Electroweak Baryogenesis in the (n)MSSM and CP-Violation

C.E.M. Wagner

Argonne National Laboratory
EFI, University of Chicago

Based on following recent works:

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

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

CP and Non-Standard Higgs Workshop, SLAC, March 25, 2005

Baryogenesis at the weak scale

- 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 Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

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

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:

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

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

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,

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

Electroweak Baryogenesis in the SM is ruled out

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

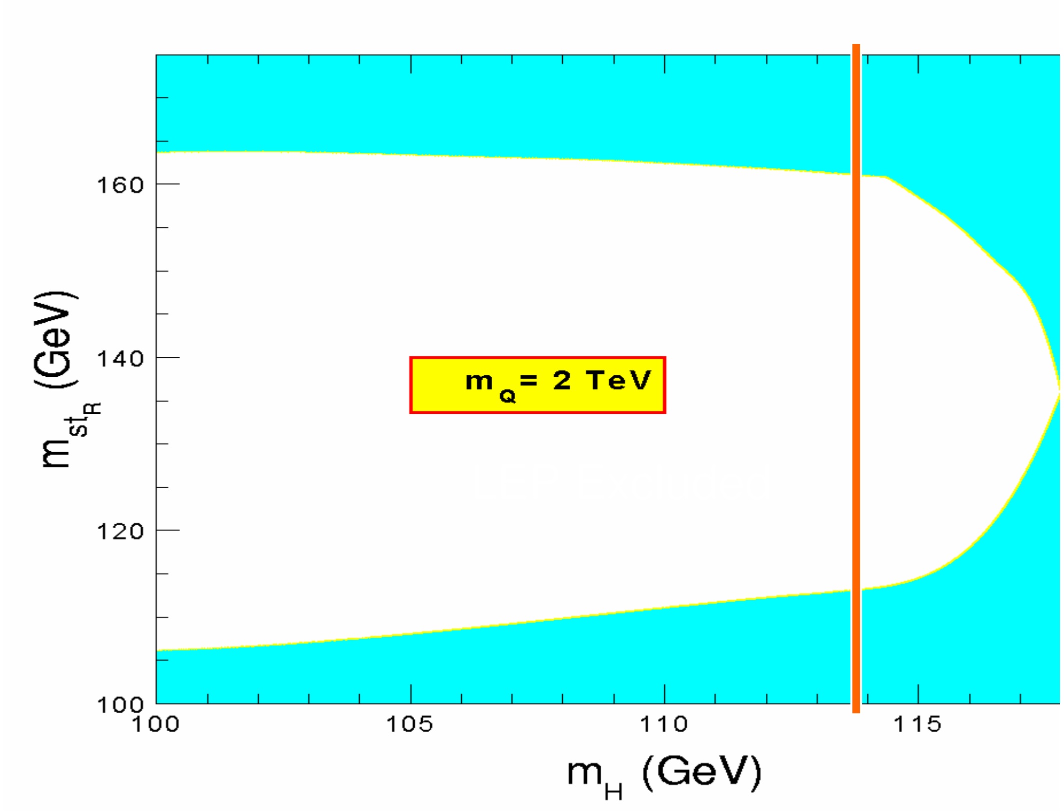
Higgs masses up to 120 GeV may be accomodated

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 β, $\tan\beta \geq 5$ 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

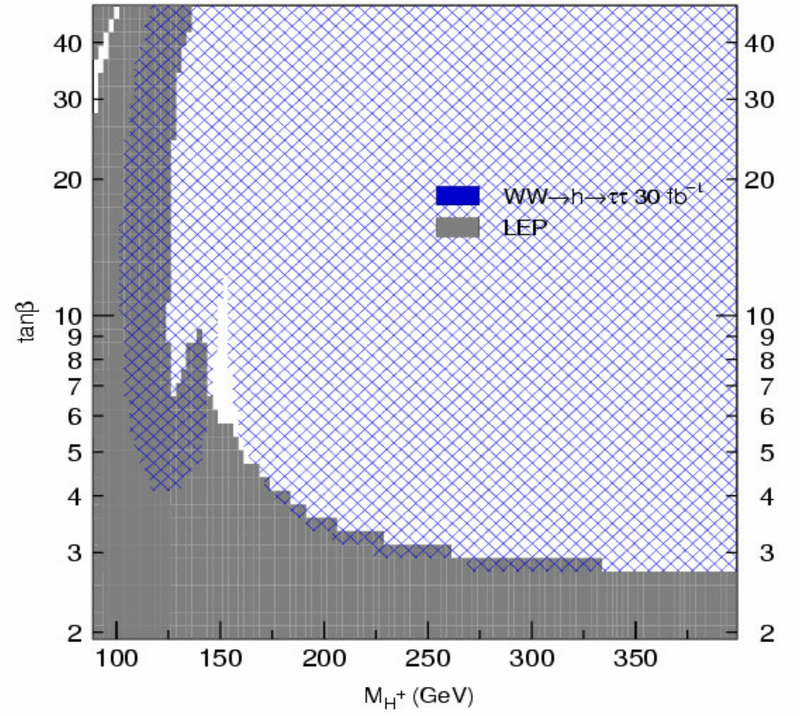
- Higgs searches beyond LEP:

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

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



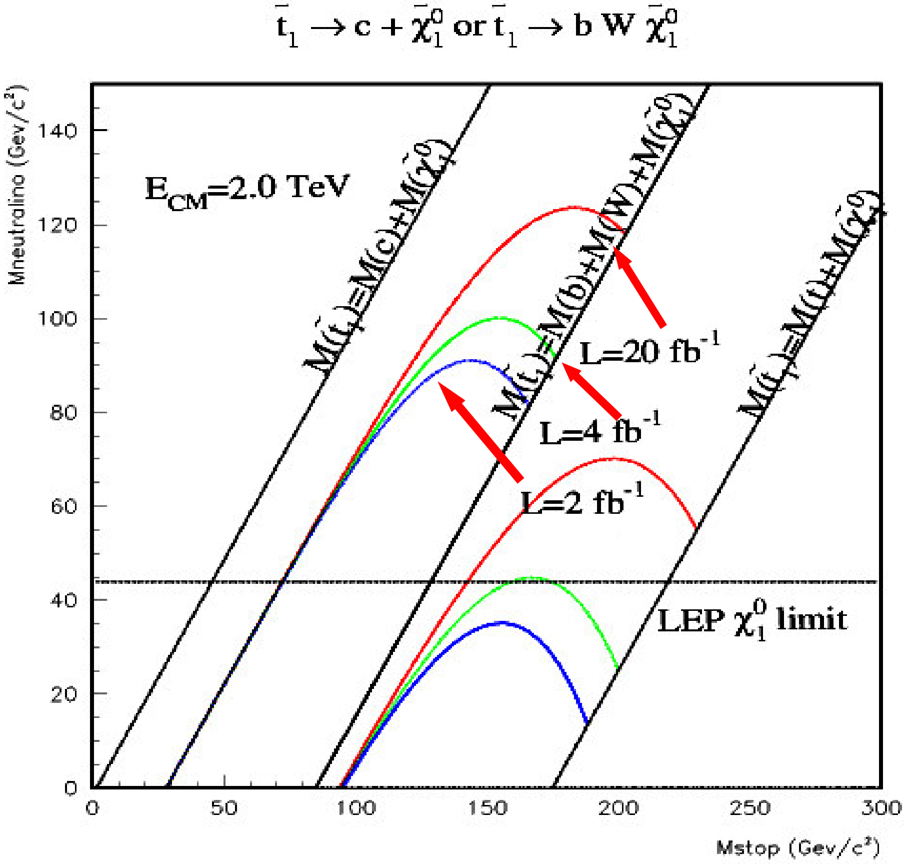
Tevatron Stop Reach when two body decay channel is dominant

Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ GeV



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

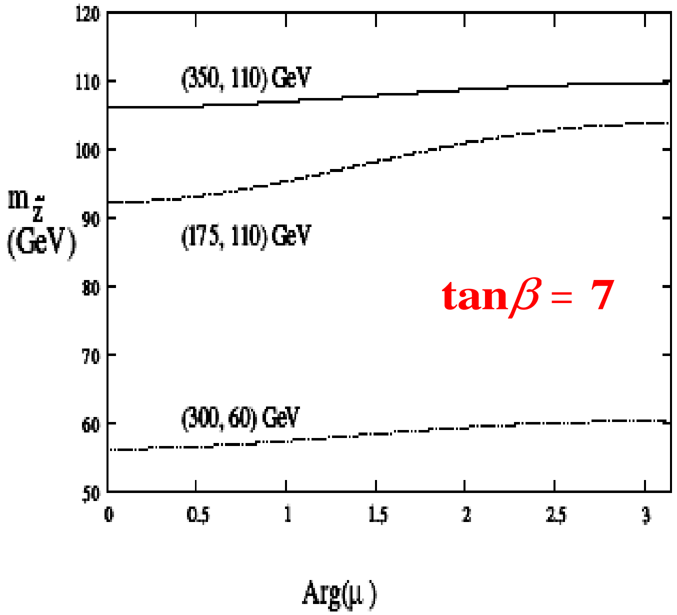
- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.
- Relic density is inversely proportional to the neutralino annihilation cross section.

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

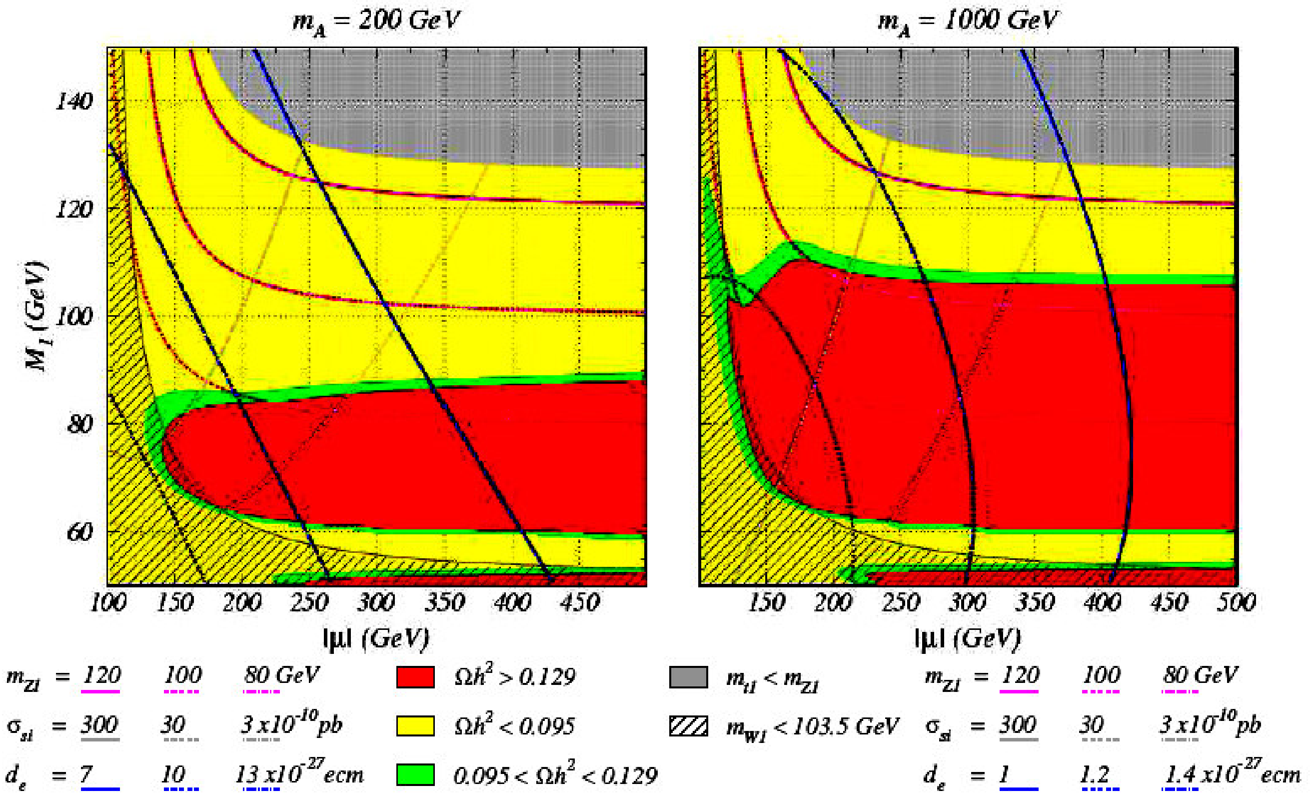
Dependence of Neutralino Masses on CP-Violating Phases

