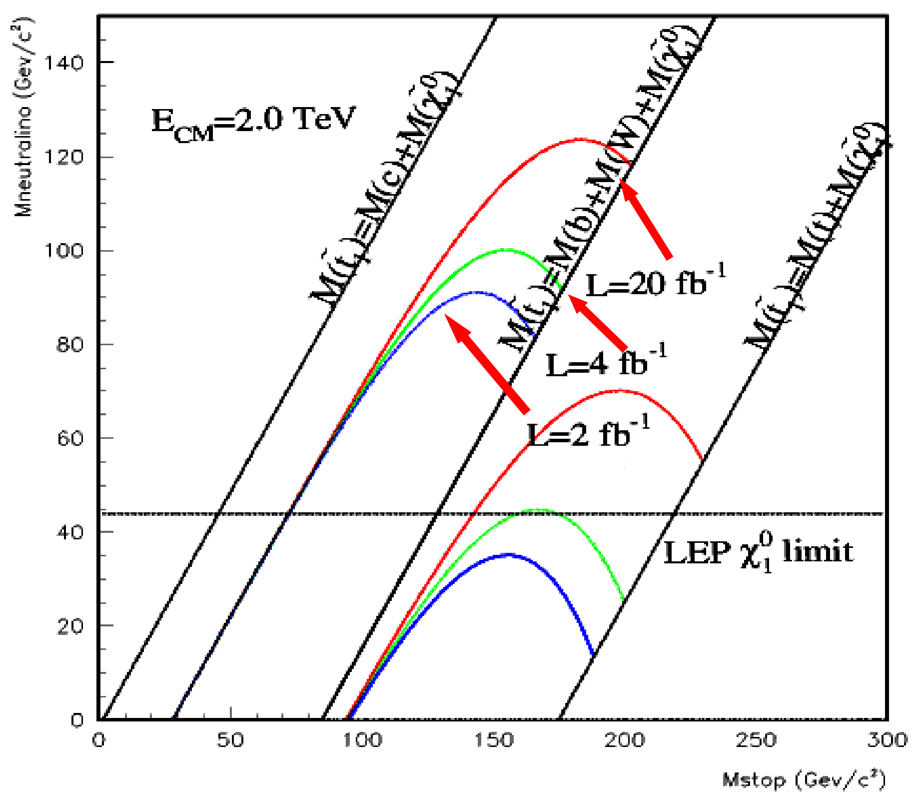
Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ 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

M. Carena, C. Balazs, A. Menon, D. Morrissey, C.W., hep-ph/0412264

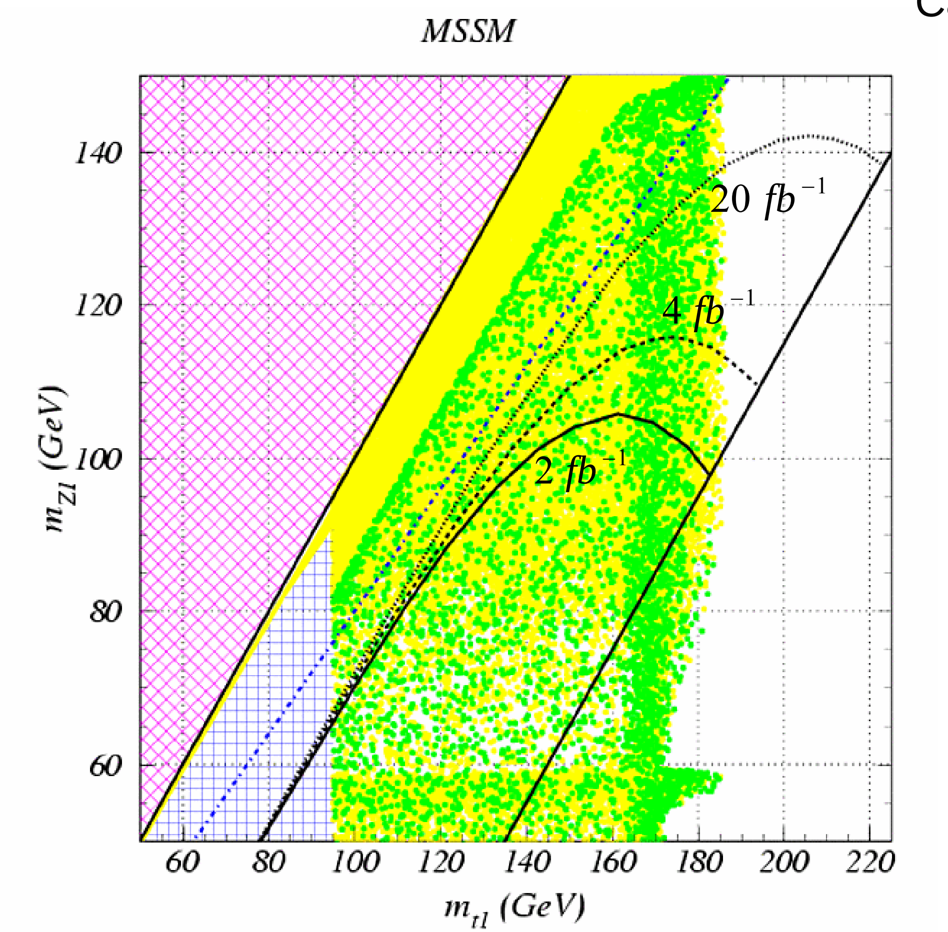
- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

- 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.

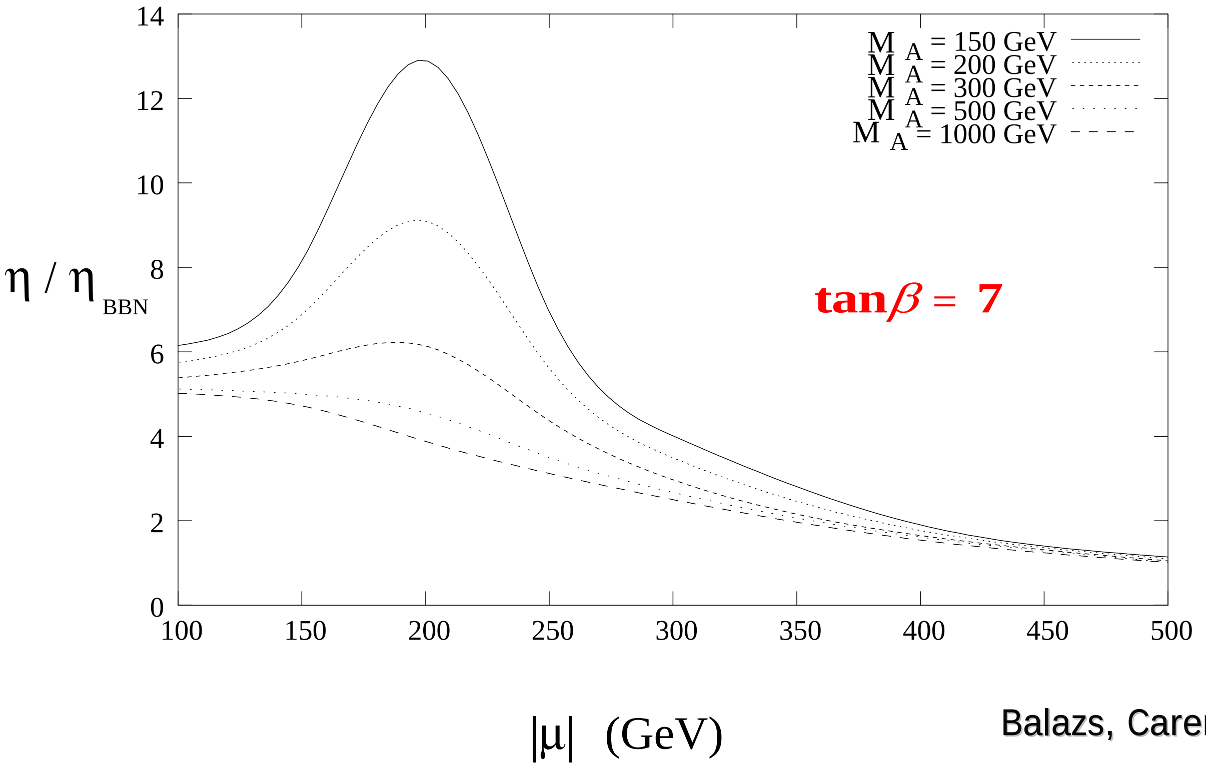
LHC will have equal difficulties. Searches become easier at a Linear Collider !

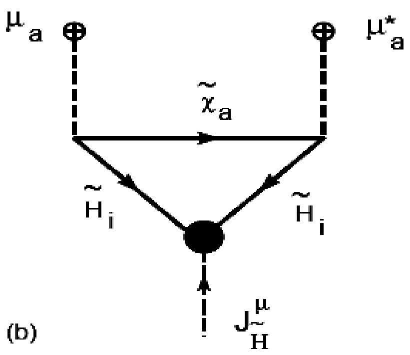
See talk by Caroline Milstene, this session.

