Theories for Baryon and Lepton Number Violation

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Snowmass Rare Processes and Precision Measurements Frontier Spring Meeting

University of Cincinnati - May 2022

RF4: Baryon and Lepton Number Violating Processes

co-Conveners: Pavel Fileviez Perez (Case Western Reserve Univ.) and Andrea Pocar (UMass, Amherst)

Main Physics Topics:

- *Theories for baryon and lepton number violation* — *P. Fileviez Perez (CWRU), M.B. Wise (Caltech)*
- *Neutrinoless double beta decays* — *V. Cirigliano (INT), A. Pocar (UMass)*
- *Baryon and Lepton number violation at colliders* — *R. Ruiz (Cracow, INP), E. Thomson (UPenn)*
- *Proton decay* — *E. Kearns (Boston Univ.), S. Raby (Ohio State Univ)*
- *n-nbar oscillations* — *K. Babu (OSU), L. Broussard (ORNL)*
- *Exotic L and B violating processes* — *S. Gardner (Univ. of Kentucky), J. Heeck (Virginia)*
- *Connections to Cosmology (Baryogenesis Mechanisms)* — *A. Long (Rice Univ.), C. Wagner (Univ. of Chicago/ANL)*

Drivers: *Explore the unknown, The origin of B and L violation is crucial to understand the nature of neutrinos and the mechanism to explain the matter-antimatter in the Universe. An unique window for physics beyond the SM.*

P5: *Strong support for these physics topics*

Plans: Finishing the RF4 Report

Overlap: Overlap with the neutrino frontier (proton decay, neutrinoless double beta decay), Cosmic Frontier (Baryogenesis), Energy Frontier (exotics at colliders)

B and L Numbers

In the Standard Model Baryon and Lepton numbers are accidental global symmetries broken by SU(2) instanton processes in 3 units !

In the *renormalizable* SM:

- proton is stable

- neutrinos are massless

- no n-nbar oscillations

$\Delta B = 3$ & $\Delta L = 3$ highly suppressed !

We want to understand the origin of B and L violation to explain :

- The origin of neutrino masses

- The origin of the matter-antimatter asymmetry in the Universe

- New Exotic BLV processes

- The origin of the SM-EFT

Theories for Physics beyond the Standard Model

Matter Unification: In theories where quarks and leptons are unified one must have B and L violating interactions (Pati, Salam, 1973).

GUTs: In grand unified theories (SU(5), SO(10),..) B and L are explicitly broken at the high scale and generically one predicts proton decay and typically Majorana Neutrinos.

SUSY: In the MSSM B and L are explicitly broken at the renormalizable level by RpV interactions and generically one predicts proton decay and Majorana neutrinos.

In simple theories where B and L are local gauge symmetries one predicts that these symmetries are spontaneously broken in 3 units and the symmetries must be broken at the low scale.

S. Weinberg, 1979

B and L Violating Effective Operators

$$\mathcal{L} \supset \frac{c_L}{\Lambda_L} \ell H \ell H$$

$$+ \frac{c_1}{\Lambda_B^2} (\overline{u^c} \gamma^\mu q)(\overline{e^c} \gamma_\mu q) + \frac{c_2}{\Lambda_B^2} (\overline{u^c} \gamma^\mu q)(\overline{d^c} \gamma_\mu \ell)$$

$$+ \frac{c_3}{\Lambda_B^2} (\overline{d^c} \gamma^\mu q)(\overline{u^c} \gamma_\mu \ell) + \frac{c_4}{\Lambda_B^2} q q q \ell + \frac{c_5}{\Lambda_B^2} u^c e^c u^c d^c + \ldots$$

What are the values for Λ_L and Λ_B?

Naive bounds: $\Lambda_L \lesssim 10^{14}$ GeV and $\Lambda_B \gtrsim 10^{15}$ GeV

These scales could be low and we could test the origin of B and L violation !