- We choose three characteristic points corresponding to the regions where neutralino-stop co-annihilation, (super)weak interactions and Higgs s-channel annihilation become relevant. We consider real gaugino masses. In brackets we give the values of $(|\mu|, M_1)$



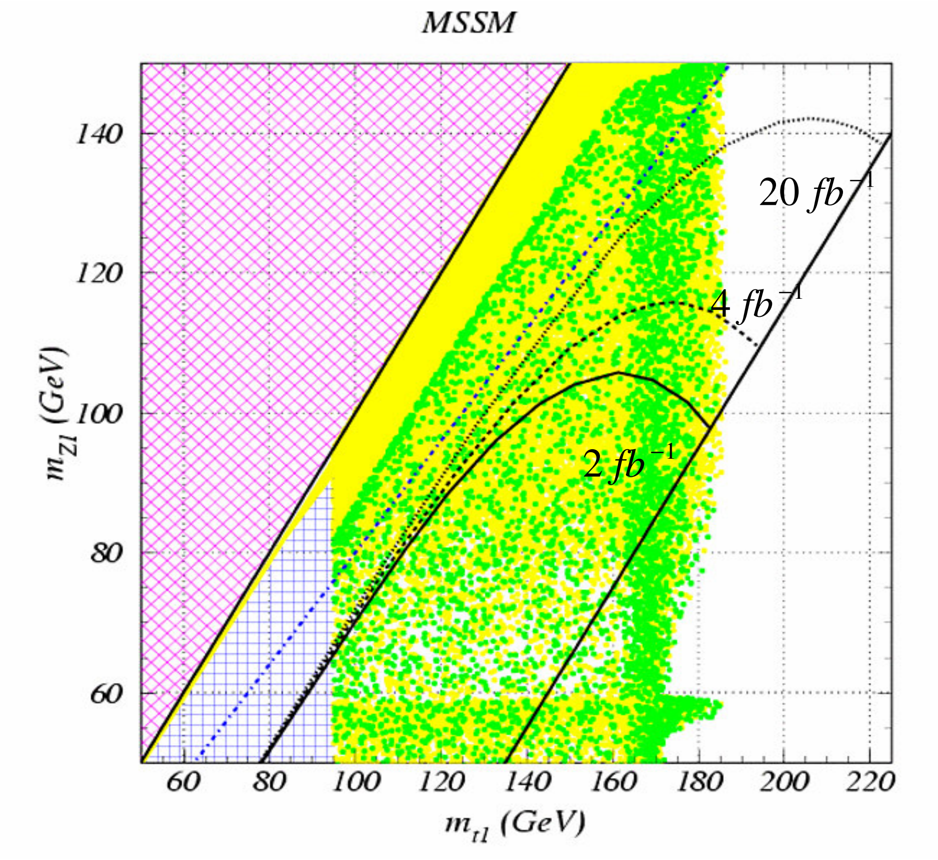
Relic Density Constraints ($\mathbf{Arg}(M_{1,2}\ \mu) = \pi/2$)

- Only CP-violating phase we consider is the one relevant for the generation of the baryon asymmetry, namely : $\mathbf{Arg}(M_{1,2}\ \mu)$
- Neutralino co-annihilation with stops efficient for stop-neutralino mass differences of order 15-20 GeV .



$\tan\beta = 7$

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.

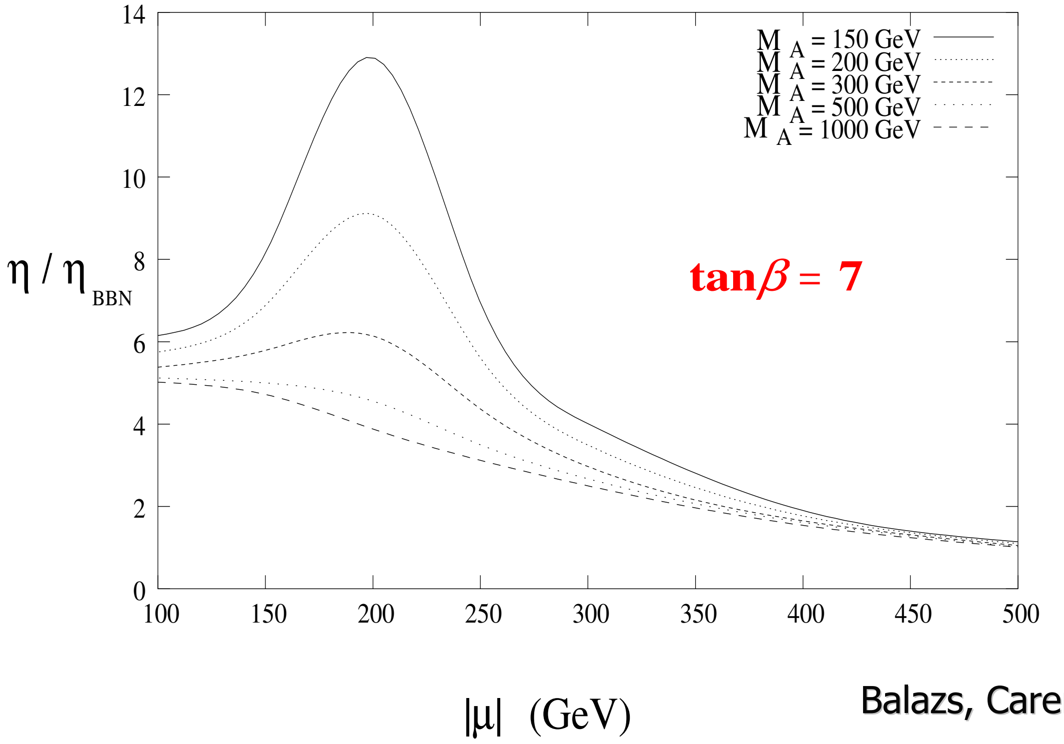
LHC will have equal difficulties. Searches become easier at a Linear Collider !

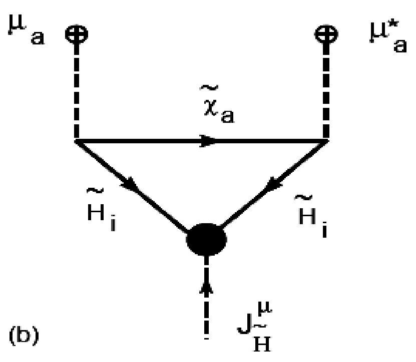
See talk by Caroline Milstene, this session.

