Physics Case for the ILC Project: Perspective from Beyond the Standard Model

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The International Linear Collider (ILC) has recently proven its technical maturity with the publication of a Technical Design Report, and there is a strong interest in Japan to host such a machine. We summarize key aspects of the Beyond the Standard Model physics case for the ILC in this contribution to the US High Energy Physics strategy process. On top of the strong guaranteed physics case in the detailed exploration of the recently discovered Higgs boson, the top quark and electroweak precision measurements, the ILC will offer unique opportunities which are complementary to the LHC program of the next decade. Many of these opportunities have connections to the Cosmic and Intensity Frontiers, which we comment on in detail. We illustrate the general picture with examples of how our world could turn out to be and what the ILC would contribute in these cases, with an emphasis on value-added beyond the LHC. These comprise examples from Supersymmetry including light Higgsinos, a comprehensive bottom-up coverage of NLSP-LSP combinations for slepton, squark, chargino and neutralino NLSP, a $\tilde{\tau}$-coannihilation dark matter scenario and bilinear R-parity violation as explanation for neutrino masses and mixing, as well as generic WIMP searches and Little Higgs models as non-SUSY examples.

1 Introduction

Experiments at the International Linear e^+e^- Collider (ILC) may be sensitive to new phenomena such as supersymmetric partners of known particles (SUSY), new heavy gauge bosons, extra spatial dimensions and particles connected with strongly-coupled theories of electroweak symmetry breaking [1]. For accessible particles, ILC can yield substantial improvements over LHC measurements. In addition, ILC will have a qualitative advantage on signatures that have high backgrounds at LHC or are difficult to trigger on.

In planning for future facilities relevant to exploring *physics beyond the Standard Model* (BSM), the proposed ILC stands out as a mature and shovel-ready project which would provide unique features which are complementary to the impending program of exploration by the LHC during the coming decade. After more than twenty years of study, the ILC design has now achieved a state of maturity culminating recently with the publication of the Technical Design Report [2]. Indeed, detailed simulations with realistic detector designs show that the ILC can achieve impressive precision [3]. The requirements of the ILC [4] include tunability between center-of-mass energies of 200 and 500 GeV, with rapid changes in energy over a limited range for threshold scans. Ultimately, expansion of the center-of-mass energy to ~ 1 TeV is envisioned. The luminosity, which must exceed 10^{34} cm^{-2} s^{-1} at 500 GeV, roughly scales proportionally with center-of-mass collision energy. Highly polarized electrons (>80%) are specified, with polarized positrons desirable. In this

whitepaper, we will discuss how these capabilities allow for compelling explorations of physics at the weak scale and beyond.

Any discussion of weak scale physics should account for the enormously successful LHC runs at $\sqrt{s} =$ 7 and 8 TeV. Their crowning achievement has been the spectacular discovery of the long-awaited Higgs boson [5, 6] with $m_h = 125.5 \pm 0.5$ GeV (ATLAS/CMS combined). But the discovery of the Higgs boson brings into sharp relief a well-known conundrum. To a good approximation, the newly discovered Higgs boson appears to be a fundamental scalar particle, and scalar particles suffer from quadratic divergences to their mass squared. In the case of the Higgs boson this leads to instability in the weak energy scale $\Lambda_{\rm weak} \sim 250$ GeV. Indeed, absent new physics up to the scale where gravity becomes strong, quantum fluctuations would drag the weak scale towards the scale 10^{19} GeV. The marked discrepancy between these scales is the gauge hierarchy problem (GHP). A natural resolution suggests that the Higgs should be accompanied by other new particles not included in the Standard Model (SM), and furthermore these particles should be near the weak scale.

The nature of this BSM physics has been a subject of intense theoretical speculation for over three decades, and a number of theoretically attractive ideas have been proposed. One solution is to implement a quantum Fermi-Bose symmetry known as supersymmetry (SUSY) which softens the troublesome divergences in the Higgs mass to merely logarithmic ones, which do not place a significant upward pressure on the weak scale. It does so while introducing a panoply of new states: squarks, sleptons, gauginos, and Higgsinos. The story-line from the past 30 years is that to naturally accommodate the weak scale, at least some of these superpartners ought to have masses around the weak scale. Alternative approaches to solving the GHP include Little Higgs models [7] (which solve the GHP at one loop level, deferring it to $\sim$ 10 TeV scale), introduction of warped (Randall-Sundrum or RS) spacetime dimension with associated Kaluza-Klein excitations, composite Higgs models (often formulated in setups with additional extra dimensions of space such as RS models), or postulating models with additional large spacetime dimensions. A qualitatively different spectrum of new matter states is predicted by each of these possibilities.

Strong new limits from the LHC do exist on new particle production. For example, for squarks and gluinos [8, 9], limits in many cases push the masses of colored particles to values beyond a TeV. In spite of these powerful null results, the complicated environment of proton collisions at the LHC does limit its power to hermetically search for new physics, and the current LHC data does not preclude a variety of well-motivated scenarios in which BSM particles are kinematically accessible at the ILC. These cases fall into several broad classes.

- BSM particles which only participate in electroweak interactions and are not charged under QCD strong force. Current LHC constraints on such particles are often much less stringent than those on colored particles, due to small production cross sections and large backgrounds. A well-motivated example is chargino pair production which is predicted in SUSY models. Even in cases where LHC production cross sections are large, the indistinct nature of the signal is difficult to extract from large $t\bar{t}$ and W^+W^- backgrounds. On the other hand, chargino pair production would be easily seen at an ILC provided $\sqrt{s} > 2m_{\tilde{\chi}^\pm}$ due to the much more constrained kinematics.

- BSM particles where decays do not release large amounts of visible energy. Current bounds on mixed chargino-neutralino production at the LHC [10] vanish if the mass splitting between the produced states and the lightest superpartner is less than 50 GeV. Difficulty exploring such regions persists even at very high luminosity [11]. Well-motivated examples of such compressed spectra exist. For instance, naturalness considerations in SUSY models suggest the existence of light Higgsinos with masses as light as $\sim 100 - 200$ GeV. And while Higgsino pair production may occur at sufficient rates at LHC, their highly compressed spectrum leads to only soft visible energy release in their decays, making detection exceedingly difficult. In the clean environment of an ILC, Higgsino pair production is straightforward to observe, provided that $\sqrt{s} > 2m_{\rm Higgsino}$.

- A third class pertains to the case where BSM particles decay to purely hadronic channels. An example– again from SUSY models– occurs when the lightest neutralinos can be pair produced, but where these decay to purely hadronic states via R-parity violating operators. In the case of LHC these may be buried beneath substantial QCD backgrounds whilst at an ILC they could be easily observed.

- A fourth class occurs when the BSM particles lie somewhat beyond the TeV scale. In this case, neither LHC nor ILC would have enough energy to produce them directly. However, quantum loop and other virtual effects in electroweak precision observables may allow an ILC to glean knowledge of their existence indirectly, perhaps determining the energy scale where the new matter states could be directly detectable. (For such studies, we defer to the Precision Electroweak Group report.)

In these scenarios, the ILC will be able to discover new physics missed by the LHC. Of course, there is also the exciting possibility that LHC makes a new physics discovery in the upcoming high energy/high luminosity runs. In this case, the role of the ILC would be to precisely characterize any new matter states which are accessible.

The Japanese government and HEP community have taken the leading role in offering to act as host country for such a machine. The European community has voiced strong support for ILC construction in Japan. Support from the US would provide critical momentum to help get this project started. In a staged approach, beginning at a center-of-mass energy of 250 GeV, a physics program would start with precision measurements of the Higgs branching ratios and properties. Raising the energy to 500 GeV would move to precision measurements of top quark properties well beyond those possible at the LHC. Should there be accessible new particles such as supersymmetric partners of gauge bosons and leptons, the ILC is the only place where they can be studied in full detail. Extension of the ILC to 1 TeV is straightforward, with lengthened linac tunnels and additional cryomodules, building on the original ILC sources, damping rings, final focus and interaction regions, and beam dumps.

This brief whitepaper is intended to highlight a variety of the unique and essential capabilities that an ILC would bring to the search for New Physics. We will conclude that:

- Even after the initial phase of LHC running, ILC remains a discovery machine. It is likely to remain so even into the next decade. A machine with true hermetic sensitivity to new physics up to a TeV will have powerful implications for whether or not the electroweak scale is, in fact, natural.

- Even if new physics is discovered at LHC, ILC with tunable energy, polarized beams, low background, theoretically well-understood interactions, precision beam energy and capacity for threshold scans would be a precision microscope for determining detailed properties of all low lying states.

- Precision measurements may allow for extrapolation to much higher mass scales, *e.g.* tests of unification.

