LHC/ILC Synergy

Jack Gunion
Davis Institute for High Energy Physics, U.C. Davis

Aspen Workshop, August 24, 2005

Based in part on work of the LHC/ILC Study Group.

- **Home page:** `www.ipp.dur.ac.uk/ georg/lhclc`
- **Report: "Physics Interplay of the LHC and the ILC": hep-ph/0410364**
- **Response to Questions from the HEPAP subpanel on LHC / ILC Complementarities as input to their report, "Discovering the Quantum Universe", submitted to the EPP2010 panel:**
  `www.ippp.dur.ac.uk/ georg/lhcilc/epp.pdf`

The LHC / LC Study Group for hep-ph/0410364.

Editors:

G. Weiglein[1], T. Barklow[2], E. Boos[3], A. De Roeck[4], K. Desch[5], F. Gianotti[4], R. Godbole[6], J.F. Gunion[7], H.E. Haber[8], S. Heinemeyer[4], J.L. Hewett[2], K. Kawagoe[9], K. Mönig[10], M.M. Nojiri[11], G. Polesello[12,4], F. Richard[13], S. Riemann[10], W.J. Stirling[1]

Working group members who contributed:

A.G. Akeroyd[14], B.C. Allanach[15], D. Asner[16], S. Asztalos[17], H. Baer[18], T. Barklow[2], M. Battaglia[19], U. Baur[20], P. Bechtle[5], G. Bélanger[21], A. Belyaev[18], E.L. Berger[22], T. Binoth[23], G.A. Blair[24], S. Boogert[25], E. Boos[3], F. Boudjema[21], D. Bourilkov[26], W. Buchmüller[27] V. Bunichev[3], G. Cerminara[28], M. Chiorboli[29], H. Davoudiasl[30], S. Dawson[31], A. De Roeck[4], S. De Curtis[32], F. Deppisch[23], K. Desch[5], M.A. Díaz[33], M. Dittmar[34], A. Djouadi[35], D. Dominici[32], U. Ellwanger[36], J.L. Feng[37], F. Gianotti[4], I.F. Ginzburg[38], A. Giolo-Nicollerat[34], B.K. Gjelsten[39], R. Godbole[6], S. Godfrey[40], D. Grellscheid[41], J. Gronberg[17], E. Gross[42], J. Guasch[43], J.F. Gunion[7], H.E. Haber[8], K. Hamaguchi[27] T. Han[44], S. Heinemeyer[4], J.L. Hewett[2], J. Hisano[45], W. Hollik[46],

C. Hugonie[47], T. Hurth[4,2], J. Jiang[22], A. Juste[48], J. Kalinowski[49], K. Kawagoe[9], W. Kilian[27], R. Kinnunen[50], S. Kraml[4,51], M. Krawczyk[49], A. Krokhotine[52], T. Krupovnic R. Lafaye[53], S. Lehti[50], H.E. Logan[44], E. Lytken[54], V. Martin[55], H.-U. Martyn[56], D.J. Miller[55,57], K. Mönig[10], S. Moretti[58], F. Moortgat[4], G. Moortgat-Pick[1,4], M. Mühlleitner[43], P. Nieżurawski[59], A. Nikitenko[60,52], M.M. Nojiri[11], L.H. Orr[61], P. Osland[62], A.F. Osorio[63], H. Päs[23], T. Plehn[4], G. Polesello[12,4], W. Porod[64,47], A. Pukhov[3], F. Quevedo[15], D. Rainwater[61], M. Ratz[27], A. Redelbach[23], L. Reina[18], F. Richard[13], S. Riemann[10], T. Rizzo[2], R. Rückl[23], H.J. Schreiber[10], M. Schumacher[41], A. Sherstnev[3], S. Slabospitsky[65], J. Solà[66,67], A. Sopczak[68], M. Spira[43], M. Spiropulu[4], W.J. Stirling[1], Z. Sullivan[48], M. Szleper[69], T.M.P. Tait[48], X. Tata[70], D.R. Tovey[71], A. Tricomi[29], M. Velasco[69], D. Wackeroth[20], C.E.M. Wagner[22,72], G. Weiglein[1], S. Weinzierl[73], P. Wienemann[27], T. Yanagida[74,75], A.F. Żarnecki[59], D. Zerwas[13], P.M. Zerwas[27], L. Živković[42]

