

Matter Instability
— *Past, Present, and Future* —



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Outline



- Brief History of Matter Instability
- Proton Decay in Grand Unification
- More Signals of GUT
- Conclusions
- Future

Brief History of Matter Instability



Problem with Anti-Matter



- Anderson discovered positron e^+ in 1932
- *A very naïve question:*

Why doesn't proton decay $p \rightarrow e^+ \square$?

- 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 $\mu \rightarrow e \gamma$?
- Inoue-Sakata made up a new conservation law:
Lepton Family number must be conserved
and predicted two neutrinos
- *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
- **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 (K^0), 2002 (B^0)
- T Fallen 1999 (K^0)
- Lepton Family Fallen 1998 (μ), 2002 (e)
- Lepton Number Still viable ($0 \ll \ll \ll ?$)
- 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 $p \rightarrow e^+ \bar{\nu}^0$ at 6.5×10^{31} years...”
- “That bound appears to rule out minimal SU(5) with a great desert” (Marciano)

Weinberg's view (1980)



- “One is tempted to conclude that the only fundamental conservation laws left in physics are the gauge symmetries: Lorentz invariance and $SU(3) \times SU(2) \times U(1)$. But then what about baryon and lepton conservation? They appear to be exact and unbroken, but they are surely not exact unbroken gauge symmetries, because we do not see the effects of a long-range vector field coupled to baryon or lepton number. The peculiar position of baryon and lepton conservation in today's physics suggests that baryon and lepton conservation may go the way of the other non-gauge symmetries, and turn out to be only approximate consequences of the gauge symmetries and renormalizability.”

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

Rare Effects from High-Energies

- Effects of physics beyond the SM as effective operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \dots$$

- Can be classified systematically (Weinberg)

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu\nu$$

□ □ $\sim 10^{15} \text{GeV!}$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He,$$


$$W_\nu^\mu W_\lambda^\nu B_\mu^\lambda, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \dots$$

Unique Role of Proton Decay



- Most $D=6$ operators can be probed only up to $\Lambda \sim 1\text{TeV}$ (precision EW) or $\sim 100\text{ TeV}$ (FCNC)
- Only operators that give rise to **proton decay** can be probed up to $\Lambda \sim 10^{15}\text{GeV}$
- *Extremely rare* $\sim (m_p/10^{15}\text{GeV})^4 \sim 10^{-60}$ but experimentally accessible
- Unique window to **extremely high-energy physics**

Baryon Number is Probably Violated



- Universe is made of baryons, no anti-baryons
 - There must have been a process in early Universe that created this asymmetry via baryon number violation
 - Such baryon number violation could lead to proton decay
- Old philosophy (*e.g.*, Yang-Mills): all conserved quantities must be local gauge charges
- Quantum gravity (virtual blackholes, wormholes) violate global (non-gauge) charges

B is Violated in the Standard Model

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

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

But Anomaly is Small

- At zero temperature, the anomaly process occurs only via tunneling $\Delta B = \Delta L = N_g$
- 't Hooft (1976) estimated its effect on two-generation case $\Delta B = \Delta L = 2$

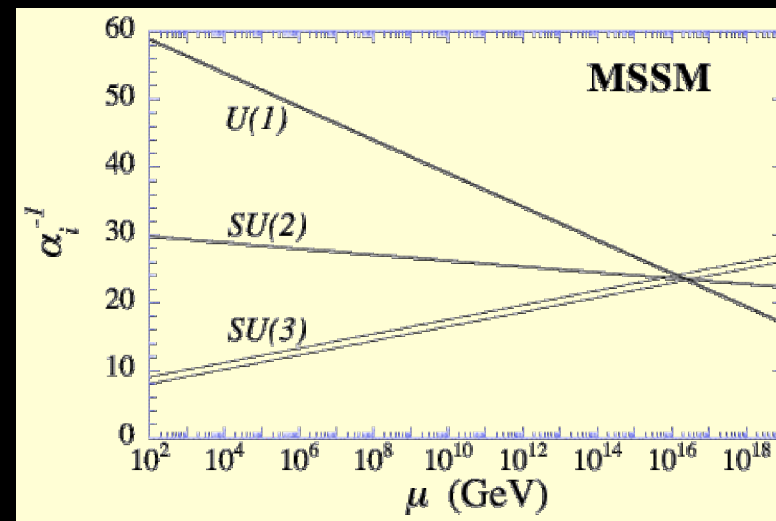
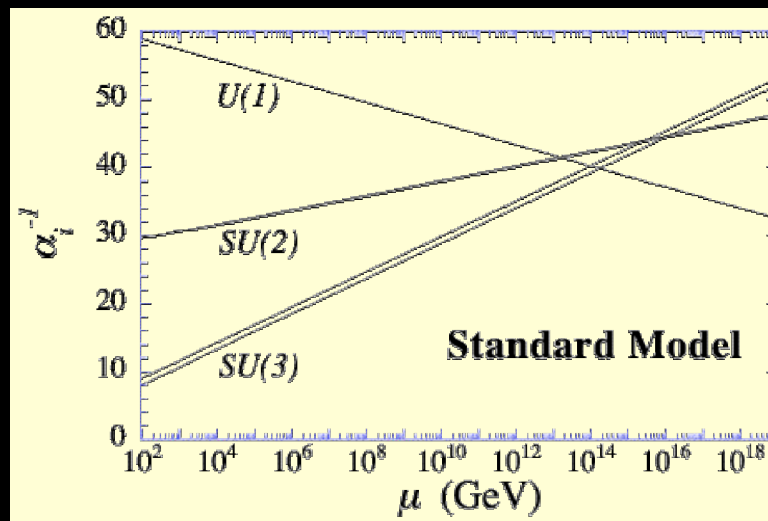
$$\tau(d \rightarrow e^+ \bar{\nu}_\tau) \sim 10^{170} \text{ years}$$

