Bilinear $R$ parity violation at the ILC

Neutrino physics at colliders?

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Outline

- Supersymmetry
- R parity violation and neutrino masses
- Potential of ILC
- Outlook
Supersymmetry

Motivation

Standard model has still some open questions (2 examples)

- **Unification**
  - Hierarchy problem

Huge loop correction to Higgs mass:

\[
\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{\text{UV}}^2 + \ldots
\]

\[\Lambda_{\text{UV}} \approx 10^{16}\text{GeV}\]

Solution: introduce massive scalar fields

\[
\Delta m_H^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{\text{UV}}^2 - 2m_s \ln \left( \frac{\Lambda_{\text{UV}}}{m_S} \right) \right] + \ldots
\]

Cancelation of quadratic divergences, if 2 massive scalars per fermion with \(\lambda_S = |\lambda_f|^2\)
Supersymmetry

What is SUSY?
- Symmetry in spin-space
- Every particle has a supersymmetric partner:
  - SM Fermions $\leftrightarrow$ SUSY scalars
  - SM bosons $\leftrightarrow$ SUSY fermions
- Many models on the market, but simplest: MSSM

SUSY breaking
In a perfect symmetry particle and sparticle mass should be degenerated $\Rightarrow$ not observed
SUSY has to be broken!

mSUGRA (105 parameters $\rightarrow$ 5 parameters)

\[
\begin{align*}
M_3 &= M_2 = M_1 = m_{1/2} \\
\tilde{m}_Q^2 &= \tilde{m}_{\tilde{u}}^2 = \tilde{m}_{\tilde{d}}^2 = \tilde{m}_{\tilde{L}}^2 = \tilde{m}_{\tilde{e}}^2 = m_0^2 \\
a_u &= A_0 y_u \\
a_d &= A_0 y_d \\
a_e &= A_0 y_e \\
tan \beta \\
\text{sgn}(\mu)
\end{align*}
\]

Planck scale

SUSY spectrum & couplings

electroweak scale

(W. Porod, arXiv:hep-ph/0301101)
Supersymmetry

Particle spectrum (MSSM - mSUGRA)

Benchmark point SPS 1a
\[ m_0 = 70 \text{ GeV}, \ m_{1/2} = 250 \text{ GeV}, \ \tan \beta = 10, \ \text{sgn}(\mu) = 1, \ A_0 = -300 \text{ GeV} \]

After EW symmetry breaking
(more complicated due to 2 Higgs doublets)

- 5 massive Higgs
- 4 neutralinos
- 4 charginos
- 8 gluinos
- squarks
- sleptons

neutralino LSP
Supersymmetry

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After EW symmetry breaking
(more complicated due to 2 Higgs doublets)

**mass eigenstates**
- 5 massive Higgs
- 4 neutralinos
- 4 charginos
- 8 gluinos
- squarks
- sleptons

neutralino LSP

Standard Model particles
R parity

What is R parity?

- $B$ and $L$ violating terms allowed in superpotential ($\Leftrightarrow$ SM)
- $B$ and $L$ violation never observed (proton decay)

→ Invent new symmetry which is a combination of $B$, $L$ (and $S$)

\[
P_R = (-1)^{3B + L + 2S}
\]

→ SM particles: $P_R = +1$
→ SUSY partners: $P_R = -1$

Consequences of conservation:

- proton decay prohibited
- sparticles can only be produced in pairs
- SUSY decay products contain odd number of LSPs
- LSP absolutely stable
What is R parity?

