BNV and LNV in MSSM

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Based on Collaborations with

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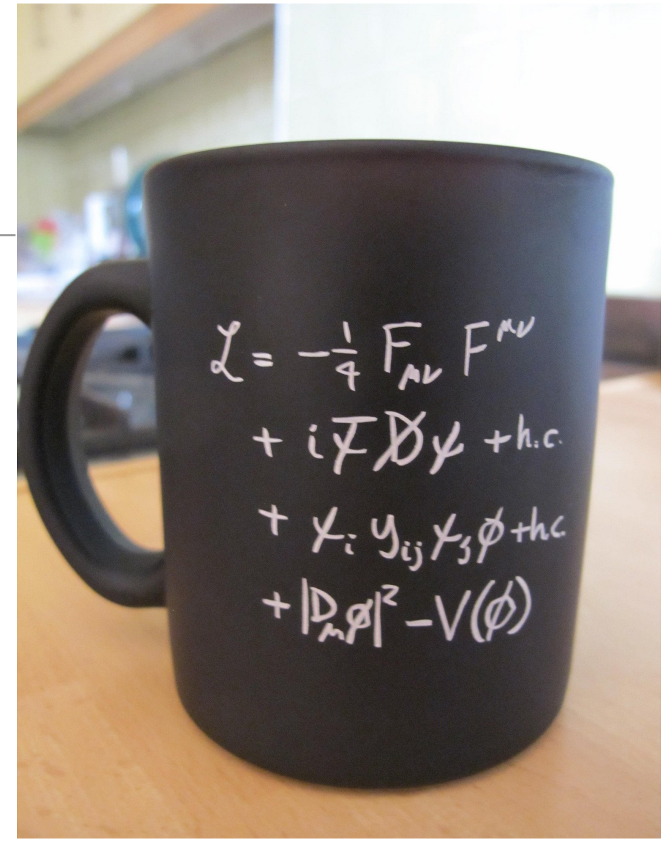
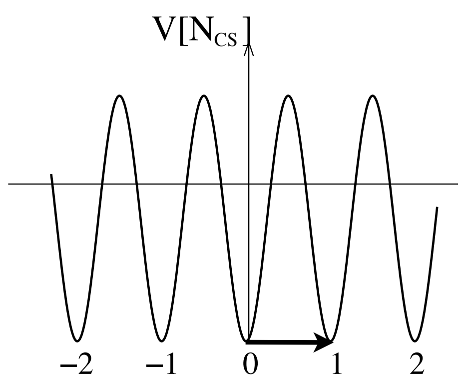
Baryon Number in the SM

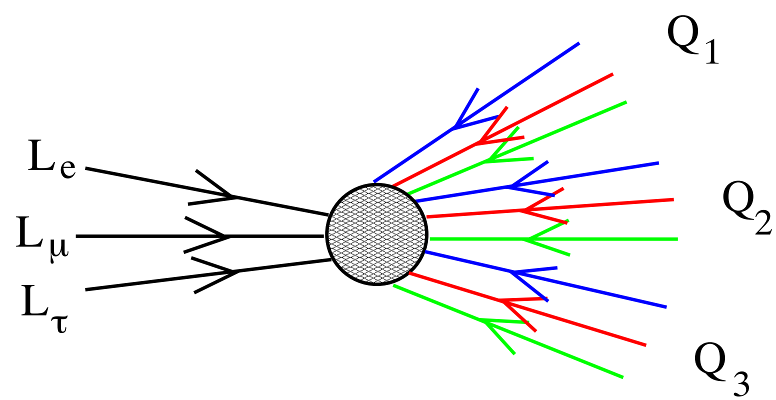


- Standard Model Lagrangian:
  - accidental symmetries
    - B: no p-decay, no n-nbar oscillation
    - L, L_e, L_μ, L_τ: no nu-oscillation, no cLFV

- Baryon Number violated at quantum level:
  - non-perturbative effects associated with $SU(2)_L$
    - $\Delta B = \Delta L = 3$
    - $\Delta(B-L) = 0$



$\Rightarrow$



  - at T=0: effects negligible

Expectation for Baryon Number Violation

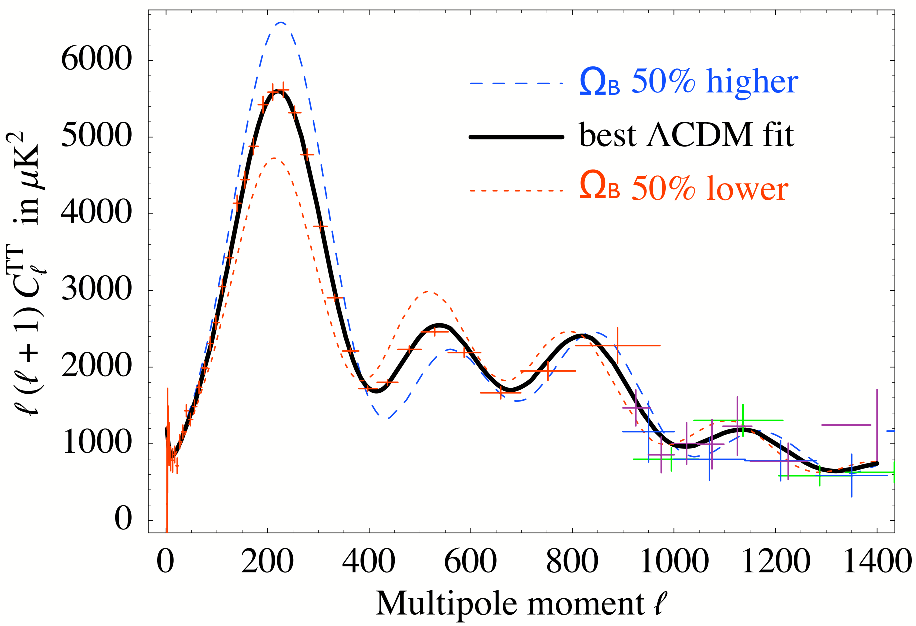
- B and L cannot be exact global symmetries
  - all global symmetries violated by quantum gravity

