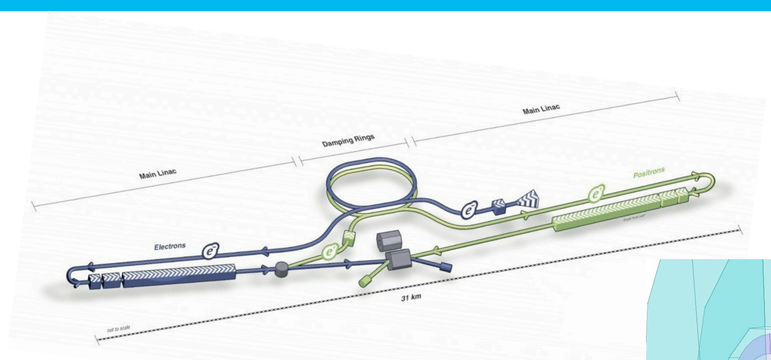
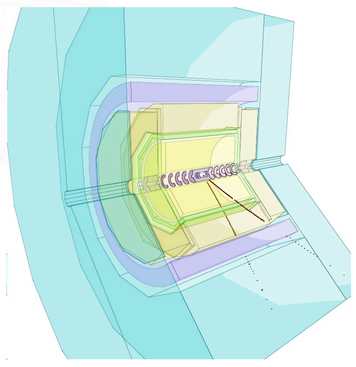
New physics searches with the ILD detector at the ILC

Mikael Berggren, DESY, on behalf of the ILD concept group



ILC and BSM

- The ILC - the International Linear Collider - is a power-efficient e^+e^- collider with initial $E_{CMS} = 250$ GeV, "easily" upgradable up to 1000 GeV.
- Colliding point-like objects ⇒ initial state known
- EW-production ⇒ Low background ⇒
  - Thin detectors w/ $\sim 4\pi$ coverage, and No trigger
- Polarised beams.
- Polarised beams + Low background + known in-state + hermetic detectors + energy upgradability: The ideal environment for Beyond the Standard Model (BSM) searches.



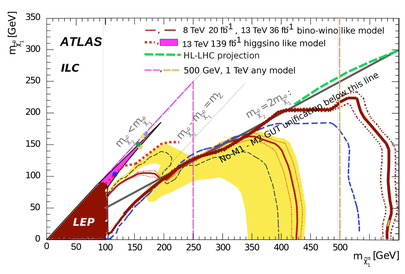
$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mu^+\mu^-$ in the International Large Detector concept, the ILD.

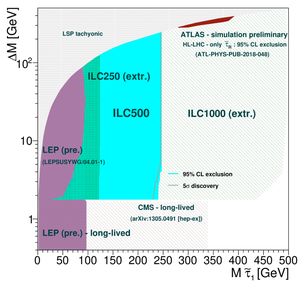
BSM at ILC: the SUSY case

- *The* most complete theory of BSM.
- Serves as a boiler-plate for BSM: almost any new topology can be obtained in SUSY...
- Most studied model with serious simulation: In most cases, full simulation of ILD, with all SM backgrounds, all beam-induced backgrounds included.
- 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.

Loop-hole free searches, even for low mass-differences

In SUSY, all is known for given masses, due to SUSY-principle: "sparticles couples as particles". This doesn't depend on the SUSY *breaking mechanism* ! Obviously: There is one Next-to-lightest SUSY particle (NLSP), and it must have 100 % BR to it's SM-partner and the lightest one (the LSP). So, one can perform model independent exclusion/ discovery reach in $M_{NLSP} - M_{LSP}$ plane - with no fine-print! One can do this for any possible NLSP, and concentrate on the "worst" cases - the ones with lowest cross-section and most difficult signatures. These are on one hand the bosinos, and on the other the $\tilde{\tau}$.





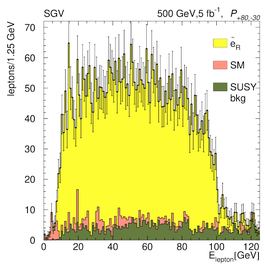
The expected exclusion and discovery reaches at ILC for bosinos and $\tilde{\tau}$:s, together with obtained or projected exclusion limits from LHC/HL-LHC. **NB:** At ILC, exclusion and discovery is almost the same, even for difficult channels!

ILC SUSY measurements

Since Discovery ≈ Exclusion at the ILC, after a possible discovery, one will enter the realm of precision messurements quite quickly.

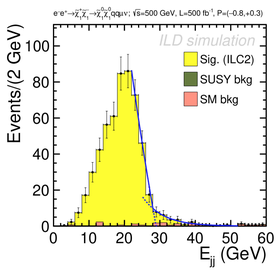
At ILC: discovery in a week...

