Physics Complementarity of LHC an LC

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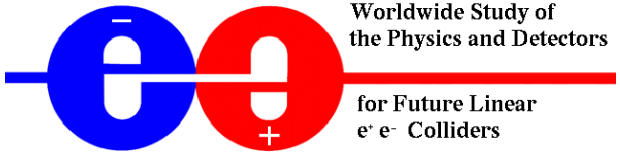
IPPP Durham

Denver 05/2004



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

1. Introduction

- Physics case is well established both for LHC and LC
- LHC: $\gtrsim 2007$, expected to run for $\mathcal{O}(20)$ years

  LC: $\gtrsim 2015$?
- LHC and LC physics is complementary in many respects, similarly to previous generations of hadron and lepton colliders

  Recent examples:

  LEP + SLC + Tevatron led to many success stories: Electroweak SM at quantum level, top quark, QCD, prediction of Higgs mass in the SM

  Belle discovery of X(3872) $\Rightarrow$ dedicated search at CDF & D0 $\Rightarrow$ independent confirmation

Some of the issues addressed at LHC and LC

- Electroweak symmetry breaking: SM-like Higgs sector, Higgs with non-standard properties, no Higgs, ...
- Hierarchy problem: Supersymmetry, extra spatial dimensions, Little Higgs scenarios, ...
- Dark Matter: lightest supersymmetric particle, Kaluza-Klein excitations of the photon, ...
- Precision physics of the electroweak and strong interaction: top, gauge couplings, α_s, electroweak precision tests, ...

LHC and LC have different capabilities, probe different aspects

$\Rightarrow$ Experimental information from both LHC and LC is crucial

LHC / LC interplay

LHC / LC interplay

$\Rightarrow$ expect mutual benefits for physics program at both machines

Qualitatively obvious,

more quantitative analyses require detailed case studies,

close collaboration of experts from LHC and LC as well as from theorists and experimentalists

LHC / LC Study Group

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

- Investigation of LHC / LC interplay:

  How can analyses at the LHC profit from results obtained at the LC and vice versa?

  Which synergy effects arise from concurrent running of LHC and LC?

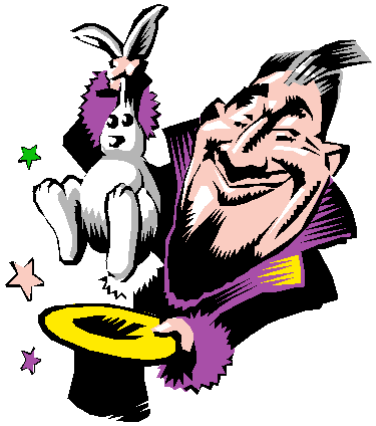
- World-wide working group, started in spring 2002

  Collaborative effort of Hadron Collider and Linear Collider communities

Why now?

Preparations for LHC physics currently move from first step:

Discovery Physics



to spectroscopy: determination of properties of physics beyond (and within) the SM

$\Rightarrow$ Design of experimental strategies

assessment of prospective accuracies

How far are we?

- We had seven working group meetings so far (most at CERN)
- First "LHC / LC Study Group report" close to completion:
  116 authors, ≈ 40 individual contributions, ≈ 500 pages
- Editors: T. Barklow, E. Boos, A. De Roeck, K. Desch, H. Haber, F. Gianotti, R. Godbole, J. Gunion, S. Heinemeyer, J. Hewett, K. Kawagoe, K. Mönig, M. Nojiri, G. Polesello, F. Richard, S. Riemann, W.J. Stirling, G. W.
- Draft available on `www.ippp.dur.ac.uk/~georg/lhclc`

LHC / LC Study Group Report

hep-ph/yymmnnn

LHC / LC Study Group Report

Editors:

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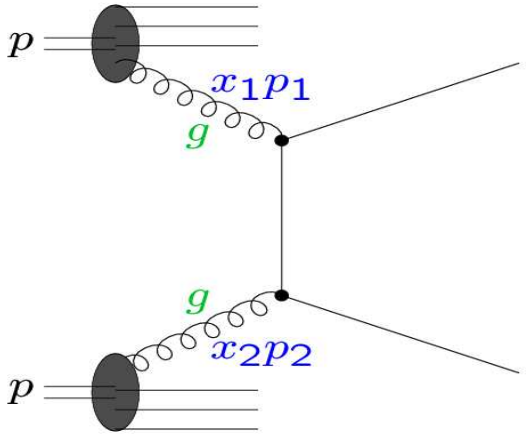
Physics at LHC and LC

LHC: pp scatt., $\sqrt{s} = 14$ TeV, contains "hard" collision proc.



