



**The Abdus Salam
International Centre for Theoretical Physics**



SMR/1847-22

Summer School on Particle Physics

11 - 22 June 2007

SPECIAL LECTURE:

Physics at the Weak Scale, Dark Matter and the Matter-Antimatter Asymmetry

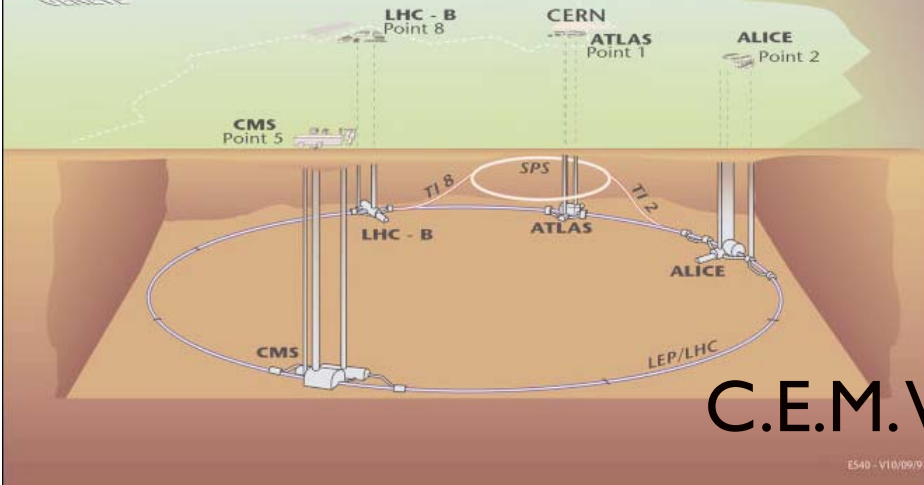
C.E.M. Wagner

EFL, Univ. of Chicago

HEP Division, Argonne National Lab.

Overall view of the LHC experiments.

Physics at the Weak Scale, Dark Matter and the Matter-Antimatter Asymmetry



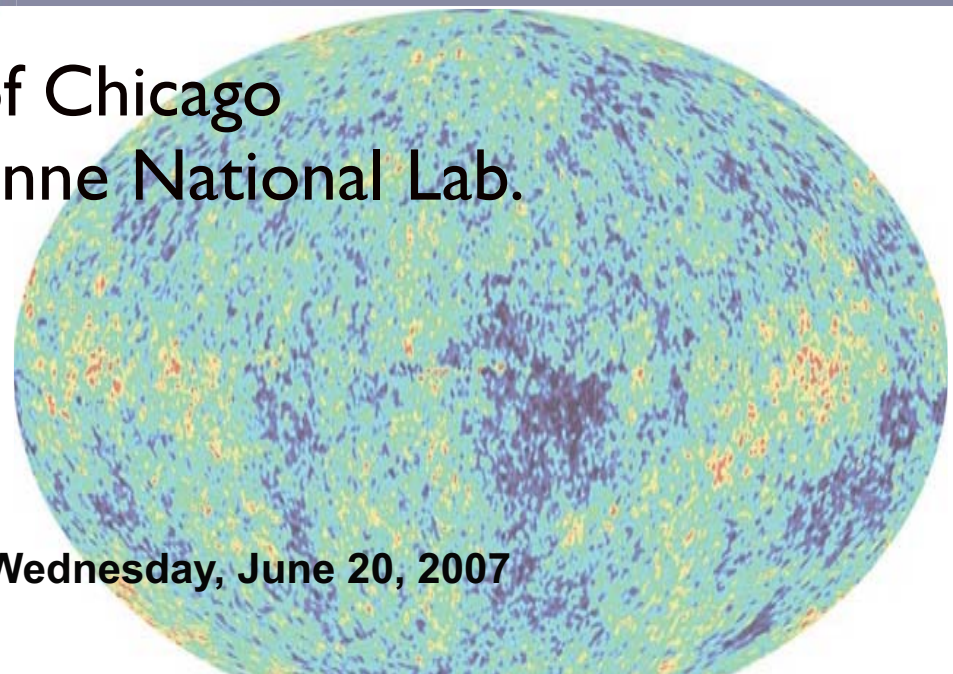
C.E.M. Wagner

ES40 - V10/09/97



EFI, Univ. of Chicago
HEP Division, Argonne National Lab.

ICTP Lecture, ICTP, Trieste, Wednesday, June 20, 2007



The new High Energy Physics Framework

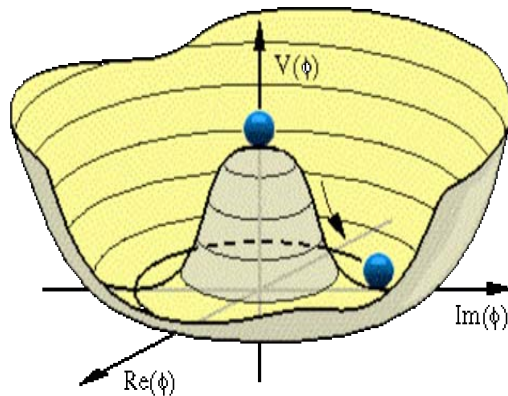
- High Energy Physics has provided an understanding of all data collected in low and high energy collider experiments
- Contrary to expectations, no signature of physics beyond the SM was observed at the LEP electron-positron collider and no large deviation is being observed at the Tevatron.
- However, there are two main reasons to believe that there is new physics around the corner. One is related to particle physics, and the other to cosmology:
 - Electroweak Symmetry Breaking
 - Origin of Dark Matter
- The aim of high energy physics experiments is, in great part, to contribute to the understanding of these two questions.

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

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

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:

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

What is Dark Matter ?

Non-luminous matter that manifest itself via
gravitational interactions



Luminous Matter



Luminous Matter

Dark Matter

Why do we think that Dark Matter may be accessible at collider experiments ?

- Dark Matter is most likely associated with new particles
- Many dark matter candidates have been proposed. They differ in mass and in the range of interaction with SM particles.
- However, if the relic density proceeds from the primordial thermal bath, there are reasons to believe that it must be part of the dynamics leading to an explanation of electroweak symmetry breaking.
- It should certainly interact with (annihilate into) ordinary matter at an observable rate !

Evolution of Dark Matter Density

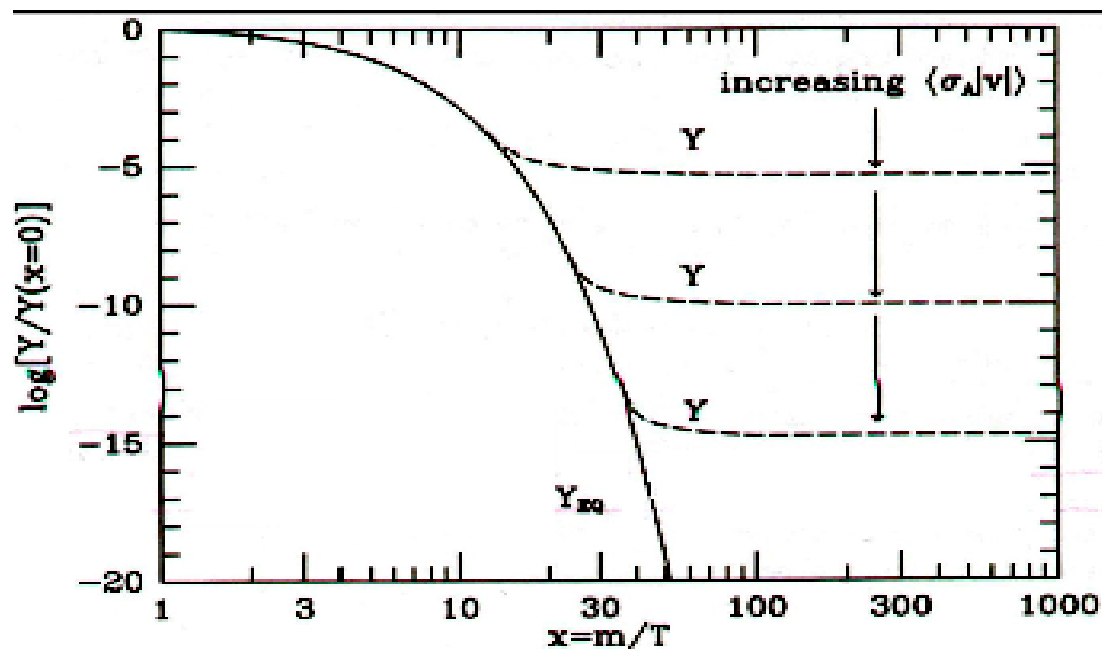
$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2), \quad n_{\text{eq}} \approx \exp(-m/T)$$

$$\langle \sigma_{\text{eff}} v \rangle$$

Thermal average of (co-)annihilation cross section

$$Y = \frac{n}{s}$$

$$s \approx g_* T^3$$



Weak-scale size cross sections and masses give the right dark-matter density

Dark Matter Annihilation Rate

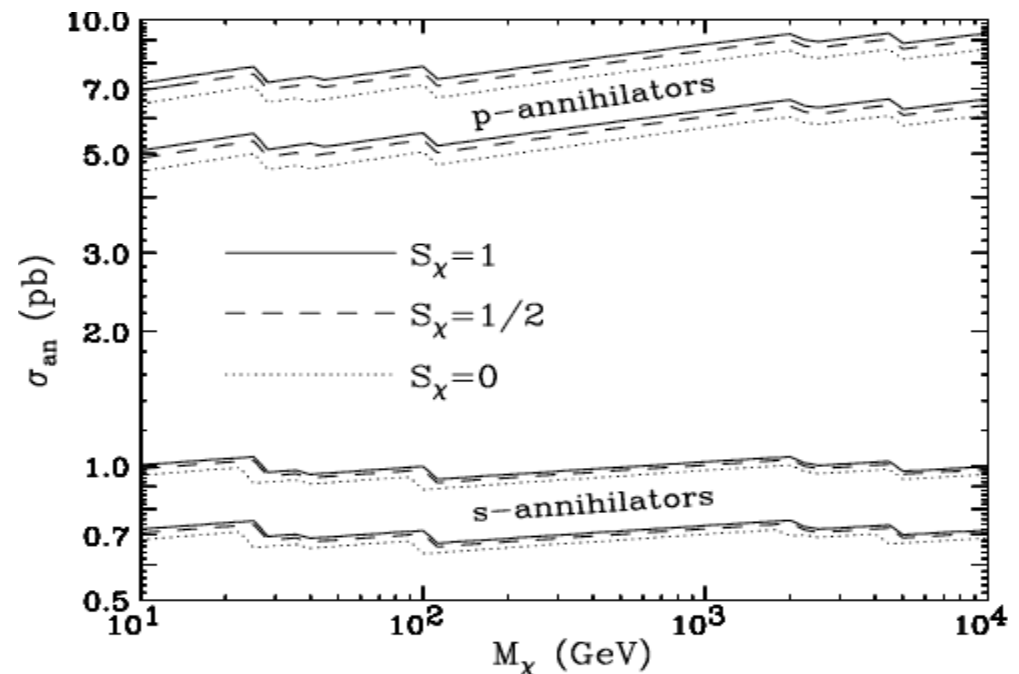
- The main reason why we think there is a chance of observing dark matter at colliders is that, when we compute the annihilation rate necessary to obtain the observed relic density, we get a cross section

$$\sigma_{\text{ann.}}(\text{DM DM} \rightarrow \text{SM SM}) \simeq 1 \text{ pb}$$

- This is precisely

$$\sigma_{\text{ann.}} \simeq \frac{\alpha_W^2}{M_W^2}$$

This suggests that it is probably mediated by weakly interacting particles



(A.B., K. Matchev and M. Perelstein, PRD 70:077701, 2004)