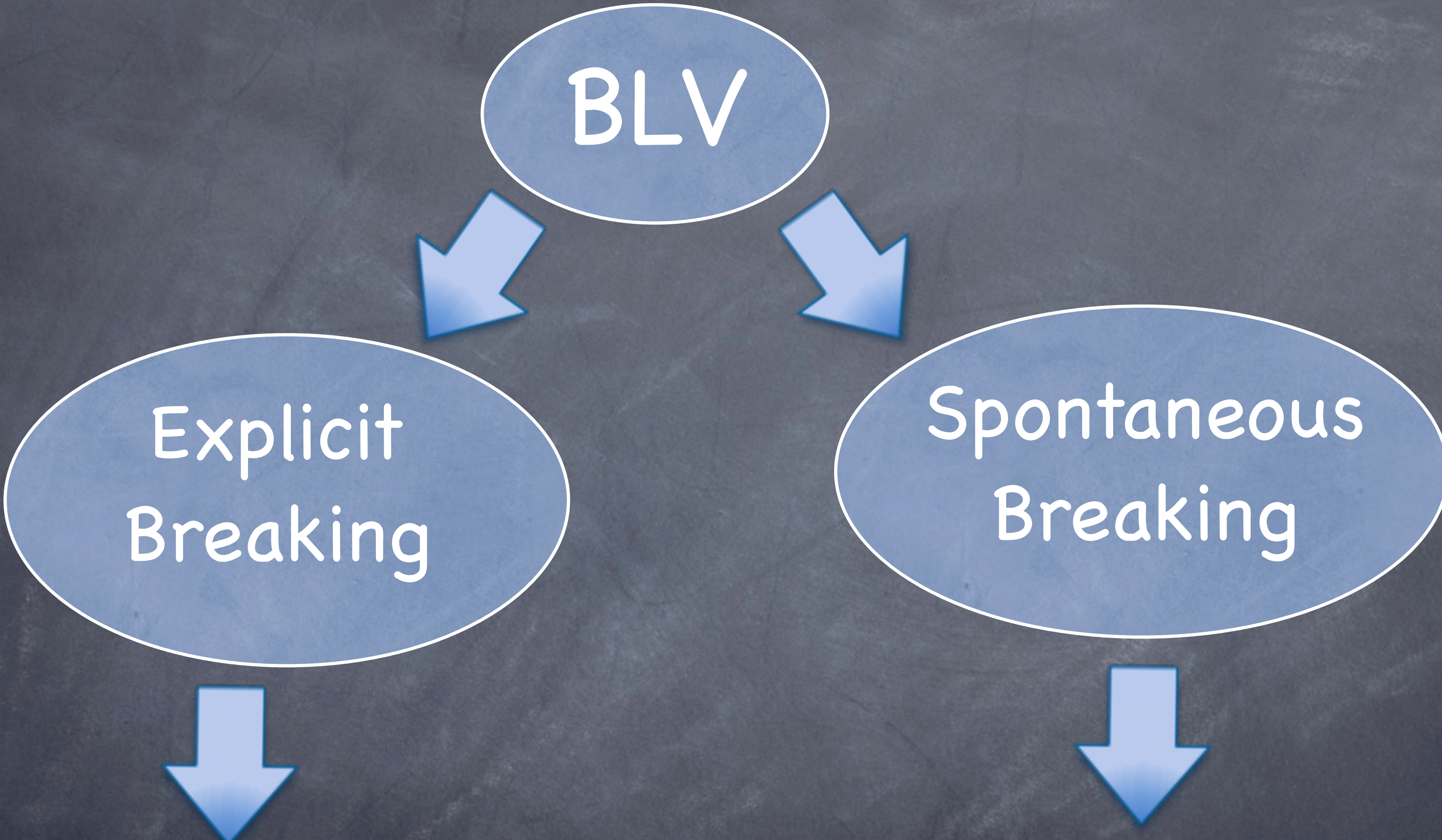
Search for Rare Processes

LNV

- Neutrino Oscillations → $U(1)_{L_i}$ broken !
- Lepton Flavour Violating Processes: $\mu \to e\gamma, \mu \to 3e, \ldots$
- Neutrinoless double beta decay $^{A}_{Z}X \;\to\; ^{A}_{Z+2}Y + 2e^-$
- LNV at Colliders: $p\,p \to e_i^+ e_j^- e_k^+ e_l^-, \mu^\pm \mu^\pm 4j, ..$

BNV

- Proton Decay: $p \to \pi^0 e^+, K^+ \bar{\nu}, \ldots$
- N-Nbar Oscillations
- Others



- Proton decay
- Majorana neutrinos

- Stable proton
- Dirac or Majorana neutrinos
- Low B and/or L Scale

Neutrino Masses

Massive Neutrinos

- Majorana Fermions

$$\mathcal{L} \ni \frac{1}{2} \nu_L^T C M_M \nu_L + h.c.$$

- Dirac Fermions

$$\mathcal{L} \ni M_D \bar{\nu}_L \nu_R + h.c.$$

Simple Scenarios for Majorana Neutrino Masses

$$\mathcal{L} \ni \frac{1}{2} \nu_L^T C M_M \nu_L + h.c.$$

- Type I Seesaw
- Type II Seesaw
- Type III Seesaw
- Zee's Model
- Colored Seesaw
- Witten's Model

…

…

Type II Seesaw

$$M_M \neq 0$$

$$\mathcal{L} \ni Y_\nu \, l_L^T C \, i\sigma_2 \, \Delta \, l_L + h.c.$$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \sim (1, 3, 1)$$

Type II Seesaw

$$M_\nu \neq 0$$

$$V(H, \Delta) \ni \mu H^T i\sigma_2 \Delta^\dagger H$$

After SSB:

$$M_\nu = \sqrt{2}\, Y_\nu v_\Delta = Y_\nu \mu \frac{v^2}{M_\Delta^2}$$

$\Rightarrow$ $v = 246$ GeV, μ ? M_Δ ?

Type II Seesaw

$$M_\nu = \sqrt{2}\, Y_\nu v_\Delta = Y_\nu\, \mu \frac{v^2}{M_\Delta^2}$$

$$v = 246 \text{ GeV}, \quad \mu\,? \quad M_\Delta\,?$$

if $\quad Y_\nu \sim 1 \qquad \mu \sim M_\Delta \quad \Rightarrow \quad M_\Delta \lesssim 10^{14}$ GeV

Maybe $\quad M_\Delta \sim 1$ TeV $\qquad Y_\nu \sim 1 \quad \Rightarrow \quad \mu \lesssim 1$ eV

μ is protected by $\mathrm{U(1)_{B-L}}$

(Minkowski, Mohapatra, Senjanovic, Glashow, Yanagida, Gell-Mann, Ramond, Slansky)

Type I Seesaw

$$-\mathcal{L}_M = Y_\nu^D \; \bar{\ell}_L i \sigma_2 H^* \nu_R + \frac{1}{2} M_R \nu_R^T C \nu_R + \text{h.c.}$$ (Canonical Seesaw)

$$M_\nu = m_D M_R^{-1} m_D^T$$

if $m_D \sim 10^2 \text{GeV}$ $\Rightarrow$ $M_R \lesssim 10^{14-15} \text{GeV}$ (Seesaw Scale)

$U(1)_{B-L}$

$$-\mathcal{L}_\nu^I = Y_\nu \, \overline{\ell_L} i \sigma_2 H^* \nu_R + \lambda_R \; \nu_R^T C \nu_R S_{BL} + \text{h.c.},$$

$$S_{BL} \sim (1, 1, 0, 2)$$

We could test the mechanism for Majorana neutrino masses if the L breaking scale can be reach at collider experiments

