The Baryogenesis Window in the MSSM

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International Linear Collider Workshop 2008

Cosmological Connections

University of Illinois at Chicago, November 18, 2008

This talk 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, 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, A. Sopczak, Phys.Rev.D72 (2005)
- A Freitas, Phys.Rev .D74 (2006).
- G. Nardini, M. Quiros and C. Wagner , JHEP 0810, 062 (2008) and arXiv:0809.3760
- A. Freitas and C.E. M. Wagner, arXiv:0808.2298

Outline

- Cosmology as Motivation for Physics BSM

  -- the Baryon Asymmetry -- Dark Matter

- Electroweak Baryogenesis in the MSSM

  -- Necessary requirements for EWBG

  -- Constraints on the Supersymmetry spectrum

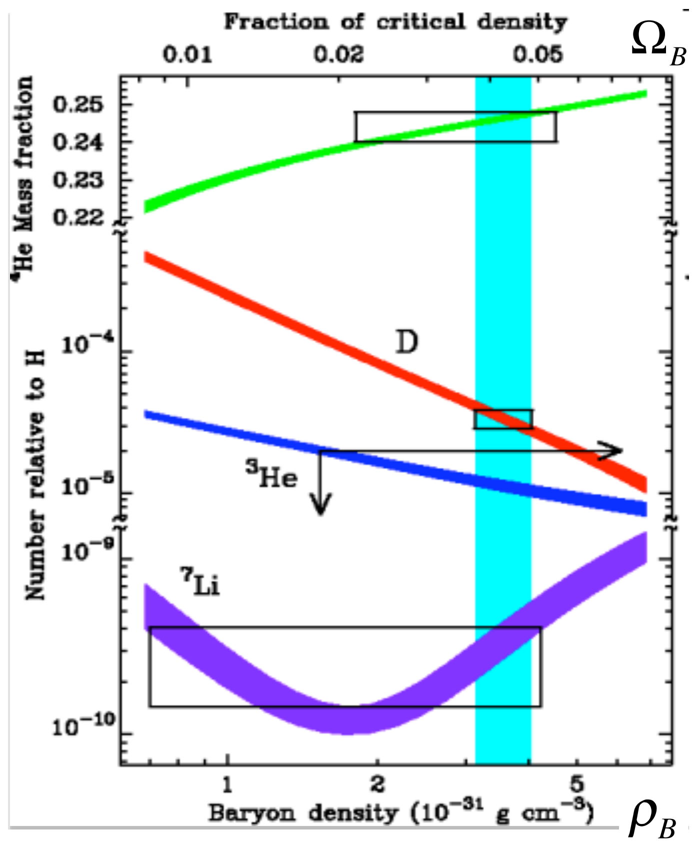
  -- The connection between Dark matter and EWBG

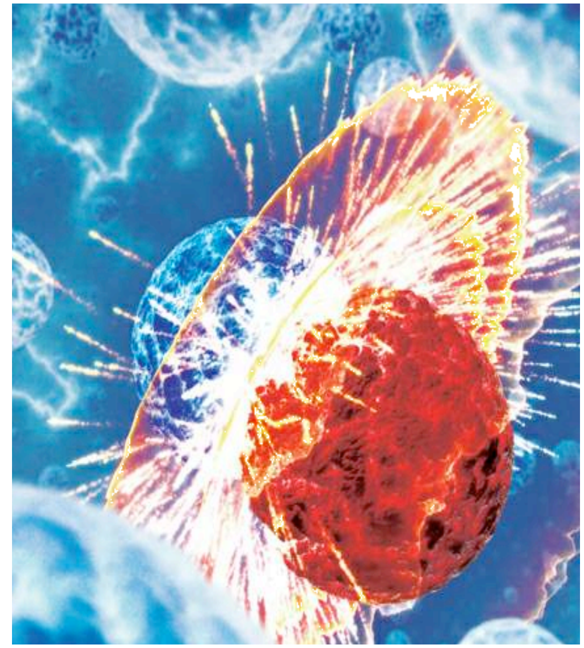
- Experimental Probes of EWBG in the MSSM

The Mystery of the Matter-Antimatter Asymmetry

- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis

$$\boxed{\eta = n_B / n_\gamma \approx 6.10^{-10}}$$





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

- Baryons, antibaryons and photons equally abundant in the early universe
- To remove preferentially antimatter, the CP symmetry relating B to $\overline{\mathrm{B}}$ must be violated
- No net Baryon number if B conserved at all times

What generated the small observed baryon--antibaryon asymmetry ?

Baryogenesis at the Weak Scale:

Sakharov's Conditions must be fulfilled for baryogenesis

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

All three requirements fulfilled in the SM

Baryon Number in the Standard Model:

conserved at classical level but violated at quantum level : $\Delta B = \Delta L$

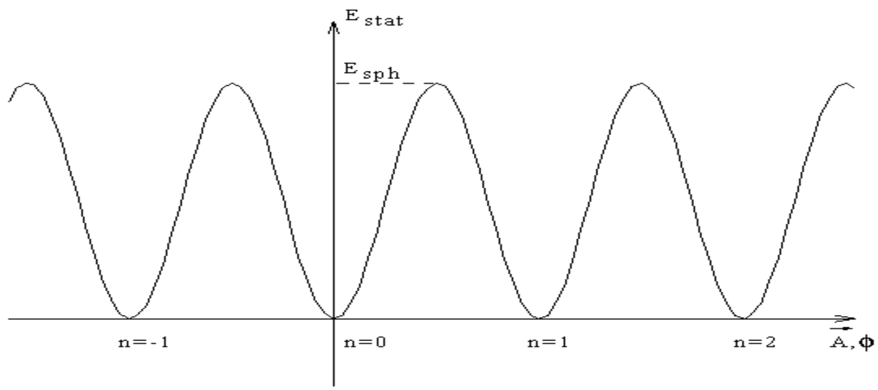
Baryon Number Violation at finite Temperature

- *At T = 0, $\cancel{B}$ 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*

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T}) / \mathrm{T}) \qquad \mathrm{E}_{\mathrm{sph}} \cong 8\,\pi\, \mathrm{v(T)} / \mathrm{g}$$

Sphaleron: 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

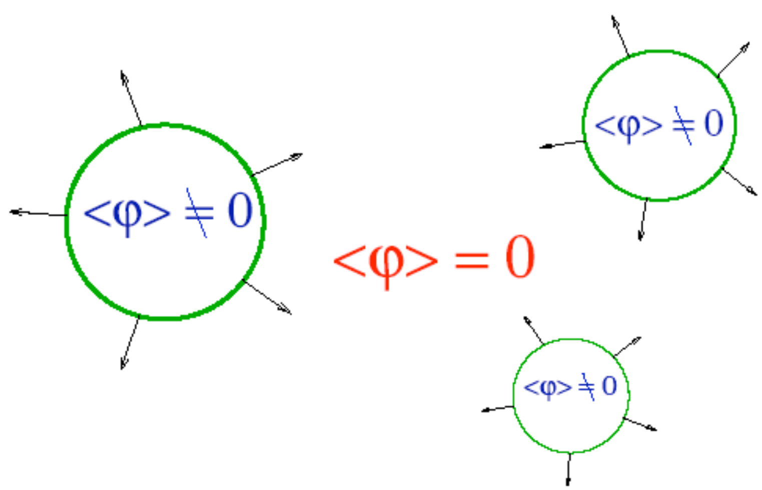


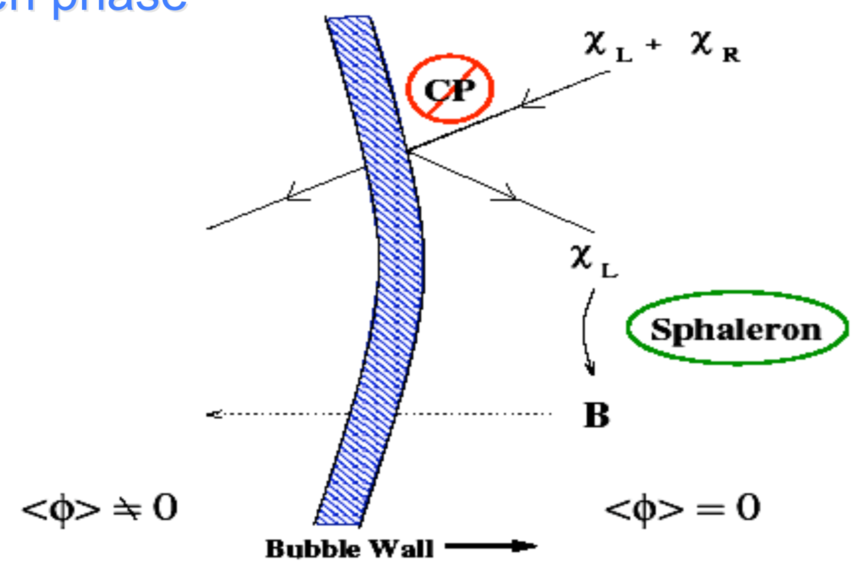
Klinkhammer and Manton'84; Arnold and Mc Lerran'88, Khlebnikov and Shaposhnikov '88

Baryon Number Generation at the Electroweak Phase Transition

Kuzmin, Rubakov and Shaposhnikov, ’85-’87 Cohen, Kaplan and Nelson ’93 Riotto, Trodden’99
M.C, Quiros, Riotto, Vilja, Wagner, Moreno,Seco’ 97-03 Cline, Joyce, Kainulainen, 00
Konstantin, Huber, Schmidt, Prokopec ‘ 00-06 Cirigliano, Profumo, Ramsey-Musolf ‘05-’06

- 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





Baryon number generated by reactions in and around the bubble walls

Baryon Asymmetry Preservation

if $n_{\mathbf{B}} = 0$ at T > Tc, independently of the source of baryon asymmetry

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

$$\Gamma_{\Delta B \neq 0} \ll H \Rightarrow \not{B} \text{ processes frozen}$$

$$\begin{aligned} &\Gamma_{\Delta B \neq 0} \cong \beta_0\ \mathrm{T} \exp(-\mathrm{E_{sph}}(\mathrm{T})/\mathrm{T}) \\ &H \cong g_*^{1/2}\ T^2 \big/ M_{Pl} \end{aligned} \quad \Rightarrow \frac{\mathrm{M_{Pl}}}{\mathrm{T}}\ \exp(-\mathrm{E_{sph}}(\mathrm{T})/\mathrm{T}) \ll 1$$

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

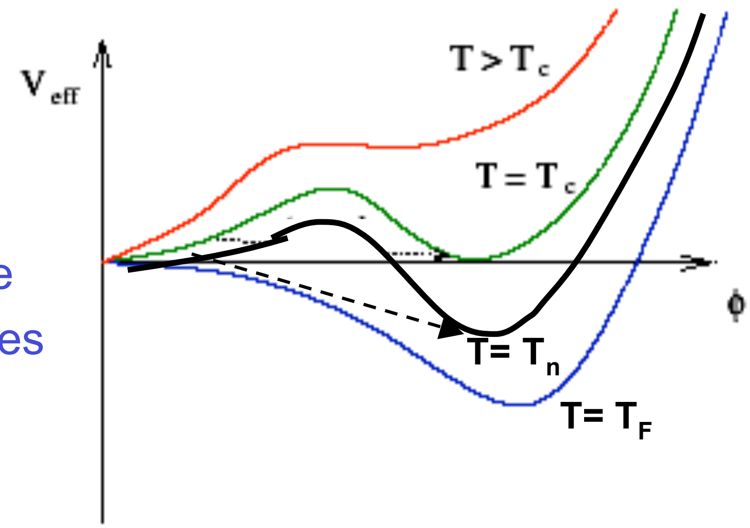
$$\mathrm{v}(T_c)/T_c > 1$$

Shaposhnikov '86-'88

Baryon number violating processes
out of equilibrium in the broken phase

Finite Temperature Higgs Potential

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



- D term is responsible for the phenomenon of symmetry restoration
- E term receives contributions proportional to the sum of the cube of all light boson particle masses

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

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

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

==> Perturbative result

Lattice:
no evidence of 1st order PT

Electroweak Baryogenesis in the SM is ruled out

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

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

- Electroweak Baryogenesis is a cool idea

… but, for it to work demands Physics Beyond the Standard Model

The SM of particle physics works amazingly well

But COSMOLOGY gives the first unambiguous evidence for New Physics

Dark Matter (or a modification of gravity ?)

