The Smoking Gun of Baryon Number Violation

\[ B_{i_1 i_2 i_3} = e^{Q_{i_2} Q_{i_3}} \prod_{n=1}^{3} P \left[ e^{ig f_{n(z,x_n) A_{n} dz \mu} q_{n}(x_n)} \right]_{\alpha_n} \]

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Fermilab
The Smoking Gun of Baryon Number Violation

- Baryon Number Violation (BNV) in SUSY
  - Implementation of 2- and 3-body decays in the PYTHIA generator

- BNV Colour Topologies
  - Baryon Number Violation and String Topologies
  - An explicit detailed model → baryon number flow

- Properties and predictions

- Summary and Outlook
R, B, or L? (Fast-forward)

- Most general MSSM Superpotential:

\[ W = \epsilon_{ab} \left[ (Y_E)_{ij} H_1^a L_i^b \bar{E}_j + (Y_D)_{ij} H_2^a Q_i^b \bar{D}_j + (Y_U)_{ij} H_2^a Q_i^b \bar{U}_j \right. \]
\[ \left. + \frac{1}{2} \lambda_{ijk} L_i^a L_j^b E_k + \lambda'_{ijk} L_i^a Q_j^b D_k - \epsilon_i L_i^a H_2^b - \mu H_1^a H_2^b \right] - \frac{1}{2} \lambda''_{ijk} U_i D_j D_k \]

- But LNV+BNV makes bad cocktail!

- To save proton, R, B, or L cons. imposed.
  - R → CDM candidate, but no deep motivation.
  - B and L more robust with higher dimension operators.

Decent physics case + interesting to explore phenomenology
Collider Phenomenology

• General problem: how to obtain fully exclusive descriptions of collider final states (in any physics model, SM or BSM)

- Non-Perturbative hadronisation, colour reconnections, beam remnants, non-perturbative fragmentation functions, pion/proton, kaon/pion, ...

- Soft Jets + Jet Structure
  Multiple collinear/soft emissions (initial and final state brems radiation), Underlying Event (multiple perturbative 2→2 interactions + … ?), semi-hard separate brems jets

- Resonance Masses …

- Hard Jet Tail
  High-\(p_T\) wide-angle jets

- Hadron Decays

\[ \text{This has an S matrix expressible as a series in } g, \ln(Q_1/Q_2), \ln(x), m^{-1}, f^{-1}_{\pi}, \ldots \]

To do precision physics:
Need to compute and/or control all large terms

\[ \rightarrow \text{EVENT GENERATORS} \]
Implementation of 2- and 3-body decays in PYTHIA

\[ W_{BNV} = \lambda_{ijk}^\prime \epsilon_{abc} \bar{U}_{ia} \bar{D}_{jb} \bar{D}_{kc} \]

\( (abc = \text{colour, } ijk = \text{generation}) \)

- **Couplings between chiral multiplets.**
  - Sfermions: 2-body decays.
  - Gauginos/Higgsinos: 3-body decays (via sfermion resonances).

\[ \epsilon_{abc} \rightarrow \text{‘baryonic’ colour flow.} \]

\[ \tilde{d}_j \rightarrow \bar{u}_i \bar{d}_k, \quad \tilde{\chi}_n^0 \rightarrow u_i d_j d_k, \quad + \text{c.c.} \quad \tilde{g} \rightarrow u_i d_j d_k, \quad + \text{c.c.} \]

\[ \tilde{u}_i \rightarrow \bar{d}_j \bar{d}_k, \quad \tilde{\chi}_n^+ \rightarrow u_i u_j d_k, \quad \bar{d}_i \bar{d}_j \bar{d}_k \]

**Partial widths:** LO ME’s, (only 3rd gen massive)

**Kinematics:** isotropic 3-body (good when intermediate states very off shell).

**Final state parton multiplicity increased by subsequent showers**

**NB:** only MSSM pair production included (no single sparticle production)
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Colour Topologies

Confinement potential: non-perturbative breakups $\rightarrow$ hadrons

Not a priori calculable $\rightarrow$ QCD-inspired phenomenological models

Semi-classical, based on colour dipoles: “Clusters” or “String pieces”

- ‘Ordinary’ colour topology
  (e.g. $Z^0 \rightarrow q\bar{q}$):

- ‘Baryonic’ colour topology
  (e.g.):

How does such a system fragment?
Could a Baryon excess be observed?

