Probing the SUSY Origin of Matter at the ILC

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Based on works done in collaboration with:

M. Quiros and C. Wagner, Phys. Lett. B380 (1996) ; Nucl. Phys. B524 (1998)
M. Quiros, A. Riotto, I. Vilja and C. Wagner, Nucl. Phys. B503 (1997)
J. Moreno; M. Quiros, M. Seco and C. Wagner, Nucl. Phys. B599 (2001); B650 (2003)

C. Balazs and C. Wagner, Phys. Rev. D70 (2004)
C. Balazs, A. Menon, D. Morrissey and C. Wagner, PRD71 (2005)
A. Finch, A. Freitas, C. Milstene, H. Nowak and A. Sopczak, Phys.Rev.D72 (2005)
D. Hooper and P. Skands, hep-ph/0603180
A. Freitas, in preparation
C. Balazs, A. Freitas and C.E. M. Wagner, in preparation

Outline

- Cosmology as Motivation for Physics BSM

    -- Dark Matter   -- the Baryon Asymmetry

- Electroweak Baryogenesis in the MSSM

    -- Necessary requirements for EWBG

    -- Constraints on the SUSY spectrum

- Dark Matter in the MSSM

    -- Dark Matter in the presence of EWBG

    -- Collider Signatures

    -- Direct DM detection and the effects of CP violation

- Conclusions

Evidence for Dark Matter:

- Rotation curves from Galaxies.

  Luminous disk ==> not enough mass to explain rotational
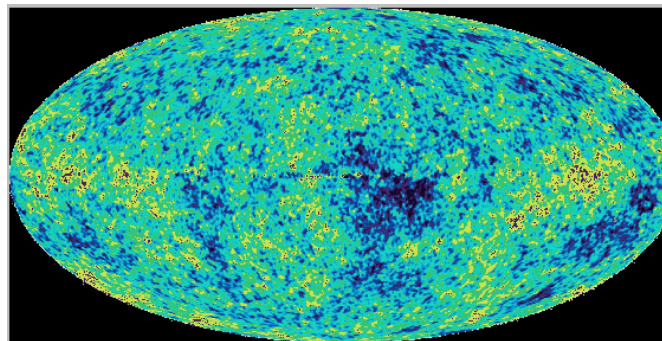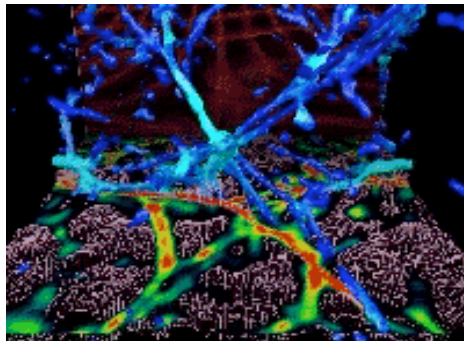 velocities of galaxies ==> Dark Matter halo around the galaxies
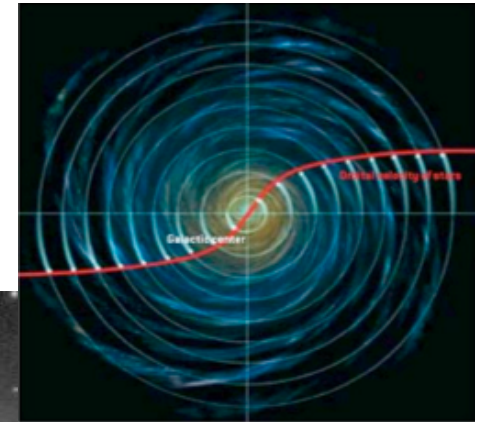
- Gravitational lensing effects

Measuring the deformations of images of a large number
of galaxies, it is possible to infer the quantity of Dark
Matter hidden between us and the observed galaxies
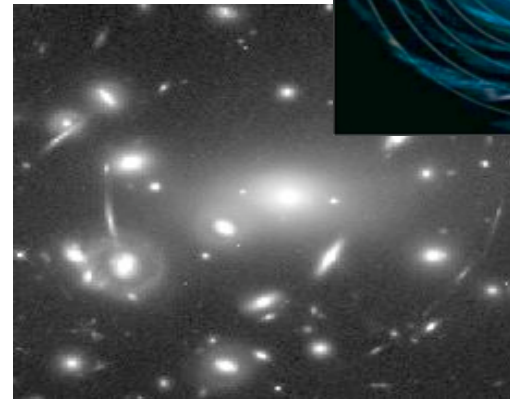
- Simulations of structure formation:
Large scale structure and CMB Anisotropies

The manner in which structure grows depends on the amount and type of dark matter present.
All viable models are dominated by cold dark matter.

Baryon Abundance in the Universe

- Abundance of primordial elements combined with predictions from Big Bang Nucleosynthesis:

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

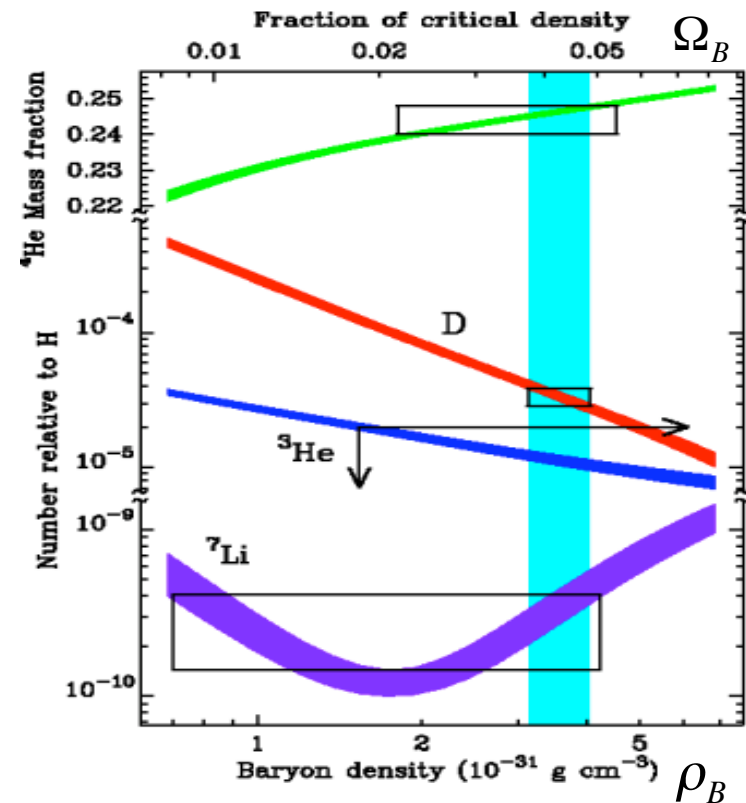- CMBR, tell us

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

There is a simple relation between These two quantities

$$\eta = \frac{n_B}{n_\gamma} = 2.68 \ 10^{-8} \Omega_B h^2 \approx 6 \ 10^{-10}$$

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

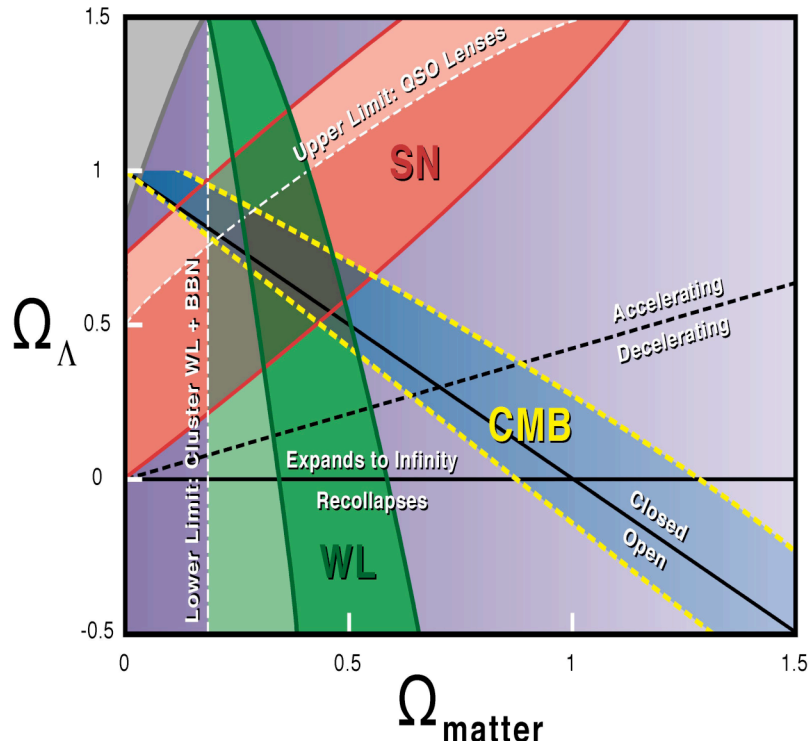- Baryon Number abundance is only a tiny fraction of relativistic species

From all the information we have ==> Precision Cosmology

CDM relic density (WMAP+SDSS):

$$\Omega_{CDM}\,h^2 = 0.1106 \pm^{0.0056}_{0.0075}$$

What is Dark Matter?

- Baryonic and hot DM ==> experiments agree that can only be a tiny part of the total DM

- Cold Dark Matter: many well motivated candidates, but **none in the Standard Model**

Most suitable candidates beyond the Standard Model:

- Axions
- Weakly interacting particles (WIMPS) with masses and interaction cross sections of order of the electroweak scale

The Puzzle of the Matter-Antimatter Asymmetry

- Anti-matter is governed by the same interactions as matter.

- Observable Universe is mostly made of matter: $N_B >> N_{\bar{B}}$

- Anti-matter only seen in cosmic rays and particle physics accelerators

What generated the small observed baryon--antibaryon asymmetry ?

$$\eta = \frac{n_B}{n_\gamma} \approx \left(6^{+0.3}_{-0.2}\right) 10^{-10}$$

Sakharov's Requirements:

✦ Baryon Number Violation (any B conserving process: $N_B = N_{\bar{B}}$)

✦ C and CP Violation: $(N_B)_{L,R} \neq (N_{\bar{B}})_{L,R}$

✦ Departure from thermal equilibrium

All three requirements fulfilled in the SM

In the SM Baryon Number conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

Anomalous processes violate both B and L number, but preserve B-L.
(Important for leptogenesis idea)

- *At T = 0, Baryon number violating processes exponentially suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \exp(-2\pi / \alpha_W)$$

- *At very high temperatures they are highly unsuppressed,*

$$\Gamma_{\Delta B \neq 0} \propto T$$

- *At Finite Temperature, instead, only Boltzman suppressed*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T) / T)$$

$$E_{sph} \cong 8 \, \pi \, v(T) / g \quad \text{and} \quad v(T) \text{ the Higgs v.e.v.}$$

Klinkhammer and Manton'84; Arnold and Mc Lerran'88, Khlebnikov and Shaposhnikov '88

Baryogenesis at the Electroweak Phase Transition

Kuzmin, Rubakov and Shaposhnikov, '85-'87
Cohen, Kaplan and Nelson '93

• Start with B=L=0   at T>Tc

• CP violating phases create chiral baryon-antibaryon asymmetry in the symmetric phase. Sphaleron processes create net baryon asymmetry.

