# 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., in preparation.

Santa Fe Physics Workshop, Santa Fe, July 25, 2006

# 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).

- 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**
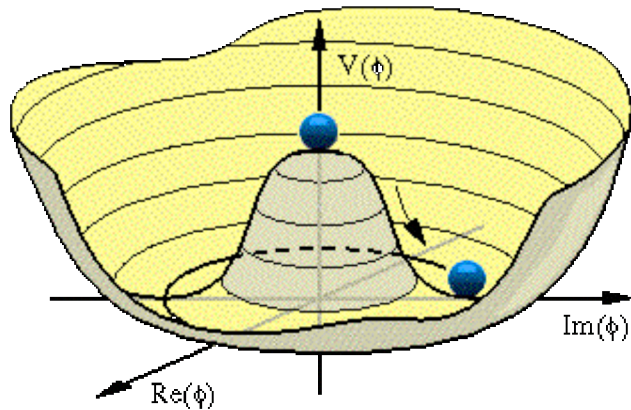


**Spontaneous Breakdown of the symmetry :**
**Vacuum becomes a source of energy = a source of mass**

$$< \phi > = v$$

*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:*

$$\mathbf{M_W} = \mathbf{g}_{W,Z}\, \mathbf{v} \qquad m_{top} = h_{top}\, v \qquad m_H^2 = \lambda\, v^2$$

# 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

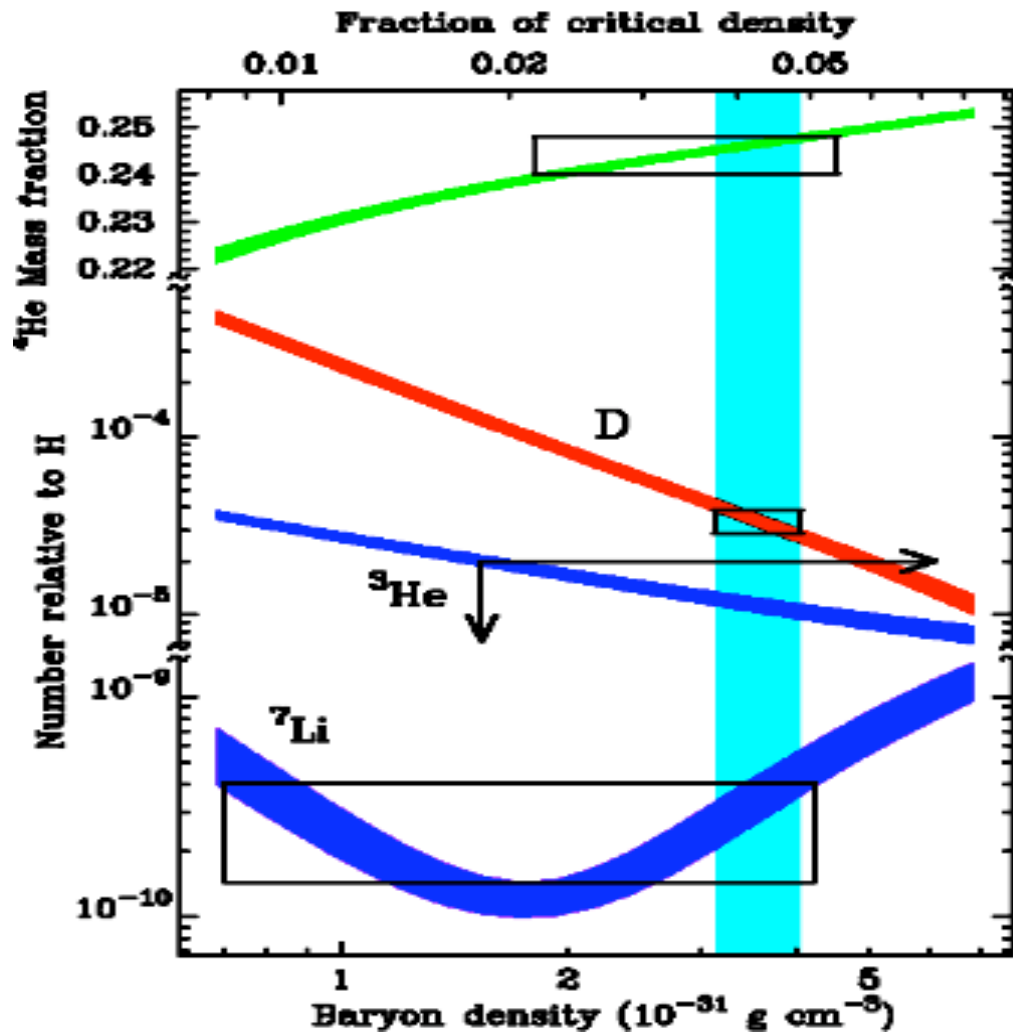$$\eta = \frac{n_B}{n_\gamma} \quad , \quad n_\gamma = \frac{421}{cm^3}$$

- CMBR, tell us ratio

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

- There is a simple relation  between these two quantities

$$\eta = 2.68 \ 10^{-8} \Omega_B h^2$$

# Element Abundance and Big-Bang Nucleosynthesis predictions



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

# 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

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

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

# Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

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

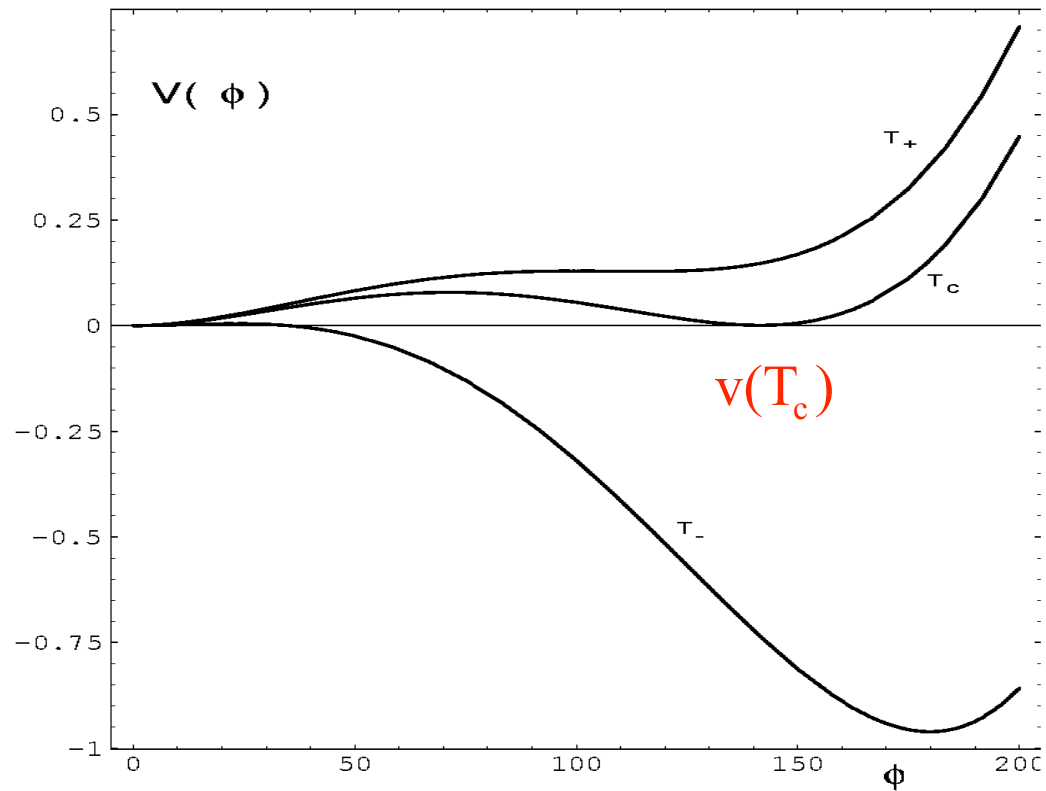Kuzmin, Rubakov and Shaposhnikov, '85—'87

