Chapter 1

Physics Beyond the Standard Model at Colliders

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These lectures introduce the modern machinery used in searches and studies of new physics Beyond the Standard Model (BSM) at colliders. The first lecture provides an overview of the main simulation tools used in high energy physics, including automated parton-level calculators, general purpose event generators, detector simulators, etc. The second lecture is a brief introduction to low energy supersymmetry (SUSY) as a representative BSM paradigm. The third lecture discusses the main collider signatures of SUSY and methods for measuring the masses of new particles in events with missing energy.

1. Introduction

These lectures attempt to introduce three topics, each of which would normally be covered by a week-long lecture series at previous TASI schools. Given the limited amount of time and space, it is impossible to cover these subjects in any great depth, so this write-up is intended mostly as a very brief introduction and a guide to the existing literature on each subject. For maximal benefit, the reader is strongly encouraged to first watch the video of these lectures which is available on the TASI-2014 website.[1]

Section 2 provides an overview of the most common software simulation tools which are currently in use in high energy physics. The knowledge of these tools is indispensable for an aspiring phenomenologist. Of course, the best way to learn a computer program is to try it. Fortunately, interested students can benefit from several online tutorials, including the month-long computer tutorial[2,3] at TASI-2011.[4] The MC4BSM workshop series[5] is another good resource, since the workshop program typically includes tutorial sessions for beginners.[6,7] The sister series of TOOLS workshops[8] also offers similar computer tutorials. Finally, the websites of the developers of the individual codes often provide useful hands-on exercises.

Section 3 presents a very short review of the main features of low energy supersymmetry (SUSY). The discussion here is not intended to be a real course in supersymmetry — for this purpose, there are many excellent TASI notes from previous schools,[9–17] as well as several recent books.[18–23] While SUSY represents only one of many possible BSM scenarios, many of its features tend to be present in other successful theory models as well, thus the study of supersymmetry is a worthy investment.

Finally, using supersymmetry as an example, Section 4 reviews the basic strategies for discovering new physics at colliders. Again, there are excellent extensive reviews on the subject from previous TASI schools.[24–27] After reviewing the main SUSY collider signatures, the discussion will focus on methods for mass measurements in SUSY-like cascade decay chains.[28,29]

2. BSM Simulation Tools

2.1. *Interlude*

These days computing is essential to advances in experimental (and many areas of theoretical) physics. In the field of high energy physics (HEP), computers are routinely used to perform higher order theoretical calculations and to simulate high-energy collision events and the subsequent detector response. Therefore, there is an urgent need to train the current generation of graduate students to be able to utilize the available high energy physics software. Unfortunately, such dedicated graduate-level courses are rarely offered as part of the standard curriculum, and students either have to learn on their own, or travel to specialized schools and workshops. Good familiarity with the basic principles of Monte Carlo simulations bodes well for HEP students even if they ultimately choose to pursue a career outside physics.

After the discovery of the Standard Model Higgs boson, the main task ahead for the Large Hadron Collider (LHC) at CERN is the search for new physics Beyond the Standard Model (BSM). Over the years, many possible extensions of the Standard Model have been proposed, and many of them can be probed by the LHC experiments. However, in order to test a given theory, its predictions must be computed at a level that allows direct comparison to the data. This necessitates the use of various

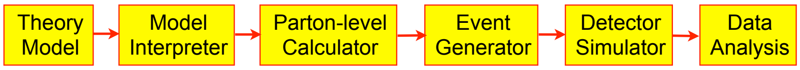

Fig. 1. The main steps in the simulation chain connecting particle theory to a collider experiment.

simulation programs, including theoretical calculators, Monte Carlo (MC) event generators, detector simulation packages, data analysis software, etc. These programs are used in stages, as illustrated in Fig. 1. The purpose of this first lecture is to provide a description of the specific tools which are schematically depicted in this figure.

There are several features of the modern-day simulation tools in Fig. 1 which make them attractive to the novice:

- *They are fully automated.* Within the last 10-15 years, we have witnessed enormous progress in the ability to do theoretical calculations of Feynman diagrams on the computer. The long, tedious calculations which tortured the previous generation of graduate students are a thing of the past — the same job can now be performed reliably and within seconds on a computer.
- *They are public (open source) and well-supported.* All programs mentioned in this lecture are publicly available, well-documented, and supported by their respective developers.
- *They are user-friendly.* The programs typically do not require the user to know how the code works (or even the computing language used to write the program). User control is usually handled by an external card file, or a graphical user interface (GUI) which allows the user to concentrate on the physics and avoid spending time looking at the guts of the code.
- *They are redundant.* As we shall see, many of the steps shown in Fig. 1 can be done by several different programs, written by different people, and using different algorithms. This allows the user to choose the program with which he/she feels most comfortable. In addition, by comparing the answers from two different programs, one can easily trace and remove possible bugs.
- *They are standardized.* With the adoption of the Les Houches accords,[30–33] the different programs become interchangeable, and can also easily be hooked up to each other to form the chain of Fig. 1.

