The LHC early phase: Implications for the Linear Collider

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IPPP Durham

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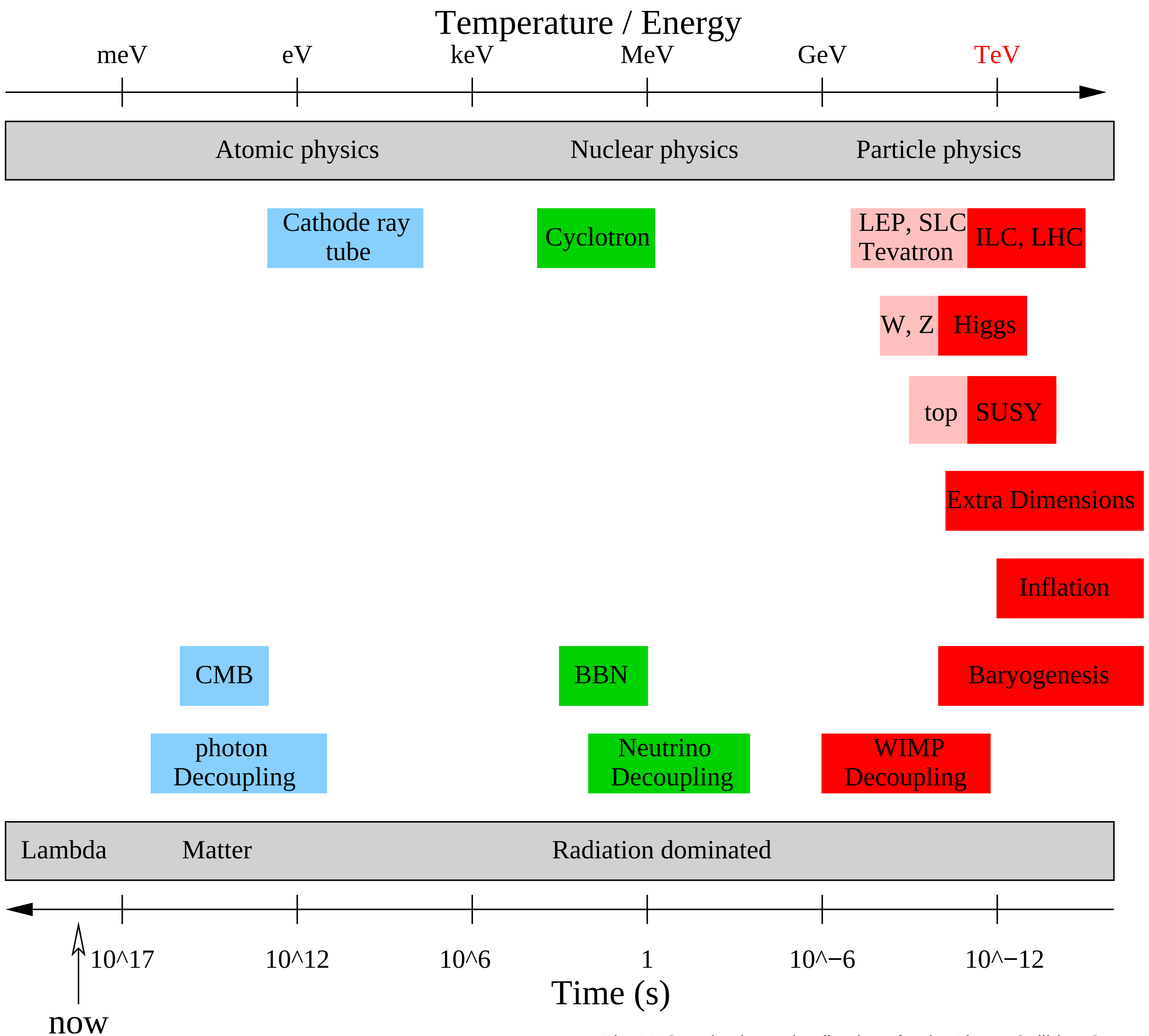
- Introduction
- Possible scenarios of early LHC results
- Input needed from the LC community
- Conclusions

Introduction: on the way to the TeV scale

$$1\ \text{TeV} \approx 1000 \times m_{\text{proton}} \Leftrightarrow 2 \times 10^{-19}\ \text{m}$$

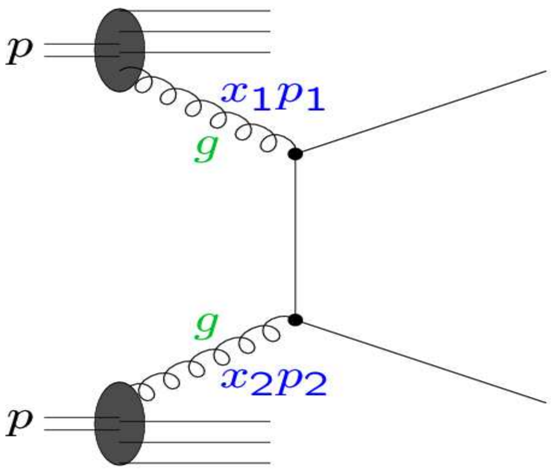


What can we learn from exploring the new territory of TeV-scale physics?

- How do elementary particles obtain the property of mass: what is the mechanism of electroweak symmetry breaking?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a “superspace”?
- Can dark matter be produced in the laboratory?
- . . .

Physics at the LHC and the LC in a nutshell

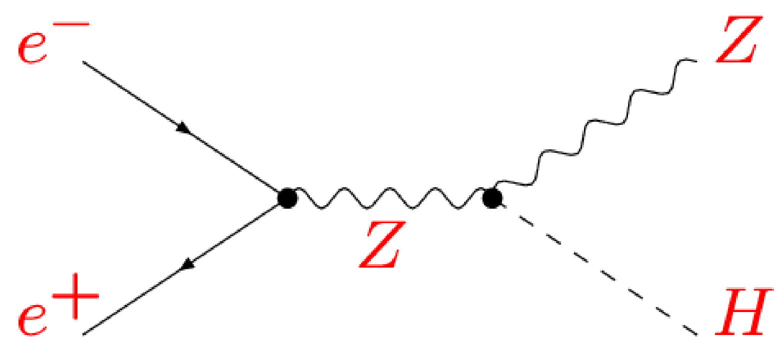
LHC: pp scattering at 14 TeV



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

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

LC: e^+e^- scattering at $\approx$0.5–1 TeV (CLIC: $\lesssim$ 3 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

LHC / LC complementarity

The results of LHC and LC will be highly complementary

LHC: good prospects for producing new heavy states
(in particular strongly interacting new particles)

LC: direct production (in particular colour-neutral new particles)
⊕ high sensitivity to effects of new physics via precision measurements

A hint from electroweak precision data?

