Baryogenesis, Dark Matter and Low Energy Supersymmetry

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Based on work done in collaboration with M. Quiros and M. Carena, and the 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.
C. Balazs, M. Carena, A. Menon, C. Morrissey and C.W., Phys. Rev. D71:075002, 2005.
C. Balazs, M. Carena, A. Freitas and C.W., **arXiv:0705.0431**.

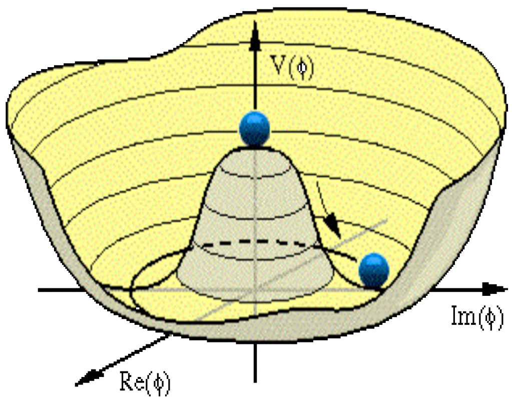
PHENO 2007, Madison, Wisconsin, May 8, 2007

Open questions in the Standard Model

- Source of Mass of fundamental particles.
- Nature of the Dark Matter, contributing to most of the matter energy density of the Universe.
- Origin of the observed asymmetry between particles and antiparticles (Baryon Asymmetry).
- Dark Energy, Quantum Gravity and Unified Interactions.

The Higgs Mechanism and the Origin of Mass

A scalar (Higgs) field is introduced. The Higgs field acquires a nonzero value to minimize its energy



Spontaneous Breakdown of the symmetry :

Vacuum becomes a source of energy = a source of mass

$$< H > = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

A physical state (Higgs boson) appear associated to fluctuations in the radial direction . Goldstone modes: Longitudinal component of massive Gauge fields.

Masses of fermions and gauge bosons proportional to their couplings to the Higgs field:

$$M_W^2 = \frac{g^2 v^2}{2}, \qquad m_{\rm top} = h_{\rm top}\, v \qquad m_H^2 = 2\lambda v^2$$

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

- 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.

- 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,

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

Kuzmin, Rubakov and Shaposhnikov, '85—'87

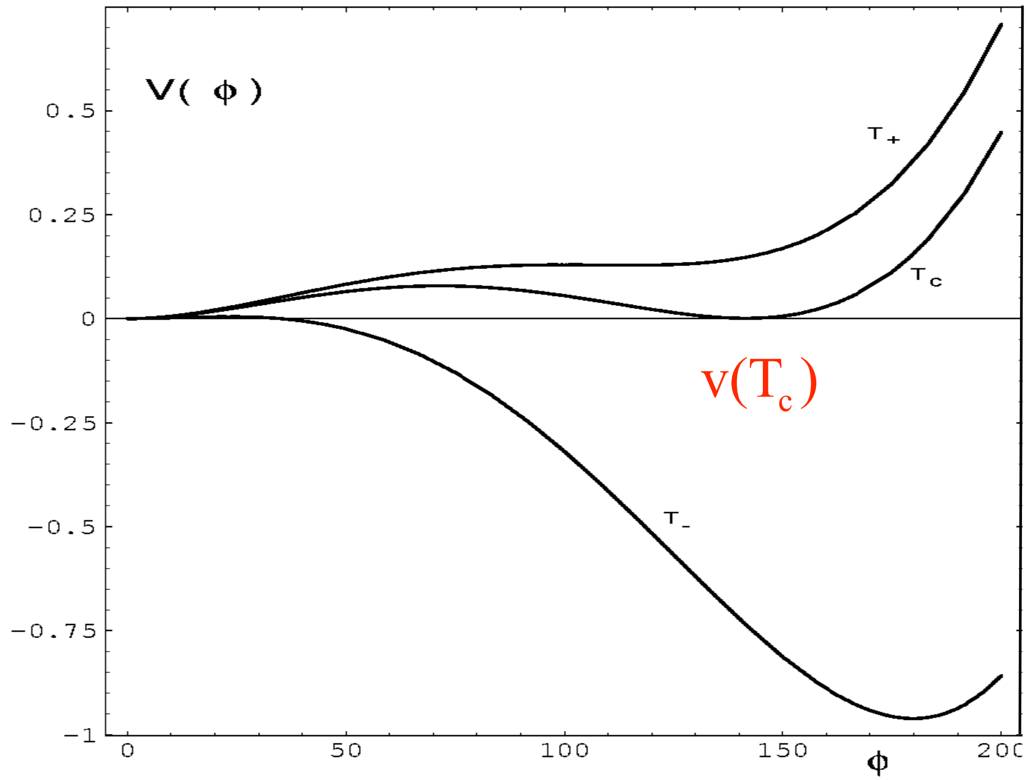
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

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

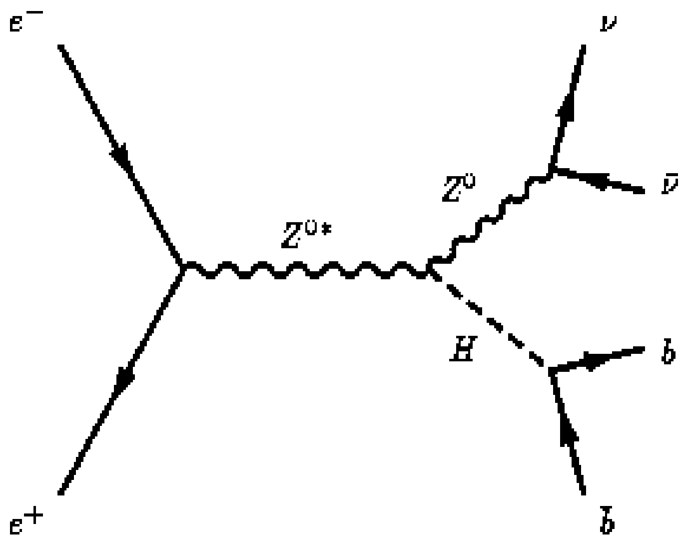
E receives contributions proportional to the sum of the cube of all light boson particle couplings

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

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

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

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

- Since

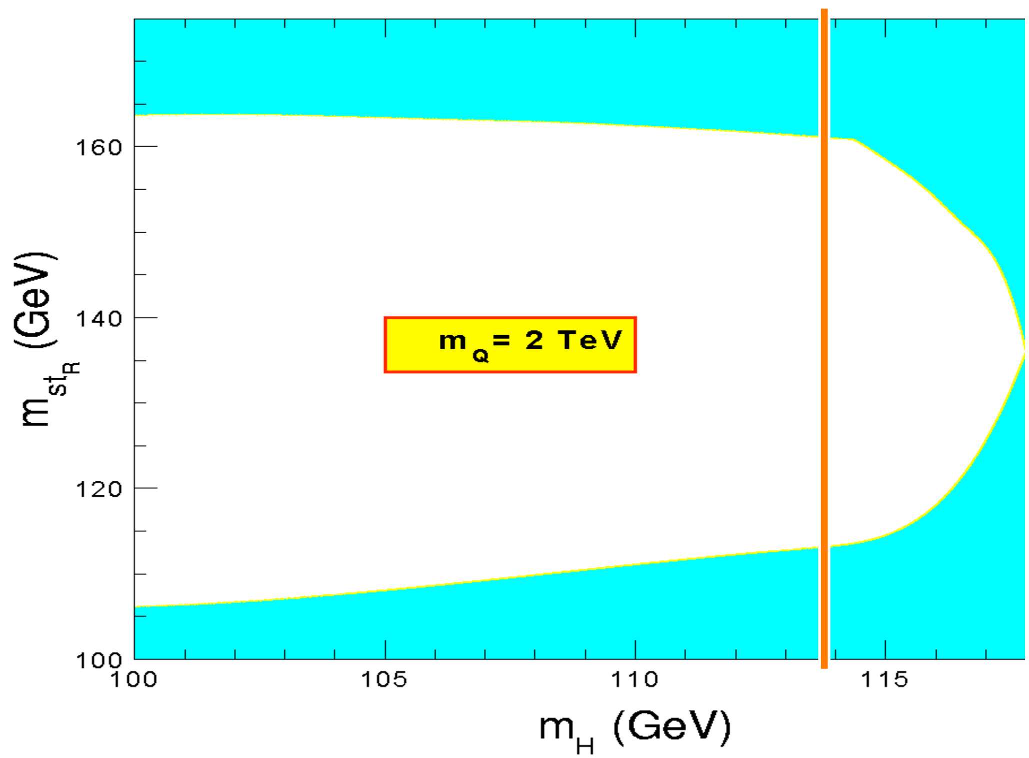
Higgs masses up to 120 GeV may be accomodated

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:

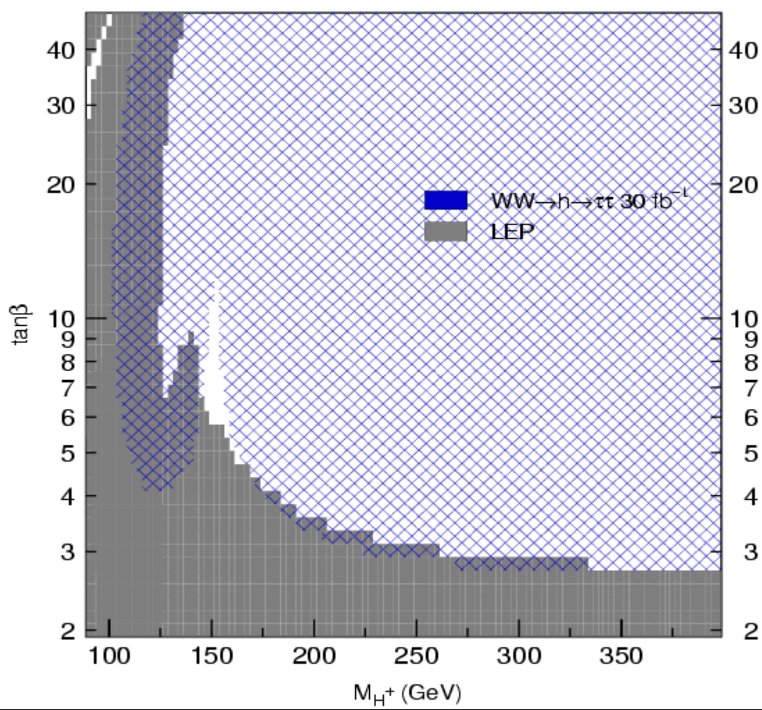
1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