2.2. *The need for simulations*

The basic question in particle phenomenology is: "For a given theory model (with a set of theory parameters $\{\alpha\}$) and for a given experimental signature, how many signal events N_{sig} do we expect to see in the detector?" The answer is given by the formula

$$N_{sig} = \sigma_{sig}(\{\alpha\}) \times BR(\{\alpha\}) \times \varepsilon_{total} \times L, \tag{1}$$

where $\sigma_{sig}(\{\alpha\})$ is the theory cross-section for producing the relevant new particles, $BR(\{\alpha\})$ is their branching fraction into the experimental signature of interest, and L is the total integrated luminosity (i.e., the amount of data collected by the experiment). The quantity

$$\varepsilon_{total} = \varepsilon_{acc} \times \varepsilon_{reco} \times \varepsilon_{trig} \times \varepsilon_{cuts}, \tag{2}$$

the total "efficiency", encompasses several penalty factors which account for various problems encountered in a real experiment:

- The geometrical acceptance, ε_{acc}, is the probability that all particles of interest fall within the instrumented region of the detector (and thus have a chance to be detected).
- The reconstruction efficiency, ε_{reco}, measures how often a real particle traversing the detector is actually recognized and reconstructed as such.
- The trigger efficiency, ε_{trig}, accounts for the fact that only a fraction of all data is collected to tape. In order to be saved, a given event must meet certain criteria (typically, we demand the presence of a sufficiently hard jet or lepton), otherwise it is lost forever.
- The efficiency of the cuts, ε_{cuts}, represents the probability that an event will pass the offline cuts designed at suppressing the relevant backgrounds.

The main problem is that ε_{reco}, ε_{trig} and ε_{cuts} are difficult to calculate analytically, because they are affected by the detector response, thus in order to compute them, one must perform some type of detector simulation.

In a realistic detector, a generator-level particle with true momentum $\vec{p}_{true}$ will be reconstructed as a detector-level object with momentum $\vec{p}_{obj}$, where in general $\vec{p}_{obj} \neq \vec{p}_{true}$. Thus the reconstruction efficiency can be modeled by introducing the so-called transfer function $T(\vec{p}_{obj}, \vec{p}_{true})$, which describes the probability that a particle with true momentum $\vec{p}_{true}$ is reconstructed as an object with momentum $\vec{p}_{obj}$.[34] Clearly, all objects come from some progenitor particle, thus

$$\int d\vec{p}_{true}\, T(\vec{p}_{obj}, \vec{p}_{true}) = 1. \tag{3}$$

However, not all particles are reconstructed, thus

$$\int d\vec{p}_{obj}\, T(\vec{p}_{obj}, \vec{p}_{true}) = \varepsilon_{reco}(\vec{p}_{true}) \leq 1. \tag{4}$$

Note that the reconstruction efficiency is in general a function of $\vec{p}_{true}$ and not a constant. Thus eq. (1) should be understood as an integral over the relevant phase space of the signal differential cross-section times the transfer function

$$N_{sig} = L \times \int d\vec{p}_{obj} \int d\vec{p}_{true}\, T(\vec{p}_{obj}, \vec{p}_{true})\, \frac{d\sigma_{sig}(\{\alpha\}; \vec{p}_{true})}{d\vec{p}_{true}}. \tag{5}$$

Note that the integral over $\vec{p}_{obj}$ necessarily involves detector *simulation*, while the integral over $\vec{p}_{true}$ only involves a Monte Carlo integration over the *true* momenta of the particles. The two integrations, however, go hand in hand, which is why the terms "Monte Carlo tools" and "simulation tools" are used interchangeably.

2.3. *The different components of the HEP simulation chain*

We are now in position to describe the different components seen in Fig. 1.

2.3.1. *Theory model*

The starting point is a BSM theory model created by a clever theorist. The model contains a certain number of particles whose interactions are described by a given Lagrangian. The question then becomes, how do we test this theory in experiment? To this end, we need to derive the expected differential distributions for relevant kinematic quantities[a] and then test whether the model predictions agree with the distributions observed in the data.

2.3.2. *Model interpreter*

The prediction for the kinematical distributions is obtained by calculating the differential cross-section with respect to the relevant variable, which involves a theory level computation of Feynman diagrams. The first step

[a]Those could be continuous variables like invariant masses, scattering angles, energies or momenta, or discrete quantities like numbers of leptons, jets, etc.

in any Feynman diagram calculation is to derive the Feynman rules for the model, i.e. the factors associated with the propagators and vertices of the diagram. These days, this step can also be done on the computer, using one of the following available packages:

- FeynRules[35] is a Mathematica package which derives the Feynman rules from a given Lagrangian and stores them in a suitable format for subsequent automated calculations. The latest version, FeynRules2.0,[36] has a number of improvements, e.g. it now includes support for two-component fermions, spin 3/2 and spin 2 propagators, and even superfield calculations (see Sec. 3 below). The developers of FeynRules introduced the so called Universal FeynRules Output (UFO) format[37] which is very flexible and can be understood by many different codes.
- LanHEP[38] was the first program to automate the derivation of the Feynman rules, but could only be interfaced with the CalcHEP event generator. The most recent version, however, has been updated to include UFO support.[39]
- Sarah[40] is similarly a Mathematica package which originally specialized in SUSY models, including one-loop renormalization and two-loop RGE evolution of the SUSY model parameters. The most recent release, Sarah4,[41] has added UFO support and can be applied to any non-SUSY BSM model.

