PHENOMENOLOGICAL STUDIES ON SUPERSYMMETRY AND THE STRONG FORCE

Ph.D. thesis by Peter Zeiler Skands
Advisor: Torbjörn Sjöstrand
Overview

1. The standard Zoology of particle physics.
2. So what’s the problem(s) ?
3. Supersymmetry – Beyond the Standard Model.
4. The thesis work:
   - What I have been doing, fast overview.
   - Spotting speculative sparticles.
   - SuSy talk, and no mistake about it.
   - Interlude: neutrino masses ?
   - Proton collisions à la Pythia 6.3.
5. To summarise...
1. The Standard Zoology...
The Standard Zoology of Particle Physics

Standard Model \equiv Quantum Field Theory with:

- 3 forces: $SU(3) \times SU(2) \times U(1)$ (+Higgs $\rightarrow$ mass).
- $3_{\text{gen}} \times 2_{\text{iso}} \times 3_{\text{col}} \times 2_{LR} = 36$ quarks.
- $3_{\text{gen}} \times 2_{\text{iso}} \times 1_{\text{col}} \times 1.5_{LR} = 9$ leptons. (Maybe 12?)

<table>
<thead>
<tr>
<th>Fermions (matter particles)</th>
<th>Bosons (force particles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$, $d$</td>
<td>$\gamma$</td>
</tr>
<tr>
<td>$c$, $s$, $t$, $b$</td>
<td>$W^+$, $Z^0$, $W^-$</td>
</tr>
<tr>
<td>$e$, $\nu_e$</td>
<td>$\nu_{\mu}$</td>
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<tr>
<td>$\mu$, $\nu_{\mu}$</td>
<td>$\tau$, $\nu_{\tau}$</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>$8 \times g$</td>
</tr>
</tbody>
</table>

Works very nicely, so what’s the problem?
2. So what’s the problem(s)?
What's the problem?

Some experiments...
What’s the problem?

A few experiments:

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

W. Pauli
What’s the problem?

A few experiments:

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

W. Pauli

Nobel prize 2002: Neutrinos have mass!

Masatoshi Koshiba
Raymond Davis Jr.

What’s the problem?

A few experiments:

Doppler shifts → Rotation profiles of galaxies
What’s the problem?

A few experiments:

“It’s a dark matter in cosmology... but then again, in that field most things are...” [A. Khodjamirian]
What’s the problem?

A few experiments:

- Looks like Universe will expand forever.
- 30% matter (incl. the dark kind)
- 70% vacuum energy density (cosmological “constant”)

What is $\Lambda$?
What's the problem?

Some experiments...

- How do Neutrino Masses fit in?
- What is Dark Matter?
- What is Dark Energy?
What’s the problem?

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Some mathematics...
Some mathematics:

The Standard Model isn’t natural!

- The Higgs is special. It’s the only scalar.
- Its mass gets huge quantum corrections from higher energies, \( m^2 = m_0^2 + \Delta m^2 \), with \( \Delta m \sim 10^{19} \text{ GeV} / c^2 \).
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- The **Higgs** is special. It’s the only **scalar**.
- Its mass gets **huge quantum corrections** from higher energies, \[ m^2 = m_0^2 + \Delta m^2 \], with \[ \Delta m \sim 10^{19} \text{ GeV} \text{c}^{-2} \].
- But **indirectly** we know \[ m \sim 100 \text{ GeV} \text{c}^{-2} \].
- There must be a **spectacular cancellation** occurring in Nature in order for this to happen.
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- But indirectly we know $m \sim 100 \frac{\text{GeV}}{c^2}$.
- There must be a spectacular cancellation occurring in Nature in order for this to happen.

The Standard Model has no explanation for this phenomenon, known as the hierarchy problem.
What’s the problem?

Some mathematics:

Gravity does not fit in the Standard Model

- The graviton is special.
- General Relativity: gravity is described by a tensor field: the metric $g_{\mu\nu}$, describing the curvature of space–time.
- → a mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.
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Some mathematics:

Gravity does not fit in the Standard Model

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General Relativity: gravity is described by a tensor field: the metric $g_{\mu\nu}$, describing the curvature of space–time.

- A mixture of $\ell = 0$, $\ell = 1$, and $\ell = 2$ fields.

