1 Supersymmetry: a bird eyes view

Why a PhD student interested in theoretical particle physics should ever follow a course on Supersymmetry? At least for two reasons.

It is more than ten years ago that at CERN Large Hadron Collider (LHC) the missing building block of the Standard Model, the Higgs particle, has been discovered. This has been an impressive achievement, one of the greatest success of the way we think Nature works at short distances and of the tool we use to describe it, quantum field theory. On the other hand, there exist many reasons which suggest that this cannot be the end of the story and new physics should show-up at energy scales higher than those we have been able to have access to at LHC, so far. It so happen that the most compelling scenario for physics beyond the Standard Model (BSM) is supersymmetry. So, when it comes to try and understand how particles behave at high energy, equivalently, at shorter and shorter distance, supersymmetry is a piece of basic knowledge any particle physicist should have. In fact, understanding how supersymmetry can be realized (and then spontaneously broken) in Nature, is one of the most important challenges theoretical high energy physics has to confront with.

One other thing we, theoretical physicists, want to understand is the behavior of quantum field theories at strong coupling. This is a regime where usual perturbative techniques fail and we lack analytical tools. But many phenomena we observe in Nature are described by the behavior of quantum field theories in such a regime, the most notable example being the way phenomena like confinement, dynamical mass generation and chiral symmetry breaking are realized in Nature. One spectacular property of supersymmetry is that it makes these phenomena more accessible: supersymmetric quantum field theories turn out to have a much more constrained dynamics with respect to non-supersymmetric ones, so constrained that it is often possible to understand their strong coupling regime analytically. In this regard, supersymmetry is seen and is being used as a theoretical laboratory to study quantum field theories at strong coupling and get some intuition on how phenomena like confinement, dynamical mass generation and chiral symmetry breaking are realized in non-supersymmetric field theories (as QCD is). Remarkably, several ideas that have been proposed to account for such phenomena and which could only be conjectural as far as ordinary quantum field theory, have been analytically proven in the supersymmetric context, notable examples being that confinement is due to monopole condensation, or that at strong coupling fermion bilinears condense.
What I have outlined above should be enough to motivate you following this long course, but this is not all in fact. Supersymmetry turns out to be relevant also outside the realm of particle physics, like in some condensed matter systems, and it has also be at the core of what is probably the more amazing and far-reaching discovery in theoretical physics in the last decades, namely the celebrated AdS/CFT correspondence. Finally, an even more profound role supersymmetry is believed to play in the dynamics and ultimate structure of space-time, in the way gravity behaves at very high energy, as high as the Planck scale, via string theory. The latter is the more successful framework to describe all interactions, including gravity, in a way consistent with quantum mechanics and it is inherently supersymmetric.

We will not be able to discuss any of these things, in this course. Our aim will just be to provide the minimal bases you need to enter such fascinating subject.

In this first lecture I will give a brief overview on what is supersymmetry and why is it interesting to study it. The rest of the course will try to provide (much) more detailed answers to these two basic questions. I hope you will enjoy the journey!

### 1.1 What is supersymmetry?

Supersymmetry (SUSY) is a space-time symmetry mapping particles and fields of integer spin (bosons) into particles and fields of half integer spin (fermions), and vice versa. The generators $Q$ act as

$$Q |\text{Fermion}\rangle = |\text{Boson}\rangle$$

and vice versa (1.1)

From its very definition, this operator has two obvious but far-reaching properties that can be summarized as follows:

- It changes the spin of a particle (meaning that $Q$ transforms as a spin-1/2 particle) and hence its space-time properties. This is why supersymmetry is not an internal symmetry but a space-time symmetry.

- In a theory where supersymmetry is realized, each one-particle state has at least a superpartner. Therefore, in a SUSY world, instead of single particle states, one has to deal with (super)multiplets of particle states.

Supersymmetry generators have specific commutation properties with other generators. In particular:
- $Q$ commutes with translations and internal quantum numbers (e.g. gauge and global symmetries), but it does not commute with Lorentz generators

$$[Q, P_\mu] = 0 \quad , \quad [Q, G] = 0 \quad , \quad [Q, M_{\mu\nu}] \neq 0 .$$  \hspace{1cm} (1.2)

This implies that particles belonging to the same supermultiplet have different spin but same mass and same quantum numbers.

A supersymmetric field theory is a set of fields and a Lagrangian which exhibit such a symmetry. As ordinary field theories, supersymmetric theories describe particles and interactions between them: SUSY manifests itself in the specific particle spectrum a theory enjoys, and in the way particles interact between themselves.