- ILC has a unique role to play in dark matter physics, including 1. the possible observation of direct WIMP (weakly interacting massive particle) pair production via the recoil of an initial state radiation (ISR) photon and 2. precision measurements of new physics properties which would constrain and test dark matter production in the early universe along with providing particle physics input to direct and indirect WIMP search experiments.

- Even if new matter states turn out to be beyond ILC reach (and beyond the scope of this report which is devoted to direct production of new matter states), precision measurements sensitive to virtual quantum effects can also provide critical information.

For these reasons, from the standpoint of BSM physics, we conclude that there is a strong case for the ILC. Its rich program of new physics exploration– especially in light of the recent Higgs discovery– offers an exciting frontier facility for the US HEP community in the coming decades.

2 Connection to Cosmic Frontier

During the past several decades, a very compelling and simple scenario has emerged to explain the presence of dark matter in the universe with an abundance roughly five times that of baryonic matter. The WIMP miracle scenario posits that weakly interacting massive particles would be in thermal equilibrium with the cosmic plasma at very high temperatures $T > m_{\rm WIMP}$. As the universe expands and cools, the WIMP particles would freeze out of thermal equilibrium, locking in a relic abundance that depends inversely on

the thermally-averaged WIMP (co)-annihilation cross section [12]. The WIMP "miracle" occurs in that a weak strength annihilation cross section gives roughly the measured relic abundance provided the WIMP mass is of the order of the weak scale [13]. The lightest neutralino of SUSY models has been touted as a WIMP candidate [14, 15, 16]. The lightest T-parity-odd particle in Little Higgs theories and the lightest Kaluza-Klein (KK) excitation in extra-dimensional models preserving KK-parity also can serve as possible WIMP candidates.

The WIMP miracle is both simple and engaging. And while the WIMP miracle gets the relic density right to within orders of magnitude, detailed agreement with the measured thermal relic density is not guaranteed for just any weak scale candidate. Indeed, in SUSY models the correct thermal abundance is often achieved in regions of parameter space that require special relationships between the underlying parameters. For example, bino-like WIMPs typically annihilate away inefficiently, and are thus overabundant. They can successfully be depleted by co-annihilation processes, *e.g.* with a stau [17], but this requires a near degeneracy (within 5%) between the stau and the neutralino. Alternatively, the DM could annihilate through a resonance, but this requires $m_{\rm DM} \approx m_{\rm res}/2$. Such considerations present an opportunity: the ILC has the precision to verify whether these special relationships are indeed satisfied [13], and thus weigh in on whether the universe does obey a thermal history back to temperatures of order 100 GeV. Such an exploration would represent a roughly four order-of-magnitude increase in knowledge of physics at temperature scales beyond those probed by Big Bang Nucleosynthesis (BBN).

It is also plausible that the WIMP miracle is not the whole story, indeed:

- In SUSY theories, gravitinos may also play a major role. In might be the case that the gravitino forms the bulk of dark matter, instead of a WIMP. Gravitinos can be produced thermally in the early universe, or via sparticle cascade decays. In addition, if gravitinos are heavier than the lightest SUSY particle (LSP), then their decays may augment the neutralino abundance; however, their production and (Planck suppressed) decays are tightly constrained by BBN.

- The presence of light moduli-fields from string theory may influence the relic abundance, either by decaying into DM particles (augmenting the standard abundance) or by decaying into SM particles (thereby diluting all relics present at the time of decay).

- The strong CP problem cries out for a solution, and so far the most compelling is that of the semi-visible Peccei-Quinn (PQ) axion. The axion can also serve as dark matter particle. Furthermore, in SUSY theories the axion is accompanied by a spin-1/2 axino and a spin-0 saxion. These particles can also augment or dilute the dark matter abundance depending on various PQ parameters.

Thus, the physics associated with dark matter production may be much more complicated than just the simple picture provided by the standard WIMP miracle scenario.

The ILC can play a unique role in providing critical information needed to identify the dark matter particle(s) and their production in the early universe. In the case of theories like SUSY, Little Higgs models or extra dimensional models with KK dark matter, then the high precision measurement of low lying new particle masses, branching fractions, spin and other quantum numbers will provide strong particle physics constraints. Such measurements would offer terrestrial laboratory input to calculations of dark matter production rates in the early universe. If the inferred relic density lies above or below the standard thermal estimate, then evidence may be gleaned for non-standard processes such as the presence of axions. Characterization of dark matter properties will also provide input to direct and indirect WIMP detection calculations.

In particular, ILC may be able to produce DM or DM-related particles (*e.g.* the next-to-lightest SUSY particle, or NLSP) either directly or via cascade decays. In the former case, $e^+e^- \to \chi\chi\gamma$ production would allow laboratory tagging of invisible particles which might make up the dark matter. We will give more details about this possibility, also in view of LHC and direct detection limits, in Sec. 4.6. In the latter case, kinematic constraints from identifying heavier DM-related particles could allow for a direct measurement of the DM particle's mass *e.g.* via the jet-jet energy distribution from $e^+e^- \to \chi^+\chi^- \to (\ell^+\nu_\ell\chi) + (q\bar{q}'\chi)$. In case the observed relic density comes about with the help of co-annihilation processes, it is not enough to measure the properties of the WIMP, but in addition precise information on the mass and mixing of its co-annihilation partner is needed. We illustrate this case with an example in Sec. 4.3.

Finally, ILC may be able to indirectly weigh in on the issue of baryogenesis. While electroweak baryogenesis seems highly constrained in light of recent LHC results, it does require rather light top squarks. If these are nearly mass degenerate with the LSP, then they may well elude LHC searches, but should still be accessible to ILC. Alternatively, the Affleck-Dine baryogenesis mechanism requires the presence of baryon- and/or lepton-number carrying scalar fields. Such fields are aplenty in SUSY models, and their discovery and characterization at ILC would lend credence, albeit indirectly, to this approach.

3 Connection to Intensity Frontier

In the last fifteen years another branch of particle physics has seen impressive advances and extension of our knowledge: flavor physics. Starting with the compelling data on atmospheric neutrinos in 1998, it has now been firmly established that neutrinos are massive, and the different flavors are strongly mixed. However, neutrino masses are much smaller than the masses of the electrically charged fermions and flavor mixing in the leptonic sector differs considerably from that in the quark sector. These experimental findings, along with the observed hierarchies in the masses of the charged leptons and quarks form the so-called flavor puzzle. Even though we can parametrize our understanding, we do not know the underlying principles leading to the experimentally observed patterns. In the last decade, in addition to substantial progress in the neutrino sector, B-factories have considerably extended our knowledge of the quark sector. Nowadays LHC– where for example a first measurement of $BR(B_s \to \mu^+\mu^-)$ has recently been performed by the LHCb collaboration– is also contributing to this endeavor.

From the theoretical side, various models have been proposed which aim to explain the observed flavor structures, and several of them predict new particles at the TeV range. Often these flavor models are combined with supersymmetry to ensure the relative stability of the various scales involved. Typical examples are supersymmetric versions of the Froggatt-Nielsen mechanism as discussed for example in Ref. [18]. In such cases traces of this additional sector are left in the supersymmetry breaking parameters. This, in turn, leads to additional contributions to flavor and CP violating observables in low energy experiments. From data in the Kaon and B-meson sectors we know that these additional contributions are either sub-dominant or they conspire for an unknown reason such that all relevant observables in the quark sector seem to be SM-like. Such a "conspiracy" can occur because one has to sum over all possible virtual contributions which usually appear only at higher order. However, such a conspiracy cannot happen for the decays of supersymmetric particles (or those of any other sector of a BSM model related to quarks) and thus the measurement of various decay properties can provide a direct window into the flavor sector. While at the LHC squarks and gluinos may well be produced copiously, it remains experimentally very challenging to determine the branching ratios of the individual particles [19]. However, theoretical arguments prefer that at least one of the stops has mass in the range of a few hundred GeV and thus might be accessible to the ILC. Detailed information on its branching ratio would give important information on flavor structures beyond the ones present in the SM [20].

Several models have been proposed to explain the smallness of neutrino masses. At low energies they usually lead to the so-called Weinberg operator $(LH)^2$ giving Majorana masses to light neutrinos after electroweak symmetry breaking. The most popular among them is the seesaw mechanism which comes in three varieties depending on the details of how this operator is generated: type I in case of gauge singlet fermions (usually the right-handed neutrinos), type II in case of an $SU(2)_L$ triplet Higgs boson and type III in case of $SU(2)_L$ triplet fermions. These additional particles are usually too heavy to be produced directly in collider experiments. In supersymmetric models they leave imprints in the RGE evolution of the mass parameters [21] and give rise to additional flavor structures which are linked to the underlying mechanism for generating neutrino masses. These flavor structures induce flavor violating decays of sleptons which can be studied at the ILC [22].