- Need motivated model of B violation \square GUT
(Note any new particles potential source of B viol.)

*Proton Decay
in Grand Unified Theories*

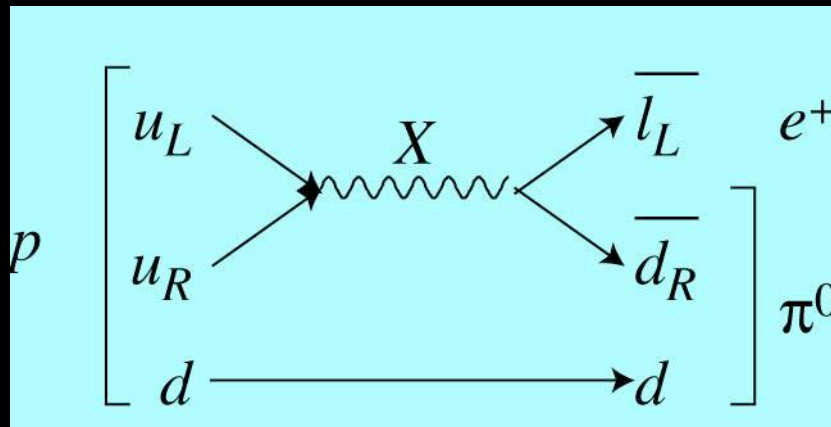


Gauge Coupling Unification



Proton Decay

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



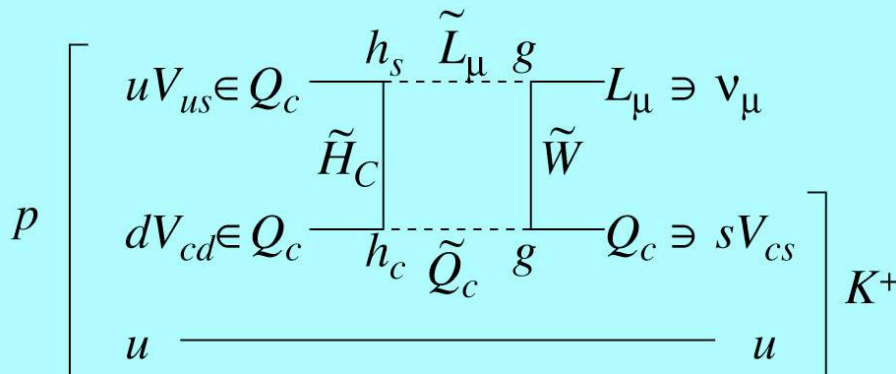
$$\left[\begin{array}{c} \square \\ \square \\ \square \\ \square \end{array} \right] \frac{g^2}{M_X^2} \left[\begin{array}{c} \square^2 \\ \square^2 \\ \square^2 \\ \square^2 \end{array} \right] m_p^5$$