A supersymmetric model which is covariant under general coordinate transformations is called supergravity (SUGRA) model. In this respect, a non-trivial fact, which again comes from the algebra, in particular from the (anti)commutation relation

$$\{Q, \bar{Q}\} \sim P_\mu ,$$  \hspace{1cm} (1.3)

is that having general coordinate transformations is equivalent to have local SUSY, the gauge mediator being a spin $3/2$ particle, the gravitino. Hence local supersymmetry and General Relativity are intimately tied together.

One can have theories with different number of SUSY generators $Q$: $Q^I \quad I = 1, \ldots, N$. The number of supersymmetry generators, however, cannot be arbitrarily large. The reason is that any supermultiplet contains particles with spin at least as large as $\frac{1}{2}N$. Therefore, $N$ can be at most as large as 4 for theories with maximal spin 1 (gauge theories) and as large as 8 for theories with maximal spin 2 (gravity). Thus stated, this statement is true in 4 space-time dimensions. Equivalent statements can be made in higher/lower dimensions, where the dimension of the spinor representation of the Lorentz group is larger/smaller (for instance, in 10 dimensions, which is the natural dimension where superstring theory lives, the maximum allowed $N$ is 2). What really matters is the number of single state supersymmetry generators, which is a dimension-independent statement.

Finally, notice that since supersymmetric theories automatically accomodate both bosons and fermions, SUSY looks like the most natural framework where to formulate a theory able to describe matter and interactions in a unified way.
1.2 What is supersymmetry useful for?

Let us briefly outline a number of reasons why it might be meaningful (and useful) to have such a bizarre and unconventional symmetry actually realized in Nature.

i. Theoretical reasons.

- What are the more general allowed symmetries of the S-matrix? In 1967 Coleman and Mandula proved a theorem which says that in a generic quantum field theory, under a number of (very reasonable and physical) assumptions, like locality, causality, positivity of energy, finiteness of number of particles, etc..., the only possible continuous symmetries of the S-matrix are those generated by Poincaré group generators, $P_{\mu}$ and $M_{\mu\nu}$, plus some internal symmetry group $G$ (where $G$ is a semi-simple group times abelian factors) commuting with them

$$[G, P_{\mu}] = [G, M_{\mu\nu}] = 0 .$$

(1.4)

In other words, the most general symmetry group enjoyed by the S-matrix is Poincaré × Internal Symmetries

The Coleman-Mandula theorem can be evaded by weakening one or more of its assumptions. One such assumptions is that the symmetry algebra only involves commutators, all generators being bosonic generators. This assumption does not have any particular physical reason not to be relaxed. Allowing for fermionic generators, which satisfy anti-commutation relations, it turns out that the set of allowed symmetries can be enlarged. More specifically, in 1975 Haag, Lopuszanski and Sohnius showed that supersymmetry (which, as we will see, is a very specific way to add fermionic generators to a symmetry algebra) is the only possible such option. This makes the Poincaré group becoming SuperPoincaré. Therefore, the most general symmetry group the S-matrix can enjoy turns out to be

SuperPoincaré × Internal Symmetries

From a purely theoretical viewpoint, one could then well expect that Nature might have realized all possible kind of allowed symmetries, given that we already know this is indeed the case (cf. the Standard Model) for all known symmetries, but supersymmetry.
The history of our understanding of physical laws is an history of unification. A famous example is Newton’s law of universal gravitation, which says that one and the same equation describes the attraction a planet exert on another planet and on... an apple! Maxwell equations unify electromagnetism with special relativity. Quantumelectrodynamics unifies electrodynamics with quantum mechanics. And so on and so forth, till the formulation of the Standard Model which describes in an unified way all known non-gravitational interactions. Supersymmetry (and its local version, supergravity), is the most natural candidate to complete this long journey. It is a way not just to describe in a unified way all known interactions, but in fact to describe matter and radiation all together. This sounds compelling, and from this view point it sounds natural studying supersymmetry and its consequences.

Finally, I cannot resist to add one more reason as to why one could expect that supersymmetry is out there, after all. Supersymmetry is possibly one of the two more definite predictions of String Theory, the other being the existence of extra-dimensions.

