Swedish String/Supergravity Course 2008

String Phenomenology

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1 Minimal Supersymmetric Standard Model

A good reference is Martin [2], a review that was first posted on `hep-ph` in 1997 but which has been updated three times, most recently in 2006.

The MSSM consists of a number of chiral and vector supermultiplets, one for each existing quark or lepton ψ or gauge boson A_μ in the Standard Model (SM): [1]

spin:	0	1/2	1
$\mathcal{N}=1$ chiral supermultiplet	ϕ	ψ	
$\mathcal{N}=1$ vector supermultiplet		λ	A_μ

The new fields, the superpartners of ψ and A_μ, are denoted by tildes and called "s-" for the new scalars, $\tilde{\psi}$, and "-ino" for the new fermions, $\tilde{A}$:

	0	1/2	1	
squarks, sleptons $\longrightarrow$	$\tilde{\psi}$	$\psi \longleftarrow$	quarks, leptons	
	gauginos $\longrightarrow$	$\tilde{A}$	A_μ $\longleftarrow$	gauge bosons

This is just the generic notation; usually one is more specific. So for example, one $\mathcal{N}=1$ chiral multiplet has the t quark as the fermionic field, and the scalar superpartner is the "stop", $\tilde{t}$. We *impose* that the superpartner masses are around the TeV scale, or even a little lower. The scale of superpartner masses is not "derived" in any real sense[2] in the MSSM, but from the point of view of particle phenomenology, an MSSM-like theory with *only* very heavy superpartners would be indistinguishable from the nonsupersymmetric standard model at any experiments done in the foreseeable future, so why bother? In fact, even string theorists should have some favored scenario what will happen at near-future experiments and observations, so let's try to understand where people who do experiments for a living have put *their* money. (Literally: the LHC costs around $3 \cdot 10^9$ euros, and even though supersymmetry is not its only *raison d'être*, ask the experimentalists if they built the LHC to see the SM Higgs.)

1.1 "Electroweak-inos"

If you don't remember what the SM electroweak gauge bosons W^0_μ and B_μ are, consult Peskin & Schroeder [1] Ch. 20.2[3]. Basically

$$W^0, B \quad \overset{\text{EWSB}}{\longrightarrow} \quad \gamma(\text{photon}), Z^0$$

where "EWSB" stands for electroweak symmetry breaking by the Higgs mechanism, i.e. the breaking of $SU(2)_{\mathrm{w}} \times U(1)_Y$ (which has 3+1=4 generators, of which W^0 and B are the electrically neutral ones), to $U(1)_{\mathrm{em}}$. The gauge boson B (corresponding to $U(1)_Y$) couples to *hypercharge* Y, which is a combination of electric charge Q and weak isospin T^3:

$$Y = Q - T^3 \ .$$

[1] Only count physical degrees of freedom, so e.g. a chiral superfield also has an auxiliary scalar F, but it's not listed here.

[2] Sometimes one hears arguments that the hierarchy problem implies low-energy supersymmetry. Although I am a firm believer in the hierarchy problem being a problem — and some people don't even believe that – I think by now there are enough models that "solve" the hierarchy problem without low-energy supersymmetry that we know that low-energy supersymmetry is not *required* by the hierarchy problem, hence cannot truly be "derived" by invoking it.

[3] There, the W^0 is called A^3.

So for example, a left-handed u-type quark (i.e. u or c or t) has electric charge $+2/3$, and sits in an $SU(2)_{\mathrm{w}}$ quark doublet written (u,d), so u has "weak isospin up", i.e. $T^3 = 1/2$, giving hypercharge

$$Y(\text{left-handed } u \text{ quark}) \;=\; \frac{2}{3} - \frac{1}{2} \;=\; \frac{1}{6}\,.$$

The fermion superpartners of the B and the W are called the *bino* and *wino*, respectively, by a simple application of the naming rule above, and are denoted $\tilde{B}$ and $\tilde{W}$. [4] More generally speaking, B and W are gauge bosons, so $\tilde{B}$ and $\tilde{W}$ are *gauginos*. Sometimes $\tilde{B}$ and $\tilde{W}$ are collectively given the horrible name "electroweak-inos". This distinguishes them from the *gluino* $\tilde{g}$, which is also a gaugino, but carries color charge like the gluon. (If the supercharges commute with gauge symmetry, all superpartners must have the same gauge charges as their SM partner. This is not true in gauged supergravity, but it's true in the MSSM.)

