Models of Baryon Number Violation

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Why is proton decay so important?

→ Window to (very) high energy physics

Does proton really decay?

Are the next generation experiments worth being pursued?

Important to understand (precisely) what we "know" and what we can "expect"

→ interplay between theory and experiment

Try to illustrate this using (relatively) recent models of unification (proton decay)

Proton will decay

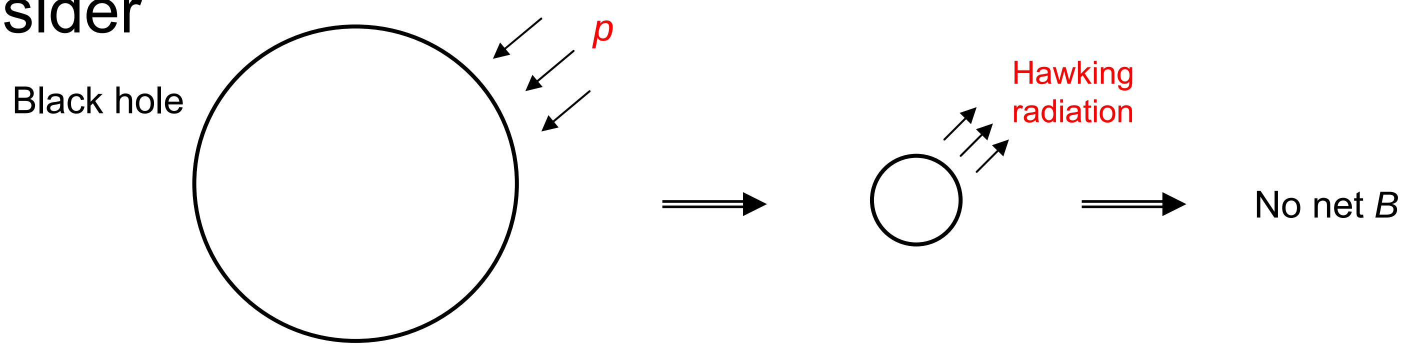
The baryon (B) and lepton (L) numbers in the SM

→ accidental symmetries at low energies

(write down the most general Lagrangian → B and L)

B and L are not the "fundamental" symmetries

Consider



→ Baryon number is violated

In quantum gravity, this process is occurring virtually

→ Proton does decay at some level (unless killed by an additional symmetry "by hand")

Importance of “Models”

The proton is expected to decay anyway

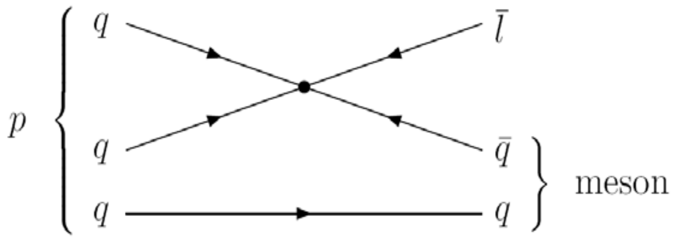
→ Who cares models?

(Just go out and look for *p* decay … it is already well motivated)

What is the rate?

In the SM,

$$\mathcal{L}_{p-\text{decay}} \sim \frac{1}{M^2}\, q\, q\, q\, l$$



The scale *M* ~ (reduced) Planck scale M_{Pl} = 2 x 10^{18} GeV

The lifetime is

$$\Gamma \approx \frac{1}{8\pi}\frac{m_p^5}{M_{\text{Pl}}^4} \sim 10^{-75}\ \text{GeV} \quad \Longrightarrow \quad \tau \sim 10^{43}\ \text{years}$$

→Yes, the proton decays,

but at the rate is outside the expected reach

Proton decay from grand unification

Proton decay will be out of reach

unless there is new physics below M_{Pl}

Is there a well-motivated candidate?

