1

New Particles Working Group Report

Conveners: Yuri Gerstein, Markus Luty, Meenakshi Narian,
LianTao Wang, Daniel Whiteson

...+ many authors ...

1.1 Introduction

Searches for new particles at colliders has historically been one of the most fruitful path to discovery of new fundamental physical phenomena and the establishment of new laws of nature. Particles with any quantum numbers can be produced in particle-antiparticle pairs as long as they are kinematically accessible and couple with sufficient strength to the colliding particles. General-purpose particle detectors provide essentially complete coverage of all particles produced in reactions, and can therefore search for almost any kind of decay, as well as new stable particles. An immense body of theoretical and phenomenological work ensures that the effects of standard model interactions are well-understood. In this way, new particles can not only be discovered above standard model backgrounds, but their detailed properties can be measured. This paradigm is well illustrated with the discovery of the Higgs boson. Within a year of its discovery, the Higgs program has progressed to detailed measurements of Higgs properties, and the full standard model of particle physics is definitely experimentally established, at least as a leading approximation.

There are many promising avenues for physics beyond the standard model that can be explored at the energy frontier. The number, diversity, and quality of the white papers submitted to the new particles group attests to the intellectual vigor of this search. Rather than attempt a summary of this work, we have decided to illustrate the many exciting possibilities with some examples. This report describes a number of scenarios in which a signal seen at the LHC with $\sqrt{s} = 14$ TeV suggests a natural candidate model that can be studied in more detail at future experimental facilities. These 'discovery stories' refer to many of the whitepapers, which give more comprehensive treatments of the subject.

1.1.1 Physics Motivation

With the discovery of the Higgs boson, particle physics is entering a new era: we now have a theory that can be consistently extrapolated to scales many orders of magnitude beyond those that we can directly probe experimentally. At the same time, there has been no observation of physics beyond the standard model at high-energy colliders, raising the question of whether there may in fact be no more discoveries accessible at the energy scales that can be explored at the energy frontier.

However, there is strong motivation for new physics at the TeV scale coming from both *big questions* and *big ideas*. For some of the big questions, the answers must lie at the TeV scale, while for others this is suggested by the principle of minimality of scales in nature. The big ideas have been forced on us by the need to reconcile the highly constrained theoretical framework of quantum field theory with the phenomena observed in nature.

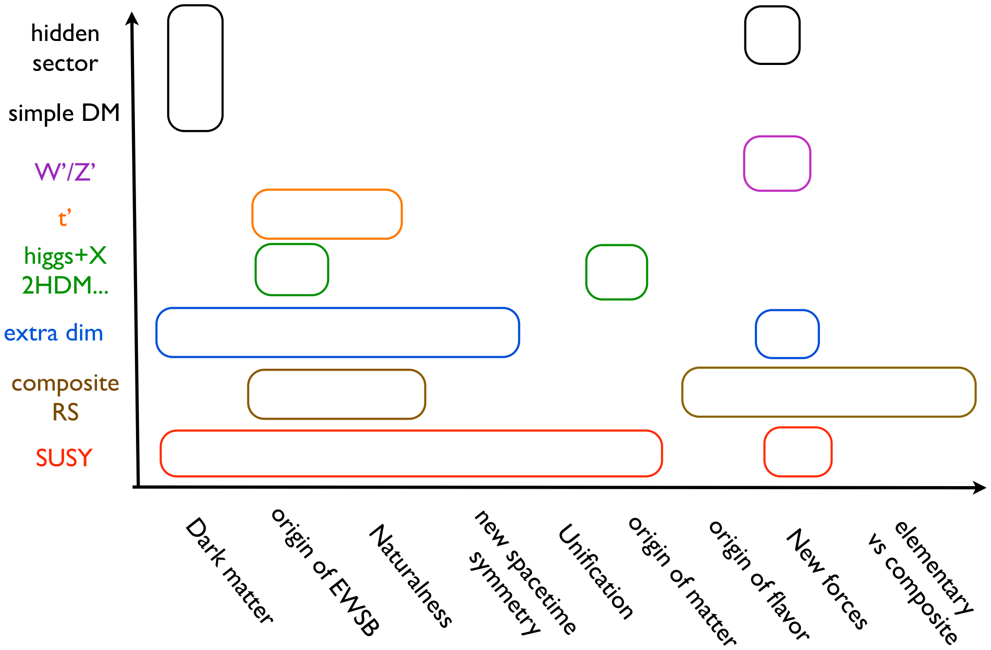


Figure 1-1. *Questions and ideas.*

Some of the big questions:

- *Is the Higgs boson solely responsible for electroweak symmetry breaking and the origin of mass?* The 125 GeV Higgs boson is apparently the first scalar elementary particle observed in nature. Its measured couplings make it clear that it plays the central role in breaking electroweak symmetry and giving mass to the other elementary particles. But the Higgs boson may be composite, or there may be additional Higgs bosons as part of a larger Higgs sector. These questions can be addressed both by detailed study of the Higgs and by direct searches for extended Higgs sectors.

- *What is the dark matter?* The cosmological and astrophysical evidence for dark matter is incontrovertible, but its particle origin is completely unknown. The most compelling candidate is a WIMP, a thermal relic with mass at the electroweak scale, whose interactions with ordinary matter determine its cosmological density today. In this scenario, dark matter can be directly produced and studied at energy frontier colliders.

- *Are fundamental parameters finely tuned?* The mass of an elementary Higgs boson is sensitive to physics at high energy scales, and if there is no physics beyond the standard model, the fundamental Higgs mass parameter must be adjusted to an accuracy order 1 part in 10^{32} in order to explain the separation between the TeV scale and the Planck scale. Avoiding this fine-tuning is one of the main motivations for physics beyond the standard model. Models that eliminate this tuning predict new particles at the TeV scale that couple to the Higgs and can be explored at collider experiments.

- *Are there new fundamental forces in nature?* Candidates for fundamental theories such as string theory generally predict additional gauge forces and other interactions that can arise at the TeV scale. Discovering these will yield invaluable clues to the structure of the fundamental interactions of nature.

- *What is the origin of quark, lepton, and neutrino mass hierarchies and mixing angles?* These 'flavor' parameters account for most of the fundamental parameters of particle physics, and their pattern remains mysterious. New particles at the TeV scale with flavor-dependent couplings are present in many models, and observation of such particles would provide an important clue to this puzzle.
- *Are 'elementary' particles really composite?* This possibility is motivated by the fact that many of the particles we observe are composite states of underlying dynamics, and by attempts to address other big questions. Uncovering evidence of compositeness at the TeV scale would be another window on new forces in nature.

Over the last few decades, advances in theoretical physics have led to big ideas about fundamental physics that can be probed at the energy frontier. Some of them are specifically designed to address one of the big questions given above, others have much broader implications.

- *Supersymmetry.* This is the unique extention of 4-dimensional spacetime symmetry, the next step beyond Einstein's theory of relativity. It is required for consistency of string theory, and holds out the promise of unifying all the fundamental forces of nature. Supersymmetry the unique theory that allows an elementary Higgs boson without fine-tuning if supersymmetry is broken at the TeV scale. Minimal versions of supersymmetry automatically predict gauge coupling unification, and provides a candidate for dark matter.
- *Extra dimensions and compositeness.* Additional dimensions of space that are too small to be seen directly are a ubquitous feature of string theory. Excitations of these extra dimensions can manifest themselves in new particles and interactions. Remarkably, some theories with extra dimensions are equivalent (or 'dual') to composite theories. This has let to a deeper understanding of both extra dimensions and compositeness, and led to many interesting and detailed proposals for new phyics based on these ideas.
- *Unification of forces.* The idea that all elementary interactions have a unified origin goes back to Einstein, and has its modern form in grand unification and string theory. There is experimental evidence for the unification of strong, weak, and electromagnetic interactions at short distances, and string theory generally predicts additional interactions that may exist at the TeV scale.
- *The Multiverse.* String theory apparently predicts a 'landscape' of vacua, and eternal inflation gives a plausible mechanism for populating them in the universe. The implications of this for particle physics and cosmology are far from clear, but it has the potential to account for apparently unnatural phenomena, such as fine-tuning.

1.1.2 Overview of Conclusions

All of the questions and ideas described above can be probed to various degrees by experiments at the energy frontier. Before getting into details, we summarize a few key lessons here.

- The high luminosity LHC can significant extend the reach in experimentally addressing many of these fundamental questions and ideas. It allows us to more thoroughly explore the TeV scale. This is especially useful for searching for light new physics particles with weak couplings. Continued running of this experiment is essential to further progress in particle physics.

- The International linear collider (ILC) is a big step in extending our reach on the energy frontier, and it is complementary to a hadron collider in many ways. It offers a much cleaner environment which enables more precise measurements, such as the properties of the Higgs boson and other potential new physics particles. In terms of searching for new physics, although it is probing somewhat lower energies, it offers a much thorough coverage. Similar conclusions can also be applied to other proposed high energy lepton colliders, such as the muon collider and CLIC.
- A TLEP Higgs factory is a new and interesting proposal. Although its reach in direct searches of new physics is more limited than the ILC, it could reach higher luminosity. Hence, it could make more precise measurements of Higgs properties. Moreover, the option of moving on to a higher energy *pp* collider at a later stage makes it highly appealing.
- A VLHC (HE-LHC), either as a later stage of a TLEP-like Higgs factory or as a standing alone program, will directly and significantly pushes forward the energy frontier. Therefore, it can address many of the important question in a definitive way. If naturalness is realized through new physics particles, they must be discovered at VLHC. At the same time, we would have a much better chance of discovering WIMP dark matter.

We emphasize a number of areas of overlap and synergy with the intensity and cosmic fronitiers, most notably in the study of dark matter and flavor. New phenomena such as neutrino mixing and dark matter are fundamental inputs into theories of new physics, and constraints from cosmology and flavor physics are crucial in models of new physics. Discovery of new physics at cosmic or intensity frontier experiments in many cases will point to a scale that can be explored directly at future energy frontier facilities. There is great complementarity and opportunities for synergy across the frontiers, and a vigorous multi-pronged approach in all frontiers is essential for progress in fundamental physics.

1.2 Discovery Stories

Each section below describes a possible discovery scenario.

1.2.1 'Simple' Supersymmetry

As discussed in the introduction, SUSY is perhaps the best motivated and most successful framework for physics beyond the standard model, and the most sensitive searches in the simplest SUSY models is jets plus missing energy coming from production of gluinos and squarks. A discovery in this channel has the possibility of establishing a new spacetime symmetry in nature, as well as producing dark matter in the laboratory.