- B or L symmetries are not exact gauge symmetries
  - unless gauge coupling $g < 10^{-26}$ e   Lee and Yang (1955)

B and L conservation not sacred,
violated by new particles and fields

Big Hint of Baryon Number Violation

- CMB anisotropy



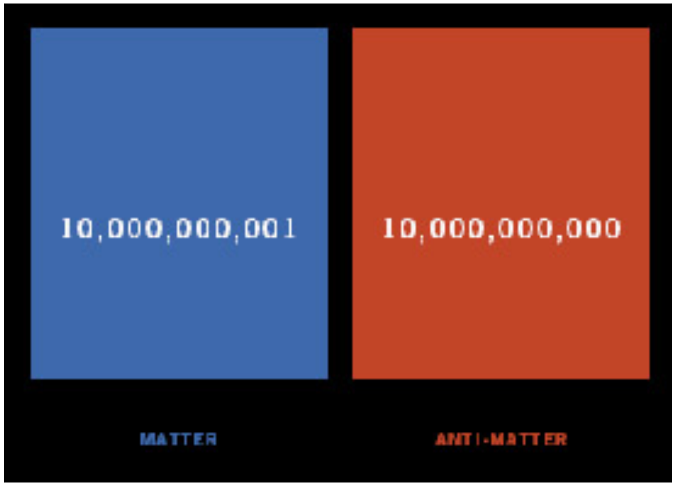
- Big Bang Nucleosynthesis
  - primordial deuterium abundance
    $\Longleftrightarrow$ agree with WMAP
  - ^4He & ^7Li
    $\Longleftrightarrow$ discrepancies

- WMAP + Deuterium Abundance

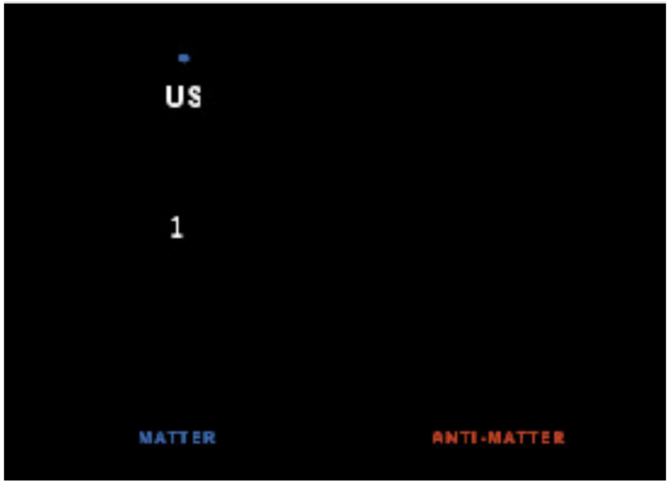
Cosmological matter-antimatter asymmetry

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

Three Sakharov Conditions



Early Universe



Universe Now

[Picture credit: H. Murayama]

- Baryon number can be generated dynamically, if
  - **violation of baryon number**
  - violation of Charge-Conjugation (C) and Charge Parity (CP)
  - departure from thermal equilibrium

Baryon Number beyond the SM

Weinberg (1979)

- SM as low energy effective theory:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\mathcal{O}_{5D}}{M} + \frac{\mathcal{O}_{6D}}{M^2} + \ldots$$

→ **new physics effects**

- EFT with quarks, leptons, and gauge fields

$$\mathcal{O}_{6D} \supset c\,\frac{QQQL}{M^2}$$

→ **ΔB = ΔL= 1**
proton decay

$$\mathcal{O}_{9D} \supset g\,\frac{QQQ\bar{Q}\bar{Q}\bar{Q}}{M^5}$$

→ **|ΔB| = 2**
neutron-antineutron oscillation

Baryon Number beyond the SM

Weinberg (1979)

- SM as low energy effective theory:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\mathcal{O}_{5D}}{M} + \frac{\mathcal{O}_{6D}}{M^2} + \ldots$$

→ **new physics effects**

- EFT with quarks, leptons, gauge fields and the Higgs:

$$\mathcal{O}_{5D} \supset y \frac{LLHH}{M}$$

→ **ΔL = 2 neutrino Majorana mass**

Unique window into high scale physics

MSSM

- Solution for gauge hierarchy problem
- BNV and LNV already at renormalizable level
- Gauge invariant superpotential terms up to order 4

$$\begin{aligned}\mathscr{W} &= \mu H_d H_u + \kappa_i L_i H_u \\ &+ Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\ &+ \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\ &+ \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell\end{aligned}$$