Grand Unification

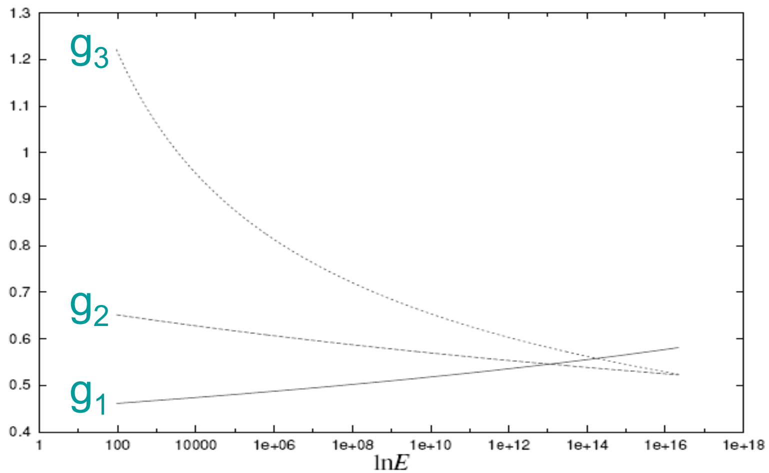
$$
\begin{array}{llll}
SU(3)_C \times SU(2)_L \times U(1)_Y & SU(5) & & SO(10) \\
q(\mathbf{3},\mathbf{2})_{1/6} & & & \\
u^c(\mathbf{3}^*,\mathbf{1})_{-2/3} & \left.\right\} T(\mathbf{10}) & & \\
e^c(\mathbf{1},\mathbf{1})_{1} & & & \\
d^c(\mathbf{3}^*,\mathbf{1})_{1/3} & \left.\right\} F(\mathbf{5}^*) & & \psi(\mathbf{16}) \\
l(\mathbf{1},\mathbf{2})_{-1/2} & & & \\
n^c(\mathbf{1},\mathbf{1})_{0} & \rightarrow N(\mathbf{1}) & &
\end{array}
$$

Predictions:

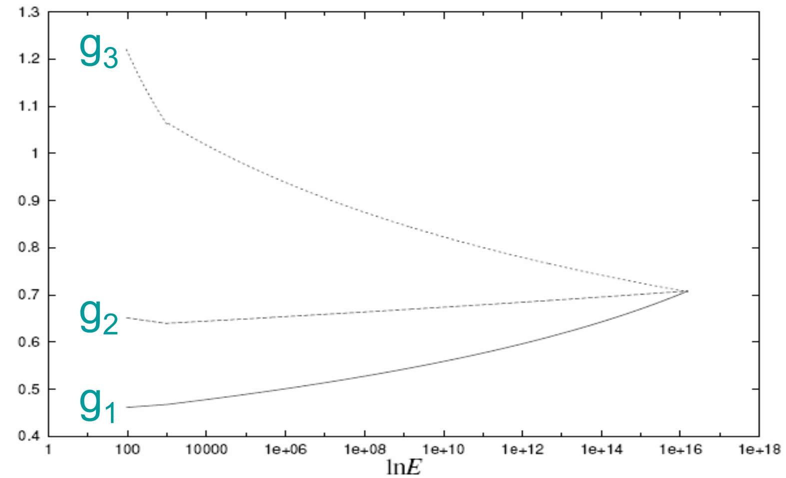
- 3 forces of the SM unified at a high energy scale M_{GUT}
- Proton decay caused by exchange of GUT bosons: $M \sim M_{\mathrm{GUT}}$ → For $M_{\mathrm{GUT}} < M_{\mathrm{Pl}}$, p decay may be within reach

Grand unification works (only) with supersymmetry

Non-SUSY



SUSY



Supersymmetry (SUSY)

Superparticle at ~ TeV

- stabilizes the weak scale
- change the RGEs for $g_{1,2,3}$

R parity

- the existence of dark matter

$M_{GUT} \sim 2 \times 10^{16}$ GeV

Proton decay in SUSY GUTs

Dimension five (d=5):