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



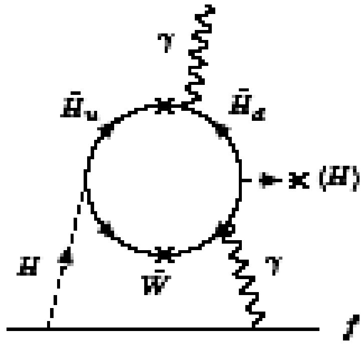


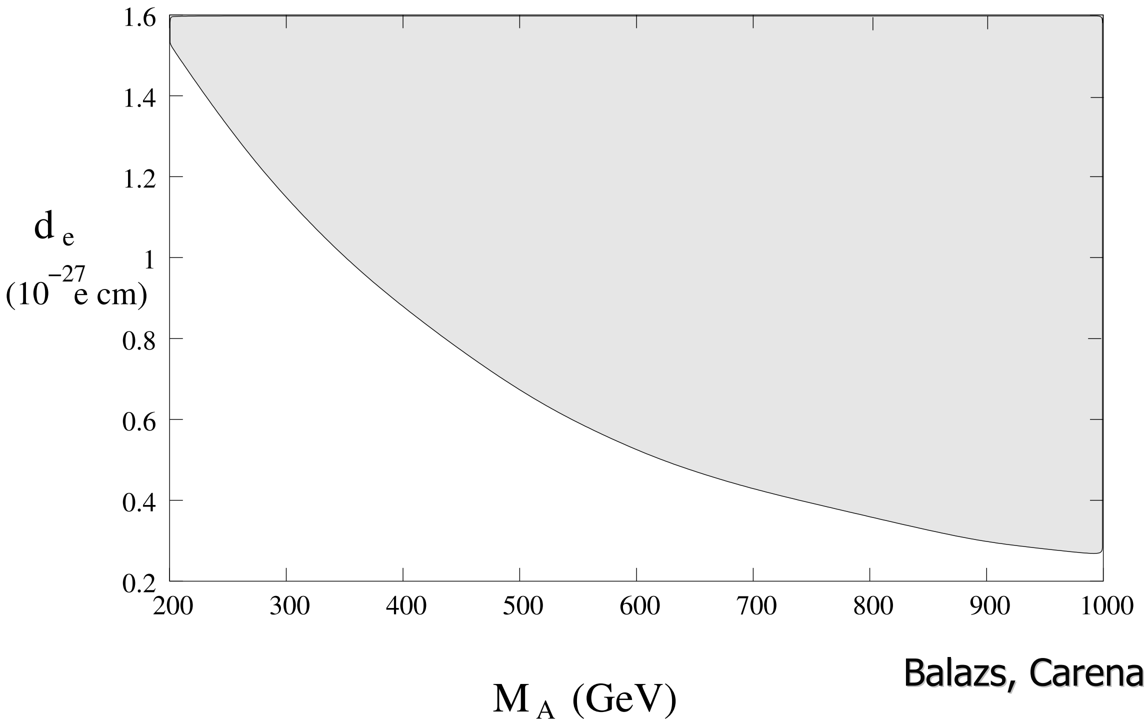
Balazs, Carena, Menon, Morrissey, C.W.'04

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, consistent with EWBG. The electric dipole moment is constrained to be smaller than $\mathbf{d_e < 1.6\ 10^{-27}\ e\ cm}$

A. Pilaftsis'02





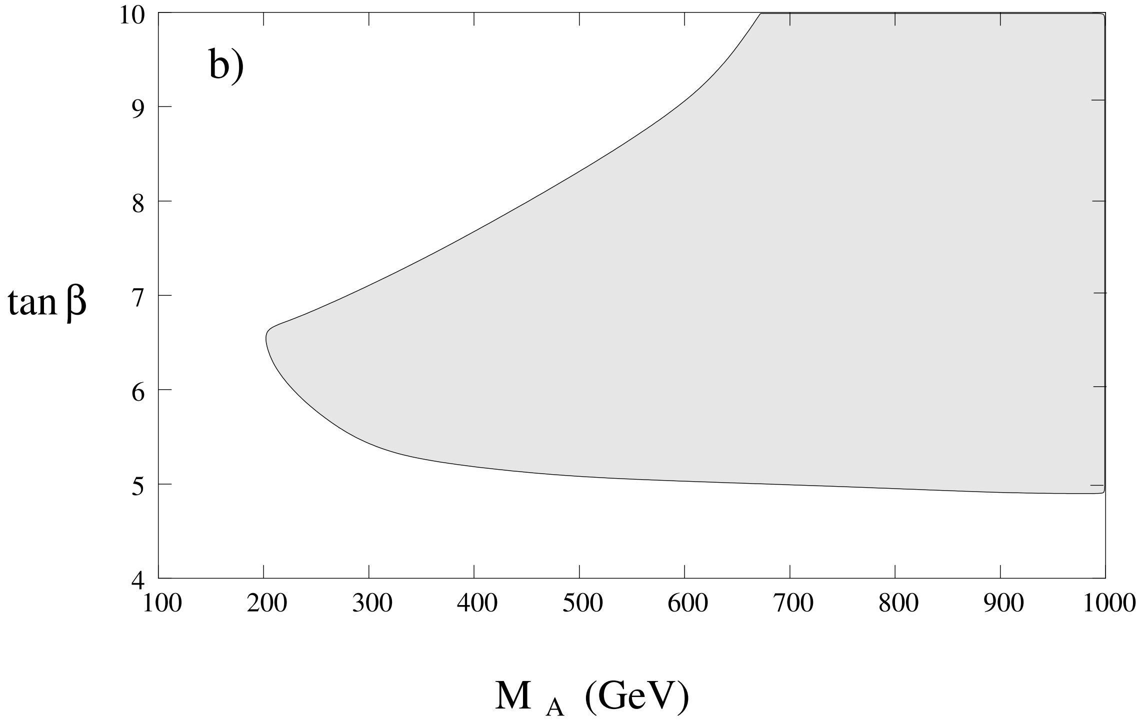
- New generation of experiments will test this scenario !

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.