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

$$qq \rightarrow qqV^*V^* \rightarrow qqh$$

with $h \rightarrow \tau^+\tau^-$



Tevatron Stop Reach when two body decay channel is dominant

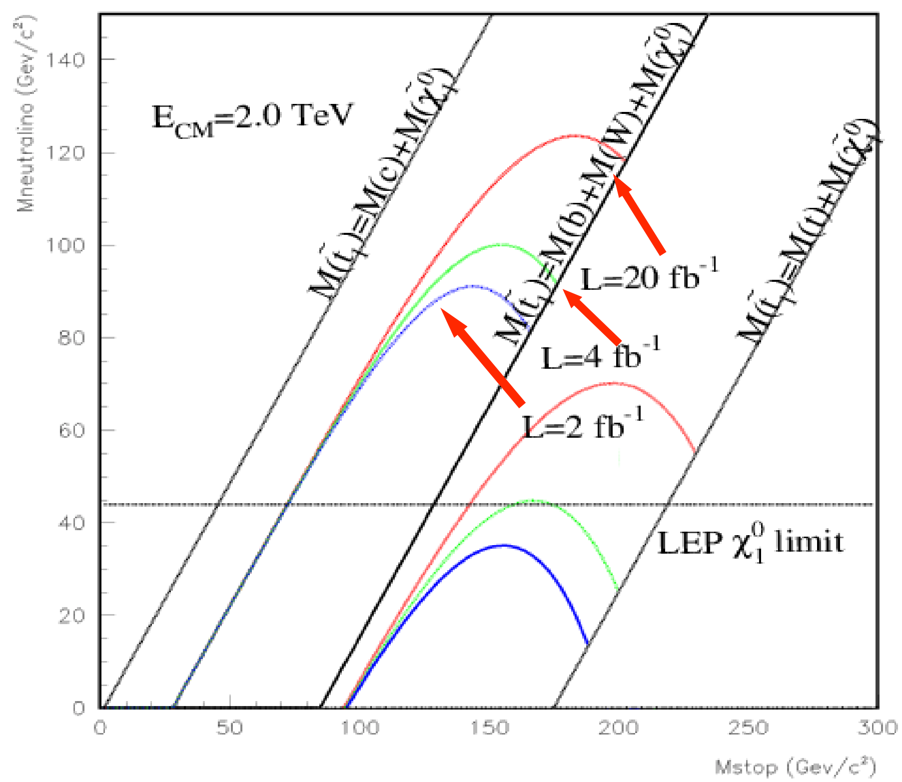
Main signature:

2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ GeV

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



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., Phys. Rev. D71:075002, 2005.

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

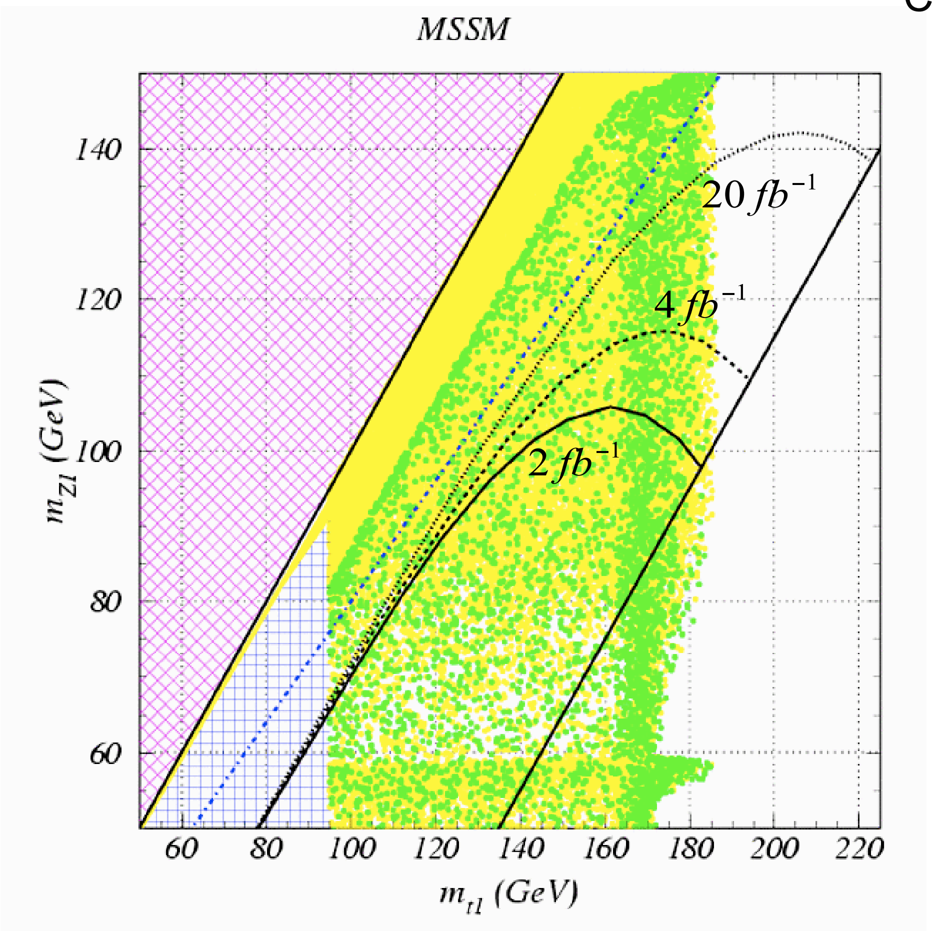
- Relic density is inversely proportional to the neutralino annihilation cross section.

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.

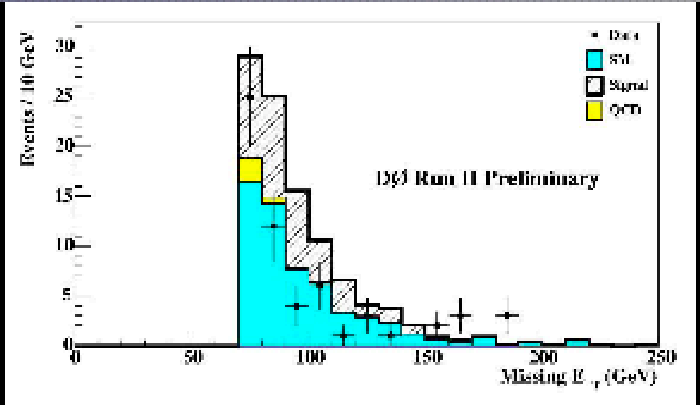
LHC will have equal difficulties. Searches become easier at a Linear Collider !

Carena, Freitas et al. '05

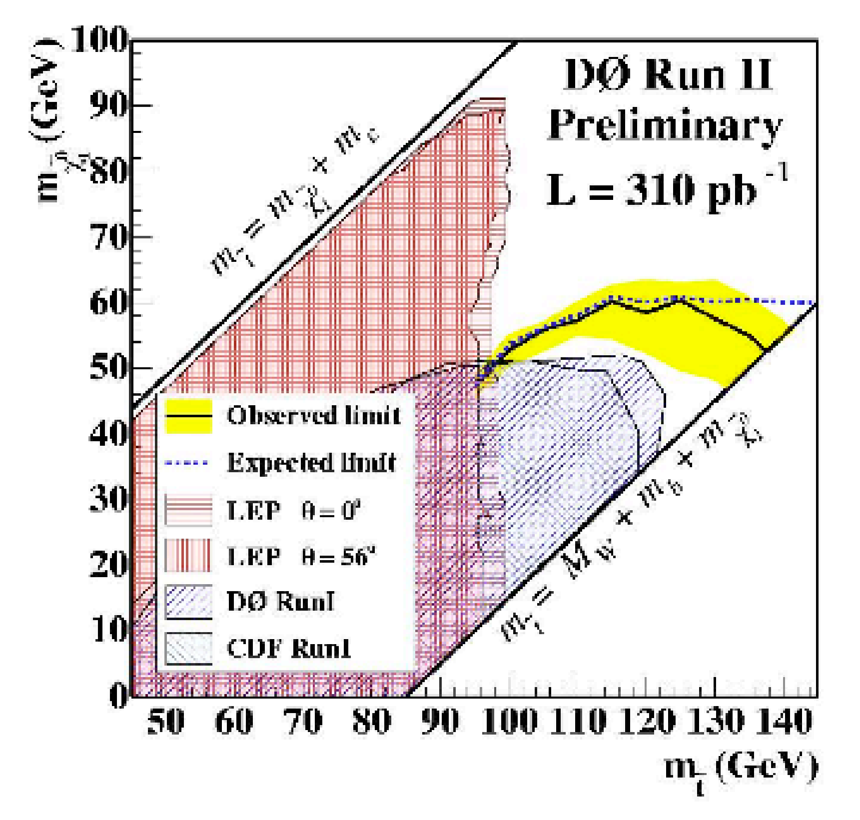
Stop in acoplanar dijet (II)

- For M(stop)=130, M(neutralino1)=50
  - Pt1>40 GeV, Pt2>20 GeV
  - MET > 70 GeV
  - $\Delta\Phi$ max+$\Delta\Phi$ min < 280 degrees

	Data	Total background
"Dijet"		59.4 ±8.3 (stat) ±9.8 (sys)



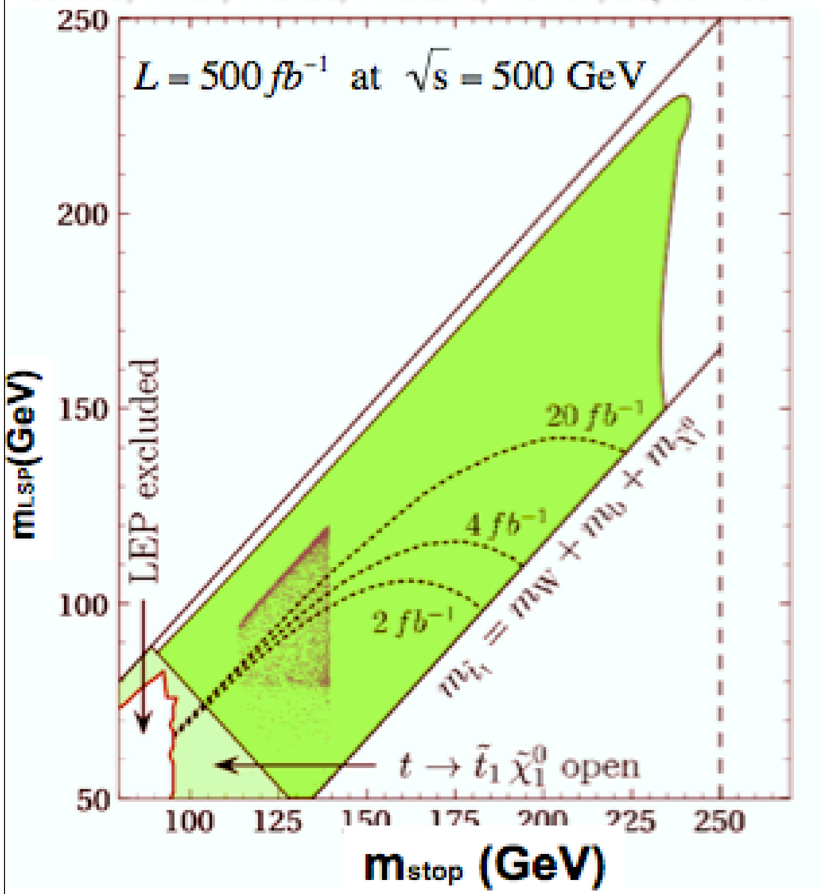
  - Dominant backgrounds are W/Z+jets
  - QCD background is 5.6% of the total back.
  - Signal efficiency = 3.7% => 39.5 signal events
- Small excess of events at very large MET:
  - 8 events for 3.0 ±1.2 for MET>150 GeV
  - not in the stop signal signal region
- Main systematic uncertainties:
  - JES (5-10%)
  - heavy flavor tagging : 7%
  - back. cross sections : 13%
- As for the squark-gluino analysis, 3 signal cross section hypotheses (PDF/Scale)
  - Excluded contour is extended
  - The largest stop mass excluded is 131 GeV