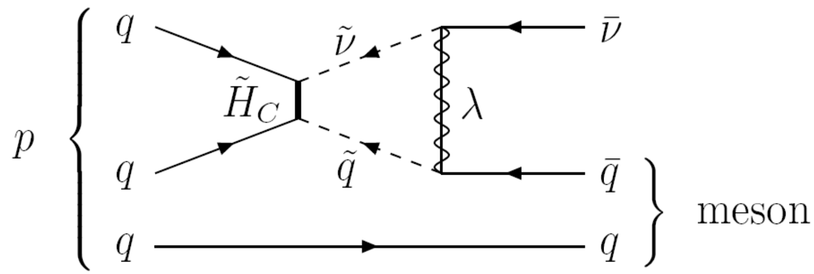
color triplet Higgsino exchange

$$H(\mathbf{5}) \;=\{\, H_u,\, H_C \,\}$$

$$\bar{H}(\mathbf{5^*}) = \{\, H_d,\, \bar{H}_C \,\}$$

Two Higgs doublets of the SUSY SM

Color triplet Higgs fields



dominantly $p \rightarrow K^+\bar{\nu}$

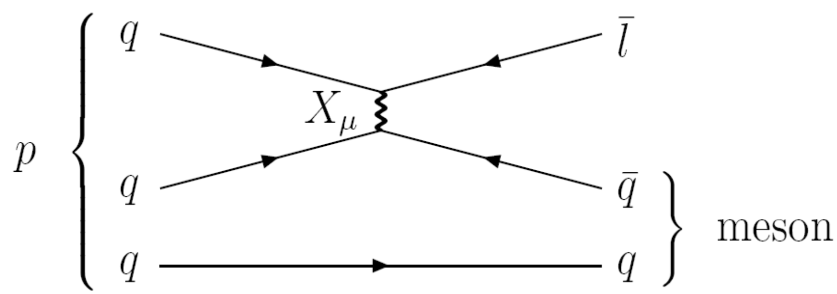
Dimension six (d=6):

GUT gauge boson exchange

$$V(\mathbf{24}) \;=\{\, V_{321},\, V_X \,\}$$

SM gauge multiplet

GUT gauge multiplet



dominantly $p \rightarrow e^+\pi^0$

Dilemma after Super-K

The minimal SUSY SU(5) GUT is "excluded"

Gauge coupling unification → $3.5 \times 10^{14}\ \mathrm{GeV} < M_{H_C} < 3.6 \times 10^{15}\ \mathrm{GeV}$

d=5 proton decay → $M_{H_C} > 9.0 \times 10^{17}\ \mathrm{GeV}$ $\left(\begin{array}{l} \tau_{p \to K^+ \bar{\nu}} > 2.3 \times 10^{33}\ \mathrm{years} \\ m_{\mathrm{SUSY}} \sim \mathrm{TeV} \end{array} \right)$

→ contradicting

e.g. Murayama, Pierce

Does this exclude SUSY GUTs?

… certainly not, but it leads to a dilemma for *p* decay exp.

Suppose *d*=5 proton decay is absent for some reason

The proton then decays by *d*=6 (gauge boson exchange)

$M_{\mathrm{GUT}} \sim 2 \times 10^{16}$ GeV $\Longrightarrow$ $\tau \sim 10^{35} - 10^{36}$ years

… *p* decay may be out of reach

Is it reasonable to "expect" *p* decay in future exp.?

(should we go to "exotics"?)

Minimal SUSY GUT had problems

$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

$T(\mathbf{10}) = \{ Q, U, E \}$ $\quad$ $H(\mathbf{5}) = \{ H_u, H_C \}$

$F(\mathbf{5^*}) = \{ D, L \}$ $\quad$ $\bar{H}(\mathbf{5^*}) = \{ H_d, \bar{H}_C \}$

Dimopoulos, Georgi; Sakai

- Gauge breaking & Doublet-triplet splitting

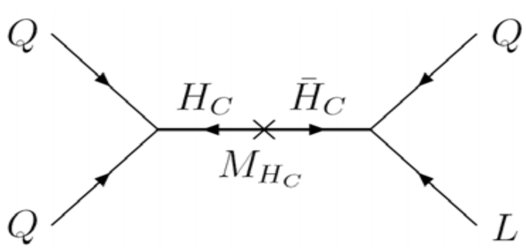
Why $M_{H_C} \gg M_{H_{u,d}}$?

$$W = H \left(M_H + \lambda \Sigma \right) \bar{H}$$

$$\langle \Sigma \rangle = \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix} V_\Sigma \Longrightarrow \left\{ \begin{array}{lcllc} M_{H_C} & = & M_H + 2\lambda V_\Sigma & \sim & M_{\rm GUT} \\ M_{H_{u,d}} & = & M_H - 3\lambda V_\Sigma & \ll & M_{\rm GUT} \end{array} \right.$$

… extreme fine-tuning

- *d*=5 proton decay



$$\Longrightarrow \quad W \approx \frac{1}{M_{H_C}} QQQL$$

… excluded by Super-Kamiokande

- Fermion mass relations

$$W = y T F \bar{H} \;\begin{cases} \nearrow \; y\, Q D H_d \\ \searrow \; y\, L E H_d \end{cases} \Longrightarrow$$

m_b/m_τ : good

m_s/m_μ : bad

… The minimal SUSY GUT is not "fully realistic"

Predictions/expectations for proton decay must be considered in the context of "realitic" models

