Baryon and Lepton Numbers: Life in the Desert

Pavel Fileviez Perez

Center for Cosmology and Particle Physics (CCPP)
New York University

Talk at PASCOS2012, Merida, June 6, 2012

Collaborators:

J. M. Arnold (Caltech)

V. Barger (UW-Madison)

B. Fornal (Caltech)

P. Nath (Northeastern Univ.)

S. Spinner (SISSA)

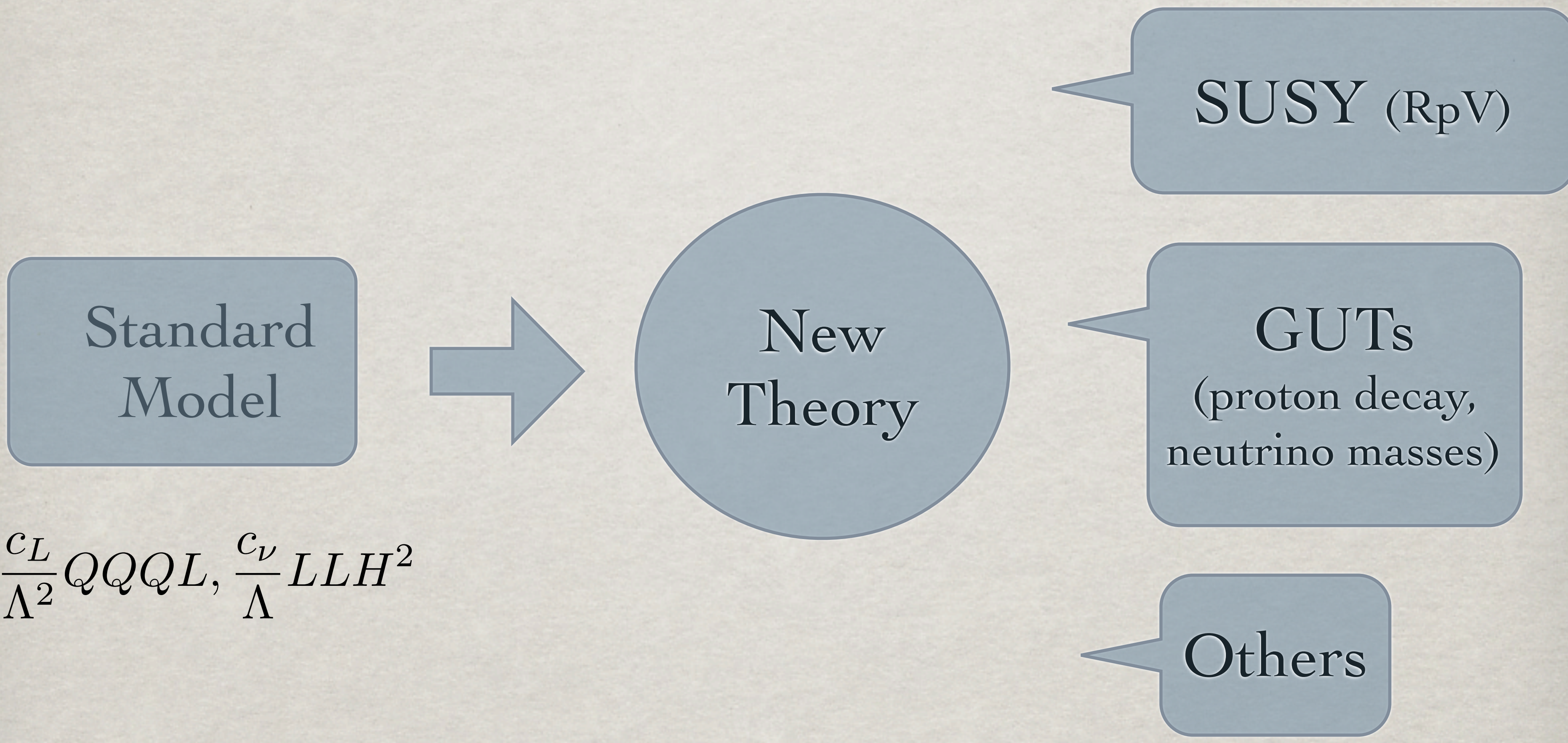
M. K. Trenkel (Germany)

M. B. Wise (Caltech)

References

- P. F. P., S. Spinner, Phys.Lett.B673:251,2009; Phys.Rev.D83:035004,2011.
- V. Barger, P. F. P., S. Spinner, Phys.Rev.Lett.102:181802,2009.
- P. F. P., S. Spinner, M. K. Trenkel, Phys.Lett.B702(2011)260;Phys.Rev.D84(2011)09528.
- P. F. P., M. B. Wise, Phys.Rev.D82:011901,2010.
- P. F. P., M. B. Wise, Phys. Rev. D84(2011)055015.
- P. F. P., M. B. Wise, JHEP1108(2011)068.
- D. Feldman, P. F. P., P. Nath, JHEP 1201 (2012) 038.
- P. F. P., Phys.Lett. B711 (2012) 353-359.
- P. F. P., S. Spinner, JHEP 04 (2012) 118.
- J. Arnold, P. F. P., B. Fornal, S. Spinner, hep-ph/1204.4458

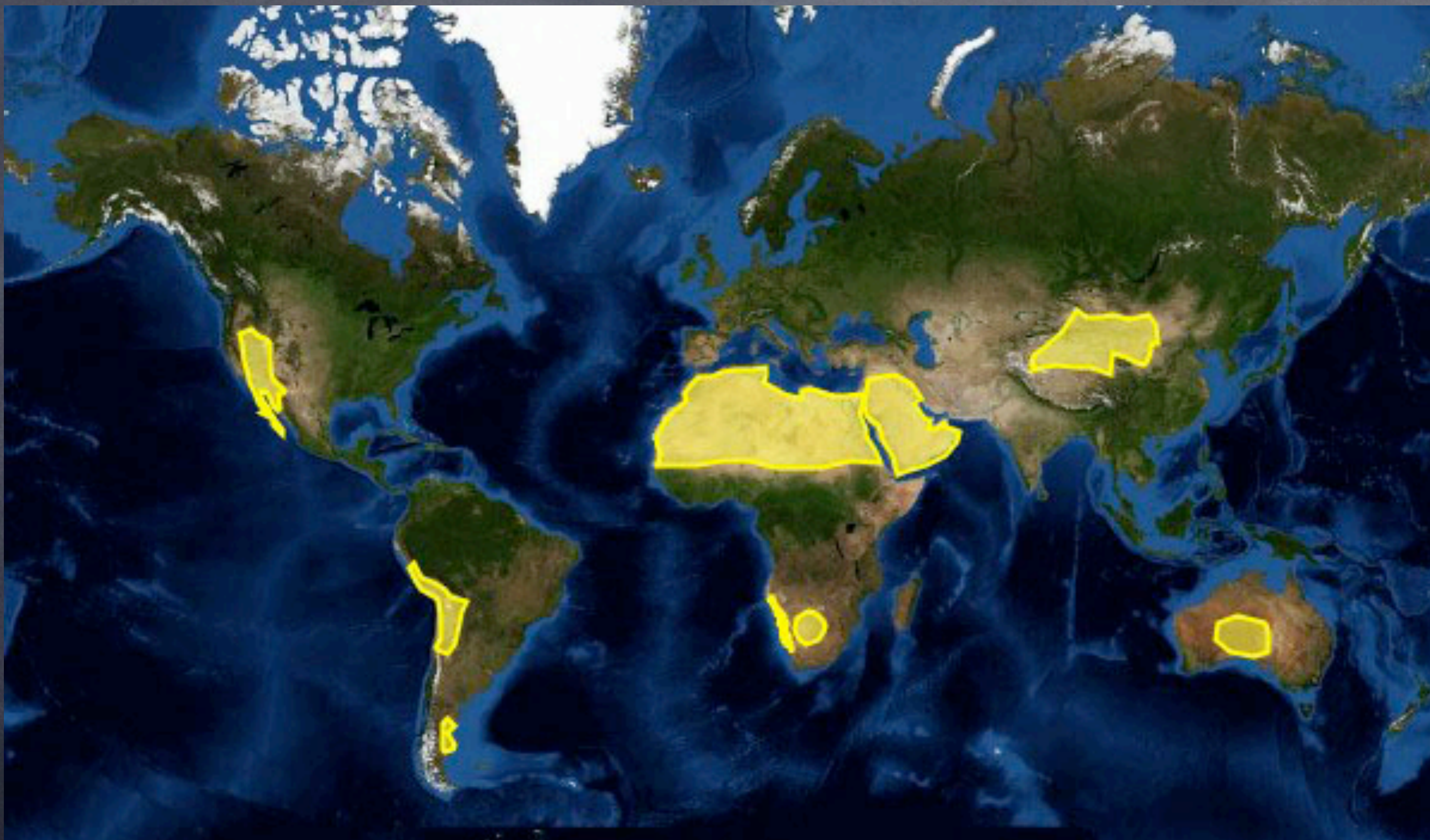
B, L and Physics beyond the SM



$$\frac{c_L}{\Lambda^2} QQQL, \frac{c_\nu}{\Lambda} LLH^2$$

Very often we need to think about the B and L violation and postulate a desert between the low and high scales !

The World Largest Deserts



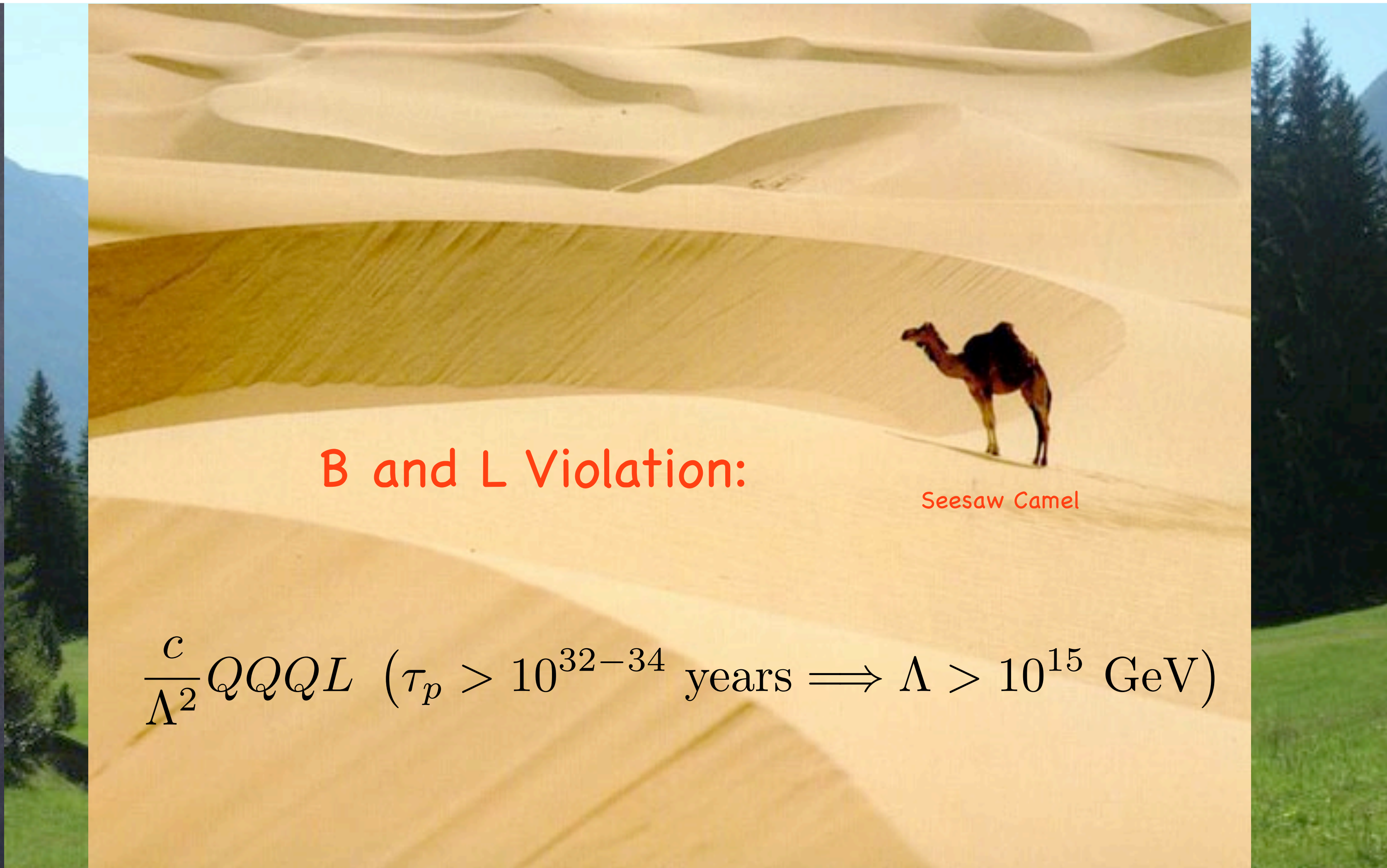
Deserts take up about one third (33%) of the Earth's land surface

Thanks to Wikipedia

The Desert Hypothesis in Particle Physics:

LOW SCALE

HIGH SCALE



B and L Violation:

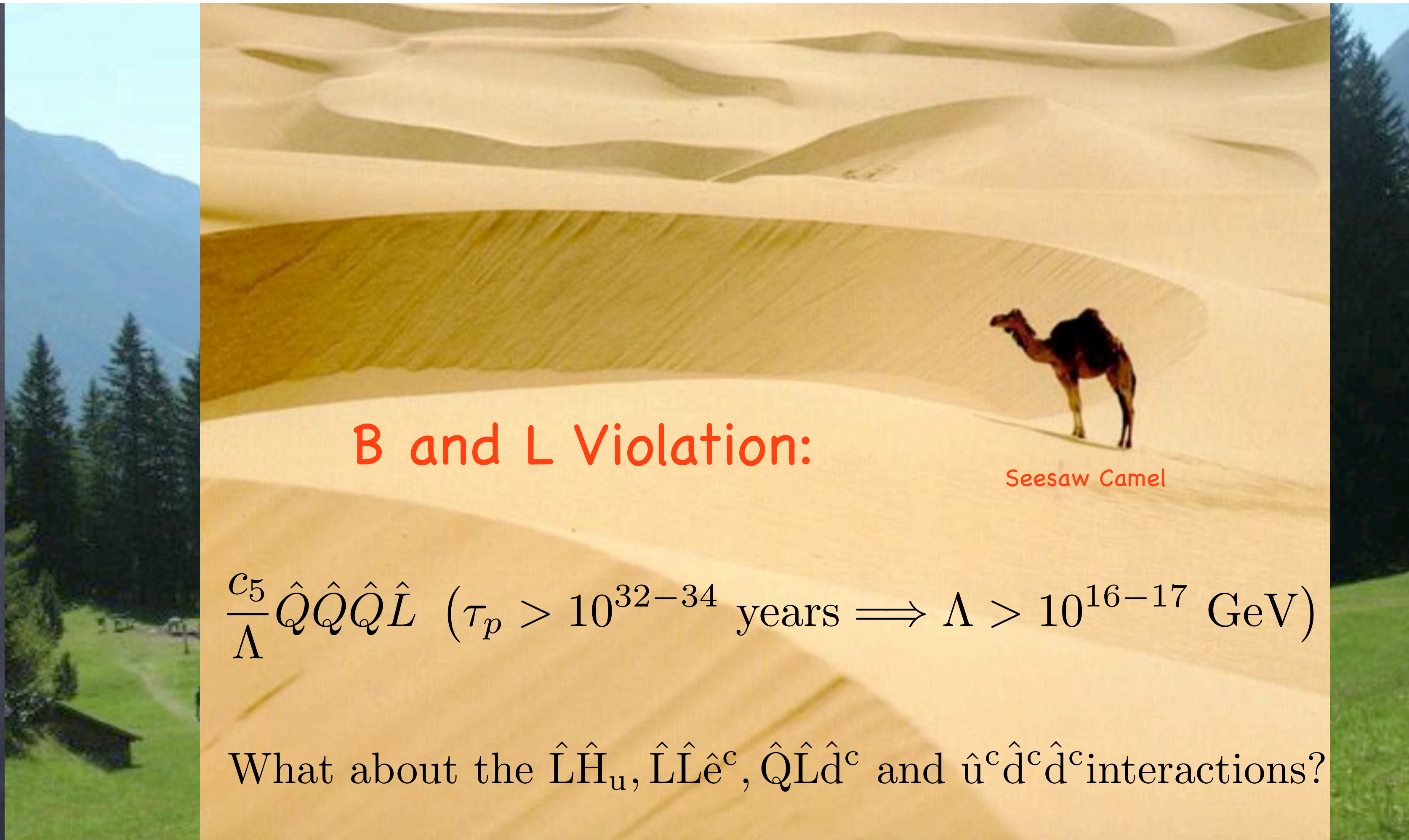
$$\frac{c}{\Lambda^2} QQQL \;\; \left(\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{15} \text{ GeV}\right)$$

Standard Model

GUTs, Strings ?

The Desert Hypothesis and Supersymmetry:

L O W S C A L E



H I G H S C A L E

B and L Violation:

$$\frac{c_5}{\Lambda}\hat{Q}\hat{Q}\hat{Q}\hat{L} \;\; \left(\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{16-17} \text{ GeV}\right)$$

What about the $\hat{\mathrm{L}}\hat{\mathrm{H}}_{\mathrm{u}}, \hat{\mathrm{L}}\hat{\mathrm{L}}\hat{\mathrm{e}}^{\mathrm{c}}, \hat{\mathrm{Q}}\hat{\mathrm{L}}\hat{\mathrm{d}}^{\mathrm{c}}$ and $\hat{\mathrm{u}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}$ interactions?

MSSM

Unification of Gauge Couplings !

10 TeV ? 100 TeV ? ...

GUTs, Strings ?

Aim:

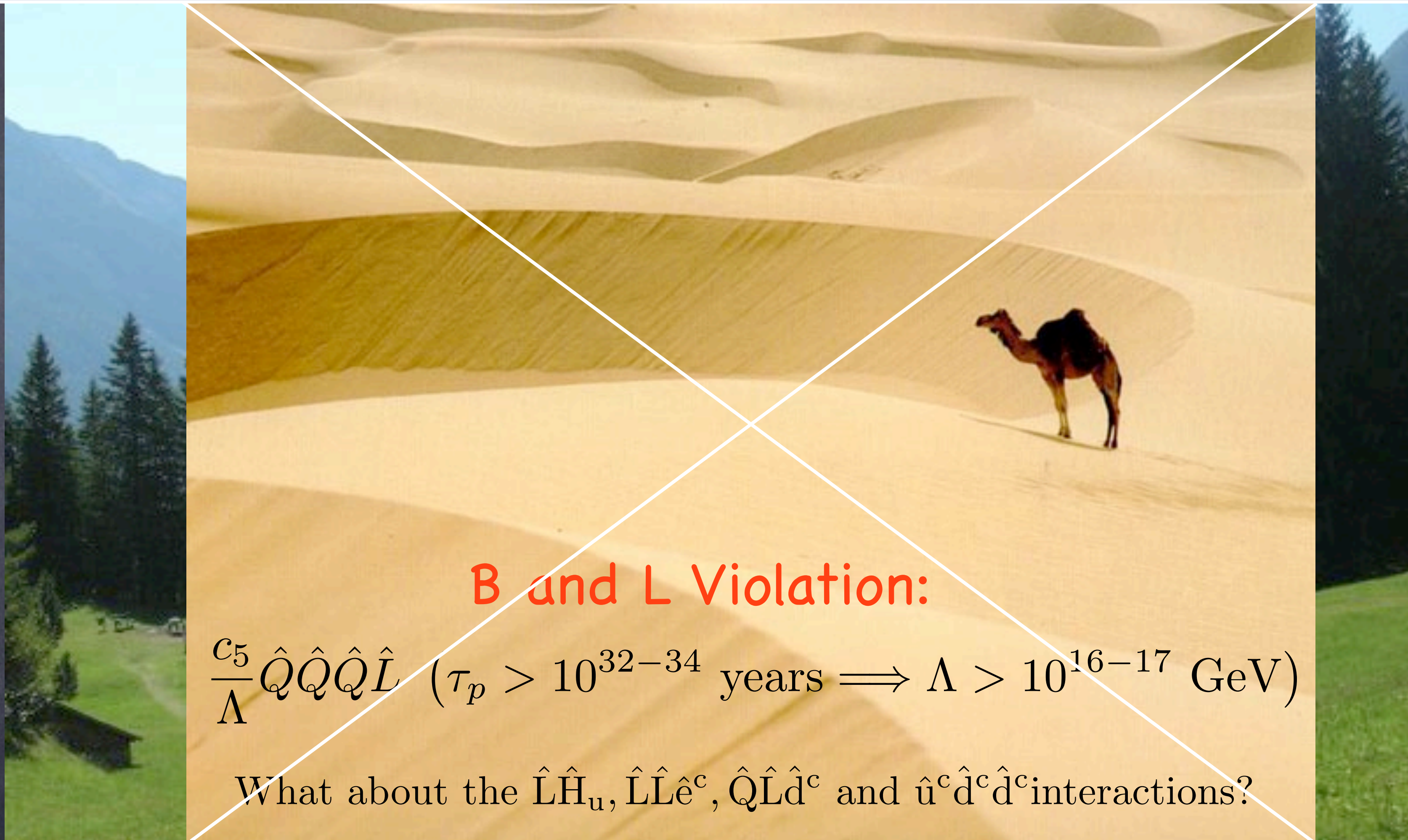
Minimal Supersymmetric Standard Model

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

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

Aim: Can we break B and L at the TeV scale?

LOW SCALE



B and L Violation:

$$\frac{c_5}{\Lambda}\hat{Q}\hat{Q}\hat{Q}\hat{L} \quad (\tau_p > 10^{32-34}\ \text{years} \Longrightarrow \Lambda > 10^{16-17}\ \text{GeV})$$

What about the $\hat{\mathrm{L}}\hat{\mathrm{H}}_{\mathrm{u}}, \hat{\mathrm{L}}\hat{\mathrm{L}}\hat{\mathrm{e}}^{\mathrm{c}}, \hat{\mathrm{Q}}\hat{\mathrm{L}}\hat{\mathrm{d}}^{\mathrm{c}}$ and $\hat{\mathrm{u}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}\hat{\mathrm{d}}^{\mathrm{c}}$ interactions?

HIGH SCALE

MSSM

10 TeV ? 100 TeV ? ...

GUTs, Strings ?

Outline

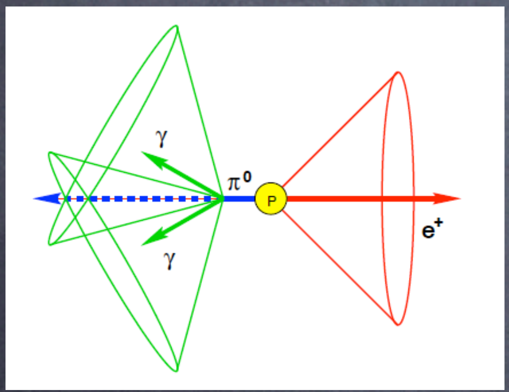
- Introduction
- B and L in the Super-World
- Minimal Theory for R-parity (Non) Conservation
- Life in the Desert
- Summary

Introduction:

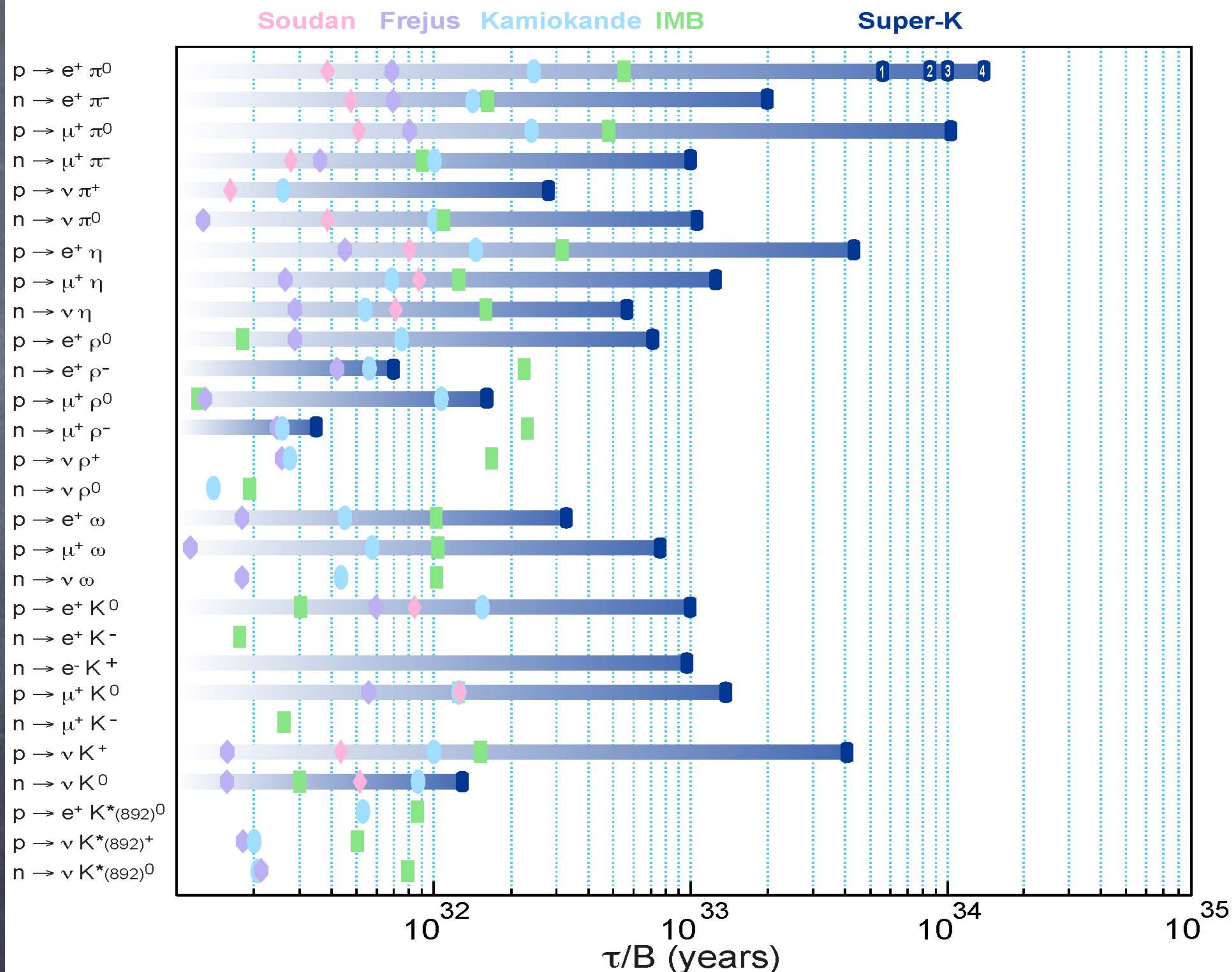
Experimental Results

- Proton Decay:

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



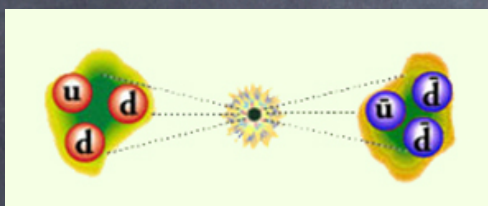
Generic Prediction from any GUT !