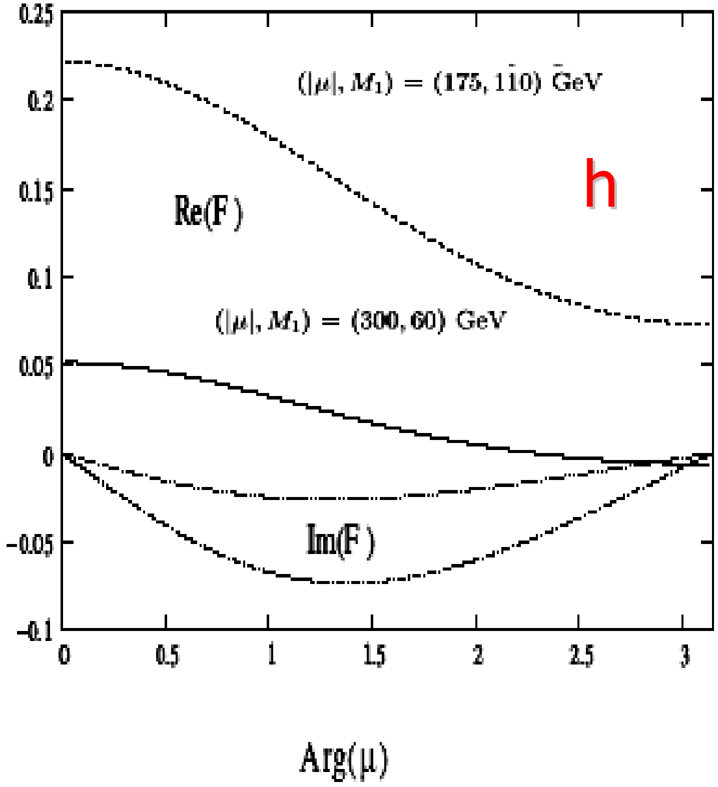
Balazs, Carena, Menon, Morrissey, C.W.'04



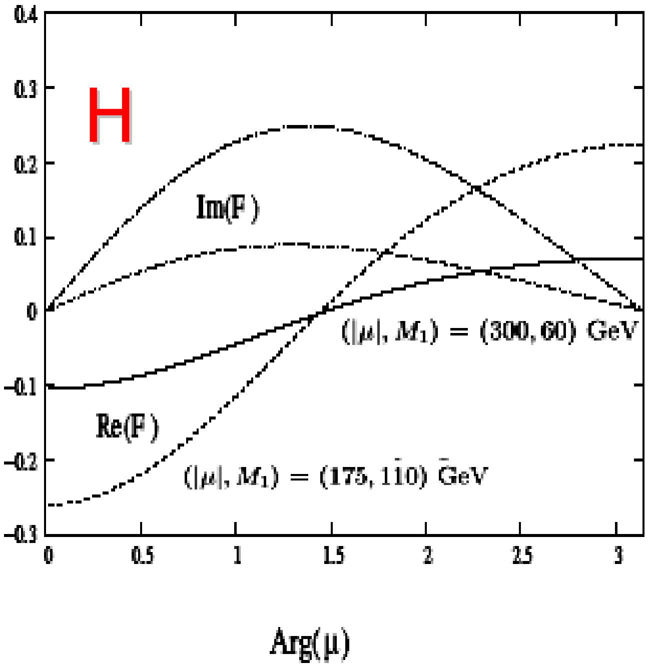
Neutralino Coupling to the lightest CP-even Higgs Boson

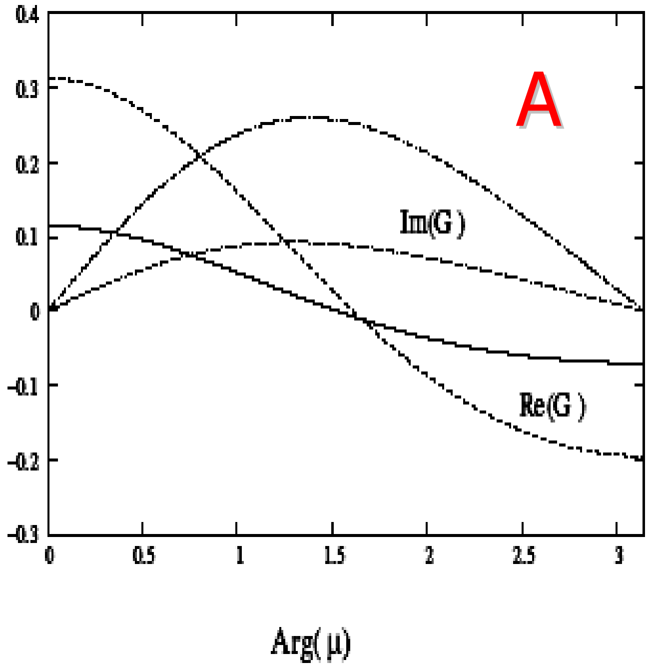
- Spin-independent cross section depends on Re(F).

$$\begin{aligned} \bar{Z}_1 \bar{Z}_1\, h^0/H^0 &\sim -i(F\, P_L + F^* P_R) \\ \bar{Z}_1 \bar{Z}_1\, A^0 &\sim -i(G\, P_L - G^* P_R) \end{aligned}$$