The Dark Matter $\longleftrightarrow$ Electroweak Scale Connection

- The hierarchy problem associated to EWSB can be solved by adding new particles at the EW scale

==> to be in agreement with precision measurement constraints, need to invoke a new discrete symmetry so that all interactions require pairs of new particles.

Lightest New Particle is stable - A stable interacting Massive Particle (WIMP)

- Thermal DM relic density is nicely compatible with a WIMP at the weak scale

Supersymmetry provides a BSM scenario with the above capabilities

Low energy supersymmetry → some SUSY particles at the TeV Scale

◈ SUSY is well motivated on purely particle physics grounds

- Stabilization of the electroweak scale
- Radiative breaking of the EW symmetry
- Unification of Gauge Couplings

◈ SUSY and Cosmology :

Dark Matter

SUSY with R-parity discrete symmetry conserved → $R_P = (-1)^{3B+L+2S}$

naturally provides a neutral stable DM candidate: LSP → $\tilde{\chi}^0$

The LSP annihilation cross section is typically suppressed
for most regions of SUSY spectrum → too much relic density

Cosmology excludes many SUSY models!

Baryon Asymmetry

- New CP violating Phases can arise when SUSY is softly broken
- Electroweak baryogenesis possible in Minimal SUSY SM extensions

Can SUSY explain both Mysteries of Matter?

Preservation of the Baryon Asymmetry

Requires new bosonic degrees of freedom
with strong coupling to the Higgs

In SUSY particles and sparticles share the same couplings to the Higgs
Two Superpartners of the top quark (one for each chirality) couple strongly to the Higgs, with Yukawa couplings of order one (same as the top quark)

SUSY provides a natural framework for this scenario
through the superpartner of the top quark

Huet, Nelson ‘91; Giudice ‘91;
Espinosa Quiros, Zwirner ‘93
M.C. Quiros, Wagner, ‘96-’ 98

Light Stop Effects on Electroweak Baryogenesis

Each stop has six degrees of freedom and a coupling of order one to the Higgs

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

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

and $\mathrm{m_t} = h_t\, \mathrm{H_2} = h_t \sin\beta\ \phi$

The lightest stop

$\mathrm{m_Q^2} >> \mathrm{m_U^2}$ ⟹ EW data

$$\Longrightarrow\quad \mathrm{m}_{\tilde{\mathrm{t}}}^2(\mathrm{T}=0) \approx \mathrm{m_U^2} + \mathrm{D^2{}_R} + \mathrm{m_t^2}\left(1 - \frac{X_t^2}{\mathrm{m_Q^2}}\right)$$

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

EW Baryogenesis demands $\mathrm{m_U^2} + \Pi_R(T) \approx 0$ ==> $m_U^2 < 0$, very light right-h. stop!

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

one stop should be quite light and the stop mixing moderate to enhance E_{MSSM}

$$\rightarrow\ \mathrm{E_{MSSM}} \approx 9\ \mathrm{E_{SM}}\quad \text{hence}\quad \mathrm{m_{h_{MSSM}}^{max.}} \approx 3\mathrm{m_{H_{SM}}^{max.}} \approx 120\ \mathrm{GeV}$$ **it can work!!**

The effective theory of the Light Stop Scenario

- In the MSSM at tree level: $m_h < M_Z$, hence relatively heavy stops necessary to raise m_h above the LEP limit $m_{H_{SM-like}} > 114.6\,\mathrm{GeV}$
- One light stop is necessary for the strength of the EWPT, hence the other stop should be heavier than about 10 TeV, after h.o. loop corrections.

- All other squarks and sleptons should be heavy, providing cancellation of FCNC effects and of one loop contributions to EDM's.
- Heavy non-SM like Higgs bosons also help raise the Higgs mass & open the space for larger CP violating phases compatible with EDM bounds

- **Heavy third generation scalars render it necessary to resum large log contributions for reliable Higgs mass calculations**

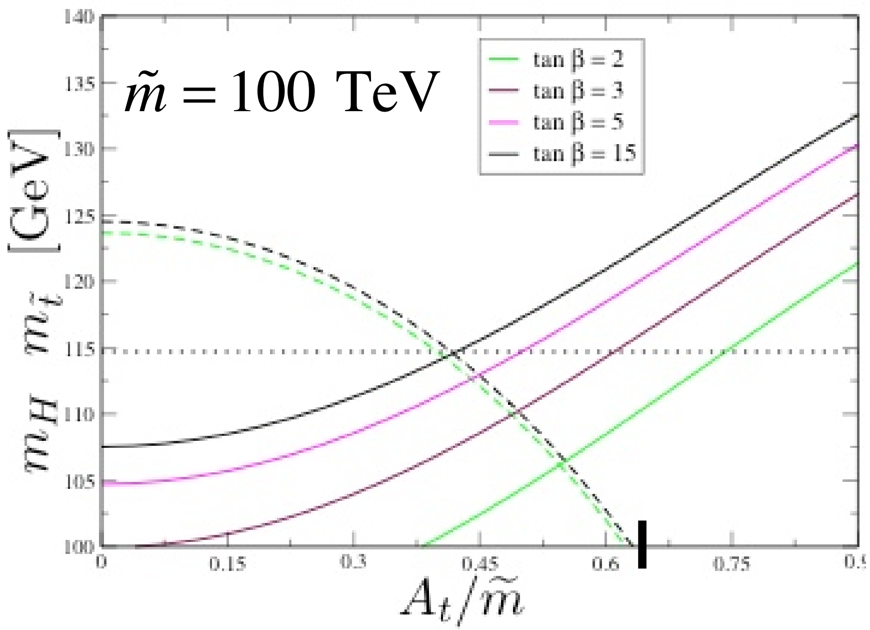
  ==> study the one-loop RG improved effective theory below the heavy scalar mass scale 10 TeV or larger

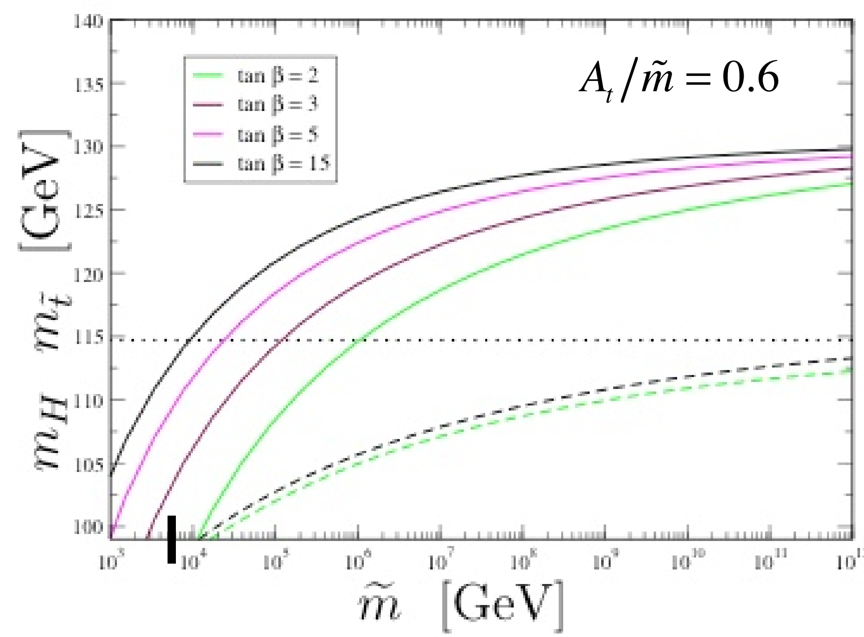
Numerical Results for the Higgs and Stop masses compatible with EWBG

M.C., Nardini, Quiros Wagner; ArXiv.0806.4297

- Light SM Higgs, RH Stop, gauginos and Higgsinos
- All rest of the particles decouple at scale $\tilde{m}$

$$m_U^2 = -(100\text{ GeV})^2$$



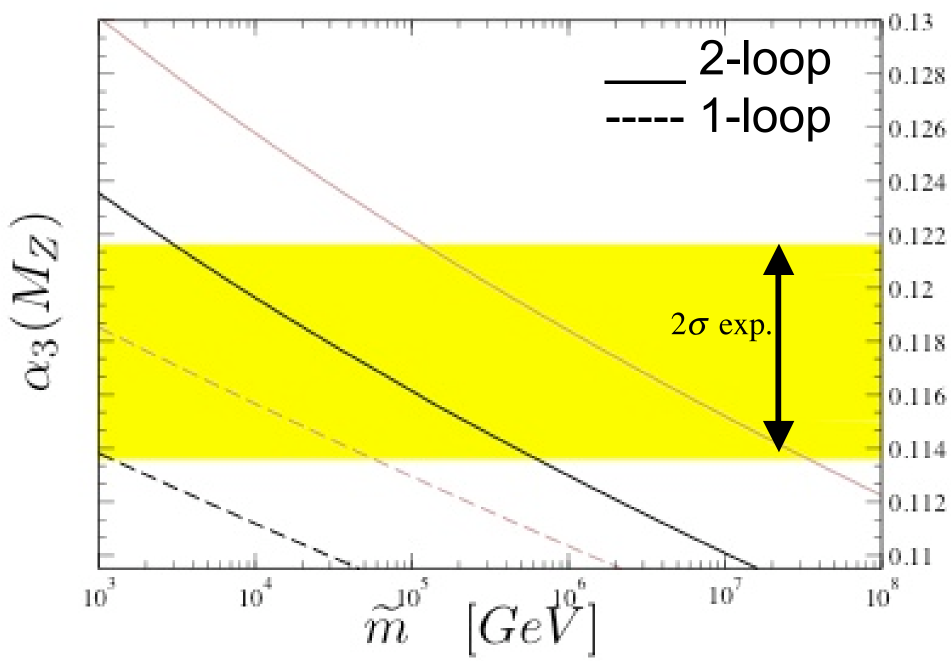


Gauge Coupling Unification: impact on the Higgs mass

Consider the MSSM above $\tilde{m}$ and the effective theory with light r.h. stop, gauginos and higgsinos below $\tilde{m}$

Values of $\tilde{m}$ above the weak scale lower the prediction for $\alpha_3(M_Z)$
==> better agreement with exp.