Spin-2 fields are non–renormalizable in quantum field theory (basically, they don’t make sense).

→ Gravity appears to be incompatible with Quantum Field Theory.
What’s the problem?

Some mathematics:

The Strong Force gives us headaches:

- In QFT we can relatively easily handle
  - A handful (maybe two) of particles,
  - with small couplings \( \ll 1 \) (e.g. \( \alpha_{\text{em}} \sim 10^{-2} \))
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Butch Cassidy and the Sundance Kid. Copyright: Twentieth Century Fox Films Inc.
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- Hadronic physics and collisions always involve:
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  - And couplings that may be $\gg$ large!

So we devise phenomenological models, to describe the effective/measurable physics.

Even so, long way still to go ...
What’s the problem?

Some experiments...
- How do Neutrino Masses fit in?
- What is Dark Matter?
- What is Dark Energy?

Some mathematics...
- What to do about the hierarchy problem? (may be relevant for experiments...)
- How to make a theory for quantum gravity (probably not relevant for experiments...)
- How to solve (or just “solve”) QCD? (very relevant for experiments...)
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Some aesthetics...
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Could there be more space–time symmetries?

Are the true fundamental objects in Nature really point-like, or are they strings, or even membranes?
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- Could bosons and fermions be related?
- Why 3 spatial dimensions?
- Could there be more space–time symmetries?
- Are the true fundamental objects in Nature really point-like, or are they strings, or even membranes?
- Could there be one fundamental theory of everything?
3. Supersymmetry — Beyond the Standard Model
So what is Supersymmetry?

**SUPERSYMMETRY**

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

- 6 leptons + 6 quarks \( S = \frac{1}{2} \)
- photon + \( W^\pm \) and \( Z^0 \) + gluon \( S = 1 \)
- Higgs \( S = 0 \)
So what is Supersymmetry?

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- 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: $S = \frac{1}{2}$
But what’s the point?
- Why should Nature respect this weird symmetry?
- Instead of reducing the mess, we’ve *doubled* the spectrum of physical states!

It makes sense because:
- SUSY gives the largest possible space–time symmetry.
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  - SUSY can solve the hierarchy problem.
SUSY can solve the Hierarchy Problem

\[ M_0(M_G) = M_{1/2}(M_G) = 200 \text{GeV} \]

\[ m_1^2 + m_2^2 - 2|m_3^2| \]

\[ m_1^2 m_2^2 - m_3^4 \]

Instability \( \text{SU(2)xU(1)} \) breaking \( \text{Unbroken SU(2)xU(1)} \)

\[ [m_i^2 = m_{\tilde{H}_i}^2 + \mu^2] \]

[Dedes]
Supersymmetry.

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- SUSY gives experimentalists something to look for.
- SUSY can solve the hierarchy problem.
- SUSY can solve the dark matter problem.
- SUSY leads to Grand Unification.
SUSY Leads to Grand Unification

GUT’s with only SM as underlying theory are ruled out, couplings don’t unify.

GUT’s with SUSY can do wonderful things:

![Graph showing the inverse of coupling constants vs. logarithmic scale of energy](image)
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- SUSY gives experimentalists something to look for.
- SUSY can solve the hierarchy problem.
- SUSY can solve the dark matter problem.
- SUSY leads to Grand Unification.
- SUSY is the “super” in superstring theory.
4. The thesis work...
lepton number violation (paper I),
baryon number violation (paper II),
supersymmetry calculations (paper III),
neutrino masses (paper IV),
proton collisions and hadronization (paper V),
proton collisions and bremsstrahlung (paper VI).

Mix it together and you get . . . not pythipanna . . .

PYTHIA 6.3
Papers I and II

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

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.
Most general (MSSM) superpotential:

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

But LNV+BNV makes bad cocktail!
Most general (MSSM) superpotential:

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

But LNV+BNV makes bad cocktail!

To save proton, R, B, or L conservation imposed.

- R \rightarrow CDM candidate, but no deep motivation.
- B and L more robust against things outside MSSM.
- No clear-cut answer.
Lepton Number Violating SuSy

Paper I concerned Lepton Number Violating SuSy.

More than 1200 decay channels of sparticles to particles were implemented in PYTHIA.

