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New Particles Working Group Report

Conveners: Yuri Gershtein, Markus Luty, Meenakshi Narain, Lian-Tao Wang, Daniel Whiteson

Authors: L. Apanasevich, G. Artoni, A. Avetisyan, H. Baer, C. Bartels, D. Berge, M. Berggren, S. Bhattacharya, K. Black, T. Bose, J. Brau, R. Brock, E. Brownson, M. Cahill-Rowley,A. Cakir, T. Cohen, R. Cotta, N. Craig, K. Dienes, B. Dobrescu, D. Duggan, R. Essig, J. Evans, A. Drlica-Wagner, S. Funk, Y. Gershtein, J. George, S. G., T. Golling, T. Han, A. Haas, M. Hance, D. Hayden, U. Heintz, A. Henrichs, J. Hewett, J. Hirschauer, K. Howe, A. Ismail, Y. Kats, K. Kaadze, K. C. Kong, A. Kumar, P. Langacker, A. Lath, J. List, T. Lin, L. Linssen, T. Liu, Z. Liu, J. Loyal, M. Luty, I. Melzer-Pellmann, M. Narain, M. M. Nojiri, S. Padhi, N. Parashar, B. Penning, M. Perelstein, M. Peskin, A. Pierce, W. Porod, C. Potter, T. Rizzo, G. Sciolla, J. Stupak III, S. Su, T.M.P. Tait, T. Tanabe, B. Thomas, S. Thomas, S. Upadhyay, N. Varelas, A. Venturini, J. Wacker, M. Walker, L.-T. Wang, D. Whiteson, M. Wood, F. Yu, N. Zhou

This version is an incomplete working version, with many details to be filled in. Please send questions, comments, and suggestions to the conveners.

1.1 Executive Summary

- With the discovery of the Higgs, we have experimentally established the standard model with a scalar particle that appears to be elementary. This gives us a model that can be extrapolated to very high energy scales and forces the question of the naturalness of elementary scalars. Additional motivation for further exploration of the TeV scale comes from supersymmetry, Higgs compositeness, and dark matter, as well as connections to the other frontiers through flavor and neutrino physics.

- The LHC run 1 new physics program is extremely broad, and has out-performed expectations due to innovative search techniques and advances in theory. It has provided strong constraints on a wide variety of new physics models.

- 14 TeV LHC with 300 fb^{-1} will provide an enormous gain in sensitivity to a wide range of new physics models due to increase of both energy and luminosity. Roughly this corresponds to an order of magnitude in tuning in supersymmetry and composite models.

- At the high-luminosity LHC, any preceding LHC run 2 discovery can be extensively studied. The high-luminosity LHC also extends the reach for new physics. For most models the improvements are in the electroweak sector and improvement in tuning can be achieved by a factor of 2 to 4 from the supersymmertic sector.

- The ILC new physics program has been studied in great detail, and has excellent capabilities to discover and measure the properties of new physics, including dark matter, with almost no loopholes. A necessary requirement is that the new physics must be accessible. Essentially this means particles at sufficiently low mass missed by LHC due to blind spots, or heavy physics indirectly accessible through precision measurement. Discovery of physics beyond the standard model at LHC that is accessible at ILC would make the case even more compelling.

- The 33 TeV LHC or 100 TeV VLHC have unprecedented and robust reach for new physics that is evident even with the preliminary level of studies performed so far. Higher energy gives significant enhancement of reach, corresponding to two orders of magnitude in fine tuning. Dark matter can be probed up to the natural WIMP scale of 1 TeV. Essentially any discovery at the LHC would be accessible at these machines and could be better studied there, making the case for these options even more compelling.

- High energy ee and muon colliders offer a long-term program that can extend precision and reach of a wide range of physics.

A summary of the energy reach for a range of physics beyond the SM at various proposed facilities is shown in Fig. 1-1. This is a simplified plot that does not show the caveats and loopholes of searches. Generally, direct searches at e^+e^- colliders are remarkly free of such loopholes.

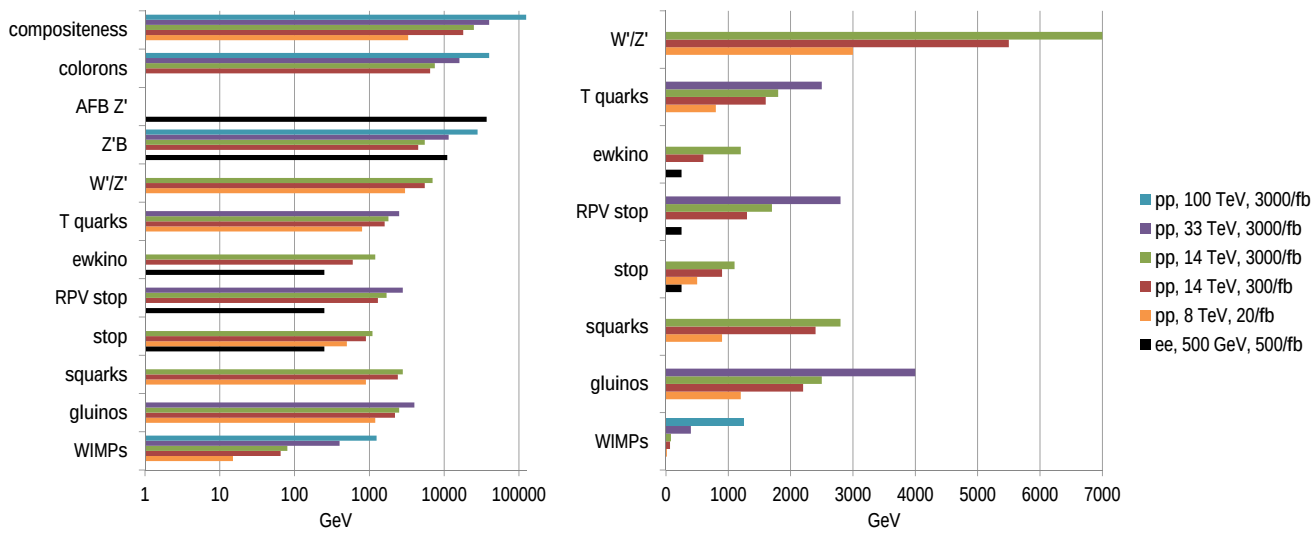

Figure 1-1. *Left Panel: 95% C.L. upper limits for several possible signals of physics beyond the standard model expected from pp colliders at different energies and from ILC. Right panel: Subset of the entries on the left panel on a linear scale.*

1.2 Introduction

Searches for new particles at high-energy particle accelerators have historically been one of the most fruitful paths to discovery of new fundamental particles and interactions, and the establishment of new laws of nature. Particles with any possible quantum numbers can be produced in particle-antiparticle pairs, provided only that they are kinematically accessible and couple with sufficient strength to the colliding particles. General-purpose particle detectors measure the kinematics of all particles with strong or electromagnetic couplings,

as well as the 'missing' momentum due to weakly interacting particles. This gives them the ability to discover almost any possible decay of new particles, as well as new stable particles. An immense body of theoretical and phenomenological work has given a detailed understanding of the effects of the standard model particles and interactions. This allows new particles to be discovered above standard model backgrounds, and their detailed properties to be measured. This is exemplified by the discovery of the Higgs boson. Within a year of the initial discovery, the Higgs program has progressed to detailed measurements of Higgs properties, and the standard model with a Higgs has been experimentally established, at least as a leading approximation.

This is a beginning, not an end. There are many reasons to think that the standard model is incomplete, and that there is new physics to be discovered in searches at the energy frontier. Many of these are discussed in the while papers submitted to the new particles group. The number, diversity, and quality of these white papers attests to the intellectual vigor of this area of research. Rather than attempt a summary of this work, we have decided to illustrate the many exciting possibilities with some examples. This report is therefore organized around a number of well-motivated signals where signs of new physics may be found. To illustrate the impact of such a discovery and the possibilities for further study, we consider in each case a particular model where a discovery can be made at LHC Run 2 (14 TeV with a luminosity of 300/fb). In each case, such a discovery suggests one or more natural candidate models that can be studied in more detail at future experimental facilities. These 'discovery stories' rely heavily on the white papers, which give more comprehensive treatments of the subject. We also consider the case for continuing the search for new physics at the energy frontier if there is no discovery at LHC run 2.

1.2.1 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. This raises the question of whether there are in fact discoveries to be made at the TeV energy scale that are accessible at the energy frontier.

Our answer is that there is strong motivation to continue the search for new physics at the TeV scale and beyond. The impetus for this comes 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 only suggested by the principle of minimality of scales in nature. The big ideas arose from the necessity of reconciling the highly constrained theoretical framework of quantum field theory with the phenomena observed in nature, as well as from theoretical investigations, especially string theory.

Some of the big questions:

- *Are fundamental parameters finely tuned?* The mass of an elementary Higgs boson is sensitive to physics at high energy scales. 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.

- *Is the Higgs boson solely responsible for electroweak symmetry breaking and the origin of mass?* The 125 GeV Higgs boson appears to be the first scalar elementary particle observed in nature. Its measured couplings make it clear that it plays a central role in breaking electroweak symmetry and giving mass to the other elementary particles. But the Higgs boson may be wholly or partially composite, and/or

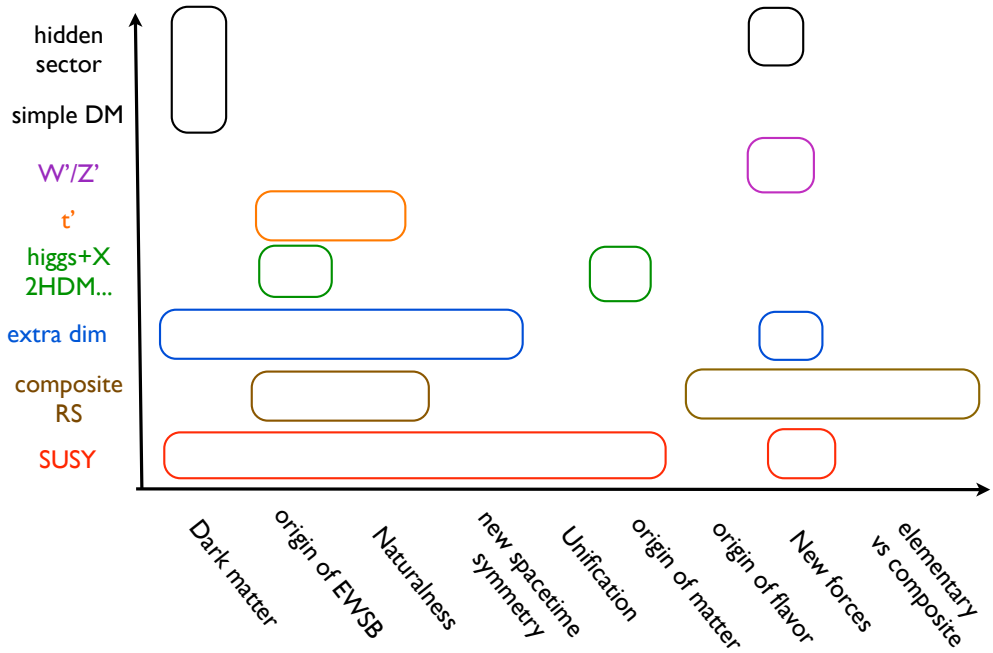

Figure 1-2. *Questions and ideas.*

there may be additional Higgs bosons as part of a larger Higgs sector. These possibilities can be explored by detailed study of the 125 GeV Higgs boson and 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 weakly interacting massive particle (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 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 additional important clues to this puzzle.

- *Are 'elementary' particles really composite?* Most of the particles we observe are composites of more elementary particles. 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.

1.3 Discovery Stories

1.3.1 Higgs Beyond the Standard Model

The discovery of the 125 GeV Higgs boson has made a fundamental change in our view of particle physics. The properties of the Higgs already measured at the LHC are in agreement with those of an elementary standard model Higgs boson at the 10% level, forcing the question of the naturalness of elementary scalars. The naturalness of the Higgs boson requires new physics at the TeV scale. The observed Higgs particle may itself be the harbinger of new physics: it may mix with other Higgs bosons in an extended Higgs sector, have modified couplings due to standard model states, or couple to new physics such as dark matter. In this section we explore some of these possibilities.

Composite Higgs models: Besides supersymmetry, the other big idea for solving the naturalness problem is compositeness of the Higgs sector. This category includes models with extra dimensions at the TeV scale, such as Randall-Sundrum models. The most basic indication that the physics of extra dimensions is closely related to compositeness is that both predict towers of resonances at the TeV scale. This connection is a major theme of modern particle theory, extending all the way from phenomenology and model-building to string theory via the AdS/CFT correspondence.

After the discovery of the 125 GeV Higgs boson, the only natural version of Higgs sector compositeness is that the observed Higgs boson is a pseudo Nambu-Goldstone boson (PNGB) arising from spontaneous breaking of a global symmetry at a scale above the TeV scale. There are corrections to the couplings of the 125 GeV Higgs boson that are proportional to $\xi = (v/f)^2$ where $v = 246$ GeV is the vacuum expectation

value of the Higgs boson and f is a compositeness scale. The ratio ξ is also a direct measure of the fine-tuning required in the model, and is presently required to be less than approximately 0.1 due to Higgs coupling measurements. Improvements on Higgs coupling measurements will improve bounds on this parameter.

These PNGB Higgs models can be probed at hadron colliders in several ways. First, additional naturalness considerations motivate the presence of top partners in these models. These can be searched for at hadron colliders, as discussed in §1.3.9 below. Second, the heavy resonances expected from the symmetry breaking sector at the scale f can be probed. Limits from LHC run 1 for these particles require them to have masses above 2 TeV, and the LHC run 2 and HL-LHC will have additional reach for these models.