At two loop level, large values of $\tilde{m}$ for weak scale gauginos/higgsinos



Black: all gauginos at EW scale
Grey: standard gaugino mass unification relation M_3=500 GeV]

Impact of $\tilde{m}$ on the Higgs mass

3 TeV < $\tilde{m}$ < 600 TeV (light gluinos)

100 TeV < $\tilde{m}$ < 3×10^4 TeV (standard gaugino unif.)

$$m_h^{\max} \leq 125\ (130)\ \text{GeV}$$ in EWBG

Cosmological Scenarios

- A strong enough phase transition demands $m_U^2 < 0$, hence at T=0
  ==> two minima of the scalar potential $\langle V_H \rangle$ and $\langle V_U \rangle$
  where $\phi = \langle H \rangle$ and $\mathrm{U} = \langle \tilde{\mathrm{t}}_{\mathrm{R}} \rangle$ at $(\phi_0, 0)$ and $(0, \mathrm{U}_0)$
- At finite T these minima evolve from the vev's $\phi(\mathrm{T})$ and $\mathrm{U}(\mathrm{T})$ and the cosmological evolution depends on the nucleation temperatures T_H^n, T_u^n and T_H^F, the temperature at which the EWPT ends
- Compute T=0 effective potential, improved by RG evolution with the large log resummation,
  and the thermal contribution at two loop order for $V(\phi, U, T)$

Four Possible Cosmological Scenarios

Instability region: $T_U^n > T_H^n$ and $\langle V_H \rangle > \langle V_U \rangle$ **unrealistic**

Two step PT region: $T_U^n > T_H^n$ and $\langle V_H \rangle < \langle V_U \rangle$ **unrealistic**

color breaking to EW breaking minima transition never occurs

Stability Region: $T_U^n < T_H^n$ and $\langle V_H \rangle < \langle V_U \rangle$ **usual EWPT** but …

due to present Higgs mass bounds, EWPT is too weak to allow for EWBG

Metastability Region: $T_U^n < T_H^F$ and $\langle V_H \rangle > \langle V_U \rangle$ **viable scenario**

EWPT occurs first and although color breaking minima is deeper, the decay rate

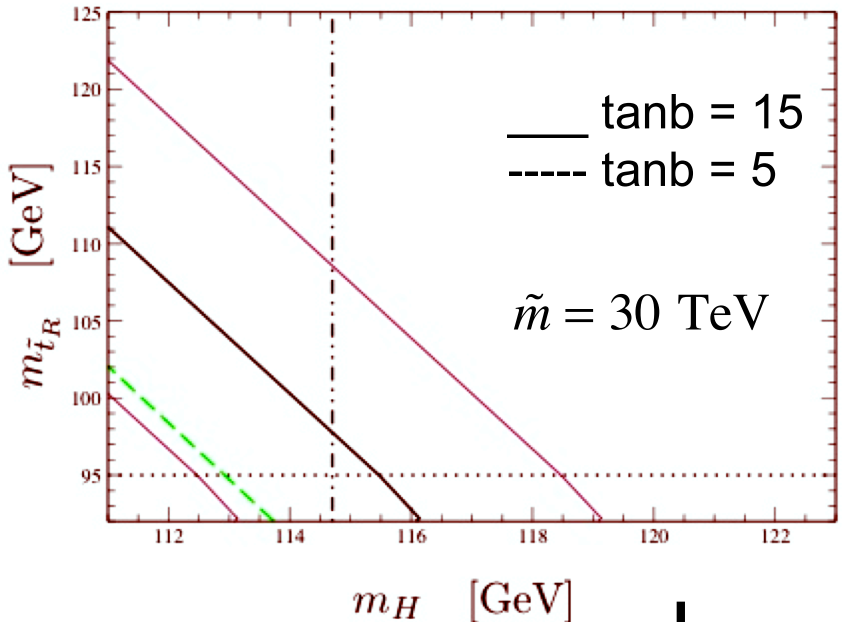
from EW to color breaking minima is slower than expansion rate of the Universe

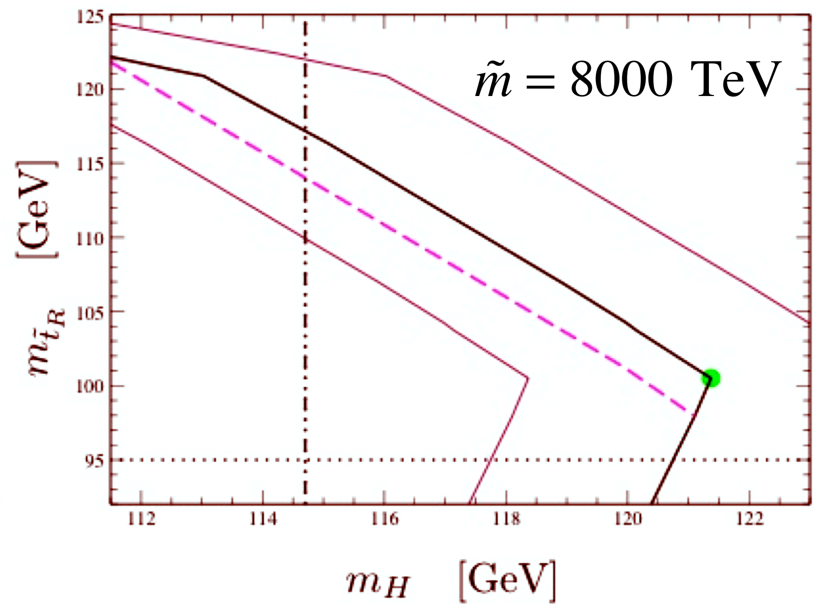
Window for EWBG in the MSSM

Baryogenesis preservation: $\phi(T_H^n)/T_H^n > 1$

Stability/Metastability condition: $T_U^n < T_H^F$

Since $\langle V_H \rangle > \langle V_U \rangle$ one needs to demand no tunneling to the color breaking minimum to assure metastability

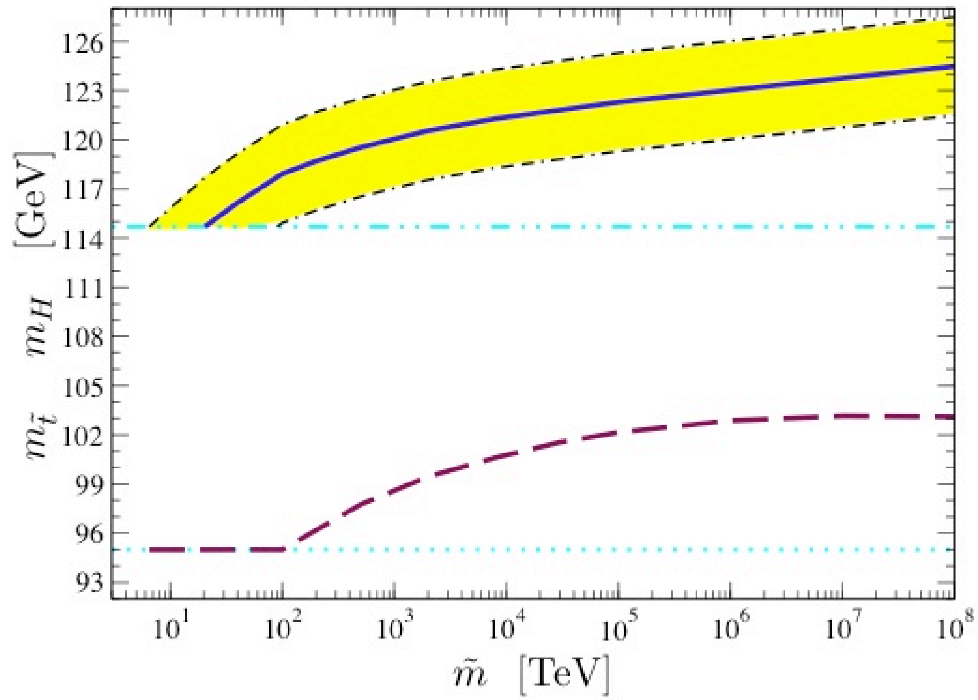




$m_h^{\max} < 125$ GeV $\quad m_{\tilde{t}}^{\max} < 125$ GeV

Metastable Vacuum

Maximum value of the Higgs mass as a function of the decoupling scale



Maximum $\tan\beta = 15$

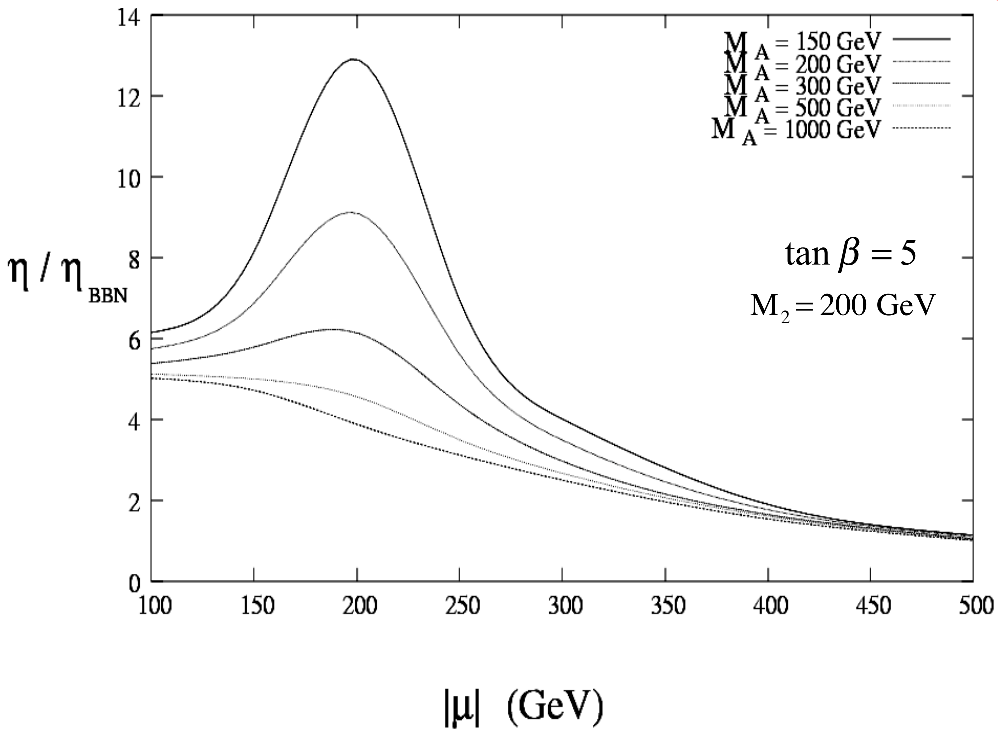
Maximum $|m_U^2|$

Minimum value of the decoupling scale consistent with EWBG

$$\tilde{m} > 6.5\ \text{TeV}$$

Baryon Asymmetry Dependence on the Chargino Mass Parameters

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



- 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

Dependence of the Baryon asymmetry on SUSY parameters

Higgs sector : $\tan\beta,\ \mathrm{m_A}$
Chargino sector : mass param. $\mu,\ \mathrm{M}_2$ with physical phase $\arg(\mu^* M_2)$

Currents prop. to sin $\arg(\mu^* M_2)$ with resonant behavior for $\mathrm{M}_2 \approx |\mu|$

Total Baryon asymmetry depends on two contributions proportional to:

★ $\varepsilon_{ij} \mathrm{H}_i\, \partial_\mu\, \mathrm{H}_\mathrm{j} = \mathrm{v}^2(\mathrm{T})\, \partial_\mu \beta$

suppressed for large $\mathrm{m_A}$ and $\tan\beta$ due to $\Delta\beta$ dependence