Beside the usual mechanisms to generate neutrino masses, supersymmetry offers an additional possibility: breaking of R-parity in the lepton sector. The simplest model is the one where only bilinear terms are present in the superpotential as well as the corresponding terms in the soft SUSY sector. As R-parity is broken, the lightest supersymmetric particle (LSP) is not stable anymore but decays. The six parameters explaining neutrino data are then also those responsible for the decay properties of the LSP: ratios of decay branching ratios are proportional to neutrino mixing angles, *e.g.* $BR(\tilde{\chi}_1^0 \to W\mu)/BR(\tilde{\chi}_1^0 \to W\tau) \simeq \tan^2\theta_{\rm atm}$ or

$BR(\tilde{\chi}_1^0 \to \nu\mu\tau)/BR(\tilde{\chi}_1^0 \to \nu e\tau) \simeq \tan^2\theta_{\rm sol}$ where $\theta_{\rm atm}$ and $\theta_{\rm sol}$ are the atmospheric and solar neutrino mixing angles. We will illustrate this possibility with a dedicated simulation study in section 4.5. Moreover, the smallness of the neutrino masses also implies that the lifetime of the LSP is measurable at the ILC in a large part of the parameter space. For completeness we note that the existence of such correlations does not depend on the nature of the LSP– *e.g.* whether it is a neutralino or a chargino or a slepton– but only the concrete form of these correlations [23].

4 ILC Stories

While there is a compelling case that new structure is needed in the laws of physics at the $100-1000$ GeV scale, exactly what that structure might be is one of the great mysteries of our time. Theoretical guidance allows one to extend the Standard Model to include new ideas such as supersymmetry, grand unification, see-saw neutrinos, Little Higgs, string theory, etc. But exactly how any of these ideas would manifest themselves at the weak scale is open to speculation; the truth will only be gleaned by a detailed program of experimental tests and scrutinization. The ILC– with its unique experimental environment and decisive advantages– is prepared for almost any possibility. Here we will present seven dossiers– each a particular story– of how nature might be constructed at the weak scale, and what role the ILC could play in revealing to us new, fundamental underlying principles in the laws of physics. The reality will have to await construction of ILC followed by a detailed program of data taking. For as R. P. Feynman once said: "the imagination of nature is far, far greater than that of man".

4.1 Coming to terms with electroweak naturalness

Supersymmetric theories provide an elegant solution to the gauge hierarchy problem. However, a lack of SUSY signals at LHC8 combined with the rather large value of $m_h \sim 125$ GeV seemingly exacerbates what has come to be known as the Little Hierarchy problem (LHP): why is there such a discrepancy between the electroweak scale, typified by $m_Z = 91.2$ GeV and $m_h = 125.5$ GeV, and the superpartner scale, which in the case of gluinos and squarks, seems to be at the TeV-or-beyond scale. Phrased differently, one might wonder why: if superpartners are at the > 1 TeV scale, how can it be that m_Z is just 91.2 GeV instead of also at the > 1 TeV scale?

An answer can be extracted from the electroweak scalar potential minimization condition which relates m_Z^2 to the SUSY breaking parameters and the superpotential Higgsino mass μ:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \ , \tag{1}$$

where Σ_u^u and Σ_d^d include a variety of radiative corrections [24, 25]. To *naturally* obtain a Z mass of 91.2 GeV, then one expects each contribution to the right-hand-side of Eq. 1 to also be $\sim m_Z^2/2$: *i.e.* there are no large uncorrelated contributions to the Z-mass.

To allow for electroweak naturalness, *e.g.* requiring no worse than cancellations at the $\sim 3\%$ level, then it is necessary that (a) $|\mu| \sim 100-300$ GeV, (b) $m_{H_u}^2$ is driven to only small negative values under RG evolution and (c) the top squarks $\tilde{t}_1$ and $\tilde{t}_2$ are highly mixed with masses $m_{\tilde{t}_1} \sim 1-2$ TeV and $m_{\tilde{t}_2} \sim 2-4$ TeV. The large mixing softens the top squark radiative corrections while at the same time lifting m_h up to ~ 125 GeV.

When these conditions are met, then one may allow for a *natural* Little Hierarchy characterized by

- $m_{\rm Higgsino} \sim m_Z \sim m_h$
- top squarks which enter Eq. 1 at one-loop level and gluinos should live in the $1-5$ TeV regime and
- first/second generation squarks and sleptons which enter Eq. 1 at two-loop level can exist at the $10-20$ TeV regime, which allows for at least a partial solution to the SUSY flavor and CP problems.

The main implication of this picture– dubbed radiatively-driven natural supersymmetry (RNS) because the soft term $m_{H_u}^2$ is radiatively driven to small negative values at the electroweak scale [24, 25]– is that there should exist four light physical Higgsinos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ with mass $\sim 100-300$ GeV (the lighter the better) where $\tilde{\chi}_1^0$ is the LSP which is dominantly Higgsino-like (albeit with a non-negligible gaugino component). Due to the compressed spectrum amongst the various Higgsino states (typically a 10-20 GeV mass gap in models with gaugino mass unification), their three-body decays yield only tiny visible energy release, making them very difficult to detect at LHC. On the other hand, the light Higgsinos should be easily detected at an ILC provided that $\sqrt{s} > 2|\mu|$.

The situation can be illustrated within the μ *vs.* $m_{1/2}$ plane in the RNS model [26], where we also take GUT scale matter scalar masses $m_0 = 5$ TeV, $\tan\beta = 15$, $A_0 = -1.6m_0$ and $m_A = 1$ TeV. From the left panel of Fig. 1, it can be seen that LHC8 has explored $m_{1/2} \lesssim 0.4$ TeV via the search for $\tilde{g}\tilde{g}$ production. The calculated LHC14 reach with 300^{-1} fb for $\tilde{g}\tilde{g}$ production [27] and for same-sign diboson production [28] extends to $m_{1/2} \sim 0.7-0.8$ TeV (corresponding to a reach in $m_{\tilde{g}} \sim 1.8-2.1$ TeV). The naturalness contours of $\Delta_{\rm EW} = 30$ (*i.e.* $\Delta_{\rm EW}^{-1} \sim 3\%$ fine-tuning) extend well beyond LHC14 reach all the way to $m_{1/2} \sim 1.2$ TeV. However, ILC600 can probe the entire parameter space with $\Delta_{\rm EW} < 30$, thus either discovering Higgsinos or ruling out SUSY electroweak naturalness.

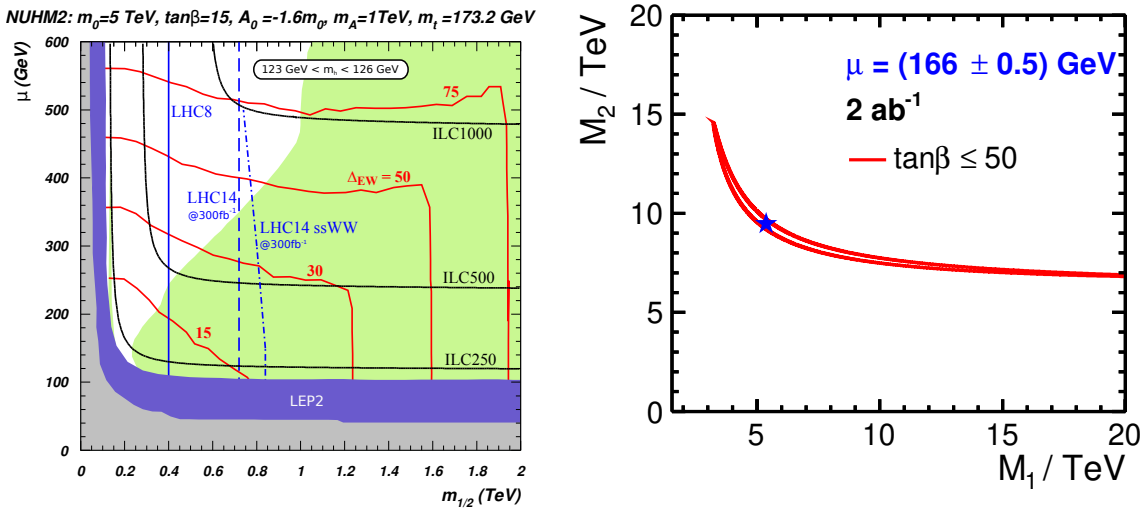

Figure 1: Left: Contours of fine-tuning $\Delta_{\rm EW} = 15,\ 30$ 50 and 75 in the $m_{1/2}$ vs. μ plane for the RNS model with parameters as shown (from Ref. [26]). The blue vertical lines show the current reach of LHC8 and the projected reach of LHC14 with 300 fb^{-1} via gluino pair searches (dashed line) and same-sign dibosons (dot-dashed). The reach of ILC with $\sqrt{s} = 250$, 500 and 1000 TeV is also shown. The green-shaded region has a thermal Higgsino relic abundance $\Omega_{\tilde{h}}h^2 \leq 0.12$. Right: Parameter determination in the M_2 vs M_1 plane in the benchmark Higgsino scenario. The star indicates the input values of M_2 and M_1, the $\Delta\chi^2 = 1$ contour of a fit to expected ILC measurements is displayed in red. From the same fit, μ is obtained with sub-GeV precision. From [31].

