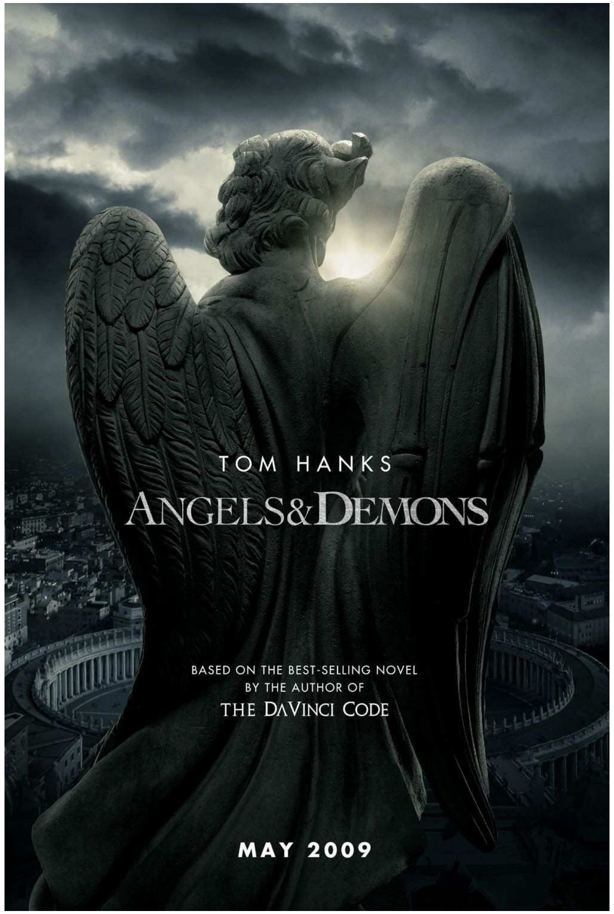
Electroweak Baryogenesis in the MSSM and its signatures

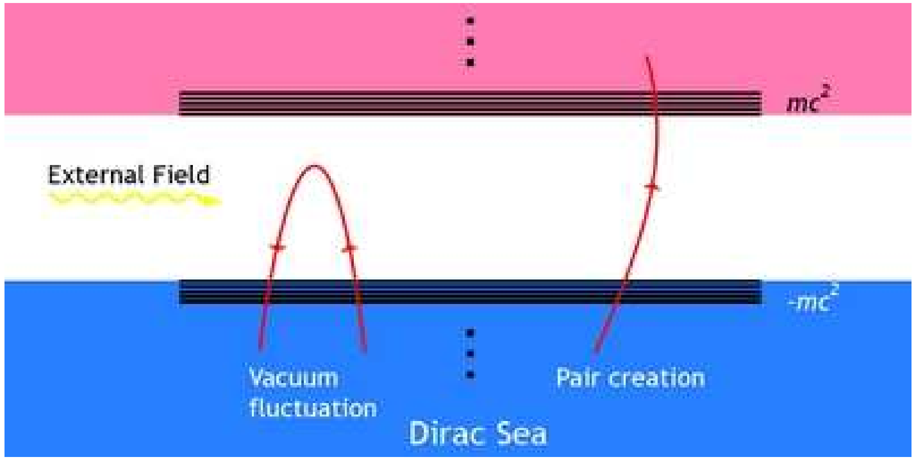
A. Menon

Illinois Institute of Technology

December 7th, 2009

Anti-Matter and the Dirac Sea



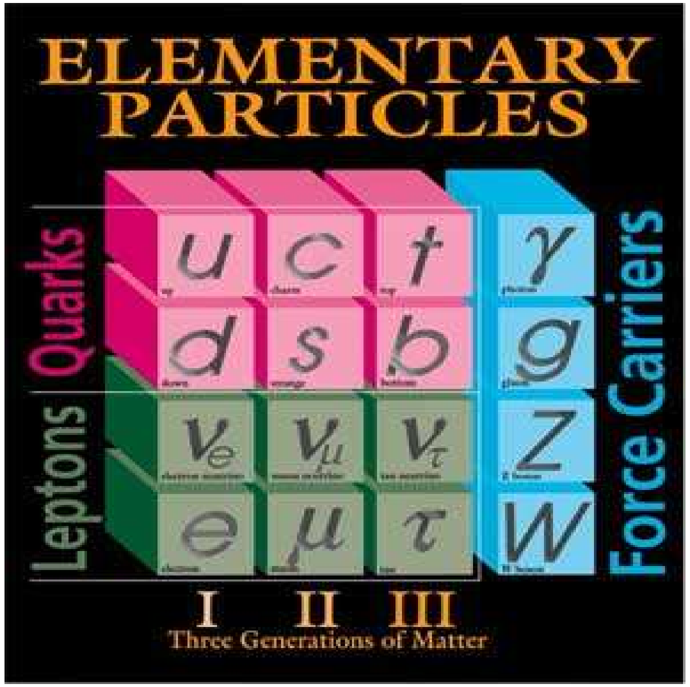


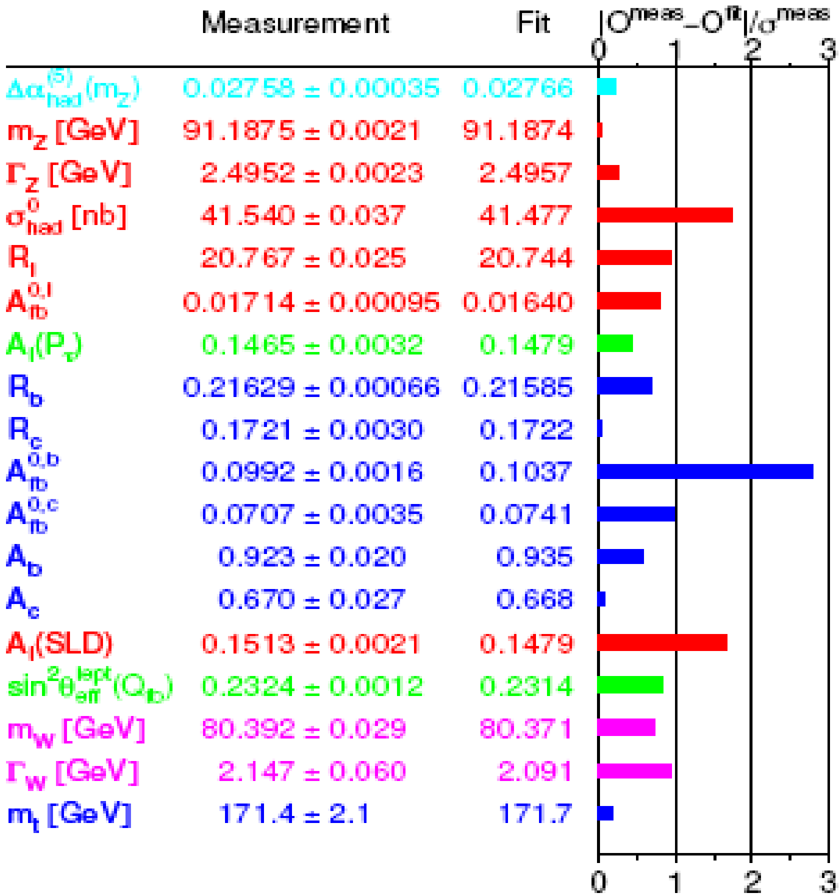
1928: Dirac showed relativity + quantum mechanics ⇒ of the positron.