# 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 $\tan\beta$

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



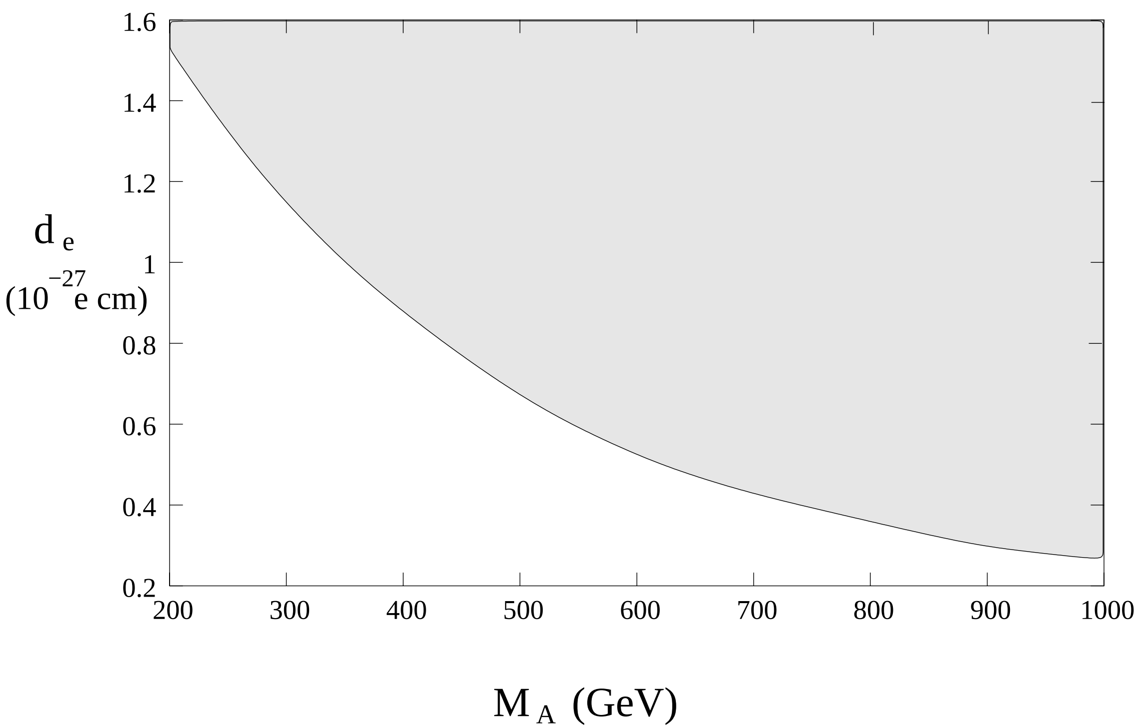

Balazs, Carena, Menon, Morrissey, C.W.'04

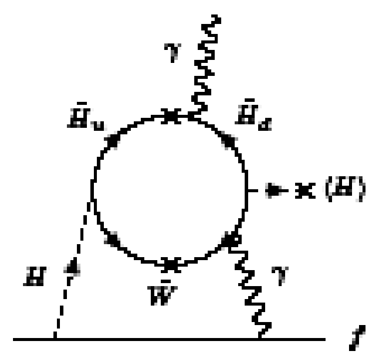
# Electron electric dipole moment

- 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. (Low energy spectrum is like a Stop plus Split Supersymmetry ).
- Chargino mass parameters scanned over their allowed values. The electric dipole moment is constrained to be smaller than

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

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

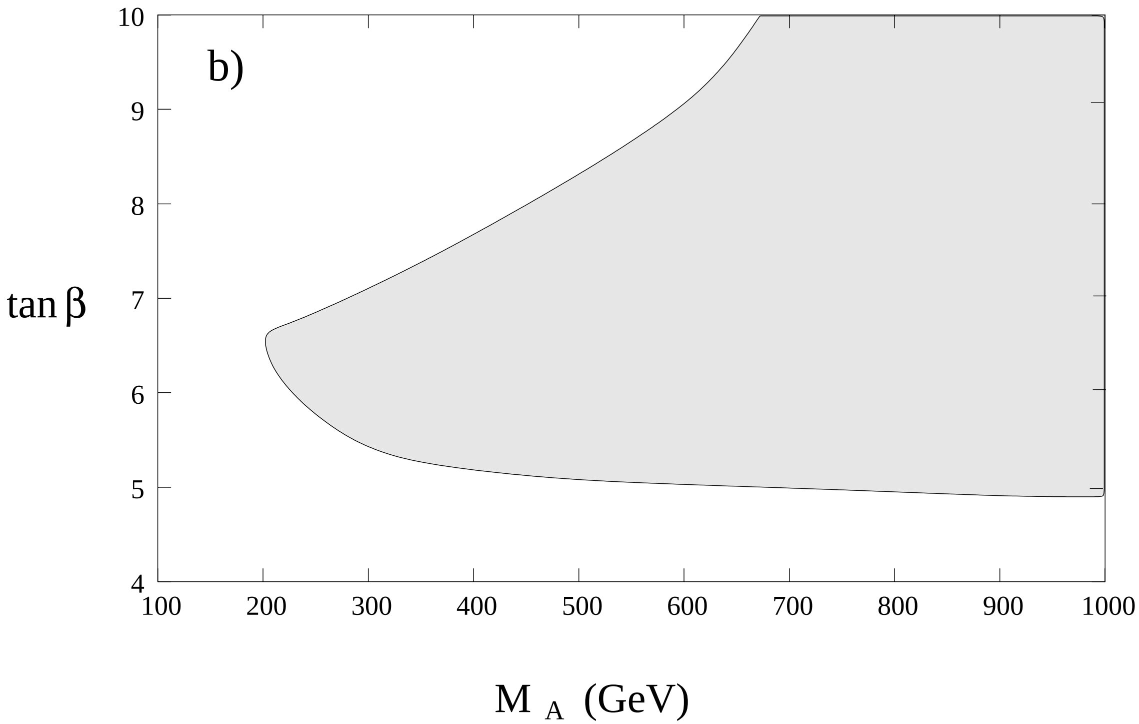


# Allowed region of parameters

- 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



# Flavor violating processes

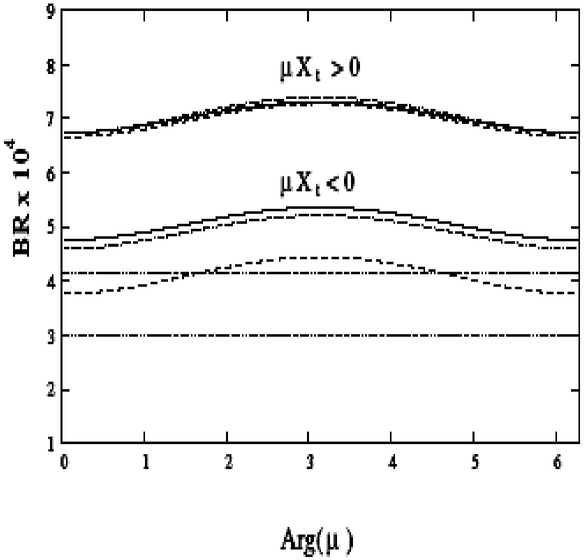
- Assuming minimal flavor violation, and three different set of values of the parameters mu and $M_1$ consistent with al constraints, and assuming gaugino mass unification, we plot the branching ratio of a b to s photon as a funcion of the argument of $M_1$.

- Experimental value is given by

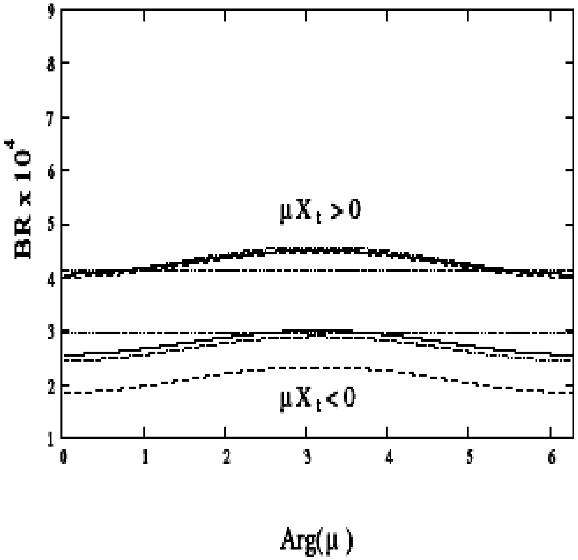
$$\boxed{\mathrm{BR}(b \to s\gamma) = (3.54^{+0.30}_{-0.28}) \times 10^{-4}}$$

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

$M_A$ = 200 GeV



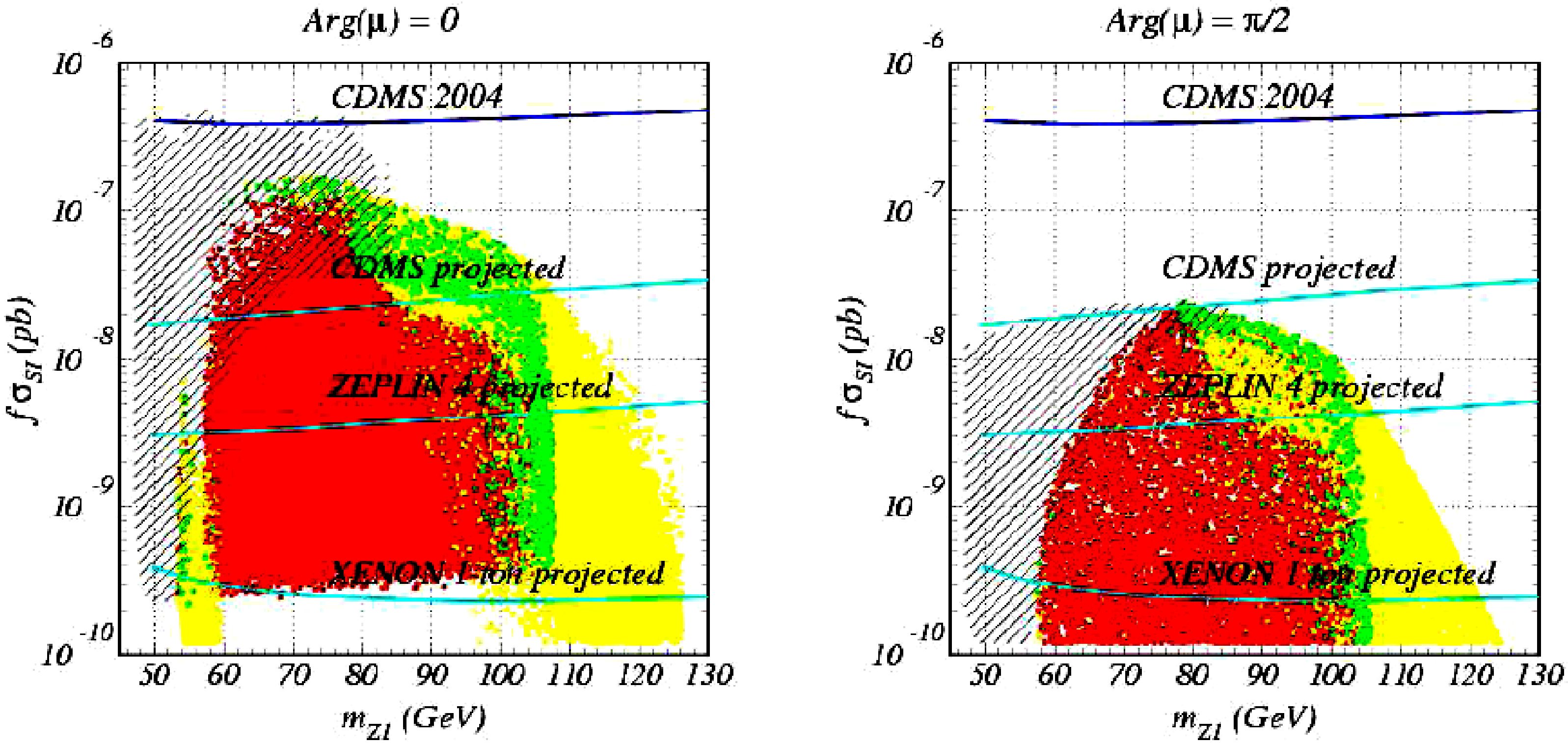

$M_A$ = 1 TeV



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

- 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 $\dfrac{\partial V}{\partial \phi_s} = 0$ , 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.

