Neutrinos, B, and Baryon Asymmetry

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Trends in Neutrino Physics

Argonne, May 14, 2003

Outline

- Introduction
- Baryon Asymmetry
- Leptogenesis
- Dirac Leptogenesis
- Neutrino, *B* connection
- Electroweak Baryogenesis
- Conclusions

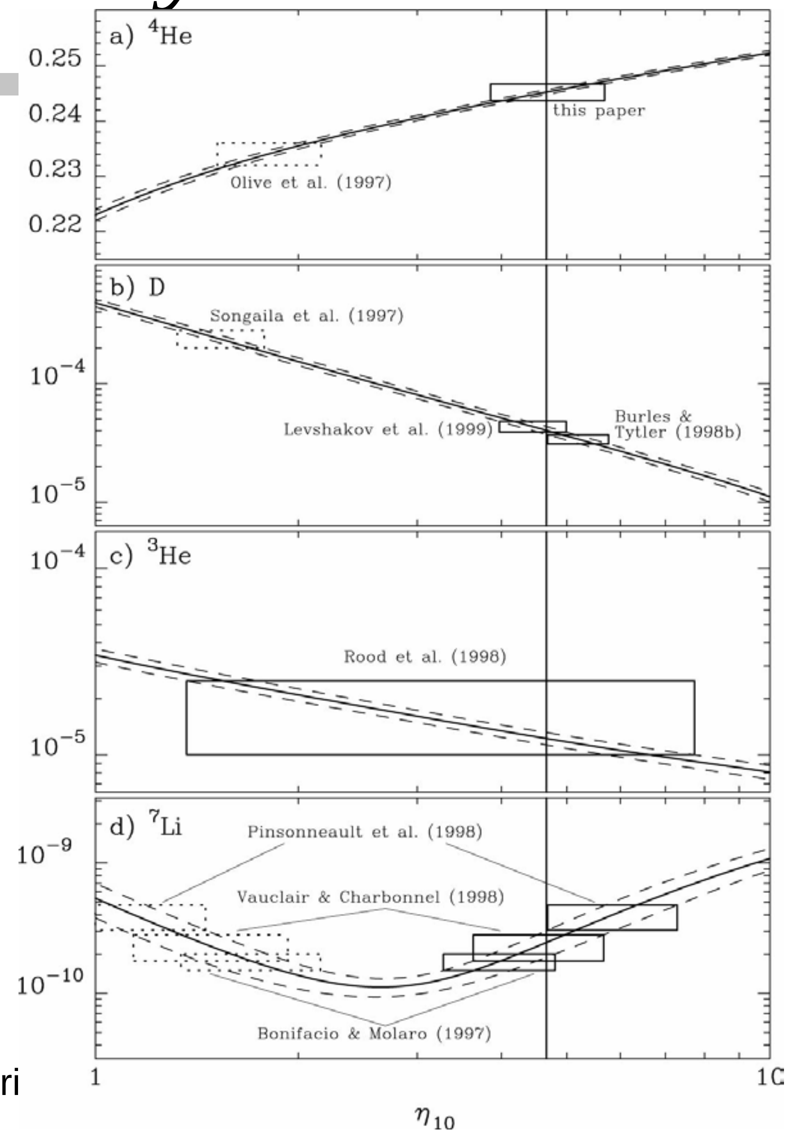
Baryon Asymmetry

Big-Bang Nucleosynthesis

- "Crisis" the past few years
- Thuan-Izotov reevaluation of ^{4}He abundance
- Sangalia *D* abundance probably false
- Now concordance