- IMB excluded the original SU(5) GUT

Supersymmetric Proton Decay

$$\begin{array}{c}
 Q_c \\
 \diagdown \\
 h_c \text{---} H \\
 \diagup \\
 c_R
 \end{array}
 =
 \begin{array}{c}
 Q_c \\
 \diagdown \\
 h_c \text{---} H_C \\
 \diagup \\
 Q_c
 \end{array}
 =
 \begin{array}{c}
 \tilde{Q}_c \\
 \text{---} \\
 h_c \text{---} \tilde{H}_C \\
 \diagup \\
 Q_c
 \end{array}$$

$$\begin{array}{c}
 Q_c \\
 \diagdown \\
 h_s \text{---} H \\
 \diagup \\
 s_R
 \end{array}
 =
 \begin{array}{c}
 Q_c \\
 \diagdown \\
 h_s \text{---} H_C \\
 \diagup \\
 L_\mu
 \end{array}
 =
 \begin{array}{c}
 Q_c \\
 \diagdown \\
 h_s \text{---} \tilde{H}_C \\
 \diagup \\
 \tilde{L}_\mu
 \end{array}$$



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

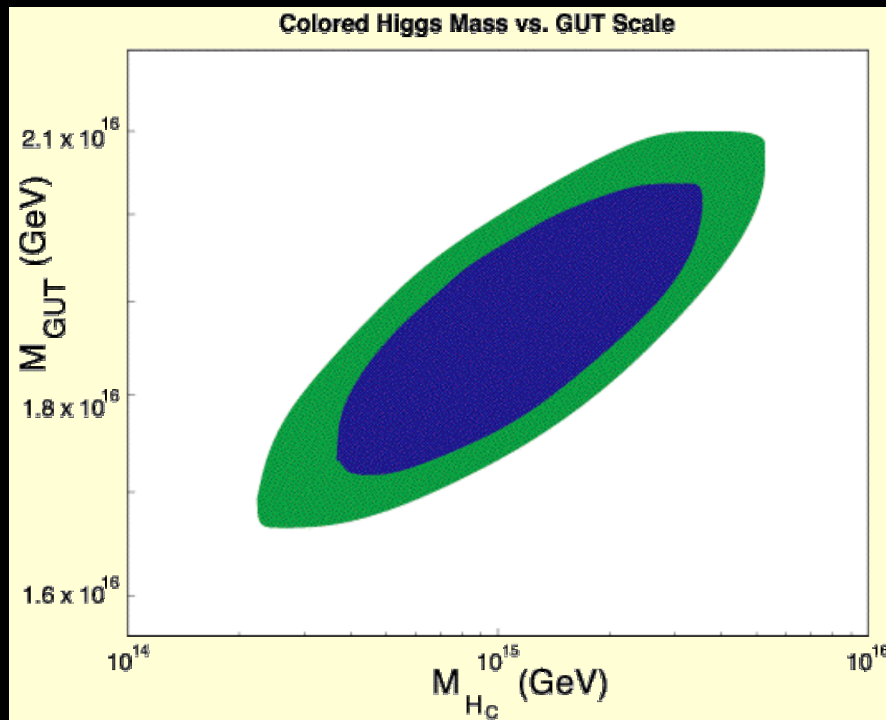
$$\left[\begin{array}{c} \square \\ \square \\ \square \\ \square \end{array} \right] \frac{g^2}{(4\pi)^2} \frac{h_s h_c \square_C^2}{M_{H_C} m_{SUSY}} \left[\begin{array}{c} \square \\ \square \\ \square \\ \square \end{array} \right]^2 m_p^5$$

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

Rest In Peace

Minimal SUSY SU(5) GUT

- RGE analysis



- SuperK limit $\langle \bar{p} \bar{K}^+ \rangle > 6.7 \times 10^{32}$ years (90% CL)
 $M_{\text{Hc}} > 7.6 \times 10^{16}$ GeV
- Even if 1st, 2nd generation scalars “decoupled”, 3rd generation contribution (Goto, Nihei)
 $M_{\text{Hc}} > 5.7 \times 10^{16}$ GeV
(HM, Pierce)

Avoiding Proton Decay



- Proton decay rate/mode is highly model-dependent
 - more threshold corrections (HM, Pierce)
 - Structure in the Higgs sector (Babu, Barr)
 - SO(10) models similar with more flexibility (Babu, Pati, Wilczek)
 - GUT breaking by orbifolds removes this operator completely (Kawamura; Hall, Nomura)
 - Depends on the triplet-doublet splitting mechanism, Yukawa (non-)unification