1932: Anderson discovered the positron.

The Standard Model and Experiment

- Gauge group: $SU_C(3) \times SU_L(2) \times U_Y(1)$





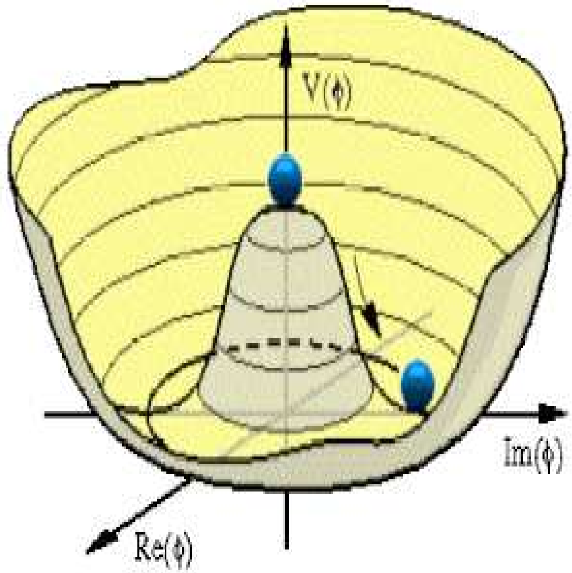
- Each particle in matter sector has an anti-particle.

The Electroweak sector in the Standard Model

- The H doublet acquires a VEV $\begin{pmatrix} 0 \\ v \end{pmatrix}$ at the minimum, breaking $SU(2)_L \times U(1)_Y \to U(1)_{EM}$ by giving mass to the W and Z bosons

- Yukawa interactions with H give the quarks their masses.

- Mismatch of the U_L and D_L rotations
$\Rightarrow u_L W^+ d_L$ CP violating couplings $\propto \arg(V_{CKM})$.



- The massive gauge bosons mediate for short range weak forces that lead to beta decay

$$n \to p + e + \bar{\nu}$$

Baryon and Lepton Number in the SM

- Two $U(1)$ global symmetries:

Baryon number (B): under which quarks are charged.
Lepton number (L): under which leptons are charged.

- Baryon number violation leads to proton decay

$$p \to e + \gamma^0 (\pi^0 K^0).$$

- B and L are conserved quantites at the classical level.

The puzzle of Baryon Asymmetry of Universe

- CPT invariance implies matter and anti-matter have the same masses and lifetimes.

- Observable Universe is composed of matter.

- Anti-matter is only observed in colliders and cosmic rays.

- Rate of observation of anti-matter in cosmic rays is consistent with secondary emission of antiprotons.

$$\frac{n_{\bar{p}}}{n_p} \sim 10^{-4}$$

Sources of Baryon Asymmetry observation

• Information of the baryon asymmetry comes from two sources:

1. Big Bang Nucleosynthesis (BBN)
2. Cosmic Microwave Background Radiation (CMBR)

• The combined observed abundances of the primodial light elements along with BBN give us

$$\eta = \frac{n_B}{n_\gamma}.$$

• CMBR tells gives us $\Omega_B \equiv \frac{\rho_B}{\rho_c}$ where $\rho_c = 10^{-5} h^2 \frac{GeV}{cm^3}$, in which case

$$\eta = 2.6810^{-8} \Omega_B h^2.$$

The observed Baryon Asymmetry

- Baryon number density in the Universe:

$$\eta = \frac{n_B}{n_\gamma} = (6.5 \pm 0.3) \times 10^{-10}$$

WMAP '06

- Baryons and anti-baryons annihilate very efficiently so what is the source of this Baryon asymmetry?

- Is this asymmetry primodial or dynamically generated as the early Universe cools?

- If the asymmetry is dynamically generated, what is the mechanism?

The Sakharov Conditions for Baryon Asymmetry

- Necessary conditions for generating baryon asymmetry (BAU) are:

  1) Baryon number B violation

  2) CP violation

  3) Violation of thermal equilibrium

- B violation clearly necessary for generating BAU

- B is odd under C and CP $\Rightarrow$ BAU

- B is also odd under T $\Rightarrow$ BAU

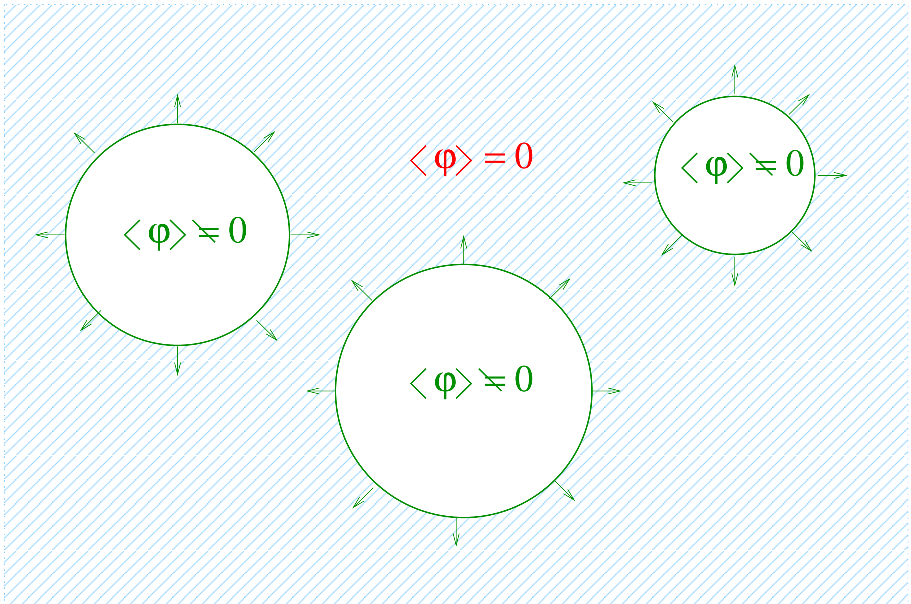
The Electroweak Baryogenesis Scenario

- Baryon production occurs at the electroweak phase transition.

[Kuzmin, Rubakov, Shaposhnikov '85]

- Electroweak symmetry breaking occurs as the Universe cools, nucleating bubbles of broken phase.

- Baryon production occurs near the walls of the expanding bubbles.



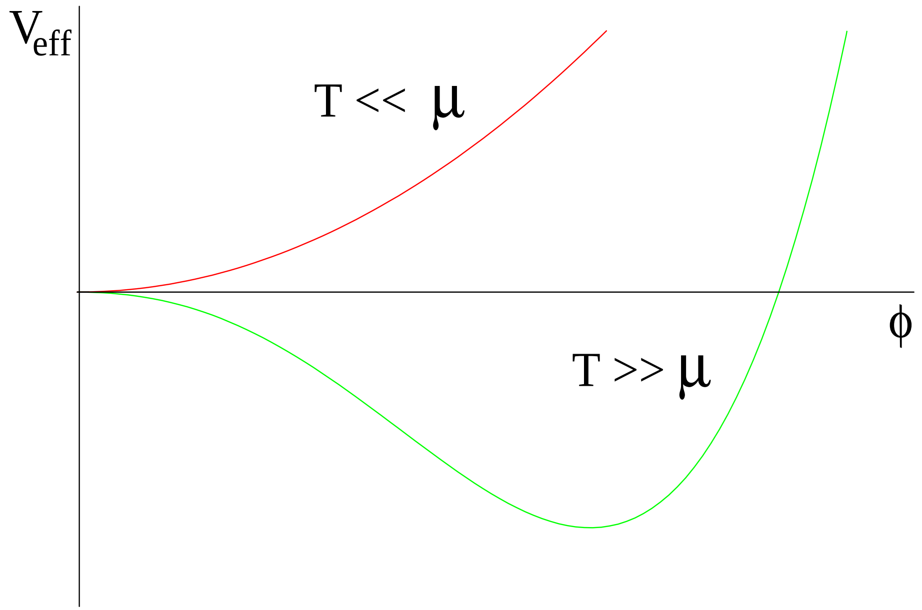
The Electroweak Phase Transition

- The Higgs VEV $\langle\phi\rangle$ is the order parameter

$$\langle\phi\rangle = 0 \Rightarrow SU(2)\times U(1)_Y \text{ Unbroken}$$
$$\langle\phi\rangle \neq 0 \Rightarrow SU(2)\times U(1)_Y \rightarrow U(1)_{em}$$

