The Supersymmetric Origin of Matter

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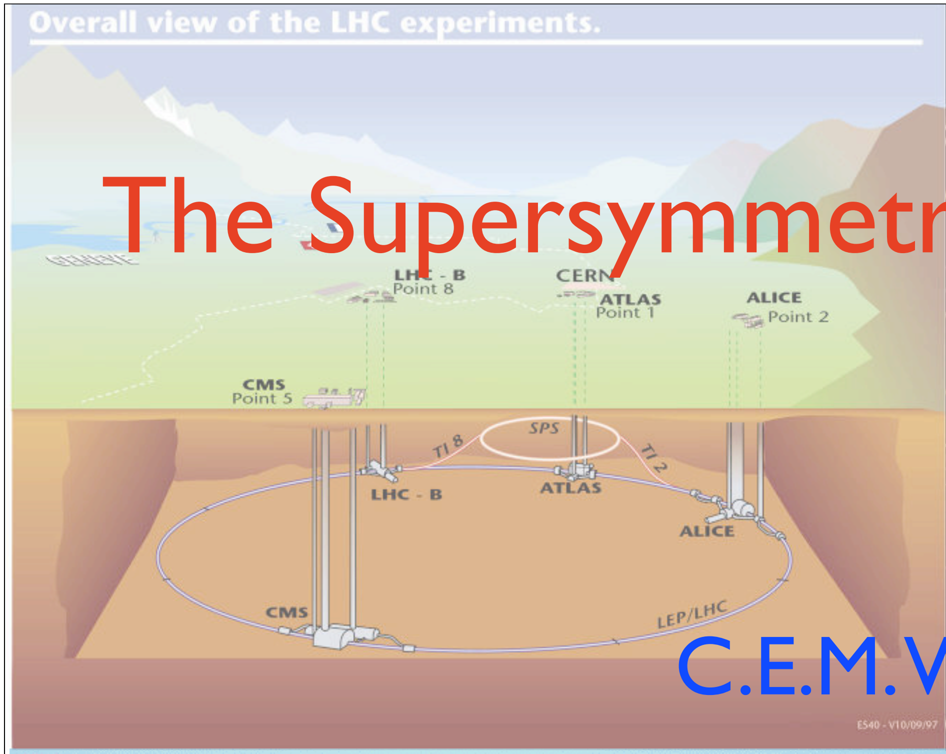
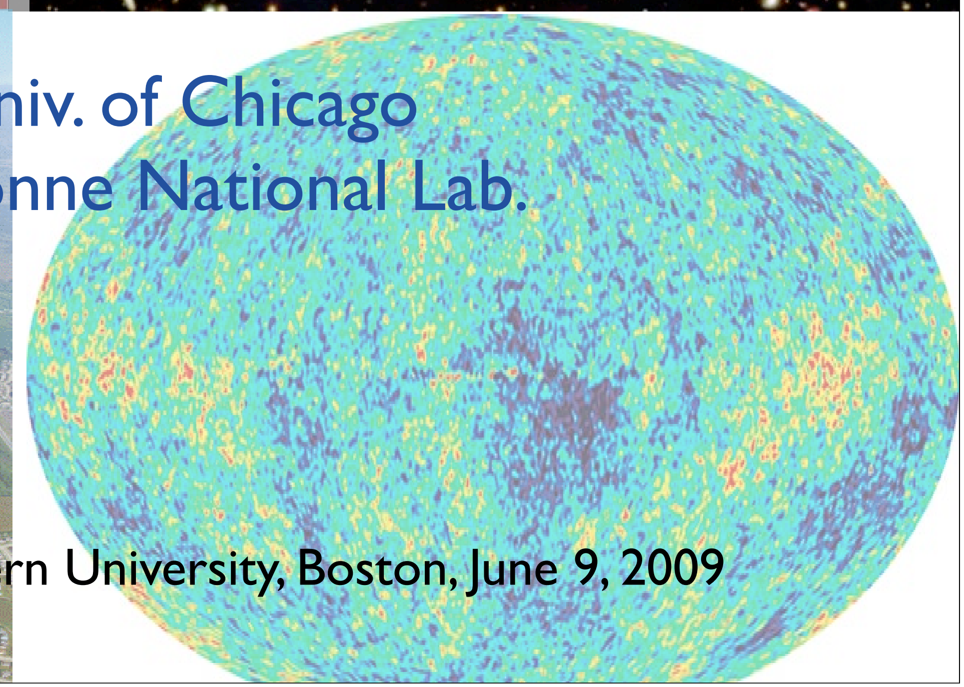




Based on work done in collaboration with M. Quiros and M. Carena, and the following recent works:

C. Balazs, M. Carena and C.W.; Phys. Rev. D70:015007, 2004.

A. Menon, D. Morrissey and C.W.; Phys. Rev. D70:035005, 2004.

C. Balazs, M. Carena, A. Menon, C. Morrissey and C.W.
Phys. Rev.D71:075002, 2005.

C. Balazs, M. Carena, A. Freitas and C.W., **JHEP 0706:066, 2007**

M. Carena, G. Nardini, M. Quiros and C.W., JHEP 0810:062, 2008 &
Nucl. Phys. B812:243, 2009.

M. Carena, A. Freitas and C.W., JHEP 0810:109, 2008.

The Puzzle of the Matter-Antimatter asymmetry

- Anti-matter is governed by the same interactions as matter.
- Observable Universe is composed of matter.
- Anti-matter is only seen in cosmic rays and particle physics accelerators
- The rate observed in cosmic rays consistent with secondary emission of antiprotons

$$\frac{n_{\bar{P}}}{n_P} \approx 10^{-4}$$

Theory vs. Observation

- Baryons annihilate with antibaryons via strong interactions mediated by mesons
- This is a very efficient annihilation channel and the equilibrium density is

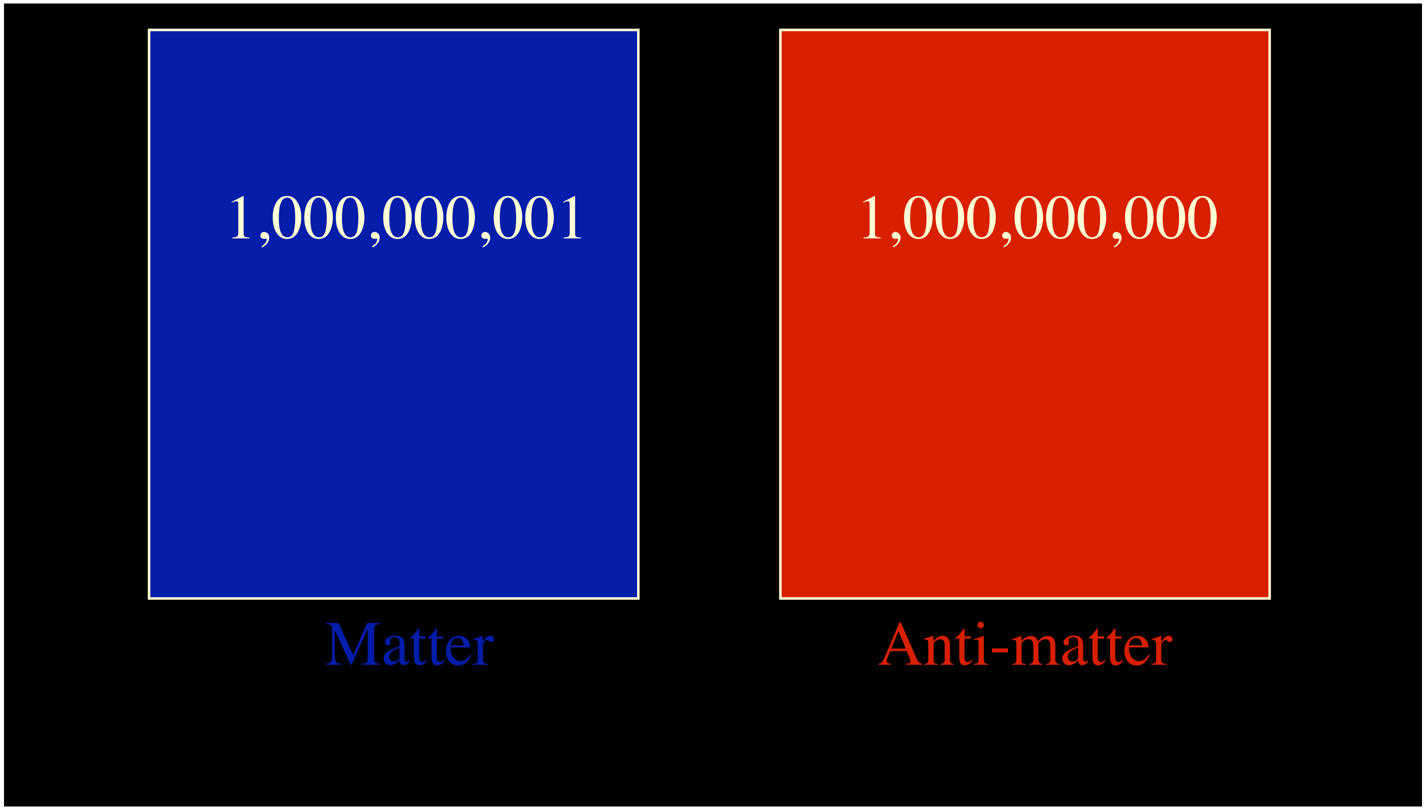
$$\frac{n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \simeq 10^{-20}$$

- The first problem is the equality of baryon and antibaryon number density. Even obviating this problem, how does this compare to experiment ? From the analysis of BBN and CMBR, one obtains, consistently

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

- How to explain the absence of antimatter and the appearence of such a small asymmetry ?

Small Asymmetry must be generated primordially



Murayama

Annihilation will occur efficiently and finally the small asymmetry will be the only remaining thing left in the Universe

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.

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.

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

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

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

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

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase

transition,

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

Kuzmin, Rubakov and Shaposhnikov, '85—'87

Baryon number erased unless the baryon number violating

processes are out of equilibrium in the broken phase.