At lepton colliders such as ILC and CLIC, the most sensitive probe of the parameter ξ is the Higgs coupling fit. For example, these can reach down to $\xi \sim 0.002$ at 3 TeV CLIC with a luminosity of 1/ab [13, 97]. The impact of other future colliders for the Higgs coupling fit is discussed in the Higgs working group report. In addition, CLIC has a high sensitivity to enhanced double Higgs production, which is a direct consequence of the compositeness of the Higgs boson and therefore a 'smoking gun' for composite modes. This also directly measures the parameter ξ and can be probed down to $\xi = 0.03$ [13].

Exotic Higgs decays: An essential component of the research program of the LHC, and any other future high-energy collider is the search for non-standard ('exotic') decays of the 125-GeV Higgs boson, *i.e.* decays of a SM-like Higgs boson into one or more particles beyond the SM. Non-standard Higgs decays have always been a well-motivated possibility as evidenced by an extensive existing, and growing, literature (see [**?**] for a comprehensive survey of the possibilities and an extensive list of references). They remain a well-motivated possibility even with the discovery of a Higgs particle that is consistent with the simplest SM expectations, and they must be searched for explicitly as they are often unconstrained by other analyses.

The Higgs is the only SM particle that can have renormalizable couplings to SM gauge singlet fields. This, together with the strikingly narrow width of the SM Higgs boson, implies that a small coupling of the Higgs to a new, light state can easily give rise to sizable branching ratios to non-standard decay modes. For example, the addition of a singlet scalar field S to the SM, which couples to the Higgs through a quartic interaction of the form $\lambda S^2 H^2$ is a common building block in models of extended Higgs sectors. Even a coupling as small as $\lambda = 5 \times 10^{-3}$ yields a 10% branching ratio of $h \to SS$ (for $m_S < m_h/2$). Exotic Higgs decays are a generic feature of extensions of the SM that contain light states, and naturally arise in many models of electroweak symmetry breaking, such as the NMSSM and Little Higgs models. A detailed experimental characterization of the Higgs boson at 125 GeV includes searches for *e.g.* $h \to$ invisible, $(1,2)\gamma + \text{MET}$, $\gamma + Z'$, $Z' + \text{MET}$, lepton- or photon-jets, isolated leptons+MET, $4x, 2x2y$ (with $x, y = e, \mu, \tau$-leptons, MET, jets, or b-jets), with or without displaced vertices.

One of the best-motivated examples of exotic Higgs decays is the decay of the 125 GeV Higgs to invisible particles. This is strongly motivated by the coupling of the Higgs to dark matter. Indeed, such a coupling gives a direct detection cross section of the size that is currently being probed in dark matter direct detection experiments.

LHC limits on the branching ratio $h \to$ invisible are 0.65 (ATLAS) [2] and 0.75 (CMS) [3]. This illustrates that there is a great deal of room for new physics in this channel. The Snowmass Higgs working group concludes that the LHC14 with 300/fb will probe branching fractions in the range 0.17–0.28, while the HL-LHC will probe branching fractions in the range 0.06–0.17. The quoted ranges depend on the control of systematics. Overall, the HL-LHC provides an order of magnitude improvement in the reach for this mode. The invisible decay of the Higgs can be cleanly studied at e^+e^- colliders via Zh production. There are no studies for VLHC, but the LHC results provide a proof of concept that this is possible.

Another example that has been studied for this report is the cascade decay $h_1 \to aa \to (\tau\tau)(\tau\tau)$ at ILC [?]. This is a potential signal in the next-to-minimal SUSY standard model (NMSSM). This is an interesting example of an early discovery mode at a 250 GeV ILC. Additionally, the masses can be measured to better than 1% at this facility.

Connection with neutrino masses: A more speculative but very interesting possibility is that the Higgs discovered at the LHC is part of an extended Higgs sector at the TeV scale that also generates naturally small neutrino masses. A very interesting example of this possibility is the type-II see-saw model consisting of a Higgs triplet coupling to left-handed leptons and the Higgs doublet. This model contains a doubly-charged Higgs scalar with lepton number violating decays to same-sign ee, $\mu\mu$, and $\tau\tau$. Searches at LHC have placed limits of $m_{H^{++}} > 400$ GeV using 4.7/fb at 7 TeV [8]. LHC run 2 can extend the reach for the charged Higgs to approximately 1 TeV in favorable cases. The branching ratios to various charged lepton flavors are correlated with the neutrino masses, so that the neutrino mass hiearchy can be determined from collider data. This provides an exciting connection with the neutrino physics program. A well-motivated extension of this model is left-right symmetric model, which contains a right-handed W boson that can be observed at the HL-LHC up to masses up to 4 TeV.

Extended Higgs sectors: Additional Higgs bosons are predicted by many well-motivated extensions of the Standard Model, including supersymmetry and some composite Higgs models. Searches for these states are also motivated simply from the need to fully explore the Higgs sector. Mixing between the 125 GeV Higgs and additional Higgs bosons modifies the couplings of the observed 125 GeV Higgs compared to standard model values. Therefore, searches for new Higgs states and precision Higgs coupling measurements are complementary approaches to the important problem of studying the newly-found Higgs particle. We will discuss this in the context of a 2 Higgs doublet model (2HDM), in which the observed 125 GeV state is the lightest CP-even neutral scalar h. In addition, this model contains another neutral CP-even scalar H, a CP-odd neutral scalar A, and a charged Higgs $H^{\pm}$. In addition to the masses of the various Higgs bosons, the model depends on the CP-even mixing angle α and the ratio of vacuum expectation values of the 2 Higgs doublets $\tan\beta = v_1/v_2$.

The Higgs coupling constant fits for the 2HDM restrict the model to small values of $\cos(\beta - \alpha)$. This is naturally realized in the decoupling limit where one linear combination of the Higgs doublets is getting heavy. Direct searches for new Higgs bosons can probe closer to $\cos(\beta - \alpha)$ if the masses of these states are sufficiently light, making these approaches complementary.

Higgs bosons generally couple most strongly to particles with the largest mass, motivating searches for new particles that decay to vector bosons, the h^0, or heavy fermions (top/bottom/tau). These couplings also lead to appreciable production rates at both hadron and lepton colliders.

At hadron colliders, two senstive searches are $H \to ZZ \to 4\ell$ and $A \to Zh$ followed by $Z \to \ell\ell$ and $h \to bb$ or $\tau\tau$. The reach for the first signal is given for the 14 TeV LHC in Fig. 1-3, and the second in Fig. 1-4.

At hadron colliders, the H and A can be copiously singly produced through gluon fusion or $b\bar{b}$ and $t\bar{t}$ associated production. Charged Higgs bosons can be produced singly via tb associated production at pp colliders or pair-produced via Drell-Yan processes at e^+e^- colliders. Decays of these additional states may be observed in standard Higgs search channels or novel resonant channels involving the 125 GeV Higgs such as Wh, Zh, or hh.

At e^+e^- colliders, for a wide range of models H^+H^- and HA can be observed as long as the sum of the masses is below the center of mass energy of the collider. Furthermore, the masses of the observed states

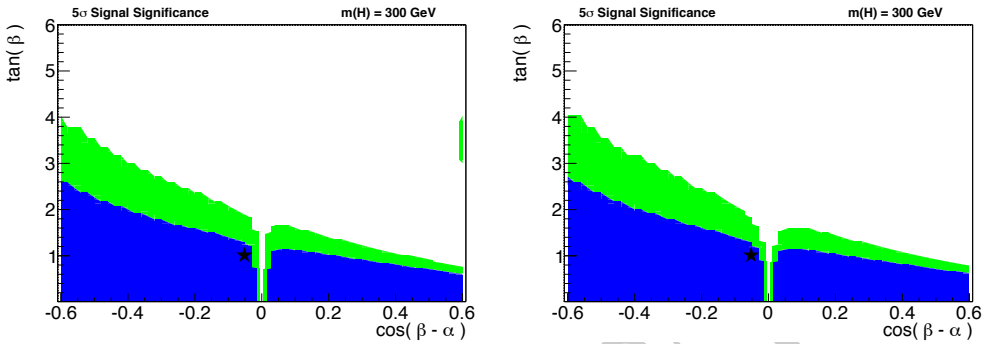

Figure 1-3. *5σ discovery reach for 300 GeV H decaying via $H \to ZZ \to 4\ell$. Blue (green) region is for LHC14 with 300/fb (3000/fb) [39]. The star denotes the parameter point used in the discovery story below.* [**should be at** $\tan\beta = 2$]

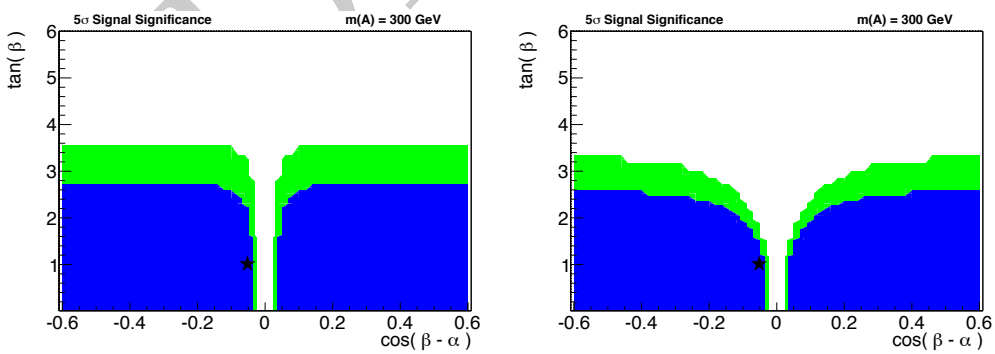

Figure 1-4. *5σ discovery reach for 300 GeV A decaying via $A \to Zh^0 \to (\ell\ell)(bb$ or $\tau\tau$. Blue (green) region is for LHC14 with 300/fb (3000/fb) [39]. The star denotes the parameter point used in the discovery story below.* [**should be at** $\tan\beta = 2$]

can be measured to better than 1% [13]. Consequently, CLIC is ideally suited for the study of Higgs bosons with masses up to 1.5 TeV.

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 Fig. 1-4. For this scenario, we assume a type-II 2HDM with $m_A = 325$ GeV, and $\alpha = -0.475$, $\tan\beta = 2$.

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 $\tan\beta \simeq 2, \cos(\beta - \alpha) \simeq -0.012$. This is in mild tension with the MSSM interpretation, for which the tree-level prediction at $\tan\beta \simeq 2$ is closer to $\cos(\beta-\alpha) \simeq -0.04$, 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 by producing a large sample of heavier Higgs scalars. In this example, although the heavy CP-even scalar H primarily decays to $t\bar{t}$ pairs, it also exhibits rarer decay modes such as $H \to ZA$ and $H \to H^\pm W^\mp$ that are kinematically squeezed but nonetheless observable provided the large number of H bosons produced at a high-energy pp machine. More generally, a high-energy proton collider has the potential to discover additional Higgs bosons that lie well beyond the reach of the LHC and ILC.

1.3.2 WIMP 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.

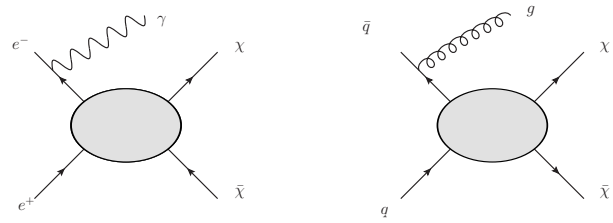

Figure 1-5. *Pair production of WIMPs ($\chi\bar{\chi}$) in e^+e^- collisions (left), or pp collisions (right), both via an unknown intermediate state, with initial-state radiation of a standard model particle.*

WIMPs appear in many theories of physics beyond the standard model (*e.g.* SUSY), or other theories which posit a rich dark sector complete with dynamical self-interactions and striking features at colliders [70]. For other examples, see Refs. [46, 17, 79, 89, 32, 76].

However, this section focusses on a phenomenological approach, searching directly for WIMPs rather than on other states which may appear in the theory. Specifically, this section describes the sensitivity of searches for pair-production of WIMPs at particle colliders, $pp \to \chi\bar{\chi}$ at the LHC or $e^+e^- \to \chi\bar{\chi}$ at a lepton collider via some unknown mediator.

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 [32, 80, 84], see Fig 1-5, 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.

1.3.2.1 Searches at *pp* colliders

The LHC collaborations have reported limits on the cross section of $pp \to \chi\bar{\chi} + X$ where X is a hadronic jet [10, 47], photon [11, 48], and other searches have been repurposed to study the cases where X is a W [29] or Z boson [9, 44]. In each case, limits are reported in terms of the mass scale $M_\star$ of the unknown interaction expressed in an effective field theory [33, 32, 80, 84, 105, 43, 85, 28, 102] though the limits from the mono-jet mode are the most powerful [114].

In Ref. [113], 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 $Z \to \nu\bar{\nu}$ 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 $Z \to \nu\bar{\nu}$ contribution from $Z \to \mu\mu$ events with large Z boson p_{T}. These results use estimates are anchored in experimentally reported values [10, 47] of the 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

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. [113].*

$\sqrt{s}$ [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

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. [113] 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. 1-6. These are then translated in limits on the χ-nucleon cross section.