Global χ^2 fit in the Constrained MSSM (CMSSM):
$m_{1/2}$, m_0, A_0 (GUT scale), $\tan\beta$, $\mathrm{sign}(\mu)$ (weak scale)

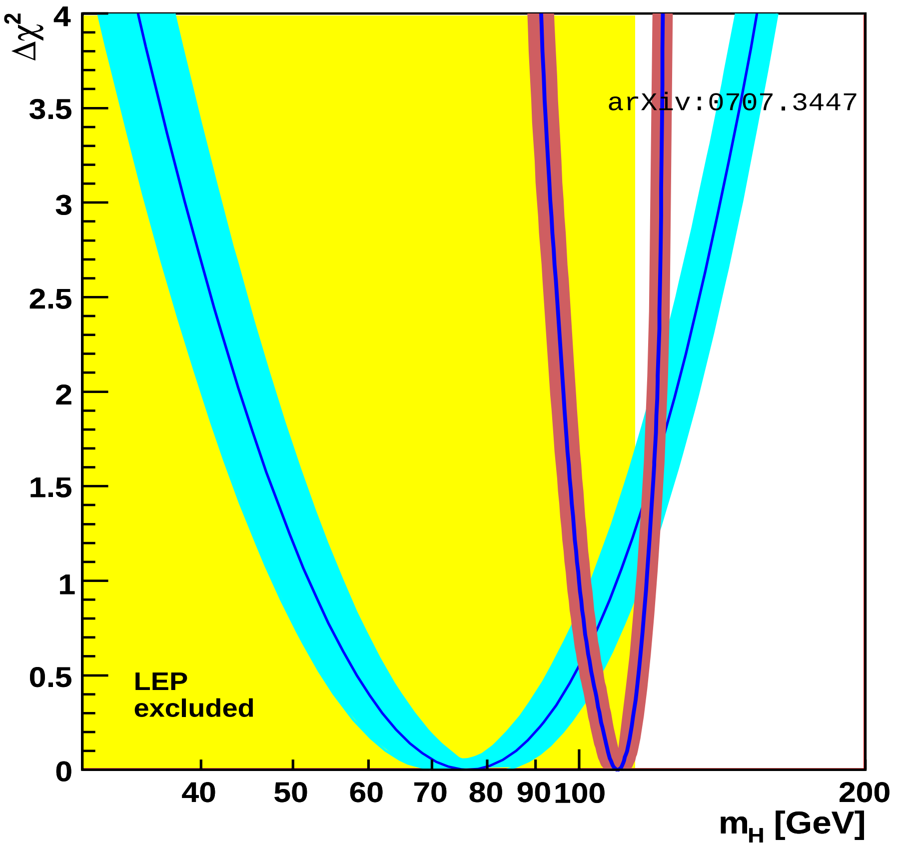
Fit includes:
[*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

- All observables used in the SM fit of the LEPEWWG
- $+$ Cold dark matter (CDM) density (WMAP, . . .), $0.094 < \Omega_{\mathrm{CDM}}\, h^2 < 0.129$
- $+ \ (g-2)_\mu$, $\mathrm{BR}(b \to s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$

Indirect limits on the light Higgs mass in the CMSSM EWPO + BPO + dark matter constraints

χ^2 fit for M_h, without imposing direct search limit [*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

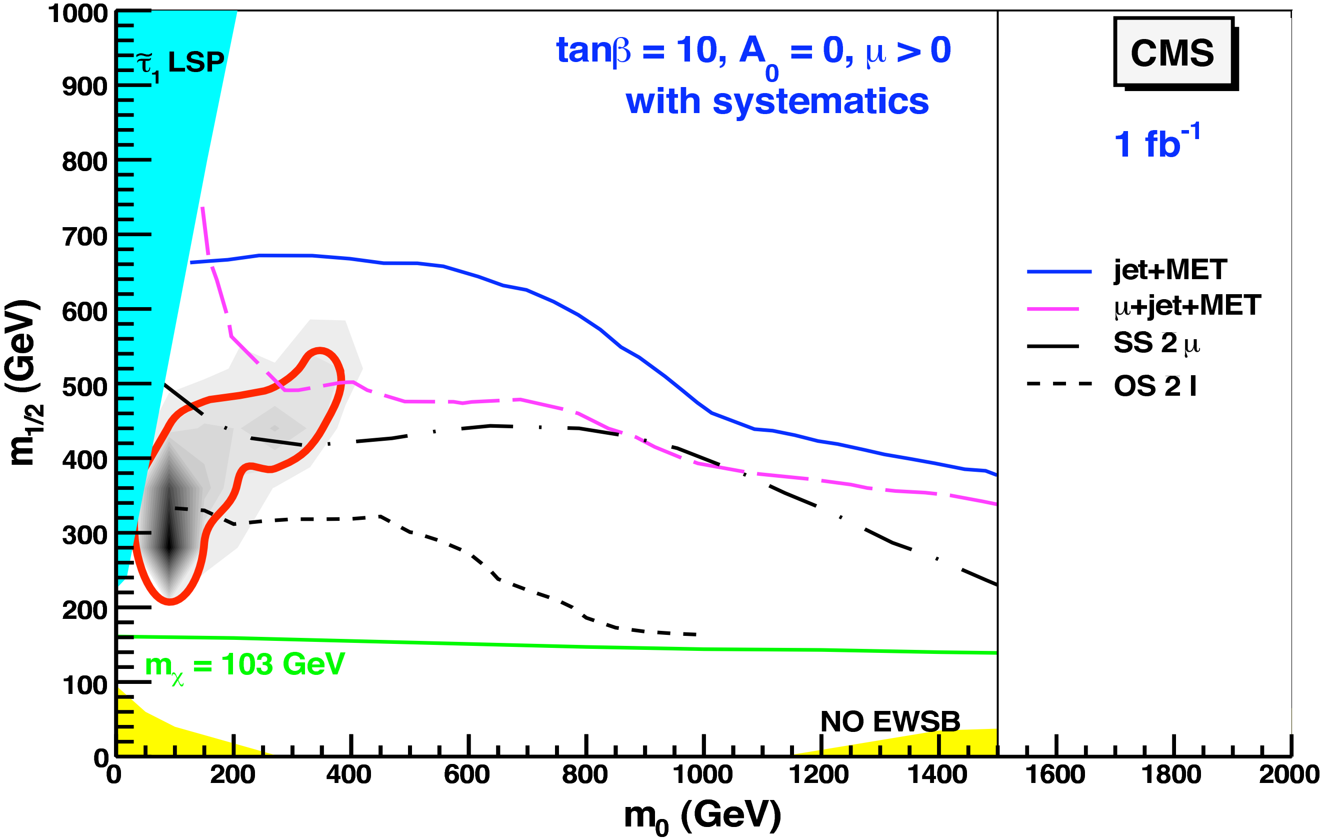
SM CMSSM



$\Rightarrow$ Accurate indirect prediction; Higgs "just around the corner"?