Therefore, to preserve the baryon asymmetry, a strongly first order

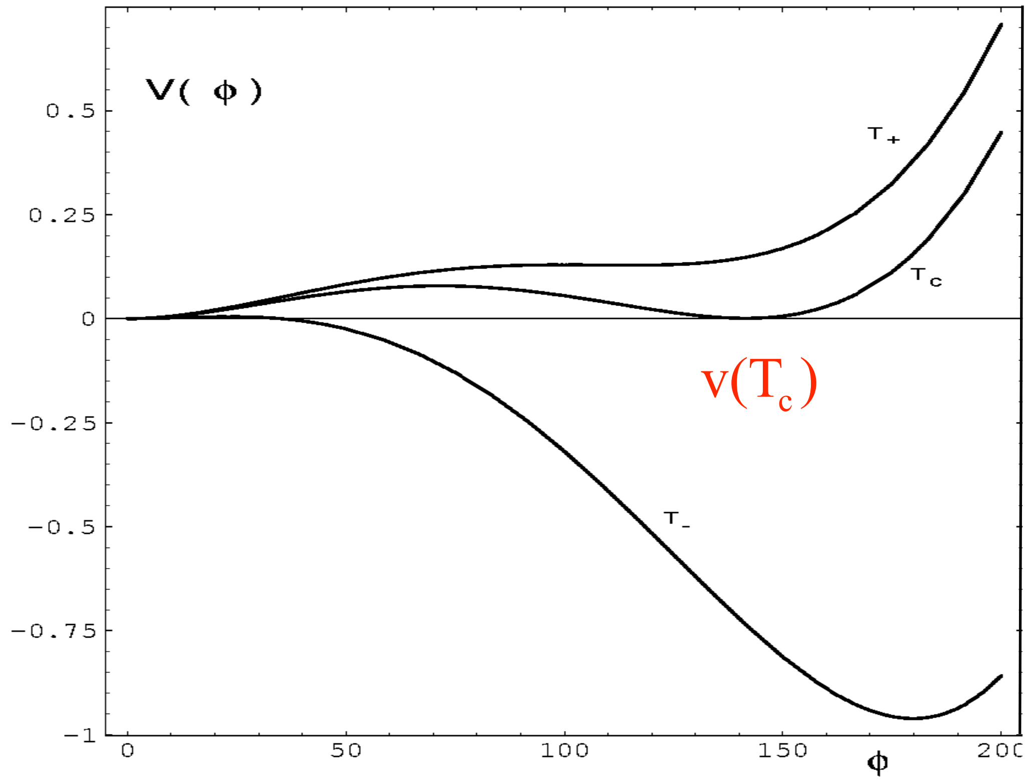
phase transition is necessary:

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

Electroweak Phase Transition

Higgs Potential Evolution in the case of a first order

Phase Transition



Finite Temperature Higgs Potential

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

D receives contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, and is responsible for the phenomenon of symmetry restoration

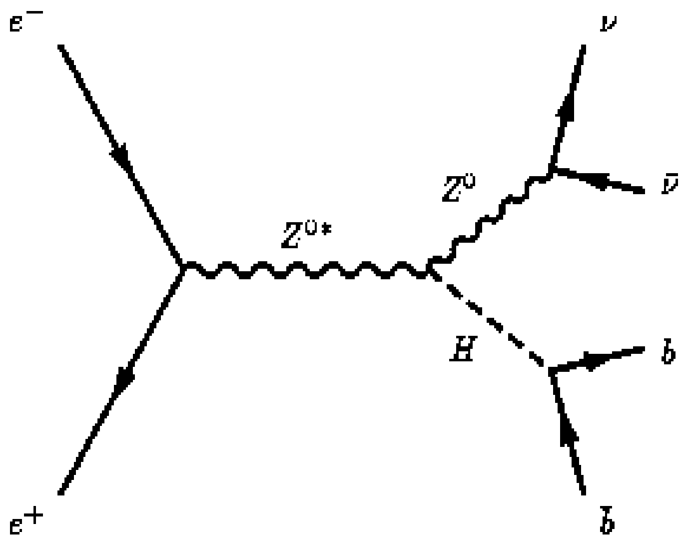
E receives contributions proportional to the sum of the cube of all light boson particle couplings

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

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

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

If the Higgs Boson is created , it will decay rapidly into other particles



At LEP energies mainly into pairs of b quarks

One detects the decay products of the Higgs and the Z bosons

LEP Run is over

- No Higgs seen with a mass below 114 GeV
- But, tantalizing hint of a Higgs with mass about 115 -- 116 GeV (just at the edge of LEP reach)

Electroweak Baryogenesis in the SM is ruled out

CP-Violation sources

- Another problem for the realization of the SM electroweak baryogenesis scenario:

- Absence of sufficiently strong CP-violating sources

- Even assuming preservation of baryon asymmetry, baryon number generation several order of magnitues lower than required

$$\Delta_{CP}^{max} = \left[\sqrt{\frac{3\pi}{2}\frac{\alpha_W T}{32\sqrt{\alpha_s}}}\right]^3 J \frac{(m_t^2-m_c^2)(m_t^2-m_u^2)(m_c^2-m_u^2)}{M_W^6}\frac{(m_b^2-m_s^2)(m_s^2-m_d^2)(m_b^2-m_d^2)}{(2\gamma)^9}$$

$$J \equiv \pm Im[K_{li}K_{lj}^{*}K_{l'j}K_{l'i}^{*}] = c_1c_2c_3s_1^2s_2s_3s_\delta$$

γ : Quark Damping rate

Gavela, Hernandez, Orloff, Pene and Quimbay'94

Electroweak Baryogenesis

and

New Physics at the Weak Scale

Preservation of the Baryon Asymmetry

- EW Baryogenesis requires new boson degrees of freedom with strong couplings to the Higgs.

- Supersymmetry provides a natural framework for this scenario. Huet, Nelson ’91; Giudice ’91, Espinosa, Quiros,Zwirner ’93.

- Relevant SUSY particle: Superpartner of the top

- Each stop has six degrees of freedom (3 of color, two of charge) and coupling of order one to the Higgs

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

M. Carena, M. Quiros, C.W. ’96, ‘98

- Since

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

Higgs masses up to 120 GeV may be accomodated

Mass of the SM-like Higgs h

- Most important corrections come from the stop sector,

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} \mathbf{m}_Q^2 + \mathbf{m}_t^2 + \mathbf{D}_L & \mathbf{m}_t \mathbf{X}_t \\ \mathbf{m}_t \mathbf{X}_t & \mathbf{m}_U^2 + \mathbf{m}_t^2 + \mathbf{D}_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $\mathbf{X}_t = \mathbf{A}_t - \mu^* / \tan\beta$

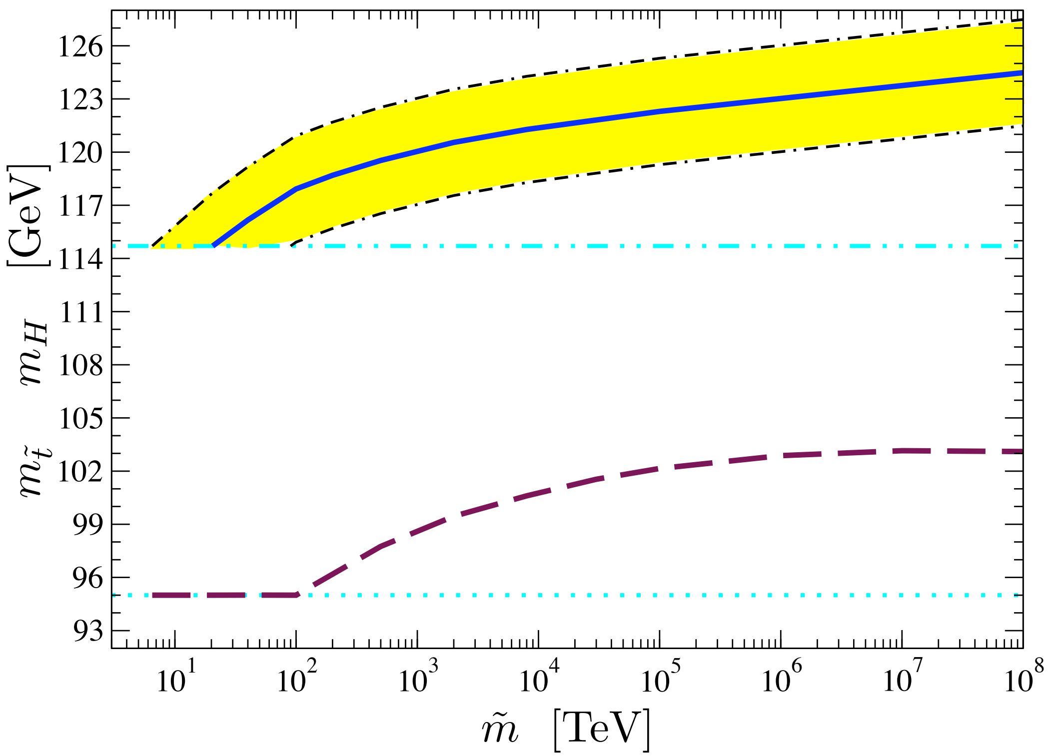
Light right-handed stop: Consistency with precision electroweak data. Higgs mass, smaller than M_Z at tree-level. Due to smallness of right-handed stop mass, Higgs mass remains close to M_Z unless m_Q is very large.

For Baryogenesis $m_U^2 < 0, \quad m_Q > 6$ TeV
Bound on $m_h < 125$ GeV.

Upper Bound on the Higgs Mass. Largest values of At

M. Carena, G. Nardini, M. Quiros, C.W. '08

$$m_Q = m_{\tilde{q}} = m_A = m_{\tilde{l}} = \tilde{m}$$



Both the Higgs and the lightest stop must be lighter than about 125 GeV for the mechanism to work. Values of the Higgs mass above 120 GeV may only be obtained for very large values of $\tilde{m}$.

Experimental Tests of Electroweak Baryogenesis in the MSSM

Experimental Tests of Electroweak Baryogenesis and Dark Matter

- Higgs searches beyond LEP:

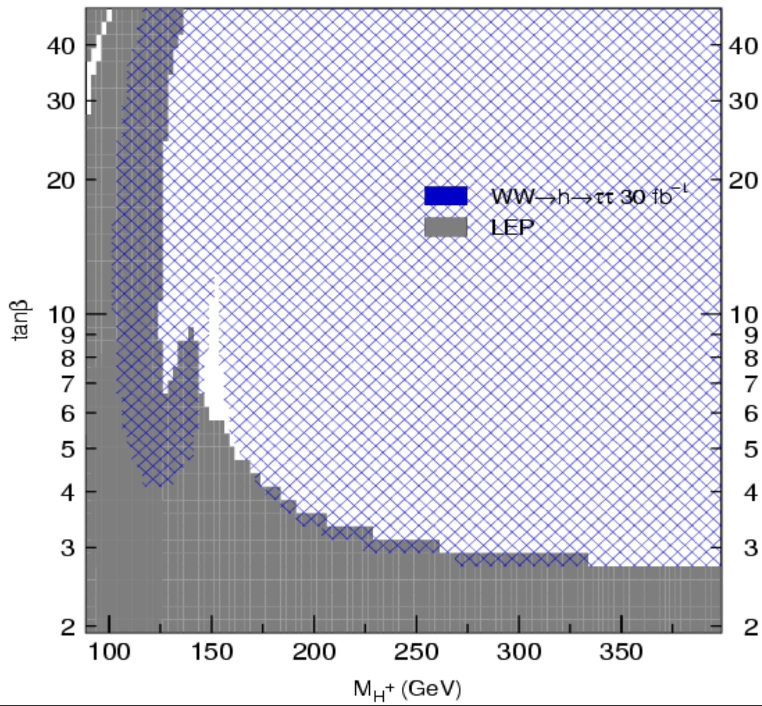
1. Tevatron collider may test this possibility: 3 sigma evidence with about 10 fb^{-1}

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

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

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

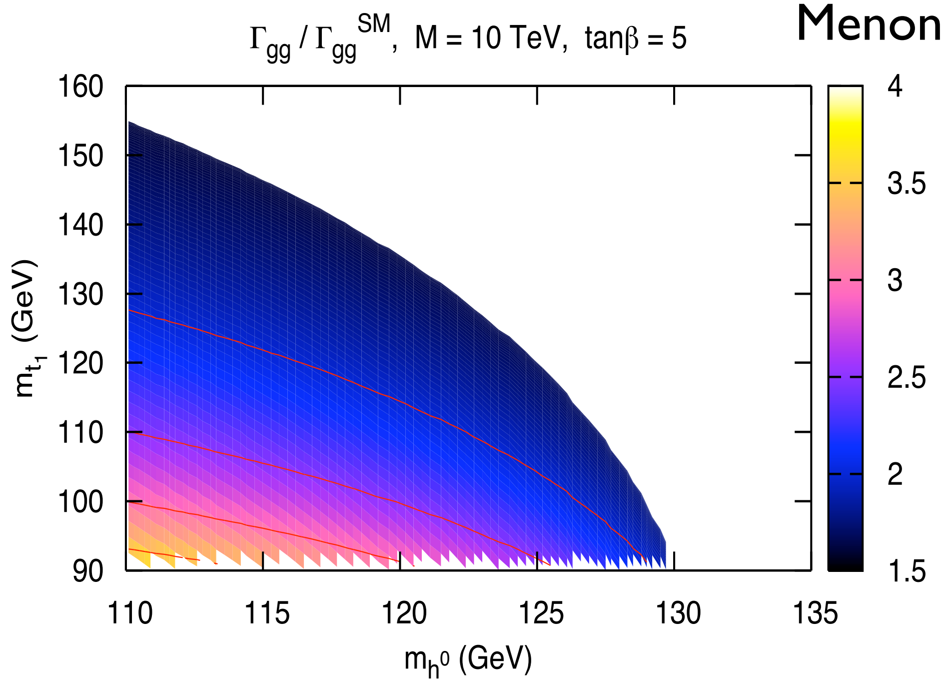


David Morriseey's talk

Higgs Boson Production via $gg \to h^0$

- $\sigma(gg \to h^0) \propto \Gamma(h^0 \to gg)$.
- Stop loops interfere constructively with tops.

