The LHC / ILC Connection

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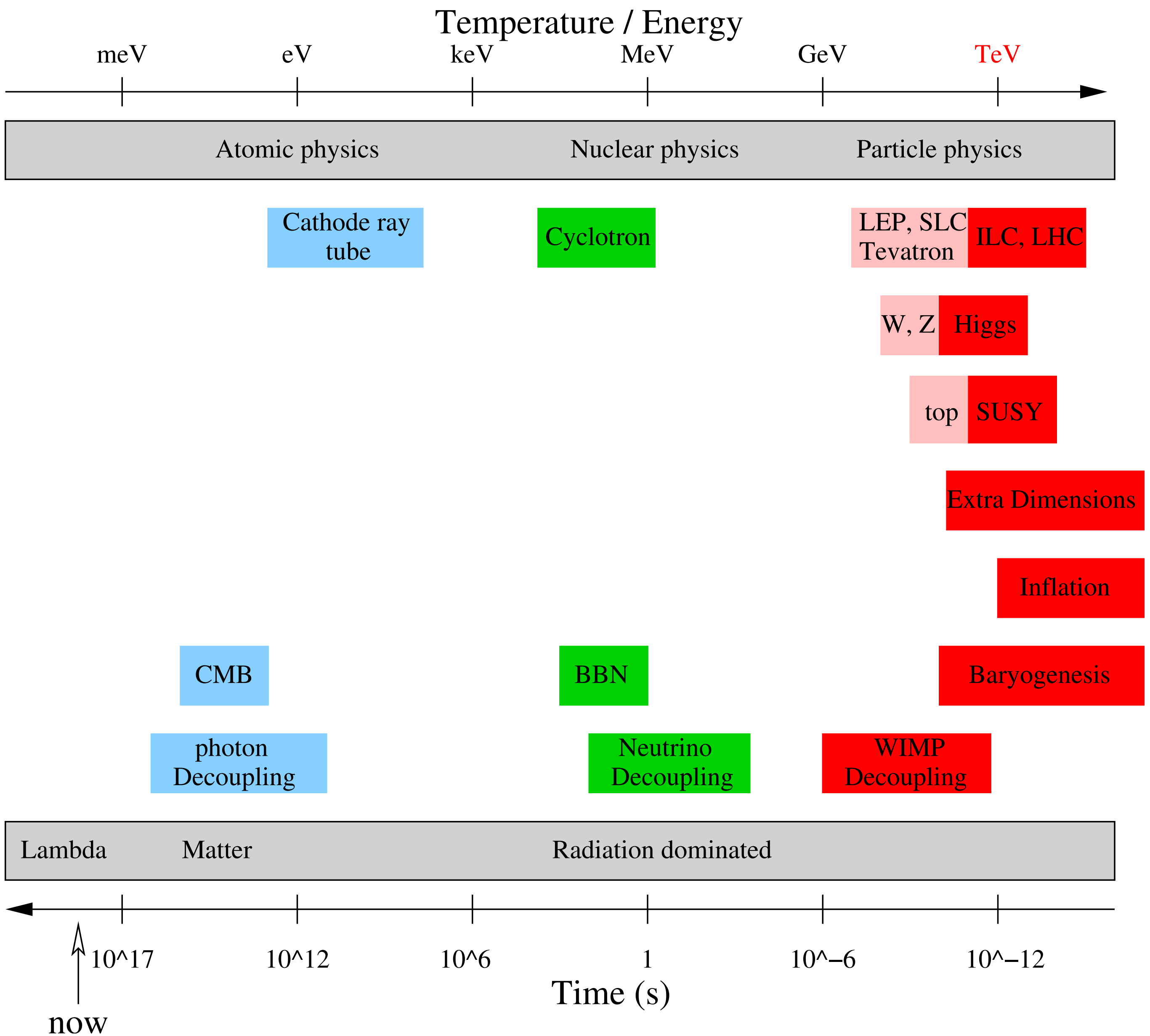
IPPP Durham