$$\eta = \frac{n_B}{n_\gamma} = \left(4.7^{+1.0}_{-0.8}\right)\times 10^{-10}$$

$$(5.0 \pm 0.5)\times 10^{-10}$$



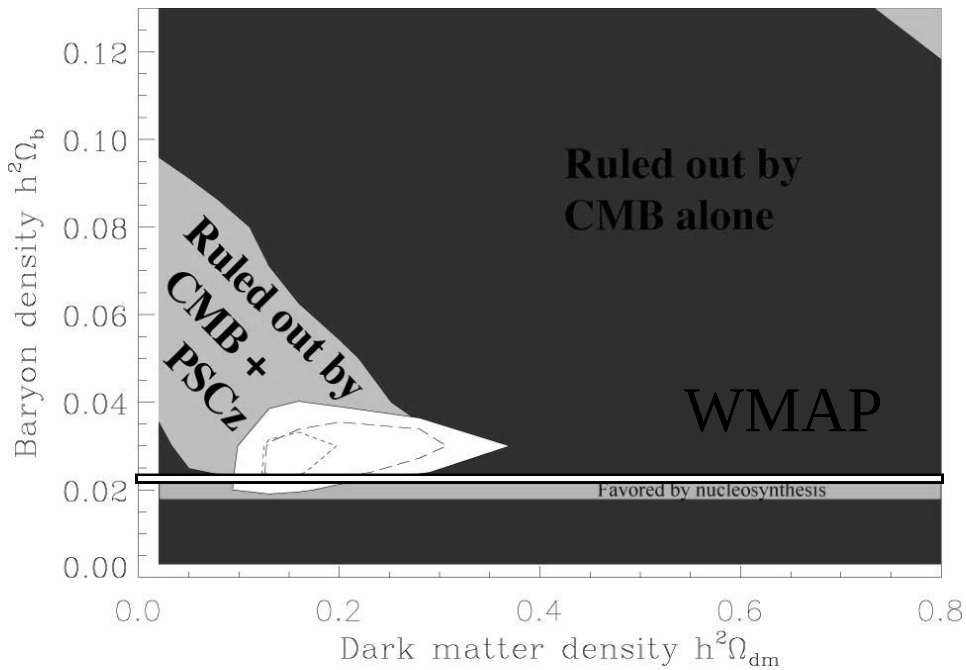
Cosmic Microwave Background *WMAP*

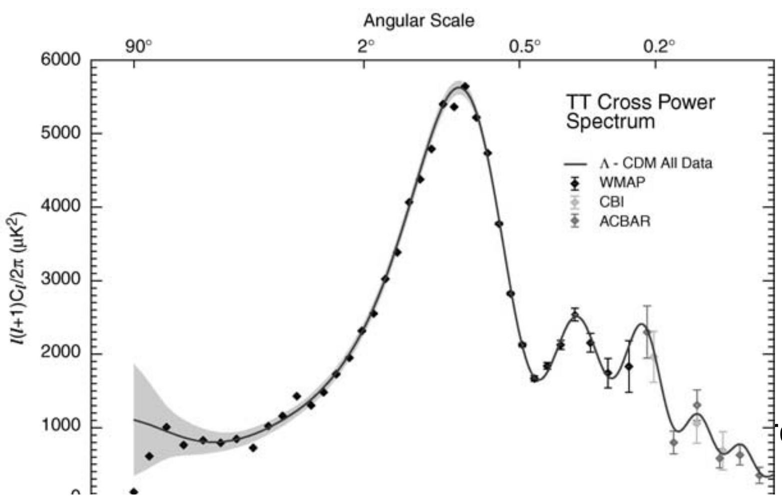
h=0.71±0.04

$\Omega_M h^2$=0.135±0.009

$\Omega_b h^2$=0.0224±0.0009

Ω_{tot}=1.02±0.02





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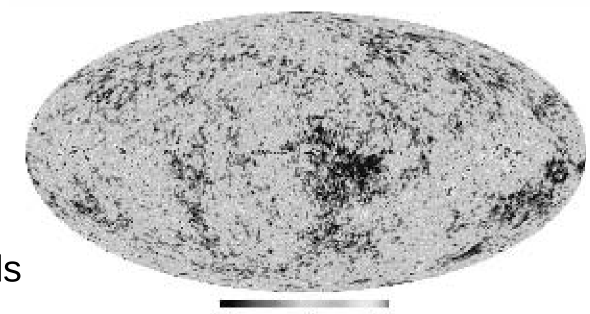
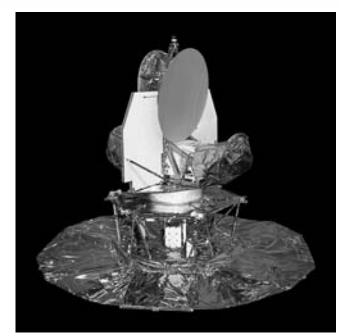
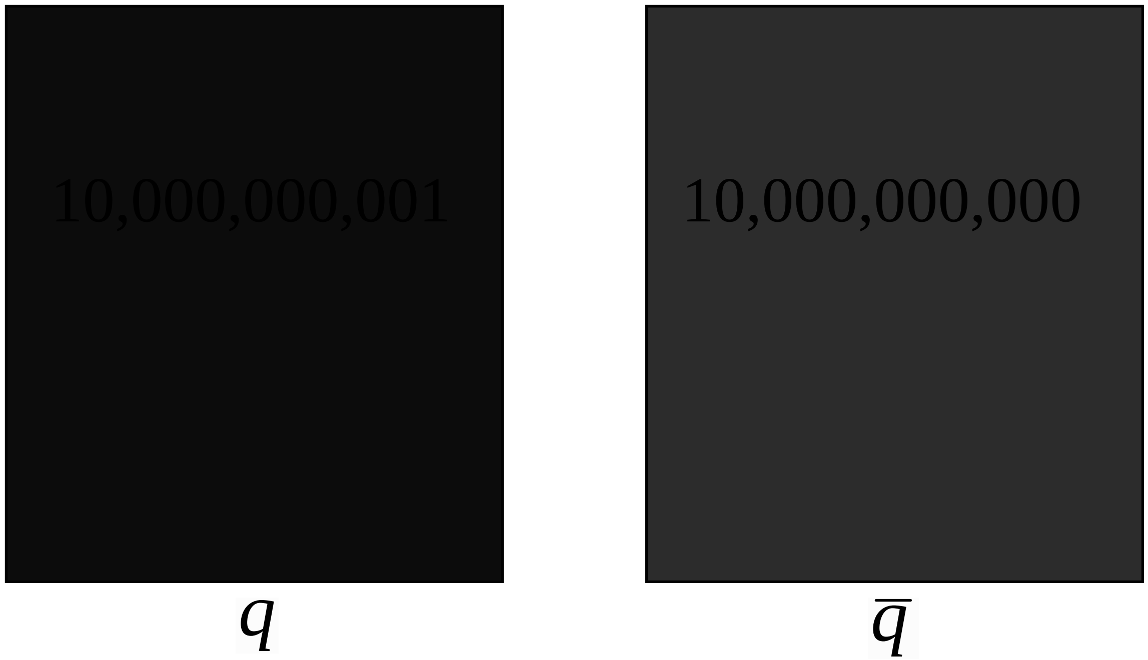




Baryon Asymmetry
Early Universe



Baryon Asymmetry Current Universe

us

1

q $\bar{q}$

The Great Annihilation

Sakharov's Conditions for Baryogenesis

- *Necessary* requirements for baryogenesis:
  - Baryon number violation
  - CP violation
  - Non-equilibrium

    $\Rightarrow \Gamma(\Delta B>0) > \Gamma(\Delta B<0)$
- Possible new consequences in
  - Proton decay
  - CP violation

Original GUT Baryogenesis

- GUT necessarily breaks *B*.
- A GUT-scale particle *X* decays out-of-equilibrium with direct CP violation

$$B(X \to q) \neq B(\overline{X} \to \overline{q})$$

- Now direct CP violation observed: ε'!

$$B(K^0 \to \pi^+\pi^-) \neq B(\overline{K}^0 \to \pi^+\pi^-)$$

- But keeps B–L=0 $\Rightarrow$ "anomaly washout"

Anomaly washout

- Actually, SM violates *B* (but not *B*–*L*).
  - In Early Universe ($T >$ 200GeV), *W/Z* are massless and fluctuate in *W/Z plasma*
  - Energy levels for left-handed quarks/leptons fluctuate correspon-dingly

QuickTime™ and a Animation decompressor are needed to see this picture.

