Particle Discovery Opportunities at the International Linear Collider

EPS-HEP 2019, Ghent

Moritz Habermehl\textsuperscript{1}
on behalf of the LCC Physics Working Group

12 July 2019

\textsuperscript{1}Deutsches Elektronen-Synchrotron DESY, Germany
The International Linear Collider

A planned electron-positron collider

Lepton colliders are complementary to the LHC
- cleaner environment, controlled initial state
- coupling to leptons is tested

Advantages of the ILC over other planned electron-positron colliders
- mature technology
- centre-of-mass energy can be tuned and increased: 250 GeV in initial stage, upgrades to 500 GeV and 1 TeV
- polarisation of both beams: $P(e^-) = \pm 80\%$, $P(e^+) = \mp 30\%$
- triggerless operation
- hermeticity of detector down to lowest angles
The BSM Physics Programme of the ILC

Large range of detailed studies

- arxiv:1702.05333: The Potential of the ILC for Discovering new Particles → focus on 500 GeV
- arxiv:1903.01629: The International Linear Collider: A Global Project → focus on 250 GeV
The BSM Physics Programme of the ILC

Large range of detailed studies

The Potential of the ILC for Discovering new Particles → focus on 500 GeV

The International Linear Collider: A Global Project → focus on 250 GeV

From generic searches …

WIMPs

SUSY

… to studies of complete BSM models
The BSM Physics Programme of the ILC

Large range of detailed studies

arxiv:1702.05333 The Potential of the ILC for Discovering new Particles → focus on 500 GeV

arxiv:1903.01629 The International Linear Collider: A Global Project → focus on 250 GeV

From generic searches …

\[<\text{additional Higgses}>\]

In addition: indirect constraints

- Higgs precision measurements
- Standard Model precision measurements

talk by S. Kawada

From WIMPs … to studies of complete BSM models
Searches for WIMP Dark Matter

WIMPs = Weakly Interacting Massive Particles

Interplay between search channels

• direct and indirect detection
• collider searches
Searches for WIMP Dark Matter

WIMPs = Weakly Interacting Massive Particles

Interplay between search channels

• direct and indirect detection
• collider searches

Example: singlet-like fermion WIMP

• likelihood analysis of Planck, PICO-2L, LUX, XENON100, LEP, LHC, plus LZ, PICO250 projections
• surviving region assuming no WIMP signals are detected → can be tested at the ILC
• framework: effective operators
  • $\Lambda$ – energy scale of new physics
  • valid: testable energies $\gg \sqrt{s}$

arxiv:1604.02230
WIMPs in the Mono-Photon Channel

Generic collider search

- WIMP pair production
- with a photon from initial state radiation
- single photon in an “empty” detector
WIMPs in the Mono-Photon Channel

Generic collider search

- WIMP pair production
- with a photon from initial state radiation
- single photon in an “empty” detector

Example: vector-like fermion WIMP

full detector study at 500 GeV
- careful ISR modelling
  - several photons possible
  - double-counting avoided
- ILC accelerator environment
  - luminosity spectrum
  - beam-induced background
effective operators
- vector
- axial-vector
- scalar
WIMPs in the Mono-Photon Channel

Generic collider search

- WIMP pair production
- with a photon from initial state radiation
- single photon in an “empty” detector

Example: vector-like fermion WIMP

full detector study at 500 GeV
- carefull ISR modelling
  - several photons possible
  - double-counting avoided
- ILC accelerator environment
  - luminosity spectrum
  - beam-induced background

effective operators
- vector
- axial-vector
- scalar
Role of $\sqrt{s}$, luminosity and polarisation

Polarisation is crucial

- suppression of neutrino background
- enhancement of signal
- provides statistically independent data sets with different polarisation configurations
  \( \rightarrow \) control of systematic uncertainties
Sensitivity to WIMP Dark Matter: Operation Scenarios

Role of $\sqrt{s}$, luminosity and polarisation

Polarisation is crucial

- suppression of neutrino background
- enhancement of signal
- provides statistically independent data sets with different polarisation configurations → control of systematic uncertainties
**Sensitivity to WIMP Dark Matter: Operation Scenarios**

**Role of $\sqrt{s}$, luminosity and polarisation**

**Polarisation is crucial**
- suppression of neutrino background
- enhancement of signal
- provides statistically independent data sets with different polarisation configurations → control of systematic uncertainties

**Higher centre-of-mass energies are favored**
- signal cross-section rises with energy
- collecting data for decades at a moderate energy is worse than running at higher energies and collect a smaller data set
Detector Hermeticity

Background suppression crucial for BSM studies

Bhabha scattering: background for WIMPs

- huge cross-section
- particles mainly in forward region
  → challenging reconstruction
  → mono-photon signal can be mimicked

Overlay

- pairs produced from beamstrahlung photons
- forward region is polluted

Hermeticity study: WIMPs as example

- sensitivity depends on number of reconstructed Bhabha scattering events
- with a larger “blind region” around beam pipes: testable energy reach is significantly reduced
Dark photon search

\[ e^+e^- \rightarrow \gamma A' \rightarrow \gamma \mu^+\mu^- \]

95% exclusion limit (no deviation from SM observed)

- amplitude \( \varepsilon \): mixing of dark photon with hypercharge gauge boson
- assumes full ILC programme
  \( \rightarrow \) shown mass range dominated by run at 250 GeV
Dark photon search

$e^+e^- \rightarrow \gamma A' \rightarrow \gamma \mu^+\mu^-$

95% exclusion limit (no deviation from SM observed)

