Theories for Baryon and Lepton Number Violation

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think beyond the possible

Rare Processes and Precision Frontier Workshop, July 27, 2020

RF4: Baryon and Lepton Number Violating Processes

co-Conveners: https://snowmass21.org/rare/blv

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Topical groups:

1- Theories for B and L number violation: P. Fileviez Perez (CWRU), M.B. Wise (Caltech)

2- Neutrinoless double beta decays: V. Cirigliano (LANL), A. Pocar (UMass)

3- B and L violation at colliders: R. Ruiz (Lovain Univ.), E. Thomson (UPenn)

4- Proton decay: E. Kearns (Boston Univ.), S. Raby (OSU)

5- n-nbar oscillations: K. Babu (OSU), L. Broussard (ORNL)

6- More exotic L and B violating processes: S. Gardner (UK), J. Heeck (UCI)

7- Connections to Cosmology: A. Long (Rice Univ.), C. Wagner (Univ. of Chicago/ANL)

RF4: Baryon and Lepton Number Violating Processes

https://snowmass21.org/rare/blv

Activities:

BLV circa 2020, July 6-8, 2020, hosted by Case Western Reserve University

https://artsci.case.edu/blv2020/

ACFI Workshop, Aug 3-6, 2020, Univ. of Massachusetts-Amherst

Introduction

Theories for Physics beyond the Standard Model

Example 1: In grand unified theories (SU(5), SO(10),..) B and L are explicitly broken at the high scale.

Example 2: In the MSSM B and L are explicitly broken at the renormalizable level by RpV interactions.

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

In general we can have explicit B and L breaking or Spontaneous B and L violation and we should investigate all new phenomena and the implications for cosmology !

B and L Violating Effective Operators

S. Weinberg, 1979

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

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

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

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

Example 1: 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

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

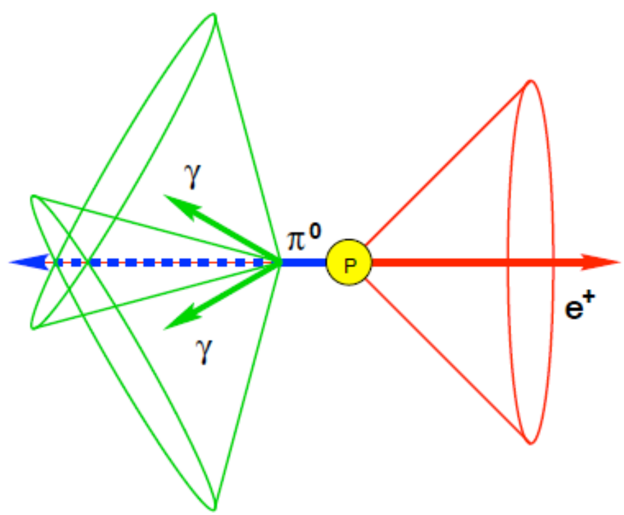
Higgs Bosons

$$5_H \qquad 24_H$$

B and L are explicitly broken !

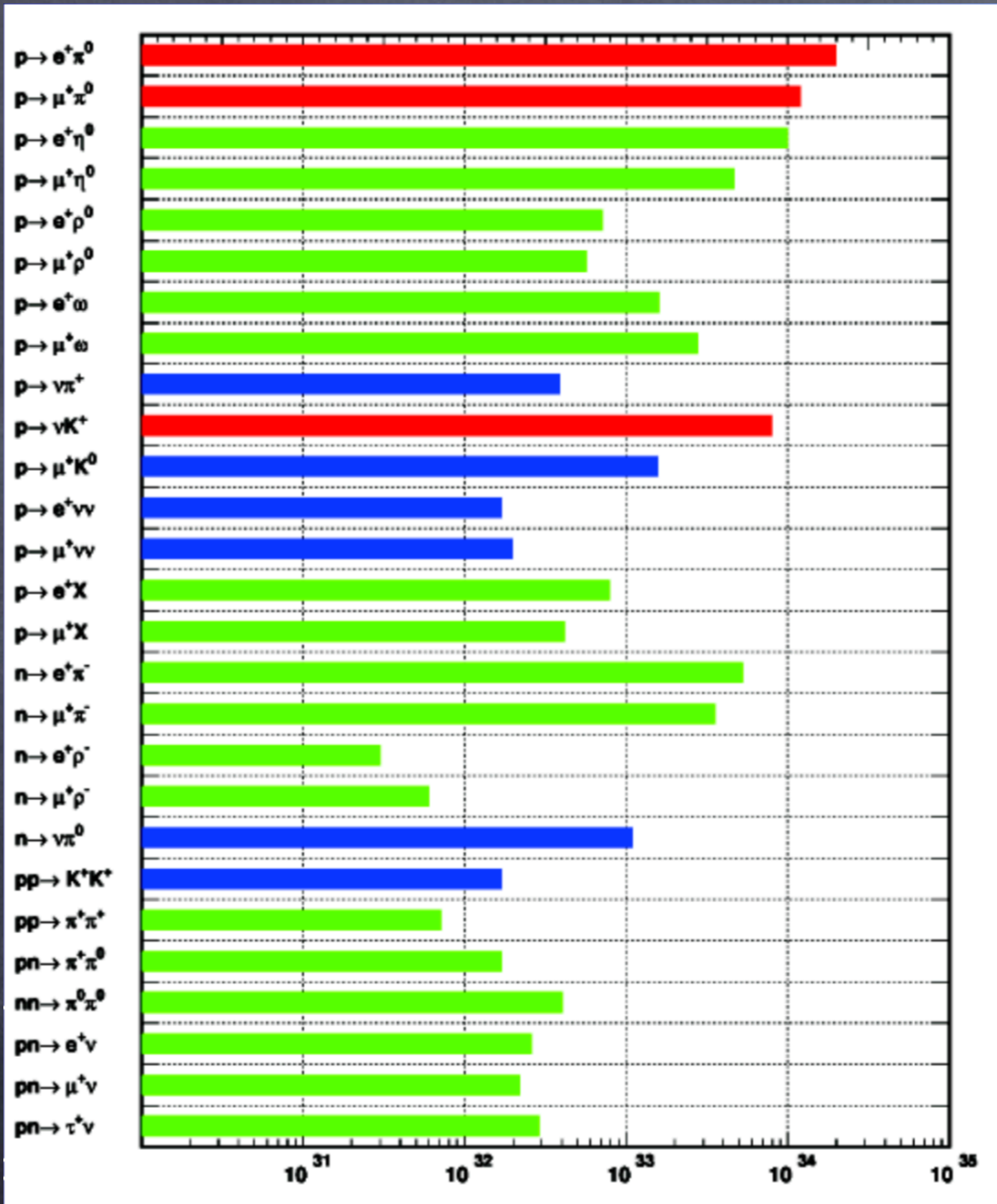
New Baryon and Lepton Number Violating Interactions