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$$\Delta L = \Delta Q = \Delta Q = \Delta Q = \Delta B = 1 \Rightarrow \Delta(B-L) = 0$$

Two Main Directions

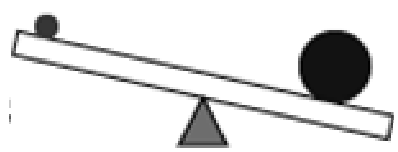
- $B{=}L\neq 0$ gets washed out at $T>T_{EW}$~174GeV
- Electroweak Baryogenesis (Kuzmin, Rubakov, Shaposhnikov)
  - Start with $B=L=0$
  - First-order phase transition $\Rightarrow$ non-equilibrium
  - Try to create $B{=}L\neq 0$
- Leptogenesis (Fukugita, Yanagida)
  - Create $L\neq 0$ somehow from L-violation
  - Anomaly partially converts L to B

Leptogenesis

Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass, but ν_R SM neutral

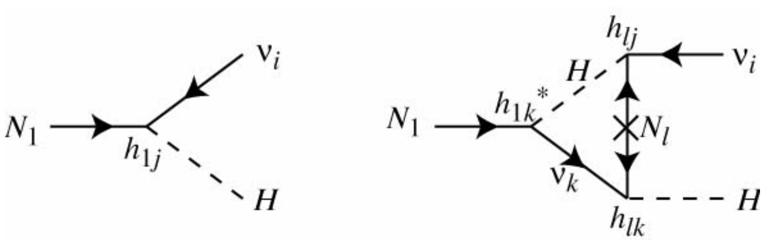
$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



To obtain $m_3 \sim (\Delta m^2_{\text{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)
Majorana neutrinos: violate lepton number

Leptogenesis

- You generate *Lepton Asymmetry* first.
- *L* gets converted to *B* via EW anomaly
  - Fukugita-Yanagida: generate *L* from the direct CP violation in right-handed neutrino decay



$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

Leptogenesis

- Two generations enough for CP violation because of Majorana nature (choose 1 & 3)

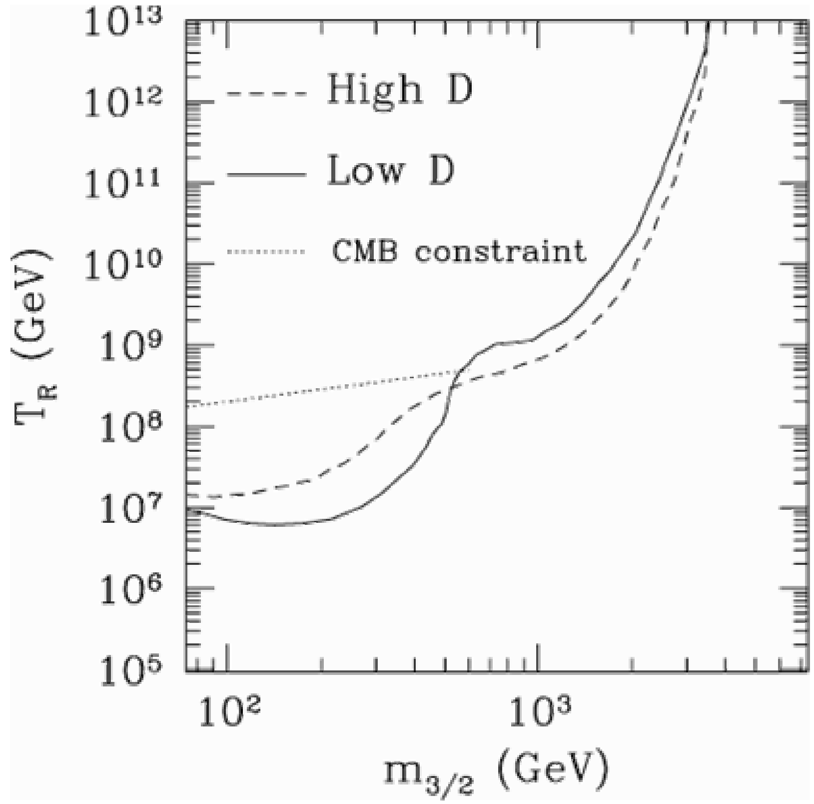
$$\varepsilon = \frac{\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H)}{\Gamma(N_1 \to \nu_i H) + \Gamma(N_1 \to \bar{\nu}_i H)} \sim \frac{1}{8\pi} \frac{\mathrm{Im}(h_{13} h_{13} h_{33}^* h_{33}^*)}{|h_{13}|^2} \frac{M_1}{M_3}$$

- Right-handed neutrinos decay out-of-equilibrium
- Much more details worked out in light of oscillation data (Buchmüller, Plümacher; Pilaftsis)
- $M_1 \sim 10^{10}$ GeV OK $\Rightarrow$ want supersymmetry

Does Leptogenesis Work?

- Some tension with supersymmetry:

  unwanted gravitino overproduction
  - Thermal production (T_{RH}<10^9 GeV)
  - Non-thermal production from preheating (T_{RH}<10^5 GeV?)
    (Giudice, Riotto, Tkachev)



(Kawasaki, Kohri, Moroi)

Leptogenesis Works!

- Coherent oscillation of right-handed sneutrino

  (Bose-Einstein condensate)
  (HM, Yanagida+Hamaguchi)
  - Inflation ends with a large sneutrino amplitude
  - Starts oscillation
  - dominates the Universe
  - Its decay produces asymmetry
  - Consistent with observed oscillation pattern
  - Possible imprint on CMBR

    (Moroi)

QuickTime™ and a Animation decompressor are needed to see this picture.

$$\frac{n_B}{s} \sim \varepsilon \frac{T}{M_1} \sim \frac{T}{10^6\,\mathrm{GeV}} \arg \frac{h_{13}^2}{h_{33}^2}$$

Preheating

- Oscillating inflaton ϕ (mass ~10^{13}GeV)
- The coupling to right-handed neutrino

  $(M+g\phi)NN$
- Mass vanishes at $\phi=M/g$

  $\Rightarrow$ non-adiabatic

  $\Rightarrow$ explosive production up to M~10^{17}GeV

  (Giudice, Riotto, Tkachev)
- The case of SUSY more subtle because ϕ complex

  (Chacko, HM, Perelstein)
- Nonetheless can produce N up to M~10^{15}GeV

Dirac Leptogenesis

Do we need seesaw?