[1] *Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK*

[2] *Stanford Linear Accelerator Center, Menlo Park, CA 94025, USA,*

[3] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow, Russia*

[4] *CERN, CH-1211 Geneva 23, Switzerland*

[5] *Universität Hamburg, Institut für Experimentalphysik, Luruper Chaussee, D-22761 Hamburg, Germany*

[6] *Centre for Theoretical Studies, Indian Institute of Science, Bangalore, 560012, India*

[7] *Davis Institute for HEP, Univ. of California, Davis, CA 95616, USA*

[8]Santa Cruz Institute for Particle Physics, UCSC, Santa Cruz CA 95064, USA
[9]Kobe University, Japan
[10]DESY, Deutsches Elektronen-Synchrotron, D-15738 Zeuthen, Germany
[11]YITP, Kyoto University, Japan
[12]INFN, Sezione di Pavia, Via Bassi 6, Pavia 27100, Italy
[13]LAL-Orsay, France
[14]KEK Theory Group, Tsukuba, Japan 305-0801
[15]DAMTP, CMS, Wilberforce Road, Cambridge CB3 0WA, UK
[16]University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[17]LLNL, Livermore, Livermore, California, USA
[18]Physics Department, Florida State University, Tallahassee, FL 32306, USA
[19]Univ. of California, Berkeley, USA
[20]Physics Department, State University of New York, Buffalo, NY 14260, USA
[21]LAPTH, 9 Chemin de Bellevue, BP 110, F-74941 Annecy-Le-Vieux, France
[22]HEP Division, Argonne National Laboratory, Argonne, IL 60439
[23]Institut für Theoretische Physik und Astrophysik, Universität Würzburg, D-97074 Würzburg, Germany
[24]Royal Holloway University of London, Egham, Surrey. TW20 0EX, UK
[25]University College, London, UK
[26]University of Florida, Gainesville, FL 32611, USA
[27]DESY, Notkestraße 85, D-22603 Hamburg, Germany
[28]University of Torino and INFN, Torino, Italy
[29]Universitá di Catania and INFN, Via S. Sofia 64, I-95123 Catania, Italy

[30]School of Natural Sciences, Inst. for Advanced Study, Princeton, NJ 08540, USA
[31]Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[32]Dept. of Physics, University of Florence, and INFN, Florence, Italy
[33]Departamento de Física, Universidad Católica de Chile, Santiago, Chile
[34]Institute for Particle Physics, ETH Zürich, CH-8093 Zürich, Switzerland
[35]LPMT, Université de Montpellier II, F-34095 Montpellier Cedex 5, France
[36]Laboratoire de Physique Théorique, Université de Paris XI,
F-91405 Orsay Cedex, France
[37]Department of Physics and Astronomy, University of California,
Irvine, CA 92697, USA
[38]Sobolev Institute of Mathematics, SB RAS, 630090 Novosibirsk, Russia
[39]Department of Physics, University of Oslo, P.O. Box 1048 Blindern, N-0316 Oslo, Norway
[40]Ottawa-Carleton Institute for Physics, Dept. of Physics, Carleton University, Ottawa K1S 5B6 Canada
[41]Physikalisches Institut, Universität Bonn, Germany
[42]Weizmann Inst. of Science, Dept. of Particle Physics, Rehovot 76100, Israel
[43]Theory Group LTP, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
[44]Dept. of Physics, Univ. of Wisconsin, Madison, WI 53706
[45]ICRR, Tokyo University, Japan
[46]Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 München, Germany
[47]Instituto de Física Corpuscular, E-46071 València, Spain
[48]Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, IL, 60510-0500
[49]Institute of Theoretical Physics, Warsaw University, Warsaw, Poland