The LHC14/300 has tremedous potential for discovery in this mode. The strongest previous bounds come from the 8 TeV run of the LHC, and the reach is significantly improved due to the increased center of mass energy of LHC14. For the simplest 'minimal supergravity' models, the jets plus missing transverse energy (MET) searches have the highest sensitivity. The reach of these searches has been studied in the the ATLAS and CMS WhitePapers [], and also for simplified models using the Delphes Snowmass LHC detector [**?**]. The reach is shown in Fig. ? Based on these results, we can expect gluinos with masses up to # and squarks with masses up to # to be visible at LHC14/300.

We now discuss a scenario based on the pMSSM benchmark point 2750334, the 'well-tempered Bino-Higgsino.' The spectrum is given in Fig. ?. Complete details of the model can be found in [**?**].

In this model, the LHC14/300 can discover new physics in jets plus MET with # expected signal events with an expected background of #, giving a significance of # [**?**]. While SUSY will clearly be seen as the most plausible explanation of this discovery, there are other possibilities that have to be considered. For example, 'universal extra dimension' models where all the standard model particles propagate in extra dimensions have massive 'partners' for all the standard model particles, and have signatures that are similar to SUSY models.

In this scenario, LHC14/300 would observe an excess in the jets+MET channel with a significance of #. The rate, energy scale, and jet multiplicity (between 2 and 5) is consistent gluino and squark production. At the same time, no other signal of new physics is observed at LHC/300.

From the energy distribution one can roughly estimate the mass difference between the gluino/squarks and the LSP. The rate and the distributions for M_{eff} and the number of jets are not a good match with what is expected from the simplest SUSY spectra, leading one to suspect that there may be additional colored superpartners. In addition, there is no sign so far of the electroweak-inos, and sleptons.

The high luminosity LHC has limited reach for sleptons [numbers/plots?], but can extend the reach for electroweak-inos up to # assuming simple decays []. In the present scenario, the electroweak-inos will be observable above 5σ with 3000/fb, even though they are not observable with 300/fb, according to ATLAS and CMS projections []. No signal for sleptons would be found, and bounds would be #.

The ILC with 500 GeV would be able to precisely measure the masses and spins of the gauginos, as well as the branching fractions in their transitions. The presence of these additional expected partners, as well as their spins, would be direct evidence for supersymmetry, which relates fermions and bosons. This would allow us to estimate the composition of the electroweak-ino mass eigensstates. This is an important step in connecting collider measurements with the dark matter relic abundance (see below).

At the same time, the sleptons would not be found at the 500 GeV ILC, and mass limits on the lightest slepton would be at around 250 GeV. This would suggest that the sleptons are not important for the thermal relic density of the LSP, and estimates of the relic abundance from collider data would give values consistent with the observed relic density, but with large errors.

[dark matter?]

At this point, it would be very clear that supersymmetry has been established, and the sleptons are the last major missing piece of the puzzle. An ILC upgrade, or CLIC or a muon collider would be strongly motivated to search for these.

The higher mass colored superpartners can only be searched for at a VLHC.

1.2.2 SUSY with a light stop

If an excess is seen in $t\bar{t} + \not{E}_T$, it may be evidence for SUSY with a light stop quark.

Light stop is necessary for low-fine-tuning SUSY to work, and this channel is going to be one of the foci of the LHC Run 2 program. The reach for 300/fb is estimated in ATLAS and CMS white papers (see figures extracted from those) and in the parametrized simulation MT2 search (figure from there).

A great example of such scenario is explored in the joint ILC-LHC study of the stau co-annihilation model. In addition to low fine-tuning, the neutralino in that model accounts for the observed amount of the Dark Matter in the Universe. The mass spectrum and allowed transitions in this model are shown in the figure ().

The top squark has multiple decay channels, and the high luminosity LHC has a chance to see soft leptons from the gaugino transitions in the cascades. It may also have sensitivity for the A0/H0 (reference to the Higgs part of the report) and some of the colored states.

At the 500 GeV ILC sleptons and lighter gauginos are accessible, and their mass and quantum numbers will be measured (figures from the WP). By measuring tau polarization one can measure higgsino fraction of the lightest neutralino.

Another example is a Focus Point SUSY (hep-ph/1306.4961). In that case the VLHC is certainly necesary to access the high mass colored particles.

The results of the direct DM detection experiments will help to discriminate between the SUSY scenarios (see figure from the FP paper).

1.2.3 Excess of Leptons+MET Events

In many scenario of supersymmetry breaking, the color neutral superpartners, gaugino, higgsino and sleptons, can be significantly lighter than the gluino and squarks. Therefore, the direct production rate at the LHC can be comparable. In addition, if kinematically allowed, they can also be produced copiously as decay products of gluino and squarks. The decays of chargino, neutralino and slepton can give rise to leptons, which is an important part of signals for SUSY.

There can be additional arguments for why some of the chargino and neutralino could be light. For example, while the fine-tuning arguments about the upper limits on masses of stop and gluino can be relaxed in NMSSM, it is much harder to avoid the requirement that μ is small. Therefore, an NMSSM reality with only light states being charged and neutral higgsinos can still be "natural".

[reach plot for simplified model]

At the LHC, discovery of such states is possible through detection of soft leptons from higgsino transitions. For small mass splittings, the analyses have to rely on the ISR jet or photon for trigger and backrgound reduction [**?**, **?**].

Recently, it's been proposed to search for VBF production of higgsinos. [**?**]. More careful estimates of backgrounds are still needed, but the method allows some sensitivity to light higgsinos no matter what the value of the mass splitting is.

If the excess of leptons+MET events is seen at the LHC Run2, one may imagine the following sequence of events.

At the high luminosity LHC, the dilepton mass edges will be measured, informing us on the mass splittings. Together with the cross sections and assuming high higgsino fraction, a rough estimate of the absolute masses might be possible.

At the ILC, one will be able to measure masses and quantum numbers of the observed states, and will search for partners of leptons.

The complementarity of the LHC and ILC searches for higgsinos is illustrated in the figure (ILC-LHC EWKino scan).

The VLHC will be eventually needed to access the colored states. Its reach for squarks and gluinos is shown in figure (from squark-gluino simplified model scan and ATLAS/CMS WPs).

1.2.4 R-parity violating SUSY

One of the ways natural SUSY may have escaped detection so far is that the R-parity does not conserve. Without it, the MET signature of SUSY events at the LHC can entirely disappear. In many scenarios the final states would have many jets and few or no leptons.

The top squark, depending on which RPV couplings dominate, can decay into a τ-lepton and a b-quark (LQD333), two light quark jets (UDD312), or top quark and three jets (UDD212).

The LHC reach in the three scenarios above was explored in the three dedicated WP and found to be, 1.3 TeV, 750 GeV, and 600 GeV for the 300/fb integrated luminosity respectively.

Signal observation in any of these channels will motivate further exploration of the signal with HL LHC. Since the stop mass is not expected to be very high and the signal to background ratio in each of these channels is small, the factor of 10 increase in luminosity will bring about factor of 3 improvement in sensitivity. The preliminary studies indicate that the sensitivity does not strongly depend on pile-up, owing to the fact that the jets from stop decays are relatively high E_T.

VLHC will be necessary to explore other colored states.

1.2.5 'Only' the Standard Model

We now consider a scenario where LHC14/300 does not discover any additional particles beyond the Higgs boson. At the end of such a run, the LHC will have not only discovered the Higgs boson, but will have made impressive progress in the program of precision Higgs measurements. The scenario we now consider also assumes that the measurements of Higgs couplings are consistent with their standard model values. In addition, we assume that there is no discovery of physics beyond the standard model from the intensity frontier program (*e.g.* new flavor violation) or the cosmic frontier program (*e.g.* dark matter direct detection). Any such discovery would potentially point to higher energy scales that can be directly explored at the energy frontier. In the scenario where there is no discovery of new fundamental physics, should we give up on searches for new physics at the energy frontier?

As discussed at the beginning of this report, there are strong motivations for new physics at the TeV scale, but they do not make unambiguous predictions for the masses and couplings of the new particles involved. The LHC14/300 has impressive reach for new physics, but many models will not be fully explored. The energy frontier program is an extremely ambitious long-term program of exploring the unknown, and the gaps in our knowledge of what we will find are also a measure of what we have to gain by continuing the search. There are a large number of well-motivated ideas in which new physics can be discovered and thoroughly explored using energy frontier facilities. These must be pursued if we are to continue to make progress in understanding the most fundamental questions of physics.

The physics that is out of reach of the LHC14/300 can be roughly divided into two categories: particles with masses beyond the energy reach of the LHC14/300, and particles with lower masses that remain hidden due to small rates and/or large backgrounds. There are two main classes of facilites for further exploration of the energy frontier, proton colliders and lepton colliders. Proton colliders allow for higher energy for direct production, but suffer from large backgrounds and many systematic errors that have to be understood. Lepton colliders have lower energy, but also lower backgrounds and smaller systematic errors, allowing a more complete exploration of physics that is kinematically accessible. Both kinds of new physics is expected in motivated scenarios for physics beyond the standard model, and we will discuss a number of examples of each kind.

The Higgs boson and precision measurements: In the scenario we are considering, enhanced precision in standard model measurements provide a well-motivated window to new physics. In particular, non-standard Higgs boson couplings and decays can provide an important window to new physics in many scenarios. Examples of the impact of precision Higgs couplings on searches for new physics are discussed in the Higgs working group report, and some further examples will be given below. Enhanced precision in other electroweak observables such as properties of the top quark and electroweak gauge bosons can also provide hints for new physics. These are discussed in the top and precision electroweak working group reports.

Naturalness: Before discussing individual physics scenarios, we comment on the notion of naturalness, which motivates much of the new physics we discuss below. Naturalness as used here is the idea that physically measurable parameters (such as masses of particles) should not depend sensitively on fundamental input parameters. In the standard model, the mass of the Higgs boson m_h is generally quadratically sensitive to larger mass scales Λ, such as the unification or Planck scale, and obtaining $m_h \ll \Lambda$ requires an accurate adjustment of fundamental parameters of order $m_h^2/\Lambda^2 \sim 10^{-32}$ for the Planck scale. Eliminating this fine-tuning has been a primary motivation for physics beyond the standard model, including supersymmetry, composite models, and extra dimensions.

Very roughly, all these extensions reduce the scale Λ to which the Higgs boson mass is sensitive to the TeV range. The LHC14/300 will perform a wide range of searches for many kinds of new physics with reach extending to several TeV. Although fine-tuning is notoriously difficult to quantify precisely, it is probably fair to say that these null results imply some degree of fine-tuning in all of these models, perhaps at the level of 10^{-2}. Even if this is the case, it is worth keeping in mind that this represents a tuning of a single parameter, and 1% accidents are not uncommon in nature. For example, the leading quadrupole moment anisotropy in the cosmic microwave background is tuned by more than 1%, even with cosmic variance taken into account. Before the other multipole moments were measured, this was seen as a problem for the standard cold dark matter cosmology, but the measurements of 100's of other multipoles have spectacularly confirmed this picture in detail. Similarly, while not finding any new physics at the LHC14/300 would be an unwelcome surprise, it does not diminish the importance of investigating the ideas that eliminate the 10^{-32} tuning of the standard model.