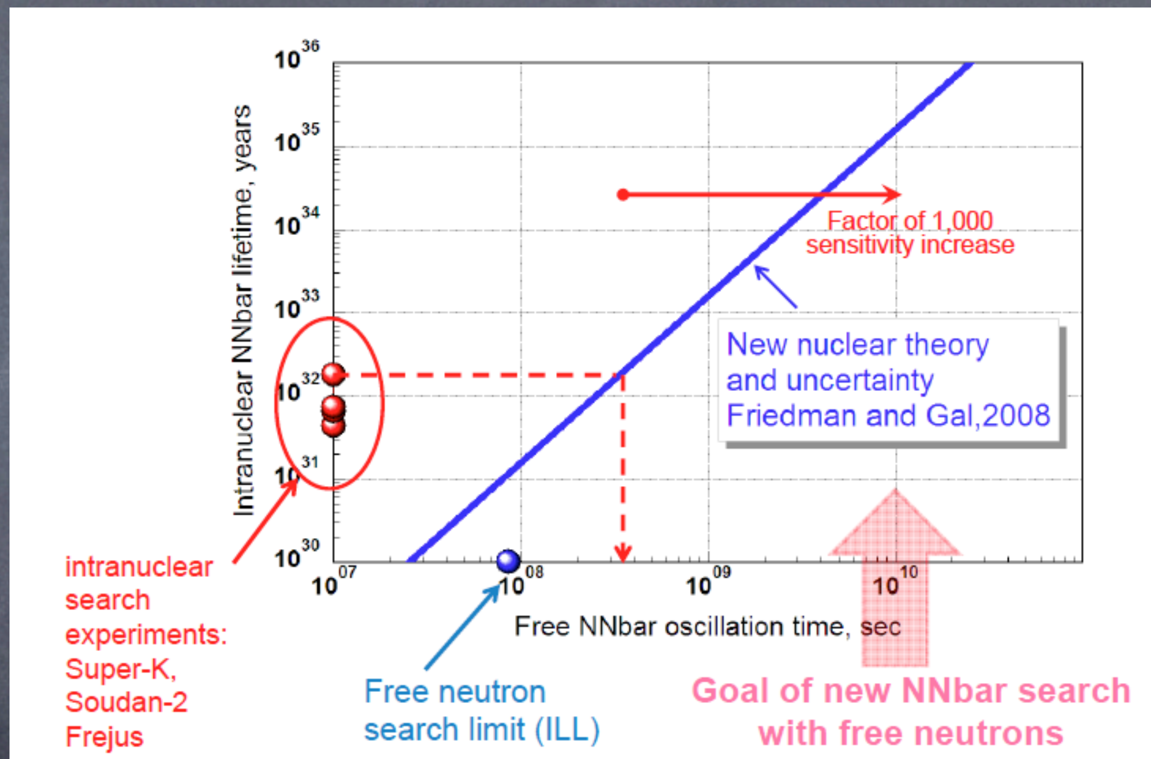


Miura, BLV2011

- N-Nbar Oscillations: $\Delta B = 2$

$$\tau_{n-\bar{n}} > 10^8\ s\ (\text{free neutrons})$$





Kamyshkov, Y
2012

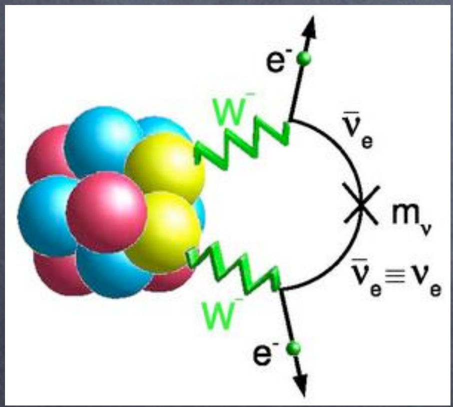
- Di-nucleon Decays: $p\,p \to K^+ K^+$ $\Delta B = 2$

$$\tau_{pp\to K^+K^+} > 10^{32}\ \text{years}$$ (SK, Litos, 2010)

- Neutrinoless double beta decay

$$(A, Z) \to (A, Z+2) + 2\,e^- \qquad (0\nu\beta\beta)$$

$$\Delta L = 2$$



Isotope	$T^{0\nu}_{1/2}$ [yrs]	Experiment
^{48}Ca	5.8×10^{22}	CANDLES[18]
^{76}Ge	1.9×10^{25}	HDM[19]
	1.6×10^{25}	IGEX[20]
^{82}Se	3.2×10^{23}	NEMO-3[21]
^{96}Zr	9.2×10^{21}	NEMO-3[22]
^{100}Mo	1.0×10^{24}	NEMO-3[21]
^{116}Cd	1.7×10^{23}	SOLOTVINO[23]
^{130}Te	2.8×10^{24}	CUORICINO[24]
^{136}Xe	5.0×10^{23}	DAMA[25]
^{150}Nd	1.8×10^{22}	NEMO-3[26]

Rodejohann, 2011

- Neutrino Oscillations:

$$\Delta L_i \neq 0$$

Talks by Lindner, Valle, A. de Gouvea.

Cosmology

Baryon Asymmetry: → **BARYON NUMBER VIOLATION**

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$

$$\Delta B \neq 0$$

Sakharov's Condition, 1967

Can we expect B and L violation at the LHC ?

B and L in the Super-World

B and L Violation in the MSSM

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

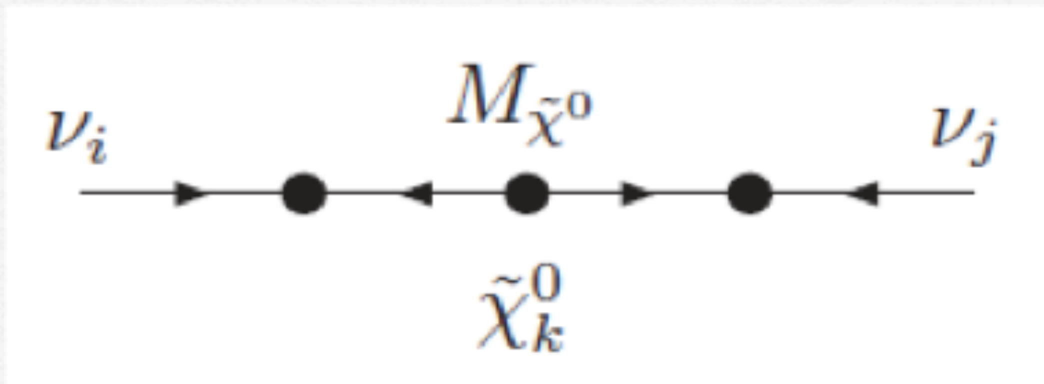
$$\mathcal{W}^5_{RPC} = \frac{\lambda_\nu}{\Lambda} L L H_u H_u + \frac{\lambda_L}{\Lambda} Q Q Q L + \frac{\lambda_R}{\Lambda} u^c d^c u^c e^c$$

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

Majorana Neutrino Masses

Example:

$\epsilon L H_u$



$$M_\nu \lesssim 1 \text{ eV}$$

$$\Rightarrow \quad \tilde{\chi}^0_1 \to e_i^\pm W^\mp, \nu Z, \nu_i h^0, e_i^\pm H^\mp$$

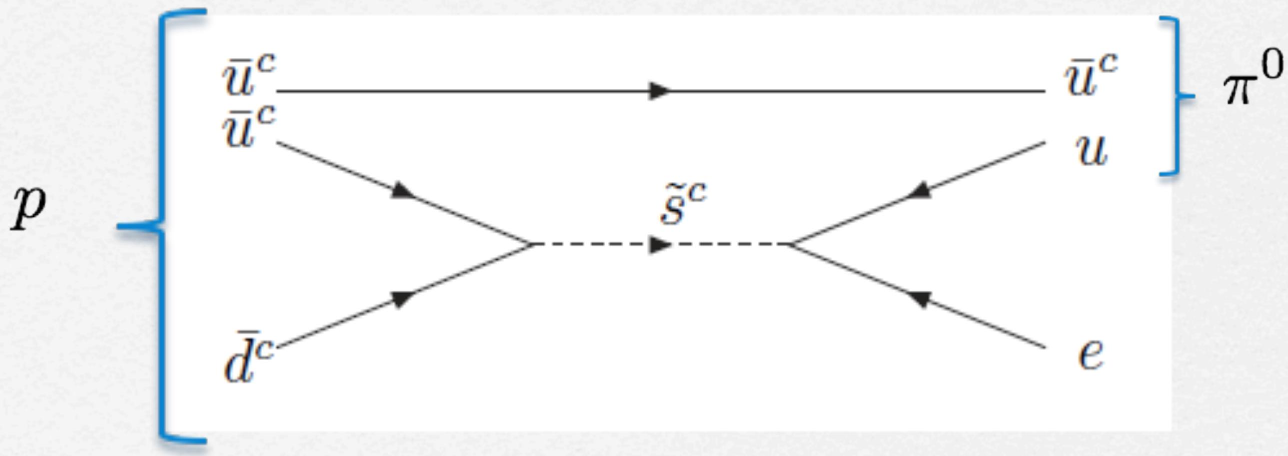
e.g. Hirsch, Diaz, Porod, Romao, Valle, 2000

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

Proton Decay and R-Parity

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

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



$$\text{Channel}: \tau_{p\to\pi^0 e^+} > 10^{33} \text{ years}$$

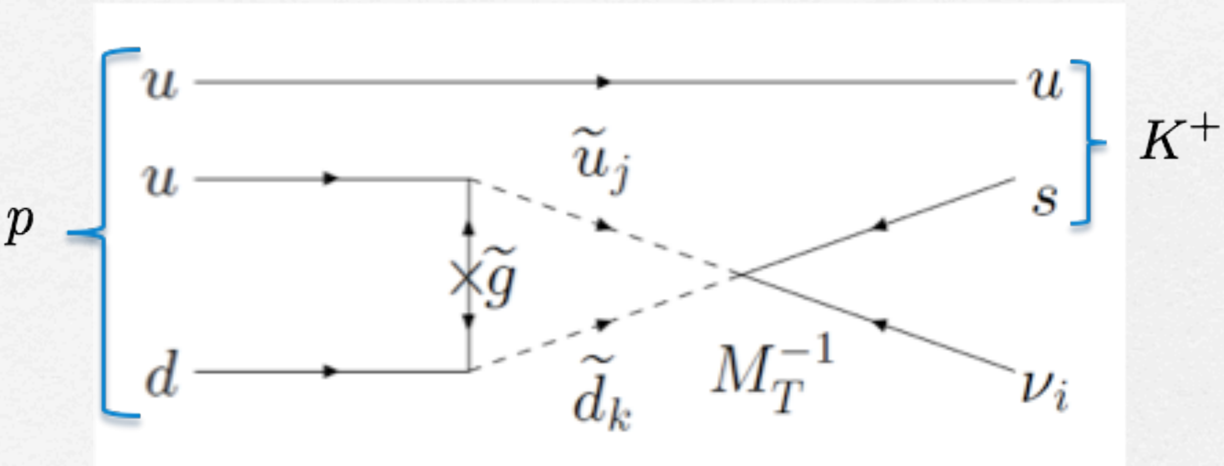
$$M_{\tilde{q}} \sim 10^3 \text{ GeV} \Rightarrow \tau_4 \sim 10^{-20} \text{ years}$$

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

d=5 operators

Example: $p \to K^+ \bar{\nu} \quad (\tau > 2.3 \times 10^{33} \text{years})$

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



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

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

Dimopoulos, Raby, Wilczek,
P. Nath, Chamseddine,
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?

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

$B - L$ ⟷ M

B-L Symmetry and R-parity

Aulakh, Mohapatra, 1982;
Hayashi, A. Murayama, 1985;
Mohapatra, 1986;
Krauss, Wilczek, 1988;
Font, Ibanez, Quevedo, 1989;
Masiero, Valle'90
Martin, 1992;
Aulakh, Bajc, Melfo, Senjanovic, 2001
P. F. P., S. Spinner, 2008-2012
V. Barger, P. F. P., S. Spinner, 2008

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

Which is the minimal SUSY Left-Right Theory ?

$$SU(2)_L \bigotimes SU(2)_R \bigotimes U(1)_{B-L}$$

$$\hat{L} = \begin{pmatrix} \hat{\nu} \\ \hat{e} \end{pmatrix} \sim (2, 1, -1) \qquad \hat{L}^c = \begin{pmatrix} \hat{\nu}^c \\ \hat{e}^c \end{pmatrix} \sim (1, 2, 1)$$

$$\hat{\Phi} = \begin{pmatrix} \hat{H}_d^0 & \hat{H}_u^+ \\ \hat{H}_d^- & \hat{H}_u^0 \end{pmatrix} \sim (2, 2, 0)$$

$$SU(2)_R \bigotimes U(1)_{B-L} \xrightarrow{\langle \tilde{\nu}^c \rangle \neq 0} U(1)_Y$$

Minimal Theory for R-parity Violation

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

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

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

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

New Theory with R-parity violation !

The Minimal 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 !

Scalar Potential and Symmetry Breaking

$$\mathcal{W}_{B-L} = \mathcal{W}_{RpC} + Y_\nu L H_u \nu^c$$

$$V_{soft} \supset M^2_{\tilde{N}^c} |\tilde{\nu}^c|^2 + \left(A_\nu \tilde{L} H_u \tilde{\nu}^c \; + \; \text{h.c.} \right)$$

$$\langle V_F \rangle = \frac{1}{4} Y_\nu^2 \left(v_R^2 v_u^2 + v_R^2 v_L^2 + v_L^2 v_u^2 \right) + \frac{1}{2} \mu^2 \left(v_u^2 + v_d^2 \right) \; - \; \frac{1}{\sqrt{2}} Y_\nu \; \mu \; v_R v_L v_d$$

$$\langle V_D \rangle = \frac{1}{32} \left[g_2^2 \left(v_u^2 - v_d^2 - v_L^2 \right)^2 + g_1^2 \left(v_u^2 - v_d^2 - v_L^2 \right)^2 \; + \; g_{BL}^2 \left(v_R^2 - v_L^2 \right)^2 \right],$$

$$\langle V_{soft}^S \rangle = \frac{1}{2} M^2_{\tilde{L}} v_L^2 + \frac{1}{2} M^2_{\tilde{N}^c} v_R^2 + \frac{1}{2} M^2_{H_u} v_u^2 + \frac{1}{2} M^2_{H_d} v_d^2 \; - \; \text{Re} B\mu \; v_u v_d + \frac{1}{\sqrt{2}} A_\nu \; v_R v_L v_u$$

