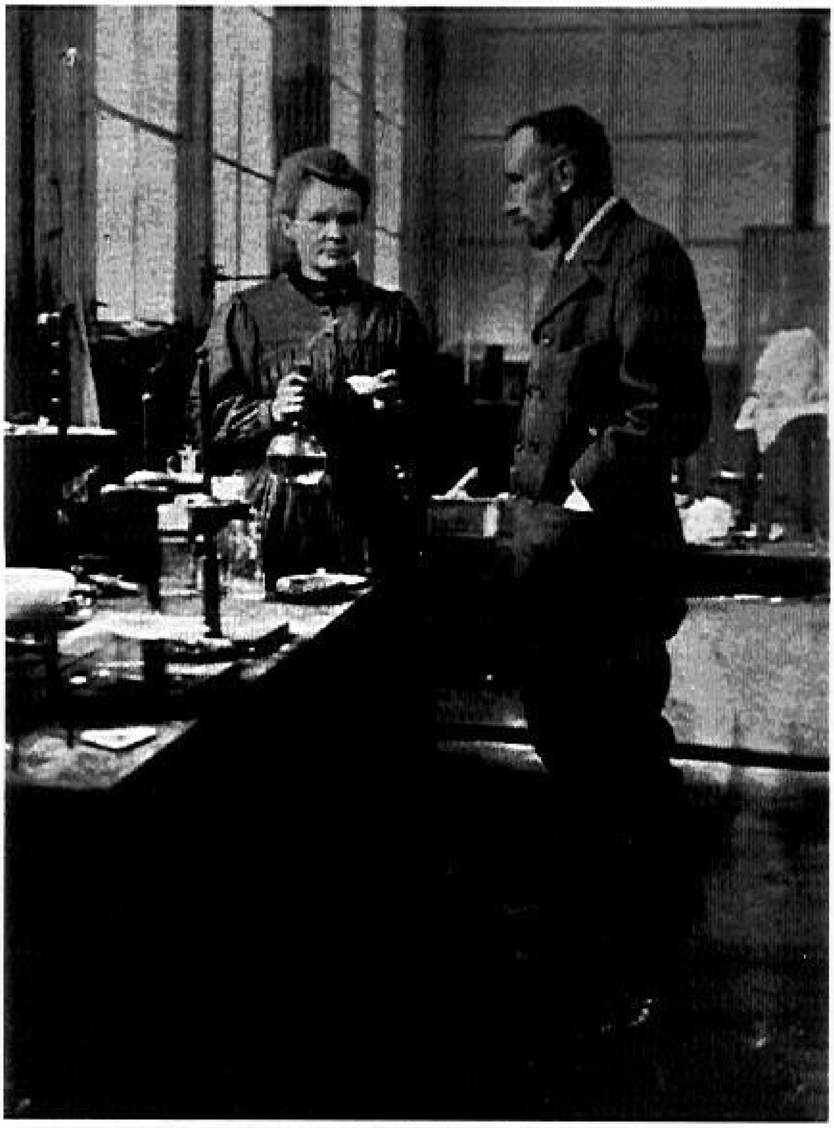
THEORETICAL BACKGROUND TO PROTON DECAY

G. F. GIUDICE
CERN

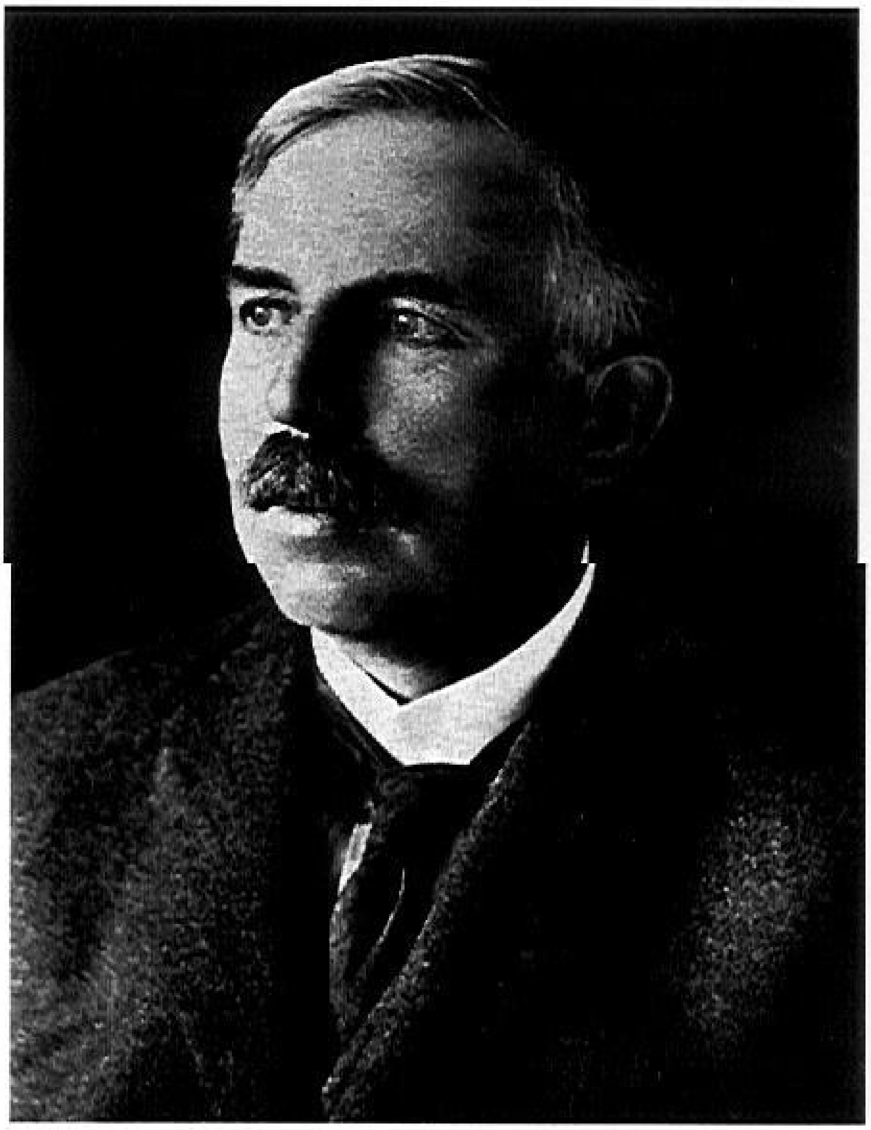
16 · 01 · 02

- matter stability
- conservation laws
- predictions for p-decay

HENRI ANTOINE BECQUEREL

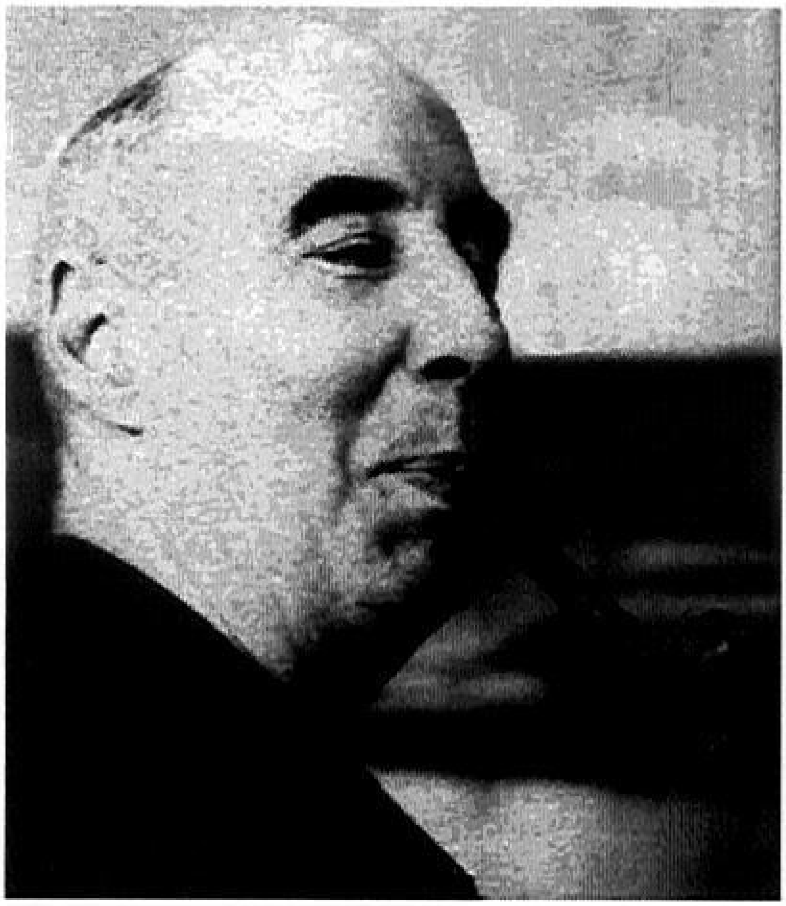


MARIE & PIERRE CURIE



ERNEST RUTHERFORD

HERMANN WEYL



ERNST CARL GERLACH

STÜCKELBERG

EUGENE WIGNER

QED

Local gauge invariance $\Rightarrow$ $\begin{cases} \cdot \text{ massless photon} \\ \cdot \text{ Coulomb's law} \end{cases}$

BARYON NUMBER

Global symmetry $\Rightarrow$ p stability

B local symmetry?

- anomalous
- new force $\Rightarrow$ difference between grav. & inertial mass

$$\alpha_B < 10^{-9} G_N m_p^2 \simeq 6 \times 10^{-48}$$

Violation of B conceivable & almost necessary!