Neutralino Coupling to the heavier CP-even and CP-odd Higgs Bosons





Spin Dependent Cross Section

- Point consistent with stop-neutralino co-annihilation

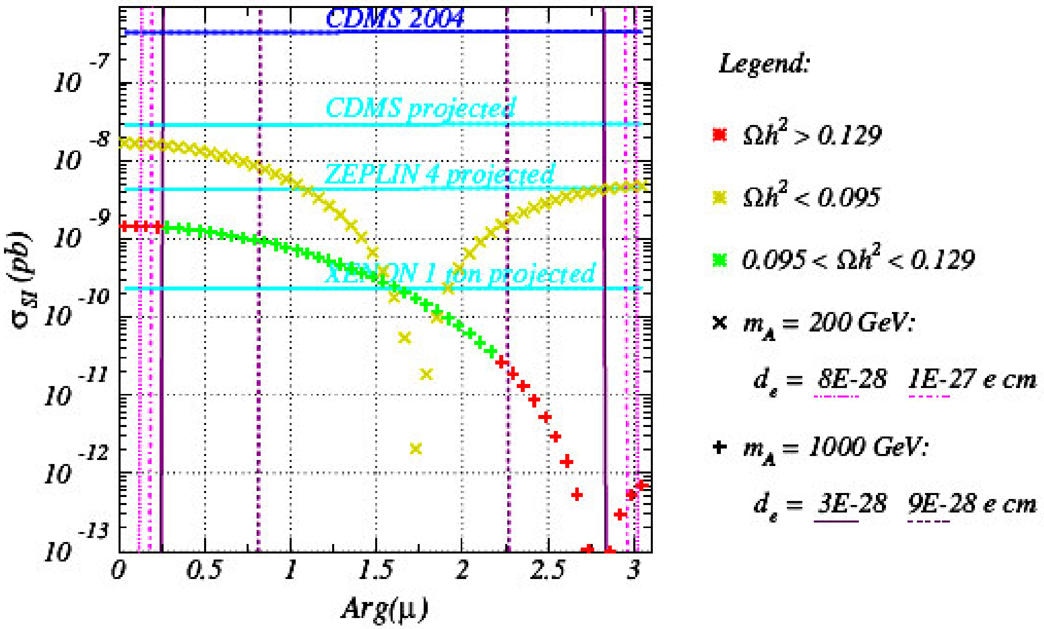
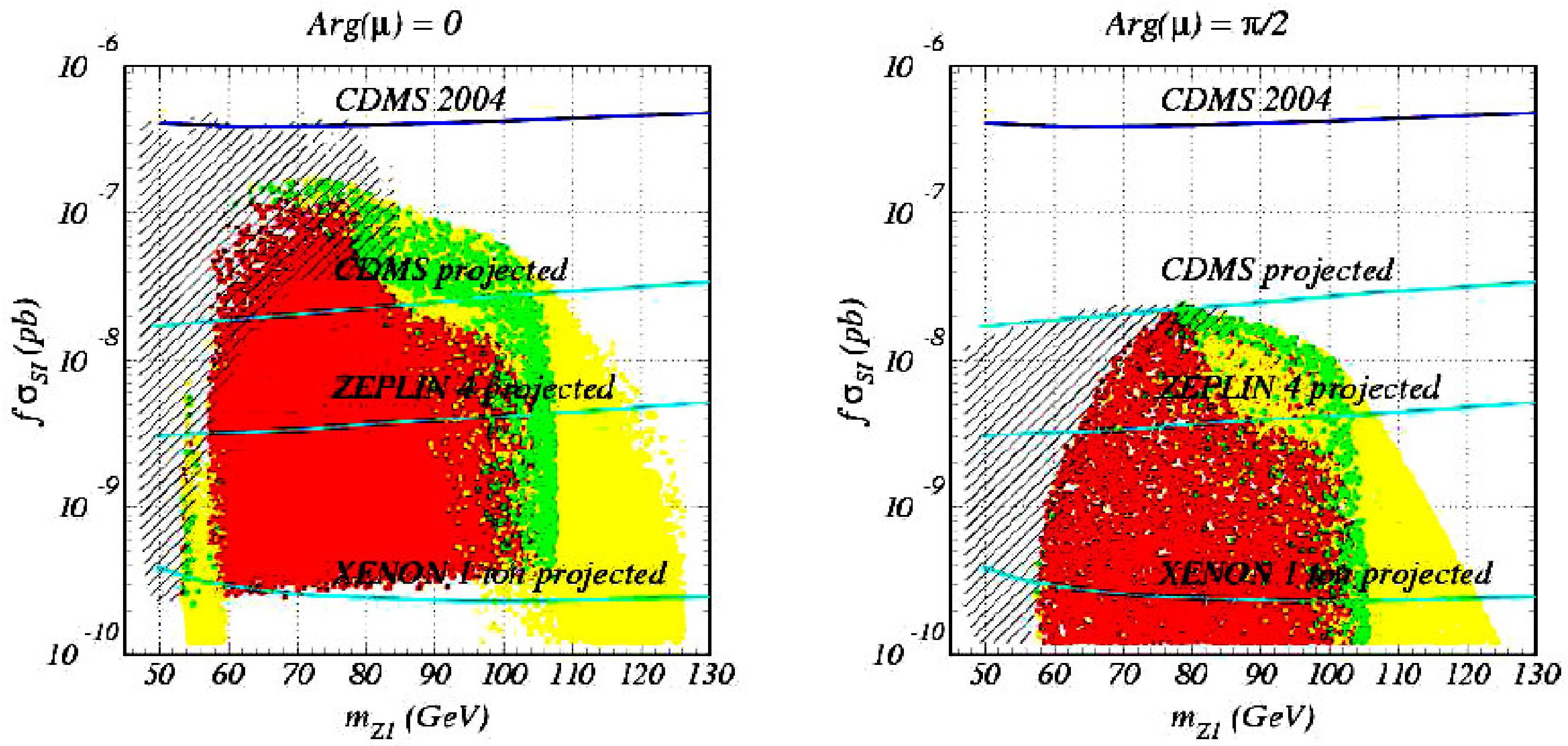


Figure 7: Spin-independent neutralino-proton scattering cross section as the function of $Arg(\mu)$, for $|\mu| = 350$ GeV and $M_1 = 110$ GeV, and for m_A= 200 (1000) GeV for the upper (lower) curve.

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



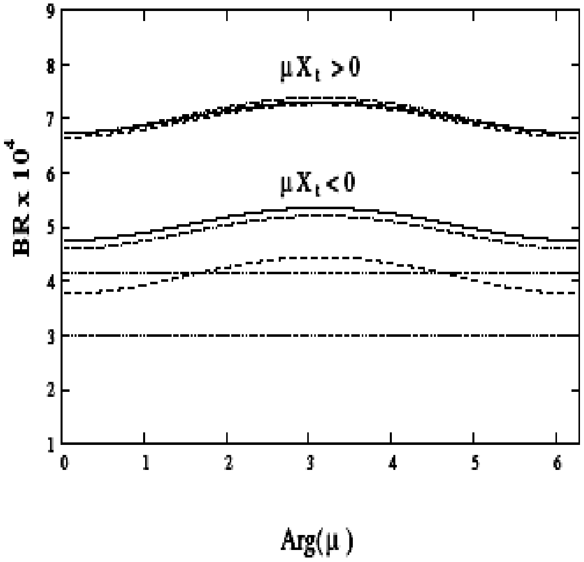
Flavor violating processes

- 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 CP-violating phase.
- Experimental value is given by