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



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

Proton Decay:



Miura @ BLV2019

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

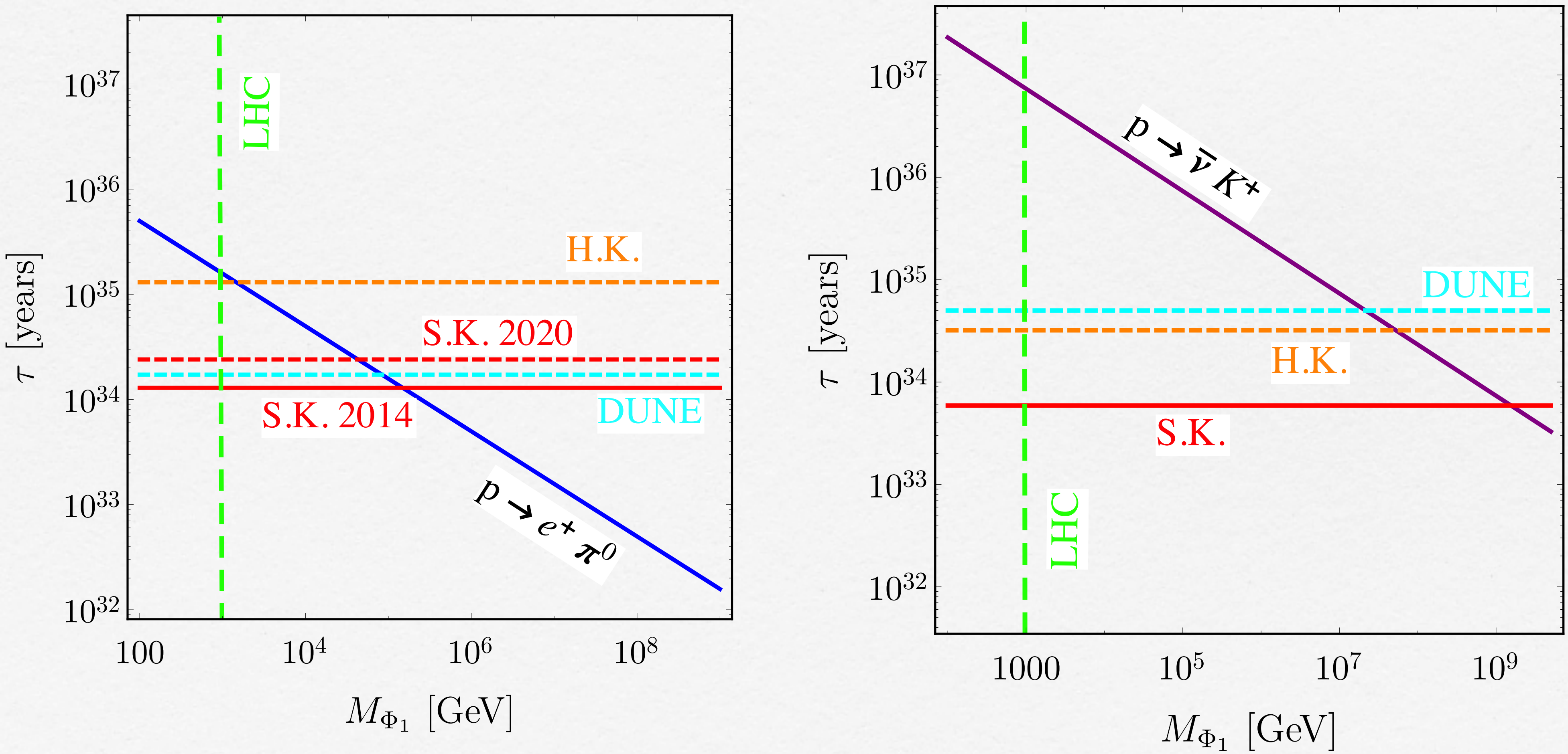
$$M_V > 10^{14-15}\text{GeV}$$

see talk by E. Kearns @ BLV circa 2020

Renormalizable SU(5)

ArXiv: 1604.03377

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



Explicit Breaking of B and L

Example 2: Supersymmetry

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

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

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:

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

Lepton Number Violation:

$$p\,p \;\rightarrow\; \tilde{g}\,\tilde{g} \;\rightarrow\; t\,t\,\tilde{t}^*\,\tilde{t}^* \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,\tilde{\chi}^0_1\,\tilde{\chi}^0_1 \;\rightarrow\; t\,t\,\bar{t}\,\bar{t}\,e^\pm_i\,e^\pm_j\,W^\mp\,W^\mp$$

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

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

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

Matter-Parity:

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

$$B - L \quad \Longleftrightarrow \quad M$$

Phys. Rev. Lett.102:181802, 2009, arXiv:0812.3661

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:

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

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

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

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

Phys. Rev. Lett.102:181802, 2009, arXiv:0812.3661

Symmetry Breaking and SRpV

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

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

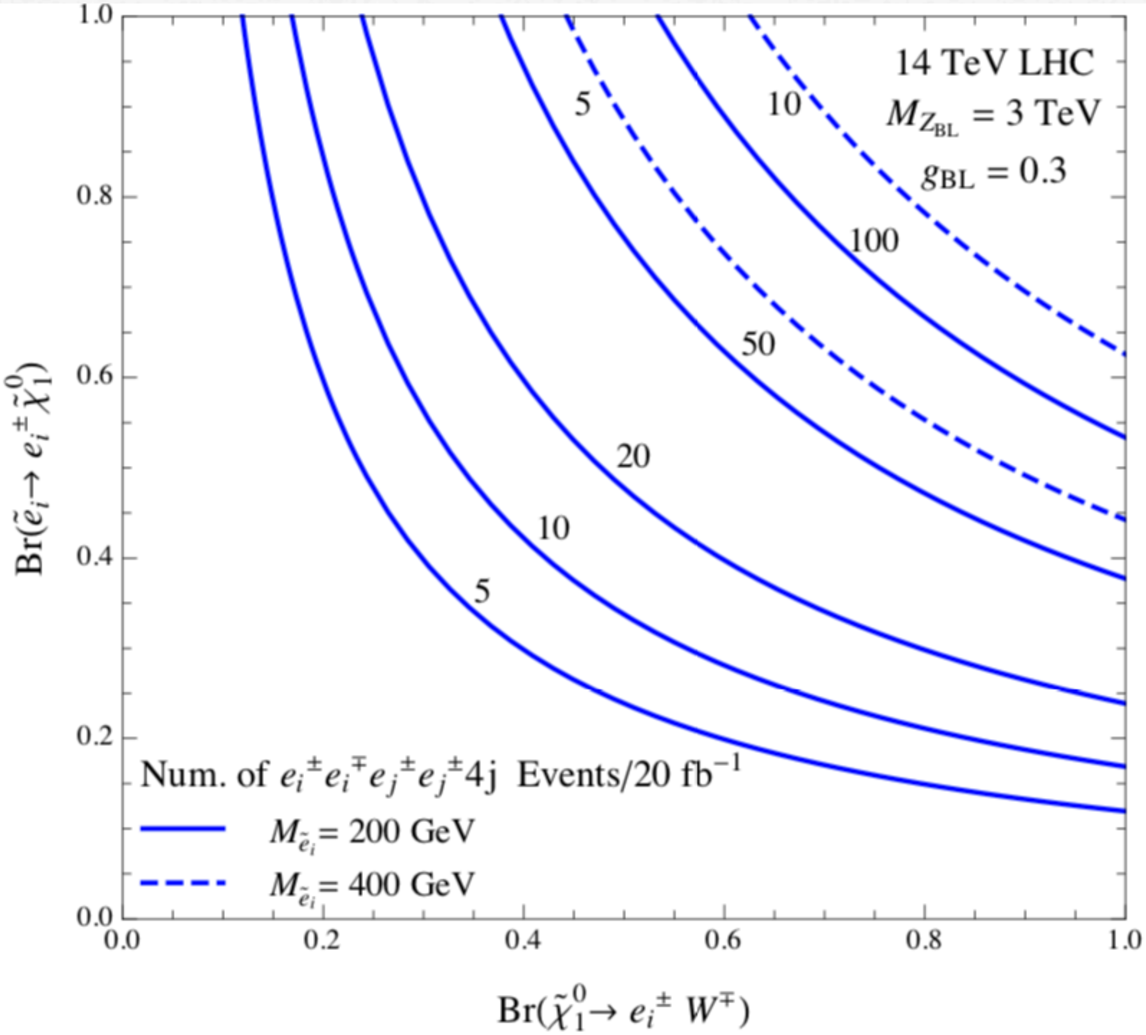
$$\langle \tilde{\nu} \rangle = \frac{v_L}{\sqrt{2}} \neq 0$$

New Theory with R-parity violation !

