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

H. Baer, M. Berggren, J. List, M. Nojiri, M. Perelstein, A. Pierce, W. Porod, T. Tanabe

Snowmass HEF WS, June 30, 2013, Seattle

Introduction

- We have many good and well-known reasons to seek for physics beyond the Standard Model of particle physics.
- But we don't know which new phenomena are out there!
- R. P. Feynman:
  The imagination of nature is far, far greater than that of man.
- be prepared for the unexpected,
- and pursue complementary approaches!

The ILC BSM Whitepaper

1. Post LHC8 physics landscape and ILC characteristics
2. Connections to the Cosmic Frontier
3. Connections to the Intensity Frontier
4. seven "stories" to illustrate the above with concrete examples for how nature could turn out to be, and what role of the ILC could play in revealing new underlying principles

Status:

1. Near-complete draft made available to BSM conveners 3 days ago
2. Stories which involved joint ILC/LHC studies depend on Delphes-LHC MC samples → just started...
3. WP will be completed and made available via arxiv and official Snowmass submission before the Minnesota meeting

Outline

Coming to terms with Electroweak Naturalness

Minimalistic approach:

- a superpotential higgsino mass parameter $\mu \lesssim 200 - 300\,\mathrm{GeV}$
- a one or few TeV spectrum of 3rd gen squarks $\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$,
- an intermediate scale gluino $m_{\tilde{g}} \lesssim$ 5 TeV
- multi-TeV 1st / 2nd gen. scalars can have $m_{\tilde{q},\tilde{\ell}} \sim 5 - 30$ TeV.
- theoretical considerations c.f. talk by Howie Baer

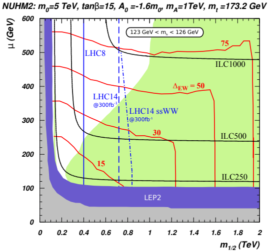
Worst Case Phenomenology:

- extreme scenario: only light Higgsinos $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_{1,2}^0$;
- all other sparticles *could* be out of direct collider reach!

Coming to terms with Electroweak Naturalness

LHC & ILC Projections [arXiv:1306.3148 [hep-ph]]

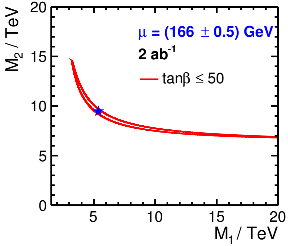
- LHC: gluino and like-sign di-boson searches
- ILC: hermetic sensitivity to $\mu \lesssim \sqrt{s}/2$



ILC Simulation Study of Light Higgsinos

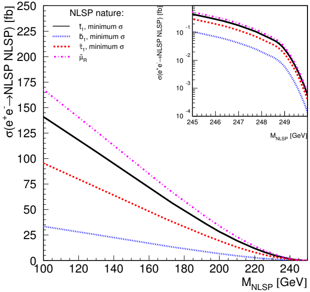
[H. Sert, K. Rolbiecki et al]

- $\mu = 167$ GeV, $M_1 = 5$ TeV, $M_2 = 10$ TeV
  $\Rightarrow \Delta M(\tilde{\chi}_1^\pm; \tilde{\chi}_1^0) \simeq 1$ GeV
- $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma_{\rm ISR}$ and $e^+e^- \to \tilde{\chi}_2^0\tilde{\chi}_1^0\gamma_{\rm ISR}$
- measure $M_{\tilde{\chi}_1^+}$ and $M_{\tilde{\chi}_2^0}$ from recoil against $\gamma_{\rm ISR}$, $\Delta M(\tilde{\chi}_1^\pm; \tilde{\chi}_1^0)$ from decay products
- can determine μ to ± 0.5 GeV, and constrain M_1 and M_2 to narrow band in multi-TeV regime!



At the ILC, SUSY *is* Simplified!