- amplitude $\varepsilon$: mixing of dark photon with hypercharge gauge boson
- assumes full ILC programme → shown mass range dominated by run at 250 GeV

Role of polarisation

- polarisation not considered in study → sensitivity around Z mass could improve
- for invisible decay products: polarisation crucial to suppress SM neutrino background
Additional Higgs Bosons
Search for extra light scalars

Recoil against Z

- lepton collider: initial state 4-mom. is known
- $Z$ reconstructed from its decay products → scalar can be reconstructed as the missing 4-mom.
- reconstruction of the scalar without “looking at the scalar” → highly model-independent

Exclusion limit

- $\sin^2(\theta)$: cross-section relative to a SM Higgs with corresponding mass
- full detector simulation → for low masses: detector effects play a role

arxiv:1902.06118, arxiv:1801.08164
Supersymmetry

UV-complete BSM models

Assumption: discovery of several new particles

- nature of new physics can be tested
- conclusions about underlying parameters

Detector simulations of the complete model

- complete particle spectrum
- model branching ratios (instead of just assuming 100% for dominant channel)
Supersymmetry

UV-complete BSM models

Assumption: discovery of several new particles
- nature of new physics can be tested
- conclusions about underlying parameters

Detector simulations of the complete model
- complete particle spectrum
- model branching ratios (instead of just assuming 100% for dominant channel)

Loop-hole free searches [arxiv:1308.1461]
- next-to-lightest SUSY particle searches
- in kinematic reach: discovery guaranteed or immutable limits
- in case of a discovery: accurate measurements
SUSY: Precision Measurements

Fitting the dark matter relic density $\Omega$

Stau coannihilation scenario

- lightest supersymmetric particle (LSP) is *the* dark matter
- study at 500 GeV
- $\tilde{\tau}_1 \rightarrow \tau \chi_1^0$ endpoint $\rightarrow$ stau mass precision 0.15%

[arxiv:1508.04383]
Fitting the dark matter relic density $\Omega$

Stau coannihilation scenario

- lightest supersymmetric particle (LSP) is *the* dark matter
- study at 500 GeV
- $\tilde{\tau}_1 \rightarrow \tau \tilde{\chi}_1^0$ endpoint → stau mass precision 0.15%

With SUSY observables as input
dark matter relic density $\Omega$ can be fitted

- using micrOMEGAs (arxiv:1305.0237)
- input: discovery of all sleptons, sneutrinos, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$ with permille mass precision
- fit precision 2% → same precision as Planck
- clear identification of LSP as dark matter constituent

arxiv:1602.08439

arxiv:1508.04383
SUSY: Precision Measurements II

Testing gaugino mass unification

talk by S. Sasikumar

Natural SUSY with light Higgsinos

- not excluded natural SUSY model
- mirage mediated breaking model → unification below GUT scale

Running gaugino masses

- gaugino masses are fitted (at 1 TeV)
  - using Fittino (arxiv:hep-ph/0412012)
  - input: Higgsino masses and polarised cross-sections
- evolving gaugino masses to higher scales
  - using renormalization group equations
  - bands show 1σ confidence levels
- unification at GUT scale can be excluded from fit
Conclusion

The ILC has the potential to find ...

- new particles that couple prefentially to leptons
- new physics
- loophole-free searches
- precision measurements
- exclusion limits
- polarisation: control of systematics
- polarisation of both beams → chirality of new process can be tested
The ILC has the potential to find a new particle that couples preferentially to leptons. Polarisation of both beams allows for the testing of chirality of new processes.

Lepton colliders cover unique parameter space, complementary to the LHC. Precision measurements and loophole-free searches are possible with polarisation control of systematics.
Contact

DESY. Deutsches Elektronen-Synchrotron
Moritz Habermehl
FLC
moritz.habermehl@desy.de

www.desy.de
SUSY: Testing Gaugino Mass Unification

Natural SUSY with light Higgsinos

talk by S. Sasikumar

Running gaugino masses

• gaugino masses are fitted (at 1 TeV)
  • using Fittino (arxiv:hep-ph/0412012)
  • with Higgsino masses and polarised cross-sections as input
• evolving gaugino masses to higher scales
  • using renormalisation group equations
  • bands show 1σ confidence levels

Case 2: unification below GUT scale

• unification at GUT scale can be excluded from fit
• good precision with 10% measurement of gluino mass from HL-LHC

Case 1: unification at GUT scale

• running of M1 and M2
• unification at GUT scale can be fitted
• running of M3 from unification to lower energies
  • matches model point at 1 TeV
  • could be cross-checked with LHC results
Limits below 250 GeV dominated by 250 GeV run

- muon momentum resolution taken from full detector simulation $\rightarrow$ propagated to mass peak width
- energy dep. BG cross-section from generator level
- around $Z$ mass
  - shape taken from CEPC study (arxiv:1503.07209)
  - more background, but interference of $Z$ and dark photon
Comparison to other experiments
Search for extra light scalars

arxiv:1902.06118, arxiv:1801.08164

- black curve: update with 500 GeV and IDR detector model
Assumption: discovery of several new particles
• nature of new physics can be tested
• conclusions about underlying parameters

Detector simulations of the complete model
• complete particle spectrum
• model branching ratios (instead of just assuming 100% for dominant channel)

Loop-hole free searches
• next-to-lightest SUSY particle searches
• in kinematic reach: discovery guaranteed or immutable limits
• in case of a discovery: accurate measurements

arxiv:1308.1461