B-L Breaking and SUSY Scales

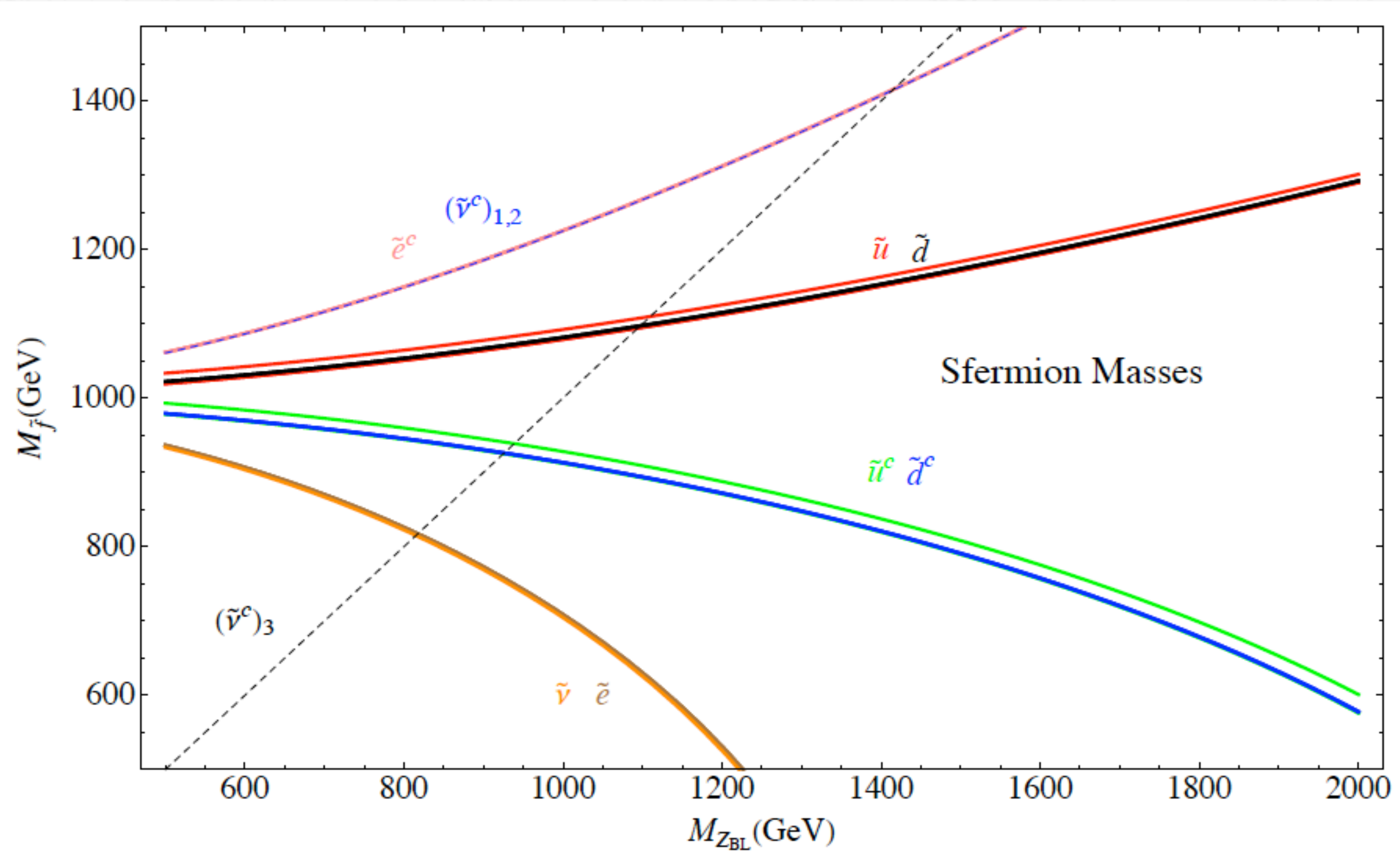
$$v_R \gg v_u, v_d \gg v_L$$

$$v_R = \sqrt{\frac{-8M^2_{\tilde{N}^c}}{g^2_{BL}}} \quad (M^2_{\tilde{N}^c} < 0)$$

$$v_L = \frac{B_\nu v_R}{M^2_{\tilde{L}} - \frac{1}{8} g^2_{BL} v^2_R}$$

$$B_\nu = \frac{1}{\sqrt{2}} (Y_\nu \; \mu \; v_d \; - \; A_\nu \; v_u)$$

Realistic Spectrum



$M_{SUSY} = 1$ TeV and $\tan\beta = 5$.

R-Parity Violating Couplings

$$\frac{1}{2} g_{BL} \; v_R \; \nu^C \;\; \tilde{B}^{'} \qquad \frac{1}{2} g_1 \; v_L \; \nu \; \tilde{B} \qquad \frac{1}{2} g_2 \; v_L \; \nu \; \tilde{W}^0$$

$$\frac{1}{\sqrt{2}} Y_\nu \; v_L \; \tilde{H}_u^0 \; \nu^C \qquad \frac{1}{\sqrt{2}} g_2 \; v_L \; e \; \tilde{W}^+$$

$$\frac{1}{\sqrt{2}} Y_\nu \; v_R \; l^T \; i\sigma_2 \; \tilde{H}_u \qquad \frac{1}{\sqrt{2}} Y_e \; v_L \; \tilde{H}_d^- \; e^C$$

Only bilinear LNV couplings and NO d=4 proton decay

Spectrum for Neutrinos

$$v_R = v_R^3 = \langle \tilde{\nu}_\tau^c \rangle \neq 0 \qquad v_R = \sqrt{\frac{-8M^2_{\tilde{N}^c}}{g^2_{BL}}}$$

$$\left(\nu_3^c, \tilde{B}'\right) \text{ Sector} \Rightarrow \mathcal{M}_{3\tilde{B}'} = \begin{pmatrix} 0 & M_{Z_{BL}} \\ M_{Z_{BL}} & M_{BL} \end{pmatrix}$$

$$M_{Z_{BL}} \gg M_{BL} \qquad M_{6,7} \approx M_{Z_{BL}} \pm \frac{1}{2} M_{BL}$$

$$\left\{ \frac{M_{Z_{BL}}}{g_{BL}} > 3 \text{ TeV} \right\}$$

The mass matrix for all light neutrinos:

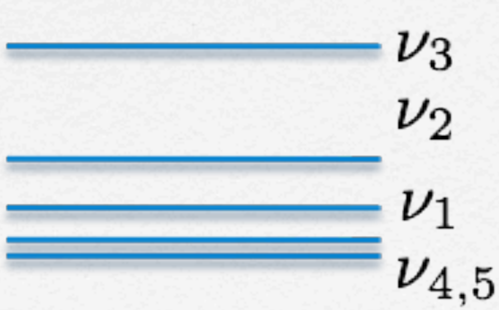
Barger, P.F.P., Spinner'10

$$(\nu_e, \nu_\mu, \nu_\tau, \nu_e^c, \nu_\mu^c)$$

$$M_\nu = \begin{pmatrix} A v_L^i v_L^j + B(Y_\nu^{i3} v_L^j + Y_\nu^{j3} v_L^i) + C Y_\nu^{i3} Y_\nu^{j3} & Y_\nu^{i\beta} v_u/\sqrt{2} \\ Y_\nu^{\alpha j} v_u/\sqrt{2} & 0_{2\times 2} \end{pmatrix}$$

Possible spectra:

NH



IH

The theory predicts two light sterile neutrinos !

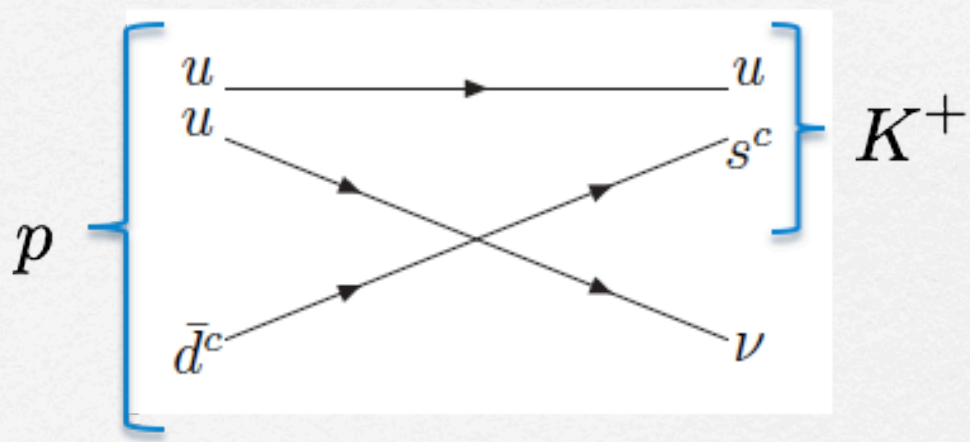
Talk by Hannestad

Mohapatra'86; Ghosh, Senjanovic, Zhang'10

Proton Decay

$$\frac{\lambda_{ijkl}}{\Lambda_B} u_i^c d_j^c d_k^c \nu_l^c \quad \Rightarrow \quad \frac{\lambda_{1123}}{\Lambda_B} \frac{v_R}{\sqrt{2}} \tilde{u}^c d^c s^c$$

$$p \to K^+ \nu$$



$$\frac{\lambda_{1123}}{\Lambda_B} \frac{Y_u Y_\nu^{i3}}{M_{\tilde{q}^2}} \frac{v_R^2}{2M_{\tilde{\chi}^0}} < 10^{-30} \ \mathrm{GeV}^{-2} \quad \left(\Lambda_B > 10^{17} \mathrm{GeV} \right)$$

The Desert Again !

What is the origin of the tachyonic mass for $\tilde{\nu}^c$?

a) $f\nu^c\nu^c X$ → Radiative Symmetry Breaking

P. F. P., Spinner, 2010

b) $S^{'} = \mathrm{Tr}\left(\mathrm{Y_{B-L}\tilde{m}^2}\right) \neq 0$ at GUT scale

M. Ambroso, B.A. Ovrut, 2009, 2010

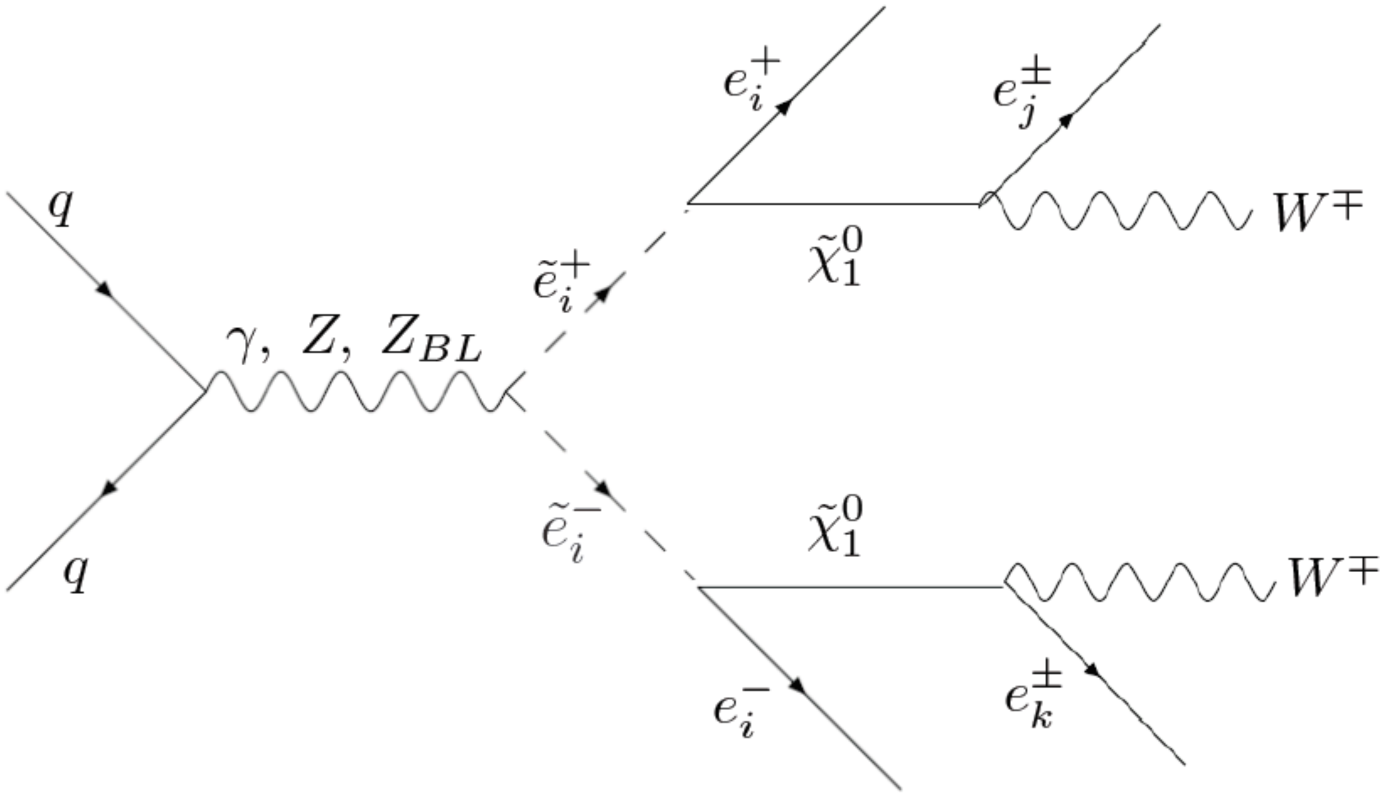
P. F. P., S. Spinner, JHEP 04 (2012) 118

Signatures at the LHC

- Gluino as the LSP
- Squark as the LSP
- Charged Slepton as the LSP
- Neutral Slepton as the LSP
- Chargino as the LSP
- Neutralino as the LSP

