GRAND UNIFICATION & PROTON DECAY: PROSPECTS FOR MAJOR DISCOVERIES AT NEXT-GENERATION DETECTORS

JOGESH PATI
SLAC, STANFORD UNIVERSITY

REFERENCES

Babu, Pati, Tavartkiladze / hep-ph/1003-2625
JHEP 2010

Babu, Pati, Tavartkiladze – 2015 (To APPEAR)

Babu, Pati, Wilczek – hep-ph/9812538 –
Nucl. Phys. (2000)

I) SM NOW BRILLIANTLY SUCCESSFUL

Since 1972, both the $SU(2)\times U(1)$ EW Theory & QCD have been confirmed by numerous experiments

→ Now Higgs discovered at LHC $(m_h \approx 125\,\text{GeV})$

→ A Triumph of Gauge Principle & SSB

But ∃ Clear Evidence For Physics Beyond SM

1) ν Masses $\left(\sqrt{(\Delta m^2)_{\text{Atmosph}}} \sim \frac{1}{20}\,\text{eV}\right)$
2) Higgs Mass Fine Tuning
3) Dark Matter (Cold): $\Omega_{CDM} \simeq 0.23$
4) Need For Inflation $\begin{cases} \to \text{Horizon} \\ \to \text{Flatness } \Omega = 1 \end{cases}$
5) Baryogenesis ⟷ Leptogenesis

All Five go well with SUSY Grand Unification

$\Downarrow$

There Exists Physics Beyond SM

6) Dark Energy: Cosm. Const? $\Omega_\Lambda \approx 0.72$ } A Mystery For All Theories

A) ① Proton Decay $qqql/M_1^2$

② ν oscillations $LL\langle\Phi_H\rangle\langle\Phi_H\rangle/M_2$

2 indispensable tools to probe nature at truly high energies ($\sim 10^{16}$ GeV), can't be reached by accelerators → Thus p-decay & ν-osc. Studies Complement physics of LHC / Future Accelerators

- Both are predictions of a well-motivated class of Grand Unif. Models → 1970's

ν oscil. Seen: $\sqrt{(\Delta m^2)_{Atm}} \sim \frac{1}{20}$ eV ! Anticipated

Proton Decay Yet to be Seen.

- Purpose of my talk is to present an Updated Version of a class of Well-motivated models of Grand Unif. based on SUSY SO(10), in light of LHC 1 results,

Upper limits on p-lifetime.

Babu, Pati, Tavartkiladze (2010)
Update in Light of LHC 1 (2015, To Appear)

BPT (2010) & Update (2015)

- Stabilize Natural Doublet-Splitting → A Generic Problem esply of SUSY GUTS – SU(5)/SO(10)..

⊕

- Include GUT-Scale Threshold Corrections

→ BONUS: An Inverse Correlation:

$$\boxed{A(d=6,\, p\to e^+\pi^0) \propto K_{SUSY}\cdot[A(d=5,\, p\to\bar{\nu}K^+)]^{-2/3}}$$

⇒ $\Gamma^{-1}(p\to e^+\pi^0)^{\text{expt}}_{\text{Lower limit}}$ ⇒ THEORETICAL UPPER LIMIT ON $\Gamma^{-1}(p\to\bar{\nu}K^+)$ dep. on SUSY SPECTRUM

&

Vice Versa:

⇒ FIND, WITH LHC 1 CONSTRAINTS, BOTH MODES ACCESSIBLE TO NEXT-GEN. DETECTORS (DUNE/LBNF HYPERK)

↓

MULTIPURPOSE: • p-decay
- ν-oscill (δ_{CP}, Mass-Hier, θ_{23}(octant), ..)
- Core-Collapse Supernova ν's

II) GRAND UNIFICATION : THE NEXT STEP

A) MOTIVATIONS (1972) → PURELY AESTHETIC

① Remove arbitrariness in choice of SM Quantum Nos. $(Y_W, SU(2)_L, SU(3)^C)$

② Quantization of Q_{em}

③ $\boxed{Q_{e^-} = -Q_p}$

④ Co-existence of q & l

⑤ Co-existence of (W, EM, strong) (g_1, g_2, g_3)

MAIN IDEA (1972-74)

① Unify {q & l} → { One kind of Matter ↓ Symmetry Group G

↕

② Unify {W, EM & Strong} → { ASPECTS OF ONE FORCE ↓ Gauge symm. G

$$G \xrightarrow[SSB]{\langle \Sigma_i \rangle \sim M} SU(2)_L \times U(1)_Y \times SU(3)^C \xrightarrow[\sim 250\ GeV]{\langle \Phi_H \rangle} U(1)_{em} \times SU(3)^C$$

Distinctions between {q & l} & {W, EM & Strong} forces → Low Energy Phenomena arising from SSB → To disappear at predictably high energies

↓

MANY TESTABLE PREDICTIONS

B) Alt. Routes To Grand Unification

$$G(213) = SU(2)_L \times U(1)_Y \times SU(3)^c$$

$$\begin{pmatrix} u_r & u_y & u_b \\ d_r & d_y & d_b \end{pmatrix}_L^{1/3}, \; (u_{r,y,b})_R^{4/3}, \; (d_{r,y,b})_R^{-2/3}, \; \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L^{-1}, \; (e^-_R)^{-2}$$

5 disconn. multiplets // Arb. Y_W, SU(2), $SU(3)^c$ Q. Nos.

↓

1972 $G(224) = SU(2)_L \times SU(2)_R \times SU(4)^c_{L+R} \times (L \leftrightarrow R)$

$$F^e_{L,R} = \begin{bmatrix} u_r & u_y & u_b & \nu_e \\ d_r & d_y & d_b & e^- \end{bmatrix}_{L,R} \quad F^e_L = (2,1,4) \quad F^e_R = (1,2,4)$$

$$Q_{em} = I_{3L} + I_{3R} + \frac{B-L}{2}$$

Advantages of G(224)

- All 16 in one L-R Conj. multiplet // L-R symm
- Explain Y_W & All Q. Nos. // Quantize Q_{em} //
- $Q_{e^-} = -Q_p$ // ν_R / B-L ← Need For Seesaw & Leptogenesis

↓

All Advantages of
G(224) retained by
SO(10), not SU(5)

SO(10): 16 (one coupling)

$SU(5)$: $\bar{5} + 10$
NO ν_R, No B-L } → Problem with ν Masses & Leptogenesis.