Comparison: preferred region in m_0–$m_{1/2}$ plane, LHC discovery reach for $1\ \mathrm{fb}^{-1}$ of understood data

[*O. Buchmueller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, P. Paradisi, F. Ronga, A. Weber, G. W. '07*]

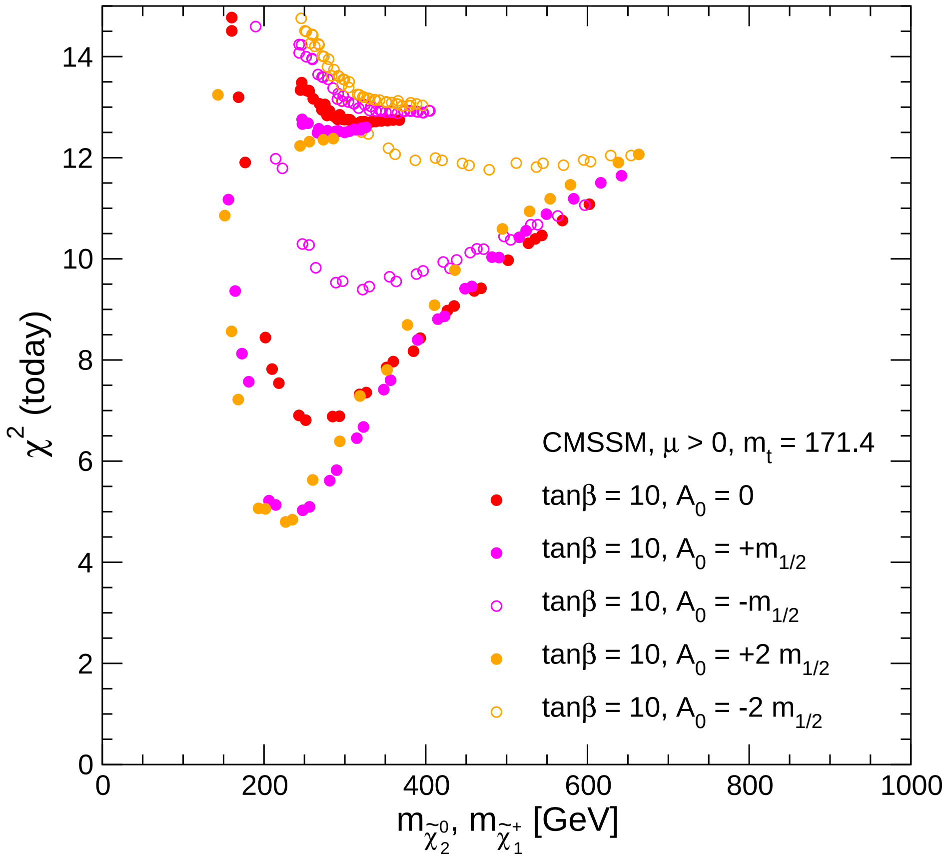


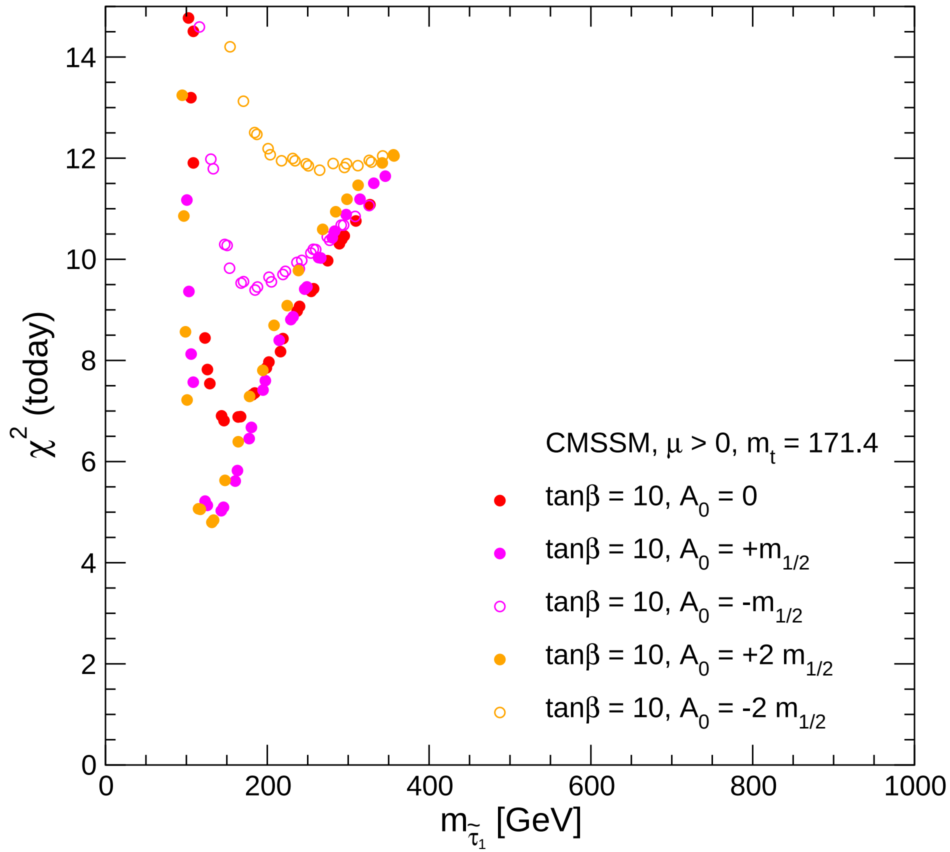
⇒ Preferred region is close to SPS1a benchmark point,
Would lead to early discovery!

Fit results for particle masses, $\tan\beta = 10$:

$$m_{\tilde{\chi}_1^+} \approx m_{\tilde{\chi}_2^0}, \quad m_{\tilde{\tau}_1}$$

[J. Ellis, S. Heinemeyer, K. Olive, A. Weber, G. W. ’07]





⇒ Good prospects for the LHC and ILC

What will be the impact of the early LHC data on the Linear Collider?

The way the case for the LC has been phrased so far (consensus documents, . . .) has been:

There is a clear and solid physics case for a 500 GeV LC, even before we know what the LHC will tell us

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The way the case for the LC has been phrased so far (consensus documents, . . .) has been:

There is a clear and solid physics case for a 500 GeV LC, even before we know what the LHC will tell us

However, LHC results will cause a phase transition putting our expectations about TeV-scale physics into a completely new context

LHC results will set the framework for discussing the physics potential for the LC, its operation parameters and its decision time-line

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- The particle physics community will have to act quickly and speak with a unanimous voice:

  We will need to come up with a convincing and scientifically solid conclusion on how to proceed

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Whatever the early LHC results will look like, they will definitely rule out many models of new physics

But it is expected that there will still be significant room for interpretation concerning the nature of new physics

Possible scenarios of early LHC results

- Detection of a state in the first 10 fb^{-1} of LHC data with properties that are compatible with those of a Higgs boson (either SM-type or non SM-type)

- No observation in the first 10 fb^{-1} of LHC data of a state with properties compatible with a Higgs boson

- Detection of new states of physics beyond the Standard Model:
  - leptonic resonances
  - multi-gauge-boson signals
  - missing energy ($+$nothing, leptons, jets)
  - all other signatures of new states of BSM physics

First Workshop: 'The LHC early phase for the ILC', April 12–14, 2007, Fermilab

Focus was on implications for the ILC; workshop charge:

- What could be the impact of early LHC results on the choice of the ultimate ILC energy range and the ILC upgrade path?

  Could there be issues that would need to be implemented into the ILC machine and detectors design from the start?

- Could there be cases that would change the consensus about the physics case for an ILC with an energy of about 500 GeV?

- What are the prospects for LHC / ILC interplay based on early LHC data?