This is true independently of the size of the mass splittings between the Higgsinos. The clean environment of the ILC allows to resolve and measure mass differences even in the sub-GeV regime. Beam polarization can not only be employed to enhance the signal, but also to verify that s-channel Z (or Z/γ) exchange is the only production mechanism as expected for Higgsinos.

The achievable precision at the ILC has recently been studied for a benchmark scenario with $\mu = 166$ GeV, assuming ILC TDR [2] machine parameters and detector performance [3]. The gaugino mass parameters are as large as $M_1 = 5.4$ TeV and $M_2 = 9.5$ TeV, resulting in a mass difference of only $\Delta(M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}) = 770$ MeV [29]. Even in such a challenging situation, all states can be fully resolved. $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_2^0}$ can be

determined to a few GeV, while the statistical uncertainty on the mass difference is a few ten MeV. The polarized cross-sections can be measured at the percent level.

Already with an integrated luminosity of 500 fb^{-1} at $\sqrt{s} = 500$ GeV and $P(e^+, e^-) = (+30\%, -80\%)$, these measurements are precise enough to determine μ at the percent level, and to put lower limits in the few TeV-range on M_1 and M_2 [30]. With higher luminosity, M_1 and M_2 can actually be constrained to a narrow region, as displayed in the right part of Fig. 1. The star indicates the input values of M_2 and M_1, the $\Delta\chi^2 = 1$ contour of a fit to expected ILC measurements is displayed in red. From the same fit, μ is obtained with sub-GeV precision. This shows that already with $\sqrt{s} = 500$ GeV, the ILC can constrain parameters in the multi-TeV range and thus predict the physical masses of the heavier states.

In summary, light Higgsinos are an important discovery opportunity for the ILC, even if no new physics is found at LHC14. Especially for $m_{1/2} \gtrsim 1$ TeV, only the ILC can systematically explore the regime of natural supersymmetry independently of any assumptions on the top squark or the gluino mass, and either exclude the notion of natural SUSY or become a *Higgsino factory* in addition to being a Higgs factory.

4.2 At the ILC, SUSY *is* simplified

At lepton colliders, one has the possibility to search for SUSY in a model-independent way [32]: The cornerstone of SUSY is that *sparticles couple as particles*. This is independent of the mechanism responsible for SUSY breaking. In particular, the coupling to the Z-boson is known, which implies that the cross-section for any $e^+e^- \to$ sparticle-antisparticle pair process in the s-channel is determined by the kinematics alone, *i.e.* by $\sqrt{s}$ and the mass of the sparticle. Furthermore, by definition there is *one* LSP, and *one* NLSP. Cosmological arguments shows that if the LSP is stable it must neutral and weakly interacting. The NLSP, on the other hand, could be any sparticle: a slepton, an electroweakino, or even a squark. However, there are only a *finite* number of sparticles.

While an arbitrary sparticle in the spectrum of any SUSY model typically would decay through cascades of other, lighter sparticles, the NLSP only has *one* decay-mode, namely to the LSP and the SM partner of the NLSP. Therefore, studying NLSP production and decay can be regarded as a "simplified model without simplification": Any SUSY model will have such a process.

Putting these observations together, one realizes that by systematically searching for signals for all possible NLSP's, the entire space of models that are reachable can be covered. At the ILC, such a program is possible *without leaving loop-holes*, even for difficult or non-standard cases.

Closing the loop-holes

If *e.g.* the LSP is unstable due to RPV, the reach would be better or equal to the R-conserving case, both for long-lived and short-lived LSP's and whether the LSP is charged or neutral.

Also in the case of an NLSP which is a mass-state mixed between the hyper-charge states, the procedure is viable. One will have one more parameter - the mixing angle. However, as the couplings to the Z of both states are known from the SUSY-principle, so is the coupling with any mixed state. There will then be one mixing-angle that represents a possible "worst case", which allows to determine the reach whatever the mixing is - namely the reach in this "worst case".

In the case of a very small mass differences between the LSP and the NLSP - less than a few GeV - the clean environment at the ILC nevertheless allows for a good detection efficiency. If $\sqrt{s}$ is much larger than the threshold for the NLSP-pair production, the NLSPs themselves will be highly boosted in the detector frame, and most of the spectrum of the decay products will be easily detected. In this case, the precise knowledge of the initial state at the ILC is of paramount importance to recognize the signal, by the slight discrepancy in energy, momentum and acolinearity between signal and background from pair production of the NLSP's SM partner. In the case the threshold is not much below $\sqrt{s}$ the background to fight is $\gamma\gamma \to f\bar{f}$ where the γ's are virtual ones radiated off the beam-electrons. The beam-electrons themselves are deflected so little that they leave the detector undetected through the out-going beam-pipes. Under the clean conditions at the ILC, this background can be kept under control by demanding that there is a visible ISR photon accompanying the soft NLSP decay products. If such an ISR is present in a $\gamma\gamma$-event, the beam-remnant will also be detected, and the event can be rejected.

Finally, the case of "several" NLSPs– *i.e.* a group of near-degenerate sparticles– can be disentangled due to the possibility to precisely choose the beam energy at the ILC. This will make it possible to study the "real" NLSP below the threshold of its nearby partner.

The strategy

At an e^+e^--collider, the following typical features of NLSP production and decay can be exploited: missing energy and momentum, high acolinearity, expected particle or jet flavor identification as well as invariant di-jet/di-lepton mass-conditions, optionally using constrained kinematic fitting. A very powerful feature due to the known initial state at the ILC is that the kinematic edges of the detected systems can be precisely calculated at any point in the $M_{\rm NLSP} - M_{\rm LSP}$ plane. In particular, close to kinematic limit where the width of the decay-product spectrum is quite small, this feature allows for an almost background-free signal with high efficiency. To estimate the background at each point, correctly normalized samples of events from all SM processes are generated, passed through detector simulation, and the analysis chain.

If the number of observed events passing the selection criteria for a given NLSP nature exceeds the expected background passing the same cuts by more than 5σ, one can claim *discovery* of the NLSP. If, on the other hand, the observed number does not exceed the expected background by more than 2σ, *exclusion* can be claimed. As this is procedure is done for *every possible NLSP*, it will constitute a complete and model-independent search for SUSY.

In order to estimate what the expected *Discovery Reach* or *Exclusion Reach* of the experiment is, it is enough to simulate the signal for each possible NLSP in a fine grid in the $M_{\rm NLSP} - M_{\rm LSP}$ at the given $\sqrt{s}$, calculate the production cross-section from the SUSY-principle and kinematics, and confront it to the relevant selection criteria.

In Fig. 2, the cross-section at $\sqrt{s} = 500$ GeV as a function of $M_{\rm NLSP}$ is shown in the left panel for a selection of NLSP-candidates. The right panel shows as example the 5σ discovery and 2σ exclusion reach for a $\tilde{\mu}_R$ NLSP after collecting 500 fb^{-1} at $\sqrt{s} = 500$ GeV.

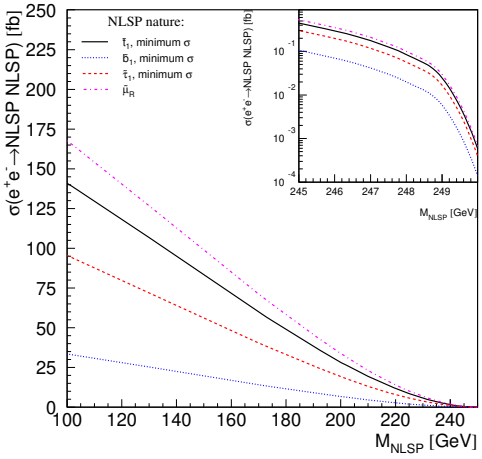

Figure 2: Left: NLSP production cross-sections as a function of $M_{\rm NLSP}$ at $\sqrt{s} = 500$ GeV (best beam-polarization) for a few NLSP hypotheses. The insert shows the last few GeV before the kinematic limit, on a log-scale. Right: Discovery-reach for a $\tilde{\mu}_R$ NLSP after collecting 500 fb^{-1} at $\sqrt{s} = 500$ GeV.
RIGHT-HAND FIGURE WILL BE ADDED BEFORE SEATTLE

4.3 LHC and ILC complementarity: SUSY is complex!

In full SUSY models, the higher states of the spectrum can have many decay modes leading to potentially long decay chains [33]. This means that the simplified approach does in general not apply beyond the the direct NLSP-production case discussed in the previous section, which renders the interpretation of exclusion limits formulated in the simplified approach non-trivial. Furthermore, also many production channels may be open, making SUSY the most serious background to itself.

