Theories for Baryon and Lepton Number Violation

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Main Goal

Discuss different theories where one can understand the origin of Baryon and Lepton number violation

Introduction

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 !

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.

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

In theories where B and L are local gauge symmetries one predicts that these symmetries are spontaneously broken in 3 units.

B and L Violating Effective Operators

S. Weinberg, 1979

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

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

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

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

Explicit Breaking of B and L

The strong, weak and electromagnetic interactions are just different manifestations of the same fundamental interaction at low energies !

H. Georgi, S. Glashow, 1974

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \quad \Rightarrow \quad SU(5)$$

$$\Lambda_{\rm Weak} \sim 100 \text{ GeV} \qquad \Lambda_{\rm GUT} \sim 10^{15-16} \text{ GeV}$$

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

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

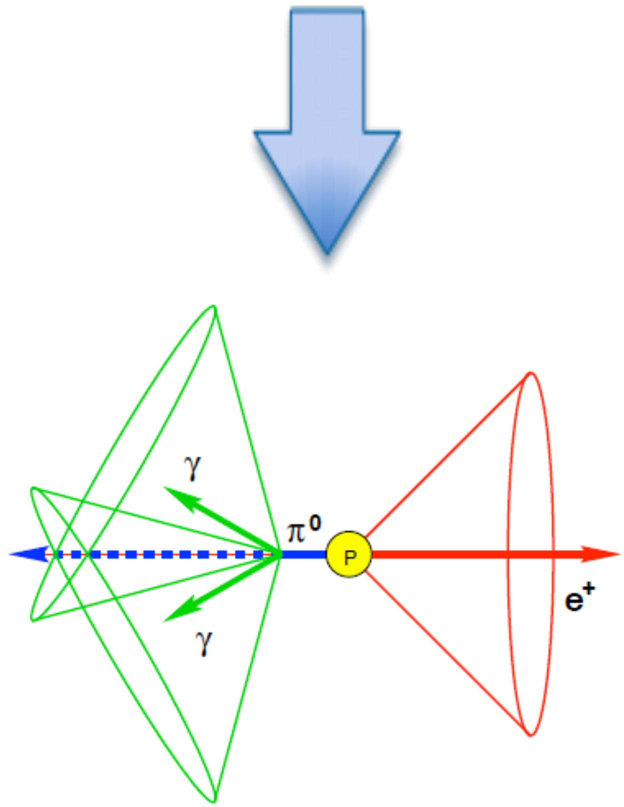
Higgs Bosons

$$5_H \qquad 24_H$$

B and L are explicitly broken !

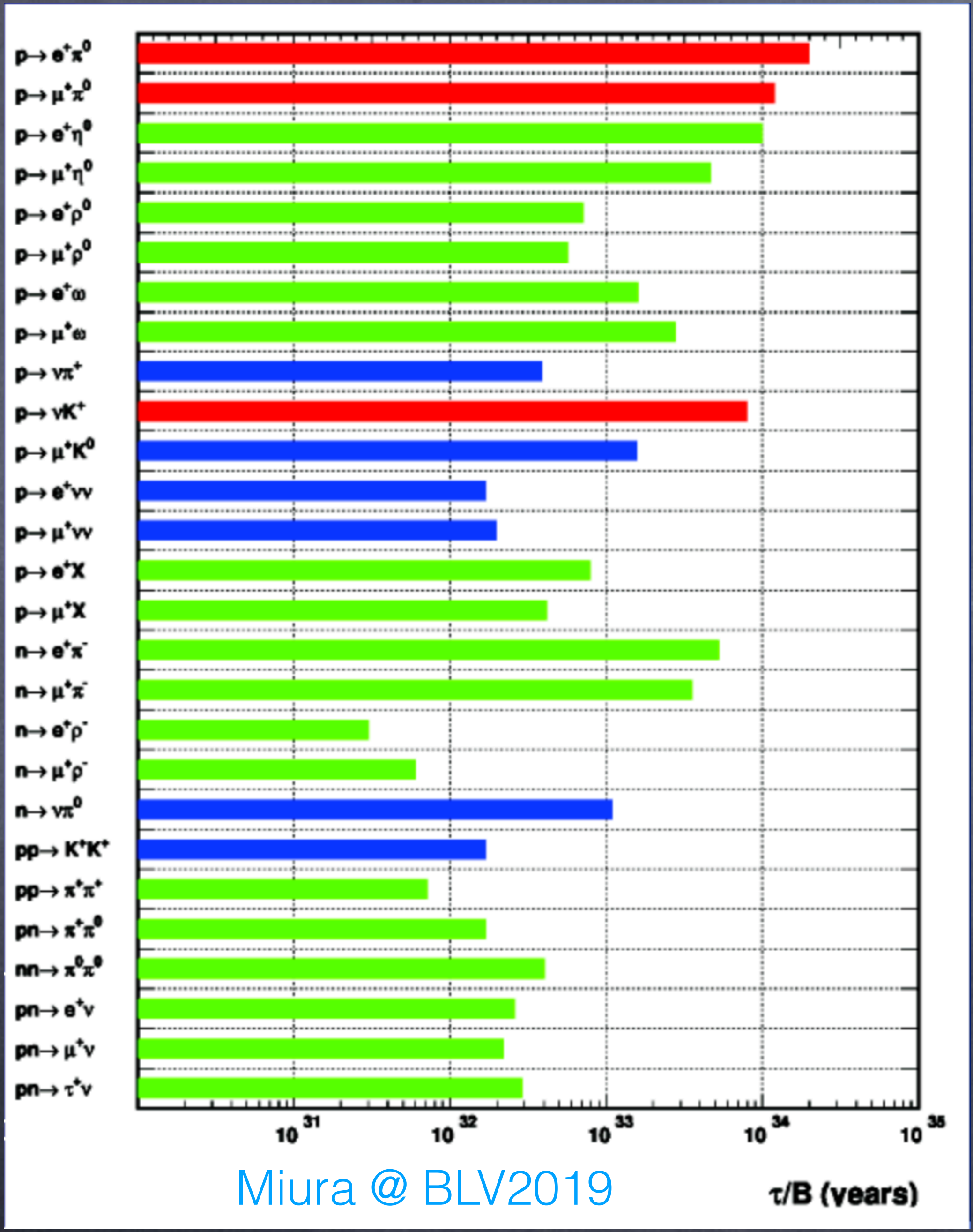
New Baryon and Lepton Number Violating Interactions