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

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

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

# Electroweak Phase Transition

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

# Finite Temperature Higgs Potential

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

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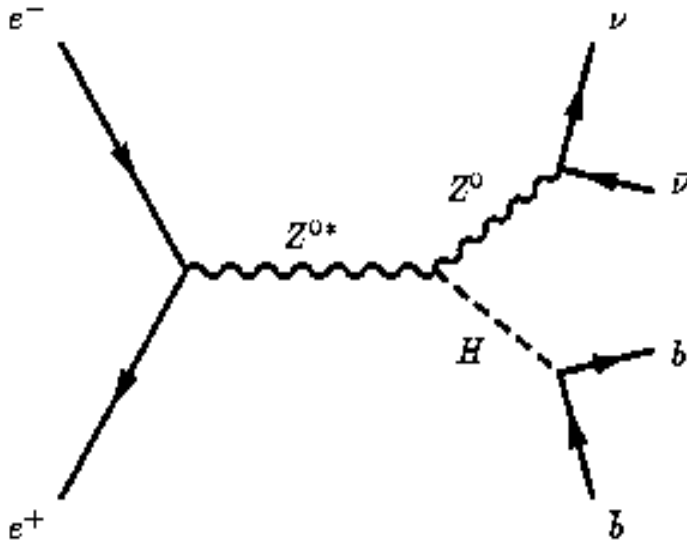
*E receives contributions proportional to the sum of the cube of all light boson particle couplings*

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

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

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

**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

$$E_{SUSY} = \frac{g_w^3}{4\pi} + \frac{h_t^3}{2\pi} \approx 8\,E_{SM}$$
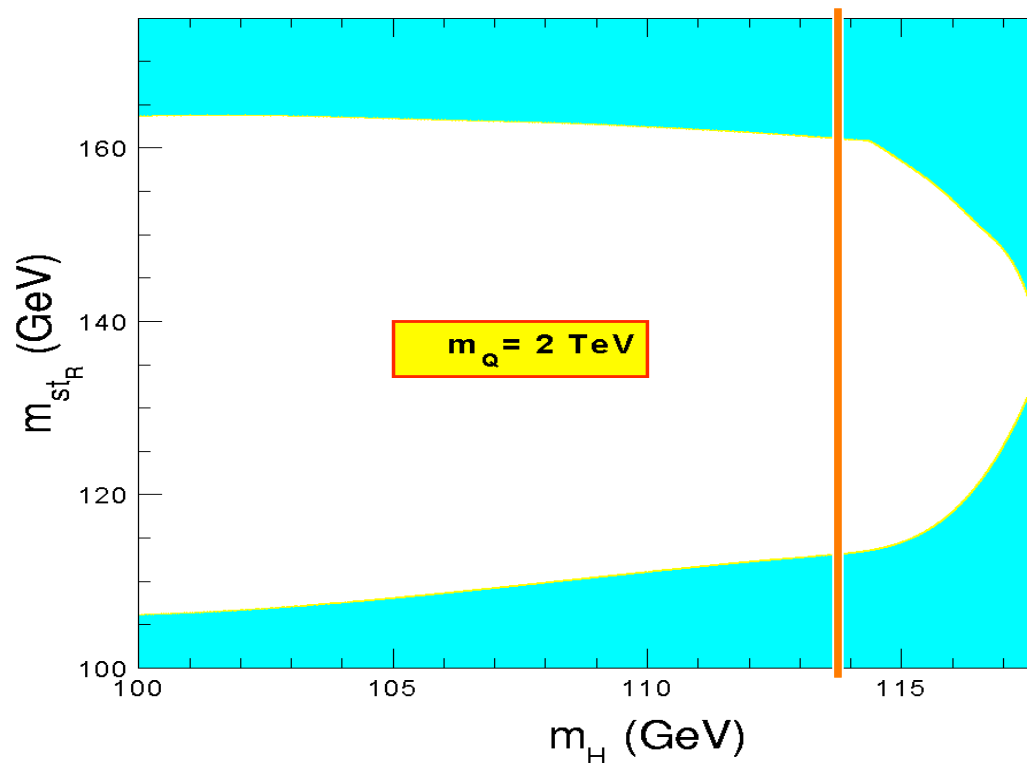
M. Carena, M. Quiros, C.W. '96, '98

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

**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

$$qq \rightarrow qqV^*V^* \rightarrow qqh$$
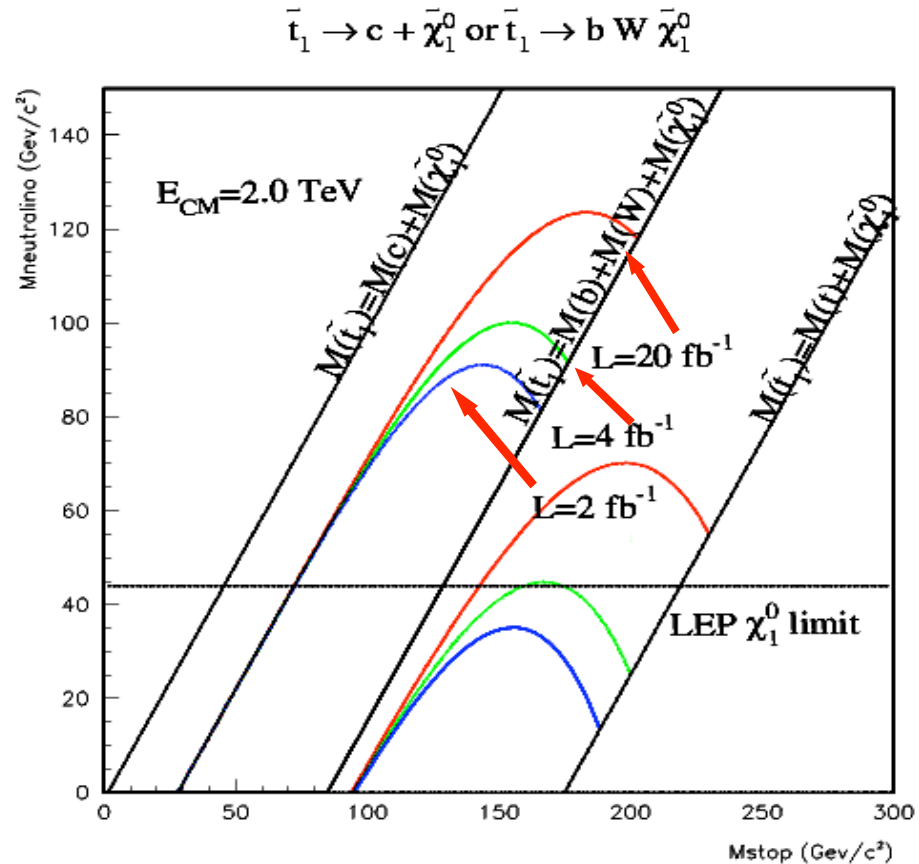
$$\text{with } h \rightarrow \tau^+\tau^-$$
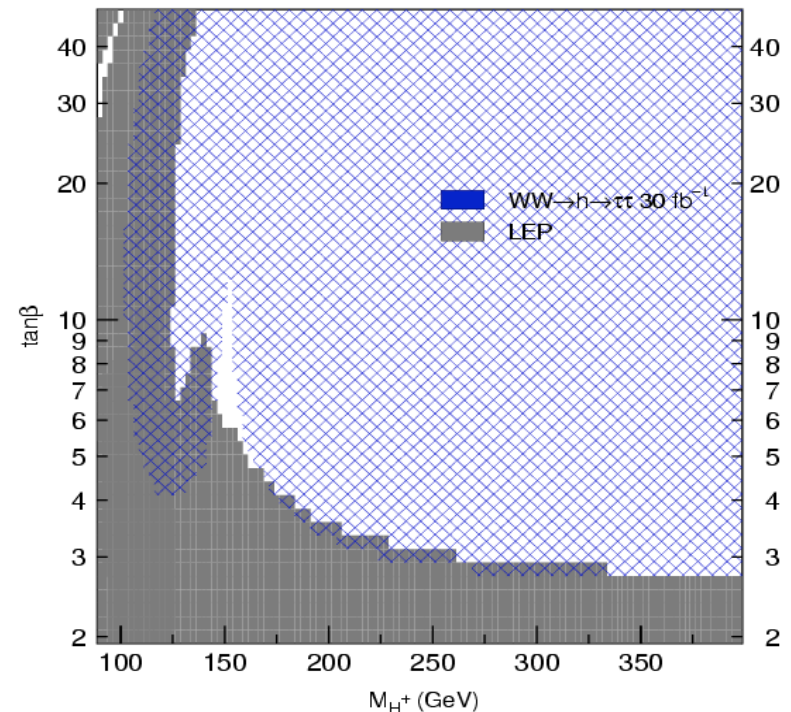
# Tevatron Stop Reach when two body decay channel is dominant

