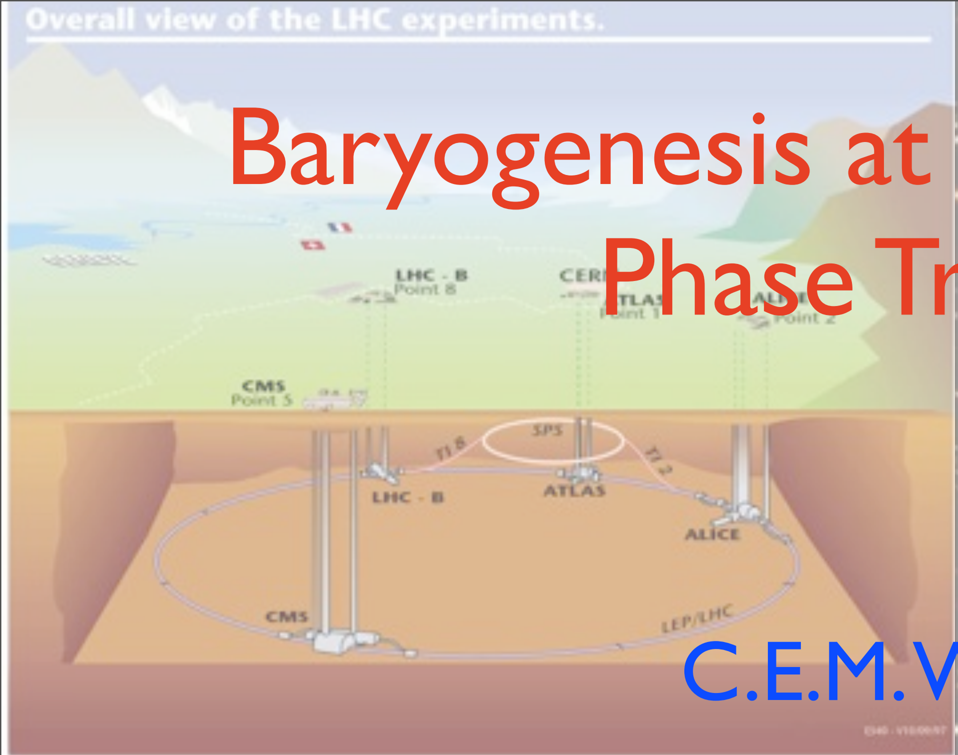
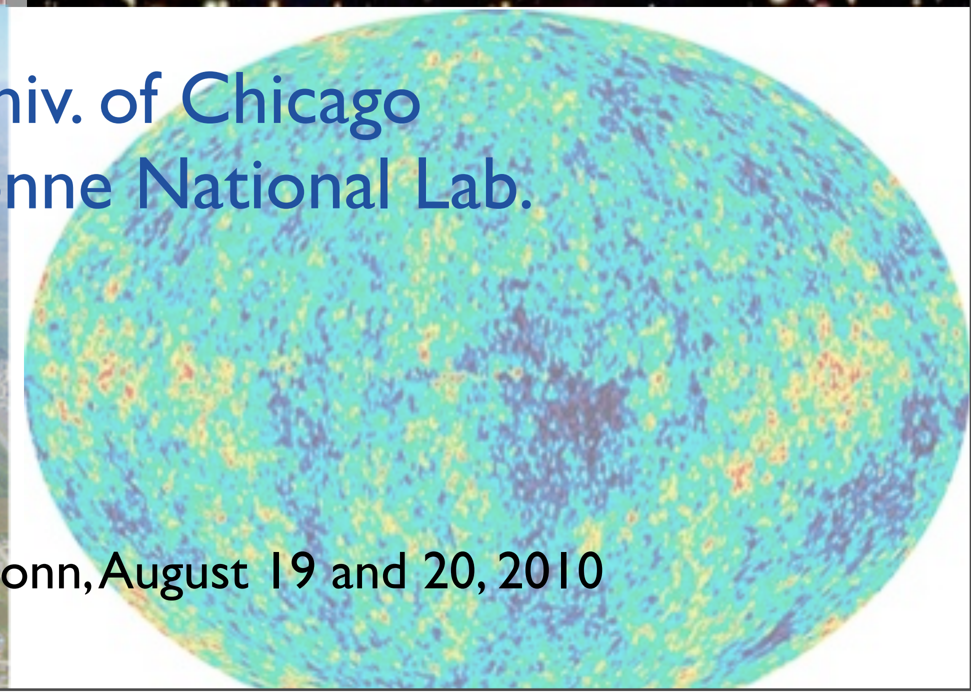
Baryogenesis at the Electroweak Phase Transition



C.E.M. Wagner

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



Pre-SUSY10 Conference, Bonn, August 19 and 20, 2010

Based on work done in longtime collaboration with M. Quiros and M. Carena, and the following, more 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

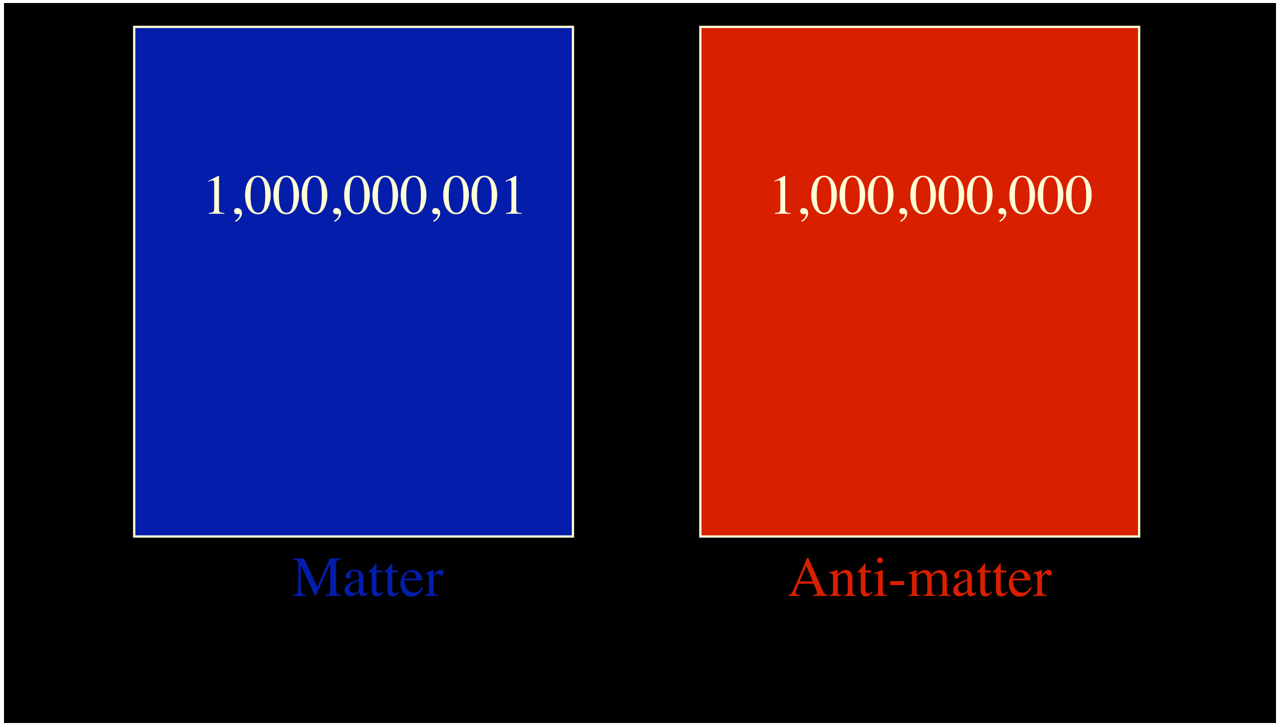
$$\frac{n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} \simeq 10^{-20}$$

- How does this compare to experiment ? First of all, we have the problem of the unobserved antimatter. Secondly, 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 may be generated primordially : Baryogenesis



Murayama

Assuming the existence of a small primordial asymmetry solves the puzzle. Indeed, matter-antimatter annihilation can now occur efficiently and finally the small asymmetry will lead to observable matter 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.

- Anomalous processes violate both baryon and lepton number, but preserve B – L. Relevant for the explanation of the Universe baryon asymmetry.

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

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

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

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

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.

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

- At zero T baryon number violating processes highly suppressed

- At finite T, only Boltzman suppression

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

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

Baryon Asymmetry Preservation

If Baryon number generated at the electroweak phase transition,

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

Kuzmin, Rubakov and Shaposhnikov, '85—'87

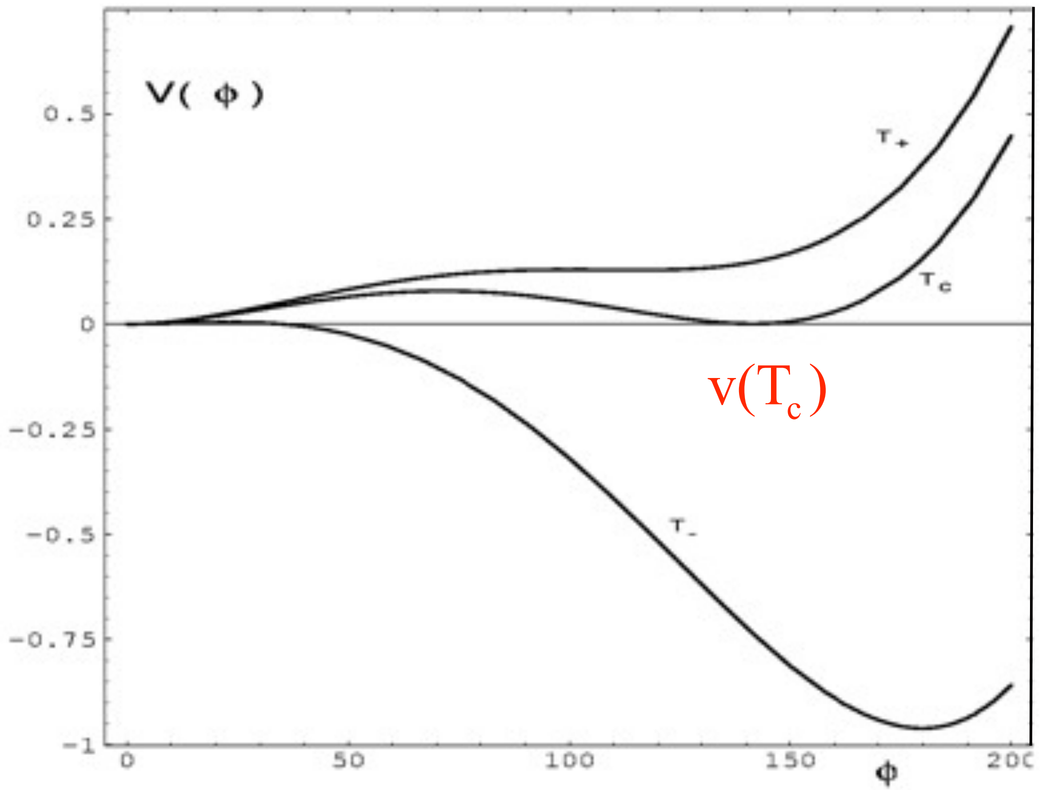
Baryon number erased unless the baryon number violating processes are out of equilibrium in the broken phase.

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

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

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

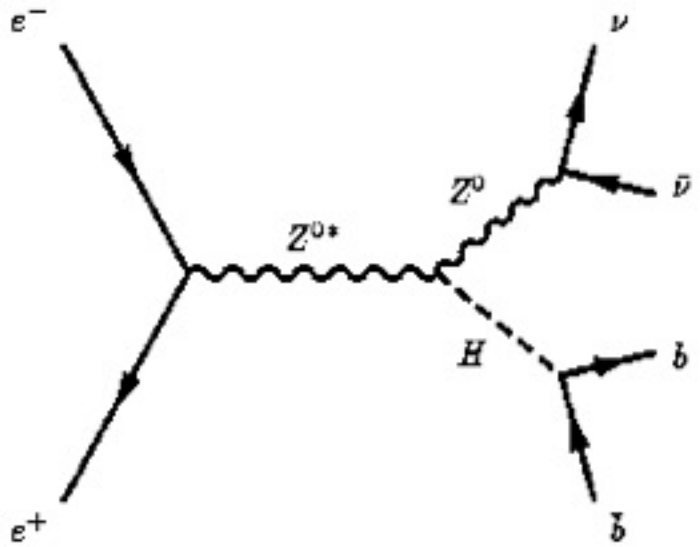
E receives contributions proportional to the sum of the cube of all light boson particle couplings

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

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

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

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

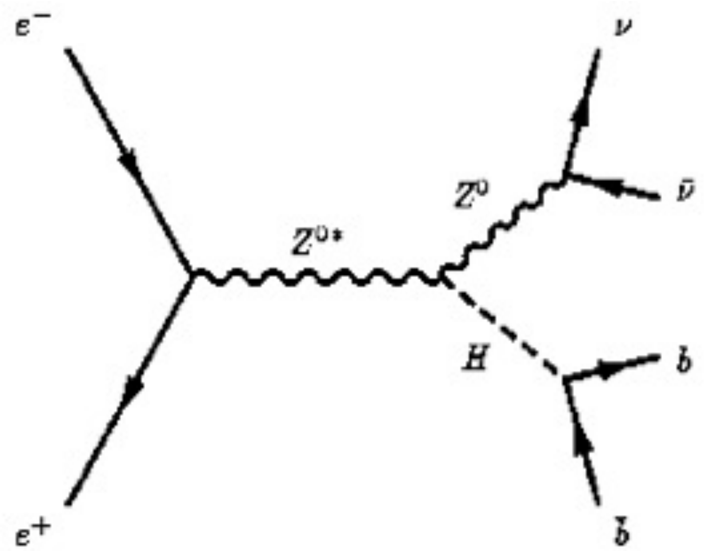


At LEP energies mainly into pairs of b quarks

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

Electroweak Baryogenesis in the SM is ruled out

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

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

$$J \equiv \pm Im[K_{li}K_{lj}^* K_{l'j} K_{l'i}^*] = c_1 c_2 c_3 s_1^2 s_2 s_3 s_\delta$$

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 would be possible in the presence of 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,

$$\mathbf{M}^2_{\tilde{t}} = \begin{pmatrix} m_Q^2 + m_t^2 + D_L & m_t X_t \\ m_t X_t & m_U^2 + m_t^2 + D_R \end{pmatrix}$$

where the off-diagonal term depends on the stop-Higgs trilinear couplings, $X_t = A_t - \mu^* / \tan\beta$

- For large CP-odd Higgs boson masses, and with $M_S = m_Q = m_U$ dominant one-loop corrections are given by,

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$

- After two-loop corrections:

M.Carena, J.R. Espinosa, M. Quiros, C.W. '95
M. Carena, M. Quiros, C.W.'95

- upper limit on Higgs mass:

$m_h \lesssim 135$ GeV

$M_S = 1 \to 2$ TeV $\Longrightarrow \Delta m_h \simeq 2 - 5$ GeV

$\Delta m_t = 1$ GeV $\Longrightarrow \Delta m_h \sim 1$ GeV

For Baryogenesis $m_U^2 < 0, \quad m_Q > 6$ TeV

MSSM Higgs Boson Spectrum

- Two Higgs doublets: Two CP-even, a CP-odd and a charged Higgs. The CP-even Higgs bosons close to the decoupling limit

$$h \simeq \cos\beta \; Re(H_1^0) + \sin\beta \; Re(H_2^0)$$

$$H + iA \simeq \sin\beta \; H_1^0 - \cos\beta \; H_2^0$$

where $\boxed{\tan\beta = \frac{v_2}{v_1}}$ $\qquad < H_i^0 >= v_i$

- Similarly, the charged CP-odd and charged Higgs bosons

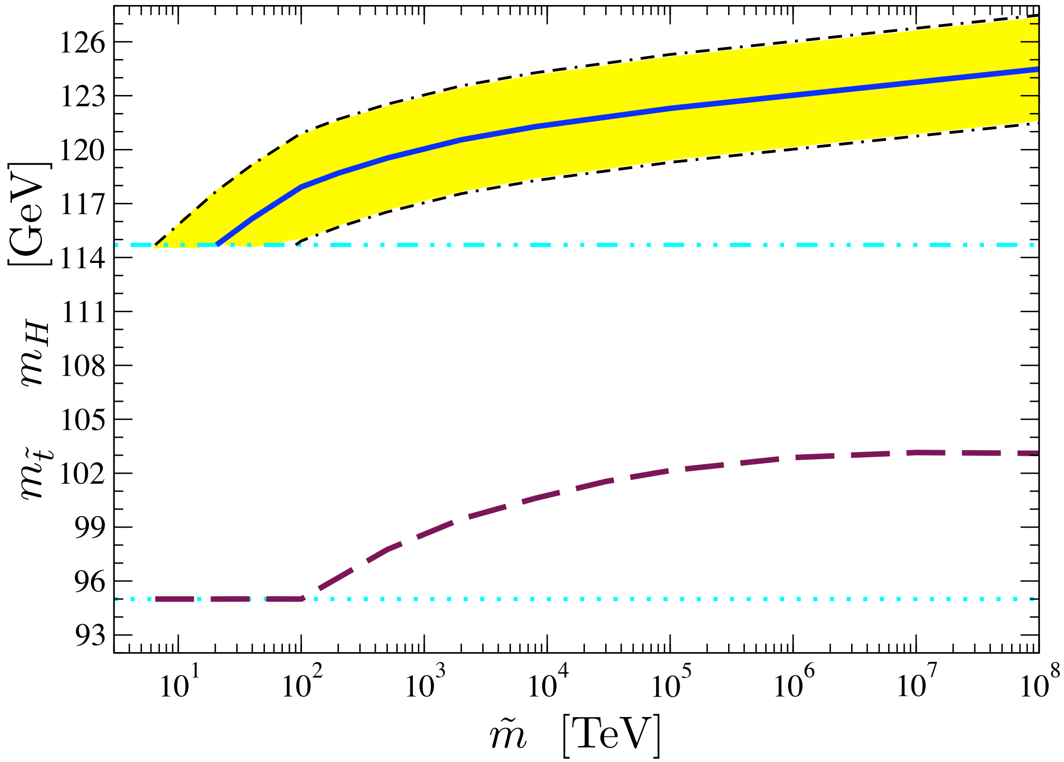
$$H^\pm = \sin\beta H_1^\pm - \cos\beta H_2^\pm$$

$$m_H^2 \simeq m_A^2 \qquad m_{H^+}^2 \simeq m_A^2 + m_W^2$$

Upper Bound on the Higgs Mass. Largest values of At

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

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



Computation using renormalization group improved Higgs and stops effective potentials

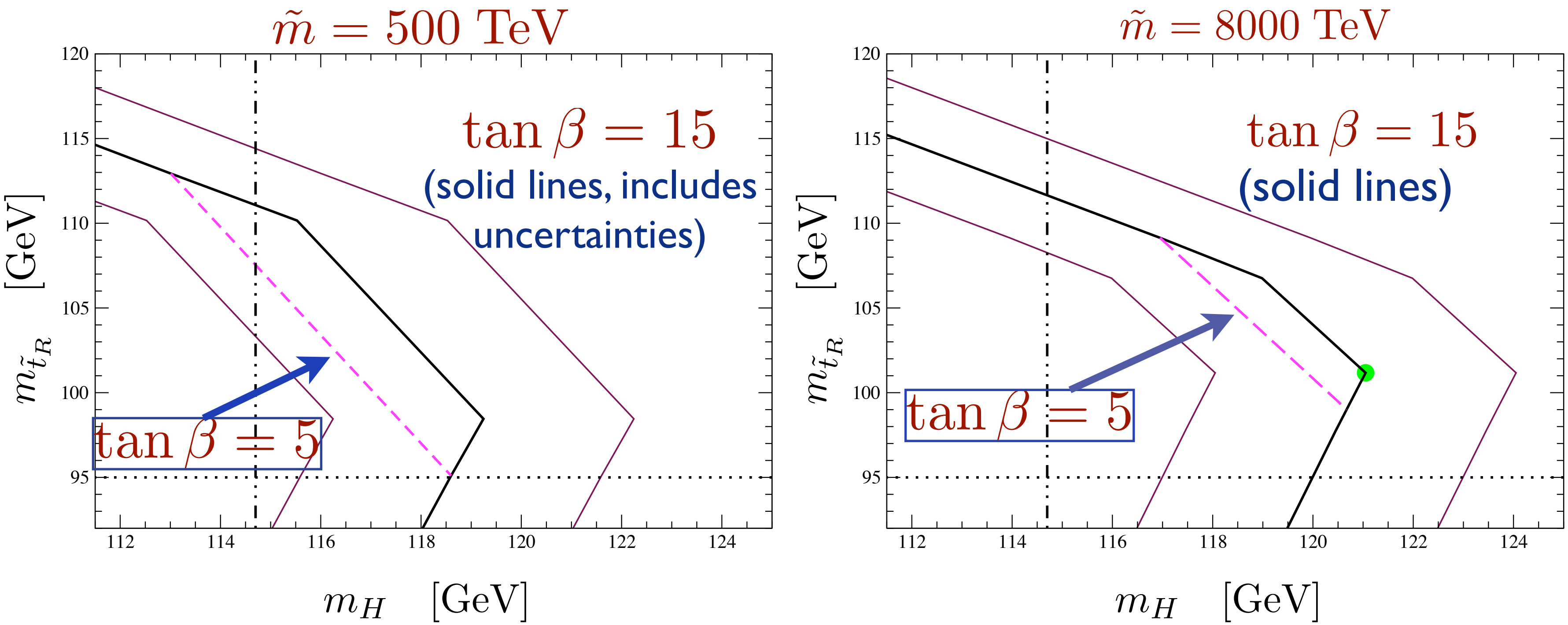
Both the Higgs and the lightest stop must be lighter than about 125 GeV for the mechanism to work. Values of the Higgs mass above 120 GeV may only be obtained for very large values of $\tilde{m}$.