$\stackrel{!}{\sim} 1/10^{15}$ GeV
in order to
explain see–saw
suppressed
ν masses

Constraints from neutrino masses

MSSM

- Gauge invariant superpotential terms up to order 4

$$
\begin{aligned}
\mathscr{W} \;=\; & \mu H_d H_u + \kappa_i L_i H_u \\
& + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
& + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
& + \kappa^{(0)}_{ij} H_u L_i H_u L_j + \kappa^{(1)}_{ijk\ell} Q_i Q_j Q_k L_\ell + \kappa^{(2)}_{ijk\ell} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}
$$

$\mu \stackrel{!}{\sim}$ TeV

☞ Problematic terms

- ☹ $\mu / B\mu$ problem(s)
  Why does μ know about the electroweak scale?

MSSM

- Gauge invariant superpotential terms up to order 4

Proton stability: $\lambda'\lambda'' \lesssim 10^{-27}$, $\lambda'\lambda_3 \lesssim 10^{-10}$, $\lambda_1 \lesssim 10^{-8},\ \lambda_2 \lesssim 10^{-8}$

$$
\begin{aligned}
\mathscr{W} &= \mu H_d H_u + \kappa_i L_i H_u \\
&\quad + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
&\quad + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
&\quad + \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}
$$

$$\kappa_{1121}^{(1)} \overset{!}{\lesssim} \frac{10^{-8}}{M_\mathrm{P}}$$

☞ Problematic terms

☹ $\mu/B\mu$ problem(s)

☹ dimension four and five proton decay operators

MSSM

- Traditional Cure of proton decay problem

$$
\begin{aligned}
\mathscr{W} \;=\; & \mu H_d H_u + \kappa_i L_i H_u \\
& + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
& + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
& + \kappa^{(0)}_{ij} H_u L_i H_u L_j + \kappa^{(1)}_{ijk\ell} Q_i Q_j Q_k L_\ell + \kappa^{(2)}_{ijk\ell} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}
$$

need to be strongly suppressed

MSSM

- Traditional Cure of proton decay problem

Farrar, Fayet (1978);
Dimopoulos, Raby, Wilczek (1981)

$$
\begin{aligned}
\mathscr{W} \; = \; & \mu H_d H_u + \kappa_i L_i H_u \\
& + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
& + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
& + \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}
$$

forbidden by matter parity

MSSM

- Traditional Cure of proton decay problem

Ibanez, Ross (1992)

$$\begin{aligned}
\mathscr{W} &= \mu H_d H_u + \kappa_i L_i H_u \\
&\quad + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
&\quad + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
&\quad + \kappa^{(0)}_{ij} H_u L_i H_u L_j + \kappa^{(1)}_{ijk\ell} Q_i Q_j Q_k L_\ell + \kappa^{(2)}_{ijk\ell} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}$$

forbidden by baryon triality

MSSM

- Traditional Cure of proton decay problem

Babu, Gogoladze, Wang (2002); Dreiner, Luhn, Thormeier (2006)

$$
\begin{aligned}
\mathscr{W} \;=\; & \mu H_d H_u + \kappa_i L_i H_u \\
& + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\
& + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\
& + \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell
\end{aligned}
$$

forbidden by proton hexality

☞ Proton hexality = matter parity + baryon triality

Proton Hexality

Babu, Gogoladze, Wang (2002);
Dreiner, Luhn, Thormeier (2006)

☞ Proton hexality P_6 = matter parity $\mathbb{Z}_2^{\mathcal{M}}$ × baryon triality B_3

	Q	$\bar{U}$	$\bar{D}$	L	$\bar{E}$	H_u	H_d	$\bar{\nu}$
$\mathbb{Z}_2^{\mathcal{M}}$	1	1	1	1	1	0	0	1
B_3	0	−1	1	−1	2	1	−1	0
P_6	0	1	−1	−2	1	−1	1	3

☞ Appealing features

- ☺ forbids dimension four and five proton decay operators
- ☺ allows Yukawa couplings & Weinberg operator $\kappa_{ij}^{(0)} H_u L_i H_u L_j$
- ☺ unique anomaly–free symmetry with the above features

☞ However:

- ☹ not consistent with unification for matter (i.e. inconsistent with universal discrete charges for all matter fields)