Possible to do in the framework of 4D SUSY GUTs

typically very complicated --- large representations, special potentials, …

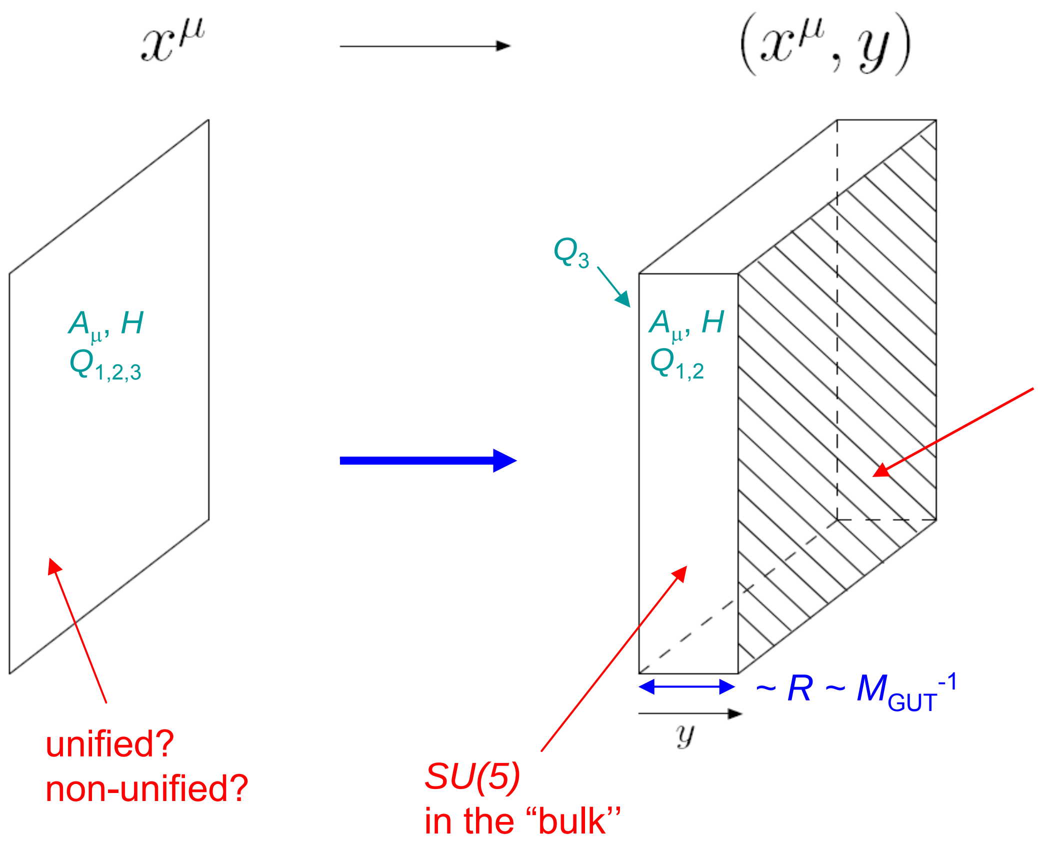
(although some recent progresses)

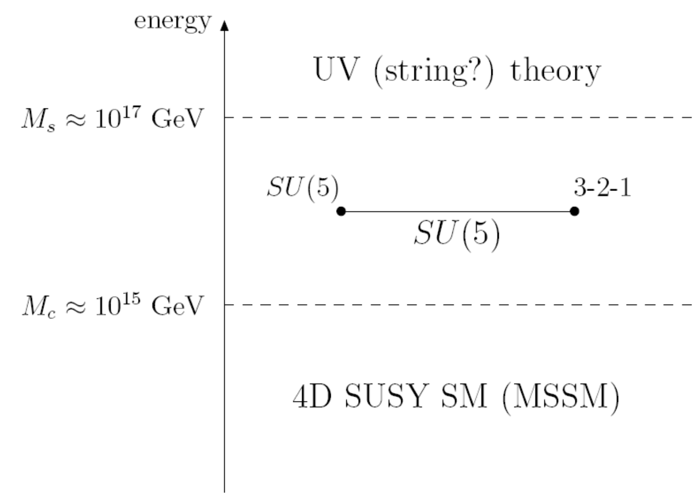
Something crucial seems to be missing

Grand unification in higher dimensions

Hall, Y.N.; Kawamura ('00 - '02)

The basic framework





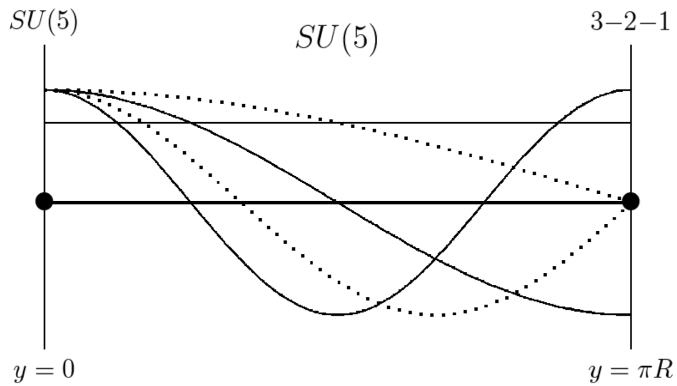
Review for a wide audience; Hall, Y.N., hep-ph/0212134