Snowmass 08/2005

Worldwide Study of the Physics and Detectors for Future Linear e^+e^- Colliders

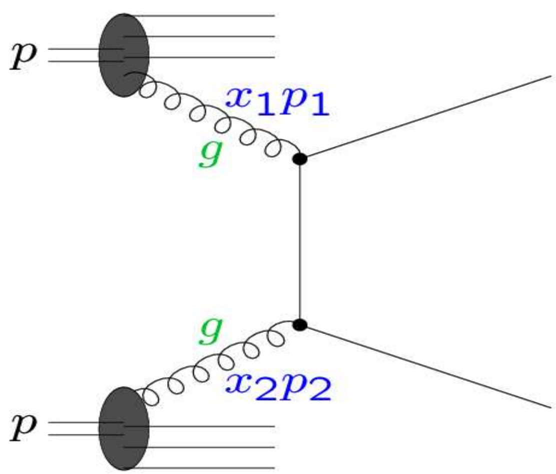
www.ippp.dur.ac.uk/ ~georg/lhc lc

Particle physics is about to enter a new territory: TeV scale ($1\ \mathrm{TeV} \Leftrightarrow 2 \times 10^{-19}\ \mathrm{m}$)



Physics at the LHC and ILC in a nutshell

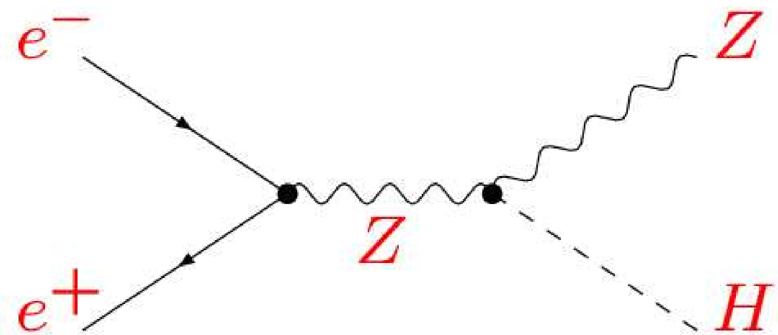
LHC: pp scattering at 14 TeV



Scattering process of proton constituents with energy up to several TeV,
strongly interacting

$\Rightarrow$ huge QCD backgrounds, low signal–to–background ratios

ILC: e^+e^- scattering at $\approx$0.5–1 TeV



Clean exp. environment:
well-defined initial state,
tunable energy,
beam polarization, GigaZ,
$\gamma\gamma$, $e\gamma$, e^-e^- options, ...

$\Rightarrow$ rel. small backgrounds high-precision physics

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"Known unknowns" vs. "unknown unknowns"

We are prepared to explore Higgs physics, SUSY, extra dimensions, mini black holes, . . .

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ILC: untriggered operation

$\Rightarrow$ can find signals of unexpected new physics (direct production $+$ large indirect reach) that manifests itself in events that are not selected by the LHC trigger strategies

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$\Rightarrow$ Need this information as soon as possible to identify the nature of new physics

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Expeditious realisation of the ILC $\Rightarrow$ period of concurrent running

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During concurrent running: LHC $\otimes$ ILC

$\Rightarrow$ Information obtained at the ILC can be used to improve analyses at the LHC and vice versa

$\Rightarrow$ Enable improved strategies, dedicated searches

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What is the added value of concurrent running?

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$\Rightarrow$ LHC / ILC Study Group

www.ippp.dur.ac.uk/~georg/lhcilc

World-wide working group, started in spring 2002

Collaborative effort of Hadron Collider and Linear Collider experimental communities and theorists

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First report has recently been completed: hep-ph/0410364

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(2) which properties can be measured; how precisely?

(3) how well are we able to tell what it is?

$\Rightarrow$ Summary given in the report

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Main focus of LHC studies so far was on (1), less results available on (2) and (3)

How far are we?

- Many possibilities of LHC / ILC synergy have been highlighted

  $\Rightarrow$ LHC / ILC interplay is a very rich field

  $\Rightarrow$ great potential for important physics gain

  $\Rightarrow$ Needs to be worked out and confirmed in detailed case studies, experimental simulations

- Many of the analyses so far were mainly LHC analyses where at the very end some ILC input was injected (or the other way round)

  $\Rightarrow$ Aim should be LHC / ILC analyses that make use of the interplay from the start

How far are we?