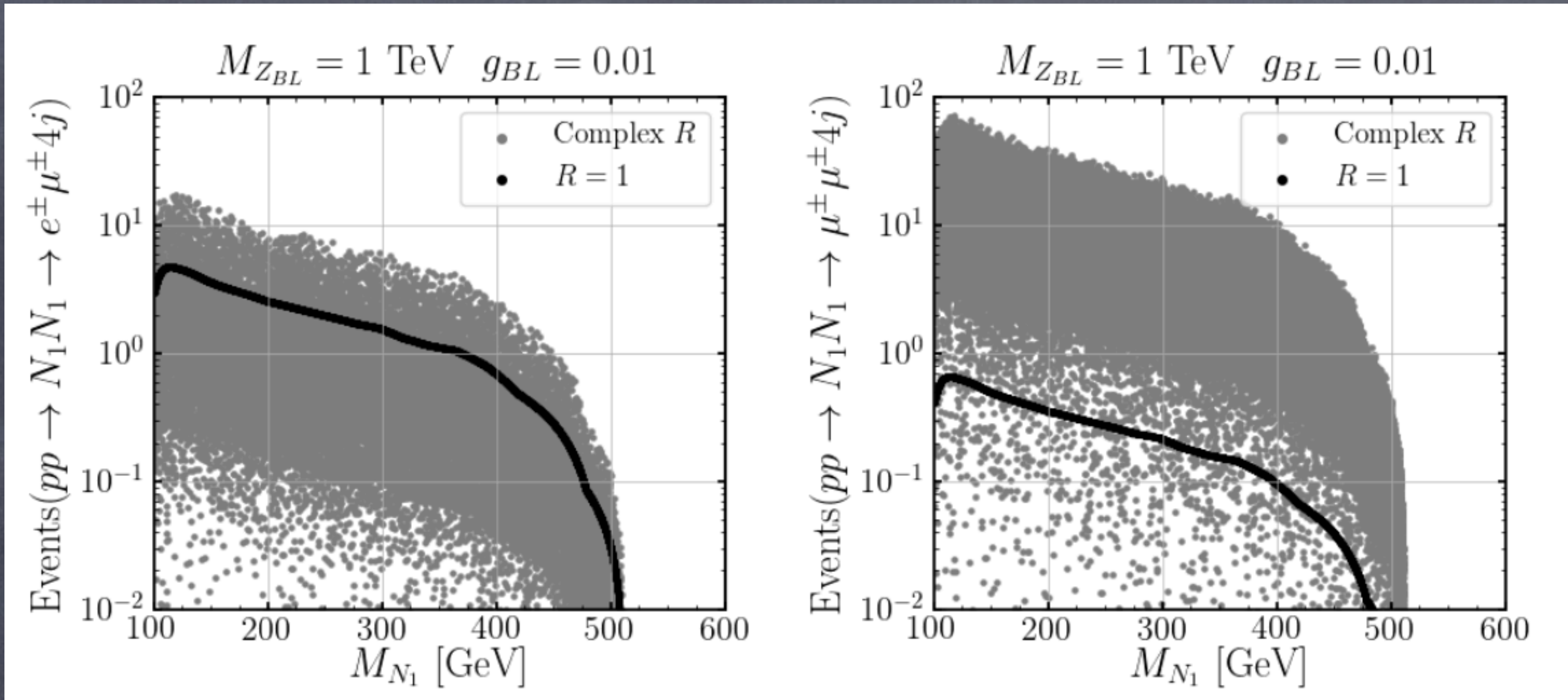


FIG. 6: Scatter plot of the expected number of events at the LHC for center-of-mass energy of 14 TeV assuming $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$ for the integrated luminosity. The black points correspond to the case with $R = 1$, while the gray points correspond to a random scan on the entries of the R matrix. These plots correspond to the case with normal hierarchy and we scan over the lightest neutrino mass, the same pattern is observed for inverted hierarchy.

Phys. Rev. D 102, 015010 (2020), arXiv:2005.04235

Explicit Breaking of B and L

Grand Unified Theories

Georgi-Glashow Model

Georgi, Glashow, Phys.Rev.Lett.32:438-441,1974

$$G_{SM} \;=\; SU(3) \bigotimes SU(2) \bigotimes U(1) \subset SU(5)$$

$$\alpha_3 \qquad \alpha_2 \qquad \alpha_1 \quad \longrightarrow \quad \alpha_5$$

Matter Assignment

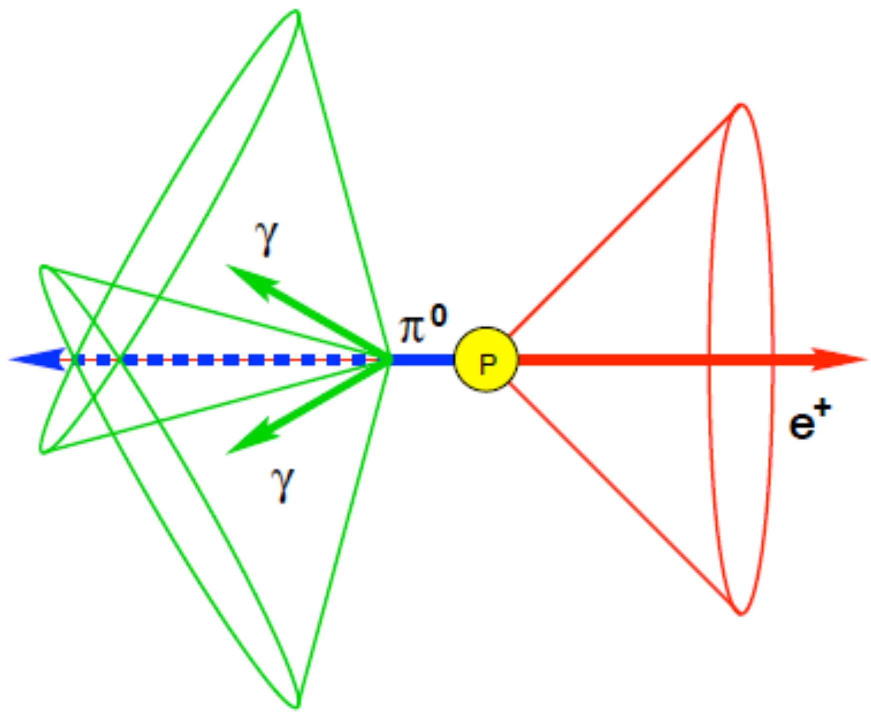
$$\bar{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}_L \qquad \mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & u_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}_L$$

Higgs Bosons $\quad 5_H \qquad 24_H$

$\mathcal{B}$ and $\mathcal{L}$ are explicitly broken !