★ $\mathrm{H}_1 \partial_\mu \mathrm{H}_2 + \mathrm{H}_2 \partial_\mu \mathrm{H}_1 = \mathrm{v}^2 \cos(2\beta)\, \partial_\mu \beta + \mathrm{v}\, \partial_\mu \mathrm{v} \sin(2\beta)$

unsuppressed for large CP-odd masses

Dark Matter and Electroweak Baryogenesis in the MSSM

EWBG conditions + Higgs mass bounds and EDM bounds on CP violation

- strong constraints on stop sector
  - -- Lightest stop lighter that the top quark
  - -- Moderate Left-Right mixing
- Other squarks heavy (> 10 TeV)
- Higgs mass m_A also heavy
- light charginos

  $\mu, M_2 \leq 500\,\mathrm{GeV}$
- sizeable CP violating phases

  $\sin(\arg(\mu\, M_2)) \geq 0.1$
- Higgs parameter

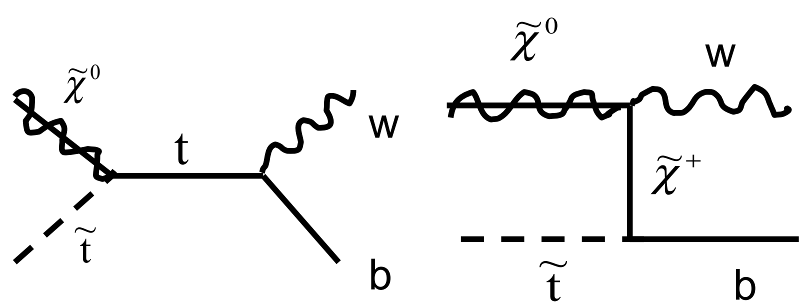
  $5 \leq \tan\beta \leq 15$

Implications for Dark Matter:

- LSP lighter that the stop

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

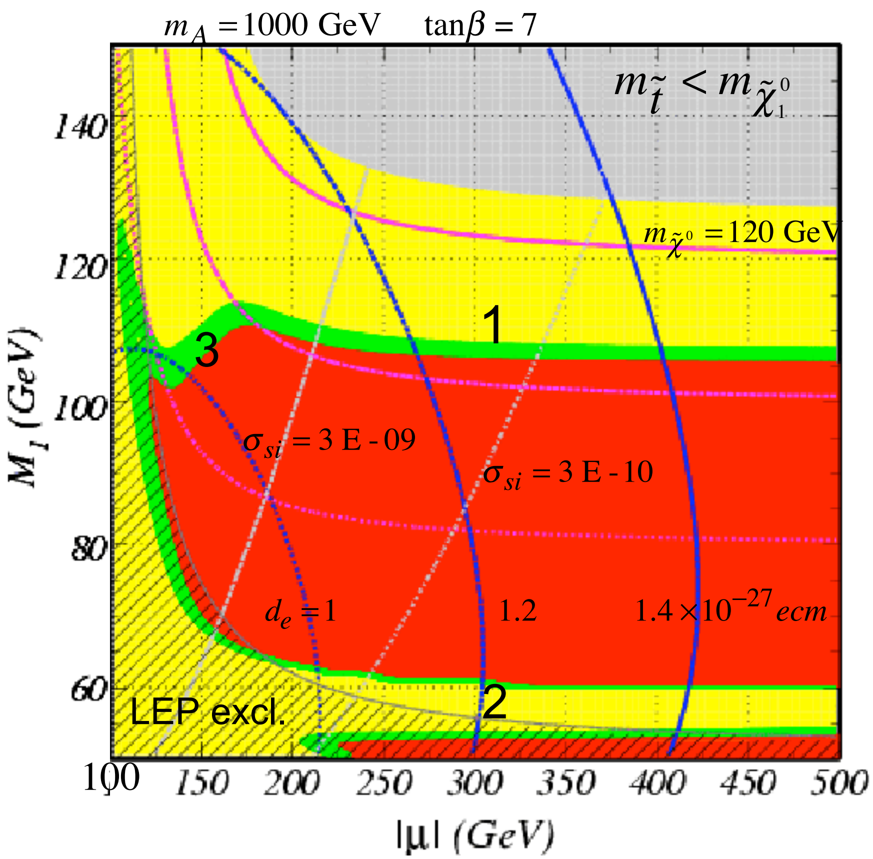
  If they are close in mass, co-annihilation greatly reduces the relic density.



Opening the window for EWBG facilitates agreement with DM relic density

- CP phases: moderately affects σ_A through the mass and couplings of the LSP

Relic Density Computation in Scenarios with EWBG



Balazs, MC, Menon, Morrissey, Wagner

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

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

new WMAP $\Rightarrow$ $0.107 < \Omega_{CDM} h^2 < 0.122$

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

2. s-channel neutralino annihilation via lightest CP-even Higgs $m_{\tilde{\chi}^0} \cong m_h/2$

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 μ phase

Some differences in the Higgs resonance region due to variations in the imaginary and real parts of the Neutralino-Higgs couplings.

The LSP-top-stop coupling varies slightly with the phase; main effect due to variation of the LSP mass which affects the co-annihilation contribution.

Collider Tests of Electroweak Baryogenesis and Dark Matter

⁕ Higgs searches

Higgs properties: SM-like couplings to W and Z (agent of EWSB) and $m_h < 120$ GeV

- $h \to b\bar{b}$ channel at the Tevatron :

may achieve a 3 sigma evidence with 6 fb^{-1} of data

- $h \to \tau^+\tau^-$ and $h \to \gamma\gamma$ channels at the LHC :

a definitive test of this scenario with the first 10 fb^{-1} of well understood data

⁕ Stop searches:

Light Stop models with Neutralino LSP Dark Matter ⟶ $\not{E}_T$ signal

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

For small Stop-Neutralino mass difference: co-annihilation region

⟶ excellent agreement with WMAP data

Very challenging region for stop searches at hadron colliders

Searches for a light stop at the Tevatron

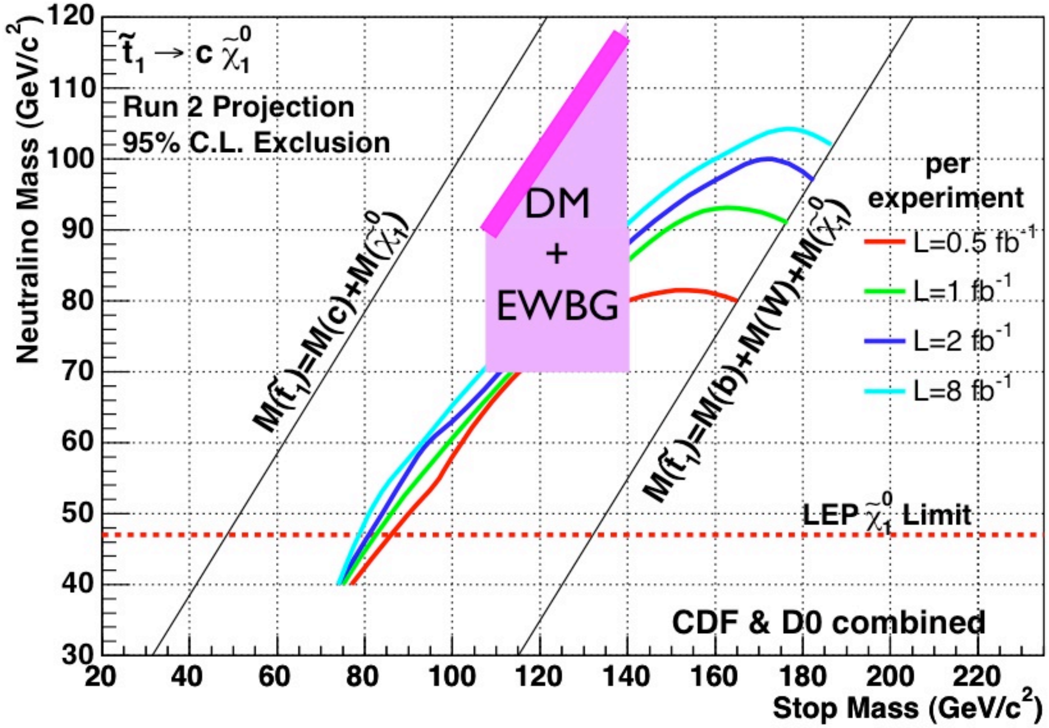
compatible with DM and Baryogenesis

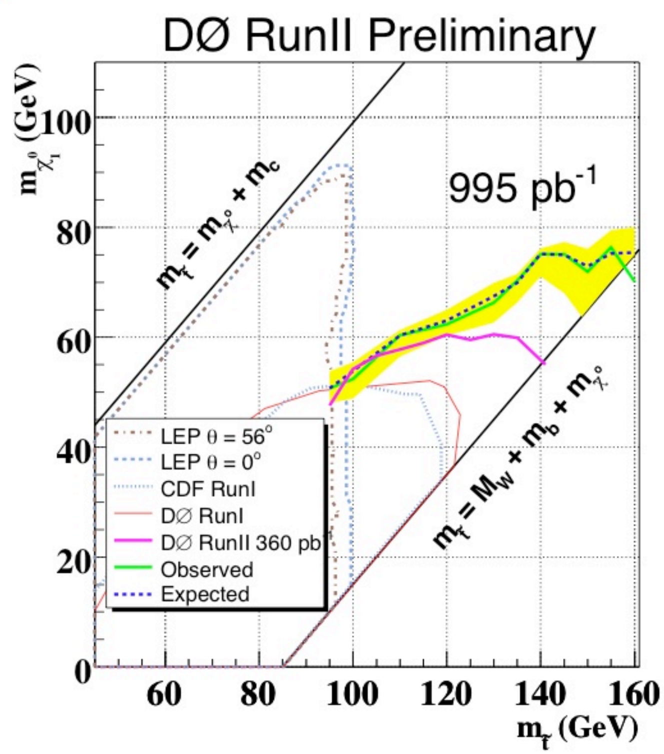
Light-stop models with neutralino dark matter → $\not{E}_T$ signal

→ dominant decay $\boxed{\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0}$

For small Stop-Neutralino mass difference: co-annihilation region $\Delta_{m_{\tilde{t}\tilde{\chi}}} < 30$ GeV

→ excellent agreement with WMAP data





Very Challenging for Hadron colliders

Light Stops at the LHC

- Same-sign tops in gluino decays

Kraml, Raklev '06

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

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

Stops with masses ~ 120 – 160 GeV at LHC

reach if gluino masses up to ~ 900 GeV

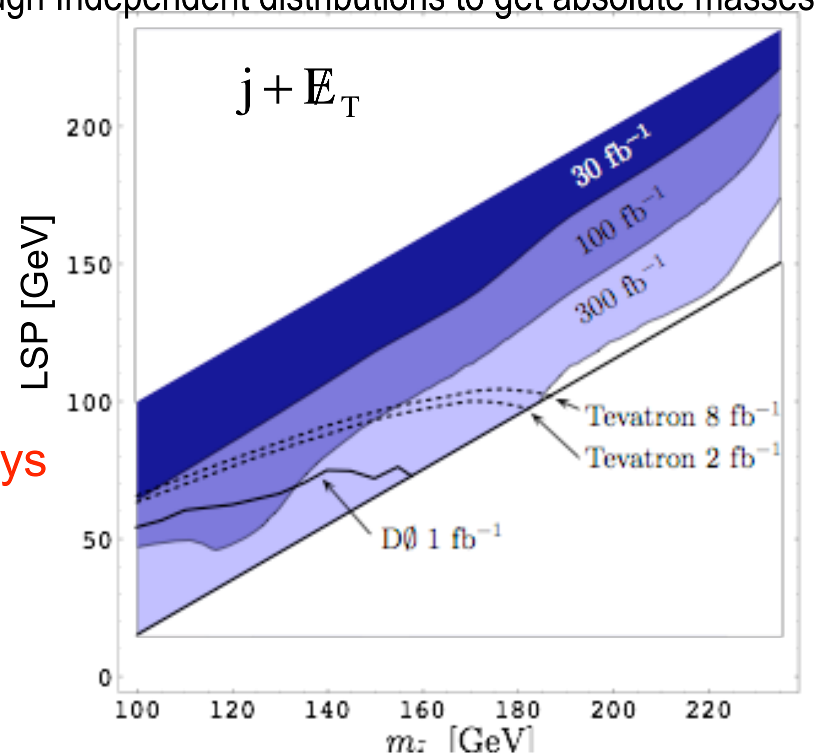
Mass measurements from distributions, but not enough Independent distributions to get absolute masses