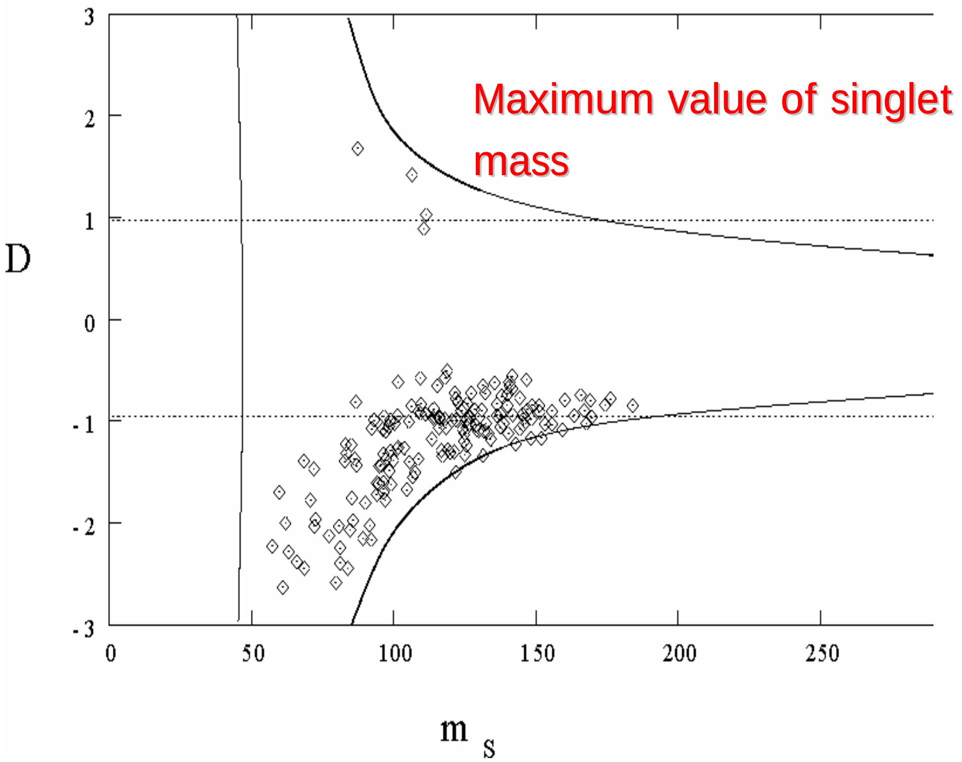
# Parameters with strongly first order transition

- 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

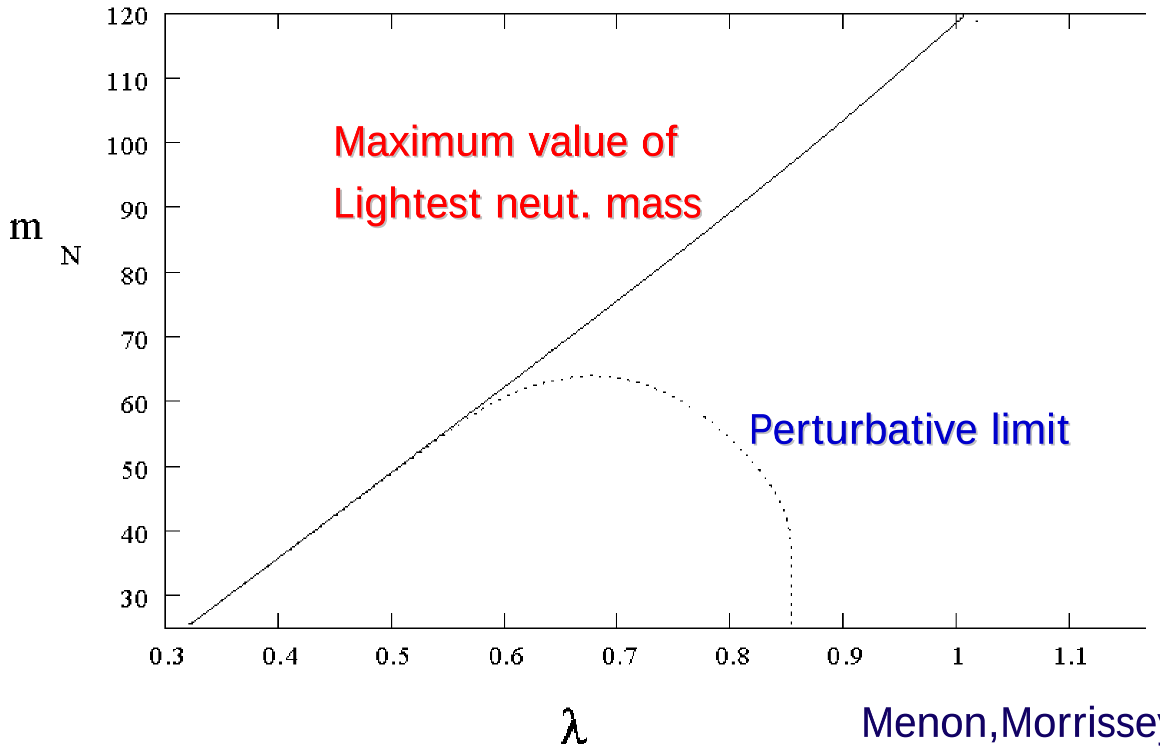
- Values constrained by perturbativity up to the GUT scale.



# Upper bound on Neutralino Masses

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

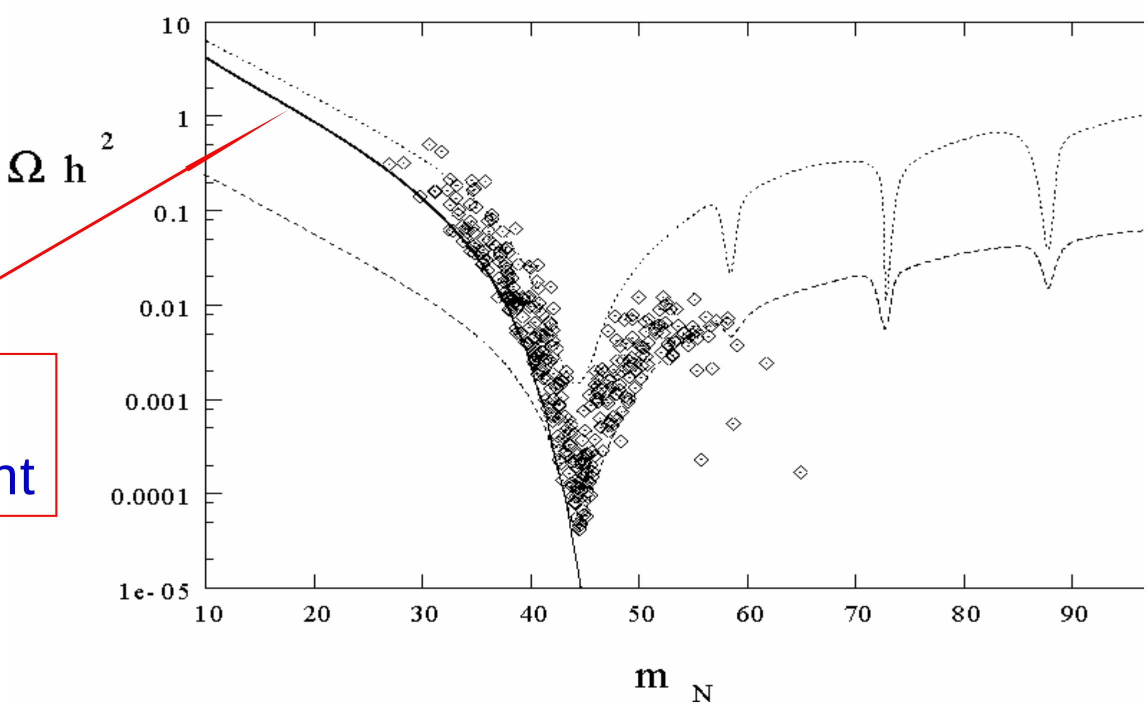
Values of neutralino masses below dotted line consistent with perturbativity constraints.




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.




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 $\lambda$ **and** $\mathbf{a}_{\lambda}$

- Values of $\lambda$ 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.

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

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

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

- The value of $\eta$ 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

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

(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, to appear in Nucl. Phys. B

# 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:

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

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

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

- 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,

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

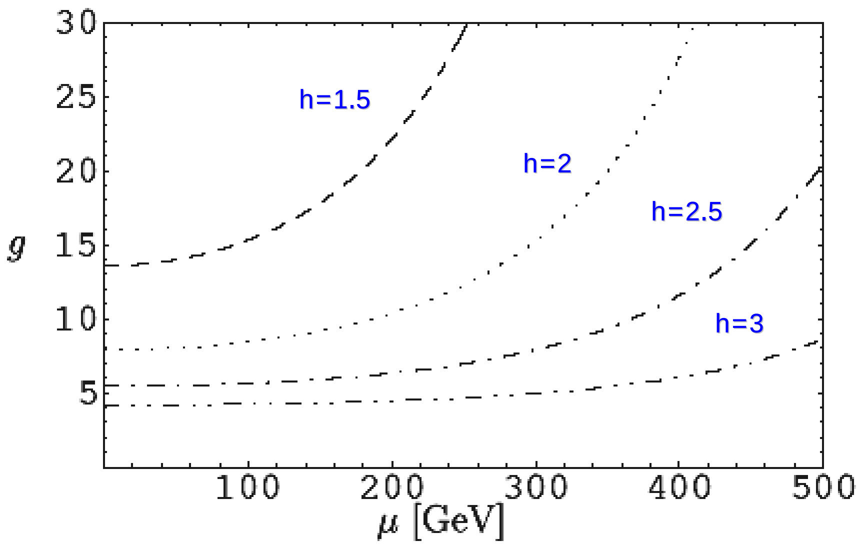
- This happenes at a lower temperature and larger values of the Higgs v.e.v. The condition of baryon asymmetry preservation is given by

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

- 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

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



# Interesting Example: Model with Charginos and Neutralinos

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

- 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, $h_2 = g \sin\beta/\sqrt{2},\ h_1 = g\cos\beta/\sqrt{2}$