1.2 Higgs sector

Problem: although the Standard Model relies on the Higgs mechanism, we haven't seen the Higgs particle. (The bound from LEP is $m_h \gtrsim 114$ GeV, though this is model-dependent). Therefore any phenomenological model of the Higgs sector will rely on some experimentally untested assumptions (explicit or implicit). The Higgs "particle" of the minimal nonsupersymmetric Standard Model could end up being a whole "Higgs sector" with more scalars, or something completely different (cf. "technicolor").

As it turns out, $\mathcal{N}=1$ supersymmetry prohibits a single Higgs field from generating masses for *both* u-type and d-type quarks. (This is due to the holomorphy of couplings in the superpotential.). Thus, we must have

$$\textit{at least} \text{ two Higgses } H_u,\ H_d \text{ in the } \mathcal{N}=1 \text{ extension of the SM}\,.$$

In the MSSM (the first M is for "Minimal"!) we take exactly two, no more. There is a common argument that we *must* have exactly two, i.e. that it is not just for simplicity. This argument is summarized for example in Weinberg's book [4, p.188-192], but it assumes standard gauge unification, which typically does not apply in the models we will be looking at here. All we really know is that we should have at least two.

1.3 Neutralinos

The new uncolored fermions are grouped together by their electric charge, and then diagonalized into mass eigenstates:

$$\begin{array}{rcll} \tilde{H}^0_u, \tilde{H}^0_d, \tilde{B}^0, \tilde{W}^0 & \longrightarrow & \tilde{N}_i \text{ (neutralinos)} & i=1,\ldots 4 \\ \tilde{H}^\pm, \tilde{W}^\pm & \longrightarrow & \tilde{C}^\pm_i \text{ (charginos)} & i=1,2 \end{array}$$

The four neutralinos $\tilde{N}_i$ (often called χ^0_i instead) are ordered by increasing mass, so for example the lightest neutralino $\tilde{N}_1$ is some linear combination of the four neutral, uncolored new fermions:

$$\tilde{N}_1 = a_1\tilde{H}^0_u + a_2\tilde{H}^0_d + a_3\tilde{B}^0 + a_4\tilde{W}^0 \tag{1}$$

for some computable numbers $a_1 \ldots a_4$ that give the *mixing angles*. (Compare how the Weinberg angle θ_{W} of the Standard Model tells you e.g. what mixture of W^0 and B is the photon.) Sometimes $|a_3|^2 + |a_4|^2$ is called the *gaugino fraction* in $\tilde{N}_1$. Based on the above information, you should be able to understand this terminology. The mixing angles tell us about the interactions of the $\tilde{N}_1$, since the different fields in (1) have different couplings.

[4] Notice that now I didn't say W^0 with the zero superscript anymore, that's because also the charged $W^\pm$ in the SM have superpartners, so the fermions $\tilde{W}^0$ and $\tilde{W}^\pm$ are distinguished by calling them "neutral wino" and "charged wino", respectively, and the naming in the rest of this paragraph applies also to the $\tilde{W}^\pm$.

1.4 R-parity and dark matter

One usually imposes an a priori unmotivated symmetry in the MSSM, called "R-parity conservation". This means we assign an "R-parity" of -1 to all (most) of the new particles (squarks, gauginos...), and $+1$ to all the known (SM) particles, and impose that this quantum number is conserved. Then, the new particles can only decay to SM particles if they find another new particle to annihilate with. This means that a single new particle will be very stable, and the lightest supersymmetric particle (LSP) will be stable over cosmological timescales.