- Natural explanation for small neutrino mass
  - Seesaw: $m_\nu \sim \langle H \rangle^2 / M$
- What about $h_\nu \sim m_{SUSY}/M$?

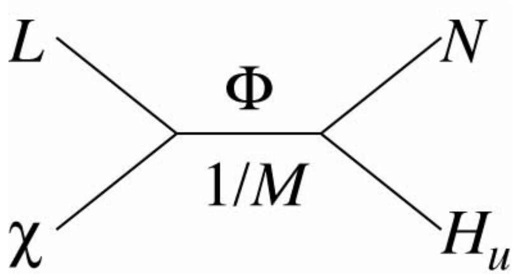
  (Arkani-Hamed, Hall, HM, Smith, Weiner)

  (Borzumati, Nomura)

  - Suppresses neutrino Yukawa coupling
  - Naturally light Dirac neutrinos
  - Light right-handed neutrinos

Small Neutrino Mass From SUSY Breaking

- $<\chi>\sim m_{SUSY}+\theta^2\, m_{SUSY}\, M_{Pl}$
  breaks SUSY and $U(1)_N$, preserves $U(1)_{L+N}$
- Heavy vector-like lepton doublets Φ, Φ^*
- Coupling: $M\Phi\Phi^* + \chi L\Phi^* + \Phi N H_u$ (HM, Pierce)
  - Most general couplings allowed by lepton number and $U(1)_N$ number
- Exchange of Φ generates



  - $<\chi>LNH_u/M$
  - Small Yukawa $<\chi>/M$
  - Large $\tilde{\nu}_L$ and $\tilde{\nu}_R$ mixing (interesting for LC)

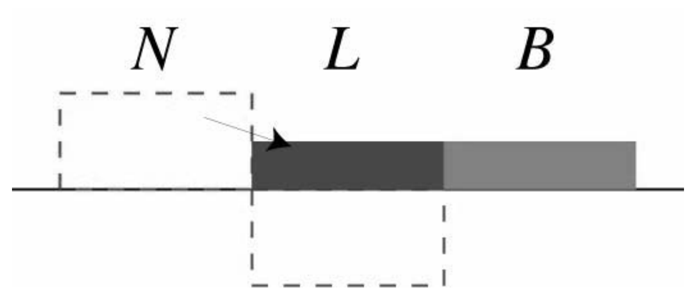
Dirac Leptogenesis

- Heavy doublets decay to $\Phi \to \chi L$ or NH_u
- Decay produces asymmetry (≥2 gener.)
  - $L_\nu + L_N = 0$, but $L_\nu = -L_N \neq 0$
  - $L_N \neq 0$ protected because of small Yukawa
  - L_ν partially converted to B
  - Practially only now ($T \sim m_\nu \sim 10^3$ K), L_ν & L_N equilibriate, but do not cancel any more

(Dick, Lindner, Ratz, Wright)

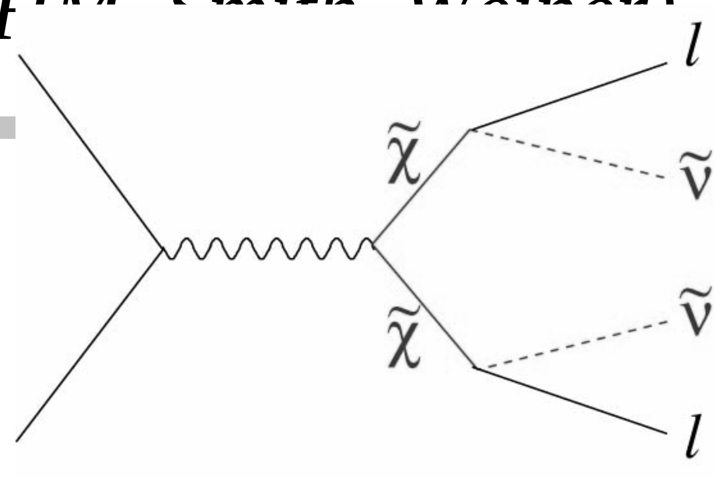
- The explanation for small neutrino mass provides the origin of baryon asymmetry!

(HM, Pierce)



Light Right-handed Sneutrino

(Arkani-Hamed, Hall, HM, Smith, Weiner)



- Neutrino oscillation

$\Rightarrow$Neutrino mass

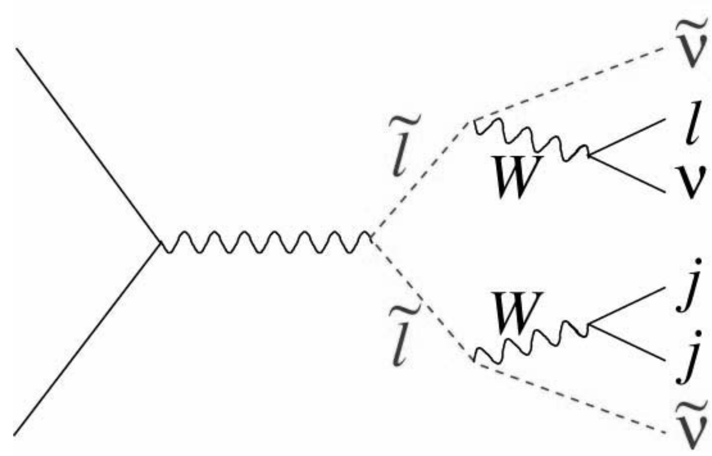
$\Rightarrow$Right-handed neutrino

- If Dirac, right-handed sneutrino < TeV scale
- May even be LSP
- Acoplanar leptons