D) EVIDENCE FOR GRAND UNIFICATION

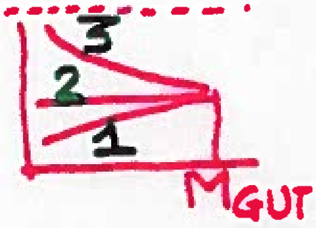
1) Family Structure - Quantum Nos. Predicted as observed

2) Charge Quantization

3) $Q_{e^-} = -Q_p$

4) Meeting of The 3 gauge Couplings SUSY Grand Unification

$$\boxed{M_{GUT} \simeq 2 \times 10^{16}\ \text{GeV}}$$



$$\boxed{5)\ \sqrt{\Delta m^2(\nu)_{23}} \approx 1/20\ \text{eV}}$$

$\leftrightarrow SU(4)^c \rightarrow \nu_R$ // B-L

$m(\nu^\tau)_{Dirac}$ //

$M_{GUT} \rightarrow M_{Maj}\ \nu_R$

Seesaw

6) $m_b(GUT) = m_\tau$

7) $m(\nu_\tau)_{Dirac} = m_{top}(GUT)$

$\rightarrow SU(4)^c$

8) $\theta(\nu_\mu - \nu_\tau) \approx \pi/4 \leftrightarrow V_{cb} \simeq 0.04$

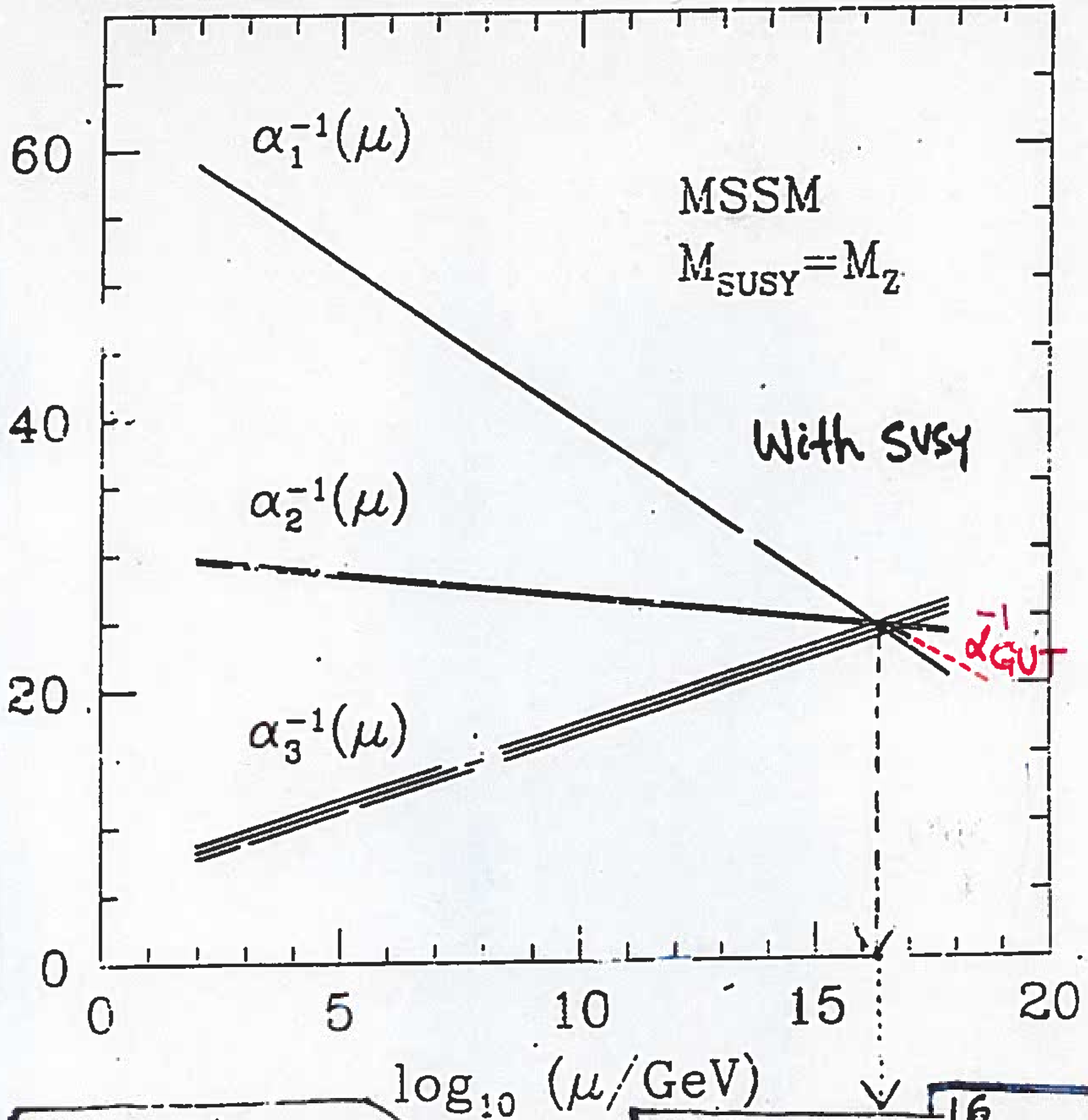
9) LEPTOGENESIS $\rightarrow Y_B \sim 10^{-10} \rightarrow \nu_R$/B-L

$\updownarrow$ SO(10)// G(224)

SUCCESS Of All 9 Features Non-Trivial !

TOGETHER MAKE A STRONG CASE FOR SUSY GRAND UNIF // SIMULT. FOR AN EFF. SYMMETRY LIKE SO(10) OR MINIMALLY A STRING-DERIVED G(224) SYMMETRY