- SUSY corner stone: sparticles couple as particles
- in particular: coupling to gauge bosons is known
- rate for $e^+e^- \to Z/\gamma \to \tilde{p}\tilde{p}$ known for each $M_{\tilde{p}}$
- cosmology: if stable, LSP must be neutral and weakly interacting



- NLSP:
  - can be any sparticle, but there's a finite number.
  - decays 100% to its SM partner and the LSP
  - simplified model without simplification!
- at the ILC, all NLSP-LSP combinations can be covered systematically – without leaving loop-holes

Closing the loop-holes

- unstable LSP (eg RPV): reach better or equal to stable case, both for long- and short-lived LSP (LEP!)
- NLSP mass-state mixed between the hyper-charge states: one more parameter, mixing angle $\Rightarrow$ can pick “worst case” value
- very small NSLP-LSP mass difference $\lesssim$ few GeV:
  - $\sqrt{s} >> 2M_{\mathrm{NLSP}}$: NLSPs highly boosted, little missing 4-momentum precise knowledge of initial state: distinguish from pairs of SM partners
  - $\sqrt{s} \gtrsim 2M_{\mathrm{NLSP}}$: NLSPs slow, little visible energy
    $\rightarrow$ no problem with ISR trick, cf. light Higgsino case
    [multi-peripheral $\gamma\gamma \rightarrow f\bar{f}$: ISR kicks beam-remnant into detector]
- several near-degenerate NLSPs with similar decay mode: isolate “true” NLSP by tunable collision energy

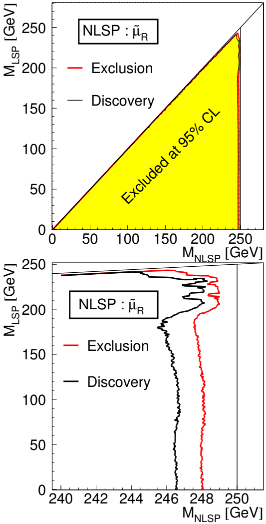
The Strategy & Example Projection [M. Berggren]

Scan $M_{\mathrm{NLSP}} - M_{\mathrm{LSP}}$ plane:

- exploit missing 4-momentum, high acolinearity, expected particle or jet flavor identification
- calculate edges of detected systems
- count signal and background in signal window
- discovery: $S > 5\sqrt{B}$; or exclusion: $S > 2\sqrt{S+B}$

Ex.: NLSP $= \tilde{\mu}_R$

- $\sqrt{s} = 500\,\mathrm{GeV}$, $\int \mathcal{L} dt = 500\ \mathrm{fb}^{-1}$
- discovery and exclusion
- significance in center part $\mathcal{O}(100)\sigma$
- reach very close to kinematic limit and $\Delta M = 0$



A $\tilde{\tau}$-Coannihilation Scenario

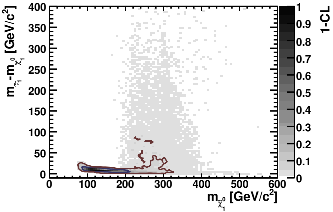
Joint LHC/ILC study

- $\tilde{\tau}$-coannihilation region was prefered by pre-LHC global fits in cMSSM
- select similar spectrum in pMSSM, but with heavier gluinos and 1./2.gen. squarks
- interplay and complementarity of both colliders
- detailed results → talk by I. Melzer-Pellmann

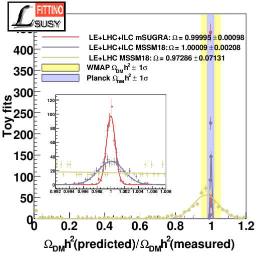
ILC

- all sleptons and electroweakinos accessible in pair or associated production
- decisive quantities for $\tilde{\chi}_1^0$ relic density prediction can be measured with sufficient accuracy, esp. $m_{\tilde{\tau}_1}$ and $m_{\tilde{\chi}_1^0}$

[arXiv:0907.5568 [hep-ph], cMSSM]



[arXiv:0907.2589 [hep-ph], Ω_{DM}]



Scanning the Electroweakino Sector

Joint LHC/ILC study

- all scalars decoupled
- fix mass of either Bino (M_1), Wino (M_2) or Higgsino (μ) LSP
- scan the other two parameters
- detailed results $\rightarrow$ talks by S. Su & T. Tanabe

(Expected) Results

- LHC will have access to (more of the) heavier ewkinos
- ILC will cover small mass differences, ie. if just (M_2) or (μ) is small and the other two very heavy
- ILC precision can predict heavier states
- demonstrate complementarity & interplay

Neutrino Physics at Colliders: Origin of neutrino masses?

