The μ-Term and a Safe Proton: A Gauge Origin in SUSY

Sogee Spinner
University of Wisconsin-Madison

29 Aug2011

SUSY11 - Fermilab

References

- P. Fileviez Perez, M. Gonzalez-Alonso, S.S. --- Gauge origin for μ and Rp
  Coming soon to an arXive near you!
- P. Fileviez Perez, S.S. --- Minimal SUSY Left-Right model
  Phys.Lett.B673:251, 2009
- V. Barger, P. Fileviez Perez, S.S. --- Minimal SUSY B-L model
  Phys.Rev.Lett.102:181802,2009
- P. Fileviez Perez, S.S. --- Minimal SUSY generic U(1) containing B-L
  Phys.Rev.D80:015004,2009
- L. Everett, P. Fileviez Perez, S. S. --- Minimal SUSY "broken" Left-Right model
  Phys.Rev.D80:055007,2009
- V. Barger, P. Fileviez Perez, S. S. --- Neutrino sector for minimal models
  arXiv:1010.4023

SUSY

- People (physicists) seem to love it
- LHC Era: time for non-standard SUSY pheno
  - Especially if result of solution to SUSY problems

Proton decay, or the origin of R-parity

Determines stability of the LSP – DM and missing energy

The size of the μ-term

EWSB (fine-tuning) and the Higgs sector

Kim, Nilles PLB 138 '84

The μ-term

$$W_\mu = \mu\, H_u\, H_d$$

$$\mathcal{L}_{\rm Soft} \supset -m_{H_u}^2 \left|H_u\right|^2 - m_{H_d}^2 \left|H_d\right|^2$$

- Important for electroweak symmetry breaking

$$\frac{1}{2} M_Z^2 = -\left|\mu\right|^2 - \frac{m_{H_u}^2 \tan^2\beta - m_{H_d}^2}{\tan^2\beta - 1}$$

$\tan\beta \to \infty$ and $m_{H_u}^2 < 0$

$$\frac{1}{2} M_Z^2 = -\left|\mu\right|^2 + \left|m_{H_u}\right|^2$$

$$\mu \lesssim m_{\rm soft} \sim 1\ {\rm TeV}$$

- But μ is SUSY-preserving! Expect: M_{GUT}
  - μ-problem

Solving the μ-problem

- Two steps:
  - Forbid using some symmetry
  - "Regrow", symmetry breaking; great if soft scale
- A discrete symmetry is a well known solution:

$$Z_3 : \psi \to \psi\, e^{i2\pi/3}$$

- No bilinears (mass terms), so μ = 0
  - But μ > 100 GeV (Higgsino searches)
- NMSSM: Intro SM Singlet, S:

$$W = \lambda S\, H_u\, H_d + \kappa S^3$$

$$\mathcal{L}_{\rm Soft} \supset -m_S^2\, |S|^2$$

$$\langle S \rangle \sim \frac{|m_S|}{\kappa}$$

$$\mu \sim \frac{\lambda}{\kappa}\, |m_S| \sim m_{\rm soft}$$

Cvetic, Demir, Espinosa, Everett, Langacker PRD '97; Cheng, Dobrescu Matchev PLB '98; Aoki Oshimo PRL '00

A Gauge origin for the NMSSM?

- Not so easy, Z_3 is not anomaly free
  - For anomaly cancellation intro exotic colored triplets
    - If couple to matter --- proton decay!
    - If not, stable colored fields!
  - Higgses charged, fermion masses still ok?
  - $\mu' H_u L$ might still be allowed in superpotential
- Our Goals:
  - Forbid all dimensionful terms in EWSB via gauge sym
  - No stable colored fields
  - All fermion masses and mixings can be generated