Gauge Coupling Unification With SUSY



Supports SUSY Unification

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

$\sin^2\Theta_W(m_Z)_{th} = 0.2315 \pm .003$

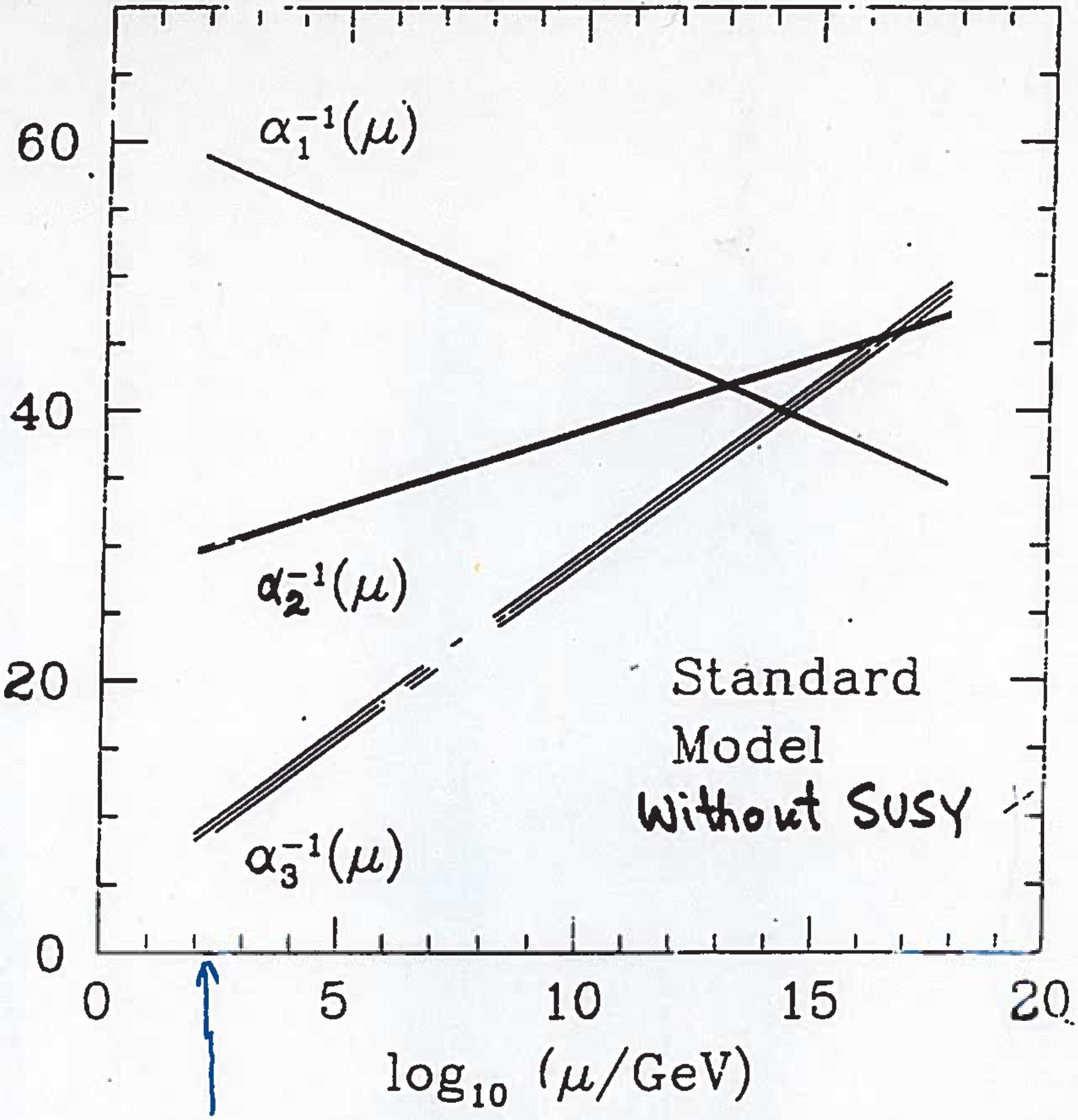
$\sin^2\Theta_W(m_Z)_{EXPT} = 0.23124 \pm .00017$

$\alpha_3(m_Z)^c_{theory} \simeq 0.125 - 0.13$

$\alpha_3(m_Z)_{obs} = 0.118 \pm .003$

GUT THRESHOLD CORRECTIONS

Coupling Unification Without SUSY



α_i's Measured at LEP
at ~ 100 GeV

II SO(10) - BREAKING

LOW DIM. HIGGSES

$45_H, 16_H, \overline{16}_H, 10_H$

HIGH DIM. HIGGSES

$126, \overline{126}, 120, 54, 210$

Generically Large GUT SCALE THRESHOLD CORR.

$$\begin{tikzcd} SO(10) \arrow[d, "\langle 45_H\rangle \sim \propto B-L"', "\langle 16_H\rangle = \langle \overline{16}_H\rangle \sim M_{GUT}"] \\ SU(2)_L \times U(1)_Y \times SU(3)^c \arrow[d, "\langle 10_H\rangle"', "\sim \langle 16_H^d\rangle \sim M_{EW}"] \\ U(1)_{EM} \times SU(3)^c \end{tikzcd}$$

Babu, Pati, Wilczek

$16_i\, 16_j\, 10_H$

$16_i\, 16_j\, 10_H \cdot 45_H/M$

$16_i\, 16_j \cdot 16_H \cdot 16_H^d/M$

ASSUME HIER. YUKAWA → $U(1)_F$

$16_i\, 16_j\, \overline{16}_H\, \overline{16}_H/M$ → MAJORANA MASS $\nu_R^i \nu_R^j$

→ A PREDICTIVE SUCCESSFUL FRAMEWORK FOR FERMION MASSES / MIXINGS / NEUTRINO OSC. / ~~CP~~ // WITH PREDICTIONS FOR $\mu \to e\gamma$, $(edm)_n$, ...

③ $\sqrt{\Delta m^2(\nu_\mu \nu_\tau)_{\text{SuperK}}} \approx \frac{1}{20}$ eV

See Saw (IGNORE MIXING For a Moment

Dirac Mass

$$\begin{array}{cc} & \begin{array}{cc}\nu_L^\tau & \overline{\nu_R^\tau}\end{array} \\ \begin{array}{c}\nu_L^\tau \\ \overline{\nu_R^\tau}\end{array} & \left[\begin{array}{cc}0 & m(\nu_D^\tau) \\ m(\nu_D^\tau) & M_R\end{array}\right]\end{array} \longrightarrow \left[\begin{array}{cc}-\frac{m(\nu_D^\tau)^2}{M_R} & 0 \\ 0 & M_R\end{array}\right]$$

Majorana Mass Superheavy

$$\Rightarrow \boxed{m(\nu_L^\tau) \approx m(\nu_D^\tau)^2/M_R}$$

(i) Get M_R From SUSY Unif Scale $M_X \sim 2\times10^{16}$ GeV

$$\underset{(\approx 1)}{f_{33}}\, 16_3\, 16_3 \frac{\langle\overline{16}_H\rangle\langle\overline{16}_H\rangle}{\underset{(2\times10^{18}\text{ GeV})}{M_{Pl}}} \Rightarrow M_R \approx \frac{(2\times10^{16}\text{ GeV})^2}{2\times10^{18}\text{ GeV}} \approx \boxed{2\times10^{14}\text{ GeV}}$$