["Early LHC data:" $\approx 10\,\mathrm{fb}^{-1}$]

First Workshop: 'The LHC early phase for the ILC', April 12–14, 2007, Fermilab

4 Working groups; convenors:

WG1: Detection of a state in the early LHC data with properties that are compatible with those of a Standard Model Higgs boson [*Howard Haber, Laura Reina, Alexei Raspereza, Markus Schumacher*]

WG 2: Observation of no state in the early LHC data with properties that are compatible with those of a Standard Model Higgs boson [*Tim Barklow, Jack Gunion, Wolfgang Kilian*]

WG 3: BSM: Leptonic resonances and Multi-Gauge-Boson signals [*Tao Han, Sabine Riemann, Tom Rizzo*]

WG 4: BSM: Missing energy (+nothing, leptons, jets) and everything else [*Filip Moortgat, Jose Santiago, James Wells, Graham Wilson*]

Proposed Workshop: ‘The LHC early phase — shaping the future of Terascale exploration’

Scope extended also to other possible accelerator-based facilities at the TeV scale beyond the first phase of the LHC: SLHC, ILC, CLIC, LHeC, DLHC, . . .

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Main questions:

- What could be the impact of early LHC results on the choice of the next facility and its (ultimate) energy reach and luminosity?
- What would be the possible implications for the machine and the detector design?
- When should one go ahead with this facility?
- What are the prospects for an interplay with results from the LHC, low-energy experiments and cosmological data?

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It will be useful to start discussing the options for the future before we have actual results from the LHC

Proposed Workshop: 'The LHC early phase — shaping the future of Terascale exploration'

Planned to take place at CERN

$\rightarrow$ received positive feedback from CERN DG-elect

Local contact at CERN: [*A. De Roeck, . . .*]

CERN TH is currently planning a "Theory Institute on Linear Colliders", which is meant to have also a significant involvement from the experimental community

Will run for three weeks, probably in February 2009

[*L. Alvarez-Gaume, J. Ellis, C. Grojean, J. Wells, . . .*]

It looks natural to schedule the "LHC early phase" workshop in close proximity to the "Theory Institute on Linear Colliders", possibly as a "kick-off" workshop $\rightarrow$ early February 09

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  But: “window of opportunity” may not be open for very long

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- Request for LC with higher energy

- . . .

LHC / LC complementarity

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But it makes it difficult to infer from LHC results what the prospects for the LC will be

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(2) The LC will be capable of studying the properties of the new states in detail

- $+$ produce additional new states
- $+$ have sensitivity to quantum effects of new physics via high-precision measurements

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How much can we infer from the LHC about (2)?

A light Higgs candidate at the LHC

Initial information from the LHC:

From decay to $\gamma\gamma$ or ZZ $\Rightarrow$ mass

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$\Rightarrow$ new state will be produced at the LC in the HZ mode

$\Rightarrow$ Bonanza for a 500 GeV ILC:

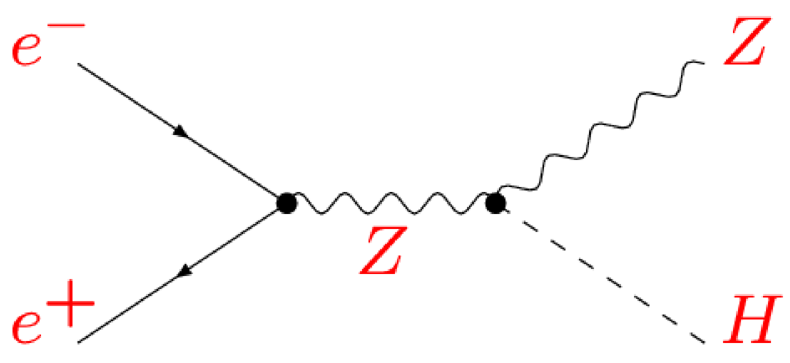
comprehensive info on the properties of the new state

$+$ top physics $+$ GigaZ $+$ ...

HZ ***production at the ILC***

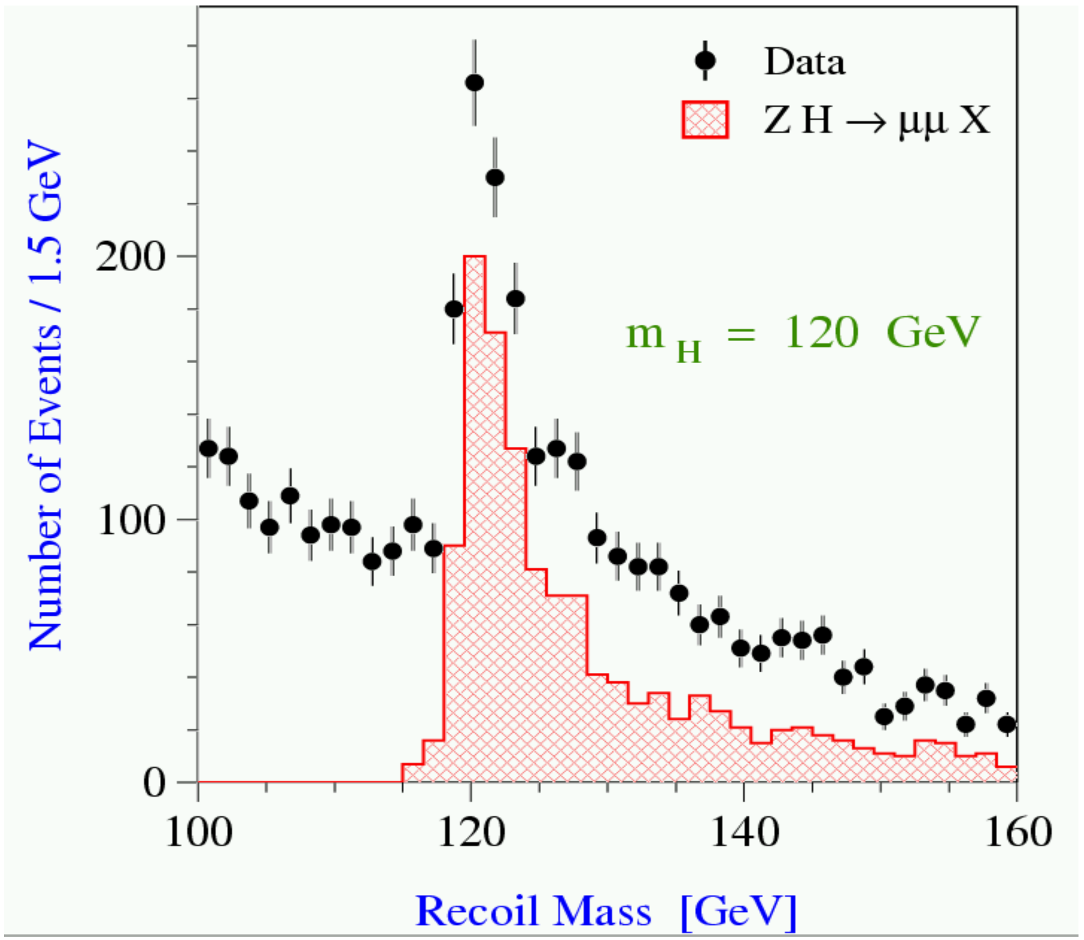
"Golden" production channel: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$

Higgs discovery possible independently of decay modes (from recoil against Z boson)



$\Delta\sigma_{\rm HZ}/\sigma_{\rm HZ} \approx 2\%$
($E_{\rm CM} = 350$ GeV,
$\int \mathcal{L}dt = 500$ fb^{-1})

[P. Garcia-Abia, W. Lohmann '00]



If a Higgs candidate has been detected: experimental questions

- Is it a Higgs boson?
- What are its mass, spin and $\mathcal{CP}$ properties?
- What are its couplings to fermions and gauge bosons? Are they really proportional to the masses of the particles?
- What are its self-couplings?
- Are its properties compatible with the SM, the MSSM, the NMSSM, . . . ?
- Are there indications that there are more than one Higgs bosons?
- Are there indications for other new states that influence Higgs physics?