The power of the ILC

- Detect light stop in the whole regime compatible with DM and EWBG

Carena, Finch, Freitas, Milstene, Nowak, Sopzak '06



Assume 100% BR for $\tilde{t} \longrightarrow c + \tilde{\chi}^0$

Signature: 2 soft charm jets plus missing E

$$e^+e^- \to \tilde{t}_1\tilde{t}_1^* \to c\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0$$

Discrimination of two-jet signature from B requires detector simulation

- Event generation with Pythia
- Detector Simulation with fast simulation Simdet for "typical" ILC detector
- Include beamstrahlung according to cold technology with Circe.

Green region: $\dfrac{S}{\sqrt{S+B}} > 5$ with $S = \varepsilon\sigma$

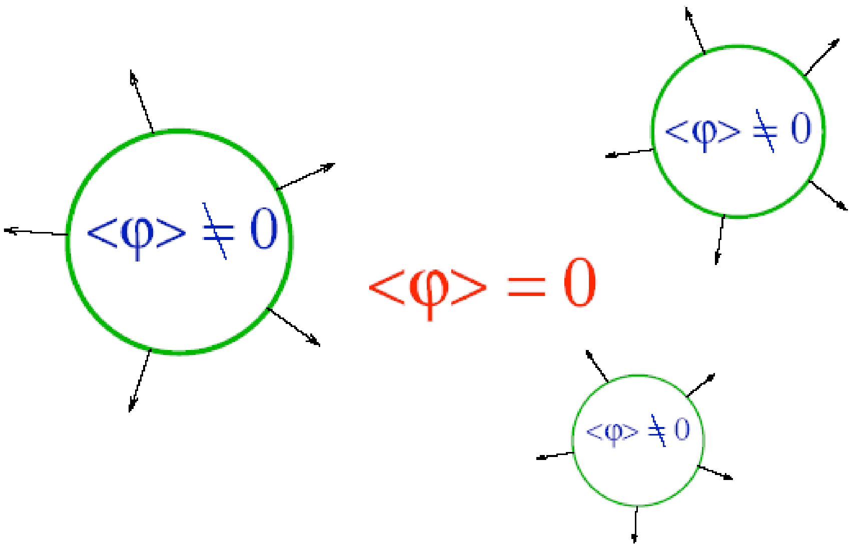
Detection of light stops possible for $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ ~5 GeV

Baryon Number Generation

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

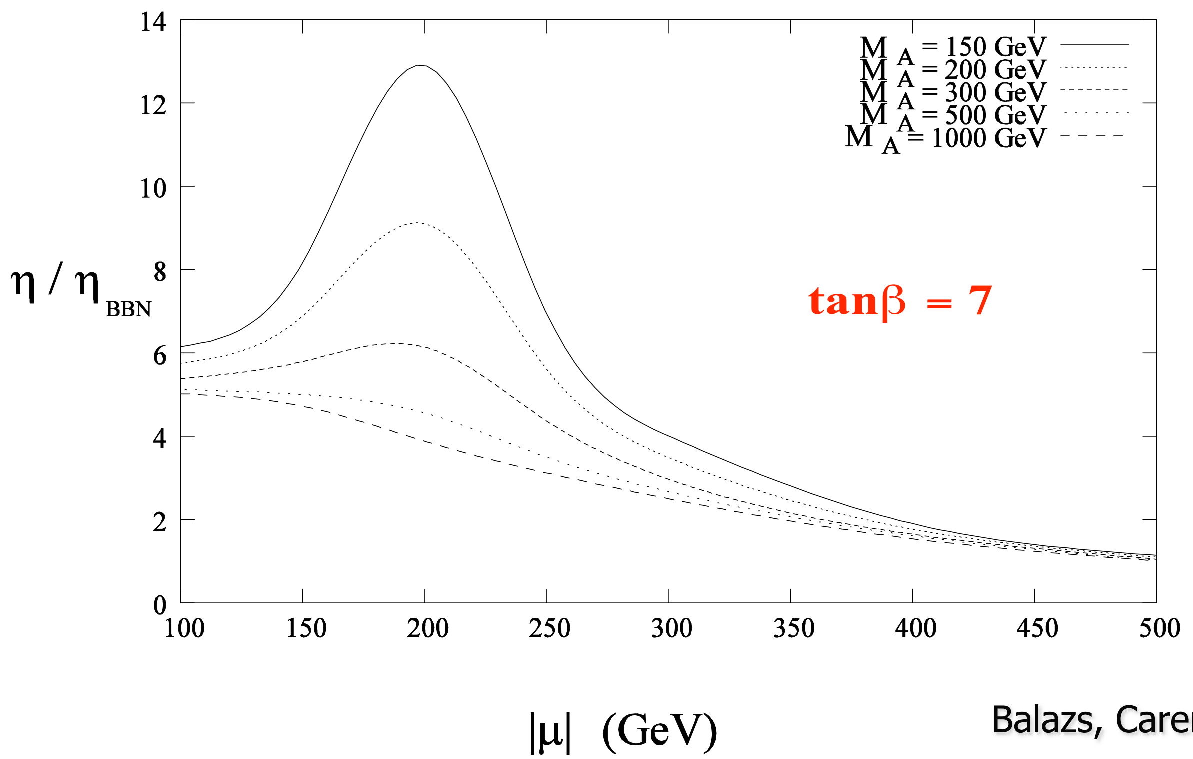
Cohen, Kaplan and Nelson, hep-ph/9302210; A. Riotto, M. Trodden, hep-ph/9901362; Carena, Quiros, Riotto, Moreno, Vilja, Seco, C.W.'97--'02.

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

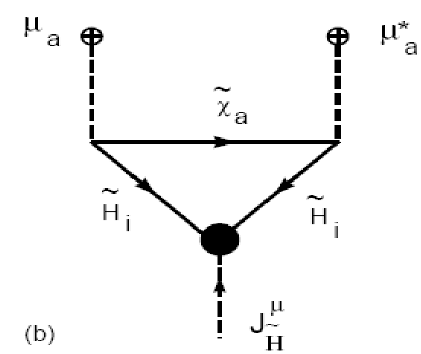


Baryon Asymmetry

- 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



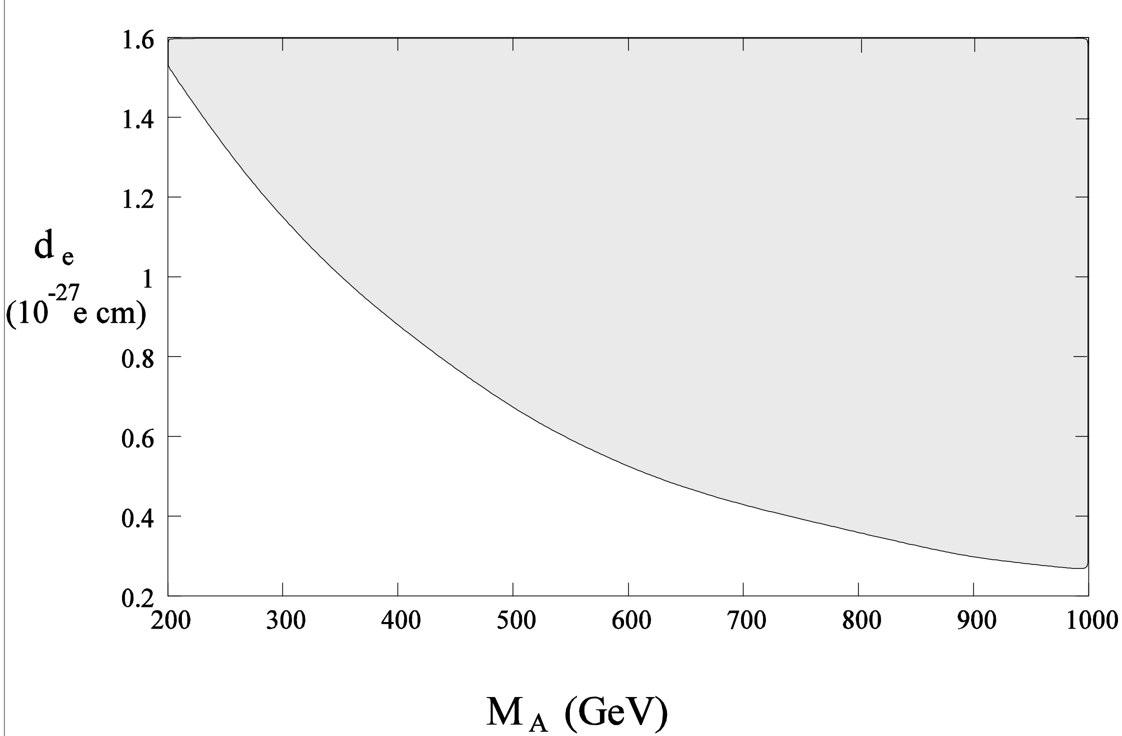
Balazs, Carena, Menon, Morrissey, C.W.'05

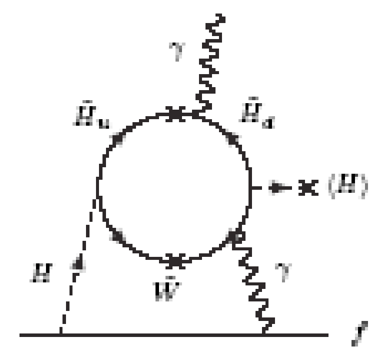
Electron electric dipole moment

- 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. (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.'05