Particle physicists have also investigated the possibility that tuning in the Higgs mass as well as the (much larger) tuning of the cosmological constant are the result of the fact that fundamental parameters may be tuned by anthropic selection effects. Even in such a scenario, the existence of dark matter and gauge coupling unification still motivate new physics at the electroweak scale.

Dark Matter One of the best motivated dark matter candidate is the Weakly Interacting Massive Particle (WIMP). It begins with the simple assumption that dark matter couples weakly to the Standard Model particles, and they are in thermal equilibrium in the early universe. In this scenario, there is an upper limit on the WIMP mass

$$m_{\mathrm{WIMP}} \leq 2\ \mathrm{TeV} \left(\frac{g_{\mathrm{eff}}^2}{0.3} \right), \tag{1.1}$$

where g_{eff} is the coupling strength between dark matter and the Standard Model particles. The most *model independent* collider search relies on the associated production of a pair of WIMPs together with a hard radiation, e.g., a jet, a photon, etc []. LHC14/300 will only cover the WIMPs up to a couple hundred GeV, while **LHC14/3000** can probably double the reach. At the same time, a higher energy **VLHC** at 33/100 TeV can really extend the reach of WIMPs into the TeV(s) regime and cover the main parameter region of the WIMP scenario.

Little Hierarchy Naturalness arguments point towards TeV scale as the place for new physics. However, there is a well known tension between this expectation and the outcome of a host of low energy precision measurements, including flavor changing neutral current processes, CP violation, as well as electroweak precision measurements. In the simplest new physics models, the absence of any deviation from the Standard Model prediction in those measurements seems to prefer at least 10 TeV as the scale of new physics. This is known as the little hierarchy problem, which is ubiquitous (although in somewhat different forms) in new physics scenarios. Many delicate models have been constructed in the past two decades to address it. However, it remains a distinct possibility that the lesson from the simplest models needs to be taken seriously. In this case, the new physics is beyond the reach of the LHC14, and but within the reach of **LHC33** and **LHC100**.

Supersymmetry: Supersymmetry predicts superpartner particles for all standard model particles. Superpartners with QCD color are expected to be heavier than those with only electroweak interactions. The reach of LHC14/300 is highly dependent on the details of the models. For the gluino (the superpartner of the gluon) with the simplest decays, the reach is approximately up to # [], while for electroweak-inos (superpartners of the W, Z, and h) with the simplest decays, the reach is approximately up to # []. The superpartner of the top (the stop) plays an especially important role in the naturalness of SUSY, and searches for stops at LHC14/300 will have a reach up to #, again assuming the simplest decays []. We emphasize that this is only a small sample of a very large number of different SUSY searches, each of which is sensitive to particular features of the superpartner spectrum [].

Null results for all these SUSY searches probably indicates that SUSY is fine-tuned at the percent level. In addition to the general remarks made above, it is worth recalling that SUSY is additionally motivated by gauge coupling unification, the fact that it has a natural dark matter candidate, and that it provides a plausible framework for addressing cosmology and particle physics at energy scales above the electroweak scale. For these reasons, SUSY remains the best motivated and complete framework for new physics at the TeV scale, even in the scenario we are considering.

We now address the capabilities of future collider facilities in exploring SUSY. The **LHC14/3000** will have significant additional reach for SUSY. For example, the mass reach for gluinos with the simplest decays is expected to increase to # [], the reach for electroweak-inos is expected to increase to # []. The searches for stops in the simplest decay scenarios will have increased reach up to #. In addition, as was done for the LHC14/300 there will be a very large number of specialized searches sentitive particular features of SUSY spectra. Another way to get a sense for the additional reach of the high-luminosity LHC is to scan over a large number of SUSY models, as described in the 'pMSSM' whitepaper [?]. A wide variety of SUSY searches was applied to the models in this scan, and it was found that well over half of the models that are not excluded at LHC14/300 can be excluded with 3000 fb^{-1}. The overall conclusion is that the LHC14/3000 will have significant additional reach for SUSY.

We now turn to e^+e^- colliders such as **ILC** and **TLEP**. These will be able to perform essentially hermetic searches for electroweak-inos up to masses of half the center of mass energy []. The mass reach of even a 1 TeV ILC is below that of the LHC14/300 for the very simplest models, but the e^+e^- collider searches will be sensitive to many models that escape the LHC searches due to reduced missing energy due to approximate mass degeneracies and reduced rate due to multiple decay modes.

Higher energy colliders such as the **VLHC** will be able to significantly increase the mass reach for SUSY. There are a limited number of studies, but studies LHC33/3000 give a reach for gluino masses of #. Although detailed studies are still needed, it is clear that these colliders will have spectacular increased high energy sensitivity to heavy SUSY particles.

Composite Higgs Models: In these models generally contain top partners for naturalness. LHC14/300 probe these up to # mass for the XXX model , and more generally top partners with masses in the TeV range can be probed []. The LHC13/3000 can extend this reach up to # for the XXX model, with similar results expected (found?) for other models. The reach can be extended further at higher energy proton machines **(any studies?)**

These models are also probed by precision Higgs coupling measurements. Deviations are expected at the level of #%. The reach for precision studies is discussed in the Higgs working group report. Comparing the reach for top partners and precision Higgs measurements is very model-dependent, but they are complementary and generally probe similar ranges of scales.

These models also contain resonances in the few TeV range associated with the symmetry breaking that gives rise to the Higgs. These are generally more difficult to probe experimentally, especially once constraints from precision electroweak measurements are imposed. They can however be searched for in high proton colliders or multi-TeV lepton colliders.

Randall-Sundrum Models: These models predict a large number of new resonances at the TeV scale that can be searched for at high-energy machines. Lower-energy states that can be probed at e^+e^- colliders are not generically present in these models. The RS model has a natural way of addressing the origin of flavor. At the same time, the corresponding constraints from flavor changing neutral current measurements can be very strong. In the simplest setup, the KK-mode of top and gluon are constrained to be in the 10 TeV range. This is clearly out of the reach of LHC14/300, which can reach to about 4 TeV. **LHC14/3000** can improve that limit to about 6 TeV. At the same time, the reach at the **VLHC** can be approximately improved by an factor of the increase in center of mass energy. Therefore, most of the ”natural” parameter space can be covered.

Heavy Resonances: Heavy neutral gauge bosons (Z') are very well-motivated, for example they are generic in many string constructions. A Z' with standard model-like couplings can be excluded up to # by LHC14/300. ILC typically can achieve a better reaching by studying the interference between Z' and Z/γ. The reach can be extended up to # at LHC14/3000, and **other machines**? The Z' can be directly studied at such colliders, as described in Z' **discovery story** in this report.

Although e^+e^- colliders do not have the energy reach of high-energy hadron machines, they can study Z' bosons indirectly via their effects on e^+e^- annihilation. For example, a 500 GeV ILC can probe Z' with standard model-like couplings with masses up to 10 TeV.

Another example is dijet resonances. LHC14/300 can exclude these up to masses of # for XXX model. The reach for discovery and study of such resonances is significant only at high energy proton colliders.

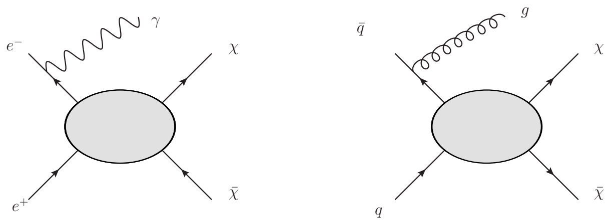


Figure 1-2. *Pair production of WIMPs ($\chi\bar{\chi}$) in e^+e^- collisions (left), or pp collisions (right), both via an unknown intermediate state, with initial-state radiation of a standard model particle.*

1.2.6 Dark Matter

Though the presence of dark matter in the universe has been well-established, little is known of its particle nature or its non-gravitational interactions. A vibrant experimental program is searching for a weakly interacting massive particle (WIMP), denoted as χ, and interactions with standard model particles via some as-yet-unknown mediator.

One critical component of this program is the search for pair-production of WIMPs at particle colliders, specifically $pp \rightarrow \chi\bar{\chi}$ at the LHC or $e^+e^- \rightarrow \chi\bar{\chi}$ at a lepton collider, both via some unknown intermediate state. If the mediator is too heavy to be resolved, the interaction can be modeled as an effective field theory with a four-point interaction, otherwise an explicit model is needed for the heavy mediator. As the final state WIMPs are invisible to the detectors, the events can only be seen if there is associated initial-state radiation of a standard model particle [13, 32, 34], see Fig 1-2, recoiling against the dark matter pair.

In this section, we describe the sensitivity of future pp and e^+e^- colliders in various configurations to WIMP pair production using the mono-jet final state (in the pp case) or mono-photon final state (in the e^+e^- case). We consider both effective operators and one example of a real, heavy Z'-boson mediator.

1.2.6.1 Searches at *pp* colliders

The LHC collaborations have reported limits on the cross section of $pp \rightarrow \chi\bar{\chi} + X$ where X is a hadronic jet [3, 18], photon [4, 19], and other searches have been repurposed to study the cases where X is a W [11] or Z boson [2, 17]. In each case, limits are reported in terms of the mass scale $M_\star$ of the unknown interaction expressed in an effective field theory [14, 13, 32, 34, 46, 16, 35, 10, 44] though the limits from the mono-jet mode are the most powerful [51].

In Ref. [50], the sensitivity of possible future proton-proton colliders is studied in various configurations (see Table 1-1) to WIMP pair production using the mono-jet final state. Both effective operators and one example of a real, heavy Z'-boson mediator are considered.