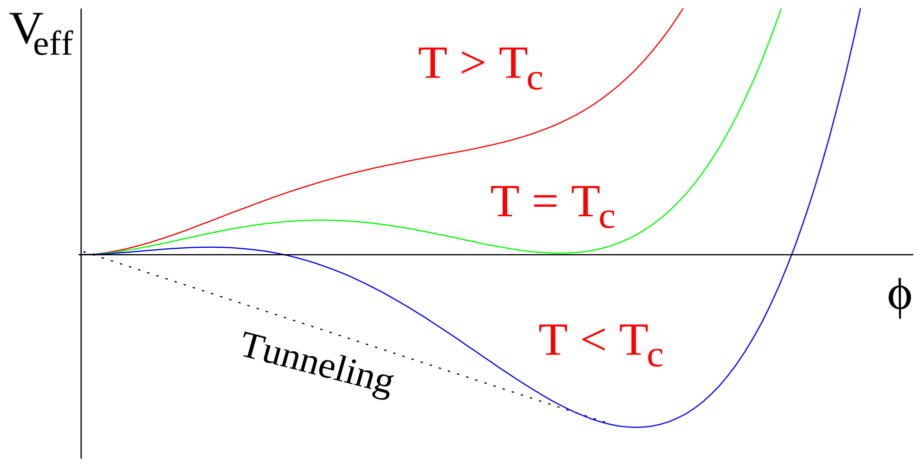
- Effective potential at finite temperature T

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \ldots$$

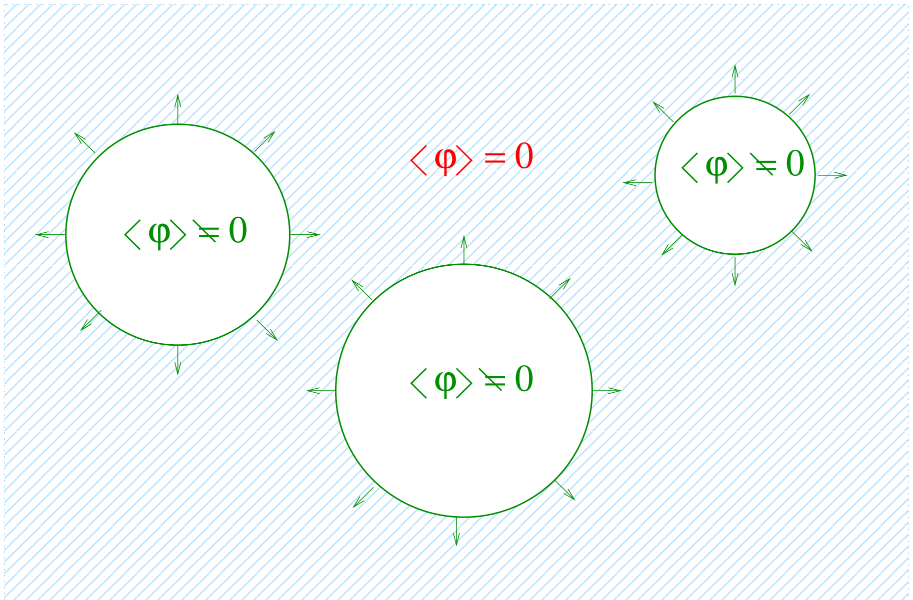


Bubble Nucleation

- First order phase transition



- Bubbles of broken phase nucleate when $T \lesssim T_c$

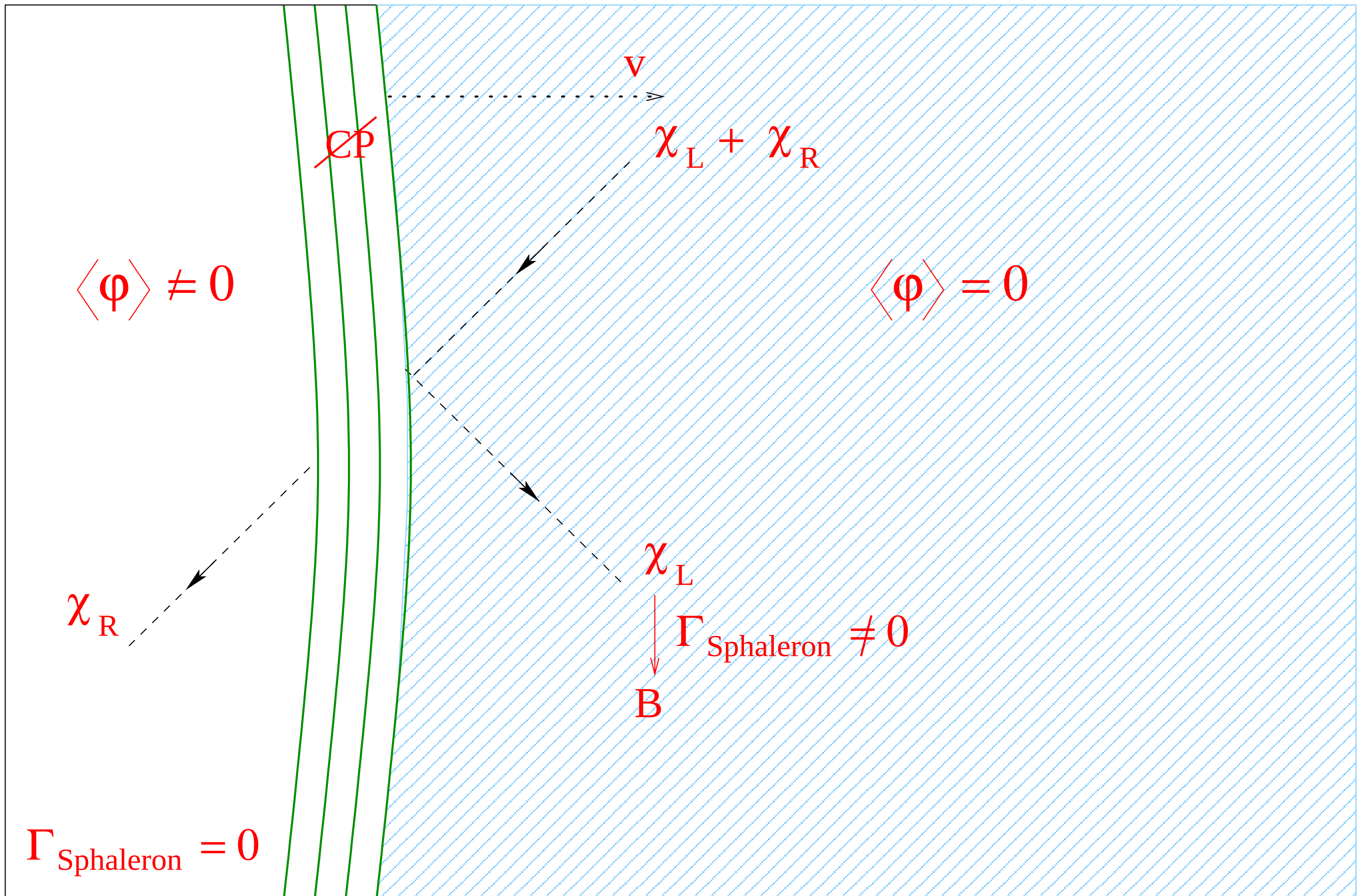


Baryon Production

- CP violation in bubble wall $\Rightarrow$ chiral flux into the unbroken phase.