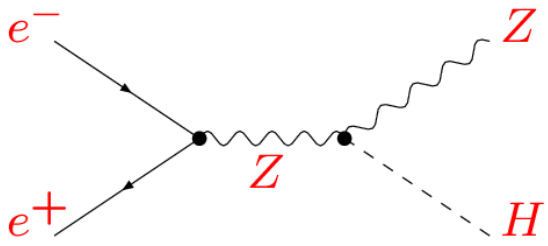
Available $(\text{energy})^2$ for partonic sub-process: $\hat{s} = x_1 x_2 s$

$\sqrt{\hat{s}}$ up to several TeV

most of available energy lost in beam pipe as proton remnant

LC: $\sqrt{s} = 0.5$–1 TeV, clean experimental environment

$\Rightarrow$ high-precision physics



well-defined initial state, beam polarization, ...

Lepton collider kinematics:

momentum conservation can be used to analyze decay products

LHC physics

LHC has large reach for direct discovery of heavy particles

Hadron collider kinematics:

can in general only use conservation of transverse momentum p_T

Composite nature of colliding protons

$\Rightarrow$ "underlying event" at the LHC

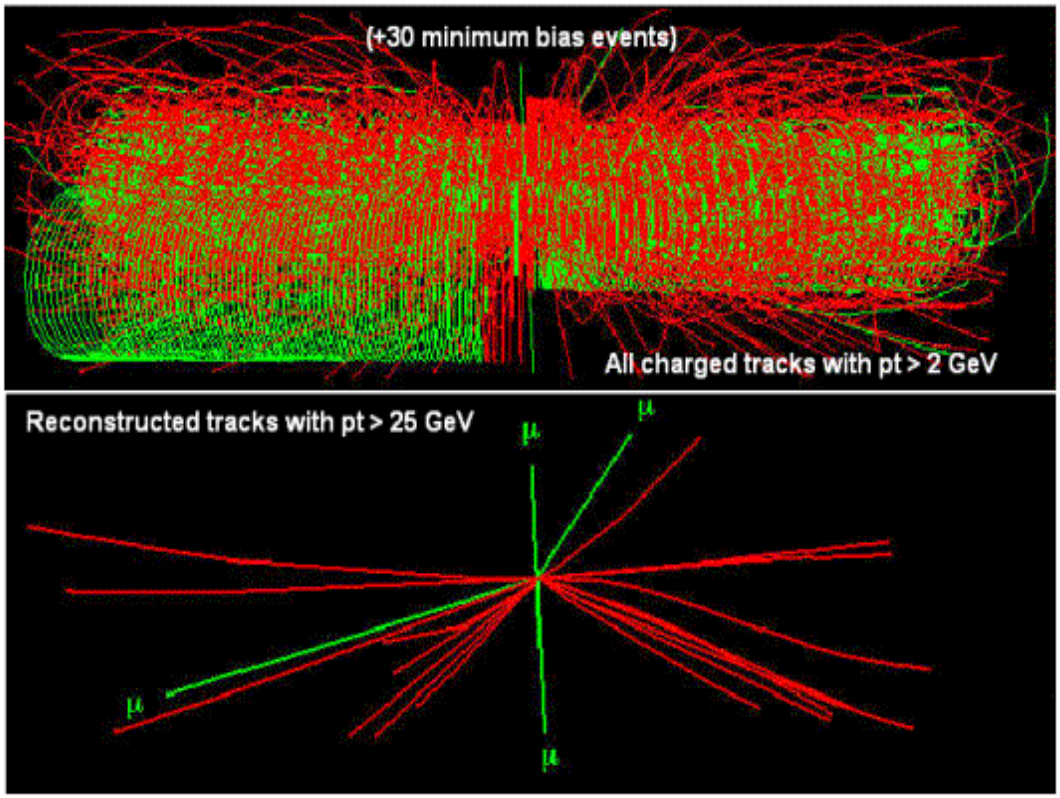
Strongly interacting particles in initial state (mostly gluons)