The analysis of jet+$\not\!\!E_T$ events uses a sample of events with one or two high p_{T} jets and large $\not\!\!E_T$, with angular cuts to suppress events with two back-to-back jets (multi-jet background). The dominant remaining background is $Z \rightarrow \nu\bar{\nu}$ in association with jets, which is indistinguishable from the signal process of $\chi\bar{\chi}$+jets. The estimation of the background at large $\not\!\!E_T$ is problematic in simulated samples, due to the difficulties of accurately modeling the many sources of $\not\!\!E_T$. The experimental results, therefore, rely on data-driven background estimates, typically extrapolating the $Z \rightarrow \nu\bar{\nu}$ contribution from $Z \rightarrow \mu\mu$ events with large Z boson p_{T}. These results use estimates are anchored in experimentally reported values [3, 18] of the

Table 1-1. *Details of current and potential future pp colliders, including center-of-mass energy ($\sqrt{s}$), total integrated luminosity ($\mathcal{L}$), the threshold in $\not{E}_T$, and the estimated signal and background yields. From Ref. [50].*

$\sqrt{s}$ [TeV]	$\not{E}_T$ [GeV]	$\mathcal{L}$ [fb^{-1}]	N_{D5}	$N_{\rm bg}$
7	350	4.9	73.3	1970 ± 160
14	550	300	2500	2200 ± 180
14	1100	3000	3200	1760 ± 143
33	2750	3000	$8.2{\cdot}10^4$	1870 ± 150
100	5500	3000	$3.4{\cdot}10^6$	2310 ± 190

background estimates and signal efficiencies (at $\sqrt{s} = 7$ TeV, $\mathcal{L} = 5$ fb^{-1}, $\not{E}_T > 350$ GeV), and use simulated samples to extrapolate to higher center-of-mass energies, where no data is currently available. At the higher collision energies and instantaneous luminosities of the proposed facilities, the rate of multi-jet production will also be higher, requiring higher $\not{E}_T$ thresholds to cope with the background levels and the trigger rates, see Ref. [50] for details.

Given the expected background and uncertainties, limits can be calculated on contributions from new sources, which can be translated into limits on M_*, see Fig. 1-3. These are then translated in limits on the χ-nucleon cross section.

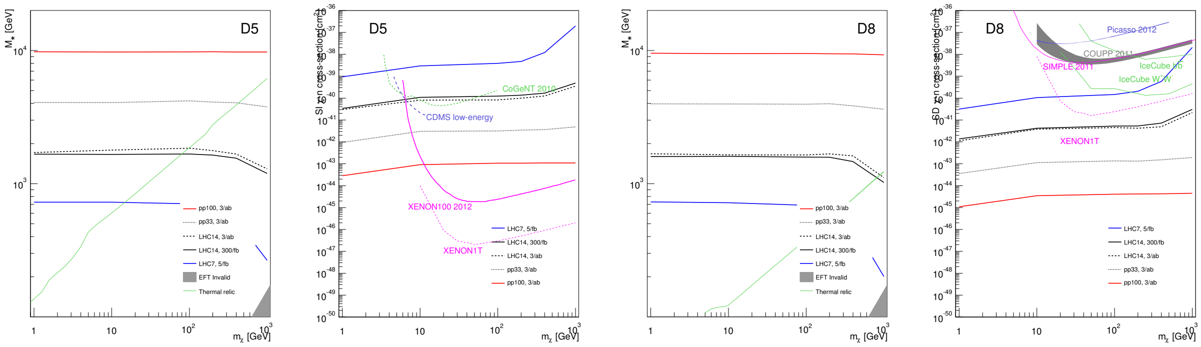


Figure 1-3. *Limits at 90% CL in $M_\star$ (left) and in the spin-independent WIMP-nucleon cross section (right) for different facilities using the D5 or D8 operator as a function of m_χ. From Ref. [50].*

The EFT approach is useful when the current facility does not have the necessary center-of-mass energy to produce on-shell mediators. The next-generation facility, however, may have such power. The sensitivity of the proposed facilities to a model in which the heavy mediator is a Z' which couples to $\chi\bar{\chi}$ as well as $q\bar{q}$ [9] is discussed. The coupling of the Z' is a free parameter in this theory, but particularly interesting values are those which correspond to the limit of previous facilities on M_*. That is, an EFT model of the Z' interaction has $\frac{1}{M_*} = \frac{g_{Z'}}{M_{Z'}}$ fixing the relationship between $g_{Z'}$ and $M_{Z'}$. Figure 1-4 shows the expected limits in terms of $g_{Z'}$ on the Z' model at the variety of pp facilities under consideration. The g' expected limits can be compared to the curve with $g_{Z'} = \frac{M_{Z'}}{M_*}$.

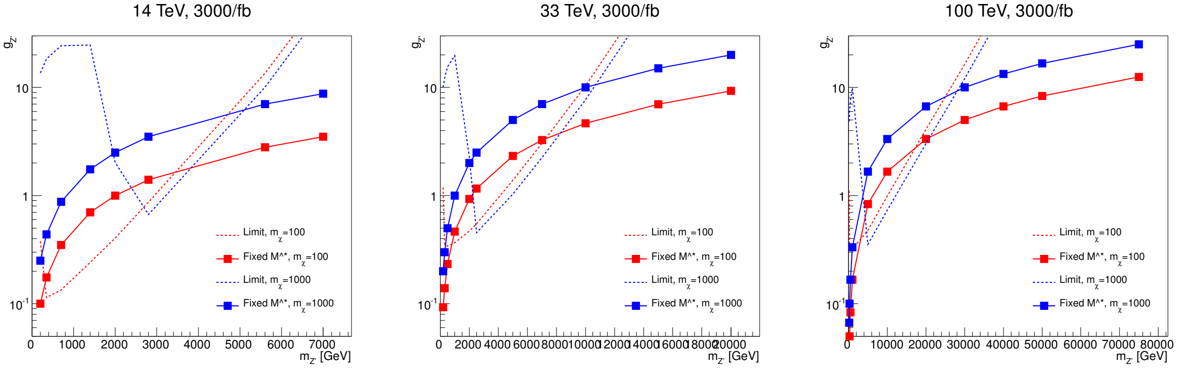


Figure 1-4. *Sensitivity of various pp facilities to a dark matter pairs produced through a real Z' mediator. In each case, expected limits on the coupling $g_{Z'}$ versus Z' mass for two choices of m_χ as well as the values of $g_{Z'}$ which satisfy $g'/m_{Z'} = 1/M_*$, where M_* are limits from a lower-energy facility. From Ref. [50]*

1.2.6.2 Searches at lepton colliders

The same mechanism which allows *pp* colliders to be sensitivie to the coupling of the initial-state quarks to WIMP pairs allows e^+e^- colliders to proble the couplings of electrons to WIMP pairs, see Fig 1-2.

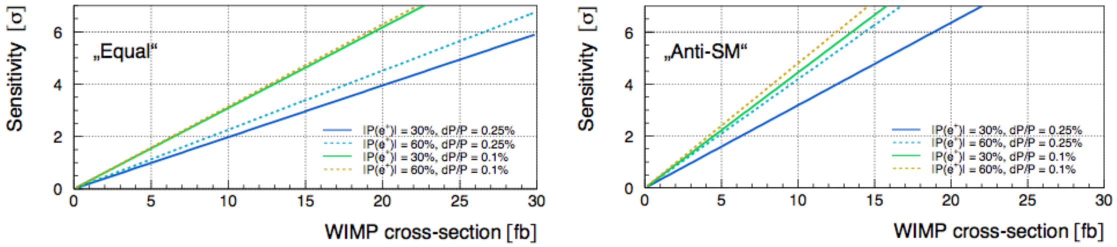


Figure 1-5. *Sensitivity as a function of WIMP pair-production cross sections, for two beam polarization options and two uncertainty scenarios. From Ref. [12]*

The final state is a high-p_T photon with missing momentum due to the invisible χ pair. The dominant background is production of neutrino pairs via a Z boson, with a photon from initial state radiation.

Studies at lepton colliders offer two important advantages compared to similar studies at *pp* machines. First, the polarization of the initial state may be controlled, which gives power to distinguish between the WIMP signal and the backgrounds, which may have distinct polarization-dependent couplings.

Following the analysis of Ref. [12], three coupling scenarious are considered:

- *equal*: couplings are independent of the helicity of the initial state,
- *helicity*: couplings conserve helicity and parity, and
- *anti-SM*: WIMPs couple oly to right-handed electrons (left-handed positrons)

where the final case has the greatest power to disentangle the SM backgrounds from WIMP production. The relative sensitivity of two of these scenarios is shown in Fig 1-5.

The second major advantage of a lepton collider is its sensitivity to the WIMP mass through its effect on the observed photon total energy, see Fig 1-6.

Such studies were possible at LEP, but the small integrated luminosity of the dataset and lack of control over beam polarization results in a significant decrease in sensitivity.

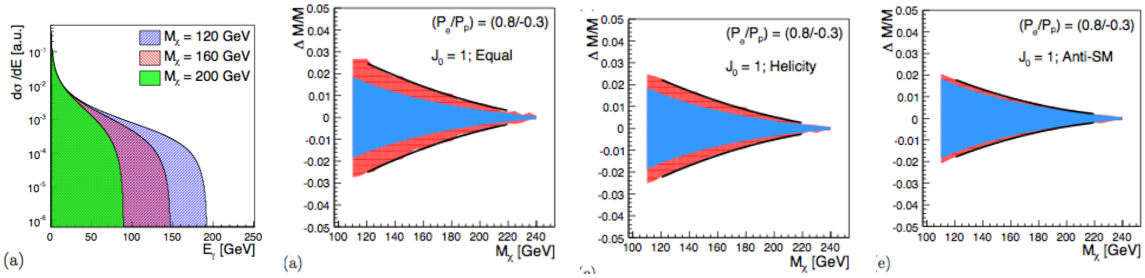


Figure 1-6. *Left, dependence of the photon energy spectrum on the dark matter mass, m_χ. Right, expected relative uncertainty on m_χ as a function of m_χ for three coupling scenarios. From Ref. [12]*

1.2.6.3 Connections to Cosmic and Intensity Frontiers

The search for WIMPs via their interactions with the standard model is clearly an area where the energy frontier overlaps with the cosmic frontier, where there are dedicated direct-detection experiments searching for recoil interactions $\chi + n \to \chi + n$. We have compared the collider sensitivity to these direct-detection experiments by translating the collider results into limits on the $\chi - n$ interaction cross section. In addition, the results may be translated to compare with indirect detection experiments, which probe WIMP annihilation into standard model particles, $\chi\bar{\chi} \to XX$. In Fig 1-7, we map *pp* sensitivities to WIMP pair annihilation cross-section limits. Predictions are compared to Fermi-LAT limits from a stacking analysis of Dwarf galaxies [5], including a factor of two to convert the Fermi-LAT limit from Majorana to Dirac fermions, and to projected sensitivities of CTA [28].

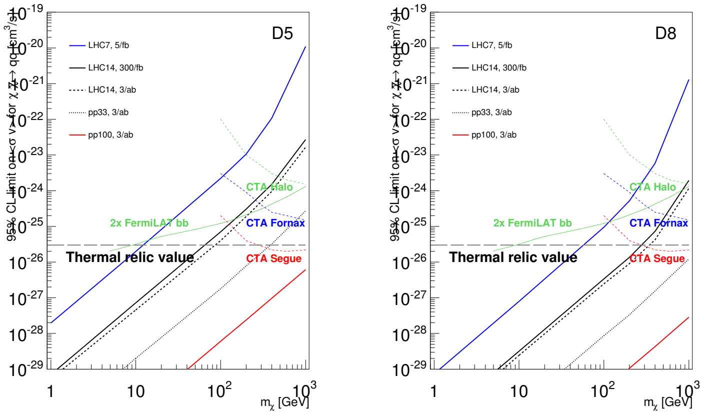


Figure 1-7. *Limits at 95% CL on WIMP pair annihilation for different facilities using the D5 (left) or D8 (right) operator as a function of m_χ. From Ref. [50].*

Connections are also possible to intensity frontier programs. Discuss friedland paper.