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.

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



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: If Higgs mass is below 120 GeV, 3 sigma evidence with about 10 fb^{-1} may be possible.

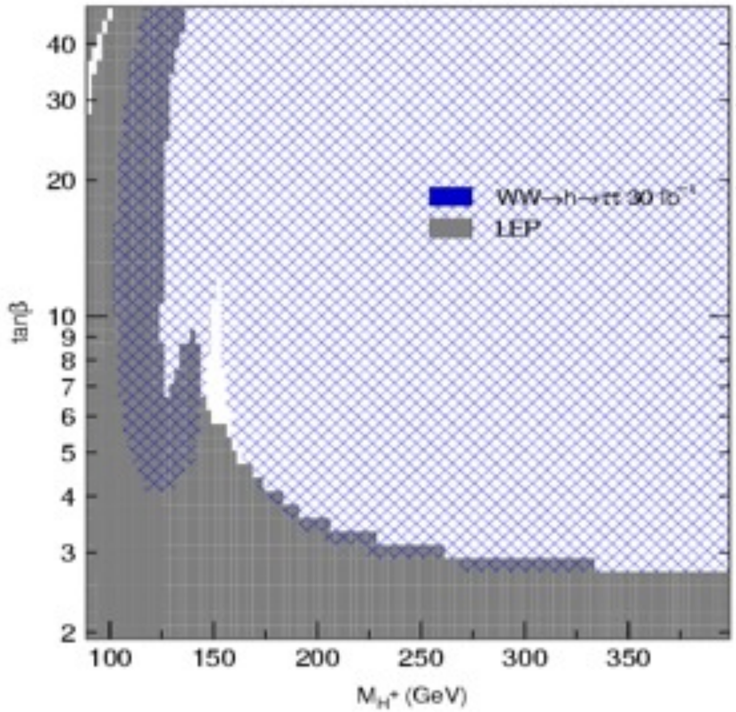
Detecting a Higgs signature will mean that the Higgs has relevant strong (SM-like) couplings to W and Z, and will require increase in efficiency or higher luminosities

2. A definitive test of this scenario will come at the LHC with the first 30 fb^{-1} of data

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

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

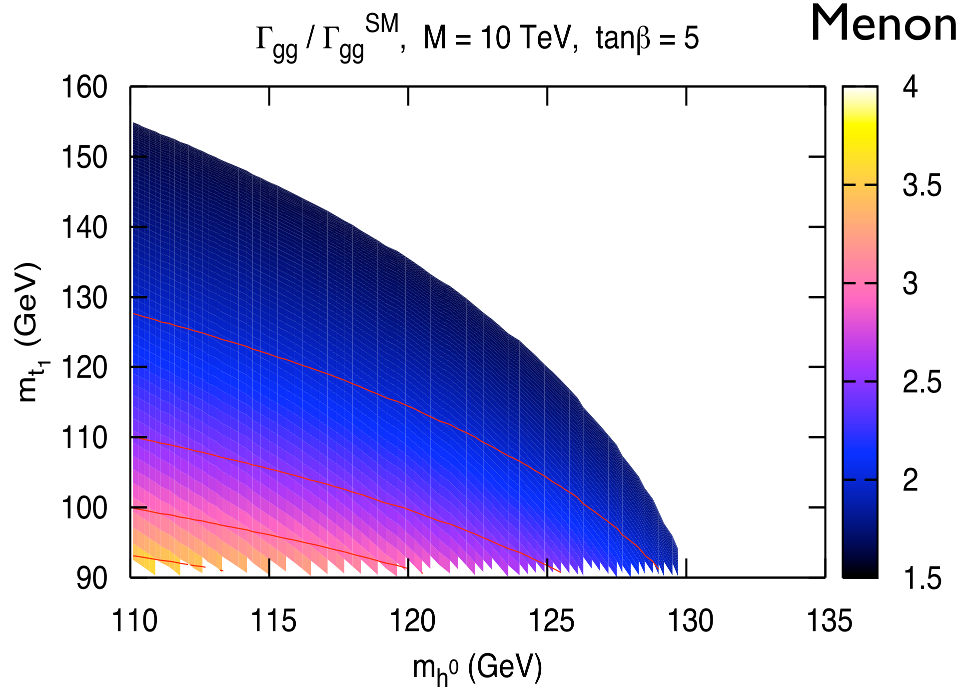
3. $h \to \gamma\gamma$ and $h \to W^+W^-$ proceeding from gluon fusion also relevant.
Light stop enhancement of gluon fusion



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

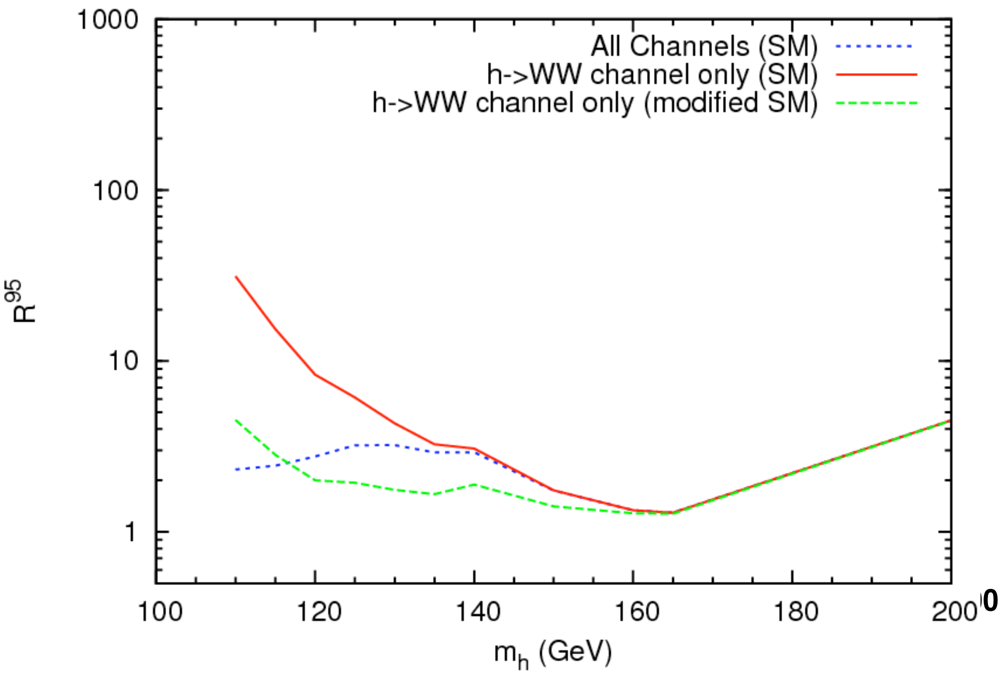


- MSSM EWBG Region: $m_{\tilde{t}_1},\, m_{h^0} \lesssim 125\,\text{GeV}$.

[Carena,Nardini,Quirós,Wagner '08]

Tevatron Search Prospects

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



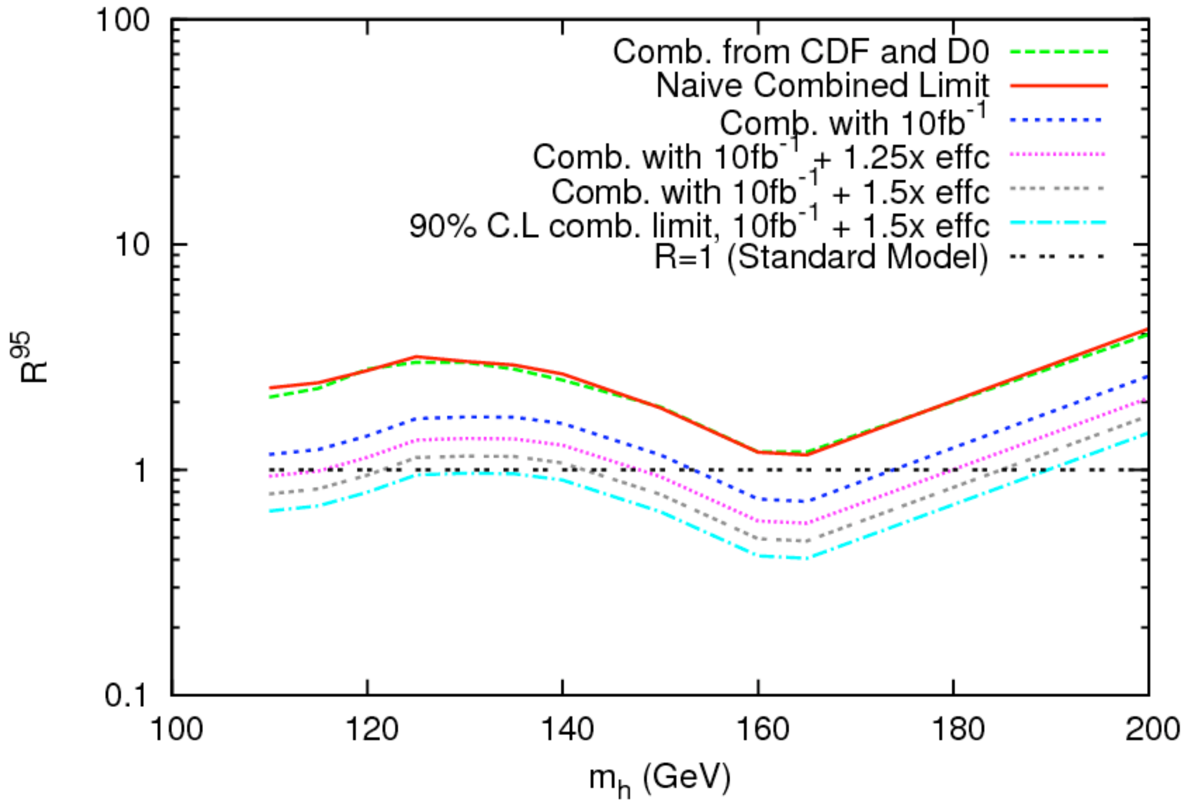
- $\sigma\, BR(h^0 \to WW)/\sigma\, BR_{SM} \lesssim 8$ for $m_{h^0} < 125\,\mathrm{GeV}$.

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

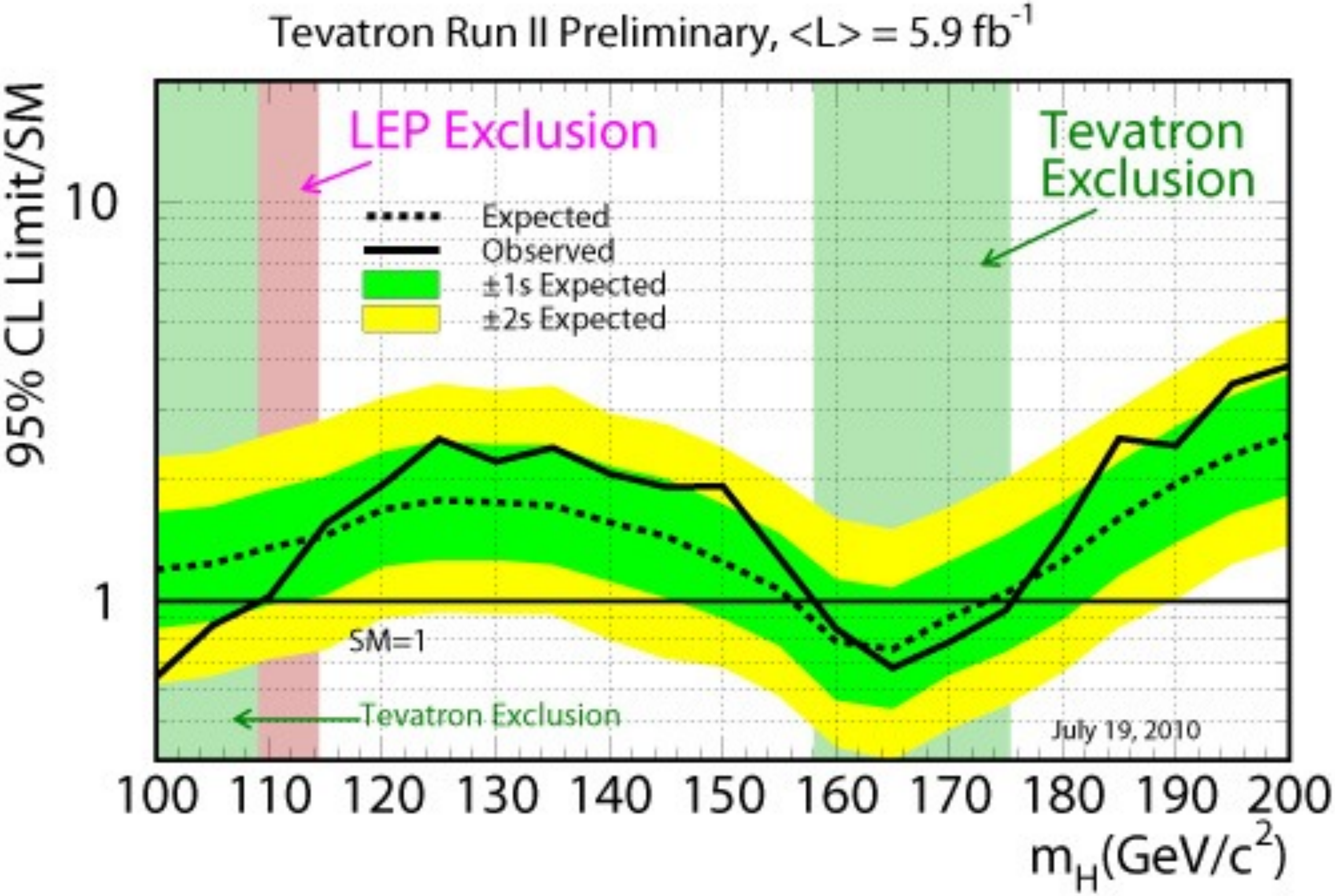
- Tevatron could be sensitive with $10\, fb^{-1}$.

Prospects for Higgs Searches at the Tevatron

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



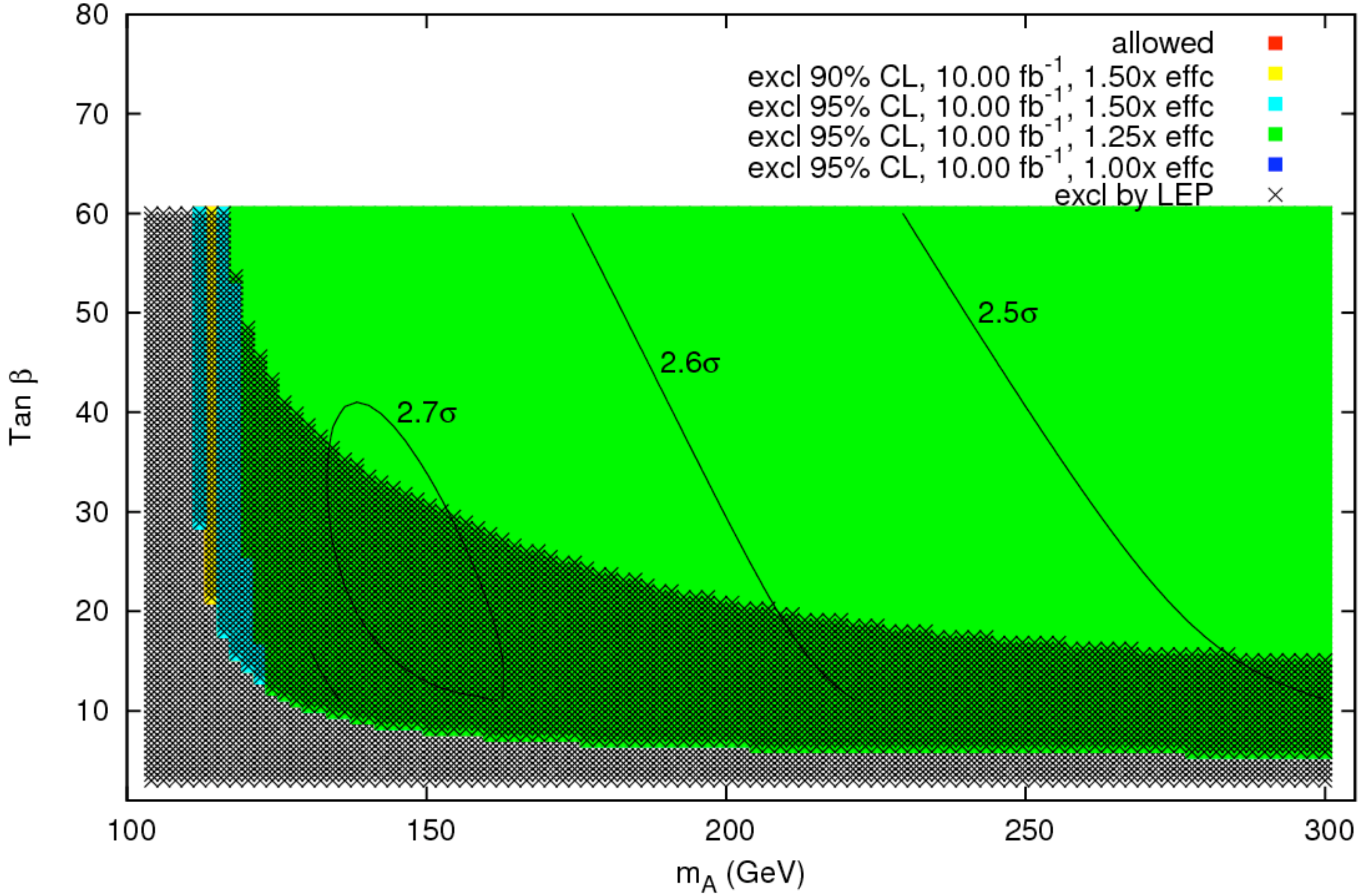
Running until the end of 2011 the Tevatron should collect more than 10 fb^{-1}
With expected detector/analysis performance, $m_H < 185$ GeV may be probed.