If the input parameters in the Lagrangian are already defined at the electroweak scale, the procedure of deriving the Feynman rules is quite straightforward. However, in BSM model building is often done at very high scales (near the Planck or the grand unified theory (GUT) scale) which then requires evolving these parameters through the Renormalization Group Equations (RGEs) down to low energies. In models like supersymmetry, where there are many new parameters, this can get quite cumbersome, and motivates the use of specialized RGE evolution and weak scale renormalization codes like SoftSusy,[42] SuSpect,[43] Spheno[44] or Isasusy.[45] The validation of these codes against each other was an important exercise in the early 2000's.[46]

2.3.3. *Parton-level calculator*

The Feynman rules derived by the model interpreter can now be passed on to an automatic "parton-level calculator" which basically does your Quantum Field Theory homework. These programs are able to

(1) construct all possible Feynman diagrams for the process of interest;
(2) write down the invariant matrix element $\mathcal{M}$ and square it;
(3) perform spin polarization sums and averaging of $|\mathcal{M}|^2$;
(4) multiply by the phase space weight.

Once again, there are several options: the sister programs CompHEP[47] and CalcHEP,[48] MadGraph,[49] sherpa[50] and whizard.[51] These programs can also integrate[b] the spin averaged $|\mathcal{M}|^2$ over phase space and compute cross-sections, decay rates and branching fractions. Since the integration is performed by Monte Carlo, these codes can also generate parton-level "events", where each event is a record containing the identity and 4-momentum of each of the initial and final state particles in the hard scattering process. The events are distributed in momenta, helicities, *etc.* according to the computed $|\mathcal{M}|^2$. In effect, these parton-level MC event generators perform "pseudo-experiments": the generated set of events is just a particular statistical realization of the distributions predicted by the theory for the process of interest.

It is worth noting that since these codes are universal and general, they can also be trained to do calculations involving potential dark matter candidates.[52] In fact, these programs often spring out offshoots dedicated to dark matter calculations, e.g., MicrOMEGAs[53] is built on CalcHEP, while MadDM[54] is based on MadGraph.

2.3.4. *Event generator*

The produced parton-level events can in turn be handed to a general purpose event generator such as pythia,[55] herwig,[56] sherpa[57] or isajet,[58] which creates complete events, including the effects of fragmentation and hadronization of colored particles, initial and final state radiation via parton showers, effects from the underlying event, decays of unstable resonances, *etc.* The communication between the two classes of generators (parton-level and general purpose) is done following the LHA standard.[30]

2.3.5. *Detector simulator*

The next step is to process the particle-level event sample through a simulation of the detector, and to reconstruct the experimental "objects", namely, the "electrons", "muons", "photons", "jets" and the "missing transverse

[b] At hadron colliders, this involves convoluting with the parton distribution functions.

energy". Note that each experimental object is defined through a prescribed algorithm, e.g., an "electron" must satisfy minimum p_T, track and calorimeter isolation requirements. Be aware that the definition of such objects may vary between experimental collaborations; in addition, there are many possible jet reconstruction algorithms on the market.[59]

Depending on their level of sophistication, there are two types of detector simulation programs:

- *Full simulation*, a.k.a. "fullsim". This includes all aspects of simulating the passage of particles through the various components of the detector[60] : the tracking of particles through materials and external electromagnetic fields, the response of sensitive detector components, the generation of event data, the storage of events and tracks, and the subsequent object reconstruction and visualization. While realistic, fullsim is relatively slow - the processing of a single event may take minutes.
- *Fast simulation*, a.k.a. "fastsim". In this approach, one parameterizes the average response of the different calorimeter components, significantly speeding up the processing of the events. While the fullsim detector simulation packages are owned and maintained by the experimental collaborations, the popular fastsim packages PGS[61] and Delphes[62] are public and available to theorists.

2.3.6. *Data analysis software*

In the final step, one uses the reconstructed objects from each event to form suitable variables which would help isolate the BSM signal over the SM background. The simplest approach would be to simply count the number of events in a given region of phase space and compare against the expected number of background events N_{bg}. If the observed number of events N_{obs} happens to exceed N_{bg}, we have an interesting situation, where the excess is either due to the discovery of new physics, or due to a statistical fluctuation of the background . In such cases, the excess is quantified in terms of the number of "sigmas", where for sufficiently large statistics, $\sigma = \sqrt{N_{bg}}$. In order to set exclusion limits, one makes a signal hypothesis which would predict a certain number of signal events N_{sig} and then compares N_{obs} to $N_{bg} + N_{sig}$, quantifying any deficit in terms of $\sigma = \sqrt{N_{bg} + N_{sig}}$.