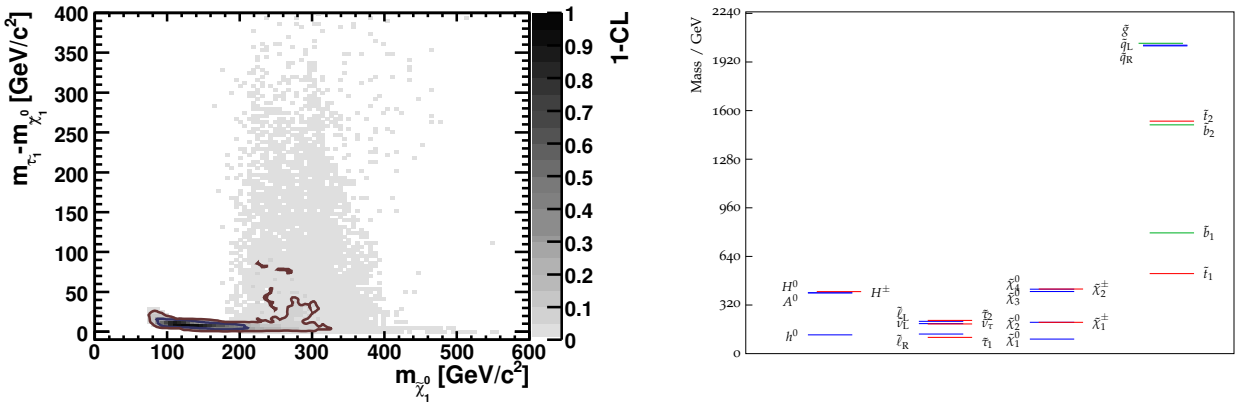

Figure 3: Left: Likelihood of a constrained MSSM fit to pre-LHC experimental data in the $\Delta M(\tilde{\tau}, \tilde{\chi}_1^0) - M_{\tilde{\chi}_1^0}$ plane. The series of example points discussed here have $\Delta M(\tilde{\tau}, \tilde{\chi}_1^0) - M_{\tilde{\chi}_1^0} = 10$ GeV, right on the strip of highest likelihood, from Ref. [34]. Right: Spectrum of one of the example scenarios, from Ref. [36]
.

Take as an example the regions in parameter space which gained the highest likelihood in fits to all pre-LHC experimental data within the constrained MSSM [34, 35]. These fits preferred scenarios with a small mass difference of about 10 GeV between the $\tilde{\tau}$-NLSP and the $\tilde{\chi}_1^0$ as LSP as illustrated by the likelihood distribution in the left panel of Fig. 3. Without the restriction of mass unification at the GUT-scale, the part of the spectrum which is of interest to electroweak and flavor precision observables and dark matter, *i.e.* which is decisive for the fit outcome, is not at all in conflict with LHC results. The right part of Fig. 3 shows the example of a spectrum fulfilling all constraints, including a Higgs boson with SM-like branching ratios at a mass in agreement with the LHC discovery within the typical theoretical uncertainty of ± 3 GeV on MSSM Higgs mass calculations. The full definition and further information can be found in Ref. [36].

A series of similar points with increasing top squark mass has been studied recently with the Snowmass version of the LHC detectors as implemented in Delphes [37]. If the $\tilde{t}_1$ is lighter than $\simeq$ 500 GeV, $\tilde{t}_1\tilde{t}_1$ production is the dominant mode with a cross-section of a few pb, followed by electroweakino production inclusively at the level of 1 pb at 14 TeV. Although in this region of stop and electroweakino masses serious constraints seem to exist in simplified models, running the Delphes mimick of the relevant analyses on the non-simplified full model revealed that the sensitivity of the current data is actually *not* sufficient. The study further shows that these points could be discovered as a deviation from the SM at LHC14, but only few states could be resolved and clearly identified. More details can be found in dedicated whitepaper on this study [38].

However at the ILC running at $E_{CMS} = 500$ GeV, all sleptons and all charginos and neutralinos can be produced, with sizable cross-sections - only one of the allowed processes would have a production cross-section below 1 fb for both beam-polarizations. The total SUSY cross-section is over 3 pb in both cases.

In the slepton sector, several of the channels are being studied, or have been in the past. *E.g.* in [39], it was shown that the $\tilde{\tau}_1$ mass could be determined to 0.2% (Fig. 4), and the $\tilde{\tau}_2$ mass to 3% . Production cross-section for both these modes can be determined at the level of a 4%, and the polarization of τ-leptons from the $\tilde{\tau}_1$ decay could be measured with an accuracy better than 10%. Further studies shows that the mass of $\tilde{\mu}_R$ can be determined to 0.1% by a threshold scan [40], see Fig. 4.

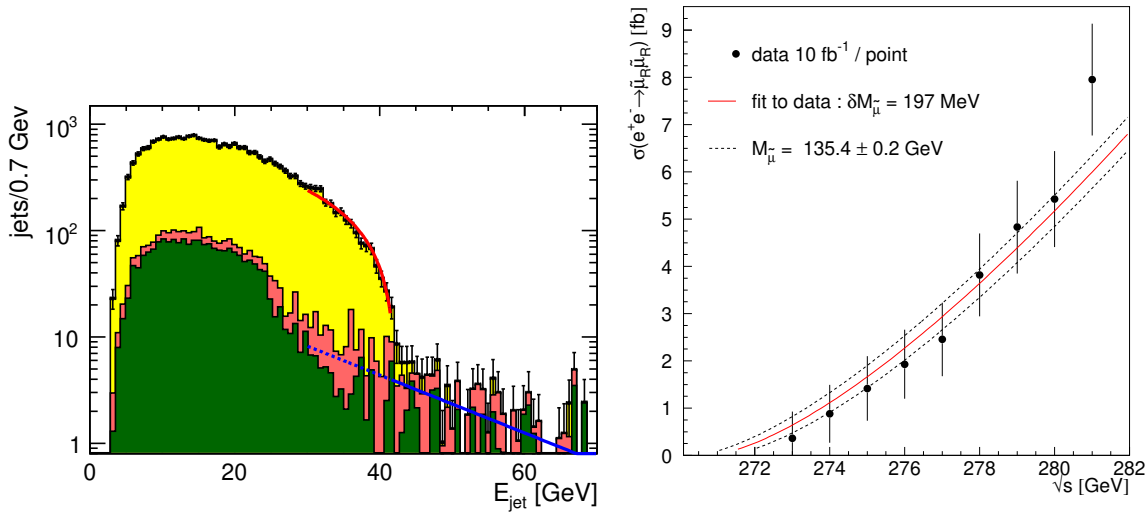

Figure 4: Left: $\tilde{\tau}_1$ spectrum (yellow) and background (SM: red, other SUSY: green), with end-point fit. From Ref. [39]. Right: Threshold scan at the $e^+e^- \to \tilde{\mu}_R\tilde{\mu}_R$ threshold. From Ref. [40]
.

In the bosino sector, further constraints on the neutralino and chargino mixing-matrices are possible. Almost all processes are kinematically accessible at 500 GeV, and all but one ($e^+e^- \to \tilde{\chi}^0_3\tilde{\chi}^0_3$) have cross-sections above 1 fb. The use of beam-polarization and tunable $\sqrt{s}$ will further enhance the power of the observations. Due to the low background, cascade decays can be disentangled, and sometimes fully kinematically constrained. When that is possible, one can hope to obtain even lower uncertainties on the slepton masses, of the order of 10 MeV [41].

This 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. In particular, the precision measurement of the LSP and NLSP properties will connect to cosmology, and answer the question if SUSY indeed does provide the correct relic density.

To conclude, this scenario is an excellent case for the LHC-ILC synergy: LHC will, at the time ILC is commissioned, have discovered the stop, and might have some insight into the bosino-sector. ILC will then be able to make detailed measurements of masses, couplings and mixings in the slepton and bosino sectors. These refined inputs will help LHC to interpret the observations in the colored sector, and possibly hint to new search strategies, including topologies that might previously not even have passed the trigger conditions. This way, the results from the two machines, running concurrently, will allow to map out the full landscape of the model.