Tevatron Run II Preliminary, <L> = 5.9 fb^{-1}
95% CL Limit/SM
10
1
LEP Exclusion
Tevatron
Exclusion
Expected
Observed
±1s Expected
±2s Expected
SM=1
Tevatron Exclusion
July 19, 2010
100
110
120
130
140
150
160
170
180
190
200
m_H(GeV/c^2)

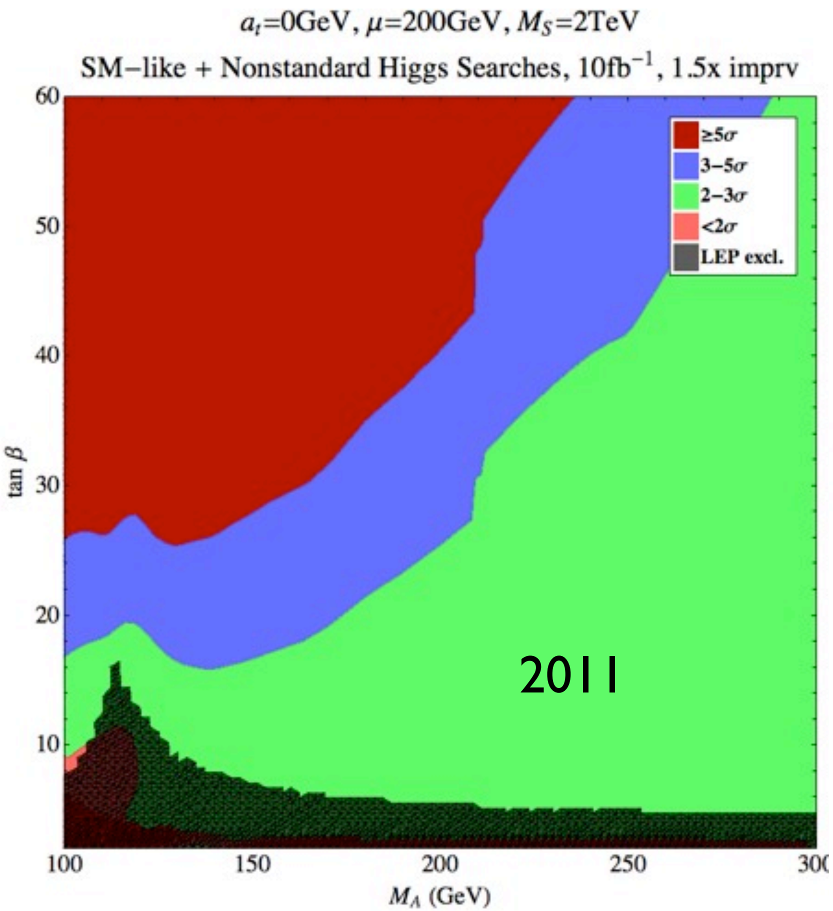
Minimal Mixing Scenario

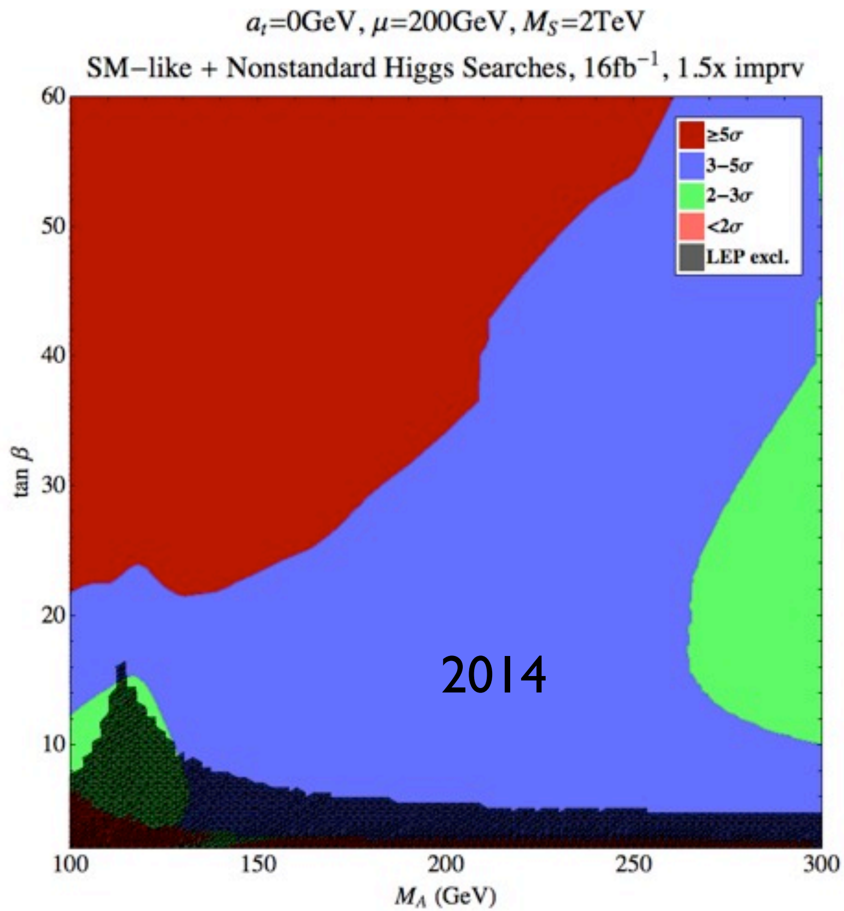
P. Draper, T. Liu and C.W. '09



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).

Combination with Non-Standard Higgs channels





Combination enlarges the region where evidence may be achieved in a considerable way

(

Dark Matter

Results from WMAP

Ω_i : Fraction of critical density

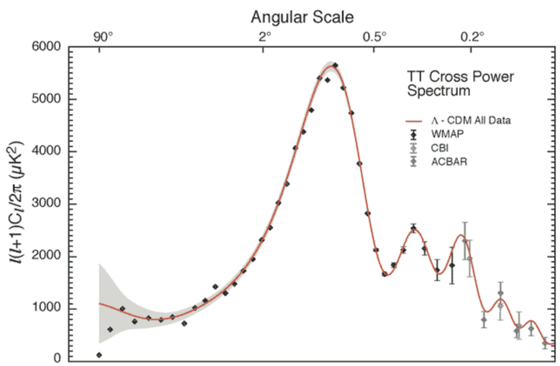
Universe density $\Omega_0 = 1.02 \pm 0.02$

Dark energy density $\Omega_\Lambda = 0.73 \pm 0.04$

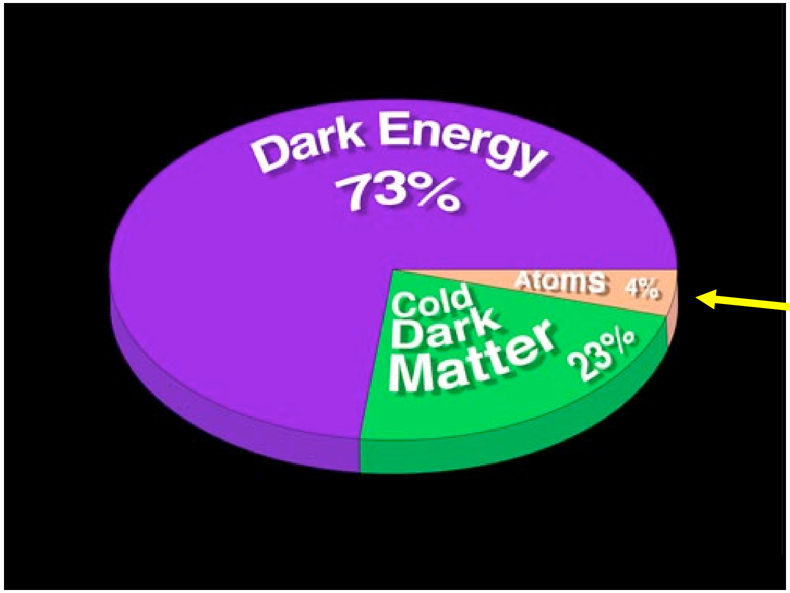
Total matter density $\Omega_M = 0.27 \pm 0.05$

Baryon matter density $\Omega_b = 0.044 \pm 0.004$

→ Dark matter is non-baryonic



Our Universe:

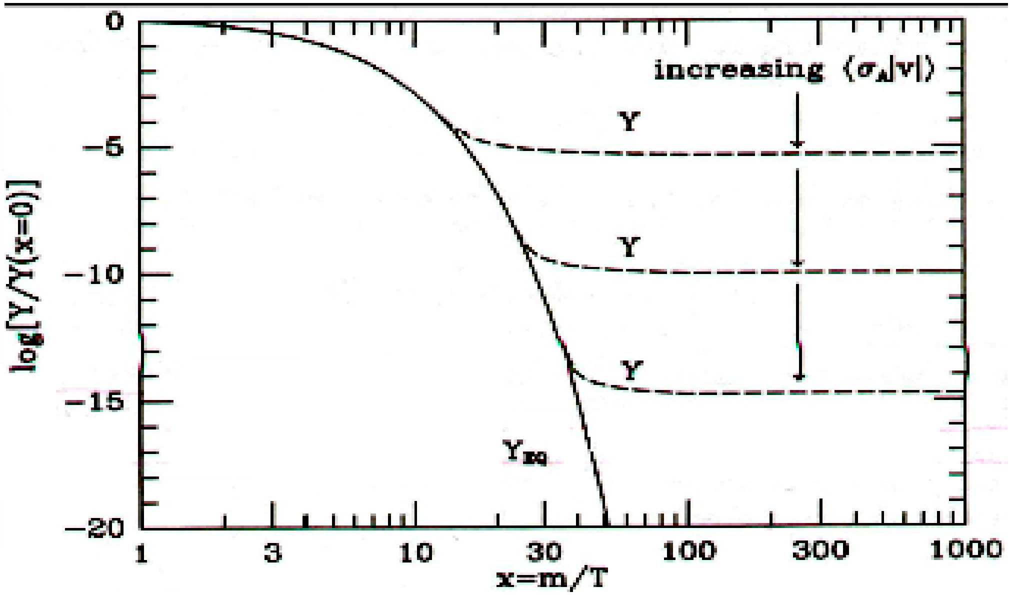


us

Evolution of Dark Matter Density

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

$\langle \sigma_{eff} v \rangle$ Thermal average of (co-)annihilation cross section



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

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

$$\Omega \simeq \frac{2\ 10^{-10}\mathrm{GeV}^{-2}}{\sigma_{\mathrm{eff}} v}$$

)

Stop-Neutralino Mass Difference: Information from the Cosmos

M. Carena, C. Balazs, C.W., PRD70:015007, 2004
M. Carena, C. Balazs, A. Menon, D. Morrissey, C.W., Phys. Rev. D71:075002, 2005.

- If the neutralino provides the observed dark matter relic density, then it must be stable and lighter than the light stop.

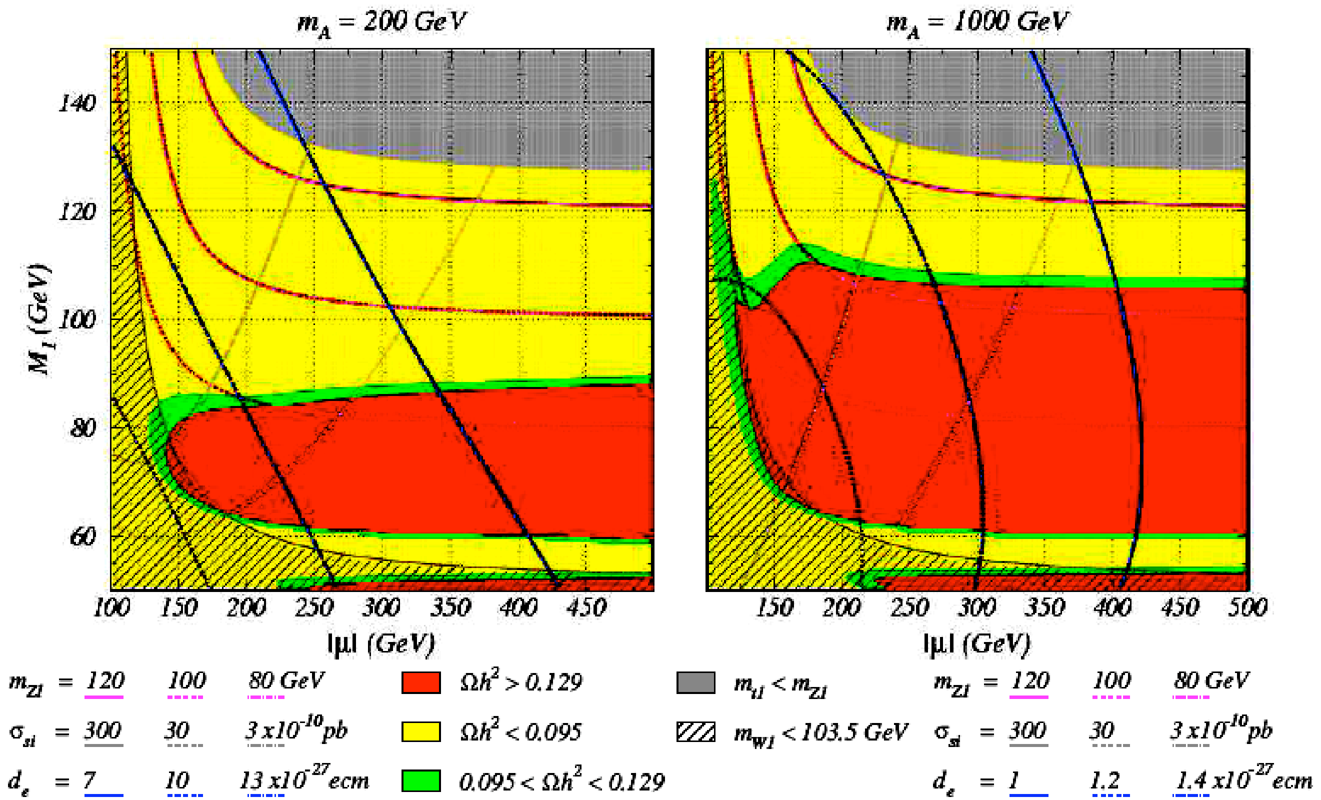
- Relic density is inversely proportional to the neutralino annihilation cross section.

If only stops, charginos and neutralinos are light, there are three main annihilation channels:

1. Coannihilation of neutralino with light stop or charginos: Small mass differences.
2. s-channel annihilation via Z or light CP-even Higgs boson
3. s-channel annihilation via heavy CP-even Higgs boson and CP-odd Higgs boson

Light Stop and Relic Density Constrain

In the presence of a light stop, the most relevant annihilation channel is the coannihilation between the stop and the neutralino at small mass differences. Relic density may be naturally of the observed size in this region of parameters.



$\tan\beta = 7$

C. Balazs, M. Carena, A. Menon, D. Morrissey, C.W. 05
Cirigliano, Profumo, Ramsey-Musolf 07, Martin'06--'07


Chicago
Booster
CDF
DØ
Tevatron
$\bar{p}$ source
Main Injector
(new)

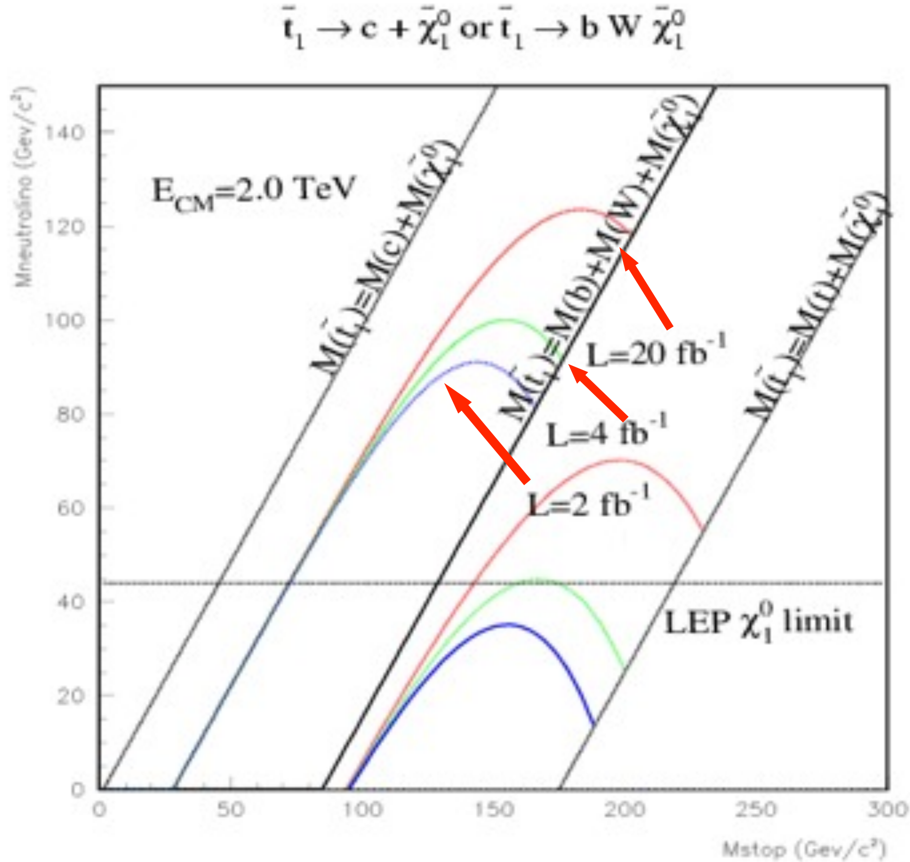
Tevatron Stop Reach when two body decay channel is dominant

Main signature:

2 or more jets plus missing energy

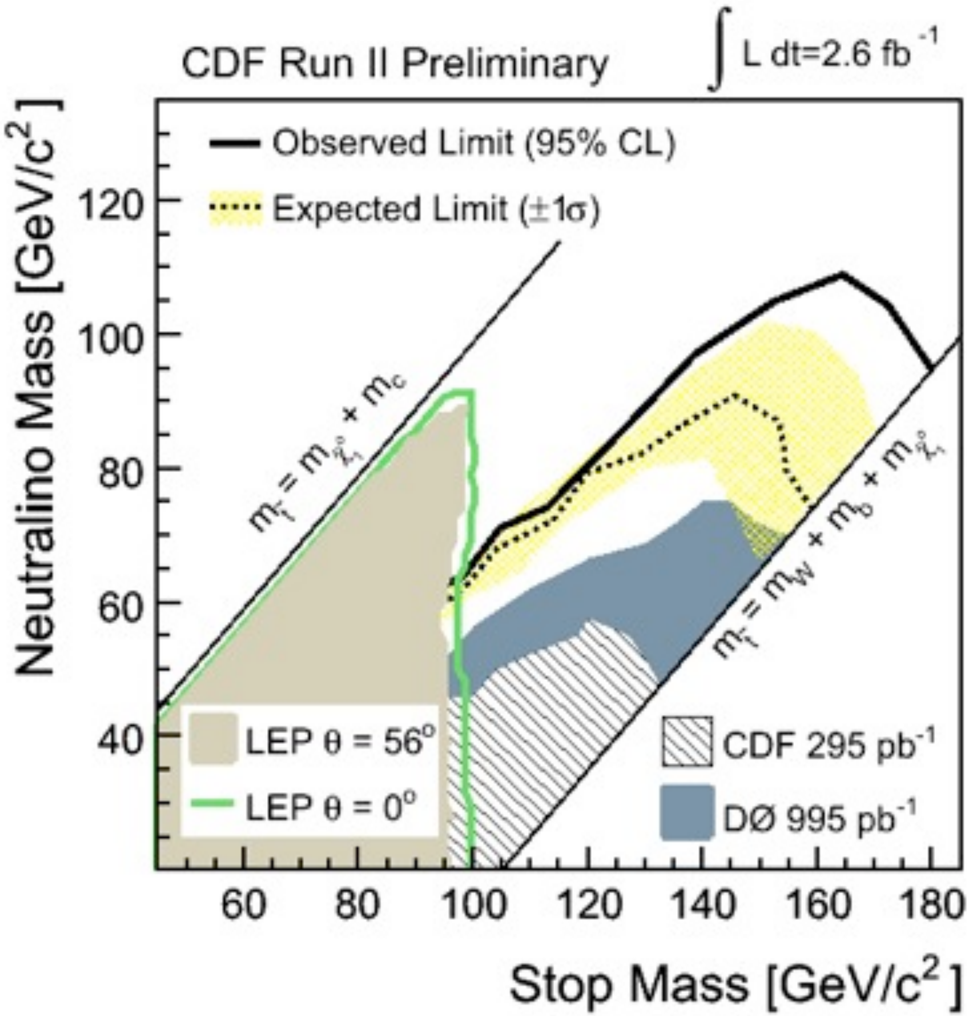
2 or more Jets with $E_T > 15$ GeV

Missing $E_T > 35$ GeV



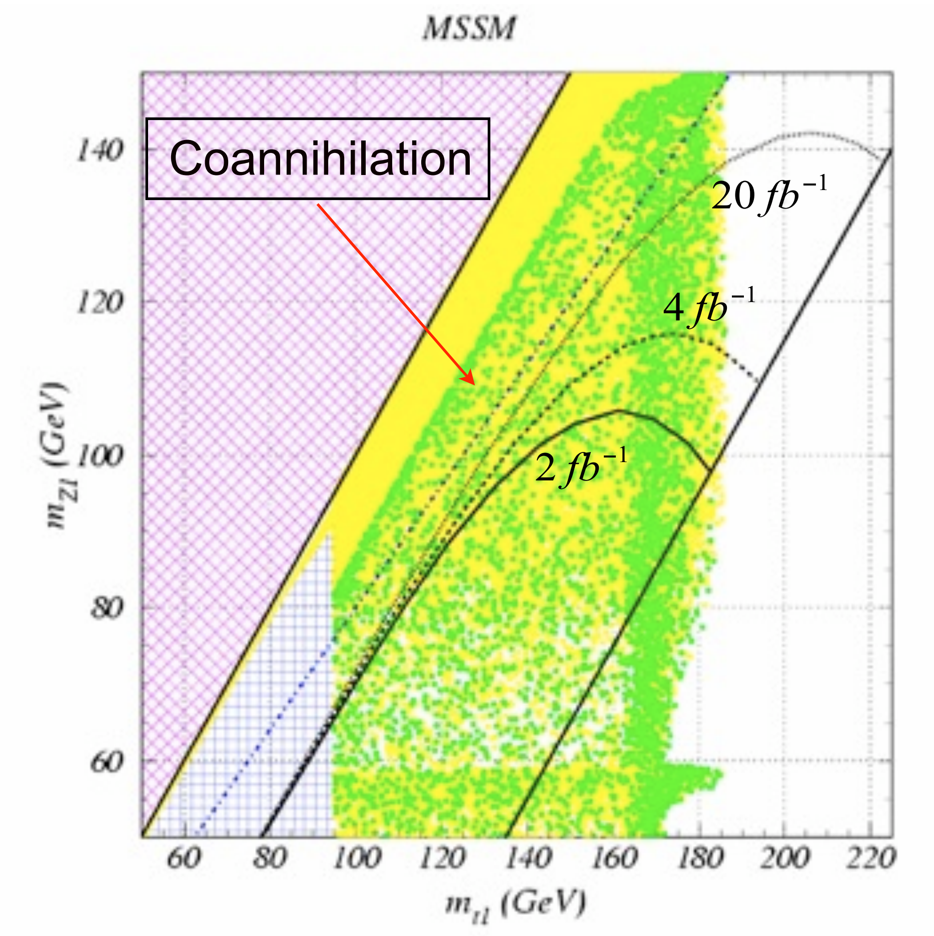
Demina, Lykken, Matchev,Nomerotsky '99

Stop searches at CDF



Tevatron stop searches and dark matter constraints

Carena, Balazs and C.W. '04

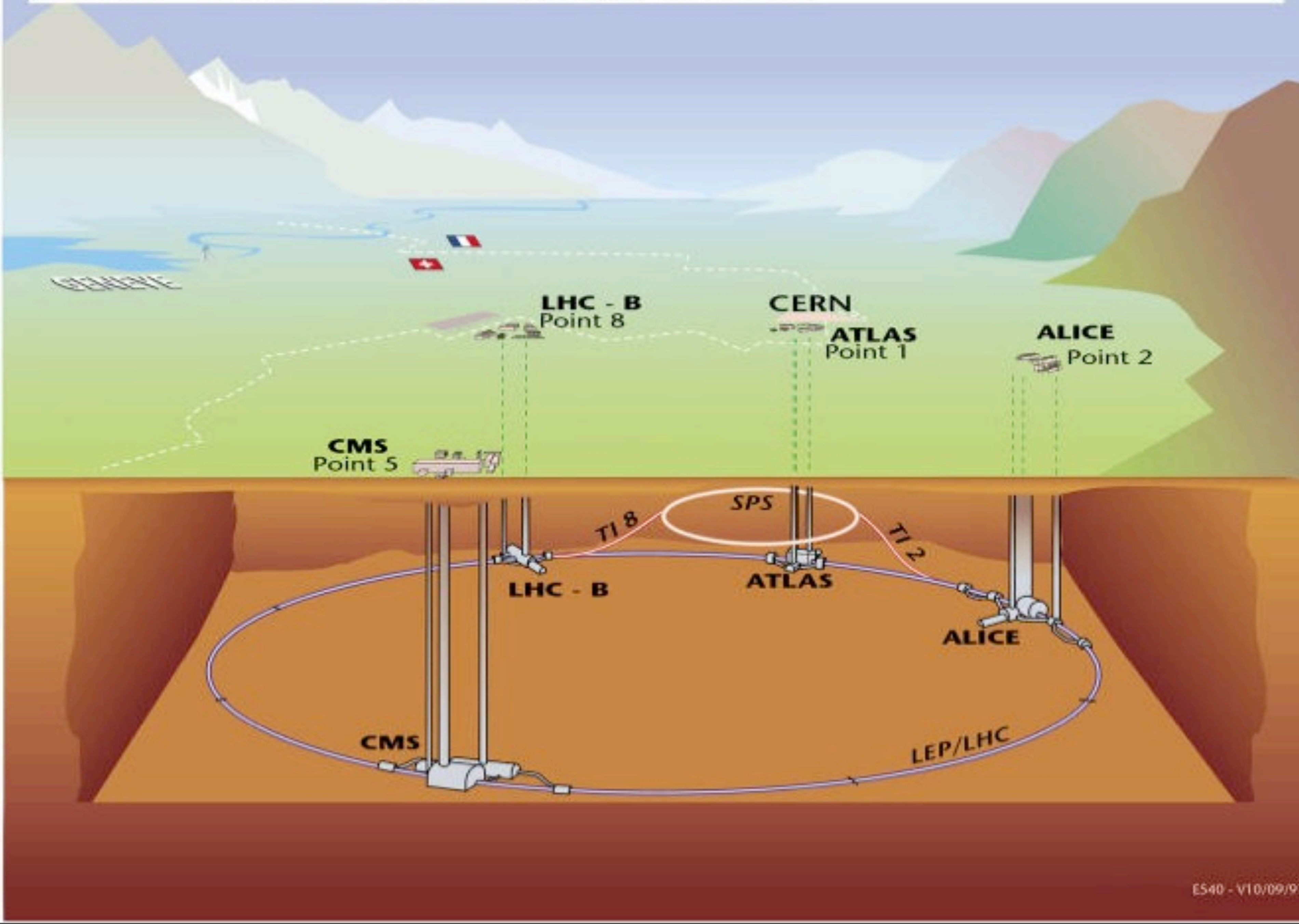


Green: Relic density consistent with WMAP measurements.

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

LHC will have equal difficulties in this particular channel.
But, LHC can search for stops in alternative channels.

Overall view of the LHC experiments.

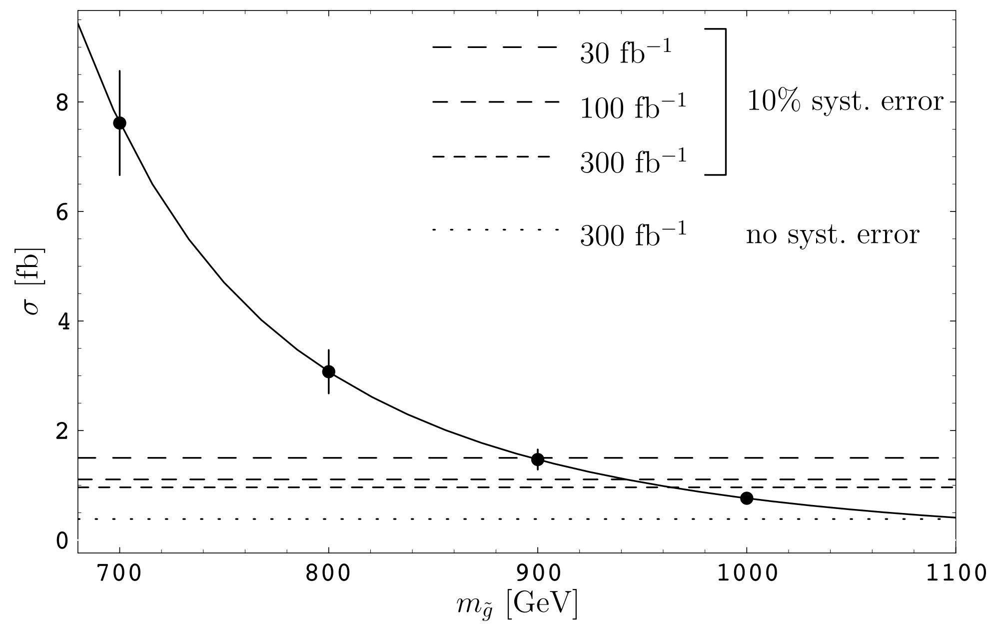


Stops from Gluino Decays

Kraml, Raklev '06, Martin 08

Take advantage of Majorana character of gluino: $\tilde{g} \to \tilde{t}_1 \bar{t},\ \tilde{t}_1^* t.$ Production of equal sign tops

- Two same-sign leptons with $p_T > 20$ GeV.
- Two b-tagged jets with $p_T > 50$ GeV (b-tag eff. 43%)
- $\not{E}_T > 100$ GeV. Invariant mass $m_{bl} < 160$ GeV



Efficient stop search channel up to gluino masses of about 1 TeV

Carena, Freitas, C.W.'09

Alternative Channels 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 or photons plus missing energy

M. Carena, A. Freitas, C.W.'09

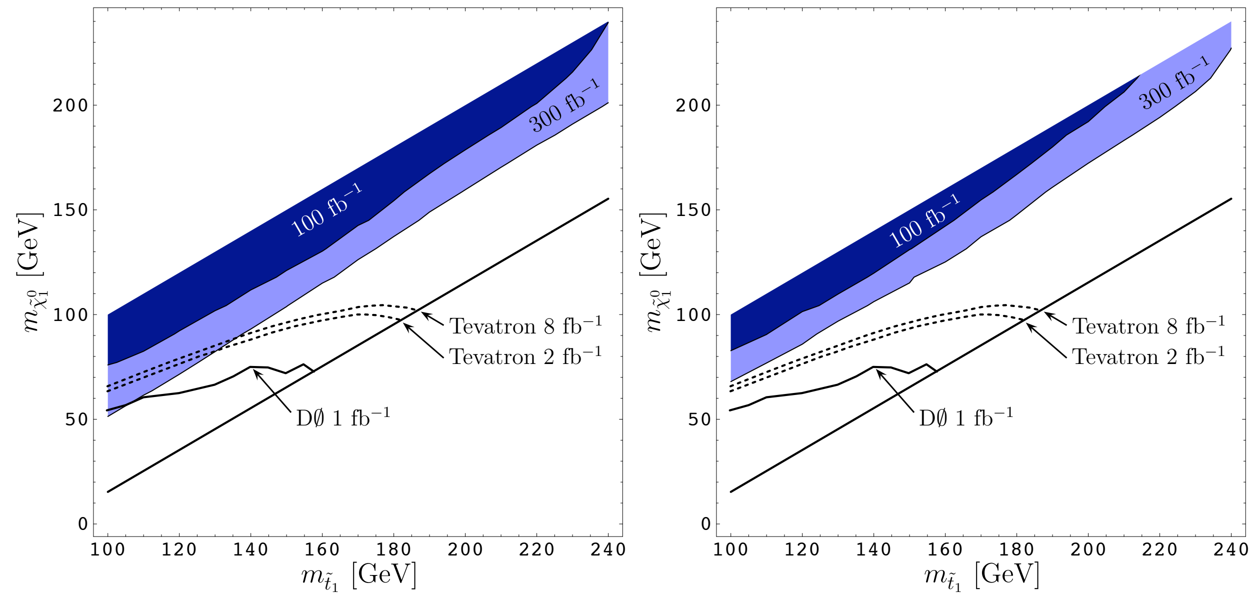
- Photon plus missing energy searches have the advantage of being cleaner, but they suffer from low statistics and large systematics
- Jet plus missing energy searches have larger backgrounds but have the advantage of having much larger production cross section compared to the photon case
- Hard photons and jets recoiling against missing energy have been simulated at the LHC experiments in the search for large extra dimensions, and we will make use of the backgrounds computed for that purpose.

Photons plus missing energy at the LHC

M. Carena, A. Freitas, C.W., arXiv:0808.2298

$$p\,p \to \tilde{t}_1\,\tilde{t}_1^*\,\gamma$$

1. Require one hard photon with $p_T > 400$ GeV and pseudo-rapidity $|\eta| < 2.4$.
2. Missing energy requirement: $\not{E}_T > 400$ GeV.
3. Veto against tracks with $p_T > 40$ GeV.
4. Require back-to-back topology for photon and missing momentum: $\Delta\phi(\not{\vec{p}}_T, \vec{p}_\gamma) > 2.5$.

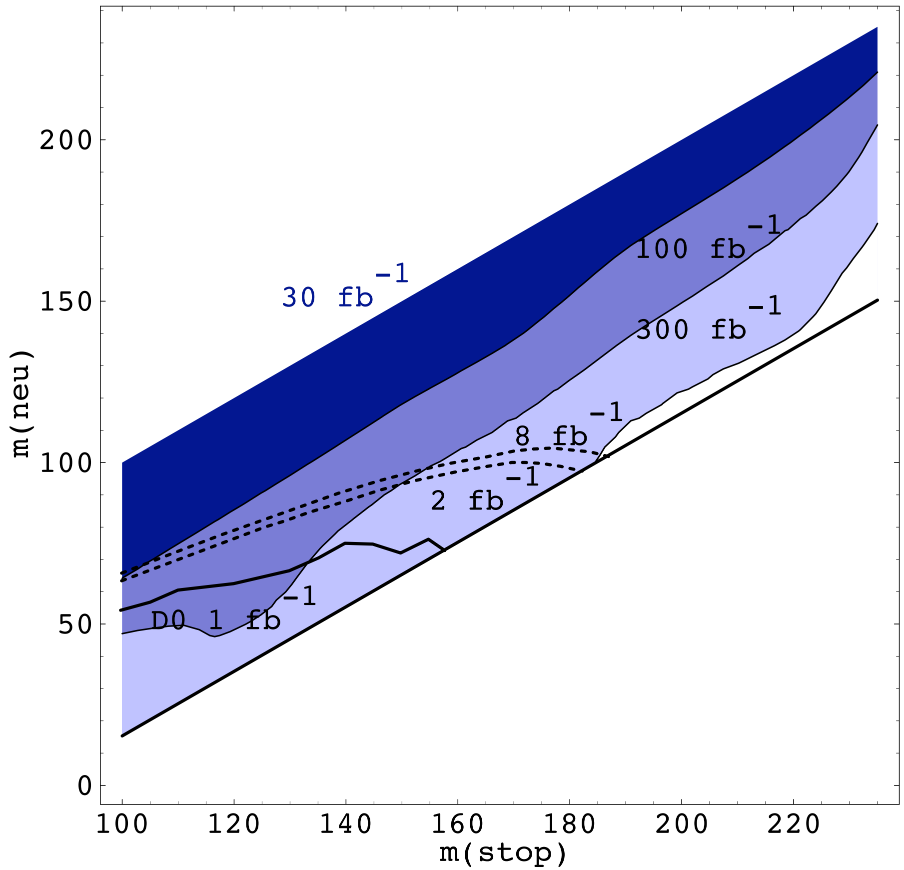


5-sigma discovery reach for the case in which systematic uncertainties associated with photon and missing energy determination are ignored (left) and taken into account (right). Total syst. uncertainty 6.5 %.

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

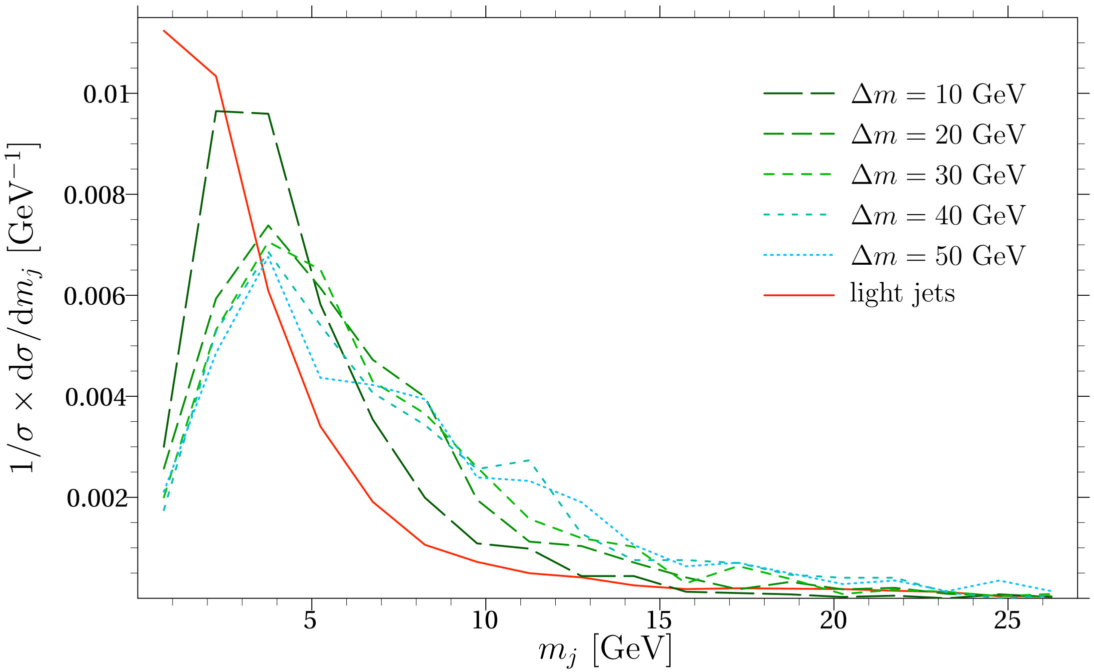


Excellent reach until masses of the order of 220 GeV and larger.

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

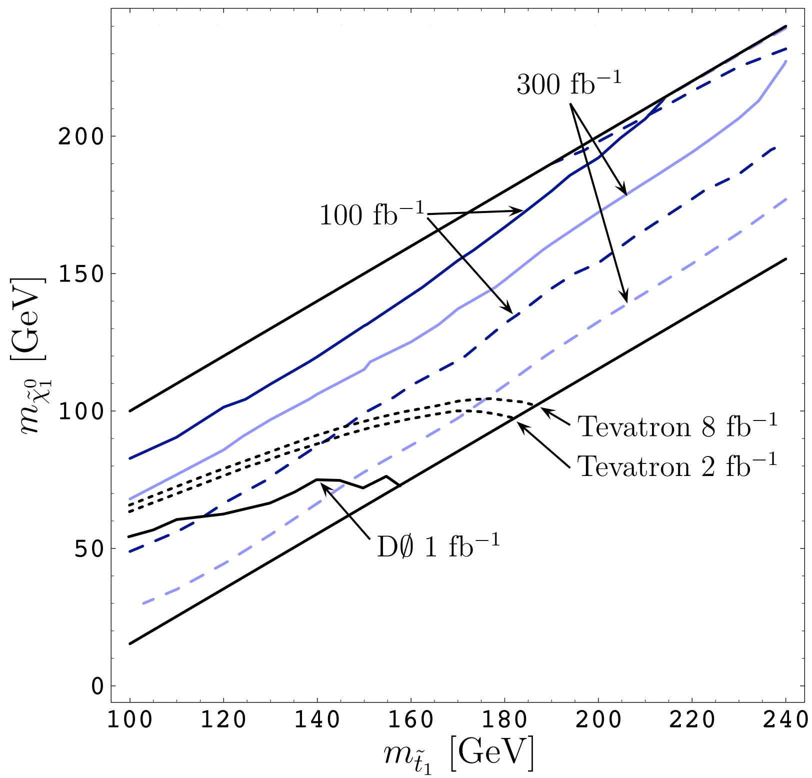
Stop Identification

- Can we detect the relatively soft jets coming from stop decay ?
- One can try to identify the charm-jets by the invariant mass and the track multiplicity
- Below we compare their invariant mass to the one of light jets coming from initial state radiation
- Cutting above 4.5 GeV leaves 60 % signal and only 25 % bkgd.