- Connection of Thermal Dark Matter to the weak scale and to the mechanism of electroweak symmetry breaking

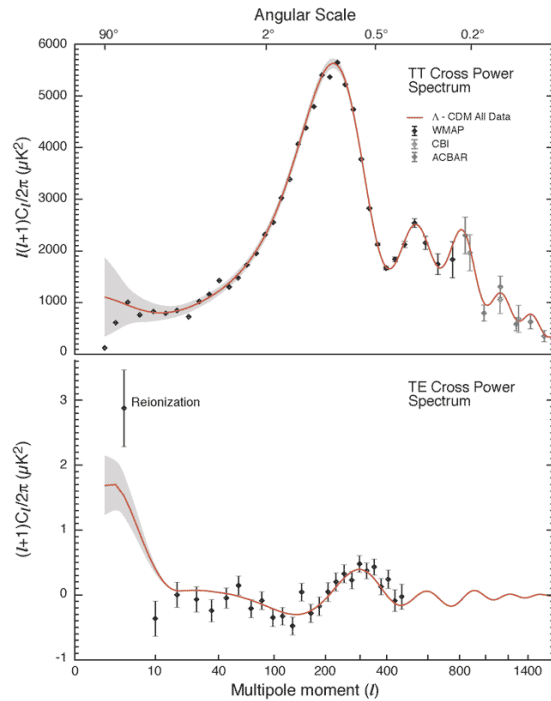
Weak Scale Models and Dark Matter

- Many different models of particle physics at the weak scale have been proposed
- Most of them lead to problems of flavor changing transitions or rapid proton decay, unless extra symmetries are invoked
- These extra symmetries lead to the stability of the lightest new particle, which tend to be neutral and weakly interacting and therefore a good candidate for dark matter
- I'll concentrate in the supersymmetric case as a well motivated example of this kind of models.

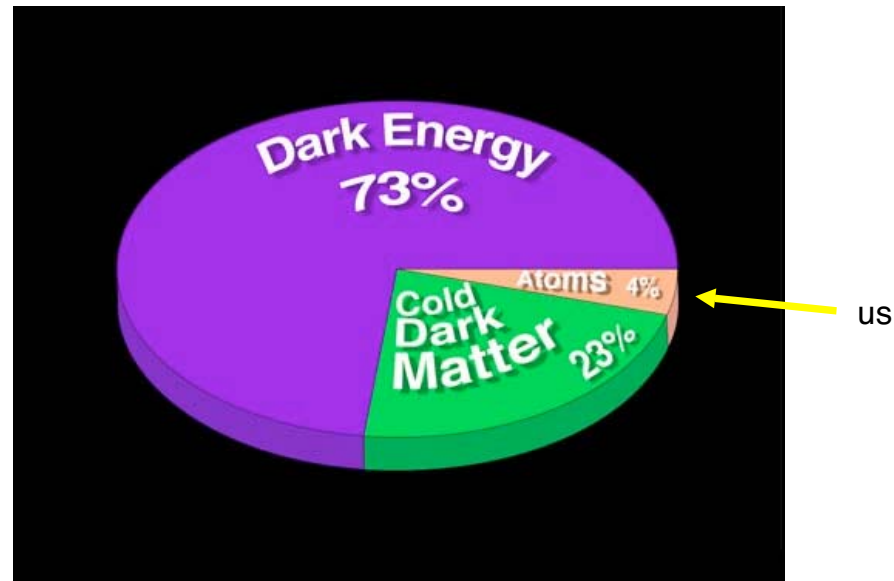
Results from WMAP

Universe density $\Omega_0 = 1.02 \pm 0.02$
Dark energy density $\Omega_\Lambda = 0.73 \pm 0.04$
Total matter density $\Omega_M = 0.27 \pm 0.05$
Baryon matter density $\Omega_b = 0.044 \pm 0.004$

→ Dark matter is non-baryonic



Our Universe:



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

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

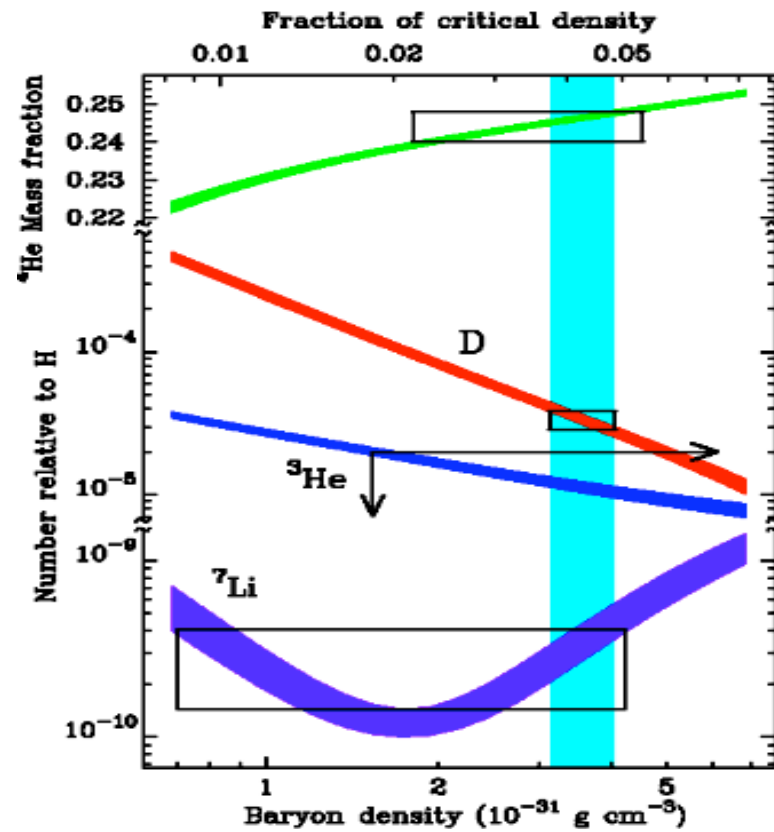
- CMBR, tell us ratio

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

- There is a simple relation between these two quantities

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

Element Abundance and Big-Bang Nucleosynthesis predictions



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

Baryon-Antibaryon asymmetry

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

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

- 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 ?

Baryon Number Generation at the Weak Scale

(Electroweak Baryogenesis)

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.

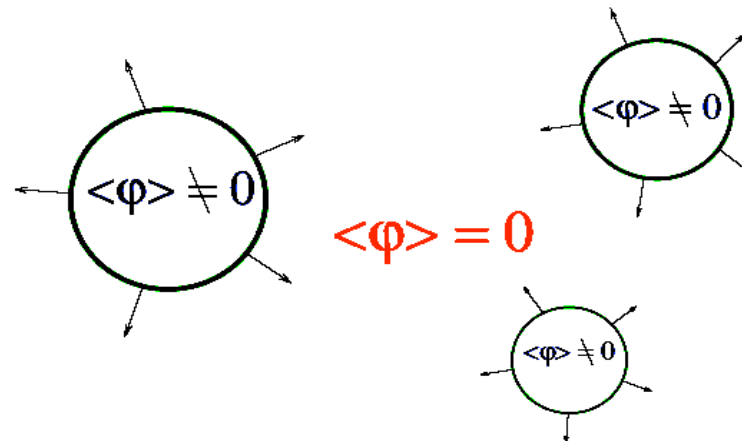
Baryogenesis at the Weak Scale

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

Pilaftsis, Underwood, hep-ph/0309342

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 in the Standard Model:

Baryon Number conserved at the classical level but
violated at the quantum level: Anomaly

$$\partial^\mu j_\mu^{B,L} = \frac{N_g}{32\pi^2} \text{Tr} \left(\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} \right)$$

Instanton configurations may be regarded as semiclassical configurations for tunnelling effect between vacuum states with different baryon number

$$S_{inst} = \frac{2\pi}{\alpha_W} \quad \Gamma_{\Delta B \neq 0} \propto \exp(-S_{inst})$$

***Weak interactions: Transition amplitude exponentially small.
No observable baryon number violating effects at $T = 0$***

Non-equivalent Vacua and Static Energy in Field Configuration Space

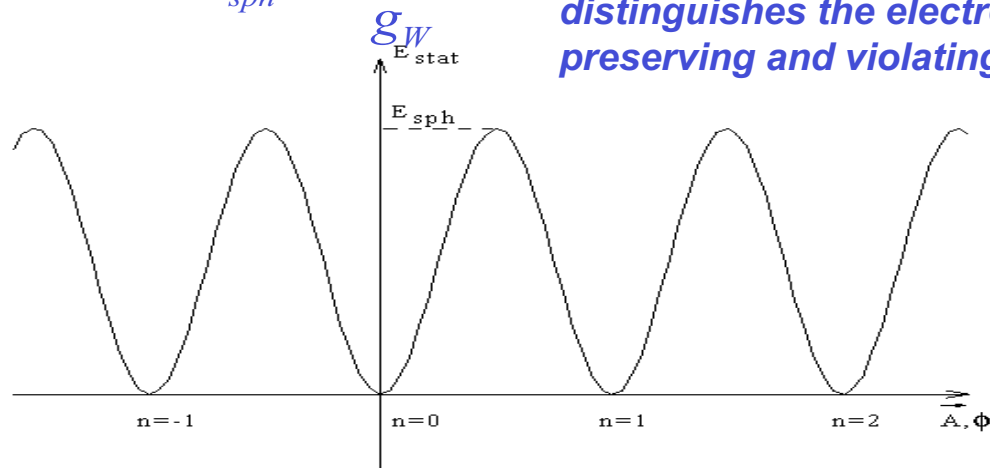
The sphaleron is a static configuration with non-vanishing values of the Higgs and gauge boson fields.

Its energy may be identified with the height of the barrier separating vacua with different baryon number

$$E_{sph} = \frac{8\pi v}{g_W}$$

The quantity v is the Higgs vacuum expectation value, $\langle H \rangle = v$.

This quantity provides an order parameter which distinguishes the electroweak symmetry preserving and violating phases.