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



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

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

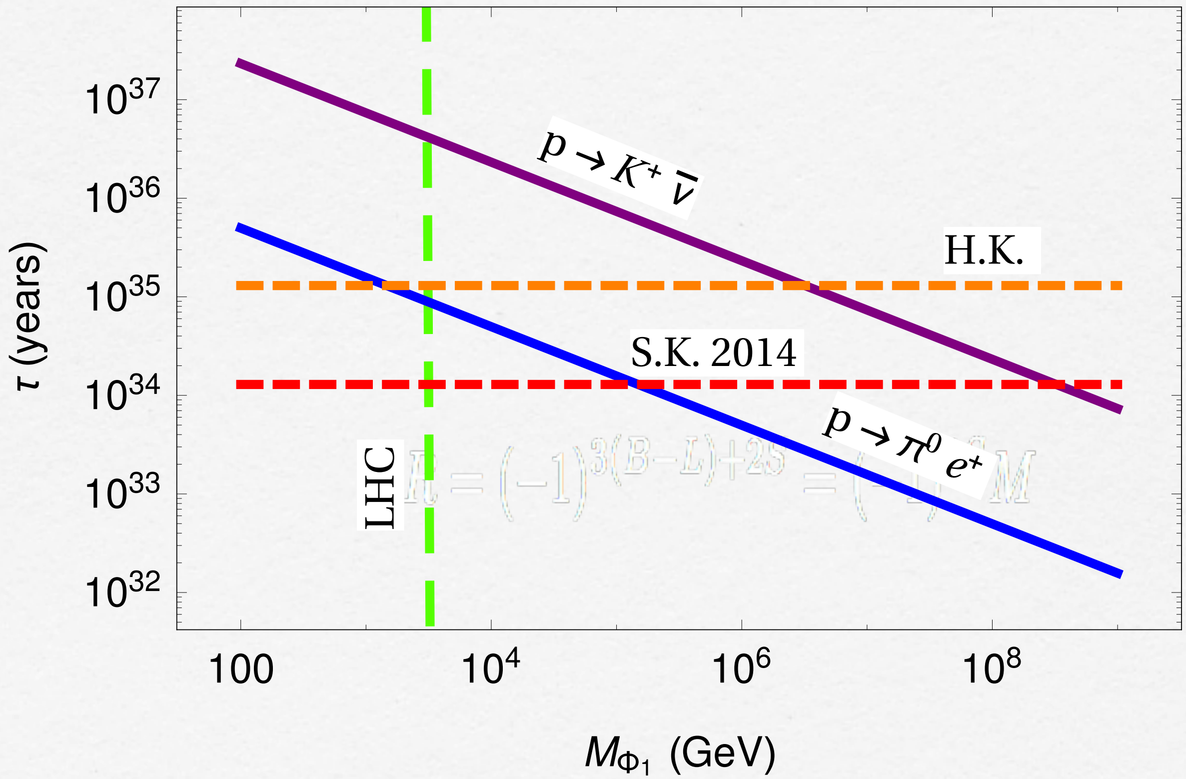


$M_V > 10^{14-15}\text{GeV}$

Renormalizable SU(5)

P.F.P., C. Murgui, 2016

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



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

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

P. F. P., A. Gross, C. Murgui, arXiv:1804.07831

Realistic SU(5) Theory

SM Matter:

$$\bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix}, \quad 10 = \begin{pmatrix} u^c & Q \\ Q & e^c \end{pmatrix}$$

$Y_e \neq Y_d$ ⇒

$$\bar{5}' = \begin{pmatrix} D^c \\ L \end{pmatrix}, \quad 5' = \begin{pmatrix} D \\ L^c \end{pmatrix}$$

$M_\nu \neq 0$ ⇒

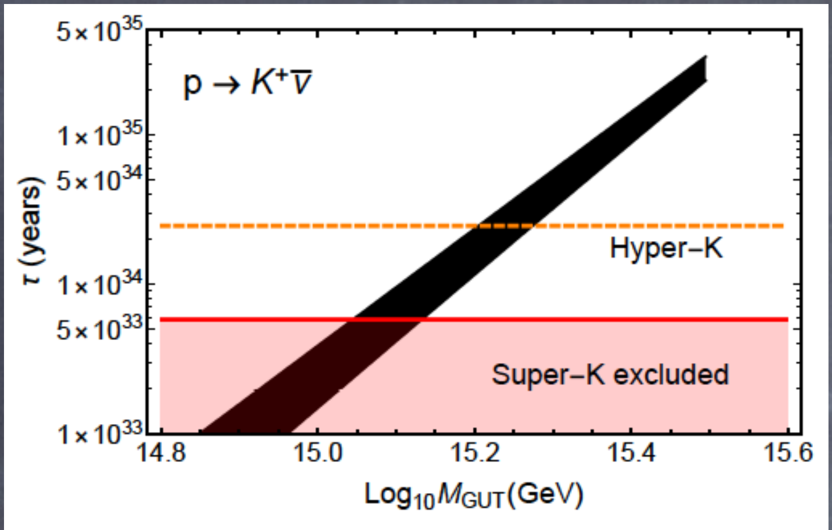
$$24 = \begin{pmatrix} \rho_8 & \rho_{(3,2)} \\ \rho_{(\bar{3},2)} & \rho_3 \end{pmatrix} + \lambda_{24}\rho_0$$

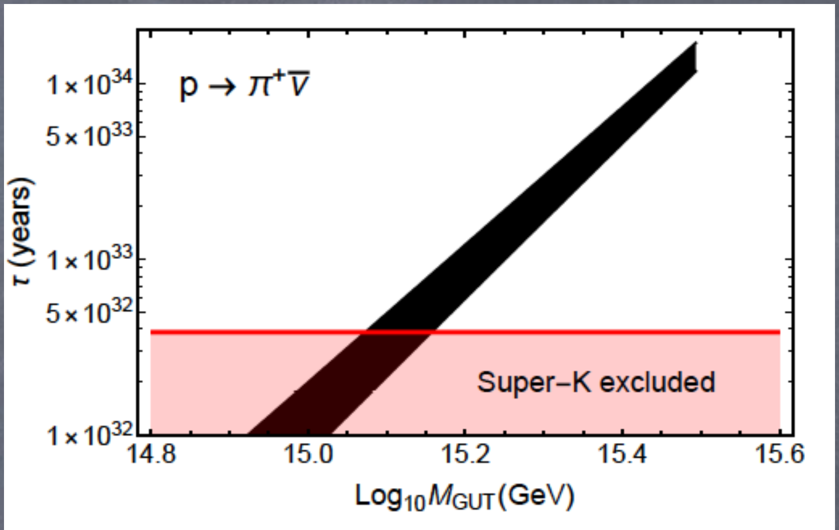
Bajc, Senjanovic'06

$$M_{\rho_8} = \hat{m}_{24} M_{\rho_3}, \quad M_{\rho_0} = \frac{1}{5}(3 + 2\,\hat{m}_{24}) M_{\rho_3}, \quad M_{\rho_{(3,2)}} = M_{\rho_{(3,2)}} = \frac{1}{2}(1 + \hat{m}_{24}) M_{\rho_3}.$$