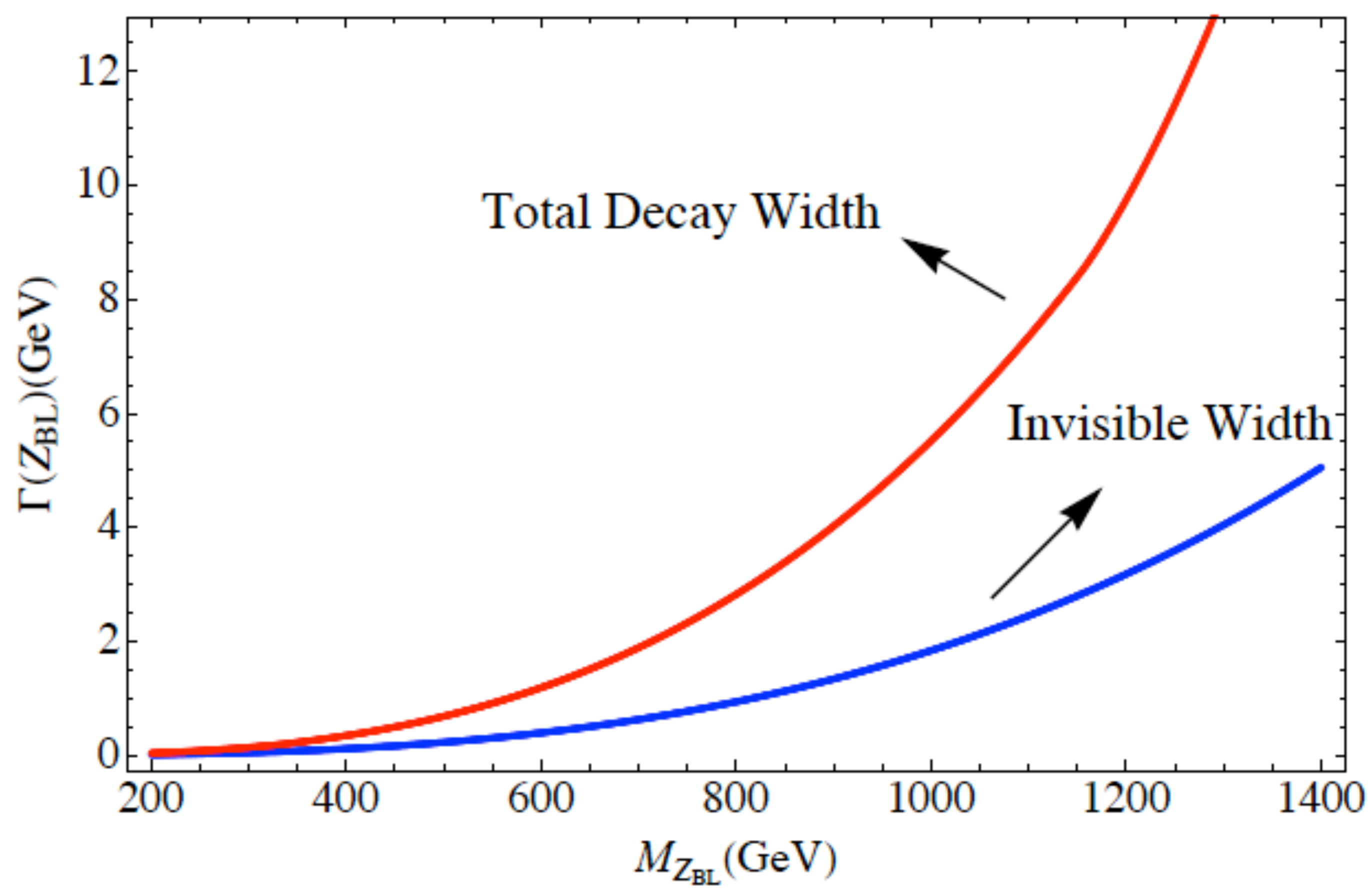
Neutralino as the LSP

P. F. P., S. Spinner, JHEP 04 (2012) 118



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

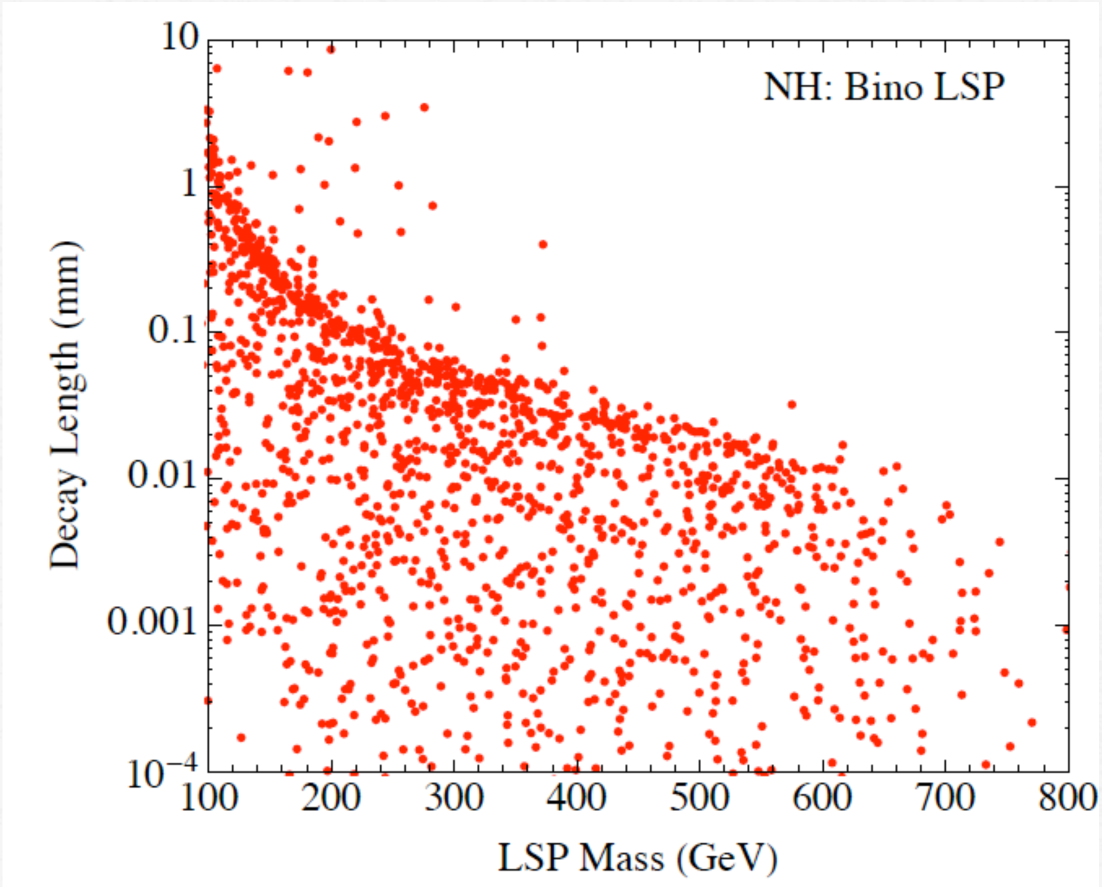
$$\mathrm{Br}(Z_{BL} \to e_i^+ e_i^-) \sim 40\%,\ \mathrm{Br}(Z_{BL} \to \nu\nu) \sim 35\%, \mathrm{Br}(Z_{BL} \to jj) \sim 20\%, \text{and } \mathrm{Br}(Z_{BL} \to \bar{t}t) \sim 5\%,$$



Decay Length

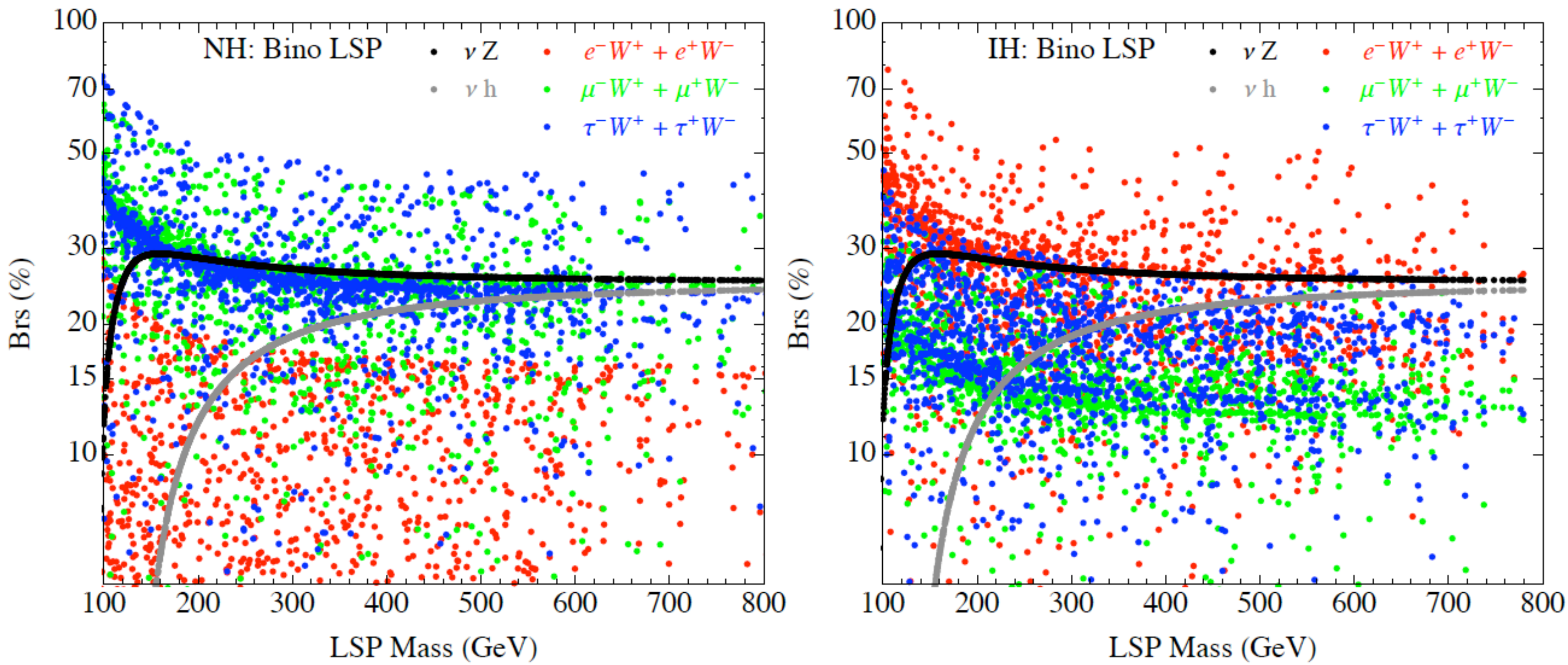
P. F. P., S. Spinner, JHEP 04 (2012) 118

$$\tilde{\chi}_1^0 \to e_i^{\pm} W^{\mp}, \;\; \tilde{\chi}_1^0 \to \nu_i Z, \;\; \tilde{\chi}_1^0 \to \nu_i h_k, \;\; \tilde{\chi}_1^0 \to e_i^{\pm} H^{\mp}.$$



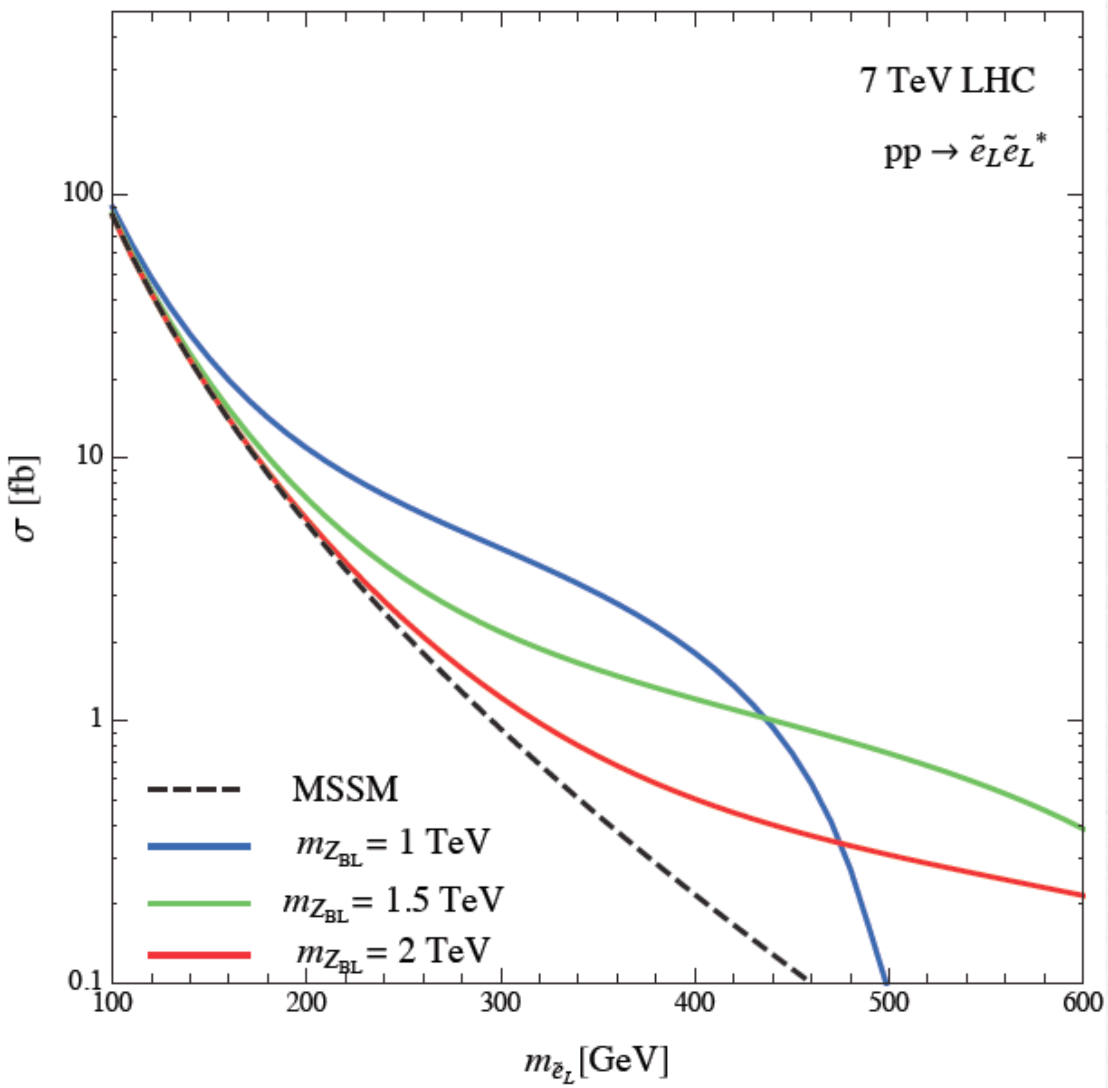
P. F. P., S. Spinner, JHEP 04 (2012) 118

Branching Ratios



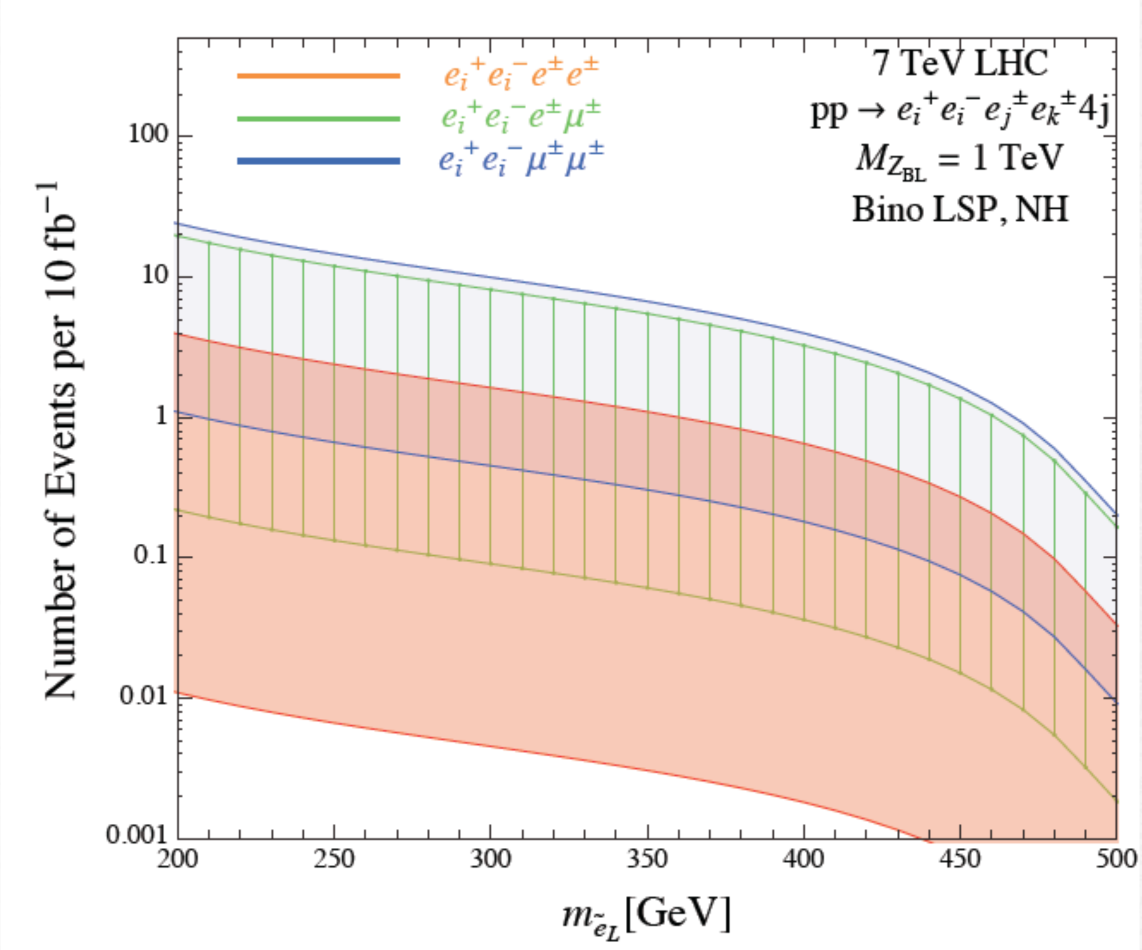
(a) (b)

$$q(p_1)\bar{q}(p_2) \rightarrow \gamma, Z^*, Z^*_{BL} \rightarrow \tilde{e}^*(p_3)\tilde{e}(p_4).$$