- Sphaleron transitions in the unbroken phase converts the chiral flux into baryons.

- Baryons produced at the bubble wall, enter the bubble as it expands.



Sphalerons

- $U(1)_{B+L}$ is anomalous in the SM and is violated by quantum effects.

- $T = 0$ Instanton effects drive transitions

$$\Gamma \sim e^{-16\pi^2/g_2^2} \simeq 10^{-320}.$$

- $T \neq 0$ Thermal fluctuations (sphaleron) drive transitions

$$\Gamma \sim \begin{cases} T^4 e^{-4\pi\langle\phi\rangle/gT} & \langle\phi\rangle \neq 0 \quad \text{[Arnold,Mclerran '87]} \\ \alpha_w^4 T^4 & \langle\phi\rangle = 0. \quad \text{[Bodeker,Moore,Rummukainen '99]} \end{cases}$$

EWBG in the Standard Model

- Electroweak phase transition is first-order only if [Kajantie et. al.'98]

$$m_h \lesssim 70 \text{ GeV}$$

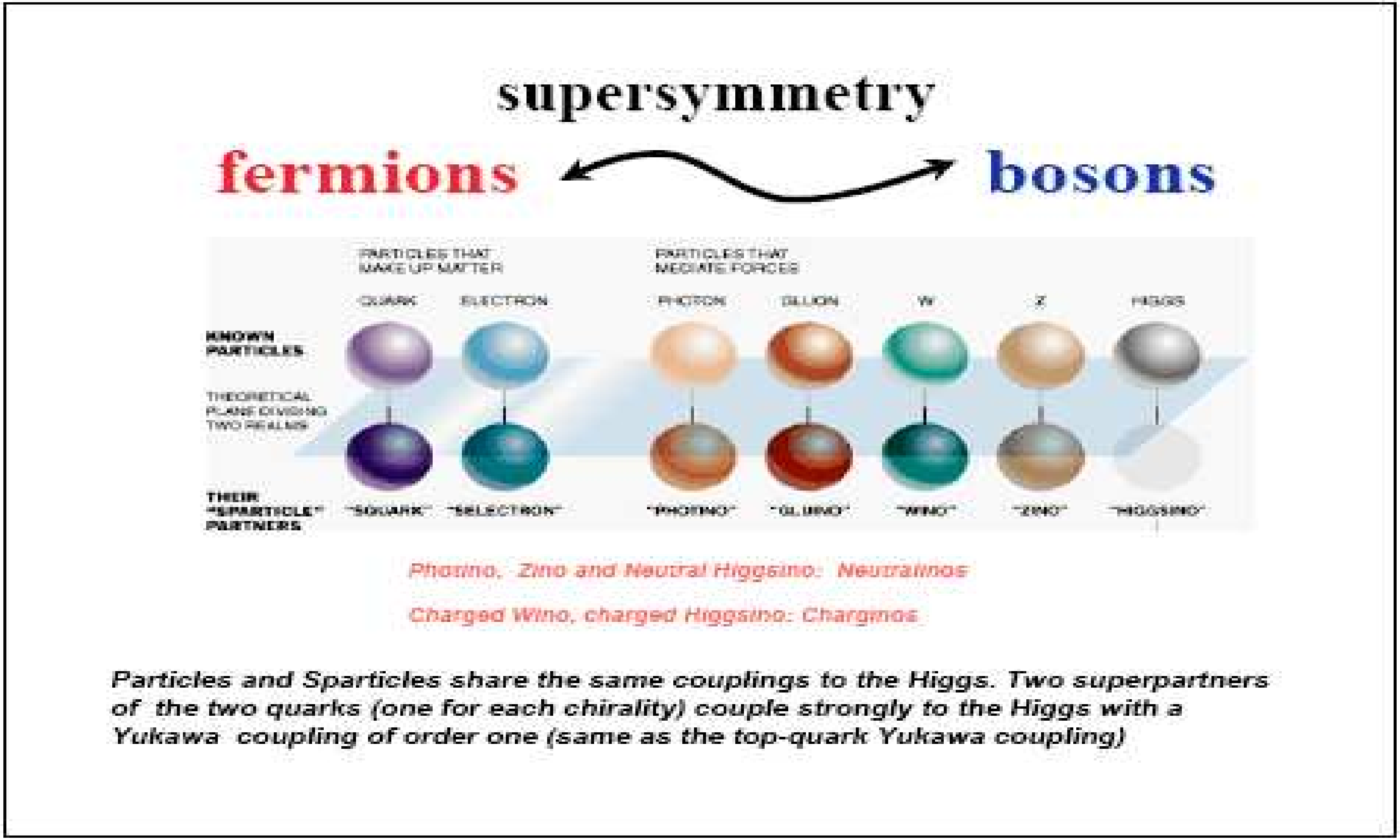
- LEP experimental mass bound

$$m_h > 114.4 \text{ GeV}$$

- Not enough CP violation is SM [Gavela et. al. '94]

EWBG does not work in the Standard Model.

The Minimal Supersymmetric Standard Model



Motivation for Supersymmetry

- Resolves the Hierarchy problem.

- Supersymmetry contains the generator for space-time translations a necessary ingredient for theory of quantum gravity.

- Gauge coupling unification is achieved with the Minimal supersymmetry extension of the Standard Model.

- Starting from positive scalar masses at the high scale, electroweak symmetry breaking is induced radiatively.

- If R-parity $P = (-1)^{3B+L+2S}$ is imposed, the Lightest SUSY Particle (LSP) is stable and is an excellent cold Dark Matter particle.

Parameters in the MSSM

- Supersymmetric interactions:

$$W = Y_u Q H_u \bar{U} - Y_d Q H_d \bar{D} - Y_E L H_d E + \mu H_u H_d$$

- Soft supersymmetry breaking terms:

Name	Lagrangian Terms
Gaugino Masses	$-\frac{1}{2} M_i \tilde{\lambda}_i \tilde{\lambda}_i$
Trilinear parameters	$a_{ijk} \phi_i \phi_j \phi_k$
Soft masses	$m_{ij} \phi^{*i} \phi_j$ and $b_{ij} \phi_i \phi_j$

- After supersymmetry breaking: 3 Higgs bosons h, H, A and charged Higgs $H^{\pm}$ with $\tan\beta = v_u / v_d$.