(ii) Get $m(\nu_D^\tau)$ Using SU(4)-Color

$\boxed{m_b^0 \approx m_\tau^0}$

$$m(\nu_D^\tau) = m_t(m_X) \approx \boxed{100\text{ GeV}}$$

$$\Rightarrow \boxed{m(\nu_L^\tau) \approx \frac{(100\text{ GeV})^2}{2\times10^{14}\text{ GeV}} \sim (1/20\text{ eV})(1/3 - 3)}$$

Also get $m(\nu_L^\mu) \sim m(\nu_L^\tau)/10 \Rightarrow \sqrt{\Delta m^2(\nu_\mu \nu_\tau)_{Th}} \sim \left(\frac{1}{20}\right)\text{eV}\left(\frac{1}{3} - 3\right)$

Thus the SuperK result brings to light the existence of $\boxed{\nu_R}$ // Reinforces the ideas of a) SeeSaw, b) SU(4)-Color & c) SUSY-unification..

COMPLEXIONS OF (B,L) VIOLATIONS

(I) PROTON DECAY

(a) $\Delta B = \Delta L = \pm 1 \,,\ \Delta(B-L) = 0$

$p \to e^+\pi^0 \quad qqq\ell/M^2 \to \boxed{d=6}$ $(M \gtrsim 10^{16}\,\text{GeV})$

$p \to \bar{\nu} K^+ \to$ Through $\boxed{d=5}$ in SUSY $\to \boxed{d=6}$

(b) $\Delta B = -\Delta L = \pm 1 \,,\ |\Delta(B-L)| = 2$

$\boxed{p \to e^-\pi^+\pi^+ ,\ n \to e^-\pi^+}$ $\left(\frac{qqq\ell H}{M'^3}\right)$ $\boxed{d=7}$

$\boxed{\text{"}M'\text{"} \gtrsim 10^{10}\,\text{GeV}}$ $G(2,2,4)/SO(10)$

JCP, Salam, Sarkar (1983) //
Babu, Mohapatra (2012)

If Seen $\longrightarrow$ Will imply Physis at Intermediate Scale

$\to \boxed{\tau_{n\text{-}\bar{n}} \sim 10^{33}\,s}$

Need Liquid Argon Detector

II) ν-less 2β DECAY: $(nn \rightarrow ppe^-e^-)$

$\Delta L = \pm 2$, $\Delta B = 0$, $|\Delta(B-L)| = 2$

Should occur with Majorana ν's

$\updownarrow$

(see saw).

$$m_{ee} = \left| \sum_i m_i U_{ei}^2 \right|$$

$$\sim (1-6)\times 10^{-3}\ \text{eV} \quad (\text{NORMAL HIERARCHY})$$

III) $n-\bar{n}$ oscillations

$\Delta B = \pm 2$, $\Delta L = 0$, $|\Delta(B-L)| = 2$

$qqq \rightarrow \bar{q}\bar{q}\bar{q}$ $\boxed{\delta m \sim \Lambda_{QCD}^6/(M''')^5}$ $\boxed{d=9}$

$\boxed{M''' \sim 10^5\ \text{GeV}} \longleftrightarrow \tau_{n\bar{n}} \sim 10^9\ \text{s}$

$10^8\ \text{s} \longrightarrow (10^9 - 10^{10})\ \text{s}$ $\boxed{\text{Project X } (n\bar{n})}$

ALL THESE SEARCHES FUNDAMENTAL & IMORTANT.

III PROTON DECAY: HALLMARK OF GRAND UNIFICATION

① $d = 6$ Gauge Med. SUSY SU(5)/SO(10)

$M_X \approx M_Y$
$\sim 10^{16}$ GeV

$\Rightarrow$ Amp $(p \to e^+ \pi^0)$ $\propto g^2/M_X^2$

Chiral Lag Param $(D+F) \simeq 1.25$ // $A_R \simeq 3.4$

$\boxed{\alpha_H = 0.012\ \text{GeV}^3}$

$$\Gamma^{-1}(p \to e^+ \pi^0) \simeq 10^{35} \left(M_X / 10^{16}\,\text{GeV}\right)^4$$

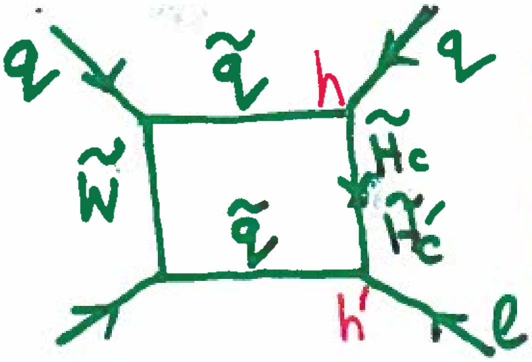
↓

LARGE UNCERTAINTY → $\sim 10^{33} - 10^{37}$ yrs ? ESTIMATE

② SUSY SU(5) / SO(10) Standard $d=5$

Color Triplet Higgsino Med   Sakai, Yanagida/ Weinberg

Need
D-T
Splitting



$$\boxed{\begin{aligned}\tilde{H}_c &\subset (10_H)_{SO(10)} \\ &= (2,2,1) + (1,1,6)\end{aligned}}$$

$$\text{Amp} \propto \left(hh'/M\right)\left(m_{\tilde{W}}/m_{\tilde{q}}^2\right)\alpha_2$$

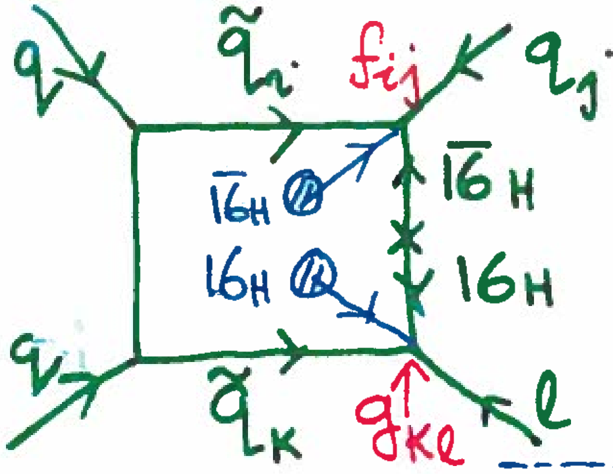
$$\boxed{\begin{aligned} M &= M_{H_c}\ (SU(5)) \\ M &= M_{eff}\ (SO(10))\end{aligned}}$$