Basic problem easy to understand:
No dipole!
String Topologies

How does the system hadronize?

• Assume vacuum still acts as dual colour superconductor
  ➔ colour vortex lines ~ string picture still applicable

• Q then: **which** string topology? Y, Δ, V, … ?

\[
B_{i_1i_2i_3} = e^{\alpha_1 \alpha_2 \alpha_3} \prod_{n=1}^{3} P \left[ e^{ig \int_{D(x_n)} A_\mu dx_\mu} q_{i_n}(x_{i_n}) \right]_{\alpha_n}
\]

& Minimization of potential energy
  ~ string length (V(r) = kr)

⇒ Picture of Y-shaped topology
  with ‘string junction’

(Warning: This picture was drawn in a “pedagogical projection” where distances close to the center are greatly exaggerated!)

The Junction

How does the junction act / move?

- The movement of the string junction is crucial, it is the smoke of the BNV gun!
- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- In junction rest frame (JRF) the angle is $120^\circ$ between the string pieces.
- Or better, ‘pull vectors’ lie at $120^\circ$:

$$p^\mu_{\text{pull}} = \sum_{i=1,N} p^\mu_i \, e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

(since soft gluons ‘eaten’ by string)

Inverse boost $\Rightarrow$ handle on motion of the baryon number, *through* fragmentation

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Hadronisation

‘Ordinary strings’ $\rightarrow$ same fragmentation functions, u:d:s, etc

Technically: 2 least energetic strings fragmented outwards-in

When little energy left, remains collapsed into diquark

$\rightarrow$ remaining qq – q string piece fragmented as usual

Note: baryon number can be entirely separated from leading flavours

(More Complicated Topologies)

2 possibilities:
• a) 2 junction baryons
• b) junction-junction annihilation

Select between a/b based on which topology has smallest 'string length' → non-trivial kinematical dependence

(More Complicated Topologies)

Colour flow in gluino decays:

Selected according to (off-shell) resonance propagators.
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Variation of Fragmentation Assumptions

**PYTHIA model**: essentially stable
(provided junction Y topology ‘agreed’ upon)

**PYTHIA vs HERWIG**: it matters whether B flow modeled or not
(HERWIG impl. focussed on perturbative part)

Central Point ➔ Junction baryons are soft, in CM of decay
Slow Baryons @ LHC – How tough to do?

For the present study:  (simplistic!)

“Detector” covers $|\eta| < 5$ with granularity $\Delta \eta \times \Delta \phi = 0.1$

For $|\eta| < 2$, all charged hadrons with $p_\perp > 1$ GeV are reconstructed (100% eff, no mis-ID).

For $|\eta| < 5$, hard jets are reconstructed using cone algorithm.

We look for cascade-produced (boosted) $\tilde{\chi}_1^0$’s which decay via BNV: (Assume $m_{\tilde{\chi}_1^0} = 96$ GeV known)

8 reconstructed jets.
Candidate $\tilde{\chi}_1^0$: systems of 3 jets with combined $p_\perp > 200$ GeV.
The 3 jets occupy a small detector region, $R_{jj}^{\text{max}} < 0.8$.
The 3 jets reconstruct to $m_{\tilde{\chi}_1^0} \pm 10$ GeV.
Candidate junction proton: within $\Delta R_{p3j} = 0.5$ of the 3-jet system momentum direction.
Not trivial. But with high cross sections (low masses) may be feasible. Would be **smoking gun of Baryon Number Violation**.

ILC highly interesting as well. Model applicable to any collider type.
Summary and Outlook

- **RPV-SUSY** → interesting phenomenology
- Esp. BNV has antisymmetric colour structure in interaction term which does not appear in SM (neglecting sphalerons …)
- Detailed model focusing on NP aspects (flow of baryon number) shows new aspects:
  - **Smoking gun of BNV = excess of soft baryons (in CM of decay)**
- Available in the PYTHIA generator (see e.g., PYTHIA 6.4 manual, published last week: JHEP05(2006)026, 582pp)
- Not trivial to ‘catch the baryon’ at LHC. Would need detailed study.
- Possibilities at ILC also remain to be explored
- Though we only applied it to BNV-SUSY, the fragmentation principles are universal, and could easily be used for other BNV physics (so far, we e.g. recycled it for proton remnant fragmentation in min-bias)