Discovery Reach at the LHC

Phys.Lett.B 728 (2014) 489-495

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

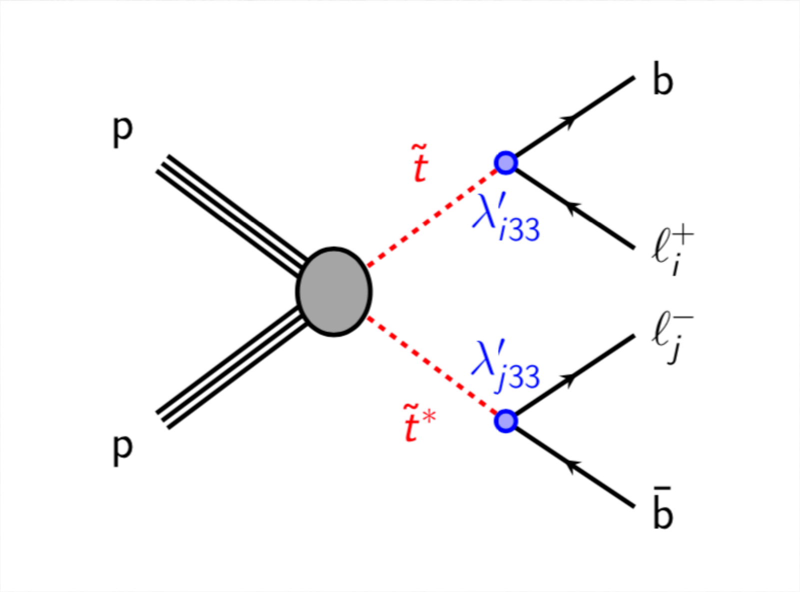


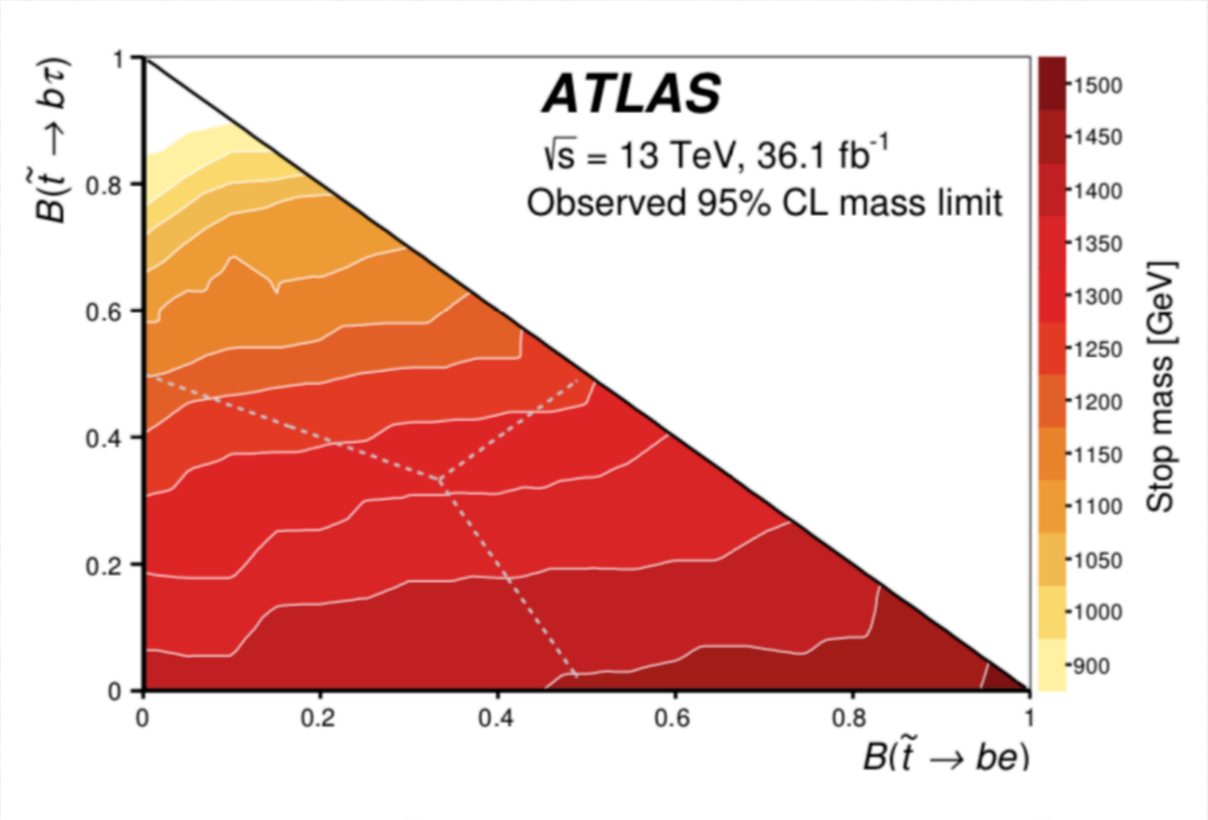
$\mathcal{L} = 20 \text{ fb}^{-1}$.

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





Spontaneous B and L Breaking

Main Idea:

Baryon and Lepton Number as Local Gauge Symmetries

see e.g. P. F. P., Physics Reports 597 (2015), arXiv:1501.01886

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

Spontaneous Breaking of B and L

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

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 ?