Note: all above arguments suggest that supersymmetry maybe realized as a symmetry in Nature. However, none of such arguments gives any obvious indication on the energy scale supersymmetry might show-up. This can be very high, in fact. Below, we will present a few more arguments, more phenomenological in nature, which deal, instead, with such an issue and actually suggest that low energy supersymmetry (as low as TeV scale or slightly higher) would be the preferred option.

ii. Elementary Particle theory point of view.

Naturalness and the hierarchy problem. Three out of four of the fundamental interactions among elementary particles (strong, weak and electromagnetic) are described by the Standard Model (SM). The typical scale of the SM, the electroweak scale, is

\[ M_{ew} \sim 250 \text{ GeV} \Leftrightarrow L_{ew} \sim 10^{-16} \text{ mm} \]

(1.5)

The SM is very well tested up to such energies. This cannot be the end of the story, though: for one thing, at high enough energies, as high as the Planck scale \( M_{pl} \), gravity becomes comparable with other forces and cannot be neglected in elementary particle interactions. At some point, we need a
quantum theory of gravity. Actually, the fact that $M_{ew}/M_{pl} << 1$ calls for new physics at a much lower scale. One way to see this, is as follows. The Higgs potential reads

$$V(H) \sim \mu^2 |H|^2 + \lambda |H|^4$$

where $\mu^2 < 0$. (1.6)

Experimentally, the minimum of such potential, $\langle H \rangle = \sqrt{-\mu^2/2\lambda}$, is at around 174 GeV. This implies that the bare mass of the Higgs particle is roughly around 100 GeV or so, $m_{H}^2 = -\mu^2 \sim (100 \text{GeV})^2$. What about radiative corrections? Scalar masses are subject to quadratic divergences in perturbation theory. The SM fermion coupling $-\lambda_f H \bar{f} f$ induces a one-loop correction to the Higgs mass as

$$\Delta m_f^2 \sim -2 \lambda_f^2 \Lambda^2$$

due to the diagram in Figure 1.1. The UV cut-off $\Lambda$ should then be naturally

around the TeV scale in order to protect the Higgs mass, and the SM should then be seen as an effective theory valid at $E < M_{eff} \sim \text{TeV}$.

What can be the new physics beyond such scale and how can such new physics protect the otherwise perturbative divergent Higgs mass? New physics, if any, may include many new fermionic and bosonic fields, possibly coupling to the SM Higgs. Each of these fields will give radiative contribution to the Higgs mass of the kind above, hence, no matter what new physics will show-up at high energy, the natural mass for the the Higgs field would always be of order the UV cut-off of the theory, generically around $\sim M_{pl}$. We would need a huge fine-tuning to get it stabilized at $\sim 100 \text{GeV}$ (we now know that the physical Higgs mass is at 125 GeV, in fact)! This is known as the hierarchy problem: the experimental value of the Higgs mass is unnaturally smaller than its natural theoretical value.

In principle, there is a very simple way out of this. This resides in the fact that (as you should know from your QFT course!) scalar couplings provide one-loop

Figure 1.1: One-loop radiative correction to the Higgs mass due to fermion couplings.
radiative contributions which are opposite in sign with respect to fermions. Suppose there exist some new scalar, $S$, with Higgs coupling $-\lambda_S |H|^2 |S|^2$. Such coupling would also induce corrections to the Higgs mass via the one-loop diagram in Figure 1.2.

![Figure 1.2: One-loop radiative correction to the Higgs mass due to scalar couplings.](Image)

Such corrections would have **opposite** sign with respect to those coming from fermion couplings

$$\Delta m_H^2 \sim \lambda_S \Lambda^2 . \quad (1.8)$$

Therefore, if the new physics is such that each quark and lepton of the SM were accompanied by two complex scalars having the same Higgs couplings of the quark and lepton, i.e. $\lambda_S = |\lambda_f|^2$, then all $\Lambda^2$ contributions would automatically cancel, and the Higgs mass would be stabilized at its tree level value! Such conspiracy, however, would be quite ad hoc, and not really solving the fine-tuning problem mentioned above; rather, just rephrasing it. A natural thing to invoke to have such magic cancellations would be to have a symmetry protecting $m_H$, right in the same way as gauge symmetry protects the masslessness of spin-1 particles. A symmetry imposing to the theory the correct matter content (and couplings) for such cancellations to occur. This is exactly what supersymmetry is: in a supersymmetric theory there are fermions and bosons (and couplings) just in the right way to provide **exact** cancellation between diagrams like the ones above. In summary, supersymmetry is a very natural and economic way (though not the only possible one) to solve the hierarchy problem.