• Net Baryon Number diffuse in the broken phase

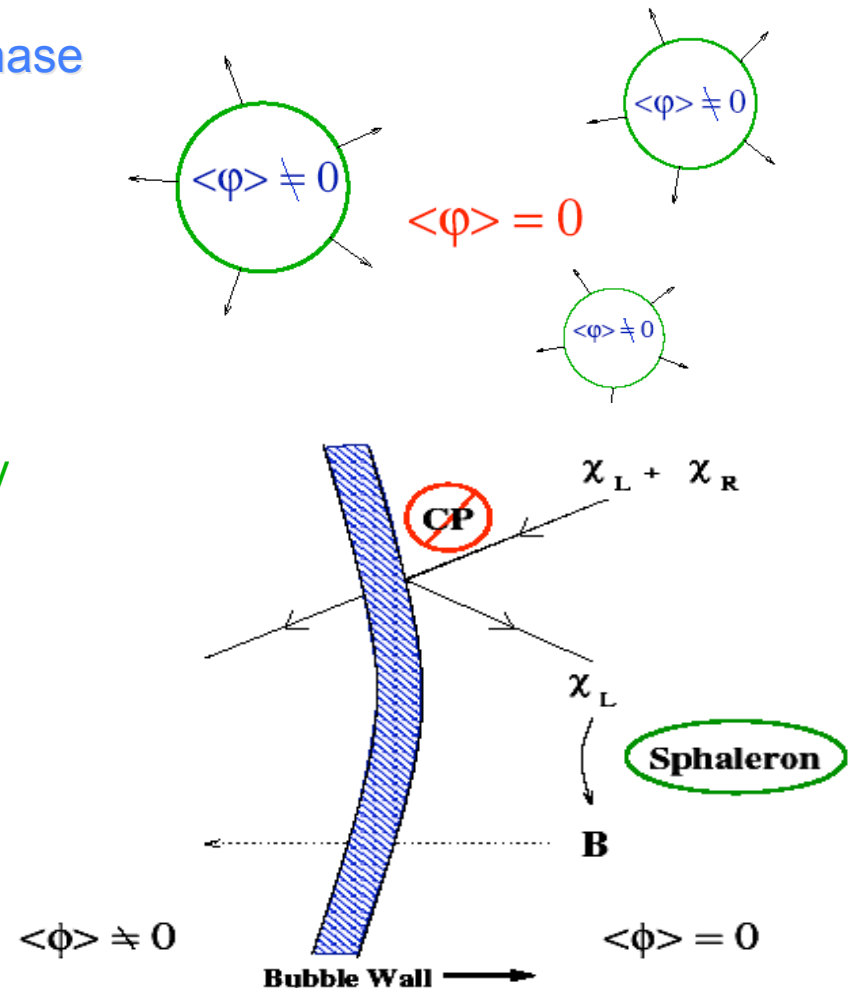if $n_{\mathbf{B}} = 0$ at T > Tc, independently

of the source of baryon asymmetry

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

To preserve the generated baryon asymmetry
strong first order phase transition:

$$\mathrm{v}(T_c)/T_c > 1$$ Shaposhnikov '86-'88

**Baryon number violating processes
out of equilibrium in the broken phase**

SM Electroweak Baryogenesis fufills the Sakharov conditions

- **SM Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V = D(T^2 - T_0^2)H^2 + E_{SM}T H^3 + \lambda(T) H^4$$

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

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

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

$$\boxed{\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \, \text{GeV} \implies \text{ruled out by LEP}}$$

- **Independent Problem: not enough CP violation**

Farrar and Shaposhnikov, Gavela et al., Huet and Satter

Electroweak Baryogenesis in the SM is ruled out

Supersymmetry and Cosmology

- SUSY is well motivated on purely particle physics grounds.
  The minimal SUSY extension of the SM leads to:

  - stabilization of the electroweak scale.

  - unification of gauge couplings.

- The MSSM also helps with cosmology.

- Dark Matter:

  - The lightest SUSY particle (LSP) is stable because of R-parity.

  - If the LSP is a neutralino, it can account for the dark matter.

- Baryon Asymmetry: [Huet, Nelson '91, Giudice '91, Espinosa, Quiros, Zwirner '93]

  - New CP violating phases can arise when SUSY is softly broken.

  - The baryon asymmetry can be generated within the MSSM
    by the mechanism of electroweak baryogenesis.

- Can the MSSM explain both simultaneously?

Baryogenesis in the MSSM:

- New bosonic degrees of freedom: superpartners of the top quark, with strong couplings to the Higgs. $\Rightarrow E_{SUSY} \approx 8\, E_{SM}$

Sufficiently strong first order phase transition to preserve generated baryon asymmetry:

- *Higgs masses up to 120 GeV*

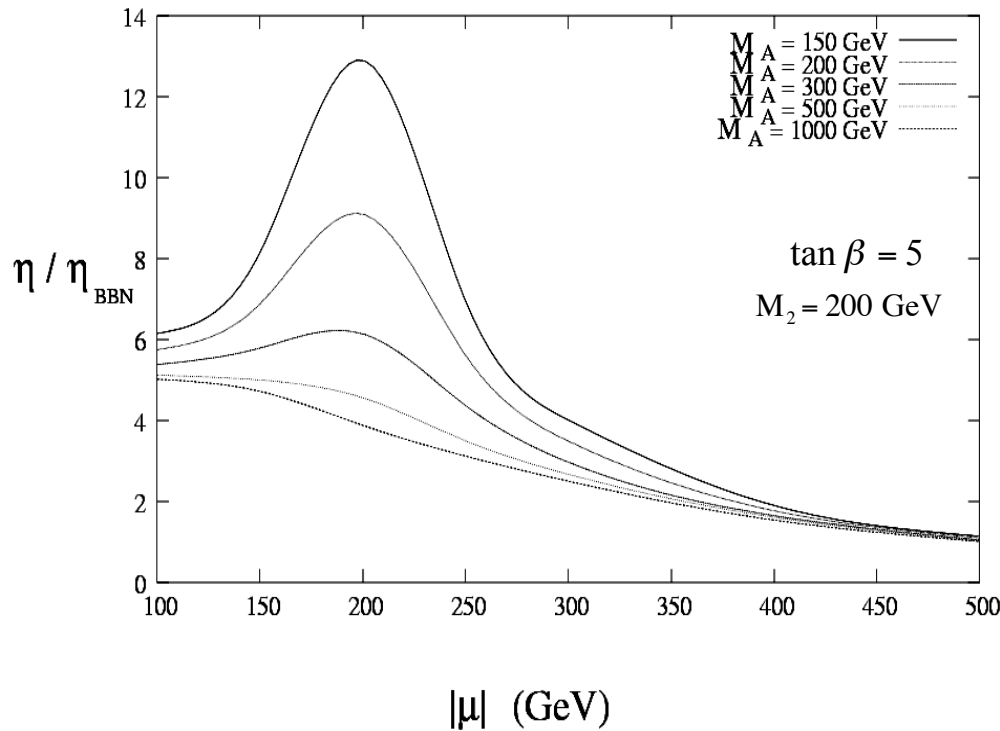- *The lightest stop must have a mass below the top quark mass.*
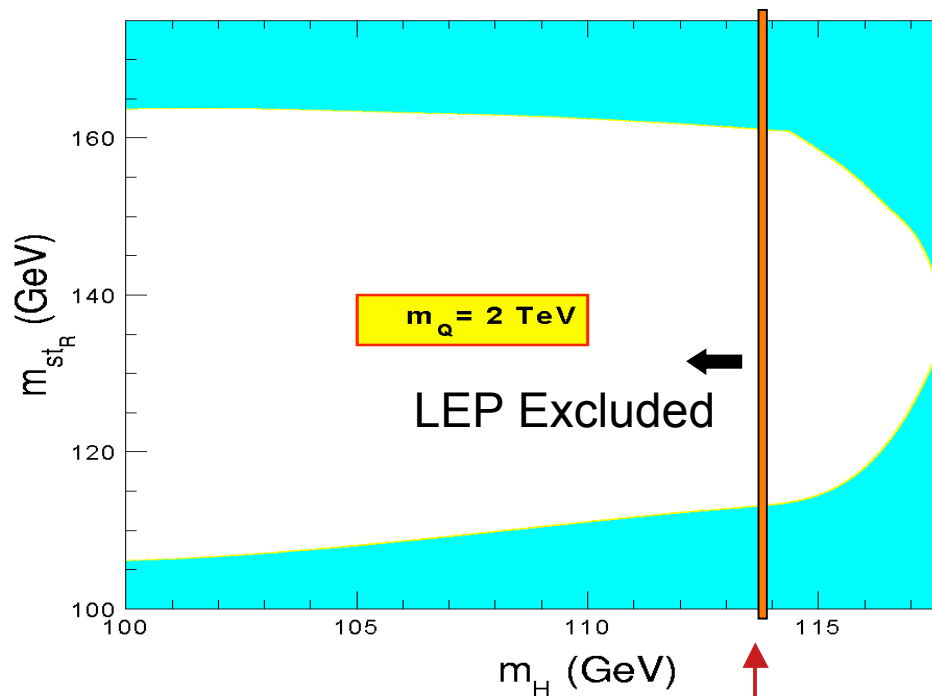
M.C, Quiros, Wagner

Present LEP bounds on the SM- like Higgs mass
$$m_{H_{SM-like}} > 114.6\,\text{GeV}$$

Baryon Asymmetry Dependence on the Chargino Mass Parameters

M.C., M.Quiros, M. Seco and C. Wagner

Plot legend:
$M_A = 150$ GeV
$M_A = 200$ GeV
$M_A = 300$ GeV
$M_A = 500$ GeV
$M_A = 1000$ GeV

$\tan \beta = 5$

$M_2 = 200$ GeV

Axes: η / η_{BBN} (vertical), $|\mu|$ (GeV) (horizontal)

• New CP violating phases are crucial

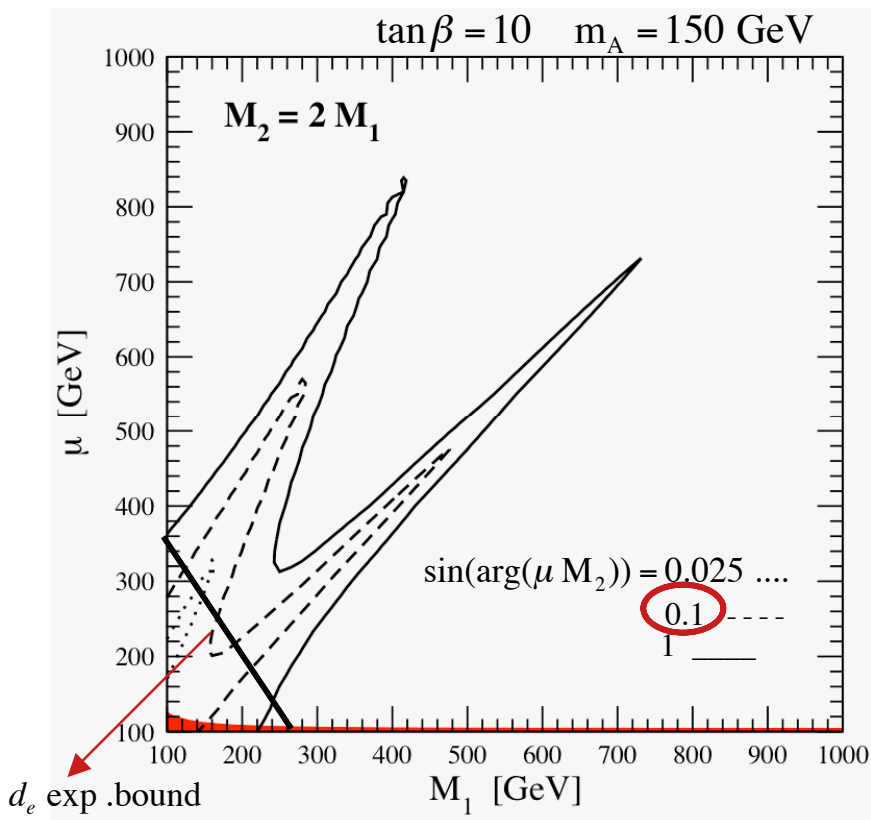Results for maximal CP violation
$$\sin(\arg(\mu\, M_2)) = 1$$

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

• Results scale with $\sin(\arg(\mu\, M_2))$
and (approx) with $\sin 2\beta$

Baryon Asymmetry Enhanced for $M_2 = |\mu|$ *and smaller values of* m_A

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

A different point of view considered by Konstandin, Prokopec, Schmidt and Seco '05

- Similar investigation considering also contributions to the Baryon Asymmetry from CP violating currents involving the lightest neutralino (LSP):
==> depend on $\sin(\arg(\mu\, M_1))$, with resonant behavior for $|\mu| \approx M_1$

$\tan\beta = 10 \quad m_A = 150$ GeV

$M_2 = 2\, M_1$

μ [GeV]

$\sin(\arg(\mu\, M_2)) = 0.025$ ....

