Measuring Neutrino Mixing at LHC?
— How to measure neutrino mixing using only a hadron collider and no water.

See also:
W. Porod+PS, hep-ph/0401077
Sanity Check

This is a detector for neutrino physics.
This is **not** a detector for neutrino physics.
1. Fast Forward SUSY Intro.

2. R–Parity and R–Parity Violation.

3. R–Parity Violation with Bilinear Terms: a SUSY origin of $\nu$ masses?

4. Measuring a $\nu$ angle at a hadron collider?
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Presumably more about this in training course tomorrow!

In fast–forward mode, supersymmetry is:

- The only (interesting) way of extending the known space–time symmetries.

- A fundamental relation between fermionic and bosonic degrees of freedom.

- The “super” in superstrings.

TeV–Scale SUSY is popular among BSM theories because:

- It provides an elegant solution to the hierarchy problem.

- It predicts a natural dark matter candidate.

- It paves the way for natural grand unification.

- It is something experimentalists can look for.
SUPERSYMMETRY

For every boson, there is a fermion
For every fermion, there is a boson

6 leptons + 6 quarks

\[ S = \frac{1}{2} \]

photons + \( W^\pm \) and \( Z^0 \) + gluon

\[ S = 1 \]

Higgs

\[ S = 0 \]
Supersymmetry.

**SUPERSYMMETRY**
For every boson, there is a fermion
For every fermion, there is a boson

6 leptons \(+\) 6 quarks \(S=\frac{1}{2}\)
2\(\times\)6 sleptons \(+\) 2\(\times\)6 squarks \(S=0\)

- Photon \(+\) \(W^\pm\) and \(Z^0\) \(+\) Gluon \(S=1\)
- Photino \(+\) Winos and Zino \(+\) Gluino \(S=\frac{1}{2}\)

- Higgs \(S=0\)
- Higgsino \(S=\frac{1}{2}\)

\(+\) (at least) another Higgs doublet.

Measuring Neutrino Mixing at LHC?, P. Skands – p.5/28
Overview

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So SUSY is really popular, but...

In any Supersymmetric extension of the Standard Model (SM), the first problem you have to deal with is how to avoid rapid proton decay!
BNV+LNV together is a bad cocktail!

Write down all (renormalizable) terms consistent with SM gauge invariance and \( (N = 1) \) Supersymmetry →

\[
W_{\text{SUSY}} = W_{\text{MSSM}} + W_{\text{BNV}} + W_{\text{LNV}}
\]
BNV+LNV together is a bad cocktail!

Write down all (renormalizable) terms consistent with SM gauge invariance and \((N = 1)\) Supersymmetry →

\[
W_{\text{SUSY}} = W_{\text{MSSM}} + W_{\text{BNV}} + W_{\text{LNV}}
\]

\[
W_{\text{MSSM}} = Y_{ij}^1 L_i L_j E^c_j + Y_{ij}^D L_i D^c_j + Y_{ij}^U H^2 Q^c_i + H^1 U^c_i
\]

\[
W_{\text{BNV}} = \chi''_{ijk} U_i D^c_j D^c_k \supset \begin{array}{c}
\nu_i \\
\chi''_{ijk} \\
\bar{\nu}_i \\
\bar{d}_k^* \\
\bar{d}_k \\
\end{array}
\]

\[
W_{\text{LNV}} = \lambda_{ijk} L_i L_j \bar{E}_k^c + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H^2 \supset \begin{array}{c}
\nu_i \\
\bar{\nu}_i \\
\epsilon_i \\
\bar{u}_j \\
\tilde{h}_2^0 \\
\end{array}
\]
BNV+LNV together is a bad cocktail!