Experiments

Early '50 $\begin{cases} \tau_p > 10^{20} - 10^{22} \text{ yrs} \\ \text{"Anthropic" arguments} \end{cases}$

Now $\tau(p \to e^+ \pi^0) > 5 \times 10^{33}$ yrs

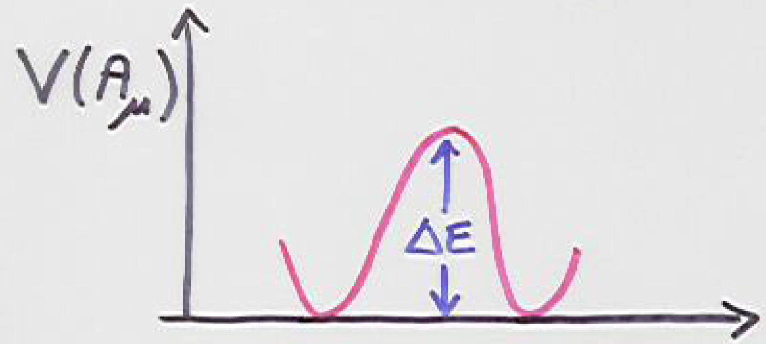
see GOODMAN

p-DECAY FROM ANOMALY IN SM

$$\partial_\mu J^\mu_{B+L} = 2 N_g \, \partial_\mu K^\mu$$

# of fermion gen

Chern-Simon



$$\text{rate} \sim \left| e^{-\frac{\Delta E \cdot \Delta t}{\hbar}} \right|^2$$

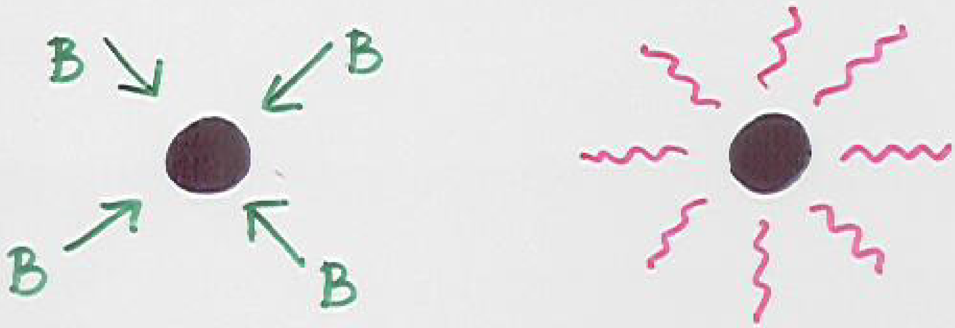
$$\frac{\Delta E \cdot \Delta t}{\hbar} \sim \frac{2\pi}{\alpha_w} \Rightarrow \text{rate} \sim 10^{-137}$$

- important conceptually (ultimate fate of the Universe)
- early Universe

see BUCHMÜLLER

p-DECAY FROM GRAVITY

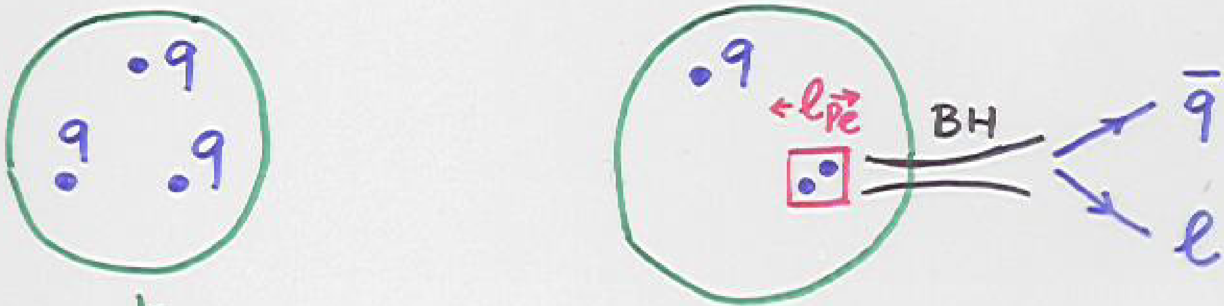
Black holes violate B



Hawking

At distances $\lesssim \frac{1}{M_{P\ell}} \Rightarrow$

space-time foam with virtual B.H.



proton

$$\tau_p \sim \frac{M_{P\ell}^4}{m_p^5} \sim 10^{45} \text{ yrs}$$

Quantum-gravity effects

$\Rightarrow$ same order of magnitude

Observable p-decay $\Rightarrow$
$\Rightarrow$ new interactions (GUTs ?)