Known fermions and bosons cannot be partners of each other. For one thing, we do not observe any degeneracy in mass in elementary particles that we know. Moreover, and this is possibly a stronger reason, quantum numbers do not match: gauge bosons transform in the adjoint reps of the SM gauge group while quarks and leptons in the fundamental or singlet reps. Hence, in a supersymmetric world, each SM particle should have a (yet not observed!)
supersymmetric partner, usually dubbed *sparticle*. Roughly, the spectrum should be as follows

<table>
<thead>
<tr>
<th>SM particles</th>
<th>SUSY partners</th>
</tr>
</thead>
<tbody>
<tr>
<td>gauge bosons</td>
<td>gauginos</td>
</tr>
<tr>
<td>quarks, leptons</td>
<td>scalars</td>
</tr>
<tr>
<td>Higgs</td>
<td>higgsino</td>
</tr>
</tbody>
</table>

Notice: the (down) Higgs has the same quantum numbers as the scalar partner of neutrino and leptons, sneutrino and sleptons respectively, \((H_0^d, H_d^-) \leftrightarrow (\tilde{\nu}, \tilde{e}_L)\). Hence, one can imagine that the Higgs is in fact a sparticle. This cannot be. In such scenario, there would be phenomenological problems, e.g. lepton number violation and (at least one) neutrino mass in gross violation of experimental bounds.

In summary, the world we already had direct experimental access to, is not supersymmetric. If at all realized, supersymmetry should be a (spontaneously) broken symmetry in the vacuum state chosen by Nature. However, in order to solve the hierarchy problem without fine-tuning this scale should be lower than (or about) 1 TeV. Including lower bounds from present day experiments, it turns out that the SUSY breaking scale should be in the following energy range

\[
100 \text{ GeV} \leq \text{SUSY breaking scale} \leq 1000 \text{ GeV}.
\]

This is the basic reason why it is believed SUSY to show-up at the LHC.

Let us notice that these bounds are just a crude and rough estimate, as they depend very much on the specific SSM one is actually considering. In particular, the upper bound can be made higher by enriching the structure of the SSM in various ways, as well as defining the concept of naturalness in a less restricted way. There are ongoing discussions on these aspects nowadays, including the idea that naturalness should not be taken as a such important guiding principle, at least in this context.

- *Gauge coupling unification*. There is another reason to believe in supersymmetry; possibly stronger, from a phenomenological point of view, then that provided by the hierarchy problem. Forget about supersymmetry for a while, and consider the SM as it stands. Interesting enough, besides the EW scale,
the SM contains in itself a new scale of order $10^{15}$ GeV. The three SM gauge couplings run according to RG equations like

$$\frac{4\pi}{g_i^2(\mu)} = \frac{b_i}{2\pi} \ln \frac{\mu}{\Lambda_i} \quad i = 1, 2, 3.$$  

(1.9)

At the EW scale, $\mu = M_Z$, there is a hierarchy between them, $g_1(M_Z) < g_2(M_Z) < g_3(M_Z)$. But RG equations make this hierarchy changing with the energy scale. In fact, supposing there are no particles other than the SM ones, at a much higher scale, $M_{GUT} \sim 10^{15}$ GeV, the three couplings tend to meet! This naturally calls for a Grand Unified Theory (GUT), where the three interactions are unified in a single one, two possible GUT gauge groups being $SU(5)$ and $SO(10)$. The symmetry breaking pattern one should have in mind would then be as follows

$$SU(5) \rightarrow SU(3) \times SU(2)_L \times U(1)_Y \rightarrow SU(3) \times U(1)_{em}$$

where $H$ is an heavy Higgs inducing spontaneous symmetry breaking at energies $M_{GUT} \sim 10^{15}$ GeV, and $H$ the SM light Higgs, inducing EW spontaneous symmetry breaking around the TeV scale. This idea poses several problems. First, there is a new hierarchy problem (generically, the SM Higgs mass is expected to get corrections from the heavy Higgs $\phi$). Second, there is a proton decay problem: some of the additional gauge bosons mediate baryon number violating transitions, allowing processes as $p \rightarrow e^+ + \pi_0$. This makes the proton not fully stable and it turns out that its expected lifetime in such GUT framework is violated by present experimental bounds. On a more theoretical side, if we do not allow for new particles besides the SM ones to be there at some intermediate scale, the three gauge couplings only approximately meet and it turns out that this cannot be taken care of just by the experimental uncertainties. The latter is an unpleasant feature: small numbers are unnatural from a theoretical view point, unless there are specific reasons (as symmetries) justifying their otherwise unnatural smallness.