4.4 LHC and ILC complementarity: Electroweakinos

In many SUSY models, colored sparticles are expected to be amongst the heaviest of the superpartners, and indeed data from LHC8 points to first/second generation squarks and gluinos beyond the $\sim 1-1.5$ TeV level (at least within the context of simple models such as CMSSM). However, electroweakinos (collectively refering to the two chargino and four neutralino states) are expected in most models to be much lighter, and perhaps within kinematic reach of both LHC14 and various ILC energy options.

At LHC, the reactions $pp \to \tilde{\chi}^+_i\tilde{\chi}^-_{i'}$, $\tilde{\chi}^0_j\tilde{\chi}^0_{j'}$ and $\tilde{\chi}^\pm_i\tilde{\chi}^0_j$ ($i,\ i' = 1,\ 2$ and $j,\ j' = 1-4$) are all expected to occur. Of this panoply of reactions, theoretical projections are that $\tilde{\chi}^+_1\tilde{\chi}^-_1$ will be buried beneath W^+W^- and $t\bar{t}$ backgrounds, while $\tilde{\chi}^0_j\tilde{\chi}^0_{j'}$ either occur at low rates or are buried beneath backgrounds. The best hope for LHC seems to be the mixed reaction $pp \to \tilde{\chi}^\pm_i\tilde{\chi}^0_j$. In the case where $|\mu| \gg M_1,\ M_2$ and sfermions are

(This is a placeholder figure for the ewkino scan as the analysis is still in progress as of this writing.)

Figure 5:

heavy, this leads to 1. the clean off-shell trilepton signature from $\tilde{\chi}_1^\pm \to \ell' \nu_{\ell'} \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell^+\ell^- \tilde{\chi}_1^0$ decay or 2. to $WZ \to 3\ell$ for $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$ or 3. to Wh production from $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$. In the first case, the $m(\ell^+\ell^-)$ invariant mass can be used to yield a high precision measurement of $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. In the case where $|\mu| < M_1,\ M_2$, then wino pair production followed by decay to same sign dibosons $pp \to \tilde{\chi}_2^\pm \tilde{\chi}_4^0 \to (W^\pm \tilde{\chi}_{1,2}^0) + (W^\pm \tilde{\chi}_1^\mp)$ yields an excellent signature with low backgrounds for models with light Higgsinos.

In contrast, at ILC the mixed production reaction isn't allowed due to charge conservation. However, the complementary reaction $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ should be easily seen above background provided that $\sqrt{s} > 2m_{\tilde{\chi}_1^+}$. Since the beam energy is precisely known, this allows for extraction of the masses $m_{\tilde{\chi}_1^+}$ and $m_{\tilde{\chi}_1^0}$ to high precision. In addition, mixed production $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ can allow access to the heavier $\tilde{\chi}_2^\pm$ chargino state even if $\sqrt{s} < 2m_{\tilde{\chi}_2^+}$. Also, the ten $\tilde{\chi}_j^0 \tilde{\chi}_{j'}^0$ reactions should be easy to spot provided that $\sqrt{s} > m_{\tilde{\chi}_j^0} + m_{\tilde{\chi}_{j'}^0}$. Threshold scans and beam polarization will help to differentiate these reactions and to discriminate the Higgsino/gaugino components of each $\tilde{\chi}_j^0$ state which is accessible. Even in the case where $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, radiation of initial state photons can be used to tag this reaction against $e^+e^- \to \nu\bar{\nu}\gamma$ background. To summarize: while LHC is sensitive to mainly mixed electroweakino production provided there are large enough mass gaps between parent and daughter particles, ILC will be sensitive to a variety of complementary reactions even when small mass gaps occur, such as for charged and neutral Higgsino pair production.

A joint LHC/ILC study has been performed [42] to demonstrate the complementarity of the LHC and the ILC. The idea is to perform a parameter scan in the context of the MSSM in the three-dimensional parameter space in the M_1, M_2, and μ variables, while fixing the value of the Higgs mass to be 125 GeV and $\tan\beta$ which does not significantly affect the electroweakino sector. The masses and branching ratios are obtained from tree-level calculations. We avoid mass differences of smaller than about 200 MeV since the loop corrections become significant.

For the ILC, two analysis strategies are employed. First, the signature of four jets plus missing energy is selected which covers the case of medium to large mass differences. Second, the recoil of the initial state radiation photon is used for the case of small mass differences. The SGV fast simulation tool [43] is used to simulate the ILC detector response including the particle flow calorimetry. The expected exclusion and observation contours are shown in Fig. 5 together with the LHC analysis. As expected, the two machines complement each other nicely. *(To be updated with concrete numbers when the analysis is complete.)* The ILC can, in addition, separate the chargino and neutralino contributions in many cases, providing cross-section and mass measurements at the $O(1)\%$ level [44].

4.5 Bilinear R-Parity Violation: Neutrino Physics at Colliders

One outstanding question the Standard Model cannot explain is the smallness of neutrino masses. As explained earlier, mechanisms of neutrino mass generation involving supersymmetry can be studied at the ILC through precise measurements of properties of new particles. As a concrete example, we will illustrate the ILC's capabilities assuming bilinear R-parity violation as the origin of neutrino masses as introduced in Sec. 3.

In this case, the atmospheric neutrino mixing angle can be accessed via the ratio of branching ratios of the LSP: $BR(\tilde{\chi}_1^0 \to W\mu)/BR(\tilde{\chi}_1^0 \to W\tau) \simeq \tan^2\theta_{\rm atm}$. At the ILC, these branching ratios can be measured from direct LSP pair production even if all other SUSY particles should be out of kinematic range for direct production. The cross-section depends on the neutralino mixing and the selectron mass, but can easily be as large as 100 fb, giving *e.g.* 25000 events per year of design ILC operation at $\sqrt{s} = 500$ GeV.

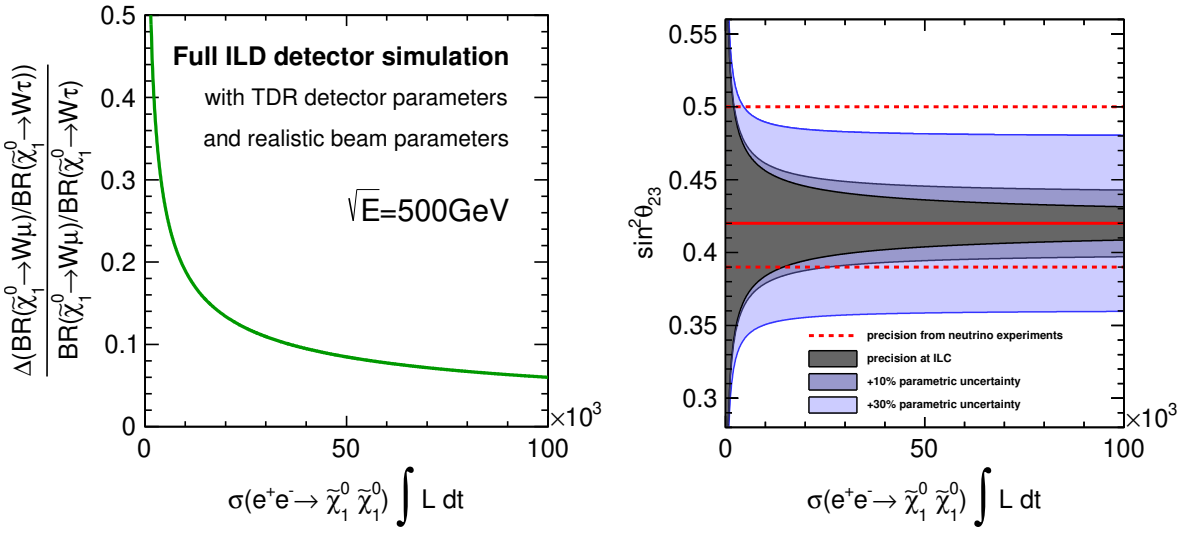

Figure 6: Left: Experimental precision on $BR(\tilde{\chi}_1^0 \to W\mu)/BR(\tilde{\chi}_1^0 \to W\tau)$ as a function of the number of produced events. Right: Derived uncertainty on the atmospheric neutrino mixing angle $\sin^2\theta_{23}$, including the additional parametric uncertainty due to limited knowledge of other SUSY parameters.