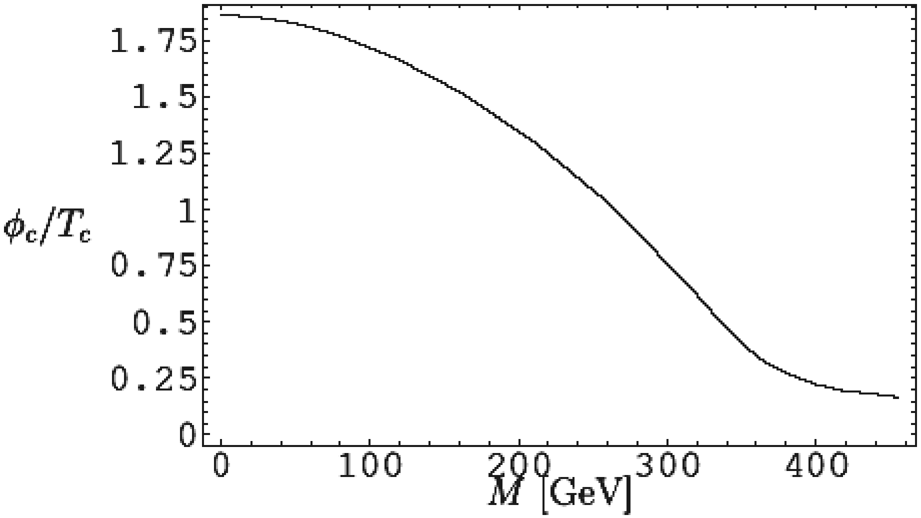
- In the MSSM, the couplings are too weak to influence the electroweak phase transition. Larger values of these couplings necessary. Let's call

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

# 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)

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

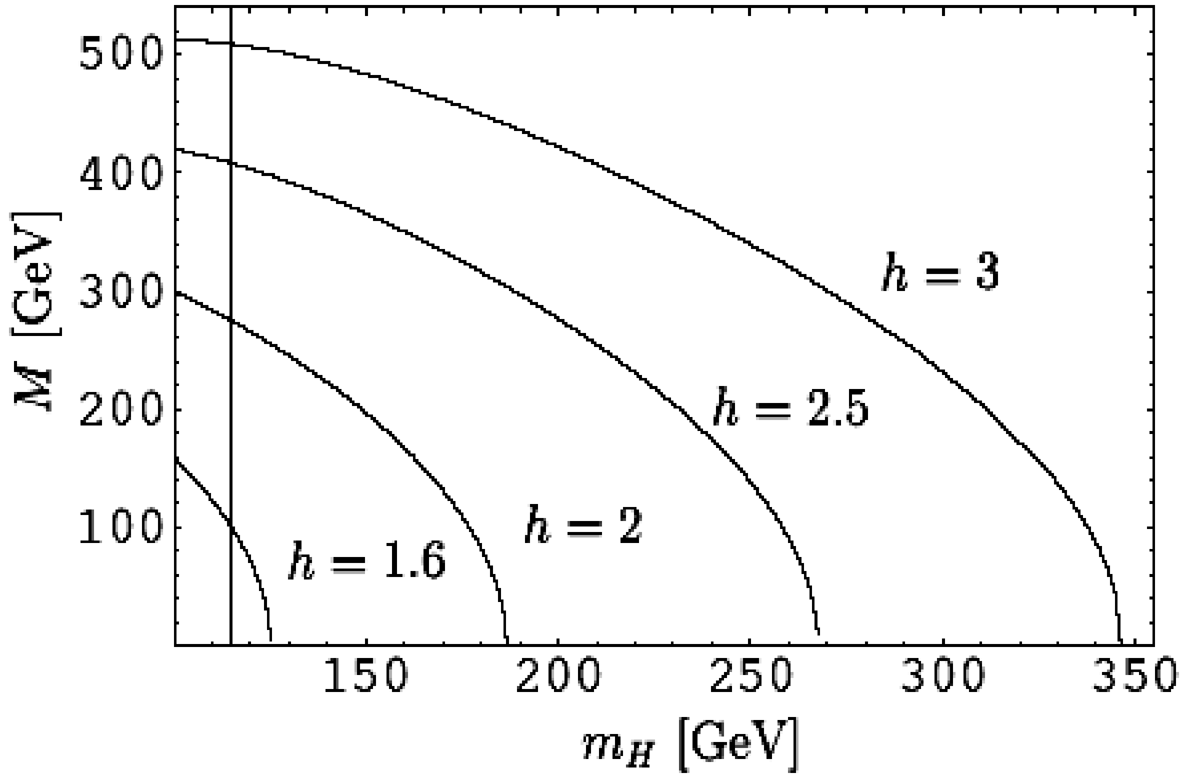



$\mathbf{m_H = 120\ GeV}$

# 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.

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



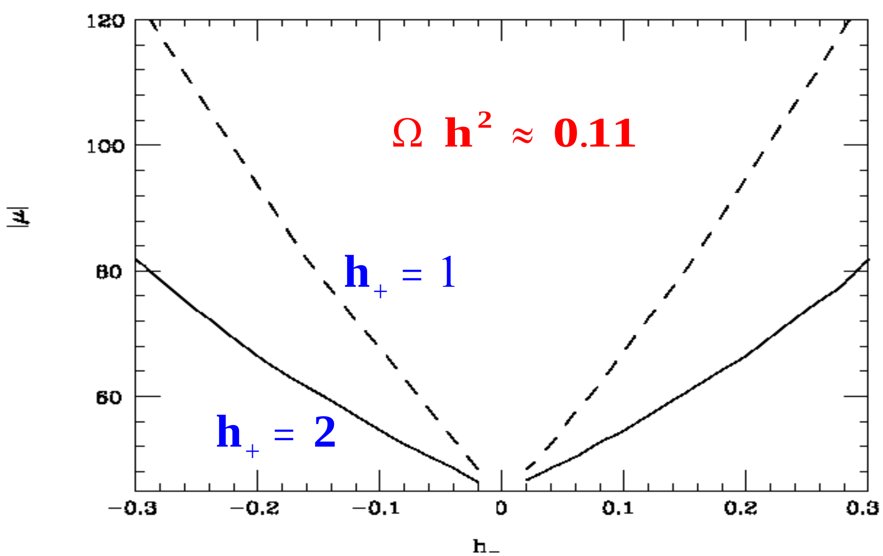
# Dark Matter

- 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:

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

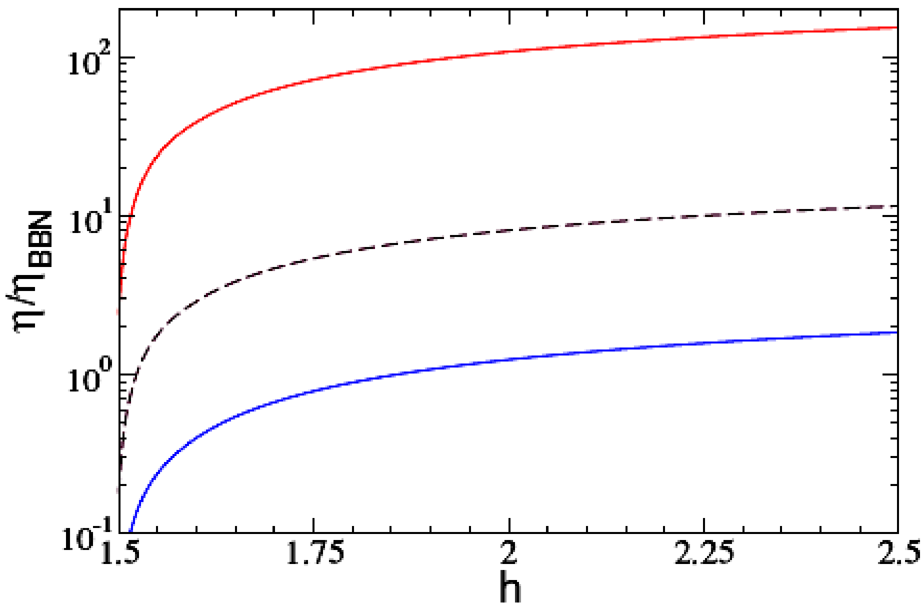
$$\boxed{g_{\tilde{\chi}Z} \propto \frac{h_1^2 - h_2^2}{h_1^2 + h_2^2}}$$




Dark matter imposes an interesting correlation between its mass and the difference of Yukawa couplings.
Values of |h_| larger than 0.15 restricted by precision measurements.

# 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.

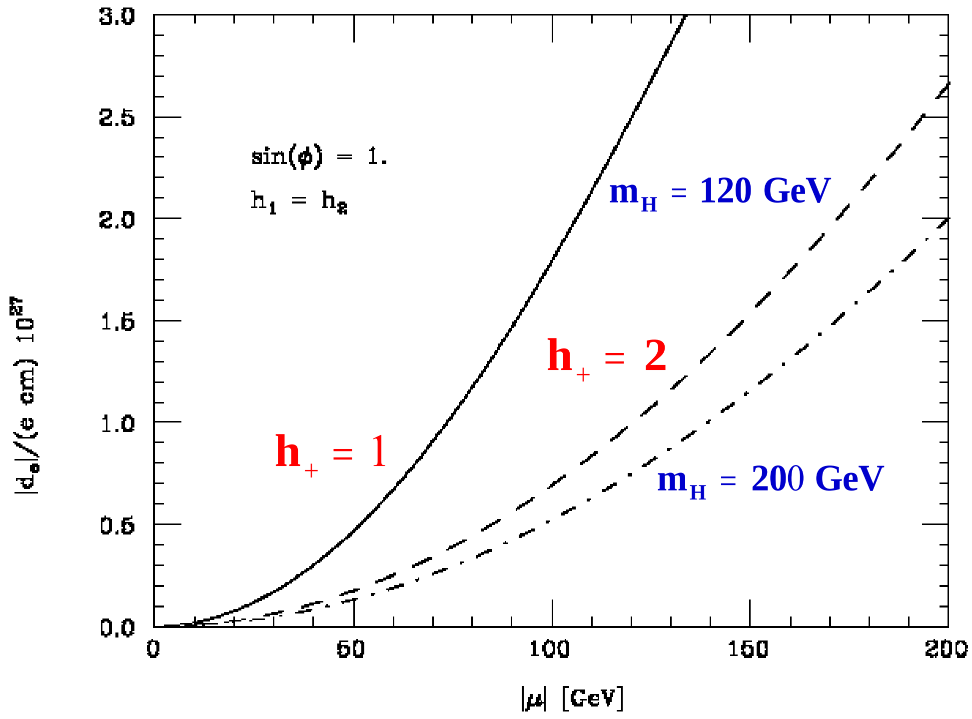


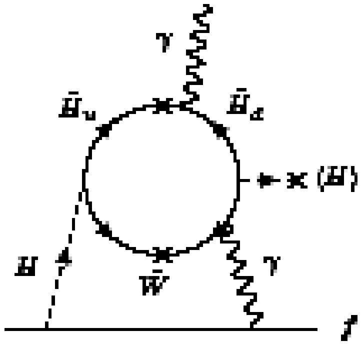

From below, results are shown for the case of no light sfermions, a 500 GeV squark and a light squark

- Phases of order one necessary to generate baryon asymmetry.