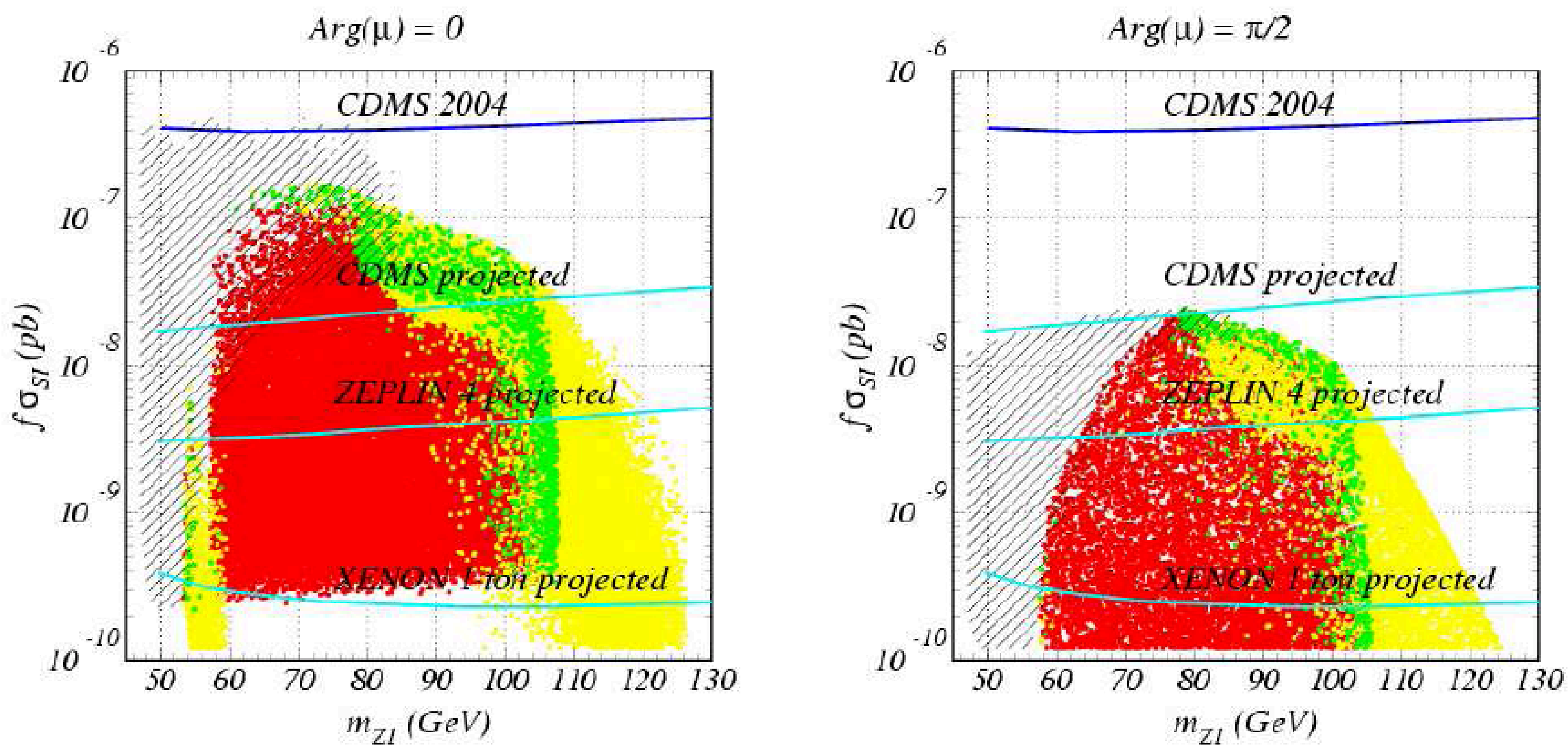


Pilaftsis' 02

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.'05



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, and V. Barger’s talk)
C. Balazs, M. Carena, A. Freitas, C.W., to appear

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

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

Electroweak Phase Transition

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

- 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

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

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

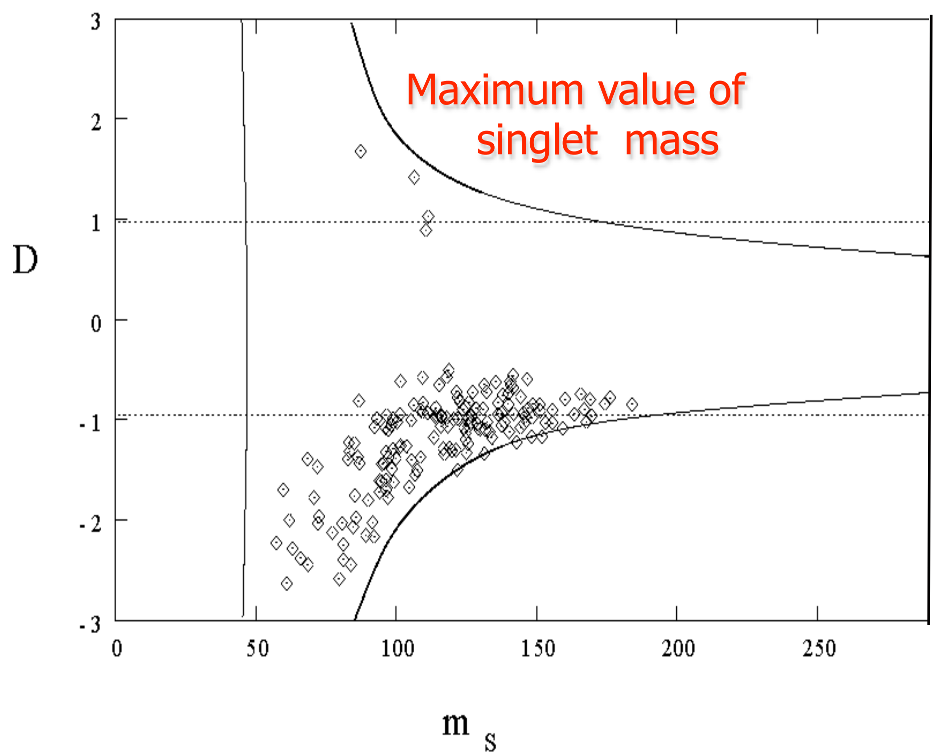
Parameters with strongly first order transition

- 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

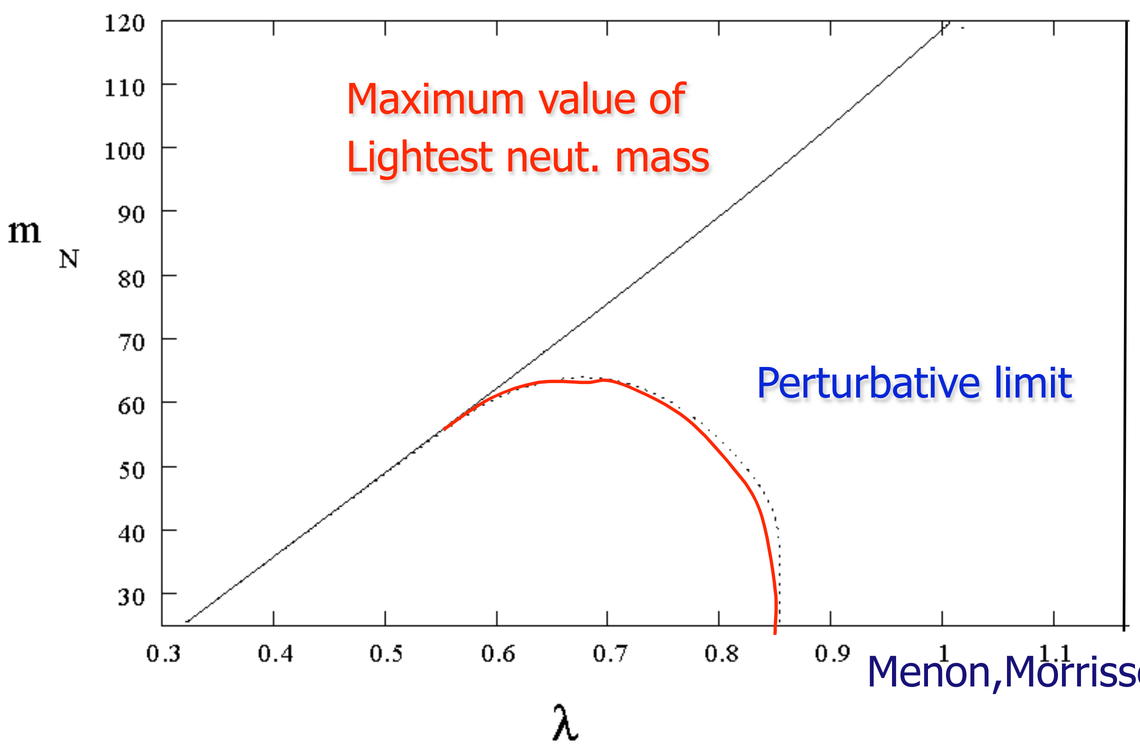
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_\mathrm{W} M_\mathrm{Z} & s_\beta s_\mathrm{W} M_\mathrm{Z} & 0 \\ 0 & M_2 & c_\beta c_\mathrm{W} M_\mathrm{Z} & -s_\beta c_\mathrm{W} M_\mathrm{Z} & 0 \\ -c_\beta s_\mathrm{W} M_\mathrm{Z} & c_\beta c_\mathrm{W} M_\mathrm{Z} & 0 & \lambda v_\mathrm{s}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

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.