Consistent quantum theory

"boundary condition"

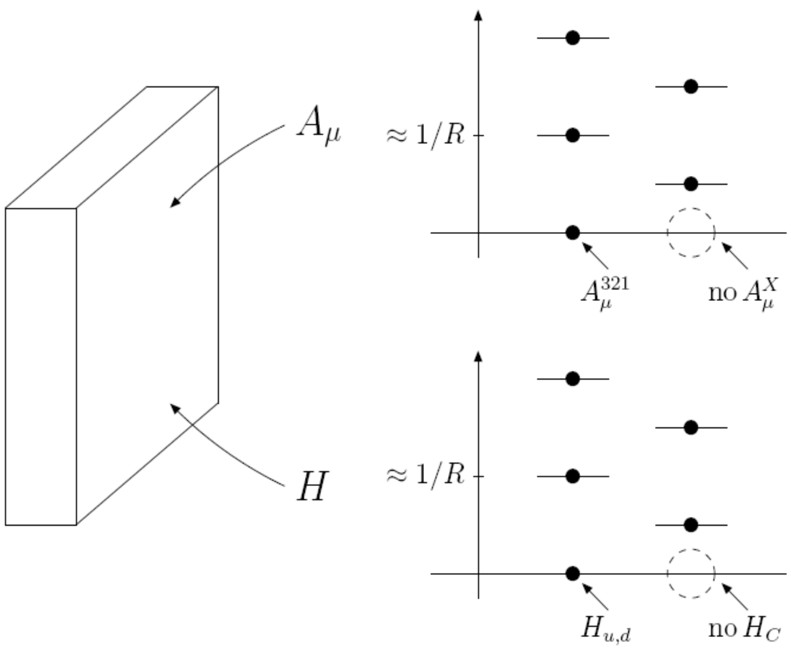
A_μ^{321} (+,+):

A_μ^{X} (+,-):



(compactified on an S^1/Z_2 orbifold)