0.1 - - - -

1 ____

M_1 [GeV]

d_e exp .bound

Cirigliano, Profumo, Ramsey-Musolf'06
Ramsey-Musolf's talk: Cosmology I

This region of parameter space, with the LSP having a relevant Higgsino-bino admixture, leads to a very efficient pair annihilation

==> too little relic density, below the CDM abundance

==> neutralino driven EWB would demand some enhancement mechanism to produce the observed DM density
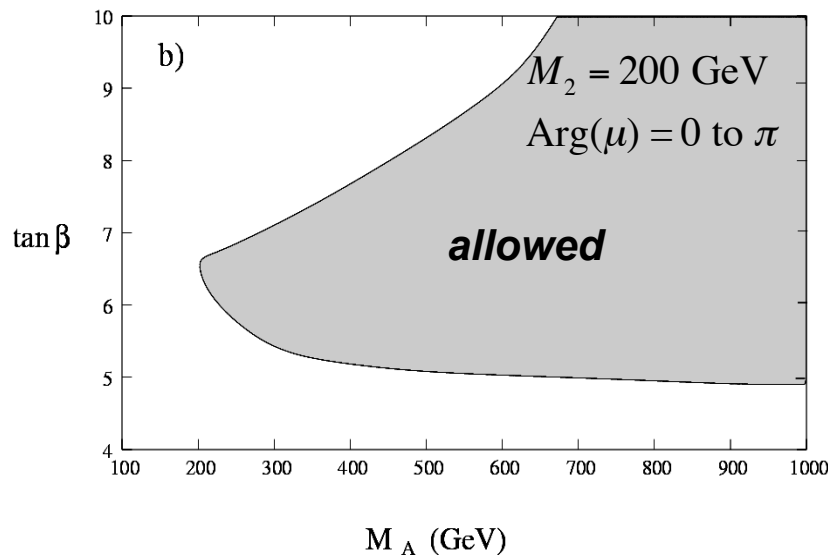
Phases in the MSSM EWBG scenario very constrained by EDM limits

- One loop contributions become negligible for
$$m_{\tilde{f}_{1,2}} \geq 10 \text{ TeV}$$

- At two loop order, contributions from virtual charginos and Higgs bosons, proportional to
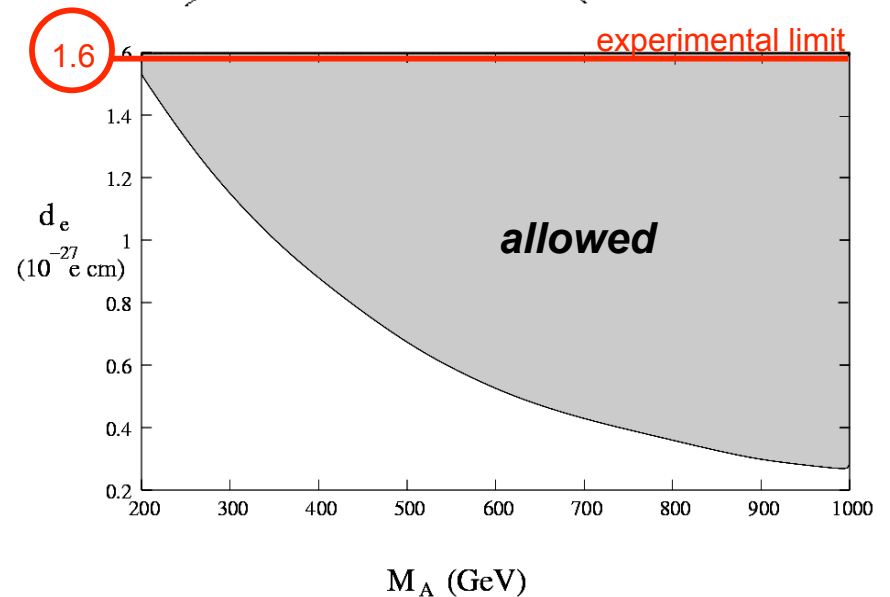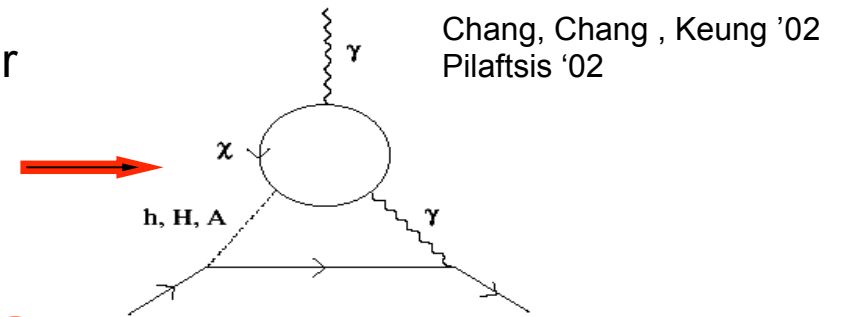$$\sin(\arg(\mu\, M_2))$$

Chang, Chang , Keung '02
Pilaftsis '02

$M_2 = 200 \text{ GeV}$

$\text{Arg}(\mu) = 0 \text{ to } \pi$

allowed

$\tan\beta$

M_A (GeV)

1.6

experimental limit

d_e

$(10^{-27} e\, cm)$

allowed

M_A (GeV)

$$\Rightarrow \underbrace{5 \leq}_{m_{Q_3} \leq 1.5\, \text{TeV}} \tan\beta \leq 10 \qquad M_A \geq 200\, \text{GeV} \qquad 110\, \text{GeV} \leq |\mu| \leq 550\, \text{GeV (not shown)}$$

Balazs, M.C, Menon, Morrissey, Wagner

- An order of magnitude improvement in the electron EDM over the present bound
==> will leave little room for this scenario.
However, uncertainties of O(1)! and one may have some specific cancellations between one and two loop contributions or lower tanb.

Dark Matter and Electroweak Baryogenesis

EWBG conditions, Higgs and EDM bounds

- light right handed stop: $m_{\tilde{U}_3}^2 \leq 0$ • heavy left handed stop: $m_{\tilde{Q}_3}^2 \geq (1\,\text{TeV})^2$

- values of stop mixing compatible with Higgs mass constraints and with a strong first order phase transition: $\left| X_t \right| = \left| A_t - \mu^* / \tan\beta \right| = (0.3 - 0.5)\, m_{\tilde{Q}_3}$

- light charginos with $\mu, M_2 \leq 500\,\text{GeV}$

- sizeable CP violating phases in the chargino sector $\sin(\arg(\mu\, M_2)) \geq 0.1$

- $5 \leq \tan\beta \leq 10$ $M_A \geq 200\,\text{GeV}$

- the rest of the squarks, sleptons (and gluinos) heavy
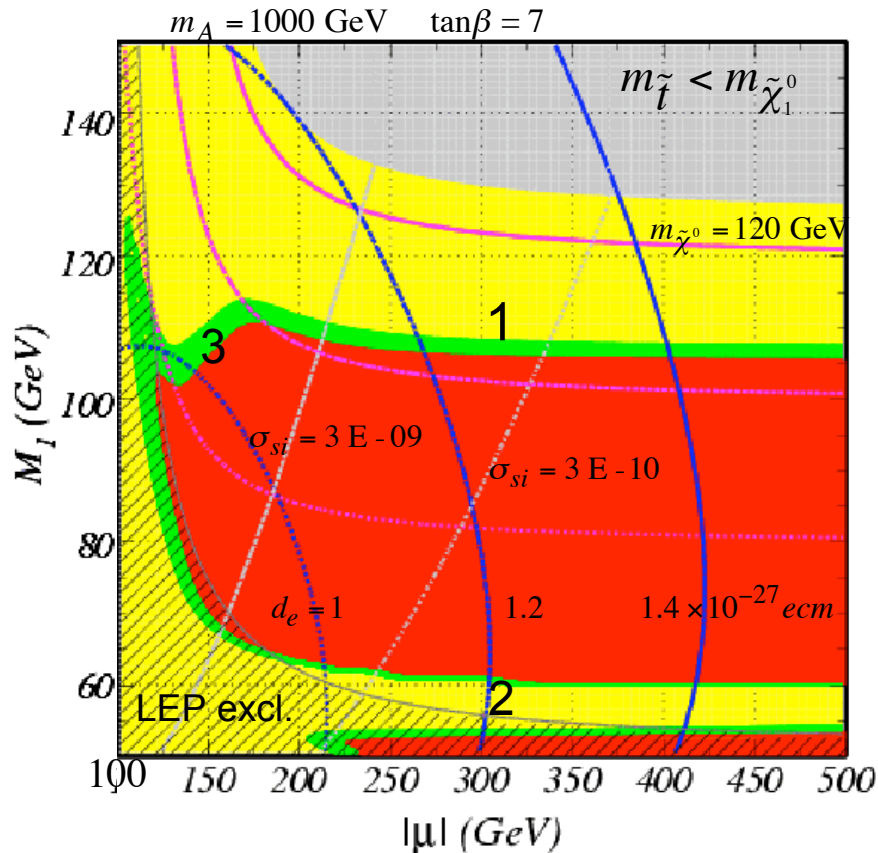
Implications for Dark Matter:

- LSP lighter that the stop $\Rightarrow m_{\tilde{\chi}_1^0} < m_{\tilde{t}} < m_{top}$

  If they are close in mass, co-annihilation greatly reduces the relic density.
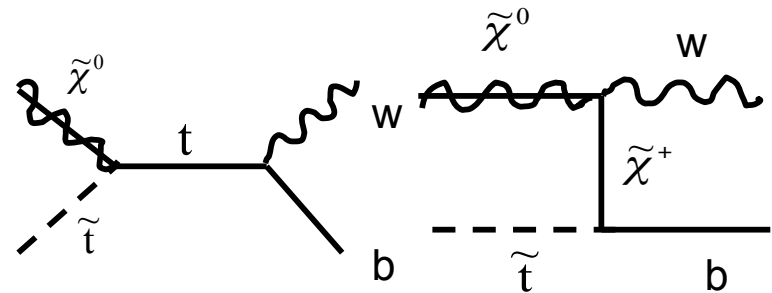
- If $m_{\tilde{\chi}^0} \cong m_h / 2$, neutralino annihilation enhanced by s-channel h resonance

- CP phases in the chargino sector affect the mass and couplings of the LSP

Relic Density Computation

$m_A = 1000$ GeV $\tan\beta = 7$

$m_{\tilde{t}} < m_{\tilde{\chi}^0_1}$

$m_{\tilde{\chi}^0} = 120$ GeV

3

1

$\sigma_{si} = 3\,E-09$

$\sigma_{si} = 3\,E-10$

$d_e = 1$ 1.2 $1.4 \times 10^{-27}\,ecm$

LEP excl.

2

M_1 (GeV)

$|\mu|$ (GeV)

Balazs, MC, Menon, Morrissey, Wagner '04

three interesting regions with neutralino relic density compatible with WMAP obs.

$$0.095 < \Omega_{CDM}h^2 < 0.129 \text{ (green areas)}$$

new WMAP + SDSS $\Rightarrow$ < 0.122

1. neutralino-stop co-annihilation: mass difference about 20-30 GeV

2. s-channel neutralino annihilation via lightest CP-even Higgs

3. annihilation via Z boson exchange

small μ and M_1 (& t-channel χ^0 and $\chi^{\pm}$)

## Similar qualitative results under variations in the phase of mu

- Some differences in the h resonance region due to variations in the imaginary and real parts of the $\tilde{\chi}^0 \tilde{\chi}^0 h$ couplings.

- The $\tilde{\chi}^0 t \tilde{t}$ coupling varies somewhat with the phase but the main effect is due to the variation of the LSP mass which affects the co-annihilation contribution.