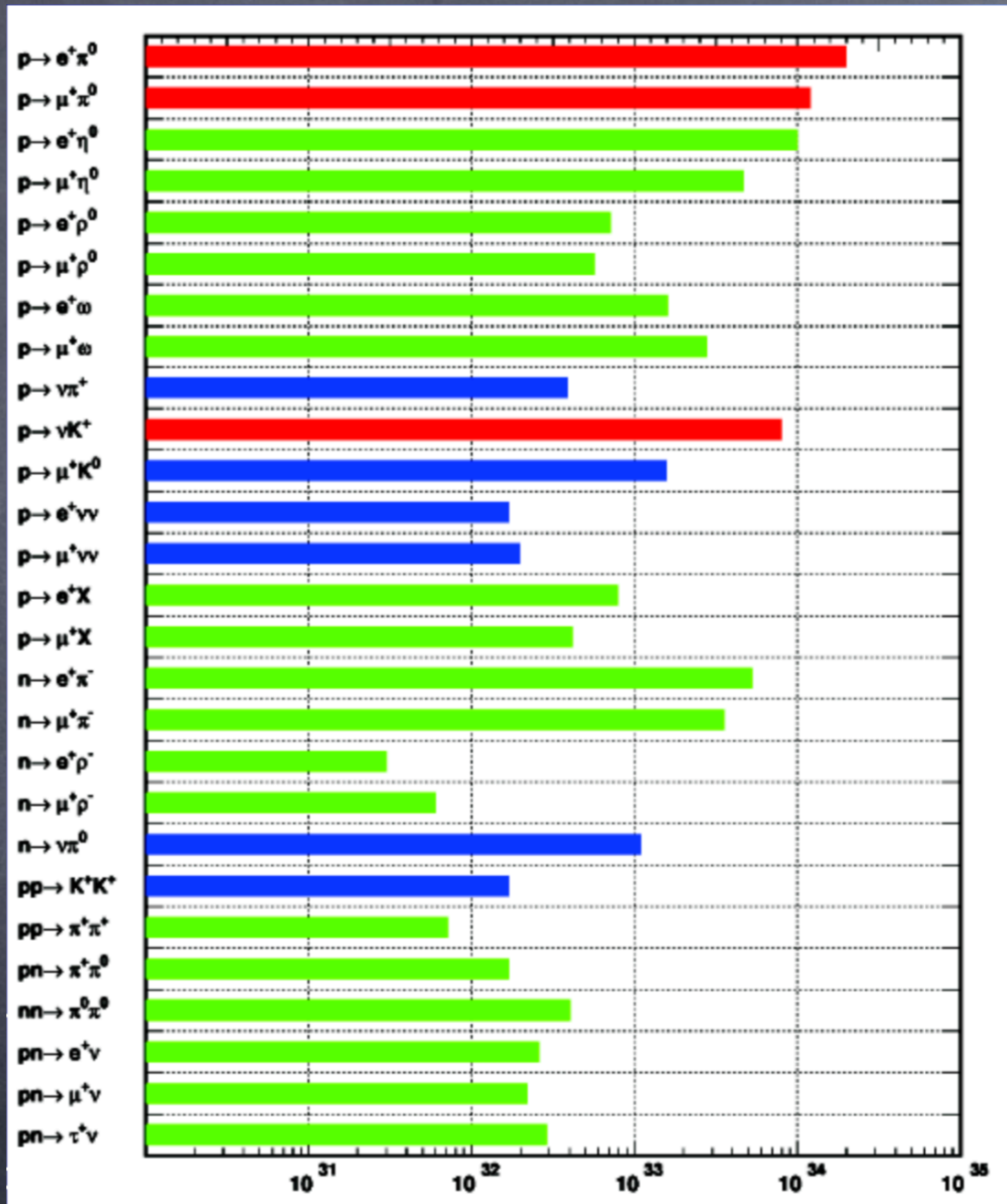
Baryon and Lepton Number Violating Interactions

$$g_5\overline{(e^c)_L}\gamma^\mu X_\mu d_L + g_5\overline{u}_L\gamma^\mu X_\mu (u^c)_L \ + \ \text{h.c.}$$



P. Nath, P. F. P., Physics Reports 441 (2007) 191

Proton Decay: $\Delta B = 1,\ \Delta L = \text{odd}$

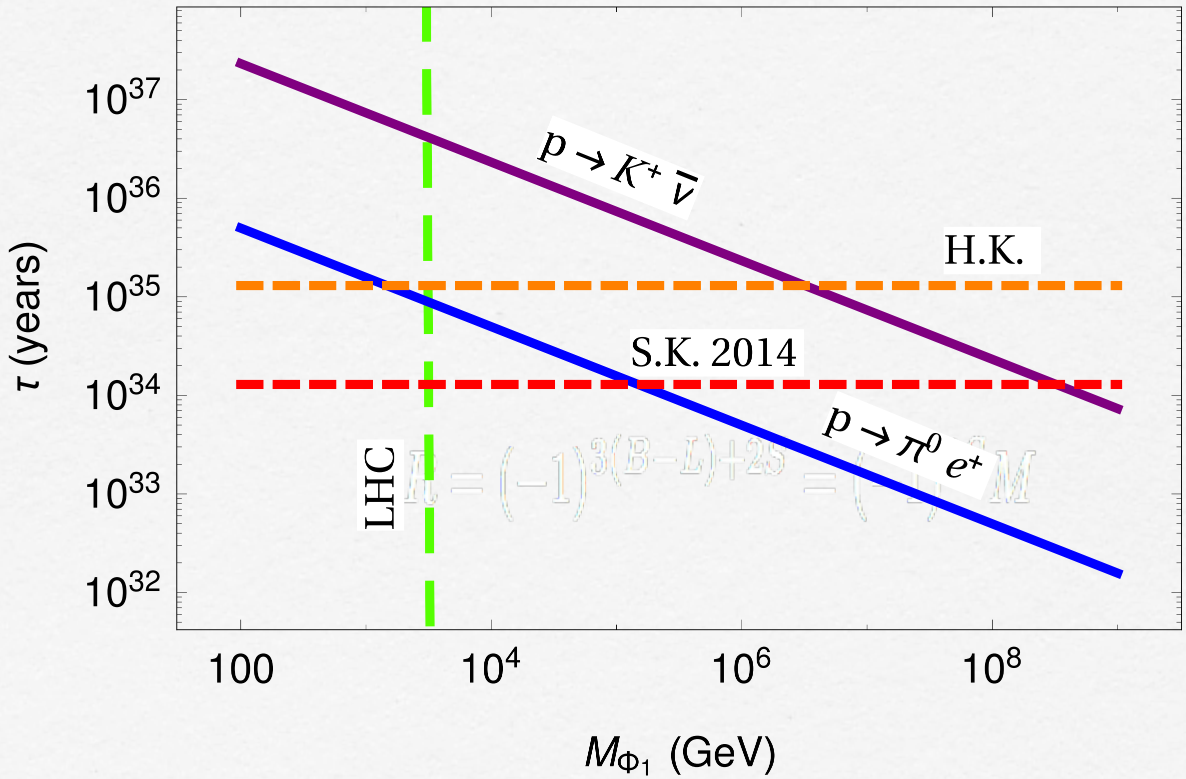


Miura @ BLV2019

$M_V > 10^{14-15}\text{GeV}$

Renormalizable SU(5)

$$5_H, 24_H, 45_H$$



$$45_H \subset \Phi_1 \sim (8, 2, 1/2)$$

- *Phys.Rev.D* 94 (2016) 7, 075014 • e-Print: 1604.03377

MSSM Interactions

$$\mathcal{W}_{RpC} = Y_u Q H_u u^c + Y_d Q H_d d^c + Y_e L H_d e^c + \mu H_u H_d$$

$$\mathcal{W}_{RpV} = \epsilon L H_u + \lambda L L e^c + \lambda^{'} Q L d^c + \lambda^{''} u^c d^c d^c$$

$$R = (-1)^{3(B-L)+2S} = (-1)^{2S} M$$

LSP $\tilde{\chi}_1^0 = \left(\tilde{B}, \tilde{W}, \tilde{H}_u^0, \tilde{H}_d^0\right)$ → **Cold Dark Matter !**