# Electron electric dipole moment

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



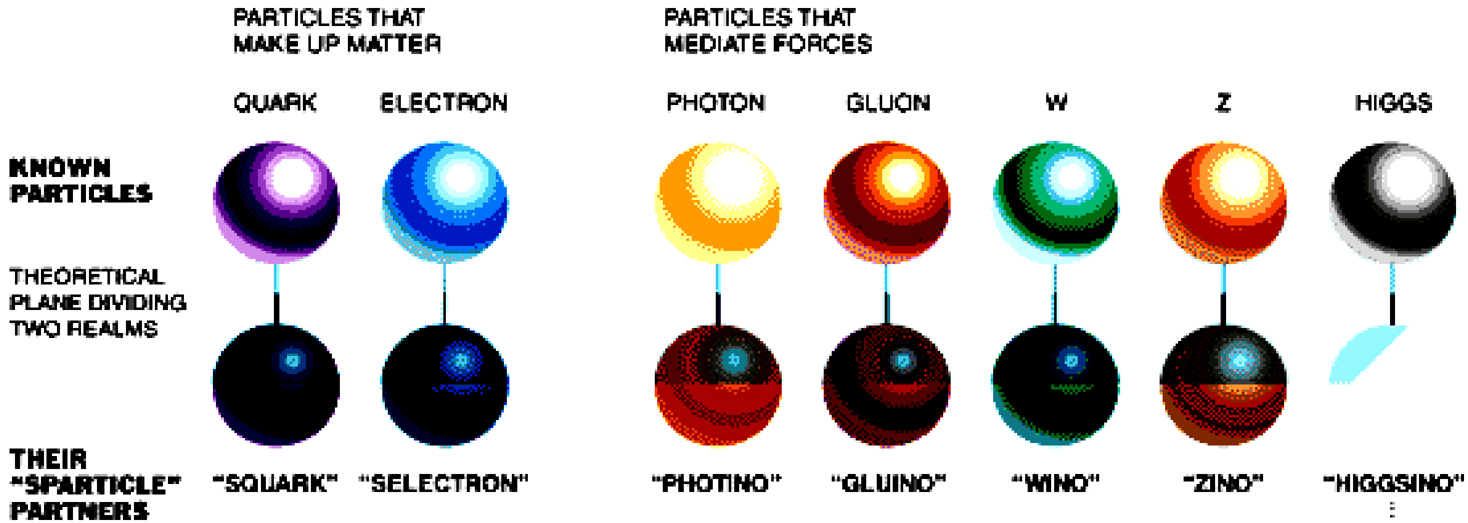

Present bound, of order 1.6, does not constrain the model. But the expected improvement of bound by three to five orders of magnitude, sufficient to test model, even for h = 2.

# 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.

# Supersymmetry

## fermions bosons



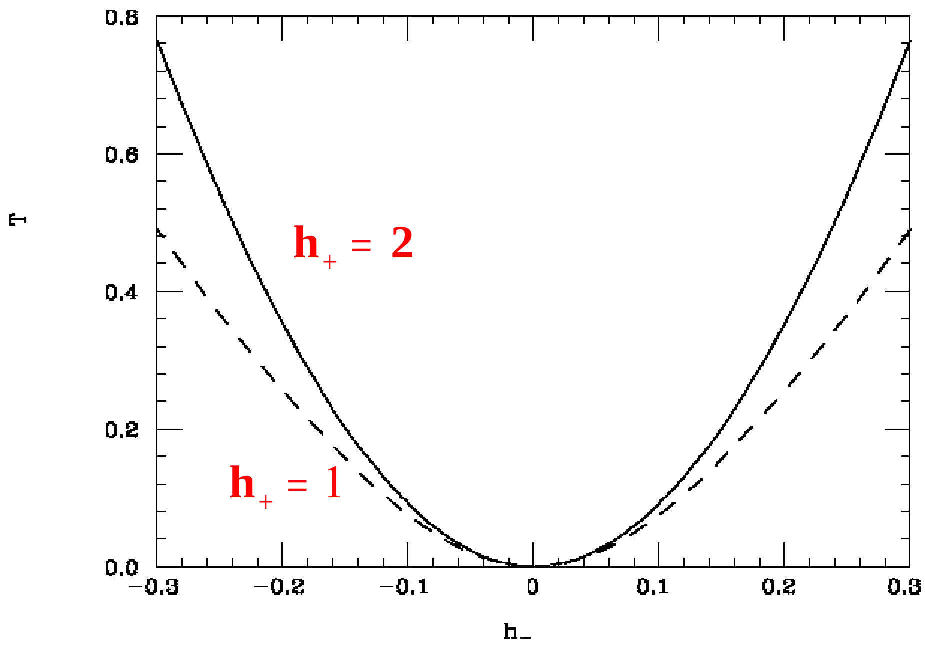

*Photino, Zino and Neutral Higgsino: Neutralinos*

*Charged Wino, charged Higgsino: Charginos*

***Particles and Sparticles share the same couplings to the Higgs. Two superpartners of the two quarks (one for each chirality) couple strongly to the Higgs with a Yukawa coupling of order one (same as the top-quark Yukawa coupling)***

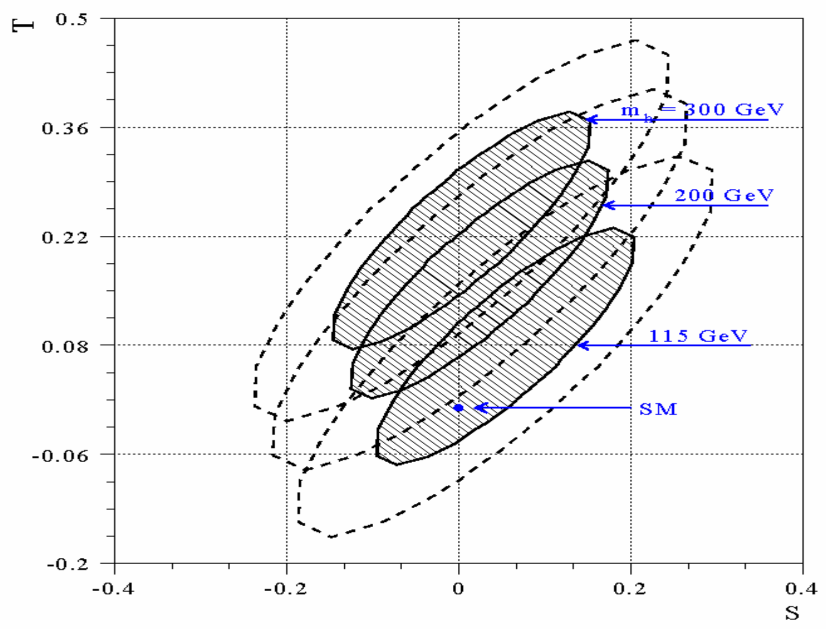
# Precision Measurements

- In spite of heavy fermions, S parameter remains small
- The T parameter, instead, increases with the value of the difference of the Yukawa couplings.



# Allowed values of S and T for different values of the Higgs mass

$$\Delta S = \frac{1}{12\pi} \log \left( \frac{m_h^2}{m_{h_{ref}}^2} \right) \qquad \Delta T = -\frac{3}{16\pi c_W^2} \log \left( \frac{m_h^2}{m_{h_{ref}}^2} \right)$$




- Precision measurement and dark matter are consistent with experimental values, for LSP masses between 45 and 70 GeV and small values of **h**_

# Finite Temperature Effective Potential

$$V(\phi,T) = V_0(\phi) + V_1(\phi,0) + \Delta V_1(\phi,T)$$

where the finite $T$ contribution is given by

$$\begin{aligned}\Delta V_1(\phi,T) &= \sum_{i=b,f}\left[\frac{n_i m_i^2(\phi)T^2}{48} - \frac{\eta_i m_i^4(\phi)}{64\pi^2}\log\left(\frac{m_i^2(\phi)}{T^2}\right)\right] \\ &- \sum_b \frac{m_b^3(\phi)T}{12\pi}\end{aligned}$$

where $\eta_i = n_i(-1)^{2S}$ and $m_i(\phi) \leq 2T$. For large values of the particle masses, $m(\phi) \gg 2T$, the finite $T$-contributions are exponentially suppressed.

$$\begin{aligned}V(T) &= D(T^2 - T_0^2)\phi^2 - E_B T\phi^3 + \frac{\lambda(T)}{2}\phi^4 \\ \frac{v(T_c)}{T_c} &\simeq E_B/\lambda(T_c)\end{aligned}$$

# The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as 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

$$\frac{n_{\bar{p}}}{n_p} \approx 10^{-4}$$

- All observations consistent with a matter dominated Universe (Cohen, Glashow, de Rujula '97)

# Electroweak Baryogenesis in the nMSSM

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

# Chargino and Neutralino Spectrum

- We impose the unification condition on gaugino masses and allow non-vanishing phases for them.
- Chargino and neutralino masses are governed by the size of the parameter $\lambda$ and the singlet v.e.v.
- Chargino spectrum similar to the MSSM, with $\mu \leftrightarrow -\lambda \mathbf{v}_S$

$$\mathbf{M}_{\chi^+} = \begin{bmatrix} \mathbf{M}_2 & \sqrt{2}\,\sin\beta \mathbf{M}_W \\ \sqrt{2}\,\cos\beta \mathbf{M}_W & -\lambda \mathbf{v}_S \end{bmatrix}$$