- ATLAS and CMS are actively preparing for the start of data taking: CMS writes physics TDR, many new studies in ATLAS (full simulations, new scenarios)

  $+$ ongoing ILC studies

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$\Rightarrow$ Further effort needed to explore LHC / ILC interplay

Examples from the U.S.

Presentation from M. Turner (NSF) to HEPAP, Sep. 23, 2004:

Complementarity

Inevitably, the question will arise of why we need a second, *less* powerful accelerator to explore the energy frontier. To educate us and to clarify this issue more generally, we would like HEPAP to form a subpanel to address complementarity, paying particular attention to the following aspects of LC/LHC complementarity:

- In the context of physics discoveries (e.g., low-energy supersymmetry) made at the Tevatron or early at the LHC, what is the role of a subTeV Collider?
- In the context of physics discoveries made an LC, what is the role of the LHC
- In the context of "known physics" (e.g., electroweak physics), what are the synergies and complementaries of these two machines?

You should assume that the LC and LHC (with possible upgrades) will have a significant period of overlapping operation.

We are looking for a short document (20 pages), accessible to knowledgeable non-experts (e.g., members of the EPP2010 Study, OSTP Staff and ourselves). We ask that the report be completed by April 2005.

Finally, to further educate us as well as giving us an opportunity to refine and discuss the charge with you in more detail, we suggest a half-day session at the next HEPAP meeting devoted to Complementarity.

HEPAP subpanel on LHC / ILC complementarities

- Official request from NSF (R. Staffin, M. Turner) to HEPAP on March 21, 2005:

  form subpanel, provide report by summer 2005

- Panel members:

  J. Lykken (Co-Chair), J. Siegrist (Co-Chair), J. Bagger, B. Barrish, N. Calder, J. Feng, F. Gilman, J. Hewett, J. Huth, J. Jackson, Y.-K. Kim, R. Kolb, K. Matchev, H. Murayama, P. Sphicas, R. Weiss

- Report: “Discovering the Quantum Universe”

Examples from the U.S.

EPP Decadal Survey:

U.S. National Academy of Science reviews each field of physics every ten years
(last survey of Particle Physics was completed in 1998)

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EPP 2010 charge:

- Identify, articulate, and prioritize the scientific questions and opportunities that define elementary particle physics
- Recommend a 15-year implementation plan with realistic, ordered priorities to realize these opportunities

$\Rightarrow$ emphasis on ranking science priorities

Some of the EPP questions on the ILC:

- What are the physics arguments for operating a Linear Collider during the same time frame as the LHC?
- How would the combination of the LHC and a Linear Collider answer questions that could not be addressed by either machine alone?
- What physics would a Linear Collider address that would be impossible to probe at the LHC?

$\Rightarrow$ The LHC / ILC Study Group was approached by the EPP, asked to provide a response to these questions

Response of the LHC / ILC Study Group to the EPP questions

Document prepared, writing team: J. Conway, J. Gunion, H. Haber, S. Heinemeyer, G. Moortgat-Pick, G. W.

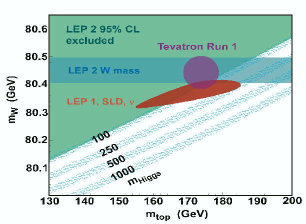
The EPP Questions

Response from the LHC/ILC Study Group

Ground-breaking discoveries are expected from the experiments under construction at the Large Hadron Collider (LHC) and those planned for the International Linear Collider (ILC). These high-energy particle accelerators will open up a new energy domain that will allow us to examine the very fabric of matter, energy, space and time. The experimental results should reveal how particles obtain the property of mass, whether the different forces that we experience in nature are in fact different manifestations of only one fundamental force, whether space and time are embedded into a wider framework of "supersymmetric" coordinates, and whether dark matter can be produced on Earth.