[50]Helsinki Institute of Physics, Helsinki, Finland
[51]Inst. f. Hochenergiephysik, Österr. Akademie d. Wissenschaften, Wien, Austria
[52]ITEP, Moscow, Russia
[53]LAPP-Annecy, F-74941 Annecy-Le-Vieux, France
[54]Kobenhavns Univ., Mathematics Inst., Universitetsparken 5,
DK-2100 Copenhagen O, Denmark
[55]School of Physics, The University of Edinburgh, Edinburgh, UK
[56]I. Physik. Institut, RWTH Aachen, D-52074 Aachen, Germany
[57]Department of Physics and Astronomy, University of Glasgow, Glasgow, UK
[58]School of Physics & Astronomy, University of Southampton,
Southampton SO17 1BJ, UK
[59]Inst. of Experimental Physics, Warsaw University, Warsaw, Poland
[60]Imperial College, London, UK
[61]University of Rochester, Rochester, NY 14627, USA
[62]Department of Physics, University of Bergen, N-5007 Bergen, Norway
[63]University of Manchester, UK
[64]Institut für Theoretische Physik, Universität Zürich,
CH-8057 Zürich, Switzerland
[65]Institute for High Energy Physics, Protvino, Moscow Region, Russia
[66]Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, E-08028, Barcelona, Catalonia, Spain
[67]C.E.R. for Astrophysics, Particle Physics and Cosmology, Univ. de Barcelona, E-08028, Barcelona, Catalonia, Spain

[68] *Lancaster University, UK*
[69] *Dept. of Physics, Northwestern University, Evanston, IL, USA*
[70] *Dept. of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822, USA*
[71] *Department of Physics and Astronomy, University of Sheffield, Hounsfield Road, Sheffield S3 7RH, UK*
[72] *Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[73] *Institut für Physik, Universität Mainz, D-55099 Mainz, Germany*
[74] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[75] *Research Center for the Early Universe, University of Tokyo, Japan*

EPP Questions Response Editors:

John Conway, Jack Gunion, Howard Haber, Sven Heinemeyer, Gudrid Moortgat-Pick, Georg Weiglein

The EPP Questions Report

Basic Questions:

- **How would the combination of the LHC and a Linear Collider answer questions that could not be addressed by either machine alone? Synergy**

  Subsidiary Questions:

  1. **What will we learn from the LHC alone?**
  2. **How much will our knowledge be improved with the addition of ILC data?**

- **What physics would a Linear Collider address that would be impossible to probe at the LHC? Uniqueness**

- **Are there physics arguments for operating a Linear Collider during the same time frame as the LHC? Concurrency**

I will give my own take on these issues, along with examples.

Our expectations based on examining many types of new physics

- Ground-breaking discoveries are expected at the LHC and the ILC, both of which will open up the new TeV energy domain that will allow us to examine the very fabric of matter, energy, space and time.
- Together, these colliders will reveal:
  - how particles obtain the property of mass;
  - whether the different forces of nature are in fact different manifestations of only one fundamental force;
  - whether there is a new super symmetry;
  - whether there is a sub-TeV particle responsible for dark matter.
- Neither collider alone can fully explore the new physics.

  Synergistic use of data from both accelerators will be needed.

  In a very real sense, this has been the principle physics topic at the Snowmass meeting and the Aspen workshop. It will be my primary emphasis here.

General Discussion of Synergy

- **Synergy is not new.** For example, Tevatron and LEP.
  - The Tevatron determines the top mass.
  - LEP measures a very precise value for m_Z.
  - Both measure m_W.
  - Combining $\Rightarrow$ light Higgs expectation.

Underlying all discussions of LHC / ILC synergy are the theoretical structures that imply that **the LHC will see some form of new physics**.

- At the very least, that is if there is no new light physics, it must see strong $WW \to WW$ scattering, which undergoes some form of self-unitarization.

- As shown in early studies, the ILC would provide crucial (indirect) sensitivity to strong WW scattering that might allow, in combination with the LHC observations, an understanding of what is going on.

  Still, it must be admitted that such an LHC observation would push us to maximize the ILC energy.

I will, however, say no more about this very unappetizing scenario. There are strong indications (e.g. gauge coupling unification in SUSY) that new physics is likely to be perturbative in nature.

- On the other side of the coin, there are a number of scenarios (one of which I mention later) for which the LHC might not see a light Higgs boson (even though it is present) and only the observation that $WW \to WW$ interactions remain weak up to the TeV scale would reveal that it must be there.