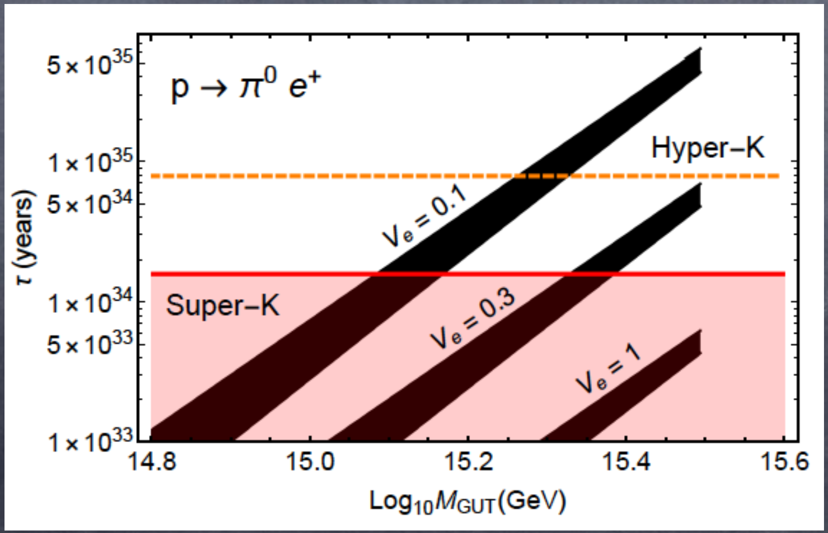
- *Phys.Rev.D* 98 (2018) 3, 035032 • e-Print: 1804.07831 [hep-ph]

P. F. P., A. Gross, C. Murgui, arXiv:1804.07831





$$\tau(p \to K^+\bar{\nu}) \lesssim 3.4 \times 10^{35} \text{ and } \tau(p \to \pi^+\bar{\nu}) \lesssim 1.7 \times 10^{34} \text{ years}$$



- *Phys.Rev.D* 98 (2018) 3, 035032 • e-Print: 1804.07831 [hep-ph]

SO(10) GUT

Fritsch, Minkowski '74

Georgi '74

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

G. Senjanovic @Neutrino2020

For the study of SO(10) theories see talks by
S. Raby and G. Senjanovic

B and L Violation in the Super-World

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 Conservation

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

If $\tilde{\chi}_1^0$ is the LSP can be a Cold Dark Matter Candidate

Signals with Multi-jets and Missing Energy at the LHC !

R-parity Violation

Baryon Number Violation:

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

Lepton Number Violation:

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

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

B and L Violation in the MSSM

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

$$\mathcal{W}^5_{RPC} = \frac{\lambda_\nu}{\Lambda} L L H_u H_u + \frac{\lambda_L}{\Lambda} Q Q Q L + \frac{\lambda_R}{\Lambda} u^c d^c u^c e^c$$

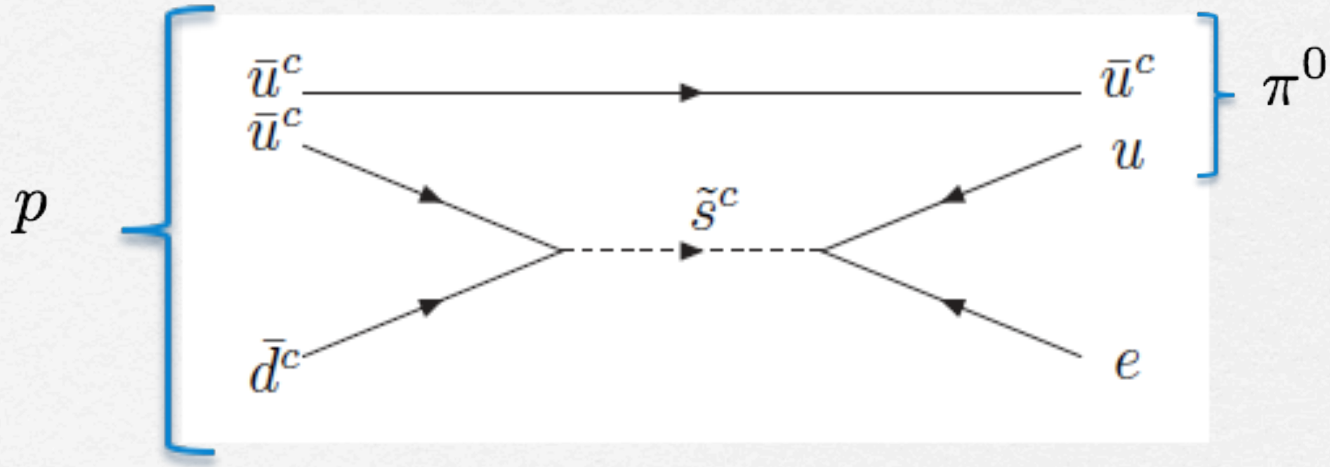
$$M = (-1)^{3(B-L)} \quad \begin{cases} M = -1 \text{ for } \hat{\mathrm{Q}}, \hat{\mathrm{u}}^{\mathrm{c}}, \hat{\mathrm{d}}^{\mathrm{c}}, \hat{\mathrm{L}}, \hat{\mathrm{e}}^{\mathrm{c}}, \hat{\nu}^{\mathrm{c}} \\ M = +1 \text{ for } \hat{\mathrm{H}}_{\mathrm{u}}, \hat{\mathrm{H}}_{\mathrm{d}}, \hat{\mathrm{V}}_{\mathrm{i}} \end{cases}$$