Often many interfering amplitudes contributing to same process → big matrix element expressions and tricky phase space integrations (for the 3–body modes).

In the end, the calculations were totally automized, using a just few generic routines.

The second part was a study of trigger sensitivities and discovery potential for the LHC, using the augmented PYTHIA in combination with the ATLFAST detector simulation, and applying a technique based on neural networks to help separate signal-like events from background-like events.
Paper II concerned Baryon Number Violating SuSy.

This time, some 200 decay channels of sparticles to particles were implemented in PYTHIA.

Again, these could have bothersome expressions etc.
\[
\Gamma(\tilde{\chi}^0 \rightarrow \tilde{u}_i \tilde{d}_j \tilde{d}_k) = \frac{1}{(2\pi)^3} \frac{1}{32M^3_{\tilde{\chi}^0}} \int \frac{\mathrm{d}m^2_{12}}{N_c!\lambda_{ij}^2} \int \frac{\mathrm{d}m^2_{23}}{\lambda_{ij}^2} |\mathcal{M}(\tilde{\chi}^0 \rightarrow \tilde{u}_i \tilde{d}_j \tilde{d}_k)|^2
\]

\[
\sum_{\alpha=1}^{2} |Q_{\alpha R}^{2i-1}|^2 R(\tilde{u}_{i\alpha}, m_{jk}^2)(m_{jk}^2 - m_{jk}^2 - m_{ij}^2)(a^2(\tilde{u}_{i\alpha}) + b^2(\tilde{u}_{i\alpha}))(m_{\tilde{\chi}^0}^2 + m_{ij}^2 - m_{jk}^2 + 4a(\tilde{u}_{i\alpha})b(\tilde{u}_{i\alpha})m_im_{\tilde{\chi}^0})
\]

\[
+ \sum_{\alpha=1}^{2} |Q_{\alpha R}^{j}|^2 R(\tilde{u}_{j\alpha}, m_{ik}^2)(m_{ik}^2 - m_{ik}^2 - m_{ij}^2)(a^2(\tilde{u}_{j\alpha}) + b^2(\tilde{u}_{j\alpha}))(m_{\tilde{\chi}^0}^2 + m_{ij}^2 - m_{jk}^2 + 4a(\tilde{u}_{j\alpha})b(\tilde{u}_{j\alpha})m_jm_{\tilde{\chi}^0})
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\]

\[
+ 2Q_{1R}^{i}Q_{2R}^{i}S(\tilde{u}_{i1}, \tilde{u}_{i2}, m_{jk}^2, m_{jk}^2)(m_{jk}^2 - m_{jk}^2 - m_{ij}^2)(a(\tilde{u}_{i1})a(\tilde{u}_{i2}) + b(\tilde{u}_{i1})b(\tilde{u}_{i2}))(m_{\tilde{\chi}^0}^2 + m_{ij}^2 - m_{jk}^2)
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\]

\[
- 2 \sum_{\alpha=1}^{2} \sum_{\beta=1}^{2} Q_{\alpha R}^{i}Q_{\beta R}^{i}S(\tilde{u}_{i\beta}, \tilde{u}_{i\alpha}, m_{ik}^2, m_{jk}^2)(m_{ij}^2m_ja(\tilde{u}_{i\beta})a(\tilde{u}_{i\alpha}) + m_{ij}^2m_ka(\tilde{u}_{i\beta})a(\tilde{u}_{i\alpha}) + m_{ij}^2m_{ik}^2a(\tilde{u}_{i\beta})a(\tilde{u}_{i\alpha}) + m_{ij}^2m_{jk}^2a(\tilde{u}_{i\beta})a(\tilde{u}_{i\alpha}) + m_{ij}^2m_{ik}^2m_{jk}^2a(\tilde{u}_{i\beta})a(\tilde{u}_{i\alpha}))
\]

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Dreiner, Richardson, and Seymour (hep-ph/9912407):

Paper II concerned Baryon Number Violating SuSy.

This time, some 200 decay channels of sparticles to particles were implemented in PYTHIA.

Again, these could have bothersome expressions etc.

But all that worked like before.
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This time, some 200 decay channels of sparticles to particles were implemented in PYTHIA.
Again, these could have bothersome expressions etc.
But all that worked like before.
The real challenge was the colour flows!
Baryon Number Violating SuSy

Special: creation of 3 colour carriers, antisymmetric in colour, at large momentum separation.