Main signature:

2 or more jets plus missing energy

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

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



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

$E_{CM} = 2.0\,\text{TeV}$

$M(\tilde{t}_1) = M(c) + M(\tilde{\chi}_1^0)$

$M(\tilde{t}_1) = M(b) + M(W) + M(\tilde{\chi}_1^0)$

$M(\tilde{t}_1) = M(t) + M(\tilde{\chi}_1^0)$

$L = 20\,\text{fb}^{-1}$

$L = 4\,\text{fb}^{-1}$

$L = 2\,\text{fb}^{-1}$

LEP $\chi_1^0$ limit

Mneutralino (Gev/c²)

Mstop (Gev/c²)

Demina, Lykken, Matchev, Nomerotsky '99

# Stop-Neutralino Mass Difference: Information from the Cosmos

- 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
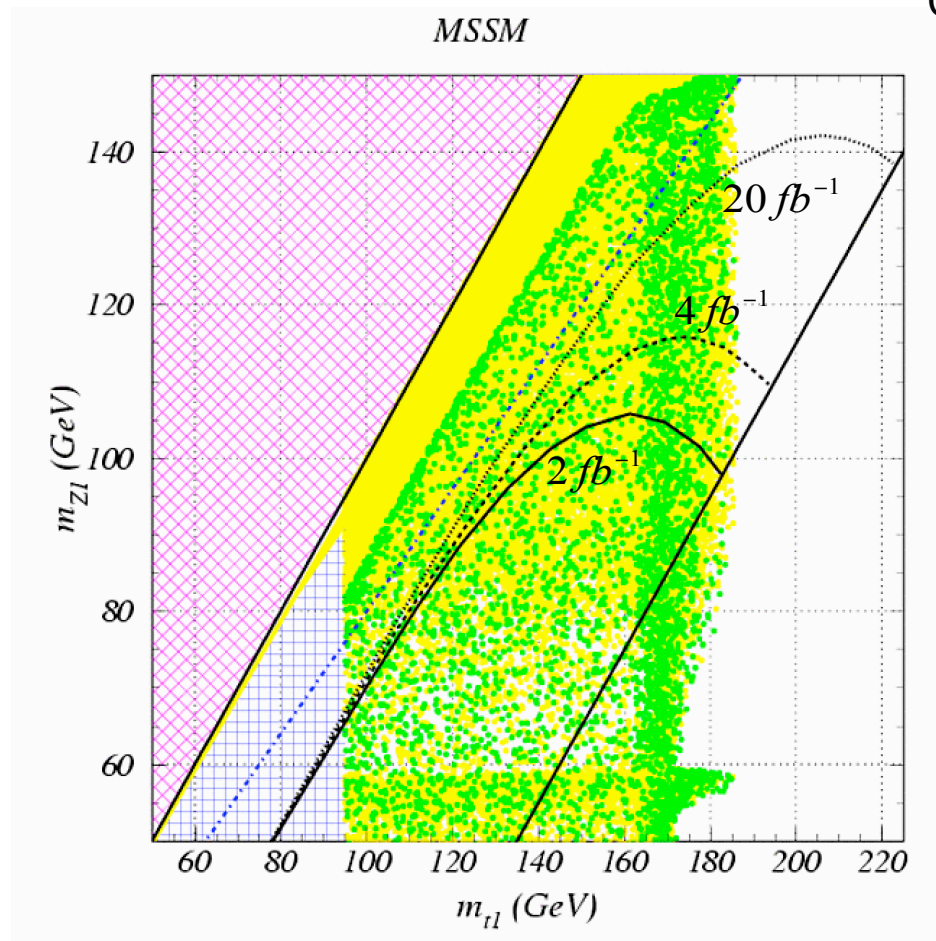
Green: Relic density consistent with WMAP measurements.