Improvement in Stop Searches by using charm identification in photon channel

M. Carena, A. Freitas, C.W., arXiv:0808.2298



Photons plus missing E_T
with charm tagging

We now demand one additional jet with pT > 20 GeV and with positive charm identification.

The charm identification
an additional improvement

Just like in the jet channel,
after charm i.d. one can
probe the whole region consistent
with electroweak baryogenesis

Baryon Number Generation

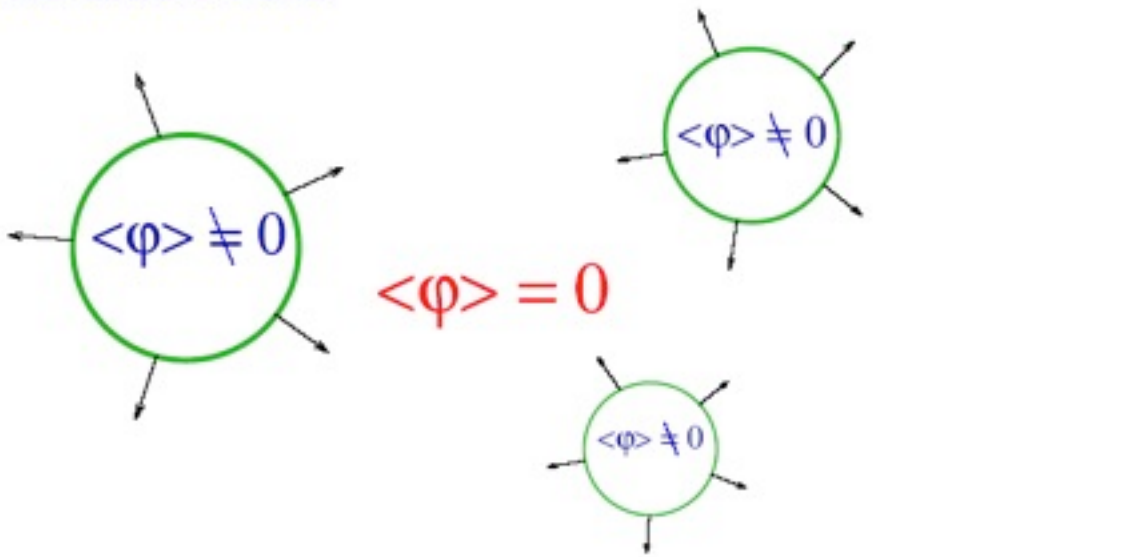
- Baryon number violating processes out of equilibrium in the broken phase if phase transition is sufficiently strongly first order.

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.



The diffusion equations for the evaluation of the baryon density takes into account the interaction rates and sources

$$v_\omega n_Q' = D_q n_Q'' - \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$-6\Gamma_{ss}\left[2\,\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\,\frac{n_Q + n_T}{k_B}\right] + \tilde{\gamma}_Q$$

$$v_\omega n_T' = D_q n_T'' + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] + \Gamma_m \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T}\right]$$
$$+3\Gamma_{ss}\left[2\,\frac{n_Q}{k_Q} - \frac{n_T}{k_T} + 9\,\frac{n_Q + n_T}{k_B}\right] - \tilde{\gamma}_Q$$

$$v_\omega n_H' = D_h n_H'' + \Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + \rho\, n_h}{k_H}\right] - \Gamma_h\,\frac{n_H}{k_H} + \tilde{\gamma}_{\tilde{H}_+}$$
$$v_\omega n_h' = D_h n_h'' + \rho\,\Gamma_Y \left[\frac{n_Q}{k_Q} - \frac{n_T}{k_T} - \frac{n_H + n_h/\rho}{k_H}\right] - (\Gamma_h + 4\,\Gamma_\mu)\,\frac{n_h}{k_H} + \tilde{\gamma}_{\tilde{H}_-}$$

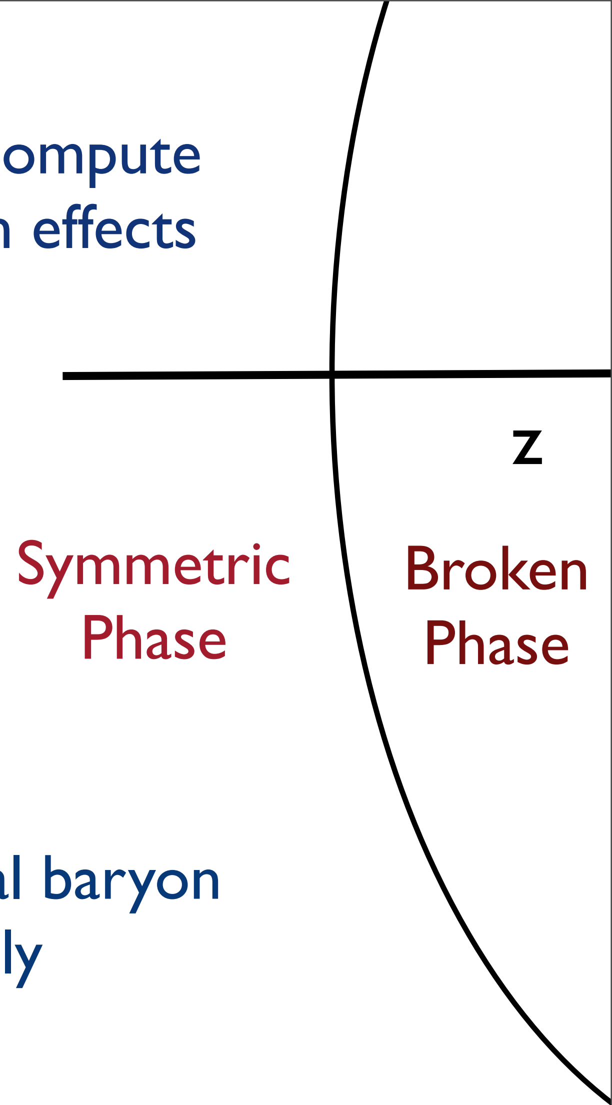
No Baryon number violation:
Chiral charges generated from CP-violating sources (gamma's)

Here the ki's are statistical factors relating the densities to chemical potentials and the Gammas are rates per unit volume. In particular,

$$\Gamma_{ws} = \;6\,\kappa_{ws}\,\alpha_w^5 T, \quad \Gamma_{ss} = \;6\,\kappa_{ss}\,\frac{8}{3}\,\alpha_s^4 T \qquad\qquad \Gamma_X = \frac{6\,\gamma_X}{T^3}$$

Once the chiral charge is obtained, we can compute the baryon number generation via sphaleron effects

$$v_\omega n_B'(z) = -\theta(-z)\left[n_F \Gamma_{ws} n_L(z) + \mathcal{R} n_B(z)\right]$$



Here R is the relaxation coefficient

$$\mathcal{R} = \frac{5}{4} n_F \, \Gamma_{ws}$$

The solution to this equation gives the final baryon number density in the broken phase, namely

$$n_B = -\frac{n_F \Gamma_{ws}}{v_\omega} \int_{-\infty}^{0} dz \, n_L(z) \; e^{z\mathcal{R}/v_\omega}$$

Computation of sources

The sources can be computed from the corresponding currents in the varying Higgs background. They take the form

Carena, Moreno, Quiros, Seco, C.W. '01--02

$$\tilde{\gamma}_Q \simeq -\, v_\omega\, h_t^2\, \Gamma_{\tilde{t}}\, \mathrm{Im}(A_t \mu_c)\;\, H^2(z)\, \beta'(z)\;\, \{\mathcal{F}_B(z) + \mathcal{G}_B(z)\}$$

$$\tilde{\gamma}_{\widetilde{H}_+} \simeq -\, 2\, v_\omega\, g^2\, \Gamma_{\widetilde{\mathcal{H}}}\, \mathrm{Im}(M_2 \mu_c)\, \Big\{ H^2(z)\, \beta'(z)\;\, [\mathcal{F}_F(z) + \mathcal{G}_F(z)] \\ +\;\, g^2\, H^2(z) \cos 2\beta(z) \left[H(z) H'(z) \sin 2\beta(z) + H^2(z) \cos 2\beta(z) \beta'(z) \right] \mathcal{H}_F(z) \Big\}$$

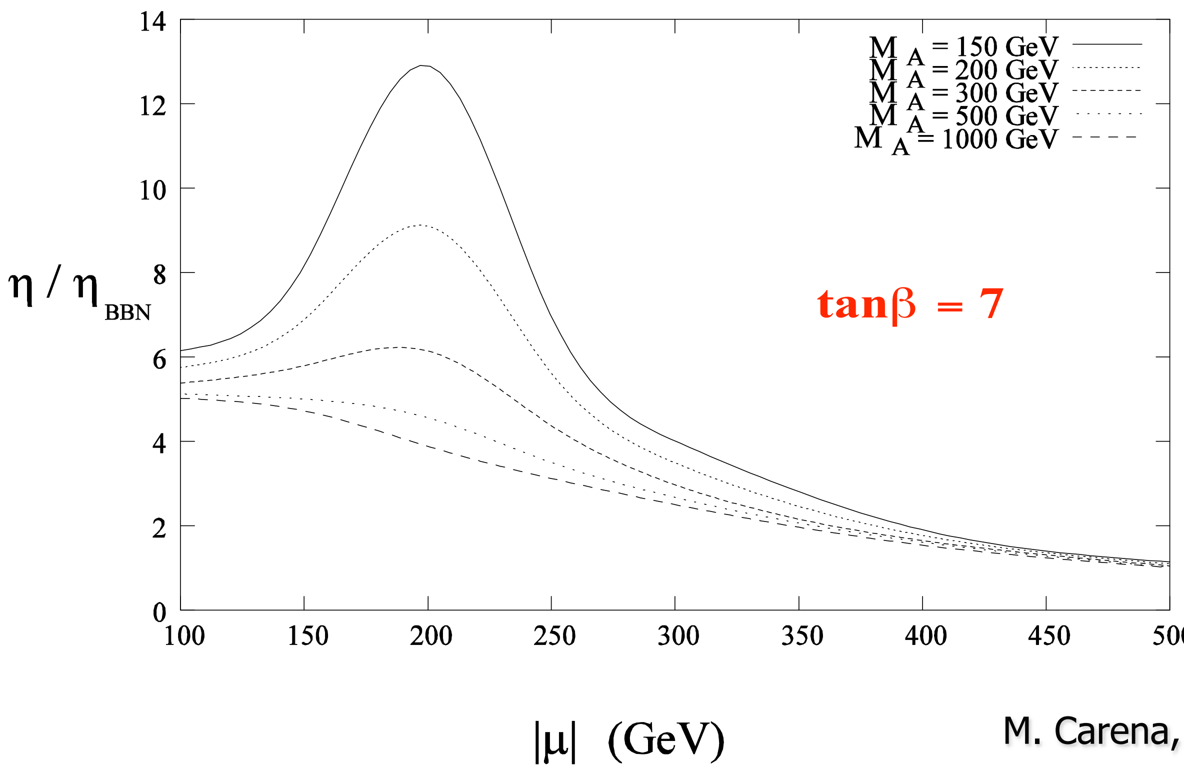
$$\tilde{\gamma}_{\widetilde{H}_-} \simeq 2\, v_\omega\, g^2\, \Gamma_{\widetilde{\mathcal{H}}}\, \mathrm{Im}(M_2 \mu_c) \left[H(z) H'(z) \sin 2\beta(z) + H^2(z) \cos 2\beta(z) \beta'(z) \right] \\ \left\{ \mathcal{K}_F(z) + 2 \left(\Delta + \bar{\Delta}\right) \mathcal{H}_F(z) \right\}\;\, .$$

Observe the dependence on the CP violating parameters in the gaugino and stop sectors. Relevant bino contribution also exists

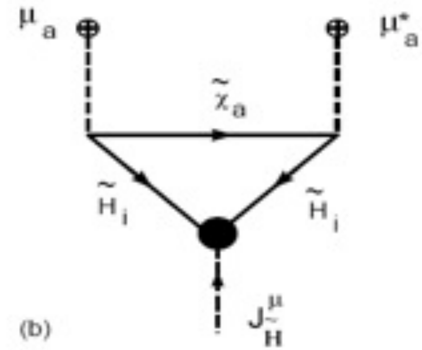
The dependence on the Higgs background reveals a dependence on the variation of the parameter beta, which vanishes at large values of the CP-odd mass, plus contribution that survives at large values of the non-standard masses

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

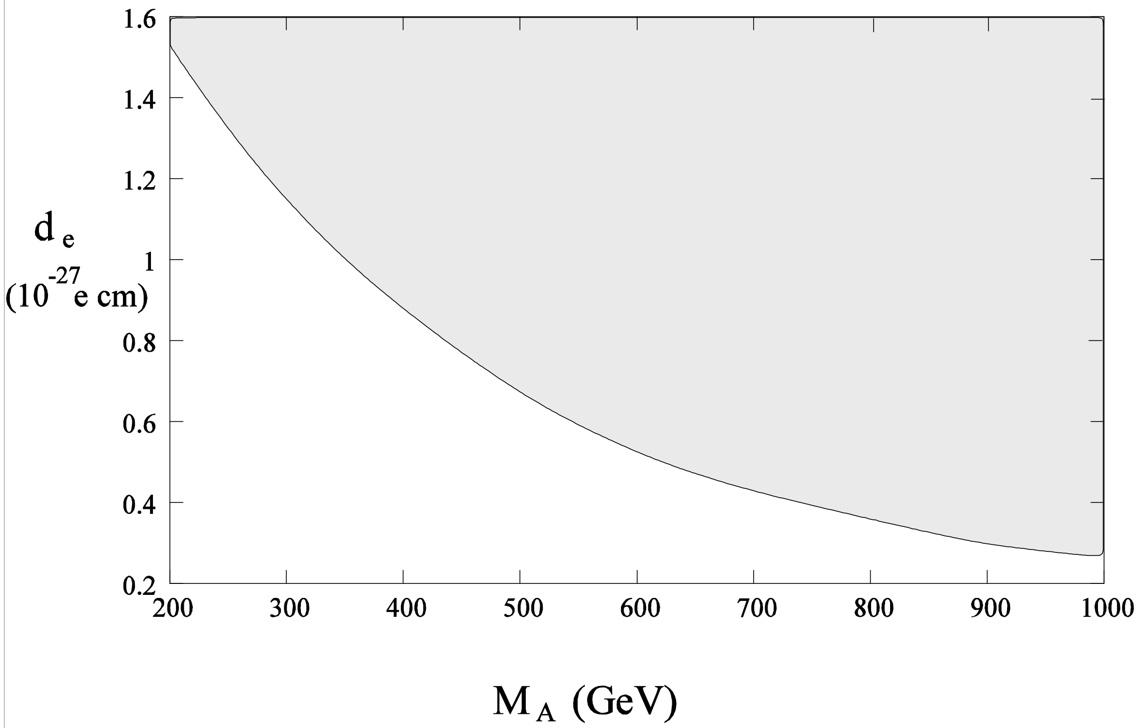
Balazs, Carena, Menon, Morrissey, C.W.'05

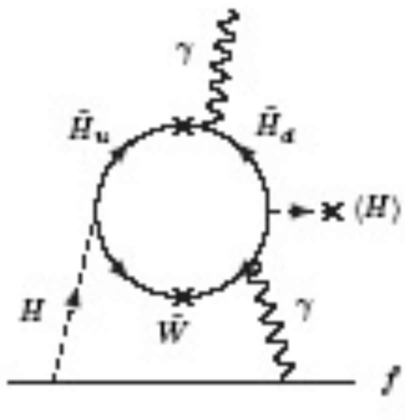
Electron electric dipole moment

- 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

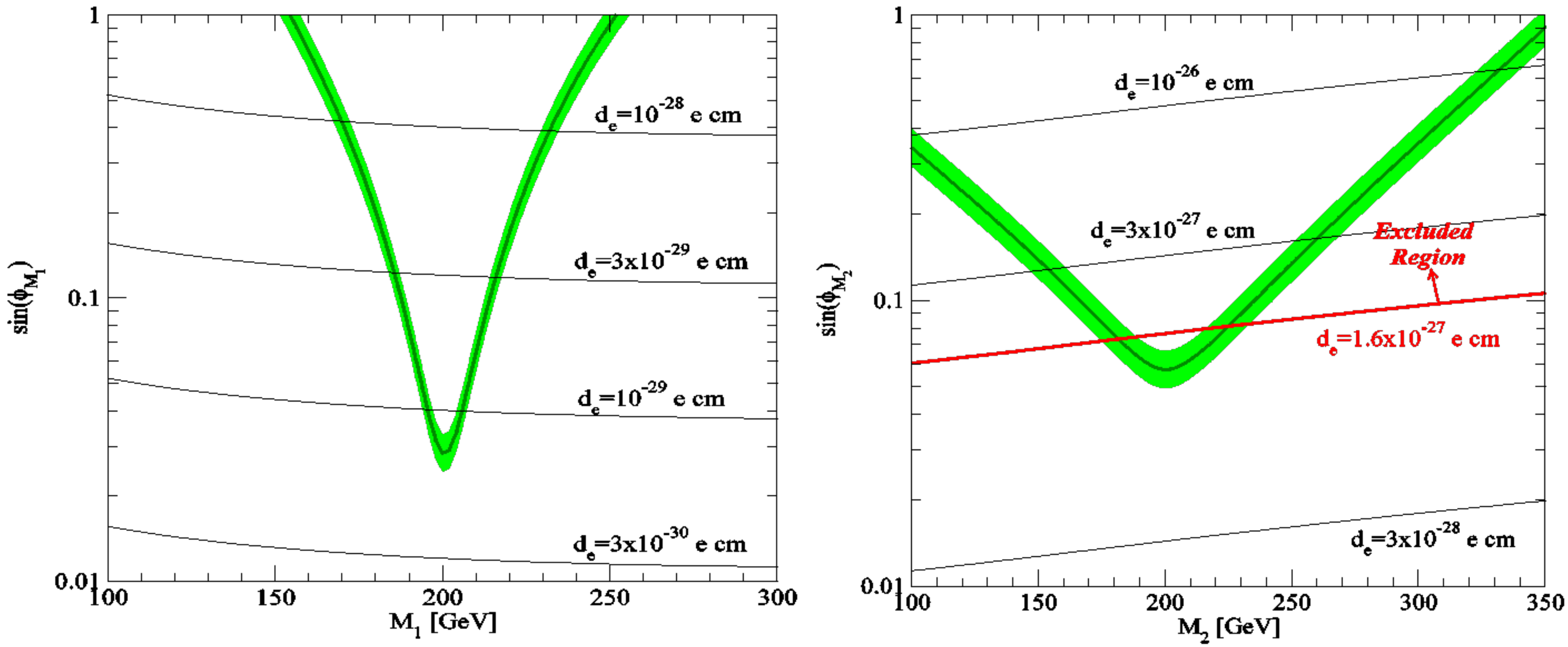




Chang, Keung, Pilaftsis '99, Pilaftsis '99
Chang, Chang, Keung '00, Pilaftsis '02

Comparing bino- and wino-driven EWB

- Electron EDM:



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

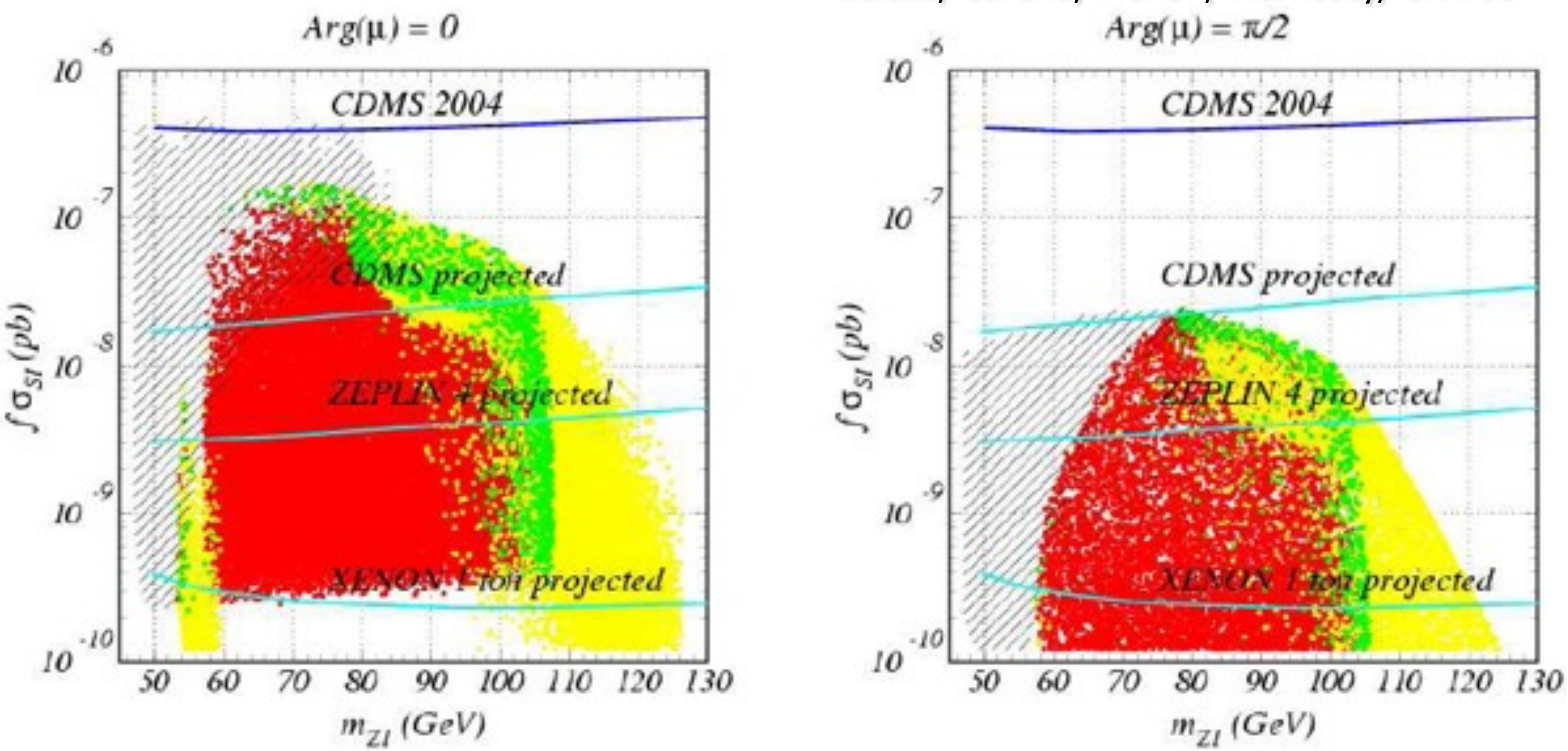
Cirigliano, Profumo, Ramsey-Musolf'06

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

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. Coannihilation region (larger Higgsino mass) difficult to probe

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



Baryogenesis in Supersymmetric Models : Beyond the MSSM

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

Electroweak Symmetry Breaking and the μ Problem

- Negative values of the soft supersymmetry breaking mass parameter induce electroweak symmetry breaking. The total Higgs masses receive a SUSY contribution

$$\mu^2 + m_{H_i}^2$$

- Electroweak symmetry breaking therefore demands a relation between these two contributions

$$\mu^2 + \frac{M_Z^2}{2} = \frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}, \qquad \tan\beta = \frac{v_u}{v_d}$$

- Therefore, μ must be of the order of the SUSY breaking parameters
- Also, the mixing term $(B_\mu H_u H_d + h.c.)$ appearing in the potential

$$\sin 2\beta = \frac{2B_\mu}{2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2}$$

must be of the same order. Is there a natural framework to solve the flavor problem, inducing weak scale values for μ and B_μ ?

Singlet Mechanism for the generation of μ

- A natural solution would be possible by introducing a singlet

$$W = \lambda S H_u H_d + h_u Q U H_u + \ldots$$

- This alllows to replace the μ-term by the vacuum expectation value of the singlet field S,

$$\mu = \lambda v_S$$

- This model, however, preserves a Peccei Quinn symmetry

$$\widehat{Q} : -1, \quad \widehat{U}^C : 0, \quad \widehat{D}^C : 0, \quad \widehat{L} : -1, \quad \widehat{E}^C : 0, \quad \widehat{H}_u : 1, \quad \widehat{H}_d : 1, \quad \widehat{S} : -2,$$

- Therefore, once the Higgs acquire v.e.v.'s there is an unacceptable massless Goldstone in the spectrum. The Peccei Quinn symmetry must be then broken

Singlet Mechanism for the generation of μ in the NMSSM

- One could break the symmetry by self interactions of the singlet

$$W = \lambda S H_u H_d - \frac{\kappa}{3} S^3 + h_u Q U H_u + \ldots$$

- No dimensionful parameter is included. The superpotential is protected by a Z_3 symmetry, $\phi \rightarrow exp(i2\pi/3)\phi$

- This discrete symmetry would be broken by the singlet v.e.v. Discrete symmetries are dangerous since they could lead to the formation of domain walls: Different volumes of the Universe with different v.e.v.'s separated by massive walls. These are ruled out by cosmology observations.

- One could assume a small explicit breakdown of the Z_3 symmetry, by higher order operators, which would lead to the preference of one of the three vacuum states. That would solve the problem without changing the phenomenology of the model.

Tadpoles in the NMSSM

- The NMSSM construction then, assumes the existence of small Z3 breaking terms that solve the domain wall problem.
- One possible construction in supergravity theories is to break the Z3 symmetry by the same sector that breaks supersymmetry.
- However, in general this also leads to the generation of tadpole terms for the singlet, $\mathcal{L}_{\rm soft} \supset t_S\, S \sim \frac{1}{(16\pi^2)^n}\, M_{\rm P}\, M_{\rm SUSY}^2\, S$, where n is the number of loops at which it is generated.
- If a large tadpole is generated, it would shift the v.e.v. of S to large values, reintroducing the mu problem. Therefore, in this case n should be larger than 5.
- One could imagine that the operators present do not lead to large tadpoles. More reassuring would be to find a way of eliminating them.
- Three natural solutions: Gauge the PQ symmetry (UMSSM) or find alternative symmetries that ensure large n (MNSSM or nMSSM) or break SUSY at lower energies.

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)

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

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

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

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

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

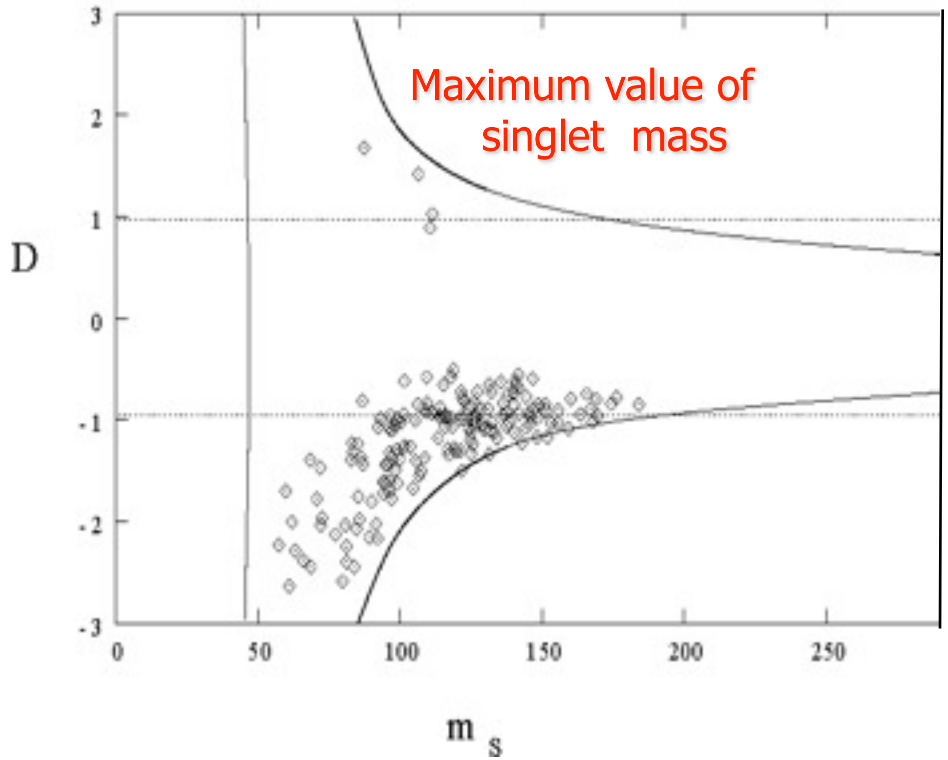
Parameters with strongly first order transition

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

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

Menon,Morrissey,C.W.'04

- Values constrained by perturbativity up to the GUT scale.



Neutralino Mass Matrix

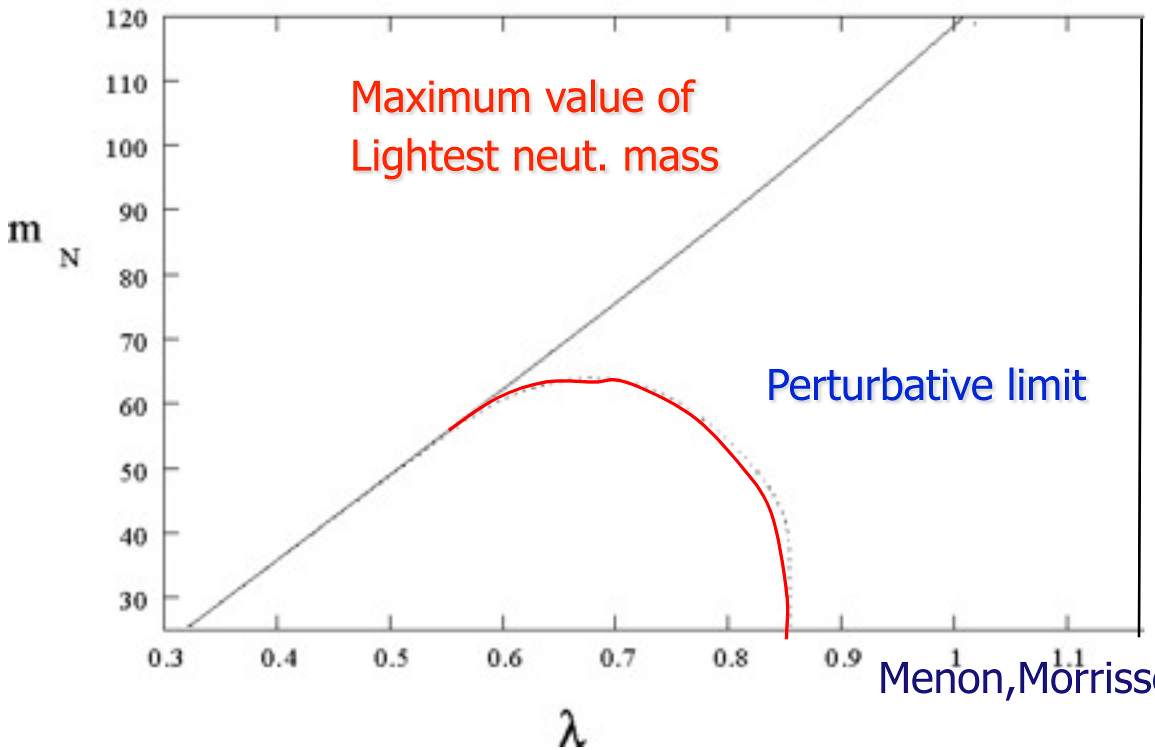
$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -c_\beta s_{\rm W} M_{\rm Z} & s_\beta s_{\rm W} M_{\rm Z} & 0 \\ 0 & M_2 & c_\beta c_{\rm W} M_{\rm Z} & -s_\beta c_{\rm W} M_{\rm Z} & 0 \\ -c_\beta s_{\rm W} M_{\rm Z} & c_\beta c_{\rm W} M_{\rm Z} & 0 & \lambda v_{\rm s} & \lambda v_2 \\ s_\beta s_{\rm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

In the nMSSM, $\kappa = 0$.

Upper bound on Neutralino Masses

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

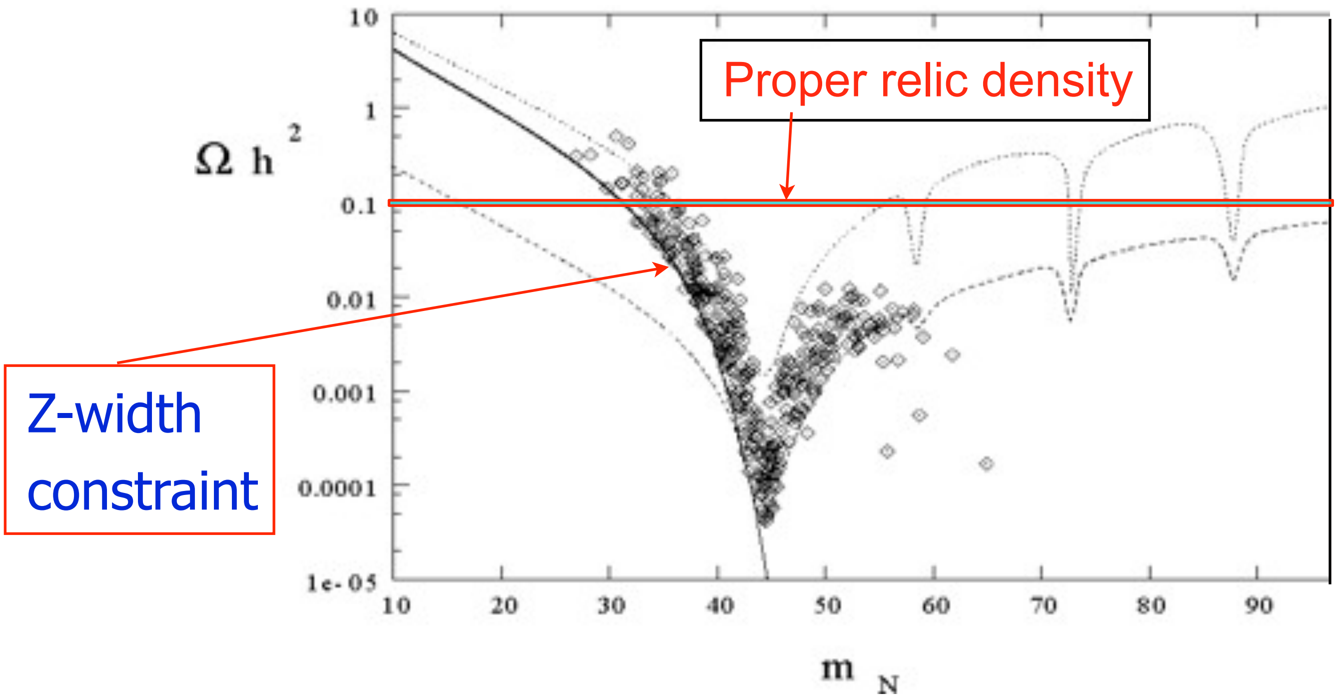
Values of neutralino masses below dotted line consistent with perturbativity constraints.



Menon,Morrissey,C.W.'04

Relic Density and Electroweak Baryogenesis

Region of neutralino masses selected when perturbativity constraints are impossed.
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.



Menon,Morrissey,C.W.'04

Higgs Spectrum

- New CP-odd and CP-even Higgs fields induced by singlet field (mass controled by m_S^2)

- They mix with standard CP-even and CP-odd states in a way proportional to 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

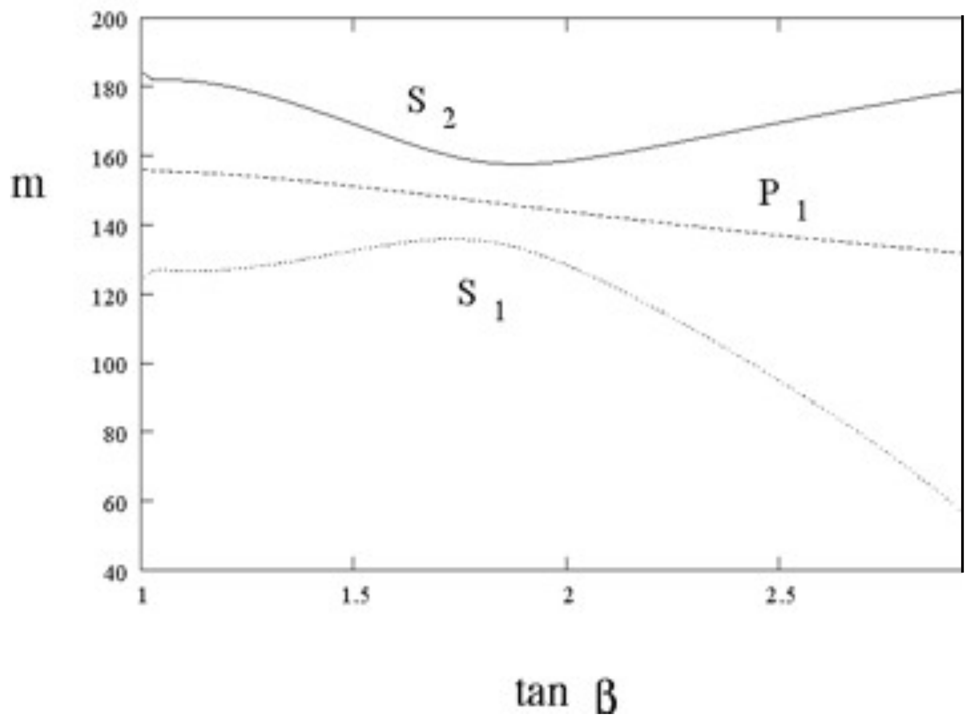
Light Higgs boson masses

- 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

Higgs Searches

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

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

- 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:

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

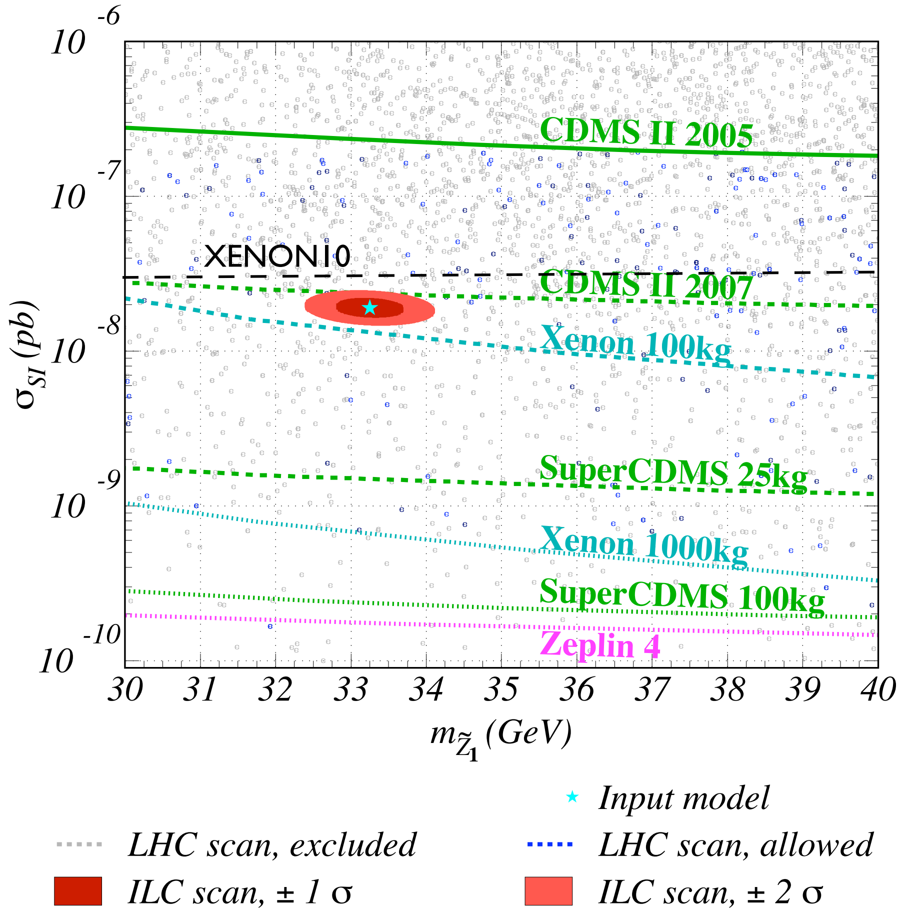
Weak Boson Fusion: Eboli and Zeppenfeld ‘00, Higgs Working Group, Les Houches’01

