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New physics searches with the International Large Detector at the ILC

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Although the LHC experiments have searched for and excluded many proposed new particles up to masses close to 1 TeV, there are many scenarios that are difficult to address at a hadron collider. This talk will review a number of these scenarios and present the expectations for searches at an electron-positron collider such as the International Linear Collider. The cases discussed include the light Higgsino, the $\tilde{\tau}$ slepton in the coannihilation region relevant to dark matter, as well as other BSM signatures. The studies are based on the ILD concept at the ILC.

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1. ILC and ILD and their strong points for searches

The International Linear Collider (the ILC [1], Fig. 1) will collide polarised electrons with polarised positrons. Centre-of-mass energies will range from 250 GeV to 500 GeV. The possibilities to upgrade to 1 TeV, and to run at $E_{CMS} = M_Z$ are also considered. The electroweak production implied by the e^+e^- initial state leads to low background rates. This is beneficial for the detector design and optimisation: The detectors do not need to be radiation hard, giving the possibility to realise a tracking system with total thickness as low as a few percent of a radiation-length. The detector system can feature close to 4π coverage, and the low rates means that it need not be triggered, so that *all* produced events will be recorded. Furthermore, the initial state is fully known at an e^+e^- machine, since point-like objects are colliding. This will be quite important for many searches for new phenomena. The ILC has a defined 20 year running plan, with integrated luminosities of 2 and 4 ab^{-1} planned at E_{CMS} = 250 and 500 GeV, respectively. It could deliver 8 ab^{-1} at the possible upgrade to 1 TeV. The construction of the ILC is currently under high-level political consideration in Japan.

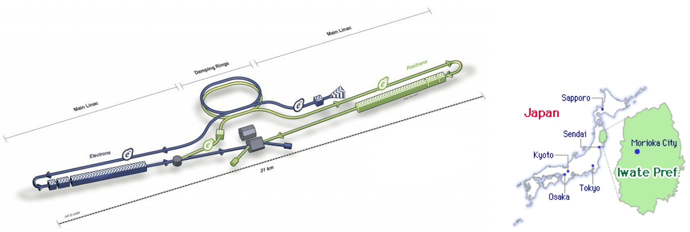


Figure 1: Schematic of the ILC and the location of the proposed site in Japan's Tohoku region.

Both Beyond the Standard Model (BSM) searches or measurements as well as precision SM measurements will require that the excellent conditions provided by the accelerator are matched by excellent performance of the detectors. Specifically, a jet energy resolution of 3-4%, an asymptotic momentum resolution of $\sigma(1/p_\perp) = 2 \times 10^{-5}$ GeV^{-1}, and measurement of impact-parameters better than 5 μm will be needed. Powerful particle identification (PID) capabilities will be an asset, and the detector should be hermetic, with the only gaps in acceptance being the unavoidable vacuum pipes bringing the beams into the detector. Furthermore, the system should be capable to register data trigger-less. In the International Large Detector concept (the ILD)[2], having a Time Projection Chamber (TPC) as the main tracker yields the needed low mass, high precision, tracker with PID capabilities. The performance is further enhanced by having silicon trackers both inside and outside the TPC. The high granularity calorimeters optimised for particle flow of ILD assures that the needed jet energy resolution can be obtained. In addition, to make it possible to avoid active cooling, the entire system can be operated in power-pulsing mode, i.e. with the electronics being switched off between bunch-trains.