Sleptons? No, charginos

- Lepton+jets+missing

Charginos? No, sleptons



Neutrino and B connection

Large θ_{23} and quarks

- Large mixing between ν_τ and ν_μ
- Make it SU(5)
- Then a large mixing between s_R and b_R
- Mixing among right-handed fields drop out from CKM matrix
- But mixing among superpartners physical

$$\begin{pmatrix} \tilde{s}_R \\ \tilde{s}_R \\ \tilde{s}_R \\ \tilde{\nu}_\mu \\ \tilde{\mu} \end{pmatrix} \longleftrightarrow \begin{pmatrix} \tilde{b}_R \\ \tilde{b}_R \\ \tilde{b}_R \\ \tilde{\nu}_\tau \\ \tilde{\tau} \end{pmatrix}$$

- Interesting effects in $b \to s$ transition?
- But constraints from $\mu \to e\gamma$ etc prevent effects >10% if ν_R all degenerate

  Goto, Okada, Shimizu, Shindou, Tanaka; Moroi

Naïve SO(10) Model

- Full 16 for each generation
- Up and down Yukawas from different 10_H
  - $Y_\nu \sim Y_u \Rightarrow \nu_R$ strongly hierarchical
  - $Y_l \sim Y_d^T$
- Large top Yukawa acts on 16_3
- In the same multiplet lie
  - $(\nu_\tau + \nu_\mu)/\sqrt{2}$, $(b_R + s_R)/\sqrt{2}$
- The mixing of first generation suppressed by U_{e3}
- Then $O(1)$ effects on $b \rightarrow s$ transition possible

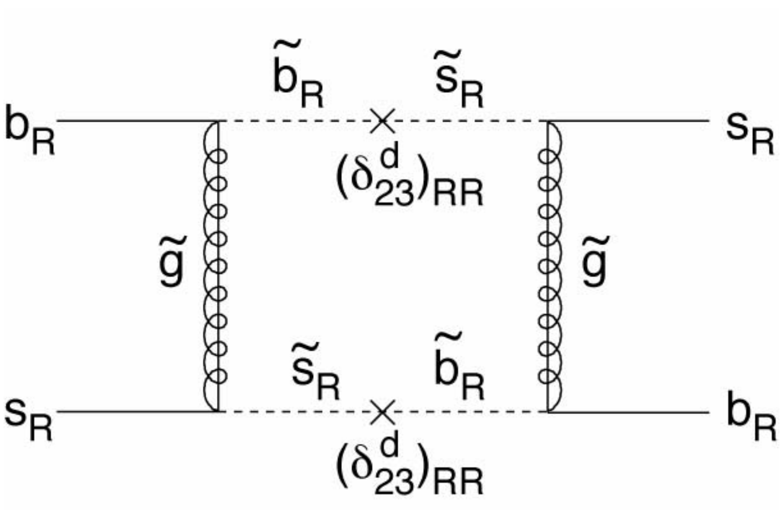
  (Chang, Masiero, HM)

Other Flavor Models

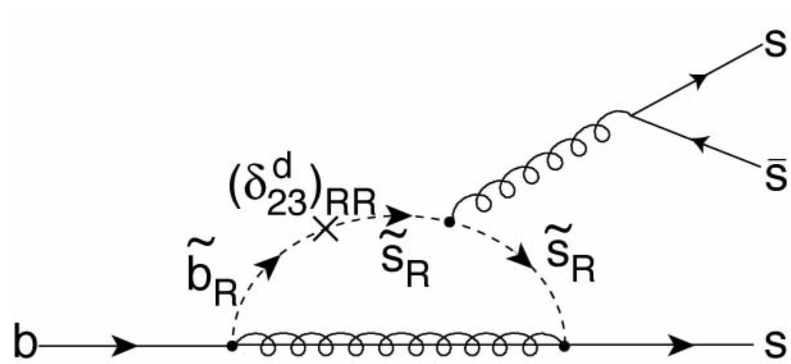
- S_3 (Hall, HM)
  - Start with three identical objects
  - Yet $(2+1_A)$ structure
  - Large top Yukawa
  - 1st & 2nd generation scalars degenerate
  - $S_3^{Q,E} \times S_3^{D,L} \times S_3^{U}$
  - Again $Y_l \sim Y_d^T$
  - Large θ_{23} gives large s_R and b_R mixing
- $U(2) \times SU(5)$ (Barbieri, Hall, Strumia, Romanino, …)
  - (2+1) structure
  - Large top Yukawa
  - 1st & 2nd generation scalars degenerate
  - Again $Y_l \sim Y_d^T$
  - Large θ_{23} gives large s_R and b_R mixing

Consequences in B physics

- CP violation in B_s mixing ($B_s \to J/\psi\, \phi$)



- Addt'l CP violation in penguin $b \to s$ ($B_d \to \phi\, K_s$)