- Stop pair production in association with a hard photon or a hard jet

Signal: Photon or Jet + Missing Energy

In co-annihilation region:
minimal activity associated with stop decays

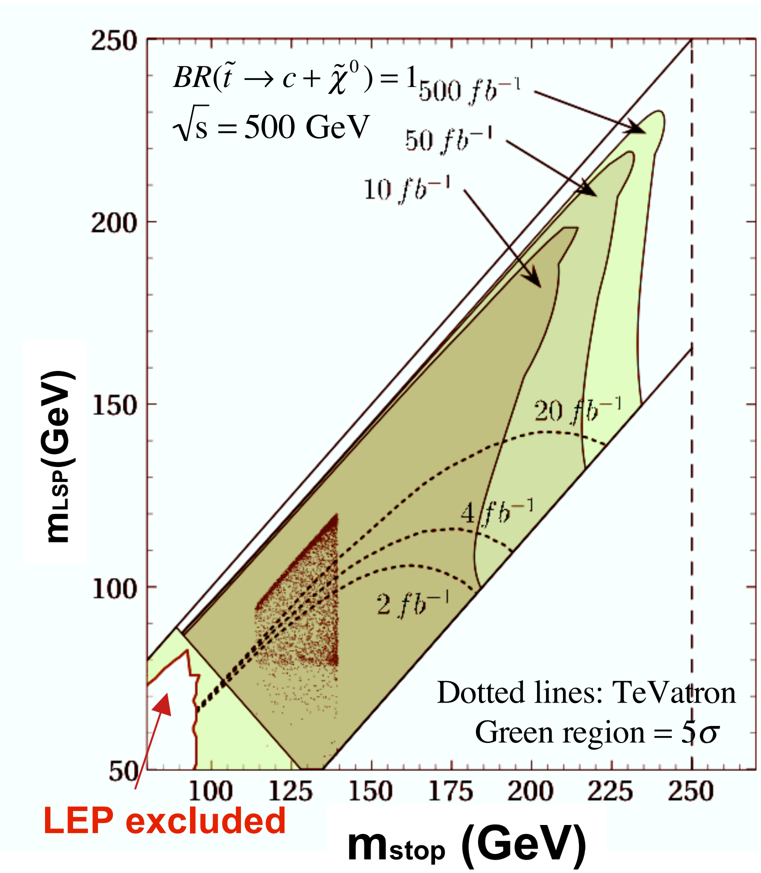
MC, Freitas, Wagner, arXiv0808.2298



The Power of a Lepton Collider: Cosmological Implications

(circa 2025)

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



Precise measurement of SUSY parameters

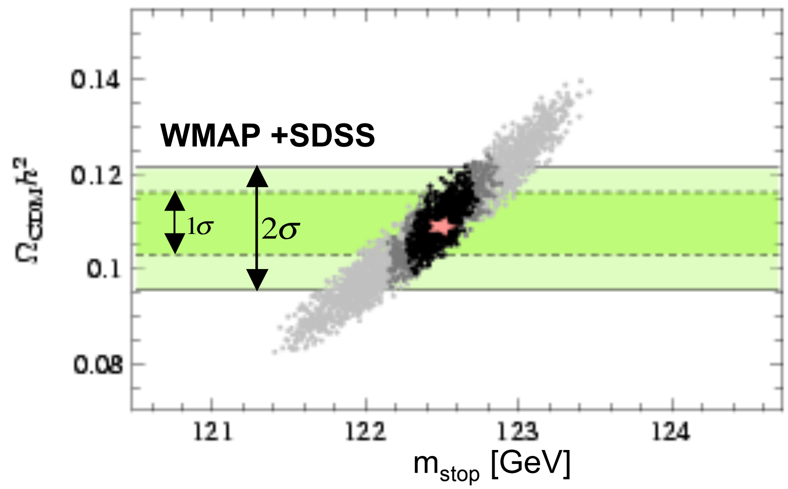
-- stop mass and mixing angles

from production cross sections at different beam polarizations.

-- LSP mass and nature

from threshold scan, energy distribution endpoints and polarized cross sections

M C, Finch, Freitas, Milstene, Nowak, Sopczak; Freitas, Milstene, Schmitt, Sopczak



DM relic density computation with precision comparable to cosmological measurements

<u>ILC</u> would provide crucial information on the SUSY origin of Matter

Conclusions

Supersymmetry with a light stop and a light SM-like Higgs

opens the window for electroweak baryogenesis

$\longrightarrow$ $m_{stop} < 125$ GeV, $m_h < 125$ GeV

Only gauginos/Higgsinos and stop at the weak scale
==> IMPROVES GAUGE COUPLING UNIFICATION

Strong constraints on CP phases from EDM's *!*

EWBG and Dark Matter in the MSSM → interesting experimental framework
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

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

Extras

Measurement of SUSY parameters for DM density computation

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

$$M_1 = 118.8 \text{ GeV} \qquad M_{u3}^2 = -99^2 \text{ GeV}^2$$
$$M_2 = 225 \text{ GeV} \qquad M_{q3} = 4330 \text{ GeV}$$
$$|\mu| = 225 \text{ GeV} \qquad A_t = -1100 \text{ GeV}$$
$$\phi_\mu = 0.2 \qquad \tan\beta = 5$$

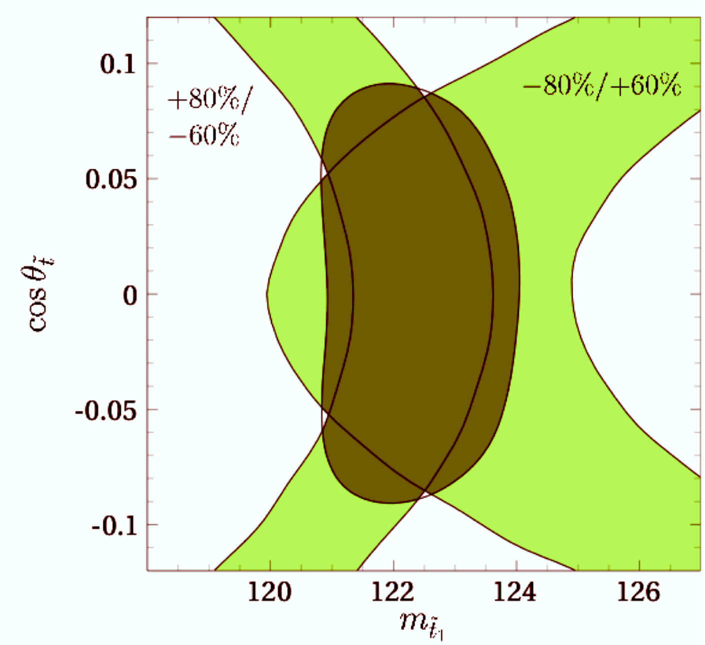
1st and 2nd generation sfermions = 10 TeV

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

-- 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

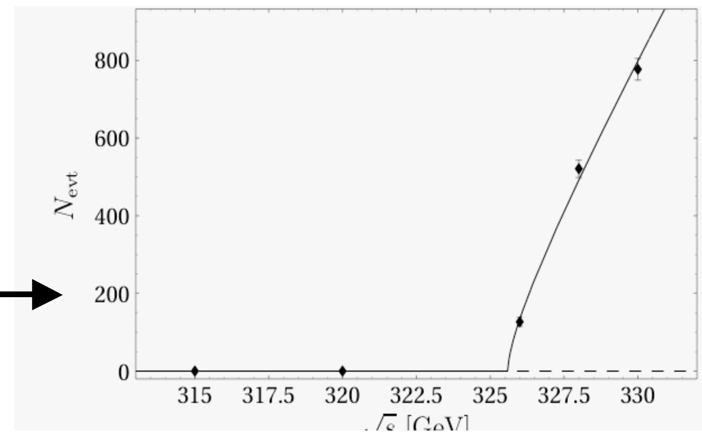
Light Neutralino/Charginos accesible at ILC with $\sqrt{s}=500$ GeV

Freitas, MC

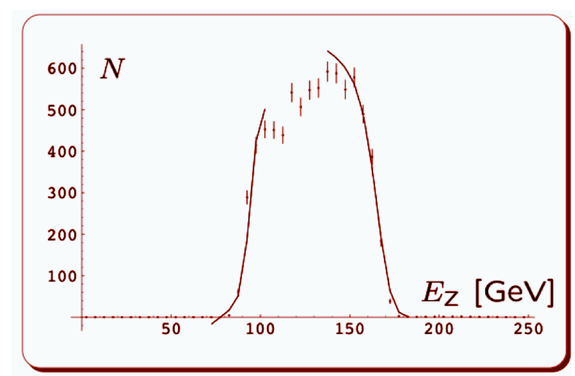
Main decay modes:

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

$\tilde{\chi}_1^{\pm}$ 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

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

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

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

and $+80\%/-60\%$

at $\sqrt{s} = 500$ 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

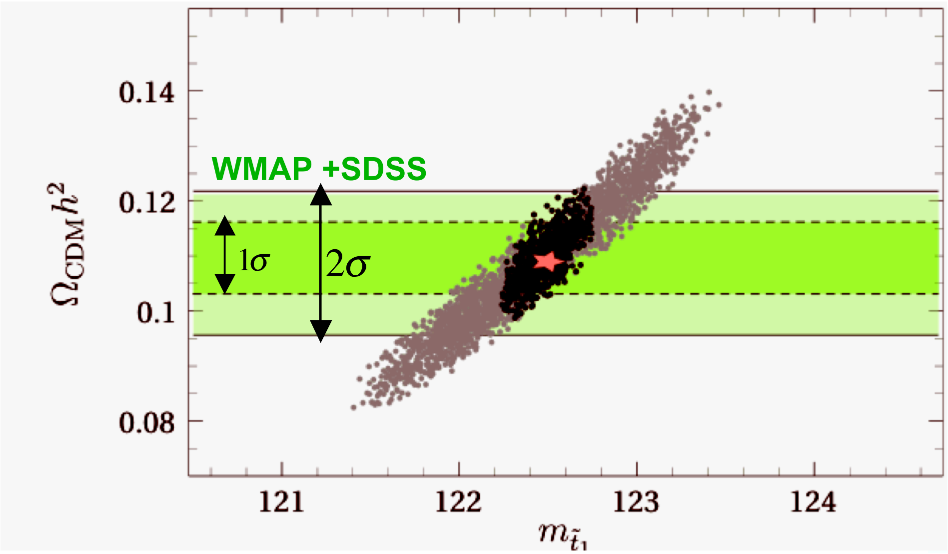
Precise measurement of SUSY parameters for DM computation