Example: Higgs coupling determination

LHC: no absolute measurement of total production cross section (no recoil method like LEP, ILC: $e^+e^- \to ZH$, $Z \to e^+e^-, \mu^+\mu^-$)

Production $\times$ decay at the LHC yields combinations of Higgs couplings ($\Gamma_{\mathrm{prod,\,decay}} \sim g^2_{\mathrm{prod,\,decay}}$):

$$\sigma(H) \times \mathrm{BR}(H \to a+b) \sim \frac{\Gamma_{\mathrm{prod}}\Gamma_{\mathrm{decay}}}{\Gamma_{\mathrm{tot}}},$$

Large uncertainty on dominant decay for light Higgs: $H \to b\bar{b}$

$\Rightarrow$ LHC can directly determine only ratios of couplings, e.g. $g^2_{H\tau\tau}/g^2_{HWW}$

Higgs coupling determination at the LHC

Absolute values of the couplings at the LHC can be obtained with an additional (mild) theory assumption:
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]

$$g^2_{HVV} \leq (g^2_{HVV})^{\rm SM}, \quad V = W, Z$$

$\Rightarrow$ Upper bound on Γ_V

Observation of Higgs production
$\Rightarrow$ Lower bound on production couplings and $\Gamma_{\rm tot}$

Observation of $H \to VV$ in WBF
$\Rightarrow$ Determines $\Gamma^2_V/\Gamma_{\rm tot}$ $\Rightarrow$ Upper bound on $\Gamma_{\rm tot}$

$\Rightarrow$ Absolute determination of $\Gamma_{\rm tot}$ and Higgs couplings

Higgs coupling determination at the ILC

Absolute determination of couplings (Z, W, t, b, c, τ) with 1–5% accuracy, no theory assumptions needed

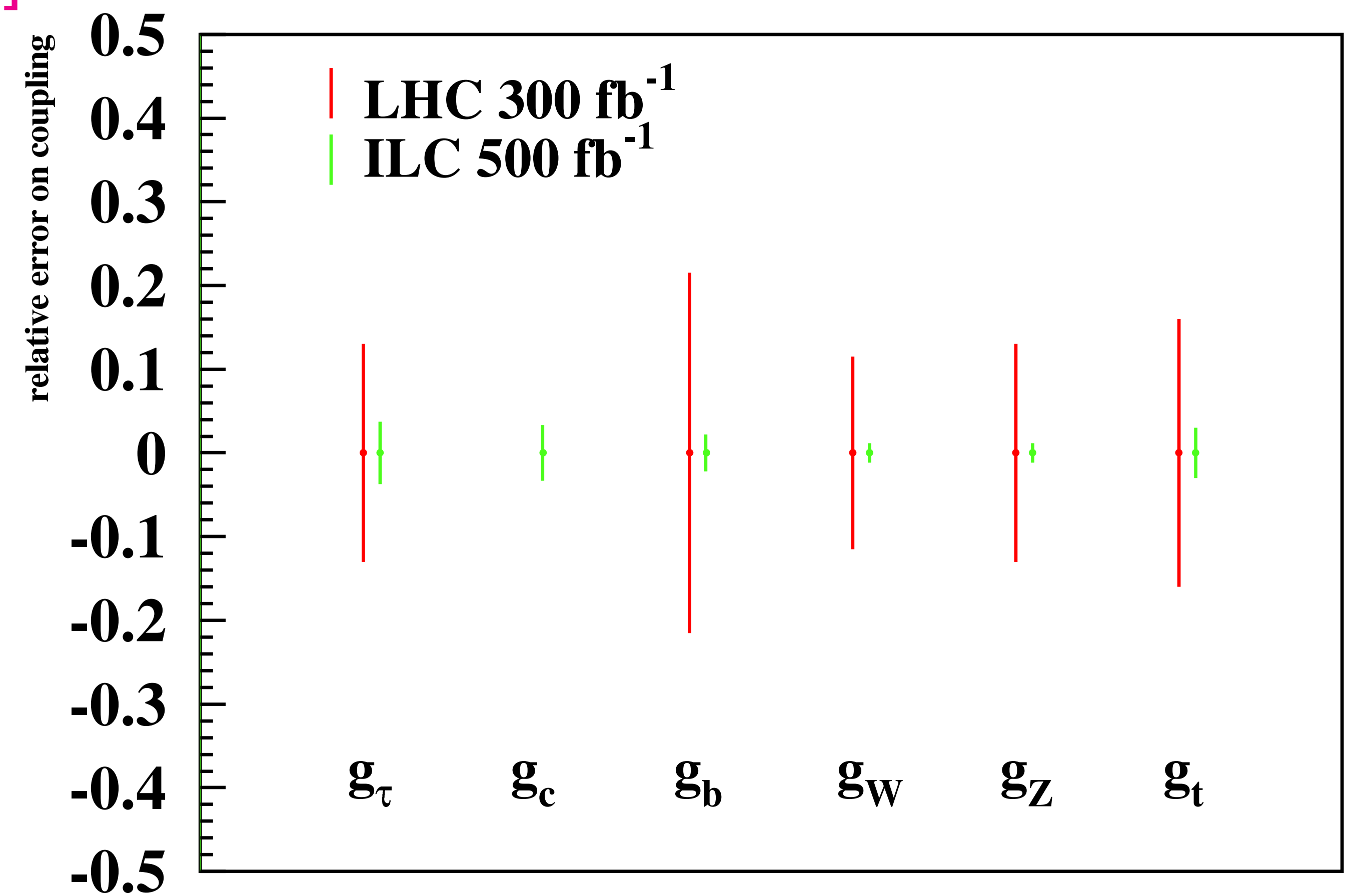
Model-independent measurement of the total width