Write down all (renormalizable) terms consistent with SM gauge invariance and \([N = 1]\) Supersymmetry →

\[
W_{\text{SUSY}} = W_{\text{MSSM}} + W_{\text{BNV}} + W_{\text{LNV}}
\]

\[
W_{\text{MSSM}} = Y_{ij} L_i L_j E^c_k + Y_{ij} D_i D^c_j + \lambda'_{ijk} L_i Q_j D^c_k + \epsilon_i L_i H_2
\]

\[
W_{\text{BNV}} = \chi''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k
\]

\[
W_{\text{LNV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_i L_i H_2
\]

\[\rightarrow\text{ fast proton decay } \propto \frac{|\lambda'| |\chi''|}{M^2_{\text{SUSY}}} \Rightarrow M_{\text{SUSY}} \sim 1\text{ TeV} \Rightarrow |\lambda'| |\chi''| \lesssim 10^{-30}.
\]
What can be done?

Start with naive, simple guesses:

1. **Lepton Number is conserved?**
2. **Baryon Number is conserved?**
3. **Both are conserved** ($R$-parity = $(-1)^{L+3B+2S}$)?
What can be done?

Start with naive, simple guesses:

1. Lepton Number is conserved?
2. Baryon Number is conserved?
3. Both are conserved ($R$-parity = $(-1)^{L+3B+2S}$)?

$R$-parity has interesting consequences:

$$\text{SM particles have } R = +1 \text{ and SUSY ones } R = -1$$

$\rightarrow$ sparticles are born and killed by the pair ...

so sparticles from Big Bang decayed to “LSP” are still around?

$\rightarrow$ solution to dark matter problem in cosmology?

But no deep theoretical motivation...
Simple guesses ain’t so bad!

What can we say about the symmetry we’re looking for?

- Only **discrete gauge symmetries** are absolutely stable.
- But you can find discretized versions of gauge symmetries which reduce to both **$R$-parity** as well as symmetries equivalent to **Baryon** and **Lepton** number conservation.

  ⟷ Again no clear preference for one or the other.

What about Beyond-the-MSSM contributions?

- **$R$–parity** does not forbid $D > 4$ proton decay.
- Anyway, all this was just to make the case...

All possibilities should be considered!

R conservation vs R violation.

\[ W_{\text{SUSY}} = W_{\text{MSSM}}( + W_{\text{BNV}} + W_{\text{LNV}} ) \]

\[ W_{\text{MSSM}} = Y_{ij}^{E} H_{1} L_{i} \bar{E}_{j} + Y_{ij}^{D} H_{1} Q_{i} \bar{D}_{j} + Y_{ij}^{U} H_{2} Q_{i} \bar{U}_{j} - \mu H_{1} H_{2} \]

Conserves \( R \rightarrow \) only allows sparticles to be produced in pairs and does not mediate LSP decay.

Signature is missing (transverse) energy from escaping LSP’s.

At the LHC, squark and gluino pair production will dominate over most of parameter space.

Typically, squarks and gluinos are among the heavier sparticles, hence other typical features are multiple jets and/or leptons which are split off in a chain of decays to lighter and lighter sparticles, ending with the (stable) LSP.

Escaping LSP \( \rightarrow \) tricky mass reconstruction (use edges).
Trilinear Lepton Number Violation

\[ W_{\text{SUSY}} = W_{\text{MSSM}} + W_{\text{LNV}} \]

\[ W_{\text{LNV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_{ijk} H \]

“LLE” (“LQD”) allows single slepton production at a linear collider (hadron collider). “LQD” also allows resonant squark/slepton production at an ep collider.

Rich phenomenology. With just 2- and 3-body decays of sparticles to particles, more than 1200 new decay channels!