see e.g. Physics Reports 597 (2015), arXiv:1501.01886

Phys. Rev. D90 (2014)3, 037701, arXiv:1403.8029

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

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

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

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

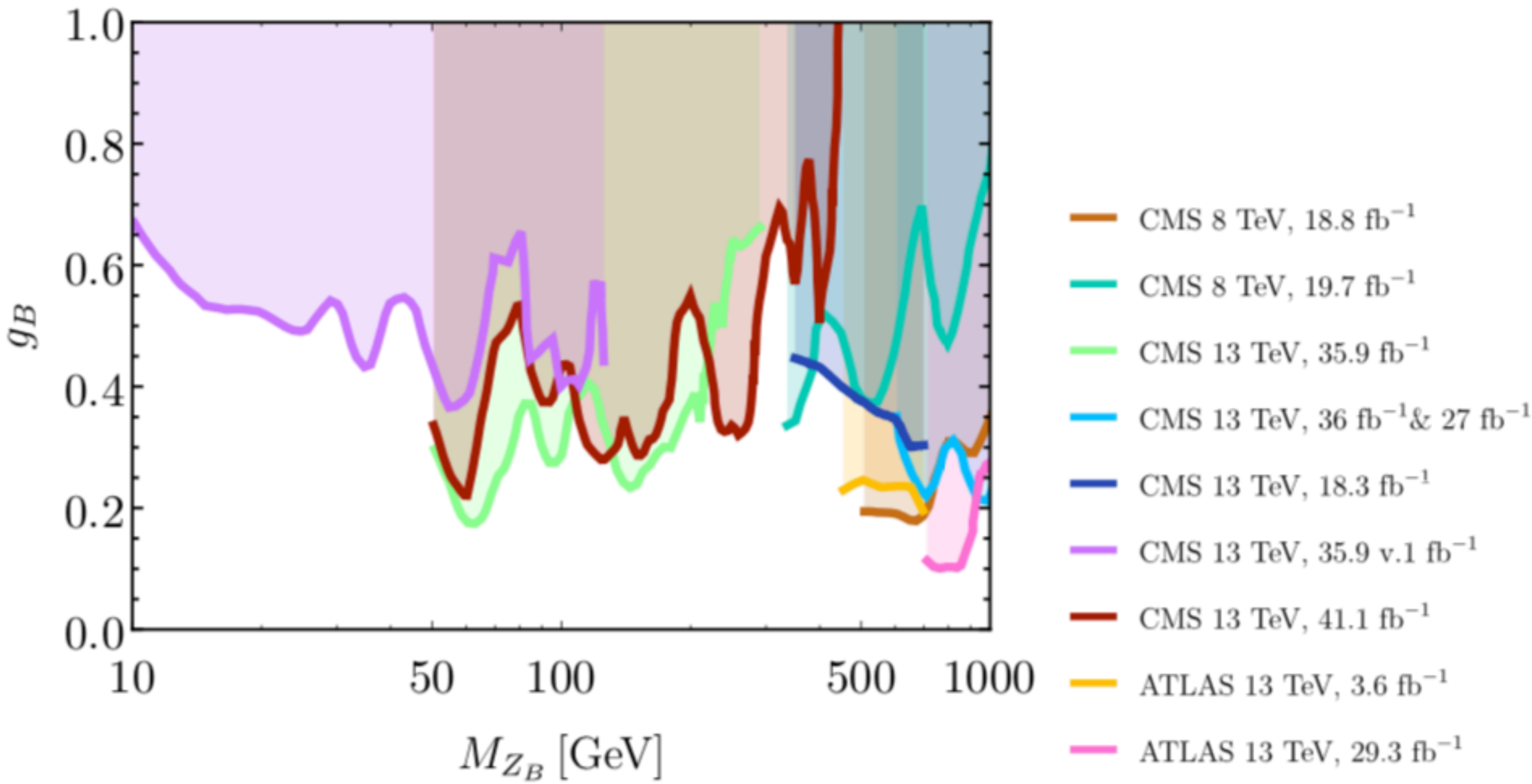
New Higgs: $S_B \sim (1,1,0,3)$

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

Gauge Theory for Proton Stability !

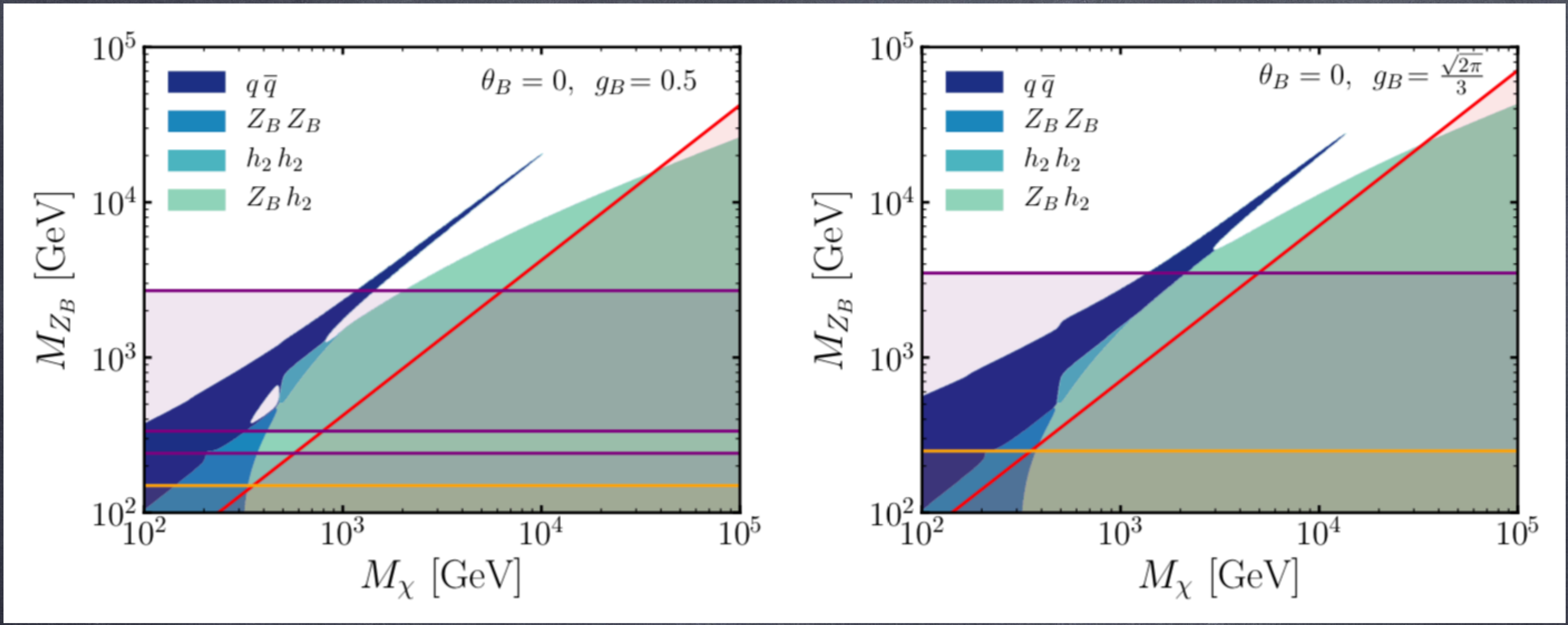
see also: Physical Review Letters 110, 231801 (2013), arXiv:1304.0576