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

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

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

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

Kuzmin, Rubakov and Shaposhnikov, '85—'87

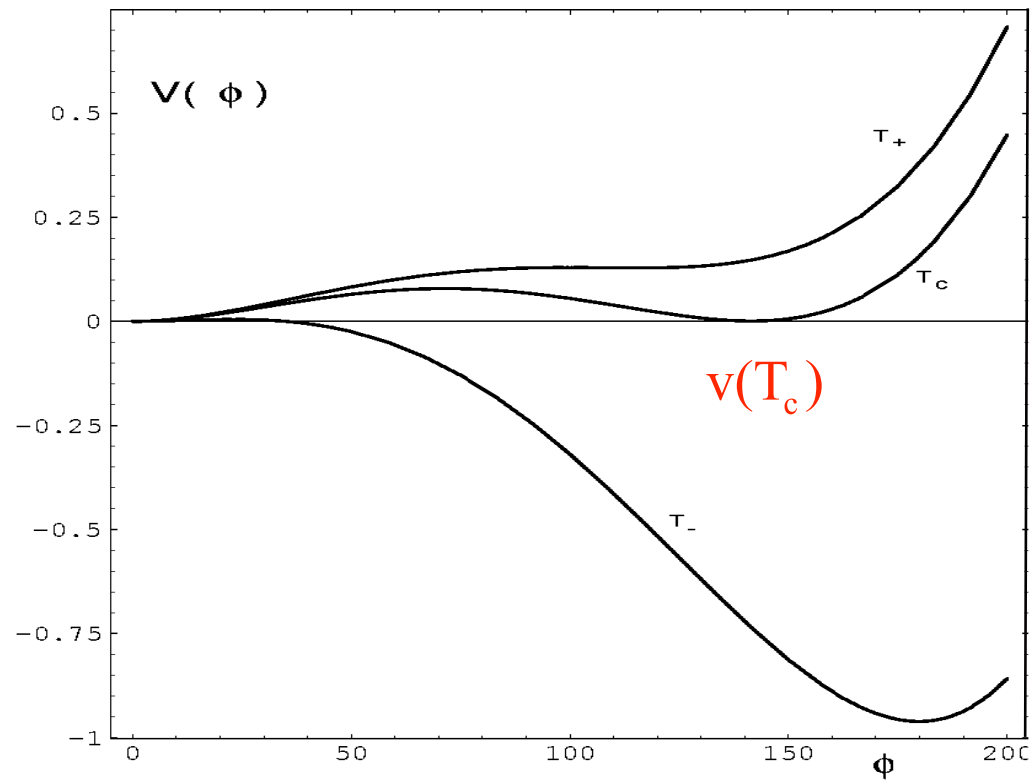
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

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

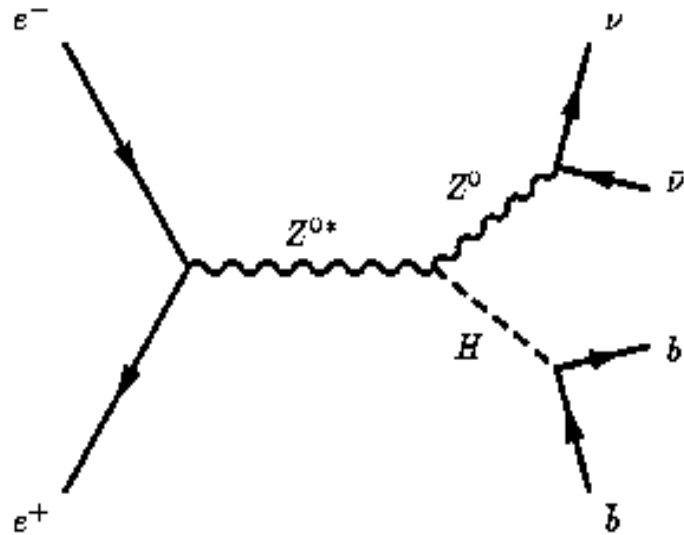
E receives contributions proportional to the sum of the cube of all light boson particle couplings

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

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

Electroweak Baryogenesis

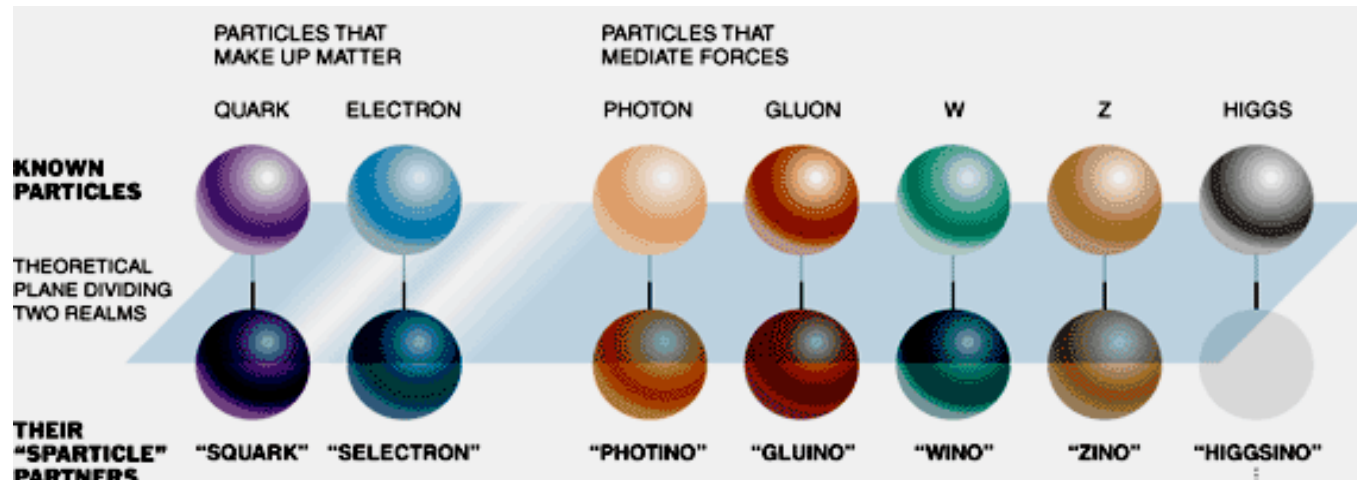
and

New Physics at the Weak Scale

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)

Two Higgs Doublets necessary: $\tan \beta = \frac{v_2}{v_1}$

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.

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

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

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

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

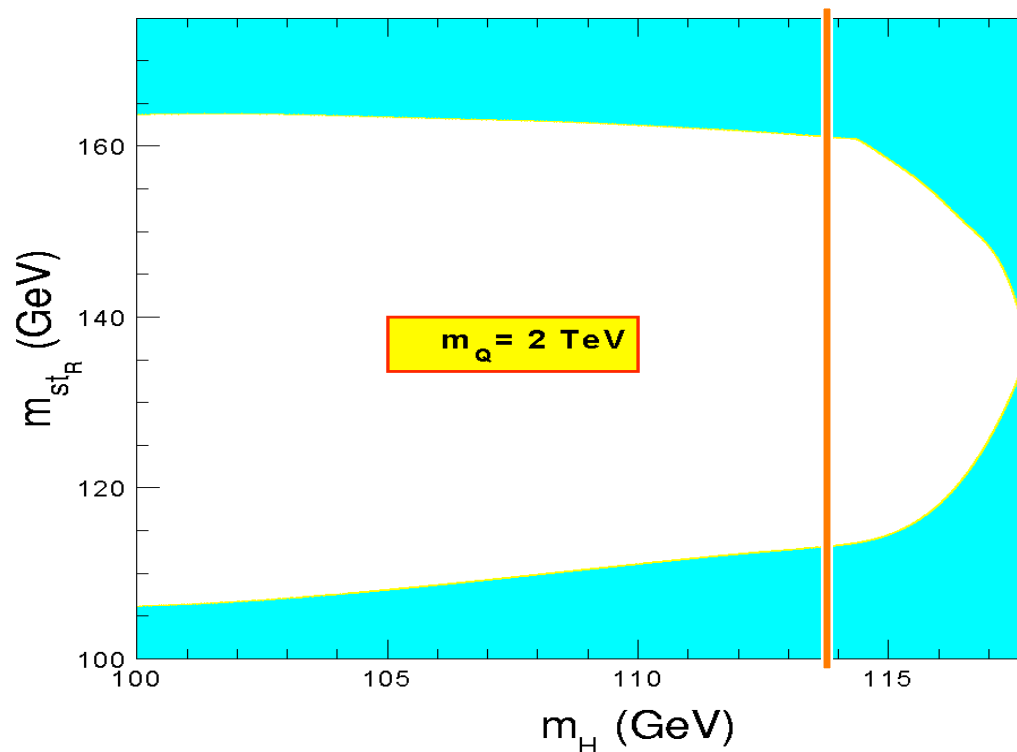
- Since

Higgs masses up to 120 GeV may be accommodated

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

Sufficiently 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:

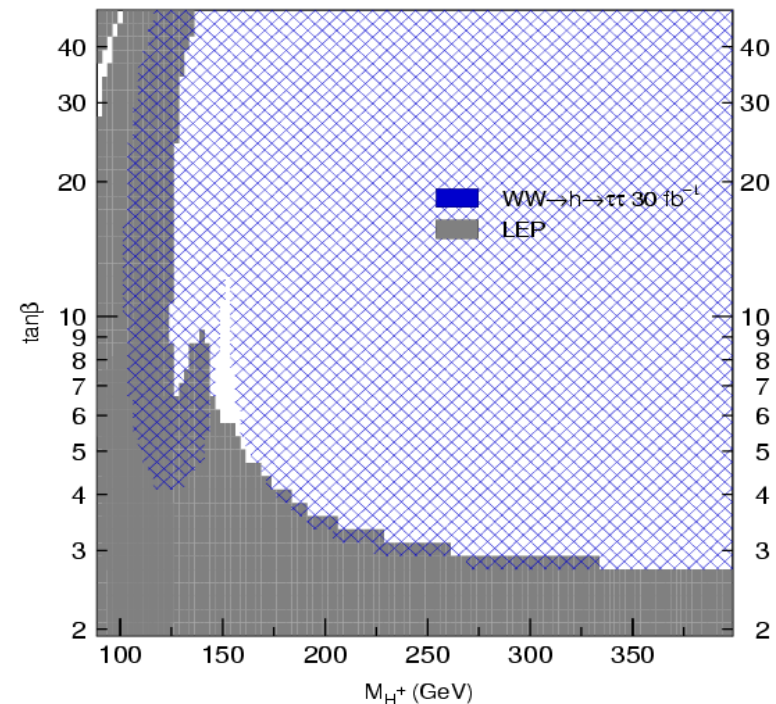
1. **Tevatron** collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

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

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

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



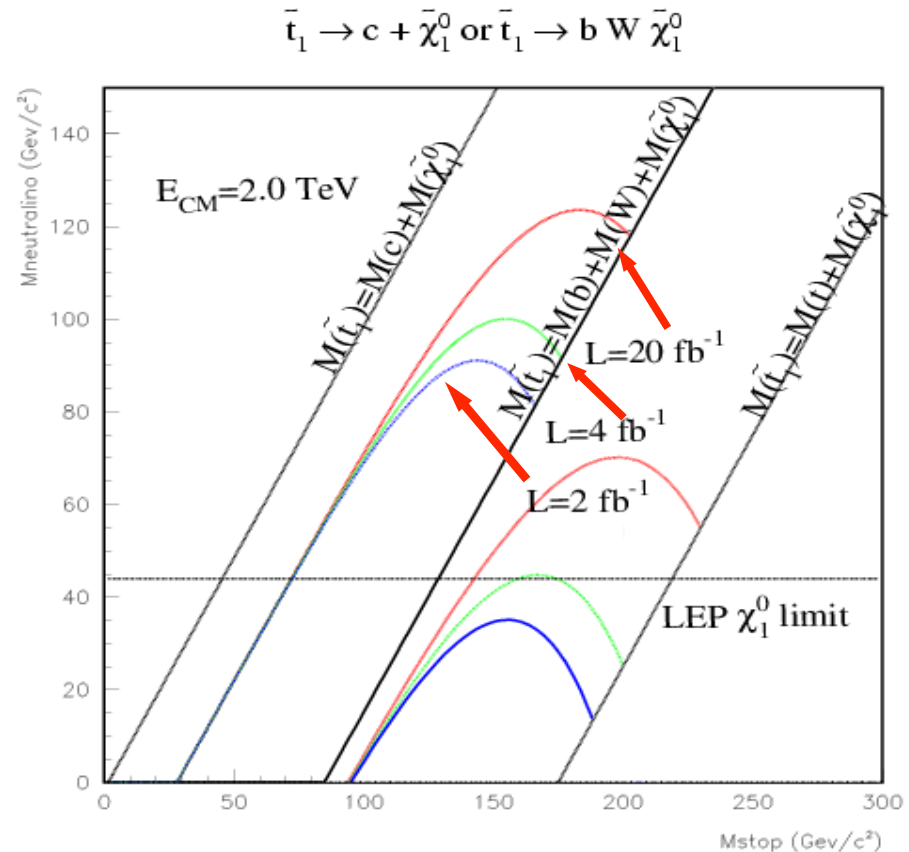
Tevatron Stop Reach when two body decay channel is dominant