$\Rightarrow$ huge QCD backgrounds

$\Rightarrow$ signal–to–background ratios in general much worse than at LC

Simulation of an LHC event: $gg \to H \to ZZ \to \mu^+\mu^-\mu^+\mu^-$

Computing in LHC experiments



1 Higgs decay in 4 muons in 10^{13} events

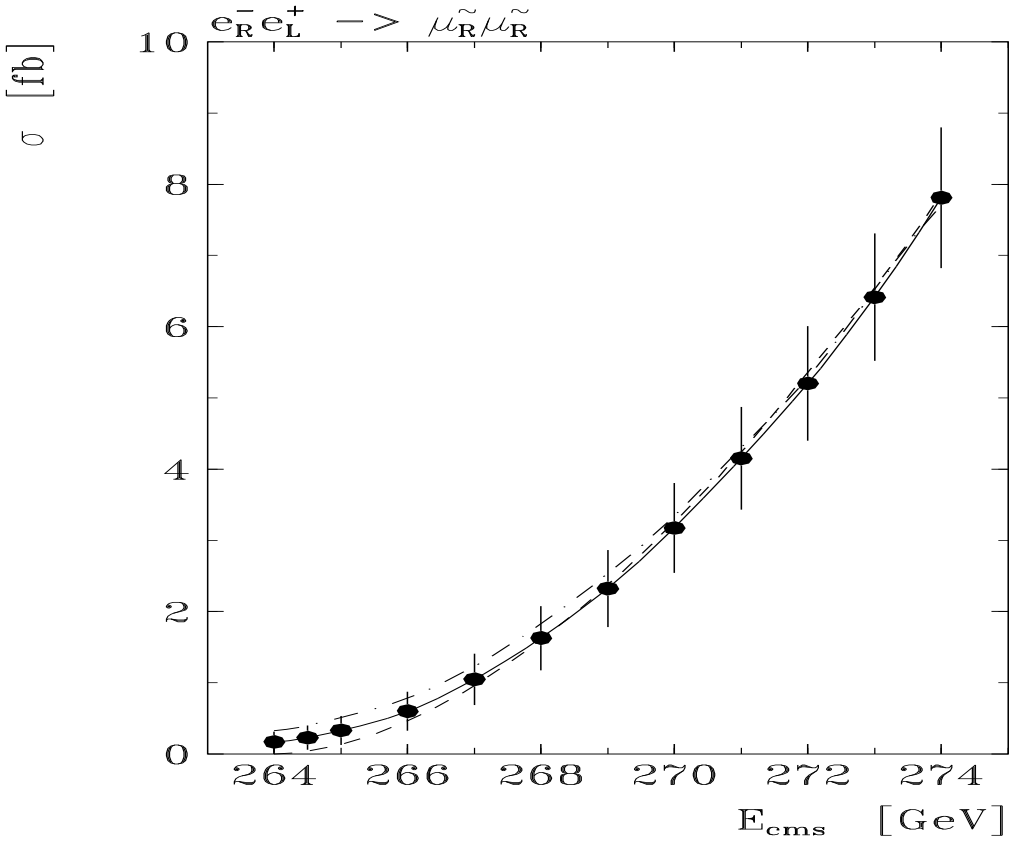
1000 charged tracks/event, most of them p<0.5 GeV

LC physics

Tunable enery $\Rightarrow$ threshold scans possible

Example: Determination of mass and spin of SUSY particle $\tilde{\mu}_R$ from production at threshold:

[*TESLA TDR '01*]



$$\Rightarrow \quad \frac{\Delta m_{\tilde{\mu}_R}}{m_{\tilde{\mu}_R}} < 1 \times 10^{-3}$$

$\Rightarrow$ test of $J = 0$ hypothesis

LC physics

LC: Clean signatures, small backgrounds

Threshold scans possible

$\Rightarrow$ precise determination of mass and spin of new particles, mixing angles, complex phases, ...