1.2.7 Z'

Additional colorless vector gauge bosons (Z') occur in many extensions of the Standard Model (SM), in part because it is generically harder to break additional abelian $U(1)'$ factors than non-abelian ones[1]. Although Z's can occur at any scale and with couplings ranging from extremely weak to strong, we concentrate here on TeV-scale masses with couplings not too different from electroweak, which might therefore be observable at the LHC or future colliders.

In this section, we summarize both the discovery reach and the potential of measuring the properties of new vector gauge bosons at future facilities. Following the notation in [38], we define the couplings of the SM and additional gauge bosons to fermions by

$$-L_{NC} = eJ^{\mu}_{em}A_{\mu} + g_1 J^{\mu}_1 Z^0_{1\mu} + g_2 J^{\mu}_2 Z^0_{2\mu}, \tag{1.2}$$

ith

$$J^{\mu}_{\alpha} = \sum_i \bar{f}_i \gamma^{\mu}[\epsilon^{\alpha i}_L P_L + \epsilon^{\alpha i}_R P_R] f_i. \tag{1.3}$$

n this report, We will focus on several well known examples, listed in Table 1.2.7.

	χ	ψ	η	LR	BL	SSM	
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1	
$\hat{\epsilon}^q_L$	–1	1	–2	–0.109	1/6	$\hat{\epsilon}^u_L$	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
						$\hat{\epsilon}^d_L$	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^u_R$	1	–1	2	0.656		$\hat{\epsilon}^u_R$	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_R$	–3	–1	–1	–0.874		$\hat{\epsilon}^d_R$	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^l_L$	3	1	1	0.327	–1/2	$\hat{\epsilon}^{\nu}_L$	$\frac{1}{2}$
						$\hat{\epsilon}^e_L$	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}^e_R$	1	–1	2	–0.438		$\hat{\epsilon}^e_R$	$\sin^2\theta_W$

Table 1-2. *Benchmark models and couplings, with* $\epsilon^i_{L,R} \equiv \hat{\epsilon}^i_{L,R}/D$.

1.2.7.1 Discovery rearches

LHC

Hadron colliders has great reaches for searching for vector resonances. Such searches typically look for a resonance peak in lepton pair invariant mass distribution. Due to its simplicity and importance, it is usually among the earliest searches to be carried out at hadron colliders.

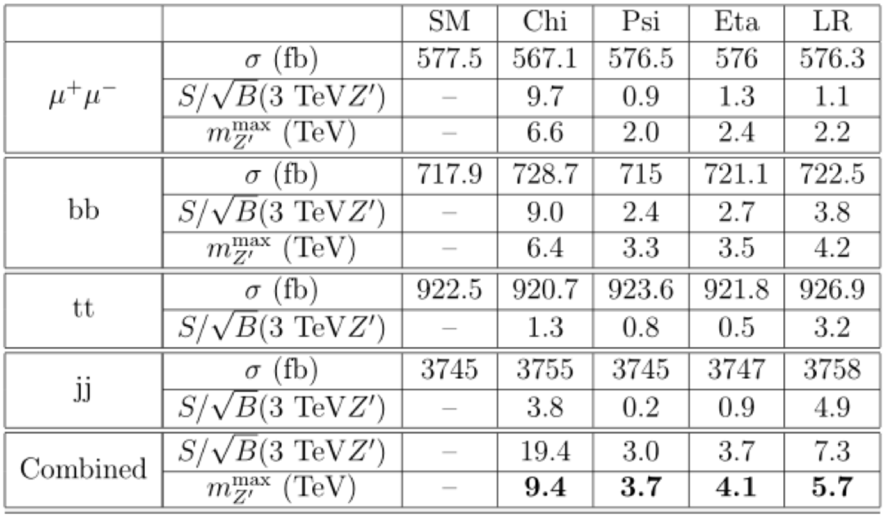
[figure of LHC reach]

ILC

ILC can search for vector resonance by observing its interference with the Standard Model Z and photon. In many cases, it can go beyond the capabilities of the 14 TeV LHC. The ILC reaches for several Z'models are presented in Fig. 1-8.

---

[1] For reviews, see [38, 23, 36, 40]. Specific properties are reviewed in [24, 31, 39, 42, 37].



		SM	Chi	Psi	Eta	LR
$\mu^+\mu^-$	σ (fb)	577.5	567.1	576.5	576	576.3
	$S/\sqrt{B}$(3 TeVZ')	–	9.7	0.9	1.3	1.1
	$m_{Z'}^{\max}$ (TeV)	–	6.6	2.0	2.4	2.2
bb	σ (fb)	717.9	728.7	715	721.1	722.5
	$S/\sqrt{B}$(3 TeVZ')	–	9.0	2.4	2.7	3.8
	$m_{Z'}^{\max}$ (TeV)	–	6.4	3.3	3.5	4.2
tt	σ (fb)	922.5	920.7	923.6	921.8	926.9
	$S/\sqrt{B}$(3 TeVZ')	–	1.3	0.8	0.5	3.2
jj	σ (fb)	3745	3755	3745	3747	3758
	$S/\sqrt{B}$(3 TeVZ')	–	3.8	0.2	0.9	4.9
Combined	$S/\sqrt{B}$(3 TeVZ')	–	19.4	3.0	3.7	7.3
	$m_{Z'}^{\max}$ (TeV)	–	**9.4**	**3.7**	**4.1**	**5.7**

Figure 1-8. *Reach for Z' at the ILC. Several search channels are combined, including $\mu^+\mu^-$, bb, tt and di-jet.* [**will have a plot here**]

1.2.7.2 After the discovery

If a Z'has been discovered, the immediate next step would be to measure its properties as much as we can. Combining the measurements at Hadron collider and lepton collider can be very valuable.

The useful observables are $\sigma_{\rm prod}\times$BR in various channels, total width. Many Z'candidates are chiral. To reveal this nature of their coupling, it is useful to consider asymmetry variable defined as

$$A_{FB} = A_c \equiv \frac{\sigma(|y_f| > |y_{\bar{f}}|) - \sigma(|y_f| < |y_{\bar{f}}|)}{\sigma(|y_f| > |y_{\bar{f}}|) + \sigma(|y_f| < |y_{\bar{f}}|)}, \tag{1.4}$$

he predicted value as well as experimental precision for the $\sigma_{\rm prod}\times$BR($Z' \to$ dilepton) and A_C are shown in Fig. 1-9.

For the LHC case, we have used e^+e^- final state since it has better resolution in the relevant energy regime. In addition to the statistical uncertainties, we take the systematic uncertainties $10\% \oplus 2\%$ ($6\% \oplus 2\%$) for the cross section for LHC 300 fb^{-1} 3000 fb^{-1}. Among those systematic uncertainties, the 10% (6%) is correlated uncertainties (e.g., PDF uncertainties and luminosity uncertainties) that will cancel when taking the ratios of cross sections, leaving 2% systematics for charge asymmetry A_c. The charge asymmetry can be determined very well for these asymmetric models as Z'_χ, $Z'_{\rm LR}$ and $Z'_{\rm SSM}$, approximately 20 % (5 %) at LHC 14 ,TeV with 300 fb^{-1} (3000 fb^{-1}). The error becomes relatively large in case of very symmetric models such as Z'_ϕ, Z'_η and $Z'_{\rm B-L}$.

[**more details on ILC study**]

Discovery of Z'leads to many new implications which can lead to further searches at colliders. There should be (at least) a associated Higgs with the Z'. Discovering this new Higgs would be much harder than discovering the Z', similar to the discovery of W/Z vs the Higgs in the Standard Model. The understanding of the nature of Z'couplings, even if a partial one, will give us insight about its embedding in the high scale (UV) and more fundamental theory. Such UV completions of Z'usually leads to additional predictions.

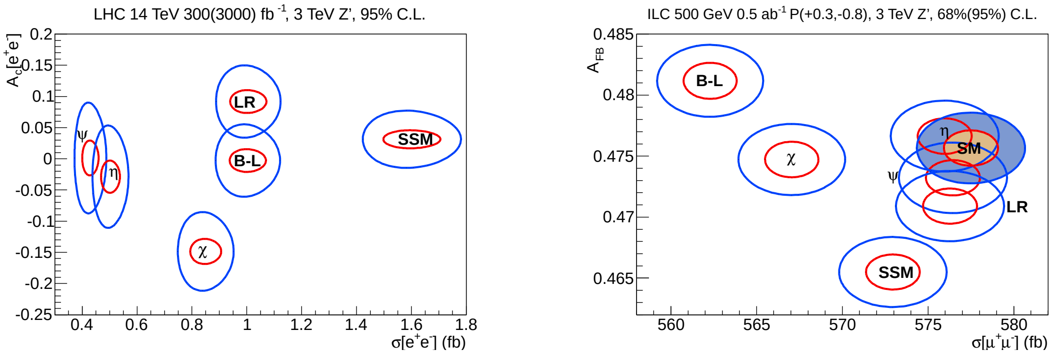


Figure 1-9. *The results from* $pp \to Z' \to e^+e^-$ *with dimuon invariant mass within* 2.8 $\sim$ 3.2 *TeV. Left panel: the charge asymmetry versus the event rate at 95% C.L. for the benchmark models. We take the systematic uncertainties* $10\% \oplus 2\%$ ($6\% \oplus 2\%$) *for the cross section at* 300 fb^{-1} (3000 fb^{-1}), *in which the* 10% (6%) *is correlated uncertainties that will cancel when taking the ratios of cross sections, leaving* 2% *systematics for charge asymmetry* A_c. *Right panel: Charge symmetry versus event rate at the ILC.*

$Z'$with the Standard Model fermions could be anomalous. Therefore, there has to be new fermions which can lead to new collider signals. If a $Z'$is consistent with the one from Left-Right symmetric model, there should also be additional heavy resonances, such as W'_R and exotic Higgses, with similar masses. In the context of supersymmetry, Z'can play an important role, such as the solution of the mu problem and the mediator of the supersymmetry breaking. Z'decaying into superpartners can be an important discovery channel.

1.2.7.3 Hadronic Z'

It is possible for $Z'$to only couple to the Standard Model quarks. Such hadronic Z'can be searched for as di-jet resonances.

1.2.8 Higgs Portal

If evidence is seen at the LHC of invisible Higgs boson decays, it may be evidence of Higgs boson couplings to dark matter, such as $h \to \chi\bar{\chi}$.

