Proton Decay in GUTs

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Outline

- Brief History of Baryon Number
- Proton Decay in Grand Unification
- Proton Decay without Grand Unification
- *B*-physics consequence of SUSY-GUT
- Conclusions

Brief History of Baryon Number

Problem with Anti-Matter

- Anderson discovered positron e^+, anti-matter of electron in 1932
- A very naïve question:

  Why doesn't proton decay $p \rightarrow e^+ \gamma$?
- Stückelberg (1939) made up a new conservation law:

  Baryon number must be conserved

  (later also by Wigner, 1949)

Lepton Family Number

- Similarly ad-hoc conservation law
- Neddermeyer-Anderson discovered muon in 1937
- A very naïve question:

  Why doesn't muon decay $\mu^- \to e^- \gamma$?
- Inoue-Sakata made up a new conservation law:

  Lepton Family number must be conserved
- Neutrino oscillations (SuperK & SNO) have disproven lepton family number conservation!

Sacred and secular laws

- Sacred conservation laws:

  consequences of fundamental principles such as gauge invariance, Lorentz invariance, unitarity

  e.g., electric charge, CPT, energy-momentum

- Secular conservation laws:

  Happen to be approximately true, but ultimately violated

  e.g., parity, CP, lepton family

Fate of Secular Conservation Laws

• Parity	Fallen 1956
• Charge Conjugation	Fallen 1956
• CP	Fallen 1964
• T	Fallen 1999
• Lepton Family	Fallen 1998 (μ), 2002 (e)
• Lepton Number	Still viable ($0\nu\beta\beta$?)
• Baryon Number	Still viable

Maurice Goldhaber's View (1977)

- "Why did these three learned gentlemen, Weyl, Stückelberg, and Wigner, feel so sure that baryons are conserved? Well, you might say that it's very simple: they felt it in their bones. Had their bones been irradiated by the decays of nucleons, they would have noticed effects considerably exceeding "permissible radiological limits" if the nucleon lifetime were $<10^{16}$ years and if at least 10% of the nucleon rest mass were to appear as radiation absorbable in the body. That is a fairly sensitive measurement, but one can do much better by a deliberate experiment."

Fourth Workshop on GUT (1983)

- "Results are presented from the first 80 days of the IMB detector… Limits are set at the 90% CL for the lifetime/branching ratio τ/B for $p \to e^+ \pi^0$ at 6.5×10^{31} years…"
- "That bound appears to rule out minimal SU(5) with a great desert" (Marciano)

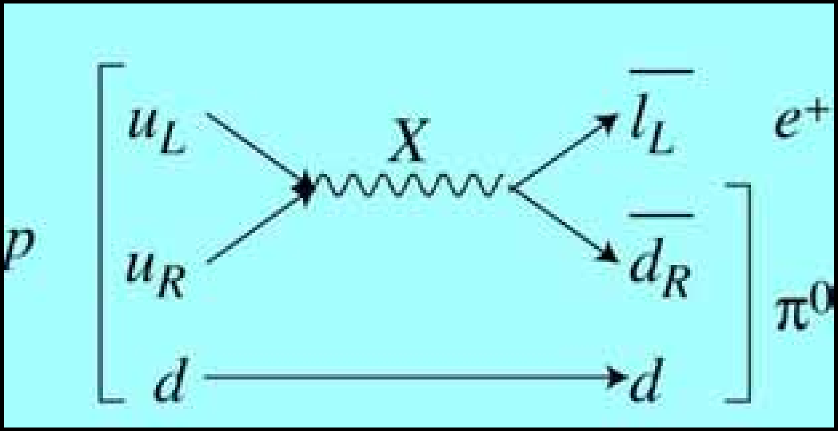
Baryon Number as an Accidental Symmetry

- In the Standard Model, the proton is absolutely stable
- Baryon Number is an "accidental" symmetry, *i.e.*, there is no renormalizable interaction you can write down that violates the baryon number with the minimal particle content
- But once beyond the Standard Model, there is no reason for baryon number to be conserved.
- Grand Unified Theories prime example of well-motivated theories that lead to proton decay
- Another example: *R*-parity violation in SUSY