- More generally, if WW scattering is perturbative at the LHC we can be certain that a modest energy ILC will find (using the $e^+e^- \to ZX$ signal) whatever it is that is responsible for regulating the bad high energy behavior.

I now summarize and elaborate on some of the remarks contained in the response to the EPP (paraphrased for a more technical audience and with more detail on examples) and in the Introduction to the LHC / ILC Report.

- **The LHC and ILC will probe the TeV energy regime in very different ways.**
  - **The LHC** has huge reach in mass, for example $6-7$ TeV for singly-produced particles with strong couplings and $2-3$ TeV for pair produced strongly interacting particles.

    But, the LHC has a somewhat "dirty" experimental environment. Evidence for new phenomena has to be extracted from a plethora of conventional processes, implying difficulty in achieving a high level of precision and the possibility of missing or being insensitive to some new physics signals.

    For example, we can see signals associated with supersymmetric particles having a large range of masses, but may have difficulty fully determining their properties. In fact, **SUSY can be its own background.**

    In addition, different kinds of hypothetical new physics can lead to similar experimental signals. For example, SUSY vs. universal extra dimensions (UED). SUSY has R parity while UED has KK parity — both lead to a lightest stable particle that is weakly interacting.
  - **The ILC** will have a clean environment, polarized beams and (especially important if there are a lot of light SUSY or other particles) tunable

collision energy.

As a result, it can perform detailed studies of directly accessible particles.

Its precision measurements will also yield exquisite sensitivity to quantum effects of unknown particles beyond the energy reach of even the LHC.

The advantage of sensitivity to quantum corrections is that they are influenced by the whole structure of the model. As a result, the first fingerprints of some new physics have, in the past and perhaps in the future, only manifested themselves in tiny deviations.

Precision measurement can thus provide a highly sensitive constraint on the parts of some new physics that are beyond the reach of any accelerator or simply impossible to detect, once some parts of the new physics are directly observed.

Higgs example

A very SM-like Higgs h_L can be quite heavy (up to about $500~\mathrm{GeV}$) without contradicting current LEP/SLD precision measurements provided there are other (typically very heavy) Higgs $H^\pm, h_H$ with masses such as to produce a compensating contribution. These other Higgs can be impossible to detect at both the LHC and ILC. Giga-Z operation at the ILC could reveal their presence.

- We expect an even greater synergy between the LHC and the ILC than between the Tevatron and LEP
  - Discoveries made at the LHC will guide the operation of the ILC (and, if we believe what we are told by DOE and others) will be required before ILC approval will be forthcoming. If this latter is the case, we will know what energy is actually needed (at least initially) for the ILC.
  - The large mass and high-energy coverage of the LHC and the highly precise measurements possible at the ILC will typically be highly complementary.

    The SUSY example

    1. The LHC will see the squarks and gluinos, and will give much information on the lighter SUSY particles present in their cascade decays.
    2. The ILC will measure the properties of the lighter SUSY particles with high precision.

Heavier W' and Z'

1. The LHC has good prospects for discovering heavy vector bosons.
2. The ILC has sensitivity often exceeding the direct reach of the LHC through virtual effects of the very heavy vector bosons.

– Precision ILC measurement can make it possible to extract (through reanalysis of existing data) LHC signals for new physics and particles that might have been initially missed in the LHC data.

– ILC precision measurements of light particles can allow extraction of the masses of heavy particles (only made at the LHC) whose masses could be only poorly determined based on LHC data alone.

SUSY provides the most obvious example.

1. The LHC measures mass differences but the absolute mass scale is limited by a somewhat imprecise determination of the LSP mass.
2. The ILC can generally determine the LSP mass with great precision, which in turn greatly increases the accuracy of the absolute mass scales for the particles that only the LHC has sufficient energy to

detect.

– It seems certain that only by combining the precision ILC measurements with the LHC data will it be possible to definitively connect TeV-scale measurements to the underlying theoretical structure.

Higgs provides a first example.