- Linear collider to study charges and coupling in detail

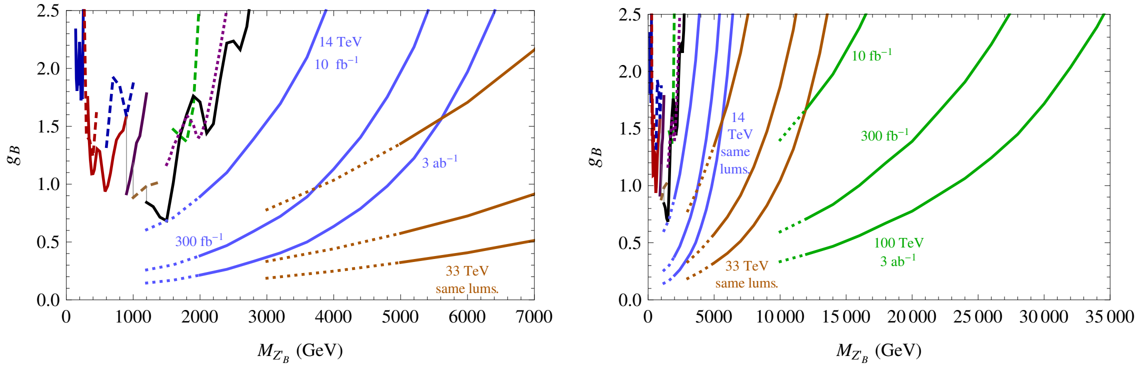


Figure 1-10. *Hadronic resonance searches at hadron colliders.*

1.2.9 Multiple Higgs Bosons

After the discovery of the Higgs boson, avery important question is whether there are additional Higgs bosons, as is predicted by many motivated models, including supersymmetry. Higgs bosons couple most strongly to particles with the largest mass, motivating searches for new particles that decay to vector bosons, the 125 GeV Higgs, or heavy fermions (top/bottom/tau).

In the scenario we now discuss, we consider a signal at LHC14/300 for $A \to Zh \to (bb)(\ell\ell)$. There is significant reach for discovery in this channel, as can be seen in [missing plot]. For this scenario, we assume a type-I 2HDM with $m_A = 325$ GeV, and $\alpha = \#$, $\beta = \#$.

By the end of the 14 TeV run with 300 fb^{-1} of integrated luminosity, an excess is observed in searches for anomalous Zh production in the $bb\ell\ell$ final state consistent with a production cross section times branching ratio of ~ 10 fb. The full $m_{\ell\ell bb}$ invariant mass distribution peaks around 325 GeV. The lepton pair production is consistent with the leptonic decay of a Z boson, while the invariant mass of the bottom quark pair is consistent with the decays of the observed SM-like Higgs boson at 125 GeV. The signal significance is $\sim 2.5\sigma$. There is also a mild $\sim 1\sigma$ excess in the $\tau^+\tau^-\ell\ell$ channel where the lepton pairs are again consistent with leptonic decay of a Z boson, but without sufficient mass resolution to conclusively relate to the excess in the $bb\ell\ell$ final state. The final states and approximate mass reconstruction in the $bb\ell\ell$ final state are consistent with the production of a pseudoscalar Higgs boson with decay to Zh.

At the same time, there are no meaningful excesses in searches for resonant WW and ZZ di-boson production in this mass range, nor are there any meaningful signals in the ongoing searches for additional MSSM Higgs bosons in the bb and $\tau\tau$ final states at large $\tan\beta$. In the context of a two-Higgs-doublet model, the natural interpretation is the CP-odd pseudoscalar A at low $\tan\beta$, where the branching ratio for $A \to Zh$ may be appreciable but the rates for gluon fusion or bbA associated production with $A \to bb, \tau\tau$ are not large enough to be distinguished from background.

Motivated by these excesses, a search conducted in the 300 fb^{-1} data set for $\ell\ell+\gamma\gamma$ consistent with anomalous Zh production yields ~ 3 events whose $m_{\ell\ell\gamma\gamma}$ accumulate at 325 GeV, further suggesting the presence of a new state decaying to Zh but not substantially increasing the significance of the excess. Given that these signals in the Zh final state are consistent with a pseudoscalar Higgs at low $\tan\beta$, both collaborations consequently extend their inclusive diphoton resonance searches to close the gap in coverage between the endpoint of the SM-like Higgs search at 150 GeV and the beginning of the KK resonance search at 500 GeV. Upon unblinding the analysis, they detect a signal consistent with the production and decay of a 325 GeV particle decaying to pairs of photons with $\sigma \cdot \mathrm{Br} \sim 7$ fb at 14 TeV. The lack of events in dijet-tagged categories indicate that there is no meaningful associated production, bolstering the case for a new pseudoscalar.

Attempts to interpret the resonance in terms of the MSSM are stymied by the resolution of Higgs coupling measurements in the 300 fb^{-1} data set. For a pseudoscalar in the MSSM at low $\tan\beta$ with $m_A = 325$ GeV, the generic expected deviation in the hbb coupling is of order $\sim 5 - 20\%$, with much smaller deviations in $h\gamma\gamma$, htt, and hVV. The precision of Higgs coupling measurements at 300 fb^{-1} only serve to bound $\tan\beta < 4$ in the MSSM. Both the high-luminosity run of the LHC and the ILC become high priorities for establishing the discovery of the new state and triangulating measurements of Higgs couplings at both 125 GeV and 325 GeV.

At the high luminosity run of the LHC, the signal reaches 5σ significance in the $bb\ell\ell$ final state by 1000 fb^{-1} of integrated luminosity, sufficient to announce the discovery of a new state. The excess in the $\tau^+\tau^-\ell\ell$ channel grows to several σ, consistent with a production cross section times branching ratio of ~ 1 fb, while the excess in the diphoton final state at 325 GeV also reaches 5σ significance by the end of the full 3000 fb^{-1}. However, the experimental and theoretical errors on the discovery-level channels are sufficiently large that interpretation based on direct coupling measurements of the new state remains challenging. Interpreted in the context of a Type II 2HDM, the best fit to the production and decay rates favors $\tan\beta \approx 2, \cos(\beta - \alpha) \approx -0.012$. This is in mild tension with the MSSM interpretation, for which the tree-level prediction at $\tan\beta \approx 2$ is closer to $\cos(\beta - \alpha) \approx -0.04$, but without sufficient experimental resolution to provide meaningful discrimination. Although the errors on the Higgs coupling measurements at 125 GeV improve to $\Delta g_{hbb} \sim 10\%$, still no significant deviation from Standard Model predictions is observed. Finally, after the full 3000 fb^{-1} are analyzed, a collection of 10 4ℓ events consistent with $H \to ZZ \to 4\ell$ are reconstructed around 450 GeV – sufficient to hint at the presence of an additional CP-even scalar but insufficient to establish discovery. Searches for a resonance in $t\bar{t}$ prove inconclusive.

A lepton collider such as the ILC or TLEP can explore the electroweak symmetry breaking sector in detail. For example, at the $\sqrt{s} = 250$ GeV run of an ILC, the coupling measurements of the 125 GeV Higgs improve to $\Delta g_{hbb} \sim 5\%$ without observing deviations from SM predictions, increasing tension with the MSSM interpretation. No direct production of the new state is kinematically possible. However, at $\sqrt{s} = 500$ GeV, the pseudoscalar is expected to be kinematically available in both $b\bar{b}A$ and Ah associated production. Indeed, after 500 fb^{-1} are on tape, $b\bar{b}A$ associated production is observed at the level of a small handful of events consistent with $\sigma(b\bar{b}A) \sim 0.1$ fb. Two Zhh events are observed consistent with $e^+e^- \to Ah \to Zhh$, but are difficult to distinguish from the SM di-Higgs background given the low statistics. By $\sqrt{s} = 1$ TeV the bbA signal increases consistent with a cross section of ~ 1 fb, leaving several hundred $b\bar{b}A$ events on tape and substantially improving the direct coupling measurements of the pseudoscalar. Most importantly, the ILC operating at $\sqrt{s} = 1$ TeV discovers additional states in the Higgs sector. The first is a 370 GeV charged Higgs with cross section of order ~ 10 fb. The primary discovery mode is H^+H^- Drell-Yan pair production in the $t\bar{t}b\bar{b}$ final state. The mass splitting between the charged Higgs and the pseudoscalar are again in tension with tree-level MSSM predictions for the mass spectrum. Reaching closer to the kinematic threshold, the ILC discovers the hinted-at CP-even scalar at 450 GeV through HA associated production in the final state $t\bar{t}Zh$ with a cross section of several femtobarn.

In addition, the improvement of Higgs coupling measurements at 125 GeV indicates a small persistent tension with SM predictions at the level of $\Delta g_{hbb} \sim 2\%$. While the departure is not statistically significant, the smallness of Δg_{hbb} is in tension with conventional MSSM predictions. In the context of a Type II 2HDM, the combination of measurements of the light SM-like Higgs at 125 GeV, the pseudoscalar at 325 GeV, the charged Higgs at 370 GeV, and the second CP-even scalar at 450 GeV imply an extended Higgs sector that is closer to the alignment limit than implied by supersymmetric decoupling alone, with the best-fit point in a Type II 2HDM ultimately corresponding to $\tan\beta = 2, \cos(\beta - \alpha) = -0.0122$, as well as with mass relations between scalars that are discrepant from the standard MSSM predictions. This ignites fervent exploration of non-standard corners of MSSM Higgs parameter space, as well as other natural theories of extended electroweak symmetry breaking.

A high-energy proton collider can also continue exploration of the extended Higgs sector.

1.2.10 Heavy Quarks

The simplest way to introduce new heavy fermions is in a standard model-like chiral new generation of heavy quarks. However, such a chiral 4th generation would couple to the Higgs boson with a Yukawa coupling that is proportional to its mass and therefore enhance Higgs boson production through gluon fusion by about a factor nine. This is clearly inconsistent with the observed Higgs production cross section. Thus a chiral 4th fermion generation seems to be ruled out.

Vector-like quarks are non-chiral, that is their left- and right-handed components transform in the same way. Therefore their mass terms do not violate any symmetry and do not have to be generated by a Yukawa coupling to the Higgs boson. They couple to the Higgs boson only through their mixing with standard model quarks. This mixing is limited to small values by measurements of the S, T, U parameters. For such small mixing angles vector-like quarks are not expected to affect the gluon fusion production rate of the Higgs boson significantly and thus are not ruled out by the observed Higgs boson production cross section.