R-parity Violation

Baryon Number Violation:

$$p\,p \;\rightarrow\; \tilde{g}\,\tilde{g} \;\rightarrow\; t\,t\,\tilde{t}^*\,\tilde{t}^* \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,3j\,3j$$

Lepton Number Violation:

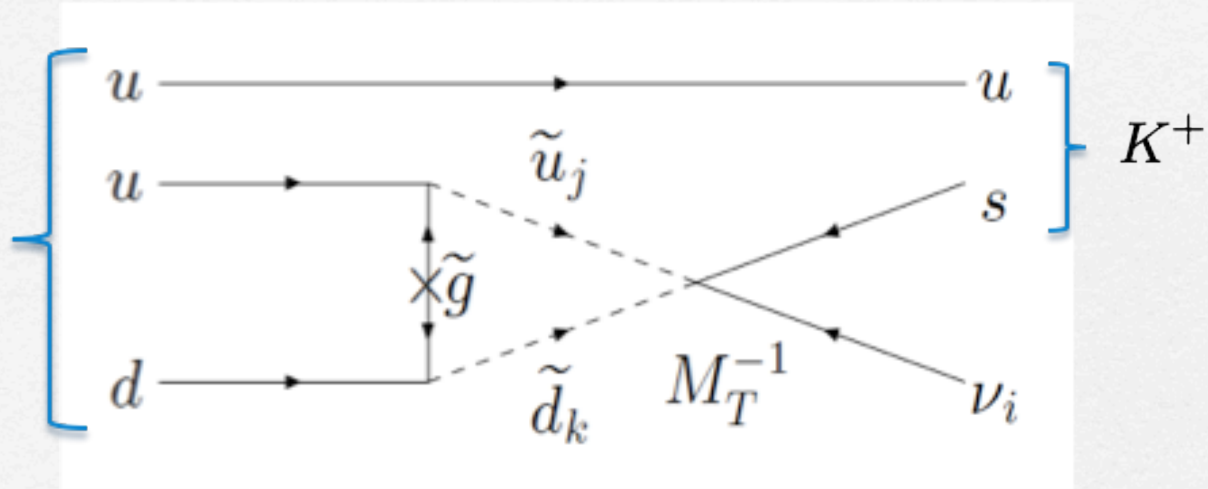
$$p\,p \;\rightarrow\; \tilde{g}\,\tilde{g} \;\rightarrow\; t\,t\,\tilde{t}^*\,\tilde{t}^* \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,e_i^{\pm}\,e_j^{\pm}\,W^{\mp}\,W^{\mp}$$

Signals with Multi-jets and Multi-leptons at the LHC !