Proton Hexality

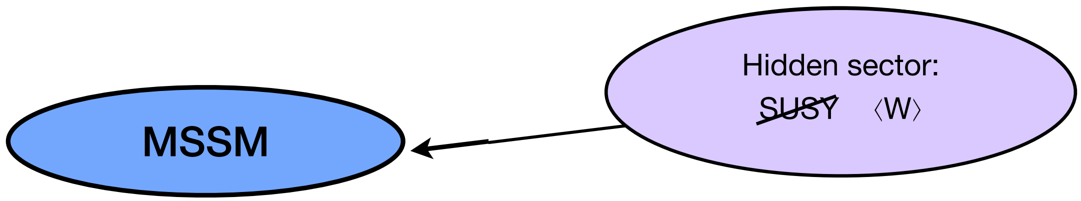
- ☹ not consistent with (grand) unification for matter
- ☹ does not address μ problem

$$\begin{aligned}\mathscr{W} \;=\; & \mu H_d H_u + \kappa_i L_i H_u \\ & + Y_e^{ij} L_i H_d \overline{E}_j + Y_d^{ij} Q_i H_d \overline{D}_j + Y_u^{ij} Q_i H_u \overline{U}_j \\ & + \lambda_{ijk} L_i L_j \overline{E}_k + \lambda'_{ijk} L_i Q_j \overline{D}_k + \lambda''_{ijk} \overline{U}_i \overline{D}_j \overline{D}_k \\ & + \kappa_{ij}^{(0)} H_u L_i H_u L_j + \kappa_{ijk\ell}^{(1)} Q_i Q_j Q_k L_\ell + \kappa_{ijk\ell}^{(2)} \overline{U}_i \overline{U}_j \overline{D}_k \overline{E}_\ell + \ldots\end{aligned}$$

needs to be suppressed as well. . .

Small mu term and SUSY Breaking

- before SUSY breaking: absence of mu term



- Giudice-Masiero Mechanism for the mu problem

Giudice, Masiero (1988)

  - after SUSY breaking: realistic effective mu term generated

$$\mu \sim \langle \mathscr{W} \rangle / M_{\rm P}^2 \sim m_{3/2}$$

- need a symmetry reason for the absence of these operators before SUSY breaking

Discrete R Symmetries

- anomaly freedom
- consistency with SU(5)

$\curvearrowright$ only R symmetries can forbid the μ term in the MSSM

- No continuous R symmetries available in MSSM — Chamseddine, Dreiner (1996)
- Only remaining option: **Discrete R symmetries**

☞ Working assumptions: — Kurosawa, Maru, Yanagida (2001); Babu, Gogoladze, Wang (2002)

(i) anomaly freedom (allow for GS anomaly cancellation)

(ii) μ term forbidden at perturbative level

(iii) Yukawa couplings and Weinberg neutrino mass operator allowed

☞ Consider $\mathbb{Z}_M^R$ symmetry which commutes with $\mathrm{SO}(10)$
i.e. quarks and leptons have universal charge q

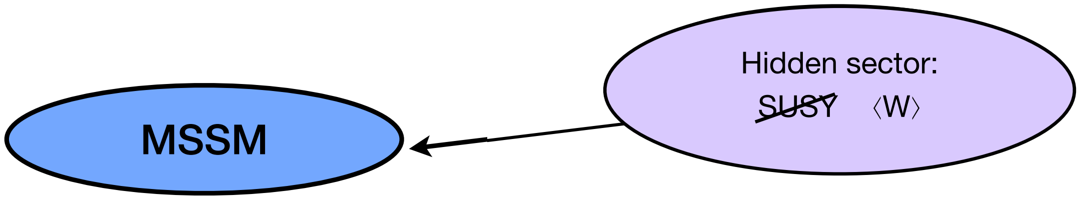
$\Rightarrow$ Z_4^R

unique symmetry : $\mathbb{Z}_4^R$ w/ $q = q_\theta = 1$ & $q_{H_u} = q_{H_d} = 0$

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevaunge (2011)

Small mu term, Dirac Neutrinos and SUSY Breaking

- before SUSY breaking: absence of Dirac neutrino masses (as well as Weinberg operator)



- Giudice-Masiero Mechanism for the mu problem

Giudice, Masiero (1988)

$$\mu \sim \langle \mathscr{W} \rangle / M_{\rm P}^2 \sim m_{3/2}$$

- after SUSY breaking: realistic effective Dirac neutrino masses generated

$$Y_\nu \sim \frac{m_{3/2}}{M_{\rm P}} \sim \frac{\mu}{M_{\rm P}}$$

Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner (2001)

- need a symmetry reason for the absence of these operators before SUSY breaking

Dirac Neutrino Mass and the μ Term

- Anomaly-free, discrete R-symmetries in MSSM:

M.-C. C., Ratz, Staudt, Vaudrevange (2012)

  - absence of perturbative mu term ⇒ constraints on R charges of Hu, Hd

    SUSY breaking ➜ mu term ~ TeV automatically arise

$$\mu \sim \langle \mathscr{W} \rangle / M_{\mathrm{P}}^2 \sim m_{3/2}$$

  - absence of perturbative Weinberg operator ⇒ constraints on R charges of leptons

    SUSY breaking ➜ realistic Dirac neutrino mass automatically arise

$$Y_\nu \sim \frac{m_{3/2}}{M_{\mathrm{P}}} \sim \frac{\mu}{M_{\mathrm{P}}}$$

  - solutions automatically forbid dim-4 proton decay, automatically suppress dim-5 proton decay in superpotential

Dirac Neutrino Mass and the μ Term

- Search Abelian discrete R symmetries, $\mathbb{Z}_M^R$ that satisfy M.-C. C., Ratz, Staudt, Vaudrevange (2012)
  - anomaly freedom (a la Green-Schwarz)
  - forbidding mu term perturbatively
  - consistent with SU(5)
  - allowing usual Yukawa couplings
  - Weinberg operators forbidden perturbatively

classes of models found

- an example: $\mathbb{Z}_8^R$ symmetry
  - after SUSY breaking: $$\mathscr{W}_{\text{eff}} \sim m_{3/2}\, H_u\, H_d + \frac{m_{3/2}}{M_\text{P}}\, L\, H_u\, \bar{\nu} + \frac{m_{3/2}}{M_\text{P}^2}\, Q\, Q\, Q\, L$$
  - Δ L = 2 operators forbidden ⇒ no neutrinoless double beta decay
  - **ΔL = 4 operators allowed ⇒ new LNV processes** M.-C. C., Ratz, Staudt, Vaudrevange (2012)

- A simultaneous solution possible with discrete generation dependent R symmetries (Abelian or non-Abelian!)