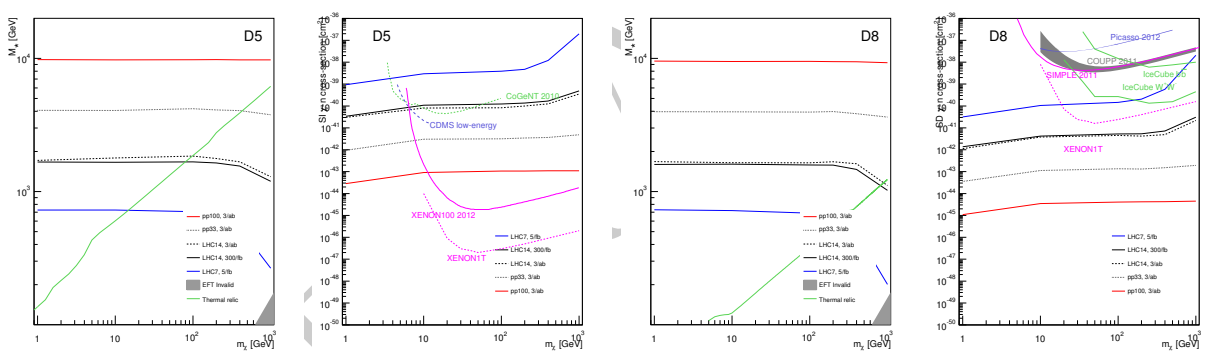

Figure 1-6. *Limits at 90% CL in $M_\star$ (left) and in the spin-independent WIMP-nucleon cross section (right) for different facilities using the D5 or D8 operator as a function of m_χ. From Ref. [113].*

Despite the kinematic and PDF suppression for producing third generation quarks, it was shown [96], that for the scalar operator, searches for $\chi\bar{\chi} + b$ and $\chi\bar{\chi} + t\bar{t}$ final states offer enhanced sensitivity due to the large suppression of background and therefore lower missing energy thresholds.

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 $q\bar{q}$ [20] 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 1-8 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 $g_{Z'} = \frac{M_{Z'}}{M_*}$.

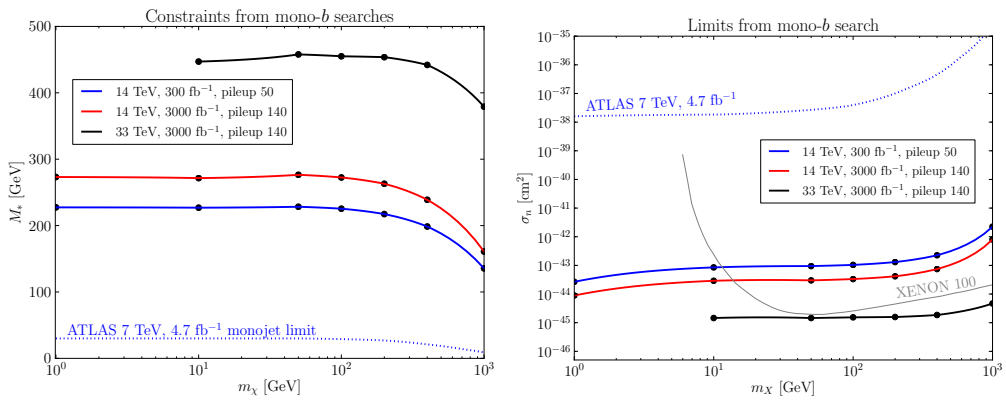

Figure 1-7. *Limits at 90% CL in $M_\star$ (left) and in the spin-independent WIMP-nucleon cross section (right) for different facilities when requiring a b-quark in the final state, as a function of m_χ. From Ref. [22].*

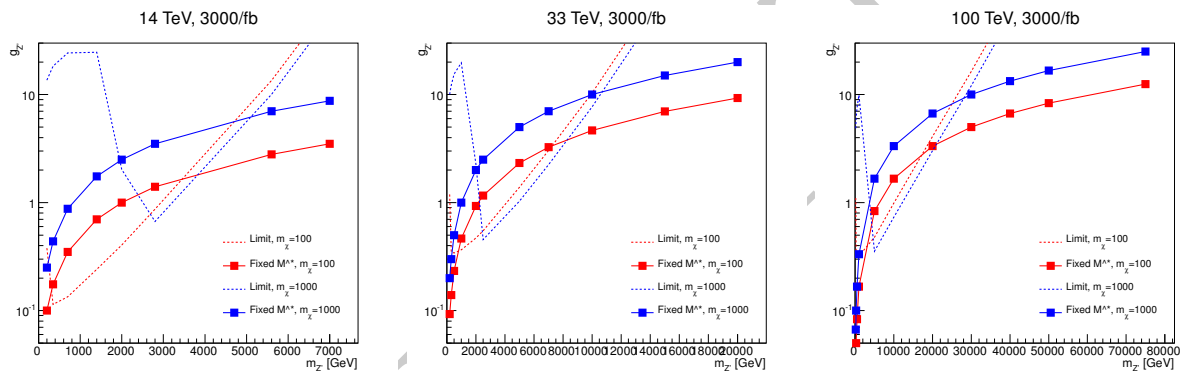

Figure 1-8. *Sensitivity of various pp facilities to a dark matter pairs produced through a real Z' mediator. In each case, expected limits on the coupling $g_{Z'}$ versus Z' mass for two choices of m_χ as well as the values of $g_{Z'}$ which satisfy $g'/m_{Z'} = 1/M_*$, where M_* are limits from a lower-energy facility. From Ref. [113]*

1.3.2.2 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 1-5.

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. The sensitivity reaches up to nearly $\sqrt{s}/2$.

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. [31], three coupling scenarious are considered:

- *equal*: couplings are independent of the helicity of the initial state,
- *helicity*: couplings conserve helicity and parity, and

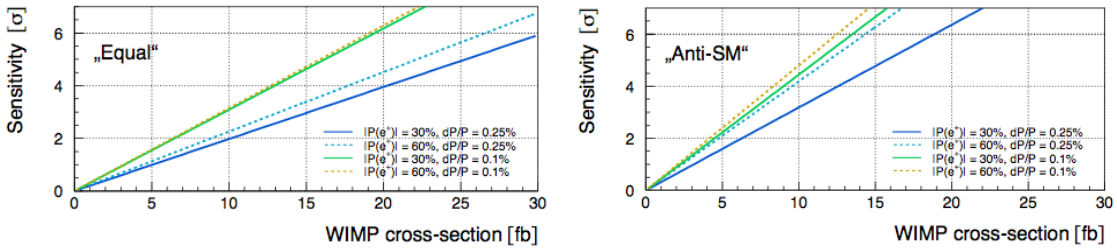

Figure 1-9. *Sensitivity as a function of WIMP pair-production cross sections, for two beam polarization options and two uncertainty scenarios. From Ref. [31]*

- *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 1-9.

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 1-10 for an ILC study. In addition, the ILC can determine spin properties of a WIMP [**?**].

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.

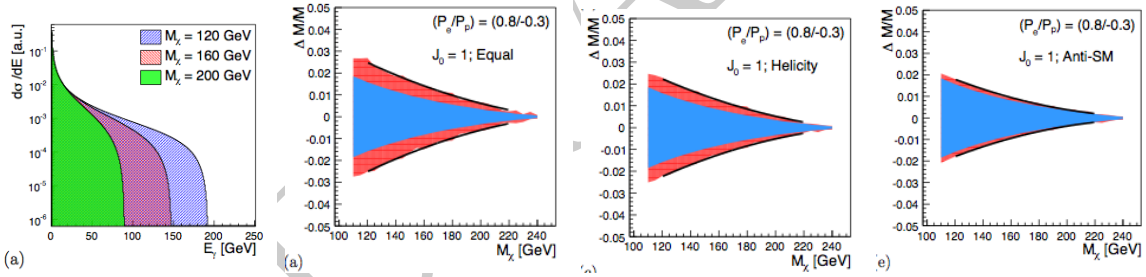

Figure 1-10. *Left, dependence of the photon energy spectrum on the dark matter mass, m_χ. Right, expected relative uncertainty on m_χ as a function of m_χ for three coupling scenarios. From Ref. [31]*

1.3.2.3 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 1-11, 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 [14], including a factor of two to convert the Fermi-LAT limit from Majorana to Dirac fermions, and to projected sensitivities of CTA [72].

These searches also probe models which are commonly considered to be the domain of the intensity frontier, such as extensions of the Standard Model modifying neutrino-quark interactions [81].

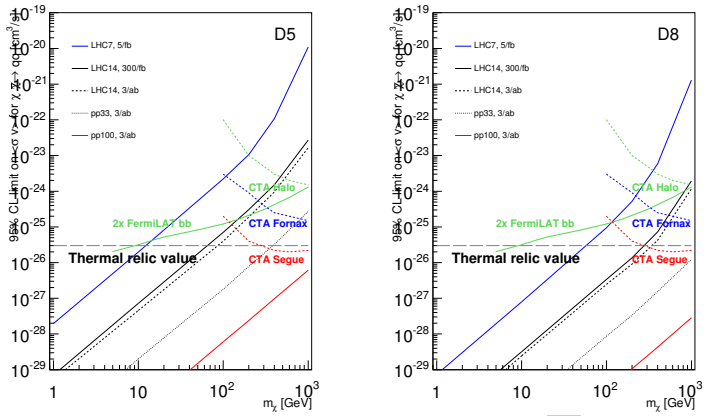

Figure 1-11. *Limits at 95% CL on WIMP pair annihilation for different facilities using the D5 (left) or D8 (right) operator as a function of m_χ. From Ref. [113].*

1.3.3 New gauge bosons

1.3.3.1 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 [93], we define the couplings of the SM and additional gauge bosons to fermions by

$$-L_{NC} = eJ^\mu_{em}A_\mu + g_1 J^\mu_1 Z^0_{1\mu} + g_2 J^\mu_2 Z^0_{2\mu},\ \ J^\mu_\alpha = \sum_i \bar{f}_i \gamma^\mu [\epsilon^{\alpha i}_L P_L + \epsilon^{\alpha i}_R P_R] f_i.$$

In this report, We will focus on several well known examples, listed in Table 1.3.3.1.

Hadron colliders are great for searching for Z'. 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 analyses to be carried out at hadron colliders. The reach at the LHC and HL-LHC are presented in the left and middle panel of Fig. 1-12. In particular, LHC Run 2 can discover Z' up to about 5 TeV, while the HL-LHC and a 33 TeV hadron collider can extend that reach to about 7 TeV and 12 TeV, respectively. Previous studies [68] that a 100 TeV VLHC can ran up to $M'_Z \sim 30$ TeV.

High energy lepton collider can search for Z' by observing its interference with the Standard Model Z and photon. As an example, the ILC reaches for several Z'models are presented in right panel of Fig. 1-12. In particular, in addition to the total rate, the asymmetry observables (defined later) are very powerful in many

[1]For reviews, see [93, 58, 88, 95]. Specific properties are reviewed in [59, 77, 94, 99, 91]

	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 $\epsilon^i_{L,R} \equiv \hat{\epsilon}^i_{L,R}/D$.*

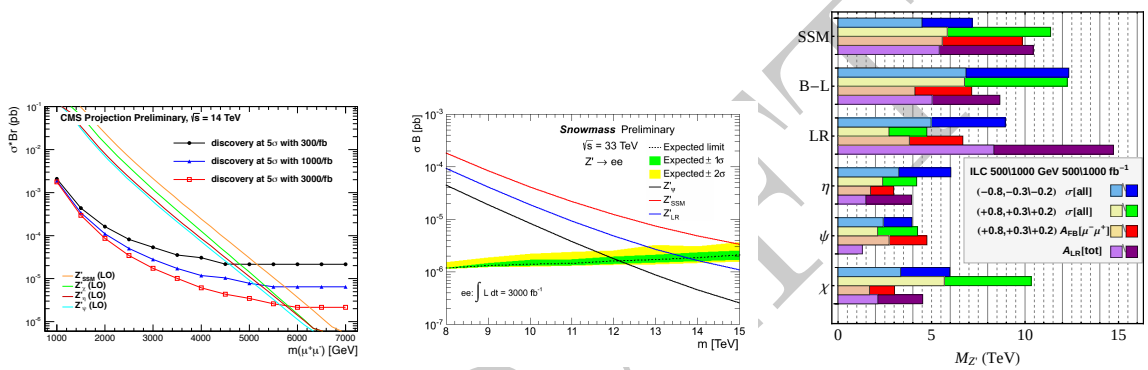

Figure 1-12. *Reaches for Z' at colliders. Left and middle panel: the reach at the LHC [112] and HL-LHC []. Right Panel: the reach at the ILC.*

cases. We see that it can go beyond the capabilities of the 14 TeV LHC. For example, this is the case for $Z'_{\mathrm{B-L}}$ and Z'_χ. The CLIC reach is significantly higher [13].

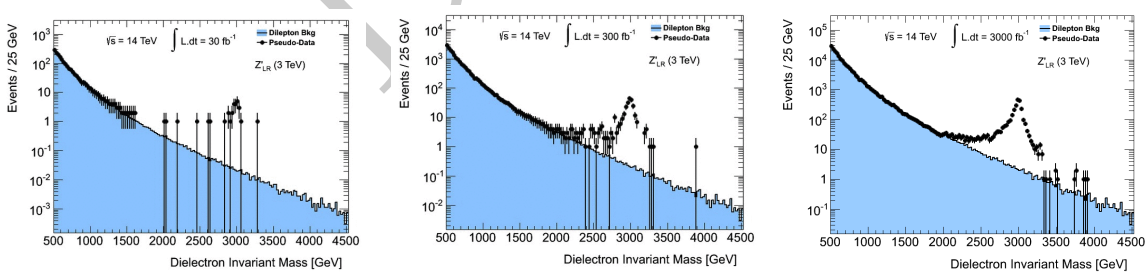

Figure 1-13. *A Z' discovery story at the LHC. []*

Z' discovery would be spectacular at the LHC. Fig. 1-13 shows a possible evolution of a signal for 3 TeV Z'_{LR} at the LHC. A potential signal will start emerging with first half year of data. By the end of LHC Run 2, a signal will be firmly established. HL-LHC will bring a high statistics sample which allows us to study the properties of Z' in detail.