One point of this is that such a stable, weakly interacting particle can solve the astrophysical/cosmological *dark matter problem*. There is a nice 11-page summary about this by Michael Peskin [7]. There are two things that are useful to understand about this: first, as Peskin explains, the cross sections we expect for new particles in some simple versions of the MSSM *turn out* to be on the order of 1 picobarn, which is the order of magnitude appropriate for dark matter cross sections – i.e. this coincidence was not put in by hand. Second, if the LSP is a *charged* particle, such as the "stau" (scalar partner of the tau lepton), it cannot work as a dark matter candidate – it must be a neutralino. [5]

Details of the characteristics of the $\tilde{N}_1$ are therefore very important. What phenomenologists (e.g. those in Stockholm! [11]) do is to calculate cross sections between the new MSSM particles and the SM particles, then use the Boltzmann equation in the early universe

$$\frac{dn}{dt} = -3Hn - (\text{ cross sections } \sigma)$$

where H is the Hubble parameter, to calculate $n(t)$, the time-dependent number density of $\tilde{N}_1$, then pass this through some cosmological model of the universe, to get the "relic abundance", i.e. the correct amount of dark matter today[6] $\Omega_{\mathrm{DM}} = 0.2$. In other words, it's not just a matter of making up some random new particle, even one with a 1pb cross section: a lot of details need to work out *if* you want your model to solve the dark matter problem.

1.5 The MSSM Lagrangian

In the MSSM, one imagines supersymmetry being broken by some *additional* sector of fields, usually called "the hidden sector", and transmitted to the MSSM fields by some mechanism called "mediation". There are many different kinds of mediation (gravity mediation, gauge mediation, anomaly mediation, mirror mediation, ...). Fortunately, if we just want to do TeV-scale physics, the effect of supersymmetry breaking in the MSSM, in whatever mediation scenario, can be summarized in the "soft supersymmetry breaking terms", regardless of *how* they were created exactly (see e.g. [3]):

$$\mathcal{L}_{\mathrm{MSSM}} = \mathcal{L}_{\mathrm{susy}} + \underbrace{\mathcal{L}_{\mathrm{soft}}}_{\text{dimension}\leq 3} \tag{2}$$

where $\mathcal{L}_{\mathrm{soft}}$ contains parameters like mass splittings $\Delta m = m_\phi - m_\psi$, deviations A_{ijk} from supersymmetric trilinear couplings (i.e. those generated by a holomorphic superpotential), etc. In all, we obtain 124 parameters, which means 105 new parameters compared to the standard model.

Of course, it is difficult to do phenomenology with so many free parameters. One thing that was noticed early on is that generic values for e.g. the A_{ijk} lead to strong violations of experimental bounds, in particular of two kinds: [4, p.198-209], [2, p.37-41]

- Flavor violation
  The SM has a special feature that the processes that let quarks change flavor are very suppressed,

[5] There are some models where it is some other neutral particle such as the *gravitino*, the spin 3/2 superpartner of the graviton, but let's focus on models with neutralino LSP. The point here was that a particle with electric charge is not a good dark matter candidate.

[6] one conventionally doesn't give Ω_{DM} by itself like this, but rather multiplies it with the Hubble parameter h squared, i.e. Ωh^2.

as seen e.g. in the $K^0 \to \mu^+\mu^-$ process (to see that this must proceed by a flavor-changing coupling: what quarks are in the K^0?), that is measured to occur only rarely, which the SM is consistent with.

- CP violation
  The SM has another feature that the only source of CP (charge conjugation + parity) violation is by a single phase in the "CKM matrix" (see Peskin & Schroeder Ch. 20.3). This is also consistent with experiments, and there are very strong bounds on CP-nonconserving processes.

The MSSM for generic parameter values has significant flavor violation and CP violation, so is easily ruled out. So to make things simple, phenomenologists tend to set such dangerous parameters to zero, and call the model "MSSM-7" or something like that instead of the full "MSSM-124". Noone knows that the dangerous parameters are actually zero, but if we don't know better, that seems like a good first assumption. However, it seems like it would be nice to try to understand where this structure comes from, rather than imposing it. In particular, models which are on the verge of being ruled out can be interesting to study.