SM effective theory

$$\mathcal{L}^{(6)}_{\not B} = \sum_i \frac{1}{\Lambda_i^2} \mathcal{O}_i$$

$$\mathcal{O}_1 = \bar{u}^c_L \gamma^\mu q_L \; \bar{d}^c_L \gamma_\mu \ell_L$$

$$\mathcal{O}_2 = \bar{u}^c_L \gamma^\mu q_L \; \bar{e}^c_L \gamma_\mu q_L$$

$$\mathcal{O}_3 = \bar{q}^c_{R\alpha} q_L^\beta \; \bar{q}^c_{R\beta} \ell_L^\alpha \qquad \alpha, \beta = SU_2 \text{ indices}$$

$$\mathcal{O}_4 = \bar{d}^c_L u_R \; \bar{u}^c_L e_R$$

- other operators are linearly dep.
- vector particles mediate only $\mathcal{O}_1$ & $\mathcal{O}_2$

$\mathcal{O}_1, \mathcal{O}_2$

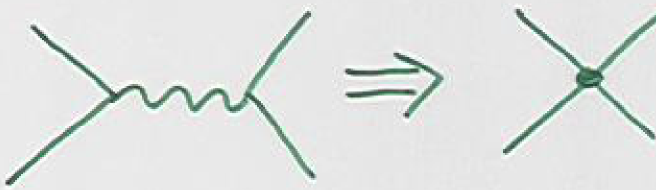
$\Delta B = \Delta L$ $\begin{cases} p \to e^+ X & p \not\to e^- X \\ p \to \bar{\nu} X & p \not\to \nu X \end{cases}$

$\dfrac{\Delta S}{\Delta B} = 0, -1$ $\begin{cases} p \to \bar{\nu} \pi^+ & p \not\to \bar{\nu} K^- \pi^+ \pi^+ \\ p \to \bar{\nu} K^+ & n \not\to e^+ K^- \end{cases}$

$\Delta S = 0 \Rightarrow \Delta I = \frac{1}{2}$ $\begin{cases} \Gamma(p \to e^+ \pi^0) = \frac{1}{2} \Gamma(n \to e^+ \pi^-) \\ \Gamma(p \to \bar{\nu} \pi^+) = 2\, \Gamma(n \to \bar{\nu} \pi^0) \end{cases}$

CALCULATING p-DECAY

GUT



If scalars negligible

$\Rightarrow \alpha_{GUT}, M_V$

$\Downarrow$ anomalous dimensions

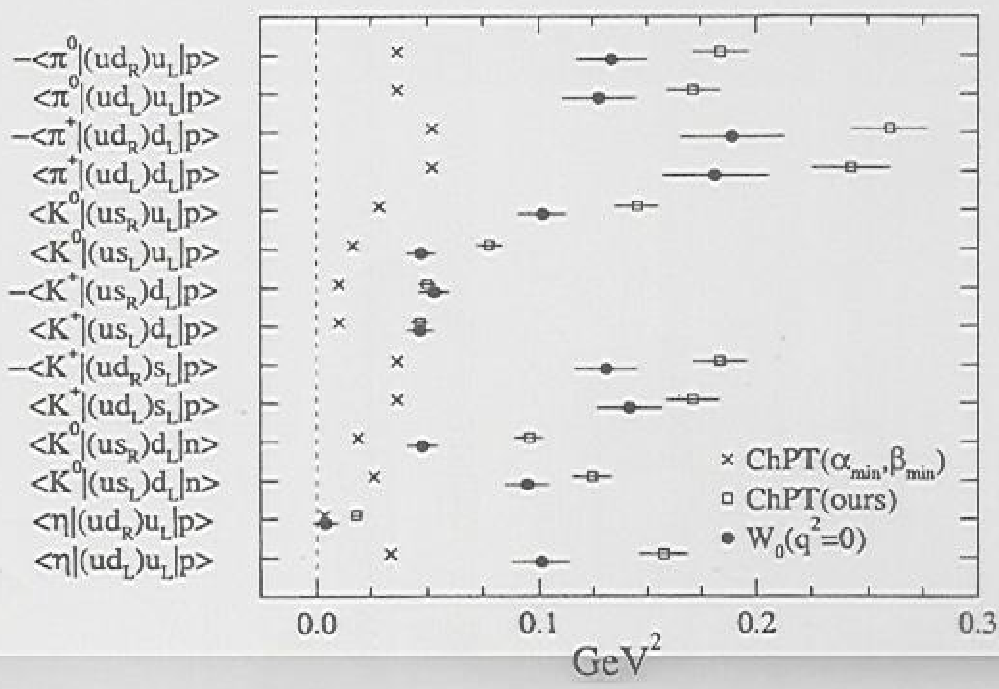
HADRONS $\langle p | O | X \rangle$ matrix element

