PHENOMENOLOGICAL STUDIES ON SUPERSYMMETRY AND THE STRONG FORCE

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October 8, 2004
Lund
Lepton Number Violating Supersymmetry
– Decays and First Studies with PYTHIA.

“Searching for L-Violating Supersymmetry at the LHC”.
By P. Skands.
Published in European Physical Journal C23 (2002) 173.
Lepton Number Violating Supersymmetry

General MSSM contains renormalizable Lepton and Baryon Number violating operators.

P. Skands, thesis defense, 8 Oct 2004 – p.3/25
Lepton Number Violating Supersymmetry

General MSSM contains renormalizable Lepton and Baryon Number violating operators.

Proton lifetime bound $\rightarrow$ either LNV or BNV, not both! (could also be neither $\equiv$ R-parity conservation.)
We have considered \( \sim 1200 \) decay processes \((1 \rightarrow 2 \) and \( 1 \rightarrow 3)\) of sparticles to particles, induced at tree level by the trilinear LNV terms in the superpotential:

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

Example: fully leptonic \( \tilde{\chi}_0 \) decay:

![Leptonic Decays Diagram](image)
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$$W_{\text{LNV}} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \epsilon_{ijk} L_i H_2$$

Matrix Elements implemented in PYTHIA for partial width calculations (only SUSY particles and $t$ and $b$ quarks treated as massive).

Initial decay products distributed isotropically in phase space, subjected to QCD and QED bremsstrahlung and (string) hadronization.
Lepton Number Violating Supersymmetry

Second part: primitive LHC study, based on cuts and neural networks, focusing on experimental triggers and overall discovery potential for LNV-SUSY at LHC.

→ Discovery with 30 fb^{-1} data down to \( \sigma = 10^{-10} \) mb.
Paper II

Baryon Number Violating Supersymmetry
– Hadronization and String Topologies.

II “Baryon Number Violation and String Topologies”.
By T. Sjöstrand and P. Skands.
LU TP 02-46, Dec 2002.
Published in Nuclear Physics B 659 (2003) 243.
This time, ~200 decay channels → PYTHIA.
Again, sometimes they had bothersome expressions...
\[
\frac{\Gamma(\tilde{\chi}^0 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k)}{\sqrt{M(\tilde{\chi}^0 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k)^2}} = \frac{1}{(2\pi)^3} \frac{1}{32 M^3 \tilde{\chi}^0} \int dm^2_{12} \int dm^2_{23} |\sqrt{M(\tilde{\chi}^0 \rightarrow \bar{u}_i \bar{d}_j \bar{d}_k)|^2}
\]

\[
\sum_{\alpha = 1}^{2} |Q_{\alpha R}^{2i-1}|^2 R(\tilde{u}_{i\alpha}, m_{j_k}^2)(m_{j_k}^2 - m_j^2 - m_k^2) \left((a^2(\tilde{u}_{i\alpha}) + b^2(\tilde{u}_{i\alpha}))(m_{\tilde{\chi}^0}^2 + m_i^2 - m_j^2) + 4a(\tilde{u}_{i\alpha})(\tilde{u}_{i\alpha} m_i m_{\tilde{\chi}^0})\right)
\]

\[
+ \sum_{\alpha = 1}^{2} |Q_{\alpha R}^{j} |^2 R(\tilde{u}_{j\alpha}, m_{i_k}^2)(m_{i_k}^2 - m_i^2 - m_k^2) \left((a^2(\tilde{u}_{j\alpha}) + b^2(\tilde{u}_{j\alpha}))(m_{\tilde{\chi}^0}^2 + m_j^2 - m_k^2) + 4a(\tilde{u}_{j\alpha})(\tilde{u}_{j\alpha} m_j m_{\tilde{\chi}^0})\right)
\]

\[
+ \sum_{\alpha = 1}^{2} |Q_{\alpha R}^{k} |^2 R(\tilde{d}_{k\alpha}, m_{i_j}^2)(m_{i_j}^2 - m_i^2 - m_j^2) \left((a^2(\tilde{d}_{k\alpha}) + b^2(\tilde{d}_{k\alpha}))(m_{\tilde{\chi}^0}^2 + m_i^2 - m_j^2) + 4a(\tilde{d}_{k\alpha})(\tilde{d}_{k\alpha} m_i m_{\tilde{\chi}^0})\right)
\]

\[
\sum_{\alpha = 1}^{2} Q_{i R}^{1} Q_{j R}^{1} S(\tilde{u}_{i_1}, \tilde{u}_{i_2}, m_{j_k}^2, m_{j_k}^2)(m_{j_k}^2 - m_j^2 - m_k^2) \left((a(\tilde{u}_{i_1})(\tilde{u}_{i_2}) + b(\tilde{u}_{i_2})(\tilde{u}_{i_2}))(m_{\tilde{\chi}^0}^2 + m_j^2 - m_k^2)\right)
\]