In addition to such number counting experiments, one may also study the shapes of the distributions of suitably defined variables. What variables should we choose for this purpose? Good discriminating variables are those

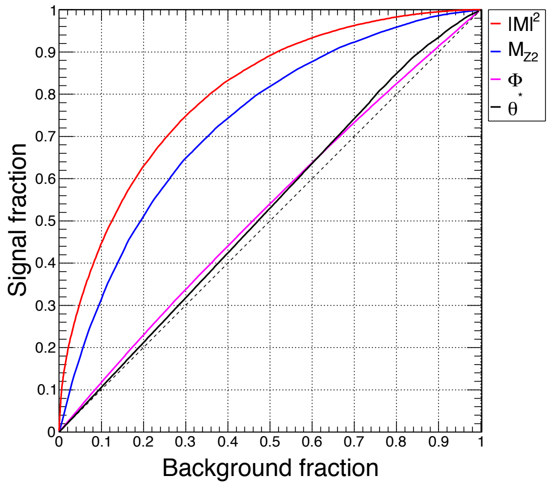

Fig. 2. ROC curves for several different kinematic variables in the Higgs golden channel $H \to ZZ^* \to 4\ell$.[64]

for which the distributions for signal events and for background events look *different*. A common method to compare the sensitivity of different variables is to construct their ROC curves.[63] One such example is shown in Fig. 2 for the Higgs golden channel $H \to ZZ^* \to 4\ell$. Since all 4 leptons are reconstructed, one can boost back to the Higgs rest frame and study different angles (Φ and θ^* are just two examples[64]) or the invariant mass M_{Z2} of the off-shell Z boson.[65] More importantly, given the measured momenta of the four leptons, one can run the parton-level calculator, compute the matrix element squared $|\mathcal{M}|^2$ and use it as a discriminating variable.[64–66] Fig. 2 shows that the $|\mathcal{M}|^2$ variable outperforms all others — indeed, such matrix-element based variables were instrumental for the Higgs discovery at LHC.[64,65]

In conclusion of this first lecture, a couple of comments are in order:

- We have just seen how each individual component of the simulation chain in Fig. 1 works. In principle, there is no reason why the whole chain cannot be packaged together and executed as a single program, and several attempts in this direction in fact already exist.[67–69]
- The best way for a student to begin learning the programs in Fig. 1 is to pick a simple example and work it through. This is precisely what was done during the simulation tutorials at the MC4BSM-2012 workshop at

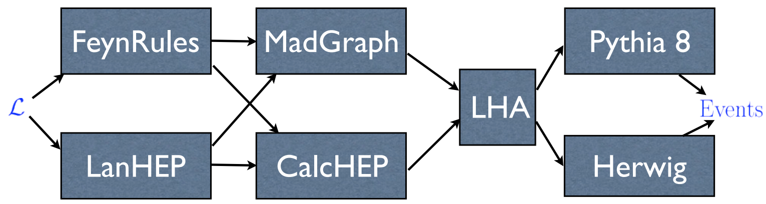

Fig. 3. The simulation path from a given Lagrangian $\mathcal{L}$ of a BSM theory to a particle-level Monte Carlo event sample, as illustrated in the computer tutorials[6] of the MC4BSM-2012 workshop at Cornell University.

Cornell, for which an extensive writeup[6] can be found on the arXiv. The flowchart of the tutorials is represented in Fig. 3. The starting point was a simple toy theory model with a dark matter candidate, whose Feynman rules were then derived via either FeynRules or LanHEP. The resulting model files were then fed into the parton-level calculators MadGraph or CalcHEP, producing parton-level events in the LHA standard. In turn, those were passed to the general purpose event generators PYTHIA or HERWIG in order to produce particle level events. I encourage the reader to try these tutorials and follow one path along the flowchart of Fig. 3, from the level of a theory Lagrangian $\mathcal{L}$ to particle events.

3. Brief Introduction to Supersymmetry

This second lecture will very briefly introduce supersymmetry as one example of a BSM theory[c].

3.1. *SUSY model building for dummies*

In order to build a BSM model, one simply has to follow the BSM model-builder's manual:

[c]For an in-depth introduction to supersymmetry the reader is referred to the classical reviews.[70–72]

BSM Model Builder's Manual

(1) Retain (the particles and symmetries of) the Standard Model.
(2) Add new particles with catchy names.
(3) (Optional) Add new gauge symmetries.
(4) Specify the representations of the new particles.
(5) (Optional) Check anomaly cancellation.
(6) Write down all gauge interactions.
(7) Write down all other gauge invariant interactions.
(8) Check experimental constraints. If the model is ruled out,
  (i) add more particles
  (ii) impose new symmetries
  (iii) when all else fails, fine-tune the model parameters

Following the manual, let us try to build the Minimal Supersymmetric extension of the Standard Model, i.e. the MSSM. We keep the same gauge structure as the SM, and then introduce a new particle, superpartner, for each known SM particle. The superpartners have the same quantum numbers as their SM counterparts (see Table 1), but differ by 1/2 unit of spin:

- The superpartners of the spin 1 gauge bosons in the SM are spin 1/2 fermions called gauginos. There are eight gluinos, three winos and one bino[d].
- The superpartners of the fermions (quarks and leptons) in the SM are spin 0 scalars, called squarks and sleptons, respectively.
- The superpartners of the two[e] Higgs bosons seen in Table 1 are spin 1/2 fermions called Higgsinos.