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

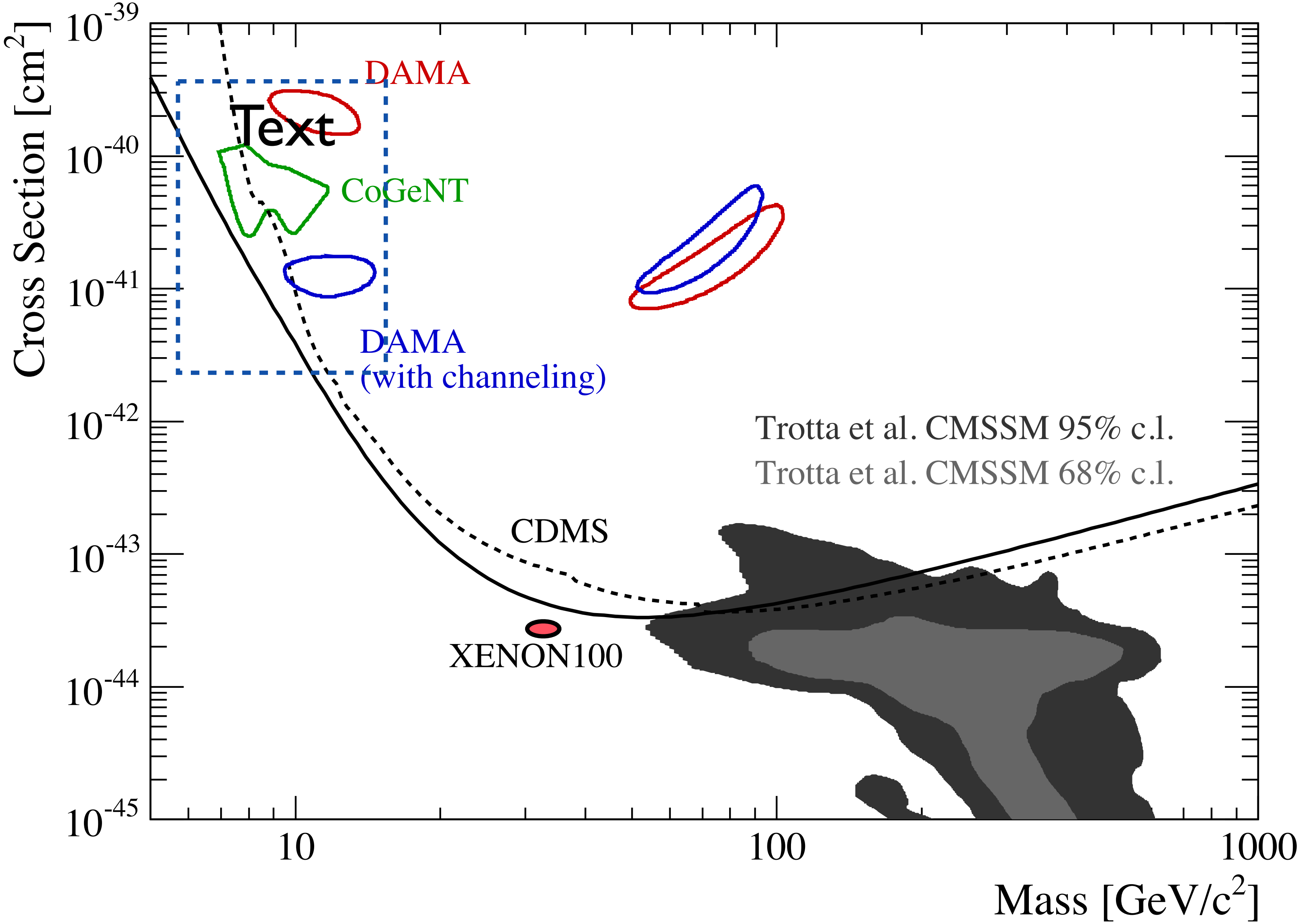


- Next generation of direct dark matter detection will probe this model

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

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

Not yet probed by current experiments



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

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

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

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

$$\arg(m_{12}^* t_s A_d), \quad (3 \text{ generations}),$$ ← 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.

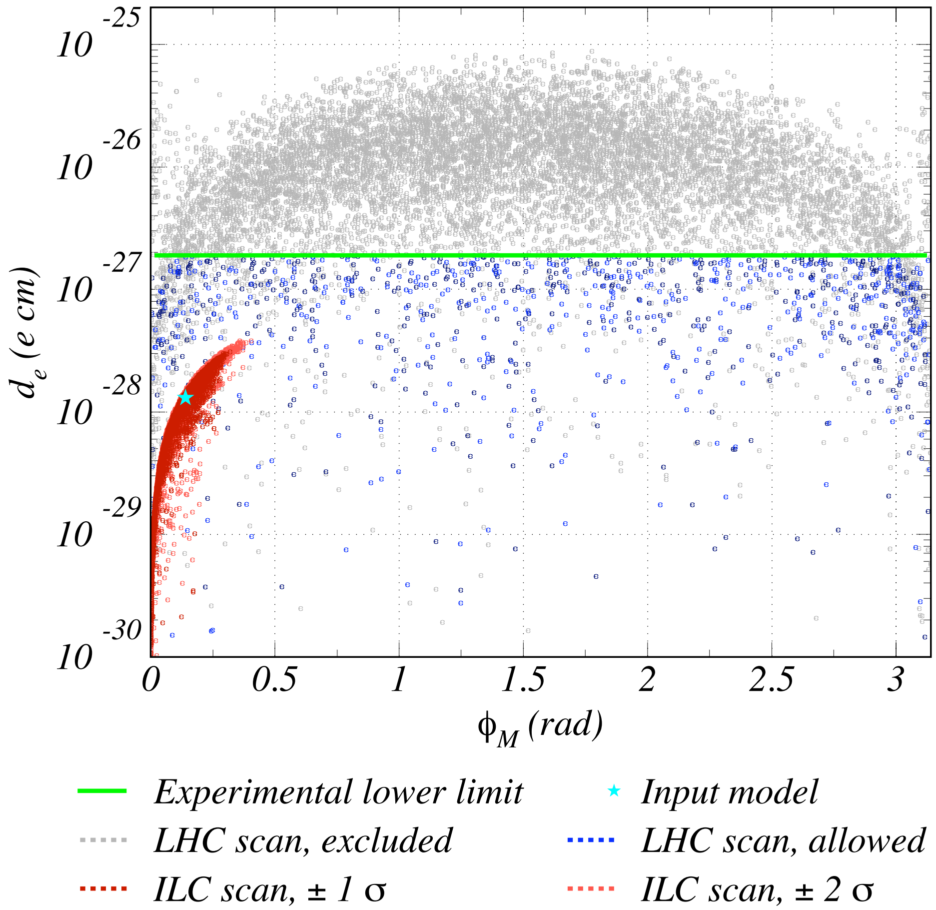
Huber, Konstantin, Prokopec, Schmidt'06

- 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. Here we assume similar chargino phases as in the MSSM

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



Gauge Extensions of the MSSM
Baryogenesis from an early phase transition
(if time allows)

Based on following works :

D.E. Morrissey, T. M.P.Tait and C.E.M.Wagner, Phys. Rev. D72:095003 (2005)

J. Shu, T.M.P. Tait and C.E.M.Wagner, Phys. Rev. D75 :063510 (2007)

A. Medina, N.R. Shah and C.E.M.Wagner, Phys. Rev. D80 015001 (2009)

Solution to the SUSY (little) Hierarchy Problem

An SU(2) Gauge Extension

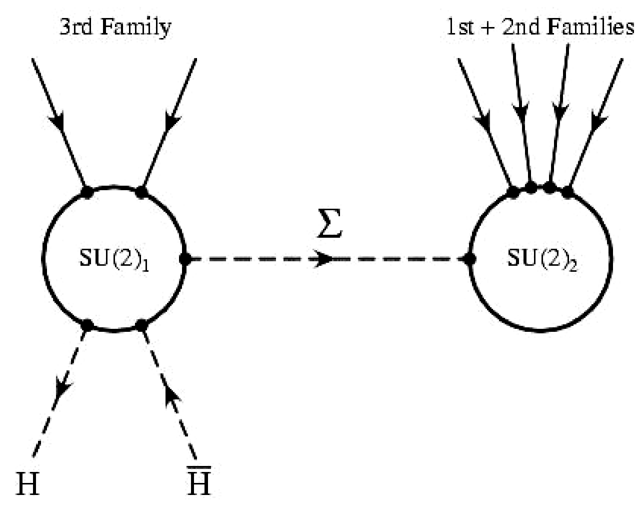
P Batra, A. Delgado, D.E. Kaplan, T Tait, JHEP 0402,043 (2004)

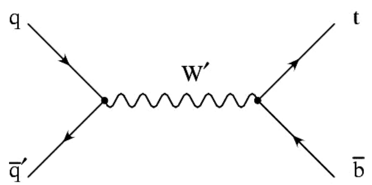
- One solution to this problem is to increase the Higgs mass by having it participate in new strong gauge interactions.

- We invoke a new SU(2) interaction under which the Higgses and third family are charged.

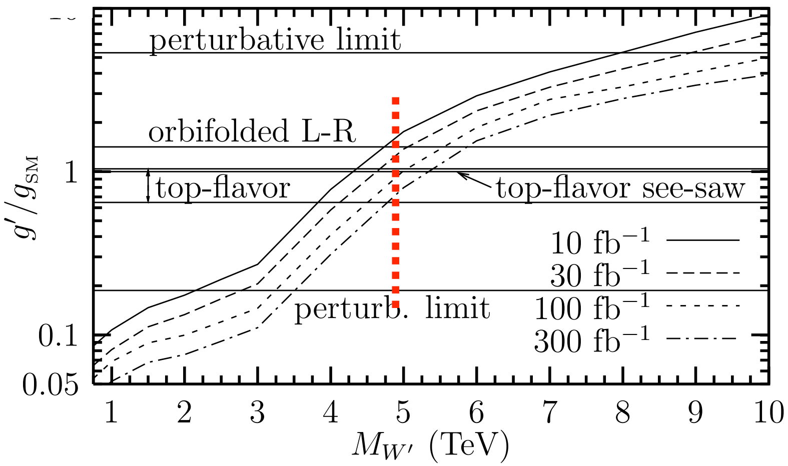
  $SU(2)_1$ x $SU(2)_2$ x $U(1)_Y$

- Because $SU(2)_1$ is asymptotically free, it has no problems with strong coupling at high energies.
- The extra W's are a hallmark of the model, and can be observed in single top at the LHC.





Z. Sullivan, hep-ph/0306266



How does this work in practice ?

If SUSY breaking scale is smaller than gauge symmetry breaking scale, decoupling occurs. Low energy D-terms are just the standard ones.

Therefore, supersymmetry breaking terms larger than the vev that breaks the gauge symmetry should be present. Calling $< \Sigma >= uI$, to this vev

$$V = m_\Sigma^2 \Sigma^\dagger \Sigma + \frac{\lambda_1^2}{4} |\Sigma\Sigma|^2 - \frac{B}{2}(\Sigma\Sigma + h.c.) + \ldots \qquad u^2 = (B - m_\Sigma^2)/\lambda_1^2.$$

$$\Delta V = \frac{g_1^2}{8}\left(\mathrm{Tr}[\Sigma^\dagger \tau^a \Sigma] + \mathrm{H}_u^\dagger \tau^a \mathrm{H}_u + \mathrm{H}_d^\dagger \tau^a \mathrm{H}_d + \mathrm{L}^\dagger \tau^a \mathrm{L} + \mathrm{Q}^\dagger \tau^a \mathrm{Q}\right)^2 + \frac{g_2^2}{8}\left(\mathrm{Tr}[\Sigma^\dagger \tau^a \Sigma] + \ldots\right)^2$$

Integrating out the sigma field, we obtain a modification of the low energy D-term

$$\Delta V_D = \frac{g^2}{2}\Delta \sum_a \left(H_u^\dagger \tau^a H_u + H_d^\dagger \tau^a H_d + L_3^\dagger \tau^a L_3 + Q_3^\dagger \tau^a Q_3\right)^2$$

$$\Delta = \frac{1 + \frac{2m_\Sigma^2}{g_2^2 u^2}}{1 + \frac{2m_\Sigma^2}{(g_2^2 + g_1^2)u^2}}.$$

As mentioned before, if the supersymmetry breaking scale is small, $\Delta \to 1$.
Observe that for $g_1^2 \gg g_2^2$ and large values of m_Σ, $\Delta \gg 1$.

Tree-level Higgs Mass modification and Sparticle Spectrum

A. Medina, N. Shah, C.W.'09

The low energy D-terms control the tree-level Higgs mass

$$m_h^2 = \frac{1}{2}\left(g^2 \Delta + g_Y^2\right) v^2 \cos^2 2\beta + \text{loop corrections}$$

So, large values of the Higgs mass may be obtained.

Same D-terms, however, modify the rest of the third generation spectrum:

$$\begin{aligned} m_{\tilde{\tau}_L}^2 - m_{\tilde{\nu}_\tau}^2 &= \Delta_D \\ m_{\tilde{b}_L}^2 - m_{\tilde{t}_L}^2 &= \Delta_D - m_t^2 \end{aligned}$$

$$\Delta_D = \frac{g^2 v^2}{2} \Delta |\cos 2\beta|$$

As well as the non-standard Higgs mass splittings

$$m_{H^\pm}^2 - m_A^2 = \frac{g^2 \Delta}{2} v^2.$$

Large values of Δ can induce large values of the Higgs mass, up to 250 GeV, but also produce large modifications of the spectrum.

Modified spectrum and precision measurements

Large values of the Higgs mass tend to induce large corrections to the T and S parameters

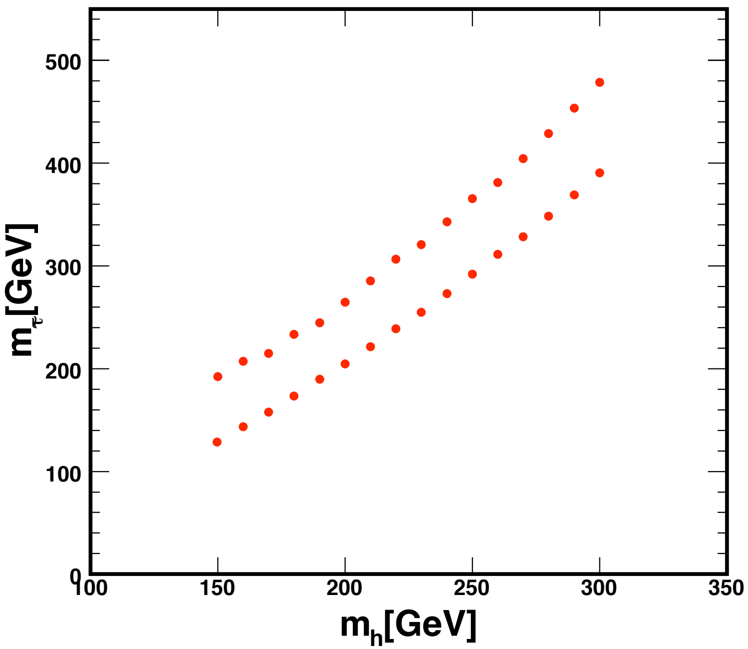
$$\Delta T = -\frac{3}{8\pi c_W^2} \ln \frac{m_h}{m_{h_{\rm ref}}}$$
$$\Delta S = \frac{1}{6\pi} \ln \frac{m_h}{m_{h_{\rm ref}}},$$

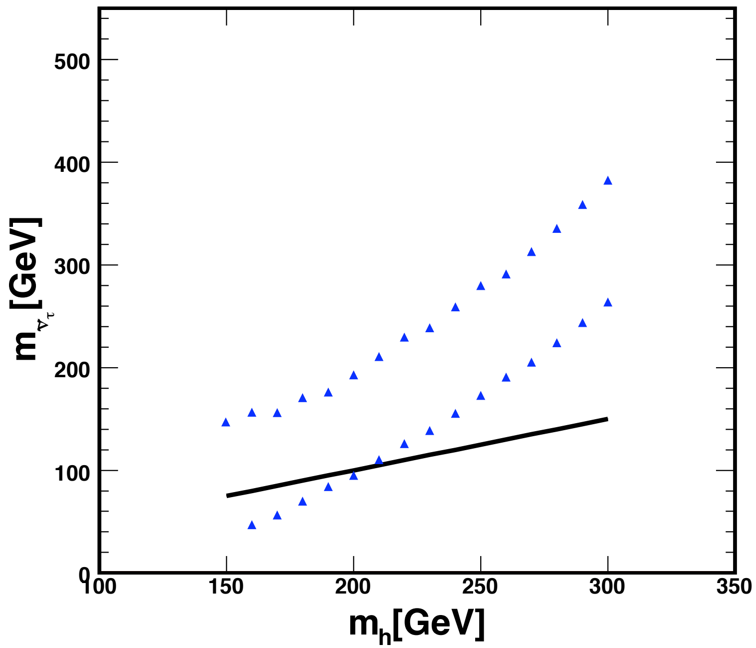
It is known, however, that if an extra positive contribution to the T parameter is present, agreement may be restored. The split sparticle spectrum provides such a contribution in a natural way. Calling Δm_{ud} the mass differrence between the upper and lower doublet component, each doublet contributes by

$$\Delta T = \frac{N_c}{12\pi s_W^2 m_W^2} (\Delta m_{ud})^2$$
$$= \frac{N_c}{12\pi s_W^2 m_W^2} \frac{(\Delta m_{ud}^2)^2}{(m_u + m_d)^2},$$

Sparticle Spectrum Consistent with Precision Measurements

A. Medina, N. Shah, C.W.'09





Sleptons acquire values that are of the order of the weak scale.
Particle physics phenomenology depends on characteristics of SUSY spectrum.
Different possibilities were studied in above reference.
Observe that when the Higgs is at the current reach of the Tevatron, sneutrinos may be light.

Light sneutrinos and Higgs searches

Presence of light sneutrinos may affect Higgs searches, in particular due to their enhanced couplings to Higgs bosons:

$$\Gamma(h \to \tilde{\nu}_\tau \tilde{\nu}_\tau) \simeq \frac{(g^2 \Delta + g_Y^2)^2 \, v^2}{128 \, \pi \, m_h} \left(1 - \frac{4 m_{\tilde{\nu}_\tau}^2}{m_h^2}\right)^{1/2}$$

This should be compared with the width into gauge bosons

$$\Gamma(h \to VV) \simeq \frac{G_F(|Q_V| + 1) \, m_h^3}{\sqrt{2} \, 16 \, \pi} \left(1 - \frac{4 m_V^2}{m_h^2} + \frac{12 m_V^4}{m_h^4}\right) \left(1 - \frac{4 m_V^2}{m_h^2}\right)^{1/2}$$

For instance, for a light sneutrino of order 70 GeV, and a Higgs mass of about 170 GeV, the gauge boson width is reduced by half.

The Tevatron bounds can be therefore avoided.

Baryon Number Violation

- In the SM, baryon and lepton number violation processes are present, induced by the anomalous currents.
- However, they don't induce proton decay. This is due in great part to the weakness of the gauge couplings.