Remark: The above statements are clear if you remember everything I said before, but if you don't: in the MSSM we *impose* that the scale of superpartner masses is around a TeV or even less – see section 1. But if we can produce them as real particles at the LHC, they could have *virtual* effects (i.e. in loops) at scales somewhat lower than the LHC energy scale — which means at experiments already performed. Indeed, if you make the superpartners much heavier than a TeV, then none of these bounds are a problem; that should be stated clearly. It's just that that's not what we want to do. To summarize, it is completely obvious that you should only consider models that are not already ruled out by *existing* data, although to a string theorist it is a real challenge to implement this in your model.

2 String phenomenology – rough overview

We could make a rough classification of string phenomenology by two things: what corner of string theory we use to make models, and the scales involved. Two major contenders for constructing models that at least appear to contain the MSSM are

- "New" Heterotic models like [13] [7]
- Intersecting branes (IIA, IIB, orientifolds) like [14]

There are many other ideas, but in fact in these notes, we will only get to the second. The two scales we will be classifying models by are the string scale $M_{\rm string}$ and the scale of superpartner masses $M_{\rm susy}$. We will not assume (though not exclude) that the string scale is close to the Planck scale 10^{18} GeV, but let's allow for what is called an "intermediate" scale around 10^{11} GeV. Since $M_{\rm string} > M_{\rm susy}$, we have three cases:

	A	B	C
10^{11} GeV	$M_{\rm string}$		$M_{\rm string}$
10^{9} GeV			$M_{\rm susy}$
10^{4} GeV		$M_{\rm string}$	
10^{3} GeV	$M_{\rm susy}$	$M_{\rm susy}$	

Models B are the "low string scale" models, where we will really produce string excitations in the next generation of colliders. This is of course exciting, but there is no reason to believe that this is really the way the world works. Models C are "high-scale supersymmetry breaking" models that have been advocated in the "landscape" context, but those don't resemble the MSSM at any energy scale, so for simplicity we will focus on models of type A.

[7] by "old" heterotic models we intend those in which the three generations of the SM arise by the Euler number χ of the Calabi-Yau threefold (cf. "Triadophilia", the "love of three" [6])

3 LHC string phenomenology

What is then the role of string theory, if as in Model A, the energy at which strings can be produced is over a million times higher than the scales probed at accelerators in the foreseeable future? In that case, the role of string theory for low-energy physics is only to calculate an effective Lagrangian:

$$\text{string theory} \quad \longrightarrow \quad \mathcal{L}_{\text{eff}} \tag{3}$$

The effective Lagrangian has two main features: first, it is an expansion in the string length $E^2\alpha'$, and the string coupling g_s.[8] Second, even at tree-level it comes with some *structure* in the couplings: to give one simple example, the Yukawa couplings in D-brane models will be strongly constrained in a given model, whereas in quantum field theory, they are free parameters.

Of course, this $\mathcal{L}_{\text{eff}}$ will be calculated close below the string scale. We then perform renormalization group (RG) evolution down to the TeV scale.

$$\begin{array}{cc}
10^{11}\ \text{GeV} & M_{\text{string}} \\
\ldots & \downarrow \\
\ldots & \text{Renormalization group evolution} \\
\ldots & \downarrow \\
10^{3}\ \text{GeV} & M_{\text{susy}}
\end{array}$$

This is explained in detail in Peskin & Schroeder, but just to give an idea, the couplings g *run*, i.e. depend on energy scale, in a way dictated by the RG equations,

$$\frac{dg}{dt} = g\beta_1 + g^2\beta_2 + \ldots \qquad (t = \log\frac{M_{\text{string}}}{\mu}) \tag{4}$$

where μ is the energy scale. (Similar equations hold for the masses, and more generally, for all parameters in the Lagrangian.) The β functions have been calculated in perturbation theory for the MSSM [3, Sec.C.6]. In fact, there are several software packages (e.g. `SoftSUSY` [15]) that do this running for you automatically, and check some experimental bounds while it's at it.