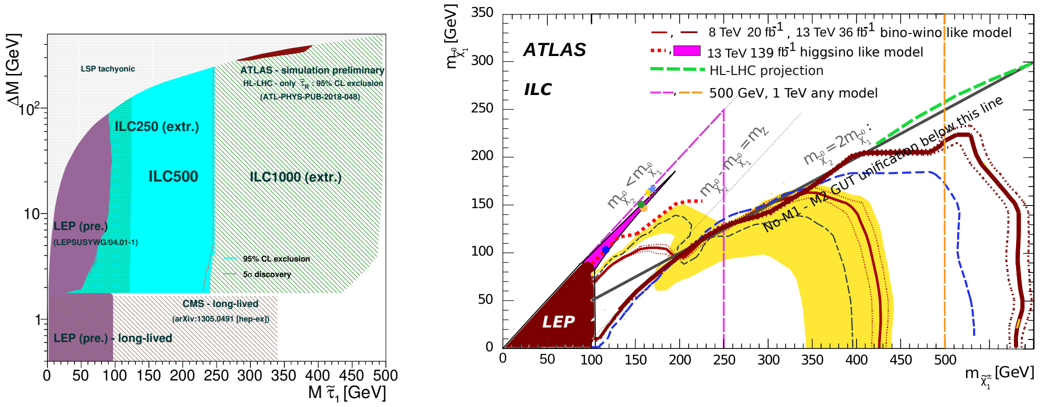
2. BSM at ILC: SUSY

SUSY [3] is the most complete theory of BSM, and therefore needs particular attention. In a recent contribution to the EPS-HEP 2021 conference [4], a more extensive discussion of SUSY at

ILC is made, and we only summarise it here.

Naturalness, the hierarchy problem, the nature of dark matter (DM), or the observed value of the magnetic moment of the muon, all prefer a light electroweak sector of SUSY. In addition, many models and the global set of constraints from observation points to a *compressed spectrum*. If the Lightest SUSY Particle (the LSP) is Higgsino or Wino, there must be other bosinos close in mass to the LSP, since the $\tilde{H}$ and $\tilde{W}$ fields have several components, leading to a close relation between the physical bosino states. Although the third possibility - a Bino-LSP - has no such constraints, an overabundance of DM is expected in this case [5]. To avoid such a situation, a balance between early universe LSP production and decay is needed. One compelling option is $\tilde{\tau}$ co-annihilation, and for this process to contribute enough, the early universe density of $\tilde{\tau}$ and $\tilde{\chi}_1^0$ should be similar, which implies that their mass must be quite similar. In the case of such compressed, low $\Delta(M)$, spectra, most sparticle-decays are via cascades, where the last decay in the cascade - that to SM particles and the LSP - features small $\Delta(M)$. For such decays, current LHC limits are for specific models, and only the limits from LEPII are model-independent. In fact, current observations from LHC run 2, LEP, g-2, DM (assumed to be 100% LSP), and precision observables taken together also point to a compressed spectrum [6].

In [4], we pointed out that at ILC, one can perform a loophole free search for SUSY because in SUSY, the properties of NLSP production and decay are completely predicted for given LSP and NLSP masses. All possible NLSP candidates can therefore conclusively be searched for. In Fig. 2, the current or projected limits are shown, for a $\tilde{\tau}$ NLSP (a) [7], or a $\tilde{\chi}_1^{\pm}$ one (b) [8, 9]. In [4], it was also pointed out that these figures shows that, contrary to the LHC case, the exclusion and discovery regions are close to identical. From this follows that, if SUSY would be discovered at the ILC, high precision measurements will also be possible. Several examples of bench-marks were shown in [4], and in all the illustrated cases, it was found that the SUSY masses could be determined at the sub-percent level, the polarised production cross-sections to the level of a few percent. Many other properties could also be obtained from the same data, such as decay branching fractions, mixing



(a) **(b)**

Figure 2: Observed or projected exclusion regions for a $\tilde{\tau}$ (a) or a $\tilde{\chi}_1^{\pm}$ (b) NLSP, for LEPII, LHC, HL-LHC and for ILC-500 and ILD-1000

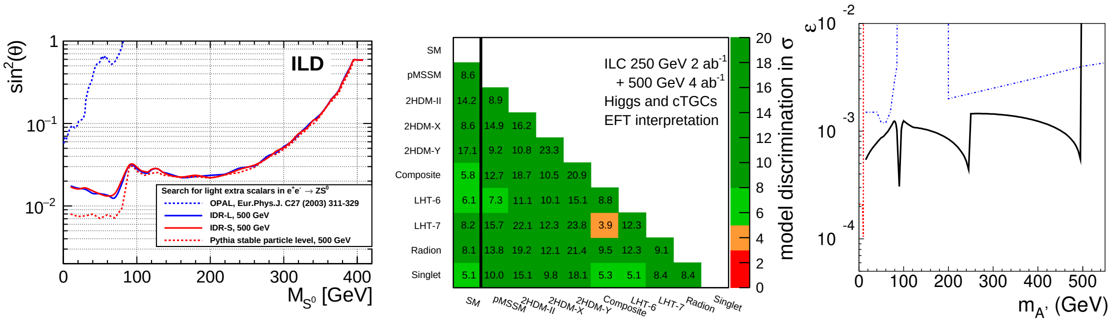
angles, and sparticle spin.