LLE(\(\lambda\)):
- \(\tilde{e}_j^- \rightarrow \bar{\nu}_i \ell^-_k, \nu_k \ell^-_i\)
- \(\tilde{\nu}_j \rightarrow \ell^+_i \ell^-_k\)
- \(\tilde{\chi}_n^0 \rightarrow \bar{\nu}_i \ell^+_j \ell^-_k, \nu_i \ell^-_j \ell^+_k\)
- \(\tilde{\chi}_n^+ \rightarrow \ell^+_i \ell^+_j \ell^-_k\)
- \(\tilde{\chi}_n^+ \rightarrow \bar{\nu}_i \ell^+_j \nu_k, \nu_i \nu_j \ell^+_k\)

LQD(\(\lambda'\)):
- \(\tilde{e}_i^- \rightarrow \tilde{u}_j d_k\)
- \(\tilde{\nu}_i \rightarrow \tilde{d}_j d_k\)
- \(\tilde{u}_j \rightarrow e^+_i d_k\)
- \(\tilde{d}_k \rightarrow \nu_i d_j, \bar{\nu}_j d_i, \ell^-_i u_j\)
- \(\tilde{\chi}_n^0 \rightarrow \bar{\nu}_i \tilde{d}_j d_k, \ell^+ \tilde{u}_j d_k, + \text{c.c.}\)
- \(\tilde{\chi}_n^+ \rightarrow \bar{\nu}_i \tilde{d}_j u_k, \nu_i \tilde{d}_k u_j\)
- \(\tilde{\chi}_n^+ \rightarrow \ell^+_i \tilde{u}_j u_k, \ell^+_i \tilde{d}_j d_k\)

Herwig: P.Richardson, hep-ph/0101105
Trilinear Baryon Number Violation

\[ W_{\text{SUSY}} = W_{\text{MSSM}} + W_{\text{BNV}} \]

\[ W_{\text{BNV}} = \lambda'_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k \]

“UDD”, violates Baryon Number. Allows single (resonant) squark production from qq initial state. Allows 2-body decays of squarks to quarks and 3-body decays of gauginos to quarks.

UDD (\(\lambda''\)):

- \(\bar{d}_j \rightarrow \bar{u}_i \bar{d}_k\)
- \(\bar{u}_i \rightarrow \bar{d}_j \bar{d}_k\)
- \(\tilde{\chi}_n^0 \rightarrow u_i d_j d_k, + \text{c.c.}\)
- \(\tilde{\chi}_n^+ \rightarrow u_i u_j d_k, \bar{d}_i \bar{d}_j \bar{d}_k\)
- \(\tilde{g} \rightarrow u_i d_j d_k, + \text{c.c.}\)

\textbf{HERWIG: P. Richardson, hep-ph/0101105}

NB: Unique colour structures → new colour topologies not addressed by standard fragmentation schemes. Detailed dynamical modelling so far developed only for string fragmentation (implemented in PYTHIA).
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Neutrino Summary

Great surprise:

Nobel prize 2002: Neutrinos have mass!

“I have done a terrible thing, I have invented a particle that cannot be detected”

W. Pauli

Masatoshi Koshiba
Raymond Davis Jr.

Nobel prize 2002: Neutrinos have mass!
Neutrino Summary

Neutrino sector: a window to physics beyond SM?

1. Too few $\nu_\mu$ from atmosphere, can be explained by oscillations into $\nu_\tau$: $\Delta m^2_{atm} = m_3^2 - m_2^2 \sim 10^{-3} - 10^{-2}$ eV$^2$

2. Too few $\nu_e$ from Sun, can be explained by oscillations into $\nu_\mu$: $\Delta m^2_{sol} = m_2^2 - m_1^2 \sim 10^{-5} - 10^{-4}$ eV$^2$

3. Bi-maximal mixing pattern: $\theta_{23}$ large, $\theta_{12}$ large, and $\theta_{13}$ small.

Explanations generally look like this:

$$
\begin{pmatrix}
0 & m \\
m & M
\end{pmatrix}
$$
Neutrino Masses

\[
\begin{pmatrix}
0 & m \\
m & M
\end{pmatrix}
\]

\(m\): Dirac mass. Electroweak scale?
\(M\): Majorana mass. High scale?