One question in string phenomenology that needs to be studied more is what the generalization is of eqs. (4) if you have something more than the minimal theory, i.e. something with the MSSM as a subset, rather than exactly the MSSM. If new heavy particle-like excitations exist even at very high energy (e.g. 10^8 GeV) this can cause a big difference in the couplings we finally obtain at low energy, i.e. at the TeV scale.

3.1 Supersymmetry breaking

In these kinds of models ("model A") supersymmetry is broken at an energy very low compared to the string scale, so the process be very well approximated by supersymmetry breaking in quantum field theory. The canonical toy model example of this is the O'Raifertaigh model, see e.g. Wess & Bagger [5, p.51-60]. There are then formulas in Brignole et al [8] for the soft terms (cf. eq. (2) above) in terms of $\mathcal{L}_{\text{eff}}$:

$$\mathcal{L}_{\text{susy}},\ \text{, i.e. } W, K, f \quad \rightarrow \quad \mathcal{L}_{\text{soft}} \tag{5}$$

Just to emphasize this point: you can calculate $\mathcal{L}_{\text{soft}}$ from the *supersymmetric* Lagrangian $\mathcal{L}_{\text{susy}}$! This is because supersymmetry breaking is spontaneous, so the vacuum structure is completely determined by the supersymmetric theory. This is true already in the O'Raifertaigh model. Even though after supersymmetry breaking the masses of superpartners are split by $\Delta m = m_\phi - m_\psi$, there are still relations between the masses, e.g. [2, eq.(6.13)].

[8] Here E is the energy scale at which we probe the effective theory. We need to consider the combination $E^2\alpha'$ since α' itself is not a true expansion parameter; it is dimensionful.

4 LHC counting signatures

Once we have $\mathcal{L}_{\text{eff}}$ at the TeV scale, it is an "exercise" in particle physics to get observables at colliders. You may at this point nurture a healthy skepticism about whether $\mathcal{L}_{\text{eff}}$ can be reliably computed directly from string theory, but assuming we have done so, there can be no skepticism that particle physicists are very good at getting from there to making predictions.

4.1 The procedure

I will not be able to explain in detail how to make such predictions, but I claim it is useful (and fun!) for even die-hard theorists to have some idea of what is done in what one could call "real physics". Consider this flowchart:

	event generator software,		detector simulator software,	
spectrum,	e.g. PYTHIA		e.g. PGS	
$\mathcal{L}_{\text{eff}}$ (TeV)	$\longrightarrow$	events	$\longrightarrow$	detector events

Software packages like PYTHIA and PGS are now so well developed and user friendly that at least for initial analyses, you can run them on your laptop. So now given $\mathcal{L}_{\text{eff}}$ we can make predictions, but the real problem is to analyze data. So although the above procedure will be useful, we would ultimately like to solve the "LHC inverse problem" [9]

$$\text{detector events} \quad \overset{?}{\longrightarrow} \quad \begin{array}{c}\text{spectrum,}\\ \mathcal{L}_{\text{eff}}\ \text{(TeV)}\end{array}$$

One reason we're spending time on this is to appreciate that the inverse problem is not completely solvable. At hadron colliders, there is only partial information available, *even if* the real world is well described by some effective theory that looks just like the MSSM.

For example, one effect at the LHC of having the MSSM at the TeV scale is that we should see "cascade decay chains", where initially a pair of squarks $\tilde{q}\tilde{q}$ or gluinos $\tilde{g}\tilde{g}$ is created, and depending on the ordering of the spectrum in mass, a chain of decays follows until we get to the LSP (here assumed to be $\tilde{N}_1$), which is stable by R-parity conservation and will escape the detector undetected. Here's an example [16] (draw the diagram!):

$$\tilde{q} \;\rightarrow\; \tilde{N}_2 + q \;\rightarrow\; (\tilde{N}_1 + \ell^+ + \ell^-) + q \tag{6}$$

There are two fairly obvious implications of this for the inverse problem: we never get to measure the cross section for neutralino production directly, and we don't get to reconstruct the momentum of the neutralino to even know the complete kinematics of the "hard" original $\tilde{q}$ process that started the decay chain (6). In other words, there will be no "bump hunting" where you just look for a bump in some observable and that's the mass of your new superpartner.