Non-Standard Higgs Mass Effects $(m_A = 200 \text{ GeV})$

A,H contribute to annihilation cross section vis s-channel:

- $m_A = 200 \text{ GeV} \Rightarrow$ new resonant region due to A,H s-channel around $m_{\tilde{\chi}_1^0} \approx m_A/2$

-- much wider band than for h due to enhanced $\tan\beta$ bb couplings --
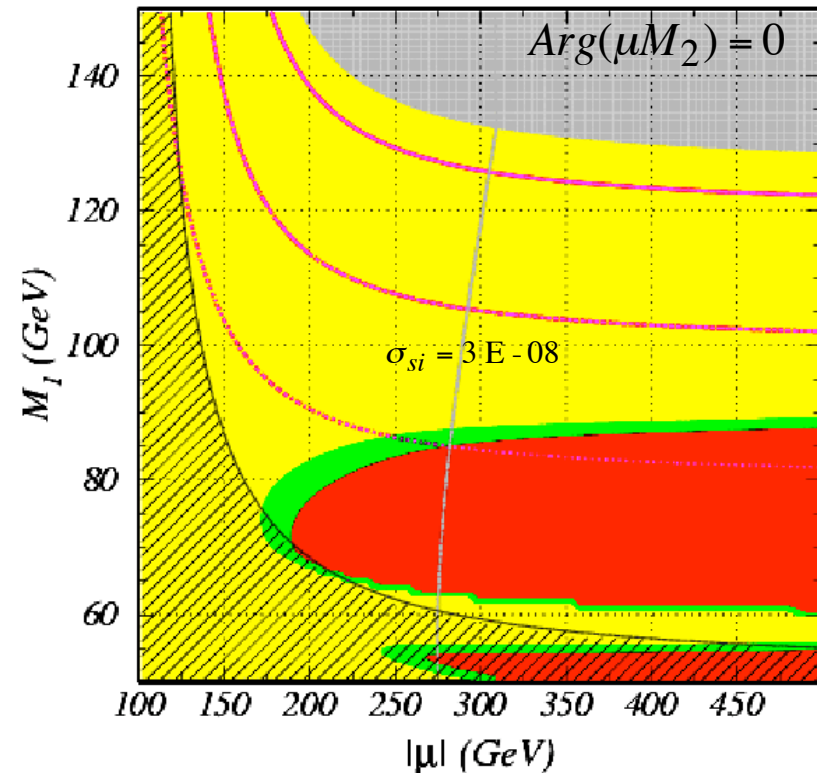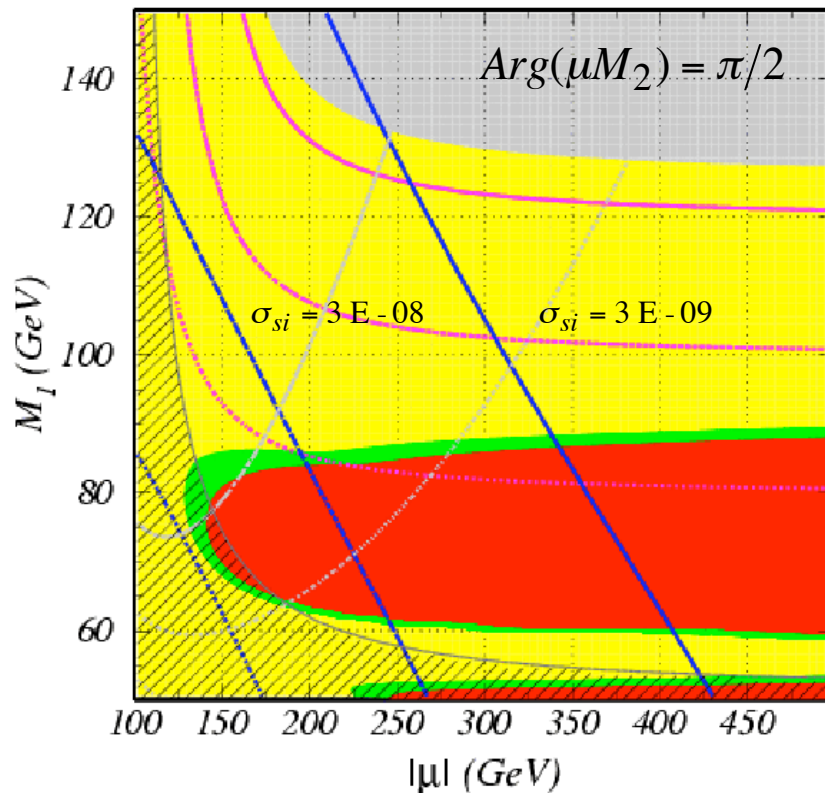
- Ω_{CDM} ==> sum of A and H contributions nearly independent of CP violating phase

(crucial difference in EDM's and Spin-Independent cross sections)

- Larger neutralino-proton scattering cross sections due to heavy Higgs H, tanb enhanced contributions

Balazs, MC, Wagner

Experimental Tests of
Electroweak Baryogenesis and Dark Matter

- Higgs searches:

Higgs associated with electroweak symmetry breaking: SM-like.
Higgs mass below 120 GeV required

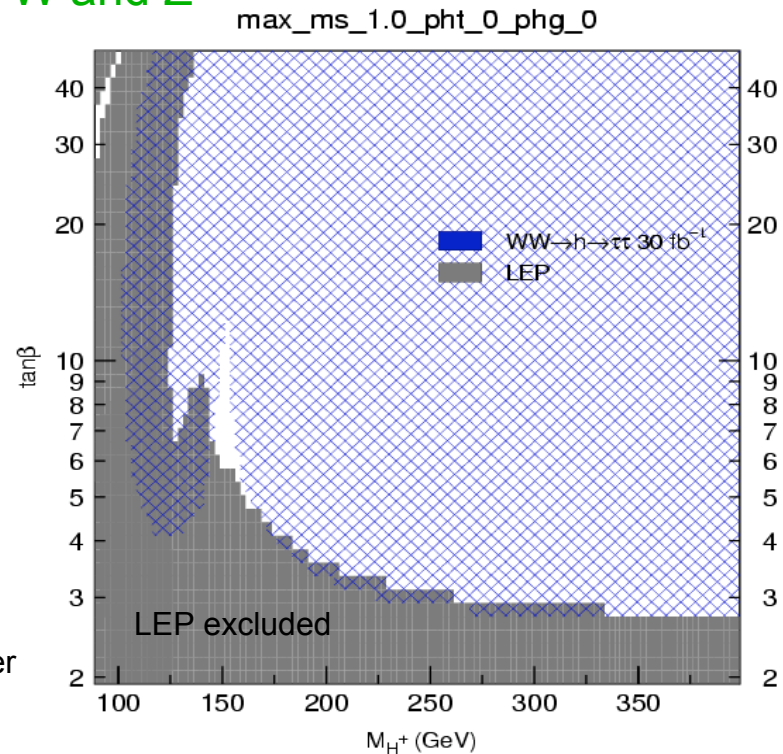1. Tevatron collider may test this possibility: 3 sigma evidence with about 4 fb^{-1}

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

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

$$\text{with } h \rightarrow \tau^+\tau^-$$

M.C, Mrenna, Wagner

max_ms_1.0_pht_0_phg_0

WW→h→ττ 30 fb⁻¹
LEP

LEP excluded

M_{H^+} (GeV)

Searches for a light stop at the Tevatron

Light-stop models with neutralino dark matter $\longrightarrow$ $\not{E}_T$ signal

Balazs, MC, Wagner'04
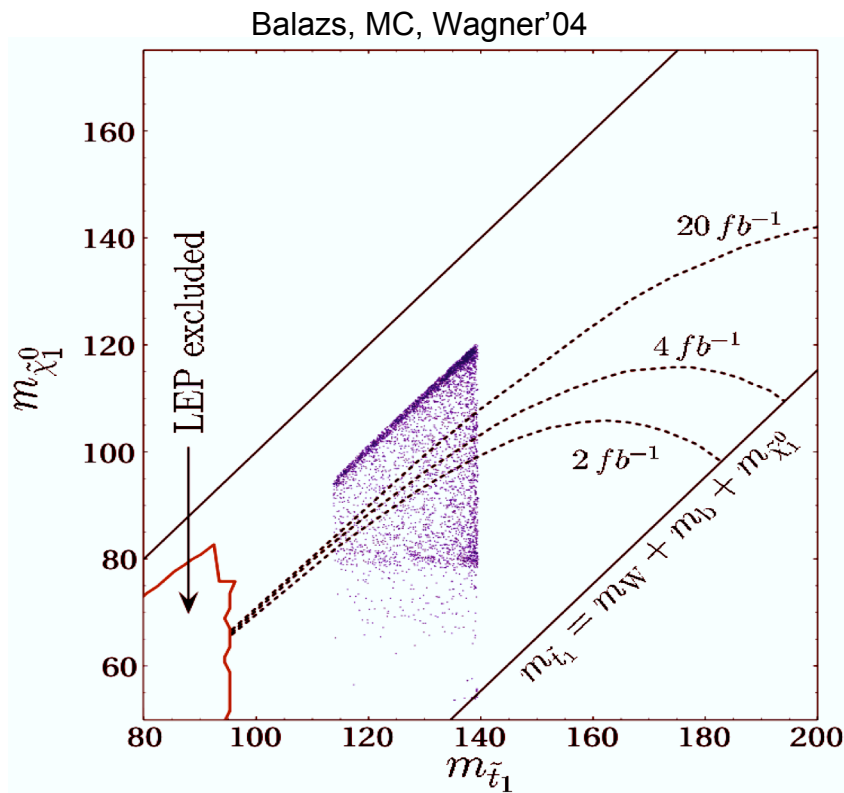
- For small stop-LSP mass difference $\Delta_{m_{\tilde{t}\tilde{\chi}}}$
  ==> dominant decay mode

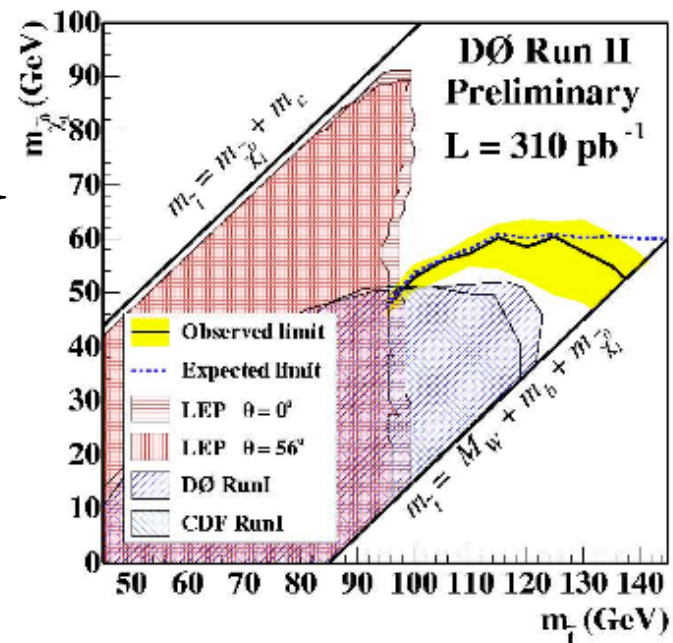$$\boxed{\tilde{t}_1 \to c\, \tilde{\chi}_1^0}$$

2- and 3 body decays kinematically forbidden:
$$\tilde{t}_1 \to b\, \tilde{\chi}_1^+ \qquad \tilde{t}_1 \to bW^+ \tilde{\chi}_1^0 \qquad \tilde{t}_1 \to bl^+ \tilde{v}_l$$

4 body decays $\tilde{t}_1 \to bl^+ v_l\, \tilde{\chi}_1^0$ sub-dominant

Blue: Relic density compatible with WMAP

Co-annihilation for $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

==> Problematic searches at Hadron Colliders

Light Stops at the LHC

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

- Look for same-sign tops in gluino decays

$$pp \to \tilde{g}\tilde{g} \to \mathrm{tt}\, \tilde{t}_1^* \tilde{t}_1^*, \qquad \mathrm{t} \to \mathrm{b}l^+ \bar{\nu}_l \qquad \tilde{t}_1^* \to c\tilde{\chi}_1^0$$