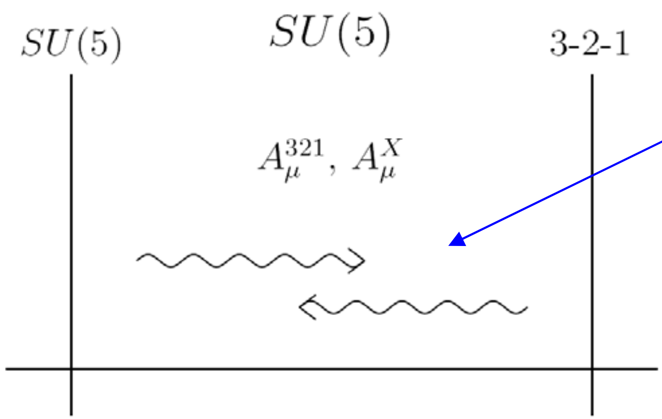
From 4 dimensional point of view,



Gauge breaking
& doublet-triplet splitting

… automatic

Gauge coupling unification preserved



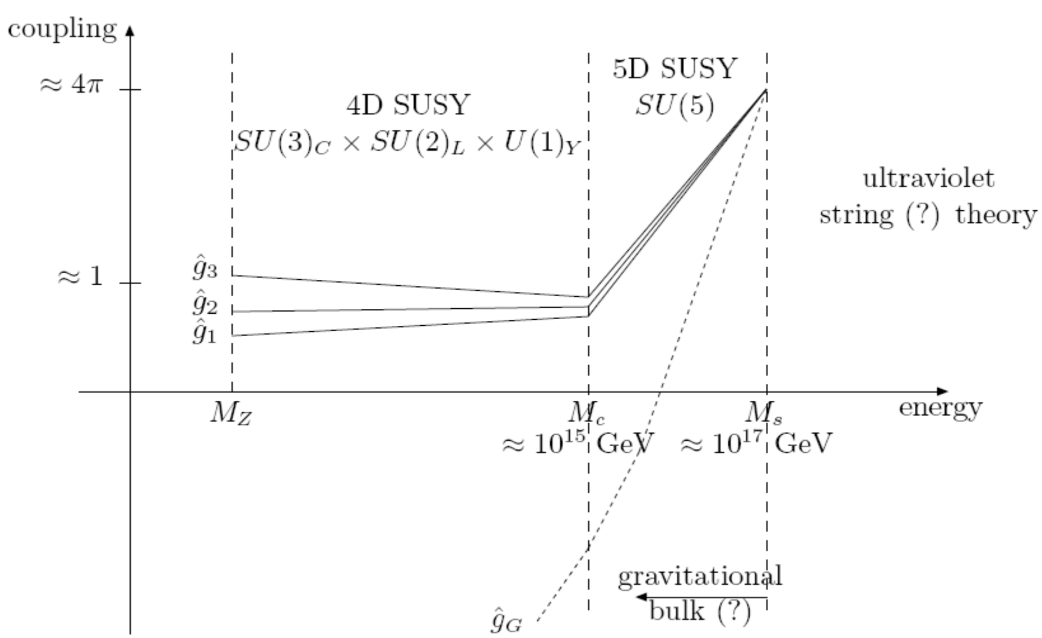
Gauge bosons propagate in the bulk

→ feel symmetry breaking defect at $y=\pi R$

$$\frac{1}{g_{4D,i}^2} = \underbrace{\frac{\pi R}{g_5^2}}_{SU(5)\text{ symmetric}} + \underbrace{\frac{1}{g_{4,i}^2}}_{SU(5)\text{ violating}} \Longrightarrow \underbrace{\frac{M_s R}{16\pi^2}}_{O(1)} + \underbrace{\frac{1}{16\pi^2}}_{O(10^{-2})}\Bigg|_i$$

$$\boxed{M_s R \approx O(100) \Longrightarrow g_{4D,i} \approx O(1)}$$

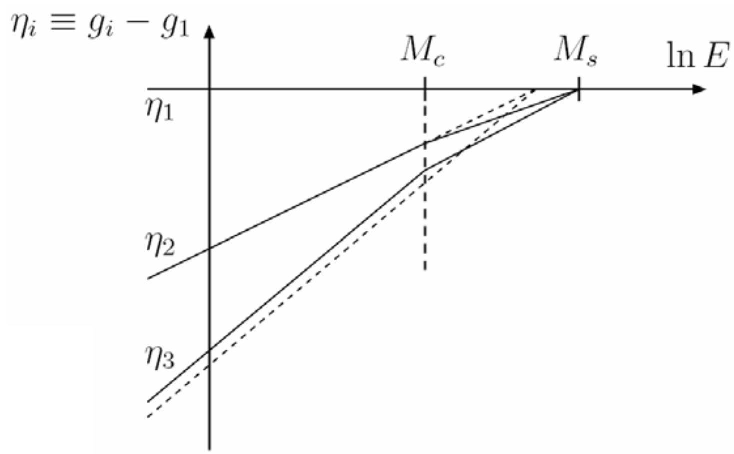
… Volume can dilute the effect of the defect

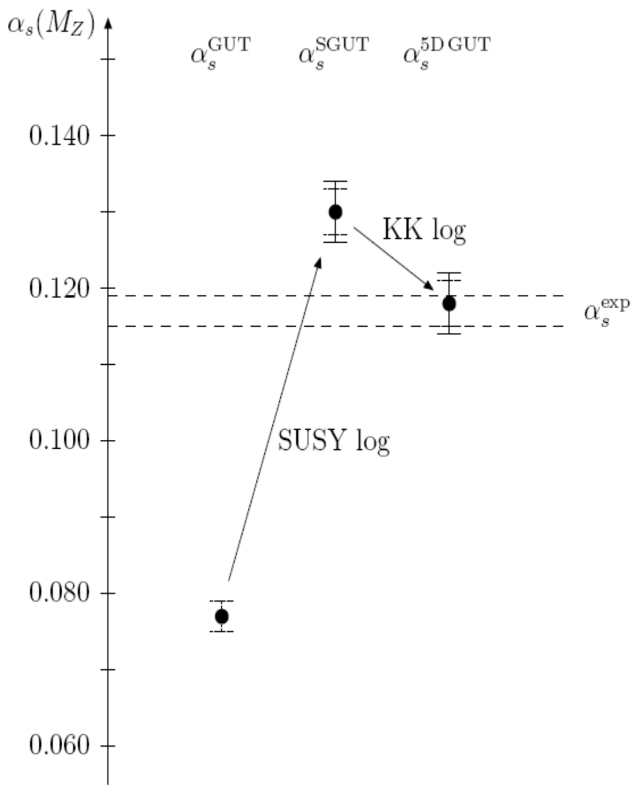


Precision unification prediction

No arbitrary parameters (masses)