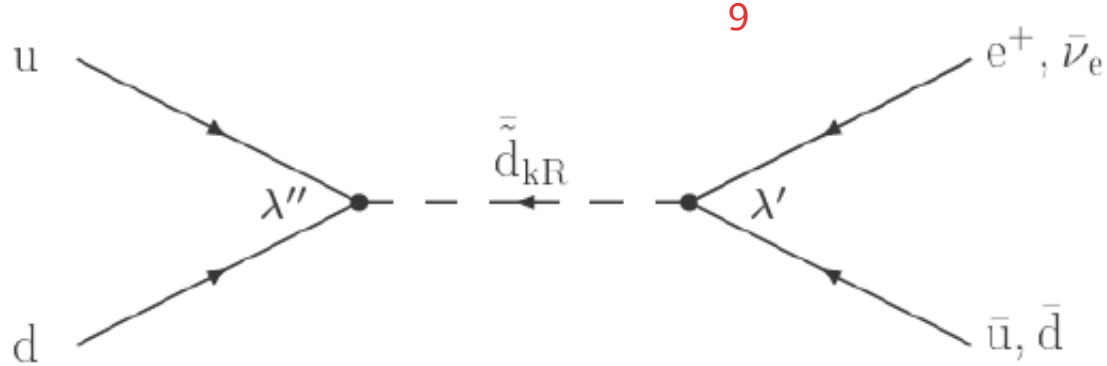
B&L Violation: Proton Decay

$$W_{\Delta L=1} = \lambda' \, Q \, L \, d^c + \lambda \, L \, L \, e^c + \mu' \, H_u \, L$$

27 9 3

$$W_{\Delta B=1} = \lambda'' \, u^c \, d^c \, d^c$$

9

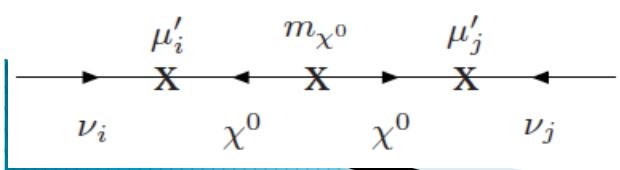


$\tau_p > 10^{32}$ years

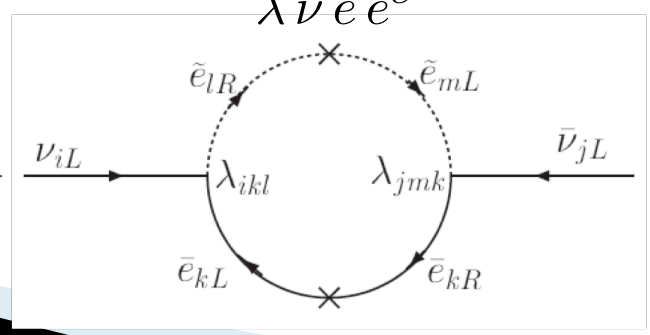
$|\lambda' \lambda''| < 10^{-26}$

- Also constraints from neutrino masses:

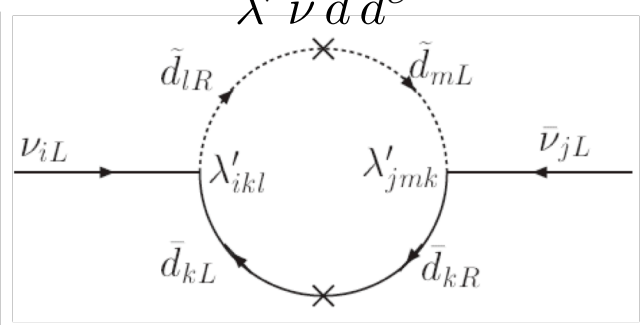
$\mu' \nu H_u^0$



$\lambda \, \nu \, e \, e^c$



$\lambda' \, \nu \, d \, d^c$



R-parity Conservation

- Impose R-parity $R_P = (-1)^{3(B-L)+2S}$
  - Super Z_2 : R_p(Particle) = 1 R_p(Sparticle) = -1
    - LSP stable: DM; missing energy
  - Forbids *all* non-SM terms (but BV or LV ok)