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

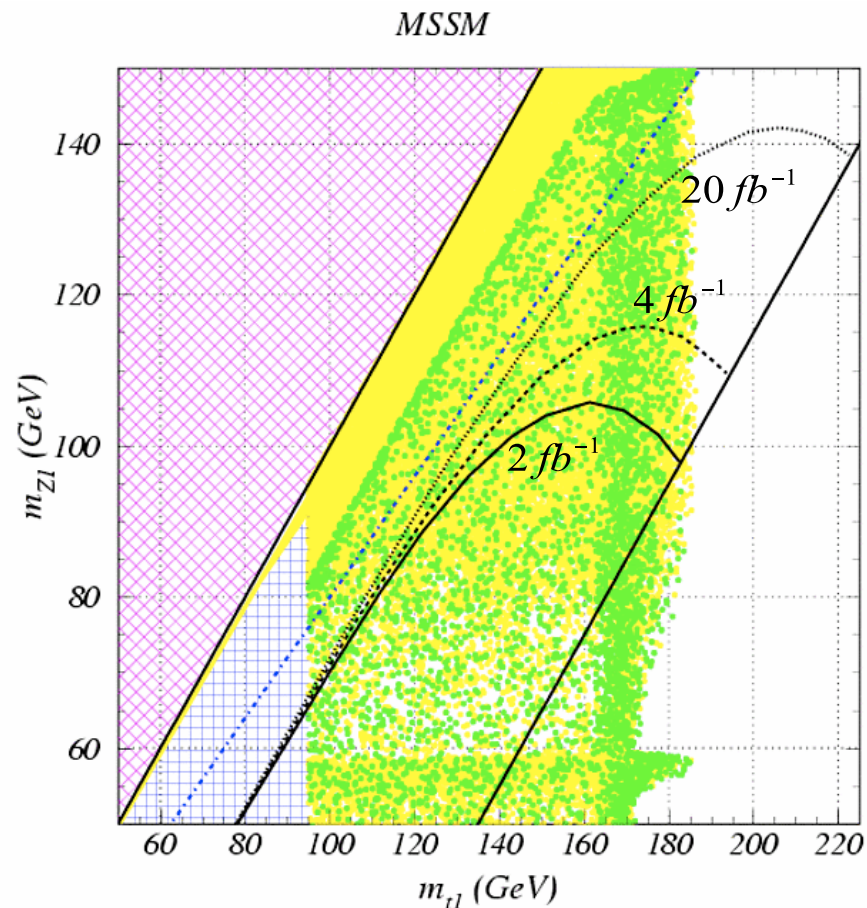
- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.
- Relic density is inversely proportional to the neutralino annihilation cross section.

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 coannihilation region.

LHC will have equal difficulties.

But, LHC can search for stops from gluino decays into stops and tops. Stops may be discovered for gluino masses lower than 900 GeV, even if the stop-neutralino mass difference is as low as 10 GeV !

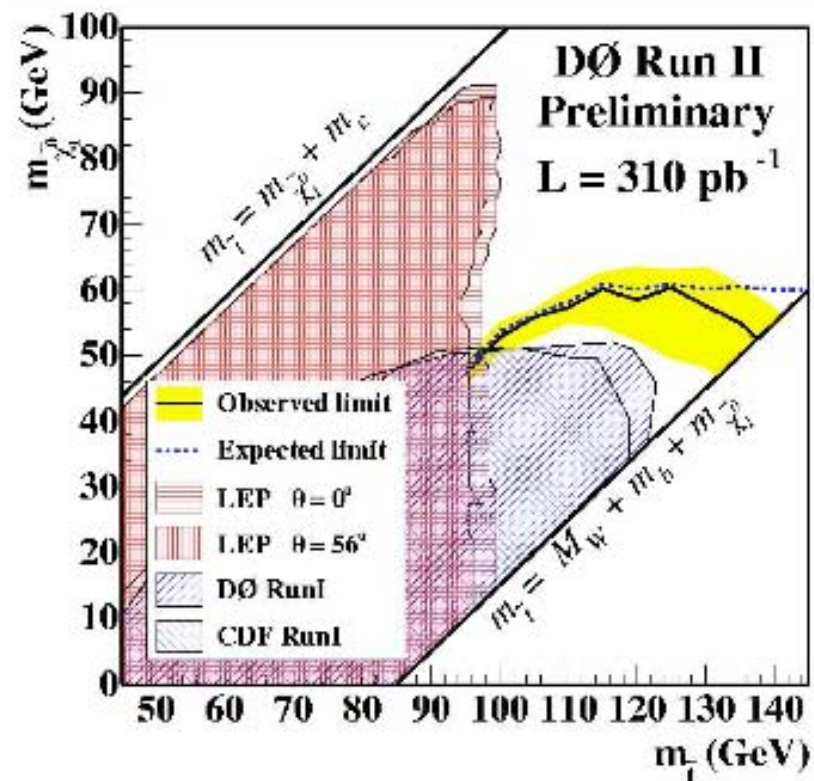
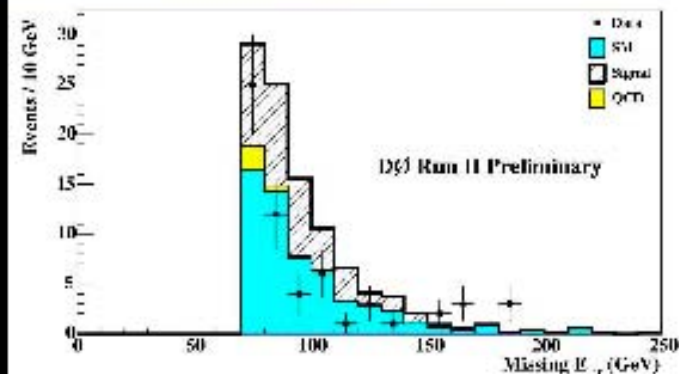
Kraml, Raklev '06

Stop in acoplanar dijet (II)

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

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

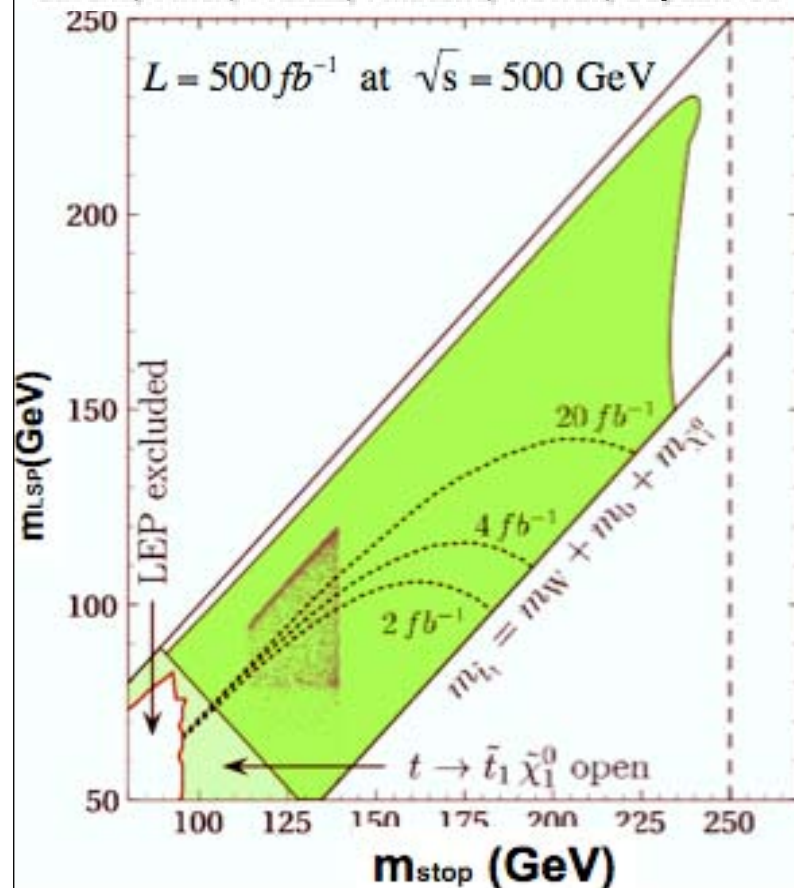
- Dominant backgrounds are W/Z+jets
- QCD background is 5.6% of the total back.
- Signal efficiency = 3.7% => 39.5 signal events
- ◆ Small excess of events at very large MET:
 - 8 events for 3.0 ± 1.2 for MET > 150 GeV
 - not in the stop signal signal region
- ◆ Main systematic uncertainties:
 - JES (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, Sopczak '06



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

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: $\frac{S}{\sqrt{S+B}} > 5$ with $S = \epsilon \sigma$

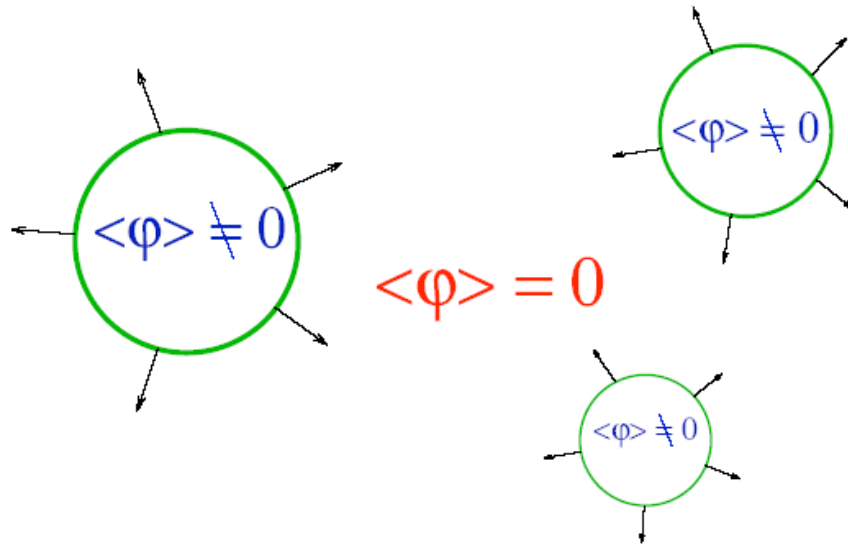
Detection of light stops possible for $\Delta_{m_{\tilde{t}\tilde{\chi}}}$ $\sim 5 \text{ GeV}$

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.



Generation of Baryon Number

- The CP-violating currents are induced by the interaction of charginos and neutralinos with the bubble wall.

Charginos and neutralinos are admixtures of the superpartners of the Higgs bosons, Higgsinos, with mass μ , and superpartners of the gauge bosons, with masses M_i where $i=1,2$ if they are the gauginos of the hypercharge or weak interactions respectively.