See e.g. P. Nath, P. Fileviez Perez, Physics Reports 441:191,2007

Proton Decay and R-Parity

$\lambda^{'} Q L d^c$

$\lambda^{''} u^c d^c d^c$

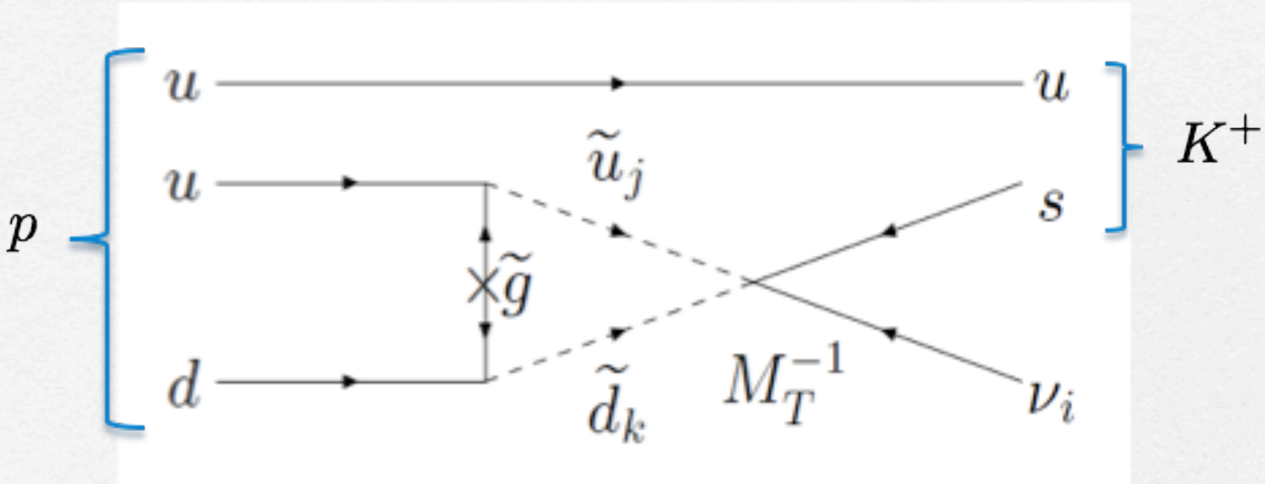


$M_{\tilde{q}} \sim 10^3$ GeV → $\tau_4 \sim 10^{-20}$ years

d=5 operators

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

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



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

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

see e.g. Bajc, P. F. P., Senjanovic

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

What is the origin of the lepton and baryon number violating interactions in the MSSM?

Matter-Parity:

$$M = (-1)^{3(B-L)}$$

$$B - L \longleftrightarrow M$$

B-L Symmetry and M-parity

Aulakh, Mohapatra, 1982
Hayashi, A. Murayama, 1985
Mohapatra, 1986
Krauss, Wilczek, 1988
Font, Ibanez, Quevedo, 1989
Masiero, Valle, 1990
Martin, 1992
Aulakh, Bajc, Melfo, Senjanovic, 2001
P. F. P., S. Spinner, 2008-2012
V. Barger, P. F. P., S. Spinner, 2008
Ovrut, Purves, Spinner, 2015
Marshall, Ovrut, Purves, Spinner, 2014
P. F. P., Spinner, 2013

P.F.P., S. Spinner, Phys. Lett. B 673 (2009)251

V. Barger, P. Fileviez Perez, S. Spinner, Phys. Rev. Lett.102:181802,2009

Minimal B-L Theory for R-Parity Violation

$$G_{B-L} = SU(3)_C \bigotimes SU(2)_L \bigotimes U(1)_Y \bigotimes U(1)_{B-L}$$

Matter:

$Q \sim (3, 2, 1/3, 1/3)$ $L \sim (1, 2, -1, -1)$

$u^c \sim (\bar{3}, 1, -4/3, -1/3)$ $e^c \sim (1, 1, 2, 1)$

$d^c \sim (\bar{3}, 1, 2/3, -1/3)$

$\nu^c \sim (1, 1, 0, 1)$ **(for anomaly cancellation)**

Symmetry Breaking and SRpV

$$G_{B-L} \Rightarrow G_{SM} \qquad \left\{ \langle \tilde{\nu}^c \rangle = \frac{v_R}{\sqrt{2}} \right\}$$

$$\left. \begin{array}{l} \langle H_u^0 \rangle = \dfrac{v_u}{\sqrt{2}} \\ \langle H_d^0 \rangle = \dfrac{v_d}{\sqrt{2}} \end{array} \right\} \qquad G_{SM} \Rightarrow SU(3)_C \bigotimes U(1)_{em}$$

$$\langle \tilde{\nu} \rangle = \frac{v_L}{\sqrt{2}} \neq 0$$

New Theory with R-parity violation !

The Minimal SUSY B-L Model predicts

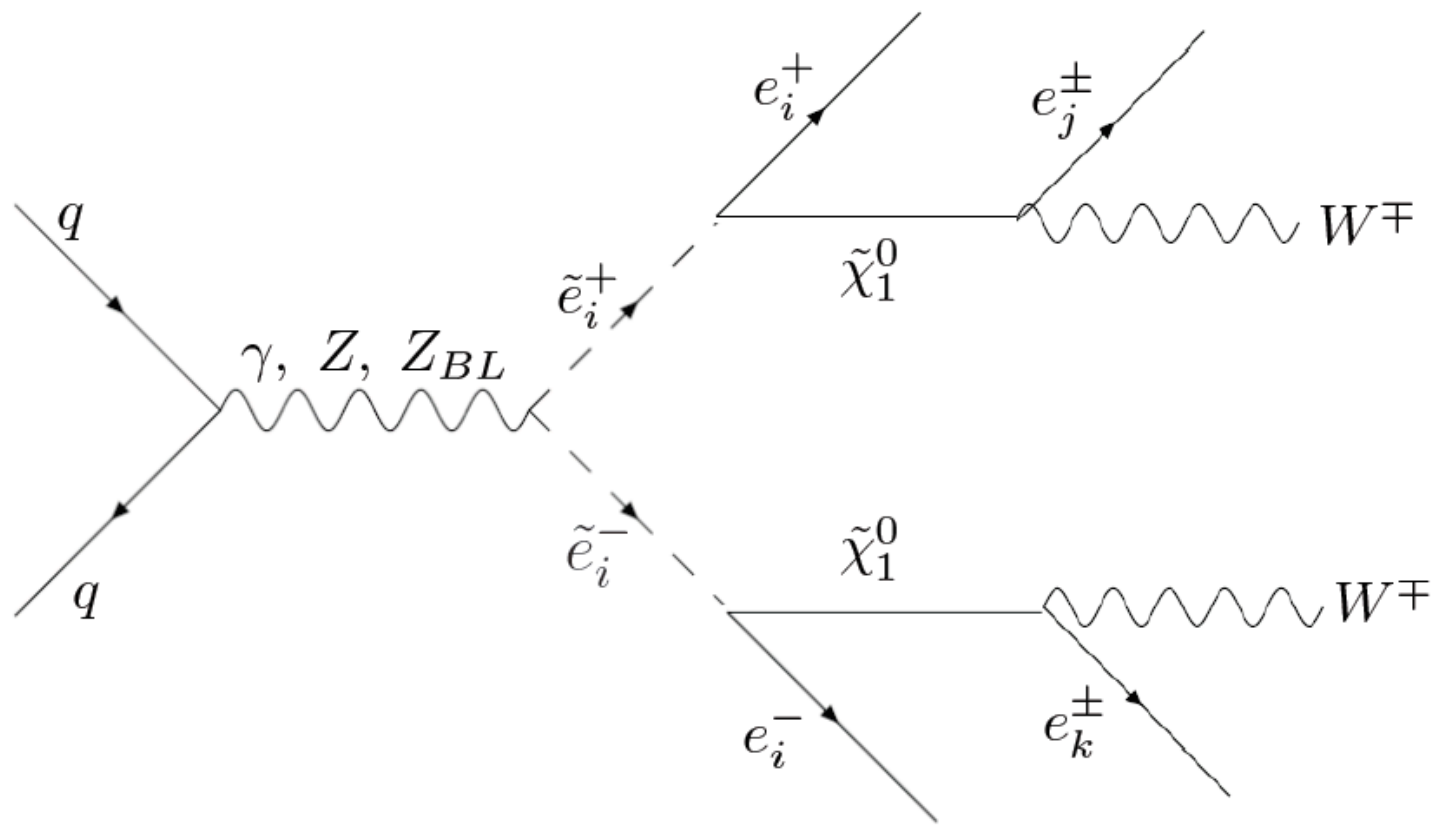
- R-parity must be spontaneously broken !