R-parity Conservation

- Impose R-parity $R_P = (-1)^{3(B-L)+2S}$
  - Super Z_2 : R_p(Particle) = 1 R_p(Sparticle) = -1
    - LSP stable: DM; missing energy
  - Forbids *all* non-SM terms (but BV or LV ok)

R-parity Conservation

- Impose R-parity $R_P = (-1)^{3(B-L)+2S}$
  - Super Z_2 : R_p(Particle) = 1 R_p(Sparticle) = -1
    - LSP stable: DM; missing energy
  - Forbids *all* non-SM terms (but BV or LV ok)
  - As Matter Parity
    - $(-1)^{2S}$: Spin – trivially satisfied
    - $(-1)^{3(B-L)}$: Subgroup of $U(1)_{B-L}$
      - Forbids $\Delta(B-L) = 1$
      - But allows seesaw: $\frac{(L\ H)^2}{M_{B-L}} \rightarrow \frac{v^2}{M_{B-L}} \nu\ \nu$

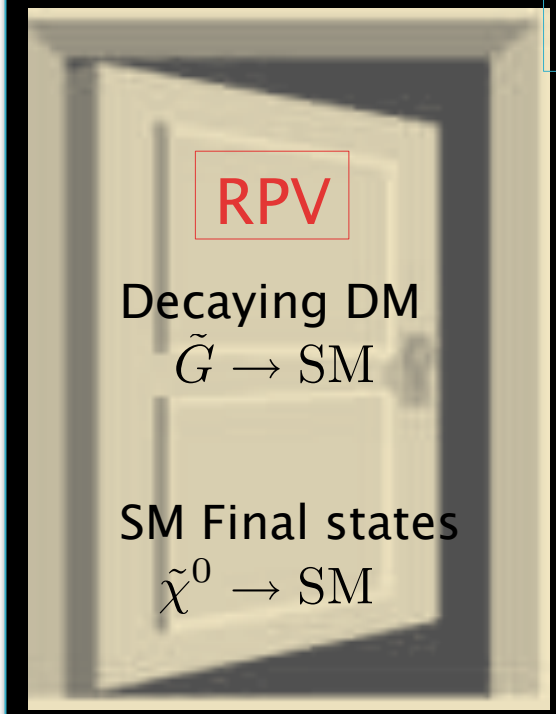
R-parity Violation

- No missing energy at collider: LSP ➔ SM
- Low energy signals: 0ν2β and meson decays
- LSP gravitino can be decaying DM
- In Spontaneous RPV, proton is safe

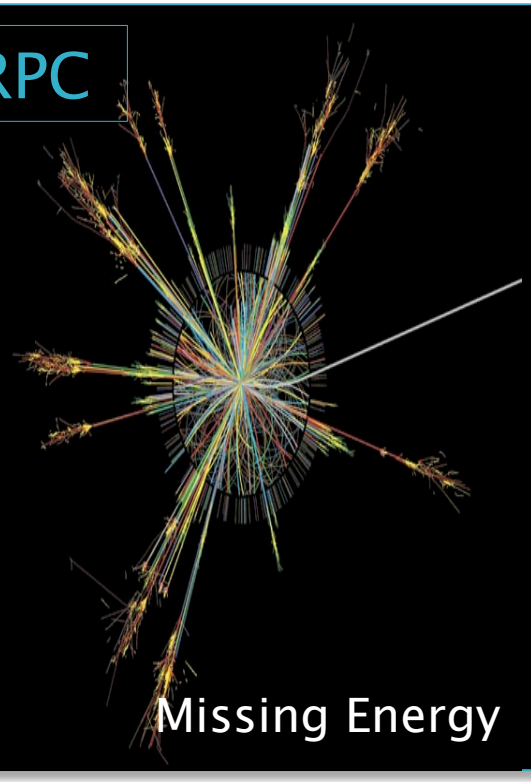
R-parity Violation

- No missing energy at collider: LSP ➔ SM
- Low energy signals: 0ν2β and meson decays
- LSP gravitino can be decaying DM
- In Spontaneous RPV, proton is safe