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\]

\[
- \sum_{\alpha = 1}^{2} \sum_{\beta = 1}^{2} Q_{i R}^{1} Q_{j R}^{2} S(\tilde{u}_{j\beta}, \tilde{u}_{i\alpha}, m_{i_k}^2, m_{j_k}^2) \left((m_{i_k} m_{\tilde{\chi}^0} b(\tilde{u}_{j\beta}))(a(\tilde{u}_{i\alpha})(\tilde{u}_{i\alpha}))(m_{i_k}^2 + m_k^2 - m_i^2 - m_j^2)\right)
\]

\[
+ m_{j} m_{\tilde{\chi}^0} b(\tilde{u}_{j\alpha})(m_{j_k}^2 - m_j^2 - m_k^2) + m_j m_{\tilde{\chi}^0} b(\tilde{u}_{i\alpha})(m_{j_k}^2 - m_i^2 - m_k^2) - b(\tilde{u}_{j\beta})(\tilde{u}_{i\alpha})(m_{i_k}^2 + m_k^2 - m_i^2 - m_j^2)\right)
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But all that worked like before.

The real challenge was the *colour flows!*

How do such systems hadronise?
New: 3 (antisym) colour carriers at large momentum separation – no corresponding (perturbative) coupling in SM!

“Ordinary” string (e.g. $Z^0 \rightarrow q\bar{q}$): 

```
q ------ \bar{q}
```

“Baryonic” string (e.g.):

```
q1     junction
\downarrow
q2
\downarrow
q3
```
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“Ordinary” string (e.g. $Z^0 \rightarrow q\bar{q}$):

```
q  \hspace{2cm} \bar{q}
```

“Baryonic” string (e.g.):

```
q_2

\text{junction}

q_1

q_3

q_4 \quad q_5 \quad q_6 \quad q_7

q_{\bar{5}} \quad q_{\bar{6}} \quad q_{\bar{7}}

q_{\bar{1}} \quad q_{\bar{2}} \quad q_{\bar{3}} \quad q_{\bar{4}}

q_{\bar{8}} \quad q_{\bar{9}}

q_{\bar{k}}
```

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“Ordinary” string (e.g. $Z^0 \rightarrow q\bar{q}$):

“Baryonic” string (e.g.):

$B \equiv$ string topologies w/ junction(s).

$N_p / N_\pi$

$P_{CM} [GeV]$
Paper III

The SUSY Les Houches Accord.
– Standardising SUSY calculations.

III “SUSY Les Houches Accord: Interfacing SUSY Spectrum Calculators, Decay Packages, and Event Generators”.


Problem: lots of people doing SuSy calculations today!
- Spectrum Calculators: \( \sim 7 \) programs.
- Relic Density Codes: \( \sim 3 \) programs.
- Dedicated Decay Packages: \( \sim 3 \) programs.
- Event Generators: \( \sim 10 \) programs.
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And everybody has their own opinion about factors of \( \sqrt{2}, \pi, i \), counterclockwise or clockwise rotations, pole or running masses, effective field content, \( \overline{\text{DR}} \) or \( \overline{\text{MS}} \) regularization/renormalization, field decomposition etc.
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This gave rise to some problems...

So why not make an Accord? I.e. agree on a standard set of conventions for SUSY theories, with standard file structures \( \rightarrow \) unambiguous communication.
At Les Houches 2003, the organisers let me gather a lot of experts in a room, to discuss this. I made sure nobody could get out for some hours.

Next day, we had another long meeting, and another one every day after that, for almost two weeks.
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There followed $O(10^3)$ mails, and more meetings at CERN, at Montpellier, and latest at Durham.

The result is the SUSY Les Houches Accord, which now is implemented in most of the relevant codes.
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Now please use it!
Paper IV

Bilinear Lepton Number Violating Supersymmetry
– Measuring Neutrino Mixing at the LHC?

IV  “Measuring Neutrino Mixing angles at LHC”.
By W. Porod and P. Skands.
LU TP 03-50, ZU-TH 20/30, Jan 2004. [hep-ph/0401077]
Bilinear $L$–violation

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

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

In context of neutrino masses, the important consequences are:

\[ \langle \nu_i \rangle = v_i \quad \text{(i.e. } m_W^2 = \frac{1}{4} g^2 (v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2)) \]

\[ \text{Neutrinos mix with neutralinos } \rightarrow 7 \times 7 \text{ mixing:} \]

In block form: \( M_N = \begin{pmatrix} 0 & m_{(3\times4)} \\ m^T_{(4\times3)} & M_{(4\times4)} \end{pmatrix} \)
Measuring a $\nu$ angle...