# Neutralino spectrum

- Neutralino spectrum more complex. Gaugino masses may have phases

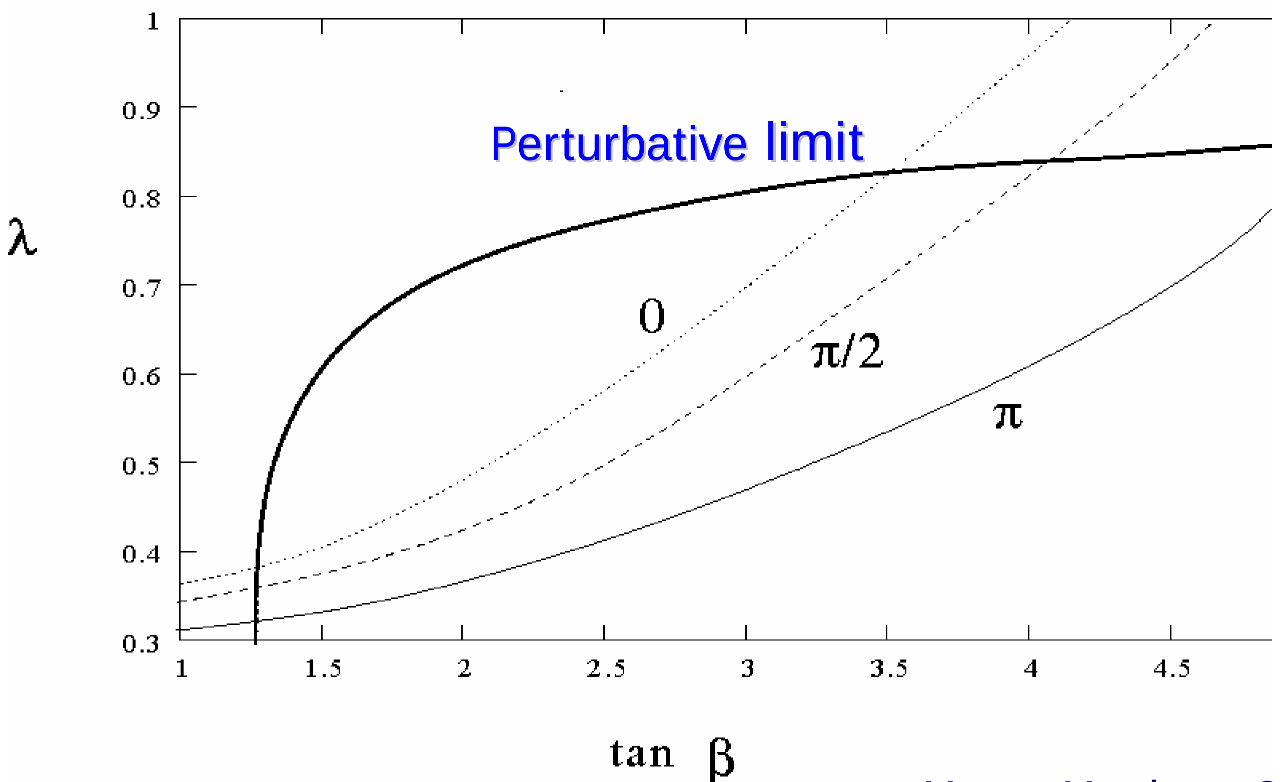
$$\mathbf{M}_{\chi^0} = \begin{bmatrix} \mathbf{M_1} & \bullet & \bullet & \bullet & \bullet \\ \mathbf{0} & \mathbf{M_2} & \bullet & \bullet & \bullet \\ -\mathbf{\cos}\beta\,\mathbf{s_W M_Z} & \mathbf{\cos}\beta\,\mathbf{c_W M_Z} & 0 & \bullet & \bullet \\ \mathbf{\sin}\beta\,\mathbf{s_W M_Z} & \mathbf{\sin}\beta\,\mathbf{c_W M_Z} & \lambda\,\mathbf{v_S} & 0 & \bullet \\ \mathbf{0} & \mathbf{0} & \lambda\,\mathbf{v_2} & \lambda\,\mathbf{v_1} & 0 \end{bmatrix}$$

For $\mathbf{M_1}$ > 100 GeV, lightest neutralino is approximately given by

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

# Values of $\lambda$ vs $\tan\beta$

- Singlet and top-quark Yukawa couplings are not asymptotically free.
- Low values of $\tan\beta$ restricted by top-Yukawa perturbative limit.




Menon,Morrissey,C.W.'04

# Electroweak Baryogenesis

- Due to the presence of tree-level trilinear terms, first order transition may be achieved even if stops are heavy

- One can solve the finite temperature minimization conditions including only the dominant loop effects, to show that

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

where $\tilde{\lambda}^2$ is the effective quartic coupling of the SM-like Higgs, is a necessary, but not sufficient, condition to obtain a first order trans.

- In general, this demands the value of $\mathbf{m_S^2}$ to be not too large

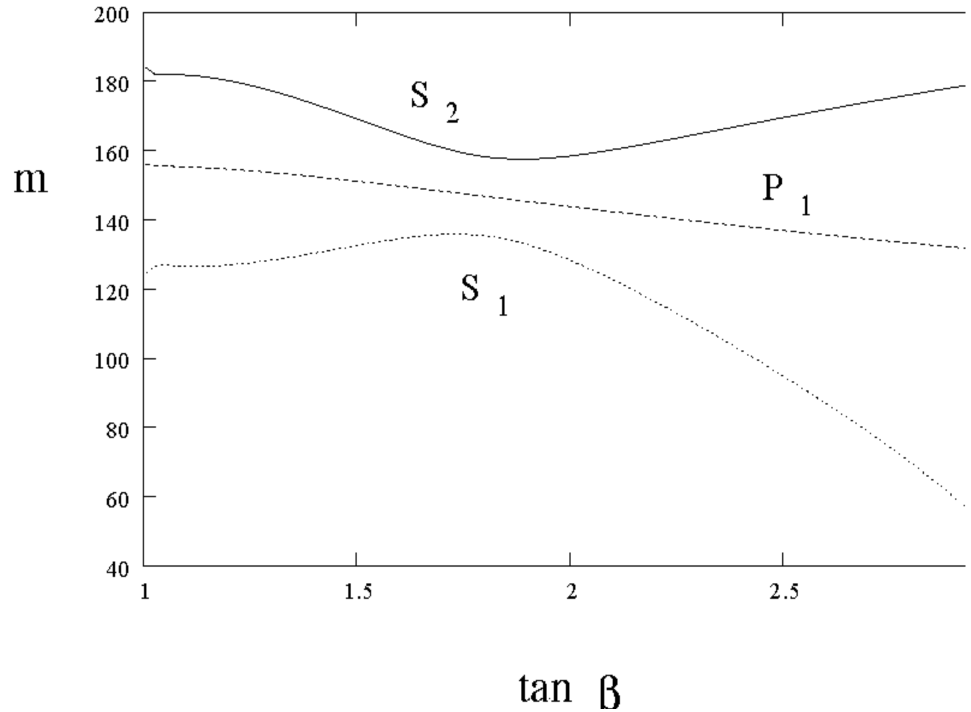
# Light Higgs boson masses

- Even in the case in which the model remains perturbative up to the GUT scale, Higgs masses up to 130 GeV are consistent with electroweak Baryogenesis.

$$M_a = 900\,\text{GeV} \qquad v_S = -300\,\text{GeV}$$

$$a_\lambda = 350\,\text{GeV} \qquad t_S^{1/3} = 150\,\text{GeV}$$

$$\lambda = 0.7$$




Menon,Morrissey,C.W.'04

# Relic Density

- Dark Matter Relic Density depends crucially on neutralino mass and composition

- We assumed all squarks and sleptons to be heavier than 300 GeV, playing no relevant role in annihilation cross sections

- Since lightest neutralinos are lighter than 70 GeV, Z-pole s-channel annihilation cross section is most relevant in determining the final relic density

- The presence of three light Higgs bosons also plays a role, when the neutralino masses are close to the resonance region

# Electroweak Baryogenesis and

# New Fermions, strongly coupled to the Higgs

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

# Large Yukawa Couplings in low energy SUSY

- Large Yukawa couplings may be obtained in strongly coupled SUSY theories.

Batra, Delgado, Kaplan, Tait '04

- Take the recently proposed theory, based on $\boxed{SU(3)_C \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y}$

- First and second generations transform under the first SU(2).
Third generation and Higgs fields under the second SU(2), which becomes strongly coupled at the weak scale.

- It has a bifundamental, whose v.e.v., which we'll call u, breaks the two SU(2)'s to the diagonal one, and a singlet field, with superpotential

$$\boxed{W = M_\Sigma \Sigma\Sigma + \lambda S H_1 H_2 + M_S S^2}$$

# Supersymmetry Breaking

- Let's assume that the gaugino masses of the two SU(2) groups fulfill the following relation

$$\boxed{\mathcal{M}_1,\ M_\Sigma \gg g_2 u, \qquad \mathcal{M}_2 \ll g_2 u}$$

- Under those conditions, the weakly coupled SU(2) gaugino as well as the bifundamental Higgsino decouple from the low energy theory.

- Low energy Wino is strongly coupled to Higgs and Higgsinos, and acquires a mass

$$\boxed{M_2 \simeq \mathcal{M}_2 - \frac{g_2^2 u^2}{M_\Sigma}}$$

# Effective Yukawa Couplings

- More precisely, low energy wino mixes mostly with the bifundamental Higgsino with mixing angle,

$$\boxed{\sin\theta_\Sigma \simeq g_2 u/M_\Sigma.}$$

- The Yukawa couplings are then given by

$$\boxed{\begin{aligned} h_1 &\simeq g_2 \cos\theta_\Sigma \cos\beta/\sqrt{2} \\ h_2 &\simeq g_2 \cos\theta_\Sigma \sin\beta/\sqrt{2} \end{aligned}}$$

- While the Higgs boson mass may be much larger than in the MSSM

$$\boxed{m_H^2 \simeq \frac{\lambda^2 v^2}{8} \sin^2 2\beta + (\mathrm{loop-effects}) + (\mathrm{D-term})}$$

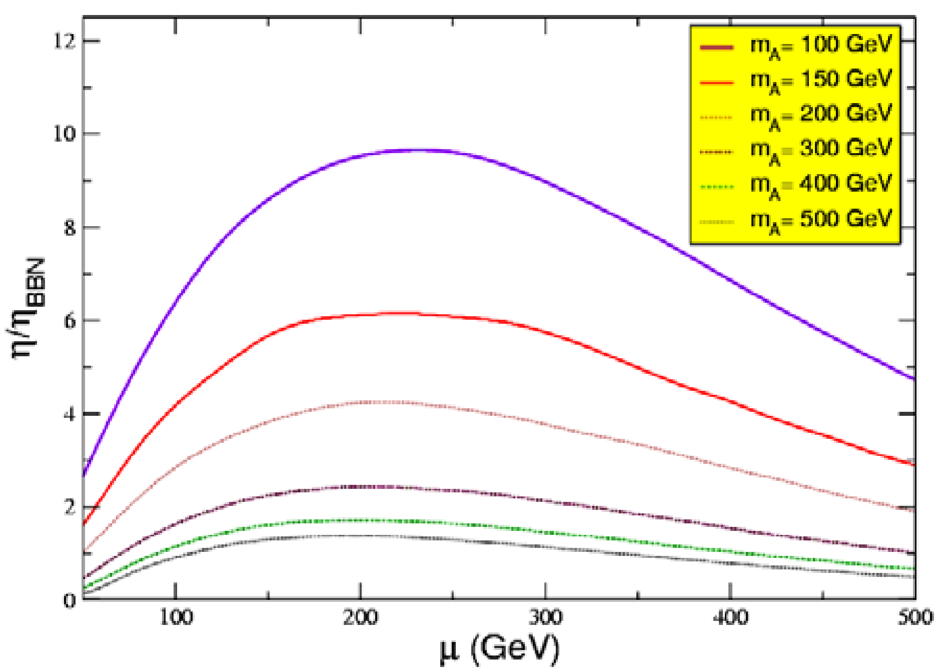
- The strong interactions keep $\lambda$ asymptotically free !