Proton Decay in Grand Unified Theories

Proton Decay

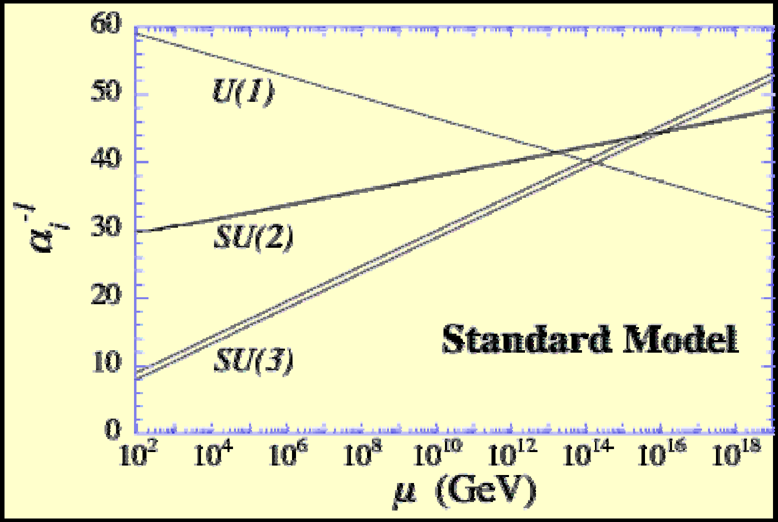
- Quarks and leptons in the same multiplet
- Gauge bosons can convert q to l
- Cause proton decay via D=6 operators! $p \to e^+ \pi^0$