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

Mass measurements from distributions,
==> but not enough independent
distributions to get absolute masses
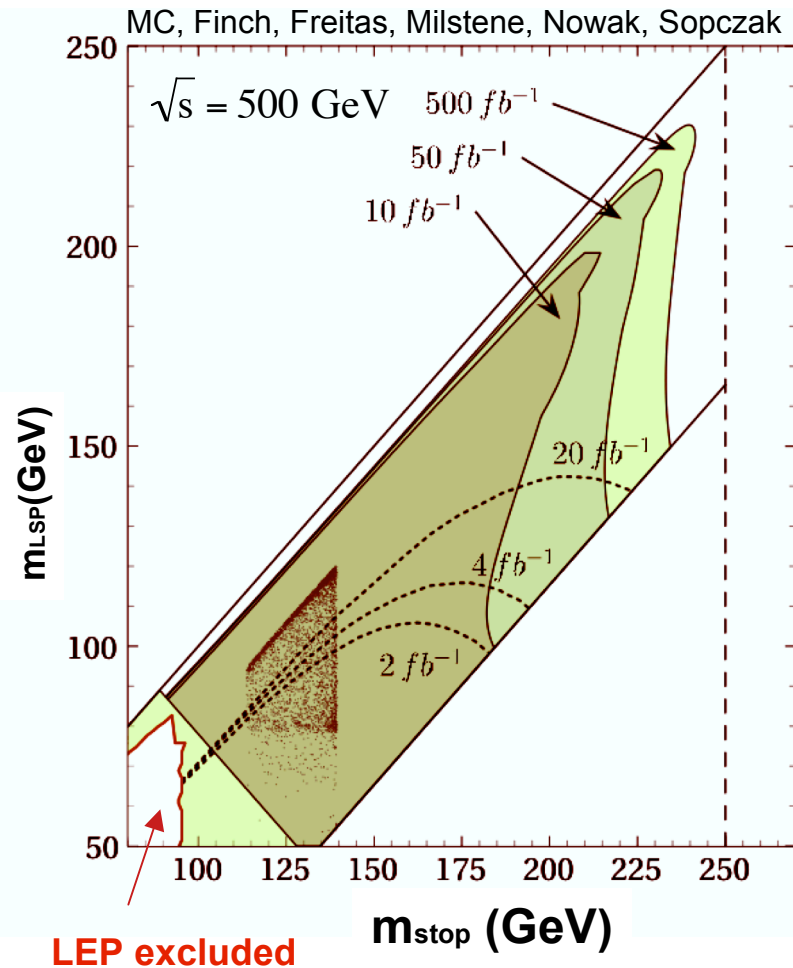
Analysis valid for gluino masses up to
~ 900 GeV
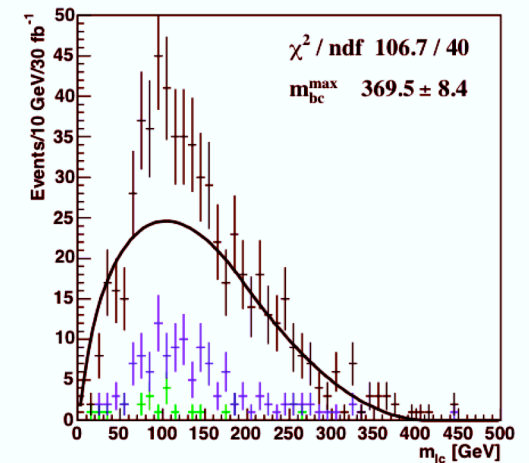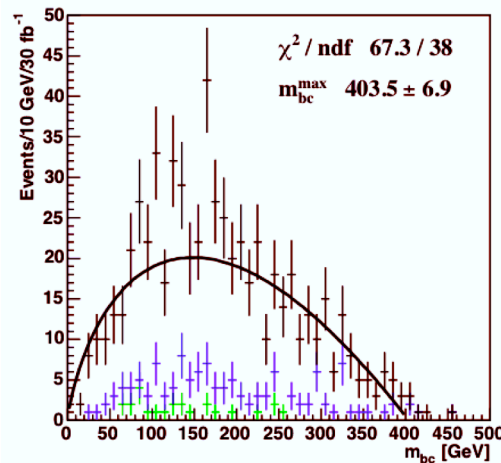
Caveat: Study done for relatively light squarks ~ 1 TeV.
For heavier squarks, gluino signal decreased by 50% from absence of
squark-gluino production: still may be possible to see the stops (under study)

The power of the ILC

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

MC, Finch, Freitas, Milstene, Nowak, Sopczak

$\sqrt{s} = 500$ GeV

500 fb^{-1}
50 fb^{-1}
10 fb^{-1}
20 fb^{-1}
4 fb^{-1}
2 fb^{-1}

m_{LSP}(GeV)

m_{stop} (GeV)

LEP excluded

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

Signature: 2 soft charm jets plus missing E

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

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

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

Even for small integrated Luminosity

of order 10 fb-1

covers cosmologically preferred region

Measurement of SUSY parameters for DM density computation

Sample parameter point:
consistent with EDM's, EWB and
Higgs mass bound

$M_1 = 118.8$ GeV $\qquad$ $M_{u3}^2 = -99^2$ GeV^2

$M_2 = 225$ GeV $\qquad$ $M_{q3} = 4330$ GeV

$|\mu| = 225$ GeV $\qquad$ $A_t = -1100$ GeV

$\phi_\mu = 0.2$ $\qquad$ $\tan\beta = 5$

1st and 2nd generation sfermions = 10 TeV

$m_{\tilde{\chi}_1^0} = 106.6$ GeV $\qquad$ $m_{\tilde{t}_1} = 122.5$ GeV $\qquad$ $\cos\theta_{\tilde{t}} = 0.01$ $\qquad$ $\Omega_{\text{CDM}}h^2 \approx 0.108$
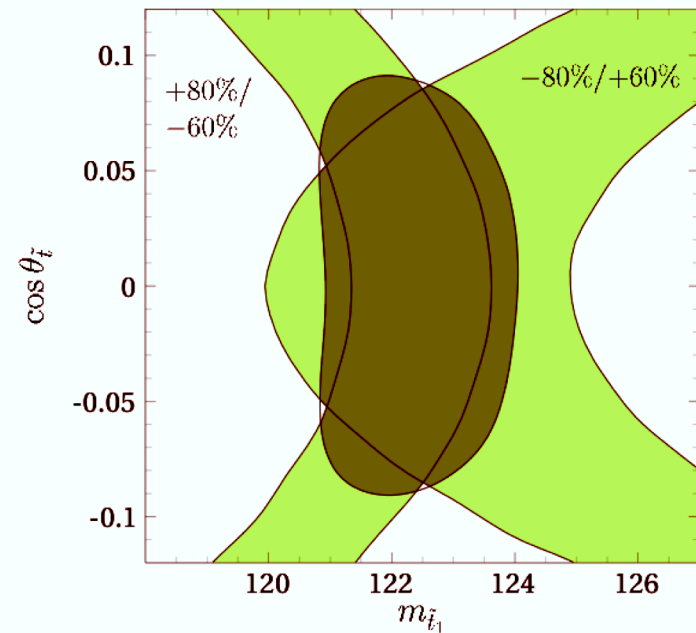
-- Stop mass and mixing angles

Consider stop production cross sections
with two different polarizations (250 fb^{-1} each)

$$P(e^-)/P(e^+) = -80\%/+60\%$$
$$+80\%/-60\%$$

Result: $m_{\tilde{t}_1} = 122.5 \pm 1.0$ GeV
$|\cos\theta_{\tilde{t}}| < 0.074$
$\Rightarrow |\sin\theta_{\tilde{t}}| > 0.9972$

M.C, Finch, Freitas, Milstene, Nowak, Sopczak

-- Chargino/Neutralino parameters (Similar analyses by Gray et al. and Desch et al.)

G. Moortgat-Pick's talk :LHC/ILC II

MASS MEASUREMENTS

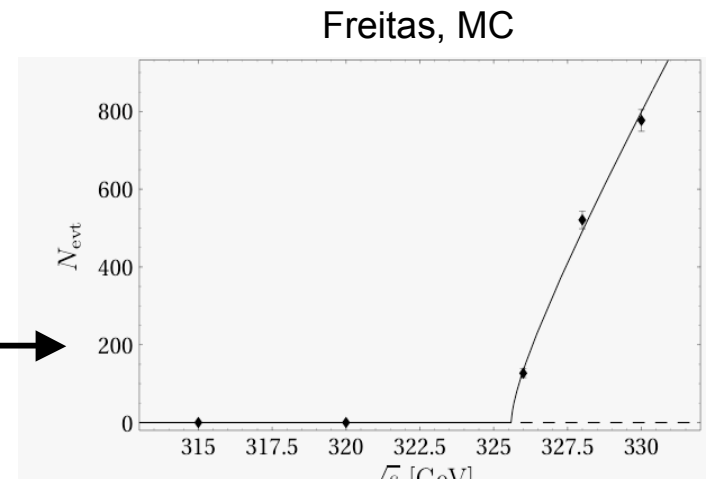Heavy 1st/2nd generation squarks and sleptons ==> masses from squark cascades at LHC difficult

Light Neutralino/Charginos accesible at ILC with $\sqrt{s} = 500$ GeV

Freitas, MC

Main decay modes:

$$\tilde{\chi}_1^\pm \to \tilde{t}_1 \bar{b} \to c\,\bar{b}\,\tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \to Z^* \tilde{\chi}_1^0 \qquad \tilde{\chi}_3^0 \to Z\,\tilde{\chi}_1^0$$
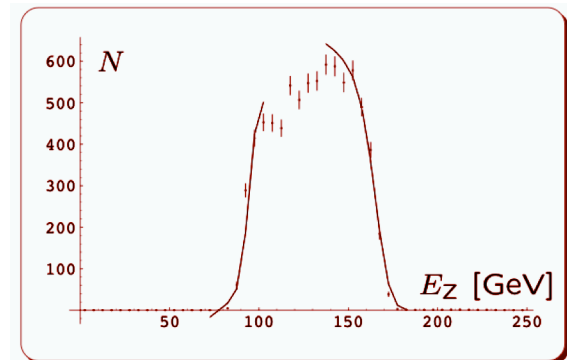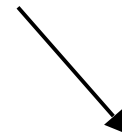
$\tilde{\chi}_1^\pm$ mass from threshold scan, ⟶

$\tilde{\chi}_{2,3}^0$ masses from energy distribution endpoints.

From parton-level simulation with SM and SUSY backgrounds:

	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_1^\pm$	
m	107	171	231	163	GeV
δm	0.3	0.6	2	0.06	GeV

-- Chargino/Neutralino parameters

CROSS SECTION MEASUREMENTS

$$e^+ e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$$
$$e^+ e^- \to \tilde{\chi}_2^0 \tilde{\chi}_3^0$$

$$P(e^-)/P(e^+) = -80\%/+60\%$$
$$\text{and } +80\%/-60\%$$
$$\text{at } \sqrt{s} = 500 \text{ GeV}$$

Signal and background studied in generator-level simulation

Combine mass and cross-section measurements:
Use χ^2 fit to extract fundamental SUSY parameters:

$$M_1 = 118.8 \pm 0.4 \text{ GeV} \qquad |\phi_\mu| < 0.7$$
$$M_2 = 225.0 \pm 1.0 \text{ GeV} \qquad \tan\beta = 5^{+0.5}_{-1.4}$$
$$|\mu| = 225.0 \pm 1.7 \text{ GeV}$$

Large correlation between $\tan\beta$ and ϕ_μ
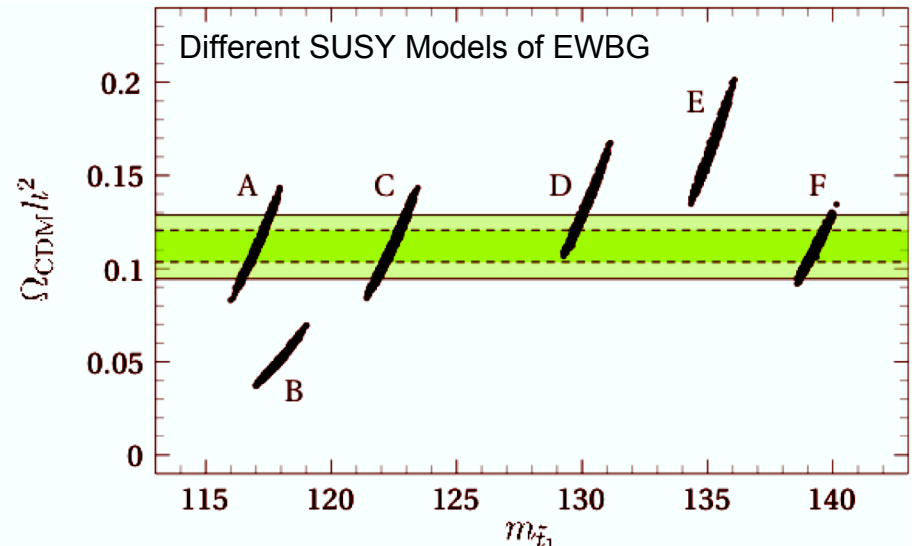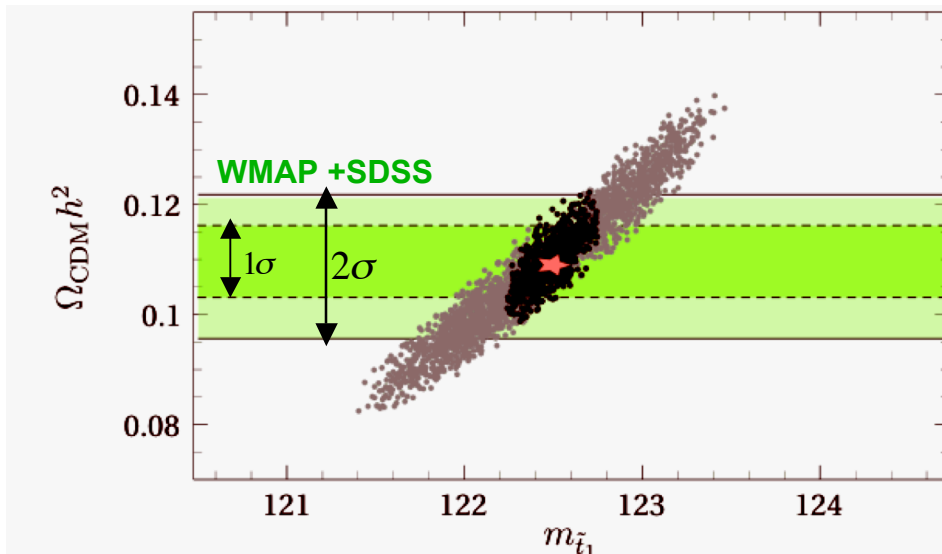
Cosmological Implications

Precise measurement of SUSY parameters for DM computation

    -- stop mass and mixing angles

from production cross sections at different polarizations.

