A Pseudo-Dirac Bino and Neutrino Masses at the LHC

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Pilar Coloma, SI, PRL. 117 no.11 111803, arXiv:1606.06372
Julia Gehrlein, Patrick Fox, SI, in preparation
Neutrinos have mass

Mass eigenstates are different than flavor eigenstates

Neutrinos are massive particles

Mixing angles
\[ \theta_{23} \sim 45^\circ \]
\[ \theta_{13} \sim 9^\circ \]
\[ \theta_{12} \sim 33^\circ \]
Origin of the masses is not known

Massless in the SM — no right-handed neutrinos

SM singlet fermions

1- Can have Dirac masses

\[ y_\nu \bar{\ell} \phi \nu_R \rightarrow m_\nu \bar{\nu}_L \nu_R \quad \leftrightarrow \quad y_\nu \sim 10^{-12} \]

Fermion masses are technically natural…

‘We’ don’t like very small numbers
Origin of the masses is not known

2- Or Majorana masses — **Seesaw mechanism**

\[ y_{\nu} \bar{\ell} \phi \nu_R + \frac{1}{2} M_R \nu_R^c \nu_R \quad \Rightarrow \quad m_{\nu} \sim \frac{y_{\nu}^2 v^2}{M_R} \]

\[ y_{\nu} \sim \mathcal{O}(1) \]

\[ M_R \sim \mathcal{O}(10^{14} \text{ GeV}) \]

Lepton number is violated

Particle numbers are accidental symmetries of the SM…

Majorana particles are their own antiparticles
Origin of the masses is not known

3- Or pseudo-Dirac masses — Inverse Seesaw Mechanism

Let’s say lepton number is (approximately) conserved

SM singlets: \( N, N' \)

\[
L = 1 \quad L = -1
\]

\[
Y_N \ell \tilde{\phi} N + \epsilon Y_{N'} \ell \tilde{\phi} N' + M_D \tilde{N} N'^c + \mu \tilde{N} N^c + \mu' \tilde{N}' N'^c
\]

\[
\psi = \begin{pmatrix} N \\ N'^\dagger \end{pmatrix} : \text{pseudo-Dirac fermion}
\]

lepton number violation
Origin of the masses is not known

3- Or pseudo-Dirac masses — Inverse Seesaw Mechanism

Light neutrino masses:

\[ m_\nu \sim \frac{\epsilon Y_N^T Y_{N'} \nu^2}{M_D} + \mathcal{O} \left( \frac{Y_N^T \mu Y_N \nu^2}{M_D^2} \right) \]

For \( Y_N \sim Y_{N'} \sim 1 \), \( M_D \sim \text{TeV} \)

need: \( \mu \sim \text{keV} \)

\( \epsilon \sim 10^{-12} \)

Why so small?
What we need

(Usually) SM singlet fermions as right-handed neutrinos

High mass scale

and/or

Small (lepton-number-violating) parameters

makes LHC searches very hard (impossible?)
My favorite model for everything!

\[ U(1)_R \text{-symmetric SUSY} \]

Pilar Coloma, SI, *PRL. 117* no.11 111803

Has Dirac gauginos

Dirac gauginos are awesome - less tuning for heavier stops

Solves SUSY CP and flavor problems, …
**$U(1)_{R-L}$ - symmetric SUSY**

SUSY particles are charged under $U(1)_{R-L}$

<table>
<thead>
<tr>
<th>Superfields</th>
<th>$SU_c(3)$</th>
<th>$SU_L(2)$</th>
<th>$U_Y(1)$</th>
<th>$U(1)_R$</th>
<th>$U(1)_{R-L}$</th>
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<tbody>
<tr>
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<td>2</td>
<td>-1/2</td>
<td>1</td>
<td>0</td>
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<tr>
<td>$E^c_i$</td>
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<td>1</td>
<td>1</td>
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<td>2</td>
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<tr>
<td>$H_u$</td>
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<td>1/2</td>
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<td>0</td>
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<tr>
<td>$W^\alpha_B$</td>
<td>1</td>
<td>1</td>
<td>0</td>
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<td>1</td>
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<td>$\Phi_S = \phi_S + \theta S$</td>
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<tr>
<td>$W'_\alpha = \theta D$</td>
<td>1</td>
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<td>1</td>
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</tr>
</tbody>
</table>

Spurion D-term

SUSY is broken in a hidden sector
Dirac bino mass

No Majorana gaugino masses due to the $R$-charges

Dirac masses come from the spurion D-term

$$\int d^2 \theta \frac{c}{\Lambda_M} W'_\alpha W^\alpha_{\tilde{B}} \Phi_S \rightarrow \frac{cD}{\Lambda_M} \tilde{B} S$$