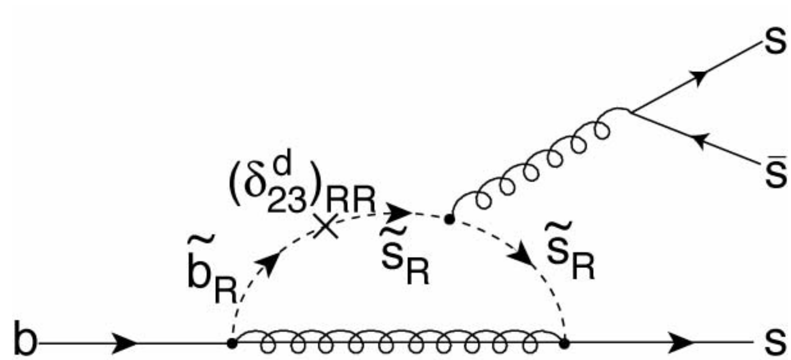


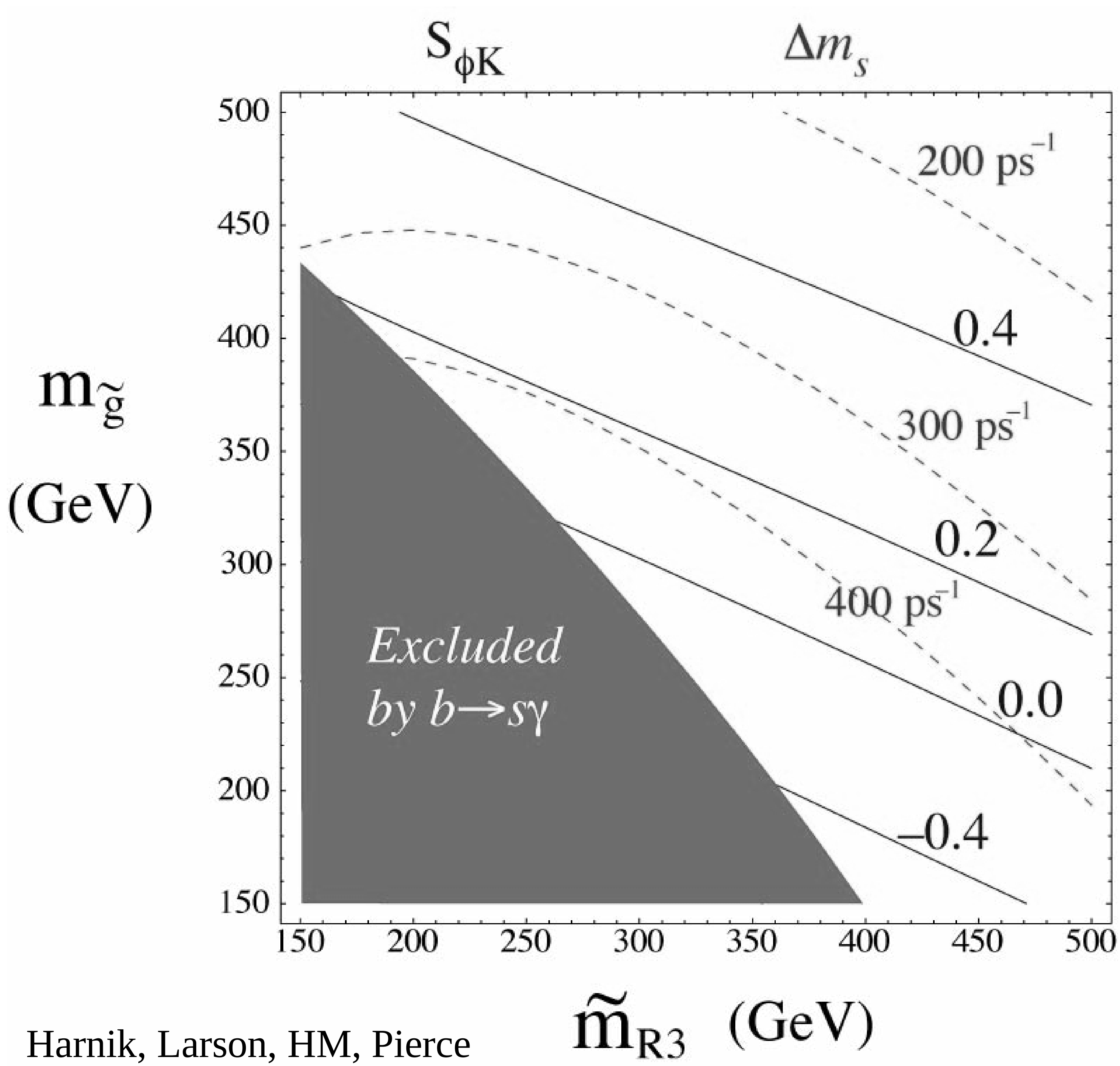
$B_d \to \phi K_s$

- ICHEP 2002 @ Amsterdam
  - "$\sin 2\phi_1$"=–0.73±0.64±0.18 (Belle)
  - "$\sin 2\beta$"=–0.19±0.51±0.09 (BABAR)
- Compared to W. A. from $J/\psi K_s$
  +0.731±0.055

  Maybe a hint (~2.7σ) *of SUSY flavor physics?*

- But $B_d \to \eta' K_s$, $K^+K^-K_s$?
- Even if the current "discrepancy" disappears, it remains true that this is a very reasonable place for new physics to show up.





Harnik, Larson, HM, Pierce

Electroweak Baryogenesis

Standard Model

- Standard Model has all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase
- Non-equilibrium
  - First-order phase transition of Higgs Bose–Einstein condensate

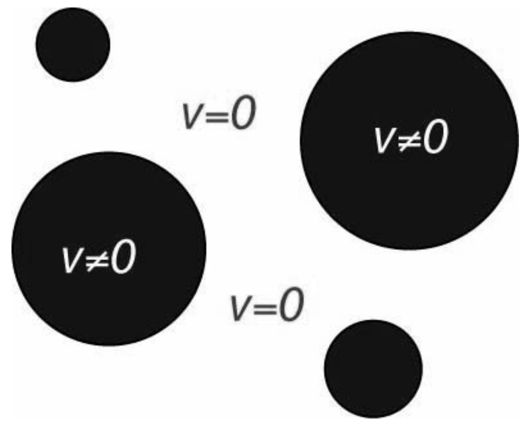
Electroweak Baryogenesis

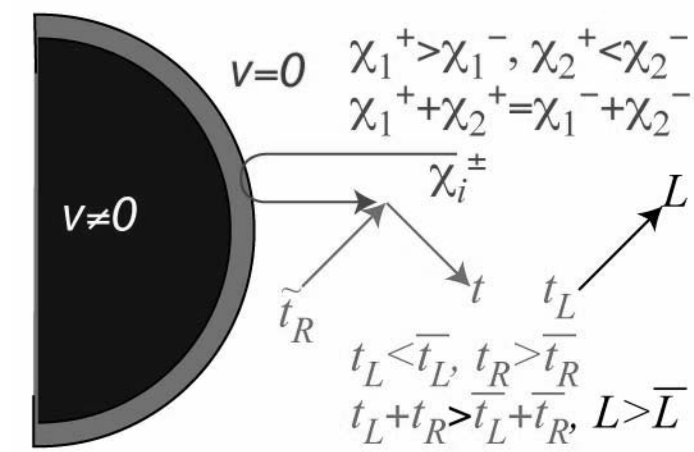
- Two big problems in the Standard Model
  - First order phase transition requires m_H<60GeV
  - Need new source of CP violation because
    $J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} << 10^{-10}$
- Minimal Supersymmetric Standard Model
  - First order phase transition possible if $m_{\tilde{t}_R} < 160\text{GeV}$
  - New CP violating phase $\arg(\mu^* M_2)$