If a Z' has been discovered, the immediate next step would be to measure its properties as much as we can. There have been studies on this topic, for example [65, 63, 64, 69, 83] The useful observables are

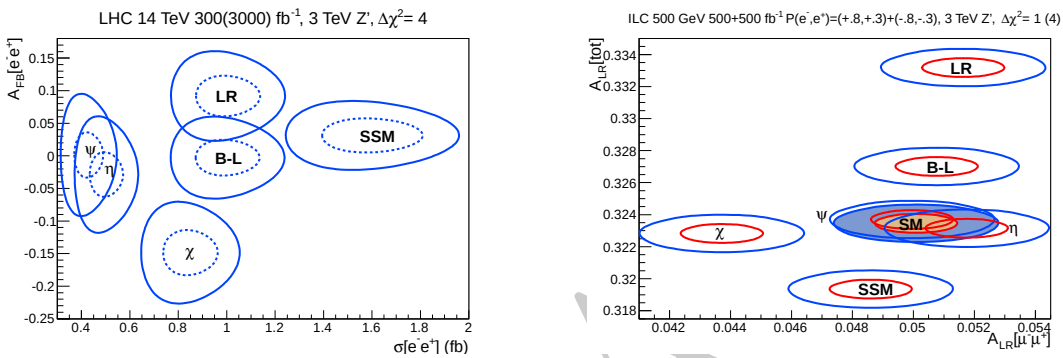

Figure 1-14. *Distinguishing Z' models at colliders. Left panel: $\Delta\chi^2 = 4$ contours of the simulated forward-backward asymmetry versus cross section for the benchmark models at LHC Run 2 (solid) and HL-LHC (dashed). Right panel: Right panel: $\Delta\chi^2 = 1$(red) and $\Delta\chi^2 = 4$(blue) contours of polarization asymmetry in dimuon final state and all di-fermion final states (excluding e^-e^+ and $\nu\nu$) at the ILC.*

$\sigma_{\rm prod}\times$BR in various channels, total width. Many Z'candidates are chiral. To reveal this nature of their couplings, it is useful to consider forward backward asymmetry variable. In addition, we can also include left right asymmetry variable at lepton collider with polarized beams. As a concrete example, we consider a benchmark with $M_{Z'} = 3$ TeV, which is within the discovery reach of the LHC Run 2. The predicted value as well as experimental precision for the $\sigma_{\rm prod}\times$BR($Z' \to$ dilepton) and $A_{\rm FB}$ ($A_{\rm LR}$) at the LHC (ILC) are shown in the left panel of Fig. 1-14. We can see that combining the measurements at Hadron collider and lepton collider can be very valuable in distinguishing different models. For example, $Z'_{\rm LR}$ and $Z'_{\rm B-L}$ can not be clear distinguished at LHC Run 2. HL-LHC can start to discern their differences. On the other hand, ILC with polarized beams can clearly tell them apart.

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. Z' with the Standard Model fermions could be anomalous, in which case there has to be new fermions that may be produced by colliders. 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. Z' can also play an important role in the dynamics of electroweak symmetry breaking, and decaying into SM gauge bosons will give us a smoking gun signal in this scenario.

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.

1.3.3.2 New hadronic resonances

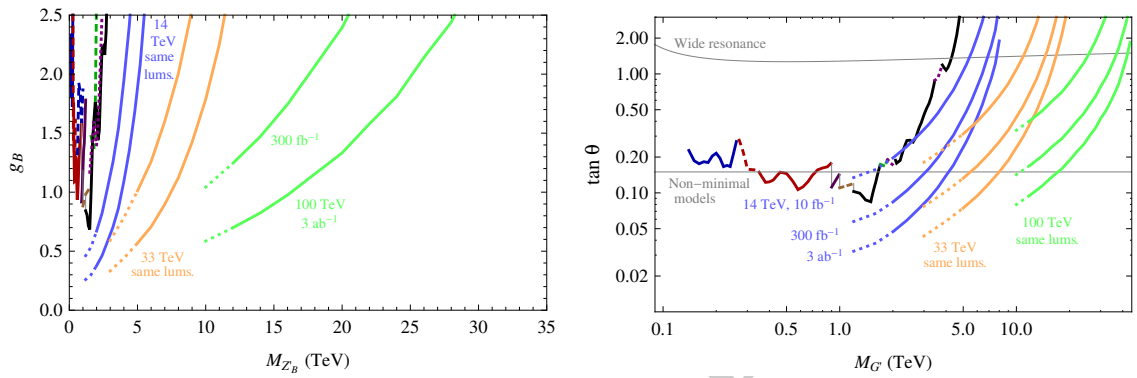

Figure 1-15. *Hadronic resonance searches at hadron colliders. Left panel: Z'_B. Right panel: Octet coloron. []*

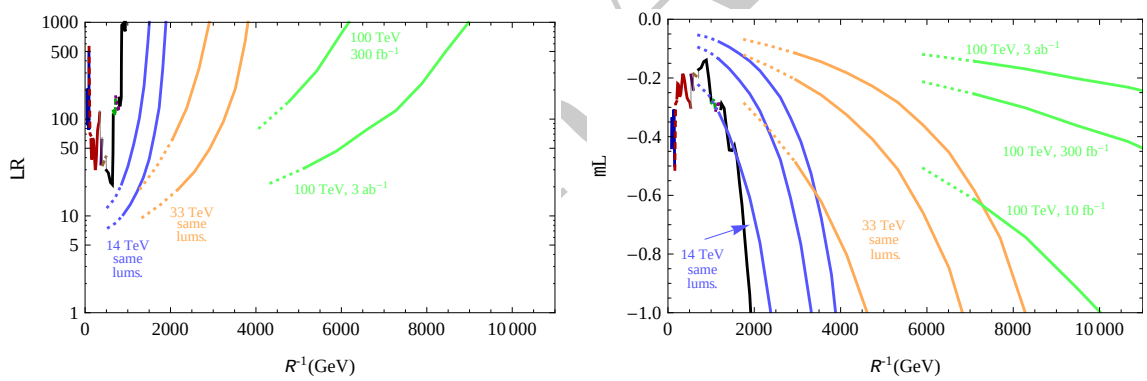

Figure 1-16. *Left panel, the discovery reaches for KK-gluon in minimal UED model at hadron colliders. Right panel, the discovery reaches for KK-gluon in next-to-minimal UED model at hadron colliders.*

Hadron colliders are also ideal for searching for new leptophobic resonances by looking for a peak in the dijet invariant mass distribution. Aside from serving as a standard candle for understanding experimental issues such as jet energy resolution, these searches are strongly motivated in theories with a new U(1) baryon number gauge symmetry, coloron models, and models of Universal Extra Dimensions (UED). The discovery reach in the coupling–mass plane [71] for LHC and HL-LHC, a 33 TeV *pp* collider, and a 100 TeV *pp* collider is shown in Fig. 1-15 for a Z'_B colorless vector resonance (left panel) and a G' color-octet vector resonance (right panel) [**?**]. Similarly, Fig. 1-16 shows the discovery reach for the level-2 Kaluza Klein gluon in minimal UED models (left panel) and next-to-minimal UED models (right panel) [**?**]. Higher energy machines clearly extend the reach for dijet resonances to higher masses, for example allowing the discovery of relatively strongly coupled Z'_B bosons (colorons) progressing from 4.5 (6.5) TeV with the LHC to 5.5 (7.5) TeV with the HL-LHC, to 11.5 (16) TeV for a 33 TeV collider and as high as 28 (40) TeV for the VLHC.

High luminosity at these machines is also critical in order to probe couplings as small as $g_B \sim 0.25$ and $\tan\theta \sim 0.08$, depending on the multijet trigger threshold.

1.3.4 Discovery in Jets + MET: 'Simple' Supersymmetry

As discussed in the introduction, perhaps the best motivated and most successful framework for physics beyond the standard model is supersymmetry (SUSY). In almost all SUSY models, the colored superpartners (gluino and squarks) are significantly heavier than the lightest supersymmetric particle (LSP), which is stable and appears in the detector as missing energy. This is due to the fact that the superpartners get large contributions to their mass from quantum corrections, and the colored particles get the largest contributions. A very general search strategy at hadron colliders is therefore to look for production of gluinos and squarks. These will decay to jets, possibly leptons, and missing energy. Superpartners of leptons (sleptons), as well as the partners of the W, Z, and Higgs (electroweak-inos) are generally lighter than the colored superpartners, and lead to decays with leptons in the final state. These provide a clean signal, but the lepton signal is highly model-dependent. A very general search strategy is therefore to search for jets plus missing energy. Detailed study has shown that this is the most sensitive search for many well-motivated SUSY models, *e.g.* 'minimal supergravity.'

The observation of any excess of missing energy immediately raises the question of whether the missing energy is due to stable dark matter particles being produced. This connection is much more general than SUSY: WIMP dark matter motivates a stable particle that can be produced at colliders, and the hierarchy problem motivates 'partner' particles with the same gauge quantum numbers as standard model particles. Colored partners generally decay to the dark matter particle, and can therefore give a signal in jets plus missing energy. Examples of such models include 'universal' extra dimension models where the standard model fields propagate in an extra dimension, and 'little Higgs' models with T-parity. A discovery in the jets plus missing energy channel is therefore potentially the first step producing and studying dark matter in the laboratory, as well as establishing new symmetries of nature. It is therefore recognized as one of the most important searches for new physics at the LHC, with both ATLAS and CMS each performing several independent searches using different background rejection strategies.

LHC sensitivity: The upcoming LHC run 2 (14 TeV 300/fb) has tremendous potential for discovery in this channel. The strongest current bounds come from the recently-completed LHC run 1, and the reach is significantly improved due to the increased center-of-mass energy of run 2.

It is impossible to discuss the reach for SUSY without caveats and assumptions. One approach is the simplified model approach, which focuses on a subset of the particles and allows exploration of a wide range of kinematics for new physics, but does not include the effects of the many decay modes present in realistic models. The reach of these searches for simplified models has been studied in the the ATLAS and CMS WhitePapers [109, 112], and also using the Delphes Snowmass LHC detector [107]. The reach is shown in Fig.1-17 and 1-18. Based on these results, we can expect squarks and gluinos with masses up to around 2 TeV to be visible at LHC run 2, provided there is no significant dilution due to other decays.

Another way to assess SUSY reach is to study scans over complete models. This approach is taken in the 'phenomenological minimal supersymmetric standard model' (pMSSM) [42]. Here 19 independent superpartner masses are independently uniformly scanned. This scan shows that of the models that are not excluded at the LHC with 300/fb, 75% are in 95% confidenct level reach of the HL-LHC, see Fig. 1-19.

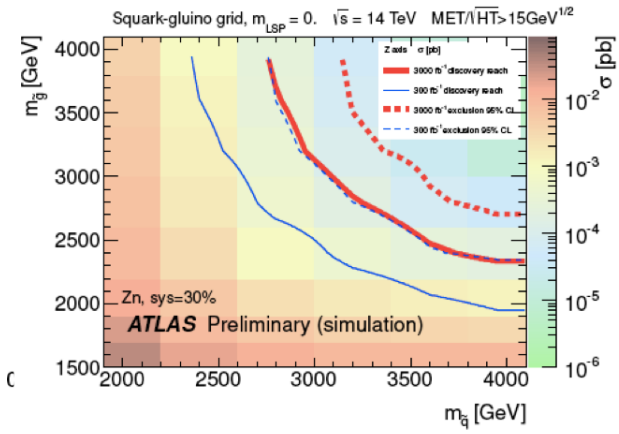

Figure 1-17. *Estimated reach of ATLAS run 2 for squarks and gluinos. CMS has similar sensitivity.*

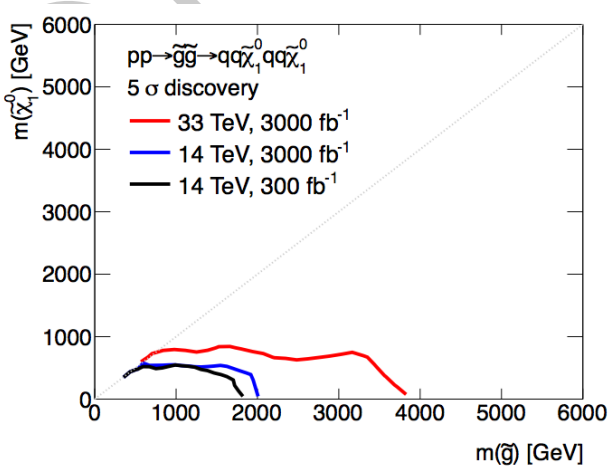

Figure 1-18. *Estimated reach for gluinos using DELPHES simulation. Only gluino and LSP are assumed to be light.*

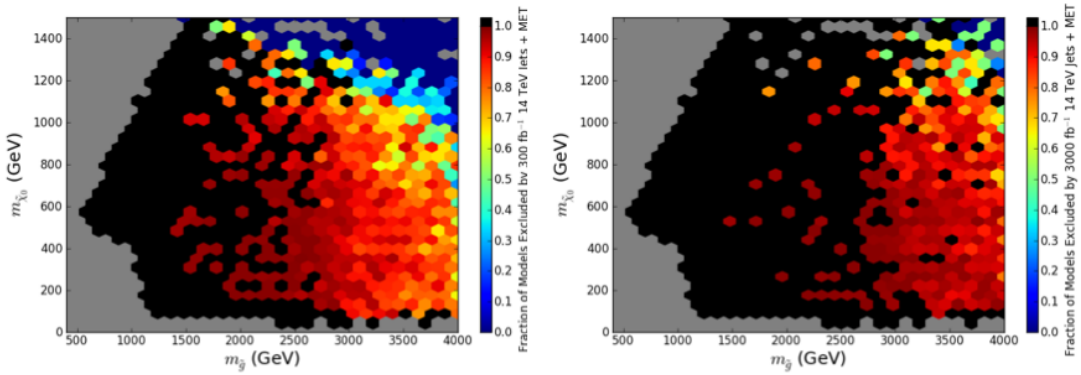

Figure 1-19. *Projections for pMSSM model coverage efficiency shown in gluino-LSP pane for 14 TeV LHC and integrated luminosity of 300/fb (left) and 3000/fb (right)*