… threshold corrections are calculable





Precise predictions for $\alpha_s(M_Z)$, M_c=1/R, M_s

$$\alpha_s(M_Z) = 0.118 \pm 0.005$$

$$M_c \equiv 1/R \approx 10^{15}\ \mathrm{GeV}$$

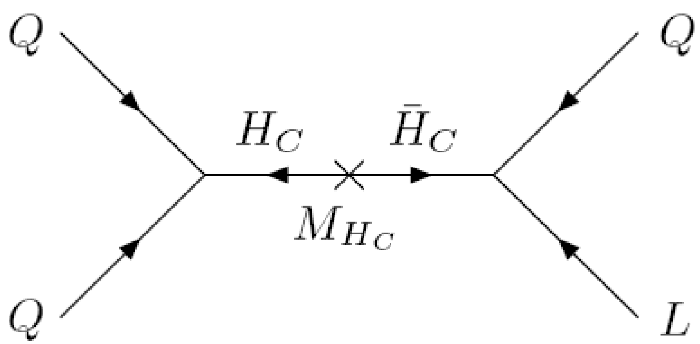
$$M_s \approx 10^{17}\ \mathrm{GeV}$$

… improved prediction for $\alpha_s(M_Z)$

Suppressed *d*=5 proton decay

- 4D

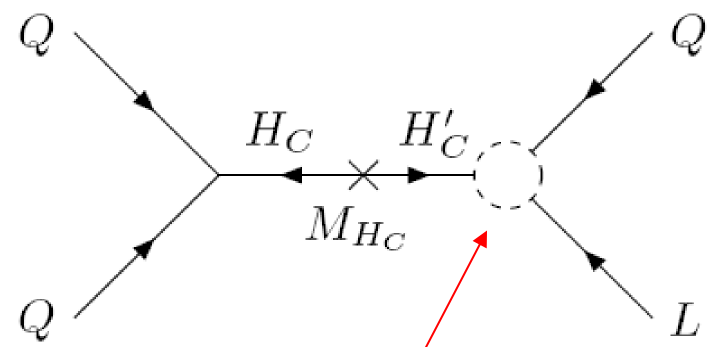
$$W = M_{H_C} H_C \bar{H}_C$$



- 5D

5D partners

$$W = M_{H_C}(H_C H'_C + \bar{H}_C \bar{H}'_C)$$



simply absent

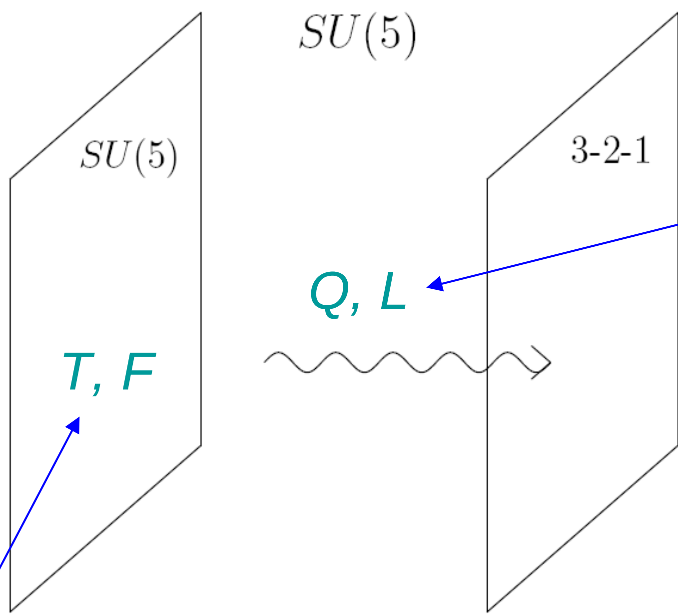
- $U(1)_R$ symmetry

$T(1)$, $F(1)$, $H(0)$, $\bar{H}(0)$, $H'(2)$, $\bar{H}'(2)$, …

… *d*=5 proton decay does not arise

Matter fields

- Matter fields can be either on a brane or in the bulk



bulk matter: touch to the defect

- *SU(5)* prediction for m_q/m_l does not arise
- No d=6 proton decay

⇓

Light (volume dilution)

brane matter: locally *SU(5)* symmetric

- *SU(5)* prediction for m_q/m_l holds

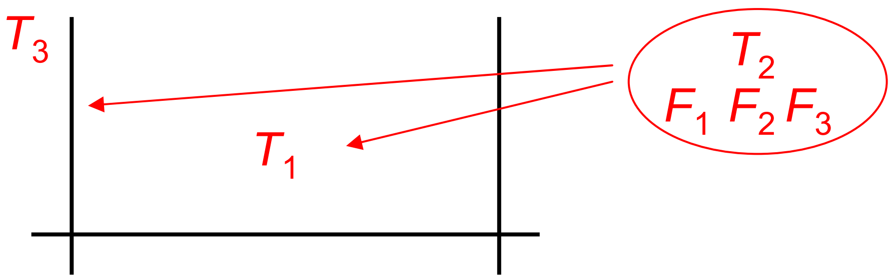
⇓

Heavy (no volume dilution)