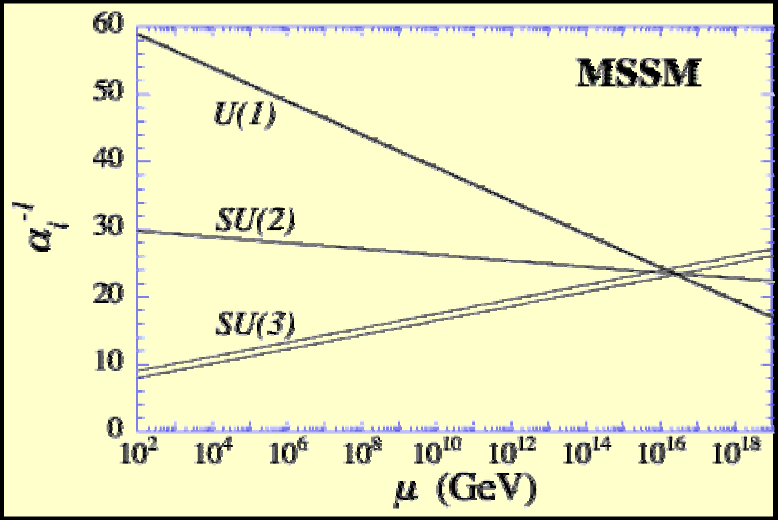


$$\Gamma \propto \left(\frac{g^2}{M_X^2} \right)^2 m_p^5$$

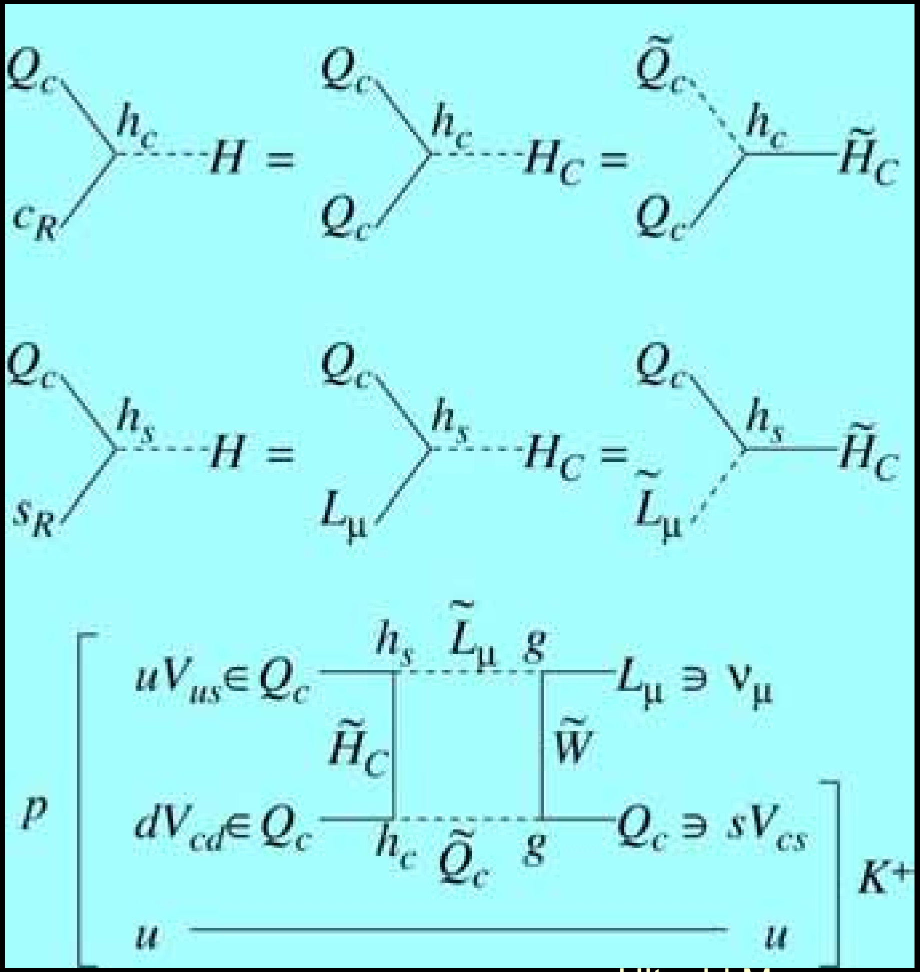
- IMB excluded the original SU(5) GUT

Gauge Coupling Unification





Supersymmetric D=5 Proton Decay



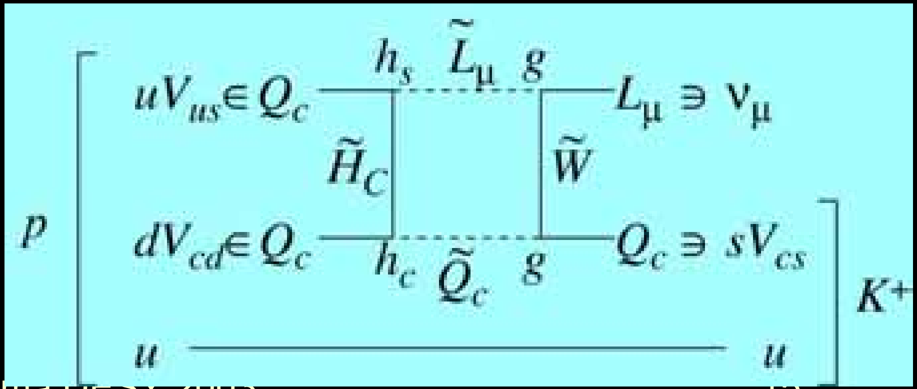
Exchange of fermionic superpartner of color-triplet SU(5) partner of Higgs boson

$$\Gamma \propto \left(\frac{g^2}{(4\pi)^2} \frac{h_s h_c \theta_C^2}{M_{H_C} m_{SUSY}} \right)^2 m_p^5$$

Suppressed only by the *second power* of GUT scale vs *fourth* in *X*-boson exchange

Supersymmetric D=5 Proton Decay

- Effective superpotential
  $W=h_c h_s M_{Hc}^{-1}\ QQQL$
  (Sakai-Yanagida;Weinberg)
- Bose symmetry of Q superfields and anti-symmetry in color contraction requires that three Q's to be different flavors
- Final state tends to contain strange quark
- Depends on M_{Hc}
- Depends also on superpartner masses
- Amplitude $\sim M_2/m_{sq}^2$
- Keep M_2 just above LEP limit, $m_{sq}\sim$1TeV



Color-triplet Higgs

- Both EW-doublet and color-triplet Higgs in SU(5) 5 and 5*
- In Minimal SUSY-SU(5) GUT, doublet is light and triplet is GUT-scale by fine-tuning
- $W=H_u(\lambda\Sigma+M)H_d$ with
  $\langle\Sigma\rangle=\mathrm{diag}(2,2,2,-3,-3)\sigma\neq 0$
  and 10^{-14} fine-tuning that
  $-3\lambda\sigma+M \ll \sigma, M$
- Even soft SUSY breaking fine-tuned
  (Kawamura, HM, Yamaguchi)
- Calling out for solutions.