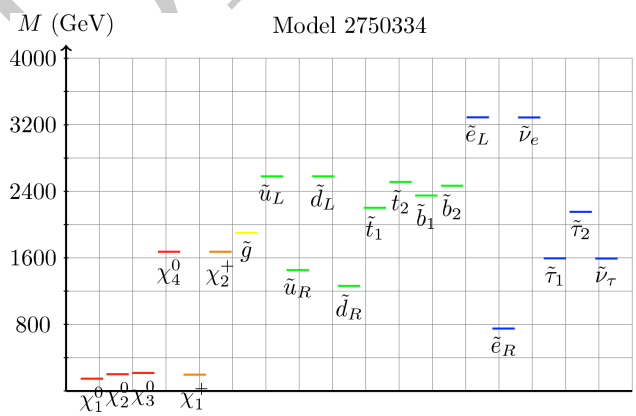

Figure 1-20. *Spectrum of the pMSSM model used for discovery scenario.*

An example model To illustrate the potential impact of a discovery in this channel, we discuss a scenario based on model 2750334 of the pMSSM scan [42]. The spectrum of the model is given in Fig. 1-20. Complete details of the model can be found in [42]. This model has light neutralinos and charginos clustered around 200 GeV; the lightest neutralino is a mixture of bino and Higgsino ('well-tempered Bino-Higgsino'), and consititues a viable dark matter candidate. The lightest squark has a mass of 1.3 TeV, and evades searches at LHC run 1.

In this model, the LHC14/300 will discover new physics in the jets plus MET channel with high significance. At the same time, no other signal of new physics would be observed.

The simplest phenomenological explanaion of this excess is production of a new colored particle, followed by decay to jets plus a stable neutral particle accounting for the missing energy. Because this is the most sensitive channel for SUSY, this is clearly the leading interpretation of the signal that must be further explored. But there are also other possibilities to be considered. For example models where all the standard model particles propagate in extra spatial dimensions ('universal extra dimensions') have have extra-dimensional excitations for all the standard model particles that give rise to similar singals. This motivates both detailed study of the jets plus MET excess as well as searches for other particles predicted in these models.

Using kinematic variables such as MT2, one can get an estimate of the mass difference between the colored particle and the stable neutral particle.

It is difficult to get additional information about the spectrum, because the energy distributions are sensitive mainly to the difference between the produced colored particle mass and the mass of the stable particle at the end of the decay. Information about the rate is also difficult to interpret because production is due to an unknown number of similar states, and there may be multiple decays. In this case, the energy are rate are not a good match with what is expected in the simplest SUSY models (which generally have addtional degenerate squarks and/or a lighter gluino), 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 that must be present if the signal is SUSY. These evade searches because this part of the spectrum is highly compressed and slepton production cross section is small.

The HL-LHC (14 TeV with 3000/fb) extends the squark discovery reach to approximately 2.5 TeV. For our example model it might be possible to claim evidence of more then one strongly interacting state.

Lepton collider reach for new particles extends up to masses of $\sqrt{s}/2$. Therefore ILC with 500 GeV would be able to precisely measure the masses and spins of the gauginos and sleptons, as well as the branching fractions in their transitions [27]. 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).

The sleptons would not be found at the 500 GeV ILC, and mass limits on the lightest slepton would be at around 250 GeV. These bounds are nominally weaker than those from the LHC, but unlike the LHC limits, they are essentially free of loopholes from complicated decays. 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.

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. In our example model, a 3 TeV CLIC [13, 97] would easily discover an 800 GeV $\tilde{e}_R$, but 1.6 TeV $\tilde{\tau}_1$ and heavier sleptons would remain out of reach.

The higher mass colored superpartners can only be searched for at a higher energy hadron machine, either a 33 TeV LHC or a VLHC (see Fig. 1-18).

1.3.5 SUSY with a light stop

One of the essential elements of any solution to the naturalness problem is a top-partner, which is responsible for temper the quantum corrections to the Higgs mass generated by the top quark. In SUSY, the superpartner of the top quark, stop, plays this role. Therefore, search for the stop is directly connected to the test of naturalness.

The simplest stop decay channel is $\tilde{t} \to t+$ LSP, giving rise to signature $t\bar{t} + \not{E}_T$. The simplest stop decay

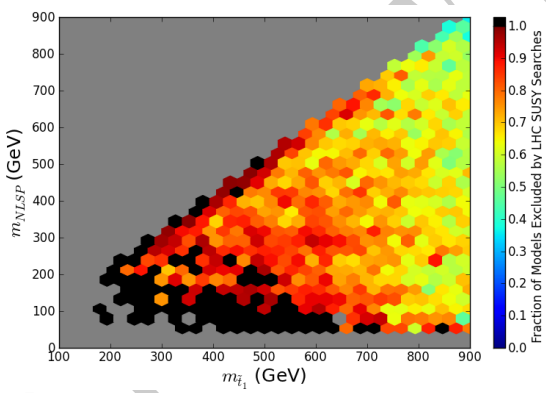

Figure 1-21. *Limits on the pMSSM parameter space from current LHC stop searches.*

channel is $\tilde{t} \to t+$ LSP, giving rise to signature $t\bar{t}+\not{E}_T$. LHC run 1 has made significant progress in exploring the relevant parameter region of light stop. At the same time, there are still large portion of model space left unconstrained, as demonstrated in the pMSSM scan shown in Fig. 1-21. This channel is going to be one of the foci of the LHC Run 2 program. The reach is estimated in ATLAS and CMS white papers [109, 112], as shown in Fig. 1-22

If an excess is observed in this channel in LHC Run 2, it may be evidence for SUSY with a light stop quark. During the subsequent run and the operation of HL-LHC, the significance of this excess will grow and reach discovery level. This would be a major discovery which marks the beginning of an new era. It gives solid evidence to naturalness, and hints at many new particles to be discovered in the coming decades. In addition to the stop discovery, the presence of $t\bar{t}$+MET signal implies the presence of a stable neutral particle. This would the first collider signal for dark matter as well!

The immediate goal after this discovery would be to measure the properties of the new particle, and check it is consistent with that of the stop. The most important properties include its mass and couplings. With some simplifying assumptions which can be checked later, we can get an initial estimate of the stop mass just from the measured production cross section.

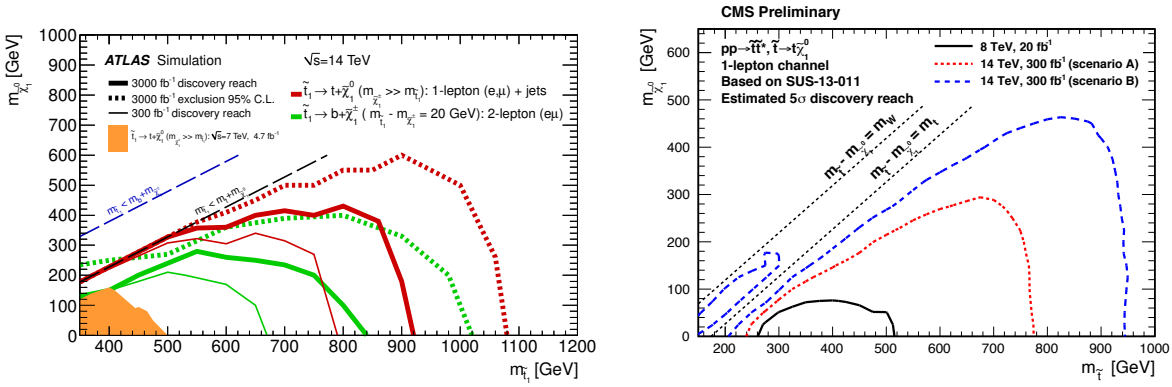

Figure 1-22. *ALTAS and CMS projections of reaches for stop in direct pair production LHC Run 2 and HL-LHC.*

The initial discovery would also tell us that stop has a significant coupling to top and the LSP so that $\tilde{t} \to t+$ LSP is a main decay mode. Indeed, this would also be one of simplifying assumption which allows us to estimate the stop mass using production rate. At the same time, the stop can have a rich collection of decay channels to charginos and neutralinos. Measuring them will paint a full picture of stop couplings. Many of these channels will be subdominant, and discovering them require large statistics. HL-LHC is indispensable in accomplishing this task.

To confirm the initial estimates of the stop properties, more detailed measurements of properties need to be carried out. Indeed, there can be other new physics scenarios, for example the Universal Extra Dimension (UED), which can have signals very similar to SUSY. Therefore, during the period after discovery, there will be competing interpretations. To distinguish them, model independent measurements of spin and mass are necessary. Such measurements are difficult, since we can not fully reconstruct the momentum of LSPs. Precise measurement of subtle features of kinematical distributions will be necessary. High statistics at the level of HL-LHC will great enhance our capability of carrying out these measurements.

The most interesting coupling of stop is probably with the Higgs boson. Confirming its consistency with SUSY prediction would be a directly proof of the stop's crucial role in solving the fine-tuning problem. To directly probe this coupling, one would have to observe the $pp \to \tilde{t}\tilde{t}^* h$ process. However, this process has an extremely low rate at 14 TeV LHC. It can only be reached at the VLHC with $E_{\rm CM} = 100$ TeV. At the same time, a robust test of the divergence cancellation can be performed by testing the "SUSY-Yukawa sum rule" [**?**], a relation among stop and sbottom masses and mixing angles which is tightly connected with this cancellation. A meaningful test of the sum rule requires precise measurements of the masses and mixing angles, which could be performed at a future lepton collider.

We note that, from Fig. 1-21, very light stop below 250(500) GeV are still not ruled out. They are within the reach of 500(1000) GeV ILC. Heavier stop would be reachable at CLIC and/or high energy muon collider. If stop can be produced at lepton collider, their properties can be studied in great detail.

The presence of a light stop implies the presence of a full set of superpartners not far away from the TeV scale. Indeed, naturalness also implies certain electroweak-inos, in particular the Higgsino, should be within a couple hundred GeV. This would be case in which a high energy lepton collider can play a crucial role in putting together a full picture of the new physics immediately above the weak scale. As discussed above, model independent measurements of spin, mass and couplings of superpartners are challenging at pp-colliders and require at least high luminosity. At the same time, high energy lepton colliders can provide a much

cleaner environment. Moreover, it is much easier to reconstruct the kinematics. In addition, it could also answer definitively another question of equal importance: the identity of the LSP dark matter.

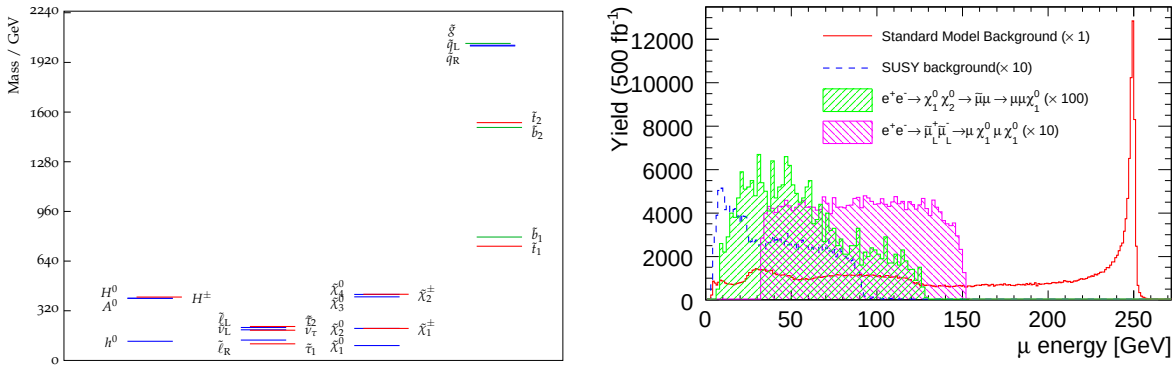

Figure 1-23. *Left panel: spectrum of the benchmark model in the $\tilde{\tau}$-coannihilation region. Right: yield of this SUSY signals at the ILC.*

A great example of such scenarios is explored in the joint ILC-LHC study of the stau co-annihilation model [35]. 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 left panel of Fig. 1-23.

At the 500 GeV ILC sleptons and lighter gauginos are accessible, and their mass and quantum numbers will be measured. In particular, the $\tilde{\tau}_1$ mass could be measured to 0.2% and $\tilde{\tau}_2$ mass to 3% [27]. The production cross section can be determined to 4%, and the polarization of τ leptons could be measured to $< 10\%$. By measuring tau polarization one can measure higgsino fraction of the lightest neutralino. In addition, CLIC would have access to almost all of the states in this benchmark model. The plethora of precision measurements will allow for precise determination of SUSY model parameters, and will help to confirm or rule out different proposed SUSY breaking mechanisms.

1.3.6 Discovery in Leptons+MET

In many scenarios of supersymmetry breaking, the color-neutral superpartners such as electroweakinos (gauginos, higgsinos) and sleptons can be significantly lighter than the colored states (gluino and squarks). In this case, the production of electroweakinos may be the initial supersymmetry discovery mode. The typical signature involves production of W- and Z-bosons when the electroweakinos decay to the stable LSP, giving signatures with charged leptons (from W- and Z-boson decays) and missing transverse momentum (from the invisible LSPs).