Menon and Morrissey '09

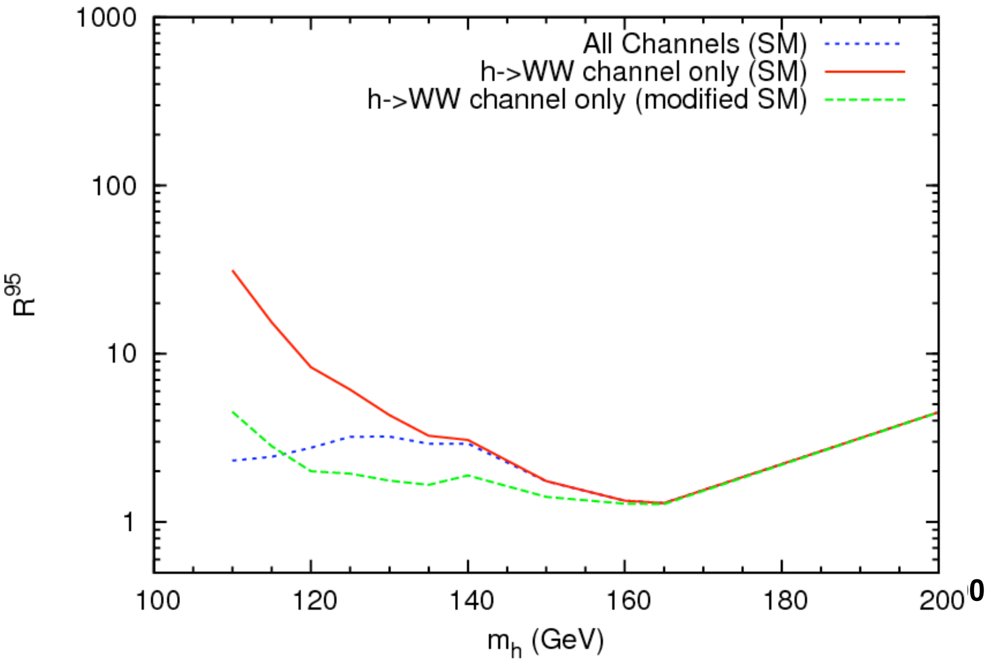


- MSSM EWBG Region: $m_{\tilde{t}_1}, m_{h^0} \lesssim 125\,\text{GeV}$.

[Carena,Nardini,Quirós,Wagner '08]

Tevatron Search Prospects

- Light Higgs search dominated by $h^0\, W/Z$ with $h^0 \to b\bar{b}$.



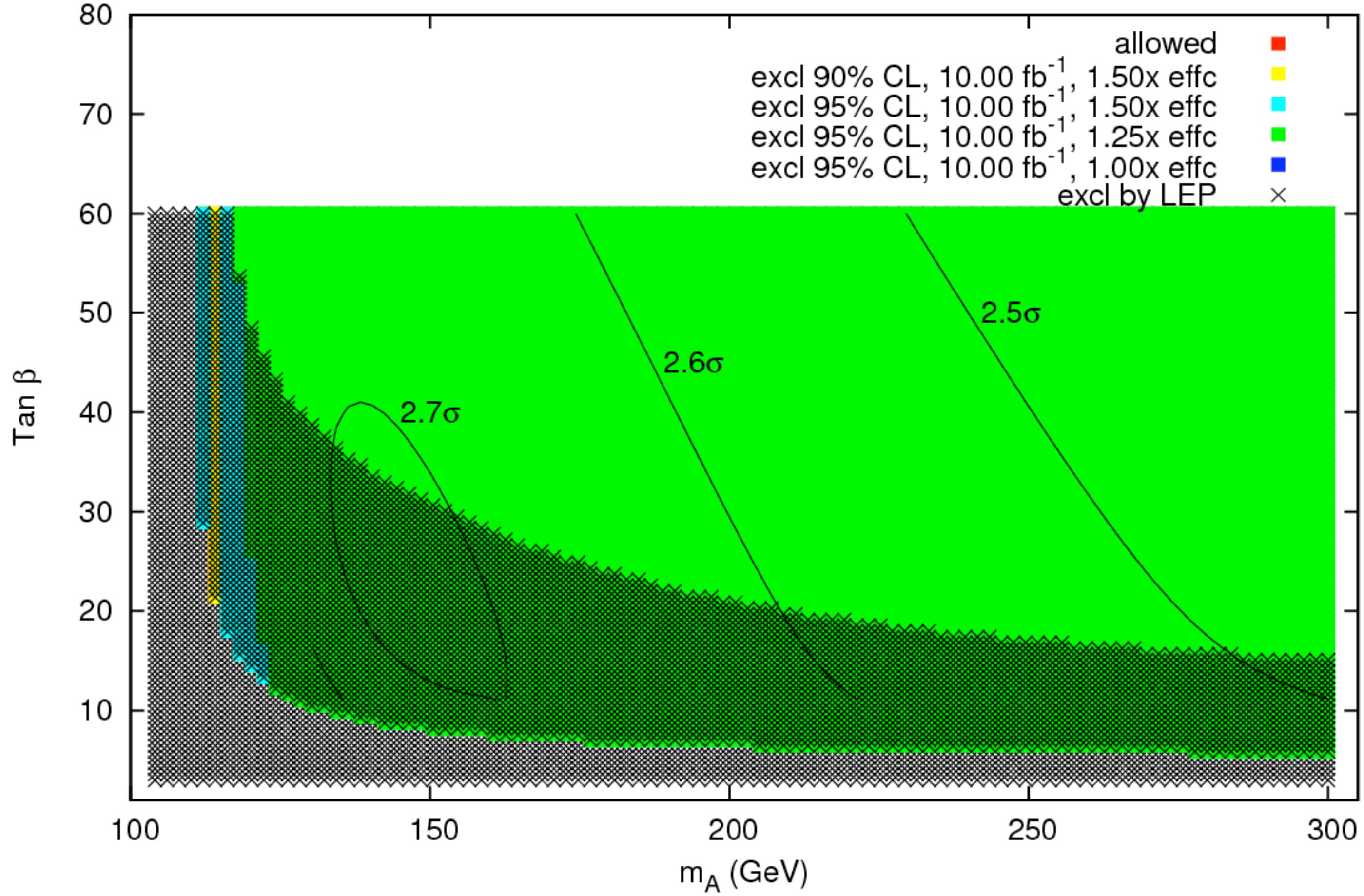
- $\sigma\, BR(h^0 \to WW)/\sigma\, BR_{SM} \lesssim 8$ for $m_{h^0} < 125\,\text{GeV}$.

  MSSM EWBG $\Rightarrow$ enhancement by 2–4.

- Tevatron could be sensitive with $10\, fb^{-1}$.

Minimal Mixing Scenario

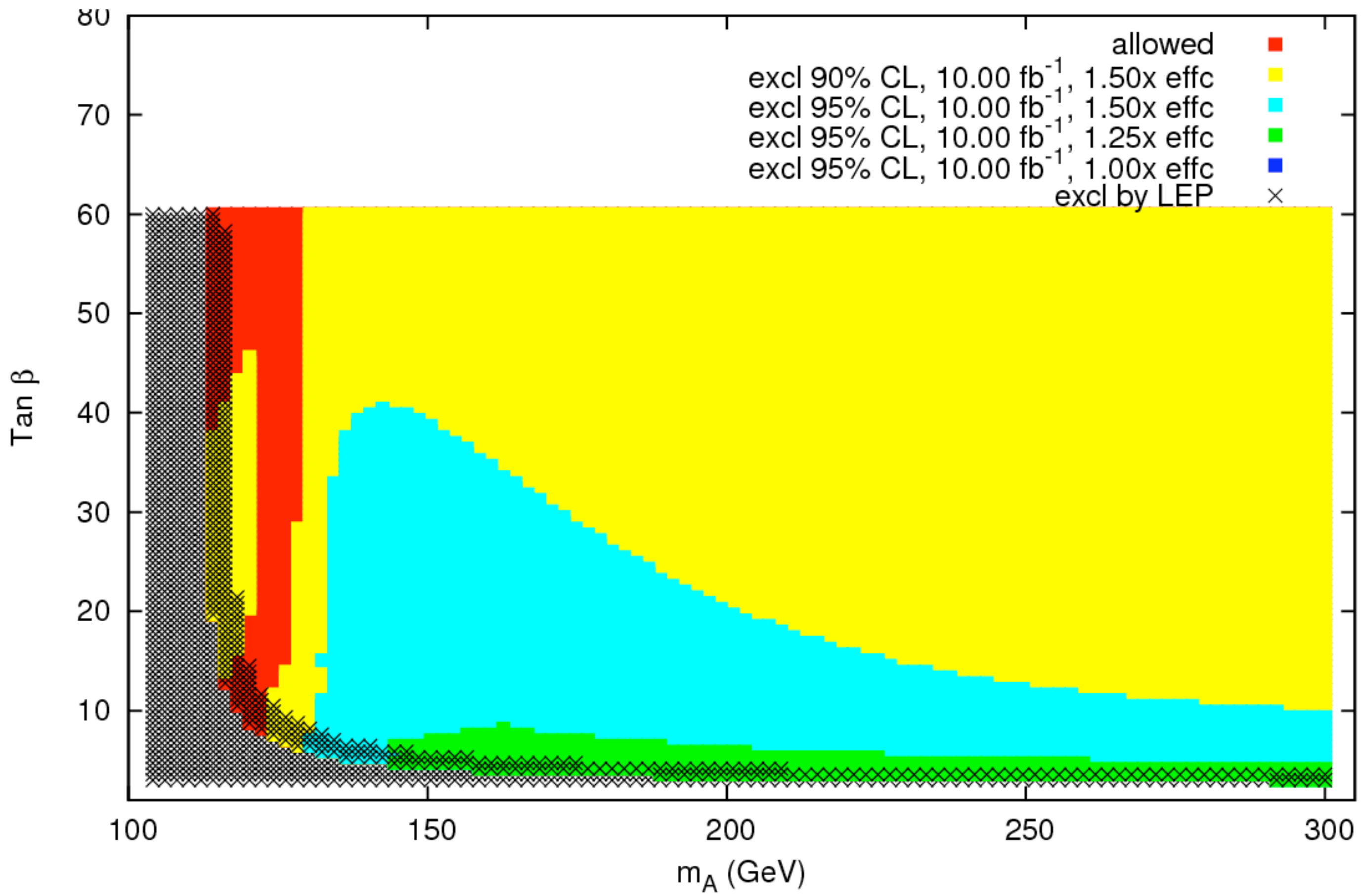
P. Draper, T. Liu and C.W. '09



Higgs mass small, $m_h < 120$ GeV. Easily probed at the Tevatron. More than 2.5 σ evidence in most of parameter space (WW enhancement will further improve reach).