The experimental performance for the branching ratio measurements has been presented in the ILC TDR [2] using state-of-the-art full simulation of the ILD detector concept [3]. The obtained relative precision on $BR(\tilde{\chi}_1^0 \to W\mu)/BR(\tilde{\chi}_1^0 \to W\tau)$ is shown in the left panel of Fig. 6. Already for 25000 produced events, a relative precision of 12% is achieved, which decreases to 6% for 100000 events. The right panel illustrates the resulting absolute precision on $\sin^2\theta_{\rm atm}$, assuming the current central value from oscillation measurements, whose precision is indicated by the dashed horizontal lines. For the collider measurement, the effect of the parametric uncertainty due to limited knowledge of other SUSY parameters which enter the relation between the branching ratios and the mixing angle is displayed in addition.

Such a measurement, if in agreement with direct oscillation measurement, could pin down the origin of neutrino masses and mixing, which would solve one of the major puzzles of our current understanding of nature.

4.6 Production of dark matter in the laboratory?

As discussed in Sec. 2, the existence of Dark Matter provides a strong indication for the appearance of new phenomena near the electroweak scale, and the ILC is a powerful tool for probing the WIMP hypothesis

If the WIMPs have a non-negligible coupling to electrons, they can be pair produced in electron-positron collisions: $e^+e^- \to \chi\chi$. The WIMPs themselves leave a collider detector without a trace. Nevertheless such events can be identified when the WIMP system recoils against an energetic photon from initial state radiation, very similar to the mono-jet and mono-photon signatures searched for at the LHC [45, 46]. In case of the ILC, the potential of the mono-photon signature has been studied at theoretical level [47, 48, 49, 50], as well as in full detector simulation of the ILD detector concept [51, 52]. The special environment at the ILC, with a fully controllable initial state of the collisions, including the beam polarization, and the backgrounds at typical electroweak level, enables sensitivities to cross-sections of the order of a few fb, depending on the

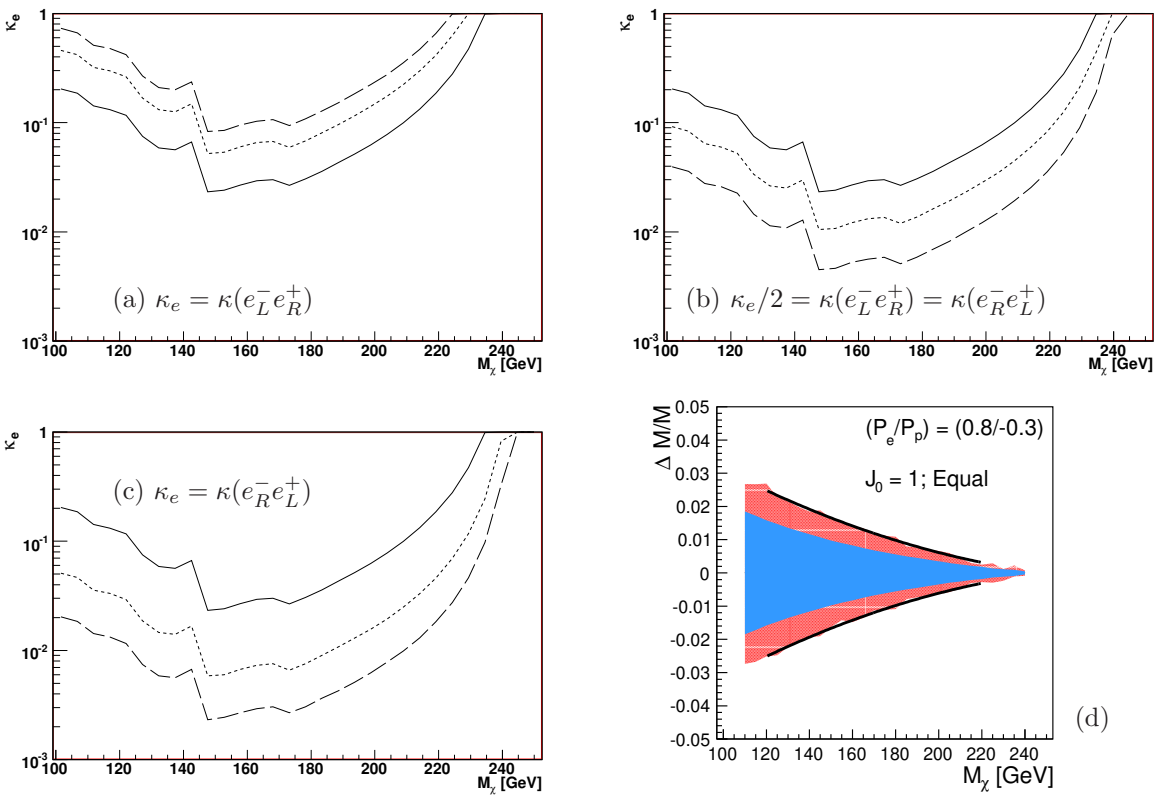

Figure 7: (a)-(c) Observational reach (3σ) of the ILC for a Spin-1 WIMP in terms of WIMP mass and κ_e for three different chiralities of the WIMP-fermion couplings. Full line: $P_{e^-} = P_{e^+} = 0$, dotted line: $P_{e^-} = 0.8, P_{e^+} = 0$, dashed line: $P_{e^-} = 0.8, P_{e^+} = 0.6$. From Ref. [51]. (d) Experimental statistical (red) and systematic (blue) precision of the mass reconstruction as a function of the WIMP mass. From Ref. [52].

details of WIMP properties and assumed operation mode of the ILC. This means that the ILC can discover this signature even if annihilation to electrons provides only a small fraction κ_e of the total dark matter annihilation rate in the early universe. This is illustrated in Fig. 7(a)-(c), which show the 3σ observation reach for an integrated luminosity of 500 fb^{-1} at a center-of-mass energy of 500 GeV for a spin-1 WIMP and three different assumptions on the helicity structure of the WIMP-fermion coupling [51]. Beam polarization increases the reach in κ_e by about an order of magnitude.

If a signal is observed, the shape of the photon energy spectrum is a powerful tool to pin down the properties of the WIMP candidate. As example, Fig. 7(d) shows the achievable mass resolution of a few percent as a function of the WIMP mass as obtained in full detector simulation, including both statistical and systematic uncertainties. The statistical uncertainties are based on an integrated luminosity of 500 fb^{-1} and an unpolarised production cross-section of 100 fb^{-1}, which eg for a WIMP mass of 150 GeV corresponds to $\kappa_e \simeq 0.5$ in case of a spin-1/2 WIMP and to $\kappa_e \simeq 0.25$ for a spin-1 WIMP. For more details, see [52].

The measurement of the polarized cross-sections for all four possible beam polarization configurations will reveal the helicity properties of the WIMP's interaction with Standard Model fermions, and the shape of the photon energy spectrum can be used to determine the dominant partial wave of the WIMP pair production process.

If the WIMP-electron interaction is mediated by a heavy particle with mass well above the WIMP mass, the interaction can be described in an effective operator language, *e.g.* as a 4-fermion operator for a spin-1/2 WIMP [49, 50]. In this case, ILC measurements can determine the structure of the effective operator(s), providing indirect information on the nature of the heavy mediator.

Currently, the LHC as well as direct detection experiments are searching for WIMPs via their interactions with quarks and gluons. The ILC will provide a complementary approach, relying on the WIMP-electron interaction instead. Since the couplings of WIMPs are very model dependent, such complementarity is of great value. Indirect detection experiments can search for photons and positrons produced in WIMP annihilations mediated by WIMP-electron interactions, but are primarily sensitive to WIMP masses in the few hundred GeV region and above, while the ILC is sensitive to lower mass WIMPs. For a more detailed discussion of complementarity between direct, indirect, and collider searches for WIMPs, see *e.g.* Refs. [53, 54].

4.7 Little Higgs: an alternative to SUSY

Many alternatives to supersymmetry have been proposed as candidates for physics at the weak scale. While the discovery of the light Higgs eliminates some of these alternatives, many viable options remain. Just as in the case of supersymmetry, the ILC can play a vital role in exploring the physics of these models. As an example, consider the Littlest Higgs model with T-parity, based on $SU(5)/SO(5)$ symmetry breaking pattern [55]. This model is a useful benchmark because its phenomenology has been studied extensively. The parameter space of the model is constrained by precision electroweak constraints [56, 57], as well as direct searches for the fermionic top partner [57] and T-odd partners of quarks [58] at the LHC. Nevertheless, viable parameter space remains where weakly-coupled new particles could be within the kinematic range of the ILC; in fact, this is precisely the part of the parameter space preferred by naturalness considerations. In particular, the lightest T-odd particle (LTP)– typically the partner of the photon and an attractive dark matter candidate [59]– is likely to be accessible. T-odd partners of the electroweak gauge bosons, as well as partners of charged leptons and neutrinos, could also be directly produced at the ILC. If this is the case, the ILC would be able to pursue a program of precise determination of the masses and couplings of all kinematically accessible states. This would in turn provide a quantitative test of the structure of the Little Higgs model, as well as allow for a precise prediction of the LTP relic density which can then be compared with the observed cosmological abundance of dark matter.

