Outline

- Introduction: Role of BSM in ILC Physics Case
- Two more detailed examples:
  - Light Higgsinos
  - WIMP Dark Matter
- Implications for ILD & SiD
- Conclusions
Introduction: The Role of BSM in the ILC Physics Case
Why think about BSM@ILC now?

1. Fascinating for the general public... c.f. Ogada, Yamashita: outreach outside HEP is one of the most important tasks now

2. ... and for our community => explain unique ILC discovery potential

3. Challenging requirements for our detector concepts and our machine => we should make sure we do not miss anything!
We cannot guarantee a discovery

- Video message from Koshiba: “If we knew already the outcome, we wouldn’t need to perform an experiment”
- Non-discoveries give crucial information, eg non-discovery of “plain-vanilla” SUSY at LHC run I:

<table>
<thead>
<tr>
<th>Naturalness, $g_\mu -2$, $M_W$, CDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
</tr>
<tr>
<td>3rd gen. Squarks, Sleptons,</td>
</tr>
<tr>
<td>Elektroweakinos</td>
</tr>
<tr>
<td>Mass Unification: $m_0$, $m_\frac{1}{2}$</td>
</tr>
<tr>
<td>LHC Results</td>
</tr>
<tr>
<td>Heavy</td>
</tr>
<tr>
<td>1st, 2nd gen. Squarks, Gluinos</td>
</tr>
</tbody>
</table>

$=>$ change in paradigm of how we think about SUSY and how we search for it: Natural SUSY, “simplified models”, ...
What can we guarantee?

Loop-hole free, model-independent sensitivity down to very small mass differences

Will revolutionize our picture of BSM!
What will we learn at LHC 13/14 TeV?

Two general scenarios:

A. Discover significant deviation from SM in some direct search channel at the LHC 13/14 TeV
   • What kind of particle is it, what is its mass, spin, couplings?
   • What is the physics behind? Are there more new particles?
   => full-glory program for the ILC!

B. No deviation anywhere
   • What does this really tell us?
   • Can there be something very well hidden?

We hope of course for A, but we have to be prepared for B!
Case A: Projections from CMS [CMS-PAS-SUS-14-012]

CMS analyzed 5 full MSSM models:

- 3 Natural SUSY models
- stau- / stop-coannihilation

Most likely LHC would discover not the lightest states!
## Case A: Projections from CMS

### Analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Luminosity (fb⁻¹)</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>all-hadronic ((H_T-H^{\text{miss}})_T) search</td>
<td>300</td>
<td>NM1</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>all-hadronic ((M_{T2})) search</td>
<td>300</td>
<td>NM2</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>all-hadronic (b_1) search</td>
<td>300</td>
<td>NM3</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>1-lepton (t_1) search</td>
<td>300</td>
<td>STC</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>monojet (t_1) search</td>
<td>300</td>
<td>STOC</td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>(m_{\ell+\ell^-}) kinematic edge</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>multilepton + b-tag search</td>
<td>300</td>
<td></td>
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<tr>
<td></td>
<td>3000</td>
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</tr>
<tr>
<td>multilepton search</td>
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<tr>
<td>ewkino WH search</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>3000</td>
<td></td>
</tr>
</tbody>
</table>

### Model

- NM1
- NM2
- NM3
- STC
- STOC

### Notes

- All-hadronic (+b-tag)
- Single lepton
- Monojet
- Dilepton
- Multilepton

### Summary

Still a lot left for ILC!
Light Higgsinos & Natural SUSY
Case B example: Light Higgsinos

- Naturalness suggests $\mu \approx O(M_Z)$ (but $> 100$ GeV, LEP)
- Lightest Sparticles: 3 light, near-degenerate Higgsinos
- Mass splittings
  - depend on $M_1, M_2$
  - few GeV $\rightarrow$ ... sub-GeV (!)


- LHC: gluino and like-sign di-boson searches
- ILC: hermetic sensitivity to $\mu \lesssim \sqrt{s}/2$

Theory-level study (H.Baer et al)
From Theory to Fast Simulation

- Detector simulation study [EPJ C73 (2013) 2660]:
  - $\mu = 167 \text{ GeV}, M_1 = 5 \text{ TeV}, M_2 = 10 \text{ TeV}$
  - $\Rightarrow \Delta M(\tilde{\chi}_1^\pm; \tilde{\chi}_1^0) \simeq 1 \text{ GeV}$
  - $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma_{\text{ISR}}$ and $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma_{\text{ISR}}$
  - Measure $M_{\tilde{\chi}_1^\pm}$ and $M_{\tilde{\chi}_2^0}$ from recoil against $\gamma_{\text{ISR}}$
  - $\Delta M(\tilde{\chi}_1^\pm; \tilde{\chi}_1^0)$ from decay products

**Extreme case!**

+ Cross sections to few %
Parameter Determination?