$p \to \bar{\nu} K^+$ (dominant)
$\to \mu^+ K^0$ (suppressed) BR $\sim 10^{-5}$

$$\boxed{\Gamma^{-1}(p \to \bar{\nu} K^+) \sim 10^{30} - 10^{34}\ \text{yrs.}}$$

③ New d=5 ν-Mass Related operators

Babu, Pati, Wilczek



$f_{ij}\, 16_i\, 16_j\, \overline{16}_H\, \overline{16}_H / M$

$\Downarrow$

Maj Masses of ν_R's

Generically $16_i\, \overline{16}_H$ in 45 & 1 of SO(10)

$g_{k\ell}\, 16_k\, 16_\ell\, 16_H\, 16_H / M$

$\Rightarrow V_{CKM} \neq \mathbb{1}$

Indep of $\tan\beta$

$\bar{\Gamma}^{-1}(p \to \bar{\nu} K^+)_{\text{New } d=5} \approx 10^{33} - 10^{34}$ yrs

SUSY SO(10) or G(224)

$BR(p \to \mu^+ K^0)_{\text{New } d=5} \approx (10-30)\%$

Note these contributions from new d=5 would generically be present, even if "Standard" d=5 (with color triplets $\subset 10_H$) absent, as in SUSY G(224)!

The $\mu^+ K^0$ mode a signature of this mechanism.

$d=5$ $p\to\bar{\nu}K^+$ in Non-GUT string solutions

For example String/M Theory ($d=10/11$)

↓

3 Families
Hierarchical
Yukawas

$G(2,2,4)\times U(1)'s\times(\text{Hidden})$

D-T splitting done naturally by string (*) compactification

But Color-triplets ~ M_{string} Exist with Coupling to fermions.

⇓

$\boxed{d=5 \quad p\to\bar{\nu}K^+ \text{ will occur}}$

They have not calculated eff. Couplings $\neq 0$

THUS p-decay a Generic Feature in GUT & String Th with rates ~ observable range

---

(*) Recently Christodoulides, Faraggi, Rizos
→ Exophobic (224) string solutions
→ hep-ph/1104.2264
Assel, Christodoulides, Faraggi, Kounnas, Rizos
– 2010 // 2011

Earlier, S. Raby & Collaborators –
& Others

IV Stabilizing D-T splitting in SO(10) and Limiting Proton Lifetimes

A Recent Work

Babu, Pati, Tavartkiladze — hep-ph/1003-2625 (JHEP) 2010

Low Dim Higgses

↓

Predictive p-decay

↓

Constrained upper limits on

$$\boxed{\begin{array}{l} \Gamma^{-1}(p \to e^+ \pi^0) \\ \& \ \Gamma^{-1}(p \to \bar{\nu} K^+) \end{array}}$$

SUMMARY OF RESULTS : Babu, Pati, Tavartkiladze

COMBINE BPW
SINGLE $45_H, 16_H, \overline{16}_H, 10, 10'$ ⊕ BARR, RABY $16', \overline{16}'$

(S, Z)

$SO(10) \times U(1)_A \times Z_2 \longrightarrow$ DESIRED SUPERPOTENTIAL

→ • D-T SPLITTING VIA DW ABSOLUTELY STABLE

- NO PGB / NO FLAT DIR.
- (EW + GUT) THRESHOLD ONLY FEW EFF. PARAMETERS

$\Downarrow$

- A NOVEL CORRELATION $d=5 \longleftrightarrow d=6$

$$\boxed{M_{eff} \propto 1/M_X^3}$$

$\Downarrow$

- LOWER LIMIT ON $\bar{\Gamma}^{1}(p \to \bar{\nu} K^+)_{expt} \Longrightarrow$ {UPPER LIMIT ON $\bar{\Gamma}^{1}(p \to e^+ \pi^0)$

& VICE VERSA

- BOTH MODES SHOULD SHOW IN MEGATON DETECTOR

- $\mu \sim m_{SUSY} \sim TeV$
- FERMION MASSES / MIXINGS (Q_4 SYMM $\uparrow$ SUSY FCNC)

IV SUSY SO(10) WITH STABILIZED D-T SPLITTING, INCLUDING GUT-THRESHOLD EFF.

Babu, Pati, Tavartkiladze (JHEP 2010)

Stabilized DW D-T splitting with no Fine Tuning

Low Dim. Higgses $\supset 45_H, 16_H, \overline{16}_H, 10_H, 10'_H, \cdots$

(no Higher Dim. Higgses: $126, \overline{126}, 120, 210 \cdots$)

$$\boxed{\alpha_U^{-1}(\Lambda) = \alpha_i^{-1}(M_Z) - \frac{b_i}{2\pi} \ln \frac{\Lambda}{M_Z} + \Delta^{(2)}_{i,W} + \Delta_i^{GUT}} \quad (1)$$

$b_i \to$ 1-loop MSSM β-FUNCN COEFFICIENTS

$\Delta^{(2)}_{i,W} \to$ 2-loop running (incl. gauge & Yukawa Int.) from $m_Z \to \Lambda$, and Weak Scale SUSY Threshold EFF.

$$\Delta_i^{GUT} = \text{1-loop GUT Scale Th. Eff} = -\frac{1}{2\pi} \sum_a b_i^{(a)} \ln \frac{\Lambda}{M_a}$$