Vector-like quarks are motivated by some solutions to the hierarchy problem[27, 45, 21, 7, 6, 26, 25]. Little Higgs theories predict top-quark partners that cancel the effects of the top-quark loops on the Higgs boson mass. Models of compositeness also predict vector-like top partners. Vector-like quarks can be weak isospin singlets, such as the charge 2/3 top quark partners predicted by little Higgs, top color, and top condensate models. However, they could also be weak isospin doublets including top and a bottom partners (T', B', $X_{5/3}$ and $Y_{-4/3}$ fermionic partners). The $Y_{-4/3}$ has a T'-like W^-b final state, with distinction only possible through a challenging measurement of the b-quark jet charge. Additional vector-like multiplets in higher representations are also possible, with the prediction of a wider range of T'-like exotica, with a collection of the possibilities outlined in [**?**]. Generically, models in which the SM fields propagate in an extra spatial dimension predict the existence of Kaluza-Klein towers of vector-like quarks. The KK partner of the top quark, for example, will in general decay to primarily 3rd generation quarks and SM gauge bosons. Additionally, ultraviolet completions of R-parity violating SUSY models that follow the philosophy of minimal flavor violation to protect against baryon number violating operators [22] contain such T' quarks [**?**]

Earlier optimized searches exist for special cases in which the T' decays with 100% branching ratio to the $W-b$ (as in the sequential 4th generation model) [**?**, **?**] or $t-Z$ [**?**] final states. For most of the well motivated constructions, three final states $b-W$, $t-Z$, and $t-h$ may result from T' decays. Note that other decays that involve the first two generation quarks are in principle also possible, but are generally suppressed in models that do not violate existing flavor constraints. A recent study which explores this possibility is [**?**].

The benchmark scenario considered for the snowmass study takes into account the three decays allowed by different models, such as $T' \to tZ$, and $T' \to tH$. For this benchmark, Goldstone's theorem applies such that in the heavy T' limit, the branching ratios for the three processes asymptotically obey $\mathrm{BF}(T' \to bW) = 2\mathrm{BF}(T' \to tZ) = 2\mathrm{BF}(T' \to th)$.

Recent studies have sought to obtain more general limits such that the three branching fractions of the T' are free parameters, albeit subject to the constraint that no other final states are allowed, such that the model spans a "triangle" of branching fractions. In fact, a large class of models follows a specific trajectory within the triangle, with this trajectory determined by quantum numbers of the T'.

An analysis of a general set of top partner final states with optimization over various branching fractions in the triangular phase space has been carried out by the CMS Collaboration[**?**]. Direct limits based on current data exclude vector-like quarks for masses below 700-800 GeV, depending on their decay branching fractions[**?**, **?**]. Earlier studies [**?**, **?**, **?**], based on ATLAS results have analyzed a more simplified "triangle" of branching fractions, with only a few points consiered. The second looks at the specific case of little Higgs models, where the T' is taken to be a singlet.

At the HL-LHC with $\sqrt{s} = 14$ TeV and 3000/fb vector-like quarks up to masses of 1.5 TeV can be observed *(reference CMS and the 4 other snowmass whitepaers - quote their results - still in flux).*

For completeness, we note that there may be other exotic decays of T's to non-SM particles (or flavor violating decays) which may reduce the sum of these three BF's below 1. For example, in the Littlest Higgs model with T-parity [**?**, **?**, **?**], there is a $T' \rightarrow T_{-}A_H \rightarrow tA_HA_H$, decay mode with the A_H playing the role of a "neutralino." This stop-like final state reduces sensitivity in the Wb, Zt, and Ht channels, but also offers a complementary final state that is part of ongoing searches [**?**].

If there is a vector-like T quark with a mass of 1200 GeV an excess of events should appear at the LHC with 14 TeV pp collisions after 300/fb have been collected. In events with a single electron or muon and several high-p_T jets of which at least one shows substructure consistent with originating from a hadronic W or Z decay one may see an excess of 500 events over an expected background of about 2000 events.

If such an excess is seen in a search for vector-like heavy quark one would first want to determine the properties of the new particle, such as production process (single or pair-production) and cross section, mass, charge, decay modes and branching fractions. *how well can these be measured at LHC?* The first order of business would be to establish the nature of the new particle. Additional evidence for a new particle could come from events with two or more leptons. If the production cross section is consistent with strong production the particle likely is colored. One would identify whether the decay modes are consistent with vector-like quarks. Vector-like quarks with charge 5/3 decay to tW, those with charge 2/3 decay to bW, tZ, and tH,and those with charge 1/3 decay to tW, bZ, and bH.

Most interestingly, observation of a vector-like quark would most likely indicate that there are other heavy new particles. In little Higgs models there would be W and Higgs boson partners, in compositeness models there would likely be other vector-like quarks.

Depending on the mass of the vector-like quark and the other new particles, collisions at higher energy might be needed to produce the particles in sufficient numbers to understand their properties. This could be done at HE-LHC or VLHC pp colliders or at the CLIC e^+e^- collider. Given the existing mass limits it is not likely that the ILC or TLEP could contribute significantly to their study. *can one determine projections for the potential mass reach for vector-like quarks and the potential measurement precision for their properties for VLHC and CLIC?*

- Very Large hadron collider or CLIC to study new heavy quarks

1.2.11 Compositeness

High-energy particles are powerful probes of physics at small scales. Experiments at escalating energy scales have historically unveiled layers of substructure in particles previously considered as fundamental, from Rutherfords probing of gold atoms which revealed the presence of a central nucleus, to deep inelastic scattering of protons which demonstrated the existence of quarks.

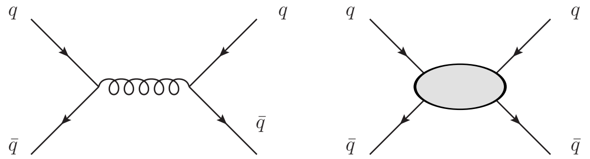


Figure 1-11. *Diagrams for QCD mediation of quark-quark interactions (left) and a four-fermion contact interaction describing an effective field theory for the mediation of a new interaction between quark constituents.*

In this section, we consider the extent to which the compositeness of today's fundamental fermions, the quarks and leptons, can be probed by future collider facilities [30, 29].

1.2.11.1 Quark Compositeness

Quarks as bound states of more fundamental particles may explain current outstanding questions, such as the number of quark generations, the charges of the quarks, or the symmetry between the quark and lepton sectors.

A typical approach to the study of quark compositeness [20] is to search for evidence of new interactions between quarks at a large characteristic energy scale, Λ. At interaction energies below Λ, the details of the new interaction and potential mediating particles can be integrated out to form a four-fermion contact interaction model (see Fig 1-11). This is well-described by an effective field theory approach [15]:

$$\begin{aligned} L_{qq} = \frac{2\pi}{\Lambda^2}[&\eta_{LL}(\bar{q_L}\gamma^\mu q_L)(\bar{q_L}\gamma_q^\mu L) \\ &+ \eta_{RR}(\bar{q_R}\gamma^\mu q_R)(\bar{q_R}\gamma^\mu q_R) \\ &+ 2\eta_{RL}(\bar{q_R}\gamma^\mu q_R)(\bar{q_L}\gamma^\mu q_L)] \end{aligned} \tag{1.5}$$

where the quark fields have L and R chiral projections and the coefficients η_{LL}, η_{RR}, and η_{RL} turn on and off various interactions. In this report, we focus on ($\eta_{LL} = 1, \eta_{RR} = 0, \eta_{RL} = 0$) to study the center-of-mass dependence of the sensitivity of the facilities and reserve the other modes for later work.

Evidence for contact interactions would appear in dijets with large m_{jj} and a center-of-mass angle relative to the beam axis, θ^*, which is smaller than what is expected for production via quantum chromodynamics, which predominantly produces jets with large θ^* peaked in the forward and backward directions.

While next-to-leading-order calculations of QCD [41] and the contact interactions expected from quark compositeness [33] are available, they are computationally intensive and for the purpose of this study, leading-order calculations are sufficient. Events are generated at leading-order with MADGRAPH [8], describe the showering and hadronization with PYTHIA [47] and the detector response with DELPHES [43] for the facilities described in Table 1-3.

Based on Ref. [49] which follows the approach of Ref [20], the analysis variable is $\chi_{jj} = (1 + |\cos\theta^*|)/(1 - |\cos\theta^*|)$ which is roughly uniform for QCD interactions and peaked at small values for the contact interactions studied here, see for example Fig. 1-12. In the analysis of Ref [20], the dominant uncertainties are statistical and theoretical, followed by experimental uncertainties such as jet energy resolution and calibration. Theoretical uncertainties are due primarily to variation in the predicted χ_{jj} shape with changes

Table 1-3. *Details of compositeness studies for current and potential future pp colliders, including center-of-mass energy ($\sqrt{s}$), total integrated luminosity ($\mathcal{L}$) and the minimum threshold in m_{jj}*

$\sqrt{s}$ (TeV)	$\mathcal{L}$ (fb^{-1})	m_{jj} threshold (TeV)
7	2	3
14	300	5
14	3000	7.5
33	3000	16
100	3000	44

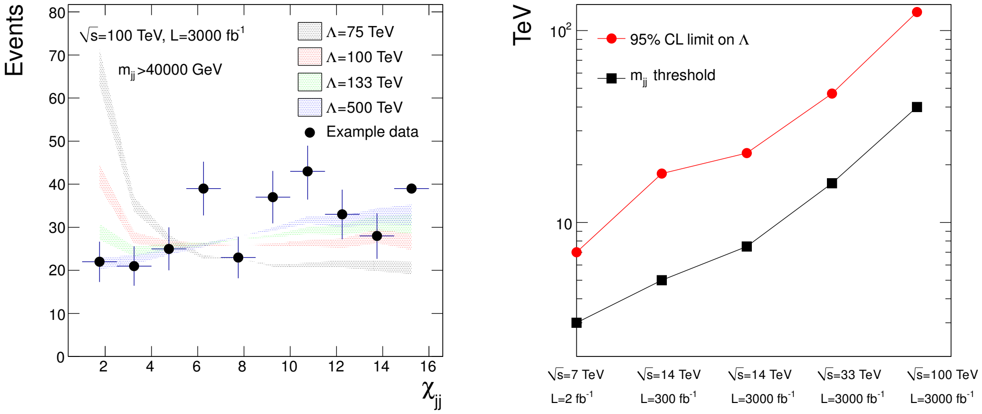


Figure 1-12. *Left, distributions of χ_{jj} for QCD and contact interactions with a variety of choices of Λ for the case of pp interactions with with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 3000$ fb^{-1}. Right, summary of m_{jj} thresholds and sensitivity to contact interaction scale Λ.*

to the renormalization and factorization scales. In this study, the approximate size and dependence on χ_{jj} of the theoretical uncertainty are extracted from Ref [20] and applied to the predictions from our simulated samples.