Maximal Mixing Scenario

P. Draper, T. Liu and C.W. '09



Higgs mass small, $m_h > 120$ GeV. Difficult to probe at the Tevatron. Enhancement of WW relevant in this region. Analysis in preparation.

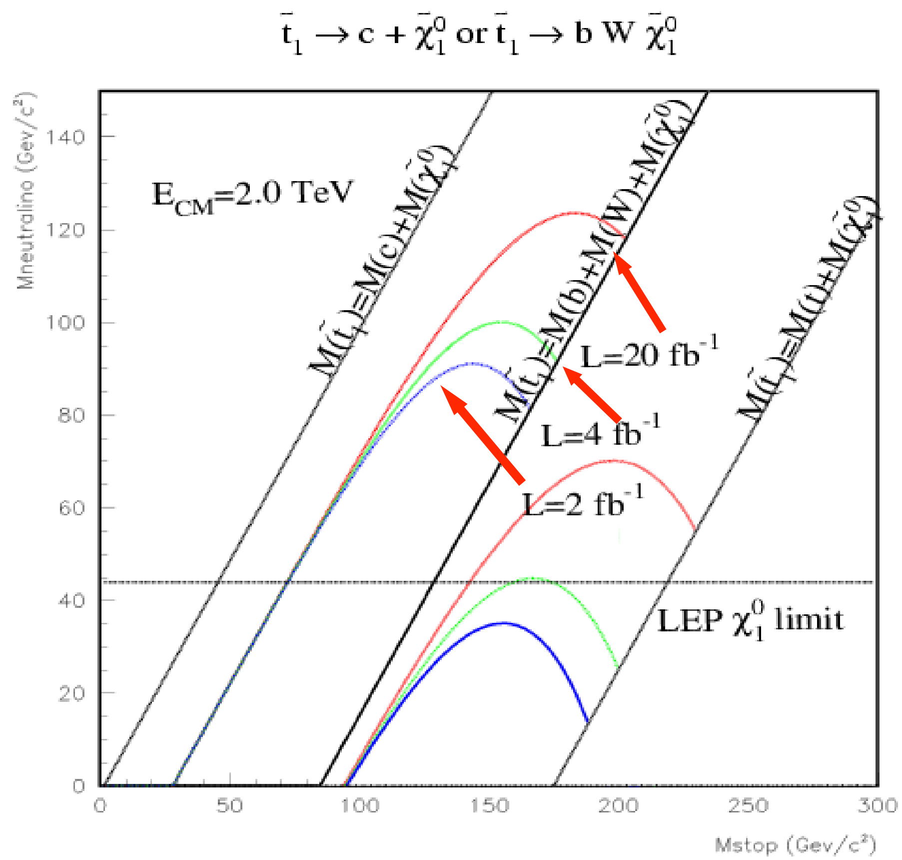
Tevatron Stop Reach when two body decay channel is dominant

Main signature:

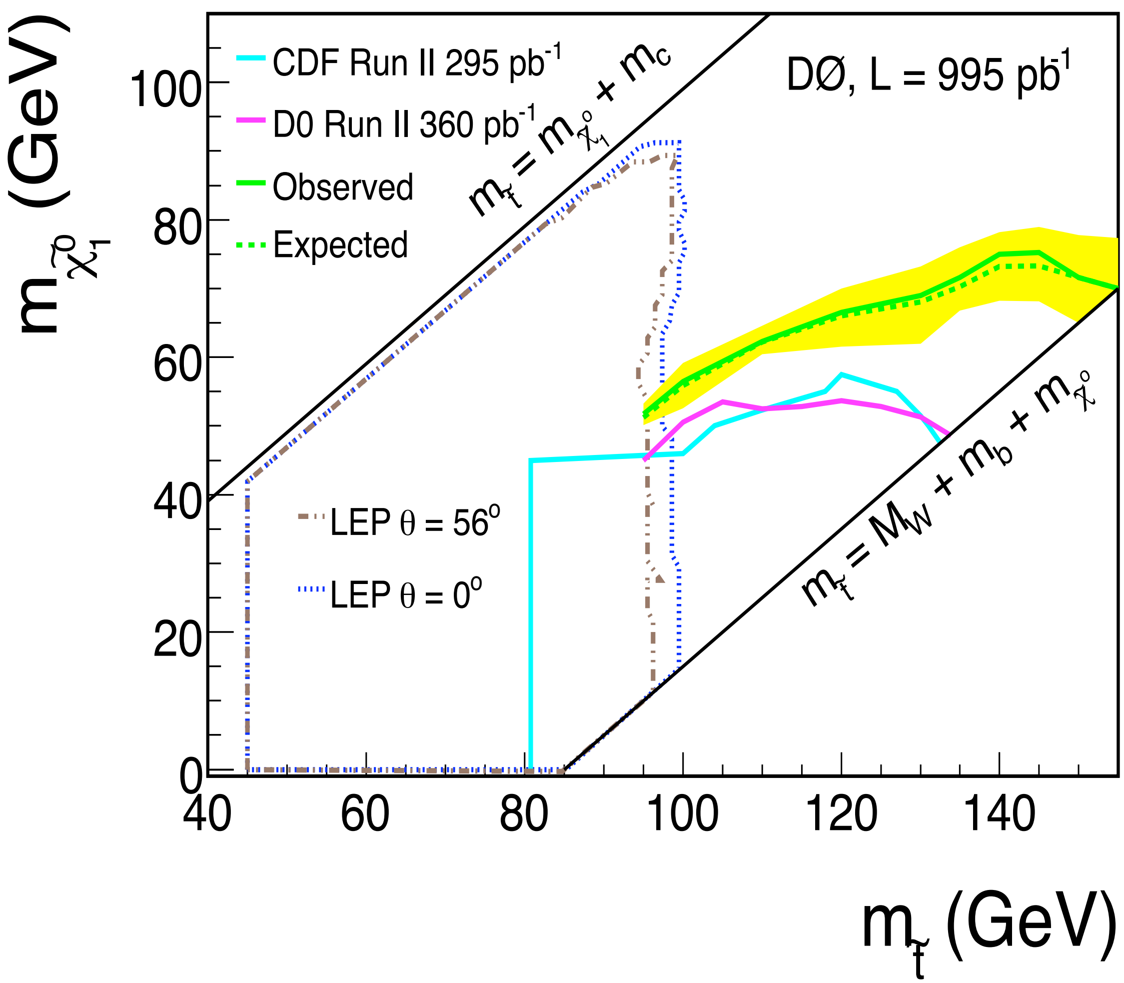
2 or more jets plus missing energy

2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ GeV



Demina, Lykken, Matchev,Nomerotsky ‘99



CDF Run II 295 pb^{-1}
D0 Run II 360 pb^{-1}
Observed
Expected
DØ, L = 995 pb^{-1}
$m_{\tilde{t}} = m_{\tilde{\chi}_1^0} + m_c$
$m_{\tilde{t}} = M_W + m_b + m_{\tilde{\chi}^0}$
LEP θ = 56°
LEP θ = 0°
$m_{\tilde{\chi}_1^0}$ (GeV)
$m_{\tilde{t}}$ (GeV)
0
20
40
60
80
100
120
140

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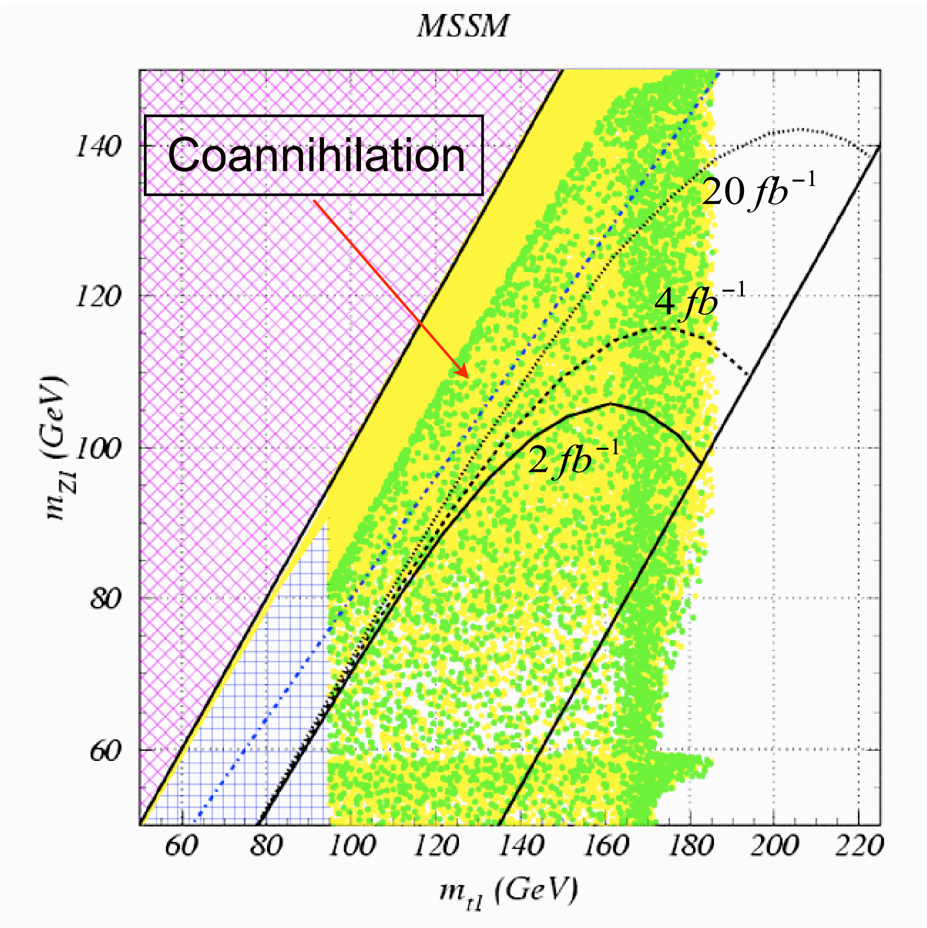
Tevatron stop searches and dark matter constraints

Carena, Balazs and C.W. '04



Green: Relic density consistent with WMAP measurements.

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

LHC will have equal difficulties.