Not so easy to push it much beyond the current limit

$$p \rightarrow e^+ \bar{p}$$

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

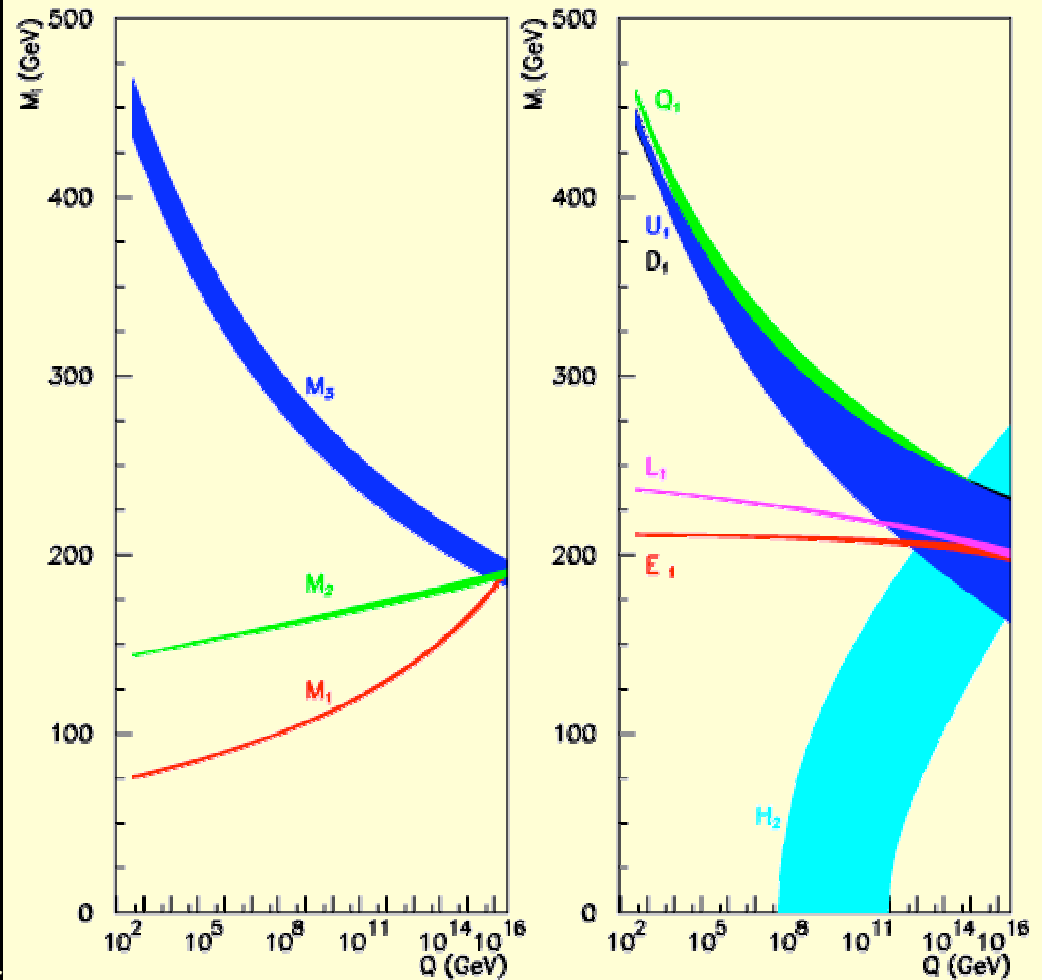
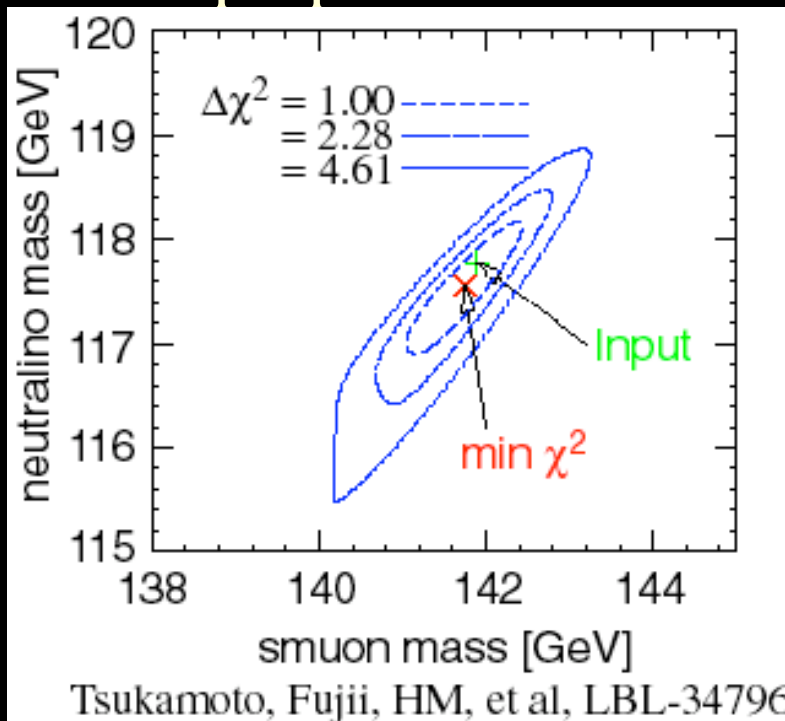
May well be just around the corner