GUT Thresholds

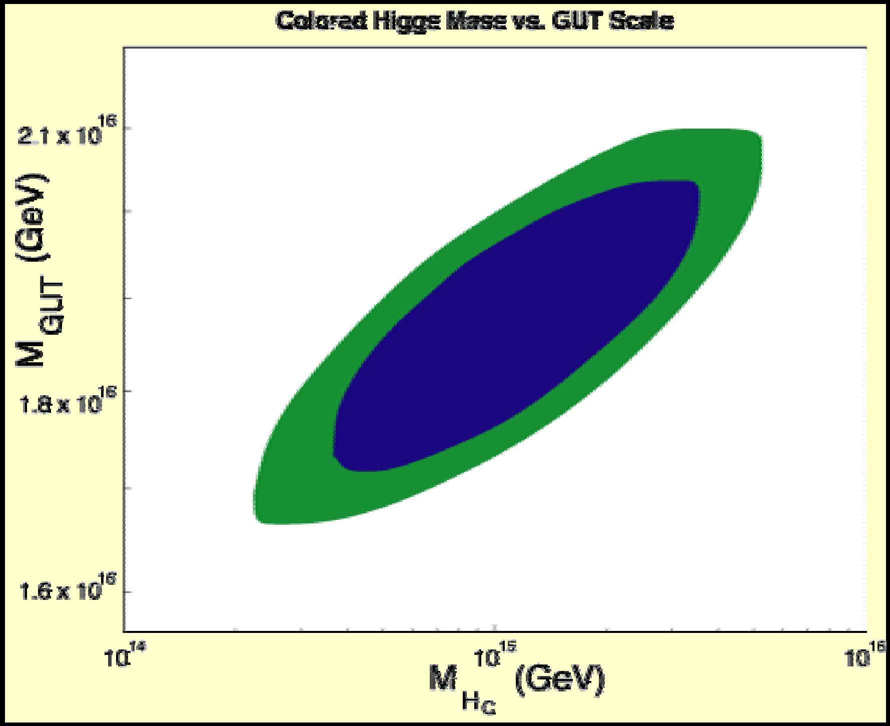
- Gauge couplings seems to unify around 2×10^{16}GeV. But how do we know what the M_{Hc} is?
- A close look at the GUT-scale threshold correction allows us to extract M_{Hc} from RGE.
- Three RGE for three couplings
- Unknown parameters at the GUT-scale: $\alpha_{\rm GUT}$ and three masses M_V, M_Σ, M_{Hc}
- Eliminate $\alpha_{\rm GUT}$ and two equations left
- Fix two combinations:

  $(M_V^2 M_\Sigma)^{1/3}$, M_{Hc}
- Can determine M_{Hc} from the couplings @LEP

(Hisano, HM, Yangida)

Rest In Peace
Minimal SUSY SU(5) GUT

- RGE analysis



- SuperK limit $\tau(p \to K^+ \nu) >$ 6.7×10^{32} years (90% CL)

  $M_{Hc} > 7.6\times10^{16}$ GeV
- Even if 1st, 2nd generation scalars "decoupled", 3rd generation contribution (Goto, Nihei)

  $M_{Hc} > 5.7\times10^{16}$ GeV

  (HM, Pierce)

It doesn't rule out SUSY-GUT

- Unfortunately, the prediction of the proton decay via D=5 operator is sensitive to the ugliest aspect of the SUSY-GUTs
  - Triplet-doublet splitting
  - Fermion mass relation $m_l = m_d$
- Any "solution" to these big problems is likely to modify the proton decay prediction.