The LHC and ILC will probe this new TeV energy regime (roughly equivalent to 1000 proton masses) in very different ways, as a consequence of the distinct features of the two machines. Due to its high collision energy and luminosity, the LHC has a large mass reach for the discovery of new heavy particles. The striking advantages of the ILC are its clean experimental environment, polarized beams, and tunable collision energy. The ILC can thus perform precision measurements and detailed studies of directly accessible new particles, and also has exquisite sensitivity to quantum effects of unknown physics. Indeed, the fingerprints of very high-scale new physics (e.g. very high mass particles) will often only be manifest in small effects whose measurement requires the greatest possible precision.

The need for instruments that are optimized in different ways is typical in all branches of natural sciences, for example earth- and space-based telescopes in astronomy. In high-energy physics there has historically been a great synergy between hadron colliders, which can reach the highest energies, and lepton colliders, at which high-precision measurements are possible. As an example, the precise knowledge of the Z boson mass from LEP and precise measurement of its decay properties led to the prediction of a heavy top quark. Its mass was well beyond the energy reach of LEP but accessible to the Tevatron. Following the Tevatron's discovery of the top quark, its mass was determined. Subsequently the Tevatron and LEP measured the W boson mass with high precision. In combination, these measurements point tantalizingly toward a light Higgs boson.



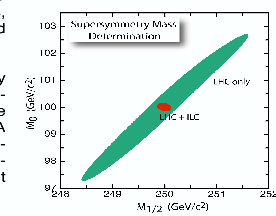
Precise measurements from concurrent running of LEP and the Tevatron experiments have brought us to the threshold of discovering the Higgs boson.

We expect an even greater synergy between the LHC and ILC. Discoveries made at the LHC will guide the operation of the ILC, and the precision ILC measurements can make it possible for the LHC to extract subtle signals for new physics and particles that may have escaped detection. Ultimately both machines will be needed to definitively connect TeV-scale measurements with the underlying theoretical structure.

In general, the LHC can most readily discover the heavy states of new physics that are "strongly coupled" (that is, produced via the strong interaction). These strongly coupled states typically decay via complicated cascades into new "weakly coupled" particles. The ILC is ideal for directly producing and detecting these weakly coupled particles. Precision ILC measurement of the properties of these particles are essential in understanding the strongly coupled ones and their decay patterns. Moreover, ILC measurements of quantum effects can be combined with direct LHC and ILC measurements to infer the existence and properties of additional heavy states at first missed by the LHC and too massive to be directly produced at the ILC. In many cases, these could then be directly discovered using modified LHC procedures.

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

As an example, the existence and properties of heavy Higgs bosons and/or difficult-to-detect scalar Higgs-like particles associated with extra dimensions can be inferred from precision ILC Higgs measurements. A dedicated LHC search can then confirm their existence. In supersymmetry and extra-dimension theories, the LHC and the ILC will typically access different parts of the spectrum of new states.



Together the ILC and LHC can measure the unified supersymmetry masses much more precisely than either machine alone.

Summary

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, and concurrent operation will maximize the impact of both. Understanding the physics of the TeV scale will have an important impact on cosmology and other fields, as well as give timely guidance regarding future facilities. The sooner the ILC can be brought into operation, the sooner these benefits can be exploited. Optimal use of the capabilities of both machines will greatly improve our knowledge of the fundamental nature of matter, energy, space and time.

We urge the international high energy physics community and the governments of all the countries involved to strive to make the ILC a reality in the coming decade.

See the full report of the LHC/ILC Study Group at http://arxiv.org/abs/hep-ph/0410364

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

May 16, 2005

Released to the EPP members at the EPP meeting in May '05 at Fermilab, see www.ippp.dur.ac.uk/~georg/lhclc

Recent workshops on LHC / ILC interply

- LHC / ILC Complementarity Meeting

  CERN, November 15, 2004

- Workshop on LHC / ILC Synergies

  SLAC, March 23, 2005

- Les Houches Workshop

  Main meeting: May 2005

Some examples of recent results

Higgs coupling determination at LHC $\oplus$ ILC:

LHC can directly determine only ratios of couplings

Need additional (mild) theory assumptions to obtain absolute values of the couplings
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