EWBG MSSM: First Order Phase Transition

- For a first order phase transition for

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \dots$$

we need

$$\frac{\langle \phi(T_c) \rangle}{T_c} \simeq \frac{\gamma}{\lambda} > 1$$

- γ is generated bosonic loops and the dominant contribution in the MSSM is from a light mostly right-handed stop. [Carena,Quiros,Wagner]

- Larger stop mass $\Rightarrow$ large λ $\Rightarrow$ larger m_h.

contd...

• The finite temperature effective Higgs potential in the MSSM has a term

$$V_{eff}^{MSSM} \subset -\frac{N_c T}{6\pi}(m_{\tilde{t}}^2 + \Pi_R(T)^2)^{3/2}$$

where $\Pi_R(T)^2$ is the positive self energy contribution and

$$m_{\tilde{t}}^2 \sim m_{U_3}^2 + y_t^2 \phi^2 \left(1 - \frac{|X_t|^2}{m_{Q_3}^2}\right)$$

• Generating a ϕ^3 term needed for a first order phase transition $\Rightarrow m_{U_3}^2$ cancels $\Pi_R(T)^2$ and $X_t \ll m_{Q_3}$.

EWBG MSSM: Light Stop Implications

- $\Delta\rho$ limits $\Rightarrow$ light stop mass must be mostly right handed.

- For a strong first order phase transition and to avoid color breaking minima

$$-(100\text{GeV})^2 \lesssim m_{U_3}^2 \lesssim 0; \quad X_t/m_{Q_3} \lesssim 0.5$$
$$\Rightarrow 120 \lesssim m_{\tilde{t}_1} \lesssim 170\text{GeV}.$$

- Avoiding LEP limit on Higgs mass:

$$m_{Q_3} \gtrsim 2\text{TeV}; \quad M_A \gtrsim 200GeV; \quad 5 < \tan\beta \ < 10$$
$$\Rightarrow m_h \lesssim 125\text{GeV} \qquad .$$

- Light stop search limits for $m_{\tilde{t}_1} \leq m_t$:

$$(m_{\tilde{t}_1} - m_\chi) \lesssim 30\text{GeV}.$$

as decay products are soft and difficult to find.

- Light stop coannihilations with Bino LSP $\Rightarrow$ viable Ωh^2 for $m_{\tilde{t}_1} - m_\chi \lesssim 30$ GeV. [Balazs,Carena,A.M.,Morrissey,Wagner '05].

EWBG MSSM: CP Violation

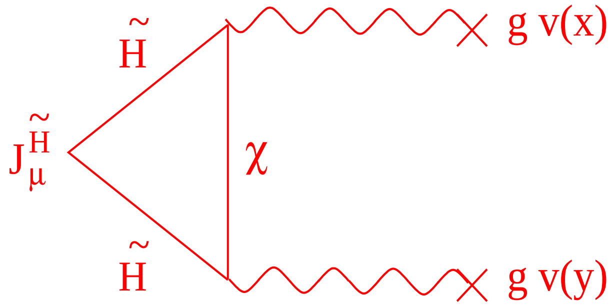
- Higgsino is an important source of MSSM CP violation phase

$$M_{\tilde{\chi}^{\pm}} \sim \begin{pmatrix} |M_2| & g_2 v_u(z) \\ g_2 v_d(z) & e^{i\phi}|\mu| \end{pmatrix}$$

where ϕ is the $Arg(\mu M_2)$.

- CP violation in bubble wall modifies the transmission and reflection coefficients leading the current

$$\langle J_\mu^{\tilde{H}} \rangle \propto Im(\mu M_2)$$



- $\langle J_\mu^{\tilde{H}} \rangle$ in turn sources B violating process through sphalerons.

EWBG MSSM: Implications of CP Violation

- Generating baryon asymmetry:

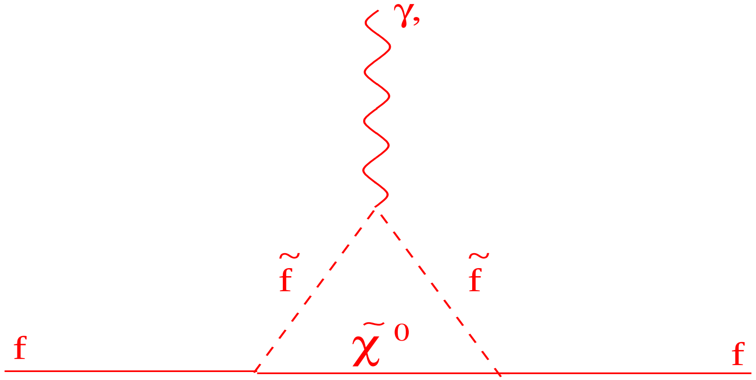
$$Arg(\mu M_{1,2}) \gtrsim 10^{-2}$$
$$\mu M_{1,2} \lesssim 400 \text{ GeV}$$

[Carena,Quiros,Seco,Wagner '02, Lee,Cirigliano,Ramsey-Musolf '04]

- EDM constraints:

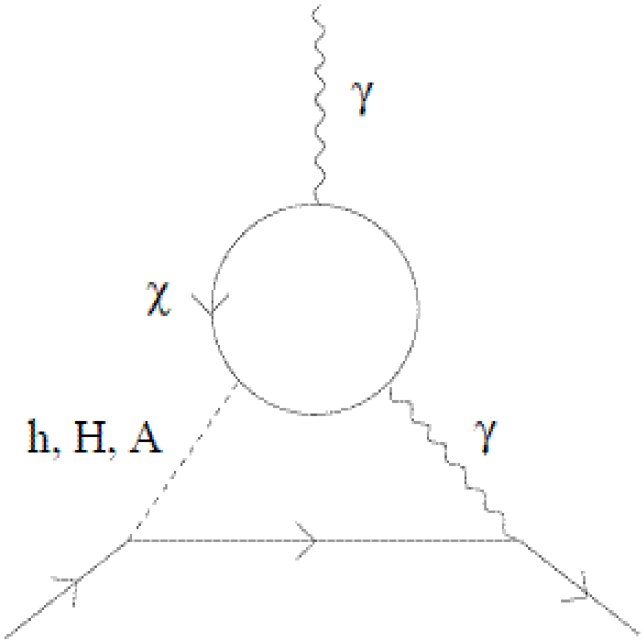
$$|d_e| < 1.6 \times 10^{-27} \text{e cm}$$ [Regan et. al. '02]
$$|d_n| < 2.9 \times 10^{-26} \text{e cm}$$ [Baker et. al. '06]