- The B-L and R-parity breaking scales are defined by the SUSY scale.

- Lepton number violating signals at the LHC ?

Neutralino as the LSP

P. F. P., S. Spinner, JHEP 1204 (2012) 118

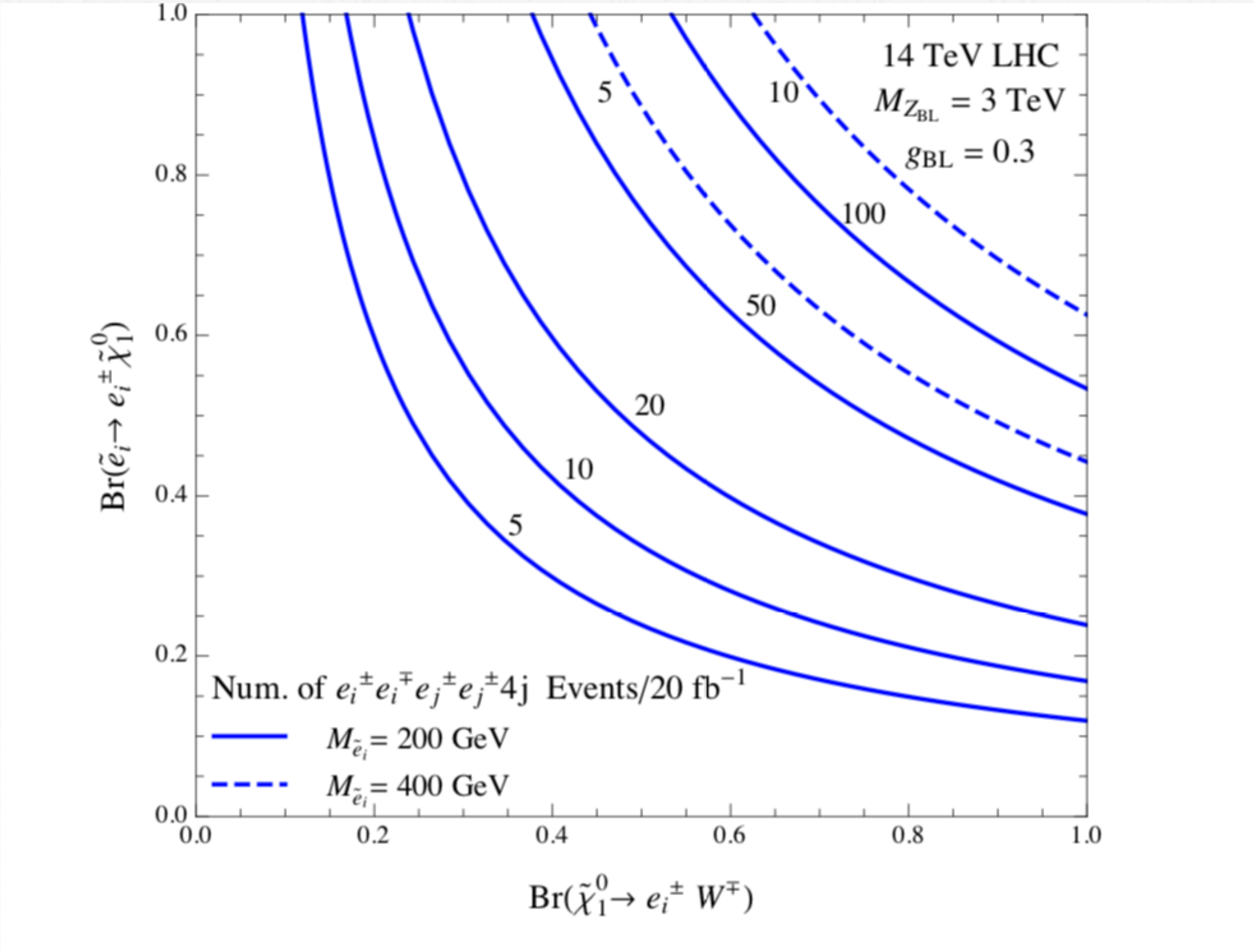


$$q\bar{q} \rightarrow \gamma, Z^*, Z^*_{BL} \rightarrow \tilde{e}_i^* \tilde{e}_i \rightarrow e_i^+ e_i^- \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow e_i^+ e_i^- e_j^\pm e_k^\pm \, 4j,$$

P. F. P., S. Spinner, Phys.Lett.B 728 (2014) 489-495

Discovery Reach at the LHC

$\mathcal{L} = 20\ \text{fb}^{-1}$.

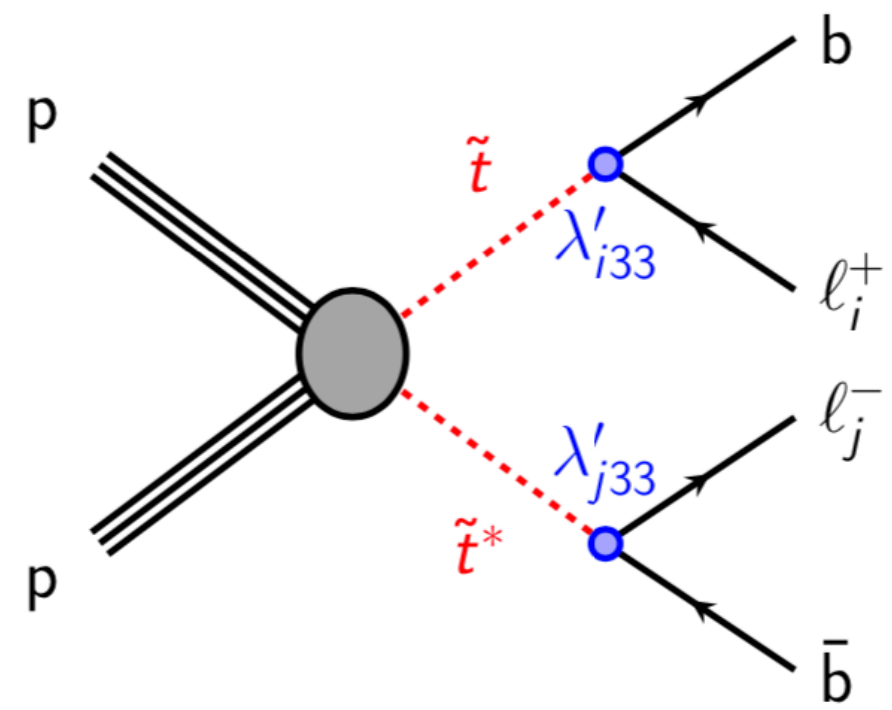


Phys. Rev. D 97 (2018) 032003
DOI: 10.1103/PhysRevD.97.032003

CERN-EP-2017-171
February 16, 2018

A search for $B - L$ R-parity-violating top squarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS experiment