e.g., (Carena, Quiros, Wagner), (Cline, Joyce, Kainulainen)

Scenario

- First order phase transition
- Different reflection probabilities for chargino species
- Chargino interaction with thermal bath produces an asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry





Parameters

- Chargino mass matrix

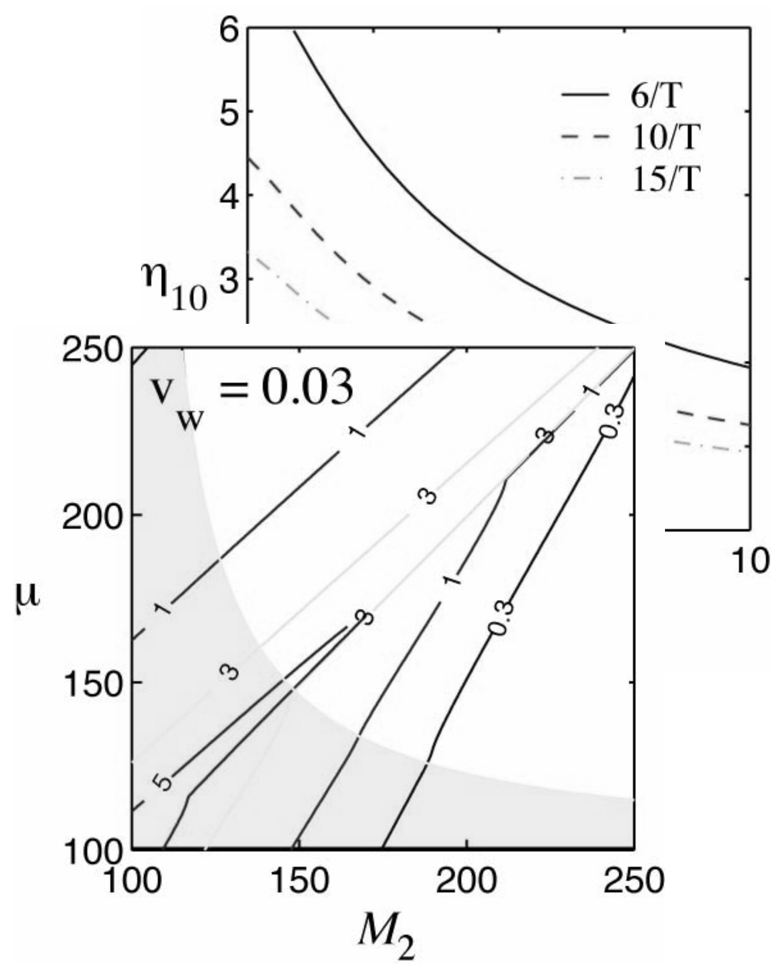
$$\begin{pmatrix} M_2 & \sqrt{2}m_W \cos\beta \\ \sqrt{2}m_W \sin\beta & \mu \end{pmatrix}$$

  Relative phase $\arg(\mu^* M_2)$

  unphysical if $\tan\beta \to \infty$

- Need fully mixed charginos $\Rightarrow \mu \sim M_2$

  (Cline, Joyce, Kainulainen)



SUSY Mass Spectrum

- To avoid LEP limit on lightest Higgs boson, need left-handed scalar top > TeV
- Light right-handed scalar top, charginos
- Need $\arg(\mu^* M_2) \sim O(1)$ with severe EDM constraints from *e*, *n*, Hg

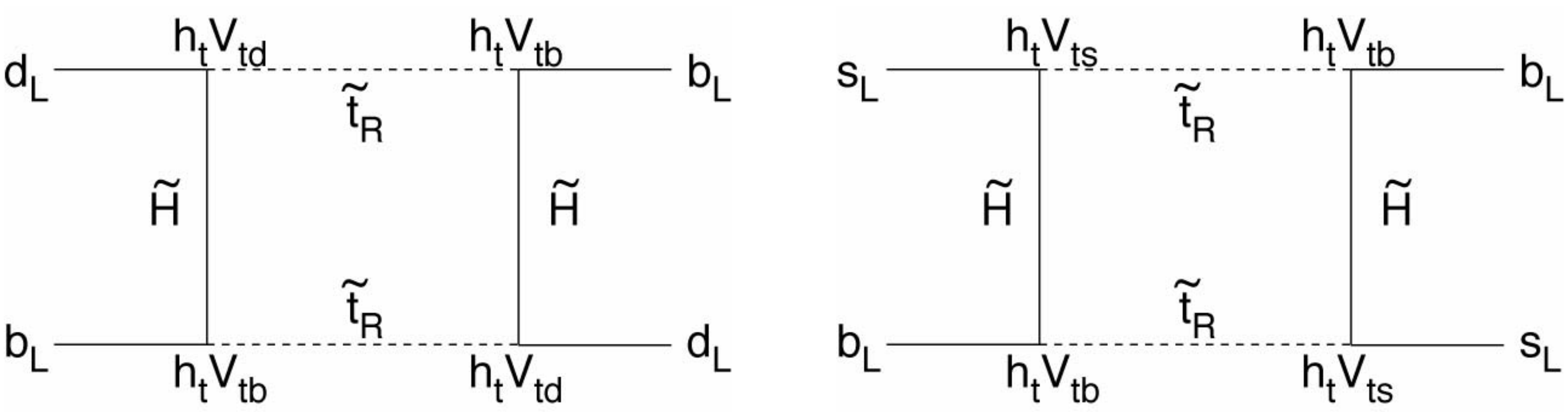
$\Rightarrow$ 1st, 2nd generation scalars > 10 TeV