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

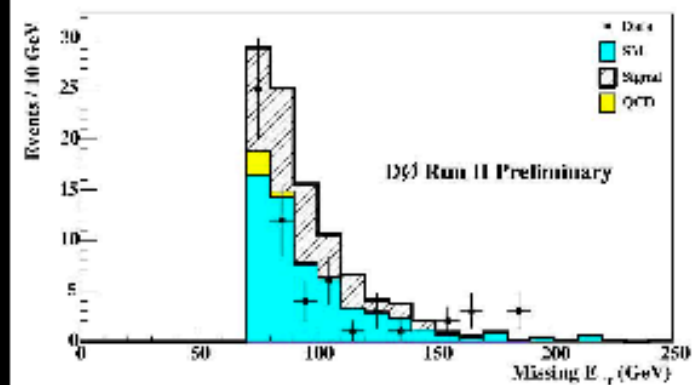LHC will have equal difficulties. Searches become easier at a Linear Collider !
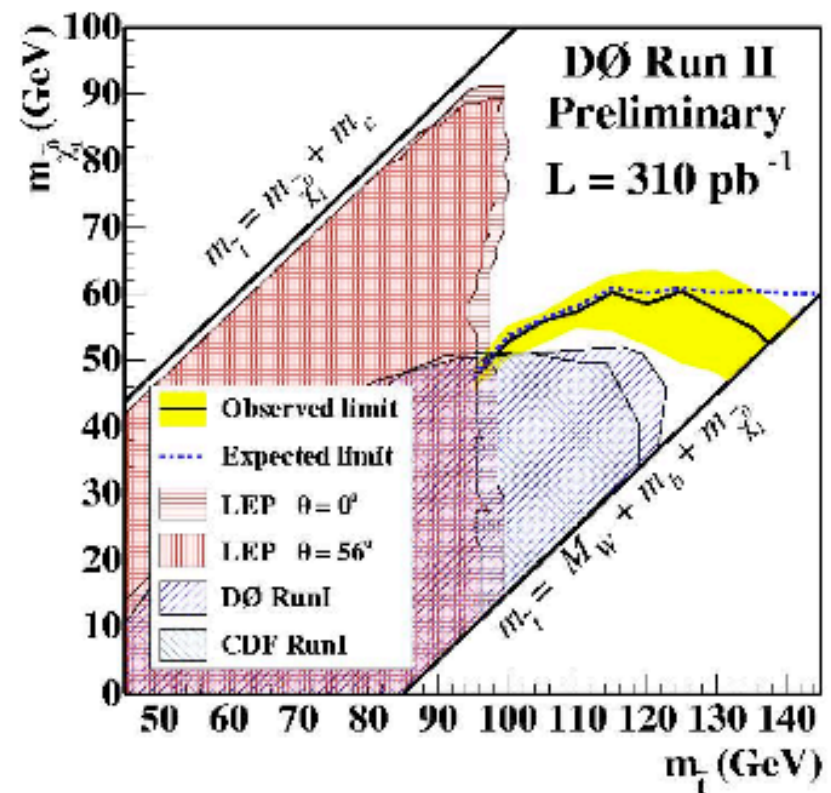
Carena, Freitas et al. '05

# Stop in acoplanar dijet (II)   (see also Bargassa's talk)

- For M(stop)=130, M(neutralino1)=50
  - Pt1>40 GeV, Pt2>20 GeV
  - MET > 70 GeV
  - ΔΦ max+ΔΦ 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
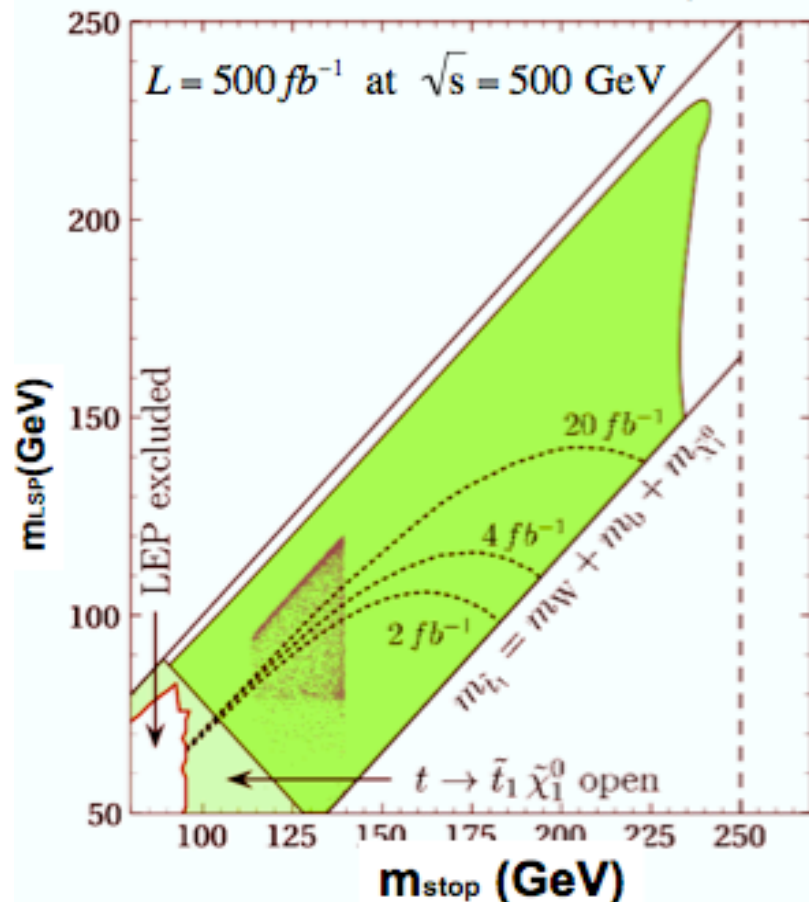  - The largest stop mass excluded is 131 GeV



DØ Run II Preliminary



DØ Run II Preliminary
L = 310 pb$^{-1}$

- Observed limit
- Expected limit
- LEP θ = 0°
- LEP θ = 56°
- DØ RunI
- CDF RunI

# The power of the ILC

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

MC, Finch, Freitas, Milstene, Nowak, Sopczak

$$L = 500\, fb^{-1} \text{ at } \sqrt{s} = 500 \text{ GeV}$$

**m_LSP (GeV)** vs **m_stop (GeV)**

LEP excluded

20 $fb^{-1}$

4 $fb^{-1}$

2 $fb^{-1}$

$m_{\tilde{t}_1} = m_W + m_b + m_{\tilde{\chi}}$

$t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0$ open

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

Signature: 2 soft charm jets plus missing E

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

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
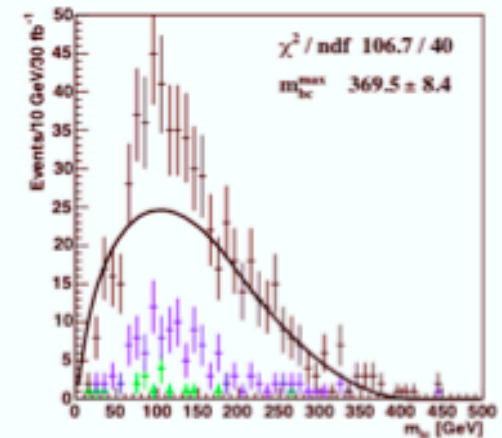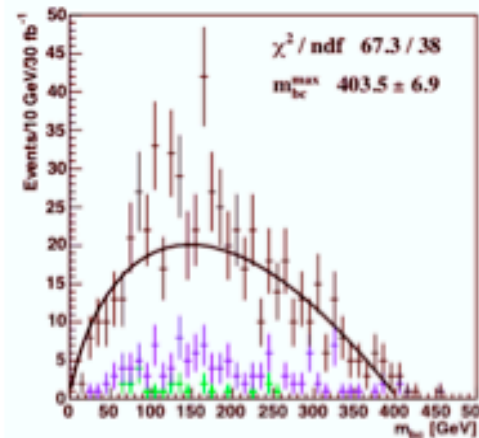
# Light Stops at the LHC

- Dominant decay mode for small mass differences $\quad \tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$

- Look for same-sign tops in gluino decays

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow tt\,\tilde{t}_1^*\tilde{t}_1^*, \qquad t \rightarrow bl^+\bar{\nu}_1 \qquad \tilde{t}_1^* \rightarrow c\tilde{\chi}_1^0$$

Signal: 2 SS leptons, 2 SS bottoms, jets plus Missing Energy

Mass measurements from distributions,
==> but not enough independent
distributions to get absolute masses

- Good reach for gluino masses
  up to 900 GeV.