Remarkably, making the GUT supersymmetric (SGUT) solves all of these problems in a glance! If one just allows for the minimal supersymmetric extension of the SM spectrum, known as MSSM, the three gauge couplings do meet (more precisely, they miss but now well within experimental uncertainties),
and the GUT scale is raised enough to let proton decay rate being compatible with present experimental bounds.

Disclaimer: the MSSM is not the only possible option for supersymmetry beyond the SM, just the most economic one. In the MSSM one just adds a superpartner to each SM particle, therefore introducing the higgsino, the wino, the zino, together with all squarks and sleptons, and no more. [There is in fact an exception. To have a meaningful model one has to double the Higgs sector, and have two Higgs doublets. One reason for that is gauge anomaly cancellation: the higgsinos are fermions in the fundamental rep of SU(2)\textsubscript{L} hence two of them are needed, with opposite hypercharge, not to spoil the anomaly-free properties of the SM. A second reason is that in the SM the field \( H \) gives mass to down quarks and charged leptons while its charge conjugate, \( H^c (\sim \tilde{H}) \) gives mass to up quarks. As we will see, in a SUSY model \( \tilde{H} \) cannot enter in the potential, which is a function of \( H \), only. Therefore, in a supersymmetric scenario, to give mass to up quarks one needs a second, independent Higgs doublet.] There exist many non-minimal supersymmetric extensions of the Standard Model (which, in fact, are in better shape against experimental constraints with respect to the MSSM). One can in principle construct any SSM one likes. In doing so, however, several constraints are to be taken into account. For example, it is not so easy to make such non-minimal extensions keeping the nice exact gauge coupling unification enjoyed by the MSSM.

The important lesson we get out of all this discussion can be summarized as follows: in a SUSY quantum field theory radiative corrections are suppressed. Quan-
tities that are small (or vanishing) at tree level tend to remain so at quantum level. This is at the basis of the solutions of all problems we mentioned: the hierarchy problem, the proton life-time, and gauge couplings unification.

iii. Supersymmetry and Cosmology.

- Let me briefly mention yet another context where supersymmetry might play an important role. There are various evidences which indicate that around 26% of the energy density in the Universe should be made of dark matter, i.e. non-luminous and non-baryonic matter. The only SM candidates for dark matter are neutrinos, but they are disfavored by available experimental data. Supersymmetry provides a valuable and very natural dark matter candidate: the neutralino. Neutralinos are mass eigenstates of a linear superposition of the SUSY partners of the neutral Higgs and of the SU(2) and U(1) neutral gauge bosons

\[ \chi_i = \alpha_{i1}\tilde{B}^0 + \alpha_{i2}\tilde{W}^0 + \alpha_{i3}\tilde{H}^0_u + \alpha_{i4}\tilde{H}^0_d. \]  

Interestingly, in most SUSY frameworks the neutralino is the lightest supersymmetric particle (LSP), and fully stable, as a dark matter candidate should be.

iv. Supersymmetry as a theoretical laboratory for strongly coupled gauge dynamics.

- What if supersymmetry will turn out not to be the correct theory to describe (low energy) beyond the SM physics? Or, worse, what if supersymmetry will turn out not to be realized at all, in Nature (something we could hardly ever being able to prove, in fact)? Interestingly, there is yet another reason which makes it worth studying supersymmetric theories, independently from the role supersymmetry might or might not play as a theory describing high energy physics.

Let us consider non-abelian gauge theories, which strong interactions are an example of. Every time a non-abelian gauge group remains unbroken at low energy, we have to deal with strong coupling. The typical questions one should try and answer (in QCD or similar theories) are:

- The bare Lagrangian is described in terms of quark and gluons, which are UV degrees of freedom. Which are the IR (light) degrees of freedom
of QCD? What is the effective Lagrangian in terms of such degrees of freedom?

- Strong coupling physics is very rich. Typically, one has to deal with phenomena like confinement, charge screening, the generation of a mass gap, etc... Is there any theoretical understanding of such phenomena?

- The QCD vacuum is populated by vacuum condensates of fermion bilinears, $\langle \Omega | \bar{\psi} \psi | \Omega \rangle \neq 0$, which induce chiral symmetry breaking. What is the microscopic mechanism behind this phenomenon?