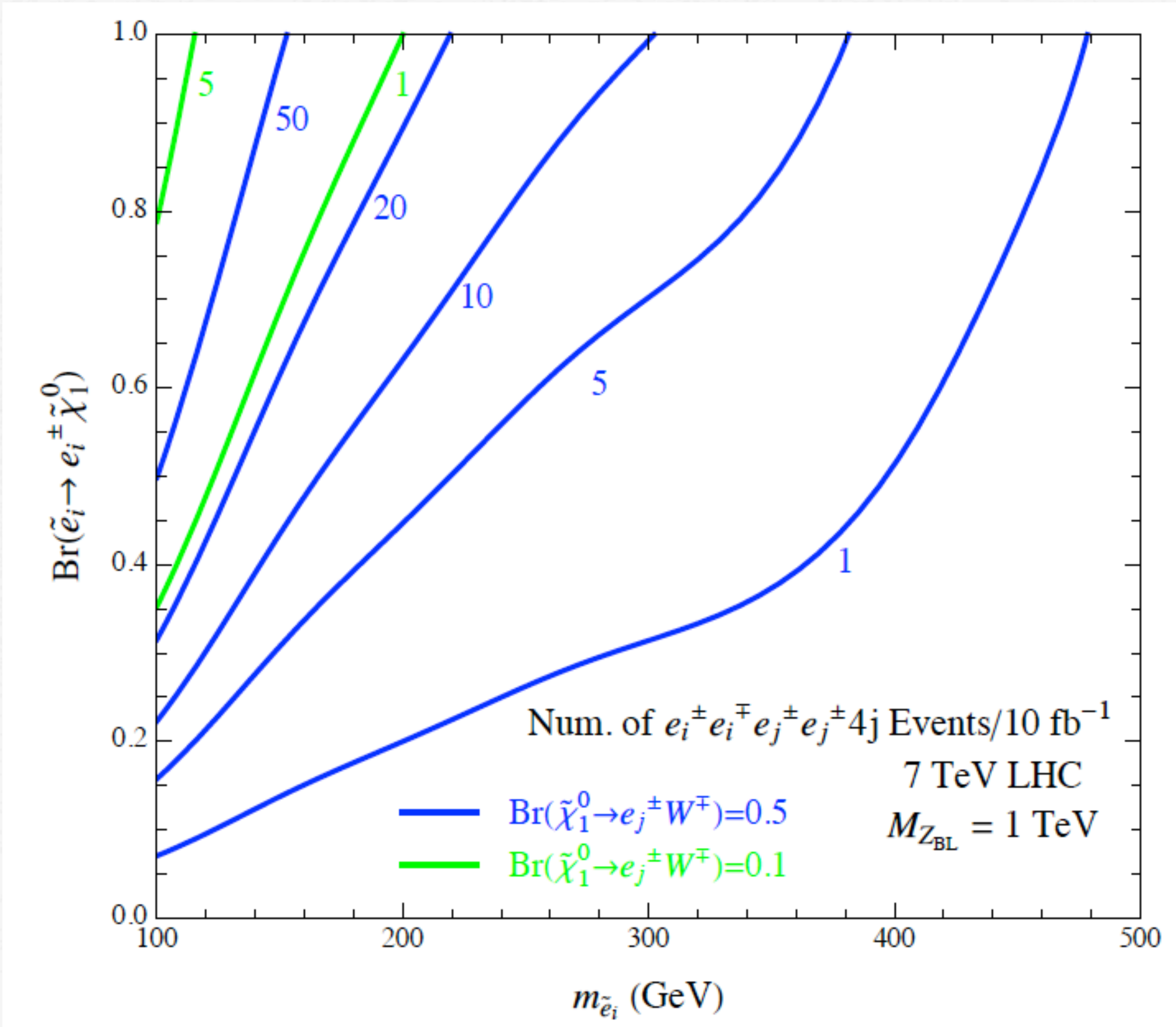


P. F. P., S. Spinner, JHEP 04 (2012) 118

Number of Events



Discovery Reach at the LHC



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.**

P. Fileviez Perez, S. Spinner, M. K. Trenkel, hep-ph/1103.5504; 1103.3824

Dynamical R-parity Conservation

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

$$\mathcal{W}_{B-L} = \mathcal{W}_{RpC} + Y_\nu L H_u \nu^c + \mathcal{W}_{extra}$$

Model I: **Majorana**

$$\mathcal{W}_{extra}^{(I)} = \mu_X X \bar{X} + f \nu^c \nu^c X$$

Model II: **Dirac**

$$\mathcal{W}_{extra}^{(II)} = \mu_S S \bar{S} \qquad n_{BL}^S = 2p/q$$

Model III: Stueckelberg B-L Model (Feldman, P.F.P., Nath'11)

R-parity and Grand Unification in 4D

$-SU(5)$

$$\mathcal{W}_{RpV} = \epsilon_i \hat{\bar{5}}_i \hat{5}_H \; + \; \lambda_{ijk} \hat{10}_i \hat{\bar{5}}_j \hat{\bar{5}}_k \; + \; \eta_i \hat{\bar{5}}_i 24_H \hat{5}_H$$

Enforce Matter Parity Conservation

$-SO(10)$

e.g. Aulakh, Bajc, Melfo, Senjanovic`2000

$$\hat{45}_H, \hat{54}_H, \hat{126}_H, \hat{\overline{126}}_H \quad (210_H)$$

$$F_{\tilde{\nu}^c} = \sigma \left\langle \tilde{\nu}^c \right\rangle = 0 \; (\text{SUSY Limit})$$

Talk by S. Raby

Remark:

We need to enforce the conservation of a discrete symmetry in models with 16_H Higgses

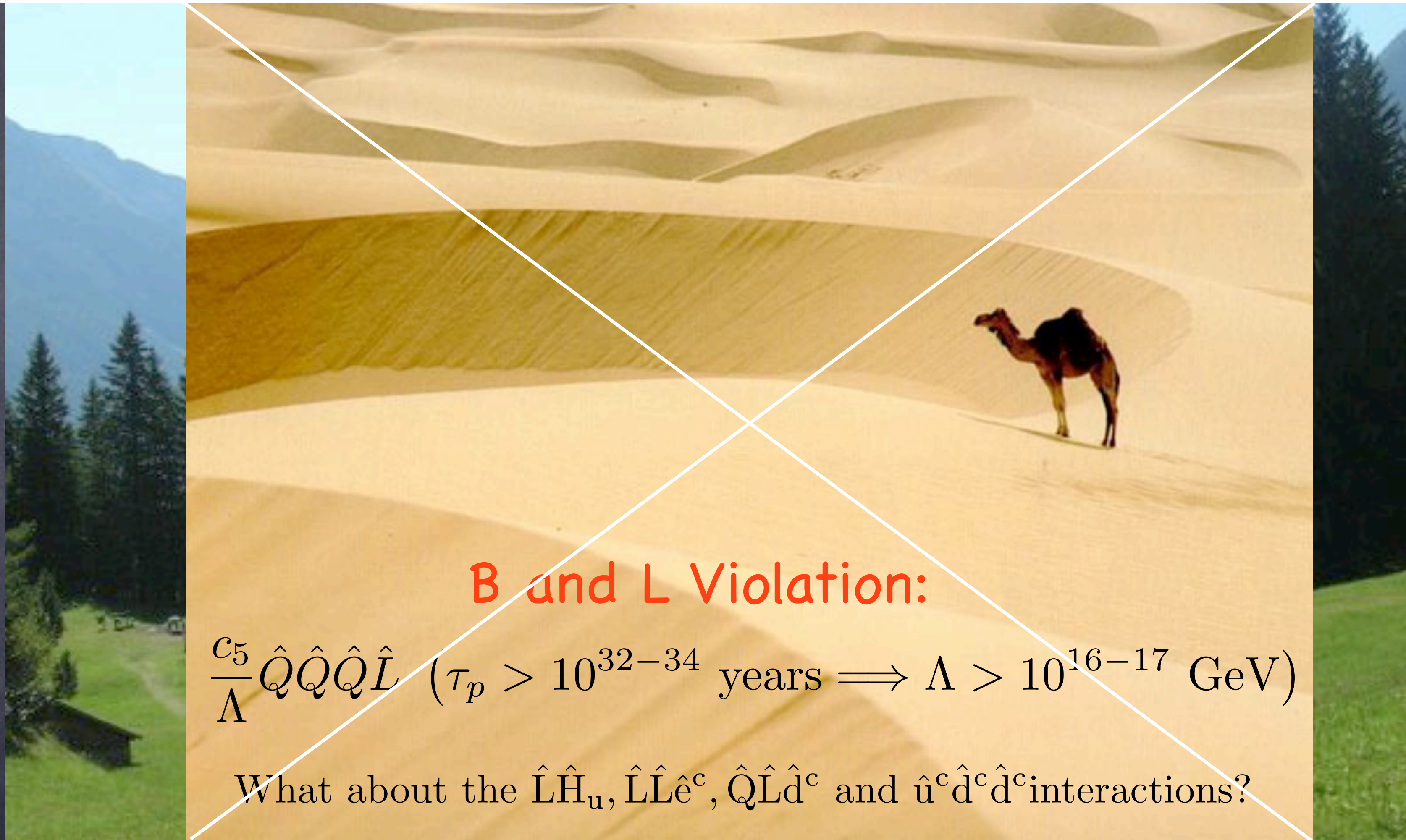
NO "simple" GUT which predicts R-parity Conservation !

Life in the Desert

Aim: Can we break B and L at the TeV scale?

LOW SCALE

HIGH SCALE



B and L Violation:

$$\frac{c_5}{\Lambda}\hat{Q}\hat{Q}\hat{Q}\hat{L} \quad (\tau_p > 10^{32-34} \text{ years} \Longrightarrow \Lambda > 10^{16-17} \text{ GeV})$$

What about the $\hat{L}\hat{H}_u, \hat{L}\hat{L}\hat{e}^c, \hat{Q}\hat{L}\hat{d}^c$ and $\hat{u}^c\hat{d}^c\hat{d}^c$ interactions?

MSSM

10 TeV ? 100 TeV ? ...

GUTs, Strings ?

B and L as Local Symmetries

E. P. Wigner, 1952

S. Rajpoot, 1987

Foot, Joshi, Lew, 1989

Carone, Murayama, 1995

P. F. P., M.B. Wise, 2010

Breaking Local Baryon and Lepton Number at the TeV Scale (NO Desert !!)

P. F. P., M. B. Wise, JHEP 1108(2011) 068

P. F. P., M.B. Wise, JHEP 1108(2011)068

Breaking B and L at the TeV Scale

$$G_{SM} \bigotimes U(1)_B \bigotimes U(1)_L$$

MSSM Matter

$$\hat{Q} \sim (1/3, 0), \hat{u}^c \sim (-1/3, 0), \hat{d}^c \sim (-1/3, 0)$$

$$\hat{L} \sim (0, 1), \hat{e}^c \sim (0, -1), \hat{\nu}^c \sim (0, -1)$$

Extra vector-like family

$$\hat{Q}_4, \hat{u}_4^c, \hat{d}_4^c, \hat{L}_4, \hat{e}_4^c, \hat{\nu}_4^c$$

$$\hat{Q}_5^c, \hat{u}_5, \hat{d}_5, \hat{L}_5^c, \hat{e}_5, \hat{\nu}_5$$

Anomaly free theory

$$B_{Q_4} + B_{Q_5^c} = -1,$$

$$L_{L_4} + L_{L_5^c} = -3$$

P. F. P., M.B. Wise, JHEP 1108(2011)068

The BLMSSM

$$\mathcal{W}_Q = \lambda_Q \hat{Q}_4 \hat{Q}_5^c \hat{S}_B \; + \; \lambda_u \hat{u}_4^c \hat{u}_5 \hat{\bar{S}}_B \; + \; \lambda_d \hat{d}_4^c \hat{d}_5 \hat{\bar{S}}_B$$

$$\mathcal{W}_L = Y_{e_4} \hat{L}_4 \hat{H}_d \hat{e}_4^c \; + \; Y_{e_5} \hat{L}_5^c \hat{H}_u \hat{e}_5 \; + \; Y_{\nu_4} \hat{L}_4 \hat{H}_u \hat{\nu}_4^c$$
$$+ \; Y_{\nu_5} \hat{L}_5^c \hat{H}_d \hat{\nu}_5 \; + \; Y_\nu \hat{L} \hat{H}_u \hat{\nu}^c \; + \; \lambda_{\nu^c} \hat{\nu}^c \hat{\nu}^c \hat{\bar{S}}_L$$

$$\mathcal{W}_X = \lambda_1 \hat{Q} \hat{Q}_5^c \hat{X} \; + \; \lambda_2 \hat{u}^c \hat{u}_5 \hat{\bar{X}} \; + \; \lambda_3 \hat{d}^c \hat{d}_5 \hat{\bar{X}} \; + \; \mu_X \hat{X} \hat{\bar{X}}$$

$$\mathcal{W}_5 = \frac{a_1}{\Lambda} \hat{u}^c \hat{d}^c \hat{d}^c \hat{S}_B$$

P. F. P., M.B. Wise, JHEP 1108(2011)068

Symmetry Breaking

$$\langle S_L \rangle \neq 0, \langle S_B \rangle \neq 0$$

$$G_{SM} \bigotimes U(1)_B \bigotimes U(1)_L \quad \Longrightarrow \quad G_{SM} \bigotimes M_L$$

$$M_L = (-1)^L$$

$$\Delta B = 1, \Delta L = 2$$

Symmetry Breaking at TeV and NO proton decay

$$\frac{a_1}{\Lambda} \hat{u}^c \hat{d}^c \hat{d}^c \hat{S}_B \quad \Longrightarrow \quad \frac{a_1 \langle S_B \rangle}{\Lambda} \tilde{u}^c d^c s^c, \ldots.$$

Local B and L are broken at the TeV Scale

$$\frac{1}{2}M_{Z_B}^2 = -|\mu_B|^2 + \left(\frac{m_{S_B}^2 - m_{\bar{S}_B}^2 \tan^2\beta_B}{\tan^2\beta_B - 1}\right)$$

$$\frac{1}{2}M_{Z_L}^2 = -|\mu_L|^2 + \left(\frac{m_{S_L}^2 - m_{\bar{S}_L}^2 \tan^2\beta_L}{\tan^2\beta_L - 1}\right)$$

$m_{S_B}, m_{S_L}, m_{\bar{S}_B}$ and $\mathrm{m}_{\bar{\mathrm{S}}_\mathrm{L}}$ are soft masses.