Once one more more Higgs particles are detected at the LHC, a comprehensive program of precision Higgs measurements at the ILC will be necessary to reveal their properties in sufficient detail to reveal the underlying physics. Indeed, only the ILC may be able to discern whether the Higgs observed at the LHC is that of the SM or the SM-like Higgs of SUSY or a Higgs-like (possibly composite) scalar tied to a more complex mechanism of mass generation.

If deviations of Higgs properties from SM expectations are found at the ILC, this will typically suggest the presence of other types of new physics at energy scales only somewhat beyond ILC reach (for example, the heavy SUSY Higgs bosons of the MSSM). A dedicated search for this new physics (e.g. the additional SUSY Higgs) in LHC data might confirm its existence even though the signals were too weak to trust or extract without ILC input.

Dark matter provides another important example.

If the LHC observes missing energy (a definitive observation requiring a really thorough understanding of jet energy scales and such) and it is associated with relatively low mass, many (especially Mike Peskin) would argue that one should proceed immediately with the ILC, since only the ILC can hope to provide the precision measurements of the missing energy object(s) that will allow us to see if it is indeed the source of dark matter.

The importance of the ILC for assessing the dark matter situation is made particularly apparent by examples from SUSY. In particular, while the LHC will see the relevant SUSY particles, their properties will not be adequately determined. Take, for instance the case where the main mechanism for getting rid of the LSP $\widetilde{\chi}_1^0$ in the early universe is via $\widetilde{\tau}_1\widetilde{\chi}_1^0$ co-annihilation. You will need to know with considerable precision the composition of the $\widetilde{\chi}_1^0$ in terms of its bino, wino and higgsino components as well as the $m_{\widetilde{\tau}_1} - m_{\widetilde{\chi}_1^0}$ mass difference and the mixing in the $\widetilde{\tau}$ sector.

Extra dimensions provide a third example

At the LHC, the most direct probe of extra dimensions in the ADD model is the observation of missing energy in association with high-p_T jet production. Significant signals are predicted for many choice of the number of extra dimensions δ and the effective Planck scale of the extra dimension theory M_D. Unfortunately, it turns out that there are ambiguities and degeneracies in the LHC predictions that make it impossible to actually determine the values of δ and M_D. (Some resolution of the degeneracies is possible if the LHC is run at several energies, but the ambiguities would still make things difficult.)

At the ILC, $e^+e^- \to \gamma + \not{E}$ can be measured for several different machine energies and a rather good determination of δ and M_D becomes possible.

In general, the combined interpretation of the LHC and ILC data will lead to a much clearer picture of the underlying physics than the results of both colliders taken separately, allowing the new laws of nature to be identified.

Summary regarding synergy from the EPP Questions Report

There will be a profound synergy between the physics results from the LHC and those from the ILC. The two machines complement and supplement one another in many ways. Understanding the physics of the TeV scale will have an important impact on cosmology and other fields, as well as provide guidance regarding appropriate future facilities. Optimal use of the capabilities of both machines will greatly improve our knowledge of the fundamental nature of matter, energy, space and time.

Quantitative and/or Definitive Examples of Synergy

A Higgs Discovery Example

Consider the NMSSM.

We (JFG+Dermisek) have shown that the fine-tuning characteristic of the MSSM can be removed in this very attractive model because of the possibility that the light SM-like Higgs boson decays to a pair of light CP-odd Higgs bosons, $h_1 \to a_1 a_1$.

This decay would have escaped LEP for $m_{h_1} \gtrsim 95-100~\mathrm{GeV}$ (rather than usual $114~\mathrm{GeV}$) even if the $a_1 \to b\bar{b}$ decay is dominant.

This leads to very low fine-tuning for the model.

The problem is that observing an h_1 that decays in this way ($h_1 \to a_1 a_1 \to b\bar{b}b\bar{b}$) is likely to be very challenging at the LHC.

LHC sees a plethora of SUSY particles, but no Higgs. We will know the Higgs is there since WW scattering will be perturbative.

The solution is to go to the ILC, where $e^+e^- \to Zh_1$ is observable using reconstructed M_X in $e^+e^- \to ZX$ will reveal the h_1 peak no matter how the h_1 decays.