3. BSM at ILC: New scalars, small deviations from the SM, dark photons

Many BSM models predict the existence of a new Higgs-like scalar (S), produced in $\mathrm{e}^{+}\mathrm{e}^{-} \rightarrow Z^{*} \rightarrow ZS$ with unknown decays of S. Such a state could have escaped detection at LEP if its production cross-section is much lower than that of a SM Higgs at the same mass. Hence, a search for such a state should be done at all accessible masses, and without any assumption on the decay modes. At an $e^{+}e^{-}$ collider this can be done using the recoil-mass, i.e. the mass of the system recoiling against the measured Z. In [10], a full ILD detector simulation study was performed, and it was found that couplings down to a few percent of the SM-Higgs equivalent can be excluded, see Fig. 3(a).

The ILC also offers powerful BSM discovery opportunities from indirect searches, i.e. from detecting deviations from the behaviour predicted by the SM. Not only can such deviations be found, but they can also often be utilised for model separation. As an example of this route to BSM physics, in Fig. 3(b) we show a Standard Model Effective Field Theory (SMEFT) study [11] using ILC results on Higgs properties and triple gauge couplings (TGCs). Here, the authors have selected models that are not discoverable at HL-LHC. One observes that at the ILC, one can both separate all the models from the SM (at the 5 σ level), and also separate them from each other, at a similar level on confidence.

Another BSM model that has recently received quite some attention is the Dark photon, the A'. In these models, the existence of a dark sector is postulated. This dark sector is assumed to contain a U(1) group, leading to the existence of a photon-like particle. This state - as well as other dark states - is assumed to be neutral under the SM gauge groups. However, it is likely that there would be kinetic mixing between "our" U(1) and the dark one, leading to a term $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu}B^{\mu\nu}$ in the Lagrangian. Depending on the value of the free parameter ϵ, this interaction can lead to a tiny, narrow resonance, which is still wide enough to make decays prompt. Hence, the experimental approach would be to search for a narrow $\mu\mu$ resonance in $\mathrm{e}^{+}\mathrm{e}^{-} \rightarrow A' + \mathrm{ISR} \rightarrow \mu^{+}\mu^{-} + \mathrm{ISR}$. Here



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.6									
2HDM-II	14.2	8.9								
2HDM-X	8.6	14.9	16.2							
2HDM-Y	17.1	9.2	10.8	23.3						
Composite	5.8	12.7	18.7	10.5	20.9					
LHT-6	6.1	7.3	11.1	10.1	15.1	8.8				
LHT-7	8.2	15.7	22.1	12.3	23.8	3.9	12.3			
Radion	8.1	13.8	19.2	12.1	21.4	9.5	12.3	9.1		
Singlet	5.1	10.0	15.1	9.8	18.1	5.3	5.1	8.4	8.4	

(a) **(b)** **(c)**

Figure 3: (a) Projected exclusion limit for new scalars, in terms of the coupling compared to the coupling an SM Higgs at the same mass would have. (b) Significances of SMEFT deviations from the expectation, both for the SM expectation and the expectation of each of the various listed models. (c) Exclusion limit projections for dark photons, for ILC (solid), BelleII (dash) and HL-LHC (dot-dash).

the excellent momentum resolution of ILD is a key issue: the better the resolution is, the more narrow the search-window can be, and hence the lower the background will be. This is also the reason why the $\mu\mu$-channel is the most promising one. In Fig. 3(c), a study of this process is shown. It is a theory study, but nevertheless with a quite reasonable assumption on the $M_{\mu\mu}$ resolution, and its dependence on the mass of the dark photon (fig 8.16 of [12], show with a linear mass-scale).

4. Conclusions

The potential for direct discovery of new particles at ILC can exceed those of the LHC in certain, well motivated, scenarios. This is because ILC provides clean environment without QCD backgrounds, and a well-defined initial state. Furthermore, detectors at the ILC, such as ILD, will be more precise, will be hermetic, and will not need to be triggered. In addition, ILC also is extendable in energy and features polarised beams.

Synergies between ILC and LHC are expected: experiments at LHC will have higher energy-reach, while those at ILC will be more sensitive for subtle signals. For instance, if SUSY is reachable at the ILC, precision measurements can be done. This input would help in the interpretation of anomalies seen at the LHC, and might even be what is needed to transform a 3σ excess to a discovery of states beyond the reach of ILC.

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