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\[ P_R = (-1)^{3B + L + 2S} \]

$\rightarrow$ SM particles: $P_R = +1$
$\rightarrow$ SUSY partners: $P_R = -1$

Consequences of conservation:

• proton decay prohibited $\quad \rightarrow$ just break $L$ or $B$
• sparticles can only be produced in pairs $\quad \rightarrow$ holds for small RPV parameters
• SUSY decay products contain odd number of LSPs
• LSP absolutely stable $\quad \rightarrow$ LSP decays!
Superpotential

\[
W = \varepsilon_{ab} \left( h_U^{ij} \hat{Q}_i^a \hat{U}_j \hat{H}_u^b + h_D^{ij} \hat{Q}_i^b \hat{D}_j \hat{H}_d^a + h_E^{ij} \hat{L}_i^b \hat{R}_j \hat{H}_u^a - \mu \hat{H}_d^a \hat{H}_u^b + \varepsilon_i \hat{L}_i^a \hat{H}_u^b \right)
\]

MSSM superpotential

- Higgs/Slepton-mixing
- Sneutrinos acquire VEV \( \langle \tilde{\nu}_i \rangle = \nu_i \)
- corresponding RPV soft SUSY breaking term

\[
L_{soft}^{BRpV} = -B_i \varepsilon_{ab} \varepsilon_i \hat{L}_i^a H_u^b
\]

masses and mixings of neutral fermions

Basis of neutral fermions:

\[
\psi^{0T} = (-i \lambda', -i \lambda^3, \tilde{H}_d^1, \tilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)
\]

Mass terms in the Lagrangian are given by:

\[
L_m = -\frac{1}{2} \left( \psi^0 \right)^T M_N \psi^0 + h.c.
\]

4x4 MSSM neutralino mixing matrix

\[
M_N = \begin{pmatrix}
M_{\chi^0} & m^T \\
m & 0
\end{pmatrix}
\]

4x3 RPV matrix
Approximate diagonalization of $M_N$

$M_N$ can be block-diagonalized for small RPV parameters via the Seesaw-like diagonalization:

$$M_N = \text{diag}(M^{\chi^0}, m_{\text{eff}})$$

$$m_{\text{eff}} = -mM^{\chi^0}m^T = \frac{M_1g^2 + M_2g'^2}{4 \text{det } M^{\chi^0}} \begin{pmatrix}
\Lambda_e^2 & \Lambda_e \Lambda_\mu & \Lambda_e \Lambda_\tau \\
\Lambda_\mu \Lambda_e & \Lambda_\mu^2 & \Lambda_\mu \Lambda_\tau \\
\Lambda_\tau \Lambda_e & \Lambda_\tau \Lambda_\mu & \Lambda_\tau^2 
\end{pmatrix}$$

where $\Lambda_i = \epsilon_i \nu_d + \mu \nu_i$ „alignment parameters“

A final diagonalization of $M^{\chi^0}$ leads to the neutralino masses $m^{\chi^0}$ and a diagonalization of $m_{\text{eff}}$ leads to one tree level neutrino mass.
Some results of this model

- largest neutrino mass at tree level
- 2 mixing angles at tree level
- remaining masses/angles at 1-loop-level
- correct scales of mass differences $\Delta m_{ij}^2$

How is that connected to colliders?

dominant part of $\tilde{\chi}_1^0 - W - l_i$ coupling: $O_i^L = \Lambda_i \cdot f(M_1, M_2, \mu, \tan \beta, \nu_d, \nu_u) \propto \Lambda_i$

$\tan^2 \theta_{23} = \left| \frac{\Lambda_\mu}{\Lambda_\tau} \right|^2 \approx \frac{BR(\tilde{\chi}_1^0 \rightarrow \mu W)}{BR(\tilde{\chi}_1^0 \rightarrow \tau W)}$

$\Rightarrow$ Neutrino physics at collider experiments
Particle spectrum (MSSM – mSUGRA - bRPV)

Benchmark point SPS 1a' with bRPV
\[ m_0 = 70 \text{ GeV}, \quad m_{1/2} = 250 \text{ GeV}, \quad \tan \beta = 10, \quad \text{sgn}(\mu) = 1, \quad A_0 = -300 \text{ GeV} \]

bRPV parameters
Fit to neutrino data

Standard Model particles
Particle spectrum (MSSM – mSUGRA - bRPV)

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bRPV parameters
Fit to neutrino data

- Higgs/Slepton mixing
- generalized particle names S, P
- particle "character" mostly unchanged
Particle spectrum (MSSM – mSUGRA - bRPV)

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bRPV parameters
Fit to neutrino data