Collider Bounds



ArXiv: 2003.09426

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



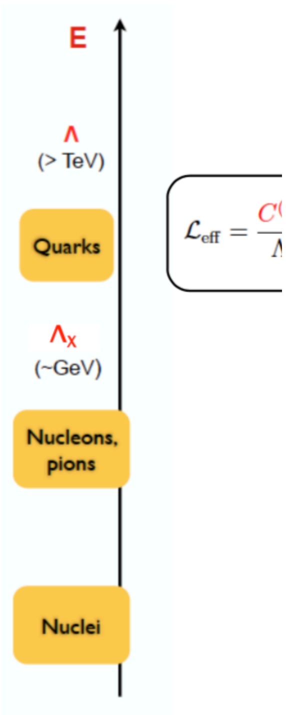
Phys. Rev. D 100, 015017 (2019), arXiv: 1904.01017

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

Other Aspects

Neutrinoless double beta decay

`End-to-end' EFT framework for $0\nu\beta\beta$



$\mathcal{L}_{\rm BSM}$

Chain of EFTs +

Hadronic matrix elements (LQCD,…
& many-body methods

Conclusions & Outlook

- Challenges & opportunities in the context of Snowmass 2021. Two coupled theoretical thrusts:
- Controlled theory uncertainty: a lot to do, but exciting prospects thanks to advances and cross fertilization in EFT, lattice QCD, and nuclear structure
- Model diagnosing: what do we learn about the underlying LNV model from a positive (null) experimental result? Tools:
  - Within $0\nu\beta\beta$: total rate variation with isotope; differential rate: single electron spectra and electron's angle.
  - $0\nu\beta\beta$ vs other probes: meson & lepton decays, collider, cLFV, …
- ….

talk by V. Cirigliano @ BLV circa 2020

Proton Decay

JHEP 06, 084 (2010)

$$M_T^{eff} \propto 10^{19} GeV \left(\frac{10^{16}}{M_X}\right)^3$$

$$\Gamma^{-1}_{d=6}\left(p \to e^+ \pi^0\right) \le 5.3\times 10^{34}\ yrs$$

$$\Gamma^{-1}_{d=5}(p \to \overline{\nu} K^+) \le 3.1\times 10^{34}\ yrs \left(\frac{m_{\tilde{q}}}{1.5\,TeV}\right)^4 \left(\frac{130\,GeV}{m_{\widetilde{W}}}\right)^2 \left(\frac{3}{\tan\beta}\right)^2$$

Meloni, Ohlsson a

Non SUSY SO(10) wi

Consistent with unif

$SO(10) \to SU$

$\tau($

$\to SU$

$\tau($

Perez, Murgui and Plascencia 1911.05738

Non SUSY SU(5) with $U(1)_{PQ}$ broken at the GUT scale

Consistent with unification and proton decay constraints

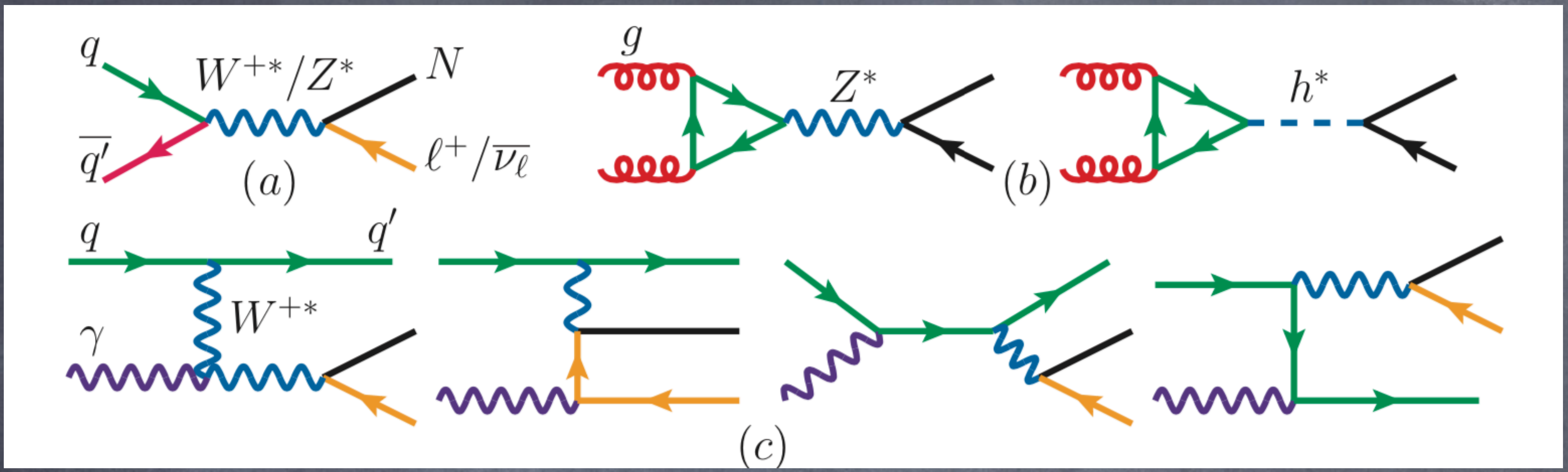
$$m_a = (2-16)\times 10^{-9}\ eV \qquad \text{correlated with}$$