Direct discoveries up to kinematic limit

$+$ large indirect reach via precision measurements

$\gamma\gamma$, $e\gamma$, e^-e^- options, precision measurements at Z resonance and WW threshold (GigaZ)

2. Electroweak symmetry breaking

Measurement of the top Yukawa coupling:

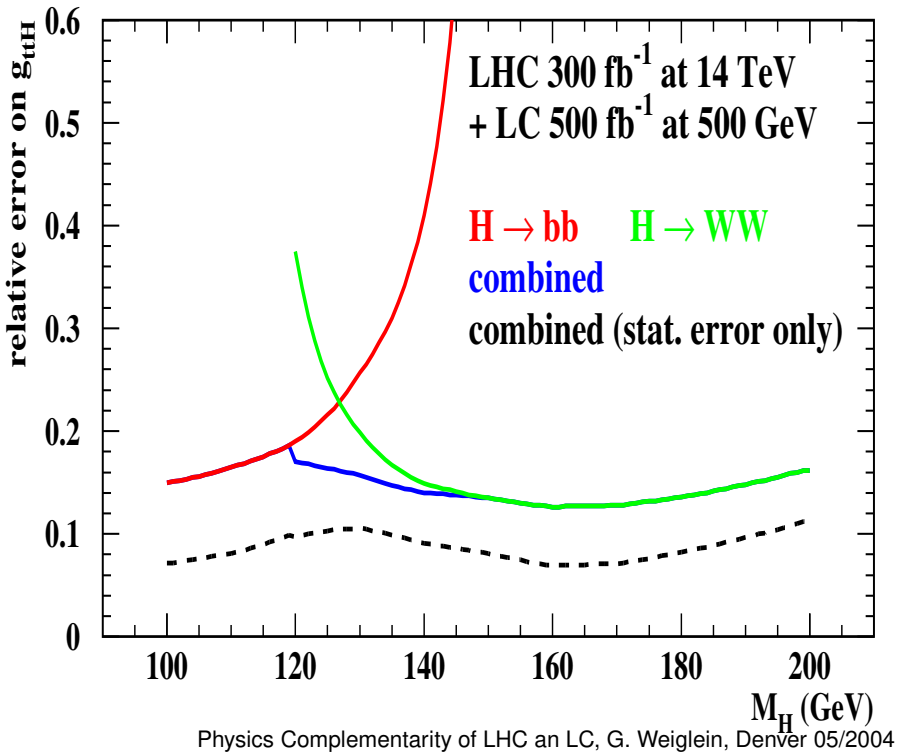
Only crude measurement of tth coupling at 500 GeV LC for light Higgs

Precision measurement requires LC with 800–1000 GeV

LHC measures ($\sigma \times \mathrm{BR}$)

$\Rightarrow$ Yukawa coupling can be extracted if precise measurement of Higgs BR's from LC are used

Combination of measurements at LHC and LC running at 500 GeV [*S. Dawson, A. Juste, L. Reina, D. Wackeroth; K. Desch, M. Schumacher*]



SUSY Higgs physics

In SUSY: $m_{\rm h}$ is not a free parameter, but a prediction

Large corrections, $\mathcal{O}(100\%)$, from top Yukawa contributions

Impact of experimental error of $m_{\rm t}$: $\Delta m_{\rm t} \approx 1$ GeV $\Rightarrow \Delta m_{\rm h} \approx 1$ GeV