The ATLAS Collaboration



Phys. Rev. D 97 (2018) 032003
DOI: 10.1103/PhysRevD.97.032003

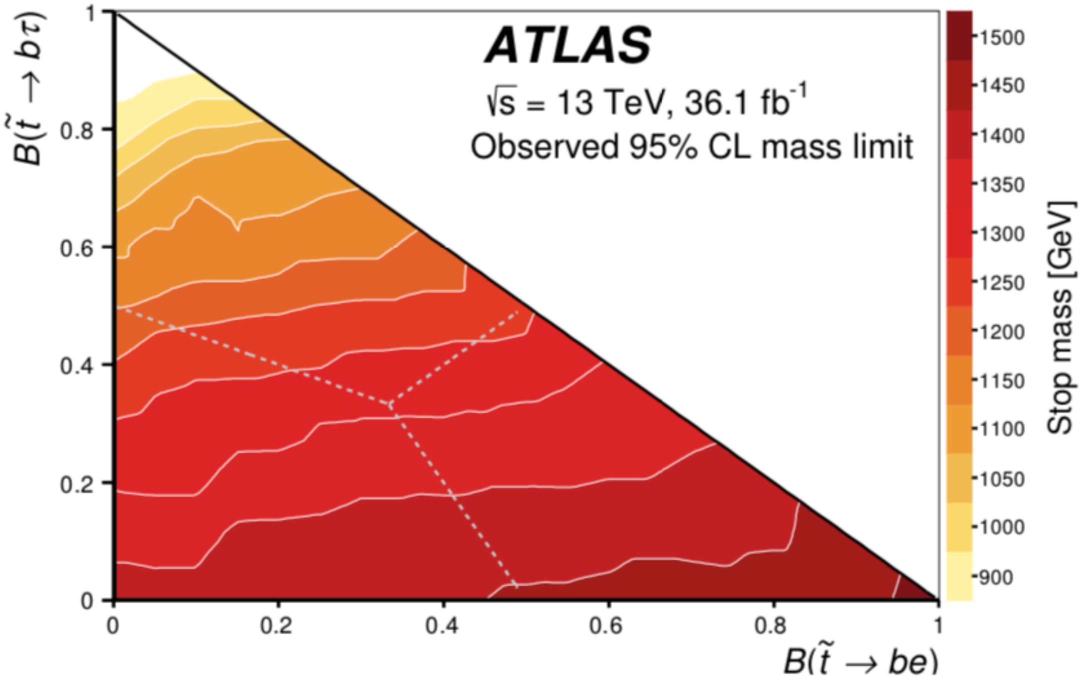


Figure 7: The observed lower limits on the $\tilde{t}$ mass at 95% CL as a function of $\tilde{t}$ branching ratios. The sum of $\mathcal{B}(\tilde{t} \to be)$, $\mathcal{B}(\tilde{t} \to b\mu)$, and $\mathcal{B}(\tilde{t} \to b\tau)$ is assumed to be unity everywhere, and points of equality are marked by a dotted gray line. The limits are obtained using the nominal $\tilde{t}$ cross-section predictions. As the branching ratio $\mathcal{B}(\tilde{t} \to b\tau)$ increases, the expected number of events with electrons or muons in the final state decreases, reducing the mass reach of the exclusion.

The Minimal B-L Theory predicts:

- **R-parity must be spontaneously broken.**
- **The B-L and R-parity violating scales are defined by the SUSY breaking scale.**
- **Two light sterile neutrinos.**
- **Lepton number violating signals and displaced vertices at the LHC.**

Spontaneous B and L Breaking

Main Idea:

Baryon and Lepton Number as Local Gauge Symmetries

A. Pais, Phys. Rev. D8 (1973), 1844

S. Rajpoot, Int. J.Theor.Phys. 27 (1988) 689

R. Foot, G. C. Joshi, H. Lew, Phys.Rev. D40 (1989) 2487-2489

C. Carone, H. Murayama,Phys.Rev. D52 (1995) 484-493

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Physical Review Letters 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P. F. P., Physics Reports 597 (2015)

P. F. P., M. B. Wise

Breaking B and L at the TeV scale !

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

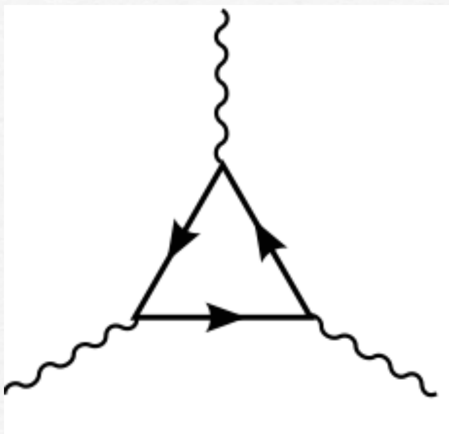
where $U(1)_B$ and $\mathrm{U(1)_L}$ can be broken at the TeV Scale !

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

How to define an anomaly free theory ?

Anomaly Cancellation

Baryonic Anomalies:



$$\mathcal{A}_1\left(SU(3)^2\otimes U(1)_B\right),\ \mathcal{A}_2\left(SU(2)^2\otimes U(1)_B\right),$$
$$\mathcal{A}_3\left(U(1)_Y^2\otimes U(1)_B\right),\ \mathcal{A}_4\left(U(1)_Y\otimes U(1)_B^2\right),$$
$$\mathcal{A}_5\left(U(1)_B\right),\ \mathcal{A}_6\left(U(1)_B^3\right),$$

In the SM: $\mathcal{A}_2 = -\mathcal{A}_3 = 3/2$

Different Solutions for Anomaly free theories:

- ~~Sequential Family~~
- ~~Mirror family~~
- Vector-like Fermions

P. F. P., M. B. Wise, PRD82 (2010)011901; JHEP1108(2011)068

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110 (2013) 231801

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3,037701

P.F.P., Physics Reports 597 (2015)

Realistic theories:

1- Four representations

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3, 037701

2- Six representations

M. Duerr, P. F. P., M. B. Wise, Phys. Rev. Lett. 110 (2013) 231801

3- One vector-like family

P. F. P., M. B. Wise, JHEP1108(2011)068

P. F. P., S. Ohmer, H. H. Patel, Phys. Rev. D90 (2014)3, 037701

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

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

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

New Higgs: $S_B \sim (1, 1, 0, 3)$

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

Gauge Theory for Proton Stability !