    -- LSP mass and composition

from threshold scan ($\tilde{\chi}_1^{\pm}$), energy distribution endpoints ($\tilde{\chi}_{2,3}^0$) and polarized cross sections

1σ constraints from ILC measurements ==> $\quad 0.082 < \Omega_{CDM} h^2 < 0.139$
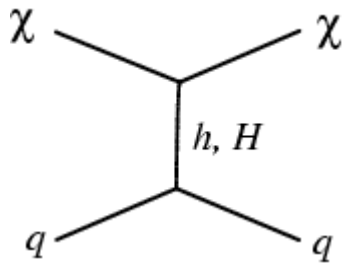
    -- dominated by error on stop mass --

• **Using input parameters into computation of effective Higgs potential ==>** $\delta \dfrac{v(T_c)}{T_c} \leq 10\%$

  • ILC measurements can provide crucial information on the SUSY origin of Matter
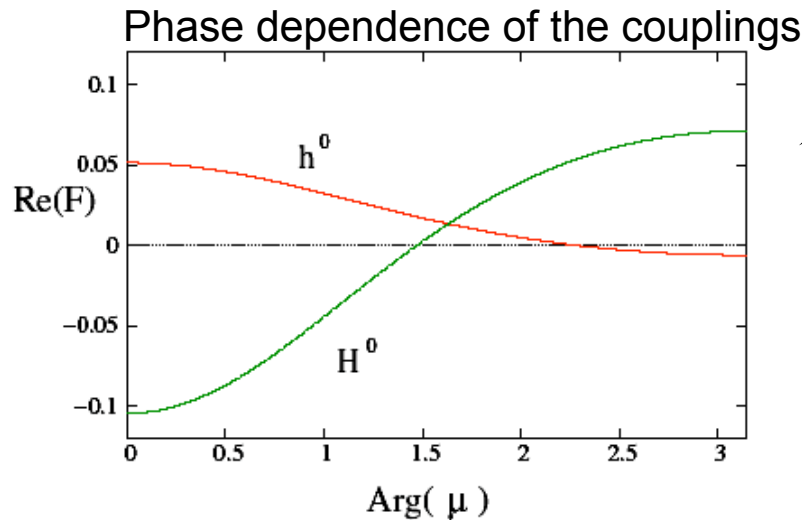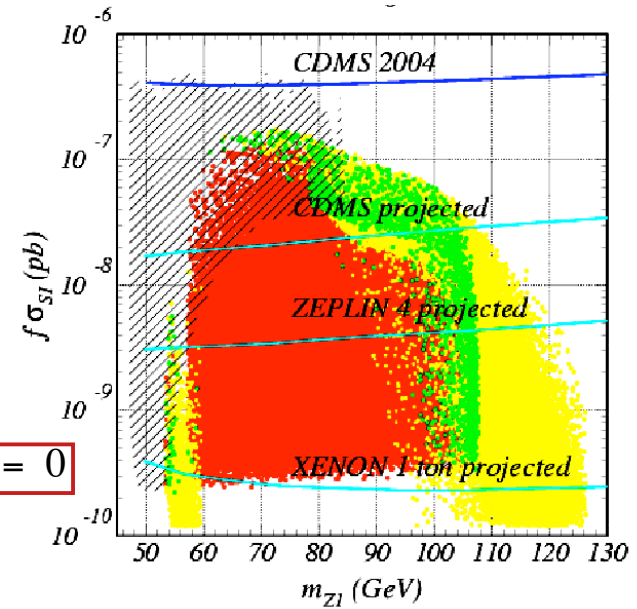
Direct Dark Matter Detection

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

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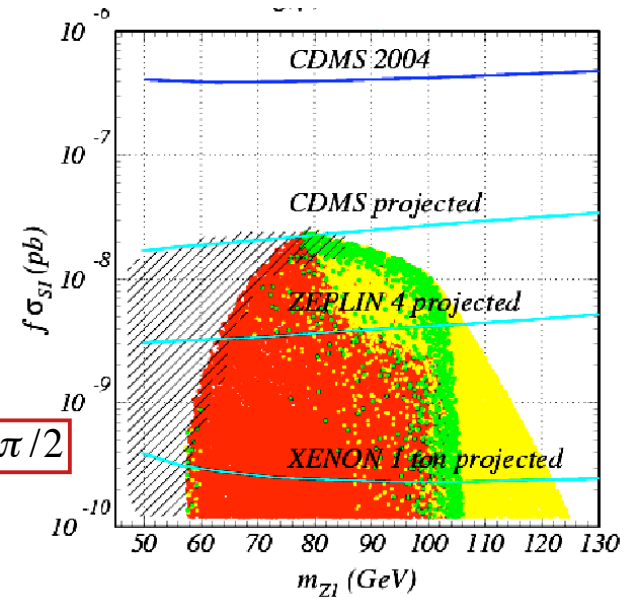detecting elastic recoil off nuclei

Only scalar (real)
part of $\tilde{\chi}^0 \tilde{\chi}^0 h/H$
couplings relevant

$\boxed{Arg(\mu) = 0}$

Phase dependence of the couplings

$\boxed{Arg(\mu) = \pi/2}$

Balazs, MC, Menon, Morrissey, Wagner '04
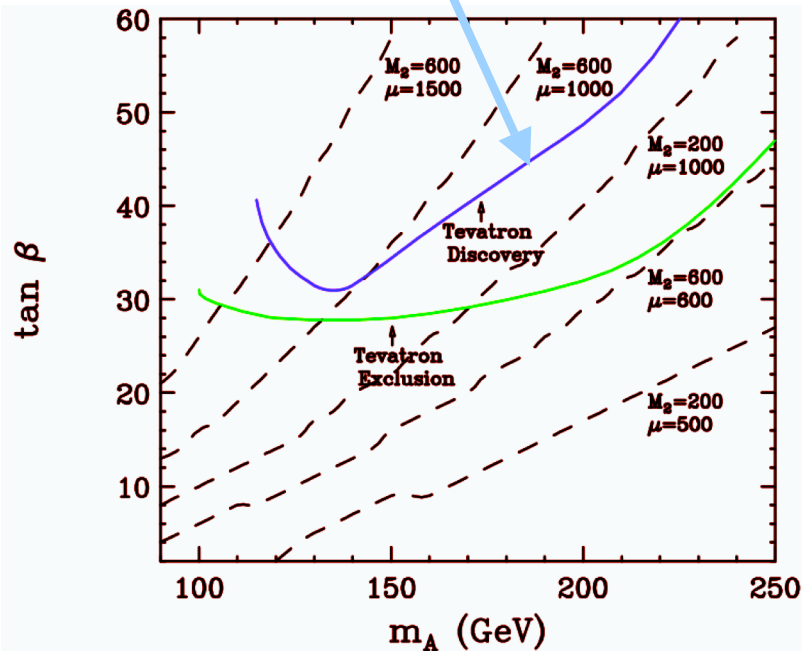
CDMS DM searches Vs the Tevatron H/A searches

• If the lightest neutralino makes up the DM of the universe

==> CDMS current limits disfavor discovery of H/A at the Tevatron, unless the neutralino has a large higgsino component $\Rightarrow \mu >> M_2$
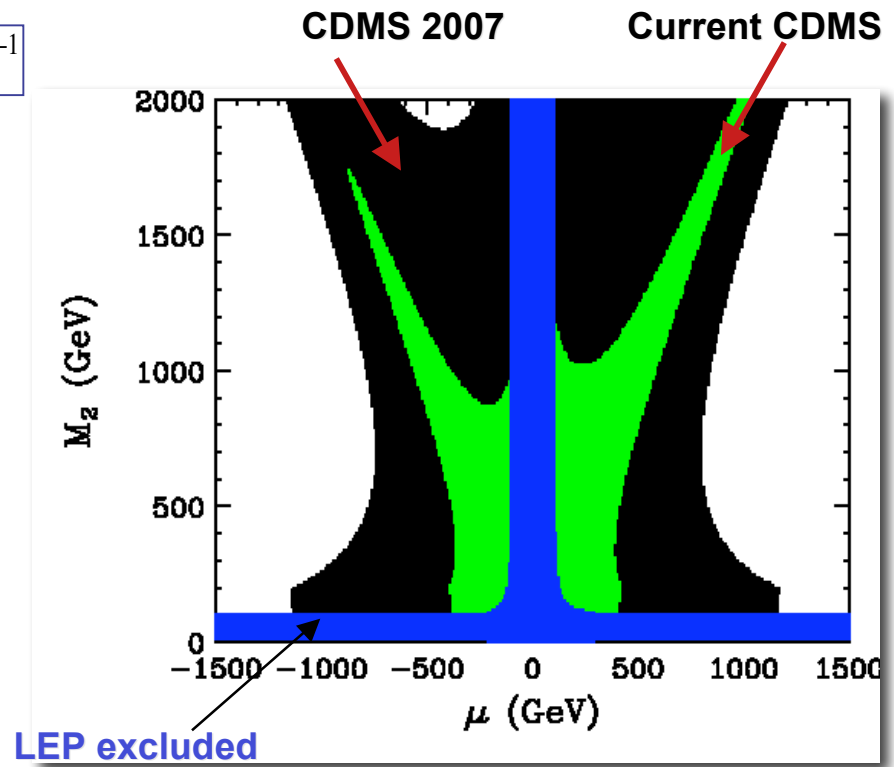
==> a positive signal at CDMS will be very encouraging for Higgs searches

==> Evidence for H/A at the Tevatron without a CDMS signal would suggest large μ

Tevatron reach in $p\bar{p} \rightarrow A/H \rightarrow \tau^+\tau^-$ with $4\,fb^{-1}$

CDMS 2007 Projection

CDMS 2007   Current CDMS

LEP excluded

M.C, Hooper, Skands, hep-ph/0603180

Precision Measurement of Parameters at the ILC and cosmological predictions for other SUSY Models

- MSSM models with all sfermions heavy (~ 10 TeV)
  ==> Split SUSY, Focus point

From fits to mass and cross section measurements (similar to Gray et al. and Desch et al.)
and including a chargino threshold scan
==> improves substantially the neutralino mass determination, hence the
    DM relic density determination.
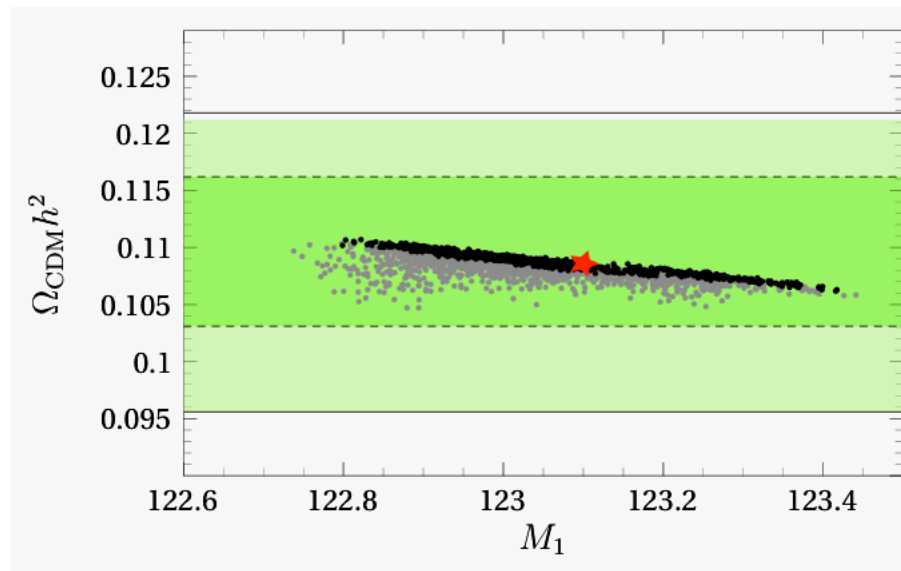
Freitas, M.C.
(preliminary)