$|\alpha| = |\beta| = 0.003 \text{ GeV}^3$ @ 1 GeV

$|\alpha| = 0.015 \text{ GeV}^3$ @ 2.3 GeV JLQCD

$|\beta| = 0.014 \text{ GeV}^3$

almost factor of 20 enhancement

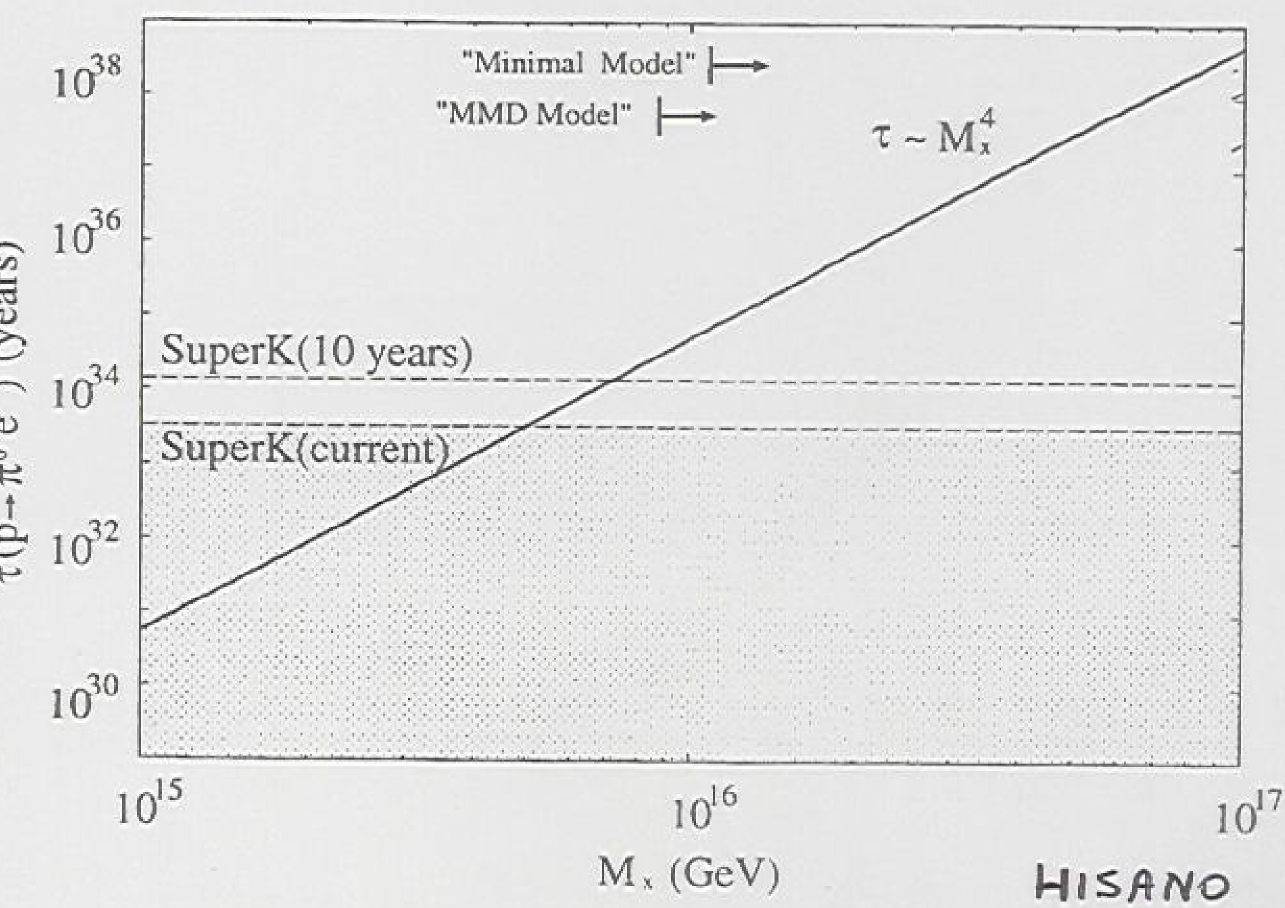


JLQCD Coll.

Using SUSY gauge coupling unification

$$\tau_p(p \to \pi^0 e^+) = 10^{35}\,\text{yrs}\left(\frac{0.015\ \text{GeV}^3}{\alpha}\right)^2 \times$$

$$\times\left(\frac{M_X}{1.0^{16}\,\text{GeV}}\right)^4\left(\frac{1/25}{\alpha_{GUT}}\right)^2$$



HISANO

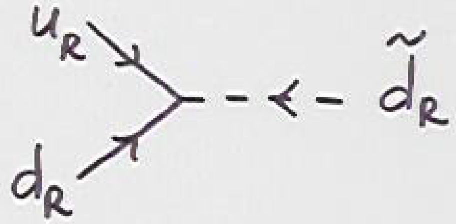
SUPERSYMMETRY

Scalars in effective theory

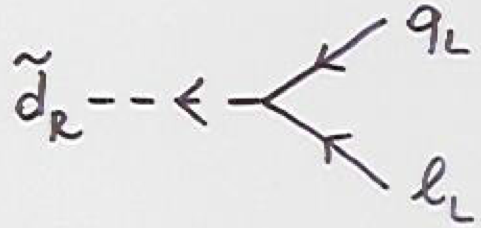
$\Longrightarrow$ operators $d < 6$

$d = 4$

$\not{B}$



$\not{L}$



$$\tau_p \sim 10^{-10}\,\mathrm{s} \left(\frac{\tilde{m}}{\mathrm{TeV}}\right)^4 \frac{1}{\lambda^4}$$

R-parity (consequence of gauge symmetry?)