P.F.P., Physics Reports 597 (2015)

Some Features:

Dark Matter: χ CDM candidate from anomaly cancellation

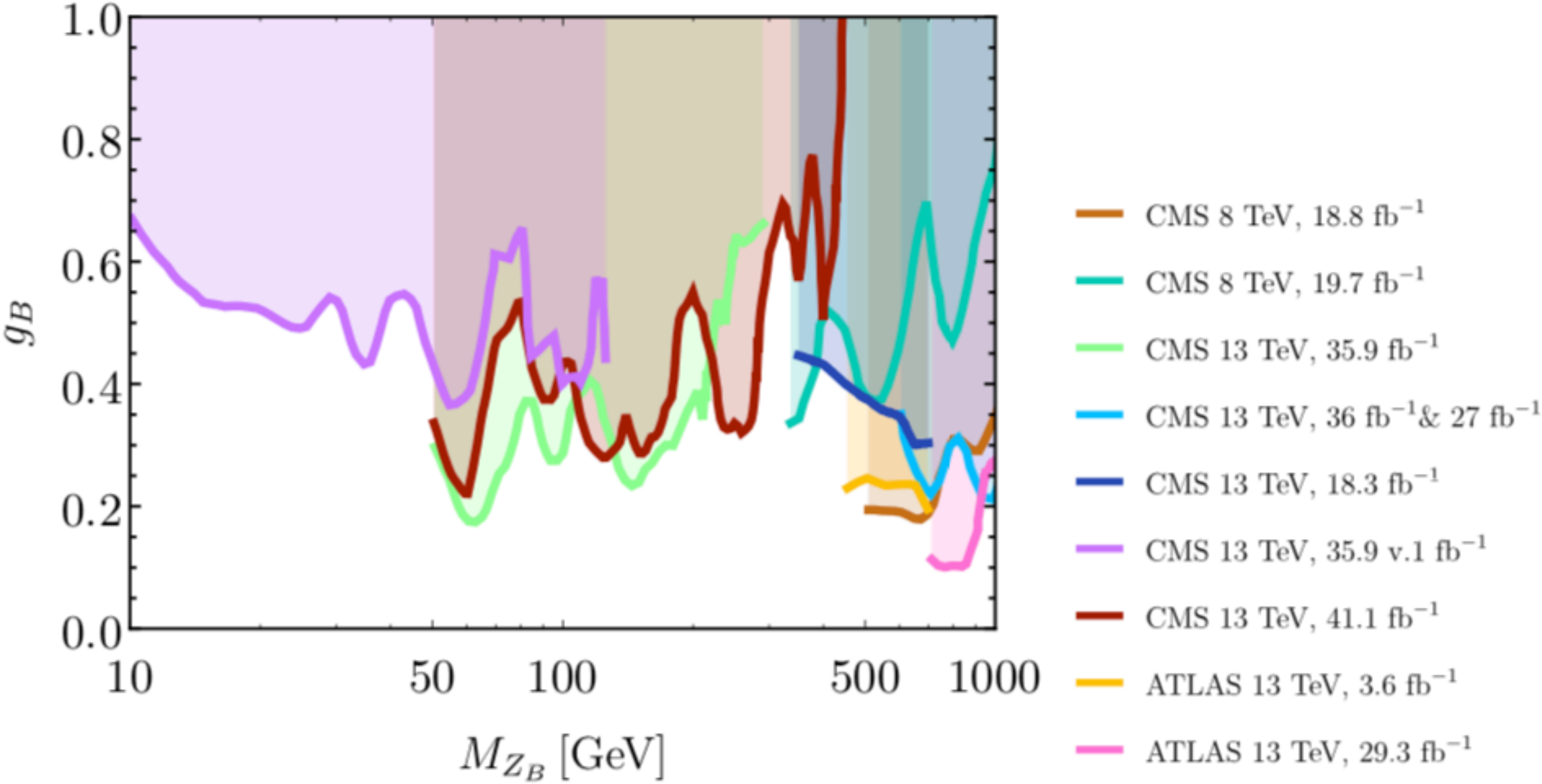
Leptophobic Gauge Boson: $Z_B \to \bar{q}q, \bar{\chi}\chi$

New Higgs Boson: $h_2 \to \bar{q}q, WW, ZZ, hh, \bar{\chi}\chi$

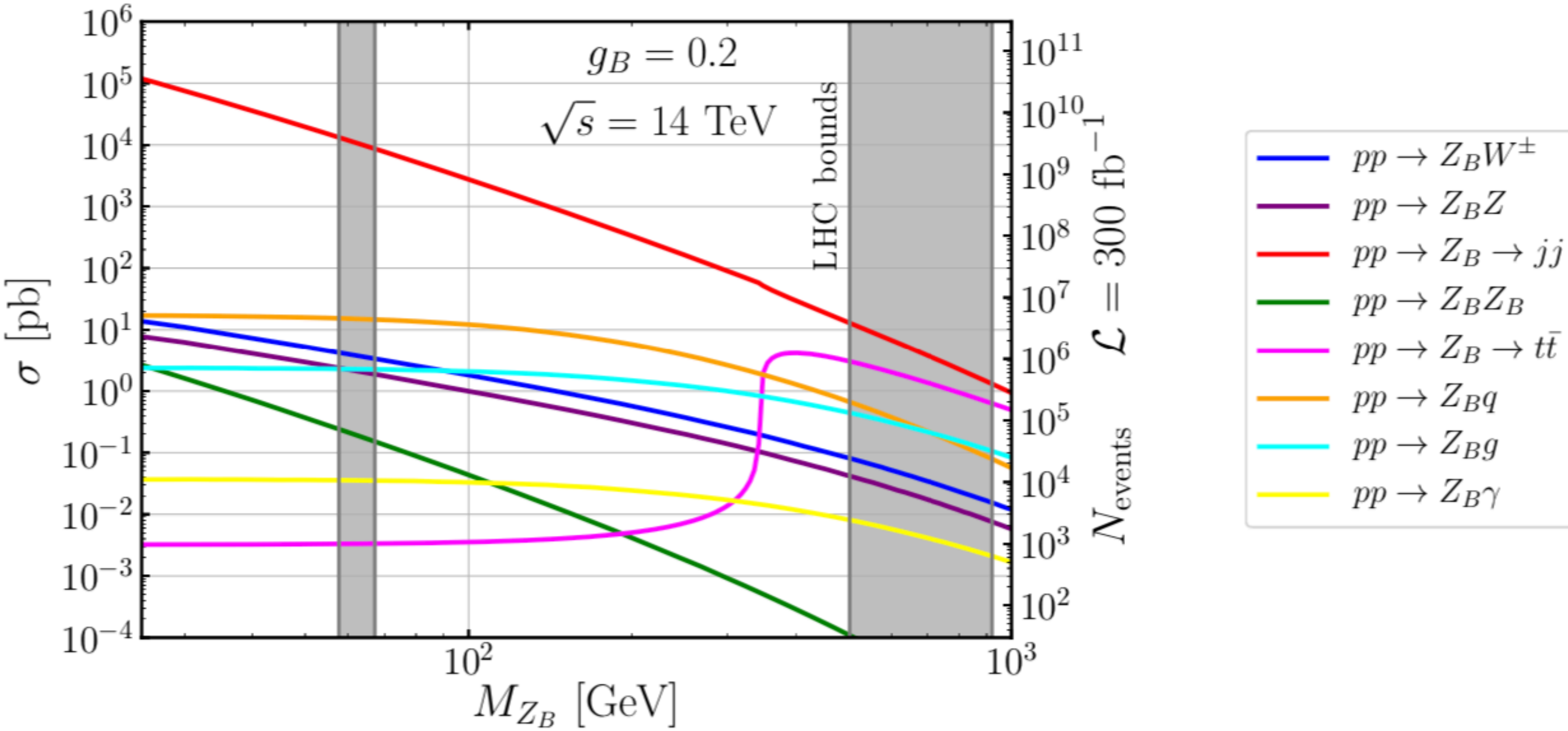
Missing Energy at the LHC: $pp \to Z_B h_2 \to \bar{t}t\bar{\chi}\chi \to \bar{t}tE_T^{\text{miss}}$