For instance, the charginos are two Dirac states and their mass matrix

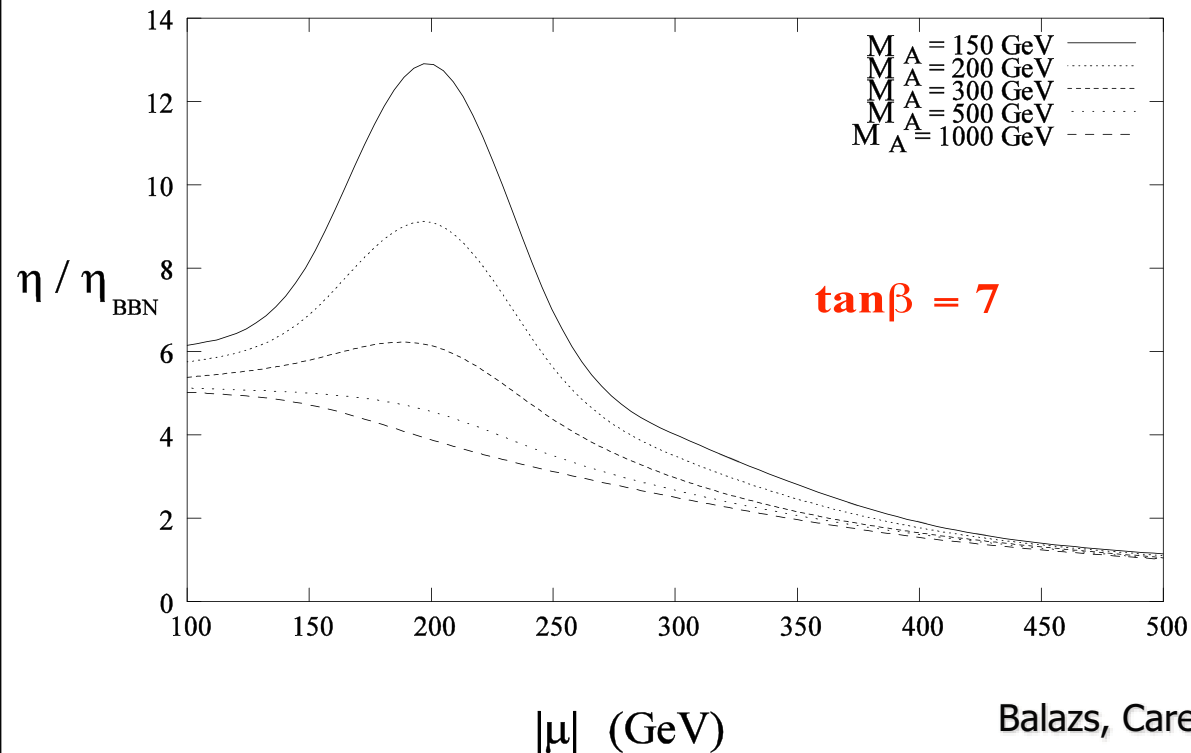
$$\mathcal{M}_{\tilde{\chi}^\pm} = \begin{bmatrix} M_2 & gv_2 \\ gv_1 & \mu \end{bmatrix}$$

Similarly, neutralinos are four Majorana states.

For Baryogenesis to work $\text{Im}[\mu M_i] \neq 0$

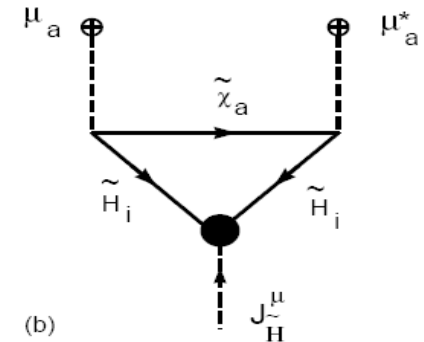
Baryon Asymmetry

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



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

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

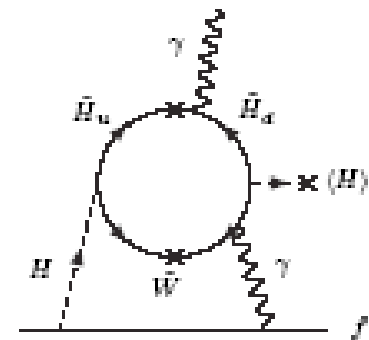
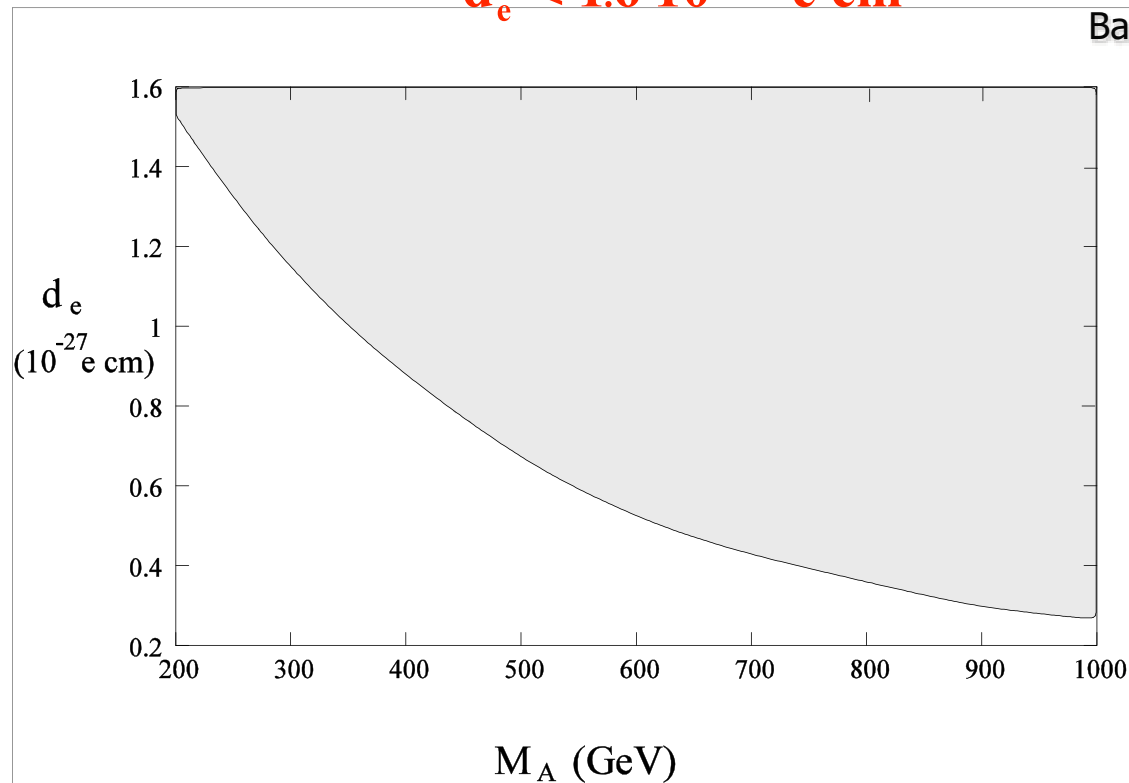


Electron electric dipole moment

- Assuming 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

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

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

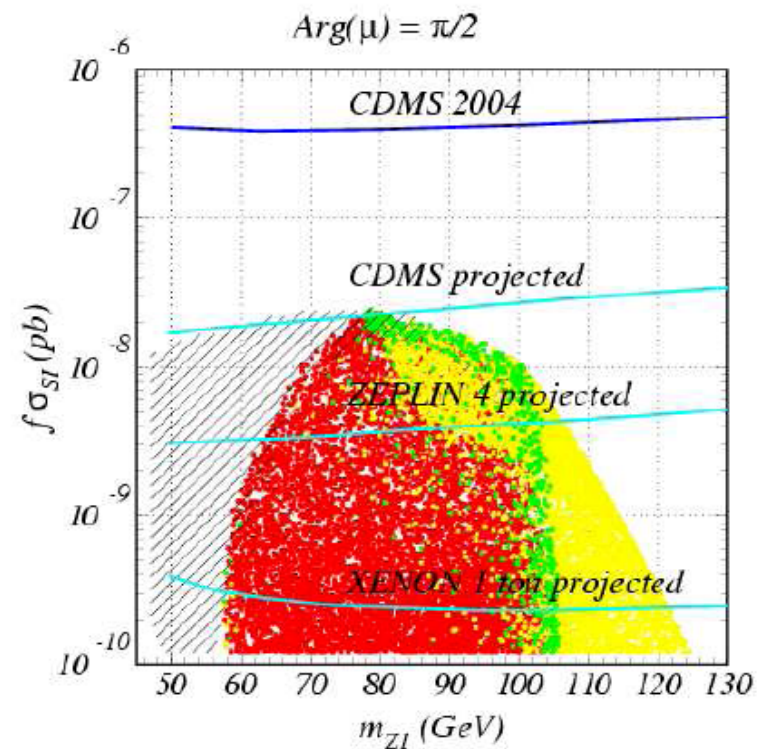
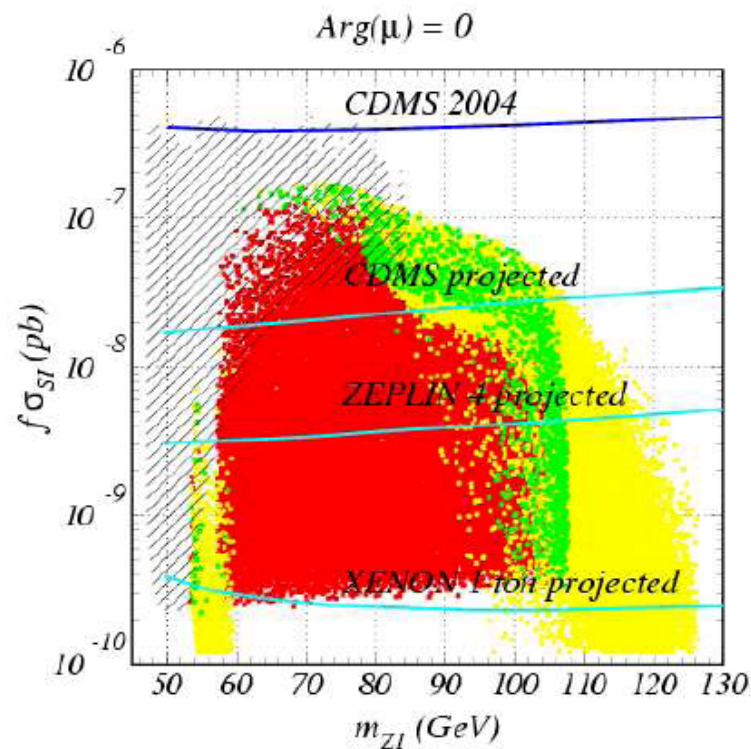


Pilaftsis' 02

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.
C. Balazs, M. Carena, A. Freitas, C.W., [arXiv:0705.0431](https://arxiv.org/abs/0705.0431)

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

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

Electroweak Phase Transition

Defining $\phi^2 = \mathbf{H}_1^2 + \mathbf{H}_2^2$, $\tan\beta = \frac{v_1}{v_2}$

- In the nMSSM, the potential has the approximate form:
(i.e. tree-level + dominant one-loop high-T terms)

$$V_{eff} \simeq (-m^2 + AT^2)\phi^2 + \tilde{\lambda}^2\phi^4 + 2t_s\phi_s + 2\tilde{a}\phi_s\phi^2 + \lambda^2\phi^2\phi_s^2$$

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

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

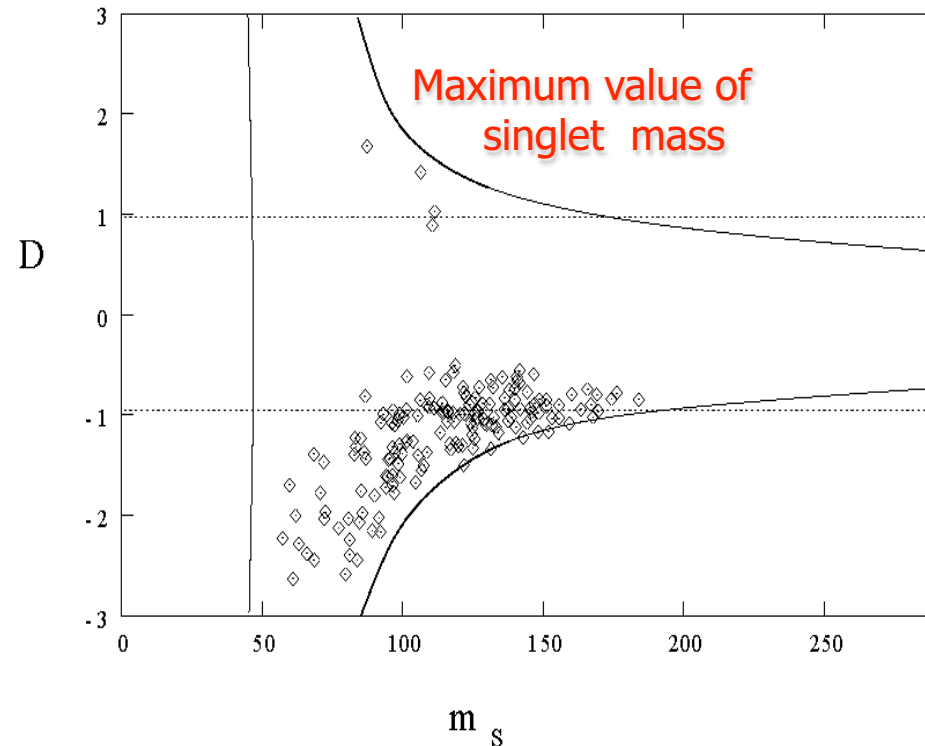
Non-renormalizable potential controlled by m_s . Strong first order phase transition induced for small values of m_s .