Caveat: Study done for relatively light squarks ~ 1 TeV.
For heavier squarks, gluino signal decreased by 50% from absense of
squark-gluino production: still may be possible to see the stops (under study)

# 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.

$$\langle\varphi\rangle \neq 0$$

$$\langle\varphi\rangle \neq 0$$

$$\langle\varphi\rangle = 0$$
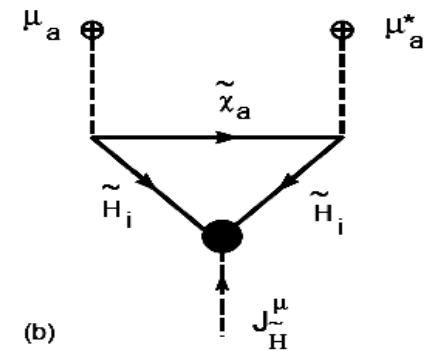
$$\langle\varphi\rangle \neq 0$$
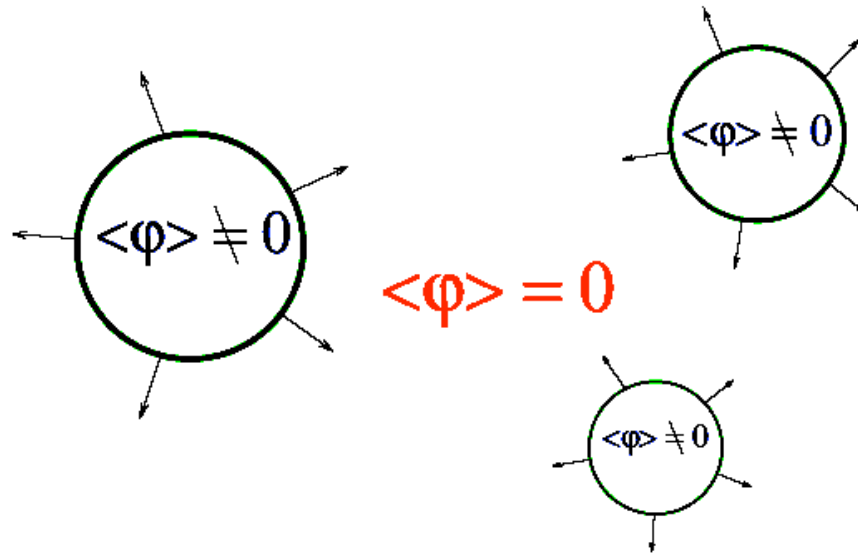
# Baryon Asymmetry

- 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 $\tan\beta$
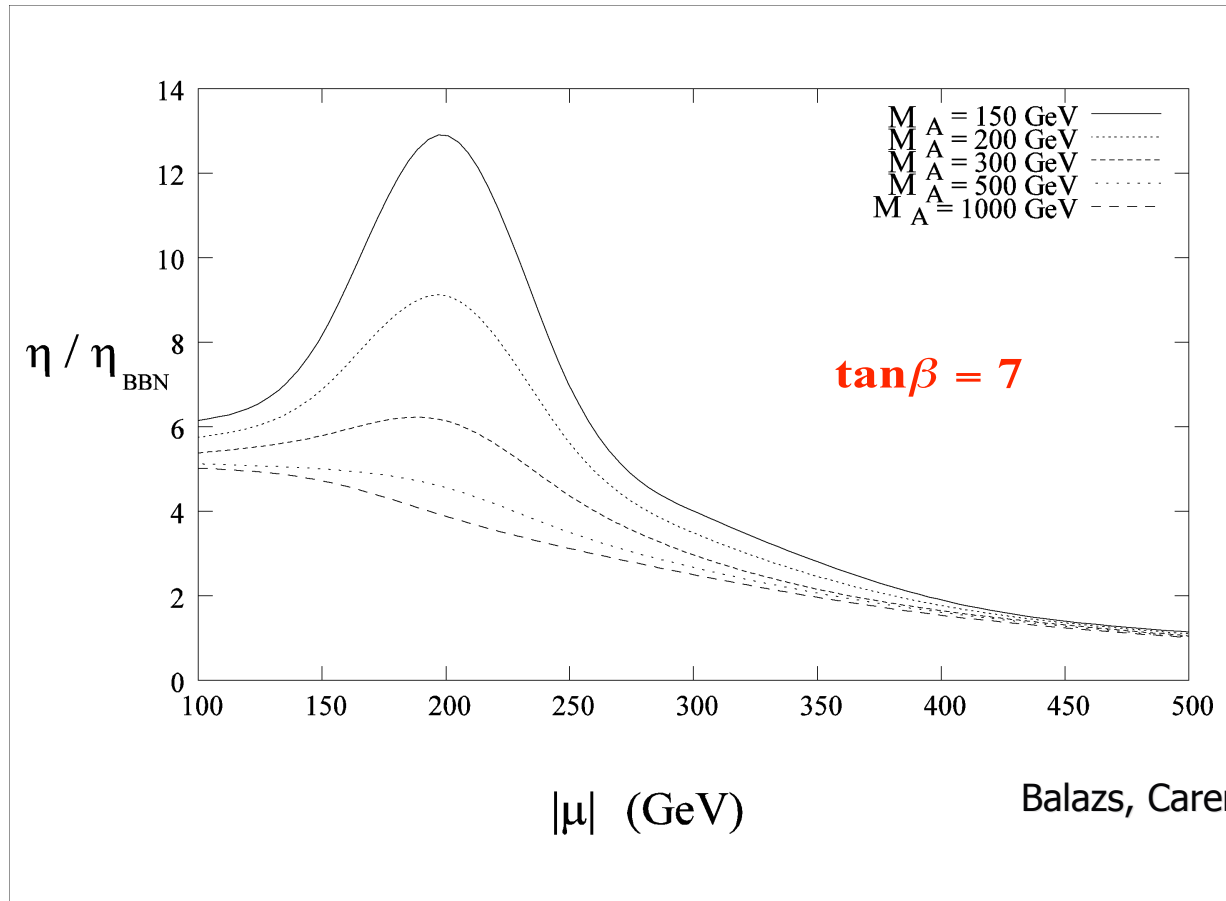