The statistical analysis is performed by evaluating a likelihood ratio where nuisance parameters are fixed at the nominal values. The extraction of the limit is done using the CLs [1, 48] technique, where the null and alternate hypothesis p-values are evaluated from distributions of q constructed using simulated experiments where the nuisance parameters have been varied according to their prior probabilites.

The distortion of the χ_{jj} shape is most distinct at large m_{jj}. However, the cross section falls sharply with m_{jj}, reducing the statistical power of the data. These two effects are in tension, and there is an optimum value of m_{jj}. Note that in Ref [20] the analysis is done in several bins of m_{jj} in order to validate the predictions at low values and capture distortions in intermediate bins. In our study, we use only the highest bin in m_{jj}. The sensitivity of Ref [20] is approximately reproduced using this approximate approach.

As seen in Fig. 1-12, increases in center-of-mass energy brings significant increases in sensitivity to the mass scale, Λ, such that a collider with $\sqrt{s} = 100$ TeV would be expected to probe scales above $\Lambda = 125$ TeV.

If a deviation from QCD production is seen at the LHC with $\sqrt{s} = 14$ TeV, then a future facility may be have the energy to directly produce the new heavy particle which mediates the interaction of the quark constituents, dependening on the mass scale. This would appear as a dijet resonance in $q\bar{q} \rightarrow q\bar{q}$ events, see Section 1.2.7. Specifically, we can relate the exclusio of the compositeness scale Λ to that of the mass of a Z' mediator as:

$$\frac{g_{Z'}^2}{36M_{Z'}^2} = \frac{2\pi}{\Lambda^2}.$$

For example, at $\sqrt{s} = 14$ TeV with =3000 fb^{-1}, an exclusion of $\Lambda > 18$ TeV would correspond to excluding a Z' with ($m_{Z'} = 1200$ GeV , $g_{Z'} = 0.12$).

1.2.11.2 Lepton Compositeness

In a similar manner to quark compositeness, lepton compositeness may appear as a new interaction which acts at very large $m_{\ell\ell}$ to modify the observed spectrum in $pp \rightarrow \ell\ell$ production.

Waiting for study from Stephane

1.3 Summary and Conclusions

1.4 Summary

This report has attempted to convey some of the opportunities for physics beyond the standard model at the energy frontier.

References

[1] A. Read. *J. Phys. G: Nucl. Part. Phys.*, 28:2693, 2002.

[2] Georges Aad et al. Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector. *JHEP*, 1303:128, 2013.

[3] Georges Aad et al. Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector. *JHEP*, 1304:075, 2013.

[4] Georges Aad et al. Search for dark matter candidates and large extra dimensions in events with a photon and missing transverse momentum in pp collision data at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys.Rev.Lett.*, 110:011802, 2013.

[5] M. Ackermann et al. Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope. *Phys.Rev.Lett.*, 107:241302, 2011.

[6] Kaustubh Agashe, Roberto Contino, Leandro Da Rold, and Alex Pomarol. A Custodial symmetry for Zb anti-b. *Phys.Lett.*, B641:62–66, 2006.

[7] Kaustubh Agashe, Roberto Contino, and Alex Pomarol. The Minimal composite Higgs model. *Nucl.Phys.*, B719:165–187, 2005.

[8] Johan Alwall, Michel Herquet, Fabio Maltoni, Olivier Mattelaer, and Tim Stelzer. MadGraph 5 : Going Beyond. *JHEP*, 1106:128, 2011.

[9] Haipeng An, Xiangdong Ji, and Lian-Tao Wang. Light Dark Matter and Z' Dark Force at Colliders. *JHEP*, 1207:182, 2012.

[10] Yang Bai, Patrick J. Fox, and Roni Harnik. The Tevatron at the Frontier of Dark Matter Direct Detection. *JHEP*, 1012:048, 2010.

[11] Yang Bai and Tim M.P. Tait. Searches with Mono-Leptons. *Phys.Lett.*, B723:384–387, 2013.

[12] C. Bartels, M. Berggren, and J. List. *arXiv:1206.6639*, 2012.

[13] Maria Beltran, Dan Hooper, Edward W. Kolb, Zosia A.C. Krusberg, and Tim M.P. Tait. Maverick dark matter at colliders. *JHEP*, 1009:037, 2010.

[14] Maria Beltran, Dan Hooper, Edward W. Kolb, and Zosia C. Krusberg. Deducing the nature of dark matter from direct and indirect detection experiments in the absence of collider signatures of new physics. *Phys.Rev.*, D80:043509, 2009.

[15] J. Beringer et al. Review of Particle Physics (RPP). *Phys.Rev.*, D86:010001, 2012.

[16] Qing-Hong Cao, Chuan-Ren Chen, Chong Sheng Li, and Hao Zhang. Effective Dark Matter Model: Relic density, CDMS II, Fermi LAT and LHC. *JHEP*, 1108:018, 2011.

[17] Linda M. Carpenter, Andrew Nelson, Chase Shimmin, Tim M.P. Tait, and Daniel Whiteson. Collider searches for dark matter in events with a Z boson and missing energy. 2012.

[18] Serguei Chatrchyan et al. Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1209:094, 2012.

[19] Serguei Chatrchyan et al. Search for Dark Matter and Large Extra Dimensions in pp Collisions Yielding a Photon and Missing Transverse Energy. *Phys.Rev.Lett.*, 108:261803, 2012.

[20] Serguei Chatrchyan et al. Search for quark compositeness in dijet angular distributions from *pp* collisions at $\sqrt{s} = 7$ TeV. *JHEP*, 1205:055, 2012.

[21] Roberto Contino, Yasunori Nomura, and Alex Pomarol. Higgs as a holographic pseudoGoldstone boson. *Nucl.Phys.*, B671:148–174, 2003.

[22] Csaba Csaki, Yuval Grossman, and Ben Heidenreich. MFV SUSY: A Natural Theory for R-Parity Violation. *Phys.Rev.*, D85:095009, 2012.

[23] Mirjam Cvetic and Stephen Godfrey. Discovery and identification of extra gauge bosons. 1995.

[24] Mirjam Cvetic and P. Langacker. Z-prime physics and supersymmetry. 1997.

[25] S. Dawson and E. Furlan. A Higgs Conundrum with Vector Fermions. *Phys.Rev.*, D86:015021, 2012.

[26] Andrea De Simone, Oleksii Matsedonskyi, Riccardo Rattazzi, and Andrea Wulzer. A First Top Partner's Hunter Guide. *JHEP*, 1304:004, 2013.

[27] F. del Aguila, L. Ametller, Gordon L. Kane, and J. Vidal. VECTOR LIKE FERMION AND STANDARD HIGGS PRODUCTION AT HADRON COLLIDERS. *Nucl.Phys.*, B334:1, 1990.

[28] M. Doro et al. Dark Matter and Fundamental Physics with the Cherenkov Telescope Array. *Astropart.Phys.*, 43:189–214, 2013.

[29] E. Eichten, I. Hinchliffe, Kenneth D. Lane, and C. Quigg. Super Collider Physics. *Rev.Mod.Phys.*, 56:579–707, 1984.

[30] E. Eichten, Kenneth D. Lane, and Michael E. Peskin. New Tests for Quark and Lepton Substructure. *Phys.Rev.Lett.*, 50:811–814, 1983.

[31] Jens Erler, Paul Langacker, Shoaib Munir, and Eduardo Rojas. Improved Constraints on Z-prime Bosons from Electroweak Precision Data. *JHEP*, 0908:017, 2009.

[32] Patrick J. Fox, Roni Harnik, Joachim Kopp, and Yuhsin Tsai. Missing Energy Signatures of Dark Matter at the LHC. *Phys.Rev.*, D85:056011, 2012.

[33] Jun Gao, Chong Sheng Li, Jian Wang, Hua Xing Zhu, and C.-P. Yuan. Next-to-leading QCD effect to the quark compositeness search at the LHC. *Phys.Rev.Lett.*, 106:142001, 2011.

[34] Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M.P. Tait, et al. Constraints on Dark Matter from Colliders. *Phys.Rev.*, D82:116010, 2010.

[35] Jessica Goodman, Masahiro Ibe, Arvind Rajaraman, William Shepherd, Tim M.P. Tait, et al. Constraints on Light Majorana dark Matter from Colliders. *Phys.Lett.*, B695:185–188, 2011.

[36] JoAnne L. Hewett and Thomas G. Rizzo. Low-Energy Phenomenology of Superstring Inspired E(6) Models. *Phys.Rept.*, 183:193, 1989.

[37] Joerg Jaeckel and Andreas Ringwald. The Low-Energy Frontier of Particle Physics. *Ann.Rev.Nucl.Part.Sci.*, 60:405–437, 2010.

[38] Paul Langacker. The Physics of Heavy Z' Gauge Bosons. *Rev.Mod.Phys.*, 81:1199–1228, 2009.

[39] Paul Langacker. The Physics of New U(1)-prime Gauge Bosons. *AIP Conf.Proc.*, 1200:55–63, 2010.

[40] A. Leike. The Phenomenology of extra neutral gauge bosons. *Phys.Rept.*, 317:143–250, 1999.

[41] Zoltan Nagy. Next-to-leading order calculation of three jet observables in hadron hadron collision. *Phys.Rev.*, D68:094002, 2003.

[42] Pran Nath, Brent D. Nelson, Hooman Davoudiasl, Bhaskar Dutta, Daniel Feldman, et al. The Hunt for New Physics at the Large Hadron Collider. *Nucl.Phys.Proc.Suppl.*, 200-202:185–417, 2010.

[43] S. Ovyn, X. Rouby, and V. Lemaitre. DELPHES, a framework for fast simulation of a generic collider experiment. 2009.

[44] Arvind Rajaraman, William Shepherd, Tim M.P. Tait, and Alexander M. Wijangco. LHC Bounds on Interactions of Dark Matter. *Phys.Rev.*, D84:095013, 2011.

[45] Martin Schmaltz and David Tucker-Smith. Little Higgs review. *Ann.Rev.Nucl.Part.Sci.*, 55:229–270, 2005.

[46] William Shepherd, Tim M.P. Tait, and Gabrijela Zaharijas. Bound states of weakly interacting dark matter. *Phys.Rev.*, D79:055022, 2009.

[47] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. A Brief Introduction to PYTHIA 8.1. *Comput.Phys.Commun.*, 178:852–867, 2008.

[48] T. Junk. *Nucl. Instrum. Methods A*, 434:425, 1999.

[49] S Upadhyay, N. Varelas, F. Yu, and D. Whiteson. *arXiv:XXXX.XXXX*, 2013.

[50] N. Zhou, D. Berge, T. Tait, L.-T. Wang, and D. Whiteson. *arXiv:XXXX.XXXX*, 2013.

[51] Ning Zhou, David Berge, and Daniel Whiteson. Mono-everything: combined limits on dark matter production at colliders from multiple final states. 2013.