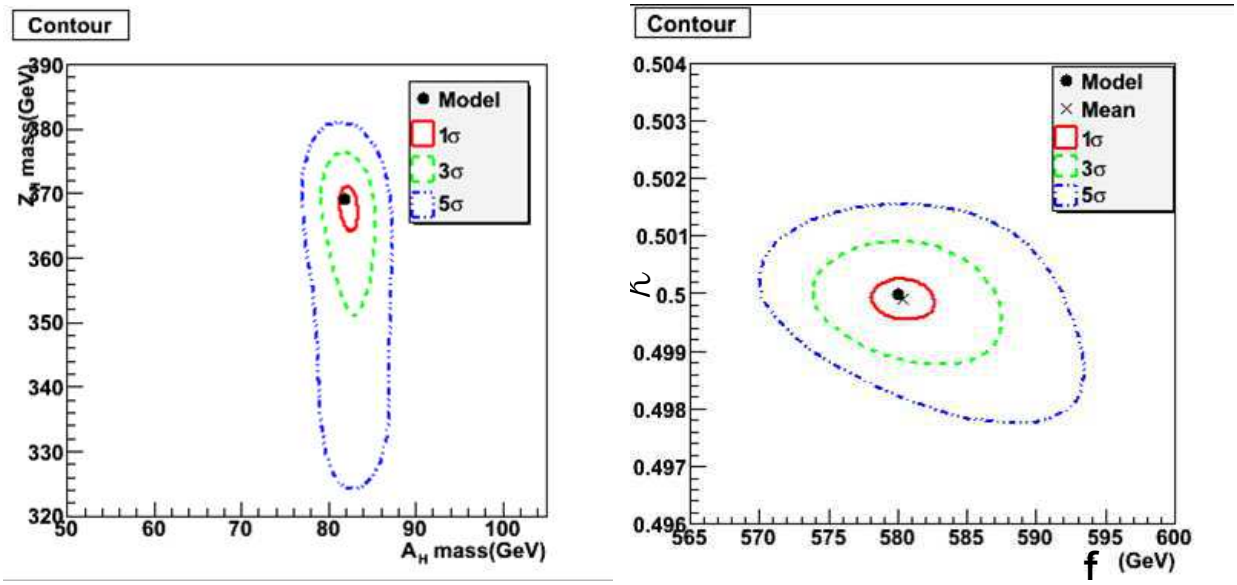

Figure 8: Accuracy of T-odd particle mass (left) and model parameter (right) determination for a representative benchmark point in the parameter space of the Littlest Higgs model with T-parity. From [60].

A quantitative study illustrating these points has been presented in Ref. [60]. This study assumed that the LHT model is realized in nature, with the non-linear sigma model scale $f = 580$ GeV, and T-odd

lepton Yukawa coupling $\kappa = 0.5$. For detailed description of the structure of the model and notation, see Refs. [56, 59]. For these parameters, the LTP is the T-odd "heavy photon" A_H, with the mass of 82 GeV. Other low-lying T-odd particles include the heavy W and Z bosons, W_H and Z_H, with masses about 370 GeV; and charged lepton and neutrino partners, e_H and ν_H, at about 400 GeV. The Higgs mass of $m_H = 134$ GeV was assumed.[1] Monte Carlo studies (including fast ILD detector simulation with JSFQuickSimulator package) were performed for the process $e^+e^- \to A_H Z_H$ at $\sqrt{s} = 500$ GeV, and for the processes $e^+e^- \to Z_H Z_H, W_H^+ W_H^-, e_H^+ e_H^-$, and $\nu_H \nu_H$ at $\sqrt{s} = 1$ TeV, with integrated luminosity of 500 fb^{-1} in each case. The main results of the analysis are summarized in Fig. 8. The accuracy of mass determination for the heavy gauge bosons A_H and Z_H is at or below 1% level. Precise determination of the LTP mass is especially interesting, since it provides a prediction of its relic abundance. The dominant LTP annihilation channel in this model is $A_H A_H \to W^+W^-$ via an s-channel Higgs exchange [59]. Since the A_H coupling to the Higgs is related to the SM gauge coupling g', and the Higgs mass is already known, the mass of A_H is the only missing ingredient in evaluating its relic density. In addition, combining the measurements of T-odd gauge boson and lepton production provides a precise determination of the LHT mass scale f and the T-odd lepton Yukawa κ, at a per-mille or better accuracy. An overall consistency of the data with the predictions of the LHT model at this level will provide a sensitive test of the structure of the model.

5 Summary

Now that the ILC TDR has been written, the blueprint is available to begin construction of the International Linear Collider. Our goal in this report was to lay out briefly and succinctly the case for strong US support for the ILC project from the perspective of Physics Beyond the Standard Model.

The case from SM physics is clear: the ILC at $\sqrt{s} \geq 250$ GeV would be a Higgs factory, allowing for precision determination of virtually all properties of the newly discovered 125 GeV resonance by LHC once the center-of-mass energy is raised to above the $t\bar{t}h$ and Zhh thresholds. In particular, we would like to know: is the new resonance a SM Higgs boson, or does its properties point to new physics, and a revision of the laws of nature as we known them?

From the perspective of BSM the argument is perhaps more subtle, but still compelling. Even if LHC running at $\sqrt{s} \sim 13 - 14$ TeV does not discover any further new states of matter, the ILC will remain a discovery machine. This is due in part to ILC's unique capacity to identify states with small $m_{\rm NLSP} - m_{\rm LSP}$ mass gaps. These latter situations are highly motivated by SUSY naturalness (with a set of highly compressed light Higgsino states) or by dark matter co-annihilation scenarios.

In the case where LHC does discover new states of matter, then ILC will likely function as a precision microscope, determining the properties of low-lying new particles using its unique capabilities of low background, known beam features, cleanliness of events, capacity for threshold scans and polarizable beams.

We presented several case studies, or stories, to illustrate our case.

- *Concluding the story of SUSY naturalness:* For SUSY to naturally accommodate the weak scale– *e.g.* $m_Z \simeq 91.2$ GeV and $m_h \simeq 125$ GeV– a necessary condition is the presence of light Higgsino states in the $100 - 300$ GeV range, the lower the better. The compressed mass spectra of the Higgsinos makes them difficult to detect at LHC, and projections indicate that *natural SUSY* can elude LHC searches. Since the light Higgsinos– small mass gap and all– are easily seen in the clean ILC environment, the ILC will either become a Higgsino factory, or rule out the idea of SUSY naturalness.

- *SUSY is simplified at ILC:* As the energy of ILC is increased, it will surpass threshold for pair production of any low-lying new states of matter. In the case of SUSY, the production and decay of NLSP modes should be highly simple, allowing for high precision determination of the new particle's properties.

[1] Since Ref. [60] appeared, LHC data provided a slightly lower value of m_H. In addition, the charged T-odd lepton mass assumed in [60] might be inconsistent with the lack of excess events in the searches for direct slepton pair-production [61], although a careful re-analysis of the data in this context would be required to establish this. In any case, the parameter point used in [60] is sufficiently close to viable regions of the parameter space to provide a useful illustration of the ILC capabilities.

- *SUSY is complex:* As $\sqrt{s}$ is raised even further, then at least in the case of SUSY more and more new states of matter should become accessible to direct production. The new particle cascade decays can become highly complex: in many cases, the largest background to SUSY comes from other SUSY processes. The high precision environment of ILC, along with information gleaned from lower energy studies of NLSP properties, will allow experimenters to disentangle the complicated cases arising from production of multiple new states of matter.

- *LHC and ILC complementarity:* In the realm of electroweakino pair production, it could be the case that LHC sees a signal of mixed chargino-neutralino production followed by decay to trileptons, or possibly production of heavy wino pairs followed by decays to same-sign dibosons in the case where Higgsinos are light. In these cases, ILC would produce the complementary reactions of chargino pair production (usually buried beneath WW and $t\bar{t}$ background at LHC) or mixed neutralino production (which is also difficult-to-impossible at LHC). In addition, while some mass gaps are measurable at LHC to high precision, ILC will be able to make model-independent individual sparticle mass measurements owing to the unique kinematics of e^+e^- collisions.

In all these cases– and in many others which are not discussed here owing to brevity requirements– it is clear that *the ILC is the precision instrument of choice* not only for discovery of new fundamental states of matter, but also for precision characterization of their quantum numbers and other properties. Such measurements will have a profound impact in restructuring the laws of physics as we know them, and upon our understanding of the cosmos and its evolution from the Big Bang up to the present day.

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