There are persuasive arguments for why some of the charginos and neutralinos could be light [24, 25]. 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".

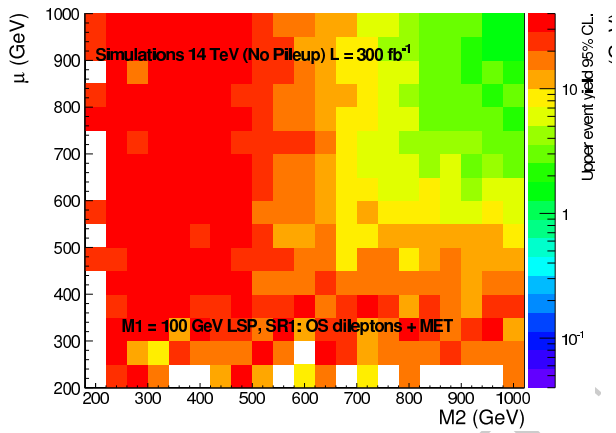

Figure 1-24. *Estimated reach of LHC run 2 for chargino production followed by $\chi^{\pm} \to W^{\pm}\chi^0$, assuming Bino LSP. 3σ significance corresponds to an event yield of 9.*

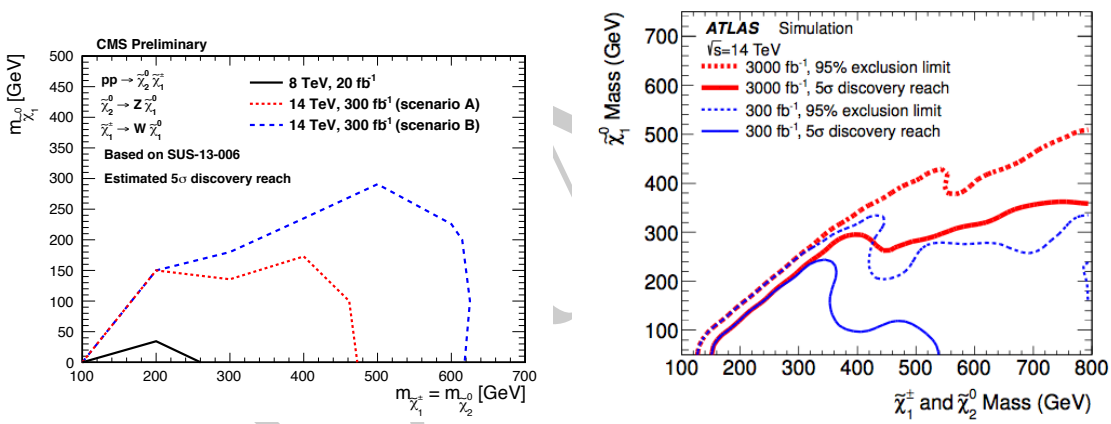

Figure 1-25. *Estimated reach for chargino-neutralino production followed by $\chi_1^{\pm} \to W^{\pm}\chi_1^0$ and $\chi_2^0 \to Z\chi_1^0$ with 100% branching ratio.*

LHC sensitivity The LHC run 2 will greatly extend the reach in searches for superpartners without strong interactions. For example the reach for $\chi_1^+\chi_1^-$ followed by $\chi_1^{\pm} \to W^{\pm}\chi_1^0$ has been estimated in [36], and shows a reach of up to $m_{\chi_1^0} = 650$ GeV (see Fig. 1-24). The reach for $\chi_1^{\pm}\chi_2^0$ has been estimated in the ATLAS and CMS WhitePapers [109, 112], and has a reach up to $m_{\chi_1^{\pm}} = 500$–600 GeV (see Fig. 1-25).

In the case of very small splitting, the final state would be essentially invisible, but analysis of events in which a jet or photon recoils from the initial state (see Section 1.3.2) would be sensitive at high integrated luminosities.

As a general point, LHC sensitivity to the EWKino states greatly increases with integrated luminosity, owing to their relatively low masses and very low production cross-sections. For example [26, 36] channels like $\ell b\bar{b} + MET$ play increasingly important role at HL-LHC (see Fig. 1-26).

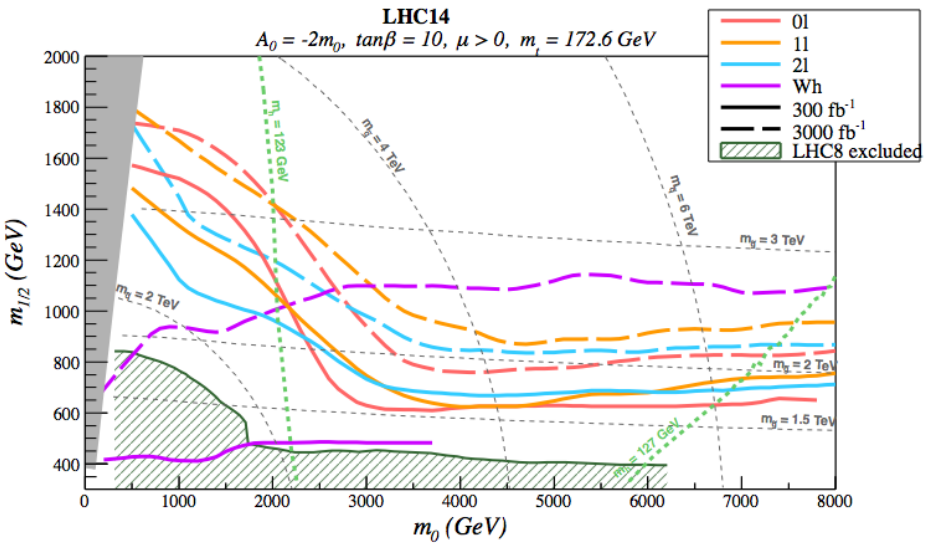

Figure 1-26. *Estimated reach of LHC for 300/fb and 3000/fb for mSUGRA model.*

Recently, studies have shown that vector-boson-fusion production of winos, with a final state of two forward jets and missing transverse energy could be sensitive to models with small splittings between the electroweakinos with masses of a few hundred GeV [67, 66].

An excess at the LHC could be studied in detail at the HL-LHC, revealing the mass splittings via the dilepton mass edges. Together with the cross sections and assuming high higgsino fraction, a rough estimate of the absolute masses might be possible.

A lepton collider such as the ILC or CLIC, would produce the complementary to LHC reactions of chargino pair production and / or mixed neutralino production, and would be able to measure masses and quantum numbers of the observed states, owing to the unique kinematics of e^+e^- collisions, and will search for partners of leptons [27], see Figure 1-27.

The HL-LHC would also extend the sensitivity to colored states from about 2 to 2.5 TeV (see Section 1.3.4), but to make significant gains in mass reach a higher energy hadron collider will be required. A 33 (100) TeV collider will be able to push the SUSY squark/gluino discovery reach to 7 (15) TeV [107].

1.3.7 R-parity violating SUSY

Naturalness suggests that superpartners must be sufficiently light to produced at the TeV scale. In particular, it suggests that $m_{\tilde{t}} < 500$ GeV and $m_{\tilde{g}} < 1$ TeV, which larger values requiring tuning to explain the small observed mass of the Higgs boson. These 'natural' values of the gluino and stop masses are ruled out in the simplest models by searches at LHC run 1, motivating the study of SUSY models where the bounds are weaker.

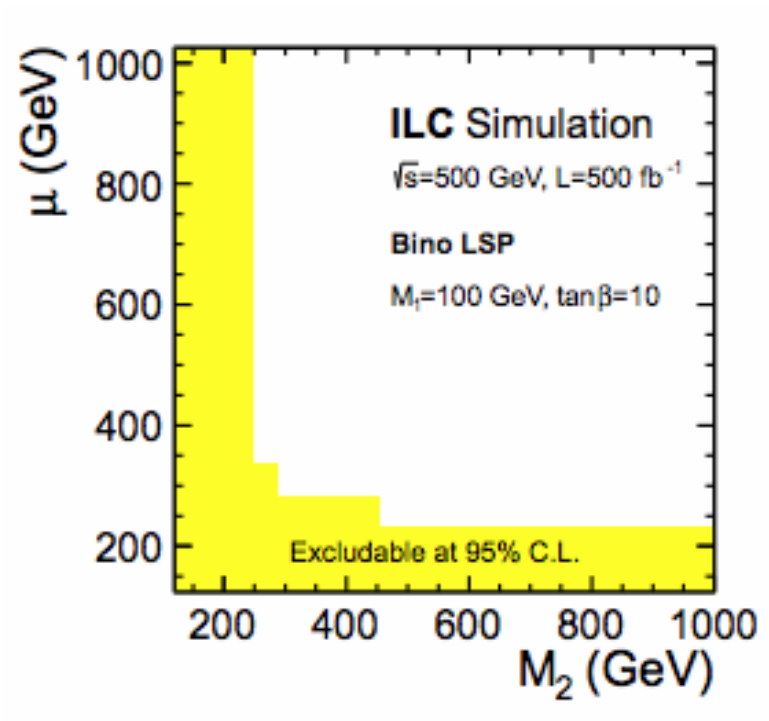

Figure 1-27. *ILC-LHC joint scan from Ref [27].*

One way that natural SUSY could have escaped detection so far is that R-parity is not conserved. R-parity is a discrete symmetry that guarantees that the superpartners are produced in pairs, and that the LSP is stable. Giving up R-parity means that missing energy is no longer a generic signature of SUSY at colliders. Dark matter would have to be explained by a particle other than the LSP.

There are a large number of possible R-parity violating (RPV) couplings, each of which have an extremely rich phenomenology. These couplings violate baryon and/or lepton number, and necessarily have a non-trivial flavor structure. For this reason, there are many constraints on these couplings coming from flavor physics and baryon and lepton-violating processes. However, these constraints generally depend on products of different RPV couplings, and individual couplings can be large enough to be relevant for collider physics. (For a review, see [30].)

In this section, we consider three different discover scenarios. Two are based on the operators $L_3Q_3D_3$ are $U_2D_1D_2$, where the subscripts denote the quark or lepton generation. These were chosen because they make searches for stops quite challenging. However, we will see that specialized searches are quite sensitive. The third scenario explores RPV bilenear terms in the superpotential and soft lagrangian, which together allow higgsino decay into W and lepton. The later scenario, which we will refer to as $bRPV$, may be related to the origin of neutrino masses [101].

$L_3Q_3D_3$**:** This coupling allows the decay $\tilde{t} \to \tau b$, so the stop appears as a third-generation leptoquark resonance. LHC run 2 can probe this mode for stop masses up to 1.3 TeV [73] (see Fig. 1-28).

RPV SUSY will be the leading interpretation of such a signal. Another possible interpretation is double higgs production in an extended Higgs sector followed by $hh \to (bb)(\tau\tau)$. This is straightforward to eliminate

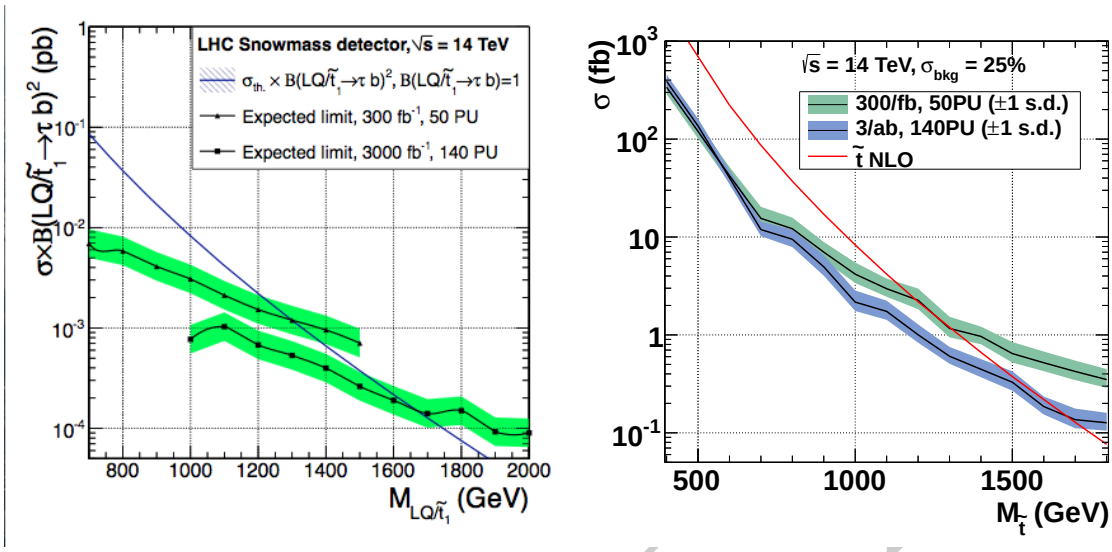

Figure 1-28. *Left: limits on stops decaying to τb via the $L_3Q_3D_3$ operator. Right: limits on stop decaying to $t\chi^0 \to t(jjj)$ via the $U_2D_1D_2$ operator*

due to the different kinematics as well as other decay modes of the Higgs. Another interpretation is a spin-1 third-generation leptoquark. This can be distinguished using rate information if the mass of the produced particle is known, but this is difficult to determine because of multiple sources of missing energy in the event.