Carena,Quiros,Seco,C.W.'02

$\tan\beta = 7$

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

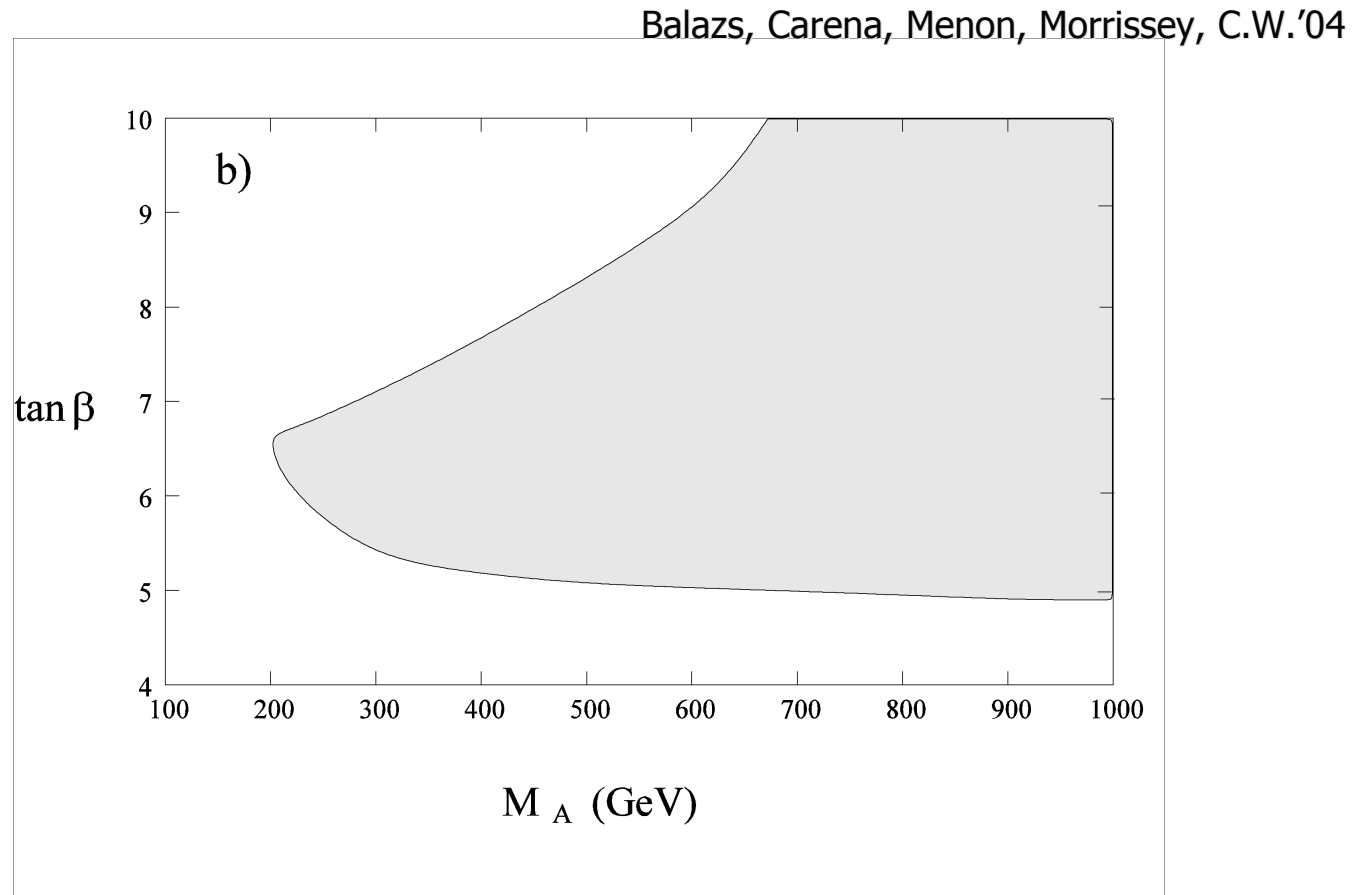$$d_e < 1.6 \, 10^{-27} \text{ e cm}$$

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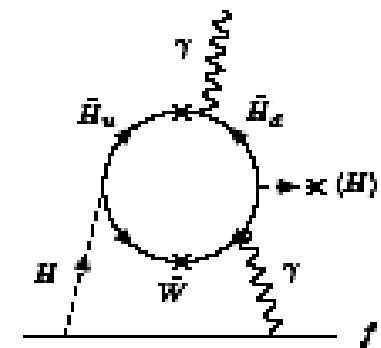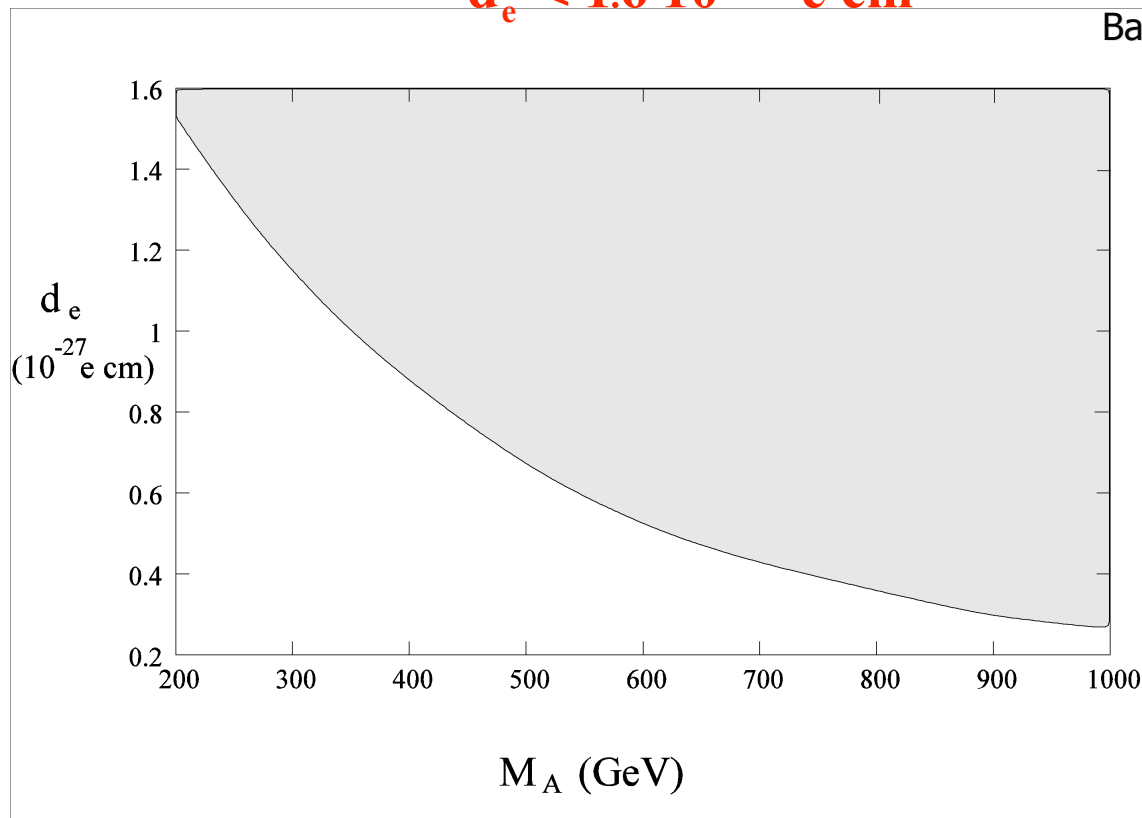