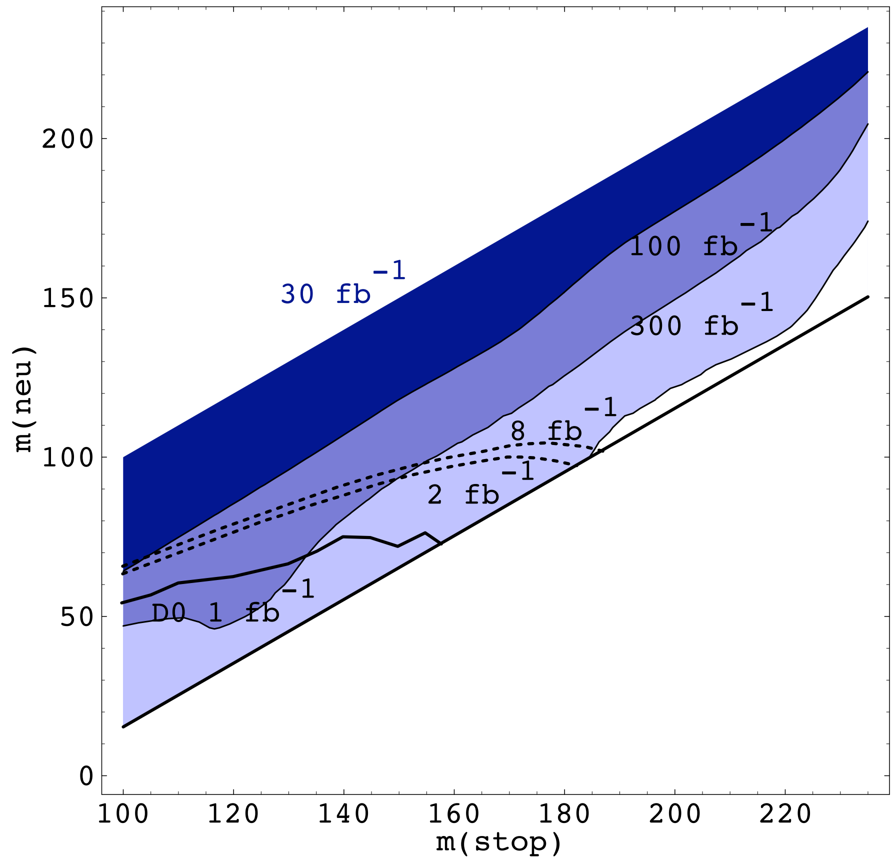
But, LHC can search for stops from gluino decays into stops and tops. Stops may be discovered for gluino masses lower than 900 GeV, even if the stop-neutralino mass difference is as low as 10 GeV ! Stop bound states, decaying to photons, may also provide a test.

Kraml, Raklev '06, Martin'08

Alternative Channel at the LHC

- When the stops and neutralino mass difference is small, the jets will be soft.
- One can look for the production of stops in association with jets or photons. Signature: Jets plus missing energy

M. Carena, A. Freitas, C.W. '08



Excellent reach until masses of the order of 220 GeV and larger.

Full region consistent with EWBG will be probed by combining the LHC with the Tevatron searches.

Baryon Number Generation

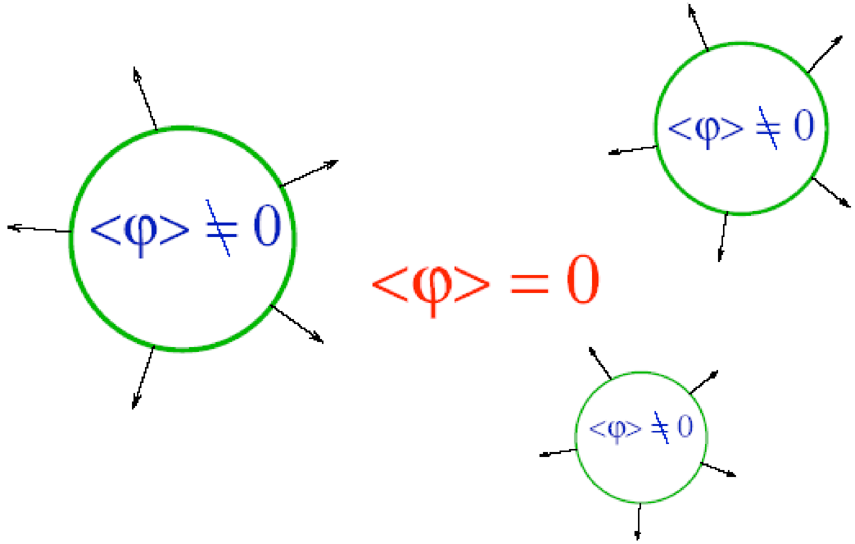
- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order.

Cohen, Kaplan and Nelson, hep-ph/9302210; A. Riotto, M. Trodden, hep-ph/9901362;
Carena, Quiros, Riotto, Moreno, Vilja, Seco, C.W.'97--'03,

Konstantin, Huber, Schmidt,Prokopec'00--'06

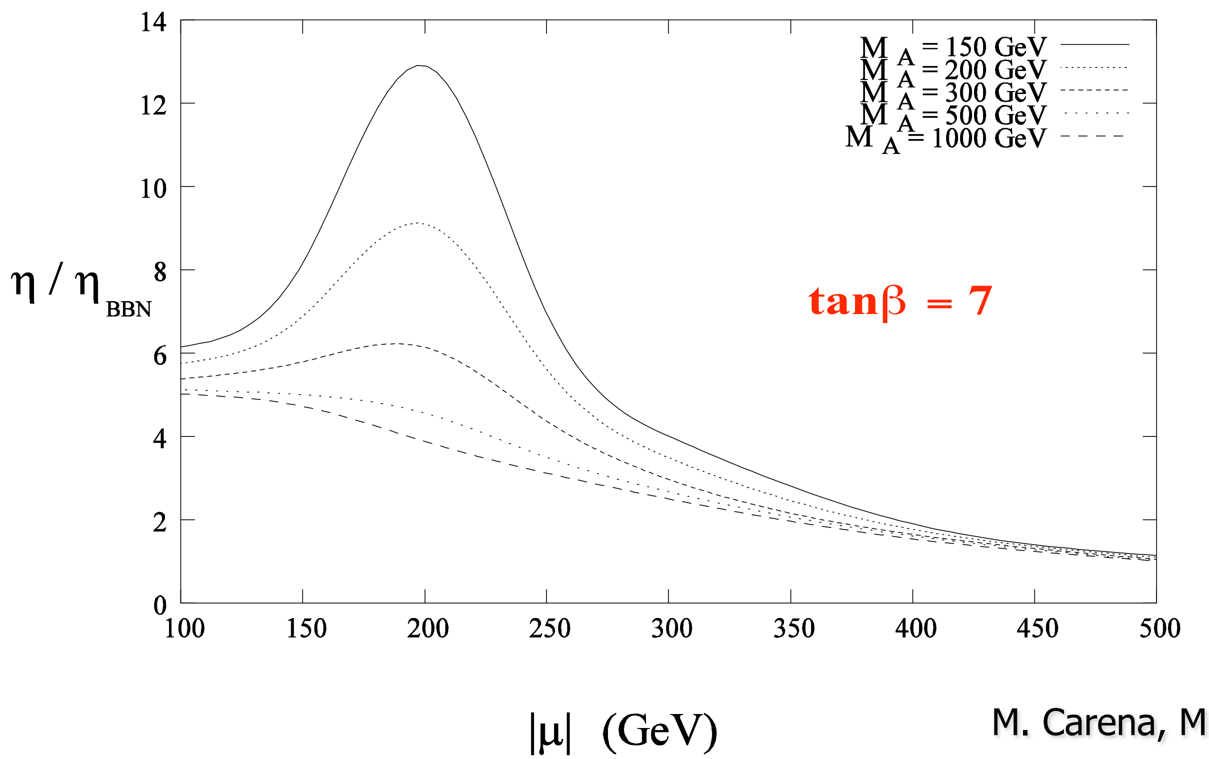
Cirigliano, Profumo, Ramsey-Musolf'05--06

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

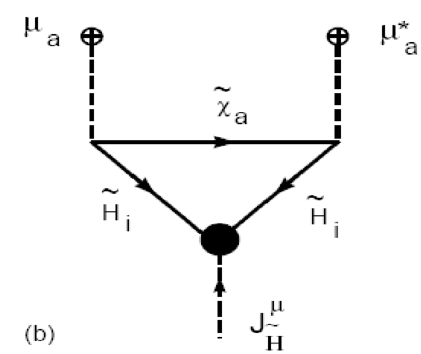


Generation of Baryon Asymmetry

- 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 $\tan\beta$



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



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

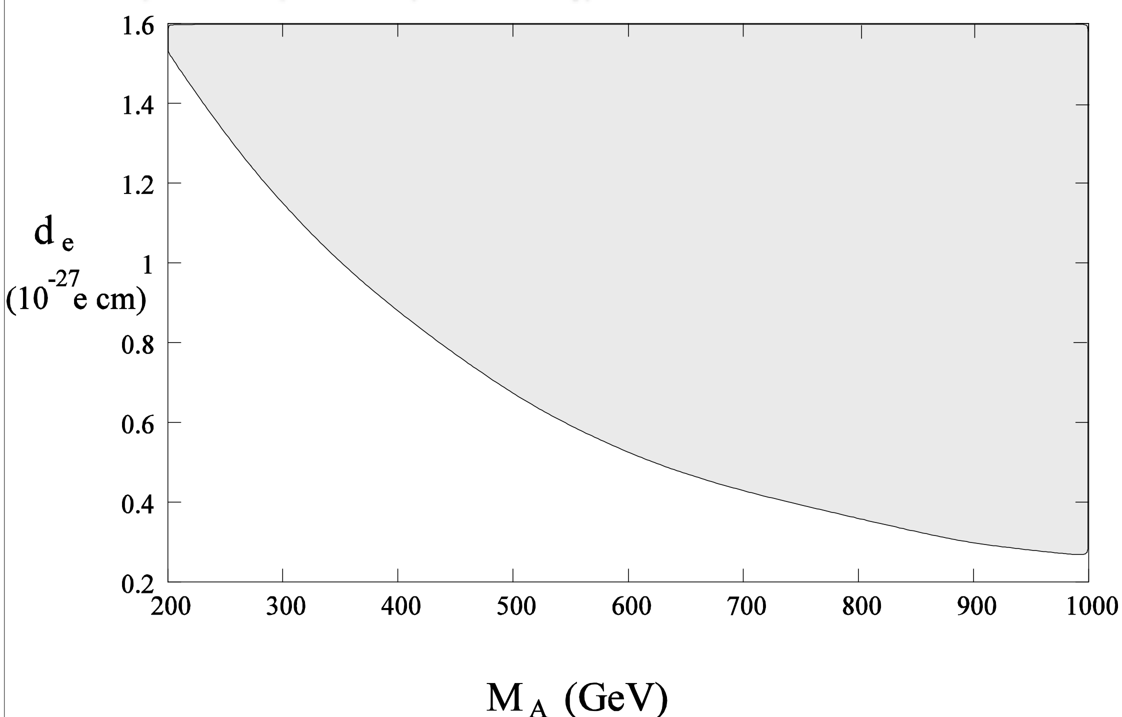
Balazs, Carena, Menon, Morrissey, C.W.'05

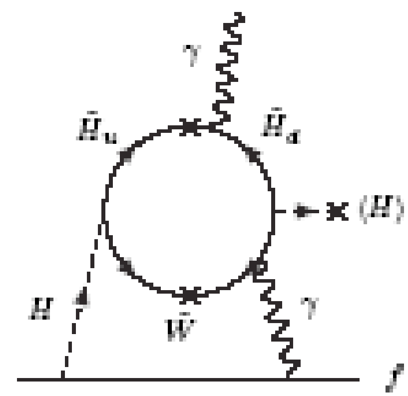
Electron electric dipole moment

- Asssuming that sfermions are sufficiently heavy, dominant contribution comes from two-loop effects, which depend on the same phases necessary to generate the baryon asymmetry. (Low energy spectrum is like a Stop plus Split Supersymmetry).
- Chargino mass parameters scanned over their allowed values. The electric dipole moment is constrained to be smaller than