Seesaw-Mechanisms

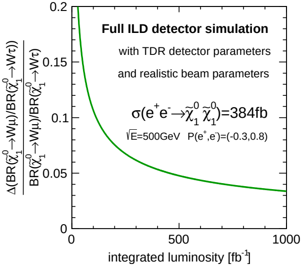
- additional particles typically way too heavy to produce at any collider
- in SUSY models, there are two handles, esp. at ILC:
  - influence RGE running of mass parameters
    $\Rightarrow$ need high precision spectroscopy!
  - give rise to additional flavour structures
    $\Rightarrow$ flavour violating decays of sleptons

Bilinear *R*-parity violation

- LSP not stable – its decay *and* neutrino mass and mixing described by the same parameters
- predict BRs of $\tilde{\chi}_1^0$ from neutrino data
- can RPV as origin of neutrino masses be tested?

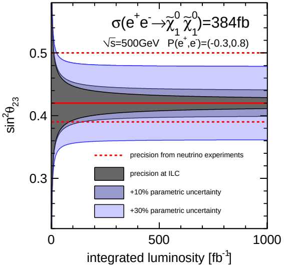
Bilinear RPV Simulation Study [B. Vormwald]

- $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1$; $\tilde{\chi}^0_1 \to W^\pm l^\mp \to q\bar{q}l$
- measure $BR(\tilde{\chi}^0_1 \to W\mu)/BR(\tilde{\chi}^0_1 \to W\tau)$
- most difficult: $M_{\tilde{\chi}^0_1} \simeq M_{W/Z}$
- benchmark: $M_{\tilde{\chi}^0_1} \simeq 100\,\text{GeV},\ M_{\tilde{e}_R} \simeq 280\,\text{GeV}$ ($\tilde{e}_R$ determines cross-section via t-channel!)



Results

- with $100\,\text{fb}^{-1}$: $\delta M_{\tilde{\chi}^0_1} = 0.13\,\text{GeV}$
- with $500\,\text{fb}^{-1}$: $\delta BR = 6.5\%$
- $\sin\theta_{23}$ is accessible with (at least) similar precision as in neutrino oscillations
- verify/falsify bRPV as origin of neutrino masses!



Producing Dark Matter in the Laboratory?

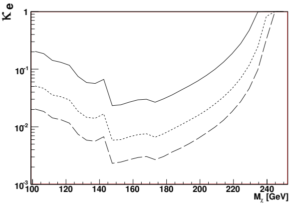
Closing in on WIMP Dark Matter

- LHC & Direct Detection:
  search for WIMPs via their couplings to quarks & gluons
- Indirect Detection:
  can search for WIMP annihilation to γ / $e^{\pm}$, but primarily sensitive for masses in few hundred GeV region
- ILC:
  probe WIMP-electron coupling at lower masses

The ILC is a powerful and complementary tool for probing the WIMP hypothesis!

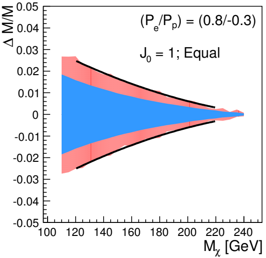
WIMP Simulation Study [0901.4890 & 1206.6639 [hep-ex]], also 1211.4008 & 1211.2254 [hep-ph]

- $\chi\chi \rightarrow f\bar{f}$ annihilation, fraction κ_e into e^+e^-
- exploit ISR recoil method ("mono-photons")
- test various WIMP spins and WIMP-fermion interaction properties, eg. helicity structure



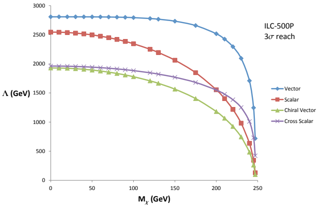
Results

- can observe WIMPs even if annihlations to e^+e^- are at percent level
- Eff. Op.: access Λ up to several TeV, down to very small WIMP masses
- measure mass at percent level
- measure polarized cross-section to few percent
- distinguish s- and p-wave annihilation



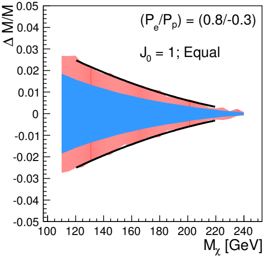
WIMP Simulation Study [0901.4890 & 1206.6639 [hep-ex]], also 1211.4008 & 1211.2254 [hep-ph]

- $\chi\chi \to f\bar{f}$ annihilation, fraction κ_e into e^+e^-
- exploit ISR recoil method ("mono-photons")
- test various WIMP spins and WIMP-fermion interaction properties, eg. helicity structure



Results

- can observe WIMPs even if annihlations to e^+e^- are at percent level
- Eff. Op.: access Λ up to several TeV, down to very small WIMP masses
- measure mass at percent level
- measure polarized cross-section to few percent
- distinguish *s*- and *p*-wave annihilation