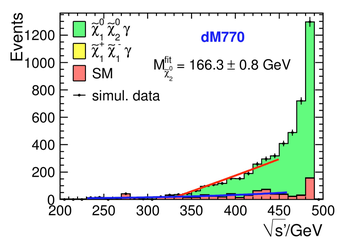
A selectron signal after 5 fb^{-1} ≈ 1 week:

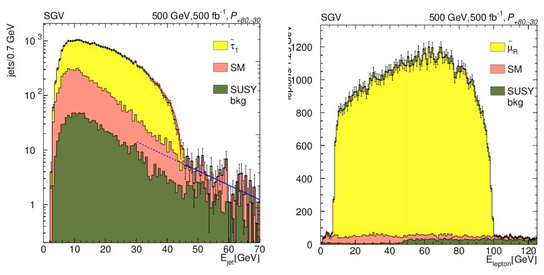


Bosinos

Here typical chargino (left) and neutralino signals (right) are shown. Both models are higgsino-LSP ones. The one to the left is one of several studied natural SUSY models with moderate mass differences (15-20 GeV), while the one to the right is a cosmology-motivated model, and has a sub-GeV difference.

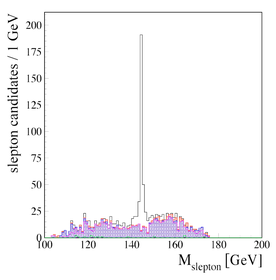






Sleptons

The end-points of the spectra of the slepton decay-products, enables to measure the slepton and LSP masses to percent level accuracy. Left are examples of $\tilde{\tau}_1$ and $\tilde{\mu}_R$ signals, in a $\tilde{\tau}$ co-annihilation model. To the right, the signal that could be obtained from evaluating the decay-kinematics in a model with cascade decays.

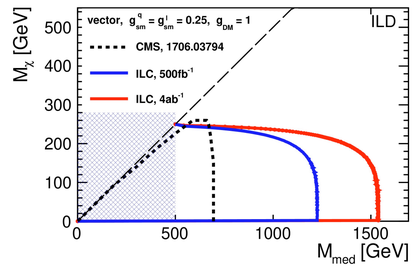


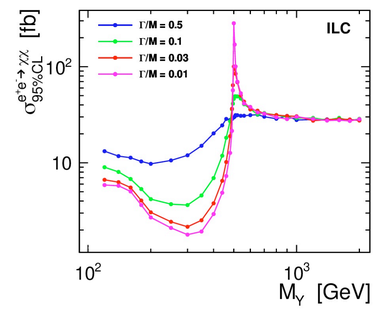
After the full ILC program, and depending on model, channel, and polarisation, we find experimentally that

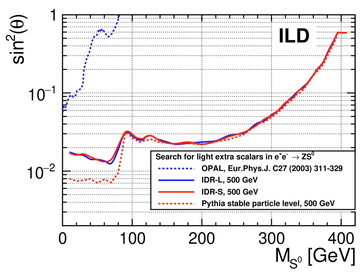
measured $\delta(\text{masses}) = 0.5\text{-}1\ \%$, $\delta(\sigma \times \text{BR}) = 1\text{-}6\%$

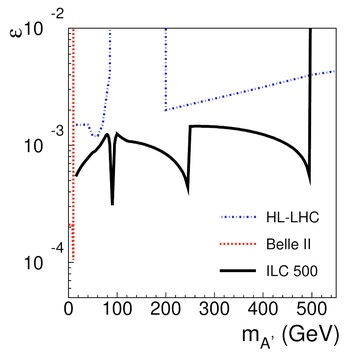
BSM at ILC: not only SUSY.

- Dark matter in $e^+e^- \to (DM)(DM) + \text{ISR}\gamma$: Mono-photon searches, shown to the right. Searches done either with an EFT approach with heavy mediator (Full simulation), or for arbitrary mediators (fast simulation).
- Search for a new Higgs-like scalar (S), shown below. produced in $e^+e^- \to Z^* \to ZS$ with unknown decays, Search for it in a decay-mode insensitive way: the recoil-mass, i.e. the mass of the system recoiling against the measured Z. Couplings down to a few percent of the SM-Higgs equivalent can be excluded.
- Dark photon/Z' : Kinetic mixing term $\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$ in the Lagrangian leads to a tiny, narrow resonance, but still wide enough to make decays prompt. One can search for it as a $\mu\mu$ resonance above background in $e^+e^- \to Z' + \text{ISR} \to \mu^+\mu^- + \text{ISR}$. Results (from EPPSU) shown below, right.