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

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



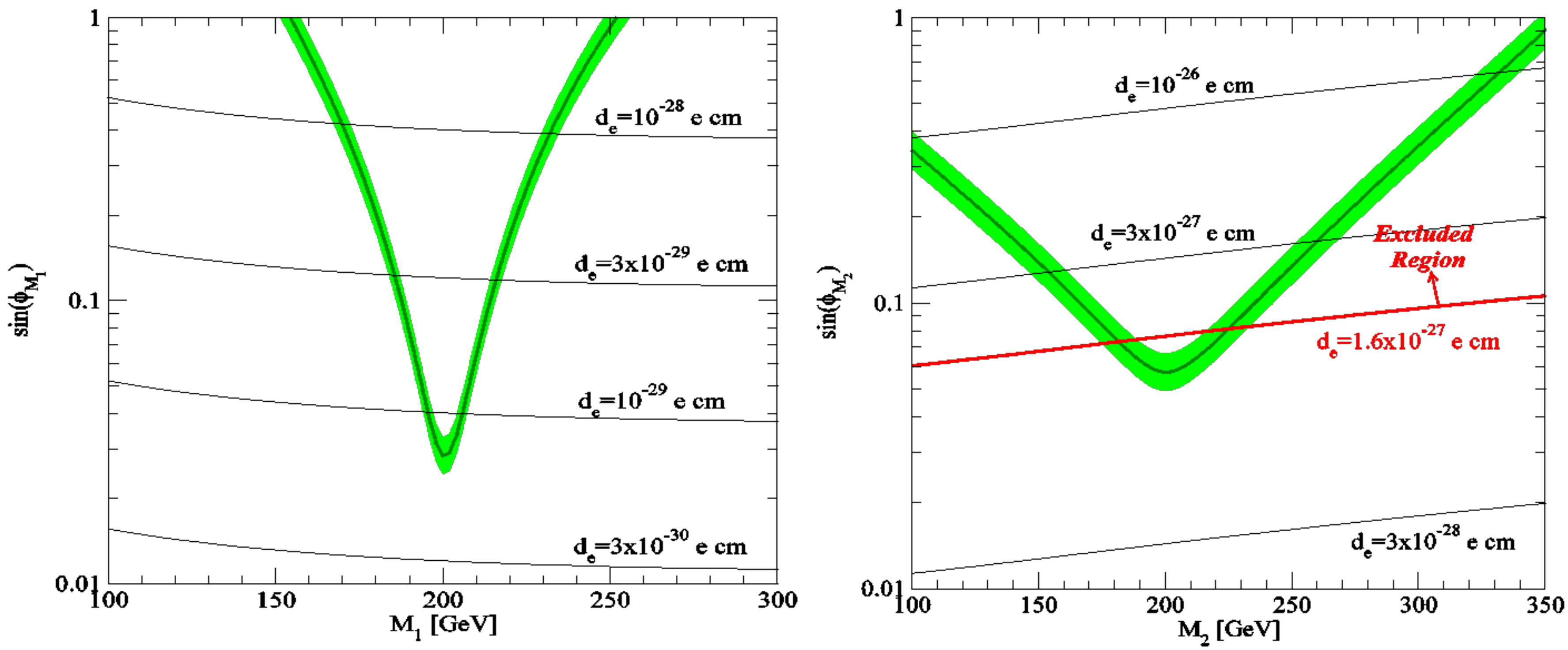


Chang, Keung, Pilaftsis '99, Pilaftsis '99
Chang, Chang, Keung '00, Pilaftsis '02

Comparing bino- and wino-driven EWB

- Electron EDM:

Yingchuan Li's talk



Ref. point: $M_1 = 95\text{GeV}, M_2 = 190\text{GeV}, |\mu| = 200\text{GeV}, \tan\beta = 10, m_{A^0} = 300\text{GeV}$

Cirigliano, Profumo, Ramsey-Musolf'06

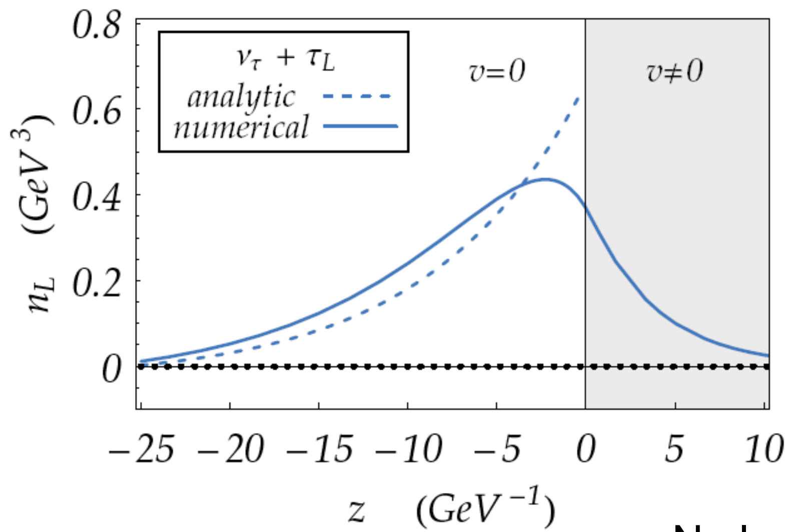
YL, S. Profumo, M. Ramsey-Musolf, arXiv:0811.1987

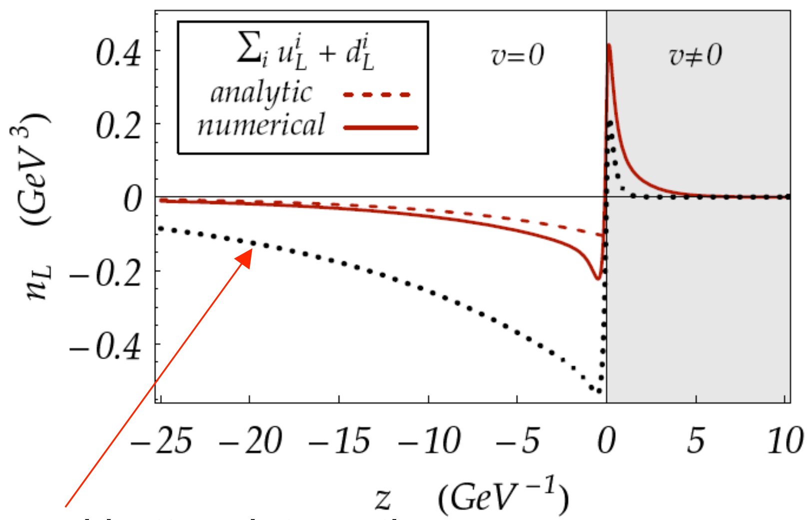
Dan J.H. Chung's talk

Detailed Profile of Lepton Mediated

μ	120 GeV	$M_{\tilde{T}}^2$	$-(60\text{ GeV})^2$
M_1	120 GeV	$M_{\tilde{B}}^2$	$(100\text{ GeV})^2$
M_2	250 GeV	$M_{\tilde{R}}^2$	$(300\text{ GeV})^2$
$\tan\beta$	20	m_A	150 GeV

[DJHC, B. Garbrecht, M. Ramsey-Musolf, S. Tulin 09]





No lepton and bottom interactions

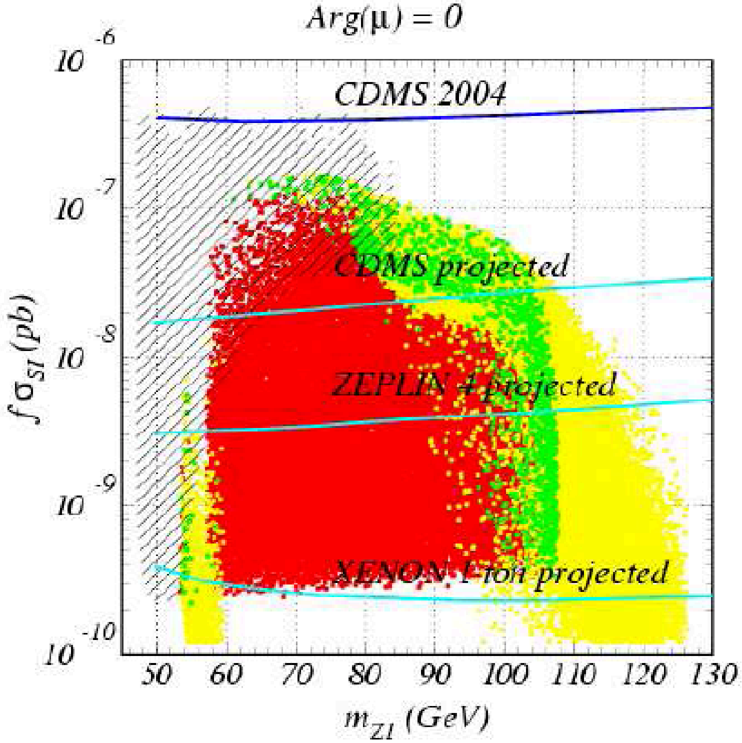
$$n_B/s \simeq \begin{cases} 8 \times \sin\phi_1 \; (n_B/s)_{\rm CMB} & \text{Bottom/tau Yukawas included} \\ -14 \times \sin\phi_1 \; (n_B/s)_{\rm CMB} & \text{Bottom/tau Yukawas neglected} \end{cases}$$

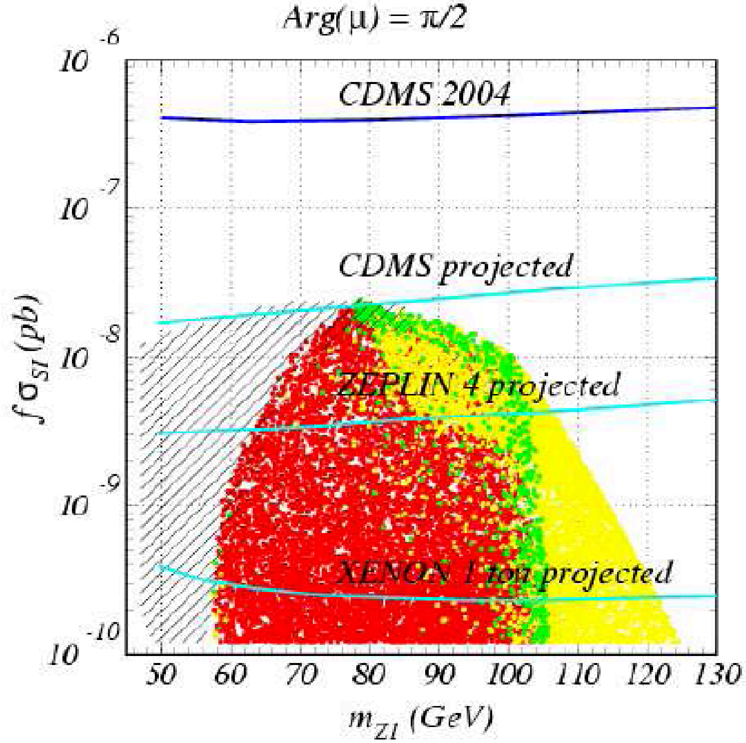
Compatible with EDM if $\arg(M_2\mu) \neq \arg(M_1\mu)$ [Li, Profumo, Ramsey-Musolf 08]

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 extensions of the MSSM, with additional Singlets

A. Menon, D. Morrissey and C.W., PRD70:035005, 2004
C. Balazs, M. Carena, A. Freitas, C.W., **JHEP 0706:066 (2007)**
Kang, Langacker, Li and Liu, hep-ph/0402086.
Barger et al '07

Early work in this direction:

M. Pietroni '93
Davies et al. '96
Huber and Schmidt '00

Minimal Extension of the MSSM

Dedes et al. , Panagiotakopoulos, Pilaftsis'01

- Superpotential restricted by Z_5^R or Z_7^R symmetries

$$W = \lambda S H_1 H_2 + \frac{m_{12}^2}{\lambda} S + y_t Q H_2 U$$

- No cubic term. Tadpole of order cube of the weak scale, instead

- Discrete symmetries broken by tadpole term, induced at the sixth loop level. Scale stability preserved

- Similar superpotential appears in Fat-Higgs models at low energies

Harnik et al. '03

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

Electroweak Phase Transition

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

- In the nMSSM, the potential has the approximate form:

(*i.e.* tree-level + dominant one-loop high-T terms)

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

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

- Along the trajectory $\frac{\partial V}{\partial \phi_s} = 0$, the potential reduces to

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

Non-renormalizable potential controlled by m_s. Strong first order phase transition induced for small values of m_s. Contrary to the MSSM case, this is induced at tree level.