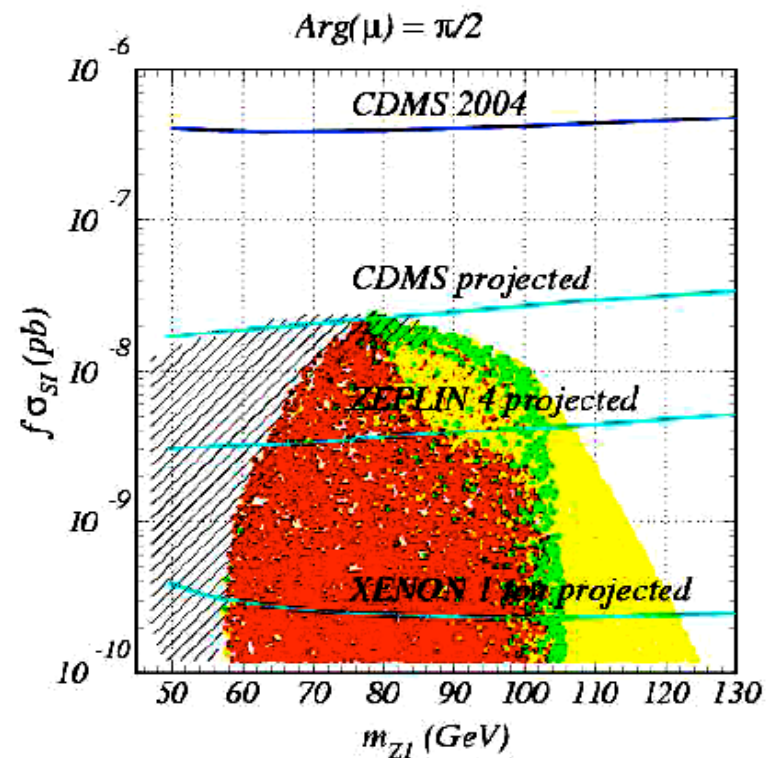Pilaftsis' 02

# 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.'05
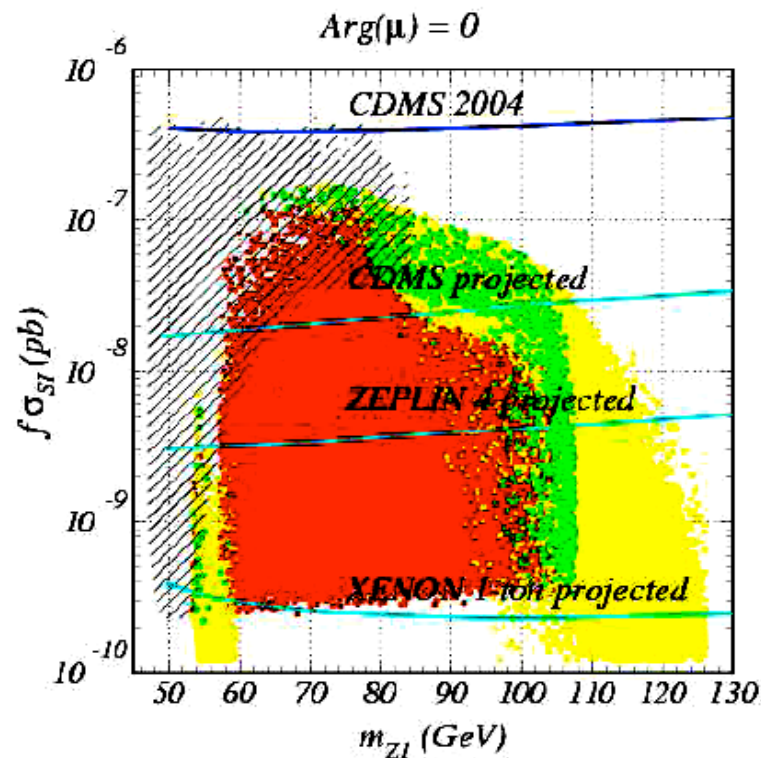
# Electroweak Baryogenesis in the nMSSM

# Minimal Extension of the MSSM

Dedes et al. , Panagiotakopoulos, Pilaftsis'01

- Superpotential restricted by $\mathbf{Z}_5^R$ or $\mathbf{Z}_7^R$ 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 $\qquad \phi^2 = \mathbf{H}_1^2 + \mathbf{H}_2^2 , \qquad \tan\beta = \dfrac{\mathbf{v}_1}{\mathbf{v}_2}$

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

- 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 $m_s$.
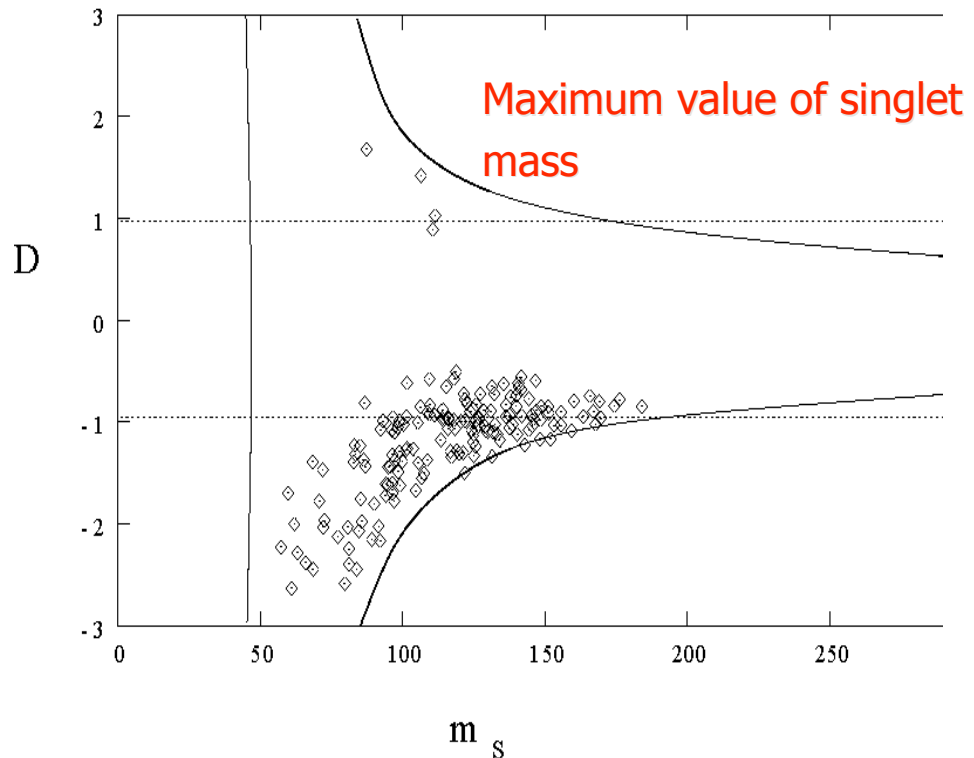
# Parameters with strongly first order transition

- All dimensionful parameters varied up to 1 TeV

- Small values of the singlet mass parameter selected

$$D = \frac{1}{\tilde{\lambda}\, m_S^2} \left\| \frac{\lambda^2\, t_S}{m_S} - m_S\, a_\lambda\, \cos\beta\, \sin\beta \right\| \geq 1$$
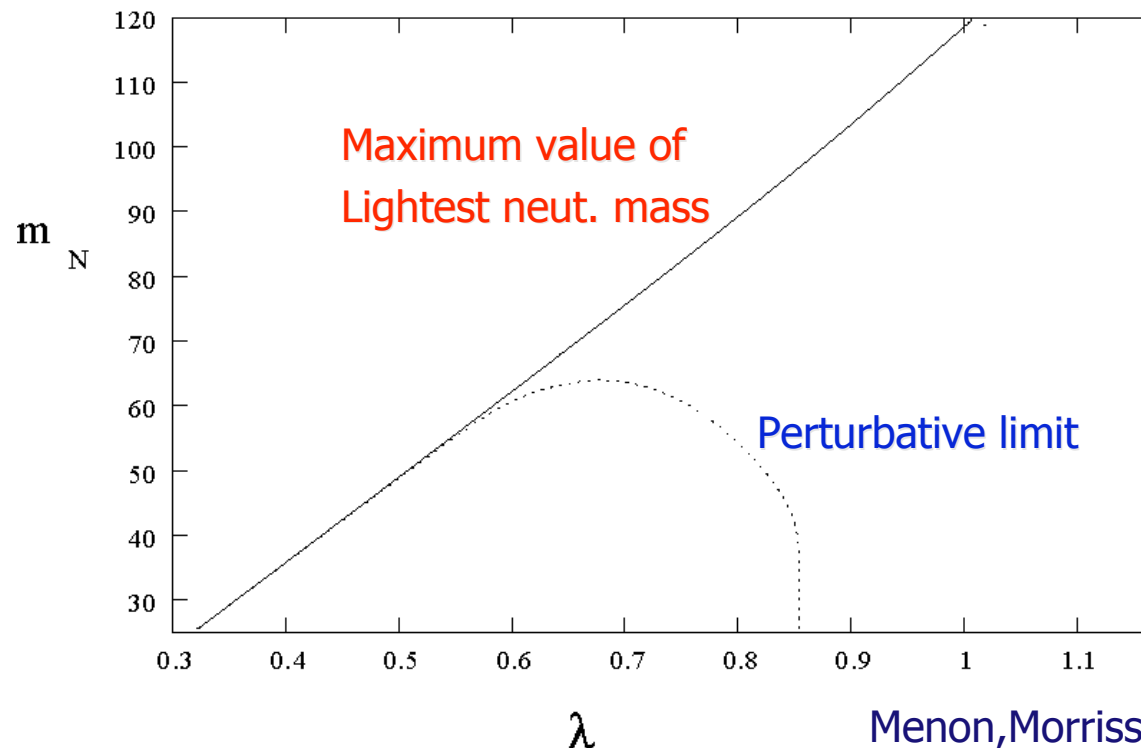
Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