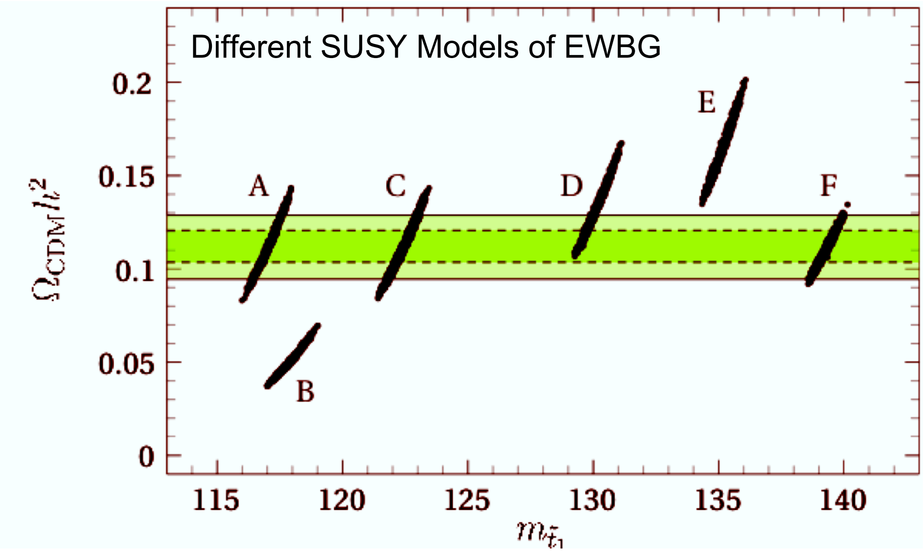
-- stop mass and mixing angles

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 ==> $0.082 < \Omega_{CDM} h^2 < 0.139$

-- dominated by error on stop mass --

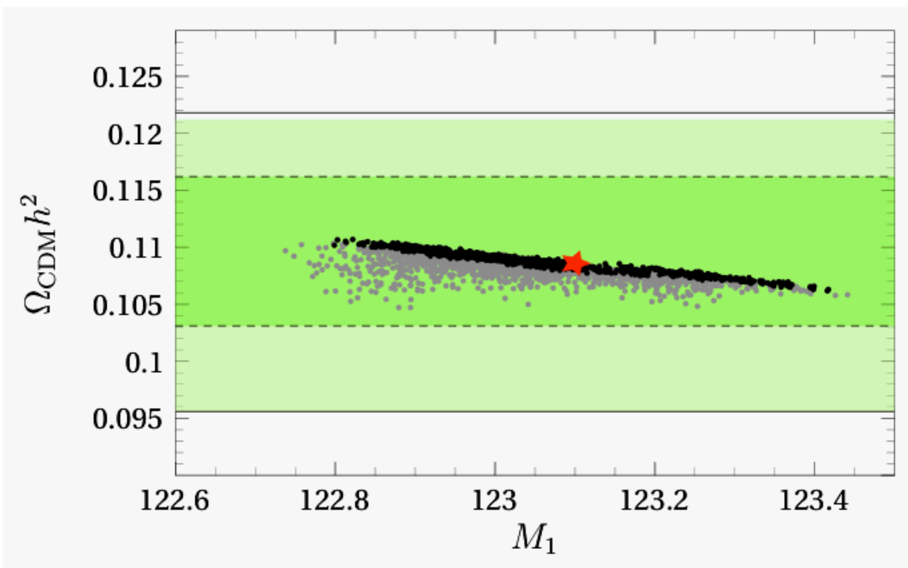
- **Using input parameters into computation of effective Higgs potential ==>** $\delta \frac{\mathrm{v}(\mathrm{T_c})}{\mathrm{T_c}} \leq 10\%$

- ILC measurements can provide crucial information on the SUSY origin of Matter

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

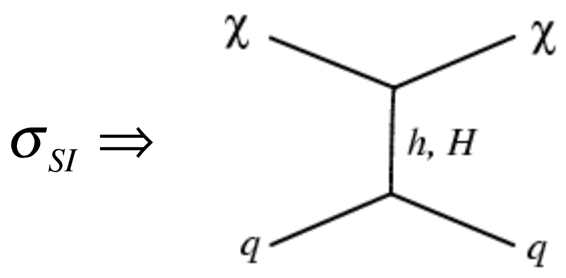
•MSSM models with all sfermions heavy (~ 10 TeV)
==> Split SUSY, Focus point

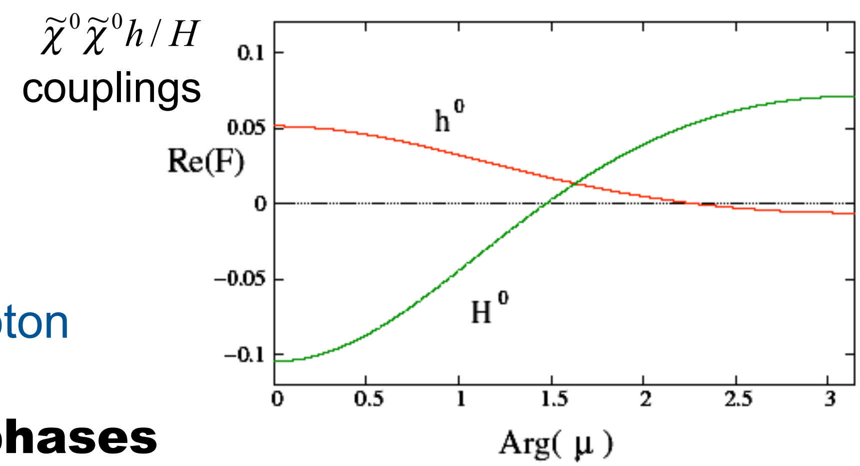
From fits to mass and cross section measurements (similar to Gray et al. and Desch et al.)
and including a chargino threshold scan
==> improves substantially the neutralino mass determination, hence the DM relic density determination.



Freitas, M.C.

Direct Dark Detection Reach in Models of EWBG

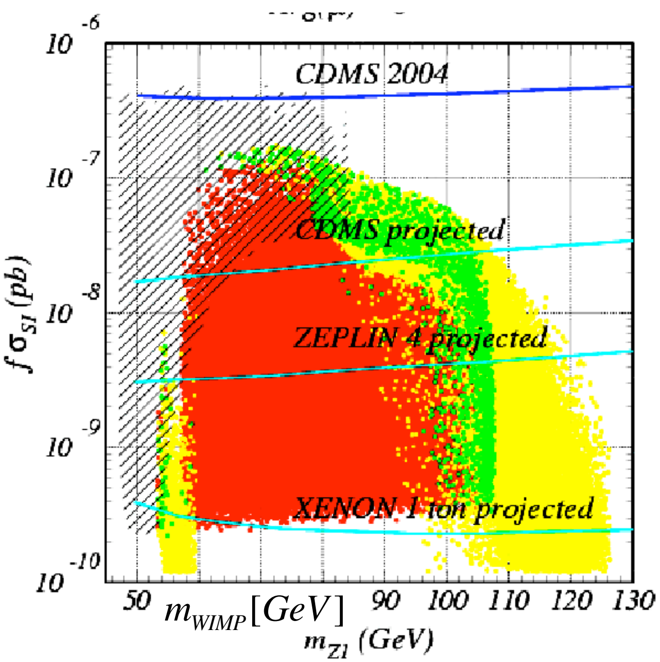


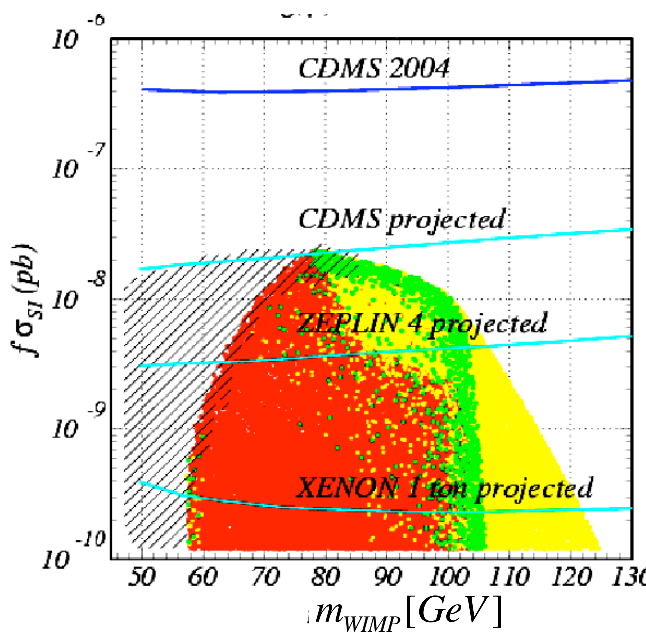


Spin Independent Neutralino-Proton scattering cross sections

Important sensitivity to CP phases

$Arg(\mu) = 0$





Green areas: Compatible with WMAP at 2 sigma

$Arg(\mu) = \pi/2$

Some Alternatives to EWBG at the Weak Scale

- Baryogenesis from out of equilibrium weak scale particle decay
  ==> Resonant Leptogenesis

  Pilaftisis, Underwood '03; See Mu Chun Chen's talk

- EWBG in SUSY models with extra singlets or gauge groups

  See Tao Liu's talk

- Baryogenesis from strongly interacting fermions

  M.C, Magevnad, Quiros, Wagner '05

- Delayed electroweak Phase transition Nardini, Quiros '07

- Early Phase Transition Dreiner, Ross; Shu, Tait, Wagner '06

- Effective theories with nonrenormilizable h.o. operators

  Xinmin Zhang '93
  Grojean, Servant, Wells '03-'04
  Grinstein, Trott '08

Cosmology data ↔ Dark Matter ↔ New physics at the EW scale

Evolution of the Dark Matter Density

• Heavy particle initially in thermal equilibrium

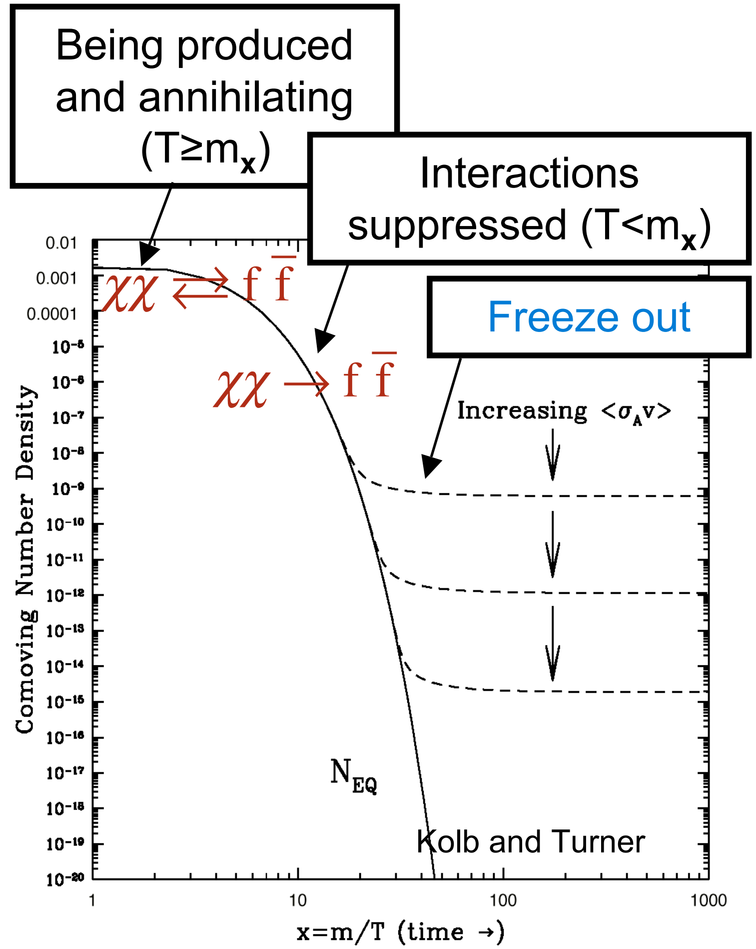
• Annihilation stops when number density drops

$$H > \Gamma_A \approx n_\chi < \sigma_A \mathrm{v} >$$

• i.e., annihilation too slow to keep up with Hubble expansion ("freeze out")