Comparison: prediction for $m_{\rm h}$ vs. experimental precision at LHC

$\Rightarrow$ In order to match

experimental precision at LHC, $\delta m_{\rm h}^{\rm exp} \approx 0.2$ GeV

with accuracy of theory prediction need

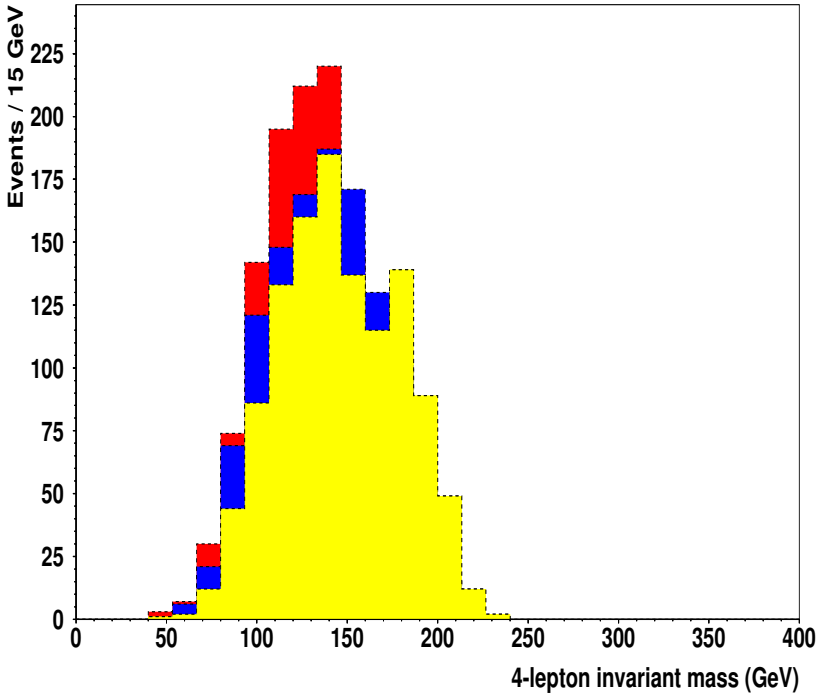
LC precision on $m_{\rm t}$, $\delta m_{\rm t}^{\rm exp} \lesssim 0.2$ GeV

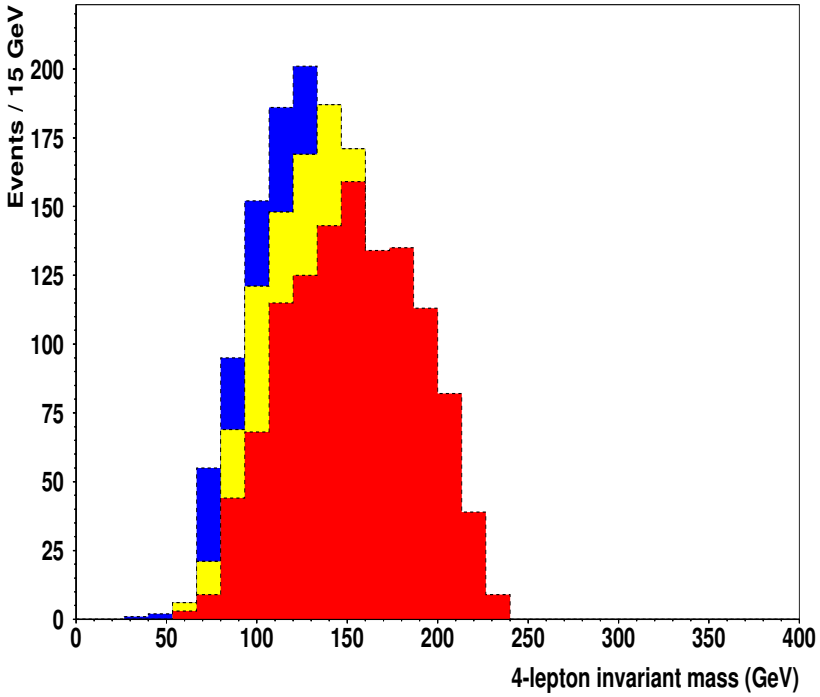
$\Rightarrow$ LC precision on $m_{\rm t}$ crucial in order to exploit LHC (and LC) precision on Higgs sector measurements

Determination of M_A from heavy Higgs decays into SUSY particles at the LHC

[*F. Moortgat '03*]

$H, A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$: Four lepton invariant mass distribution for $M_A = 350 \pm 20$ GeV (left) and $M_1 = 60 \pm 10$ GeV (right)





$\Rightarrow$ Precise knowledge of LSP mass from LC crucial for determination of M_A

Indirect constraints on M_A from Higgs BR measurements at the LC using LHC / LC input