M.-C.C., M. Ratz, A. Trautner (2013)

MSSM with RPV Operators

- No sign of SUSY (yet!) at the LHC
- Rich phenomenology, though need to be careful about proton decay

- Classifications of $\mathbb{Z}_M^R$ symmetries compatible with MSSM models with RPV operators (BNV, LNV) Dreiner, Hannusek, Luhn (2012)
  - allowing BNV, LNV at dim-3, 4, 5; mu term
  - allowing GS anomaly cancellation
  - compatibility with GUT
  - only for $q_\theta = 1$ with all R charges being integers

MSSM with RPV Operators

- Classifications of $\mathbb{Z}_M^R$ symmetries compatible with MSSM models with RPV operators (BNV, LNV)

  Dreiner, Hannusek, Luhn (2012)

  - allowing BNV, LNV at dim-3, 4, 5; mu term
  - allowing GS anomaly cancellation
  - compatibility with GUT
  - only for $q_\theta = 1$ with all R charges being integers

- Complete Classifications

  M.-C. C, Ratz, Takhistov (2014)

  - with $q_\theta > 1$ with all R charges being integers
  - allowing for non-universal GS cancellation of discrete anomalies

Anomaly Cancellation

- For a $U(1)_R$ symmetry:

$$
\begin{aligned}
A_3 &= \frac{1}{2}\sum_f \Big[2q_Q^f + q_{\overline{U}}^f + q_{\overline{D}}^f - 4q_\theta\Big] + 3q_\theta \\
&= \frac{3}{2}\Big[2q_Q + q_{\overline{U}} + q_{\overline{D}}\Big] - 3q_\theta\ , \qquad (2.20a) \\
A_2 &= \frac{1}{2}\Big[q_{H_u} + q_{H_d} - 2q_\theta + \sum_f \Big(3q_Q^f + q_L^f - 4q_\theta\Big)\Big] + 2q_\theta \\
&= \frac{1}{2}\Big[q_{H_u} + q_{H_d} + 3\left(3q_Q + q_L\right)\Big] - 5q_\theta\ , \qquad (2.20b) \\
A_1 &= \frac{1}{2}\left[q_{H_u} + q_{H_d} - 2q_\theta + \frac{1}{3}\sum_i \Big(q_Q^f + 8q_{\overline{U}}^f + 2q_{\overline{D}}^f + 3q_L^f + 6q_{\overline{E}}^f - 20q_\theta\Big)\right] Y_L^2 \\
&= \frac{3}{10}\left[q_{H_u} + q_{H_d} + q_Q + 8q_{\overline{U}} + 2q_{\overline{D}} + 3q_L + 6q_{\overline{E}} - 22q_\theta\right]. \qquad (2.20c)
\end{aligned}
$$

- Cancelled by GS axion with coupling to field strengths

Anomaly Cancellation

- For a discrete $\mathbb{Z}_N^R$ symmetry:
  - A_1, A_2, A_3 defined only up to modulo

$$\eta = \begin{cases} N/2 & \text{if } N \text{ is even} , \\ N & \text{if } N \text{ is odd} . \end{cases}$$

- Anomaly universality: universal axion couplings to field strengths

Anomaly freedom
+
Grand unification
+
Green–Schwarz anomaly cancellation
$\Bigg\}$ $\rightarrow$ "Anomaly universality"

M.-C. C, Fallbacher, Ratz (2012)

$$A_3 \equiv A_2 \equiv A_1 ,$$

where now '$\equiv$' means modulo η.

- Pati-Salam partial unification: non-universal anomaly cancellation allowed

R-parity Violating MSSM

- Renormalizable Superpotential

$$\mathscr{W}_{\rm ren} = \mu\, H_u H_d + Y^u_{fg}\, Q_f\, \overline{U}_g\, H_u + Y^d_{fg}\, Q_f\, \overline{D}_g\, H_d + Y^e_{fg}\, L_f\, \overline{E}_g\, H_d$$
$$+ \kappa^f\, L_f\, H_u + \lambda^{fgh}\, L_f\, L_g\, \overline{E}_h + \lambda'^{\,fgh}\, L_f\, Q_g\, \overline{D}_h + \lambda''^{\,fgh}\, \overline{U}_f\, \overline{D}_g\, \overline{D}_h$$