Maximum value of singlet mass

# Upper bound on Neutralino Masses

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

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

$m_N$

Maximum value of
Lightest neut. mass

Perturbative limit

$\lambda$

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
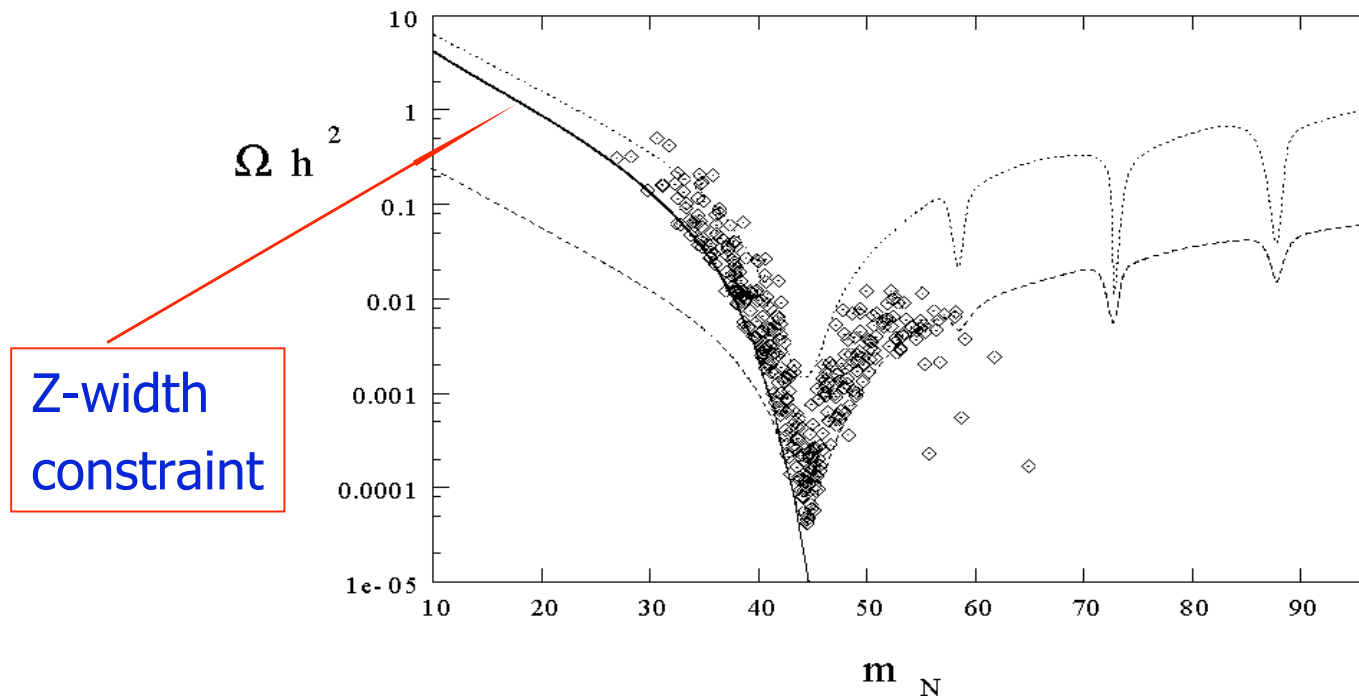
# Higgs Spectrum

- 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 $\lambda$ **and** $a_\lambda$

- 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 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.

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

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

$$\lambda = 0.7$$

Menon,Morrissey,C.W.'04
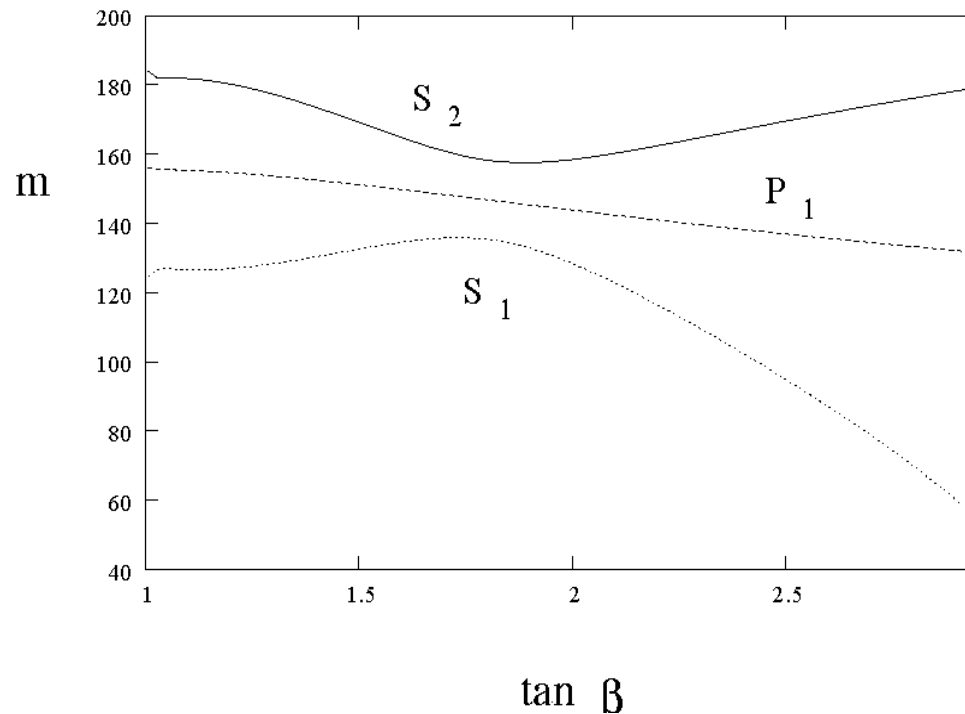
# Higgs Searches

- 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 $\eta$ 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:

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

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.

- LHC and Linear collider will provide an efficient way of searching for some of the Higgs and SUSY particles    (Balazs, Carena, Freitas, C.W. in preparation)

# 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 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.