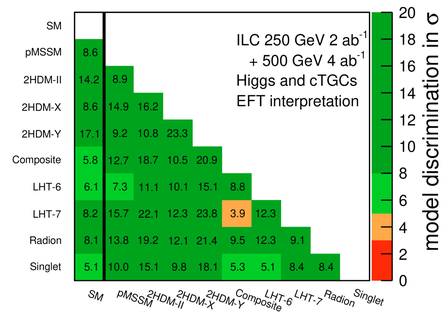


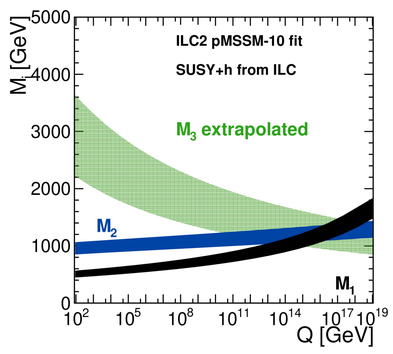




Indirect BSM: discovery and model separation

- SM effective field theory study, using ILC results on Higgs properties and TGCs
- Select models that are not discoverable at HL-LHC.
- At ILC: Both separate at 5 σ from the SM, but also from each other !





Hints of the GUT scale

In the natural SUSY analysis - thanks to the combination of the measured masses, BR's and Higgs properties - all 10 weak-scale parameters gets constrained, for all three bench-marks. In particular, the bino and wino SUSY breaking masses M_1 and M_2 - the ones most directly related to the higgsino masses - can be determined at percent level.
The fitted weak-scale parameters can be evolved with the appropriate RGE's to higher scales. This allows to verify or discard the idea of GUT-scale unification of M_1 and M_2

Take-home message

- Sometimes, the capabilities for the direct discovery of new particles at the ILC exceed those of the LHC, since ILC provides:
  - Well-defined initial state
  - Clean environment without QCD backgrounds
  - Extendability in energy and polarised beams
  - Detectors like ILD, factors more precise,hermetic, and with no need for triggering
- Many ILC - LHC synergies from energy-reach vs. sensitivity.
  - SUSY: High mass vs. Low $\Delta(M)$. If SUSY is reachable at ILC, it means 5 σ discovery, and precision measurements. This input might be just what is needed for LHC to transform a 3 σ excess to a discovery of states beyond the reach of ILC.
  - Dark matter, FIPS, ...: Leptophilic vs. Leptophobic - Higher mass and higher coupling vs. lower mass and lower coupling.

More info:

- ILC: P. Bambade et al. "The International Linear Collider: A Global Project" (2019), arXiv:1903.01629 [hep-ex] and T. Behnke et al. "The International Linear Collider Technical Design Report - Volume 1: Executive Summary" (2013), arXiv:1306.6327 [physics.acc-ph].
- ILD: T. Behnke et al. "International Large Detector: Interim Design Report" arXiv:2003.01116 [physics.ins-det].
- BSM at ILC and LHC: K. Fujii et al. "The Potential of the ILC for Discovering New Particles" (2017), arXiv:1702.05333 [hep-ph] and M. Berggren " What pp SUSY limits mean for future e^+e^- colliders" arXiv:2003.12391 [hep-ph]
- Sleptons: M Berggren et al. "Non-Simplified SUSY: Stau-Coannihilation at LHC and ILC" Eur. Phys. J. C 76, (2016) 183 arXiv:1508.04383 [hep-ph], M.T. Núñez Pardo de Vera et al. "$\tilde{\tau}$ searches at the ILC" arXiv:2105.08616 [hep-ph] and M. Berggren "Reconstructing sleptons in cascade-decays at the linear collider" arXiv:hep-ph/0508247
- Bosinos: H. Baer et al. "The ILC as a natural SUSY discovery machine and precision microscope: from light higgsinos to tests of unification" Phys. Rev. D 101, 095026 (2020) arXiv:1912.06643 [hep-ex], M. Berggren et al. "Tackling light higgsinos at the ILC" Eur. Phys. J. C 73, 2660 (2013) arXiv:1307.3566 [hep-ph] and M.T. Núñez Pardo de Vera et al. "Chargino production at the ILC" arXiv:2002.01239 [hep-ph].
- WIMPs: M. Habermehl et al. WIMP Dark Matter at the International Linear Collider" Phys. Rev. D 101, 075053 (2020) arXiv:2001.03011 [hep-ex] and J. Kalinowski et al. "Sensitivity of future linear e^+e^- colliders to processes of dark matter production with light mediator exchange" Eur. Phys. J. C 81, 955 (2021) arXiv:2107.11194 [hep-ph].
- New scalars: Y. Wang et al. "ILD Benchmark: Search for Extra Scalars Produced in Association with a Z boson at $\sqrt{s}$=500 GeV" arXiv:2005.06265 [hep-ex].
- Indirect BSM : T. Barklow et al. "Improved Formalism for Precision Higgs Coupling Fits" Phys. Rev. D 97, 053003 (2018) arXiv:1708.08912 [hep-ph].

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