- Non-renormalizable BNV and LNV operators

$$\mathcal{O}_1 = [Q\,Q\,Q\,L]_F\ , \qquad \mathcal{O}_2 = \left[\overline{U}\,\overline{U}\,\overline{D}\,\overline{E}\right]_F\ ,$$
$$\mathcal{O}_3 = [Q\,Q\,Q\,H_d]_F\ , \qquad \mathcal{O}_4 = \left[Q\,\overline{U}\,\overline{E}\,H_d\right]_F\ ,$$
$$\mathcal{O}_5 = [L\,H_u\,L\,H_u]_F\ , \qquad \mathcal{O}_6 = [L\,H_u\,H_d\,H_u]_F\ ,$$
$$\mathcal{O}_7 = \left[\overline{U}\,\overline{D}^\dagger\,\overline{E}\right]_D\ , \qquad \mathcal{O}_8 = \left[H_u^\dagger\,H_d\,\overline{E}\right]_D\ ,$$
$$\mathcal{O}_9 = \left[Q\,\overline{U}\,L^\dagger\right]_D\ , \qquad \mathcal{O}_{10} = \left[Q\,Q\,\overline{D}^\dagger\right]_D\ ,$$

R-parity Violating MSSM

- To satisfy proton decay constrains

(i) with renormalizable B violation:

- demand existence of $U^c D^c D^c$,
- forbid LLE^c (thus automatically LQD^c),
- forbid $H_d H_u$,
- forbid LH_u (thus automatically $\mathcal{O}_4$, $\mathcal{O}_7$, $\mathcal{O}_8$, $\mathcal{O}_9$),
- forbid $\mathcal{O}_1 = QQQL$;

(ii) with renormalizable L violation:

- demand existence of LLE^c (thus automatically LQD^c),
- forbid $U^c D^c D^c$,
- forbid $H_d H_u$ (thus automatically LH_u, $\mathcal{O}_4$, $\mathcal{O}_7$, $\mathcal{O}_8$, $\mathcal{O}_9$),
- forbid $\mathcal{O}_1 = QQQL$ (thus automatically $\mathcal{O}_3$ and $\mathcal{O}_{10}$).

Not compatible with SU(5): $U^c D^c D^c \Leftrightarrow LLE^c$

R-parity Violating MSSM

- Pati-Salam Compatible $q_Q = q_L \, , \; q_{\overline{U}} = q_{\overline{D}} = q_{\overline{E}} \, , \text{ and } q_{H_u} = q_{H_d} \, ,$
- Allowing Yukawa couplings
- Allowing $U^c D^c D^c$ and forbidding LH_u

$$
\begin{aligned}
-3q_{H_u} - 3q_L + 4q_\theta &= 0 \mod N \quad (\overline{U}\,\overline{D}\,\overline{D}) \, , \\
q_{H_u} + q_L - 2q_\theta &\neq 0 \mod N \quad (L\,H_u) \, .
\end{aligned}
$$

$$
2q_{H_u} + 2q_L - 2q_\theta \neq 0 \mod N
$$

$$
\left.
\begin{aligned}
\text{PS compatibility} \\
\text{allow } \overline{U}\,\overline{D}\,\overline{D} \\
\text{forbid } L\,H_u
\end{aligned}
\right\} \curvearrowright \text{Weinberg operator is forbidden.}
$$

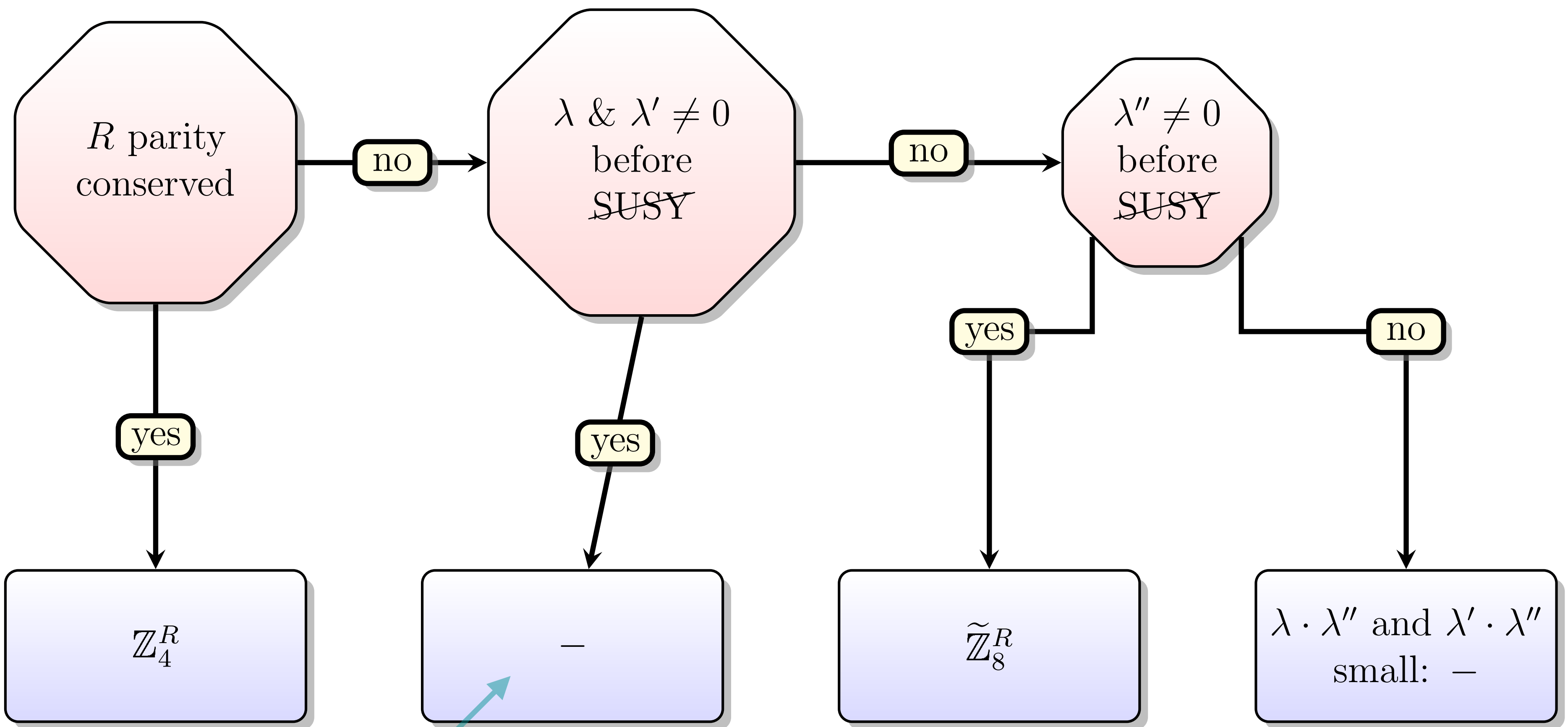
PS compatible RPV models with BNV prefer Dirac neutrinos