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

“Baryonic” string (e.g.):

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

$\chi$ decay. Junction protons.
$\chi$ decay. Non-junction protons.
+ $qqbar$ w. $E_{CM} = m_\chi$.
○ $qqbar$ w. $E_{CM} = 2/3 m_\chi$. 

P. Skands, Informal thesis presentation, 6 Oct 2004 -- p.30/49
Paper III

SuSy talk, and no mistake about it.

“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.
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And everybody has their own bloody opinion about factors of \( \sqrt{2}, \pi, i \), counterclockwise or clockwise rotations, pole or running masses, \( \overline{\text{DR}} \) 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 the Les Houches meeting in 2003, the organisers had agreed to 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. Only a few people got out.

At the end, everybody was tired and agreed.

Then we had lots of mails, $O(10^3)$, 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.
At the Les Houches meeting in 2003, the organisers had agreed to let me gather a lot of experts in a room, to discuss something for some hours. Only a few people got out.

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Paper IV

Interlude: neutrino masses?

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]

Neutrino sector: a window to physics beyond SM?

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

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

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

Explanations generally look like this:

$$
\begin{pmatrix}
0 & m \\
m & M
\end{pmatrix}
$$
Bilinear $R$–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:

- **EW symmetry is broken by Higgs and sneutrino vev's**,
  \[
  \langle \nu_i \rangle = v_i \quad \text{(i.e. } m^2_W = \frac{1}{4} g^2 (v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2)) \]

- **Neutrinos mix with neutralinos** → $7 \times 7$ mixing:

  In block form:
  \[
  M_N = \begin{pmatrix}
  0 & m_{(3\times4)} \\
  m^T_{(4\times3)} & M_{(4\times4)}
  \end{pmatrix}
  \]
Mixing depends on
\[ \Lambda_i = \mu \nu_i + \nu_d \epsilon_i \]

BRPV couplings also responsible for LSP decay.

\[ \rightarrow \text{Ratio of } \tilde{\chi}_1^0 \text{ semileptonic branching ratios is strongly correlated with } \Lambda_i/\Lambda_j! \]
Papers V and VI

**Proton Collisions**

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

VI “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”.
   By T. Sjöstrand and P. Skands.
   LU TP 04-29, Aug 2004.
   To be submitted to the European Physical Journal C.
1 hadron collision =

\( (2 \rightarrow 2 \oplus \text{ISR} \oplus \text{FSR} \oplus \text{UE}) \otimes \text{hadronisation etc.} \)

Eff. resum. of multiple (semi-)soft gluon emission effects

- \( 2 \rightarrow 2 \): ‘hard subprocess’ (on–shell).
- ISR: Initial–State Radiation (spacelike).
- FSR: Final–State Radiation (timelike).
- UE: Underlying Event – any additional (perturbative) activity.
1 hadron collision =
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Eff. resum. of multiple (semi-)soft gluon emission effects

2 \to 2: ‘hard subprocess’ (on–shell).
ISR: Initial–State Radiation (spacelike).
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+ additional 2 \to 2 scatterings
  = “multiple interactions”
+ hadronisation
+ hadron decays
What we have done:

1. Developed a new complete model for multiple interactions in hadron-hadron collisions.

2. Developed a new (dipole) parton shower, both for final state and initial state radiation.

For both of these, we use transverse momentum as the “resolution” parameter.
Why Develop a New MI Model?

Need to understand correlations and fluctuations. 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!
Why Develop a New Shower?

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

± explore alternative $p_{\perp}$ definitions
+ $p_{\perp}$ ordering ⇒ 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
  ⇒ well suited for ME/PS matching
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  $\Rightarrow$ well suited for ME/PS matching
- allows to combine $p_\perp$ evolutions of showers and multiple interactions $\rightarrow$ common (competing) evolution of ISR, FSR, and MI!

≡ ‘Interleaved Multiple Interactions’
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:

\[ \text{Interleaved evolution} \]

(\( \rightarrow \) 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...
5. To Summarise...
Working in Lund

Has been an upward climb!
I have come a long way
I have come a long way

Not standing still...
Plans for the future...