One alternative is so-called "counting signatures", which is just what it sounds like, some signature of some feature of the spectrum and $\mathcal{L}_{\text{eff}}$ that causes some particular type of event to happen with increased or decreased efficiency, so you count the number of that kind of event, and try to correlate it with some broad feature of the underlying theory. There are two broad possibilities:

plot of	$\longrightarrow$ no correlation
signature S_1 versus	
signature S_2	$\longrightarrow$ some correlation

This is clearly a trial and error procedure, and in [9], they list 1808 signatures S_i that can be used for this purpose. Fortunately, some people have intuition for which observables might be sensitive to what feature of $\mathcal{L}_{\text{eff}}$, so it's more like a *educated guess* trial and error, as in Kane et al [10], where there are many nice plots that clearly show some correlation. Two examples of useful signatures are

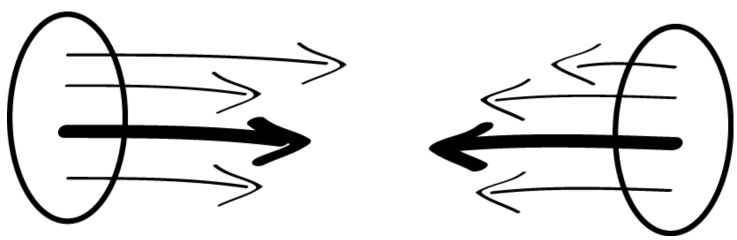
- number of b-jets
- lepton charge asymmetry $(N_{\ell^+} - N_{\ell^-})/(N_{\ell^+} + N_{\ell^-})$

Note immediately that the analysis in Kane et al is quite optimistic; the plots in [10] show a large amount of events beyond the standard model, which is the black box in the bottom left corner. But this is what we have to assume if we are to discover anything really new; if all we find at the LHC is the standard model, clearly everything in these lectures will be redundant. At least for the LHC.

4.2 Collider physics

The previous section hopefully gave you some flavor of what people do to get LHC observables from an $\mathcal{L}_{\text{eff}}$ at the TeV scale, but you probably have some particle physics questions at this point, like what the two example signatures mean, or how these "cascade decay chains" really work. The best way to deal with this is to go read Peskin and Schroeder Ch. 17 and 18, and read all its references about collider physics in turn. To motivate you to at least want to do this in the future, here are a few remarks about collider physics.

The LHC is a proton-proton collider. Surprisingly few string theorists (and I don't just mean graduate students) seem to be aware of this first fact about the biggest particle physics experiment ever built. People who prefer e.g. e^+e^- colliders sometimes call hadron (e.g. proton-proton) colliders "throwing trash cans at each other to see what comes out". This is because of the following picture of a proton-proton collision:



The momenta of the protons (thick arrows) are dictated by the people controlling the beam, but the momenta of the individual "partons" (the thin arrows, that's quarks and gluons) are not known. Also the longitudinal momentum is in general difficult to use at hadron colliders; only transverse momentum p_{T} kinematics is used. (See e.g. [1, p.476])

There are more problems: perturbative QCD only makes sense for small values of the QCD fine structure constant α_{s}, which by asymptotic freedom is small at high energy, high momentum transfer (called "hard" processes). Low-energy ("soft") processes are inherently nonperturbative in α_{s} and are modelled by so-called Parton Distribution Functions (PDFs!). In interesting events, such as the aforementioned "cascade decay chains", one can hope to separate the calculation into a "hard" perturbative QCD calculation, and a "soft" process, which has to be modelled phenomenologically. Equation (17.40) in P & S gives you some impression of how this is done for two protons at momentum P_1 and P_2 going to some hadronic final state:

$$\begin{aligned}
&\sigma(p(P_1) + p(P_2) \to Y + X) \\
&\quad = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2)\, \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to Y)
\end{aligned} \tag{7}$$