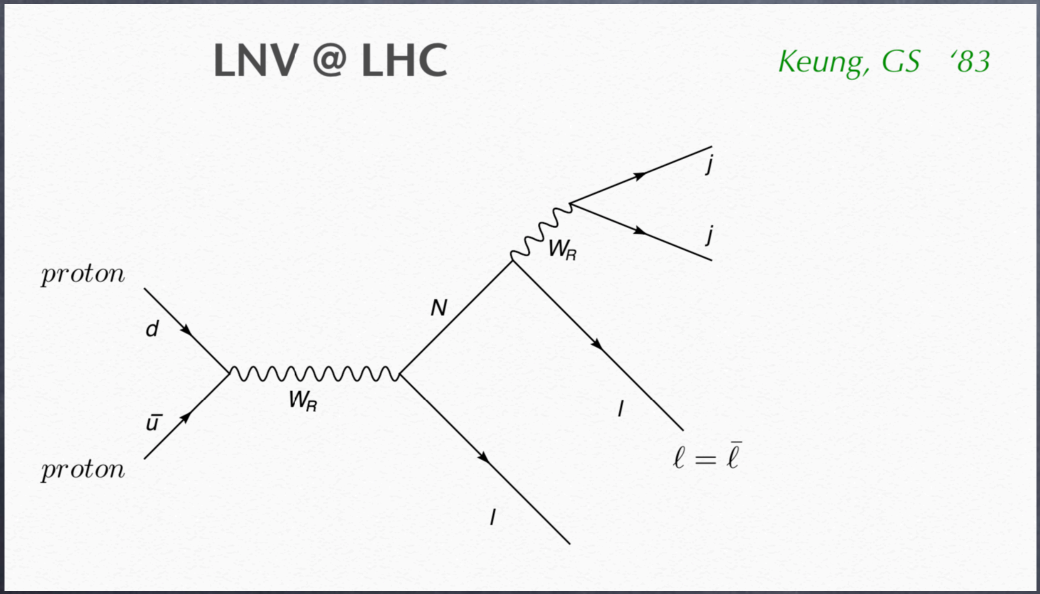
$$\tau\left(p \to \pi^+ \overline{\nu}\right) \le 2\times 10^{36}\ yrs.\ \&\ \text{SK} \le \tau\left(p \to K^+ \overline{\nu}\right) \le 4\times 10^{37}\ yrs.$$

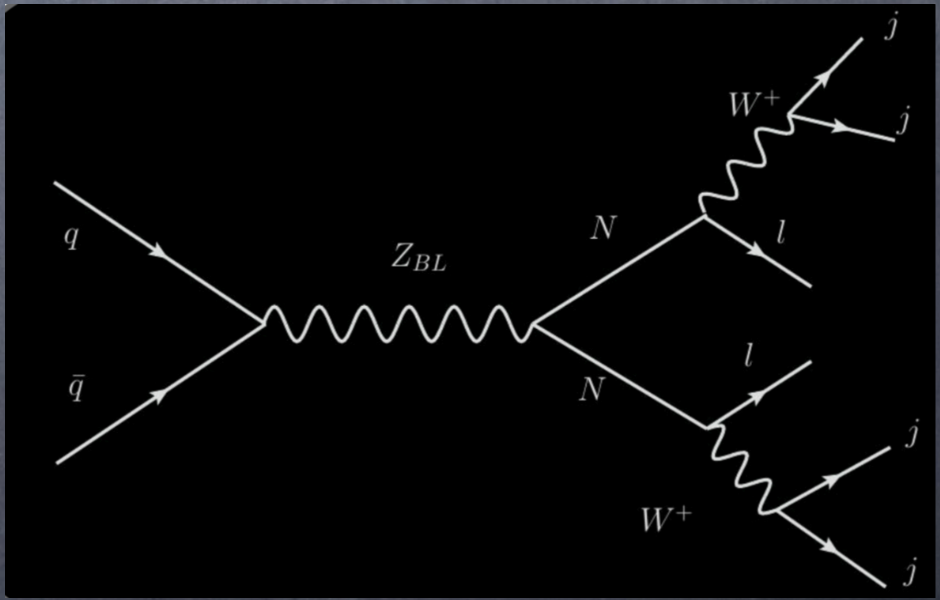
$$10^{34}\ yrs. \le \tau\left(p \to e^+ \pi^0\right) \le 10^{38}\ yrs.$$

talk by S. Raby @ BLV circa 2020

B and L violation at colliders







talks by T. Han, A. Plascencia, R. Ruiz and G. Senjanovic @ BLV circa 2020

N-Nbar oscillations

$n - \bar{n}$ oscillation Phenomenology (cont.)

- $n \to \bar{n}$ transition probability:

$$P(n \to \bar{n}) = \sin^2(2\theta)\sin^2(\Delta E t/2)e^{-\lambda t}$$
$$\Delta E \simeq 2|\vec{\mu_n}.\vec{B}|, \quad \tan(2\theta) = -\frac{\delta m}{\vec{\mu_n}.\vec{B}}$$

- Quasifree condition holds:

$$|\vec{\mu_n}.\vec{B}|t << 1$$

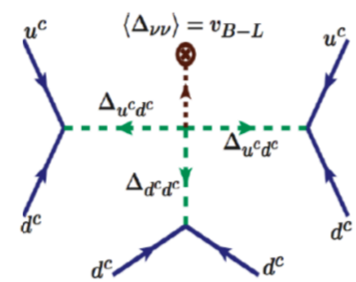
$$P(n \to \bar{n}) \simeq [(\delta m)t]^2 = [t/\tau_{n-\bar{n}}]^2$$

- Number of $\bar{n}$ created after time t is

- Best limit on
  Baldo-ceolin e

- Effective $\Delta B = 2$ operator that mediates neutron oscillation is:

$$\mathcal{L}_{\rm eff} = \frac{(udd)^2}{\Lambda^5}$$



- Tied to post-sphaleron baryogenesis in quark-lepton symmetric models within experimental reach:

talk by K. Babu @ BLV circa 2020

Exotic B and L processes

"Exotic" B and L Violation

HERE: |ΔB|>1 (& |ΔL=1) to non-SM final states;
|ΔB|>1 (& |ΔL>1) beyond 0ν ββ decay or n-n̄ oscillations