Triplet-Doublet Splitting Flipped SU(5)

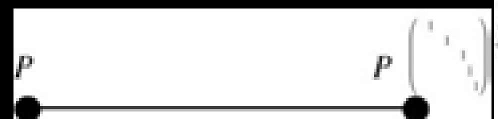
- Flipped SU(5)
  - Ellis et al
  - Not quite a unification SU(5)×U(1)
  - Broken by 10_{-1} (not 24)
  - Triplet massive by $W = 10_{-1}\ 10_{-1}\ H$
  - No triplet-doublet splitting problem
  - Eliminates D=5 operator completely
  - M_{GUT} where SU(3) and SU(2) meet is $\sim 10^{15}$ GeV
  - D=6 can be important

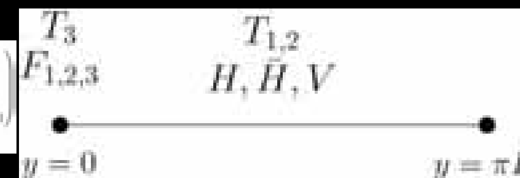
- SuperK:
  $\tau(p \to e^+ \pi^0) > 1.6 \times 10^{33}$year
  (90% CL, 25.5 kt year)
- Minimal SUSY GUT:
  $\tau(p \to e^+ \pi^0) = 8 \times 10^{34}$year $(M_V/10^{16}\text{GeV})^4$
  $M_V > 1.4 \times 10^{16}$GeV
- Flipped SU(5):
  $\tau(p \to e^+ \pi^0) = 4 \times 10^{35}$year $(M_V/10^{16}\text{GeV})^4$
  $M_V > 2.6 \times 10^{15}$GeV
  (HM, Pierce)

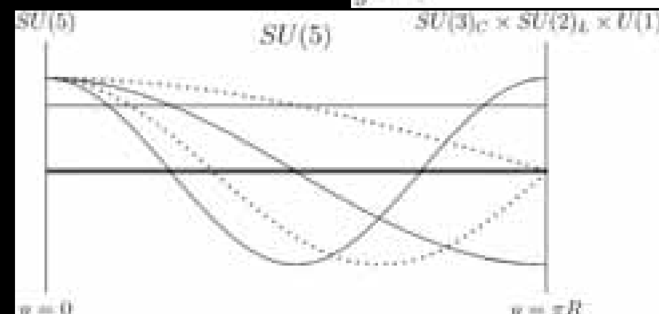
Triplet-Doublet Splitting Orbifold GUT Breaking

- (Kawamura; Hall, Nomura)
- $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$ normally achieved by $\langle \Sigma(\text{adjoint}) \rangle \neq 0$
- New way to break SU(5) by boundary conditions on extra line segment S^1/Z_2
- Boundary conditions explicitly break SU(5)
- Still unitarity OK

  (Hall, HM, Nomura)
- Natural triplet-doublet splitting
- Gauge coupling unification improved







- No D=5 operator
- Compactification scale $M_c \sim 10^{15}$ GeV
- Can have new D=6 operators on the fixed point $\sim 1/M_c^2$