Main Features:

- Local B and L can be spontaneously broken at the TeV scale.

- The Proton is stable.

- No Flavour Violation at Tree Level.

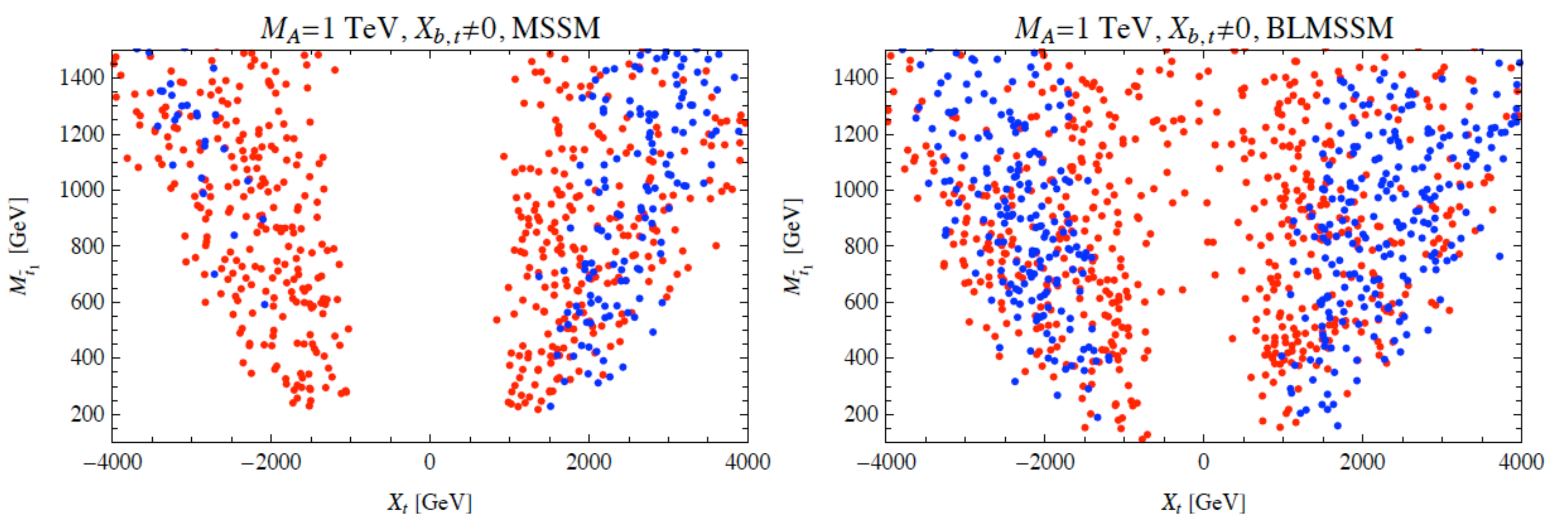
- No Landau poles at the low scale.

- The LHC bounds from SUSY searches could be avoided due to B violation.

- The Higgs boson mass can be large without assuming a large stop mass and left-right mixing.

P.F.P., Phys.Lett. B711 (2012) 353; J.M.Arnold, P.F.P., B. Fornal, S. Spinner, hep-ph/1204.4458

Predictions for the Light Higgs Boson Mass



M_h { $115 - 122$ GeV ; $122 - 128$ GeV

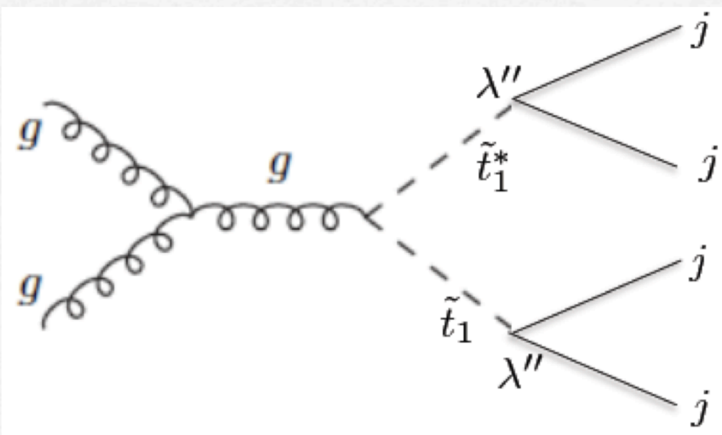
$$M_{\nu_4} = M_{\nu_5} = 90 \text{ GeV}$$

$$M_{e_4} = M_{e_5} = 100 \text{ GeV}$$

J.M.Arnold, P.F.P., B. Fornal, S. Spinner, hep-ph/1204.4458

Stop as the LSP and BNV:

$$\frac{a_1}{\Lambda}\hat{u}^c\hat{d}^c\hat{d}^c\hat{S}_B \quad \Rightarrow \quad 2\lambda^{''}_{ijk}u^c_i d^c_j \tilde{d}^c_k, \;\; \lambda^{''}_{ijk}\tilde{u}^c_i d^c_j d^c_k$$



$$\lambda^{''}_{ijk} = a_1^{ijk}\frac{v_B}{\sqrt{2}\Lambda}$$

$$\mathrm{L}(\tilde{q}_i \to q_j q_k) \; > \; 1\ \mathrm{mm}\left(\frac{10^2\ \mathrm{GeV}}{M_{\tilde{q}}}\right)\left(\frac{10^{-7}}{\lambda''}\right)^2 .$$

Form bounded states and
give rise to displaced vertices !

Summary

- The Minimal B-L Theories predict that R-parity should be spontaneously broken and one expects Lepton Number Violation at the LHC.

- There is no "simple" grand unified theory in 4D for R-parity conservation.

- There is no need for a desert if B and L are gauged and broken at the low scale.

- A simple theory where B and L are local gauge symmetries spontaneously broken at the SUSY scale was presented. This theory predicts B and L violation at the LHC !

Muchas Gracias !