$\rightarrow$ Higgs/Slepton mixing
$\rightarrow$ generalized particle names S, P
$\rightarrow$ particle “character“ mostly unchanged

$\rightarrow$ Neutralino/neutral lepton (neutrino) mixing
$\rightarrow$ effect very small
$\rightarrow$ BUT visible in LSP-to-SM decay

Standard Model particles
ILC potential

Production cross section

**s-channel**

\[ e^+ e^- \rightarrow Z \rightarrow \tilde{\chi}_i^0 \]

**t/u-channel**

\[ e^+ e^- \rightarrow \tilde{e}^{L,R} \rightarrow \tilde{\chi}_i^0 \]

**LSP mixing character** (at SPS1a):
- 97.9% Bino
- 0.1% Wino
- 1.8% up-type Higgsino
- 0.2% down-type Higgsino

Higgsino part of neutralino only couples to Z

Gaugino part of neutralino only couples to scalar SUSY partners

→ t/u-channel main production process
Production cross section

cross section: $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ production

- main production processes: t-, u-channel

- „selectron“ exchange

- $m(\sim e^-_L) > m(\sim e^-_R) \rightarrow \sigma_+ < \sigma_-$
ILC potential

Production cross section

cross section: \( \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \) production

- small RPV parameters
  \( \rightarrow \) LSP decays into SM

- typical SUSY cascades with LSP decay in the end

- almost all sparticle-production processes can be used to study LSP decays

\[ e^+ e^- \rightarrow \ldots \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \]

- green: \( P(e^+) = -0.8, P(e^-) = 0.3 \)
- dark green: \( P(e^+) = -0.8, P(e^-) = -0.3 \)
- black: \( P(e^+) = 0.0, P(e^-) = 0.0 \)
- grey: \( P(e^+) = 0.8, P(e^-) = 0.3 \)
- blue: \( P(e^+) = 0.8, P(e^-) = -0.3 \)
Decay channels of LSP (BR>0.01)

| LSP decay | Branching ratio |
|-----------|-----------------|
| W μ       | 0.034           |
| W τ       | 0.031           |
| ν₂ b b    | 0.035           |
| ν₁ τ e    | 0.159           |
| ν₁ τ μ    | 0.279           |
| ν₁ τ τ    | 0.453           |

Study neutrino parameters
- neutrino mixing, ...

Study LSP parameters
- mass (endpoint), mixing character, ...

Decay width of LSP

\[ \Gamma = 3.77 \cdot 10^{-13} \text{ GeV} \Rightarrow \Gamma \approx 523 \mu m \]

Displaced vertices expected!

Analysis strategy
- LFV signal
- two displaced vertices per event (+cascade products from IP)
- high effective mass per event
Statistical uncertainties (one example)

\[ \int L \, dt = 500 \text{ fb}^{-1} \] (4 years of ILC running)
\[ \sigma_{\text{SMBG}}(500 \text{ GeV}) = 2200 \text{ fb} \]
Detection efficiency = 0.5

Signal/background estimation
- tree level cross sections for SM BG
  (Whizard 2.0; arXiv:0708.4233)
- just looking for similar final states

\[ e^+ e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow (\nu \tau \tau)(\nu \tau \mu) \]
\[ e^+ e^- \rightarrow \text{SM} \rightarrow \tau \tau \nu \mu \nu \]
\[ = 3\tau + 1\mu + \text{MET} \]

\[ \rightarrow N_{W\mu} = 37500 \cdot 0.5 = 18750 \quad \sigma_{\text{rel}}^{\text{stat}} = 0.74\% \]
\[ \rightarrow N_{W\tau} = 34100 \cdot 0.5 = 17050 \quad \sigma_{\text{rel}}^{\text{stat}} = 0.77\% \]

\[ \sigma_{\text{rel}}^{\text{stat}}(\text{Br}(\chi \rightarrow W\mu)/\text{Br}(\chi \rightarrow W\tau)) \approx 1\% \]
\[ \rightarrow \theta_{\text{atm}} = (46.36 + 0.15)^\circ \]

→ Comparable results for almost all decay channels (at least \( S/\sqrt{B} > 10 \)
Conclusion