A General SUSY Issue

Is there a problem going from the LHC (maybe also LHC + ILC?) data to a unique SUSY model?

G. Kane and collaborators (see Liantao's talk) claim that a given set of LHC data (perhaps not as full as others might wish to employ — no shapes, ..., only event counting and edges) will be compatible with many little islands of SUSY parameter space.

The addition of more observables will undoubtedly help and people from the SPA initiative (Kalinowski etal) and Sfitter (Plehn etal) and Fittino (Bechtle etal) claim there is no redundancy. They should combine to form "Sfittino".

This is an ongoing debate.

However, what is clear is that the ILC precision data should help enormously to remove the redundant parameter possibility.

A specific example of this is provided by B. K. Gjelsten, D. J. Miller and P. Osland, arXiv:hep-ph/0507232.

They consider two SPS1a line points and how well masses of the SUSY particles can be determined from the end points in cascade decays

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{l}_R^{\mp} l_{\rm n}^{\pm} q \to \tilde{\chi}_1^0 l_{\rm f}^{\mp} l_{\rm n}^{\pm} q \quad (1)$$

The two points they consider are

Table 1: SPS 1a masses

	$m_{\tilde{q}_L}$ [GeV]	$m_{\tilde{\chi}_2^0}$ [GeV]	$m_{\tilde{l}_R}$ [GeV]	$m_{\tilde{\chi}_1^0}$ [GeV]
(α)	537.2	176.8	143.0	96.1
(β)	826.3	299.1	221.9	161.0

They find multipled solutions based on expected LHC errors:

Table 2: Region borders for $m_{\tilde{\chi}_1^0}$ [GeV]

	SPS 1a nominal	Region *(1,1)* vs. *(1,2)*	Region *(1,2)* vs. *(1,3)*
(α)	96.1	98.2	115.7
(β)	161.0	95.0	164.6

The incorrect solutions are removed when ILC data is brought in and higher precision at the true minimum is achieved.

Meanwhile, the Sfitter people (Lafaye, Plehn and Zerwas) claim no ambiguity for an SPS1a type point and excellent precision of mass determinations once all data is put in. However, their results are somewhat out of date now and they did not really fit in some parameters.

Recent results are available from the Fittino collaboration of P. Bechtle, K. Desch and P. Wienemann, arXiv:hep-ph/0506244. A table is presented below.

Note that the LHC errors can be quite big before including ILC input.

Parameter	"True" value	ILC Fit value	Uncertainty (ILC+LHC)	Uncertainty (LHC only)
$\tan\beta$	10.00	10.00	0.11	6.7
μ	400.4 GeV	400.4 GeV	1.2 GeV	811. GeV
X_τ	-4449. GeV	-4449. GeV	20. GeV	6368. GeV
$M_{\tilde{e}_R}$	115.60 GeV	115.60 GeV	0.27 GeV	39. GeV
$M_{\tilde{\tau}_R}$	109.89 GeV	109.89 GeV	0.41 GeV	1056. GeV
$M_{\tilde{e}_L}$	181.30 GeV	181.30 GeV	0.10 GeV	12.9 GeV
$M_{\tilde{\tau}_L}$	179.54 GeV	179.54 GeV	0.14 GeV	1369. GeV
X_{t}	-565.7 GeV	-565.7 GeV	3.1 GeV	548. GeV
X_{b}	-4935. GeV	-4935. GeV	1284. GeV	6703. GeV
$M_{\tilde{u}_R}$	503. GeV	503. GeV	24. GeV	25. GeV
$M_{\tilde{b}_R}$	497. GeV	497. GeV	8. GeV	1269. GeV
$M_{\tilde{t}_R}$	380.9 GeV	380.9 GeV	2.5 GeV	753. GeV
$M_{\tilde{u}_L}$	523. GeV	523. GeV	10. GeV	19. GeV
$M_{\tilde{t}_L}$	467.7 GeV	467.7 GeV	3.1 GeV	424. GeV
M_1	103.27 GeV	103.27 GeV	0.06 GeV	8.0 GeV
M_2	193.45 GeV	193.45 GeV	0.10 GeV	132. GeV
M_3	569. GeV	569. GeV	7. GeV	10.1 GeV
$m_{\mathrm{A run}}$	312.0 GeV	311.9 GeV	4.6 GeV	1272. GeV
m_{t}	178.00 GeV	178.00 GeV	0.050 GeV	0.27 GeV
χ^2 for unsmeared observables: 5.3×10^{-5}				

Table 3: Fittino results for SPS1a parameter determination.