$\Lambda_M$ : messenger scale

$\tilde{B} \equiv (1, 1, 0)_{+1}$ : Dirac bino

$S \equiv (1, 1, 0)_{-1}$

$\Psi = \left( \begin{array}{c} \tilde{B} \\ S^\dagger \end{array} \right)$ : Dirac bino

Dirac bino mass: $M_D$
$U(1)_{R-L}$ must be broken

...because (anomaly mediation)

(Small) Majorana mass for the bino

$$m_{\tilde{B}} = \frac{\beta(g_Y)}{g_Y} m_{3/2}$$

$m_{3/2}$ : gravitino mass

Can also have a singlino Majorana mass

$$m_{\tilde{B}} \sim m_S \ll M_D$$

$U(1)_{R-L}$ is only approximately broken

$$\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix}$$

: pseudo-Dirac bino
All the mass terms

\[-\mathcal{L} \supset \frac{f_i M_D}{\Lambda_M} \ell_i h_u \tilde{B} + \frac{d_i m_{3/2}}{\Lambda_M} \ell_i h_u S + M_D \tilde{B} S + m_{\tilde{B}} \tilde{B} \tilde{B} + m_S S S\]

This is an Inverse SeeSaw scenario!

\[U(1)_{R-L} \text{ violation} \propto m_{3/2}\]

\[\Psi = \begin{pmatrix} \tilde{B} \\ S^\dagger \end{pmatrix} : \text{We call this “bivo” (pronounced exactly like ‘bino’) (like ‘too’ and ‘two’)}\]

important for small neutrino masses
Neutrino masses

\[ m_1 = 0 \quad \Rightarrow \quad 1 \text{ neutrino is massless} \]

\[ m_2 = \frac{m_3/2 v^2}{\Lambda^2_M} (1 - \rho) \]

\[ m_3 = \frac{m_3/2 v^2}{\Lambda^2_M} (1 + \rho) \]

\( \rho \simeq 0.7 \text{ from mass splittings} \)

Neutrino masses are proportional to the gravitino mass

No dependence on \( M_D \)
Parameter space

Neutrino masses + Lepton flavor violation constraints

\[ m_{3/2} \sim \mathcal{O}(\text{keV}) \]
\[ \Lambda_M \sim \mathcal{O}(100 \text{ TeV}) \]

No constraints from neutrinoless double-beta decay
LHC Phenomenology of Bivo

Julia Gehrlein, Patrick Fox, SL, in preparation
RH neutrinos are usually produced via mixing with the SM neutrinos.

Pay a mixing price on top of EW interactions:

\[ \theta^2 \sim 10^{-5} \]

There are better ways to produce a bino!
LHC pheno: production

Assumptions for the phenomenology:

- Lightest neutralino is a pure bino
- Gravitino is the LSP - a few keV
- Bino is the NLSP
- Degenerate squarks
Can produce bino via squark decays:

Gluon fusion is the main production channel at 14 TeV LHC
LHC pheno: decays

1) Decays to a gravitino and a photon

\[ \tilde{B} \rightarrow \tilde{G} \gamma \]

\[ \Gamma(\tilde{B} \rightarrow \tilde{G} \gamma) \sim \frac{M_D^5}{M_{Pl}^2 m_{3/2}^2} \sim 10^{-8} \text{ eV} \]

2-4) Decays to \( W\ell, Z\nu, h\nu \)

\[ \tilde{B} \rightarrow \nu W \]

total width:

\[ \Gamma_{tot} \sim \frac{M_D^3}{\Lambda_M^2} \sim O(\text{MeV}) \]
LHC pheno: signals

Bino decays promptly, no displaced vertices
A combination of jets, leptons and missing energy is expected

e.g.
LHC pheno: signals

~ 20% branching ratio

⭐ ATLAS-CONF-2017-022
CMS-SUS-16-033

~ 3% branching ratio

⭐ CMS-PAS-EXO-17-003
CERN-EP-2016-074 (ATLAS)

Huge thanks to Angelo Monteux for the analysis codes!
Preliminary results
CMS – EXO – 2017 – 003

leptoquark searches

$m_{sq} = 1 \, \text{TeV}$

$M_{\text{Bino}}$

- 300 GeV
- 500 GeV
- 700 GeV
- 900 GeV

red background

Preliminary results
Smoking gun signal

electron : muon : tau ratios are fully determined by the neutrino sector: 1:2:1
Preliminary results

Bino heavier than squarks

Missing energy only from neutrinos

Searches exclude heavy bins

1st and 2nd generation squarks

M_\text{squark} (GeV)

M_\text{bino} (GeV)

0

1000

800

900

950

850

800

600

400

200

0