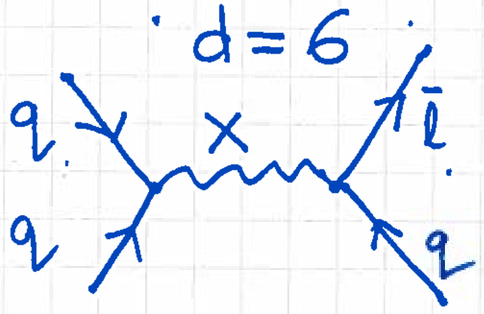
$\downarrow$

Fewer Parameters due to Low Dim. Higgses

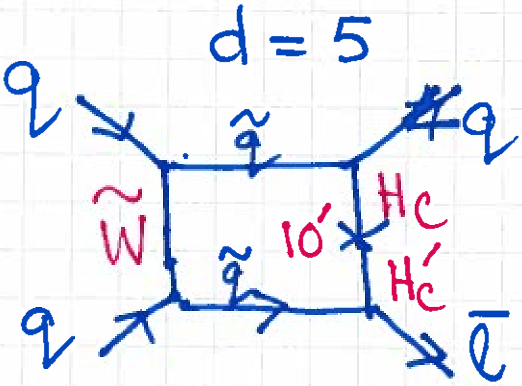
$\downarrow$

Can Eliminate & Get a NOVEL INVERSE CORRELATION BETWEEN $d=6$ & $d=5$ AMPLITUDES

Recall



$A_{d=6}(e^+\pi^0) \propto \frac{1}{M_X^2}$



$A_{d=5}(\bar{\nu}K^+) \propto 1/M_{eff}$ ☒

UNIFICATION OF 3 COUPLINGS WITH GUT-THRESHOLD

$\Rightarrow \boxed{M_{eff} \propto \frac{K_{SUSY}}{M_X^3} \quad (A)}$ INVERSE CORRELATION

$\Gamma^{-1}(e^+\pi^0) \propto M_X^4$; $\Gamma^{-1}(\bar{\nu}K^+) \propto M_{eff}^2$

$\therefore \Gamma^{-1}_{expt}(\bar{\nu}K^+) > 6\times10^{33}$ yrs $\Rightarrow M_{eff} > M_{eff}^{Min.}$ (depending on SUSY SPECT)

By (A) $\Rightarrow \boxed{M_X < M_X^{Max}} \Rightarrow$ $\boxed{\text{UPPER LIMIT ON } \Gamma^{-1}(e^+\pi^0)\,!}$

Similarly $\Gamma^{-1}_{expt}(e^+\pi^0) > 1.3\times10^{34}$ yrs $\Rightarrow M_X > M_X^{Min}$

By (A) $\Rightarrow \boxed{M_{eff} < M_{eff}^{Max}} \Rightarrow$ $\boxed{\text{UPPER LIMIT ON } \Gamma^{-1}(\bar{\nu}K^+)\,!}$

☒) $M_{eff} \sim M^2_{Color\ Triplet}/M_{10'} \sim M^2_{GUT}/M_{10'}$
$\gg M_{GUT}$

Recent Update

Babu, Badziak, Pati, Tavartkiladze (To appear, 2014)

Using LHC results on SUSY searches & $m_h \simeq 125$ GeV, Vary SUSY spectrum & parameters with GUT-Scale Boundary Condns & Reasonable Naturalness

$\left(\Delta_a \equiv \left| \frac{\partial \ln m_h}{\partial \ln a} \right| \sim (150-300) \right)$, in accord with phenomenology of DM, $b \to s\gamma$, etc.

- primarily with light stops ($\tilde{t}_1 \approx 500-700$ GeV, $\tilde{t}_2 \approx 2$ TeV), Heavy 1st Two Families ($\sim 15-20$ TeV), gluino ~ 3 TeV, Wino $\sim 550-800$ GeV, $A_0 = 0 \to -2$TeV, $\mu \sim 800$ GeV $- 1$ TeV.

To be specific – e.g. Badziak, Dudas, Olechowski, Pokorski (Arxiv: 1205.1675), & other Cases with Intermediate 1st Two Families $\sim 3-4$ TeV.

$\hookrightarrow$ $m_0(1,2) \gg m_0(3) \gg m_{1/2}$, $|A_0| = 0 \to 2$TeV

INVERTED HIERARCHY SUSY SPECTRUM OF BDOP TYPE * MODIFIED BY GUT THRESHOLD CORRECTIONS

GUT SCALE INPUTS:

$m_{1/2} = 2031\ GeV,\ \ m_0(3) = 3.4$ TeV,

$m_0(1{,}2) = 21.1$ TeV

$$\tan\beta = 10, \qquad A_0 = 0$$

EW SCALE SPECTRUM:

$$m_h \simeq 125\ \mathrm{GeV}$$

$$M_{\tilde{B}} = 652.7\ \mathrm{GeV} \quad M_{\tilde{W}} = 1295.3\ \mathrm{GeV} \quad M_{\tilde{g}} = 3561\ \mathrm{GeV}$$

$$m_{\tilde{q}_{1,2}} = 21122\,\mathrm{GeV} \qquad m_{\tilde{l}_3} = 3115\,\mathrm{GeV}$$

$$m_{\tilde{t}_1} = 735.02\ \mathrm{GeV}, \quad m_{\tilde{t}_2} = 1503.2\ \mathrm{GeV}$$