R-parity Violating MSSM

- Complete Classifications of discrete symmetries
  - non-universal GS anomaly cancellation
  - absence of mu term in renormalizable superpotential

  - with
    - R parity conserving
    - renormalizable BNV
    - renormalizable LNV
    - no-perturbative BNV and LNV

Solutions w/ Universal Anomaly Cancellation



$$\mathscr{W}_{\text{ren}} = \mu\, H_u H_d + Y^u_{fg}\, Q_f\, \overline{U}_g\, H_u + Y^d_{fg}\, Q_f\, \overline{D}_g\, H_d + Y^e_{fg}\, L_f\, \overline{E}_g\, H_d$$
$$+ \kappa^f\, L_f\, H_u + \lambda^{fgh}\, L_f\, L_g\, \overline{E}_h + \lambda'^{\,fgh}\, L_f\, Q_g\, \overline{D}_h + \lambda''^{\,fgh}\, \overline{U}_f\, \overline{D}_g\, \overline{D}_h$$

BNV at renormalizable superpotential

- universal anomaly cancellation up to order 12

symmetry									residual symmetry									
N	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	θ	N'	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	W	GS
5	2	2	0	2	0	3	0	1	–								–	✓
6	1	2	5	1	5	3	0	0	6	1	2	5	1	5	3	0	–	✓
6	1	0	1	3	5	1	0	1	2	1	0	1	1	1	1	0	✓	✓
6	1	4	3	3	1	5	0	2	2	1	0	1	1	1	1	0	✓	✓
8	4	6	6	4	6	0	0	1	–								–	✓
9	1	2	8	1	8	6	0	0	9	1	2	8	1	8	6	0	–	–
9	1	5	5	1	5	0	0	3	3	1	2	2	1	2	0	0	–	–
10	2	2	0	2	0	8	0	1	–								–	✓
10	7	2	5	7	5	3	0	1	2	1	0	1	1	1	1	0	–	✓
12	2	2	0	2	0	10	0	1	–								–	–
12	0	10	2	4	10	4	0	1	–								–	✓
12	0	10	2	8	6	4	0	1	–								–	✓
12	2	2	0	10	4	10	0	1	–								–	–
12	0	6	6	4	2	0	0	3	3	0	0	0	2	1	0	0	–	✓