- From $M_{\tilde{\chi}_1^+}$ and $M_{\tilde{\chi}_2^0}$ => $\mu$ to $\pm 0.5$ GeV
- But can we learn about $M_1$ & $M_2$?
Parameter Determination!

- 500 fb\(^{-1}\): determine \( \mu \) to \( \pm 0.5 \) GeV
- 2 ab\(^{-1}\) and neutralino mass difference
  \( \Rightarrow \) constrain \( M_1 \) & \( M_2 \) to narrow band in multi-TeV regime:
Parameter Determination!

- 500 fb$^{-1}$: determine $\mu$ to $\pm 0.5$ GeV
- 2 ab$^{-1}$ and neutralino mass
  $\Rightarrow$ constrain $M_1$ and $M_2$ to narrow band in multi-TeV regime:

**Challenges:**
- reconstruction and PID for < 2 GeV particles
- fake tracks from pair background
- $YY \rightarrow$ low-pt hadrons overlay

$\Rightarrow$ c.f. Yorgos’ presentation tomorrow
WIMP Dark Matter
Case A or B example: WIMPs at the ILC

Know $\sqrt{s}$: $E_\gamma$ spectrum offers

- Clean endpoint $\rightarrow$ mass
- Shape $\rightarrow$ dominant partial wave (s-channel: Spin of mediator)
- Can distinguish eg SUSY vs UED
Effective Operator approach:

- vector / axial-vector type of WIMP - fermion interaction
- suppression scale $\Lambda$

Note:

suppression scale $\Lambda$ refers to

- LHC: WIMP – quark interaction
- ILC: WIMP – electron interaction

=> showing them in same plot is model-dependent!
Effective Operators Approach:
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This does crucially depend on the ability to veto radiative Bhabha events in the BeamCal!
Implications for ILD & SiD
1. Hermeticity in the forward region

- veto of radiative Bhabha events (eg WIMPs)
- veto of $\gamma \gamma / e\gamma$ events (BSM with small mass differences)

$\Rightarrow$ BeamCal, LumiCal and LHCAL to close acceptance gap outside of LumiCal in ILD

evaluate for new ILD forward region, up-to-date pair background & BeamCal reconstruction

... and using a dedicated Bhabha generator (eg BHWIDE)
2. Tracking for sub-GeV particles

- small mass differences => soft decay products!
- ILD-DBD tracking: efficiency not bad, but fakes from pair bkg?
- VTX & SIT stand-alone tracking?
- better time resolution in VTX?
- furthermore: masses of p, K etc not negligible in tracking
3. Particle ID

- \(dE/dx\) : cf talk by Masakazu in TPC session (Tue) particularly effective at low \(p\)
- cluster shapes (\(\mu/\pi\)):
  
  \[\gamma \sim 1\]
  \[\chi \sim 1\]
  \[\chi \sim 0\]
  
  \( \approx \) watch it: \(\sim \leq 1\) GeV looks very different, need dedicated low E ID!

- cf Yorgos (Fri)

- *neutral* Higgsinos decay to soft photons – any chance for these?
Conclusions
Conclusions

• $e^+e^-$ collisions are essential to complement the LHC picture of BSM physics

• We cannot guarantee new particles, but we can guarantee the exploration of unknown territory highly relevant for our picture of BSM

• There are important requirements on the detectors for realizing the full BSM potential of the ILC

• We need still significant work on reconstruction tools before we can appreciate and evaluate the full capabilities of our proposed detectors.
Backup
How could ILC operation look like? [unofficial]

**Initial run at 500(+x) GeV**

- 500fb⁻¹ with \(f_p(+-,-+,++,--=(0.4,0.4,0.1,0.1)\)
- exclude / discover SUSY with \(M<250\) GeV
- best results for 4 years running for
  - most Higgs couplings
  - ew top couplings
  - anom. gauge couplings
  - \(m_W, m_H\) from kinematic reconstruction
- first glimpse at \(ttH, ZHH\)

**TT threshold scan**

- 200fb⁻¹ at 350 GeV
- ultimate \(m_t, \Gamma_t, \alpha_s\)
- QCD effects for \(ttH\)

**ZH run**

- 500 fb⁻¹ at 250/350 GeV
- \(g_{HZZ}, H\rightarrow\text{inv.}\)

**Discoveries at LHC and/or ILC?**

scan thresholds (~100fb⁻¹ each) for precision BSM program

**More 500(+x) GeV data**

- ~4ab⁻¹ with \(f_p= (0.4,0.4,0.1,0.1)\)
- more precision ZHH, \(ttH\) et al
- increased Dark Matter sensitivity
- precision BSM spectroscopy
- model discrimination

**Further options**

depend on results & money

- **TeV upgrade**
  - more 250 GeV if needed
  - WW threshold, Z pole, ...
What does this tell us about BSM?