$d = 5$

$$W = -\tilde{C}_L \tilde{O}_L - \tilde{C}_R \tilde{O}_R$$

$$\tilde{O}_L = Q_L^k \, Q_L^\ell \, Q_L^i \, L_L^j$$

$$\tilde{O}_R = \bar{U}_R^i \, \bar{D}_R^j \, \bar{U}_R^k \, \bar{E}_R^\ell$$

- $\tilde{O}_L$ vanishes if $k = \ell = i$
- $\tilde{O}_R$ vanishes if $i = k$

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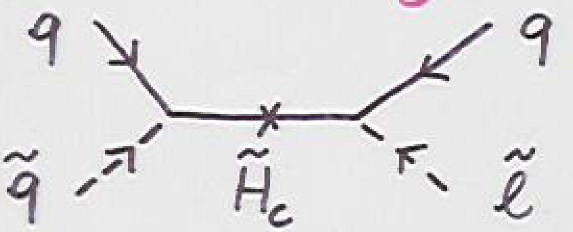
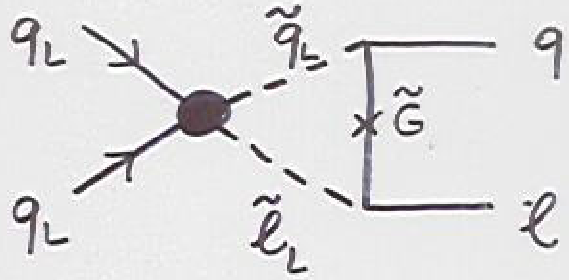


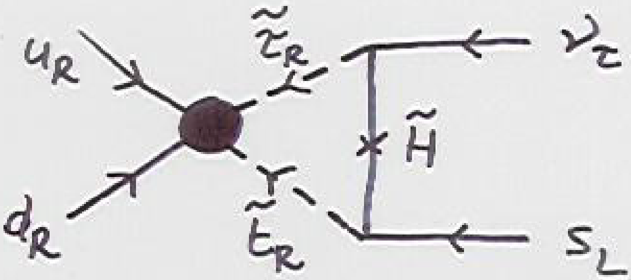
$$\tilde{C}_L^{ijk\ell} = \frac{1}{2 M_{H_c}} \left(\lambda_D\right)^{ij} \left(V^T P \lambda_u V\right)^{k\ell}$$

$$\tilde{C}_R^{ijk\ell} = \frac{1}{M_{H_c}} \left(P^* V^* \lambda_D\right)^{ij} \left(\lambda_u V\right)^{k\ell}$$

- Yukawa coupling (with naive SU_5 mass relations)
- M_{H_c}
- Two new phases $P = \begin{pmatrix} e^{i\phi_{13}} & & \\ & e^{i\phi_{23}} & \\ & & 1 \end{pmatrix}$

DRESSING





$p \to K^+ \bar{\nu}$ dominates over

$p \to \pi^+ \bar{\nu}$ Cabibbo-suppressed

$p \to K^0 \mu^+$ suppressed by m_u

Rate depends upon

- susy mass spectrum
- flavour violation in susy sector
- couplings and mass of H_C
- new phases