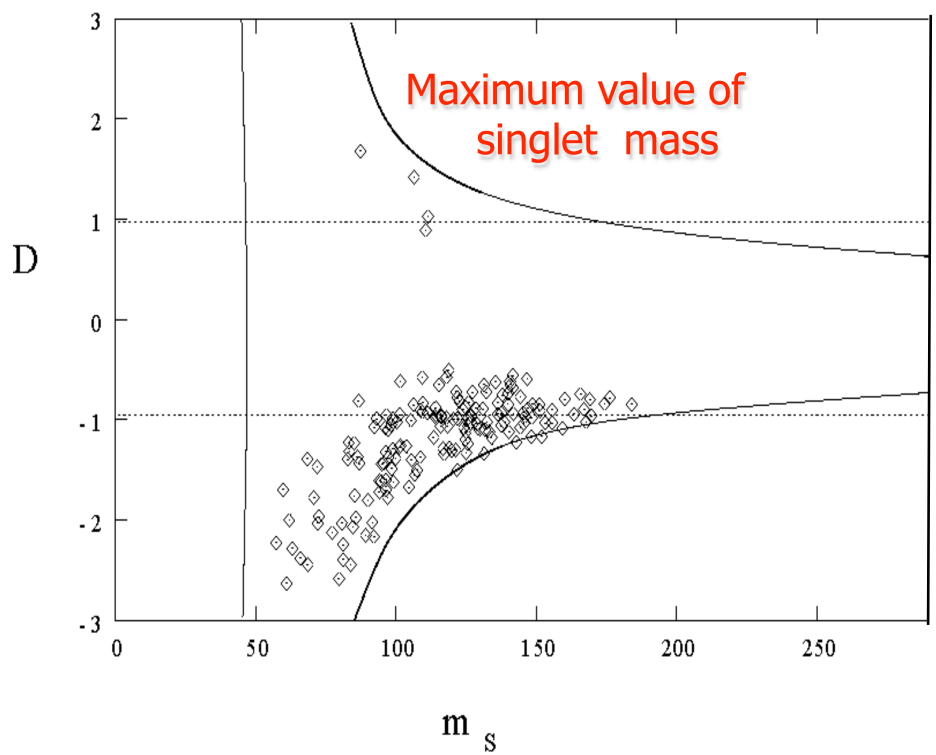
Parameters with strongly first order transition

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

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

Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



Neutralino Mass Matrix

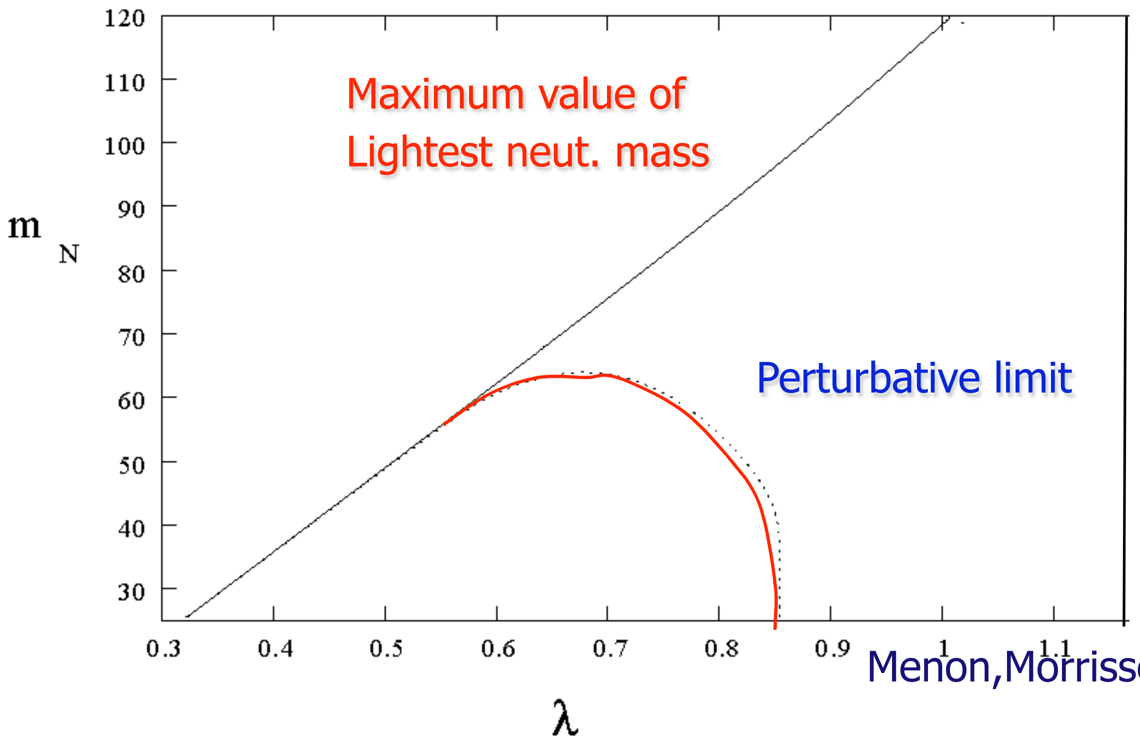
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_{\rm W} M_{\rm Z} & s_\beta s_{\rm W} M_{\rm Z} & 0 \\ 0 & M_2 & c_\beta c_{\rm W} M_{\rm Z} & -s_\beta c_{\rm W} M_{\rm Z} & 0 \\ -c_\beta s_{\rm W} M_{\rm Z} & c_\beta c_{\rm W} M_{\rm Z} & 0 & \lambda v_{\rm s} & \lambda v_2 \\ s_\beta s_{\rm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

In the nMSSM, $\kappa = 0$.

Upper bound on Neutralino Masses

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

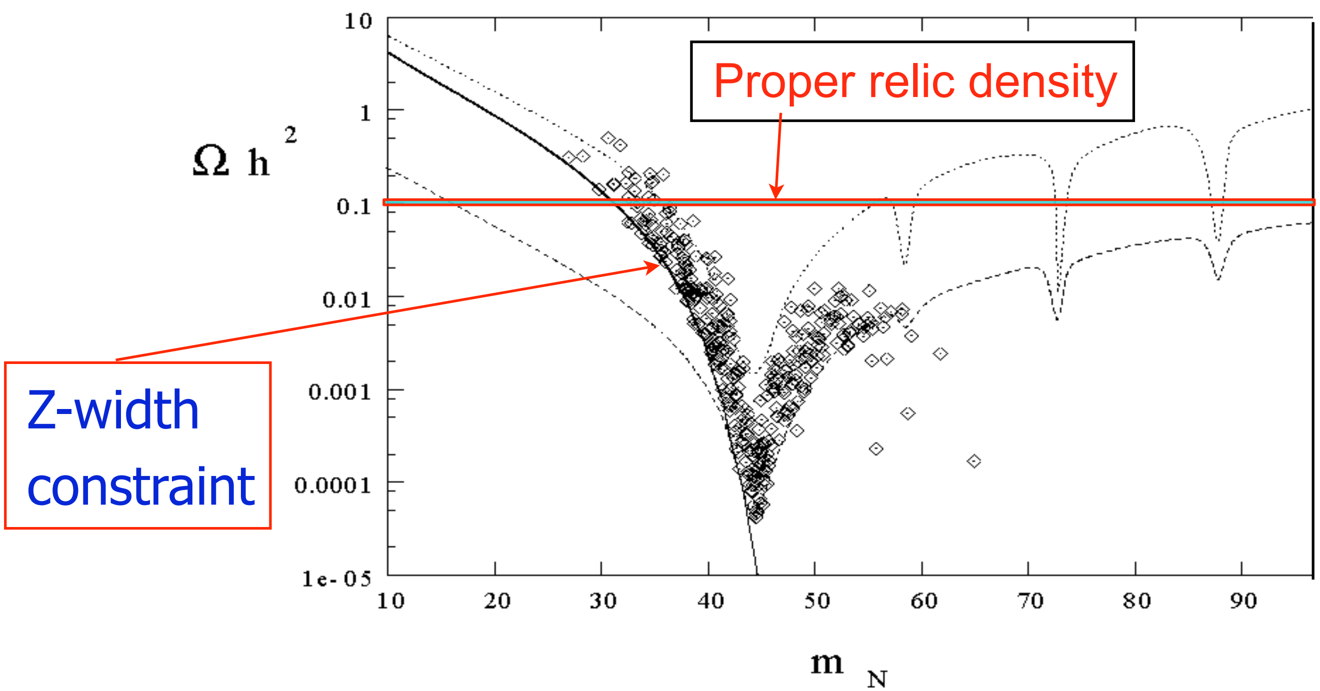
Values of neutralino masses below dotted line consistent with perturbativity constraints.



Menon,Morrissey,C.W.'04

Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are imposed.
Z-boson and Higgs boson contributions shown to guide the eye.
Neutralino masses between 35 GeV and 45 GeV.
Higgs decays affected by presence of light neutralinos. Large invisible decay rate.



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Higgs Searches

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

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

- The value of η varies between 0.5 and 0.9 for the lightest CP-even Higgs boson.
- Minimal luminosity required to exclude (discover) such a Higgs boson, with mass lower than 130 GeV:

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

Weak Boson Fusion: Eboli and Zeppenfeld '00, Higgs Working Group, Les Houches'01

Associated Production : Davoudiasl, Han, Logan, hep-ph/0412269 Tevatron ?

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

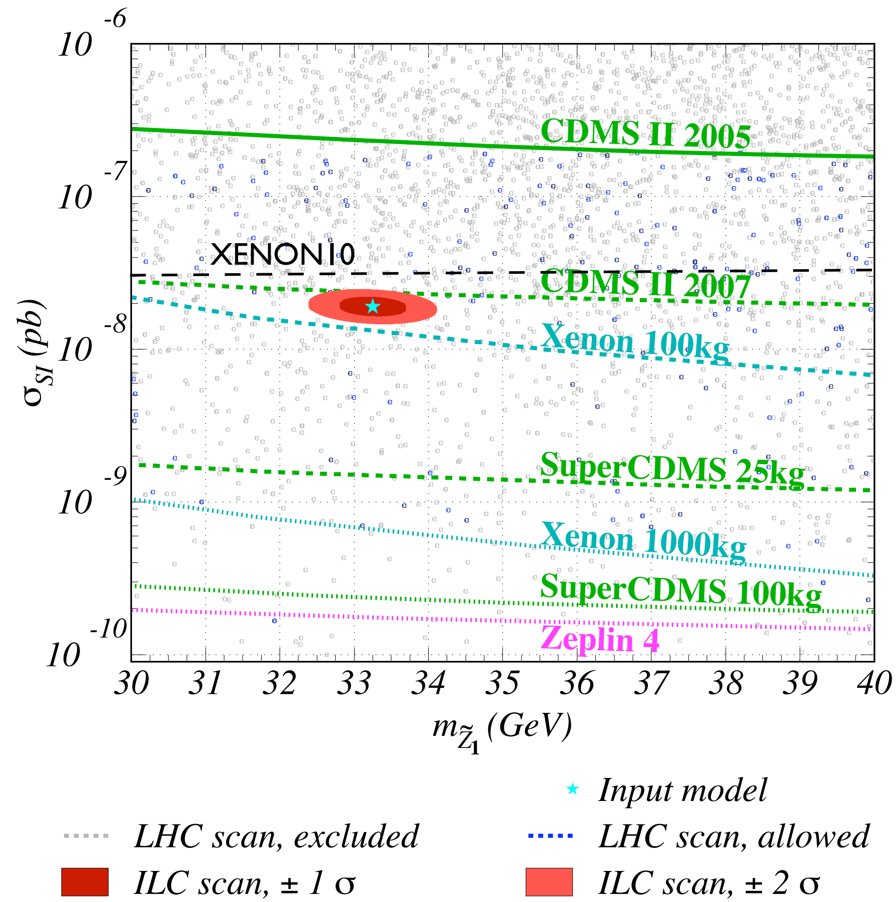
Direct Dark Matter Detection

- Since dark matter is mainly a mixing betwen 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