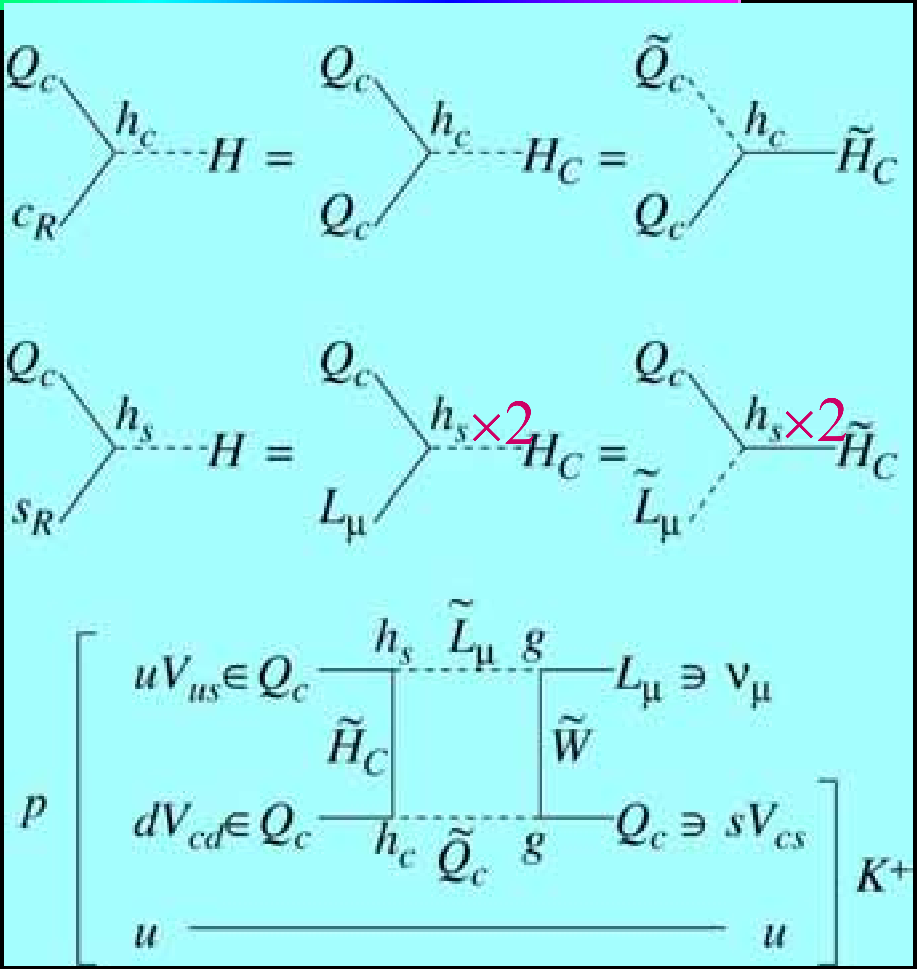
$p \to e^+ \pi^0$

- SuperK: $\tau(p \to e^+ \pi^0) > 1.6 \times 10^{33}$year
  (90% CL, 25.5 kt year)
- Minimal SUSY GUT:
  $\tau(p \to e^+ \pi^0) = 8 \times 10^{34}$year $(M_V/10^{16}\text{GeV})^4$
  $M_V > 1.4 \times 10^{16}$GeV
- Flipped SU(5):
  $\tau(p \to e^+ \pi^0) = 4 \times 10^{35}$year $(M_V/10^{16}\text{GeV})^4$
  $M_V > 2.6 \times 10^{15}$GeV
- 5-D orbifold GUT: $\tau(p \to e^+ \pi^0) \approx 10^{34}$year

May well be just around the corner

Fermion Mass Relation Georgi-Jarlskog

- Georgi-Jarskog relation
  - $m_e \sim m_d/3$
  - $m_\mu \sim m_s * 3$
- Can be achieved using Higgs in 45* rather than 5*
- Different Clebsch-Gordan factors
- *D*=5 operator worse by a factor of two



Threshold Corrections

- Add an otherwise unmotivated additional 5+5*
- Split them using <Σ> in the opposite way from Higgs:
  - Triplet lighter
  - Doublet heavier
- Changes the threshold correction and allows M_{Hc} raised (HM,Pierce)
- SO(10) models have many more fields at the GUT-scale
- Typically worse than SU(5)
- But larger possible range in threshold correction
- Allows M_{Hc} raised somewhat
- Just above the current limit $\tau(p \rightarrow K^+ \nu) < 10^{34}$yrs (Babu, Pati, Wilczek)

Proton Decay Without GUT

Planck-scale D=5 operators

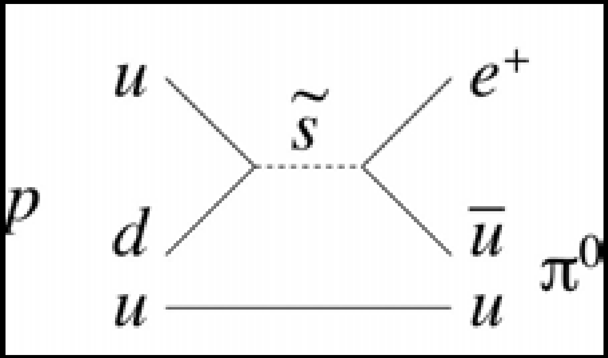
- D=5 operators in SUSY suppressed by only one power of the high scale
- Even Planck-scale operator bad
- $W=\lambda M_{Pl}^{-1} QQQL$
- Requires $\lambda \sim 10^{-7}$
- "Generic" string compactification excluded
- Need suppression