d=5 operators in SUSY GUTs

Example: $p \to K^+ \bar{\nu}$

$\frac{\lambda_L}{M_T} QQQL$



$M_T > 10^{17}\text{GeV (NAIVE)}$

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

- e-Print: 2203.08771

Model	Decay modes	τ_N $(N=p,n)$ [years]	Ref.
Non-SUSY minimal $SU(5)$	$p\to e^+\pi^0$	$10^{30}-10^{32}$	Georgi, Glashow [16]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p\to e^+\pi^0$	$\lesssim 2.3\times 10^{36}$	Doršner, Saad [82]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p\to e^+\pi^0$ $p\to \bar\nu K^+$	$10^{32}-10^{36}$ $10^{34}-10^{37}$	Perez, Murgui [74]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-II seesaw)	$p\to\nu+(K^+,\pi^+,\rho^+)$ $n\to\nu+(\pi^0,\rho^0,\eta^0,\omega^0,K^0)$	$10^{31}-10^{38}$	Doršner, Perez [64]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-III+I seesaw)	$p\to e^+\pi^0$	$\lesssim 10^{36}$	Bajc, Senjanović [65]
Non-SUSY Extended $SU(5)$ (neutrino mass: 2-loop)	$p\to e^+\pi^0$	$10^{34}-10^{40}$	Saad [80]
Minimal flipped non-SUSY $SU(5)$	$p\to e/\mu^+\pi^0$	$10^{38}-10^{42}$	Arbeláez, Kolešová, Malinský [175]
Non-SUSY Minimal $SO(10)$	$p\to e^+\pi^0$	$\lesssim 5\times 10^{35}$	Babu, Khan [165]
Minimal $SO(10)$ with 45 Higgs	$p\to e^+\pi^0$	$\lesssim 10^{36}$	Bertolini, Di Luzio, Malinský [176]
Minimal non-Renormalizable $SO(10)$	$p\to e^+\pi^0$	$\lesssim 10^{35}$	Preda, Senjanović, Zantedeschi [173]
Non-SUSY Generic $SO(10)$ $M_{\rm int}:\ G_{422}$ $M_{\rm int}:\ G_{422D}$ $M_{\rm int}:\ G_{3221}$ $M_{\rm int}:\ G_{3221D}$	$p\to e^+\pi^0$	 $10^{34}-10^{46}$ $10^{31}-10^{34}$ $10^{36}-10^{46}$ $10^{33}-10^{43}$	Chakrabortty, King, Maji [164]
Non-SUSY Generic E_6 $M_{\rm int}:\ G_{4221}$ $M_{\rm int}:\ G_{4221D}$ $M_{\rm int}:\ G_{333}\to G_{3221}$ $M_{\rm int}:\ G_{4221D}\to G_{421}$ $M_{\rm int}:\ G_{4221}\to G_{421}$	$p\to e^+\pi^0$	 $10^{27}-10^{36}$ $10^{27}-10^{36}$ $10^{32}-10^{36}$ $10^{26}-10^{48}$ $10^{25}-10^{48}$	Chakrabortty, King, Maji [164]
Minimal SUSY $SU(5)$	$p\to\bar\nu K^+$ $n\to\bar\nu K^0$	 $10^{28}-10^{32}$	Dimopoulos, Georgi [42], Sakai [100] Hisano, Murayama, Yanagida [99]
Minimal SUSY $SU(5)$ (cMSSM)	$p\to\bar\nu K^+$ $p\to e^+\pi^0$	$\lesssim(2-6)\times 10^{34}$ $10^{35}-10^{40}$	Ellis et. al. [107]
Minimal SUSY $SU(5)$ ($\mathbf{5}+\bar{\mathbf{5}}$ matter fields)	$p\to\bar\nu K^+$ $p\to\mu^+\pi^0/K^0, n\to\bar\nu\pi^0/K^0$	$\lesssim 4\times 10^{33}$ $10^{33}-10^{34}$	Babu, Bajc, Tavartkiladze [177]
SUGRA $SU(5)$	$p\to\bar\nu K^+$	$10^{32}-10^{34}$	Nath, Arnowitt [103, 178]
mSUGRA $SU(5)$ (Higgs mass constraint) NUSUGRA $SU(5)$ (Higgs mass constraint)	$p\to\bar\nu K^+$ $p\to\bar\nu K^+$	$3\times 10^{34}-2\times 10^{35}$ $3\times 10^{34}-10^{36}$	Liu, Nath [111]
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	$p\to e^+\pi^0$	$\sim 10^{34.9\pm 1}$	Pati [179]
Flipped SUSY $SU(5)$ (cMSSM)	$p\to e/\mu^+\pi^0$	$10^{35}-10^{37}$	Ellis et. al. [180–182]
Split SUSY $SU(5)$	$p\to e^+\pi^0$	$10^{35}-10^{37}$	Arkani-Hamed, et. al. [183]
SUSY $SU(5)$ in 5D	$p\to\mu^+K^0$ $p\to e^+\pi^0$	$10^{34}-10^{35}$	Hebecker, March-Russell[184]
SUSY $SU(5)$ in 5D variant II	$p\to\bar\nu K^+$	$10^{36}-10^{39}$	Alciati et.al.[185]
Mini-split SUSY $SO(10)$	$p\to\bar\nu K^+$	$\lesssim 6\times 10^{34}$	Babu, Bajc, Saad [146]
SUSY $SO(10)\times U(1)_{\rm PQ}$	$p\to\bar\nu K^+$	$10^{33}-10^{35}$	Babu, Bajc, Saad [147]
Extended SUSY $SO(10)$ Type-I seesaw Type-II seesaw	$p\to\bar\nu K^+$	 $10^{30}-10^{37}$ $\lesssim 6.6\times 10^{33}$	Mohapatra, Severson [186]
Extended SUSY $SO(10)$ Inverse seesaw	$p\to\bar\nu K^+$	 $\lesssim 10^{34}$	Dev, Mohapatra [187]
SUSY $SO(10)$ with anomalous flavor $U(1)$	$p\to\bar\nu K^+$ $n\to\bar\nu K^0$ $p\to\mu^+K^0$	$10^{32}-10^{35}$	Shafi, Tavartkiladze [188]
SUSY $SO(10)$ MSSM	$p\to\bar\nu K^+$ $n\to\bar\nu K^0$	$10^{33}-10^{34}$ $10^{32}-10^{33}$	Lucas, Raby [189], Pati [179]
SUSY $SO(10)$ ESSM	$p\to\bar\nu K^+$	$10^{33}-10^{34}$ $\lesssim 10^{35}$	Pati [179]
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	$p\to\bar\nu K^+$ $p\to\mu^+K^0$	$\lesssim 2\cdot 10^{34}$ $B\sim(1-50)\%$	Babu, Pati, Wilczek [190–192], Pati [179]
SUSY $SO(10)\times S_4$	$p\to\bar\nu K^+$	$\lesssim 7\times 10^{33}$	Dev, Mohapatra, Dutta, Severson [193]
SUSY $SO(10)$ in 6D	$p\to e^+\pi^0$	$10^{34}-10^{35}$	Buchmuller, Covi, Wiesenfeldt [194]
GUT-like models from Type IIA string with D6-branes	$p\to e^+\pi^0$	$\sim 10^{36}$	Klebanov, Witten [195]

Spontaneous B and L Breaking

Breaking B and L at the TeV scale !

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B \otimes U(1)_L$$

where $U(1)_B$ and $\mathrm{U}(1)_\mathrm{L}$ can be broken at the TeV Scale !

$$B(\text{quark}) = 1/3 \qquad L(\text{lepton}) = 1$$

How to define an anomaly free theory ?

P. F. P., Physics Reports 597

Spontaneous B Breaking ! $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B$

$$\Psi_L \sim (1,\ 2,\ 1/2,\ 3/2), \qquad \Psi_R \sim (1,\ 2,\ 1/2,\ -3/2),$$

$$\Sigma_L \sim (1,\ 3,\ 0,\ -3/2), \qquad \chi_L \sim (1,\ 1,\ 0,\ -3/2)\,.$$

$$-\mathcal{L} \supset h_1 \bar{\Psi}_R H \chi_L + h_2 H^\dagger \Psi_L \chi_L + h_3 H^\dagger \Sigma_L \Psi_L + h_4 \bar{\Psi}_R \Sigma_L H + \lambda_\Psi \bar{\Psi}_R \Psi_L S_B^* + \lambda_\chi \chi_L \chi_L S_B + \lambda_\Sigma \mathrm{Tr}\, \Sigma_L^2 S_B$$