• Leaves a relic abundance:

$$\Omega_{DM} h^2 \approx \; < \sigma_A \mathrm{v} >^{-1}$$



If m_x and σ_A determined by electroweak physics,

$$\sigma_A \approx k\alpha_W^2 \,/\, \mathrm{m}_X^2 \approx \text{a few pb}$$

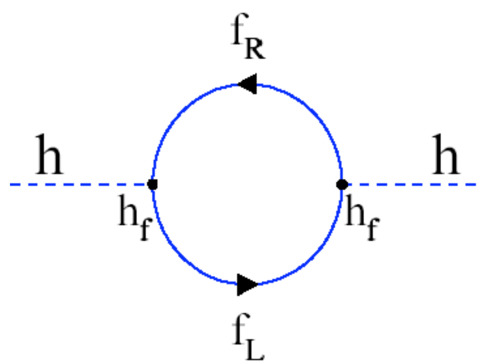
then Ω_{DM} h^2~ 0.1 for m_x~ 0.1-1 TeV

Remarkable agreement with data →

$$\Omega_{CDM} h^2 = 0.114 \pm 0.007$$

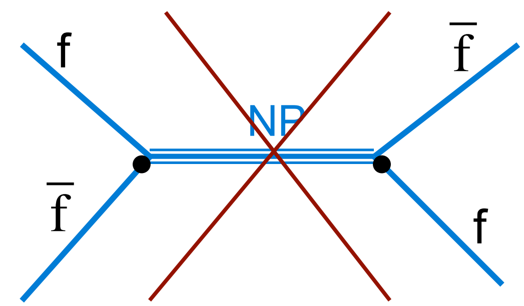
The EWSB mechanism + Collider data ↔ Dark Matter

EWSB scale << M_{Pl} ⟶ Hierarchy problem



Quantum corrections to the Higgs potential mass parameter μ are quadratically divergent

Need new particle/s with masses of order of the EWSB scale to cancel them



LEP, SLD &Tevatron precision data constrains the existence of interactions of SM particles with a single new particle with mass below a TeV.

Therefore many models of EWSB introduce an extra discrete symmetry, hence all interactions require pairs of new particles. This also makes the lightest new particle stable - a stable Weakly Interacting Massive Particle (WIMP)

Cheng and Low; Wudka

Solution to the hierarchy problem plus EW precision data lead naturally to the existence of a WIMP

⟶ Dark Matter

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}

$$\Rightarrow E_{MSSM} \approx 9\, E_{SM} \quad \text{hence} \quad m^{max.}_{h_{MSSM}} \approx 3 m^{max.}_{H_{SM}} \approx 120\ \text{GeV}$$ **it can work!!**

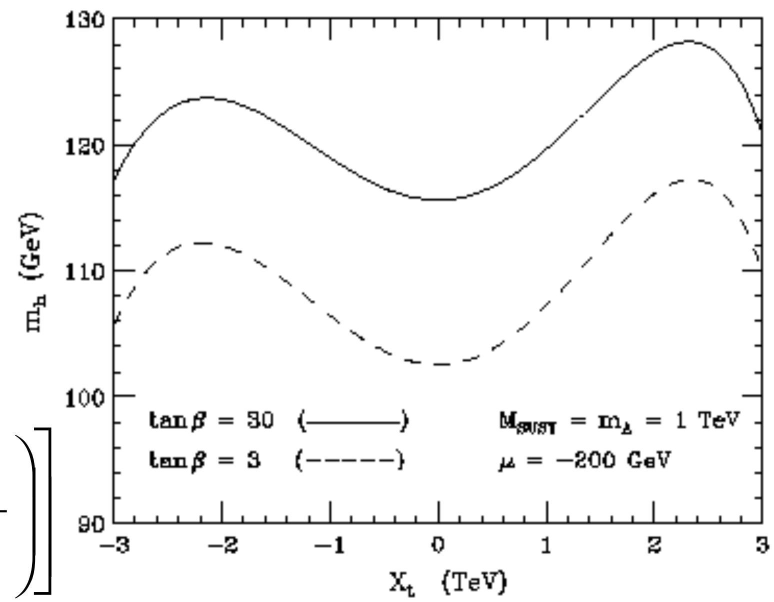
Present LEP bounds on the SM- like Higgs mass imply extra demands!

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

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

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

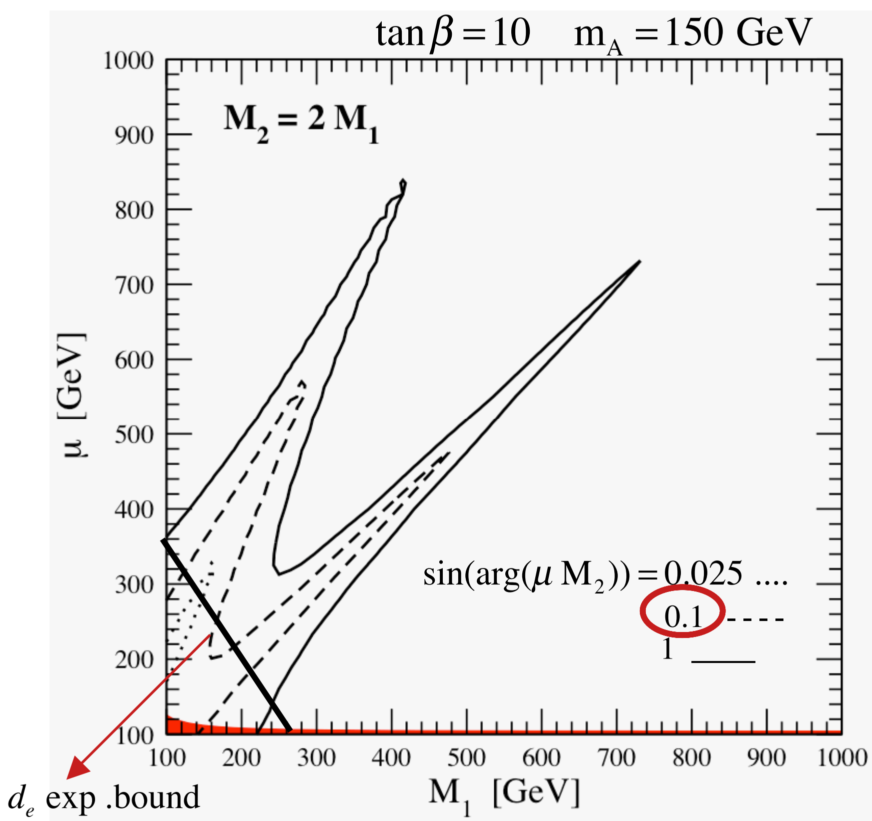
$$\frac{3 m_t^4}{8\pi^2 v^2}\left[\log\left(\frac{m_{\tilde t_l}^2 m_{\tilde t_H}^2}{m_t^4}\right) + 2\frac{|X_t|^2}{m_Q^2}\log\left(\frac{m_{\tilde t_H}^2}{m_{\tilde t_l}^2}\right) + \vartheta\left(\frac{|X_t|^4}{m_Q^4}\right)\right]$$



EW Baryogenesis demands $m_Q \geq 10\ \text{TeV}$

• Similar investigation considering also contributions to the Baryon Asymmetry from CP violating currents involving the lightest neutralino (LSP):

==> depend on $\sin(\arg(\mu\, \mathrm{M}_1))$, with resonant behavior for $|\mu| \approx M_1$



Cirigliano, Profumo, Ramsey-Musolf'06

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

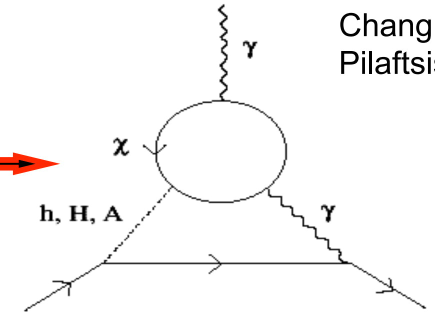
- One loop contributions become negligible for

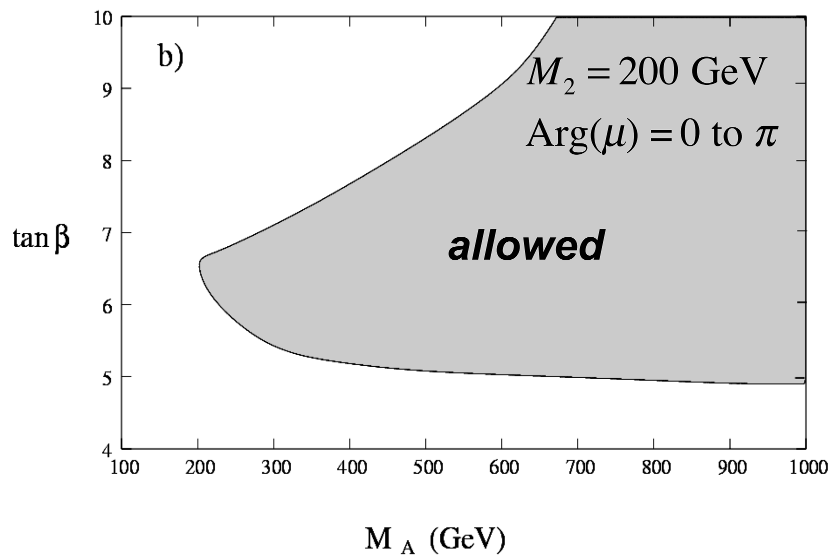
$$m_{\tilde{f}_{1,2}} \geq 10 \text{ TeV}$$

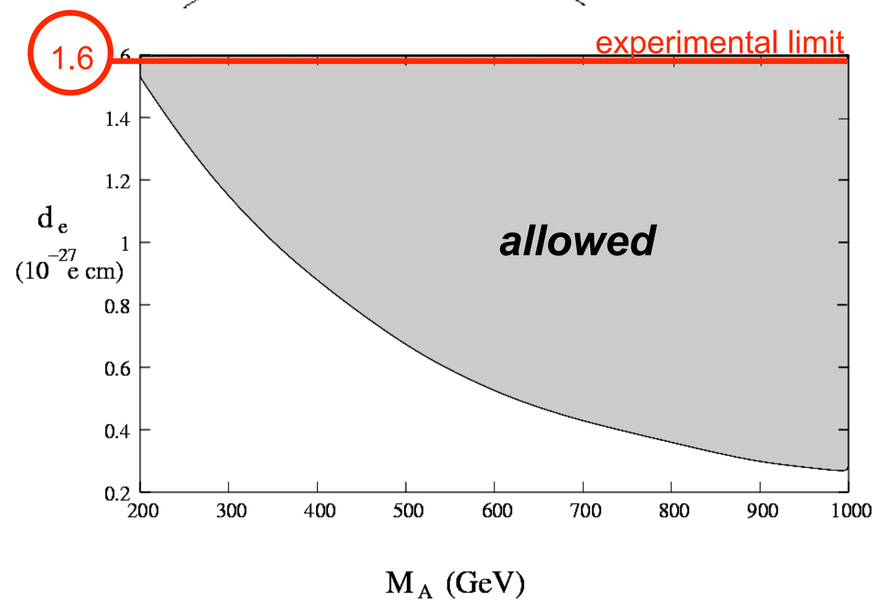
- At two loop order, contributions from virtual charginos and Higgs bosons, proportional to

$$\sin(\arg(\mu\, M_2))$$

Chang, Chang , Keung ’02
Pilaftsis ‘02







$$\Rightarrow 5 \leq \tan\beta \leq 10 \qquad M_A \geq 200 \text{ GeV} \qquad 110 \text{ GeV} \leq |\mu| \leq 550 \text{ GeV (not shown)}$$

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)!