To Rp or not to Rp

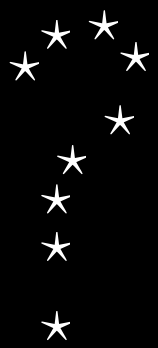


RPC



Missing Energy

SUSY: Cosmo & Pheno hinges on R-parity.



Stable DM

- Rp a subgroup $U(1)_{B-L}$: $R_P = (-1)^{3(B-L)+2S}$
  - Study B-L theories: an origin for R-parity or SRPV
    - Especially interesting if low-energy : LHC

Outline

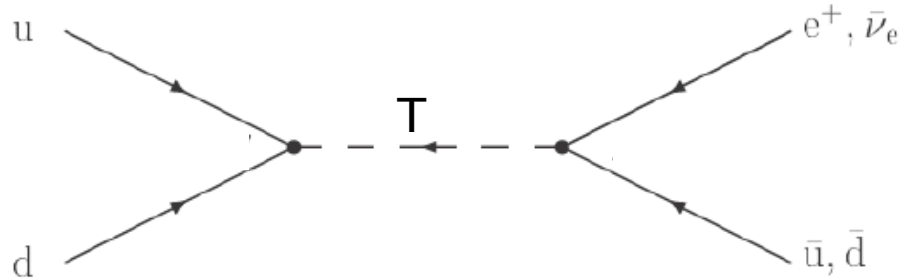
1. Model Building
2. Spectrum
3. Pheno
4. Conclusions

Model Building

Gauging the μ-term – UMSSM

- Anomaly cancellation? Motivated by E_6 (rank 6)
  - 27 contains following with two extra U(1) charges
    - 1 complete family of fermions (right-handed ν): 12 + 4
    - H_u and H_d : 4
    - A standard model singlet: 1
  - Perfect! Setup for $W = \lambda\, S\, H_u\, H_d$
  - Well almost: $T \sim \left(\bar{3}, 1, \frac{1}{3}, z_T\right)$ $\bar{T} \sim \left(3, 1, -\frac{1}{3}, z_{\bar{T}}\right)$: 6

$$W_T \supset u^c\, d^c\, T + Q\, L\, T$$



Proton Decay!

P. Fileviez Perez, Gonzalez-Alonso, S.S.; P. Fileviez Perez S.S. PLB '09; V. Barger P. Fileviez Perez, S.S. PRL '09

Avoiding Proton Decay

- Switch color: $T \sim 3 \to \bar{3}; \quad \bar{T} \sim \bar{3} \to 3$
  - Doesn't couple to matter, stable colored fields!
- Have 3 copies of these: one per generation

Charge only the third generation!

Proton decay suppressed by loops and CKM factors.

Only need one copy

- RPV in the first two generation, *e.g.*

$$\lambda''_{112} u^c\, d^c\, s^c + \lambda'_{122} Q_1\, L_1\, s^c$$

- R-parity subgroup of $U(1)_{B-L}$

Gauge B-L, ~ second Abelian factor from E_6

Already have right-handed neutrinos

Quest for Fermion Masses

- Satisfy anomalies & 3rd gen masses
  - Two degrees of freedom left: z_t and z_{u^c}
- 1st and 2nd masses, mixing hard: $Q_i\, H_u\, u_j^c$ $\quad$ $Q_1\, H_u\, u_3^c$

  0 $\quad z_{H_u}$ 0 $\quad$ 0 $\quad z_{H_u}\, z_{u^c}$
- Choose $z_{H_u} =$ 0, $z_T = -3$; get
  - Up type masses at tree-level
  - Down type masses at NR:
  - 3rd – 1st and –2nd mixing at NR: $\frac{S}{\Lambda} Q_i H_d d_j^c$
  - 3rd generation masses at tree-level $\frac{S}{\Lambda} Q_i H_u t^c$
  - $T, \bar{T}$ coupling to 3rd generation at tree-level
  - RPC because of B-L
  - $\lambda\, S\, H_u\, H_d$ and $\lambda_T\, S\, T\, \bar{T}$

Particle Content

TABLE I: Field Content ($a = 1..2$).