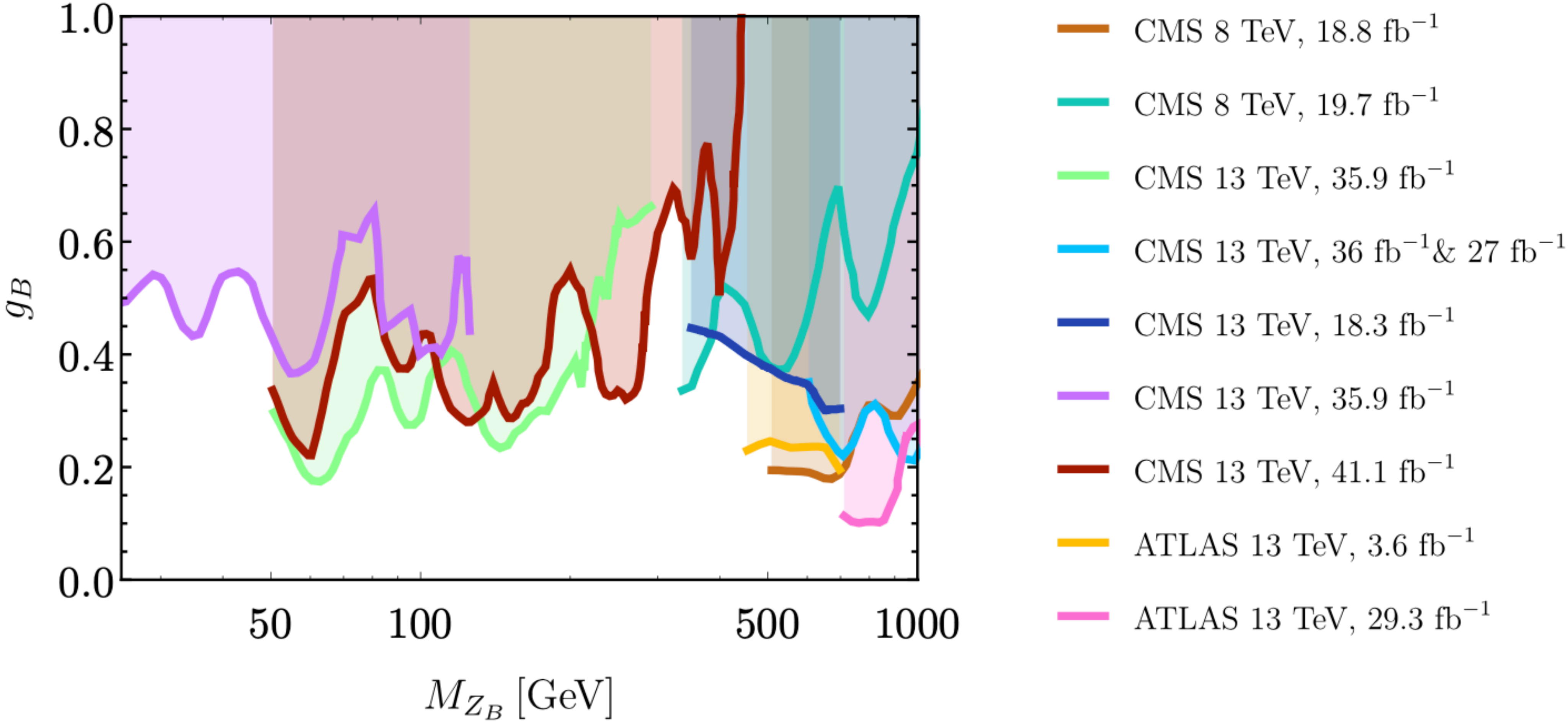
⇒ New Higgs: $S_B \sim (1, 1, 0, 3)$

$\Delta B = \pm 3$ ⇒ **Stable Proton !**

Gauge Theory for Proton Stability !

Phys. Rev. D90 (2014)3, 037701

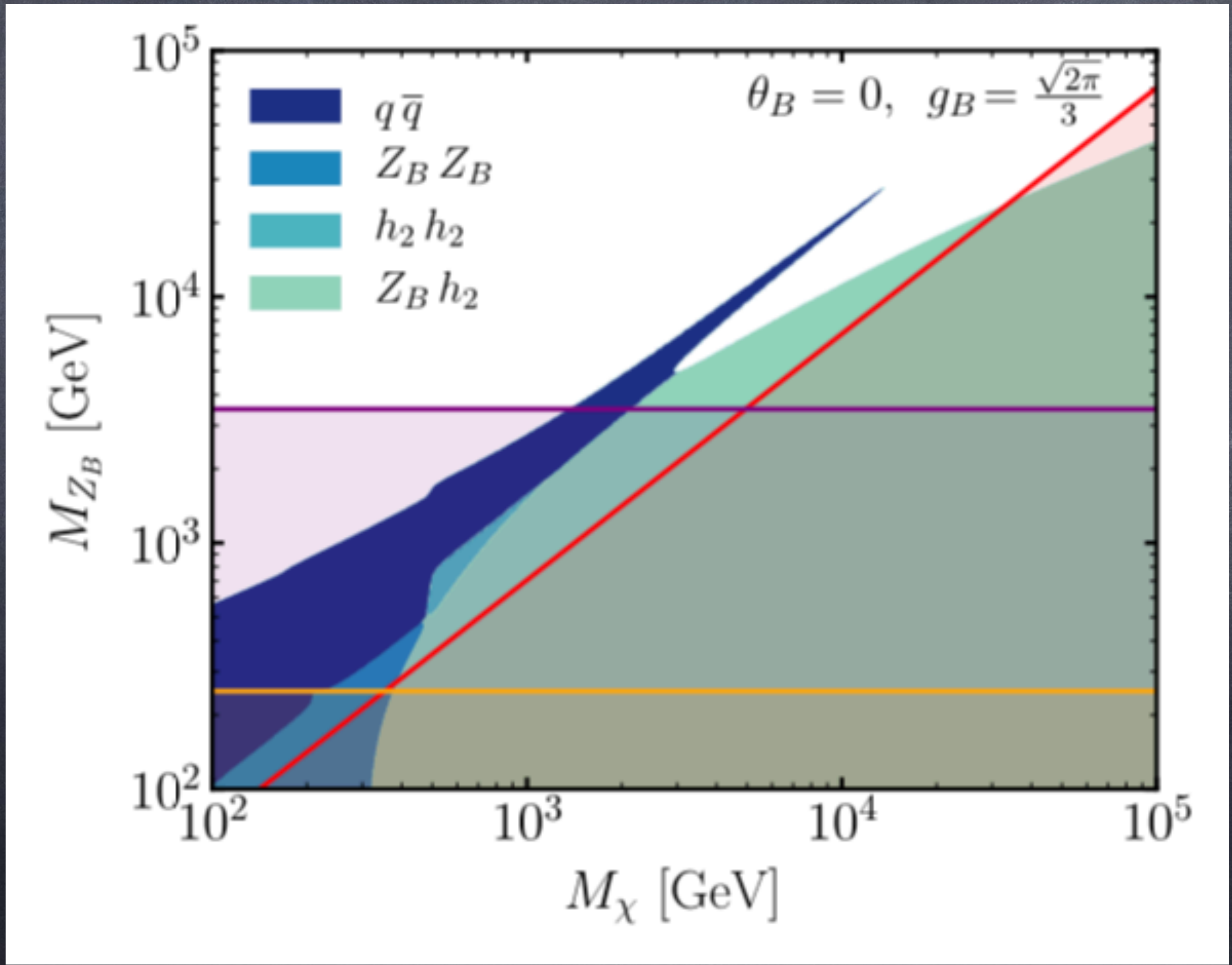
Collider Bounds



Phys. Rev. D 100, 015017 (2019)