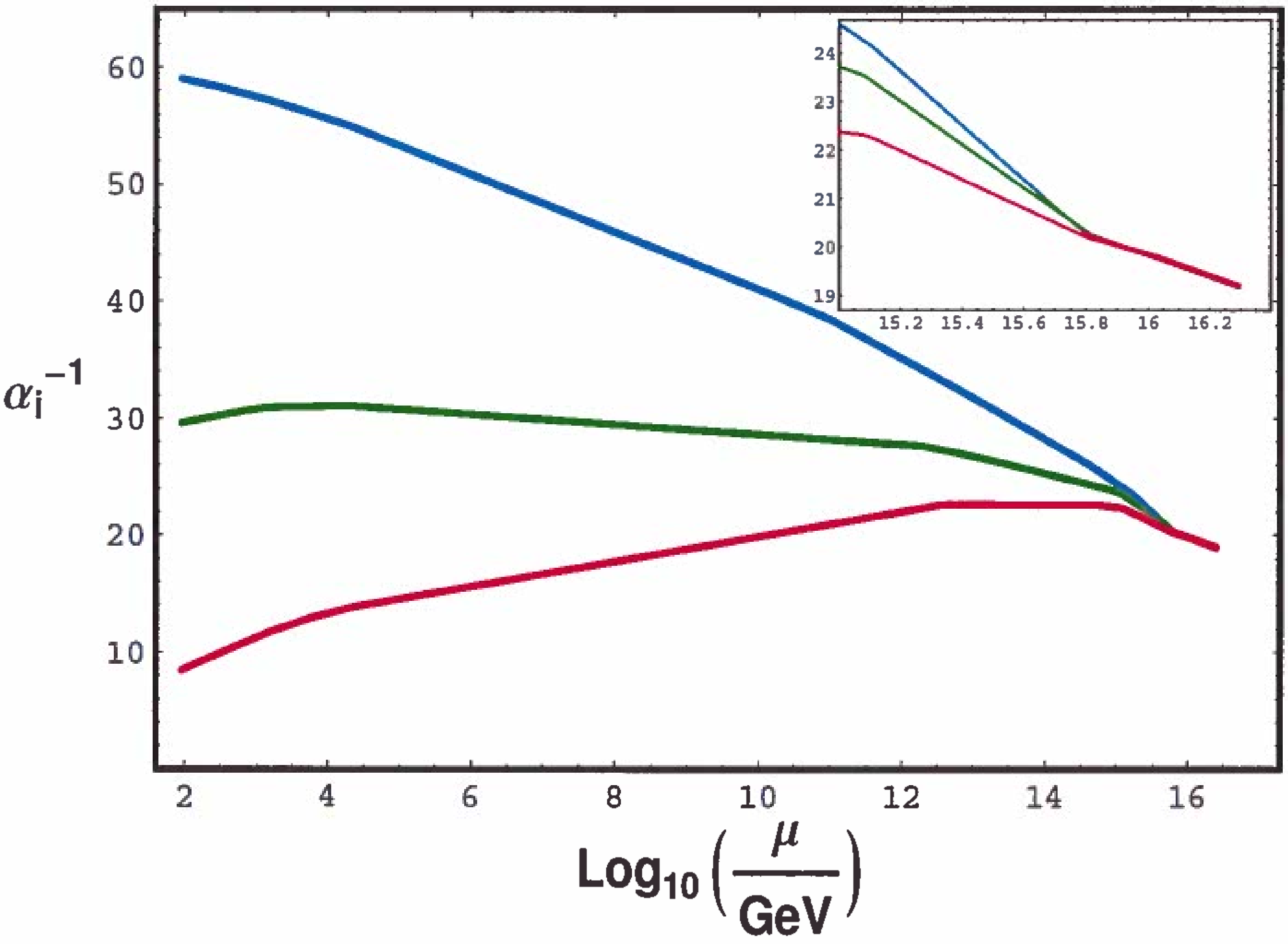
$$m_{\tilde{\tau}^c} = 3227.6\,\mathrm{GeV} \qquad \mu\ =\ 759.6\ \mathrm{GeV}$$

$$\text{Neutralinos :} \qquad m(\tilde{\chi}_i^0) \simeq (653 - 1295)\ \mathrm{GeV}$$

$$\text{Charginos :} \qquad m(\tilde{\chi}_i^\pm) \simeq (759 - 1295)\ \mathrm{GeV}$$

* Badziak, Dudas, Olechowski, Pokorski, Arxiv: 1205.1675

UNIFICATION FOR SUSY SO(10) MODEL INCLUDING GUT THRESHOLD EFFECTS



$\alpha_3(M_Z) = 0.1184,\ (M_{\text{eff}}, M_X) = (7\cdot 10^{19}, 6.52\cdot 10^{15})$ GeV

$(r, p, \hat{p}/p) = \left(\frac{1}{1752},\ 4,\ 6.431\cdot 10^{-5}\right)$, $\tan\beta = 10$

Varying SUSY Spectrum With Reasonable naturalness & Using the Inverse Correlation (A) → Get Theoretical Upper Limits :

$$\Downarrow$$

$$\Gamma^{-1}(p \to e^+\pi^0)^{Th} \lesssim (2-10)\times 10^{34}\ \text{yrs}$$

$$\Gamma^{-1}(p \to \bar{\nu}K^+)^{Th} \lesssim (1-8)\times 10^{34}\ \text{yrs}$$

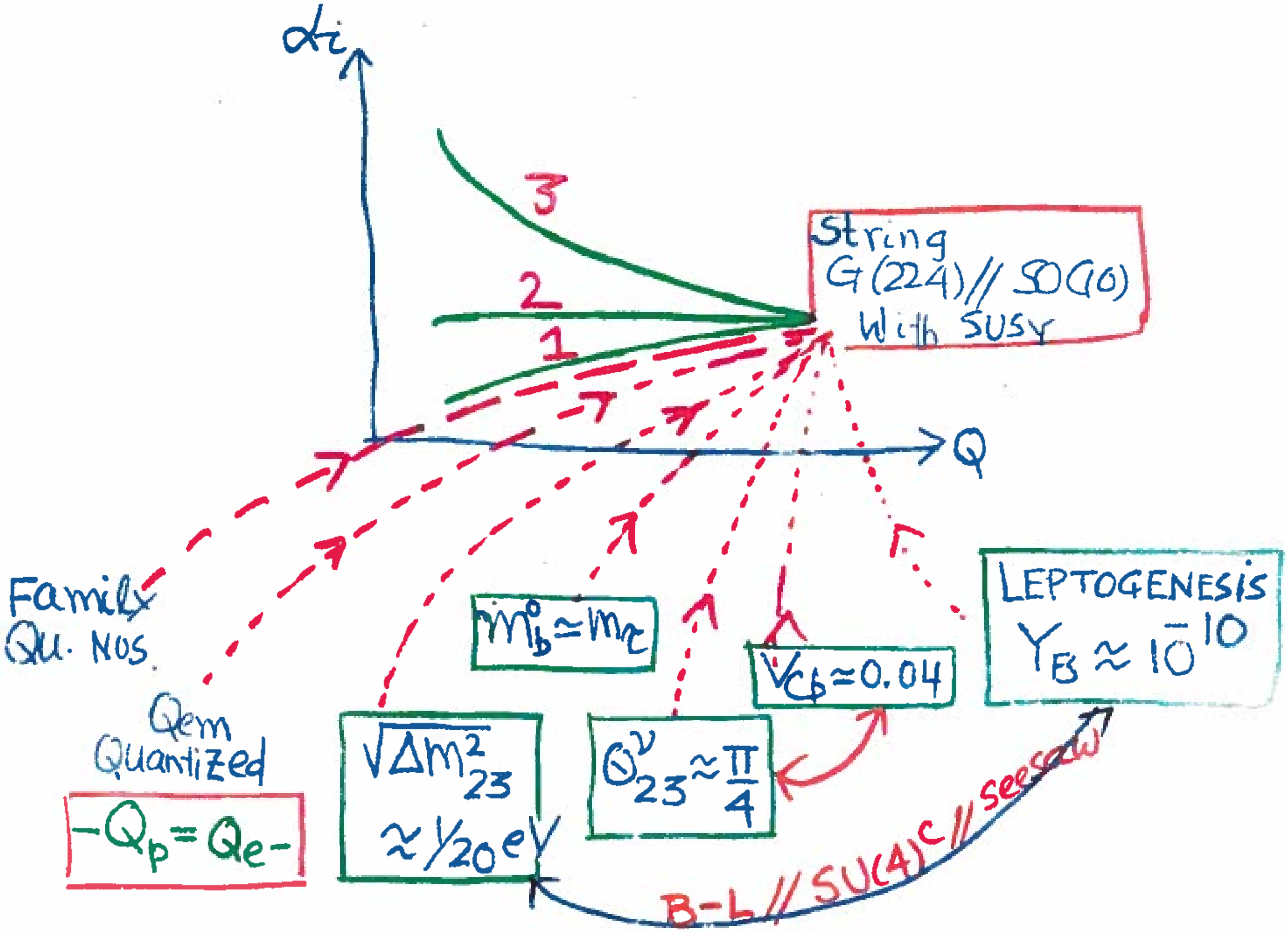
Within Factors of 5 to 10 above SuperK limits → Within striking distance.