\[
\lambda_{\pm} = \frac{1}{2}M^2 \pm \frac{1}{2}\sqrt{M^2 + 4m^2} \sim \begin{cases}
-m^2/M &= m_{\nu} \\
M + m^2/M &\gtrsim 10^9 \text{GeV}
\end{cases}
\]

\[\leftarrow \text{No fun for high energy colliders...}\]

An alternative possibility could be \(M\) of order \(M_Z\), with \(m\) thus being rather small...

\[\leftarrow \text{Testable at high energy colliders...}\]
Bilinear $R$–violation

$$W_{\text{SUSY}} = W_{\text{MSSM}} + \epsilon_i L_i H_2$$

(Occurs e.g. when $R$–parity is broken spontaneously)

For us, the important consequences are:

- EW symmetry is broken by Higgs and sneutrino vev's,

  $$\langle \nu_i \rangle = v_i \text{ (i.e. } m^2_W = \frac{1}{4}g^2(v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2)) \text{.}$$

- Neutrinos mix with neutralinos $\rightarrow 7 \times 7$ mixing:

  In block form: $M_N = \begin{pmatrix} 0 & m_{(3 \times 4)} \\ m^T_{(4 \times 3)} & M_{(4 \times 4)} \end{pmatrix}$
Bilinear $R$–Violation

Determining the masses:

Find diagonalizing matrix: $N^* M_N N^{-1} = \text{diag}(m_{\nu_i}, m_{\tilde{\chi}_j^0})$.

First transform $M_N$ to block-diagonal:

$$N^* M_N N^{-1} = \tilde{N}^* \begin{pmatrix} m_{\text{eff}} & 0 \\ 0 & M_{\tilde{\chi}^0} \end{pmatrix} \tilde{N}^{-1} ; \quad \tilde{N} = \begin{pmatrix} V^\dagger_\nu & 0 \\ 0 & N_{\tilde{\chi}^0} \end{pmatrix}$$

The matrix $m_{\text{eff}}$ is projective, looks like:

$$m_{\text{eff}} = \frac{M_1 g^2 + M_2 g'^2}{4 \det(M_{\tilde{\chi}^0})} \begin{pmatrix} \Lambda^2_e & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\ \Lambda_e \Lambda_\mu & \Lambda^2_\mu & \Lambda_\mu \Lambda_\tau \\ \Lambda_e \Lambda_\tau & \Lambda_\mu \Lambda_\tau & \Lambda^2_\tau \end{pmatrix}$$

$$\Lambda_i = \mu v_i + v_d \epsilon_i$$
Bilinear $R$–Violation

So only 1 non-zero eigenvalue in $m_{\text{eff}}$!

$$N^*_{\tilde{\chi}^0} M_{\tilde{\chi}^0} N^\dagger_{\tilde{\chi}^0} = \text{diag}(m_{\tilde{\chi}^0_i})$$

$$V^T_{\nu} m_{\text{eff}} V_{\nu} = \text{diag}(0, 0, m_{\nu}) \ ; \ m_{\nu} = \text{Tr}(m_{\text{eff}}) \propto \Lambda^i \Lambda_i$$

1 neutrino becomes massive at tree level.
(Remaining neutrinos acquire mass at 1 loop).

$$V_{\nu} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & -\sin \theta_{23} \\ 0 & \sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & -\sin \theta_{13} \\ 0 & 1 & 0 \\ \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix}$$

NOTE: $\tan \theta_{13} = \frac{\Lambda_e}{\sqrt{\Lambda_\mu^2 + \Lambda_\tau^2}}$; $\tan \theta_{23} = -\frac{\Lambda_\mu}{\Lambda_\tau}$. 
Details depend on the particular SUSY scenario, but the general results are:

- The **tree-level mass** \( m_\nu \) generates the **atmospheric mass scale**.

- The **loop-induced** (=small) corrections generate the **Solar mass scale** (\( \rightarrow \) **hierarchical mass pattern**).