Most of the IR properties of QCD have eluded so far a clear understanding, since we lack analytical tools to deal with strong coupling dynamics. Most results come from lattice computations, but these do not furnish a theoretical, first principle understanding of the above phenomena. Moreover, they are formulated in Euclidean space and are not suited to discuss, e.g. transport properties.

Because of their nice renormalization properties, supersymmetric theories are more constrained than ordinary field theories and let one have a better control on strong coupling regimes, sometime. Therefore, one might hope to use them as toy models where to study properties of more realistic theories, such as QCD, in a more controlled way. Indeed, as we shall see, supersymmetric theories do provide examples where some of the above strong coupling effects can be studied exactly! This is possible due to powerful non-renormalizations theorems supersymmetric theories enjoy, and because of a very special property of supersymmetry, known as holomorphy, which in certain circumstances lets one compute several non-perturbative contributions to the Lagrangian. We will spend a sizeable amount of time discussing these issues in the second part of this course.

This is all we wanted to say in this short introduction, that should be regarded just as an invitation to supersymmetry and its fascinating world. Let us end by just adding a curious historical remark. Supersymmetry did not first appear in ordinary four-dimensional quantum field theories but in string theory, at the very beginning of the seventies. Only later it was shown to be possible to have supersymmetry in ordinary quantum field theories.
1.3 Some useful references

The list of references in the literature is endless. I list below few of them, including books as well as some archive-available reviews. Some of these references may be better than others, depending on the specific topic one is interested in (and on personal taste). In preparing these lectures I have used most of them, some more, some less. At the end of each lecture I list those references (mentioning corresponding chapters and/or pages) which have been used to prepare it. This will let students having access to the original font, and me give proper credit to authors.

1. Historical references

- J. Wess and J. Bagger
  *Supersymmetry and supergravity*

- P. C. West
  *Introduction to supersymmetry and supergravity*

- M. F. Sohnius
  *Introducing Supersymmetry*

2. More recent books

- S. Weinberg
  *The quantum theory of fields. Vol. 3: Supersymmetry*

- J. Terning
  *Modern supersymmetry: Dynamics and duality*

- M. Dine
  *Supersymmetry and string theory: Beyond the standard model*

- H.J. Müller-Kirsten and A. Wiedemann
  *Introduction to Supersymmetry*
3. On-line reviews: bases

- J. D. Lykken
  *Introduction to Supersymmetry*
  arXiv:hep-th/9612114

- S. P. Martin
  *A Supersymmetry Primer*

- A. Bilal
  *Introduction to supersymmetry*
  arXiv:hep-th/0101055

- J. Figueroa-O’Farrill
  *BUSSTEPP Lectures on Supersymmetry*
  arXiv:hep-th/0109172

- M. J. Strassler
  *An Unorthodox Introduction to Supersymmetric Gauge Theory*
  arXiv:hep-th/0309149

- R. Argurio, G. Ferretti and R. Heise
  *An introduction to supersymmetric gauge theories and matrix models*

4. On-line reviews: advanced topics

- K. A. Intriligator and N. Seiberg
  *Lectures on supersymmetric gauge theories and electric-magnetic duality*

- A. Bilal
  *Duality in N=2 SUSY SU(2) Yang-Mills Theory: A pedagogical introduction to the work of Seiberg and Witten*
  arXiv:hep-th/9601007

- M. E. Peskin
  *Duality in Supersymmetric Yang-Mills Theory*
  arXiv:hep-th/9702094

- M. Shifman
  *Non-Perturbative Dynamics in Supersymmetric Gauge Theories*
• P. Di Vecchia  
  *Duality in supersymmetric \( N = 2, 4 \) gauge theories*  
arXiv:hep-th/9803026

• M. J. Strassler  
  *The Duality Cascade*  
arXiv:hep-th/0505153

• P. Argyres  
  *Lectures on Supersymmetry*  

5. **On-line reviews: supersymmetry breaking**

• G. F. Giudice and R. Rattazzi  
  *Theories with Gauge-Mediated Supersymmetry Breaking*  

• E. Poppitz and S. P. Trivedi  
  *Dynamical Supersymmetry Breaking*  

• Y. Shadmi and Y. Shirman  
  *Dynamical Supersymmetry Breaking*  

• M. A. Luty  
  *2004 TASI Lectures on Supersymmetry Breaking*  
arXiv:hep-th/0509029

• Y. Shadmi  
  *Supersymmetry breaking*  
arXiv:hep-th/0601076

• K. A. Intriligator and N. Seiberg  
  *Lectures on Supersymmetry Breaking*  