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 !**

ν_i → **Massless Neutrinos !**

Radiative Symmetry Breaking

P.F.P., S.Spinner'10

RpC

$\langle X \rangle \neq 0, \langle \bar{X} \rangle \neq 0$

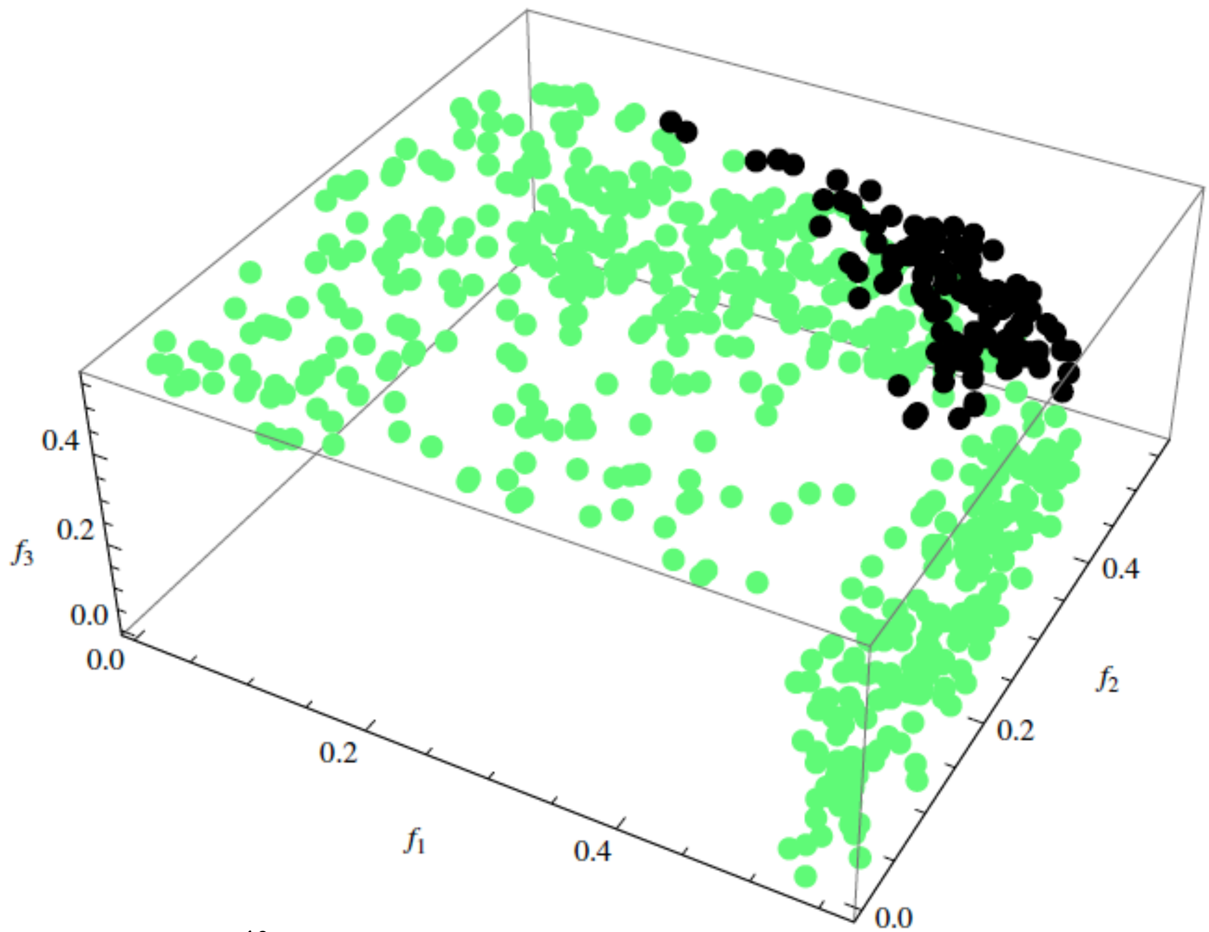
RpV

$\langle \tilde{\nu}^c \rangle \neq 0$

$$M_0 = 2 \text{ TeV},$$
$$M_{1/2} = 200 \text{ GeV},$$
$$A_0 = 0.$$

$f \nu^c \nu^c X$

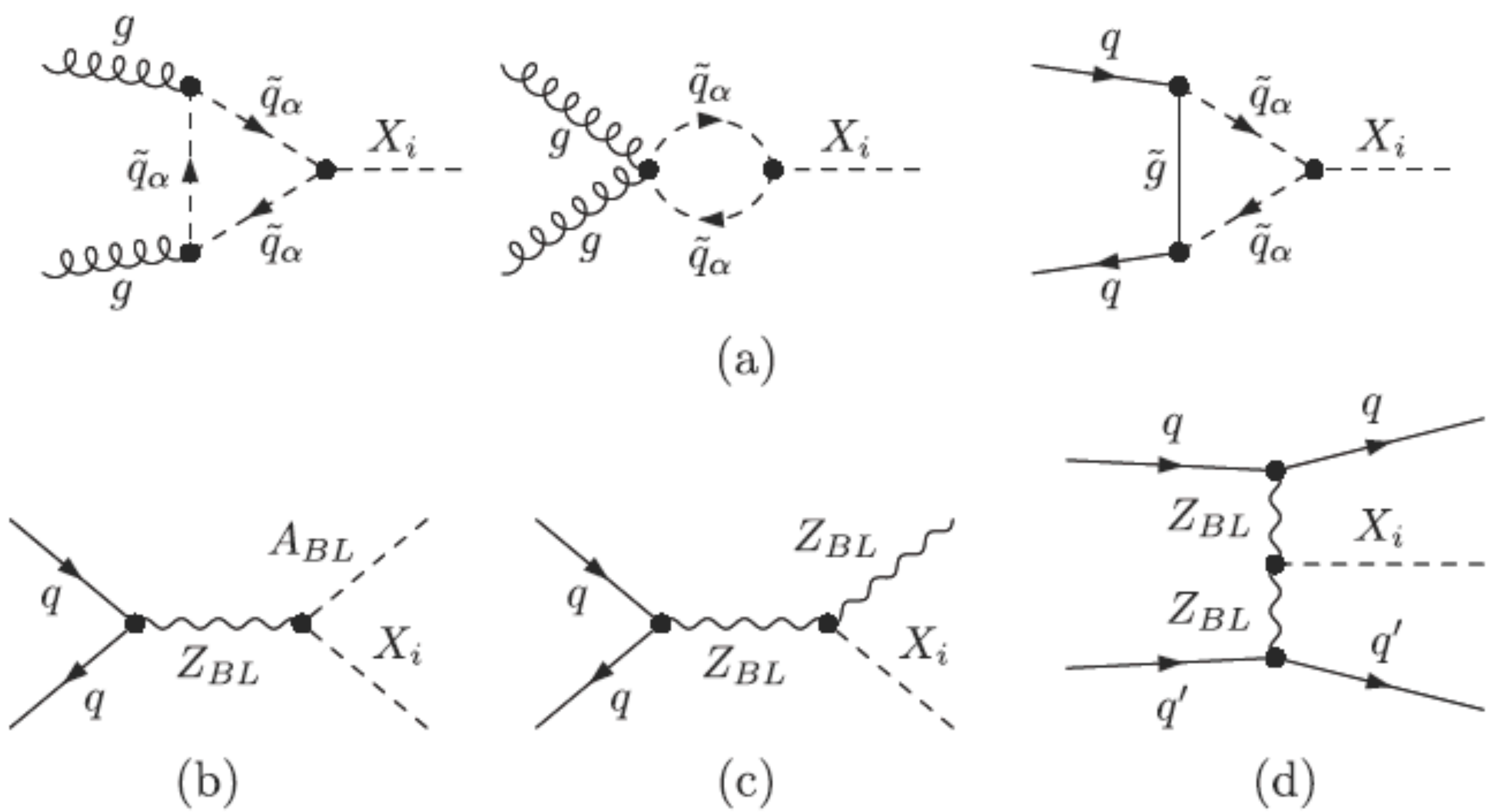
FATE OF *R* PARITY



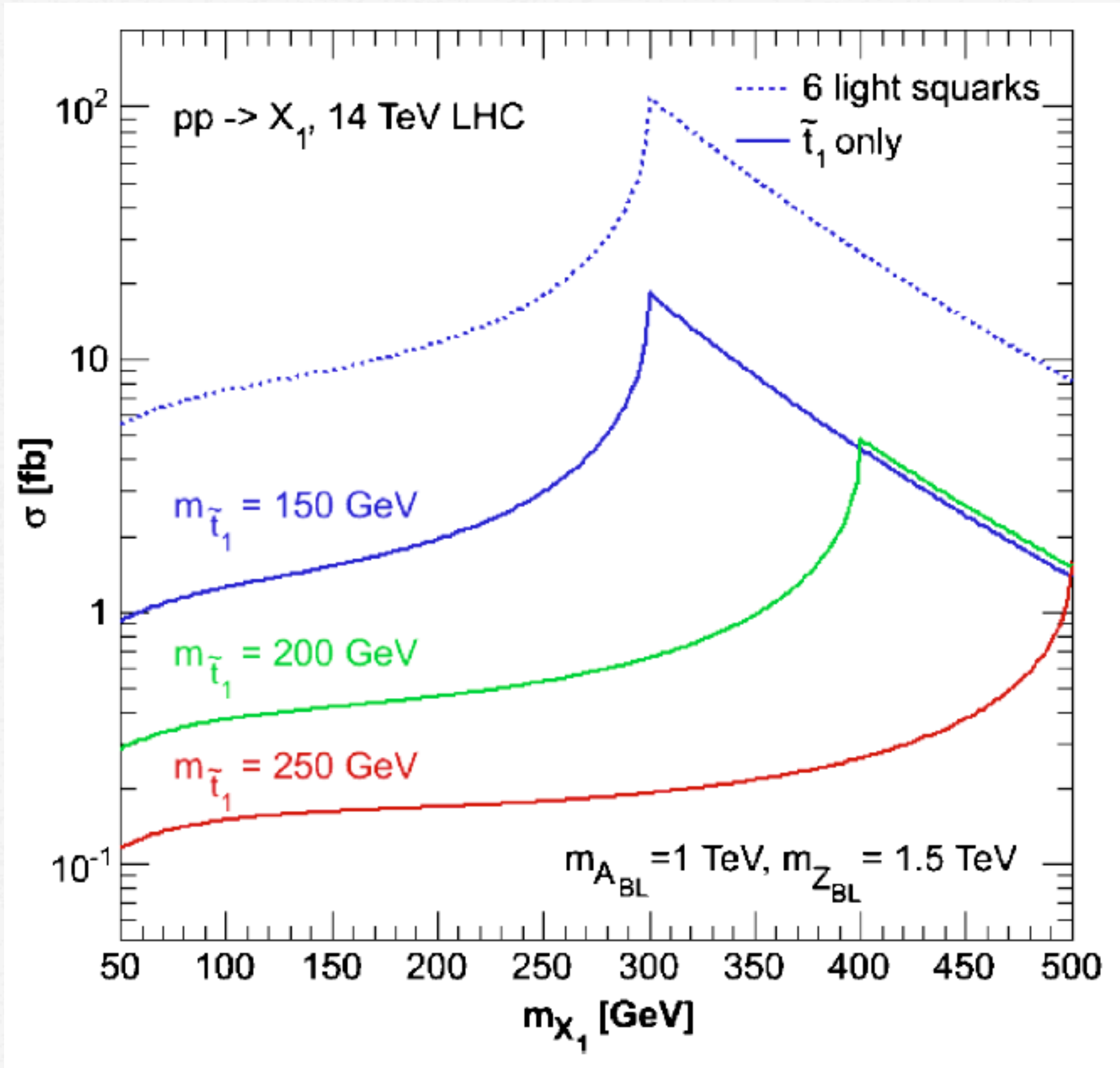
Production Mechanisms:

B-L Higgses: X_1, X_2, A_{BL}

PHYSICAL REVIEW D **84,** 095028 (2011)

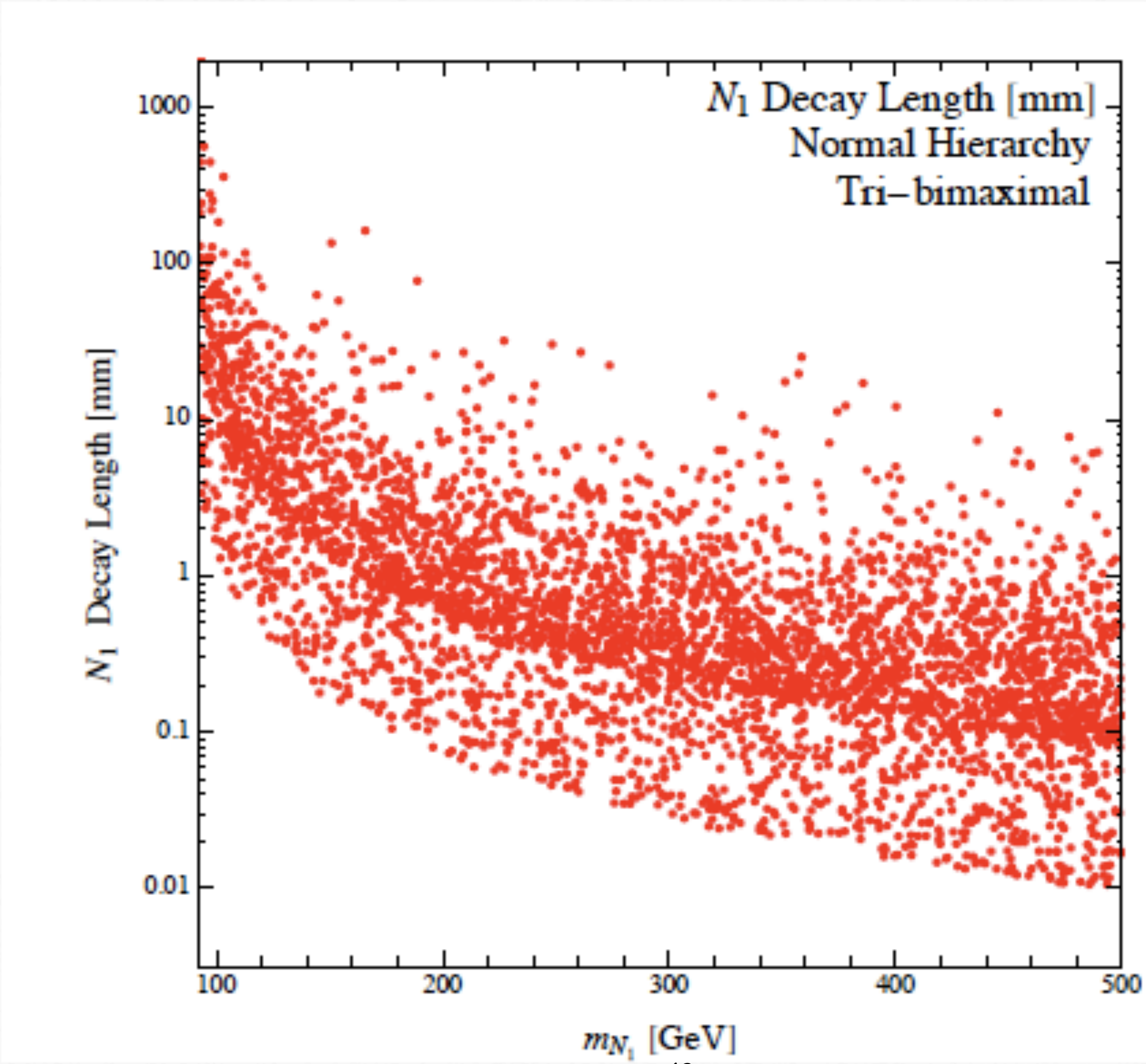


$p\,p \;\to X_1$



pp -> X1, 14 TeV LHC
6 light squarks
t̃1 only
m t̃1 = 150 GeV
m t̃1 = 200 GeV
m t̃1 = 250 GeV
m ABL =1 TeV, m ZBL = 1.5 TeV
σ [fb]
mX1 [GeV]
10^2
10
1
10^-1
50
100
150
200
250
300
350
400
450
500

Right-Handed Neutrino Decay Length



Signals at the LHC

Single Production: $pp \to X_1 \to NN \to e_i^{\pm} e_j^{\pm} 4j$

Benchmark I: $\mathcal{L} = 100 \text{ fb}^{-1}$

$$m_{A_{BL}} = 1 \text{ TeV}, m_{X_1} = 300 \text{ GeV}, m_{Z_{BL}} = 1.5 \text{ TeV},$$
$$m_{\tilde{t}_1} = 150 \text{ GeV}, m_{\tilde{q},\tilde{l}} = 1 \text{ TeV}, m_{N_i} = 95 \text{ GeV},$$
$$\sigma_{pp \to X_1} = 16.3 \text{ fb}$$

Final State	Combinatorics	Signal	Background
$2\,e^{\pm}\,4\,j$	0.038	62	6
$e^{\pm}\,\mu^{\pm}\,4\,j$	0.030	50	12
$2\,\mu^{\pm} 4\,j$	0.027	43	6

Lepton number violation plus two displaced vertices

P. F. P., M.B. Wise, JHEP 1108(2011)068

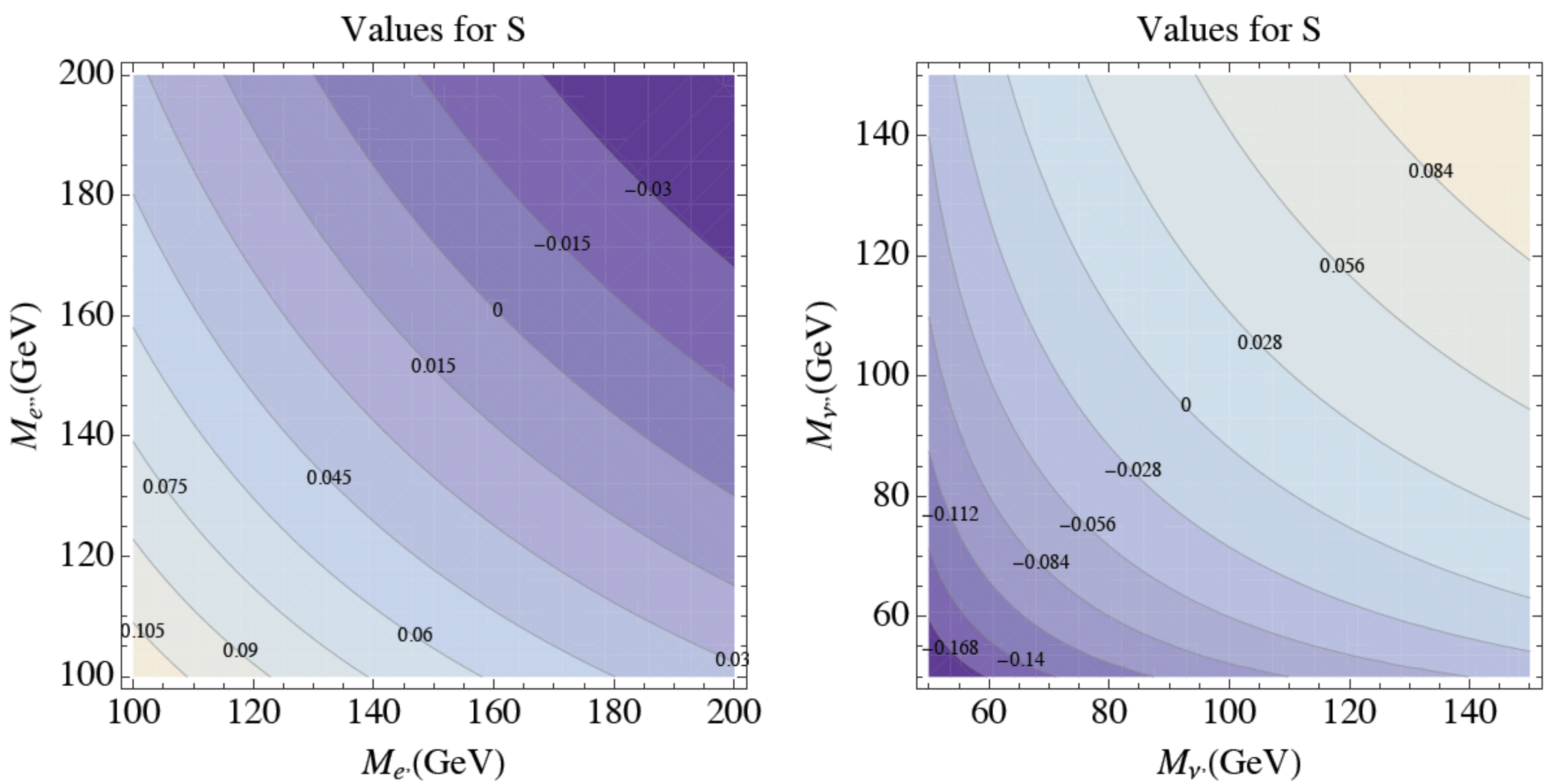


FIG. 1: Values for the S parameter when the masses of the fourth generation neutrinos is equal to 100 GeV (left panel) and when the masses of the new charged leptons is 150 GeV (right panel).

P. F. P., S. Spinner, hep-ph/1201.5923

Gluino as the LSP

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow tt\, \bar{b}\bar{b}\, e_i^- e_j^-, \; tt\, \bar{t}\bar{t}\, \nu\nu$$

$$pp \rightarrow \tilde{g}\tilde{g} \rightarrow 4j\, e_i^- e_j^-, \; 4j\, \nu\nu$$

Inclusive study by ATLAS: **arXiv:1201.1091**

$$\sigma(\mu^\pm \mu^\pm) < 58 \text{ fb}$$

$$M_{\tilde{g}} > 1 \text{ TeV}$$

Heavy Spectrum !

P. F. P., S. Spinner, hep-ph/1201.5923

Squark as the LSP

$$pp \to \tilde{t}^* \tilde{t} \to b\bar{b}\ e_i^{\pm} e_j^{\mp},\ \bar{t}t\ \nu\nu$$

$$pp \to \tilde{q}^* \tilde{q} \to 2j\ e_i^{\pm} e_j^{\mp},\ 2j\ \nu\nu$$

Charged Slepton as the LSP

$$pp \to \tilde{e}_i^* \tilde{e}_i \to \bar{t}t\ b\bar{b},\ e_i^{+} e_i^{-}\, \nu\nu$$

Neutral Slepton as the LSP

$$pp \to \tilde{\nu}_i^* \tilde{\nu}_i \to \bar{b}b\ b\bar{b},\ \nu\nu\nu\nu$$

P. F. P., S. Spinner, hep-ph/1201.5923

Chargino as the LSP

$$pp \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \rightarrow e_i^+ e_j^- \; ZZ, \; \nu\nu \; W^+ W^-$$

Neutralino as the LSP

$$pp \rightarrow Z^* \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow 4j \; e_i^\pm e_j^\pm$$ (Higgsino Case)

$$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^\pm \rightarrow 4j \; \nu \; e_i^\pm e_j^\pm e_k^\pm$$

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

The Most Interesting Signals !

P. F. P., S. Spinner, JHEP 04 (2012) 118

$$m_\nu = V_{\text{PMNS}}^T \, M_\nu \, V_{\text{PMNS}},$$