Distinguishing between the MSSM and the NMSSM

In a recent paper, G. Moortgat-Pick, S. Hesselbach, F. Franke and H. Fraas, (JHEP 0506, 048 (2005) [arXiv:hep-ph/0502036]) considered whether or not the MSSM for appropriate parameter choices could be distinguished from the NMSSM when the latter was the correct model.

Using only LHC data, a perfectly consistent set of MSSM parameters was found that fit the observations within errors.

Even more precise ILC measurements of $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ would not be in obvious contradiction to the MSSM.

However, by inputing these much more precise ILC measurements for $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_1^{\pm}$, the mass and mixing character of the $\widetilde{\chi}_3^0$ (too heavy to be observable at the ILC) could be determined and could be checked against the LHC observation. A contradiction would be apparent for the MSSM parameterizations whereas the NMSSM parameters would be consistent with the LHC data on the $\widetilde{\chi}_3^0$.

ADD Extra Dimension Parameter Determination

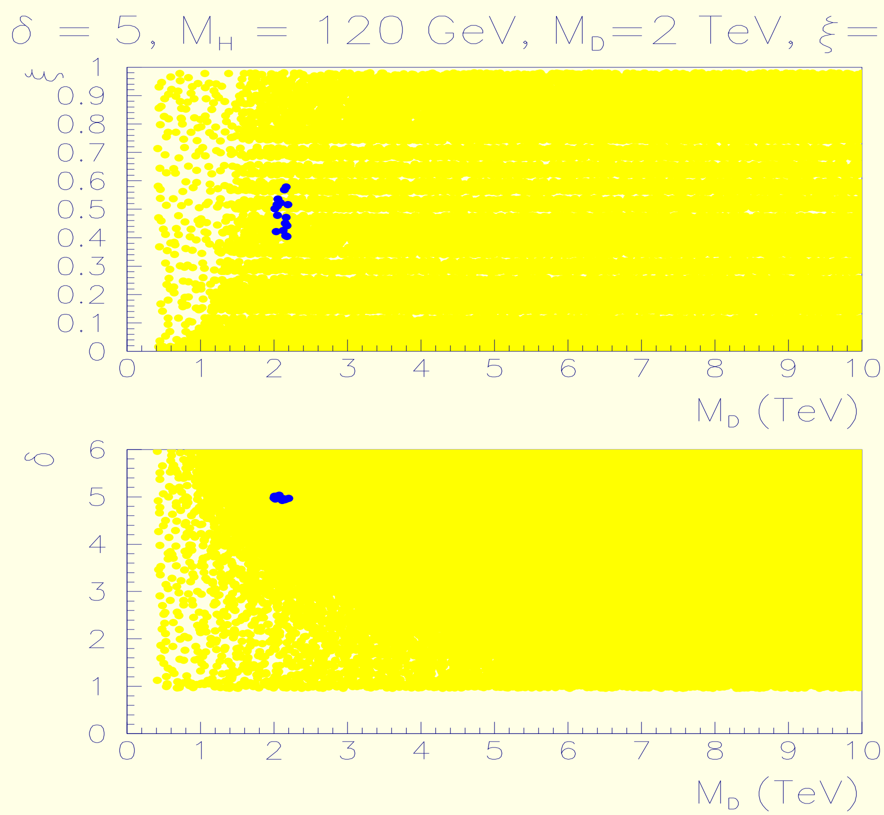

Figure 1: **95% CL contours for determination of M_D, ξ and δ assuming $m_h = 120$ GeV, input $\xi^0 = 0.5$ and input δ^0 and M_D^0 values as indicated above the figures. All results are obtained assuming $L = 100$ fb^{-1} Higgs measurements at the LHC, $\sqrt{s} = 350$ GeV (500 GeV) invisible (visible) mode Higgs measurements at the LC, and $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV $\gamma+$ missing energy measurements at the LC with $L = 1000$ fb^{-1} and $L = 2000$ fb^{-1} at the two respective energies. The larger light gray (yellow) regions are the 95% CL regions in the ξ, M_D and δ, M_D planes using only $\Delta\chi^2(LHC)$. The smaller dark gray (blue) regions or points are the 95% CL regions in the ξ, M_D and δ, M_D planes using $\Delta\chi^2(LHC + LC)$.**