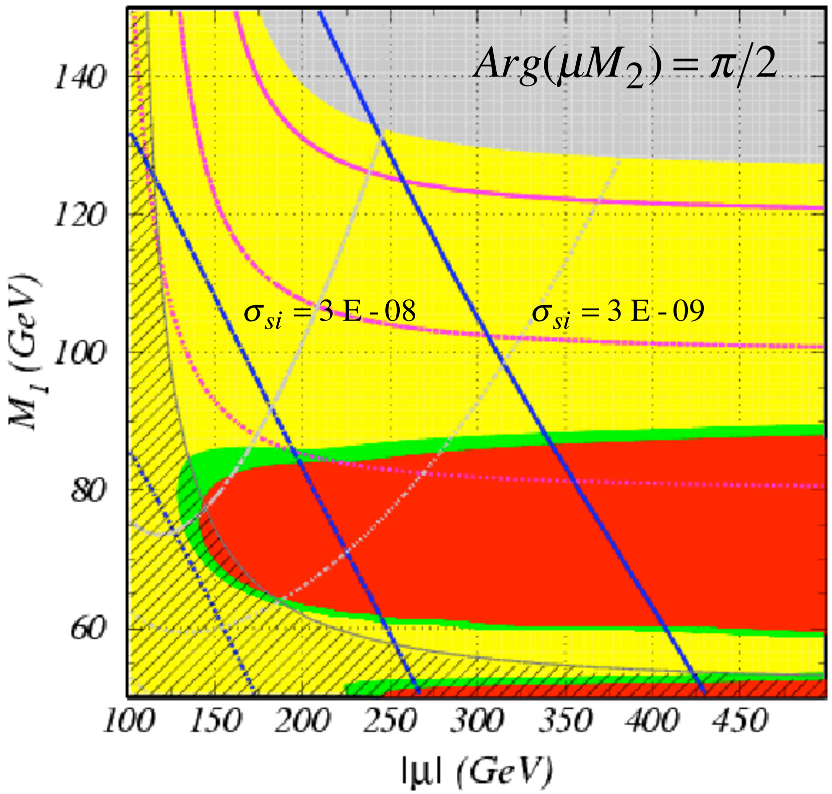
Non-Standard Higgs Mass Effects

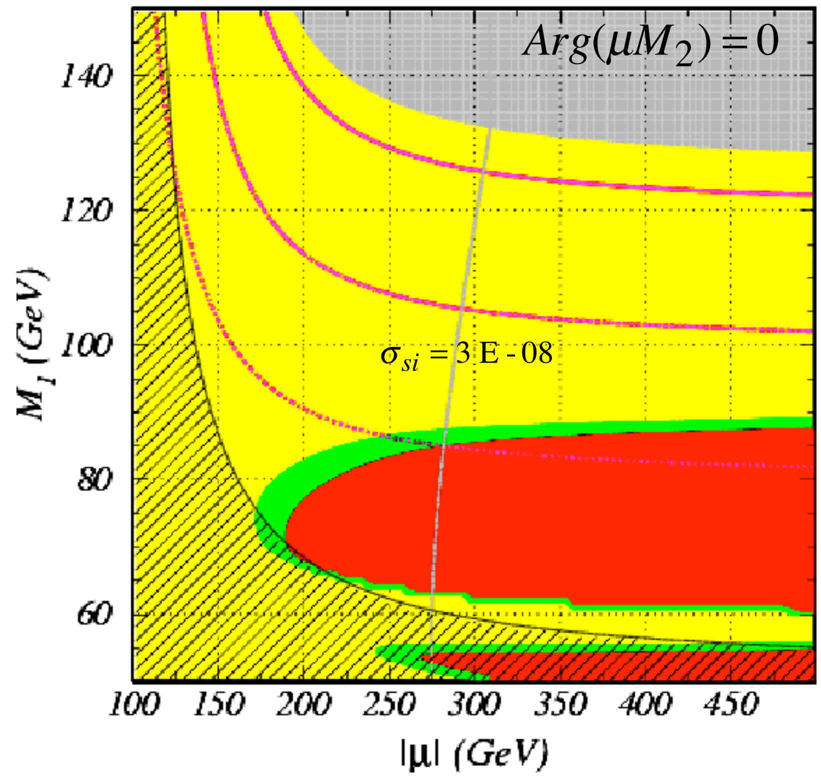
$(m_A = 200 \text{ GeV})$

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)

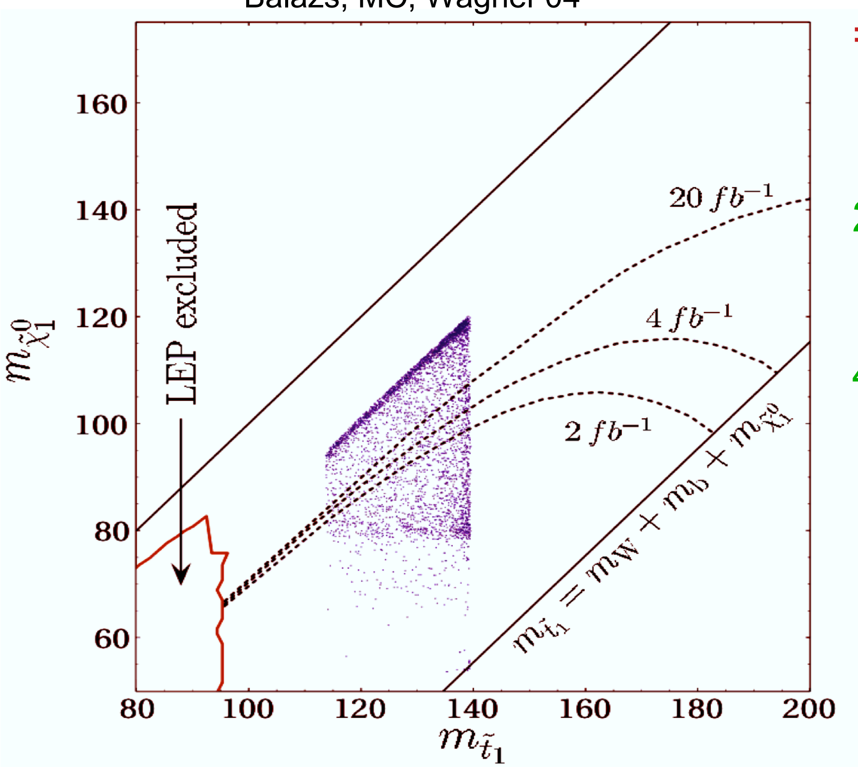
- Larger neutralino-proton scattering cross sections due to heavy Higgs H, tanb enhanced contributions

Balazs, MC, Wagner

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 $\Delta_{m_{\tilde{t}\tilde{\chi}}}$

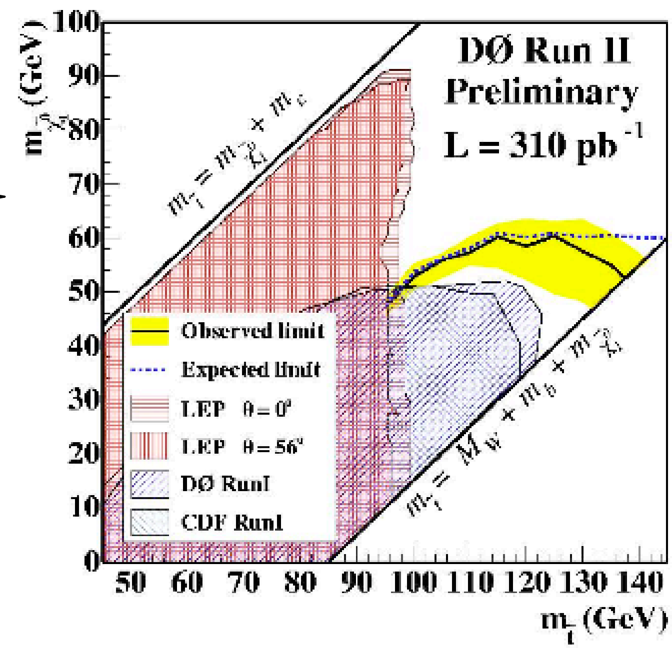
==> dominant decay mode

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

2- and 3 body decays kinematically forbidden:

$$\tilde{t}_1 \to b\, \tilde{\chi}_1^+ \qquad \tilde{t}_1 \to bW^+\, \tilde{\chi}_1^0 \qquad \tilde{t}_1 \to bl^+ \tilde{\nu}_l$$

4 body decays $\tilde{t}_1 \to bl^+ \nu_l\, \tilde{\chi}_1^0$ 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

Kraml, Raklev '06

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

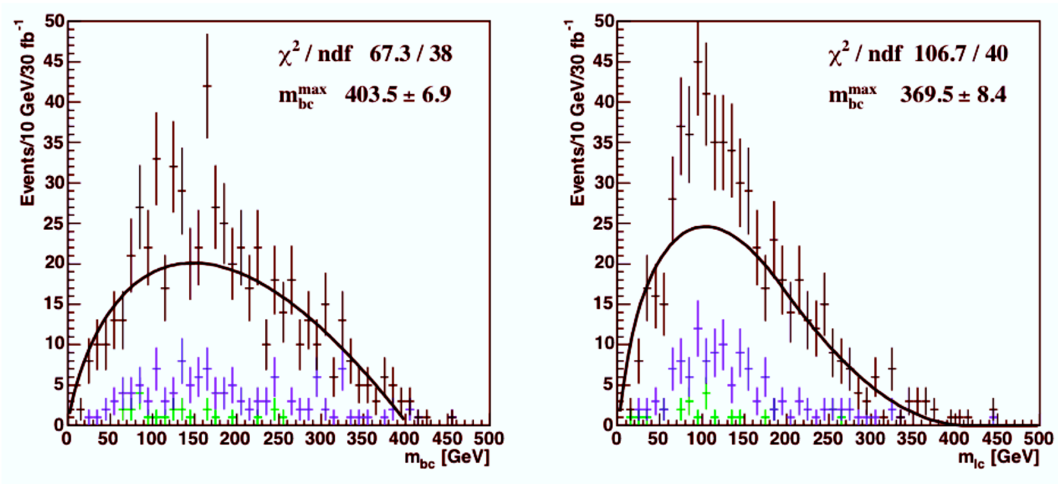
- Look for same-sign tops in gluino decays

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

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)

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