- bRPV enables access to neutrino parameters at colliders
- Predicted cross sections are quite promising
- SM background small
- Need for very good vertex detection
- Polarization is a very useful tool to increase signal over background
- ILC is highly capable to look at that kind of models

Outlook

- Implementation of bRPV in Whizard on the way
- Detailed study in progress
Thank you for your attention.
Backup slides
cross sections ($P(e^-) = 0.8, P(e^+) = -0.3$)

production channels
- $e^-e^+ \rightarrow \text{bRPV SUSY}$
- $e^-e^+ \rightarrow \ldots \rightarrow \text{LSP pair} + X$
- $e^-e^- \rightarrow \text{chi}_i \text{chi}_j$
- $e^-e^+ \rightarrow \text{S}^i \text{S}^j$
- $e^-e^+ \rightarrow q\bar{q}$

$\sqrt{s}/\text{GeV}$

cross sections ($P(e^-) = 0.8, P(e^+) = 0.3$)

production channels
- $e^-e^+ \rightarrow \text{bRPV SUSY}$
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$\sqrt{s}/\text{GeV}$

cross sections ($P(e^-) = 0.8, P(e^+) = 0.0$)

production channels
- $e^-e^+ \rightarrow \text{bRPV SUSY}$
- $e^-e^+ \rightarrow \ldots \rightarrow \text{LSP pair} + X$
- $e^-e^- \rightarrow \text{chi}_i \text{chi}_j$
- $e^-e^- \rightarrow \text{S}^i \text{S}^j$
- $e^-e^+ \rightarrow q\bar{q}$

$\sqrt{s}/\text{GeV}$
**cross section: neutralino production**

```
\sigma / \text{fb}
```

- $e^+ e^- \rightarrow \text{ch}_i \chi_j$
- $P(\chi') = -0.8, P(e') = 0.3$
- $P(\chi') = -0.8, P(e') = -0.3$
- $P(\chi') = 0.0, P(e') = 0.0$
- $P(\chi') = 0.8, P(e') = 0.3$
- $P(\chi') = 0.8, P(e') = -0.3$

**cross section: chargino production**

```
\sigma / \text{fb}
```

- $e^+ e^- \rightarrow \text{ch}_i \chi_j$
- $P(\chi') = -0.8, P(e') = 0.3$
- $P(\chi') = -0.8, P(e') = -0.3$
- $P(\chi') = 0.0, P(e') = 0.0$
- $P(\chi') = 0.8, P(e') = 0.3$
- $P(\chi') = 0.8, P(e') = -0.3$
cross section neutral scalar production

$e^+e^- \rightarrow \chi_i \chi_j$
- $P(\epsilon') = -0.8, P(\epsilon'') = 0.3$
- $P(\epsilon') = -0.8, P(\epsilon'') = -0.3$
- $P(\epsilon') = 0.0, P(\epsilon'') = 0.0$
- $P(\epsilon') = 0.8, P(\epsilon'') = 0.3$
- $P(\epsilon') = 0.8, P(\epsilon'') = -0.3$

cross section charged scalar production

$e^+e^- \rightarrow S_i S_j$
- $P(\epsilon') = -0.8, P(\epsilon'') = 0.3$
- $P(\epsilon') = -0.8, P(\epsilon'') = -0.3$
- $P(\epsilon') = 0.0, P(\epsilon'') = 0.0$
- $P(\epsilon') = 0.8, P(\epsilon'') = 0.3$
- $P(\epsilon') = 0.8, P(\epsilon'') = -0.3$
Backup Slides
The model

Mass matrices

\[ M_{\chi^0} = \begin{pmatrix}
  M_1 & 0 & -\frac{1}{2} g' v_d & \frac{1}{2} g' v_u \\
  0 & M_2 & \frac{1}{2} g v_d & -\frac{1}{2} g v_u \\
 -\frac{1}{2} g' v_d & \frac{1}{2} g' v_u & 0 & -\mu \\
 \frac{1}{2} g v_d & -\frac{1}{2} g v_u & -\mu & 0 \\
\end{pmatrix} \]

\[ m = \begin{pmatrix}
  -\frac{1}{2} g' v_1 & \frac{1}{2} g v_1 & 0 & \varepsilon_1 \\
  \frac{1}{2} g' v_2 & -\frac{1}{2} g v_2 & 0 & \varepsilon_2 \\
  \frac{1}{2} g' v_3 & -\frac{1}{2} g v_3 & 0 & \varepsilon_3 \\
\end{pmatrix} \]
Phenomenology