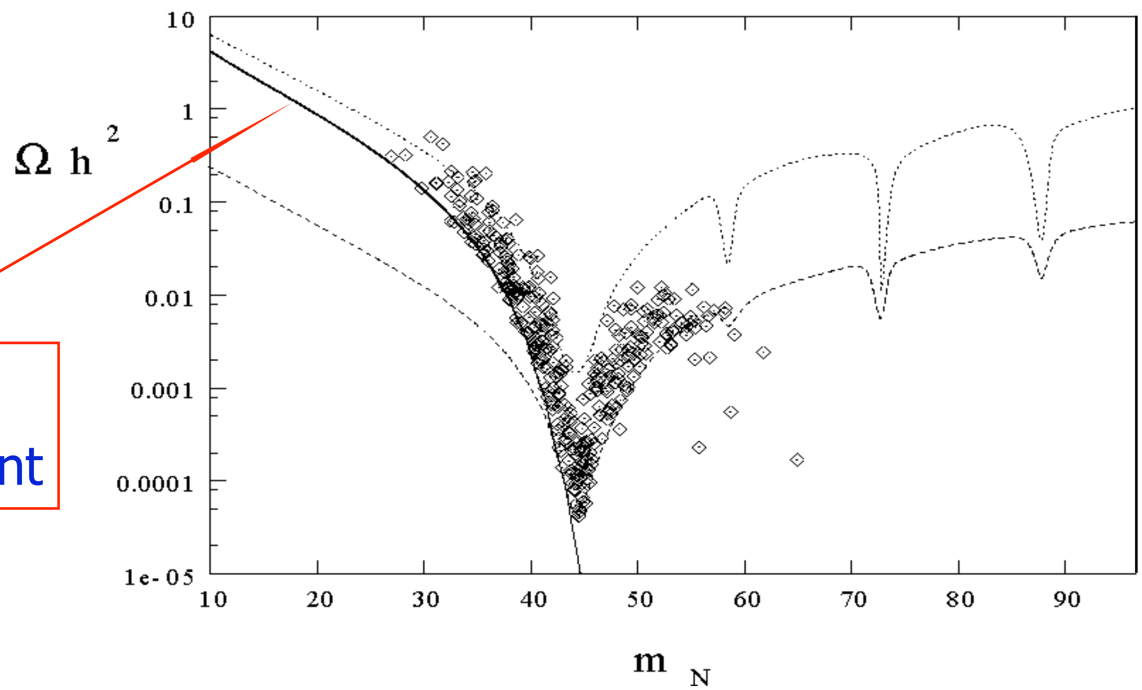


Menon,Morrissey,C.W.'04

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.

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 m_S^2)
- They mix with standard CP-even and CP-odd states in a way proportional to λ **and** a_λ
- 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 MSSM, upper bound on Higgs that couples to weak bosons
- Extra tree-level term helps in avoiding LEP bounds.

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

Espinosa,Quiros '98; Kane et al. ;98

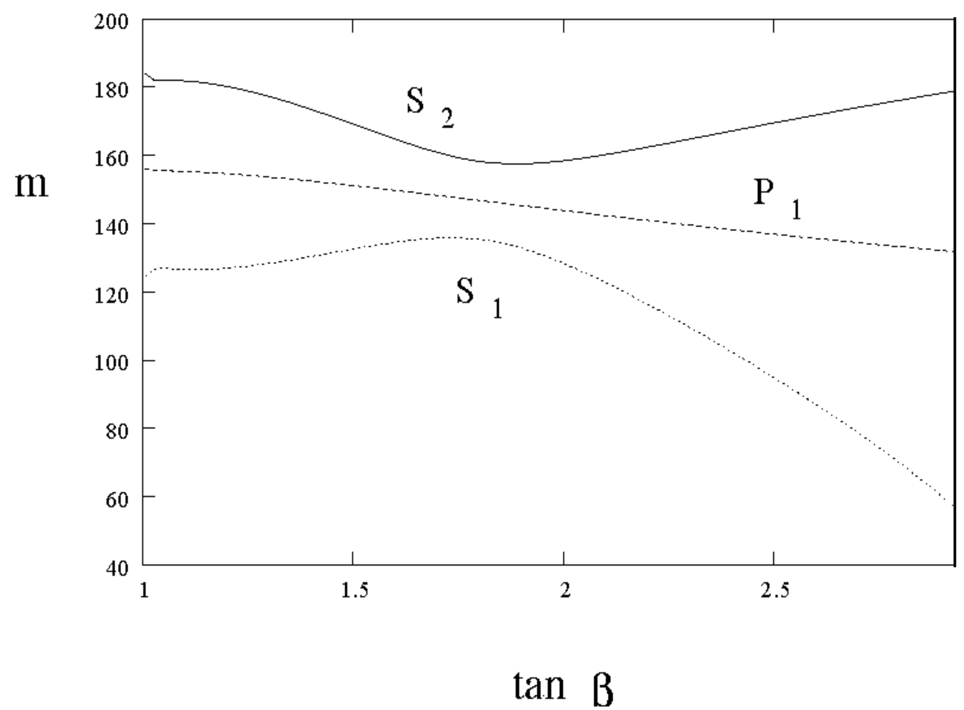
Light Higgs boson masses

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

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

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

$\lambda = 0.7$



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

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

- 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:

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

Higgs Working Group, Les Houches'01

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

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

Information from LHC/ILC

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

- Assuming the presence of gluinos with masses dictated by gaugino mass unification, as well as one squark, with mass of the order of 500 GeV:

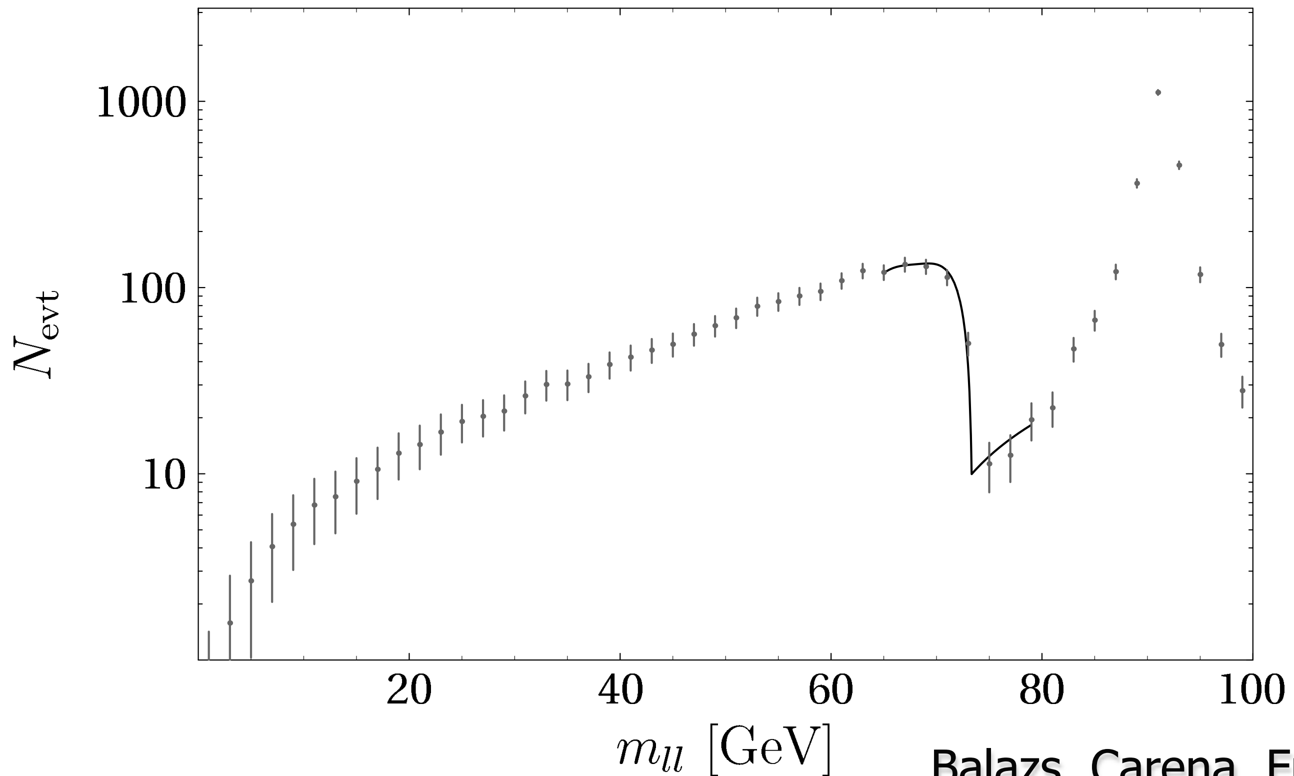
- The LHC may be able to determine the chargino and second neutralino masses, as well as the lightest neturalino mass with some precision. The presence of one Higgs decaying invisibly provides further information.

- A 500 GeV ILC will allow to measure four of the five neutralino masses, as well as the chargino masses. It will also verify the existence of two light CP-even Higgses, which decay mainly invisibly.

Sparticle	Mass m [GeV]	Width Γ [GeV]	Decay modes	
$\tilde{\chi}_1^0$	33.3	—	—	
$\tilde{\chi}_2^0$	106.6	0.00004	$\tilde{\chi}_2^0 \to Z^* \, \tilde{\chi}_1^0$	100%
$\tilde{\chi}_3^0$	181.5	0.09	$\tilde{\chi}_3^0 \to Z \, \tilde{\chi}_1^0$	74%
			$\to S_1 \, \tilde{\chi}_1^0$	26%
			$\to P_1 \, \tilde{\chi}_1^0$	0.4%
$\tilde{\chi}_4^0$	278.0	1.5	$\tilde{\chi}_4^0 \to Z \, \tilde{\chi}_1^0$	11%
			$\to Z \, \tilde{\chi}_2^0$	22%
			$\to Z \, \tilde{\chi}_3^0$	1%
			$\to W^\pm \, \tilde{\chi}_1^\mp$	43%
			$\to S_1 \, \tilde{\chi}_1^0$	7%
			$\to S_1 \, \tilde{\chi}_2^0$	0.2%
			$\to S_2 \, \tilde{\chi}_1^0$	8%
			$\to P_1 \, \tilde{\chi}_1^0$	7%
			$\to P_1 \, \tilde{\chi}_2^0$	0.7%
$\tilde{\chi}_1^\pm$	165.0	0.136	$\tilde{\chi}_1^+ \to W^+ \, \tilde{\chi}_1^0$	100%
$\tilde{\chi}_2^\pm$	319.5	2.0	$\tilde{\chi}_2^+ \to W^+ \, \tilde{\chi}_1^0$	32%
			$\to W^+ \, \tilde{\chi}_2^0$	1%
			$\to W^+ \, \tilde{\chi}_3^0$	34%
			$\to Z \, \tilde{\chi}_1^+$	29%
			$\to S_1 \, \tilde{\chi}_1^+$	5%
			$\to P_1 \, \tilde{\chi}_1^+$	0.3%

$$pp \to \tilde{g}\tilde{g}, \qquad \tilde{g} \to b\tilde{b}^* \text{ or } \bar{b}\tilde{b} \to b\bar{b}\tilde{\chi}_2^0 \qquad\qquad \tilde{\chi}_2^0 \to Z^*\,\tilde{\chi}_1^0$$

$$m_{ll,\max,2} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \qquad\qquad m^2_{jll,\max,2} = \frac{1}{m^2_{\tilde{\chi}_2^0}}(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0})(m^2_{\tilde{b}} - m^2_{\tilde{\chi}_2^0})$$