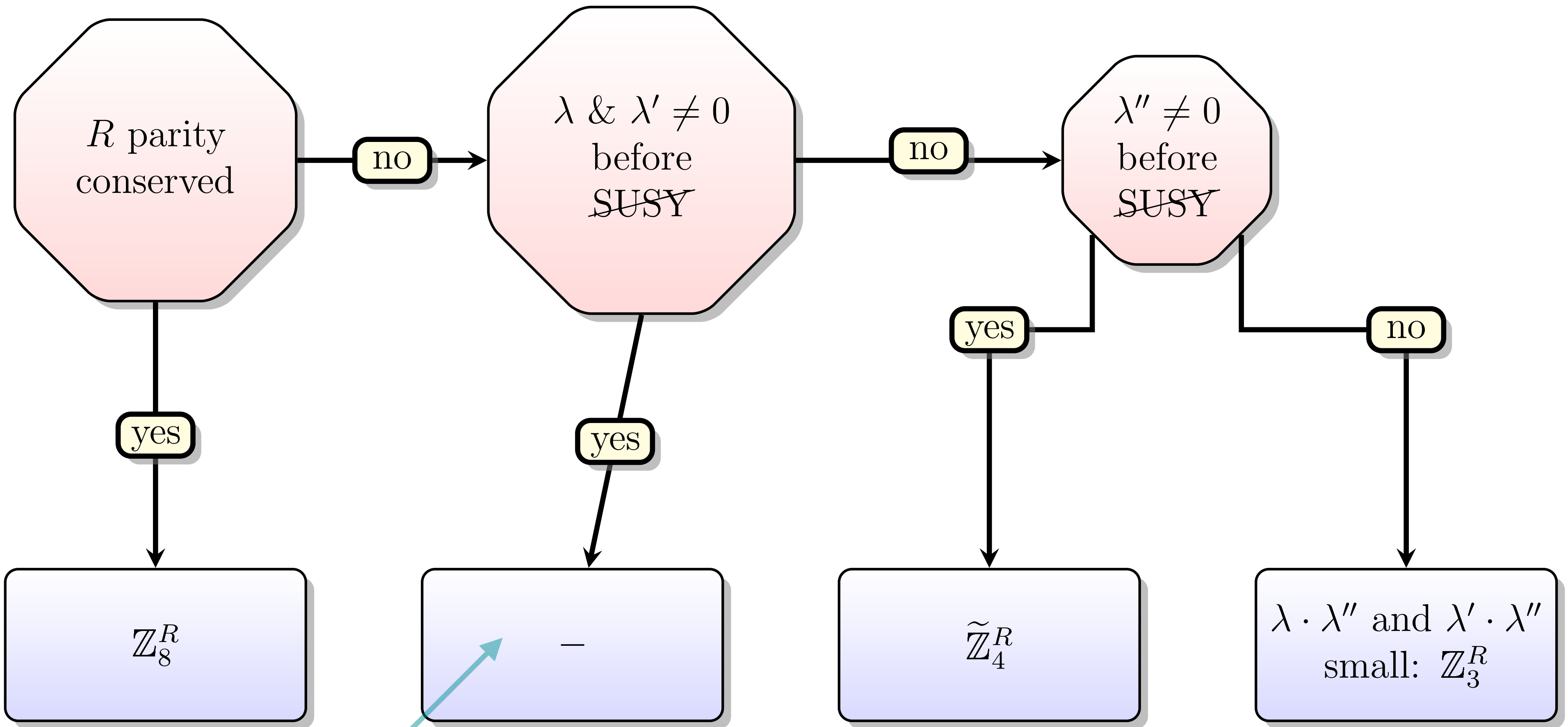
Example: Z_8^R Symmetry

- BNV at renormalizable super potential
- $U^cD^cD^c$ allowed at renormalizable superpotential

Field	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	θ
$\widetilde{\mathbb{Z}}_8^R$	4	6	6	4	6	0	0	1

- Compatible with Pati-Salam partial unification
- no neutron-antineutron oscillation

Solutions w/ Non-universal Anomaly Cancellation



$$
\begin{aligned}
\mathscr{W}_{\text{ren}} \;=\; & \mu\, H_u H_d + Y^u_{fg}\, Q_f\, \overline{U}_g\, H_u + Y^d_{fg}\, Q_f\, \overline{D}_g\, H_d + Y^e_{fg}\, L_f\, \overline{E}_g\, H_d \\
& + \kappa^f\, L_f\, H_u + \lambda^{fgh}\, L_f\, L_g\, \overline{E}_h + \lambda'^{\,fgh}\, L_f\, Q_g\, \overline{D}_h + \lambda''^{\,fgh}\, \overline{U}_f\, \overline{D}_g\, \overline{D}_h
\end{aligned}
$$

Example: Z_3^R Symmetry

- BNV and LNV forbidden at renormalizable superpotential

field	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	θ
$\mathbb{Z}_3^R$	1	1	1	1	1	0	0	1

- Non-universal anomaly cancellation
- BNV and LNV generated after SUSY breaking

$$\mathscr{W}_{\text{eff}} \supset \frac{m_{3/2}}{M_{\text{P}}} L\, L\, \overline{E} + \frac{m_{3/2}}{M_{\text{P}}} Q\, L\, \overline{D} + \frac{m_{3/2}}{M_{\text{P}}} \overline{U}\, \overline{D}\, \overline{D}$$

neutron-antineutron oscillations allowed, and can be enhanced if $M_p \rightarrow M < M_p$

Example: Z_3^R Symmetry

- BNV and LNV forbidden at renormalizable superpotential

field	Q	$\overline{U}$	$\overline{D}$	L	$\overline{E}$	H_u	H_d	θ
$\mathbb{Z}_3^R$	1	1	1	1	1	0	0	1

- Non-universal anomaly cancellation
- BNV and LNV generated after SUSY breaking

$$\mathscr{W}_{\rm eff} \supset \frac{m_{3/2}}{M_{\rm P}} L\,L\,\overline{E} + \frac{m_{3/2}}{M_{\rm P}} Q\,L\,\overline{D} + \frac{m_{3/2}}{M_{\rm P}} \overline{U}\,\overline{D}\,\overline{D}$$

LH_u is suppressed by $m_{3/2}^2/M_P$, but the μ term is of order $m_{3/2}$

counter example: allowing LNV ⇒ mu ~ kappa ~ $m_{3/2}$ in SO(10)

Acharya, Kane, Kumar, Lu, Zheng (2014)