We now arrive at item (5) on the list: checking the triangle anomalies. We already know that they cancel in the SM. If there is a single Higgs boson, the presence of its superpartner will reintroduce anomalies, thus its contribution will need to be cancelled by an additional piece. The easiest way to accomplish this is to add another multiplet with the opposite hypercharge, as shown in Table 1.

At this point, and without any detailed knowledge of how exactly supersymmetry works, we can easily write down the gauge interactions of the superpartners:

[d]In the SUSY literature, it is customary to use the notation B^μ for the hypercharge gauge boson.
[e]The reason why the MSSM needs two Higgs doublets will become clear shortly.

Table 1. Superfields of the MSSM and their quantum numbers.

Superfield	Notation	$SU(3)$	$SU(2)$	$U(1)$
Left-handed quarks	Q	3	2	1/6
Right-handed up quark	U	$\overline{3}$	1	−2/3
Right-handed down quark	D	$\overline{3}$	1	1/3
Left-handed lepton	L	1	2	−1/2
Right-handed lepton	E	1	1	+1
Down-type Higgs doublet	H_d	1	2	−1/2
Up-type Higgs doublet	H_u	1	2	1/2

- The sfermions (squarks and sleptons) are scalars, thus they will have the usual 3-point and 4-point interactions with gauge bosons *à la* scalar electrodynamics.
- The Higgsinos are fermions and have the usual 3-point couplings to gauge bosons.
- The bino belongs to an Abelian group and has no direct interactions with any other gauge bosons.
- The winos and gluinos have 3-point gaugino-gaugino-gauge boson interactions due to the non-Abelian nature of their respective gauge groups.
- Finally, and this is the only new gauge interaction dictated by SUSY, there is a Yukawa-type 3-point gaugino-fermion-sfermion vertex.

Homework exercise. Use the graphical user interfaces of the parton-level calculators mentioned in the first lecture (MadGraph, CalcHEP or CompHEP) to draw the Feynman diagrams for:

(1) Gluino pair production at the LHC.
(2) Squark pair production at the LHC.
(3) Antisquark pair production at the LHC.
(4) Squark-antisquark production at the LHC.
(5) Gluino-squark associated production at the LHC.
(6) Gluino-antisquark associated production at the LHC.

Identify the gauge interaction vertices mentioned above. Do you see any vertices which are not on the list? For extra credit, compare the cross-sections for these 6 processes. *Hint: the MSSM model files can be obtained from the developers' websites and loaded easily into these three programs.*

3.2. *Superspace formalism*

Perhaps the most concise and elegant way of talking about supersymmetry is the superspace formalism.[73–75] Think of SUSY as a theory with extra fermionic dimensions spanned by some Grassmann coordinates, θ^α. Then the usual action, which is an integral over space-time of the Lagrangian (which in turn is a function of the fields), is replaced by a *super*action, which is a *super*integral over *super*space of the *super*potential, W, which is now a function of the *super*fields! Very schematically,

$$\int d^4x \mathcal{L}(\varphi(x)) \longrightarrow \int d^4x\, d^2\theta\, W(\Phi(x,\theta)). \tag{6}$$

Due to the anti-commuting nature of the Grassmann variables, the Taylor expansion of the superfield Φ is quite short:

$$\Phi(x,\theta) = \varphi(x) + \psi_\alpha(x)\theta^\alpha + F(x)\varepsilon_{\alpha\beta}\theta^\alpha\theta^\beta. \tag{7}$$

We see that each superfield necessarily contains bosons (in this case a scalar $\varphi(x)$) and fermions (here a Weyl fermion $\psi(x)$). The field $F(x)$ has mass dimension 2 and is not a dynamical field.

Supersymmetry requires that the superpotential $W(\Phi)$ be a function of the chiral superfields Φ and not their conjugates $\Phi^\dagger$ (this is another reason why the MSSM requires two Higgs doublets - otherwise we cannot give mass to the down-type fermions at tree level). Counting mass dimensions in (6) and (7), we see that the superpotential has mass dimension 3 and therefore contains products of up to three superfields. By inspection of the quantum numbers in Table 1, we see that one can write down the following gauge invariant terms in the superpotential

$$W_{RPC} = \lambda_u QUH_u + \lambda_d QDH_d + \lambda_e LEH_d + \mu H_u H_d. \tag{8}$$

Note that all those terms conserve both baryon number and lepton number. Upon further reflection, we see that one could also consider the following terms

$$W_{RPV} = \lambda'' UDD + \lambda' QDL + \lambda LLE + \mu' H_u L, \tag{9}$$

which break either baryon number b (the first term) or lepton number l (the last three terms). The simultaneous presence of these terms in the superpotential would have disastrous consequences for proton decay, thus we need to forbid (9) while preserving (8). Following the prescription (8)(ii) of the BSM model builder's manual, we impose a discrete symmetry, called matter parity:

$$P_M \equiv (-1)^{3(b-l)}. \tag{10}$$

Under matter parity, the quark and lepton superfields are odd, while the two Higgs superfields are even. Thus matter parity forbids all terms in (9), saving the proton[f].

Note that since $(-1)^{2s}$, where s is the spin, is also a symmetry, matter parity is equivalent to R-parity

$$P_R \equiv (-1)^{3(b-l)+2s}. \tag{11}$$

This is why the dangerous interactions (9) are commonly referred to as "R-parity violating".