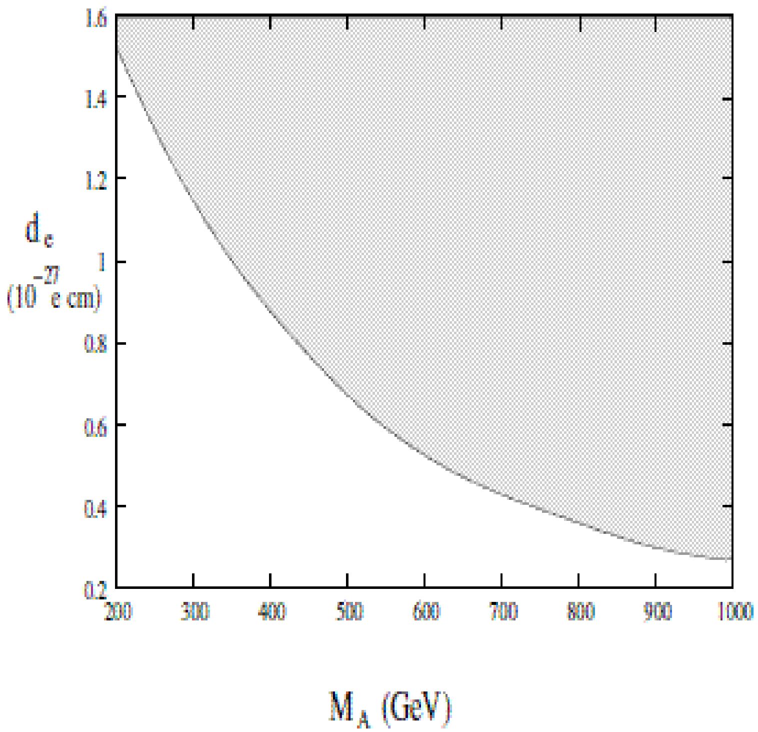
- One loop EDM constraints $\Rightarrow m^2_{\tilde{f}} > 2-5$ TeV or the first two generations are decoupled. [Nath,Ibrahim '98]



contd ...

- Two-loop contribution: $\propto Im(\mu M_2)$ [Chang, Chang, Kueng '02; Pilatfsis '02]





- EDM constraints weaker for $M_A \gtrsim 1$ TeV.

Split Stop Supersymmetry

- EDM constraints ⇒ large sfermion and pseudo scalar masses.

$$m_{\tilde{f}} \gtrsim 5 \text{ TeV}$$

- LEP Higgs mass limit ⇒ heavy mostly left-handed stop

$$m_{\tilde{t}_2} \gtrsim 2 \text{ GeV}.$$

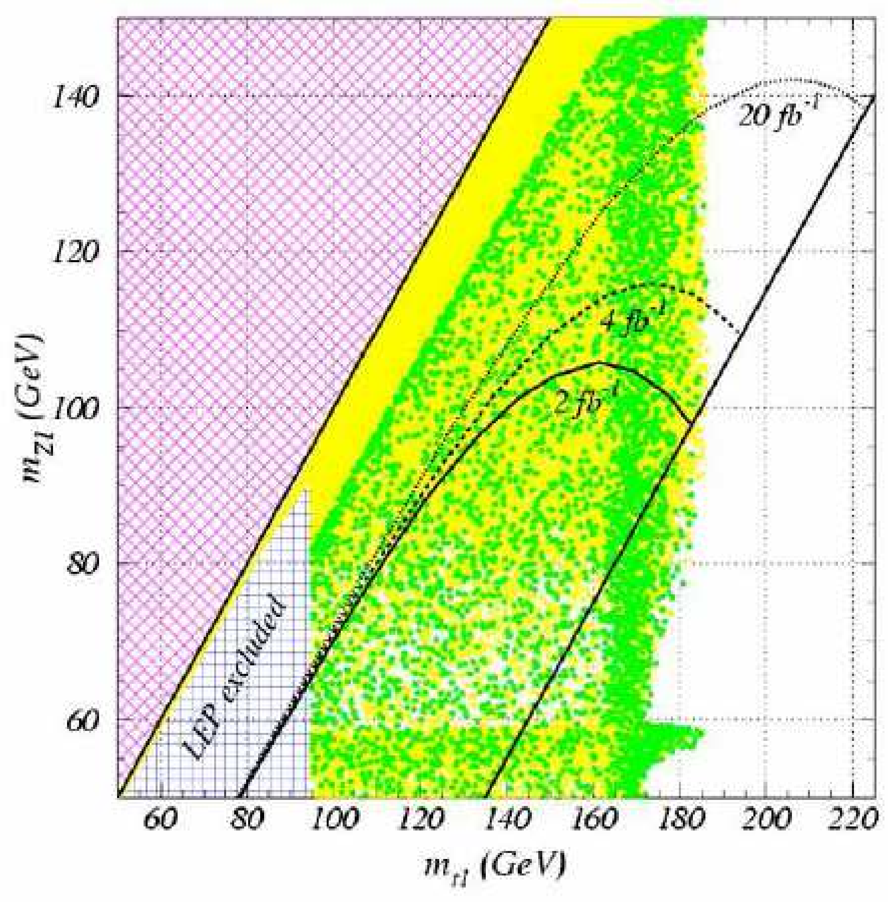
- EWBG ⇒ light charginos, neutralinos and right handed stops.

$$m_{LSP} < m_{\tilde{t}_1} \lesssim m_t$$

⇒ Stop Split Supersymmetry. [Carena,Nardini,Quiros,Wagner '09]

Direct light stop searches: Tevatron

- Light stop searches the in $\tilde{t} \to c\tilde{\chi}^0$ channel: [Balazs, Carena, Wagner '04]



Direct light stop searches: LHC

- $\tilde{t}_1$ produced copiously, but decays into soft jets so hard to find.

- Possible channels $\tilde{t}_1 \to c\chi_1^0$, $\tilde{t}_1 \to bW^*\chi_1^0$, $\tilde{t}_1 \to b\chi_1^{+*}$.

[Balazs et. al. '04; Demina et. al. '99; Hiller, Nir'08]

- Can be seen in gluino pair production and decay into same sign leptons, jets and MET with 30 fb^{-1} for $m_{\tilde{g}} \lesssim 1$ TeV. [Kramel, Raklev '05,06]

- For small mass splitting, searches in the j + MET or γ + MET can probe EWBG scenario with 100 fb^{-1}. [Carena et. al. '08]

- Parameter space determination is generally challenging.

Direct light stop searches: Stoponium

- $\eta_{\tilde{t}_1} = \tilde{t}_1 \tilde{t}_1^*$ can form as $\Gamma_{\tilde{t}_1 \to c\chi_1^0} \ll$ binding energy of $\eta_{\tilde{t}_1}$.

[Nojiri, Dress '95]

- $\eta_{\tilde{t}_1} \to \gamma\gamma$ may be observable with 100 fb^{-1} for $m_{\eta\tilde{t}_1} \lesssim 250$ GeV.

[Martin '08]

Precise measurement of stoponium mass.

Indirect light stop effects on Higgs Searches

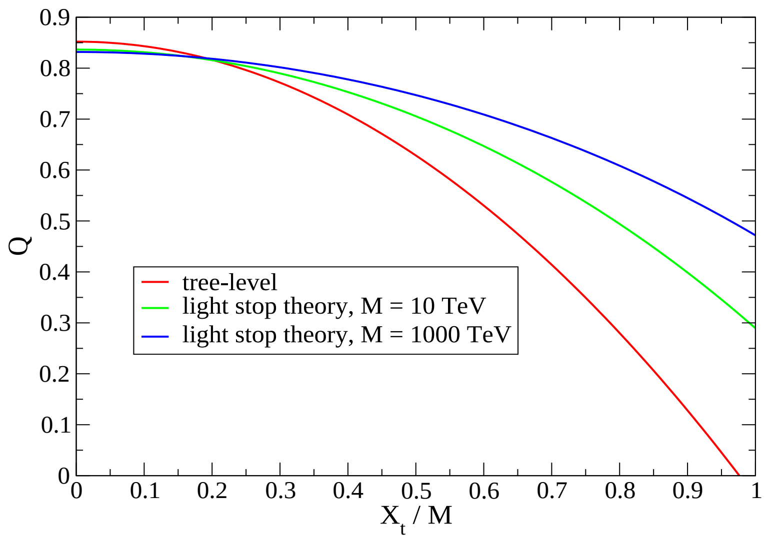
- Light stops can modify Higgs production cross-sections.