	Field	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)_S$
1st and 2nd Generation	$\hat{Q}_a$	3	2	1/6	1/3	0
	$\hat{u}^c_a$	$\bar{3}$	1	-2/3	-1/3	0
	$\hat{d}^c_a$	$\bar{3}$	1	1/3	-1/3	0
	$\hat{L}_a$	1	2	-1/2	-1	0
	$\hat{e}^c_a$	1	1	1	1	0
	$\hat{\nu}^c_a$	1	1	0	1	0
3rd Generation	$\hat{Q}_3$	3	2	1/6	1/3	-1
	$\hat{u}^c_3$	$\bar{3}$	1	-2/3	-1/3	1
	$\hat{d}^c_3$	$\bar{3}$	1	1/3	-1/3	2
	$\hat{L}_3$	1	2	-1/2	-1	4
	$\hat{e}^c_3$	1	1	1	1	-3
	$\hat{\nu}^c_3$	1	1	0	1	-4
Higgs	$\hat{H}_d$	1	2	-1/2	0	-1
	$\hat{H}_u$	1	2	1/2	0	0
Singlet	$\hat{S}$	1	1	0	0	1
Exotics	$\hat{T}$	$\bar{3}$	1	1/3	2/3	-3
	$\hat{\bar{T}}$	3	1	-1/3	-2/3	2

Symmetry Breaking

- $U(1)_S$ is easy: $\langle S \rangle = \frac{v_s}{\sqrt{2}} \sim 2\sqrt{\frac{-m_S^2}{g_S^2}}$
- Mass terms:

$$\frac{\lambda}{\sqrt{2}} v_S H_u H_d + \frac{\lambda_T}{\sqrt{2}} v_s T \bar{T}$$

- $U(1)_{B-L}$ use $\tilde{\nu}^c,\ B-L=1;\ \langle \tilde{\nu}^c \rangle = \frac{v_R}{\sqrt{2}} \sim 2\sqrt{\frac{-m_{\tilde{\nu}^c}^2}{g_{BL}^2}}$
  - Bilinear RPV:

$$Y_\nu\, v_R\, L\, H_u$$

- No RPV proton decay:

$$\lambda'' u^c d^c d^c = 0$$

Spectrum

- 4 Neutral Gage Bosons: γ, $Z_{\rm ew}$, $Z_{\rm S}$, $Z_{\rm BL}$
- $Z_{\rm ew}$ mixes with $Z_{\rm S}$ due to $H_d, Z_{H_d} = -1$

$$\theta_{ZZ'} \approx \frac{g_S}{\sqrt{g_2^2 + g_1^2}} \cos^2\beta \, \frac{M^2_{Z_{\rm ew}}}{M^2_{Z_S}} \lesssim 10^{-3}$$

- $Z_{\rm S}$ couples only to third generation – FCNC
  - Small 1,2-3 mixing in down sector
  - Bounds are mild, can be lighter than Z
  - Bad collider prospects, hard to produce
- $Z_{\rm BL}$ no kinetic mixing and $\langle \tilde{\nu}_3^c \rangle = 0$
  - Otherwise can mix with $Z_{\rm S}$ help collider prospects

A. A. Andrianov et. al. PRD '98

V. Barger, P. Fileviez Perez, S.S. **PLB**, 2011; **Ghosh, Senjanovic, PLB**, 2011

Three Layers of Neutrinos

- LNV in only one generation:
  - Only one heavy Majorana r-h neutrino
- 2: Dirac-like or Majorana but $m_{\nu_s} \lesssim m_{\nu_a}$