$\Gamma_{\gamma\gamma}$: 2% measurement at photon collider option

Higgs coupling determination: LHC vs. ILC

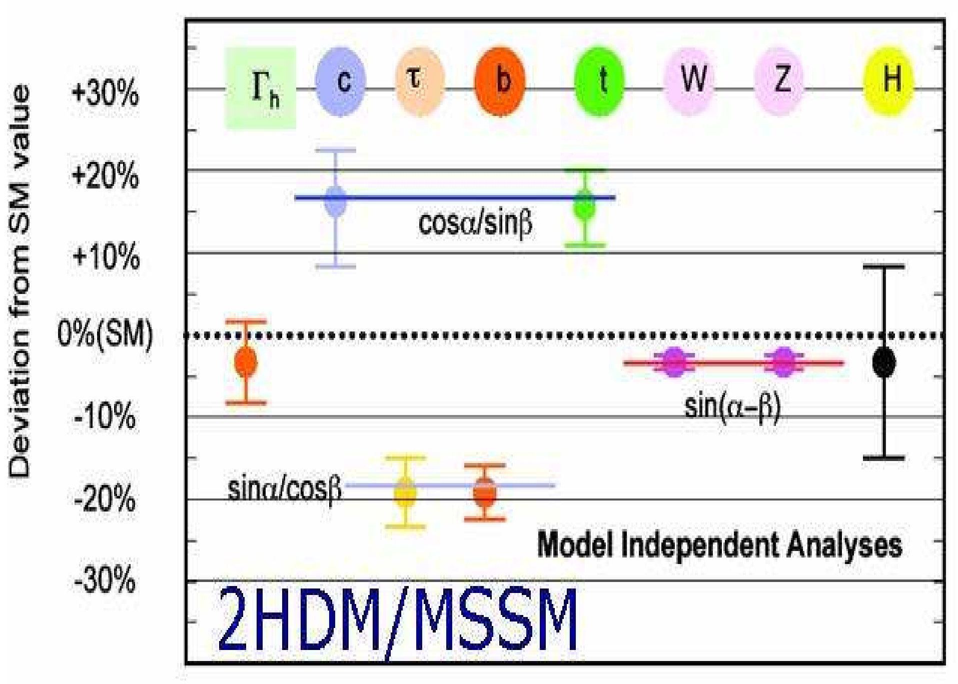
Comparison: LHC (with mild theory assumptions) vs. ILC (model-independent)

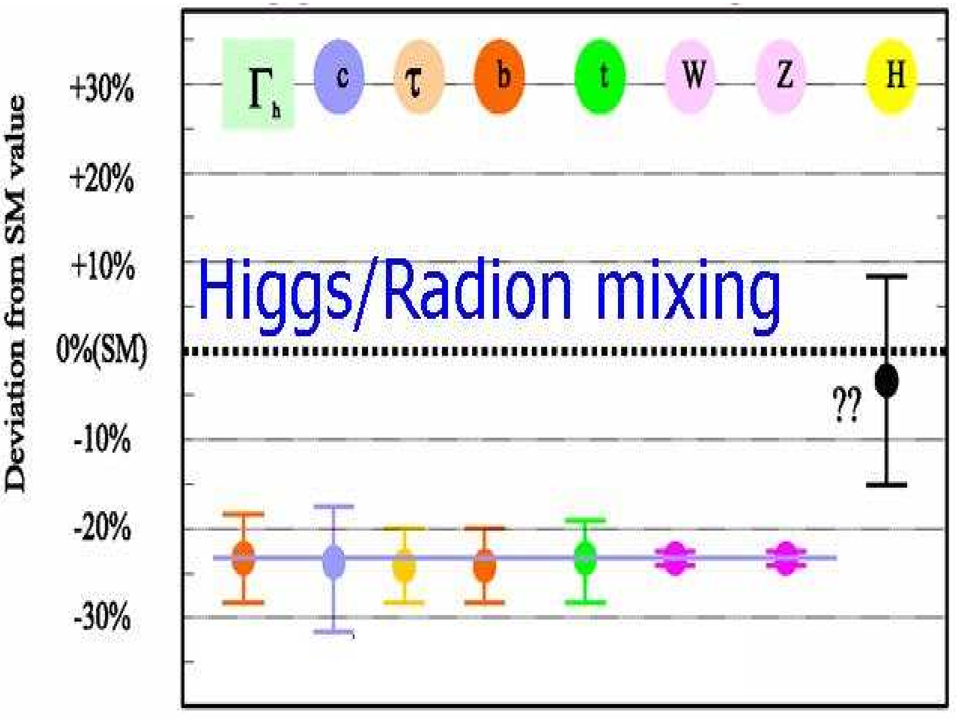
[*M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. W., D. Zeppenfeld '04*]
[*K. Desch '06*]



Impact of ILC precision for the Higgs couplings

SM vs. BSM physics:





⇒ Precision measurement of Higgs couplings allows distinction between different models

The Higgs as a composite object

Renewed interest in composite Higgs models, mostly from extra dimensions

[*N. Arkani-Hamed, A. Cohen, H. Georgi '01*]

[*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Composite Higgs: light remnant of a strong force

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Relation extra dimensions $\Leftrightarrow$ new strong forces?

Correspondence (AdS/CFT):

Warped gravity model $\Leftrightarrow$ Technicolour-like theory in 4D

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Signatures at LHC: new resonances, W', Z', t', KK excitations

Under pressure from electroweak precision tests

Effective field-theory description of a composite Higgs

Agreement with electroweak precision data can be improved if there is a strongly interacting light Higgs, e.g.

Little Higgs [*N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson '02*]

Holographic Higgs [*R. Contino, Y. Nomura, A. Pomarol '03*], [*K. Agashe, R. Contino, A. Pomarol '05*], . . .

Effective Lagrangian formalism for model-independent analysis of effects of a Strongly-Interacting Light Higgs (SILH) [*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]

$\Rightarrow$ Specific pattern of modified Higgs couplings

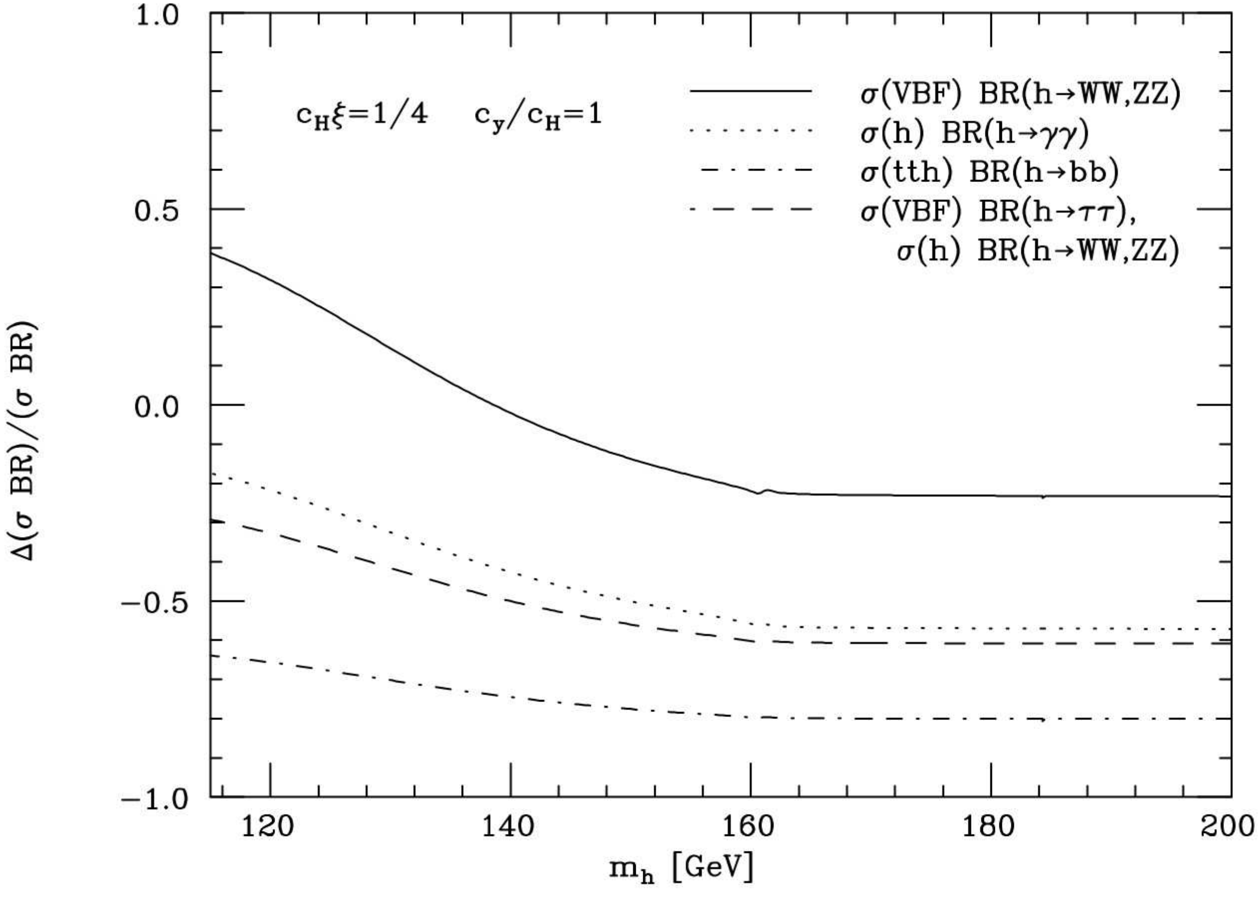
Strong WW scattering at high energies despite light Higgs