# Baryon Asymmetry Generation

# New sources of CP violation from the sfermion sector

- Generation of the baryon asymmetry: Charginos with masses $\mu$ and $M_2$ play most relevant role.
- CP-violating Sources depend on $\arg(\mu M_2)$
- Higgs profile depends on the mass of the heavy Higgs bosons.

$\tan\beta = 10$ $\quad M_2 = \mu$




We plot for maximal mixing: within uncertainties, values of $\sin\phi_\mu \geq 0.05$ preferred

*Gaugino and Higgsino masses of the order of the weak scale highly preferred*

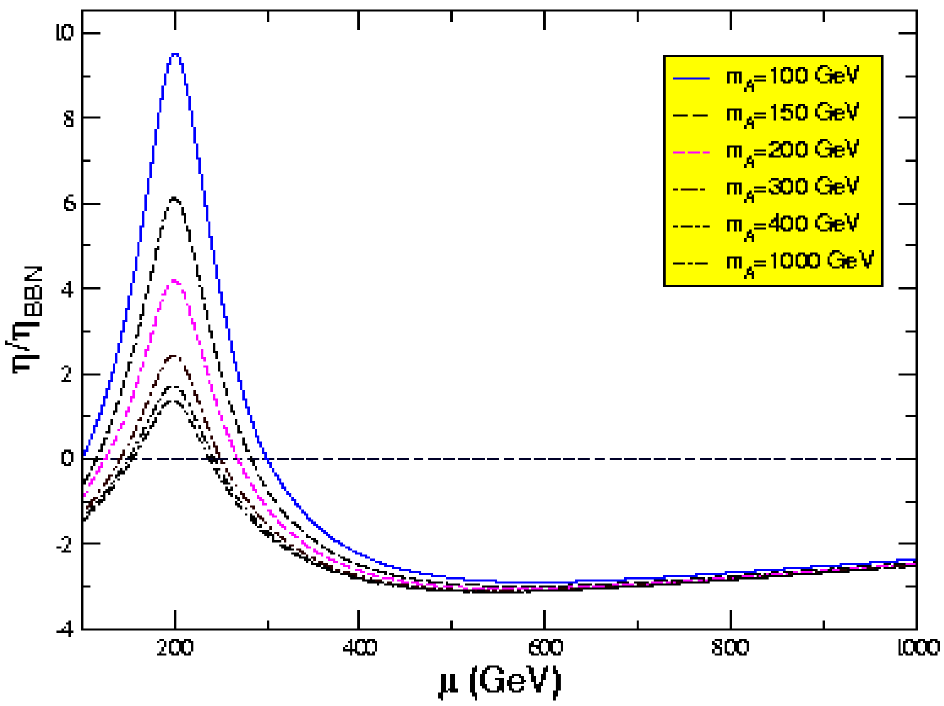
*Large CP-odd Higgs mass values are acceptable*

***M.Carena, Quiros,. Seco and C.W.'02***

# Baryon Asymmetry Dependence on the Chargino Mass Parameters

$\tan\beta = 10$ $M_2 = 200$ GeV

*Results for maximal CP violation*




***Gaugino and Higgsino masses of the order of the weak scale highly preferred***

*M.Carena, M.Quiros, M. Seco and C.W. '02*

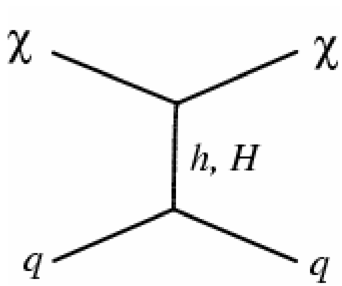
***Baryon Asymmetry Enhanced for*** $M_2 = |\mu|$

***Even for large values of the CP-odd Higgs mass, acceptable values obtained for phases of order one.***

# Direct Dark Matter Detection

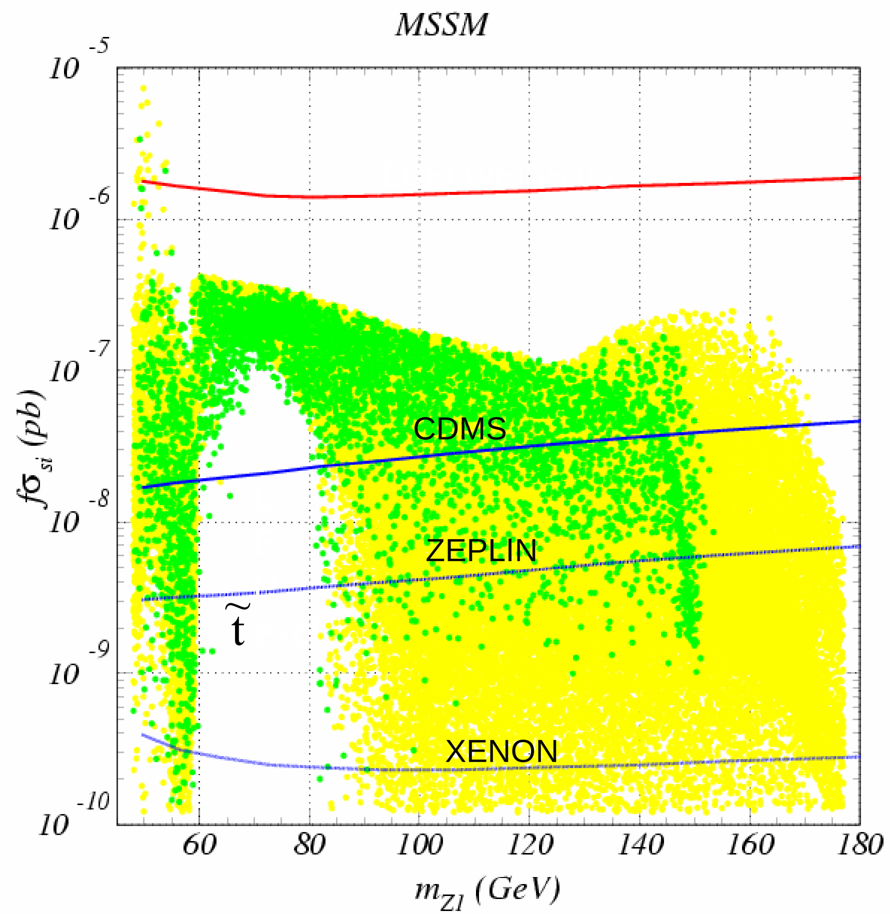
$\not{E}_T$ at colliders important evidence of DM candidate,
but, stability of LSP on DM time scales cannot be chekced at colliders

- Neutralino DM is searched for in neutralino-nucleon scattering exp. detecting elastic recoil off nuclei




upper bounds on Spin independent cross sections

Next few years: $\sigma_{SI} \approx 10^{-8}\,\mathrm{pb}$
Ultimate goal: $\sigma_{SI} \approx 10^{-10}\,\mathrm{pb}$




small $\sigma_{si}$ for large $\mu$ : co-annihilation and h-resonant regions

Balazs, MC, Wagner '04

# Why Supersymmetry ?

- Helps to stabilize the weak scale—Planck scale hierarchy

- Supersymmetry algebra contains the generator of space-time translations.
  Necessary ingredient of theory of quantum gravity.

- Minimal supersymmetric extension of the SM :
  Leads to Unification of gauge couplings.

- Starting from positive masses at high energies, electroweak symmetry breaking is induced radiatively.

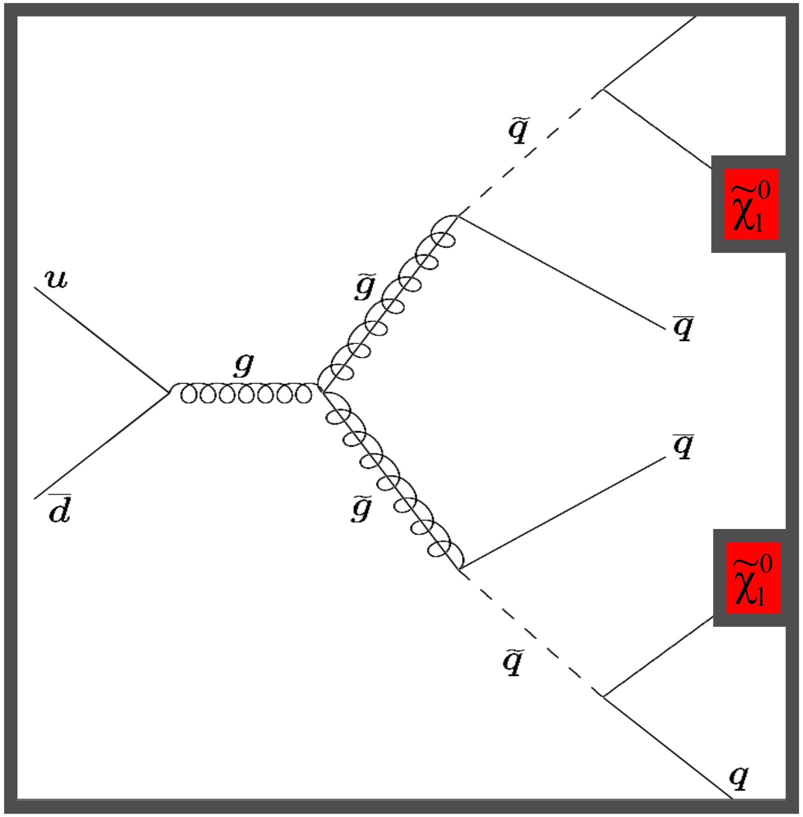
- If discrete symmetry, $P = (-1)^{3B+L+2S}$ is imposed, lightest SUSY particle neutral and stable: Excellent candidate for cold Dark Matter; Missing Energy at Collider Experiments.