(Semi-)leptonic LSP decay channels (SU3)

\[ \tilde{\chi}_1^0 \rightarrow \tau^\pm + e^\mp + \nu \quad 9\% \]
\[ \tilde{\chi}_1^0 \rightarrow \tau^+ + \tau^- + \nu \quad 24\% \]
\[ \tilde{\chi}_1^0 \rightarrow \mu^\pm + \tau^\mp + \nu \quad 16\% \]
\[ \tilde{\chi}_0^0 \rightarrow W + l \quad 13\% \]

(data created with Spheno 3beta36)

Why muon channel?

\[ \rightarrow ATLAS \text{ has a very good muon spectrometer!} \]
\[ \rightarrow \text{Working group is interested in muons} \]

Group in Valencia working on \[ \tilde{\chi}_1^0 \rightarrow W\mu \]

(CERN-ATL-COM-PHYS-2009-543)

Typical bRPV SUSY decay chain

\[ 2x \]
\[ \tilde{g} \langle d \tilde{d}_L \tilde{\chi}_1^- \rangle \langle u \tilde{\nu}_3 \rangle \langle \tau \tilde{\chi}_1^0 \rangle \langle \mu \tilde{\nu}_1 \rangle \]

\[ \text{MSSM} \]

\[ \text{bRPV} \]

- bRPV (in that case) doesn't affect SUSY cascade
- two cascades with two neutralino decays in each event
- neutralino decays!
ATLAS detector
Software workflow

Reconstruction chain

- SPheno: bilinear RPV model
- Generation
- Simulation
- Digitization
- Reconstruction
- GRID
- Analysis

SUSY? bRPV?

Backgrounds

Cuts
**Standard model backgrounds:**
- ttbar
- single top
- W+jets
- Z+jets
- WW+WZ+ZZ
- QCD dijets

(officially produced samples, CM=10TeV)

**Reasonable Triggers**

**Signal final state signature:**
mu, tau, missing $E_T$

| Trigger    | Signal eff. | BG eff.   |
|------------|-------------|-----------|
| mu10       | 0.58        | 4.15 $10^{-5}$ |
| tau20i     | 0.65        | 8.81 $10^{-4}$ |
| tau20i_mu10| 0.38        | 1.35 $10^{-6}$ |

→ trigger **mu10** chosen
→ available in L31 trigger menu
→ very good background reduction

| Trigger   | BG eff.   |
|-----------|-----------|
| mu10      |           |
| QCD dijets| 4.1 $10^{-5}$ |
| W+jets    | 0.29      |
| Z+jets    | 0.43      |
| ttbar     | 0.36      |
| single top| 0.30      |
| WW+WZ+ZZ  | 0.39      |
Observables

Number of mu/tau

Asking for at least one muon and one tau in final state is very selective!
\[ M_{\text{eff}} = E_T^{\text{miss}} + \sum_{1\ldots4} p_T^{\text{jet}} + \sum p_T^{e} + \sum p_T^{\mu} \]

**Observables**

Effective mass

**Cuts:**
- **loose:** \( M_{\text{eff}} > 600 \) GeV
- **medium:** \( M_{\text{eff}} > 800 \) GeV
- **tight:** \( M_{\text{eff}} > 1000 \) GeV

Mu10 trigger, mu/tau, preselection cuts, CM=10TeV

Maximum of (SUSY) signal \( M_{\text{eff}} \) at higher energy
Observables

Transverse sphericity

\[ S_T = \frac{2\lambda_2}{\lambda_1 + \lambda_2} \]