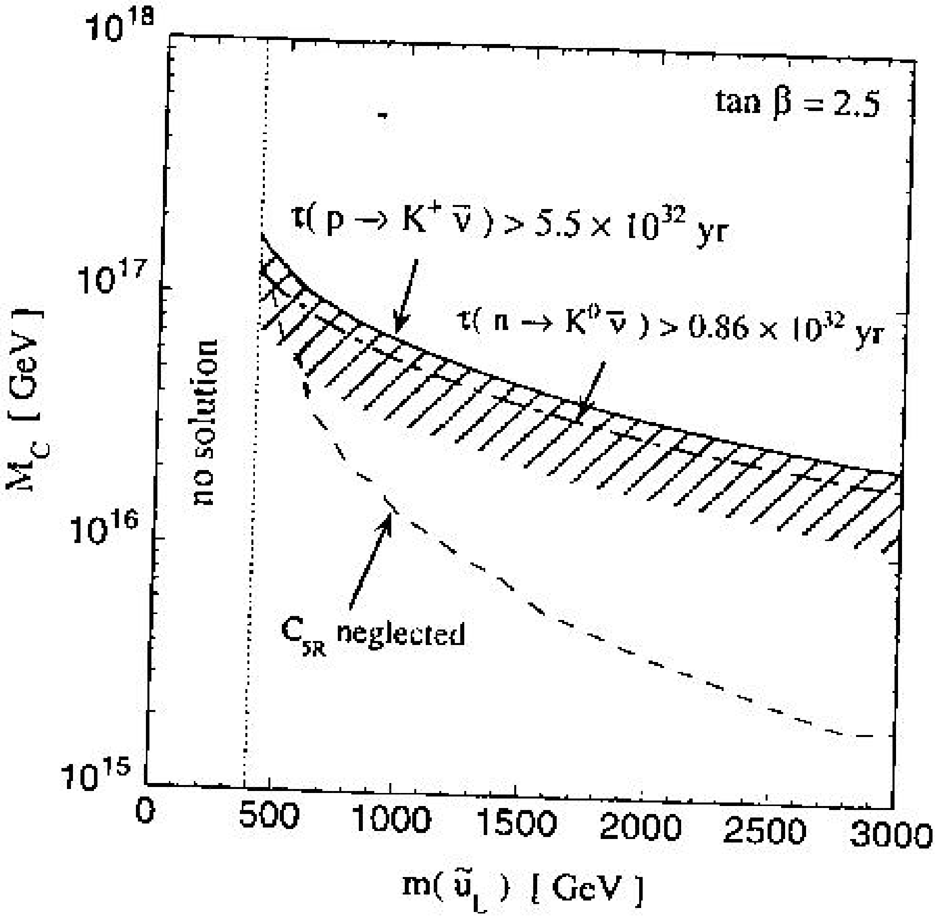
$$\mathcal{A}(p \to K^+ \bar{\nu}_e) = e^{i\phi_{23}} A_e(\tilde{c}_L) + A_e(\tilde{t}_L)$$

$$\mathcal{A}(p \to K^+ \bar{\nu}_\mu) = e^{i\phi_{23}} A_\mu(\tilde{c}_L) + A_\mu(\tilde{t}_L)$$

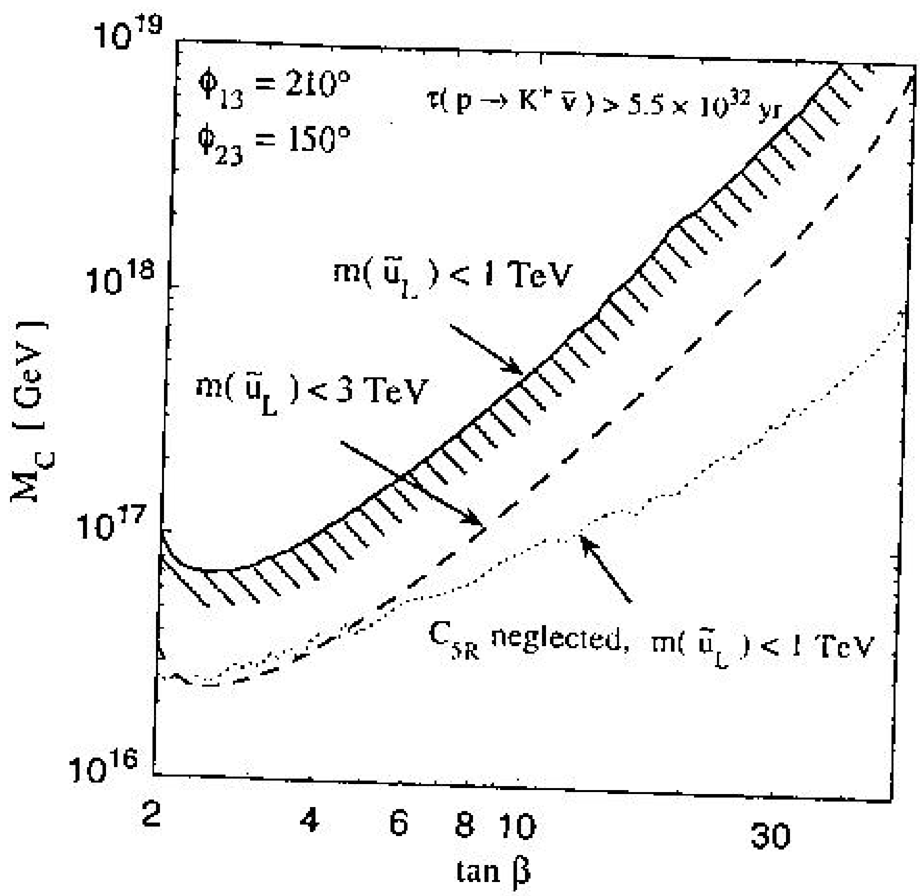
$$\mathcal{A}(p \to K^+ \bar{\nu}_\tau) = e^{i\phi_{23}} A_\tau(\tilde{c}_L) + A_\tau(\tilde{t}_L) + e^{i\phi_{13}} B(\tilde{t}_R)$$

ϕ_{23} such that $\mathcal{A}(p \to K^+ \nu_{e,\mu}) \simeq 0 \Rightarrow \mathcal{A}(p \to K^+ \nu_\tau)$ large