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

Using similar methods for $\tilde{\chi}_3^0$, one obtains

$$m_{\tilde{\chi}_1^0} = 33^{+32}_{-17.5}\ \text{GeV}, \quad m_{\tilde{\chi}_2^0} = 106.5^{+32.5}_{-17.5}\ \text{GeV}, \quad m_{\tilde{\chi}_3^0} = 181^{+20}_{-10}\ \text{GeV}, \quad m_{\tilde{b}} = 499^{+30}_{-17}\ \text{GeV}$$

At the ILC, one can use

- Charginos pair production
- Lightest chargino threshold scans
- Neutralino $(\tilde\chi^0_2\tilde\chi^0_3)$, $(\tilde\chi^0_2\tilde\chi^0_4)$ $(\tilde\chi^0_3\tilde\chi^0_4)$ production
- Higgs production provides a good determination of CP-even Higgs masses

$$m_{\tilde\chi^0_2} = 106.6^{+1.1}_{-1.3}\ \mathrm{GeV}, \qquad m_{\tilde\chi^0_3} = 181.5 \pm 4.9\ \mathrm{GeV}, \qquad m_{\tilde\chi^0_4} = 278.0^{+2.5}_{-3.5}\ \mathrm{GeV}.$$

$$m_{\tilde\chi^0_1} = 33.3^{+0.4}_{-0.3}\ \mathrm{GeV}, \qquad m_{\tilde\chi^\pm_1} = 164.98 \pm 0.05\ \mathrm{GeV}, \qquad m_{\tilde\chi^0_4} = 319.5^{+5.5}_{-4.3}\ \mathrm{GeV}.$$

Information after 500 GeV ILC run

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

- From measurements in the neutralino and chargino sectors (masses and cross sections)

$$M_1 = (122.5 \pm 1.3)\ \mathrm{GeV}, \qquad |\kappa| < 2.0\ \mathrm{GeV}, \qquad m_{\tilde{\nu}_\mathrm{e}} > 5\ \mathrm{TeV},$$
$$M_2 = (245.0 \pm 0.7)\ \mathrm{GeV}, \qquad \tan\beta = 1.7 \pm 0.09, \qquad m_{\tilde{e}_\mathrm{R}} > 1\ \mathrm{TeV}.$$
$$|\lambda| = 0.619 \pm 0.007, \qquad |\phi_\mathrm{M}| < 0.32,$$
$$v_\mathrm{s} = (-384 \pm 4.8)\ \mathrm{GeV},$$

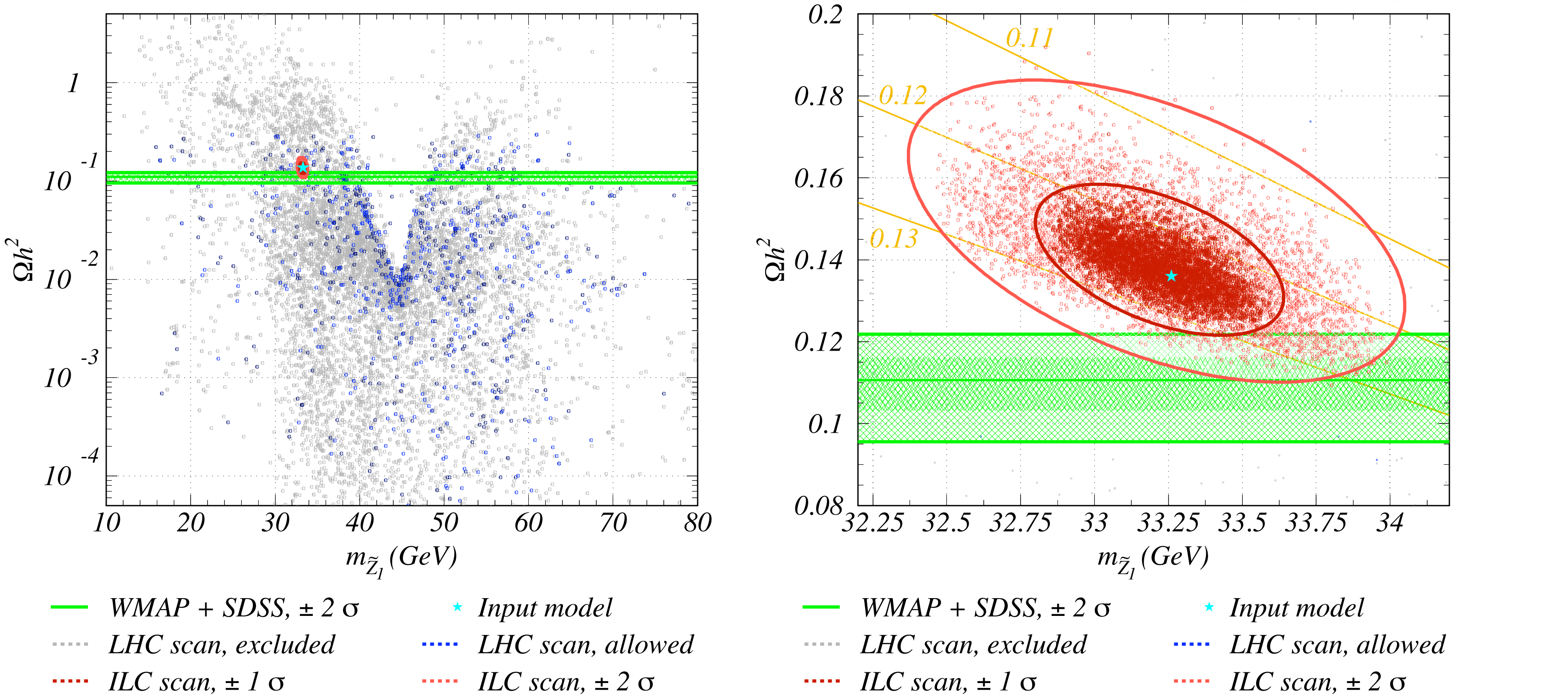
- From measurements in the Higgs sector (two CP-even Higgs bosons) combined with the information above,

$$a_\lambda = (373^{+17}_{-21})\ \mathrm{GeV}, \qquad m_\mathrm{s} = (106 \pm 18)\ \mathrm{GeV},$$
$$t_\mathrm{s}^{1/3} = (156^{+25}_{-39})\ \mathrm{GeV}, \qquad |D| \sim 1.0 \pm 0.65.$$
$$m_\mathrm{s}^2 = -a_\lambda v_1 v_2 / v_\mathrm{s} - t_\mathrm{s}/v_\mathrm{s} - \lambda^2 v^2$$

Dark Matter Density Determination

From the information obtainable at the ILC/LHC, one can determine the dark matter density

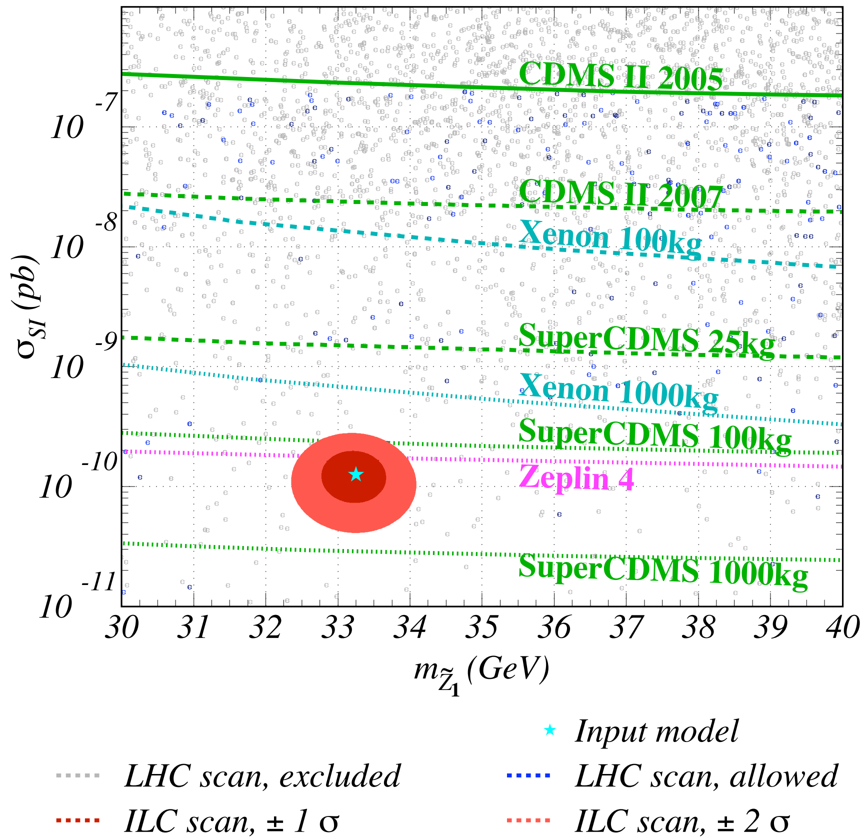
Balazs, Carena, Freitas, C.W. '07



Direct Dark Matter Detection

- Since dark matter is mainly singlino, neutralino nucleon cross section is suppressed

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



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_{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

Choice of CP-violating Phases

- We will assume phases in the (universal) gaugino mass parameters
- This choice leads to signatures in electric dipole moments similar to those ones present in the MSSM
- Choosing the phase in the Higgs sector, however, may lead to a realistic scenario (Huber, Konstantin, Prokopec, Schmidt'06). It is an open question if this can be tested.
- Hard to realize this scenario with only phases in the squark sector.