Conclusions

Supersymmetry with a light stop and a light SM-like Higgs $\longrightarrow$ $m_{stop} < m_{top}$

opens the window for electroweak baryogenesis $m_h < 120\ GeV$

EWBG and Dark Matter in the MSSM → interesting experimental framework
Strong constraints on CP phases from EDM's *!*
Gaugino and Higssino masses of order of the electroweak scale
and moderate CP-odd Higgs mass preferred

stop-neutralino co-annihilation → challenging for hadron colliders

Tevatron: good prospects in searching for a light stop (for $\Delta_{m_{\tilde{t}\tilde{\chi}}} \geq 50\ GeV$)

LHC: good prospects in searching for light stops

ILC: covers completely stop-LSP co-annihilation region in the MSSM
gives information on nature and composition of light gauginos and stop
→ prediction of Ω_{CDM} with precision comparable to cosmological measurements

• A similar study in the NMSSM **==>** C.Balazs' talk: Cosmology II

Direct Dark Matter detection: nicely complementary to collider searches
becomes more challenging for larger CP phases

Extras

SM Electroweak Baryogenesis fufills the Sakharov conditions

- **Baryon number violation: Anomalous Processes**
- **CP violation: Quark CKM mixing**
- **Non-equilibrium: Possible at the electroweak phase transition.**

Finite Temperature Higgs Potential

$$V_{\text{eff}}^{\text{SM}} = - \, m^2(T)H^2 + E_{\text{SM}} \, T \, H^3 + \lambda(T) \, H^4$$

a cubic term is induced, proportional to the sum of the cube of all light boson particle masses

$$-\sum_b \frac{m_b^3(H)}{12\pi} T \quad \text{with} \quad m_b^2(H) \approx g_{bH}^2 H^2$$
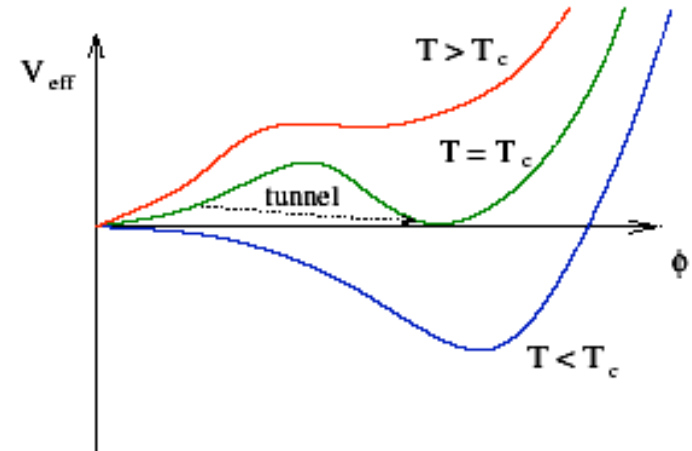
In general: $m_b^2(H, T) = m_b^2 + g_{bH}^2 H^2 + \Pi(T)$ which can spoil the behaviour of the cubic term therefore jeopardizing first order phase transition

In the SM the only contribution comes from the transversal components
of the gauge bosons

$$E_{SM} \approx \frac{2}{3} \left(\frac{2M_W^3 + M_z^3}{\sqrt{2}\pi \, v^3} \right)$$

➡ hence a first order first transition occurs

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

the quartic coupling is proportional to the square of the Higgs mass

$$\frac{v(T_c)}{T_c} > 1 \quad \text{implies} \quad m_H < 40 \text{ GeV} \implies \text{ruled out by LEP!}$$

• **Independent Problem: not enough CP violation**

Electroweak Baryogenesis in the SM is ruled out

Light Stop Effects on Electroweak Baryogenesis

The left- and right-handed stops mix:

$$M_{\tilde{t}}^2 = \begin{bmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{bmatrix}$$

with $X_t = A_t - \dfrac{\mu^*}{\tan\beta}$

and $m_t = h_t H_2 = h_t \sin\beta \; \phi$

Hierarchy in soft SUSY breaking param:

$$m_Q^2 \gg m_U^2 \quad \Longrightarrow \quad \text{best fit to precision electroweak data}$$

The lightest stop $\Longrightarrow$ $\quad m_{\tilde{t}}^2(T=0) \approx m_U^2 + D^2{}_R + m_t^2\left(1 - \dfrac{X_t^2}{m_Q^2}\right)$

has six degrees of freeedom and a coupling of order one to the Higgs

$$V_{eff}^{MSSM} = -m^2(T) \; \phi^2 - T\left[E_{SM}\phi^3 + 2N_c \frac{(m_{\tilde{t}}^2 + \Pi_R(T))^{3/2}}{12\,\pi}\right] + \frac{\lambda(T)}{2}\phi^4$$

No stop contrib. to cubic term unless $\quad m_U^2 + \Pi_R(T) \approx 0$, very light right-h. stop!

$$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3\beta}{2\pi}\left(1 - \frac{X_t^2}{m_Q^2}\right)^{3/2}$$

One Stop should be quite light, lighter than the top and the stop mixing moderate to enhance E_{MSSM}

In the MSSM:
$$E_{MSSM} \approx E_{SM} + \frac{h_t^3 \sin^3 \beta}{2\pi} \left(1 - \frac{X_t^2}{m_Q^2} \right)^{3/2}$$

one stop should be quite light and the stop mixing moderate to enhance E$_{MSSM}$

- For small stop mixing: $E_{MSSM} \approx 9\, E_{SM}$ hence $m_{h_{MSSM}}^{max.} \approx 3 m_{H_{SM}}^{max.} \approx 120\, \text{GeV}$
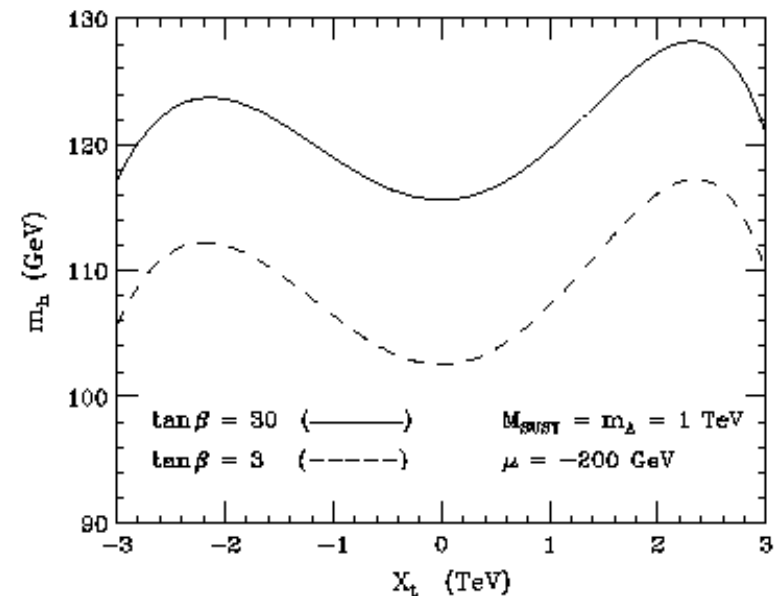
  it can work!!

Present LEP bounds on the SM- like Higgs mass imply extra demands!

$$m_{H_{SM-like}} > 114.6\, \text{GeV}$$

- MSSM lightest Higgs mass depends crucialy on m_t^4, on the stop mixing X$_t$ and logarithmically on the stop masses

$$m_h^2 \approx M_Z^2 \cos^2 2\beta +$$

$$\frac{3 m_t^4}{8\pi^2 v^2} \left[\log\left(\frac{m_{\tilde{t}_l}^2 m_{\tilde{t}_H}^2}{m_t^4} \right) + 2\frac{|X_t|^2}{m_Q^2} \log\left(\frac{m_{\tilde{t}_H}^2}{m_{\tilde{t}_l}^2} \right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4} \right) \right]$$

hence $m_Q \geq 1\, \text{TeV}$ and $X_t \geq 0.3 m_Q$ needed

Computation of the baryon asymmetry

New CP violating phases in the stop and chargino sector are crucial
[for large values of m_Q, only the chargino –neutralino currents are relevant]

- Interaction with varying Higgs background in the bubble wall creates
net neutral and charged Higgsino currents through CP-violating interactions

- Higgsino interactions with plasma creates an excess of left-handed
  anti-baryons (right-handed baryons)

- Left-handed baryon asymmetry is partially converted to lepton
  asymmetry via anomalous processes (weak sphalerons: net B violation)

- Baryon asymmetry diffuses into broken phase and gets frozen there
  since $v(T) / T > 1$

Assuming time relaxation of charge is large (no particle decays)
1. compute CP-violating currents
2. solve diffusion equations describing the above processes

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : $\tan\beta, \ m_A$

Chargino sector : mass param. $\mu, \ M_2$ with physical phase $\arg(\mu^* M_2)$

currents proportional to $\sin(\ \arg(\mu^* M_2)\ )$, with resonant behavior for $M_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $\quad \varepsilon_{ij} H_i \ \partial_\mu H_j = v^2(T) \ \partial_\mu \beta$

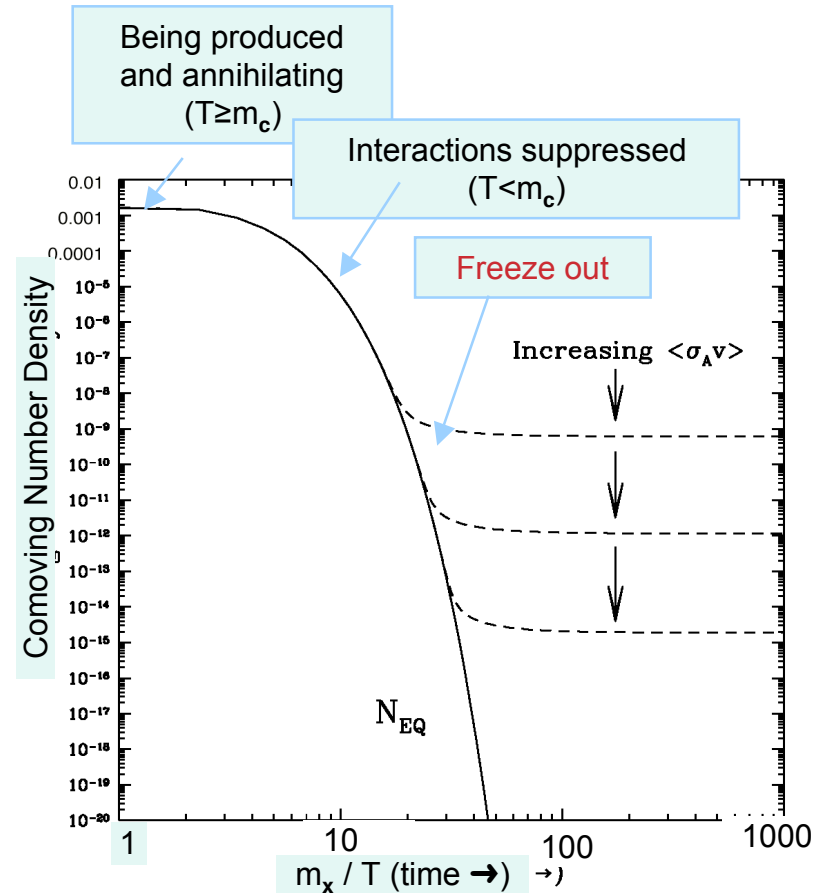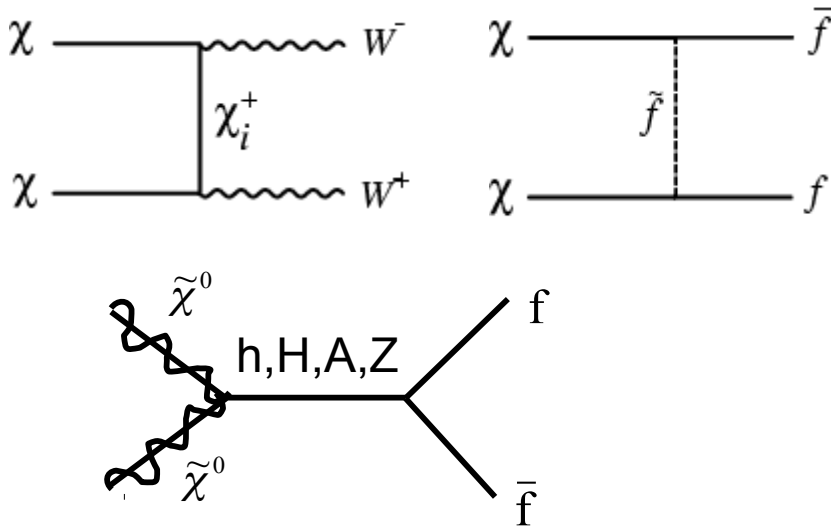suppressed for large $\quad m_A$ and $\tan\beta$ due to $\Delta\beta$ dependence