Thus Prospects of Discovery of p-decay, within these well-studied & Well-motivated Class of SUSY SO(10) Models, in the next-Generation Detectors (Both Water Cherenkov ~500 kt & Liquid Argon ~ 30-50 kt) High.

Will Nature oblige Wrt Both

SUSY &
PROTON Decay ?

Rendevouz In Particle Physics



ALL THESE FEATURES & MORE HANG TOGETHER NEATLY IN A SINGLE UNIFIED FRAMEWORK → HARD TO IMAGINE THIS CAN BE MERE COINCIDENCE

⇓

TWO MISSING PIECES

- PROTON DECAY → Need NEXT GEN. DETECTOR
- SUPERSYMMETRY → LHC

PROTON DECAY THE HALLMARK OF GRAND UNIF.

Provides a Unique Window To View Physics at truly short dist $\lesssim 10^{-30}$ cm

$p \to \bar{\nu} K^+$ If Seen $\Rightarrow \begin{cases} q\text{-}\ell,\ q\text{-}\bar{q},\ q\text{-}\bar{\ell} \text{ unif //} \\ \text{SUSY UNIF //} \\ M_X \sim 10^{16} \text{ GeV} \end{cases}$

$p \to \mu^+ K^0$ If Seen $\Rightarrow \begin{cases} \nu \text{ MASS Rel op} \\ \text{IMPORTANT} \end{cases}$

$\left.\begin{matrix} \text{If } e^+\pi^0 \text{ not seen} \\ \text{Say upto } 10^{36} \text{ yrs, but} \\ \bar{\nu} K^+ \text{ seen} \end{matrix}\right\} \Rightarrow \begin{cases} \text{EFF. } G(224) \ \& \\ \nu \text{ MASS Rel} \\ d=5 \text{ IMPORTANT} \end{cases}$

THUS PROTON DECAY IF SEEN WILL BRING A **WEALTH** OF KNOWLEDGE THAT CAN NOT BE GAINED BY ANY OTER MEANS

⇓

DISCOVERY POTENTIAL HIGH

⇓

MEGATON SIZE DETECTOR (or EQUIVALENT) SENSITIVE TO

- PROTON DECAY,
- ν oscillations (LONG BASELINE)

AND

- SUPERNOVA ν's.

C

A Large Number of GUT or GUT-Like Approaches To p-decay, With, Without SUSY

① $SO(10) \to 126, \overline{126}, \cdots$

② $SO(10)$ - 2 Step Breaking Via $G(2,2,4)$

2 Recent Attempts (Non-SUSY)

(i) $SO(10) \to G(2,2,4) \times D$ With all threshold eff. included (Babu & Khan, 2013)

$$\tau(p \to e^+\pi^0) < 5 \times 10^{35} \text{ yrs.}$$

(ii) $SO(10) \to G(2,2,4)$ (Altarelli, Meloni JHEP (2013))

They address strong CP Problem Via axion soln

$$\tau(p \to e^+\pi^0) > 5 \times 10^{35} \text{ yrs}$$

③ SUSY $SO(10)$ – $126, \overline{126}, \cdots$ Many Attempts → Generically

Some modes $(p \to \bar{\nu}\pi^+, \mu^+K^0, \mu^+\pi^0, \cdots)$

$\tau \sim 10^{34}$ yrs (estimates)

$\tau(p \to e^+\pi^0) \sim 10^{35}$ yrs (estimates) d

Summary (Theoretical Expectations)

Fair to say that well-motivated SUSY GUT's generically predict proton decay rates → Accessible to next-generation WC (>500 Kt) LAr (40 Kt) underground detectors

Next-Gen. Detectors

Now Have SuperK (22 Kt fid. mass WC – 1996)

$p \to e^+\pi^0$ (40 % efficiency) $\to \boxed{\tau(e^+\pi^0) \geq 1.4 \times 10^{34}\ \text{yrs}}$

280 Kt yr exposure

$p \to \bar{\nu} K^+$ ($\sim$16 % efficiency)

$$\boxed{\tau(\bar{\nu} K^+)_{\text{SuperK}} > 6 \times 10^{33}\ \text{yrs}}$$

Next (& Next to Next) Generation

e

		Fid Mass	
HyperK	WC	560 Kt	Japan
DUNE/LBNF	LAr TPC	(10×4) Kt	U.S.
LENA	Scintillator	50Kt	Europe
MICA	WC (Ice)	Multi-Mton	South Pole
TITAND	WC	Multi-Mton	Ocean
Moon (No Atmosphere)	?	?	

LAr TPC (Efficiency ($\bar{\nu}K^+$) ~ 96%, ($e^+\pi^0$) ~ 16%)

	16 yrs	20 yrs
10 Kt	1.7×10^{34}	2×10^{34}
34 Kt	5×10^{34}	6×10^{34}
100 Kt	1.2×10^{35}	1.8×10^{35}

4850 ft Depth Homestake

SuperK long term (40 yrs) ≈ $(3 \text{ to } 4)\times10^{34}$ yrs ($\bar{\nu}K^+$)

HYPERK LIMIT

$\tau^{-1}(e^+\pi^0) \longrightarrow 1.5\times10^{35}$ yrs (17 yrs)

$\tau^{-1}(\bar{\nu}K^+) \longrightarrow 1.5\times10^{34}$ yrs (17 yrs)

SuperK long term ($e^+\pi^0$)–(40 yrs running) ≈ 2.1×10^{34} yrs