Precision measurement of

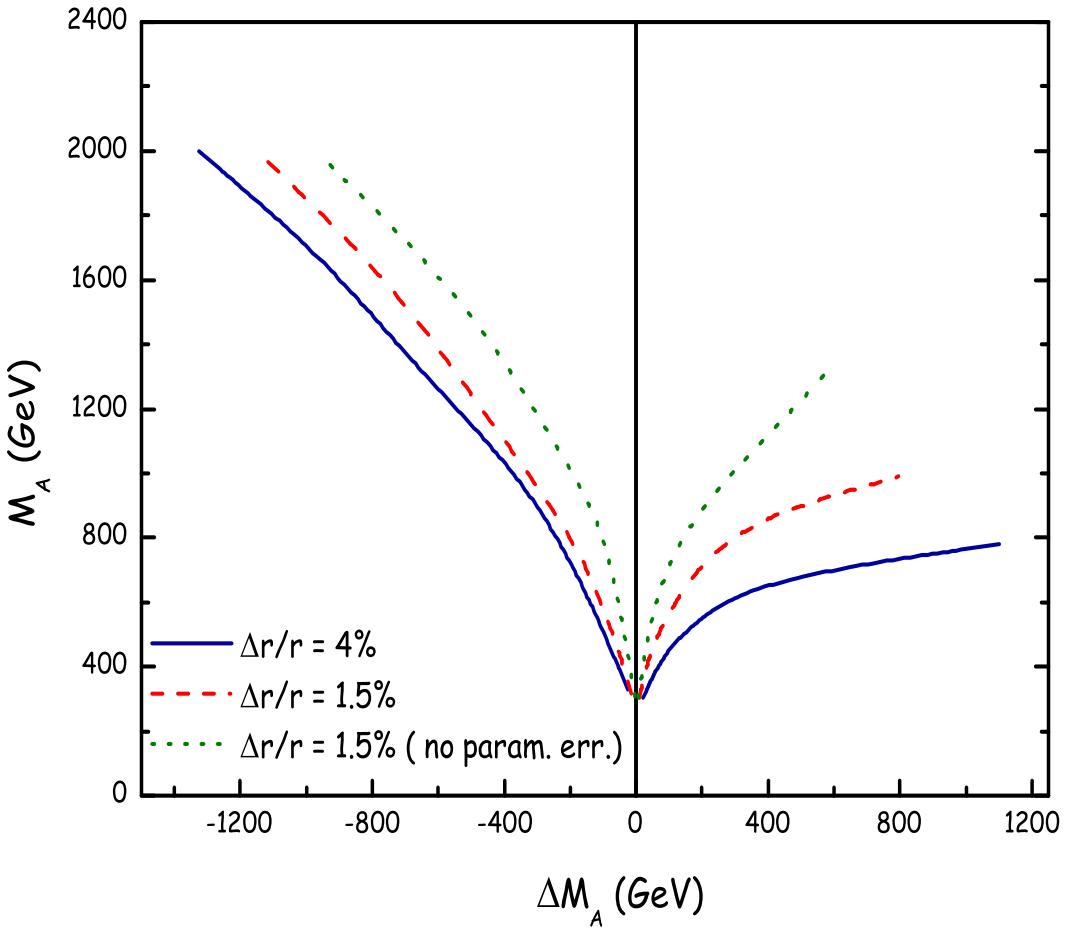
$$r \equiv \frac{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{MSSM}}}{\left[\mathrm{BR}(h \to b\bar{b})/\mathrm{BR}(h \to WW^*)\right]_{\mathrm{SM}}}$$

at the LC

and

LHC + LC information on SUSY spectrum (SPS1a scenario)

[*K. Desch, E. Gross, S. Heinemeyer, G. W., L. Zivkovic '04*]



⇒ Sensitive indirect bounds on m_A only with high-precision measurements, LHC + LC information

Higgs–radion mixing

[*M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici, J. Gunion '03*]

Models with 3-branes in extra dimensions predict radion ϕ, can mix with the Higgs