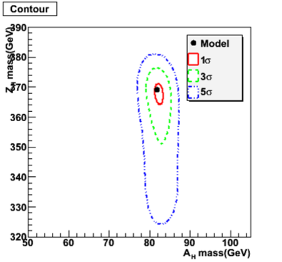
Little Higgs: An Alternative to SUSY

a well studied example:

- Littlest Higgs with T-parity (LHT), based on $SU(5)/SO(5)$ symmetry breaking pattern
- constrained by EWPO and direct searches at LHC, esp. fermionic top partner and T-odd partners of quarks.
- naturalness prefers weakly-coupled new particles in ILC range
- Lightest T-odd particle (typically photon partner A_H):
  - dark matter candidate
  - M_{A_H} is only free parameter to predict relic density
  - can it be measured at the ILC?

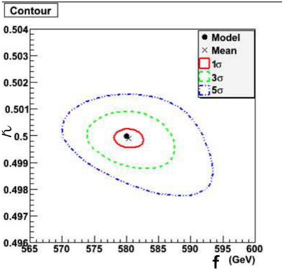
LHT Simulation Study [1203.0762 [hep-ph]]

- non-linear sigma model scale $f = 580\,\text{GeV}$
- T-odd lepton Yukawa coupling $\kappa = 0.5$
- $e^+e^- \to A_H Z_H$ at $\sqrt{s} = 500\,\text{GeV}$
- $e^+e^- \to Z_H Z_H, W_H^+ W_H^-, e_H^+ e_H^-, \nu_H \nu_H$ at $\sqrt{s} = 1\,\text{TeV}$



Results

- determine A_H and Z_H masses at $\leq 1\%$ level
- predict relic density, test if LTP is Dark Matter!
- plus T-odd leptons: f and κ at $\leq 0.1\%$ level
- sensitive test of the structure of the model



Conclusions

- 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.
- 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.

Conclusions (cont'd)

- 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, precision measurements sensitive to virtual quantum effects can also provide critical information.

  [This case is addressed by a separate Whitepaper on EWPOs at the ILC.]

Outlook

after Markus Luty's presentation this morning:

- offer to add a further section to whitepaper
- comment there on each of the "Discovery Stories"

Coming to terms with Electroweak Naturalness

Minimalistic approach:

- minimizing the scalar potential gives relation for Z mass:

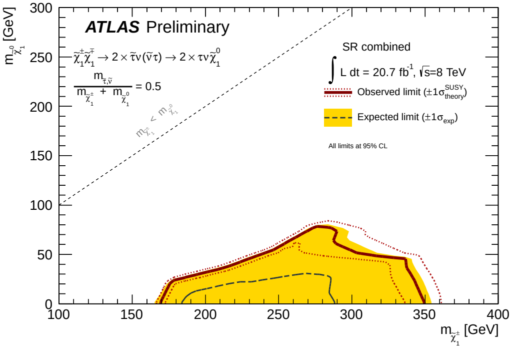
$$\frac{{m_Z}^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- avoiding large cancellations between uncorrelated terms leads to:
  - a superpotential higgsino mass parameter $\mu \lesssim 200 - 300$ GeV
  - a sub- or few TeV spectrum of 3rd gen squarks $\tilde{t}_1$, $\tilde{t}_2$ and $\tilde{b}_1$,
  - an intermediate scale gluino $m_{\tilde{g}} \lesssim$ 3-4 TeV
  - multi-TeV 1st / 2nd gen. scalars can have $m_{\tilde{q},\tilde{\ell}} \sim 10 - 50$ TeV.
- more theoretical considerations c.f. talk by Howie Baer
- extreme scenario: only light Higgsinos $\tilde{\chi}_1^\pm$, $\tilde{\chi}_{1,2}^0$;
- all other sparticles *could* be out of direct collider reach!

A $\tilde{\tau}$-Coannihilation Scenario - more details

Joint LHC/ILC study

- Chargino / neutralino with decay via stau: eg. ATLAS-13-028, CMS similar
- difficult already for $(m_{\tilde{\tau}_1} - m_{tz_1})/m_{\tilde{\tau}_1} = 0.5$
- $\tilde{\tau}$ coannihilation: rather have $\simeq 0.05$



ILC: $\tilde{\tau}_1$ mass measurement

[arxiv:0908.0876 [hep-ex]]