Constraining the pMSSM via Higgs couplings (combining $h\gamma\gamma$, $h\tau\tau$, $hbb$)

**HL-LHC 3000 fb$^{-1}$**

**ILC (1150 fb$^{-1}@250$ GeV & 1600 fb$^{-1}@500$ GeV)**


Precision Higgs coupling measurements sensitive probe for heavy Higgs bosons $m_A \sim 2$ TeV reach for any tan$\beta$ at the ILC
And now a “case B” example

LHC 8 TeV probes Chargino masses up to 450 GeV ....

..but the most stringent general limit is still from:

No gaugino mass unification!

ATLAS projection 14 TeV 3 ab$^{-1}$
ATLAS projection 14 TeV 300 fb$^{-1}$

...let’s take a look at the star points ★★

M. Berggren, ICHEP2014
WIMP characterisation

- Mass measurement:
  \( \text{eg ILC @ 500 GeV, 500fb}^{-1}, \kappa_e = 10\% \)
  \( P(e^+,e^-) = (-30\%, 80\%) \)
  - 1-2\% resolution
  - Dominated by conservative assumption on knowledge of beam energy spectrum

- Dominant partial wave determination: correct hypothesis clearly favoured

From EPJC 72 (2012) 2213, Bartels et al
Helicity Structure of WIMP-Fermion Interaction

- Measure cross-section with different beam helicities! Eg $|P| = 80\% / 30\%$, all four sign combinations (lumi split 200fb$^{-1}$ +/−/, 50fb$^{-1}$ ++/--)
  NB: the more positron polarisation, the better!

- Three examplatory coupling scenarios:

  "Equal"  
  "Helicity & Parity conserving"  
  "Anti-SM"

Clear distinction possible!
How to relate $e^+e^-$ to Direct Searches?

- Will be model-dependent!
- Most conservative, ie minimal “unavoidable” X-Nucleon cross-section:
  - Assume no tree-level coupling to quark
  - Leaves us with loop contributions
- Direct searches need sensitivity of $\sim 10^{-46..47}$ cm$^2$ to rule out model-independently lepton-WIMP couplings observable at ILC
e^+e^- and pp / XN

- Relation between WIMP – lepton and WIMP – quark / nucleon interaction is *model-dependent*
- Is suppression scale $\Lambda$ the same for quarks and leptons?
  - A priori not!
  - Eg: t-channel exchange of “squark / selectron”
  - Direct couplings vs loop couplings

=> *$e^+e^-$ provides orthogonal and independent information, regardless whether LHC or DD discovers (case A) or just excludes (case B)*

- Interesting interplay with indirect detection: how big is annihilation fraction into $e^+e^-$?
Higgs Self-Coupling – $\text{eg 2HDM}$

- Loop-contributions with heavy Higgses ($m_{\phi}$) modify $\lambda$
- Interference with different sign leads to opposite effects in $ZHH$ and $\nu\nuHV$

deviations in double Higgs cross-sections:

<table>
<thead>
<tr>
<th>Model</th>
<th>$m_h$[GeV]</th>
<th>$\Delta r_{gg\rightarrow hh}^{\text{NP}}$</th>
<th>$\Delta r_{e^+e^-\rightarrow hhZ}^{\text{NP}}$</th>
<th>$\Delta r_{ee\rightarrow hh}^{\gamma\gamma}$</th>
<th>$\Delta r_{e^+e^-\rightarrow hh\nu\bar{\nu}}^{\text{NP}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>THDM</td>
<td>120</td>
<td>+120%</td>
<td>-50%</td>
<td>+$(80-70)$%</td>
<td>+50%</td>
</tr>
</tbody>
</table>

beware when comparing numbers for $\delta \lambda / \lambda$!
Impact of BSM on Top Sector

Composite Higgs models can be tested at the ILC through precise measurements of the top couplings. Beam polarization is essential to distinguish the $ttZ$ and $tty$ couplings.