The SUSY interpretation of this signal can be probed in a number of ways. The sbottom mass is different from the stop mass in general, but the masses are similar in many models. This motivates searches for sbottoms, which decay via $\tilde{b} \to b\nu$ or $t\tau$. These can be searched for with good sensitivity at the LHC [52]. Also, the electroweak-inos are expected to be lighter than the stops. These are expected to have the decays $\chi^\pm \to tb\nu$, $bb\tau$, or $\chi^0 W^\pm$, and $\chi^0 \to tb\tau$ or $bb\nu$. These can be searched for both in direct production and from stop decays $\tilde{t} \to t\chi^0$ or $b\chi^\pm$. Another plausible signal is gluino pair production followed by $\tilde{g} \to t\tilde{t}$ or $b\tilde{b}$, followed by any of the decays discussed above. All of these possibilities can be extensively probed at the HL-LHC.

Precision flavor physics also gives a complementary probe of other LQD operators. Mixing in the B meson system probes $L_3Q_3D_1$, and $B \to X_s\nu\nu$ probes $L_iQ_3D_2$ and $L_iQ_2D_3$ for $i = 1, 2, 3$.

The HL-LHC can increase the signifance to 5σ for the 1 TeV stops in our scenario. In the $\mu\tau_h$ channel alone, there are 270 events with a significance of 4.4σ. The addition of the $e\tau_h$ channels would give enough to claim discovery.

$U_2D_1D_2$: In this case, stops can decay via $\tilde{t} \to t\chi^0$ followed by $\chi^0 \to jjj$ from the RPV coupling. If the stops have a mass of 900 GeV, a search for a lepton (from the top decay) with multiple additional jets would be sensitive to these at LHC run 2, yielding 9 events above background and a significance of 3.4σ (estimated with 50PU and assuming $m_{\tilde{t}} : m_{\chi^0} = 2 : 1$ [73].

At the same mass, LHC 14 with 3000/fb and 140PU, would yield 15 events (with expected similar background) and a significance of 5.6σ. The number of signal events has been suppressed to increase significance, but looser cuts can give larger samples. These may be important to address the question of whether the

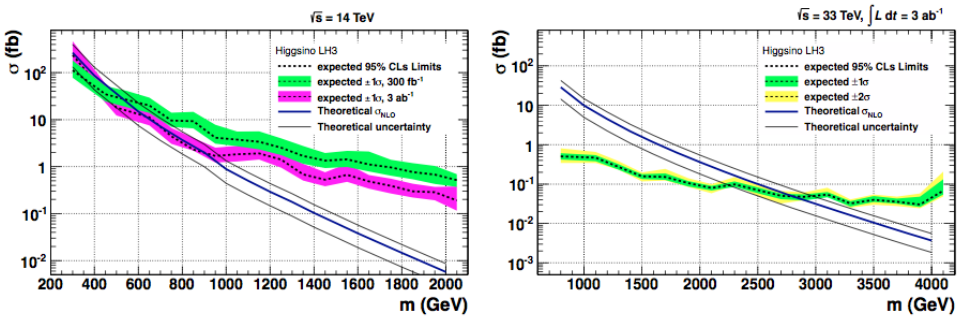

Figure 1-29. *Projected LHC sensitivity to the bi-linear RPV SUSY at 14 TeV (left) and 33 TeV (right).*

excess is due to a misunderstanding of QCD tails. For example, the possibility of reconstructing the boosted χ^0 could help to resolve this question.

There are a number of associated channels that can be studied in the SUSY interpretation of this signal. One is gluino pair production, followed by the decay $\tilde{g} \to jjj$ via virtual squarks, or $\tilde{g} \to t\tilde{t}$ followed by $\tilde{t} \to tjjj$.

Future colliders will also be able to probe this scenario. Lepton colliders will be able to probe the electroweakino sector essentially without loopholes for chargino and neutralino masses up to half the center of mass energy. In this scenario, the 500 GeV ILC will probe a significant region of the parameter space, higher energy lepton colliders such as 1 TeV ILC, CLIC, or muon colliders will further extend the reach. The remaining colored superpartners can be explored only at LHC33 or a VLHC.

bRPV: At the LHC, higgsino pair production with subsequent decays $\tilde{H} \longrightarrow W\tau$ would give rise to excess in multi-lepton production (see left frame of Fig. 1-30).

As an example, let's assume that the higgsino mass is 210 GeV. LHC will establish the excess with significance above 5 σ, but the interpretation of the excess at the 14 TeV LHC would be highly ambiguous.

At the ILC [27], however, one would not only establish the RPV nature of the higgsino, but also detect companion decay into $W\mu$. This would allow to make a very powerful connection to the neutrino physics: if the R-parity violation is the origin of the neutrino mass, one predicts the value of the mixing angle Θ_{23} (see Fig. **??**).

It's important to note that the sensitivity to such signatures at hadron colliders dramatically improves with energy. A 33 TeV proton collider will be sensitive to LH scenario up to the 2.5 TeV higgsino masses (see right frame of Fig. 1-30).

1.3.8 Long-lived Heavy Particles

Massive long-lived particles are predicted by numerous extensions of the SM [78]. For example, in SUSY the lightest SUSY particle (LSP) or next-to lightest SUSY particle (NLSP) gives many possibilities. Assuming R-parity conservation, the NLSP may be long-lived due to either approximate mass degeneracy in the spectrum or suppression of the coupling to the LSP due to the higher scale of SUSY breaking. Typical models include

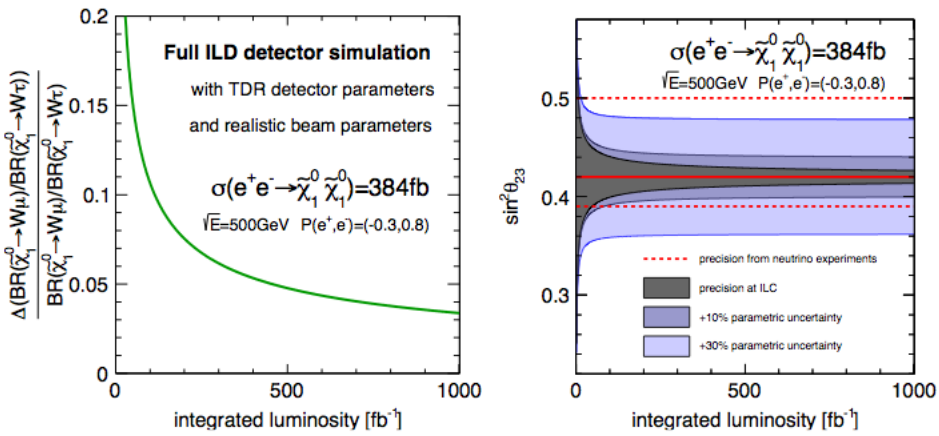

Figure 1-30. *Left: Experimental precision on the ratio of $W\mu$ and $W\tau$ branching fractions. Right: Derived uncertainty on the Θ_{23} neutrino mixing angle.*

a long-lived stau, chargino, gluino, stop, or sbottom. In many cases the discovery mode for SUSY is a new detector-stable particle.

In the case of a colored long-lived particle, it is expected to hadronize on the QCD distance scale, leading to a color-neutral 'R-hadron' being observed at longer distances in the detector. This R-hadron can be either electrically neutral or charged, depending on the (unknown) R-hadron spectrum. R-hadrons can also undergo nuclear interactions in the detector, changing their charge as they traverse the detector. Simulation of R-hadron hadronization and energy deposits and interactions in detector material (and decay) have been implemented in Pythia (6 and 8) and through Geant4 extensions.

Massive, charged, long-lived particles will typically escape the detector since they begin with large kinetic energy, although they lose more energy in material through ionization than minimum-ionizing particles. The speed of the particle can be directly measured using timing information from several detectors, such as calorimeters and muon systems. The slow speed also causes the particle to deposit more charge per unit length in the detectors, due to the Bethe-Block relations, which can be measured particularly well in silicon tracking detectors. Combined with a momentum measurement from the radius of curvature of the charged particle, the speed measurement can be used to infer the mass of the particle.

ATLAS and CMS have both performed very general searches for long-lived, massive, stable, charged tracks, from new particles such as long-lived squarks, gluinos, or staus [110, 51]. The data are compared to models of background derived from data, given measured amounts of timing and ionization mis-measurements based on studies of Z decays. No excess is observed at high mass (large ionization and/or slow time) for any of the searches, so limits are placed on the particles' masses. At ATLAS, the long-lived stau is excluded at 95% C.L. below 310 GeV, gluinos below 985 GeV, and stop/sbottom below about 600 GeV; similar limits are observed by CMS.

Backgrounds to detector-stable particles are small, given the excellent performance of detectors such as ATLAS and CMS. Thus the ability to discover these new particles mainly relies on being able to produce them in sufficient numbers. Running at 14 TeV with 300 fb^{-1} of data will greatly enhance the mass reach for detector-stable particles by factors of 2–3, to 3 TeV for gluino and 2 TeV for stop/sbottom R-hadrons, and 1 TeV for staus (see Figure 1-31). The discovery of a new long-lived heavy particle at the LHC would of course be of fundamental significance and require detailed further study. We would already know some

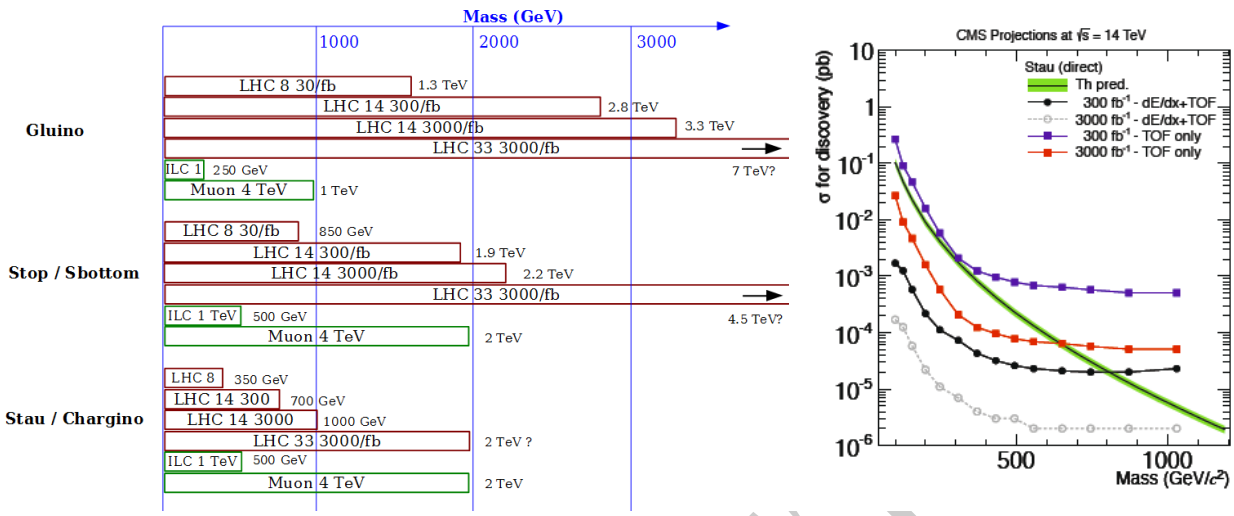

Figure 1-31. *Left: Summary of detector-stable partitcle reach at future colliders. Right: CMS study of future LHC reach for long-lived stau, from [6].*

basic propoerties of the particle from its discovery channel and cross section: a rough estimate of its mass, whether it is colored, and whether it is pair-produced.

Due to the large masses involved, lepton colliders would have difficulty producing these new long-lived particles. They can produce stau-like states and observe them cleanly up to roughly half the CM energy. Thus, a 4 TeV muon collider would have the ability to study staus up to about 2 TeV, comparable to the reach of even an energy-upgraded 33 TeV LHC. Studies of the new particle at the muon collider could probe its mass and spin precisely.

Learning about whether the new particle decays, and its lifetime and decay channels if it does, would also be critical. Doing so would be challenging, since it typically escapes the detector, but some fraction of them would be expected to come to rest in the detector (through ionization energy loss), where they could later be observed to decay. ATLAS and CMS have both developed searches for long-lived particles that stop in the dense detectors (calorimeters) and decay much later during accelerator bunch-crossings without collisions (or when beams are off). Assuming the "generic" model of R-hadron interactions, a gluino with mass below 857 GeV and a stop with mass below 340 GeV are excluded, for lifetimes between 10 microseconds and 1000 seconds [111, 6]. The LHC experiments can trap and study long-lived heavy particles up to nearly the mass at which they can be discovered and provide reasonable estimtates of their lifetimes and decay properties, over a large rage of potential lifetimes. Should a new particle be discovered, specialized detectors could be constructed to trap a larger fraction of the particles and optimized to study their decay properties as accurately as possible [86]. Large luminosity, from an upgraded LHC, would be essential for this program of study.

1.3.9 Top Partners

A natural extension to the standard model would be a new chiral generation of quarks and leptons. However, such a chiral fourth fermion generation would couple to the Higgs boson with a Yukawa coupling that is proportional to its mass and therefore give a large enhancement Higgs-boson production through its

contributions to the fermion triangle in gluon fusion. This is clearly inconsistent with the observed Higgs production cross section, ruling out a chiral fourth generation of fermions.

Vector-like quarks are non-chiral, in that 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 electroweak precision oblique 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[62, 104, 56, 16, 15, 61, 60]. 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 [40]. 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 [57] contain such T' quarks [92]

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) [49, 12] or $t - Z$ [53] 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 [41].

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[1]. Direct limits based on current data exclude vector-like quarks for masses below 700-800 GeV, depending on their decay branching fractions [1, 4, 5]. Earlier studies [103, 34, 18], based on ATLAS results have analyzed a more simplified "triangle" of branching fractions, with only a few points considered. The second looks at the specific case of little Higgs models, where the T' is taken to be a singlet.