I will not even define everything in this equation, but notice that the perturbative quark cross section σ on the right is *convolved* with the PDFs $f_f(x_1)$ and $f_{\bar{f}}(x_2)$ to get the proton cross section σ on the left, so some of the detailed perturbative information will get "lost" in the convolution.[9]

[9] We theorists usually protest that nothing gets "lost" in a convolution; if you Fourier transform, for example, you get another function with just as much information, and you can invert the integral transform. Experimentalists, however, care about error bars, and since the PDFs themselves are extracted from experiment, there is great uncertainty if we wanted to extract details about the hard cross section on the right from measuring the cross section on the left.

So how are the PDFs extracted from experiment, what do they look like, and what do they mean? They are extracted from "deep inelastic scattering" experiments (that you might have heard about), they look like figure 17.6 in P & S, and they tell you what is "in the proton". To understand in detail what happens when you collide protons, it seems reasonable that you need to know what's in the proton.

Looking at figure 17.6, you first reaction might be skepticism; you know that the proton consists of two u-quarks and one d-quark. That is reflected in

$$\int_0^1 dx\,(f_u(x) - f_{\bar{u}}(x)) = 2 \quad , \quad \int_0^1 dx\,(f_d(x) - f_{\bar{d}}(x)) = 1 \; . \tag{8}$$

You might be prepared to accept that apart from u, u and d, the proton also contains gluons, and even that at some values of the momentum transfer, *most* of the proton is gluon. But what's this business about $\bar{u}$ and s quarks in fig. 17.6? That's part of the issue here: since in an strong color field we can create quark-antiquark pairs, the proton at given energy and momentum may contain some amount of e.g. $s-\bar{s}$ pairs! The "*uud*" configuration describes the "valence quarks", but deep in the proton, things are more complicated.

When you have a complicated physical situation, it is useful to step back and ask what is really observed. When a quark or gluon has a "hard" interaction, it is manifested in the detector as a *jet*, a shower of hadrons that is well *collimated*, i.e. it looks like a "broom" that points in some direction, rather than just a "cloud". From the jet direction (that will of course be some collective, approximate quantity) one can try to reconstruct the kinematics of the process that created the jet. In this way, jets are the only way we "see" individual quarks and gluons. In QCD, as you probably know, particles with color charge are never seen by themselves.

The cross sections are then passed to a Monte Carlo "event generator" such as the Lund product PYTHIA, whose job is among other things to take the quarks and gluons and make hadrons that then form the jets. One of the ingredients in this, a string theorist might be interested to know, is a phenomenological model for *string fragmentation*, i.e. the creation of more hadrons by stretching some quark-antiquark pair far enough from each other that another pair is created in the color field in between. The resulting collection of hadrons then makes up a jet, which can be compared to the real jet in the detector.

A typical susy event (see e.g. [12], [2]) has missing transverse energy, denoted $\not{E}_T$, some number of energetic jets (e.g. 0, 2 or more), and possibly some leptons in various charge and flavor combinations ("no lepton", "dilepton" or "trilepton" events – why not just one lepton?) from the cascade decay chain. We can measure the momentum of the leptons well, and this gives some measure of the mass difference of e.g. $\tilde{N}_1$ and $\tilde{N}_2$ in the decay chain (6).

When picking signatures to study, it is obviously useful if your signature has low standard model background. As it turns out, there is no way in the SM to get "prompt" (i.e. immediately formed) same-sign leptons[10], so that is one way to reduce background that is so popular that the signature received its own acronym, e.g. SSDF for "same sign different flavor" dilepton events.

I close this section with a few challenges in the present state of LHC collider physics that you might be interested to learn more about (for references, see Peskin's web page! [16] The 3-lecture series from 2007 is quite readable even without narrative.)