Normal Hierarchy:

Potentially explain LSND/MiniBooNE and cosmology

Hamann, et al. **PRL**, 2010 – BBN favors 1 or 2 additional neutrinos

Kopp, Maltoni, Shcwetz, arXiv, 2011 – LSND and MiniBooNE

Higgs Bosons

- 1 pseudoscalar:

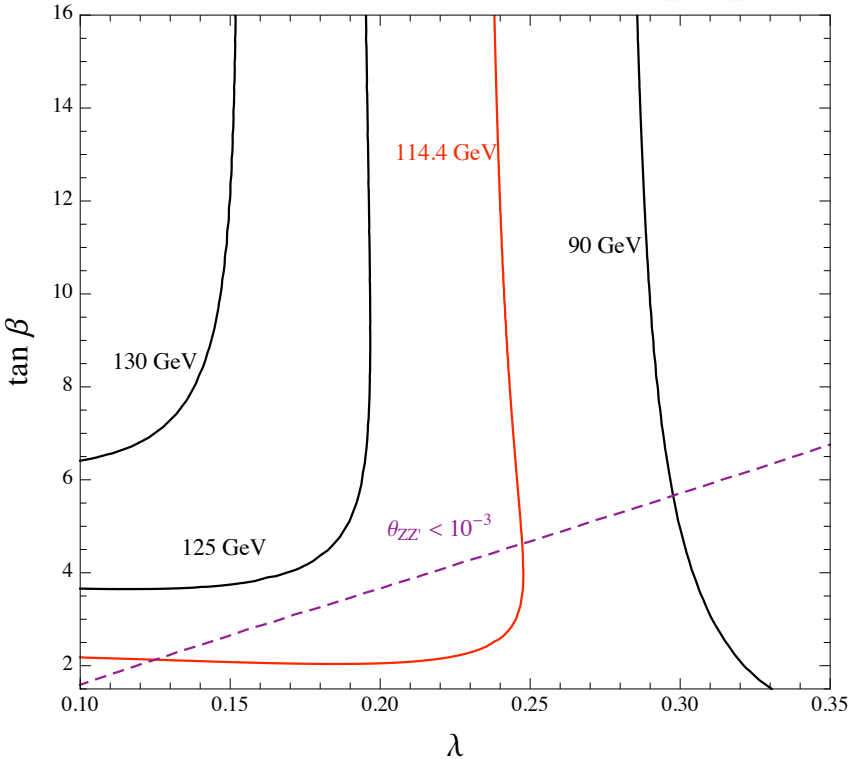
$$m_{A^0} \sim \frac{2b}{\sin 2\beta}$$

- 4 scalars
  - SM-like h
  - $H_1,\ H_2$ mostly singlet and mostly H_d
  - Mostly sneutrino $H_{BL};\ M_{H_{BL}} = M_{Z_{BL}} = \frac{1}{2} g_{BL} v_R$

- MSSM charged Higgs:

$$m_{H^\pm}^2 = \frac{2b}{\sin 2\beta} + M_W^2 - \frac{1}{2}\lambda^2 v^2$$

SM-like Higgs Mass



- Stop soft masses at 1 TeV
- Maximal mixing
- 1-Loop stop/top results

- Highest mass at low λ - MSSM limit, and large tan β MSSM-like
  - Typical NMSSM-like enhancement ruled out by $\theta_{ZZ'}$