With LHC running at $\sqrt{s} = 14$ TeV and a dataset corresponding to an integrated luminosity of 300 fb^{-1}, the reach for discovering heavy vector-like quarks with charge 2/3 and exotic charge 5/3 will be extended significantly. As demonstrated in Fig. 1-32, the 5σ (3σ) reach for discovering heavy top-like quarks with mass

around 1.3 (1.4) TeV is achievable [38, 23]. In the absence of such heavy quarks, we can probe masses up to 1.5 TeV. Similar conclusion is also reached in the whitepaper by CMS [6]. At the HL-LHC with $\sqrt{s} = 14$ TeV and 3000/fb vector-like quarks up to masses of around 1.5 TeV can be observed or alternatively in the absence of such quarks we can exclude masses up to 1.8 TeV (see Fig.1-32). With HE-LHC, the reach increases to heavy top-like quark with masses up to 2.5 TeV.

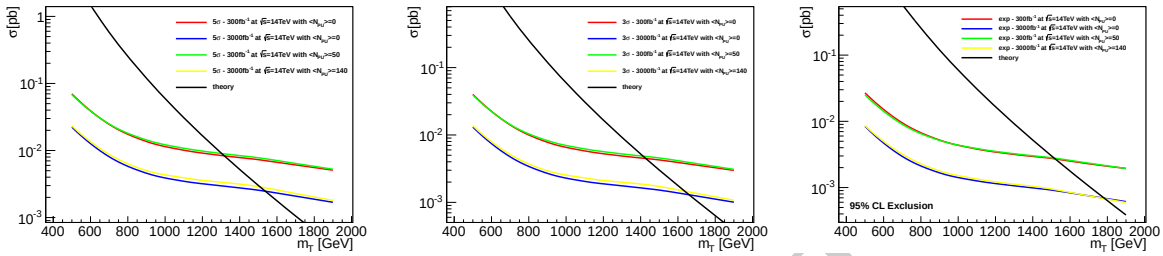

Figure 1-32. *Discovery reach (left and middle panel) and exclusion (right panel) as a function of the mass of a heavy vector-like quark at $\sqrt{s} = 14$ TeV*

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 [54, 55, 90], there is a $T' \to T_- A_H \to tA_H A_H$, 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 [7].

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-boson 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. 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.

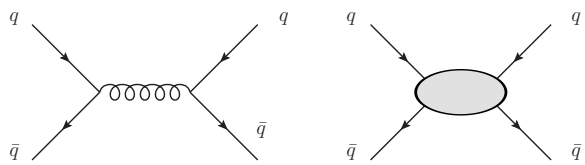

Figure 1-33. *Diagrams for QCD mediation of quark-quark interactions (left) and a four-fermion contact interaction describing an effective field theory for the mediation of a new interaction between quark constituents.*

1.3.10 Fermion 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. In this section, we consider the extent to which the compositeness of quarks can be probed by future collider facilities [75, 74].

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 [87, 106, 45].

A typical approach to the study of quark compositeness [50] 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 1-33). This is well-described by an effective field theory approach [37]:

$$L_{qq} = \frac{2\pi}{\Lambda^2}[\eta_{LL}(\bar{q_L}\gamma^\mu q_L)(\bar{q_L}\gamma_\mu q_L) + \eta_{RR}(\bar{q_R}\gamma^\mu q_R)(\bar{q_R}\gamma_\mu q_R) + 2\eta_{RL}(\bar{q_R}\gamma^\mu q_R)(\bar{q_L}\gamma_\mu q_L)] \tag{1.1}$$

where the quark fields have chiral projections L and R, and the coefficients η_{LL}, η_{RR}, and η_{RL} turn on and off various interactions. In this study, we examine the cases of energy scales Λ^+_{LL}, Λ^+_{RR}, and Λ^+_{V-A} with couplings $(\eta_{LL}, \eta_{RR}, \eta_{RL}) = (1,0,0), (0,1,0)$ and $(0,0,1)$, respectively, in order to demonstrate the center-of-mass dependence of the sensitivity of possible future pp facilities.

Evidence for contact interactions would appear as an enhancement of dijet production with large dijet invariant mass m_{jj} and angle relative to the beam axis, θ^*, in the center of mass frame. Quantum chromodynamics (QCD) predominantly produces jets with small θ^* peaked in the forward and backward directions.

While next-to-leading-order calculations of QCD [98] and the contact interactions expected from quark compositeness [82] are available, they are computationally intensive and for the purpose of this study, leading-order calculations are sufficient. For events generated at leading-order with MADGRAPH [19], the showering and hadronization is described by PYTHIA [108] and the detector response by DELPHES [100] for the facilities described in Fig. 1-34.

Based on Ref. [21] which follows the approach of Ref [50], the analysis variable is $\chi_{jj} = e^{|y_1 - y_2|}$ where y_1 and y_2 are the rapidities of the two highest transverse momentum (leading) jets. The distribution for QCD interactions is slightly increasing with χ_{jj}, while contact interaction models predict angular distributions

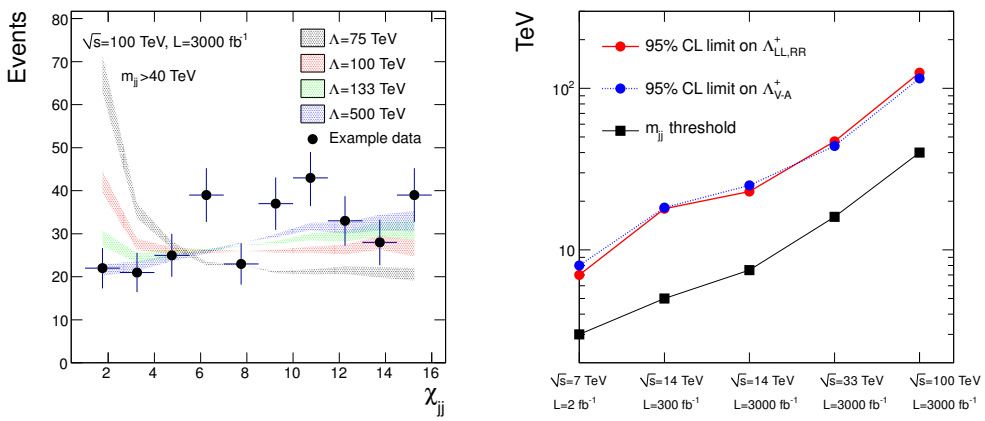

Figure 1-34. *Left: distributions of χ_{jj} for QCD and contact interactions with a variety of choices of Λ for the case of pp interactions with with $\sqrt{s} = 100$ TeV and $\mathcal{L} = 3000$ fb^{-1}. Right: summary of m_{jj} thresholds and sensitivity to the contact interaction scale Λ.*

that are strongly peaked at low values of χ_{jj}. 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 the minimum m_{jj} threshold.

As seen in Fig. 1-34, higher center-of-mass energies bring 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 facility with higher energy will be needed to directly produce the new heavy particle that mediates the interaction of the quark constituents, dependening on the mass scale. This would appear as a dijet resonance in $q\bar{q} \to q\bar{q}$ events. Specifically, we can relate the exclusion of the compositeness scale Λ to that of the mass of a Z' mediator as:

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

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 , $g_{Z'} = 0.12$). Figure 1-15 shows the sensitivity and current limits.

1.3.11 'Only' the Standard Model

We now consider an 'anti-discovery' scenario where LHC14 with 300/fb does not discover any additional particles or observe any anomalies. Such a run will have significant acheivements: the LHC will have not only discovered the Higgs boson, but will have made impressive progress in the program of precision Higgs measurements. Projections for these are discussed in the Higgs working group report. The scenario we are now considering also assumes that the improved measurements of Higgs couplings from LHC14 300/fb are consistent with their standard model values. It also assumes 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 be a sign of new physics that could be at the

TeV scale, giving additional motivation for continued exploration of the energy frontier. But if there is no discovery of new fundamental physics, is our motivation for exploring the TeV scale reduced?

As discussed throughout this report, there are a number of big questions and big ideas that can be explored at the TeV scale. However, some of these do not point unambiguously to the TeV scale, and therefore remain as motivations for further exploration at the energy frontier. The big questions that have the strongest link to the TeV scale are the origin of dark matter and the naturalness of the Higgs boson. We discuss these questions in the context of the no-discovery scenario below.

1.3.11.1 Dark Matter

Probably the best-motivated dark matter candidate is a weakly interacting massive particle (WIMP). This requires only that the dark matter is a neutral stable particle that couples weakly to the standard model, and that the dark matter particles are in thermal equilibrium with the standard model particles in the early universe. In this scenario, there is an upper limit on the WIMP mass

$$m_{\rm WIMP} \leq 2 \text{ TeV} \left(\frac{g_{\rm eff}^2}{0.3}\right), \tag{1.2}$$

where $g_{\rm eff}$ is the coupling strength between dark matter and the SM particles, which we have normalized to the weak coupling in the SM. From this estimate, we see that the dark matter mass can easily be at the TeV scale, and LHC14 with 300/fb does not have sensitivity to direct production of non-colored states with this high mass. Alternatively, the dark matter may be much lighter, but is not observed at LHC14 with 300/fb because of 'low-mass' loopholes.

The most model-independent collider search relies on the associated production of a pair of WIMPs together with hard radiation, *e.g.* a jet, photon, *etc.* LHC14 with 300/fb will only cover this scenario up to dark matter masses of a few hundred GeV, while HL-LHC 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. Alternatively, one may worry that the dark matter has been missed e^+e^- colliders can perform a model-independent search for dark matter up to essentially $\frac{1}{2}E_{\rm cm}$.

The scenario we are now envisioning may motivate a 'minimal' scenario such as that considered in §? of this report, and the results there are very relevant to this scenario. Unsurprisingly, hadron colliders can greatly extend the reach for dark matter if it couples to colored particles, while e^+e^- colliders are sensitive if it couples to leptons. We refer the reader to that section for quantitative results.

1.3.11.2 Naturalness

If nature is described by the standard model with an elementary Higgs boson up to the Planck scale, then the observed Higgs boson mass is the sum of different contributions that must cancel to an accuracy of $\epsilon \sim (125 \text{ GeV}/M_{\rm Planck})^2 \sim 10^{-30}$. This arises because the mass-squared parameter in the SM Lagrangian is quadratically sensitive to large mass scales. If this divergence is cut off by new physics at a scale $M_{\rm NP}$ the tuning is reduced to $\epsilon \sim (125 \text{ GeV}/M_{\rm NP})^2$. This is the basic naturalness argument for new physics at the TeV scale. The normalization and quantitative interpretation of naturalness estimates are not clear, but the quadratic scaling with $M_{\rm NP}$ is robust, and fine tuning can be used as a rough guide for where to expect new physics. This argument is independent of supersymmetry or any other scenario for physics beyond the standard model.

In the standard model, the largest contribution to the Higgs mass that must be cut off by new physics comes from the top loop. Although this is a loop effect, the coefficient is large because of the large top coupling and the QCD color factor. This directly motivates searches for new physics in the top sector, such as searches for stops in SUSY and fermionic top partners in composite scenarios. These are discussed respectively in §? and §? of this report, where we see that LHC14 with 300/fb has sensitivity for these new states to approximately the TeV scale. Taken at face value, this implies roughly a tuning of $\epsilon \sim 1\%$.

Should this be taken as evidence that nature is unnatural? A possibly useful historical analogy from cosmology is that in the early 1990s the quadrupole anisotropy of the cosmic microwave background appeared to be below expectations from cold dark matter cosmology. This was arguably the 'discovery mode' for this cosmological model, and the reason it was not found earlier is that it is coindidentally small, with a probability from cosmic variance of roughly 1%. The lesson may be that unfavorable accidents at the 1% level do happen in discovery modes for fundamental new physics.

We can therefore ask how well future experiments will probe naturalness. A rough summary is that the HL-LHC increases the reach for new heavy particles by 10% to 20%. This does not make a dramatic impact on naturalness, although it should be kept in mind that the new mass range that is being probed is in the most interesting range in a wide range of well-motivated models. We will discuss some of these individually below. In addition, the HL-LHC can close many (but not all) low-mass loopholes due to higher luminosity and improved systematics.

If we push to higher energies with a 100 TeV VLHC, we can probe colored SUSY partners at the 10 TeV scale. Based on the scaling of tuning, we expect this to probe tuning to the level $\epsilon \sim 10^{-4}$. This is a very strong motivation to expect the discovery of new physics.

On the other hand, in the scenario we are considering it may be that the top partners have been missed at the LHC14 with 300/fb because of highly compressed spectrum of other low-mass loopholes. In SUSY, e^+e^- colliders can probe another source of tuning: the Higgsino mass generically contributes directly to the Higgs mass, and therefore SUSY models with heavy Higgsinos require tuning at the level of $\epsilon \sim (125\ \mathrm{GeV}/m_{\tilde{H}})^2$ [**?**]. An e^+e^- collider can search for Higgsinos in a model-independent way up to half the center of mass energy. At a 1 TeV e^+e^- collider, we can therefore probe tuning at the level of $\epsilon \sim 1\%$ in a very model-independent way.

1.3.11.3 Flavor, CP, and Precision Measurements

Many models of new physics have potential contributions to flavor, CP, and precision electroweak observables at a level that may point to new physics at a scale of roughly 10 TeV. For example, SUSY has additional sources of flavor mixing and CP violation, and if they are not suppressed by special flavor structure point to a scale of new physics above 10 TeV. On the other hand, composite models generally give rise to corrections to precision electroweak observables that also point to a scale above 10 TeV. This scale is therefore the scale that will be probed by precision electroweak and flavor studies, primarily at the intensity frontier. Therefore, in the present scenario, flavor, CP, precision electroweak observables, and the energy frontier are arguably exploring the 10 TeV energy scale.

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