[Kane et. al. '95; Dawson et. al. '96; Djouadi '98; Dermisek, Low '07]

- Effective light stop Higgs coupling in EWBG

$$g_{h\tilde{t}_1\tilde{t}_1} \sim m_t^2 \left(1 - \frac{|X_t|^2}{m_{Q_3}^2}\right)$$

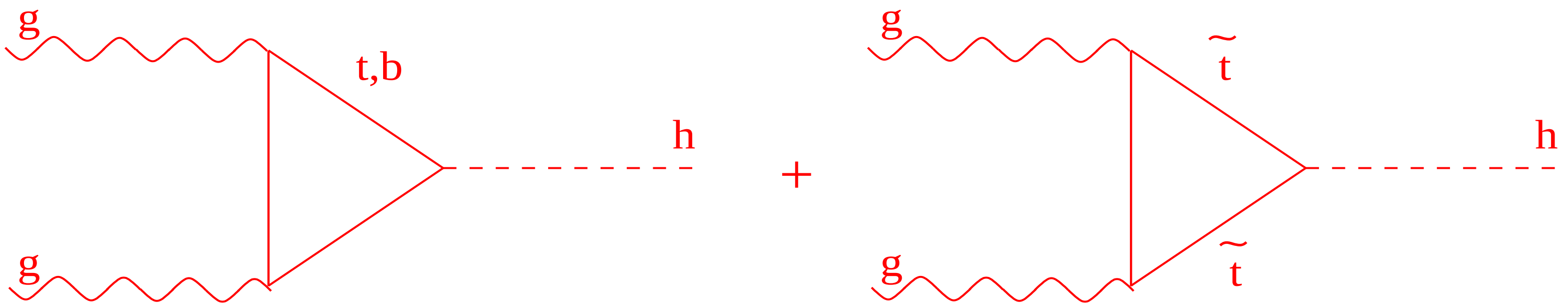
where $Q = \sqrt{2} v g_{h\tilde{t}_1\tilde{t}_1}$



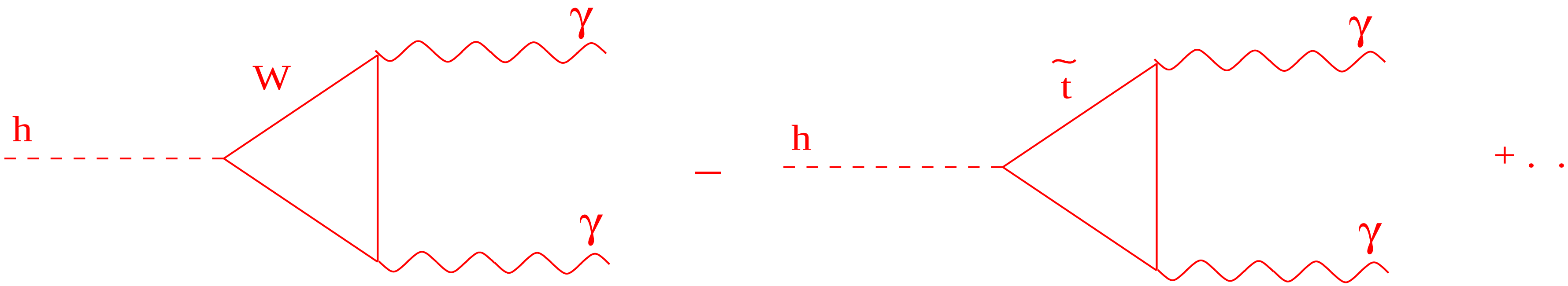
- Stronger first order EW phase transition $\Rightarrow$ larger $g_{h\tilde{t}_1\tilde{t}_1}$ coupling, if $X_t \ll m_{Q_3}$.

Light stop loop effects on Higgs Branching Ratios

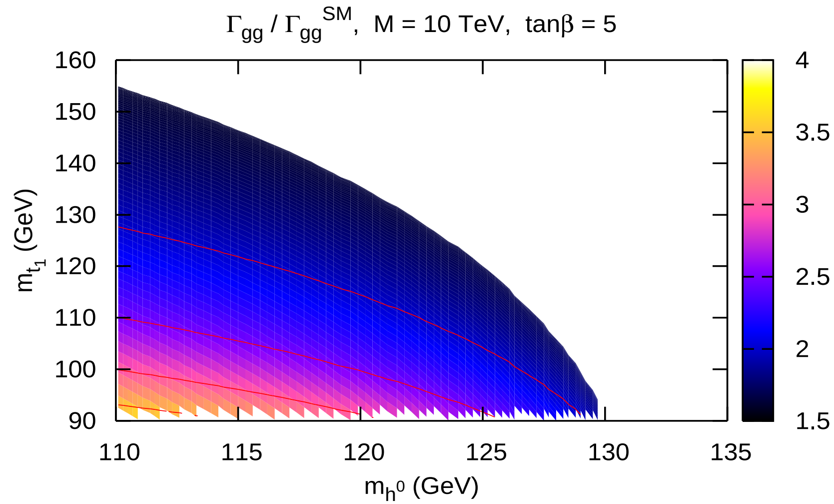
Gluon Fusion

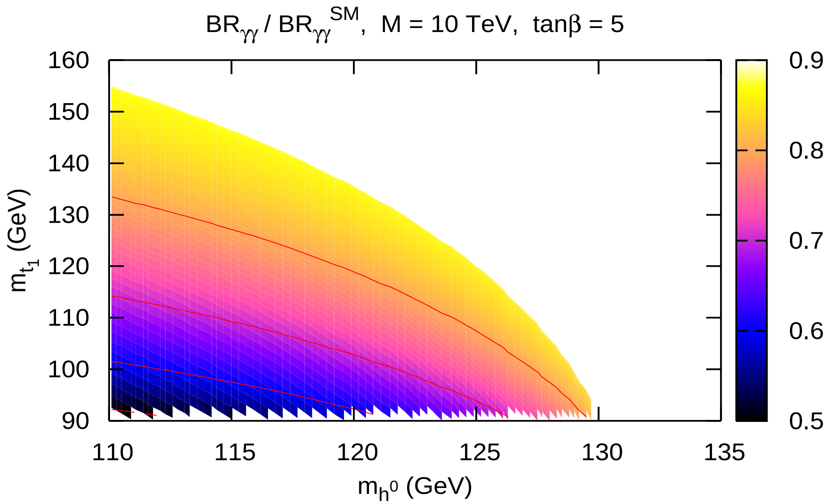


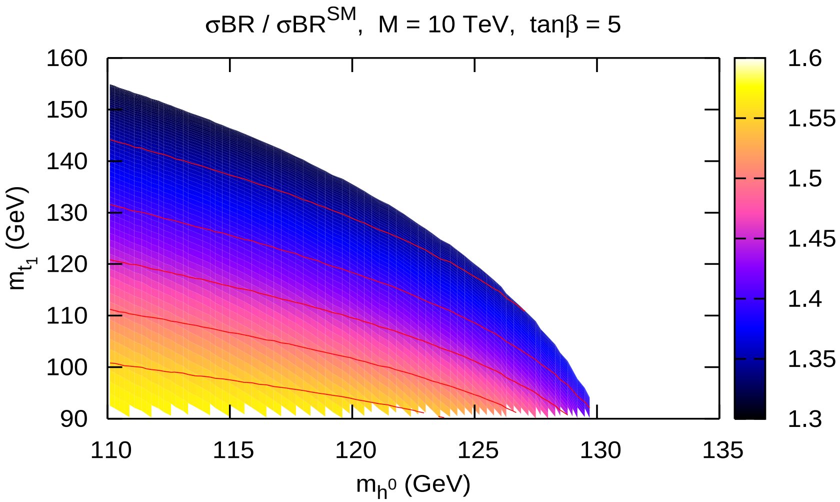
Higgs Photon coupling



contd ...