P. F. P., E. Golias, C. Murgui, A.D. Plascencia, 2020

Collider Bounds



P. F. P., E. Golias, C. Murgui, A.D. Plascencia, 2020



P. F. P., E. Golias, RH. Li, C. Murgui, A. D. Plascencia, Phys. Rev. D 100, 015017 (2019)

Majorana Leptophobic DM

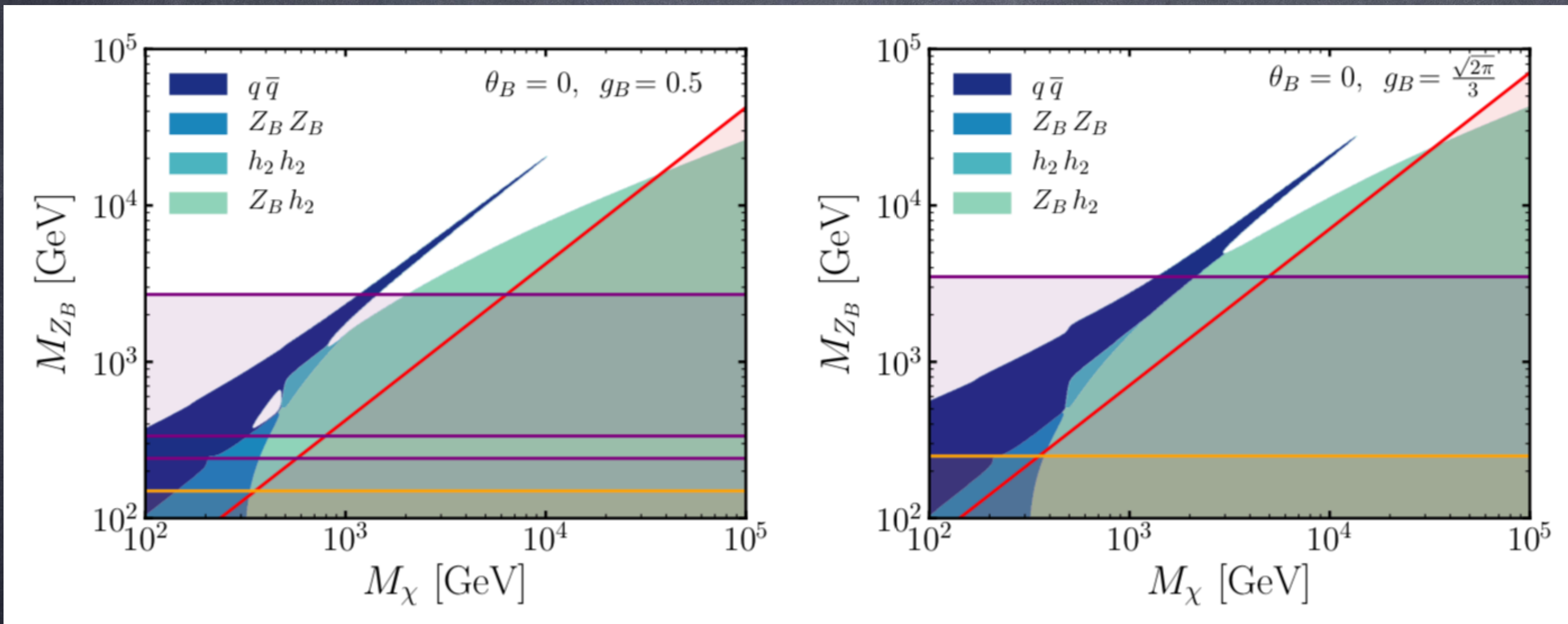
$$\mathcal{L} \supset i\overline{\chi}_L \gamma^\mu D_\mu \chi_L - \left(\frac{\lambda_\chi}{\sqrt{2}} \chi_L^T C \chi_L S_B^* + \text{h.c.} \right),$$

$$S_B \sim (1, 1, 0, 3).$$

$$\mathcal{L} \supset \frac{3}{4} g_B \bar{\chi} \gamma^\mu \gamma^5 \chi Z_\mu^B - \frac{1}{3} g_B \bar{q} \gamma^\mu q Z_\mu^B + \frac{M_\chi}{2 v_B} \sin\theta_B \bar{\chi}\chi h_1 - \frac{M_\chi}{2 v_B} \cos\theta_B \bar{\chi}\chi h_2 - \frac{1}{2} M_\chi \bar{\chi}\chi,$$

$$\chi\chi \to \bar{q}q,\ Z_B Z_B,\ Z_B h_1,\ Z_B h_2,\ h_1 h_1,\ h_1 h_2,\ h_2 h_2,\ WW,\ ZZ.$$

P. F. P., E. Golias, RH. Li, C. Murgui, A. D. Plascencia, Phys. Rev. D 100, 015017 (2019)



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

Spontaneous Baryon Number Violation

The scale for baryon number violation must be low to be in agreement with cosmology and one could test the spontaneous breaking of baryon number at colliders

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 at the TeV scale. The existence of B and L violating interactions could play a major role in the discovery. The minimal SUSY B-L predicts spontaneous R-parity (or L) violation at the SUSY scale.

B and L could be local gauge symmetries spontaneously broken at the low scale. The minimal theory 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.

P. Fileviez Perez