Planck-scale D=5 operators

- $W = \lambda M_{Pl}^{-1} QQQL$ requires $\lambda \sim 10^{-7}$
- Flavor symmetry suppressed Yukawa couplings
- Same suppression appears for other flavor operators
- Likely suppression by powers of Yukawa couplings, e.g., $\sim h_s h_c$
- Typically "intersting size" (HM, Kaplan)

R-parity Violation

- R-parity = $(-1)^{3B+L+2S}$
- Forbids baryon and lepton number violation
  $W = udd + QdL + LLe + LH_u$
- If it exists:
  $\tau_p \sim m_{sq}^4/m_p^5 \sim 10^{-12}$ sec!



- Product of two couplings $< 10^{-26}$
- If GUT, 10 5* 5* contains both *udd* & *QdL*

B-physics Consequence of SUSY-GUTs

Large θ_{23} and quarks

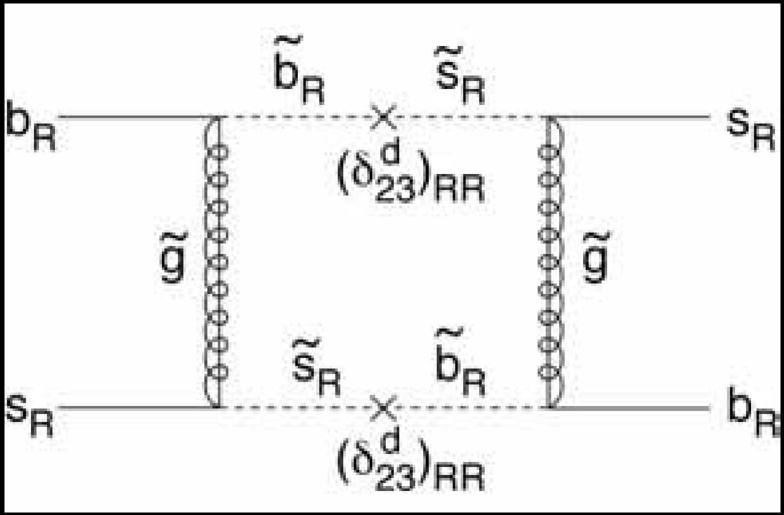
- Large mixing between ν_τ and ν_μ
- Make it SU(5) GUT
- Then a large mixing between s_R and b_R
- Mixing among right-handed fields drop out from CKM matrix
- But mixing among superpartners physical

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

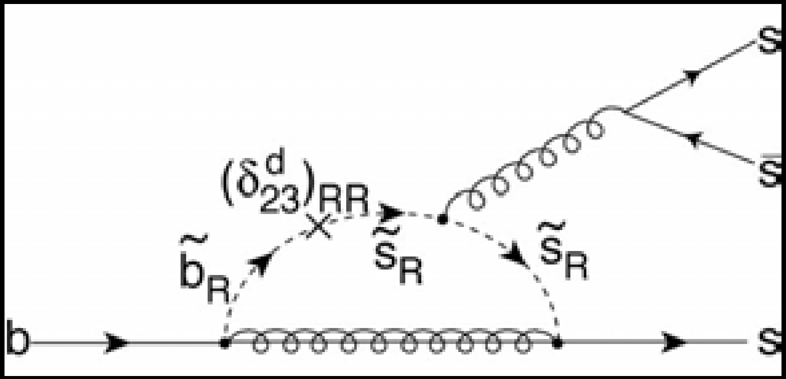
- $O(1)$ effects on $b \rightarrow s$ transition possible
  (Chang, Masiero, HM)
- Expect CP violation in neutrino sector especially if leptogenesis