- With \( \Lambda_e \ll \Lambda_\mu \sim \Lambda_\tau \), the bi–maximal mixing can be accommodated.

\[
\sin^2(2\theta_{\text{atm}}) = \frac{|\Lambda_\mu/\Lambda_\tau|}{10^3}
\]
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Measuring a $\nu$ angle...

BRPV couplings also responsible for LSP decay.

$\rightarrow$ Ratio of $\tilde{\chi}_1^0$ semileptonic branching ratios is strongly correlated with $\Lambda_i/\Lambda_j$!
→ model of SUSY origin of $\nu$ mass can be checked by “measuring” $\theta_{\text{atm}}$ at a hadron collider:

$$\tan^2 \theta_{\text{atm}} \simeq \left| \frac{\Lambda_\mu}{\Lambda_\tau} \right|^2 \simeq \frac{BR(\tilde{\chi}_1^0 \rightarrow \mu^{\pm}W^{\mp})}{BR(\tilde{\chi}_1^0 \rightarrow \tau^{\pm}W^{\mp})}$$

Note: this prediction is independent of the $R$–conserving MSSM parameters.

To illustrate method, we have investigated a specific example, based on the SPS1a mSUGRA point.

(Using SPHENO 2.2 together with PYTHIA 6.3, and SLHA interface to pass parameters)

The $R$–Violating parameters are (in MeV):

$$\epsilon_i = (43, 100, 10) \quad \nu_i = (-2.9, -6.7, -0.5)$$

(chosen to fit neutrino data)
Total SUSY cross section for SPS1a: $\sigma_{\text{SUSY}} \sim 41\text{pb}$.

Some shortcuts:
- Detector resolution and hadronization effects are ignored

The “detector”:
- Calorimeter: $|\eta| < 4.9$. Inner detector: $|\eta| < 2.5$.
- Electrons ($|\eta| < 2.5$, $p_\perp > 5\text{GeV}$, $\varepsilon = 75\%$)
- Muons ($|\eta| < 2.5$, $p_\perp > 6\text{GeV}$, $\varepsilon = 95\%$)
- Taus ($|\eta| < 2.5$, $p_\perp > 20\text{GeV}$, $\varepsilon_{3\text{-prong}} = 85\%$)
- Vertex resolution: 20$\mu$ transverse and 0.5mm longitudinal.
- “Triggers”: 4j100, 2j100+e20/mu20, j100+2(e20/mu20).
Measuring a $\nu$ angle...

Events characterized by:

- Since $R$–Violating parameters are small, the only real deviation from MSSM phenomenology is LSP decay.

- Pair production of squarks/gluinos dominate, with cascades down to LSP, which subsequently decays through LNV.

- Also due to smallness of LNV parameters, LSP is long–lived. Decay length here is $c\tau = 0.5\text{mm}$.

- Very clean signature: 2 reconstructed detached vertices in fair fraction of signal events (define vertex reconstruction ellipsoid $= 5$ times resolution and reject tracks that intersect it).

$100\text{fb}^{-1}$ of data:

- $\sim 10000$ reconstructed $\tilde{\chi}_1^0 \rightarrow \mu W \rightarrow \mu q\bar{q}'$ decays.
- $\sim 1500$ reconstructed $\tilde{\chi}_1^0 \rightarrow \tau W \rightarrow \tau_3$–prong $q\bar{q}'$ decays.

$\rightarrow$ precision on $\tan^2 \theta_{\text{atm}}$ is $\sim$ couple of percent
Summary & Conclusion

$R$–parity: conserved or violated?
Nobody knows...

Possible sources of RPV:
UDD, LLE, LQD, and **Bilinear**.

Bilinear RPV has interesting consequences:

Sneutrinos play rôle of extra Higgses and acquire vevs.

**Neutrinos mix with Neutralinos.**

A “low-scale” seesaw mechanism results, whereby neutrinos become massive.

Models consistent with neutrino data give predictions which can be tested at hadron colliders.
So all we can really say is:

This may not *seem* to be a detector for neutrino physics...