… Successful correlation

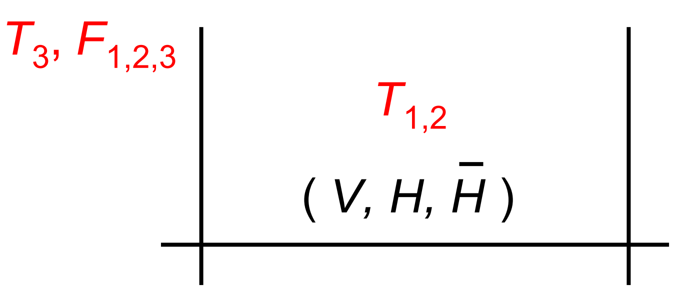
Flavor physics: matter geography

- T_1 in the bulk ($M_X = 1/2R \sim 10^{15}$ GeV)
- T_3 on the brane (top Yukawa coupling)



- b/τ unification $\longrightarrow$ F_3 on the brane
- s/μ, d/e mass ratio $\longrightarrow$ either T_2 or F_2 in the bulk

Example)



… realistic fermion masses

$$M_u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & \underline{1} \end{pmatrix}, \quad M_d \sim M_l^T \sim \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon & \epsilon \\ \underline{1} & \underline{1} & \underline{1} \end{pmatrix}$$

SU(5)

$\epsilon \sim O(0.1)$

Implications on proton decay

- No d=4 or d=5 proton decay
- No d=6 proton decay at leading order (${T}_1$ in the bulk)

d=6 proton decay occurs through flavor mixing / brane op.

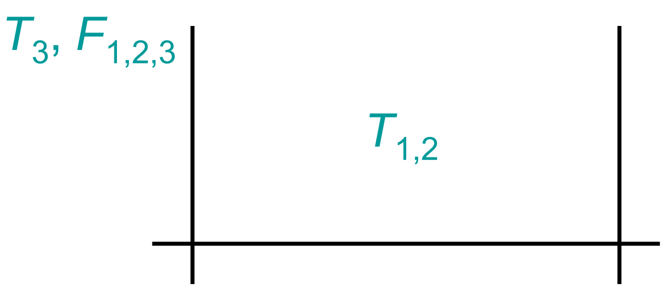
Y.N.; Hebecker, March-Russell

CKM / volume suppressed, but

$$M_X = 1/(2R) \sim 10^{15}\ \text{GeV} < M_{\text{GUT}} \sim 2 \times 10^{16}\ \text{GeV}$$

→ A variety of final states with the rates within reach

Example)



$p \to e^+\pi^0,\ \mu^+\pi^0,\ e^+K^0,\ \mu^+K^0,\ \pi^+\bar{\nu},\ K^+\bar{\nu}$

comparable rates
calculable branching ratios

$\tau \sim 10^{34}$ years $\quad \dfrac{\Gamma(p \to \mu^+\pi^0)}{\Gamma(p \to e^+\pi^0)} \simeq \dfrac{\Gamma(p \to e^+K^0)}{\Gamma(p \to \mu^+K^0)}, \cdots$

Hall, Y.N.

Proton decay as a probe of geometry at the unification scale!

Conclusions

- Proton decay --- window for extremely high energies
- Despite the non-discovery at Super-K (so far), there are possibilities of discovery in "near" future

(Prospect for *p* decay should be discussed in realistic models)

- Grand unification in higher dimensions

p decay final states $\longleftrightarrow$ geometry of extra dim. $R \sim M_{GUT}^{-1}$

- Important to push limits on all possible decay modes: $p \to e^+\pi^0,\ \mu^+\pi^0,\ e^+K^0,\ \mu^+K^0,\ \pi^+\bar{\nu},\ K^+\bar{\nu},\ \ldots$
- Next generation nucleon decay experiments --- "unique" opportunity to explore super-high energies

(cf. superparticle masses in gravity mediation)