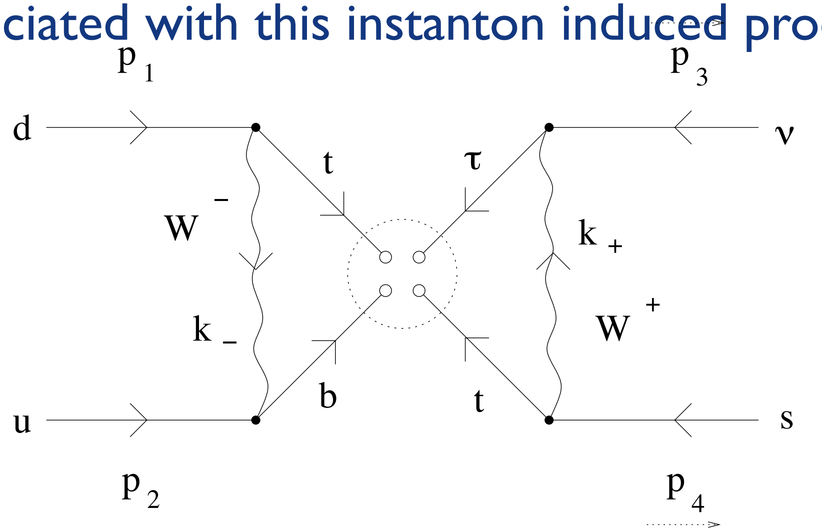
$$S_{\rm inst} = \frac{2\pi}{\alpha_{\rm ew}} \qquad \Gamma_{\Delta B \neq 0} \propto \exp(-2 S_{\rm inst})$$

- On the other hand, lepton and baryon number change in three units, one per generation.
- For strong gauge couplings, the situation may be different. Also, in the model at hand, we have strong "weak-like" interactions coupled strongly to only one generation. Baryon and lepton number are violated by only one unit in instanton processes
- This is precisely what is needed for proton decay. However, the relevant generation is the third generation. Does this protect the proton from decaying ?

Proton Decay

D. Morrissey, T. Tait and C.W. '05

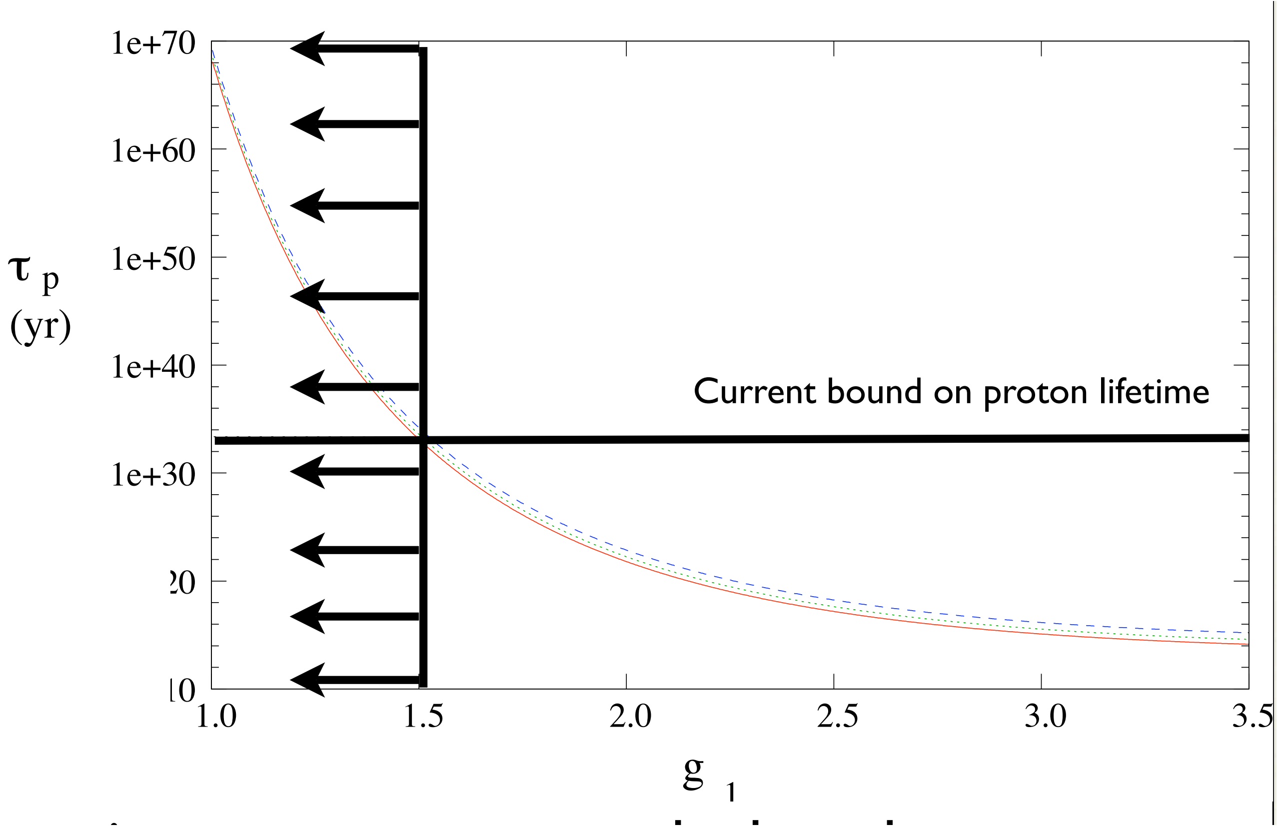
- Actually, the proton will decay due to the standard mixing between generations
- One can follow the usual instanton computation developed by t'Hooft, to estimate the rate of proton decay under these considerations
- A typical diagram associated with this instanton induced process is:



$$\mathcal{O}_{\rm eff} = -\left(\frac{24\pi^2}{3V_g}\right) V_f\, I_f\, L_f\, \epsilon^{abc}\left[(u_L^a\cdot s_L^b)(d_L^c\cdot \nu_L^\tau) + (u_L^a\cdot d_L^b)(s_L^c\cdot\nu_L^\tau)\right], \quad V_f = \left(\frac{g}{\sqrt{2}}\right)^4 V_{ts}V_{ub}^* V_{td}$$

$$I_f = \frac{C}{g_1^8} e^{-8\pi^2/g_1^2}\left(\frac{\mu}{\mathcal{V}}\right)^{b_0}(4\pi^2)^{1-b_0/2}2^{b_0/2}\Gamma(1+b_0/2)\,\frac{1}{\mathcal{V}^2}\ ,\qquad \mathcal{V}\simeq\sqrt{2}u$$

Computation of Proton Lifetime



For large values of the gauge coupling, sizeable effects on proton lifetime

Bound on the value of the gauge coupling may be obtained.

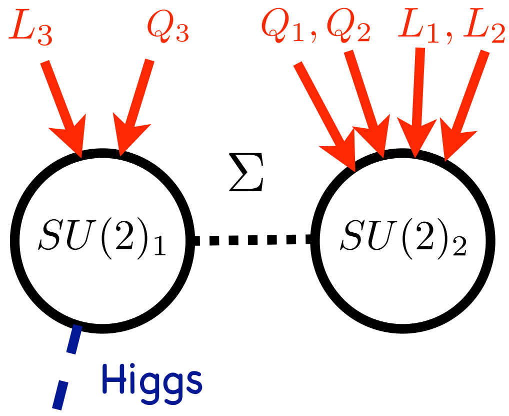
First low energy bound of this kind I know of.

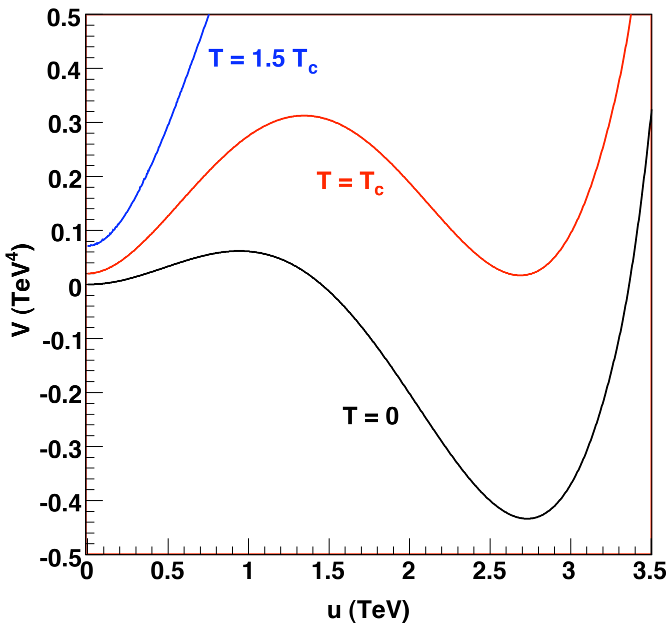
Higgs mass bound is only slightly affected. Values close to 250 GeV can still be obtained for the largest values of g_1.

Baryogenesis from an Earlier Phase Transition

Shu, Tait, Wagner
PRDD75, 063510 (2007)

- Baryogenesis from a phase transition requires the phase transition be strongly first order. A major obstacle to EW baryogenesis is the fact that in the SM the EW phase transition is predicted to be second order.
- We explore an SU(2) gauge extension of the SM, and use the strongly coupled instantons of the extended interactions to distribute lepton number unevenly through the three families at the time the theory transitions to the SM gauge symmetry.
- We find parameters of the extension leading to a first order phase transition



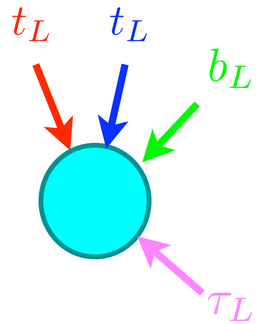


Reason: Large gauge couplings

Baryogenesis from an Earlier Phase Transition

- We solve the coupled differential equations describing the particle number densities near the surface of the bubble.
- An uneven distribution of lepton number is produced in each of the three families, because the SU(2)1 sphalerons only couple to the third family.

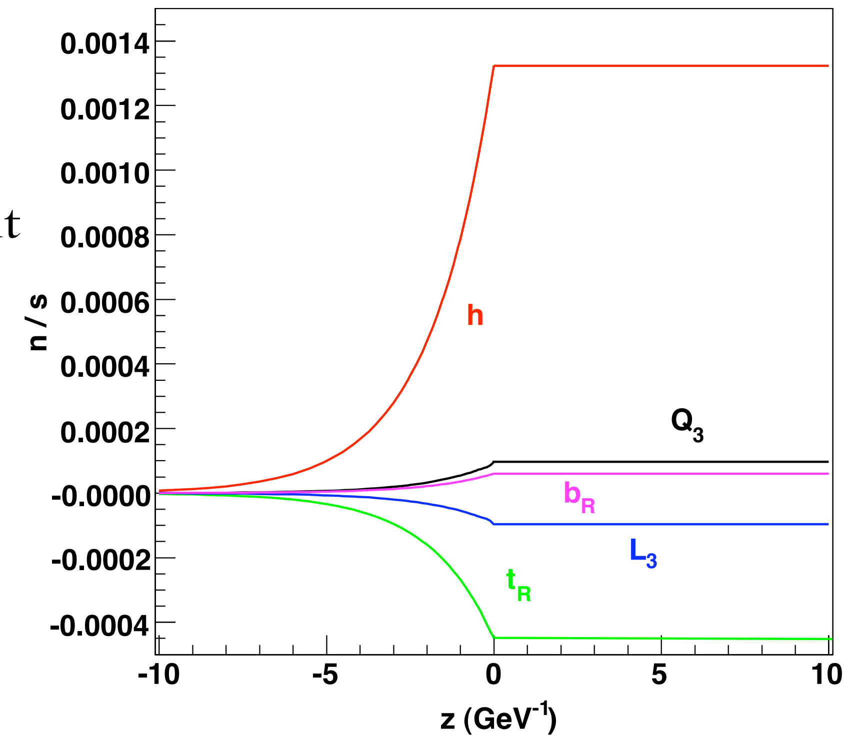
Morrissey, Tait, Wagner, PRD72, 095003 (2005)



We proceeded in a similar way as the computations at the weak phase transition, but at the one leading to

$$SU(2)_1 \times SU(2)_2 \to SU(2)_w$$

Diffusion equations were solved. Main difference: Sphaleron rate large, and these transitions were incorporated into equations.



Diffusion Equations

Following Nelson and Huet,

$$Q_{1L} = Q_{2L} = -2U_R = -2D_R = -2S_R = -2C_R = -2b\,.$$

$$Q \equiv t_L + b_L$$

$$\begin{aligned}
v_w Q' - D_Q Q'' &= -\Gamma_y \left[\frac{Q}{k_Q} - \frac{h}{k_h} - \frac{t}{k_t}\right] - 6\Gamma_{QCD}\left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b}\right] \\
&\quad -6\Gamma_1 \left[3\frac{Q}{k_Q} + \frac{L_3}{k_L}\right], \\
v_w t' - D_Q t'' &= -\Gamma_y \left[-\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t}\right] + 3\Gamma_{QCD}\left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b}\right], \\
v_w h' - D_h h'' &= -\Gamma_y \left[-\frac{Q}{k_Q} + \frac{h}{k_h} + \frac{t}{k_t}\right] + \gamma_h\,, \\
v_w b' - D_Q b'' &= 3\Gamma_{QCD}\left[2\frac{Q}{k_Q} - \frac{t}{k_t} - 9\frac{b}{k_b}\right], \\
v_w L_3' - D_L L_3'' &= -2\Gamma_1 \left[3\frac{Q}{k_Q} + \frac{L_3}{k_L}\right],
\end{aligned}$$

$$k_Q = 6; \quad k_L = 2; \quad k_t = k_b = 3; \quad k_h = 8\,.$$

Sources

The sources here come from CP-Violating couplings in the Higgs sector.
The phase of the Higgs vev carries a phase and the fermion number induced is proportional to variations of such a phase. For that purpose, a more general potential than the one introduced before was considered.

$$V_\Sigma = m^2|\Sigma|^2 + \lambda|(\Sigma\Sigma)|^2 + \lambda'|\Sigma|^4 + (-\frac{1}{2}D(\Sigma\Sigma) + \widetilde{\lambda}(\Sigma\Sigma)|\Sigma|^2 + h.c.\ ),$$

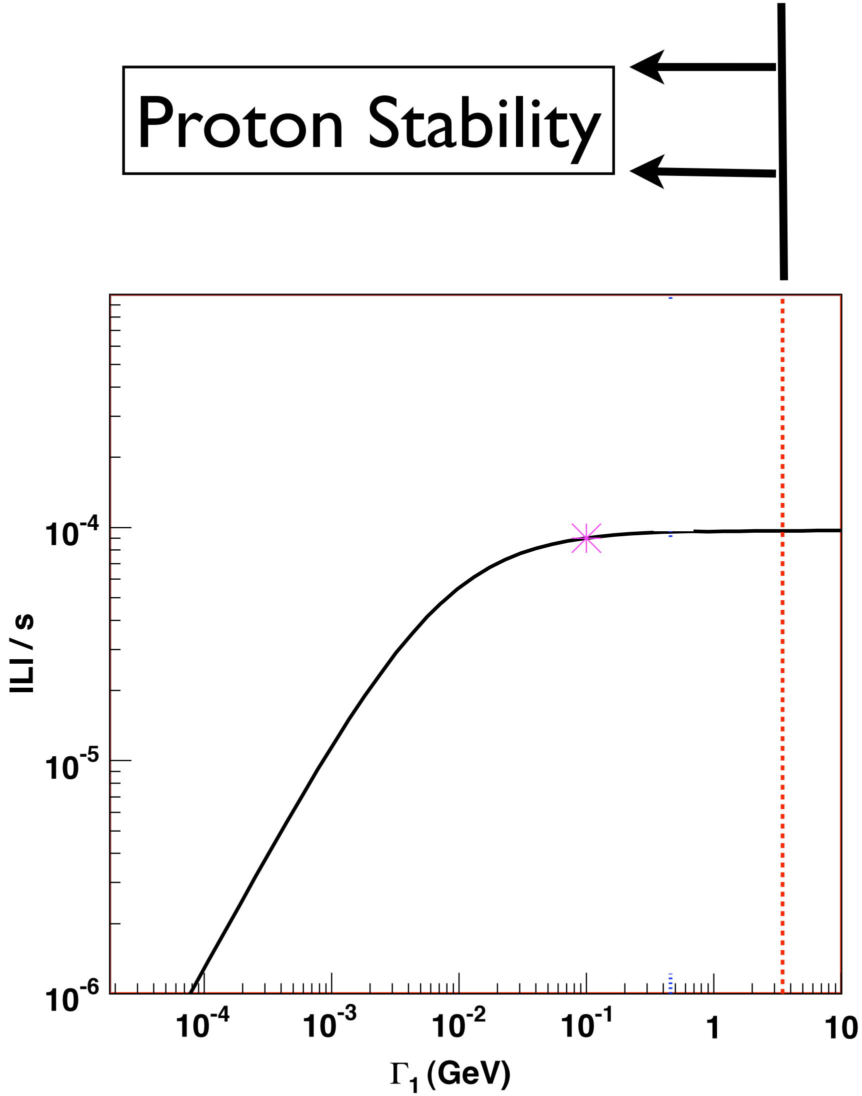
$$u_0^2 = \frac{De^{2i\theta_0} + D^* e^{-2i\theta_0} - m^2}{\lambda + \lambda' + \widetilde{\lambda}e^{2i\theta_0} + \widetilde{\lambda}^* e^{-2i\theta_0}}$$

$$\theta_0 = -\frac{1}{4}\text{acos Re}\left[\frac{-2D^* + \widetilde{\lambda}^* u_0^2}{-2D + \widetilde{\lambda}u_0^2}\right]$$

$$\widetilde{\gamma}_{h_d} = \left(\frac{\Delta\theta}{L_w}v_w\right) u^2(x)\left\{\left[|c_1\mu|^2 - |c_2\mu'|^2\right]\mathcal{I}_{H_d H_d'} + \left[|A_2|^2 - |A_2'|^2\right]\mathcal{I}_{H_d H_u'}\right\}$$

$\Delta\theta$ is the variation of the phase from inside the bubble of true vacuum to the unbroken phase

Example before consider a fast sphaleron transition rate.
Is this consistent with the proton lifetime constraints ?



Shu, Tait, C.W. '07

Baryogenesis

- At the phase transition, a baryon and lepton number of the third generation is obtained

- For large gauge couplings, this amount can be large. However, it is diluted by low energy weak sphalerons, that tend to dilute the obtained baryon number. But they preserve an asymmetry in the three generation lepton numbers :

$$\Delta(B/3 - L_i) = 0$$

- Final baryon number is obtained by effects of this asymmetry during the second order electroweak phase transition. This was studied by Dreiner and Ross. They showed that the tau mass effects are enough to induce a final asymmetry in the baryon number. Assuming the sphalerons are in equilibrium during the phase transition,

$$B = \begin{cases} \frac{4}{13}(B-L) & B-L \neq 0 \\ -\frac{4}{13\pi^2}\sum_{i=1}^{N}\Delta_i \frac{m_{l_i}^2}{T^2} & B-L=0\ . \end{cases} \qquad \Delta_i \equiv L_i - \frac{1}{3}B$$

Baryogenesis from an early Phase Transition

- At the early phase transition, an asymmetry of order 10^{-4} may be obtained

- This early result is, however, diluted by standard sphaleron effects

- For a standard transition temperature of order of 100 GeV, the tau mass effects are approximately equal to 10^{-6}, leading to a final result for the baryon asymmetry

$$\frac{n_B}{n_S} \simeq 10^{-10}$$

- Consistency with observatioins therefore may be obtained within this framework

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.

Conclusions (addendum)

- Electroweak Baryogenesis provides a very attractive framework for the obtention of the observed baryon asymmetry
- Supersymmetry provides a natural realization of this scenario, for either light stops or light singlets, discussed before
- We explored the alternative possibility of generating the baryon number from an early phase transition, associated with strong interactions in the weak sector.
- This scenario is motivated by a solution to the hierarchy problem and/or to explain the large differences in quark masses of different generations. Splitting between sparticles can compensate the precision electroweak corrections associated with a heavy Higgs.
- Proton decay may be induced in this models, for sufficiently large values of the strong gauge couplings.
- Baryogenesis may occur, in spite of standard sphaleron dilutioin, and for values of the gauge couplings consistent with proton stability.

Backup Slides