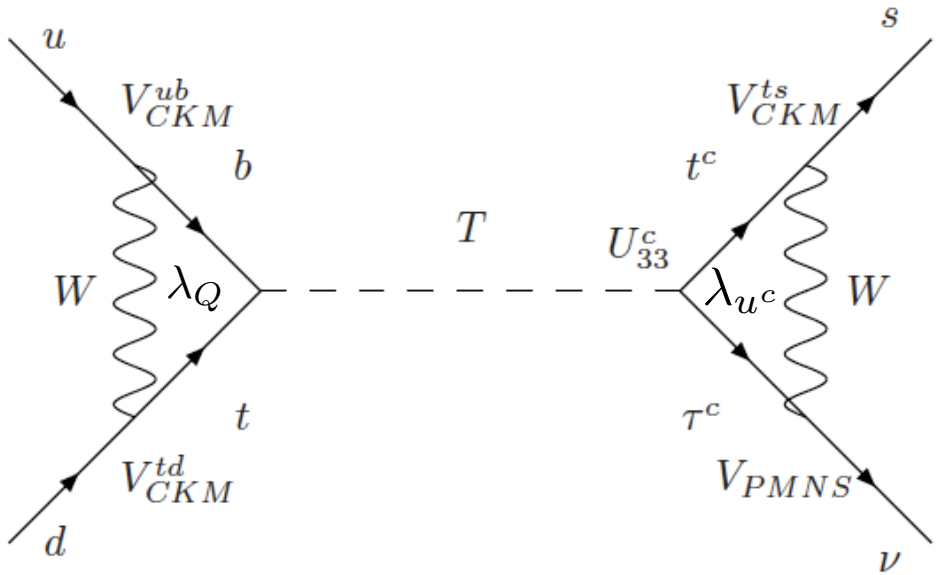
Pheno: B&L Violation

Proton Decay

- Depends on unknown right-handed rotation matrices

$$u_i^c = U_{ij}^c u^{c\prime}{}_j \quad d_i^c = D_{ij}^c d^{c\prime}{}_j$$

- Assuming fairly diagonal, $U_{33}^c \sim 1$, two loop:



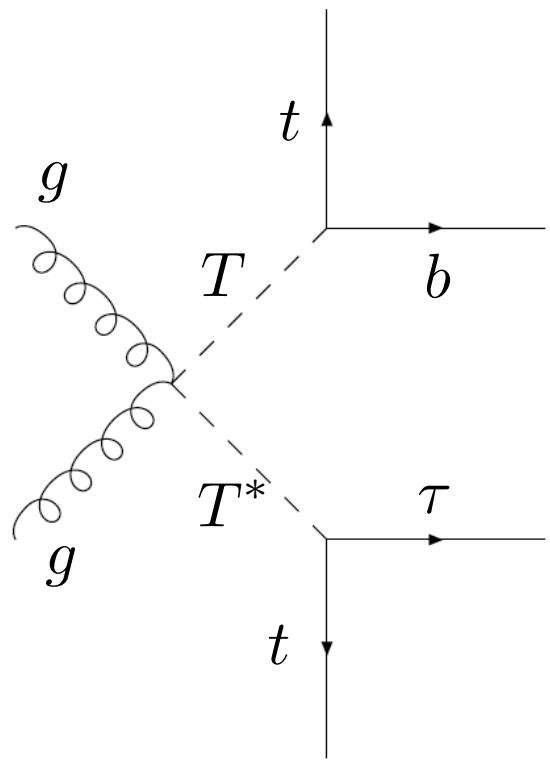
$$\sim \left(\frac{1}{16\pi^2}\right)^2 V_{CKM}^3 \lambda_Q \lambda_{u^c} < 10^{-26}$$

Also loop functions, helicity flip

$$\lambda_Q \lambda_{u^c} \lesssim 10^{-12}$$

Each coupling at 10^{-6} not so severe

Proton Decay ➔ B&L Violation at the LHC



Conclusion

- Discrete symmetries get the job done
  - Experimentally not very revealing
- Gauge symmetries are more testable solutions
- Solved μ-problem and proton stability
  - 2 Z': B-L and third generation
  - Color triplet exotics: safe proton decay and BV&LV