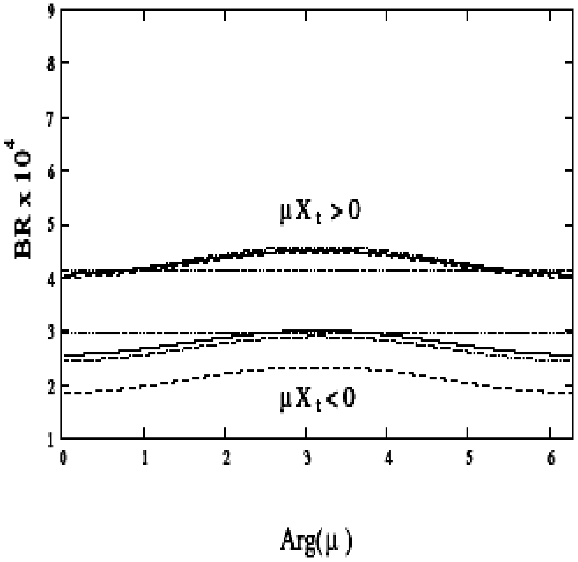
$$\boxed{\mathrm{BR}(b \to s\gamma) = (3.54^{+0.30}_{-0.28}) \times 10^{-4}}$$

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

M_A = 200 GeV



M_A = 1 TeV



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

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

Neutralino spectrum

- Neutralino spectrum more complex. Gaugino masses may have phases

$$M_{\chi^0} = \begin{bmatrix} M_1 & \bullet & \bullet & \bullet & \bullet \\ 0 & M_2 & \bullet & \bullet & \bullet \\ -\cos\beta s_W M_Z & \cos\beta c_W M_Z & 0 & \bullet & \bullet \\ \sin\beta s_W M_Z & \sin\beta c_W M_Z & \lambda v_S & 0 & \bullet \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 0 \end{bmatrix} \qquad \mu \leftrightarrow -\lambda v_S$$

For $M_1 > 100$ GeV, lightest neutralino is approximately given by

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

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)

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

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 ms. Strong first order phase transition induced for small values of ms.

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

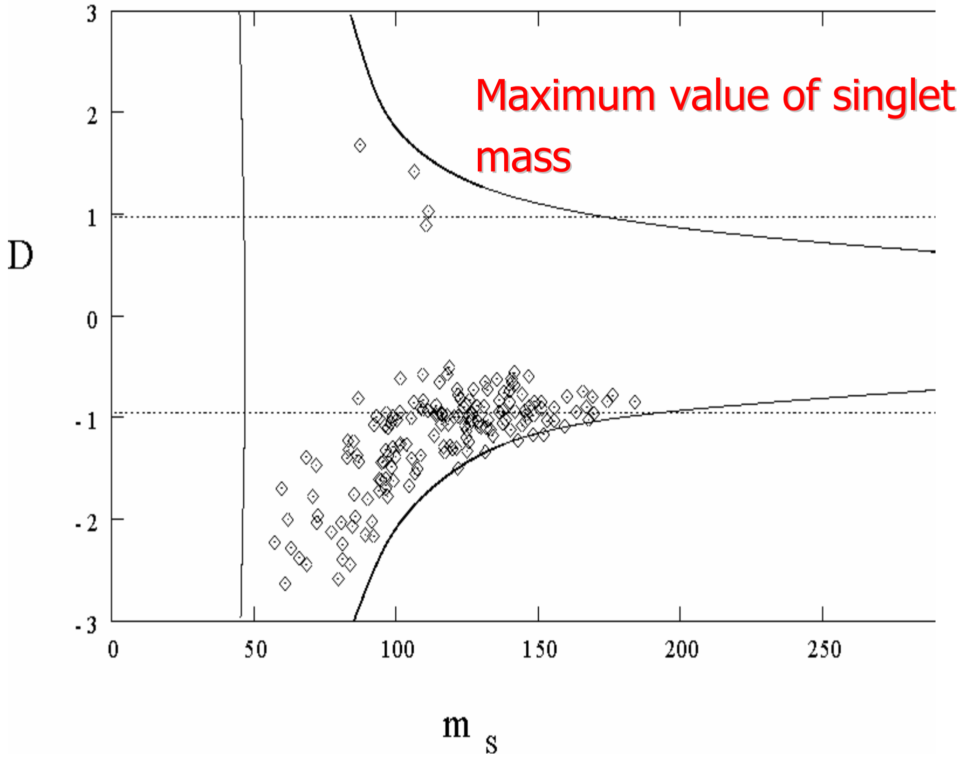
Parameters with strongly first order transition

- 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

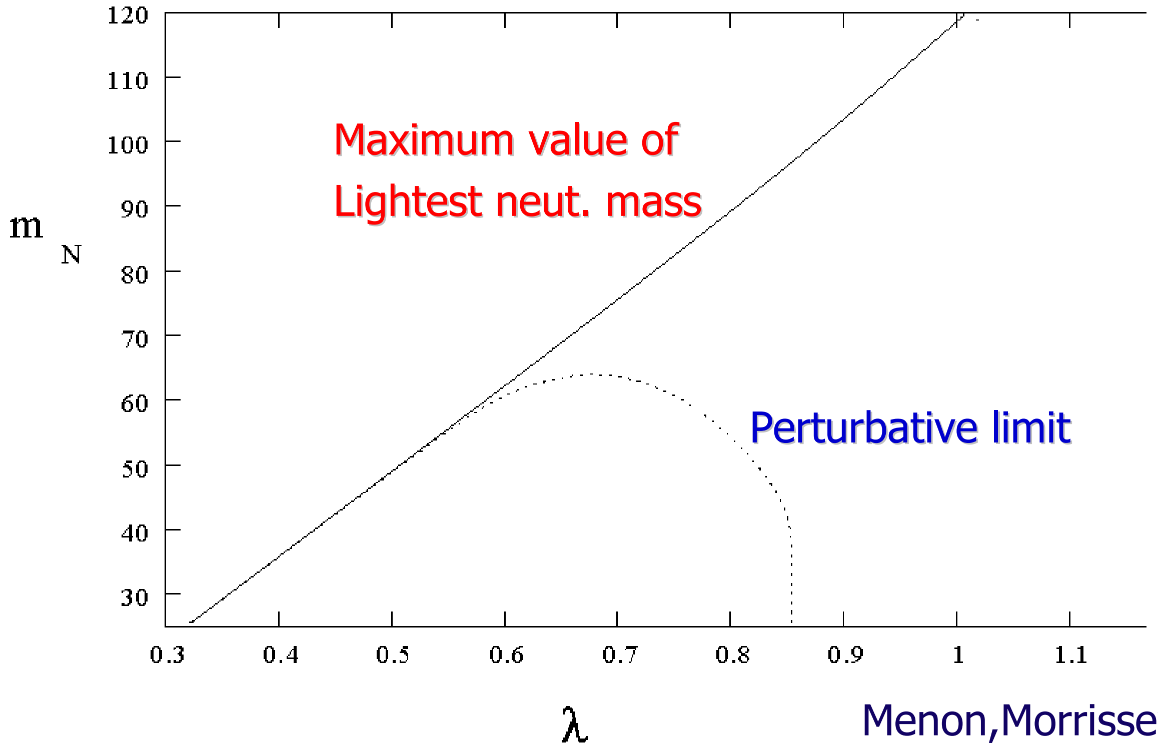
- Values constrained by perturbativity up to the GUT scale.