Parameters with strongly first order transition

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

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

- Values constrained by perturbativity up to the GUT scale.



Neutralino Mass Matrix

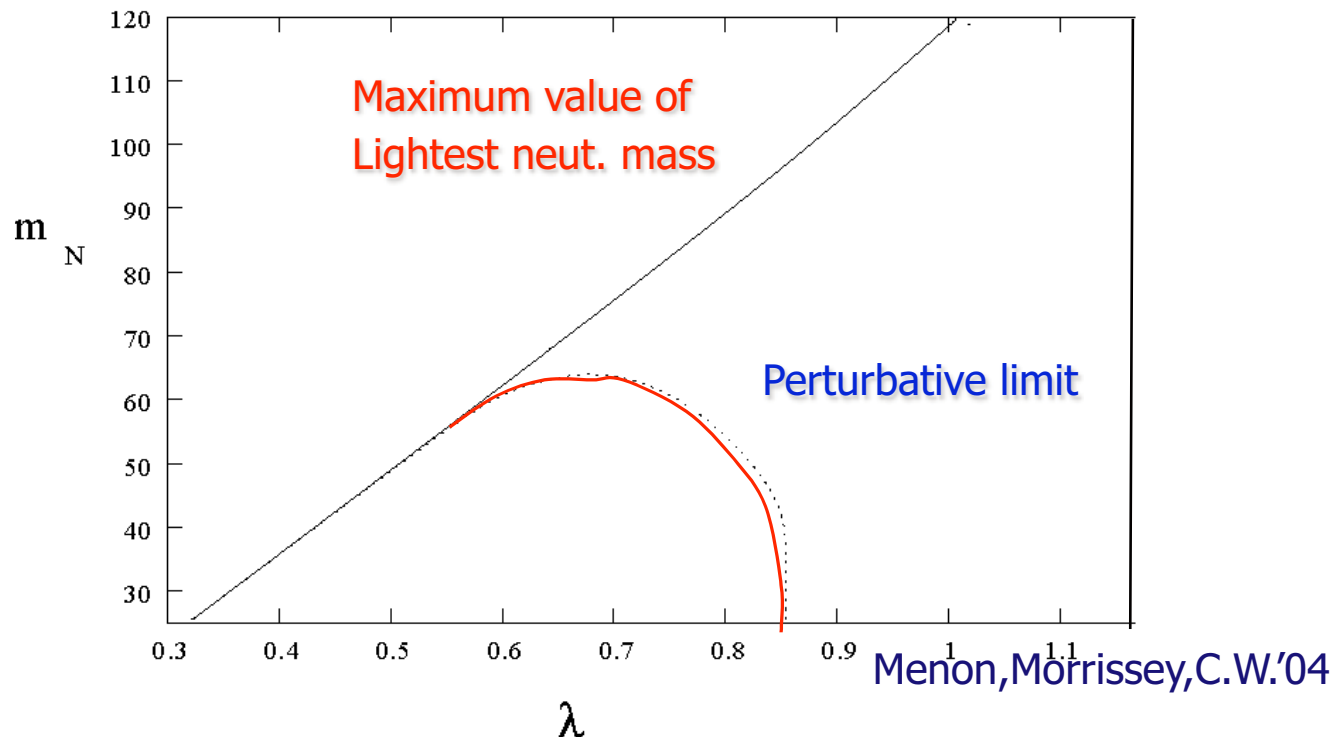
$$M_{\tilde{0}} = \begin{pmatrix} M_1 & 0 & -c s_W M_Z & s s_W M_Z & 0 \\ 0 & M_2 & c g_W M_Z & -s g_W M_Z & 0 \\ -c s_W M_Z & c g_W M_Z & 0 & v_s & v_2 \\ s s_W M_Z & -s g_W M_Z & v_s & 0 & v_1 \\ 0 & 0 & v_2 & v_1 & 0 \end{pmatrix},$$

In the nMSSM, $\kappa = 0$.

Upper bound on Neutralino Masses

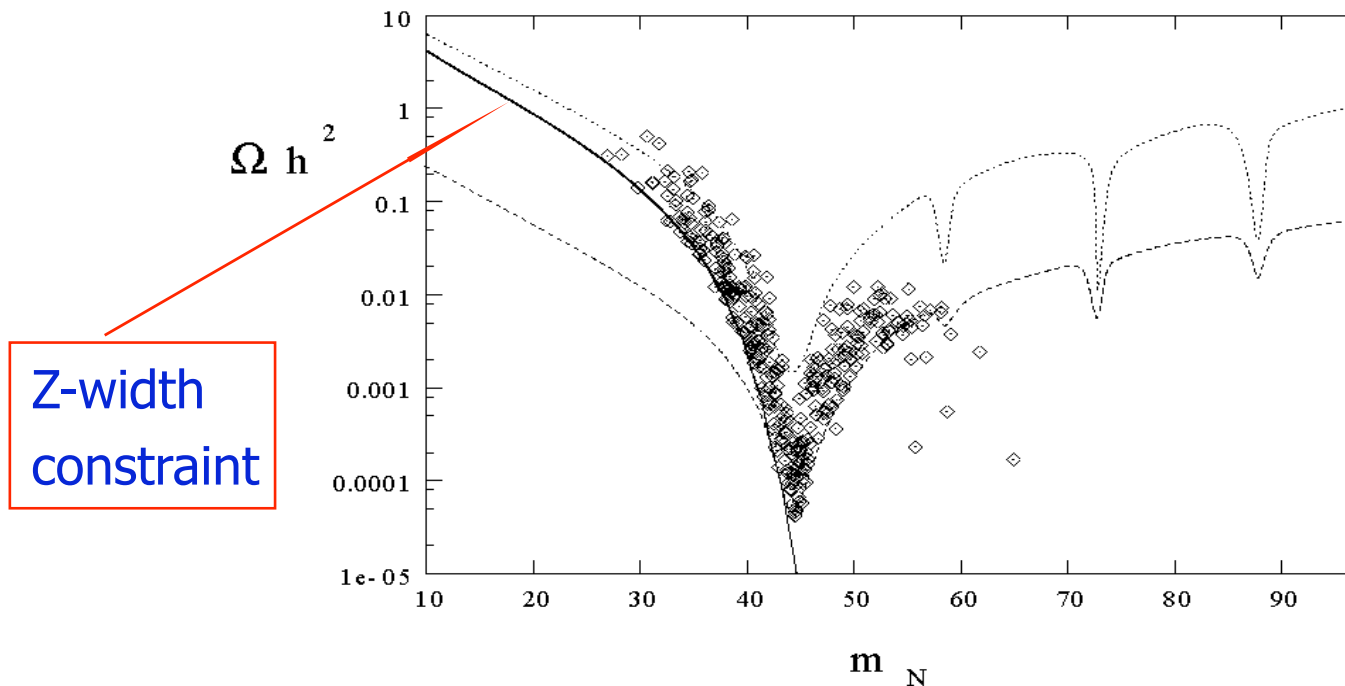
$$m_1 = \frac{2\lambda v \sin\beta x}{(1 + \tan^2\beta + x^2)} \quad \text{with} \quad x = \frac{v_s}{v_1}$$

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



Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are imposed.
Z-boson and Higgs boson contributions shown to guide the eye.



Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controlled 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.

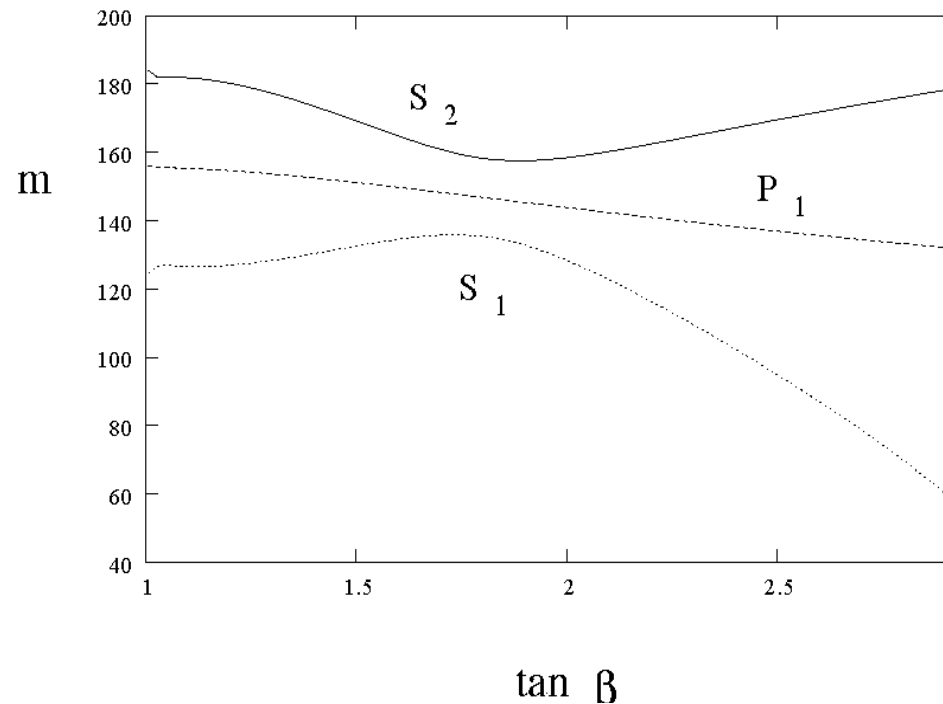
$$m_h^2 \leq M_Z^2 \cos^2 \beta + \lambda^2 v^2 \sin^2 2\beta + \text{loop corrections}$$

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.

$$\begin{aligned} M_a &= 900 \text{ GeV} & v_S &= -300 \text{ GeV} \\ a_\lambda &= 350 \text{ GeV} & t_S^{1/3} &= 150 \text{ GeV} \\ \lambda &= 0.7 \end{aligned}$$



Higgs Searches

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

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

- 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:

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

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

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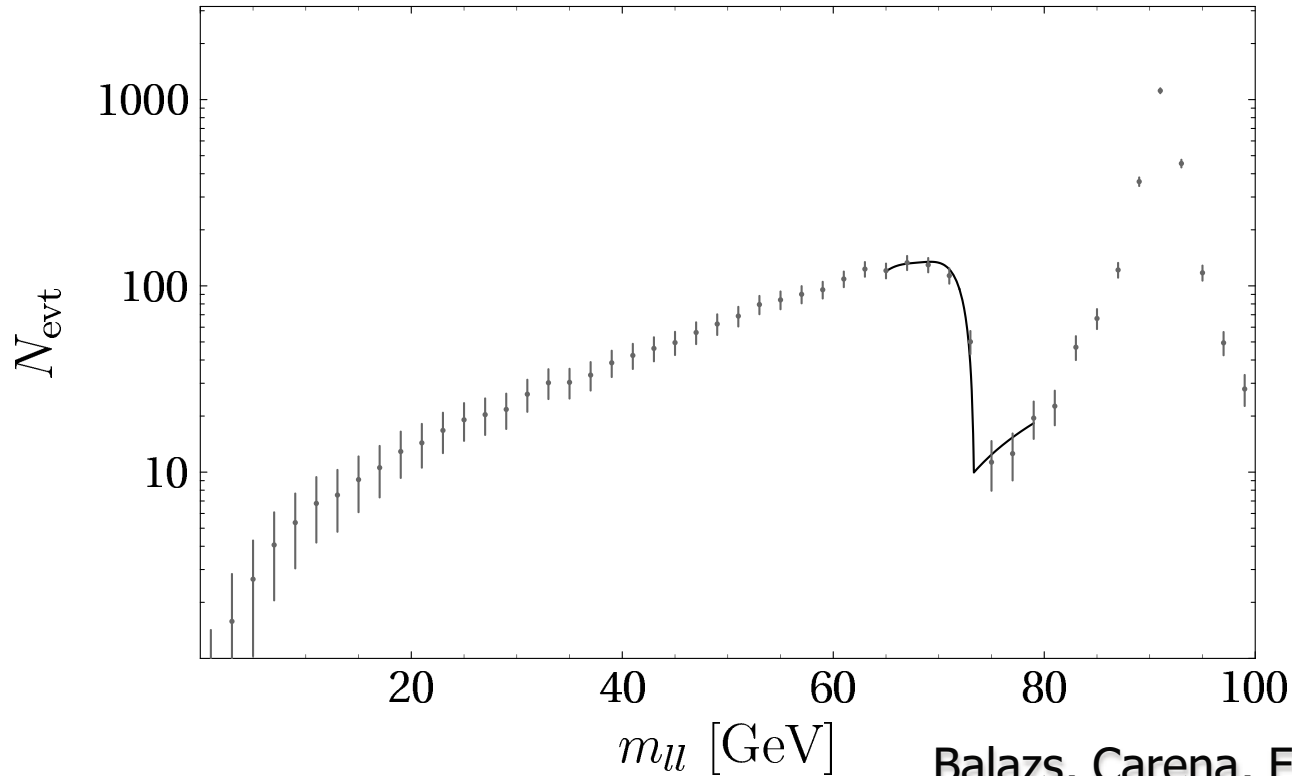
- Assuming the presence of gluinos with masses dictated by gaugino mass unification, as well as one squark, with mass of the order of 500 GeV:
- The LHC may be able to determine the chargino and second neutralino masses, as well as the lightest neutralino mass with some precision. The presence of one 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 [GeV]	Decay modes
$\tilde{\chi}_1^0$	33.3	—	—
$\tilde{\chi}_2^0$	106.6	0.00004	$\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ 100%
$\tilde{\chi}_3^0$	181.5	0.09	$\tilde{\chi}_3^0 \rightarrow Z \tilde{\chi}_1^0$ 74% $S_1 \tilde{\chi}_1^0$ 26% $P_1 \tilde{\chi}_1^0$ 0.4%
$\tilde{\chi}_4^0$	278.0	1.5	$\tilde{\chi}_4^0 \rightarrow Z \tilde{\chi}_1^0$ 11% $Z \tilde{\chi}_2^0$ 22% $Z \tilde{\chi}_3^0$ 1% $W^\pm \tilde{\chi}_1^\pm$ 43% $S_1 \tilde{\chi}_1^0$ 7% $S_1 \tilde{\chi}_2^0$ 0.2% $S_2 \tilde{\chi}_1^0$ 8% $P_1 \tilde{\chi}_1^0$ 7% $P_1 \tilde{\chi}_2^0$ 0.7%
$\tilde{\chi}_1^\pm$	165.0	0.136	$\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ 100%
$\tilde{\chi}_2^\pm$	319.5	2.0	$\tilde{\chi}_2^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ 32% $W^\pm \tilde{\chi}_2^0$ 1% $W^\pm \tilde{\chi}_3^0$ 34% $Z \tilde{\chi}_1^\pm$ 29% $S_1 \tilde{\chi}_1^\pm$ 5% $P_1 \tilde{\chi}_1^\pm$ 0.3%

pp $\tilde{g}\tilde{g}, \tilde{g} \text{ b}\tilde{\text{b}} \text{ or } \tilde{\text{b}}\tilde{\text{b}}$ $\text{b}\tilde{\text{b}}^{\sim 0}_2$ $\tilde{\chi}^0_2$ Z $\tilde{\chi}^0_1$

$$m_{ll, \text{max}, 2} = m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$$

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



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

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

At the ILC, one can use

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

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

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

Information after 500 GeV ILC run

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

$$\begin{aligned}
 M_1 &= (122.5 \pm 1.3) \text{ GeV}, & |\mu| &< 2.0 \text{ GeV}, & m_{\tilde{e}} &> 5 \text{ TeV}, \\
 M_2 &= (245.0 \pm 0.7) \text{ GeV}, & \tan\beta &= 1.7 \pm 0.09, & m_{\tilde{e}_R} &> 1 \text{ TeV}. \\
 |\mu| &= 0.619 \pm 0.007, & |\mu_M| &< 0.32, \\
 v_s &= (-384 \pm 4.8) \text{ GeV},
 \end{aligned}$$

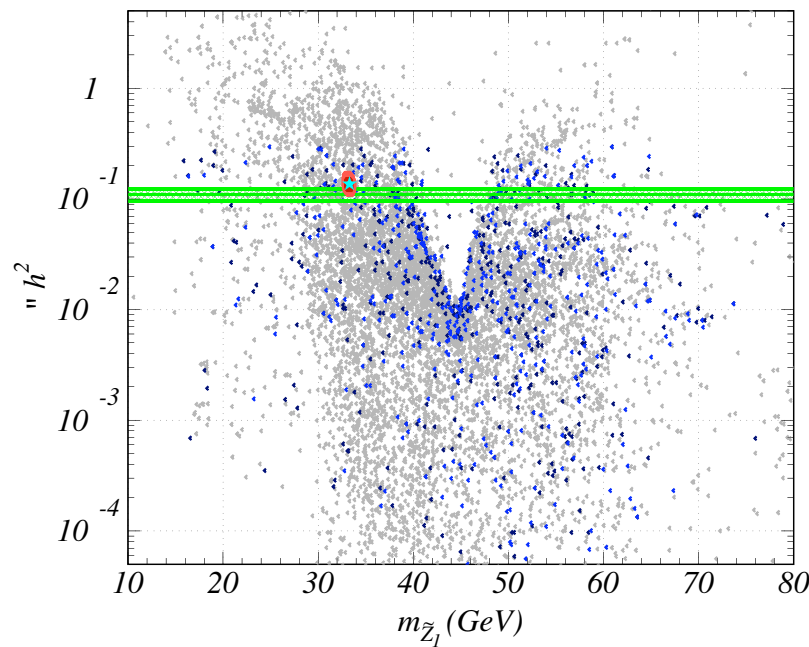
- From measurements in the Higgs sector (two CP-even Higgs bosons) combined with the information above,

$$\begin{aligned}
 a &= (373_{-21}^{+17}) \text{ GeV}, & m_s &= (106 \pm 18) \text{ GeV}, \\
 t_s^{1/3} &= (156_{-39}^{+25}) \text{ GeV}, & |\mu| &= 1.0 \pm 0.65. \\
 m_s^2 &= -a v_1 v_2 / v_s - t_s / v_s - \frac{1}{2} v^2
 \end{aligned}$$

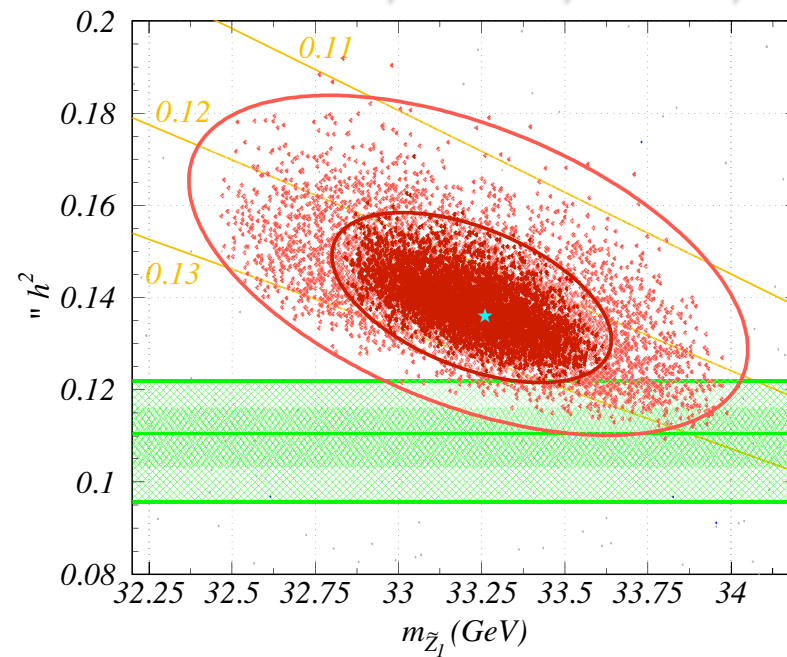
Dark Matter Density Determination

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

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- WMAP + SDSS, ! 2 !
- LHC scan, excluded
- ILC scan, ! 1 !
- ★ Input model
- LHC scan, allowed
- ILC scan, ! 2 !



- WMAP + SDSS, ! 2 !
- LHC scan, excluded
- ILC scan, ! 1 !
- ★ Input model
- LHC scan, allowed
- ILC scan, ! 2 !

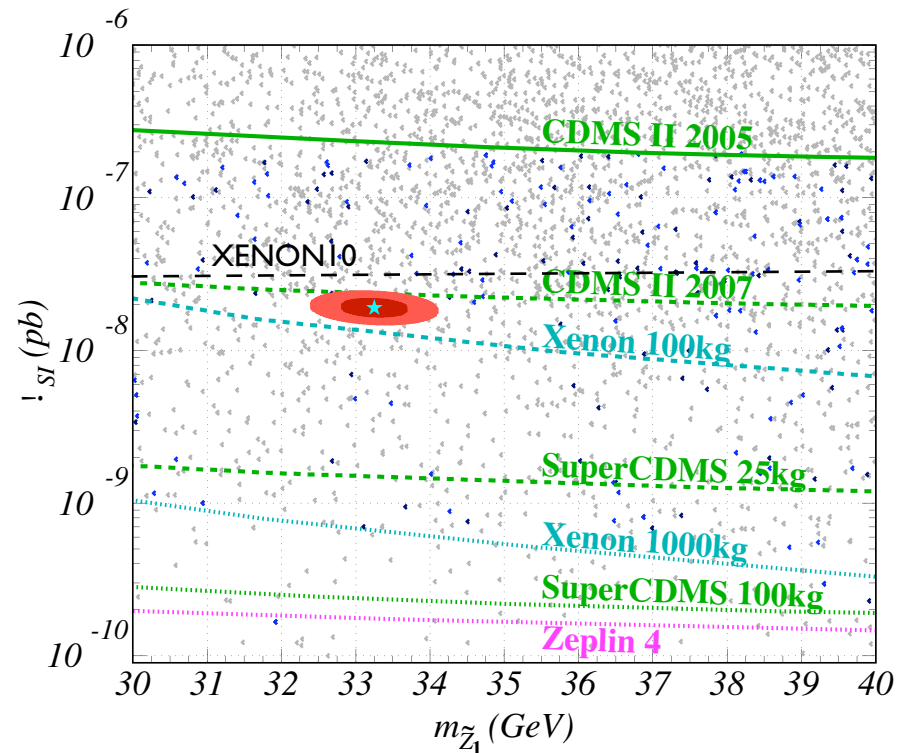
Direct Dark Matter Detection

Since dark matter is mainly a mixing between singlinos (dominant) and Higgsinos, neutralino nucleon cross section is governed by the new, λ -induced interactions, which are well defined in the relevant regime of parameters

Next generation of direct dark matter detection will probe this model

Barger, Langacker, Lewis, McCaskey, Shaughnessy, Yencho '07

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



★ Input model
⋯ LHC scan, allowed
■ ILC scan, ! 1 !
■ ILC scan, ! 2 !