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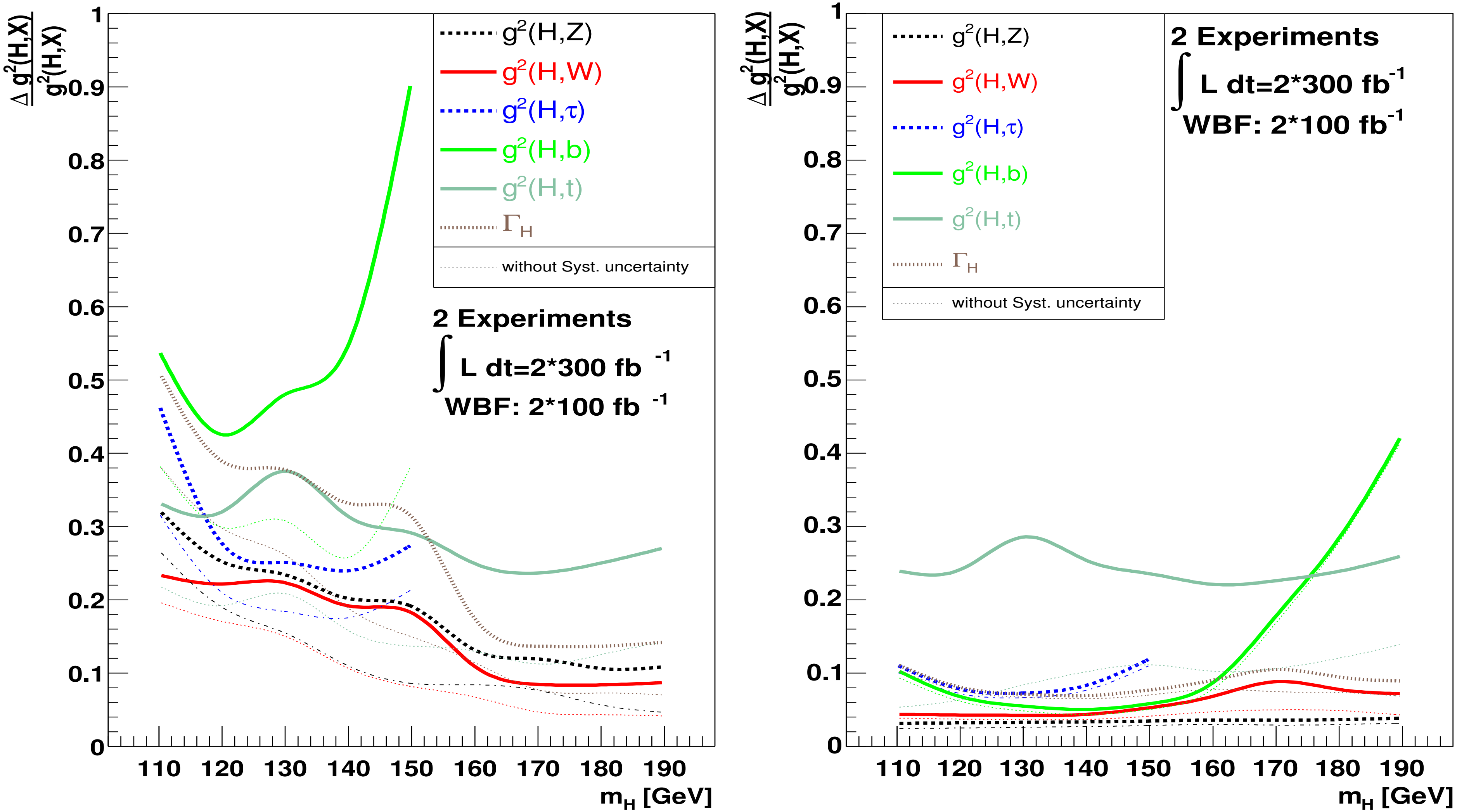
Fit of Higgs couplings with input from LHC and ILC

[*K. Desch, M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '05, preliminary*]