$\Gamma_{gg} / \Gamma_{gg}^{SM}$, M = 10 TeV, tanβ = 5
160
150
140
130
120
110
100
90
$m_{\tilde{t}_1}$ (GeV)
110
115
120
125
130
135
m_{h^0} (GeV)
4
3.5
3
2.5
2
1.5

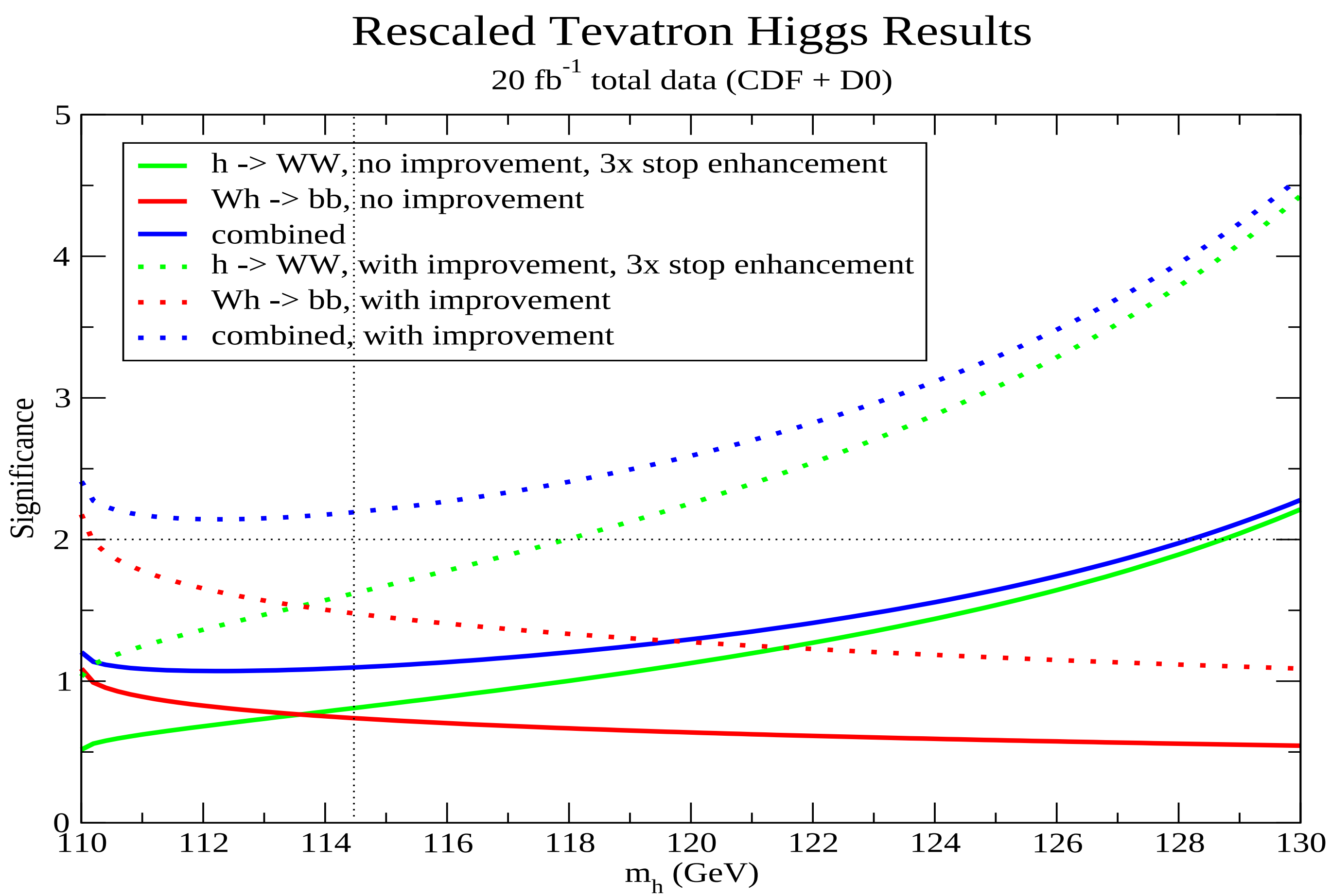

$BR_{\gamma\gamma} / BR_{\gamma\gamma}^{SM}$, M = 10 TeV, tanβ = 5
160
150
140
130
120
110
100
90
$m_{\tilde{t}_1}$ (GeV)
110
115
120
125
130
135
m_{h^0} (GeV)
0.9
0.8
0.7
0.6
0.5


$\sigma BR / \sigma BR^{SM}$, M = 10 TeV, tanβ = 5
160
150
140
130
120
110
100
90
$m_{\tilde{t}_1}$ (GeV)
110
115
120
125
130
135
m_{h^0} (GeV)
1.6
1.55
1.5
1.45
1.4
1.35
1.3

Light stop effects on Higgs searches at the Tevatron

- For $m_h \lesssim 135$ GeV: Associated Higgs production $Wh \to Wb\bar{b}$ is dominant

- For $m_h \gtrsim 135$ GeV: $gg \to h \to WW^*$ dominant.



Improvements in analysis $\Rightarrow 2-3\sigma$ observation of the Higgs?

Light stop and Higgs searches at LHC

- 5 σ Higgs discovery in $gg \to h \to \gamma\gamma$ with 30fb^{-1} and error in Higgs mass 0.2 GeV. [ATLAS Collaboration'09; CMS Collaboration '07]

- 30 % error in Γ_{hgg} with 200fb^{-1} of data.
[Zeppenfeld et. al. '00,02; Belyaev, Reina '02; Duhrssen et. al. '04]

- 20 % error in $\Gamma_{h\gamma\gamma}$ with 200fb^{-1} of data.
[Zeppenfeld et. al. '00,02; Belyaev, Reina '02; Duhrssen et. al. '04]

Large enhancements of Γ_{hgg} in EWBG $\Rightarrow$ deviations in $\Gamma_{ggh}/(\Gamma_{ggh})_{SM}$
should be observable with 200fb^{-1} at 3σ.

- Finding deviations in $\Gamma_{h\gamma\gamma}$ is more challenging.

Summary

• EWBG MSSM is a very predictive scenario $\Rightarrow$ stop split SUSY - light stop, charginos and neutralinos with the remaining scalars being heavy.

• Observing this scenario at the LHC is very challenging.

• Higgs branching fractions are a potential indirect probe of this scenario and could lead to an enhancement of the signal significance at the Tevatron.

Future avenues

• Stoponium decays into leptons are velocity suppressed but lower backgrounds in this channel may make it a viable channel at the LHC.

• Light charginos and neutralino decays involving intermediate stops could be an additional way of probing this scenario at the LHC.