\( \lambda_1, \lambda_2 \) eigenvalues of sphericity tensor

Cuts:
- loose: \( S_T > 0.10 \)
- medium: \( S_T > 0.15 \)
- tight: \( S_T > 0.20 \)

Cut useful for QCD background reduction

mu10 trigger, mu/tau, preselection cuts, CM=10TeV

ATLAS work in progress
Cuts - summary

triggered/preselected

mu/tau & loose

mu/tau & medium

mu/tau & tight

|            | loose | medium | tight |
|------------|-------|--------|-------|
| # events SUSY | 1913  | 1339   | 727   |
| # events BG  | 1493  | 160    | 54    |
| S/B         | 1.3   | 8.4    | 13.4  |
| S/\sqrt{B}  | 49.5  | 106.0  | 98.6  |

→ very good background reduction!
→ medium cuts are used
Signal channel/ SUSY background

Calculation of invariant mass of $\mu$ and $\tau$

Truth:

Reco:

$\tilde{\chi}_1^0 \rightarrow \mu \nu$

$\rightarrow$ dilepton edge (Three-body-decay)

$\rightarrow$ reduction of combinatorical BG necessary
Signal channel/ SUSY background

1. $\Delta R_{\mu \tau}$ cut for different $\mu \tau$-pairs (truth)

$\Delta R_{\mu \tau}$ distribution of signal and BG pairs:

Resulting $m_{\mu \tau}$ distribution:

$\Rightarrow$ reasonable cut: $\Delta R_{\mu \tau} < 1.2$ (χ decay products boosted)
Mass reconstruction of LSP

Signal channel/ SUSY background

2. Opposite sign- same sign subtraction (truth)

ATLAS work in progress

- OS
- SS
- OS-SS
- signal

entries/10GeV/2fb vs. $m_{\mu\tau}$ [GeV]
Signal channel/ SUSY background

Invariant mass of $\mu$ and $\tau$ after $\Delta R_{\mu\tau}$ cut and OS-SS subtraction (reco)

Simple linear fit leads to mass-endpoint:

$$m^{EP}_\chi = (107 \pm 14) \text{GeV}$$

$$m^{\text{theory}}_\chi = 118 \text{GeV}$$
Conclusion

• bRPV enables access to **neutrino physics at the collider**

• selected trigger and cuts lead to a **very good background reduction**

• RPV signal can be observed

• dilepton edge can be used to **determine the mass of neutralino**
  
  • linear fit shows good results
  
  • advanced fitting methods under study (inflection point method) (CERN-ATL-COM-PHYS-2008-038)

• effort to tau identification and object selection

• Waiting for 7 TeV MC samples
Benchmark scenarios

mSUGRA

SUSY has to be broken!  

\[ M_3 = M_2 = M_1 = m_{1/2} \]
\[ m_{\tilde{Q}}^2 = m_{\tilde{u}}^2 = m_{\tilde{d}}^2 = m_{\tilde{L}}^2 = m_{\tilde{e}}^2 = m_0 \]
\[ m_{H_u}^2 = m_{H_d}^2 = m_0^2 \]
\[ a_u = A_0 y_u \quad a_d = A_0 y_d \quad a_e = A_0 y_e \]
\[ \tan \beta \]
\[ \text{sgn}(\mu) \]

Planck scale

SUSY spectrum & couplings  
electroweak scale

RGE
SPheno 3.0

(W. Porod,  
arXiv:hep-ph/0301101)
## Benchmark scenarios

**SUSY benchmark points**

Special benchmark points for ATLAS:

| Name  | $m_0$ [GeV] | $m_{1/2}$ [GeV] | $A_0$ [GeV] | $\tan \beta$ | $\text{sgn } \mu$ | Characteristics                     |
|-------|-------------|-----------------|-------------|-------------|----------------|-------------------------------------|
| SU1   | 70          | 350             | 0           | 10          | +              | Coannihilation region                |
| SU2   | 3550        | 300             | 0           | 10          | +              | Focus point region                   |
| SU3   | 100         | 300             | -300        | 6           | +              | Bulk region                          |
| SU4   | 200         | 160             | -400        | 10          | +              | Low mass point                       |
| SU6   | 320         | 375             | 0           | 50          | +              |                                     |
| SU8.1 | 210         | 360             | 0           | 40          | +              | Funnel region                        |
| SU9   | 300         | 425             | 20          | 20          | +              |                                     |