$M_{\rm H}$, $\sigma(e^+e^- \to HZ)$, $\mathrm{BR}(H \to b\bar{b}, \tau^+\tau^-, gg, WW^*)$,
$\sigma(e^+e^- \to \nu\bar{\nu}H) \times \mathrm{BR}(H \to b\bar{b})$

Comparison: LHC only vs. LHC $\oplus$ ILC



$\Rightarrow$ higher accuracy on $g_{\mathrm{Ht\bar{t}}}$ (and also $g_{\mathrm{H\gamma\gamma}}$) than for LHC alone (+ theory) and ILC$_{500}$ alone: $\Delta g_{\mathrm{Ht\bar{t}}}/g_{\mathrm{Ht\bar{t}}} \approx 11\text{–}14\%$

SUSY at LHC and ILC

LHC: good prospects for strongly interacting new particles

long decay chains $\Rightarrow$ complicated final states,

e.g.: $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$

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SUSY phenomenology investigated in detail for SPS 1a benchmark point: “best case scenario”

more results needed for less favourable points (in progress at ATLAS & CMS)

It quacks like SUSY, but . . .

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- does every SM particle really have a superpartner?
- do their spins differ by $1/2$?
- are their gauge quantum numbers the same?
- are their couplings identical?
- do the SUSY predictions for mass relations hold, . . . ?

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- is the lightest SUSY particle really the neutralino, or the stau or the sneutrino, or the gravitino or . . . ?
- is it the MSSM, or the NMSSM, or the mNSSM, or the N^2MSSM, or . . . ?
- what are the experimental values of the 105 (or more) SUSY parameters?
- does SUSY give the right amount of dark matter?
- what is the mechanism of SUSY breaking?

We will ask similar questions for other kinds of new physics

When and how will we find out?

- How much will we learn from the LHC alone?
- How much more will we know once we have ILC data?
- What is the added value of having the LHC and the ILC run concurrently?

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SUSY at the ILC: clean signatures, small backgrounds

$\Rightarrow$ precise determination of masses, spin, couplings, mixing angles, complex phases . . . ,

good prospects for weakly interacting SUSY particles

precision measurement of mass of lightest SUSY particle (factor 100 improvement)

Some results from the first report:

- Precise determination of the properties of the SUSY particles accessible at the ILC

  $\Rightarrow$ identify whether or not these particles appear in the decay cascades at the LHC

- Precision measurement of the LSP mass at the ILC as input for LHC analyses

  $\Rightarrow$ significantly improves precision of mass determination of heavier SUSY particles at the LHC

- From part of the SUSY spectrum accessible at the ILC

  $\Rightarrow$ can predict the properties of heavier particles

  $\Rightarrow$ tell the LHC where to look

Recent results on SUSY searches

Determination of the gluino mass: using ILC input to resolve ambiguities at the LHC