# Supersymmetry at colliders

## Gluino production and decay: Missing Energy Signature

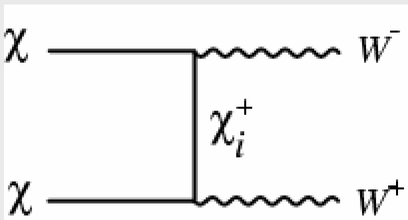
*Supersymmetric Particles tend to be heavier if they carry color charges.*

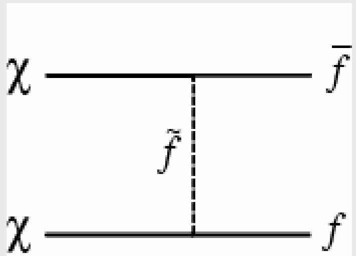
*Charge-less particles tend to be the lightest ones.*

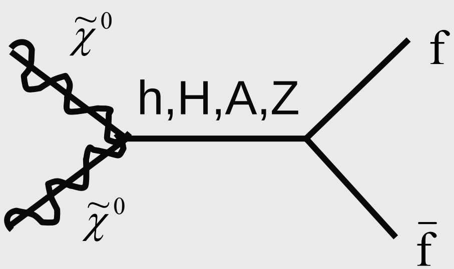


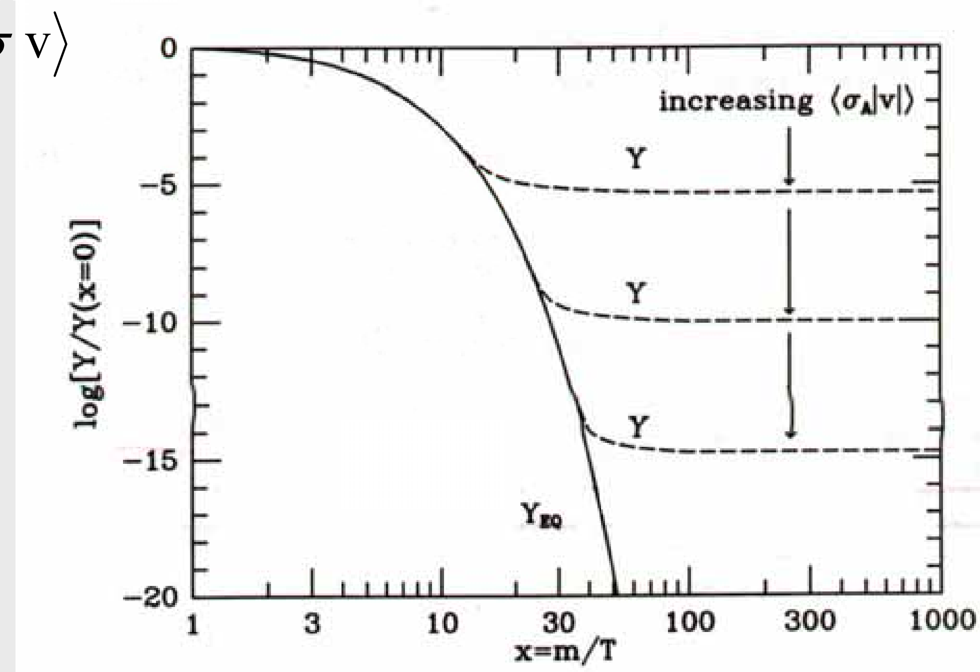

Lightest Supersymmetric Particle: Excellent cold dark matter candidate

Relic density is inversely proportional to the thermally averaged $\tilde{\chi}^0\tilde{\chi}^0$ annihilation cross section $\langle\sigma \, v\rangle$

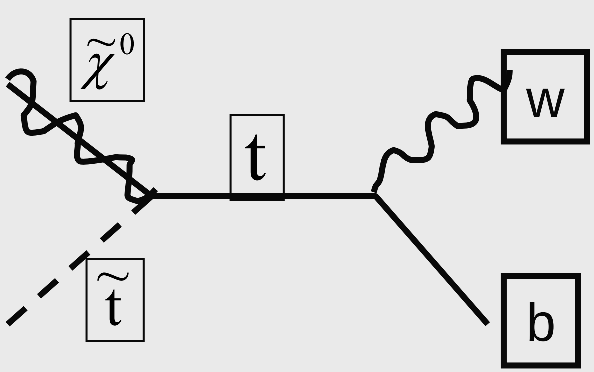


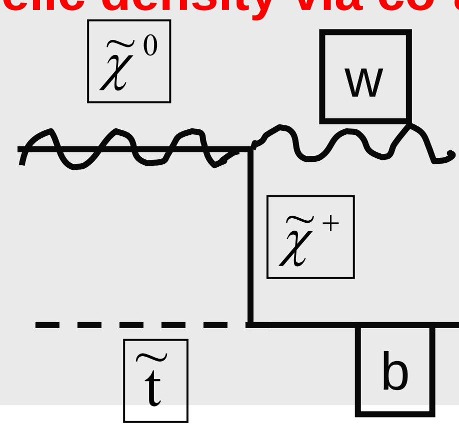




**If any other SUSY particle has mass close to the neutralino LSP, it may substantially affect the relic density via co-annihilation**




if stops NLSP

neutralino-stop

co-annihilation

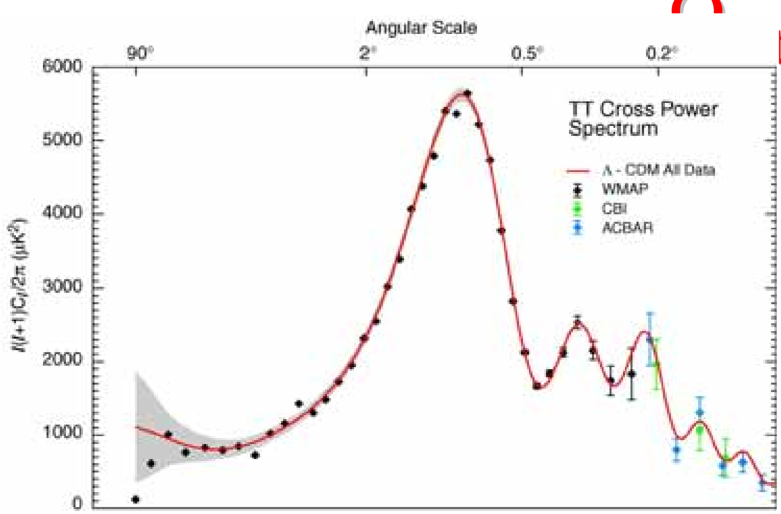
# Relic Density values (WMAP)

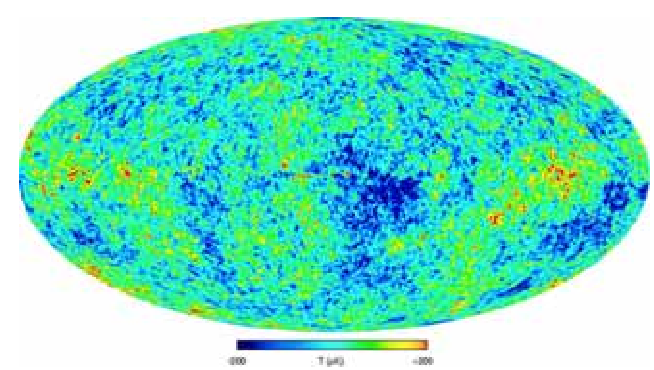
$h$=0.71±0.04

$\Omega_M h^2$=0.135±0.009

$\Omega_B h^2$=0.0224±0.000
9

$\Omega_{tot}$=1.02±0.02



# Motivation

- EWBG may be realized in the MSSM, but only in a limited region of parameter space.
- Higgs boson mass must be at the edge of the LEP bounds.
- Minimal supersymmetric extension of the MSSM: Addition of a gauge singlet. Preserves all the properties of the MSSM and leads to a natural explanation of the value of the parameter $\mu$

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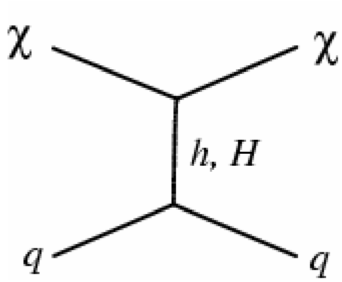


→ upper bounds on Spin independent cross sections

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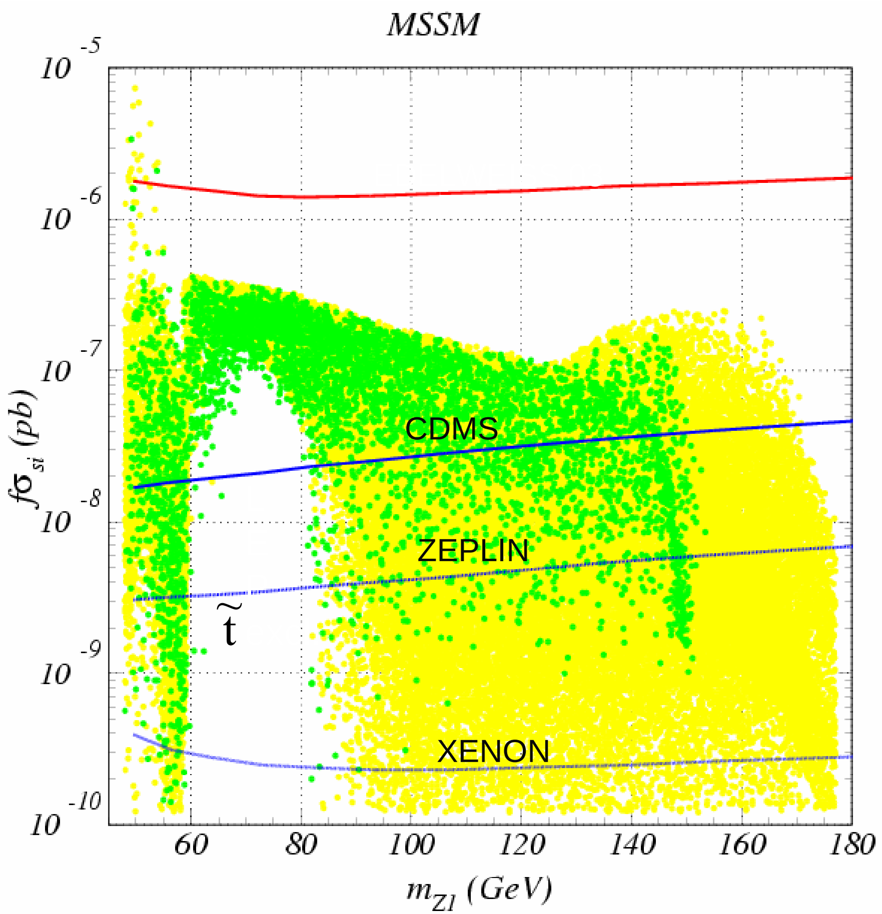


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