$\Rightarrow$ Need precision measurement of Higgs couplings

$+$ test of longitudinal gauge-boson scattering

Strongly-Interacting Light Higgs: deviation of $\sigma \times \mathrm{BR}$ *from the case of a SM Higgs*

[*G. Giudice, C. Grojean, A. Pomarol, R. Ratazzi '07*]



Sensitivity at LHC: 20–40%, ILC: 1%

⇒ ILC can test scales up to ~ 30 TeV

A ‘nightmare’ scenario at the LHC: just a SM-like Higgs candidate and nothing else

Can be realised in SUSY if the squarks and the gluino are very heavy

Example:

SPS1a benchmark point where squark and gluino masses are scaled up by a factor of 6

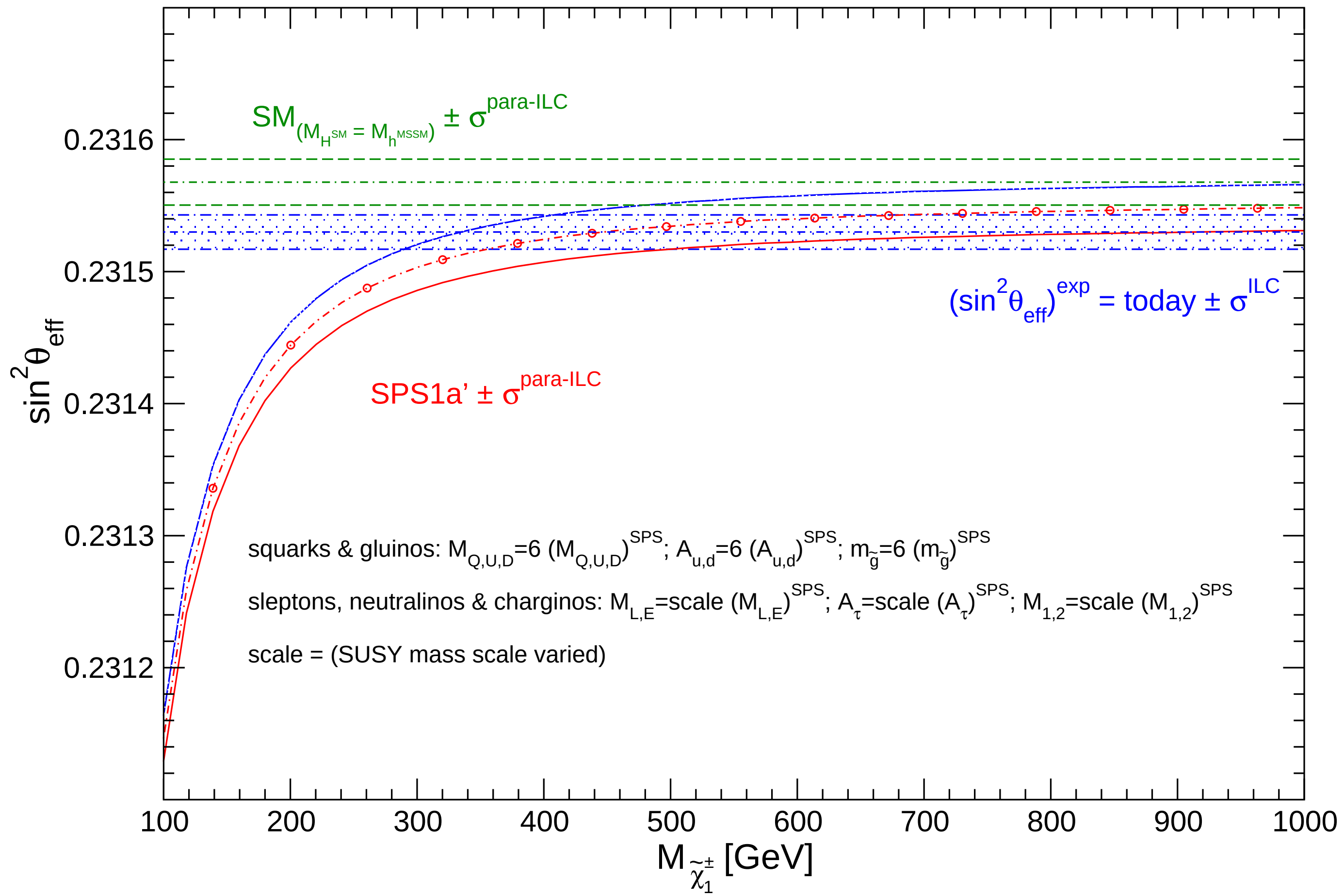
$\Rightarrow$ beyond the reach of the LHC

$\Rightarrow$ Precision Higgs programme, see above, $+$

Even in such a scenario GigaZ can reveal a new-physics effect

GigaZ: sensitivity to the scale of SUSY in a scenario where no SUSY particles are observed at the LHC

[S. Heinemeyer, W. Hollik, A.M. Weber, G. W. '07]



⇒ GigaZ measurement provides sensitivity to SUSY scale, extends the direct search reach of ILC(500)

A heavy Higgs candidate at the LHC

LC energy needs to be sufficiently high to produce it

What can the LC tell about the properties of a Higgs candidate with $M_{\mathrm{H}} \gtrsim 160\ \mathrm{GeV}$?
Further work needed: see below

Search for an additional light Higgs that may have been missed at the LHC

Search for other new physics affecting the electroweak precision observables: Ztt, Wtb, ZWW, ZZH couplings, . . .