Mixing depends on
\[ \Lambda_i = \mu \nu_i + \nu_d \epsilon_i \]

 BRPV couplings also responsible for LSP decay.

$\rightarrow$ Ratio of $\tilde{\chi}_1^0$ semileptonic branching ratios is strongly correlated with $\Lambda_i / \Lambda_j$!
Paper V

High Energy Proton Collisions 1
– Improving the Description of Underlying and Minimum Bias Events.

V  “Multiple Interactions and the Structure of Beam Remnants”.
By T. Sjöstrand and P. Skands.
LU TP 04-01, Feb 2004.
The Motivation:

Example: minimum-bias at the Tevatron

Proton beam remnant

\[ p \]

\[ g \]

\[ g \]

Antiproton beam remnant

\[ \bar{p} \]
The Motivation:

Real life is more complicated...
Why Develop a New MI/UE Model?

Need to understand correlations and fluctuations in hadronic collisions. From QCD point of view: many interesting questions remain unanswered.

Any reliable extrapolation to LHC energies will require a good understanding of the physics mechanisms. Simple parametrizations not sufficient.

Random and systematic fluctuations in the underlying activity can impact precision measurements as well as New Physics searches: more reliable understanding is needed.

Lots of fresh data from Tevatron: → great topic for phenomenology right now!
Towards a realistic model

How are the hard scattering initiators and beam remnant partons correlated?

- In impact parameter?
- In flavour?
- In longitudinal momentum?
- In colour?
- In (primordial) transverse momentum?
The “intermediate” model:

- Dependence on non-trivial transverse density profile of incoming hadrons.
- Fully correlated multi-parton densities calculated event by event, respecting momentum conservation and flavour sum rules, and reducing to standard PDF’s for the hardest interaction.
- Final state multiplicity increased by ISR and FSR, for all interactions. (including correlated PDF’s for ISR.)
- Non-vanishing “primordial” $k_\perp$ for shower initiators.
- Junction hadronisation (from BNV studies) adapted for description of baryon beam remnants.
- Colour flow ambiguous at the non–perturbative level. Interesting (and thorny!) issues here, to be continued...
Paper VI

High Energy Proton Collisions 2
– Unifying the Description of Radiation and Interactions.

VI “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”.
By T. Sjöstrand and P. Skands.
LU TP 04-29, Aug 2004.
Submitted to the European Physical Journal C.
Incorporate several of the good points of the dipole formalism within the shower approach

± explore alternative $p_\perp$ definitions

+ $p_\perp$ ordering $\Rightarrow$ coherence inherent

+ Merging with Matrix Elements unproblematic. (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same $z$)

+ $g \rightarrow q\bar{q}$ natural

+ kinematics constructed after each branching (partons explicitly on-shell until they branch)

+ showers can be stopped and restarted at any $p_\perp$ scale $\Rightarrow$ well suited for ME/PS matching
Why Develop a New Shower?

Incorporate several of the good points of the dipole formalism within the shower approach

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  (unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same $z$)

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+ kinematics constructed after each branching
  (partons explicitly on-shell until they branch)

+ showers can be stopped and restarted at any $p_\perp$ scale
  ⇒ well suited for ME/PS matching

+ allows to combine $p_\perp$ evolutions of showers and multiple interactions → common (competing) evolution of ISR, FSR, and MI!

≡ ‘Interleaved Multiple Interactions’
Proton Collisions... The New Picture

The building blocks:

- $p_\perp$—ordered initial–state parton showers. ✓
- $p_\perp$—ordered final–state parton showers. ✓
- $p_\perp$—ordered multiple interactions. ✓
- $p_\perp$ used as scale in $\alpha_s$ and in PDF’s. ✓
- (Model for) correlated multi–parton densities. ✓
- Beam remnant hadronization model. ✓
- Model for initial state colour correlations. (✓ — but far from perfect!?)
- Other phenomena? (e.g. colour reconnections (✓), ...)
- Realistic tunes to data (not yet!)
The new picture: start at the most inclusive level, \(2 \rightarrow 2\). Add exclusivity progressively by evolving everything downwards in one common sequence:

\[ \rightarrow \text{Interleaved evolution} \]

(\(\rightarrow\) also possible to have interactions intertwined by the ISR activity?)
The new description represents a new generation in terms of detail and sophistication of the physics description of hadron collisions.

But there is still some way to go...
Plans for the future

To work hard!