(ATLAS CSC Note)
### Phenomenology

#### Comparison of SU points for LSP decay

Chosen LSP-decay to investigate: \( \tilde{\chi}_1^0 \rightarrow \mu^+ + \tau^- + \nu \)

| Name  | \( m_{\chi^0} \times 10 \) | Decay length [m] | BR(2BD) | BR(3BD-non/semilept.) | BR(3BD-leptonic) | BR(\( \chi^0 \rightarrow \tau \tau \nu \)) | BR(\( \chi^0 \rightarrow \mu \tau \nu \)) |
|-------|----------------------------|------------------|---------|-----------------------|------------------|--------------------------------|--------------------------------|
| SU1   | 139                        | 1,2 10^{-4}      | 0,32    | 0,02                  | 0,66             | 0,33                            | 0,10                            |
| SU2   | 120                        | 2,0 10^{-3}      | 0,85    | 0,09                  | 0,06             | 0,01                            | 0,01                            |
| SU3   | 118                        | 2,9 10^{-4}      | 0,46    | 0,05                  | 0,49             | 0,25                            | 0,08                            |
| SU4   | 60                         | 0,1              | ~0      | 0,36                  | 0,64             | 0,30                            | 0,08                            |
| SU6   | 152                        | 4,1 10^{-4}      | 0,73    | 0,01                  | 0,26             | 0,14                            | 0,03                            |
| SU8.1 | 145                        | 3,1 10^{-4}      | 0,48    | 0,01                  | 0,51             | 0,28                            | 0,06                            |
| SU9   | 173                        | 2,0 10^{-5}      | 0,88    | 0,01                  | 0,11             | 0,06                            | 0,01                            |

(data created with Spheno 3beta36, W. Porod, arXiv:hep-ph/0301101)
SPheno Parameters in bRPV

9 extra parameters for bRPV

Define them explicitly

OR

Constraints:
• Successful electroweak symmetry breaking corresponds to minimization of effective potential; technically:
  3 extra tadpole equations linear in $B_i$

• Results from neutrino oscillation data (2 mass differences, 3 mixing angles) fix 5 bilinear parameters ($\epsilon_i, \nu_i$)

• Remaining parameter should be of the same order as the others
Signal channel/ SUSY background

Calculation of invariant mass of $\mu$ and $\tau$

$p_T$ distribution of neutralinos:

$\Delta R_{\mu\tau}$ distribution of signal and BG pairs:

$\Rightarrow$ Decay products should be boosted

$\Rightarrow$ Reasonable cut: $\Delta R_{\mu\tau} < 1.2$
Reconstruction of muons

- Figure 1: Distribution of the number of $\mu^\pm$ per event.
- Figure 2: Distribution of $\mu^\pm p_T$ (GeV).
- Figure 3: Efficiency and fake rate of muon reconstruction.
- Figure 4: Distribution of $(p_T^{reco} - p_T^{truth})/p_T^{truth}$.
Reconstruction of taus

Truth including leptonic tau decays
Object Selection

Muons:
- combined muon
- $p_T > 10$ GeV
- $|\eta| < 2.7$
- isolation cone $0.2/10$ GeV

Electrons:
- isEm flag: „medium“
- $p_T > 10$ GeV
- $|\eta| < 2.5$ and $|\eta| \notin [1.37,1.52]$

Jets:
- $p_T > 20$ GeV
- $|\eta| < 2.5$

Taus:
- 1 / 3 tracks
- charge = $\pm 1$
- $p_T > 10$ GeV
- $|\eta| < 2.5$ and $|\eta| \notin [1.37,1.52]$
- Likelihood flag: „Loose“

Overlap removal:
- remove electrons within $0.2<\Delta R<0.4$ to a jet
- remove jets within $\Delta R<0.2$ to an electron
- remove jets within $\Delta R<0.4$ to another particle
References

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