Heavy Higgs at the LC

- Accuracy of ZZH, WWH couplings compared to LHC?
  Improve precision using hadronic Z, more luminosity, . . . ?
- Fully explore WW-fusion, total width measurement from $WW \to H \to WW$
- Yukawa couplings hard to access
  - $\mathrm{BR}(H \to bb)$ measurable up to ≈220 GeV (redo with new vertex tag)
  - $H \to tt^*$ below threshold?
  - ttH needs high $\sqrt{s}$ (studied up to $M_\mathrm{H} = 200\ \mathrm{GeV}$ so far)
- Total width from HZ threshold scan?
- Self-coupling from $\nu\nu HH \to \nu\nu WWWW$ ($\sqrt{s}$, luminosity)?

+ electroweak precision measurements: GigaZ, . . .

No Higgs candidate at the LHC

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$\Rightarrow$ LC searches can reveal Higgs with unusual properties:

- suppressed couplings to $\gamma\gamma$, gg, WW, . . .
- decays into non-standard particles:
  $H_i \to H_j H_j \to 4b, 4\tau$
  $H \to$ invisible
  $H \to$ soft jets, . . .
- mixing with exotic states, “continuum” Higgs states, . . .
- . . .

No Higgs candidate at the LHC, example: SUSY

[*LHC4ILC WS '07, WG2 report*]

Case for 500 GeV ILC when SUSY Higgs Bosons are Present but not Seen by LHC in First 10 fb^{-1}

- If phenomena consistent with SUSY has been seen and there is evidence for light SUSY particles (charginos, neutralinos) in cascade decays of gluinos and squarks, then we may have in this case the best motivation for a 500 GeV ILC: study the light gauginos and find the lightest Higgs boson with mass < 130 GeV.
- If phenomena consistent with SUSY has been seen but there is no evidence for light SUSY particles then the 500 GeV ILC might be a harder sell. How far can we push the need to search for the lightest Higgs boson with mass < 130 GeV?
- If SUSY Higgs bosons are present but haven't been seen, and gluinos and squarks are too massive to have been seen at LHC in first 10 fb^{-1}, then we are in a tough situation because the LHC hasn't seen anything in the first 10 fb^{-1}. It is to the advantage of the ILC to start preparations now for the detection of Higgs decays to scalars at the LHC, and to improve LHC searches for objects such as light stop squarks (which may be present even if gluinos and light flavor squarks are very massive).

No Higgs candidate at the LHC, example: little Higgs

[*LHC4ILC WS '07, WG2 report*]

Juergen Reuter – Little Higgs Models

Outlook/Discussion

- Higgs is always present in Little Higgs models
- Higgs is generically heavy in LHM; will be captured by VV mode
- Higgs might be confused with other members from its Goldstone multiplet, especially with light pseudo-axions
- Three possible scenarios interesting for ILC:
  - very heavy and broad Higgs, (very) light pseudoaxion; both missed at early stage of LHC
  - heavy Higgs detected in $H \to ZZ \to 4\ell$; light partner missing
  - inverted hierarchy: Higgs light, pseudoaxion heavy; both are missed at early stage of LHC
- Possible degeneracies between Higgs/pseudoaxion
- Cross references from heavy quark and Z', W' discoveries
- LHM mimicking Higgsless models?
- Importance of invisible decays?

No Higgs candidate at the LHC, example: little Higgs

[*LHC4ILC WS '07, WG2 report*]

Case for 500 GeV ILC when Higgs Boson of Little Higgs Model is not Seen in First 10 fb^{-1}

- Situation will be similar to case that there truly is no Higgs boson. Resonances above 500 GeV will have been seen at LHC. (Note: it probably is not possible to distinguish between no-Higgs and little Higgs models after 10 fb^{-1} if no Higgs boson has been seen.)
- Indirect probes of Ztt, Wtb, ZWW couplings at the ILC with Ecm=500 GeV will be valuable. The ILC at Ecm=500 GeV would be very effective in discovering any light Higgs bosons in the Little Higgs Model.
- Discovery of resonances in 500 – 1000 GeV range at LHC would create demand for a rapid upgrade in ILC energy from Ecm=500 GeV, although this demand would be tempered by any discovery of a light Higgs boson in higher luminosity LHC running.
- We need to understand better the circumstances under which a Higgs boson will not be seen by the LHC in 10 fb^{-1} in the little Higgs scenario.

No Higgs candidate at the LHC: Electroweak symmetry breaking without Higgs

If no light Higgs boson exists

$\Rightarrow$ dynamics of electroweak symmetry breaking can be probed in quasi-elastic scattering processes of W and Z at high energies

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ILC: detailed measurements of cross sections and angular distributions

⇒ combination of LHC results with ILC data on cross-section rise essential for disentangling new states

No Higgs candidate at the LHC: Higgs-less models from extra dimensions

Kaluza–Klein towers of gauge bosons yield improved unitarity behaviour of longitudinal W and Z scattering

$\Rightarrow$ New gauge bosons cannot be too heavy (unitarity) and not too light (electroweak precision data)

$\Rightarrow$ Good prospects at LHC and ILC

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For how long?

A missing energy signal at the LHC

[*LHC4ILC WS '07, WG4 report*]

G. Wilson

- Suppose:
  - A light Higgs is found. Consistent with SM, SUSY.
  - Only a jets+MET signal is found at LHC.
- What is the minimum √shat involved in the signal ?
  - Can we estimate the e^+e^- production threshold reliably ?
- Can the signal be produced in e^+e^- (does it couple to the γ, W, Z, h) ?
  - Presumably no info will be available.
  - If it's a gluino, e^+e^- is probably irrelevant for direct tests ...
- Is there ANY robust logical inference on the masses of lighter particles that can be made, e.g. M_{LSP} ???

We may find that LHC can't tell very much of value in diagnosing this new physics.
And that ILC at any energy may not be a useful diagnostic tool for certain hadron collider signatures.

LHC4ILC workshop, April 14, 2007

Filip Moortgat, ETH Zurich

Input needed from the LC community

- LC physics programme will have to be formulated within the context of the results obtained by the LHC
- Can be more focussed: many models with which we used to play for many years will be ruled out . . .
- But there will still be a significant scope of possible scenarios:

  SUSY or UED or . . . ?

  What kind of SUSY / ED scenario? . . .

Input needed from the LC community

- Will the ILC "minimum machine" coming on-line $\gtrsim 2020$ be sufficient for fulfilling the physics requirements?
- Viability of the ILC upgrade path to 1 TeV?
- Viability of e^+ polarisation, GigaZ, $\gamma\gamma$, . . . ?

$\Rightarrow$ LHC results will put us into a certain scenario

We will need convincing answers for this particular scenario very soon

Conclusions

- The LHC will open the new territory of TeV-scale physics, where we expect to observe manifestations of the mechanism(s) responsible for EWSB and for stabilising the hierarchy between M_{weak} and M_{Planck}

  $\Rightarrow$ Looking forward to exciting results from the LHC

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Please join the discussion session on LHC–LC activities, Tuesday, 18:30, room E, Klaus Desch & G.W.