More Signals of GUT



Superpartners as probe

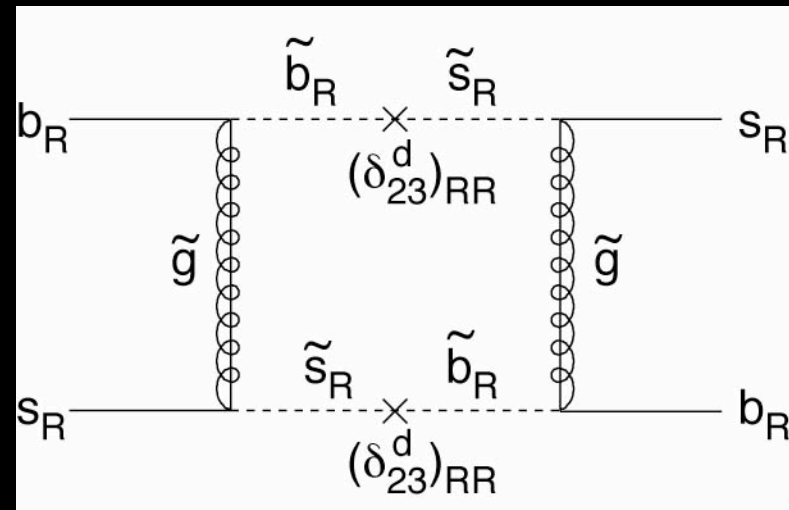
- Precise mass measurements of superparticles



Large \square_{23} and quarks

- Large mixing between $\square_{\bar{d}}$ and $\square_{\bar{u}}$
- 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
- B_s mixing, B_d \square \square K_s
(Chang, Masiero, HM)

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



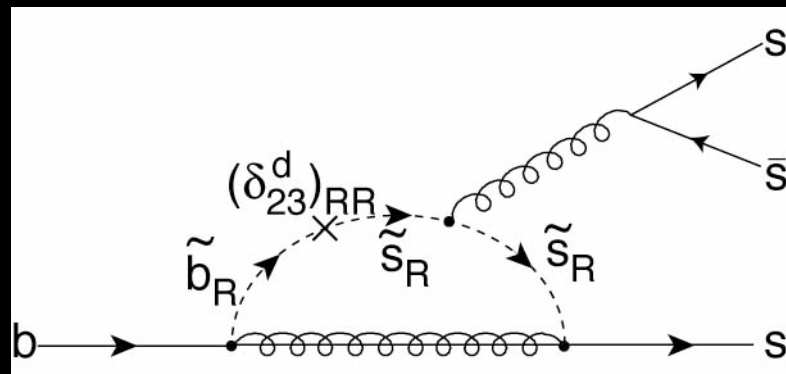
$B_d \rightarrow \bar{K}_s$

- ICHEP 2002 @ Amsterdam
 - “ $\sin 2\beta_1$ ” = $-0.73 \pm 0.64 \pm 0.18$ (Belle)
 - “ $\sin 2\beta$ ” = $-0.19 \pm 0.51 \pm 0.09$ (BABAR)
- Compared to W. A. from $J/\psi \rightarrow K_s$

$$+0.731 \pm 0.055$$

Maybe a hint ($\sim 2.7\sigma$) of SUSY GUT?

- But $B_d \rightarrow \bar{K}_s, K^+K^-K_s$?
- Even if the current “discrepancy” disappears, it remains true that **this is a very reasonable place for new physics to show up.**



Conclusions



- Baryon/lepton numbers very likely violated
- Neutrino mass and proton decay: **window to extreme high-energy physics**
- Current limits on proton decay had already excluded the original GUT and the Minimal SUSY GUT
- Many modifications of GUT predict proton decay **within 1–2 orders of magnitude above current limit**
- GUT must be checked from many angles

Future



Future will be painful
Because we will probably
find proton decay
And we'll feel it in our bones.