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

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



CP-Violating Phases

The conformal (mass independent) sector of the theory is invariant under an R-symmetry and a PQ-symmetry, with

	$\hat{H}_1$	$\hat{H}_2$	$\hat{S}$	$\hat{Q}$	$\hat{L}$	$\hat{U}^c$	$\hat{D}^c$	$\hat{E}^c$	$\hat{B}$	$\hat{W}$	$\hat{g}$	$W_{\rm nMSSM}$
$U(1)_R$	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

$$\arg(m_{12}^* t_s a_\lambda), \quad \leftarrow \text{Higgs Sector}$$

$$\arg(m_{12}^* t_s M_i), \quad i = 1, 2, 3, \quad \leftarrow \text{Chargino-Neutralino Sector}$$

$$\arg(m_{12}^* t_s A_u), \quad (3 \text{ generations}), \quad \leftarrow \text{S-up sector}$$

$$\arg(m_{12}^* t_s A_d), \quad (3 \text{ generations}), \quad \leftarrow \text{S-down sector}$$

Choice of CP-violating Phases

- We will assume phases in the (universal) gaugino mass parameters

- This choice leads to signatures in electric dipole moments similar to those ones present in the MSSM

- Choosing the phase in the Higgs sector, however, may lead to a realistic scenario. It is an open question if this can be tested.

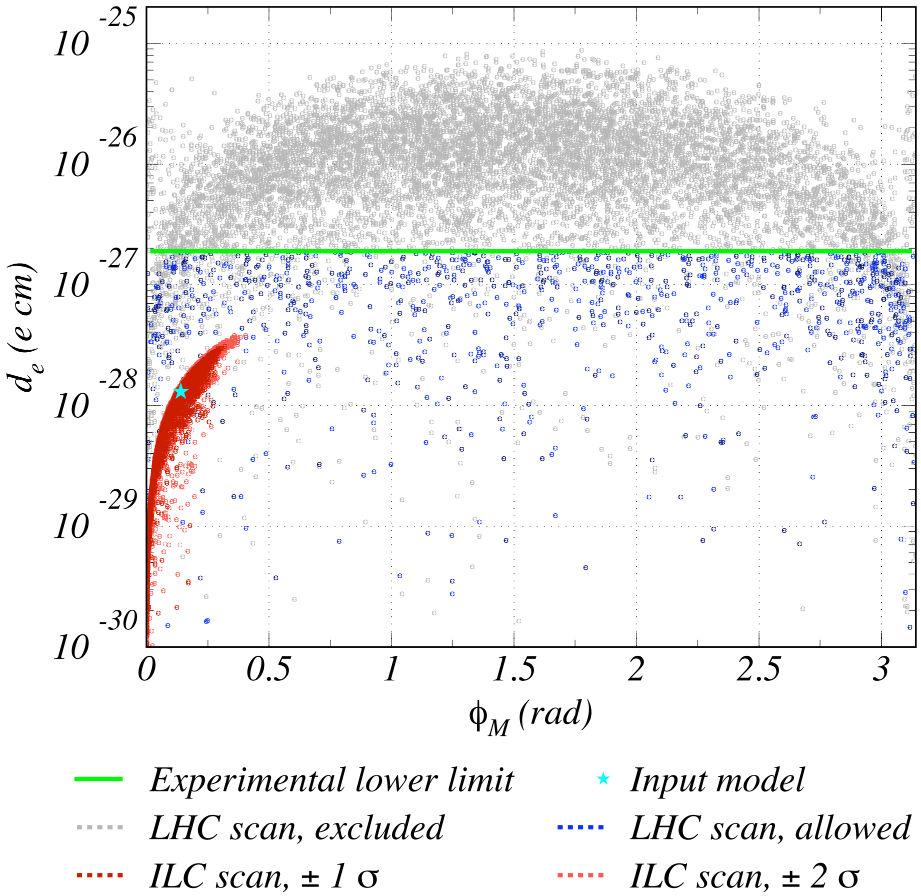
Huber, Konstantin, Prokopec, Schmidt'06

- 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



Conclusions

- Electroweak Baryogenesis in the MSSM demands a light Higgs and a light stop, with masses lower than about 125 GeV.

- Dark Matter : Even lighter neutralinos. If coannihilation channel relevant, searches for stops at hadron colliders difficult. Alternative promising search channels exist and should be explored.

- To be tested by electron e.d.m. experiments, Tevatron, LHC 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.

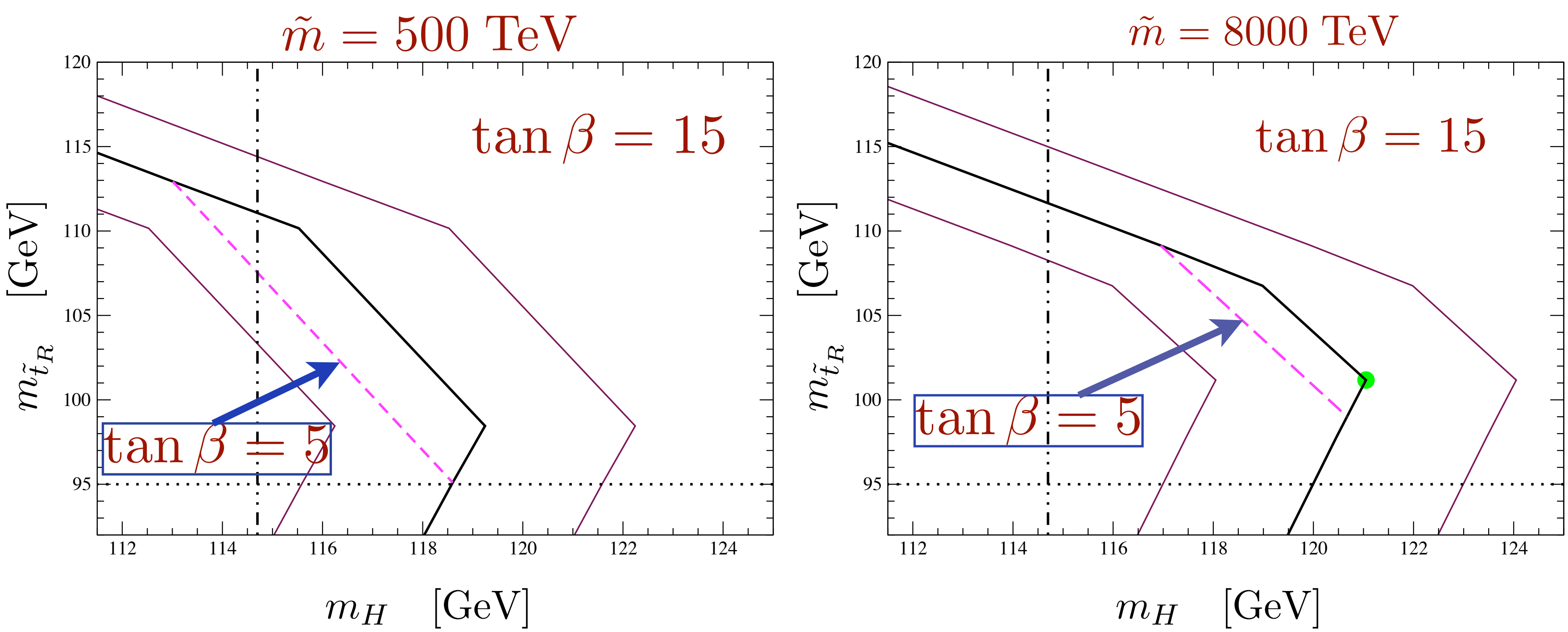
Backup Slides

Allowed parameter space for Electroweak Baryogenesis

M. Carena, G. Nardini, M. Quiros, C.W. '08

- Values of $\tan\beta \geq 5$ preferred to keep the Higgs mass large
- Values of At cannot be too large to keep the phase transition strongly first order
- Higgs remains light, with values below 125 GeV.

$$m_Q = m_{\tilde{q}} = m_A = m_{\tilde{l}} = \tilde{m}$$



Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controled by m_S^2)
- They mix with standard CP-even and CP-odd states in a way proportional to λ and a_λ
- Values of λ restricted to be lower than 0.8 in order to avoid Landau-pole at energies below the GUT scale.
- As in the MSSM, upper bound on Higgs that couples to weak bosons
- Extra tree-level term helps in avoiding LEP bounds.

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

Espinosa,Quiros ’98; Kane et al. ;98

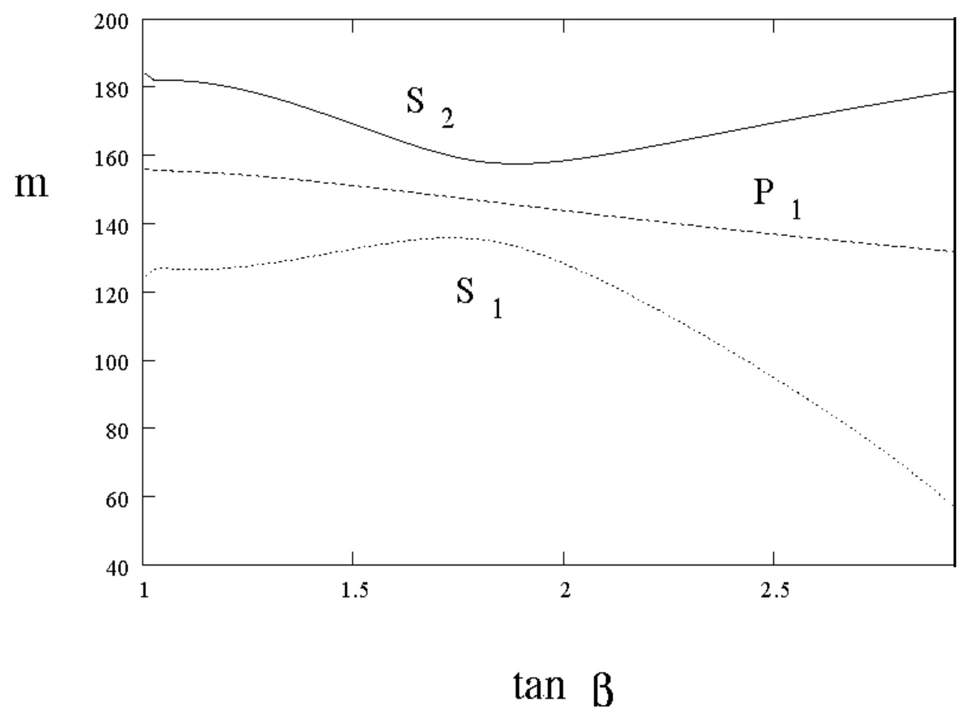
Light Higgs boson masses

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

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

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

$\lambda = 0.7$



Menon,Morrissey,C.W.'04