Under R-parity, all SM particles (quarks, leptons, Higgs and gauge bosons) are even, while their superpartners are all odd. The imposition of R-parity (11) therefore has three very important phenomenological consequences:

- Each superpartner must couple to an odd number of other superpartners.
- As a consequence, when superpartners decay, they can do so only into an odd number of superpartners (typically just one). Thus, if we follow a superpartner decay chain, once we reach the lightest superpartner (LSP), we are "stuck", and the LSP is absolutely stable, even on cosmological time scales. This provides a great opportunity for supersymmetry (supplemented with R-parity) to provide a dark matter candidate, if the LSP turns out to be neutral. There are 4 types of neutral superpartners: bino, wino, higgsino and sneutrino, and they have all been considered in the literature as dark matter candidates, see, e.g.[78–81]
- Since colliders collide SM particles with even R-parity, the initial state is even, therefore superpartners must be pair-produced (or more generally, produced in even numbers).

3.3. *The allure of supersymmetry*

Without a doubt, supersymmetry is currently the most popular BSM framework. This is due to a number of reasons, among which:

- As already mentioned, supersymmetry may provide an elegant solution to the dark matter problem. It contains suitable dark matter candidates, which, by the way, are all weakly interacting particles, and are therefore touched by the "WIMP miracle".[82]
- Supersymmetry ensures exact cancellation of quadratic divergences between diagrams containing loops with regular particles and diagrams with

[f] A discrete Z_2 symmetry like (10) is the most popular, but not the only option. For alternatives, see Refs.[76,77]

superpartner loops. It is instructive to see how this works in a specific example.

Homework exercise. Consider the top Yukawa term in the superpotential (8). In a supersymmetric theory, the scalar interactions are obtained from the potential

$$V(\varphi) \supset \sum_i \left| \frac{\partial W}{\partial \Phi_i} \right|^2_{\Phi_k=\varphi_k} + \frac{1}{2} \sum_a g_a^2 \left(\varphi^* T^a \varphi\right)^2 \tag{12}$$

while the Yukawa interactions follow from

$$\frac{1}{2} \sum_{i,j} \left(\frac{\partial^2 W}{\partial \Phi_i \partial \Phi_j} \right)_{\Phi_k=\varphi_k} \psi_i \psi_j + h.c. \tag{13}$$

Use these formulas to identify all superpartner interactions which are proportional to the top Yukawa coupling λ_t. In the SM, the top quark loop causes the Higgs mass to diverge like $\lambda_t^2 \Lambda^2$. Construct the diagrams with top superpartners which cancel this divergence. *Extra credit.* Which are the diagrams which ensure that the top squark mass does not diverge like $\lambda_t^2 \Lambda^2$?

- The presence of the superpartners above some scale M_{SUSY} modifies the running of the three gauge couplings g_1, g_2 and g_3, modifying the unification picture obtained in the SM.

  Homework exercise. In terms of the measured values of the gauge couplings at the electroweak scale $g_1(M_Z)$, $g_2(M_Z)$ and $g_3(M_Z)$, derive formulas for:

  (1) The unification scale M_{GUT} at which all three couplings meet.
  (2) The unified value $g_{GUT}(M_{GUT})$ of the gauge coupling at the GUT scale.
  (3) The value of the SUSY scale M_{SUSY} at which we need to transition from the SM to the MSSM in order to achieve perfect unification. Plugging in numbers, determine M_{SUSY}. Is it near the TeV scale?

- In the SM, the quartic Higgs coupling is arbitrary. In SUSY, on the other hand, it arises from the last term in (12) and is related to the gauge couplings, which are relatively small. This places an upper limit on the tree-level mass of the lightest neutral Higgs boson in the MSSM, which is only slightly modified by radiative corrections. Thus, perhaps the only robust and generic prediction of the MSSM was that the Higgs should be relatively light, not more than about 130 GeV. Now that this indeed turned out to be the case, some SUSY aficionados feel that the Higgs discovery has strengthened the case for low energy supersymmetry.[83–86]

4. Supersymmetry at Colliders

4.1. *Breaking supersymmetry*

The MSSM as introduced in the last lecture has one very big problem — it is ruled out. Supersymmetry predicts that except for the spins, all other quantum numbers of the SM particles and their superpartners should be the same, including the mass. Since we haven't found any superpartners degenerate with their SM counterparts, SUSY must be broken. There are various ways to break supersymmetry and communicate this to the visible sector;[14] the challenge in doing so is to preserve the nice features discussed in Sec. 3.3, and, above all, the cancellation of quadratic divergences. One is therefore led to consider the so called "soft" SUSY breaking, where one adds by hand mass terms for the superpartners (as they do not affect the ultraviolet behavior of the diagrams) and trilinear and bilinear scalar couplings to the Lagrangian (trilinear scalar couplings can only cause logarithmic divergences). The resulting "soft" SUSY Lagrangian has over 100 parameters in addition to the SM inputs, but many of those are very severely constrained by flavor and CP constraints. As it turns out, there are a total of 19 "important" parameters which determine the SUSY collider phenomenology:

- three gaugino mass parameters M_1, M_2 and M_3 for the bino, winos and gluinos, respectively.
- 5 masses squared $m^2_{Q_1}$, $m^2_{U_1}$, $m^2_{D_1}$, $m^2_{L_1}$ and $m^2_{E_1}$ for the squarks and sleptons of the first[g] generation.
- 5 masses squared $m^2_{Q_3}$, $m^2_{U_3}$, $m^2_{D_3}$, $m^2_{L_3}$ and $m^2_{E_3}$ for the squarks and sleptons of the third generation.
- Three trilinear scalar couplings A_t, A_b and A_τ, corresponding to the interaction between a pair of third generation sfermions and a Higgs boson.
- Two more parameters, m_A and $\tan\beta \equiv v_2/v_1$, parameterizing the mass spectrum in the Higgs sector.

The vastness of the resulting 19 dimensional parameter space of this "phenomenological" MSSM (pMSSM) presents a formidable challenge for phenomenology. Three possible approaches have been tried:

- *Complete agnosticism.* In this aptly named "pMSSM approach"[87,88] one avoids any bias from theory model building and simply scans the full

[g]In order to alleviate the FCNC constraints, one assumes that the scalars from the first two generations are degenerate, i.e. $m^2_{Q_1} = m^2_{Q_2}$, etc.

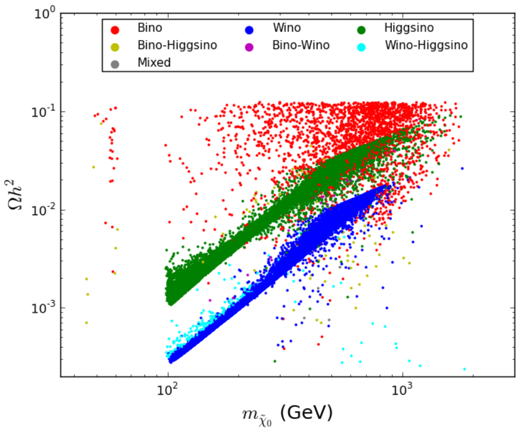

Fig. 4. Thermal relic density as a function of the LSP mass for a scan of pMSSM models, surviving current constraints from collider and astrophysical experiments, color-coded by the electroweak properties of the LSP.[89]

19-dimensional pMSSM parameter space by brute force. For each parameter space point, one imposes all available experimental constraints, and if they are satisfied, the point is retained, otherwise it is thrown away. Typical results from such a scan are shown in Fig. 4, which was prepared for the Snowmass 2013 report of the Dark Matter Complementarity working group.[90] The advantage of the pMSSM approach is that it is model-independent, the disadvantage is that any reasonable scan of N points is necessarily very sparse, effectively probing only $\sqrt[19]{N}$ points along each axis of parameter space.

- *Specific SUSY breaking scenarios.* This is a diametrically opposite approach, whereby one considers a very specific model of SUSY breaking (ideally, with very few input parameters). The prototypical scenario is the so called minimal supergravity (MSUGRA), a.k.a. "constrained MSSM" (cMSSM), in which there are 5 input parameters: M_0, a universal scalar mass at the GUT scale; $M_{1/2}$, a universal gaugino mass at the GUT scale; A_0, a universal trilinear coupling; $\tan\beta$; and the sign of the μ parameter in (8). While historically the MSUGRA model has probably received much more attention that it truly deserves, some of its broad features are likely to be preserved in other models of SUSY breaking. For example, a simple analysis of the gaugino mass RGEs reveals that the

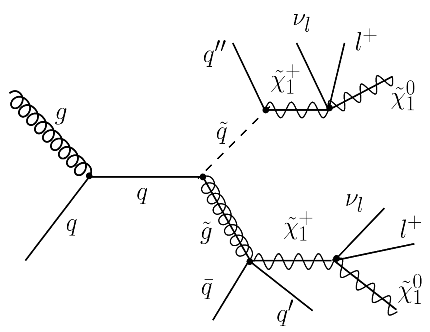

Fig. 5. An example of a process involving associated gluino-squark production and decay, which gives rise to two same-sign prompt leptons, jets, and missing transverse energy.[92]

quantity M_a/g_a^2 is an RGE invariant:

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2} = \frac{M_{1/2}}{g_{GUT}^2}. \tag{14}$$

Given the measured values of the SM gauge couplings g_a, we expect that among the three types of gauginos the bino is the lightest (good news for dark matter!) while gluino is the heaviest. A similar analysis of the scalar RGE's reveals that the squarks tend to be heavier than the sleptons, and for a given flavor of sfermions, the $SU(2)$ doublet state tends to be heavier than the $SU(2)$ singlet state. To the extent that these conclusions are based on an analysis of the MSSM RGE's, these superpartner mass patterns tend to be present in other models of SUSY breaking as well.