Dark Matter from Anomaly Cancellation

$$\Omega_{DM} h^2 \leq 0.12$$



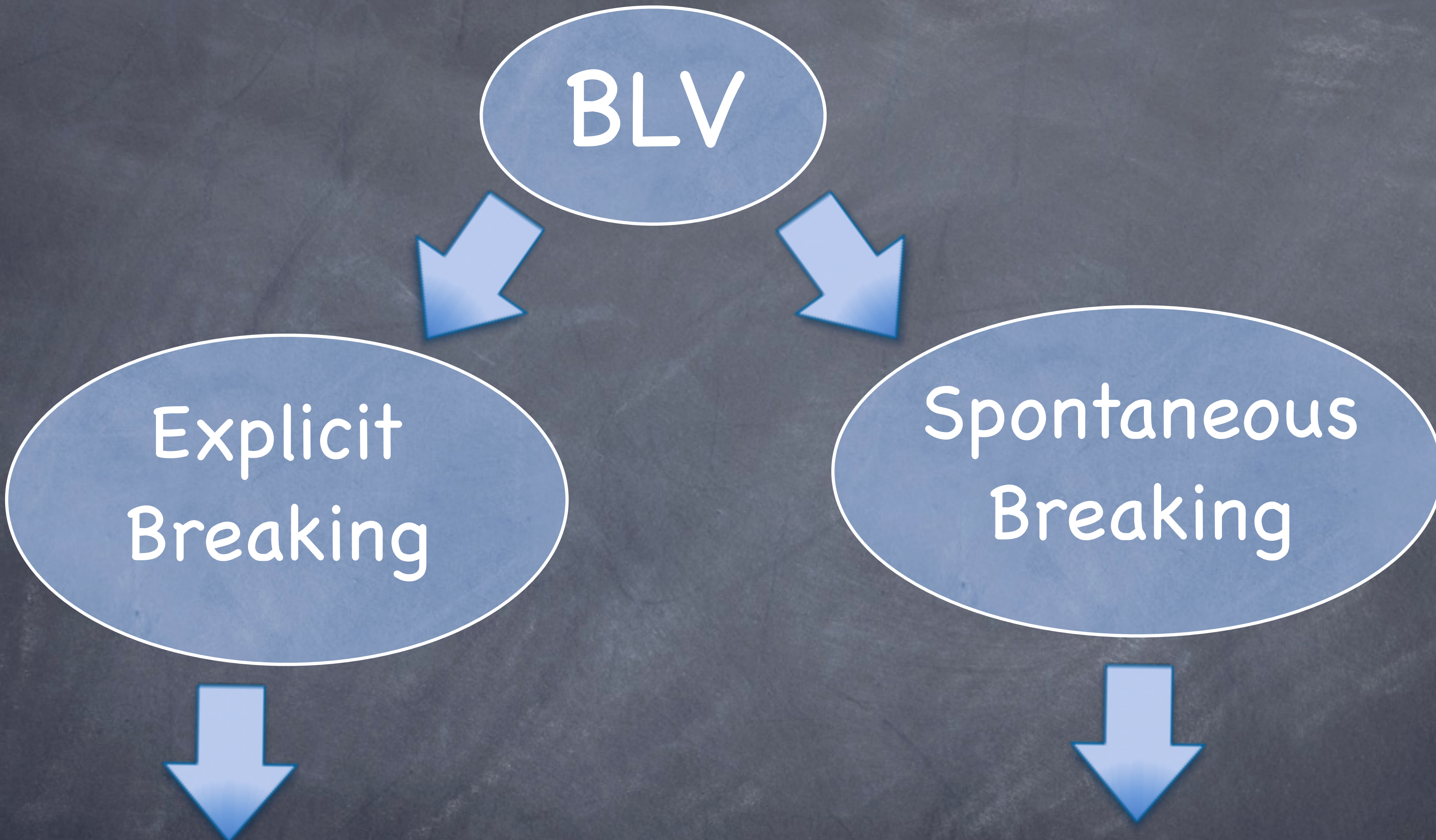
Summary

Grand Unified Theories predict proton decay. Experiments should keep looking for proton decay. Simple GUTs predict a lifetime for the proton decay channels close to the current experimental limits.

Supersymmetry could describe physics below the multi-TeV scale. The existence of B and L violating interactions could play a major role in the discovery at colliders.

B and L could be local gauge symmetries spontaneously broken at the low scale. The simplest theories predict the proton stability and the existence of dark matter from anomaly cancellation. The cosmological bound on the dark matter relic density implies that these symmetries must be broken at the low scale and one can test these theories at current or future colliders.

We should look for exotic B and L signatures at colliders and for rare processes such as neutrinoless double beta decay, n-nbar oscillations and others.



- Proton decay
- Majorana neutrinos

- Stable proton
- Dirac or Majorana neutrinos
- Low B and/or L Scale

RF4 Report

II. THEORIES FOR BARYON AND LEPTON NUMBER VIOLATION

Pavel Fileviez Pérez (CWRU), Mark B. Wise (Caltech)

III. NEUTRINOLESS DOUBLE BETA DECAY

Vincenzo Cirigliano (INT), Andrea Pocar (UMass)

IV. BARYON AND LEPTON NUMBER VIOLATION AT COLLIDERS

Richard Ruiz (Cracow, INP), Evelyn Thomson (UPenn)

V. PROTON DECAY

Ed Kearns (Boston Univ.), Stuart Raby (Ohio State Univ.)

VI. N-NBAR OSCILLATIONS

Kaladi Babu (OSU), Leah Broussard (ORNL)

VII. MORE EXOTIC L AND B VIOLATING PROCESSES

Susan Gardner (Univ. of Kentucky), Julian Heeck (Univ. of Virginia)

VIII. CONNECTIONS TO COSMOLOGY

Andrew J. Long (Rice Univ.), Carlos Wagner (Univ. of Chicago/ANL)