Electric Dipole Moments. Heavy Sleptons

Low values of $\tan\beta$ and heavy CP-odd scalars suppress the electric dipole moments

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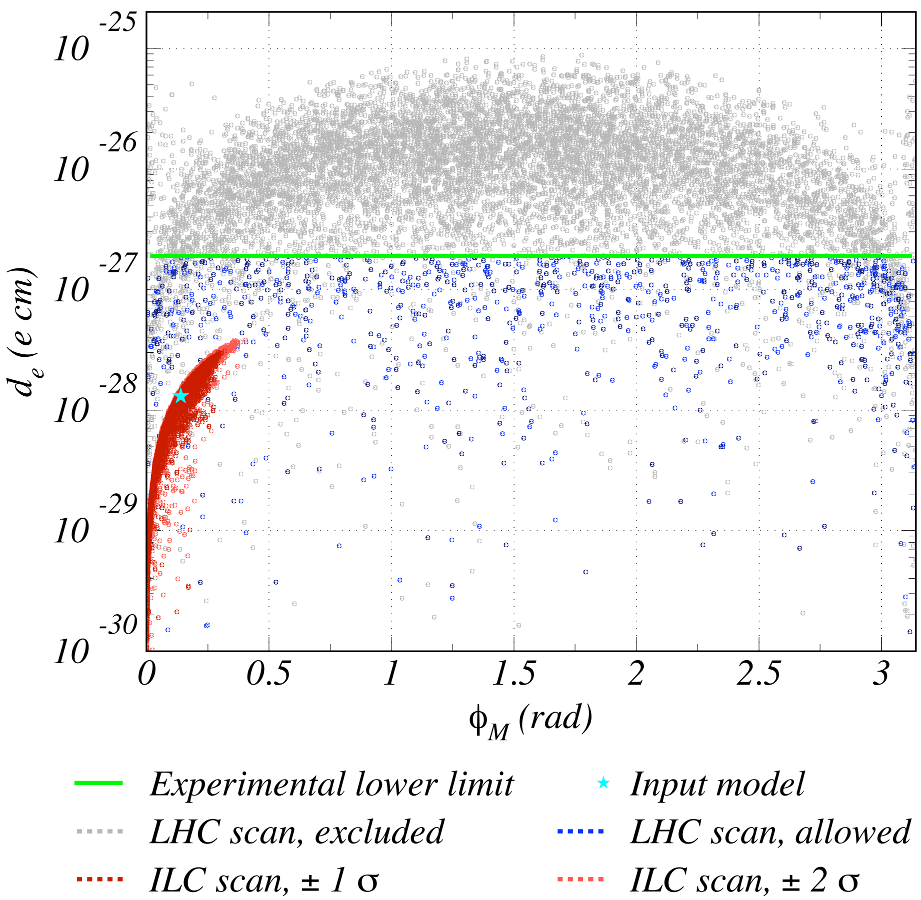


Baryogenesis at an Earlier Phase Transition

Alternative Mechanism for Baryogenesis

T. Tait, S. Shu and C.W. '06

- Gauge Extension based on

$$SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L$$

- Baryogenesis may take place at this phase transition
- Stronger gauge interactions make it easier to generate a strongly first order phase transition

$$\frac{1}{g^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

- Third generation couples to one of the two SU(2) groups
- Baryon and lepton number are generated in the third generation, with $B - L = 0$

$$L_3 = B_3 \neq 0, \qquad L_{1,2} = B_{1,2} = 0$$

Erasure of Baryon Asymmetry

- Electroweak Sphaleron Processes tend to erase the baryon asymmetry at high temperatures
- Baryon and lepton number are zero before the phase electroweak phase transition. However, lepton flavor asymmetry $(L_i - L_j)$ and $\Delta_i = L_i - B/3$ are conserved

$$L_3 = -2L_1 = -2L_2 \qquad (L_3 = 2L_3^{\text{gen.}}/3)$$

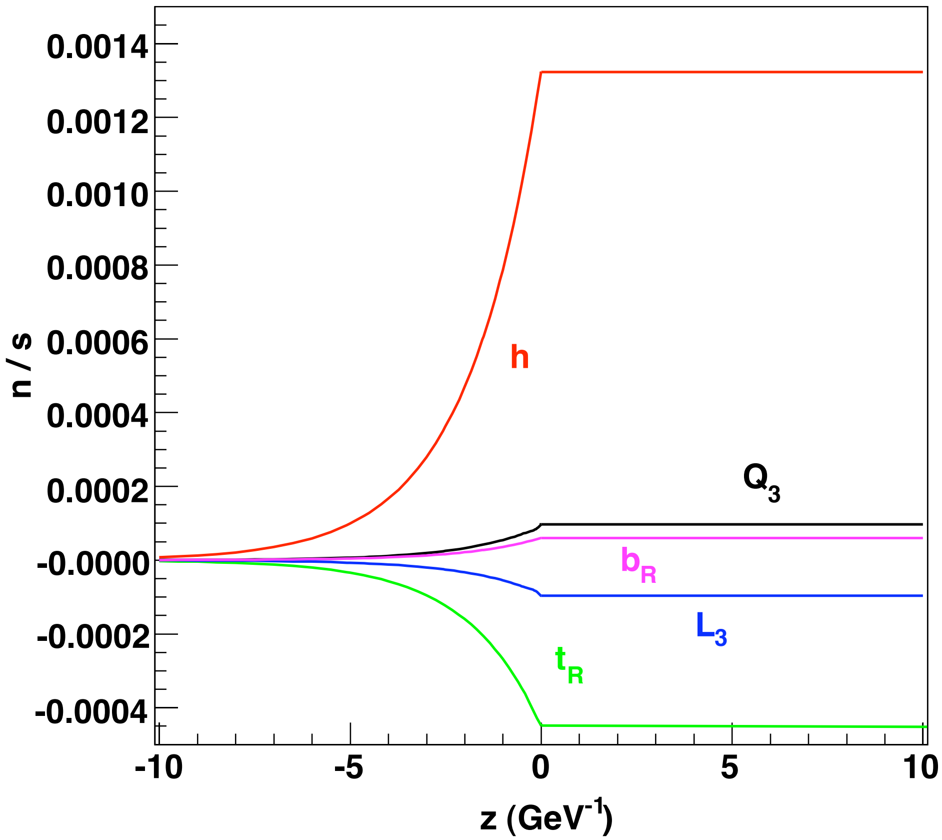
- This asymmetries become important after the electroweak phase transition. Assuming it to be second order, a final baryon number is generated due to the heaviness of the tau lepton

Dreiner and Ross'93

$$B = -\frac{4}{13\pi^2}\sum_{i=1}^{N}\Delta_i\frac{m_i^2}{T^2} \quad \rightarrow B \simeq 10^{-6}\Delta_3$$

Lepton and Baryon Number Generated at the Earlier P.T.

T. Tait, S. Shu and C.W. '06



Generated Lepton number density for $g_1 \simeq \mathcal{O}(1)$

$$\frac{n_{L_3}^{\text{gen.}}}{s} \simeq 10^{-4}$$

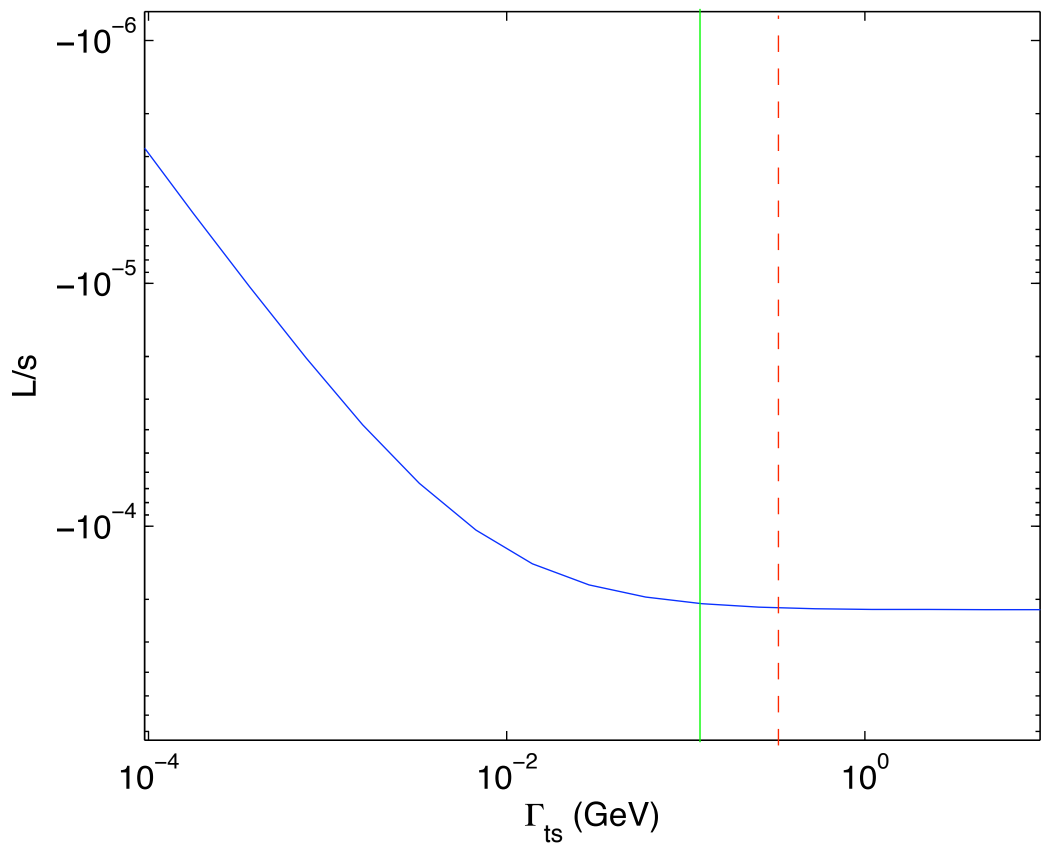
Leading to a final Baryon number density

$$\frac{n_B}{s} \simeq 10^{-10}$$

in good agreement with observations !

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,ILC and direct dark matter detection experiments.
- nMSSM provides an attractive alternative scenario.
- Origin of Dark Matter and Baryogenesis may explained in a natural way in this model, provided singlet mass is small.
- Invisible decaying Higgs signature of this model, as well as an extended and light neutralino sector. Direct dark matter detection harder in this case.