- *Simplified models.* This is an intermediate approach, where one still does not assume a specific model of SUSY breaking, but instead considers one collider signature at a time and keeps only those of the 19 pMSSM parameters which are relevant for the search.[91] Two such examples are shown in Figs. 5 and 6. Fig. 5 depicts a SUSY event with jets, two *same-sign* leptons and missing transverse energy (MET)[h]. Note the production of leptons in the decays of charginos. The lepton in the squark decay chain inherits the electric charge of the parent squark, but since the gluino is a neutral particle, the resulting lepton can have either sign of the electric charge. Therefore, 50% of the time, such gluino-squark events

[h]MET is an unfortunate misnomer which has stuck around for historical reasons — of course, what is actually measured is the missing transverse *momentum*.

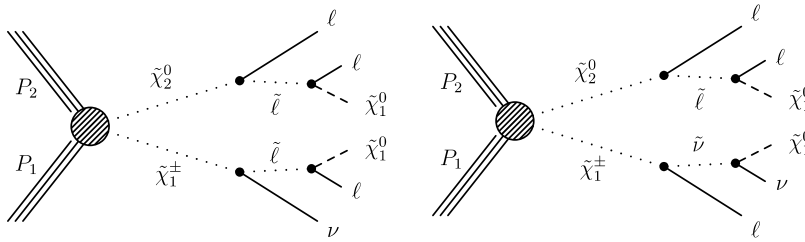

Fig. 6. Production diagrams for the clean trilepton SUSY signal at a hadron collider.[93]

will contain *same-sign* leptons, providing a relatively clean signature at hadron colliders.[94] The same like-sign dilepton plus jets signature can also be obtained from guino pair events.[95,96]

At hadron colliders, strong production dominates and LHC has already been able to set stringent limits on the masses of colored superpartners. Thus, the focus has recently shifted to direct electroweak production, e.g. of chargino-neutralino pairs which leads to the gold plated trilepton mode[97–99] for SUSY as shown in Fig. 6.

4.2. *SUSY mass measurements*

A long standing problem in SUSY phenomenology has been the measurement of the superpartner masses along a SUSY decay chain, in models where the LSP is a dark matter candidate (typically a neutralino, i.e., some mixture of the bino, neutral wino and the two neutral Higgsinos). The problem is that a neutral LSP escapes the detector and its energy and momentum cannot be measured, which invalidates the traditional approach of reconstructing an invariant mass peak and requires an influx of new fresh ideas. Two common approaches are (for a complete review, see[28])

- *Kinematic endpoints.* Consider the generic SUSY decay chain of Fig. 7. The three visible particles whose momenta are measured in the detector are: a QCD jet j, a "near" lepton $\ell_n^\pm$ and a "far" lepton $\ell_f^\mp$. One now studies the distributions of invariant masses of different combinations of visible particles:

$$\left\{m_{j\ell_n}, m_{j\ell_f}, m_{\ell\ell}, m_{j\ell\ell}\right\}. \tag{15}$$

  Each distribution exhibits a well defined upper kinematic endpoint which is a function of the masses of particles A, B, C and D. Armed with these four measurements, one should be able to solve for the particle masses in terms of the measured endpoints.

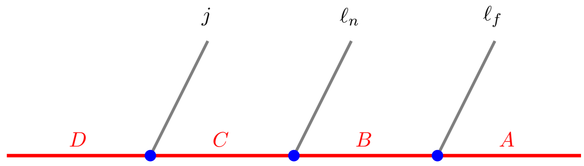

Fig. 7. The typical cascade decay chain used in kinematic endpoint studies. Here D, C, B and A are new BSM particles, while the corresponding SM decay products are: a QCD jet j, a "near" lepton $\ell_n^{\pm}$ and a "far" lepton $\ell_f^{\mp}$. This chain is quite common in SUSY, with the identification $D = \tilde{q}$, $C = \tilde{\chi}_2^0$, $B = \tilde{\ell}$ and $A = \tilde{\chi}_1^0$, where $\tilde{q}$ is a squark, $\tilde{\ell}$ is a slepton, and $\tilde{\chi}_1^0$ ($\tilde{\chi}_2^0$) is the first (second) lightest neutralino.

There are several complications with this procedure. First, we cannot distinguish ℓ_n from ℓ_f, which motivates trading $m_{j\ell_n}$ and $m_{j\ell_f}$ for the alternative set

$$m_{j\ell(lo)} \equiv \min\left\{m_{j\ell_n}, m_{j\ell_f}\right\}, \tag{16}$$

$$m_{j\ell(hi)} \equiv \max\left\{m_{j\ell_n}, m_{j\ell_f}\right\}. \tag{17}$$

Second, the functions which express the kinematic endpoints in terms of the underlying masses are piece-wise defined,[100,101] and duplicate solutions may exist.[101,103] This ambiguity can be resolved by studying the *correlations* between the invariant mass variables.[102–104]

- M_{T2} *kink.* The previous method requires that the SUSY decay chain is sufficiently long, otherwise we do not have enough invariant mass combinations to study. A particularly troublesome case arises when each of the two SUSY decay chains consists of a single two-body decay. The Cambridge variable M_{T2}[105,106] was cleverly designed to deal with precisely this type of situation. A particularly useful property of M_{T2} is that when we consider its kinematic endpoint as a function of the *a priori* unknown LSP mass, this function exhibits a kink at precisely the correct values of the masses of the SUSY particles.[107–110]

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   2012: http://lepp.cornell.edu/Events/MC4BSM/Tutorials.html
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