- PYTHIA: standard version contains 2→2 events only. This is probably not sufficient at high p_{T}. Also, could the Lund string fragmentation model need corrections at the new energy scale?
- Detector event analysis: $\sim 1\%$ of leptons escape detector through "cracks" (this doesn't mean the detector is broken, but that you need to leave room for cables and such). This is actually simulated in PGS, amongst many other similar practical things. How much of a difference does this make?

[10] There *can* be non-prompt same sign dilepton events in the SM, but then they arise by some subsidiary process, so those diagrams will have more factors of coupling constants. These kinds of statements take some effort to verify, but ask a phenomenologist! Asking is also a good way to find loopholes in statements of this kind, e.g. if we see a large number of SS dilepton events with the requisite jets and missing $\not{E}_T$, that should then be beyond the SM physics, but is it really special to supersymmetry?

- jet reconstruction: if you have a mess of 10 jets, can you really separate them?
- "tagging": some jets are tagged as "b-jets", because they are reconstructed to have been created by a heavy quark (there are no hadrons made of t quarks, as they decay faster than they can hadronize). Were they really created by a b quark or not ("mis-tagging" by $\sim 1\%$)?

References

[1] M. E. Peskin and D. V. Schroeder, "An Introduction To Quantum Field Theory," *Reading, USA: Addison-Wesley (1995) 842 p*

[2] S. P. Martin, "A supersymmetry primer," arXiv:hep-ph/9709356.

[3] D. J. H. Chung, L. L. Everett, G. L. Kane, S. F. King, J. D. Lykken and L. T. Wang, "The soft supersymmetry-breaking Lagrangian: Theory and applications," Phys. Rept. **407** (2005) 1 [arXiv:hep-ph/0312378].

[4] S. Weinberg, "The quantum theory of fields. Vol. 3: Supersymmetry," *Cambridge, UK: Univ. Pr. (2000) 419 p*

[5] J. Wess and J. Bagger, "Supersymmetry and supergravity," *Princeton, USA: Univ. Pr. (1992) 259 p*

[6] P. Candelas, X. de la Ossa, Y. H. He and B. Szendroi, "Triadophilia: A Special Corner in the Landscape," arXiv:0706.3134 [hep-th].

[7] M. E. Peskin, "Dark Matter and Particle Physics," J. Phys. Soc. Jap. **76**, 111017 (2007) [arXiv:0707.1536 [hep-ph]].

[8] A. Brignole, L. E. Ibanez and C. Munoz, "Soft supersymmetry-breaking terms from supergravity and superstring models," arXiv:hep-ph/9707209.

[9] N. Arkani-Hamed, G. L. Kane, J. Thaler and L. T. Wang, "Supersymmetry and the LHC inverse problem," JHEP **0608** (2006) 070 [arXiv:hep-ph/0512190].

[10] G. L. Kane, P. Kumar and J. Shao, "Unravelling Strings at the LHC," arXiv:0709.4259 [hep-ph].

[11] P. Gondolo, J. Edsjo, P. Ullio, L. Bergstrom, M. Schelke and E. A. Baltz, "DarkSUSY: Computing supersymmetric dark matter properties numerically," JCAP **0407** (2004) 008 [arXiv:astro-ph/0406204].

[12] H. E. Haber, "Low-energy supersymmetry and its phenomenology," Nucl. Phys. Proc. Suppl. **101** (2001) 217 [arXiv:hep-ph/0103095].

[13] V. Braun, Y. H. He, B. A. Ovrut and T. Pantev, "The exact MSSM spectrum from string theory," JHEP **0605** (2006) 043 [arXiv:hep-th/0512177].

[14] M. Cvetic, G. Shiu and A. M. Uranga, "Chiral four-dimensional N = 1 supersymmetric type IIA orientifolds from intersecting D6-branes," Nucl. Phys. B **615**, 3 (2001) [arXiv:hep-th/0107166].

[15] B. C. Allanach, "SOFTSUSY: A C++ program for calculating supersymmetric spectra," Comput. Phys. Commun. **143**, 305 (2002) [arXiv:hep-ph/0104145].

[16] `http://www.slac.stanford.edu/~mpeskin/peskin.html`