-10^{-6}
-10^{-5}
-10^{-4}
L/s
10^{-4}
10^{-2}
10^{0}
Γ_{ts} (GeV)

Additional Slides

Baryon Abundance in the Universe

- Information on the baryon abundance comes from two main sources:
- Abundance of primordial elements. When combined with Big Bang Nucleosynthesis tell us

$$\eta = \frac{n_B}{n_\gamma} \quad , \qquad n_\gamma = \frac{411}{\mathrm{cm}^3}$$

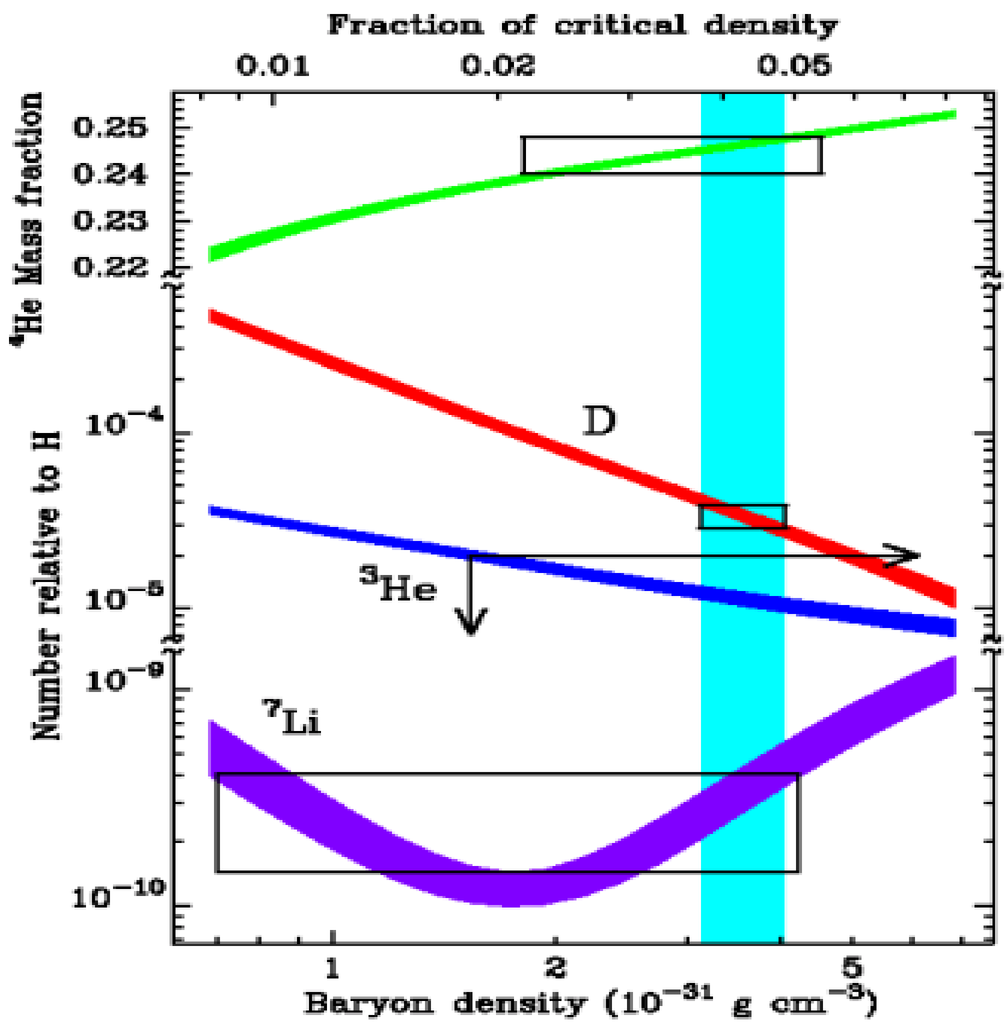
- CMBR, tell us ratio

$$\frac{\rho_B}{\rho_c} \equiv \Omega_B , \qquad \rho_c \approx 10^{-5} h^2 \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

- There is a simple relation between these two quantities

$$\eta = 2.74 \; 10^{-8} \Omega_B h^2$$

Element Abundance and Big-Bang Nucleosynthesis predictions

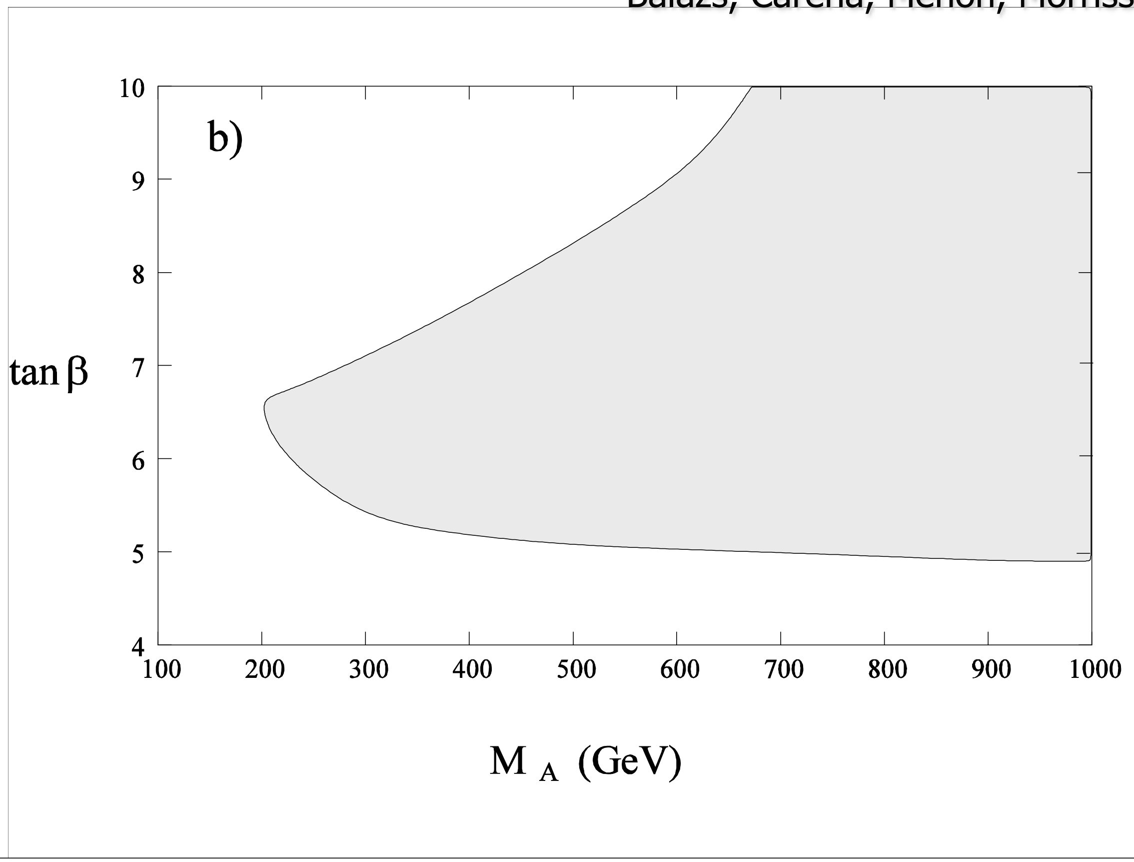


$1\,\mathrm{GeV} \approx 1.6\ 10^{-24}\,\mathrm{g}$

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



Cirigliano, Profumo, Ramsey-Musolf'06

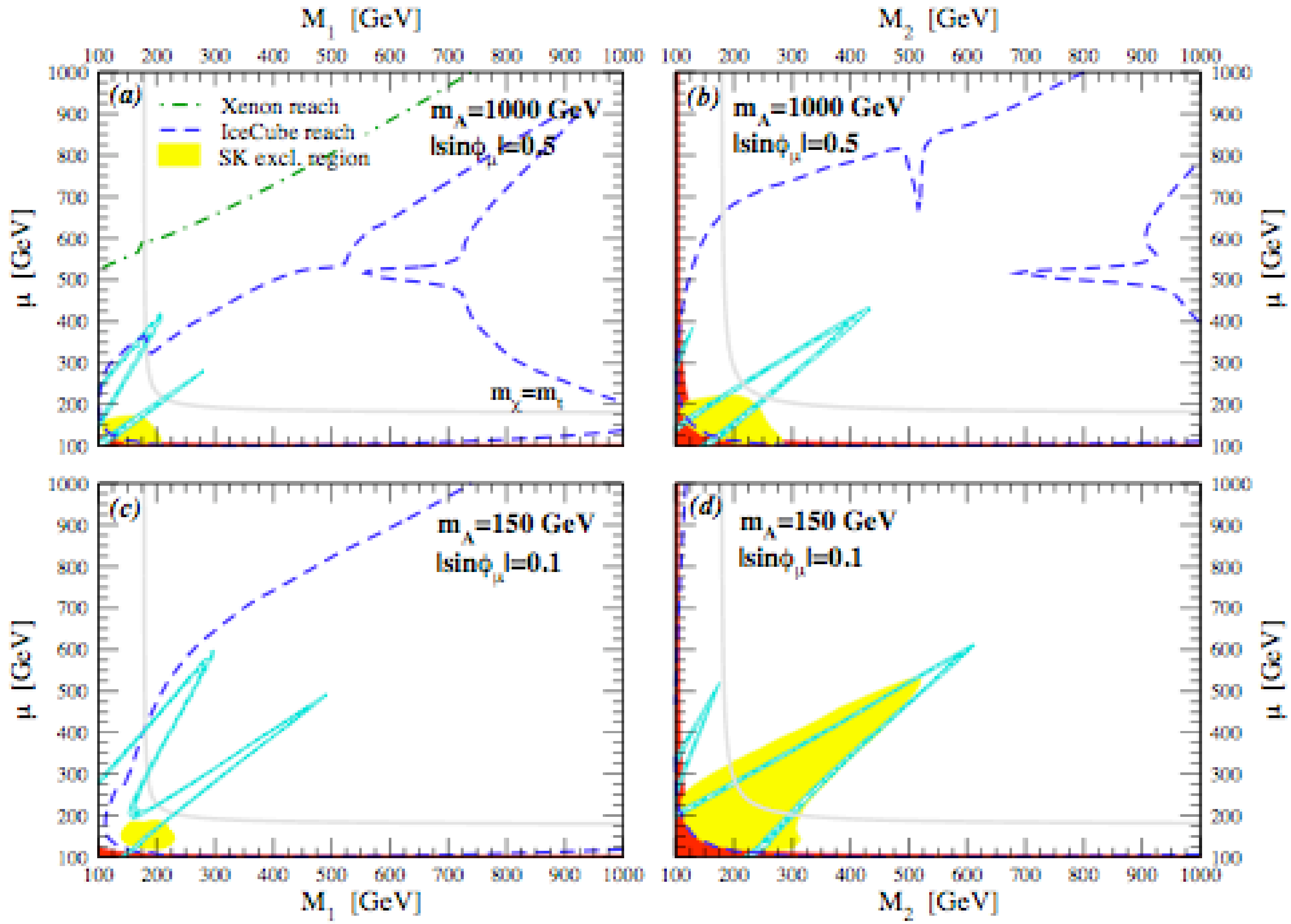


Figure 8: *Current exclusion limits from the SuperKamiokande collaboration [58] (yellow shaded region) and future sensitivity reach of IceCube [13] and of Xenon-1t [8] on the $(M_{1,2}, \mu)$ planes at $|\sin\phi_\mu| = 0.5$ (panels* (a) *and* (b)*) and 0.1 (panels* (c) *and* (d)*); we also show the contours of maximal neutralino masses compatible with a stop as heavy as the top quark (grey lines), and the regions of the parameter space which produce a BAU compatible, at the 2-σ level, with the WMAP result [20]. The two upper panels refer to a heavy scalar mass*