**ILC, $\sqrt{s} = 500$ GeV**

**Lumi = 500 fb$^{-1}$**

- RS with $SU(2)_R \times SU(2)_L \times U(1)_X$
- $5D$ Emergent
- AdS$_5$ with Custodial O(3)

**Deviation in $ttZ$ coupling of left-handed top quark**

**Deviation in $ttZ$ coupling of right-handed top quark**

**HL-LHC 3000 fb$^{-1}$ (approx.)**

Based on Baur, Juste, Orr, Rainwater, PRD71, 054013 (2005)

Deviations for different models for new physics scale at ~1 TeV.

Based on F. Richard, arXiv:1403.2893

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Charged Triple Gauge Couplings

- most general lorentz-invariant $W^+ W^- Z$ and $W^+ W^- \gamma$ vertices: 14 complex couplings
- assume $C$ and $P$ conservation:
  - 6 real couplings: $g_1^\gamma$, $g_1^Z$, $k_\gamma$, $k_Z$, $\lambda_\gamma$ and $\lambda_Z$
- $g_1^\gamma$ fixed by em gauge invariance
- enforce $SU_L(2) \times U_Y(1)$ gauge relation:
  - 3 real couplings:
    \[ \Delta k_Z = -\Delta k_\gamma \tan^2 \theta_W + \Delta g_1^Z \]
    \[ \lambda_\gamma = \lambda_Z \]
- SM: $g_1^Z = k_\gamma = 1$, $\lambda_\gamma = 0$
- status: few percent precision from single parameter fits (LEP & LHC)

ILC: gains ~ 2 orders of magnitude, multi-parameter fits
With the discovery of a Higgs boson, we are now confident that electroweak symmetry breaking (EWSB) occurs via the expectation value of the Higgs field. However, we do not yet know the physics behind the EWSB.

Many new physics models which attempt to explain EWSB predict the existence of new forces/particles and modifications to the (SM) properties of Higgs boson, top quark, and W/Z bosons.

It is important to test these predictions since they could be connected to the well-established observed phenomena which must require new physics, e.g.

- baryon asymmetry
- neutrino mixing
- dark matter
- ...

The Higgs boson and the top quark are crucial probes for the mechanism of EWSB.
Physics behind EWSB at TeV scale

There are two possible scenarios for the physics behind EWSB around the TeV scale:

1. **Supersymmetry (SUSY):** SUSY breaking triggers EWSB.

2. **Composite Higgs:** a QCD-like theory is behind EWSB.

The Higgs boson and the top quark are crucial probes to distinguish these possibilities.
Operating the ILC: Beam Polarisation

\[ W^+ W^- \text{ (Largest SM BG)} \]

In the symmetry limit, \( \sigma_{WW} \rightarrow 0 \) for \( \theta_R^- \)!

\[ \text{Slepton Pair} \]

In the symmetry limit, \( \sigma_R = 4 \sigma_L \)!

Note: \( e^-_L e^+_R + e^-_R e^+_L \neq \text{unpolarised data!} \)

BG Suppression

Chargino Pair

Decomposition

Signal Enhancement

[K. Fujii]
Two theoretical approaches

"Cosmological" Approach - relate to $\Omega_{DM}$ and $\sigma_{an}$:

A. Birkedal et al. [hep-ph/0403004]

Effective Operator Approach - well known from LHC.

ILC-Special: beam polarisation

- Vector:
  $\sigma_{LR} = \sigma_{RL} > 0, \sigma_{LL} = \sigma_{RR} = 0$

- Axial-vector and scalar:
  $\sigma_{LR} = \sigma_{RL} = 0, \sigma_{LL} = \sigma_{RR} > 0$

- $M_\chi$ - WIMP mass
- $S_\chi$ - WIMP spin
- $k_e$ - Fraction of WIMP pair annihilation into $e^+e^-$, $\sigma \sim \kappa_{e}^{pol}$
- $J$ - Angular momentum of dominant partial wave

BSM Physics at the ILC, ALCW 2015  J.List
**Observation reach:** 500 GeV, $2\text{ab}^{-1}$

“Cosmological” Approach
- Spin $-1/2$
- P-wave

Can observe down to $\sim1\%$ annihilation fraction to $e^+e^-$

Effective Operator Approach
- Spin $-1/2$

Can observe up to $\Lambda\sim2.5$ TeV

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**ILC Physics Opportunities, WHIZARD 16-18 March 2015**

J.List