$\Rightarrow$ Higgs properties modified, can be difficult to detect at the LHC

LHC may observe radion instead

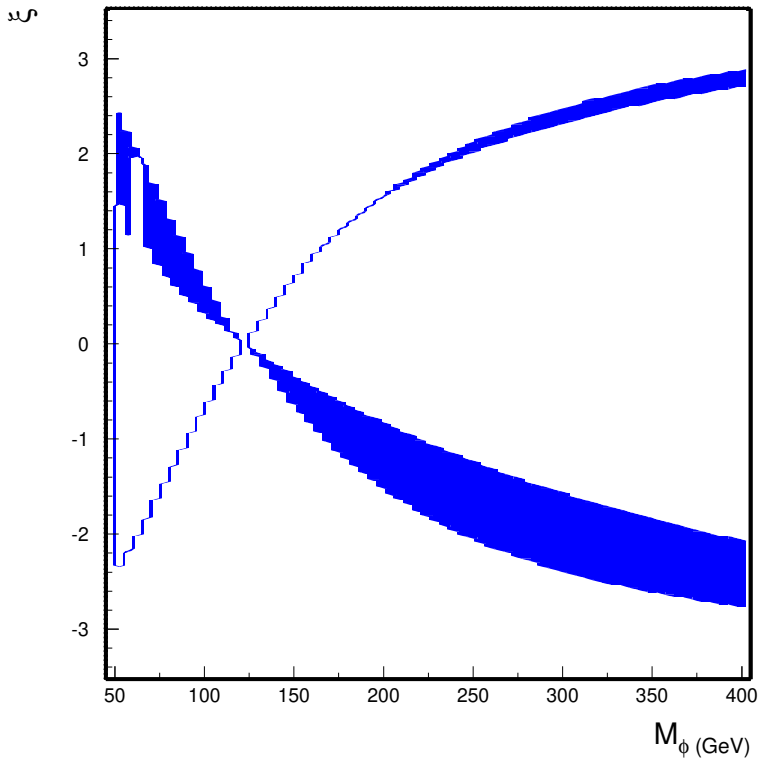
LC guarantees Higgs observation over full parameter space

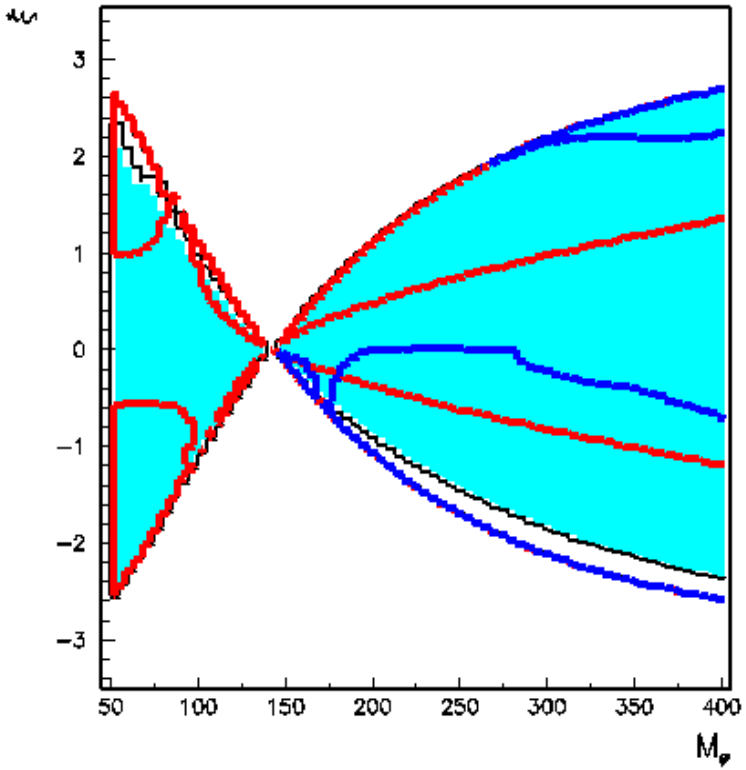
$\Rightarrow$ precision measurements at LC crucial to disentangle the nature of the observed state

LHC: large sensitivity to production of Kaluza-Klein excitations

Higgs–radion mixing

Parameter regions where Higgs significance is below 5σ at the LHC with 30 fb^{-1} (left), regions where the precise measurements of the $hb\bar{b}$ and hWW couplings at the LC provide $> 2.5\sigma$ evidence for the radion mixing effect (right):





Strong electroweak symmetry breaking

[*T. Barklow, S. Boogert, G. Cerminara, W. Kilian, A. Krokhotine, K. Mönig, A.F. Osorio '04*]

If no light Higgs boson exists $\Rightarrow$ dynamics of EWSB can be probed in quasi-elastic scattering processes of W and Z at high energies

LHC / LC sensitive to different scattering channels, yield complementary information

LHC: direct sensitivity to resonances

LC: detailed measurements of cross sections and angular distributions

$\Rightarrow$ combination of LHC results with LC data on cross-section rise essential for disentangling new states

3. Supersymmetry

SUSY searches at the LHC:

Dominated by production of colored particles:
gluinos, squarks

Very large mass reach in the searches for
jets + missing energy
$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV

SUSY searches at the LC:

Good prospects for production of uncolored particles

$\Rightarrow$ discovery of SUSY particles at LHC / LC expected if low-energy SUSY is realized

In order to establish SUSY experimentally:

Need to demonstrate that:

- every particle has superpartner
- their spins differ by $1/2$
- their gauge quantum numbers are the same
- their couplings are identical
- mass relations hold
- ...