Both (and much more!) ap

[Marshak and M

but also in minimal scalar mo

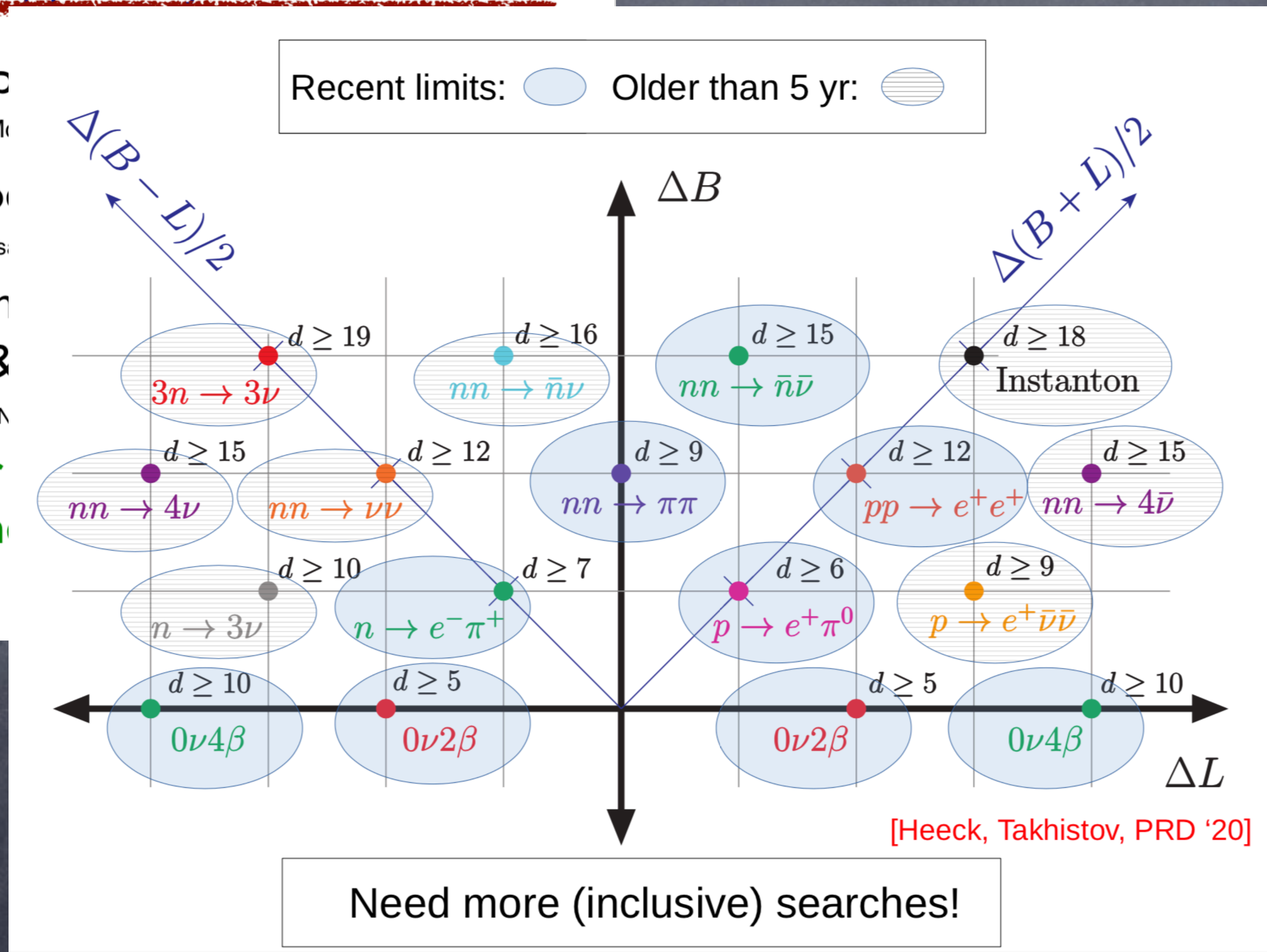
[Arnold, Fornal, & Wise, 2013; Davies & He, 1991; Ass

We can also use exotic ch
"Majorana ν" must exist (&

[cf. Babu & Mohapatra, 2015 (plus N

Akin to light hidden sector
must be determin

S. Gardner (w/ J. Heeck)



talks by S. Gardner and J. Heeck @ BLV circa 2020

Baryogenesis

talks by A. Long and C. Wagner @ BLV circa 2020

Models of baryogenesis

- in general: building a *compelling* model is "easy"
  … building a *testable* model is "hard"
  … building a *compelling & testable* model is "very hard"

When a good model comes along, it is worth exploring closely.

① High-Scale (FY) Leptogenesis
probes of Majorana nu: $0\nu\beta\beta$, ^{3}H cap
falsify high-scale LG with colliders

② Low-Scale (ARS) Leptogenesis
brings HNL within reach of colliders;
LLP search @ beam dump, LHC, futu

③ CPV B-meson Oscillations
rare B-meson decay; semileptonic ch
asymmetric DM

Electroweak Baryogengesis

Demands a strongly first order phase transition and CP violation, establishing a link between cosmology and physics at the weak scale

Transition via thermal effects induced by colored scalars strongly constrained

Additional Higgs bosons may lead to a strongly first order phase transition

Relevant constraints : Higgs precision measurements and searches for new Higgs bosons at the LHC.

Modification of Higgs trilinear couplings is an interesting signature, but will probably demand going beyond the LHC and should be part of a global fit.

It is very relevant to study the nucleation patterns, and not just the critical temperature. Relevant differences may be present.

CP-violating sources remain as the least explored chapter and tend to be in tension with electric dipole moment bounds.

Summary

We investigate the theories for physics beyond the SM where B and L are explicitly broken or spontaneously broken.

It is important to investigate the testability of theories with B and L violation at colliders.

We should discuss in detail the predictions for more exotic B and L violating processes together with proton decay, neutrinoless double beta decay and n-nbar oscillations.

It is important to investigate the different baryogenesis mechanisms and the testability at low energy experiments and colliders.