Maximum value of singlet mass

Upper bound on Neutralino Masses

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



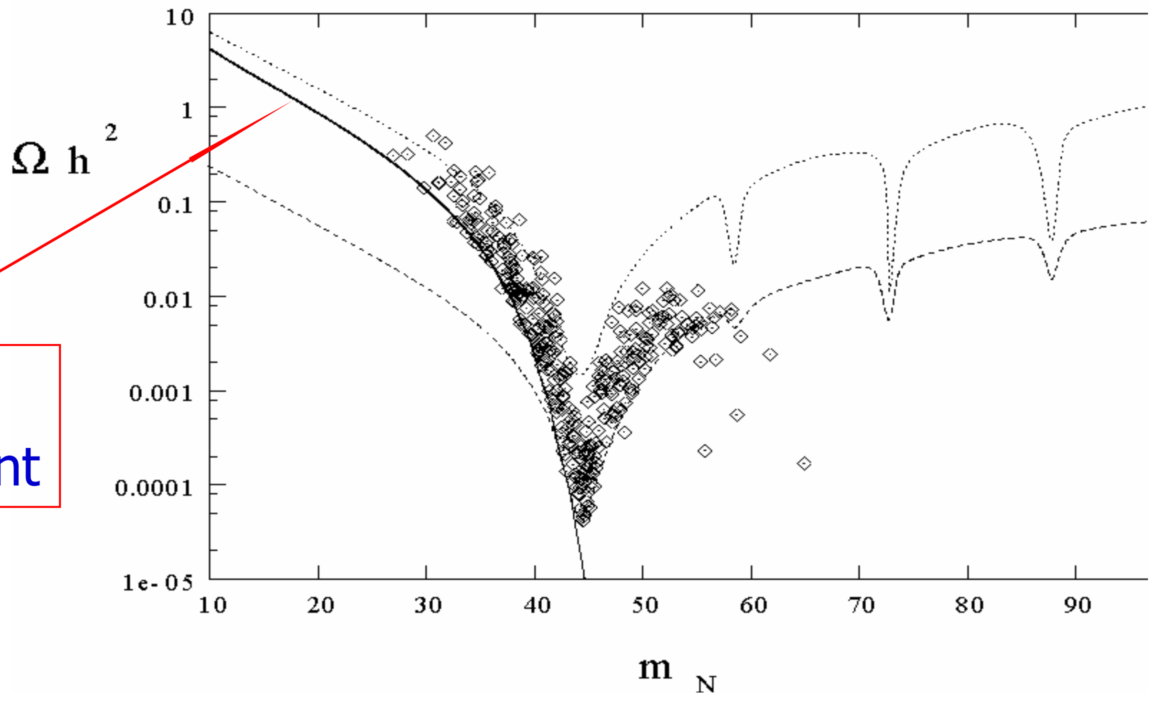
Maximum value of
Lightest neut. mass

Perturbative limit

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 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.

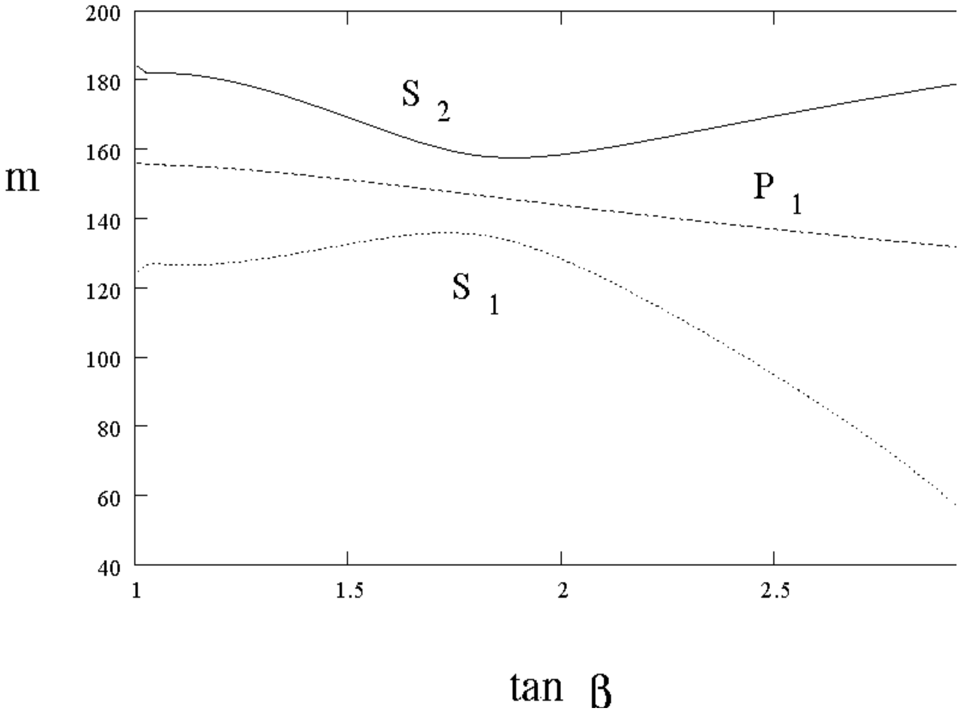
Light Higgs boson masses

- 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.

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

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

$\lambda = 0.7$



Menon,Morrissey,C.W.'04

Higgs Searches

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

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

- 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

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

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

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

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. Much easier at a Linear Collider.
- Direct dark matter detection becomes difficult in co-annihilation region, particularly for maximal phases.
- To be tested by electron e.d.m. and collider experiments
- NMSSM: Interesting alternative. Tree-level terms dominate phase transition
- Effects depend on the singlet mass. One light CP-odd and two CP-even Higgs
- Perturbative limit: Light neutralino, with mass below 45 GeV. Higgs bosons decay mostly invisibly. CP-odd state detection difficult.