Light Dark Matter in the NMSSM

We (JFG+Hooper+McElrath) have found the the $\widetilde{\chi}_1^0$ could be very light in the NMSSM ($100~\mathrm{MeV} - 5~\mathrm{GeV}$, for example).

All that is needed is that the a_1 of the model be light and have $m_{a_1} \sim 2m_{\widetilde{\chi}_1^0}$. In this way, annihilation can be sufficiently strong to yield exactly the right amount of dark matter.

At the LHC, we will of course see the effects of the $\widetilde{\chi}_1^0$ through missing energy, but endpoints and such will at best give some kind of upper bound on $m_{\widetilde{\chi}_1^0}$. And typically the a_1 will simply not be observed.

The ILC will be required to pin down the $\widetilde{\chi}_1^0$ mass and composition using the usual techniques. And the ILC also has substantial cross sections for a_1 production and has a chance to determine is properties well-enough to give a precision check of whether this is a consistent dark matter scenario.

Uniqueness

Generally speaking, scenarios in which the LHC is ineffective and the ILC is absolutely essential are somewhat contrived, but they do exist.

Expanded Higgs sectors provide the most food for thought.

As an example, consider the case in which there is a SM Higgs boson and many other singlet Higgs bosons. (NNNNNNNNN....NMSSM, but without the supersymmetry.)

The example is contrived in the sense that there is no solution to the naturalness/hierarchy problems.

- For an appropriately constructed Higgs potential, the SM Higgs will mix with the singlets enough that it will tend to decay to the other Higgs bosons or create many closely spaced states of mixed character.

- **LHC**

  If the SM-like guy decays Higgs signals can be missed at the LHC in the same way that the NMSSM $h_1 \to a_1 a_1$ decay is missed.

  Alternatively, if the Higgs bosons are overlapping, they will yield a very broad "fat" signal without the clear resonance bump(s) that the LHC requires to be able to detect something above backgrounds.

  WW scattering will be perturbative, so we will know the Higgs bosons are there, but we cannot see them (or anything else if the only new physics is the Higgs).

- **ILC**

  One can always rely on the $e^+e^- \to ZX$.

  Espinosa and I showed that even if the signal is very broad, the LEP precision data is sufficient to tell us that the Higgs spectrum cannot lie too high in mass or be so spread out that an enhancement in the M_X distribution would be missed.

Concurrency

It is not clear to me that concurrent running of the LHC and ILC is a necessity **provided** we archive all LHC data and have been sufficiently clever in our choices of triggers and other strategies to avoid leaving out LHC physics in the data we keep.

I think some careful thought must go into very long lived particle that might be produced in large numbers at the LHC but would simply appear to be stable to the LHC detectors without special efforts.

- If they are strongly interacting they can be trapped (eg. by the detector itself) and their decays looked for after the fact.
- If they are not trapped? Far out (literally) detectors have been suggested by various people (including me) for increasing sensitivity to long-lived $\widetilde{\chi}_1^0$'s that would eventually decay to gravitinos and similar scenarios.

Of course, the systems would need to be put in place for archiving the data in such a way that knowledgeable people would still know how to get at it once the ILC has operated for a while.

Maybe this will be automatic given that the LHC will morf into the SLHC and so the relevant people will be around for many years.

Concurrency would be a lot more convenient and lead to a lot more understanding sooner.

Conclusions

Get the LHC running on schedule.

Get the ILC design finalized and costed by the time we start to get early LHC physics.

Start to discover some fantastic new physics (missing energy or Higgs or both or ...) and show it will be accessible to the ILC.

Get construction funding and proceed.