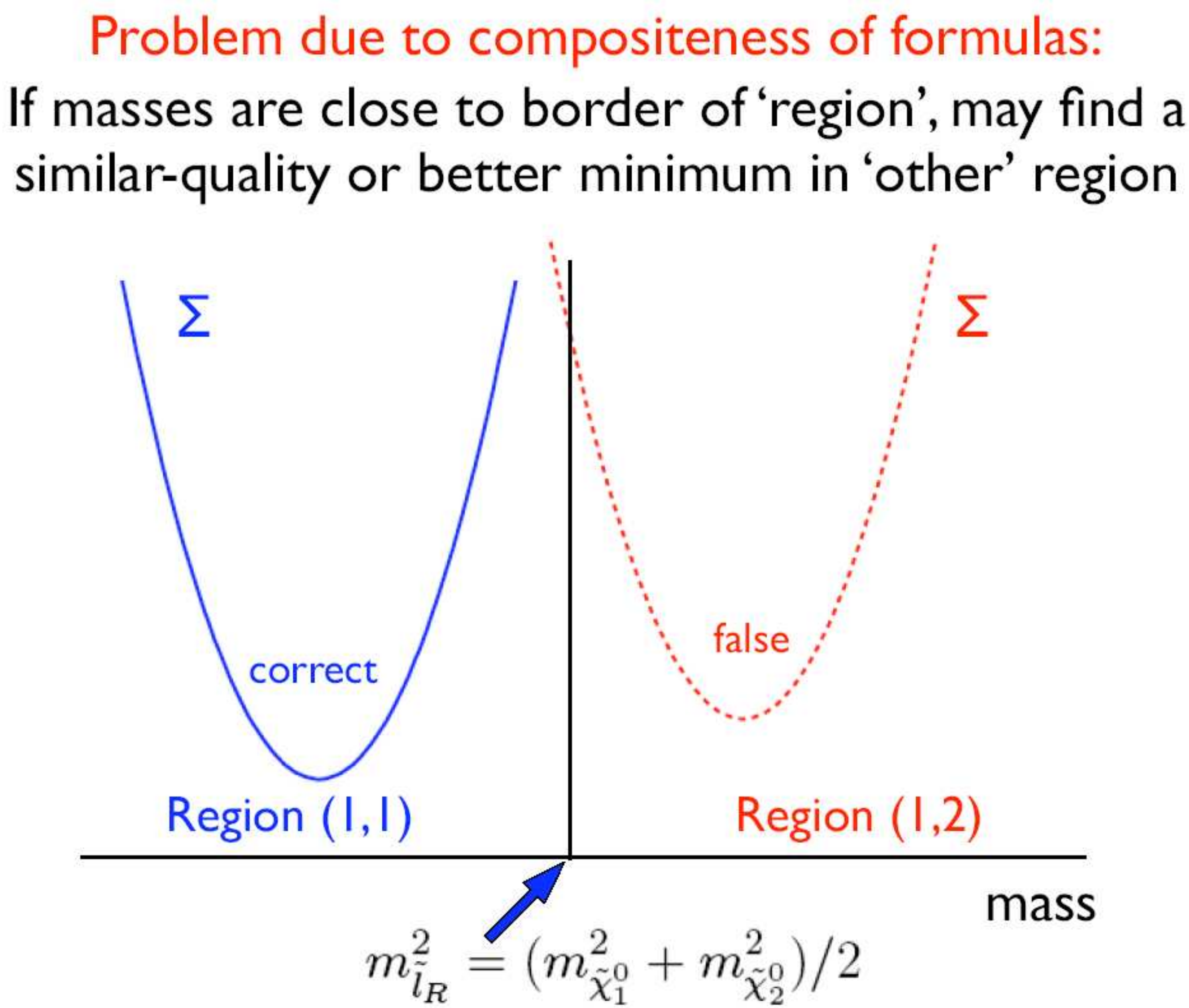
[*B. Gjelsten, D. Miller, P. Osland '05*]

Mass determination from cascade decays: invert endpoint formulas, fit masses

$\Rightarrow$ yields correct minimum

$+$ false minima (can be off by 10–20 GeV)

Determination of the gluino mass: using ILC input to resolve ambiguities at the LHC



ILC input on LSP mass

⇒ correct minimum can be identified, ambiguities resolved

Distinguishing between MSSM and NMSSM

Case study of scenario where Higgs sector and light neutralino / chargino spectra and cross sections are almost identical in the two models

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$\Rightarrow$ Detection of $\tilde{\chi}_3^0$ at LHC yields contradiction with MSSM prediction

$\Rightarrow$ Evidence for NMSSM $\longrightarrow$ *See talk by S. Hesselbach*

Determination of SUSY parameters: global fit

Use *Fittino* to compare the ability of LHC only and LHC $\oplus$ ILC for SPS1a' point

[*P. Bechtle, K. Desch, P. Wienemann '05*]

LHC input:

mass measurements and precision as in LHC / ILC report

$+$ assumption on $\tilde{t}_{1,2}$ mass measurement

$+$ ratios of Higgs branching ratios (see above)

Fittino: LHC only vs. LHC $\oplus$ ILC

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
$m_{A_{run}}$	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}

$\Rightarrow$ most of the Lagrangian parameters can hardly be constrained by LHC data alone

$\Rightarrow$ precise determination of SUSY parameters only possible with LHC $\oplus$ ILC

Conclusions

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- Next LHC / ILC workshop: probably mid November at CERN