★ $\quad H_1 \partial_\mu H_2 + H_2 \partial_\mu H_1 = v^2 \cos(2\beta) \ \partial_\mu \beta + v \ \partial_\mu v \sin(2\beta)$

unsuppressed for large CP-odd masses

Dark Matter in the MSSM

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

if m_x and σ_A determined by electroweak physics, then $\Omega_x \sim 0.3$

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

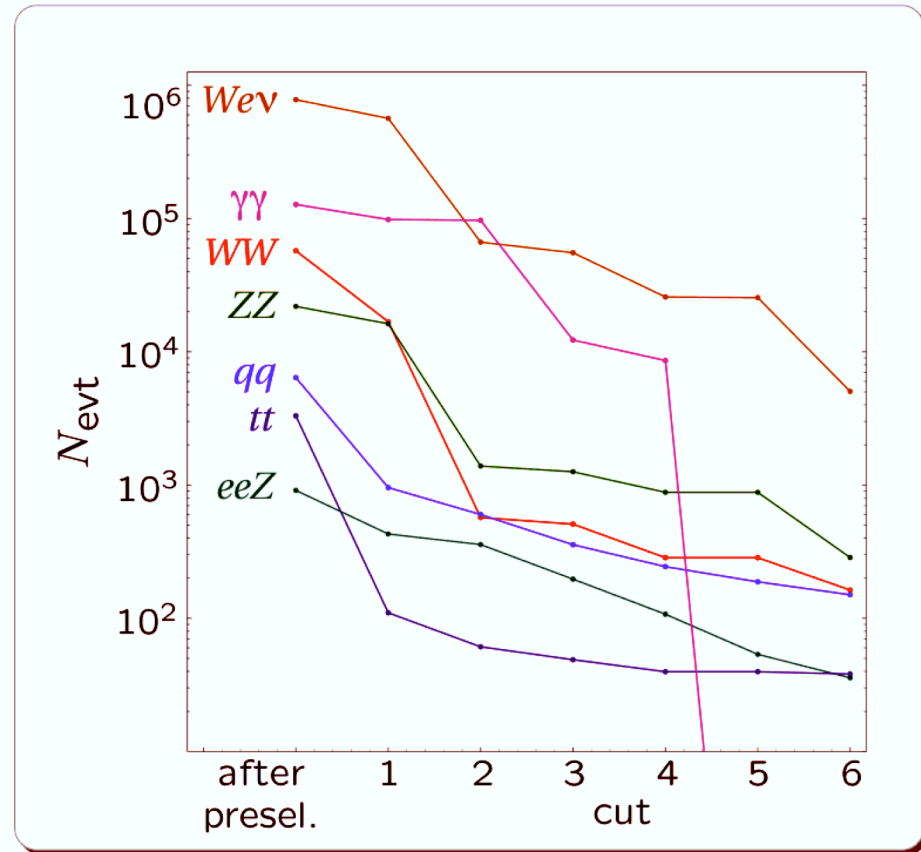# Reduction of background

Preselection:

1. $4 < N_{chargedtracks} < 50$
2. $p_t > 5$ GeV
3. $|\cos\theta_{Thrust} < 0.8|$
4. $|p_{long,tot}/p_{tot}| < 0.9$
5. $E_{vis} < 0.75\sqrt{s}$
6. $m_{inv} < 200$ GeV

Selection:

1. $N_{jets} = 2$
   (Durham $y_{cut} = 0.003$)
2. $E_{vis} < 0.4\sqrt{s}$
3. $\cos\phi_{aco} > -0.9$
4. $|\cos\theta_{Thrust} < 0.7|$
5. $p_t > 12$ GeV
6. 3500 GeV$^2 < m_{inv}^2 < 8000$ GeV^2, c-tagging

Analysis results

Largest remaining background from $e^+e^- \to W^\pm e^\mp \nu$, about 5000 events for $\mathcal{L} = 500$ fb^{-1}

$\to$ Good theoretical control

Signal rates after selection
for $\Delta m \sim 10\ldots 50$ GeV and $m_{\tilde{t}_1} \lesssim 150$ GeV:
5000...20000 events

$\to$ Signal same order as remaining background

Neutralino Elastic Scattering Cross Section -- CDMS Reach

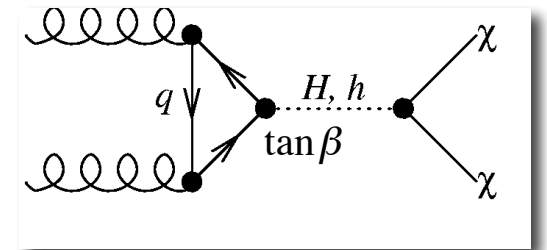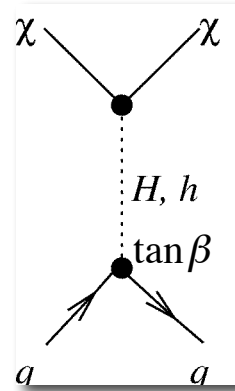Current and near future experiments sensitive only to spin-independent scattering

$$\sigma_{SI} \leq 10^{-8}\, pb$$

==> dominated by t-channel exchange of
H and h, coupling to strange quarks
and to gluons via bottom loops

$\tan\beta$ enhanced couplings

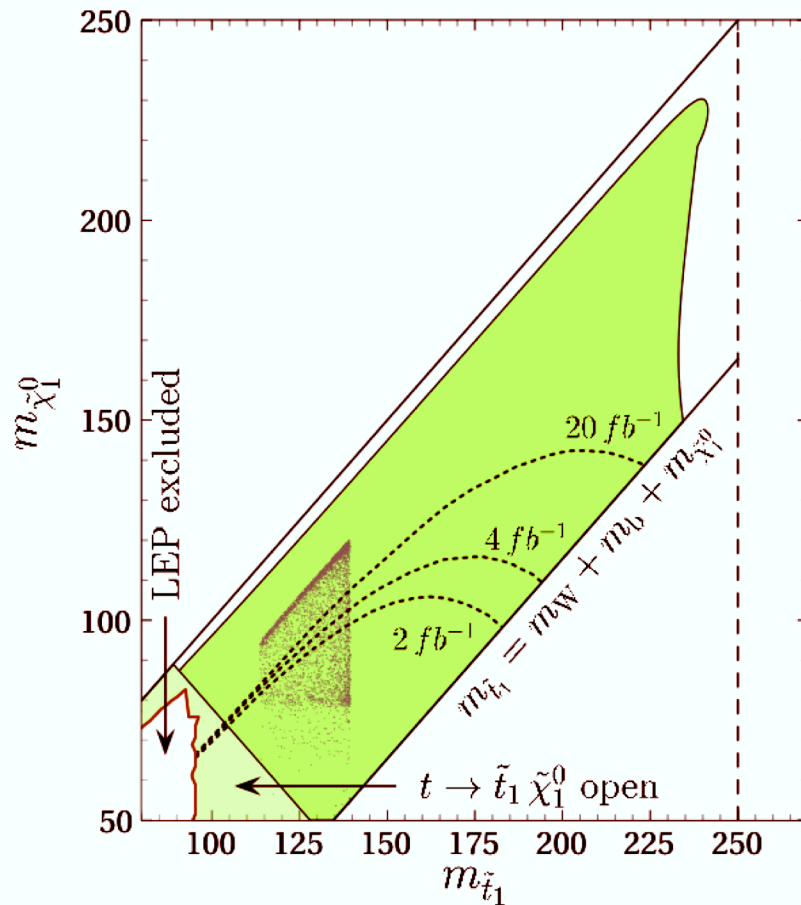Bino-like Neutralino example:

$$\sigma_{SI} \approx 4 \times 10^{-7} \left(\frac{N_{11}^2}{0.9}\right)\left(\frac{N_{13}^2}{0.1}\right)\left(\frac{300\text{GeV}}{m_A}\right)^4\left(\frac{\tan\beta}{50}\right)^2$$

If m_A and $\tan\beta$ are within Tevatron reach, a substantial elastic cross section ,
at the reach of CDMS , is expected

Light Stop Discovery reach at the ILC

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

MC, Finch, Freitas, Milstene, Nowak, Sopczak '05

Measurement of SUSY parameters for DM density computation

Sample parameter point:
consistent with EDM's, EWB and
Higgs mass bound

$M_1 = 118.8$ GeV

$M_2 = 225$ GeV

$|\mu| = 225$ GeV

$\phi_\mu = 0.2$

$M_{u3}^2 = -99^2$ GeV^2

$M_{q3} = 4330$ GeV

$A_t = -1100$ GeV

$\tan\beta = 5$

1st and 2nd generation sfermions = 10 TeV

$m_{\tilde{\chi}_1^0} = 106.6$ GeV $\qquad m_{\tilde{t}_1} = 122.5$ GeV $\qquad \cos\theta_{\tilde{t}} = 0.01 \qquad \Omega_{\text{CDM}}h^2 \approx 0.108$
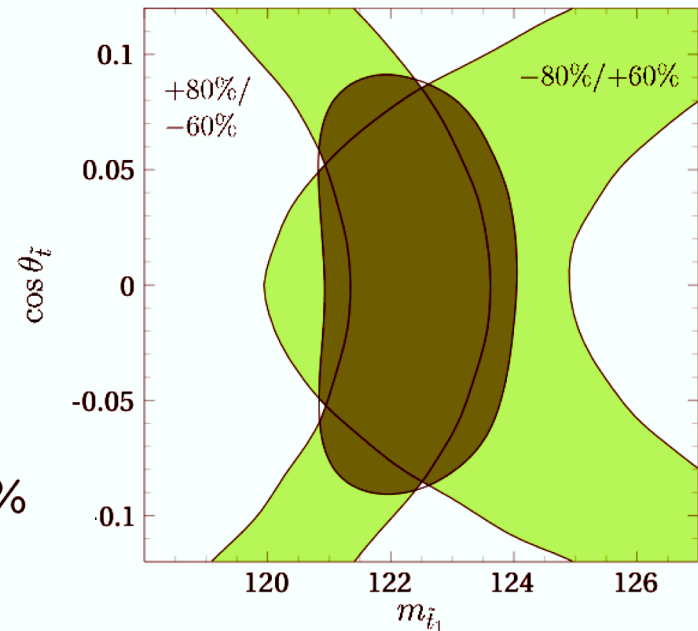
-- Stop mass and mixing angles

Consider stop production cross sections
with two different polarizations (250 fb^{-1} each)

$$P(e^-)/P(e^+) = -80\%/+60\%$$
$$+80\%/-60\%$$

Systematic Errors

- $\delta m_{\tilde{\chi}_1^0} = 0.1$ GeV
- $\delta P/P = 0.5\%$
- backgr. $\delta B/B = 0.3\%$
- $\delta\mathcal{L}/\mathcal{L} = 5\times 10^{-4}$
- $\tilde{t}_1$ hadroniz./fragment.: $\sim 1\%$
- charm tagging/fragm.: 0.5%

- detector calibration: 0.5%
- beamstrahlung

Result: $m_{\tilde{t}_1} = 122.5 \pm 1.0$ GeV

$|\cos\theta_{\tilde{t}}| < 0.074$

$\Rightarrow |\sin\theta_{\tilde{t}}| > 0.9972$

Relic Density and Electroweak Baryogenesis in the NMSSM

Region of neutralino masses selected to be consistent with perturbativity constraints.
Z-boson and Higgs boson contributions shown to guide the eye.

Scattered points ==> consistent with EW Baryogenesis

Z-width constraint

Ωh^2

m_N

Menon, Morrissey, Wagner '04