Consequences in B physics

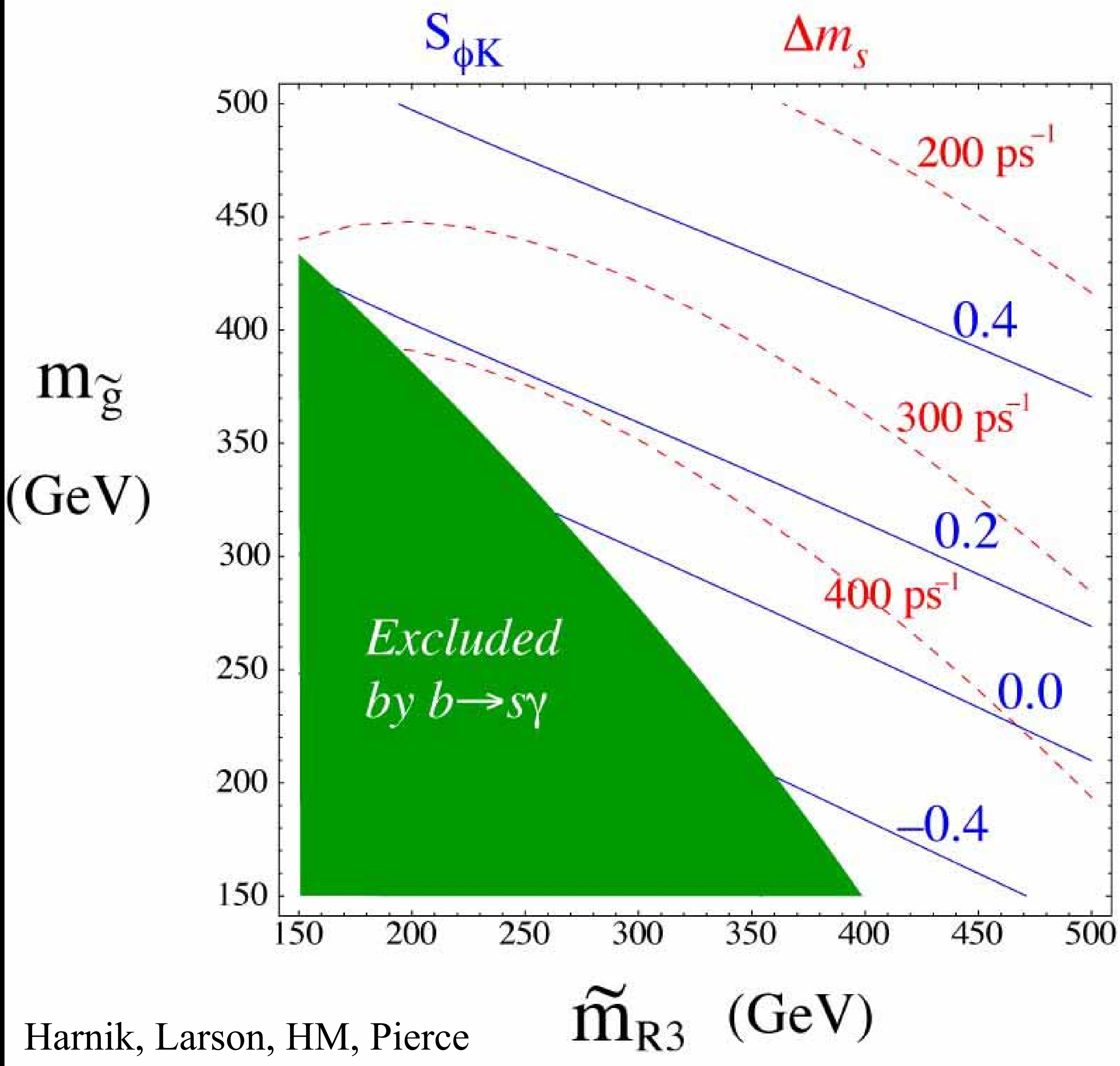
- CP violation in B_s mixing ($B_s \to J/\psi\ \phi$)



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



Very reasonable place for new physics to show up!



Harnik, Larson, HM, Pierce

Conclusions

- Baryon/lepton numbers very likely violated
- Neutrino mass and proton decay: window to extreme high-energy physics even up to Planck scale
- Current limits on proton decay had already excluded the original GUT and the Minimal SUSY GUT
- Many modifications of GUT predict proton decay within the reach of next generation (~1Mt) experiments

Future

Future will be painful

Because we will most likely find proton decay

And we'll feel it in our bones.