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}
$U(1)_R$	0	0	2	1	1	1	1	1	0	0	0	2
$U(1)_{PQ}$	1	1	-2	-1	-1	0	0	0	0	0	0	0

These symmetries allow to absorb phases into redefinition of fields. The remaining phases may be absorbed into the mass parameters. Only physical phases remain, given by

$$\begin{aligned}
 & \arg(m_{12}^t), \quad \leftarrow \text{Higgs Sector} \\
 & \arg(m_{12}^t M_i), \quad i = 1, 2, 3, \quad \leftarrow \text{Chargino-Neutralino Sector} \\
 & \arg(m_{12}^t A_u), \quad (3 \text{ generations}), \quad \leftarrow \text{S-up sector} \\
 & \arg(m_{12}^t A_d), \quad (3 \text{ generations}), \quad \leftarrow \text{S-down sector}
 \end{aligned}$$

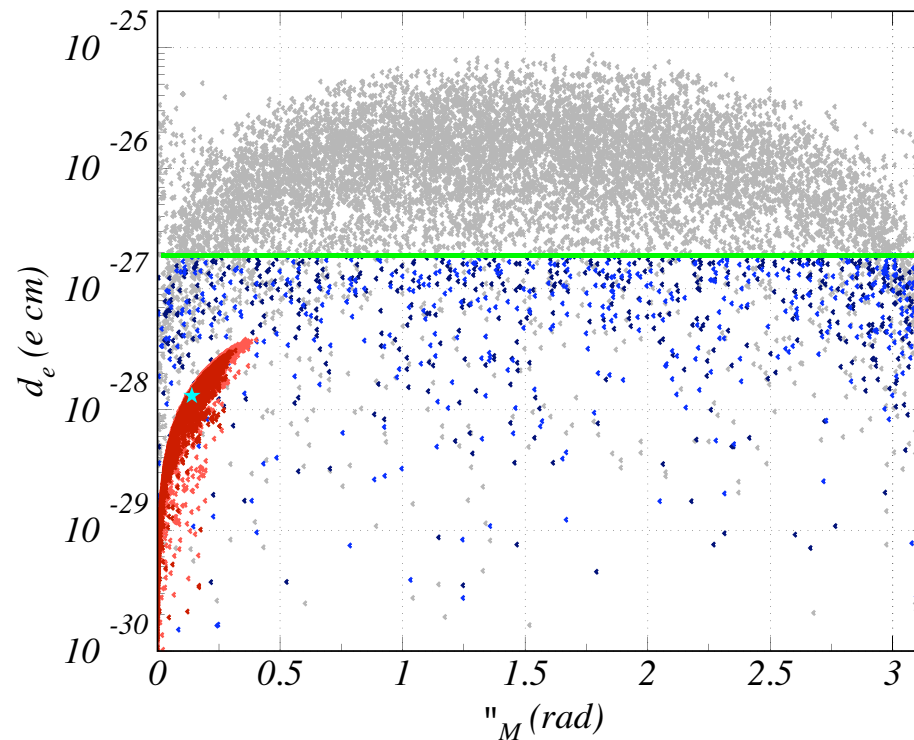
Choice of CP-violating Phases

- 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

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



- Experimental lower limit
- LHC scan, excluded
- ... ILC scan, ! 1 !
- * Input model
- ... LHC scan, allowed
- ... ILC scan, ! 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, 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 rate well predicted, and about to be tested in the near future.

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.

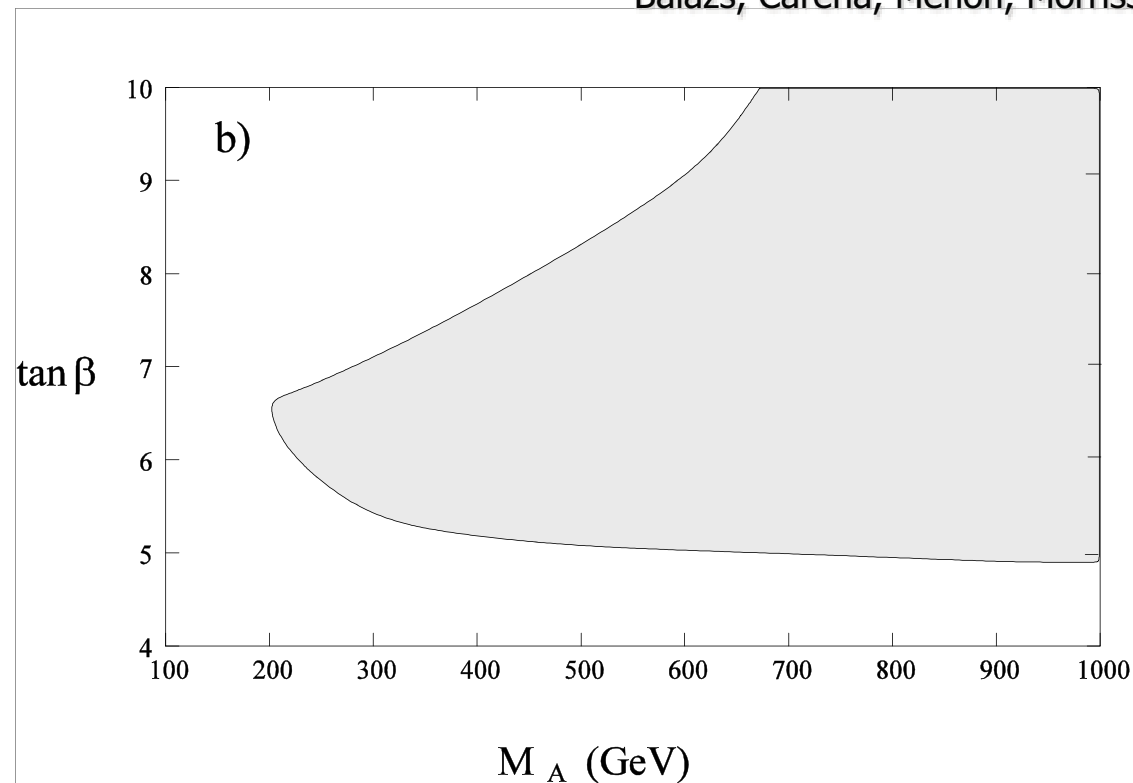
C. Balazs, M. Carena, A. Freitas and C.W., arXiv:0705.0431.

- **Additional Slides**

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



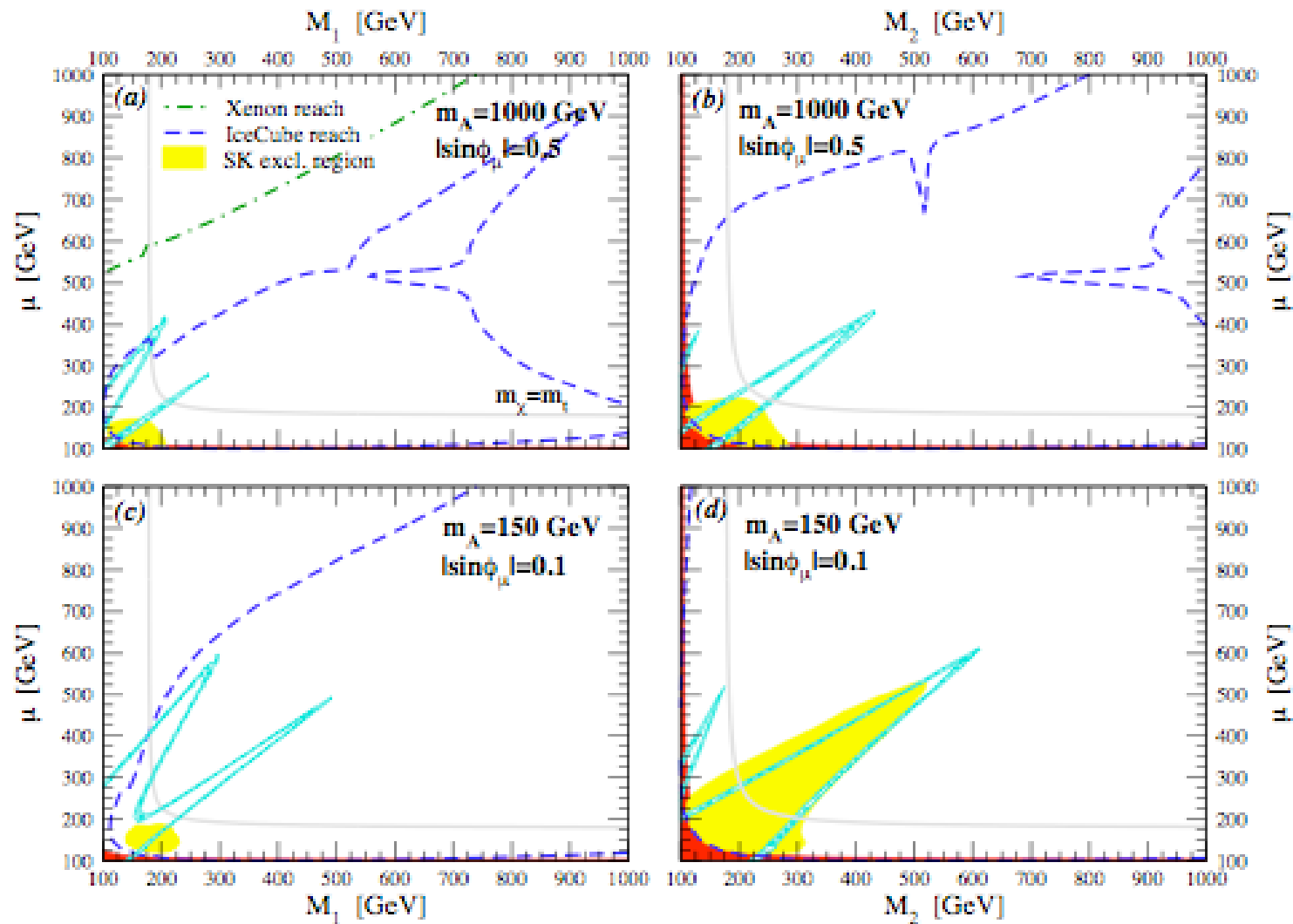


Figure 8: Current exclusion limits from the SuperKamiokande collaboration [58] (yellow shaded region) and future sensitivity reach of IceCube [13] and of Xenon-1t [8] on the $(M_{1,2}, \mu)$ planes at $|\sin \phi_\mu| = 0.5$ (panels (a) and (b)) and 0.1 (panels (c) and (d)); we also show the contours 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 $2\text{-}\sigma$ level, with the WMAP result [20]. The two upper panels refer to a heavy scalar mass