ϕ_{13} " $p \to K^+ \nu_\tau$ " $p \to K^+ \nu_\mu$ "


tan β = 2.5
τ(p → K+ ν̄) > 5.5 × 10^32 yr
τ(n → K0 ν̄) > 0.86 × 10^32 yr
C5R neglected
no solution
MC [GeV]
m(ũL) [GeV]

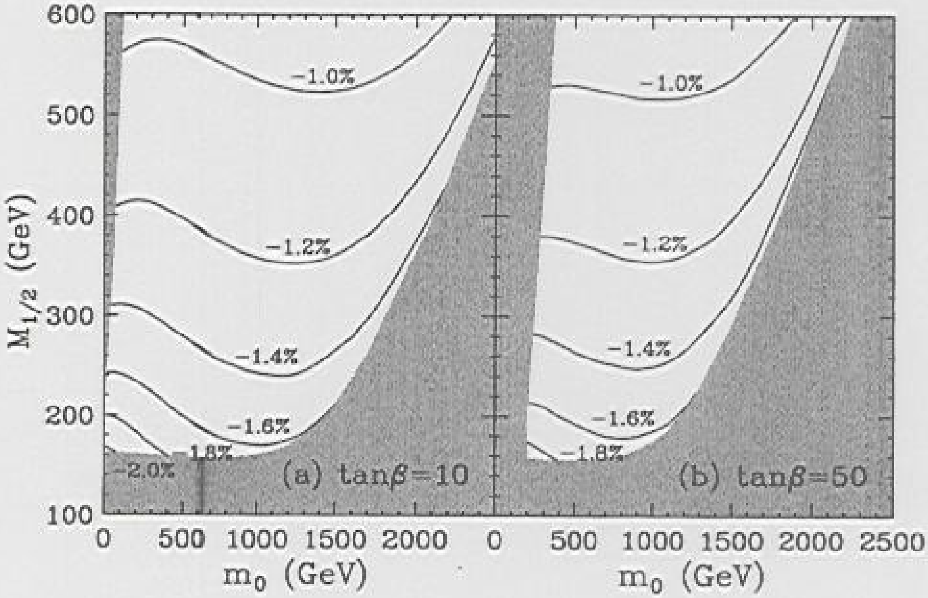
GOTO-NIHEI


φ13 = 210°
φ23 = 150°
τ(p → K+ ν̄) > 5.5 × 10^32 yr
m(ũL) < 1 TeV
m(ũL) < 3 TeV
C5R neglected, m(ũL) < 1 TeV
MC [GeV]
tan β

Determining M_{H_c} from threshold corrections

Define $g_1(M_{GUT}) = g_2(M_{GUT})$

$$\varepsilon \equiv \frac{g_3(M_{GUT}) - g_1(M_{GUT})}{g_1(M_{GUT})}$$



FENG MATCHEV

$$\delta\alpha_s \simeq 0.7\,\varepsilon$$

$$\varepsilon_{H_c} = 0.3\,\frac{\alpha_{GUT}}{\pi}\ln\left(\frac{M_{H_c}}{M_{GUT}}\right)$$

$$\Rightarrow 3.5\times10^{14} < M_{H_c} < 3.6\times10^{15}\ \text{GeV}$$

(90% CL)

- Thresholds from other GUT particles ?

$d=5$ PROTON DECAY

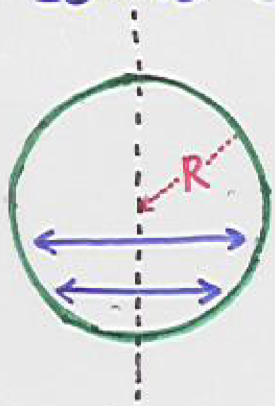
- depends on unknown aspects of SUSY GUT
  - doublet-triplet splitting
  - fermion mass relations

most plausible estimate in conflict with observations

- mechanism to suppress or eliminate $d=5$ operators

GUT in $D > 4$

Compactification geometry eliminates some states



$S_1 / \mathbb{Z}_2$

identify opposite points

5-dim field $\Leftrightarrow$ tower of 4-dim fields

For fields with definite parity

$$\phi(x,y) \rightarrow \phi(x,-y) = \pm \phi(x,y)$$

$$\phi_+(x,y) = \sum_{n=0}^{\infty} \phi_+^{(n)}(x) \cos \frac{ny}{R}$$

$$\phi_-(x,y) = \sum_{n=0}^{\infty} \phi_-^{(n)}(x) \sin \frac{ny}{R}$$

ϕ_- has no massless 4-D mode

Theory in 4-D may have smaller gauge group

SU_5 in 5-D

- no H_c in 4-D
- no $d=5$ p-decay
- $d=6$ p-decay may be enhanced

CONCLUSIONS

p-decay fundamental test of conservation laws

Implications for:

- understanding of short-distance interactions
- GUTs
- baryogenesis
- matter stability
- ultimate fate of the Universe