cf. Carena, Quiros, Wagner claim $\arg(\mu^* M_2) > 0.04$ enough

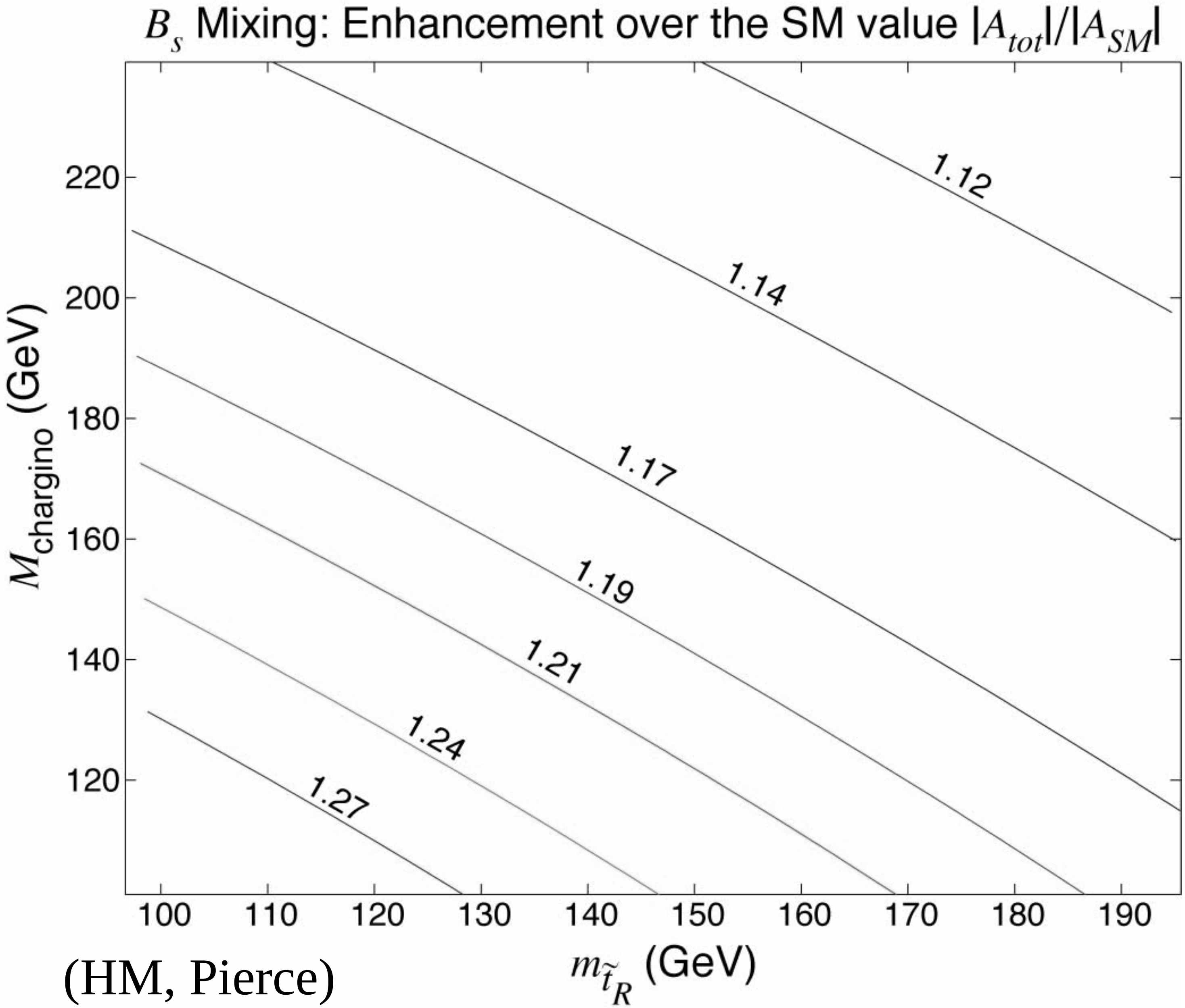
EDM constraint is weaker, but rest of phenomenology similar

Signals of Electroweak Baryogenesis

- ~20% enhancements to Δm_d, Δm_s with the same phase as in the SM (HM, Pierce)



- Find Higgs, stop, charginos (Tevatron?)
- Eventually need to measure the phase in the chargino sector at LC to establish it (Barger et al)



B_s Mixing: Enhancement over the SM value $|A_{tot}|/|A_{SM}|$
1.12
1.14
1.17
1.19
1.21
1.24
1.27
220
200
180
160
140
120
M_{chargino} (GeV)
100
110
120
130
140
150
160
170
180
190
$m_{\tilde{t}_R}$ (GeV)

(HM, Pierce)

B-physics Challenges

- Lattice QCD: need B parameters at 5%

  $\Rightarrow$ then B_s mixing in business
- V_{td} has been determined from B mixing

  Not legitimate in presence of SUSY loop
- Need to determine V_{td} from other sides, angles

  V_{ub} (from q^2 distribution?)

  $\beta=\phi_1$ (from $B\rightarrow J/\psi K_s$)

  possible help from $\alpha=\phi_2$ (from $B\rightarrow\pi\pi$ with isospin analysis)

Conclusions

- Flavor Physics going through a *revolution*
- MSSM baryogenesis getting cornered
  - Interesting challenge to *B*-physics
- Leptogenesis gaining momentum
  - Many viable models (coherent oscillation, preheating)
  - *But Majorana neutrino not mandatory*
- Interesting possible consequences of neutrino mixing in $b \to s$
  - through GUT, models of flavor
  - Hints for SUSY-GUT?