Necessary experimental information

$\Rightarrow$ Precise measurements of masses, branching ratios, cross sections, angular distributions, . . . mandatory for

- establishing SUSY experimentally
- determining how SUSY is realized (particle content, . . .)
  MSSM, NMSSM, . . .
  MSSM: 105 low-energy parameters
- disentangling underlying mechanism of SUSY breaking
- verifying SUSY nature of Dark Matter?

Production of SUSY particles at LHC — LHC / LC interplay

LHC: mainly colored states, in general heavier than uncolored ones

long decay chains $\Rightarrow$ complicated final states,

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

$\Rightarrow$ Production of uncolored particles mainly via cascade decays

direct production at LHC: small rates, large backgrounds

Many states are produced at once

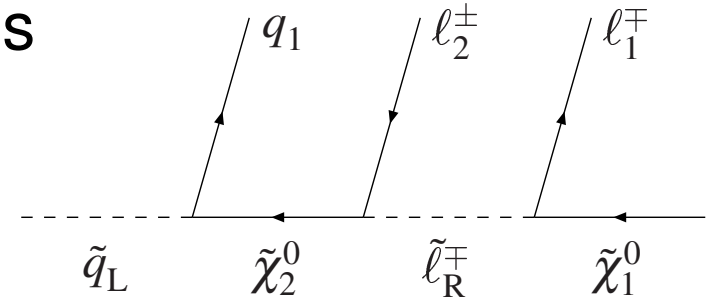
$\Rightarrow$ Main background for SUSY at LHC is SUSY itself!

LC: precise determination of properties of lighter part of SUSY spectrum $\Rightarrow$ important for disentangling cascade decays at LHC

Example: Determination of SUSY parameters at LHC / LC

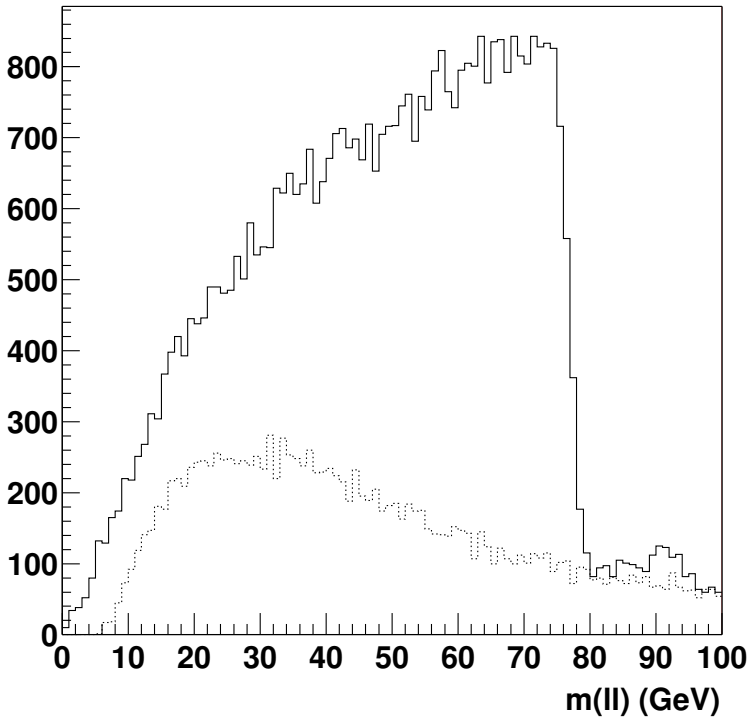
[*M. Chiorboli, B.K. Gjelsten, J. Hisano, K. Kawagoe, E. Lytken, U. Martyn, D. Miller, M. Nojiri, P. Osland, G. Polesello, A. Tricomi '03*]

Cascade decays: complicated decay chains for squarks and gluinos



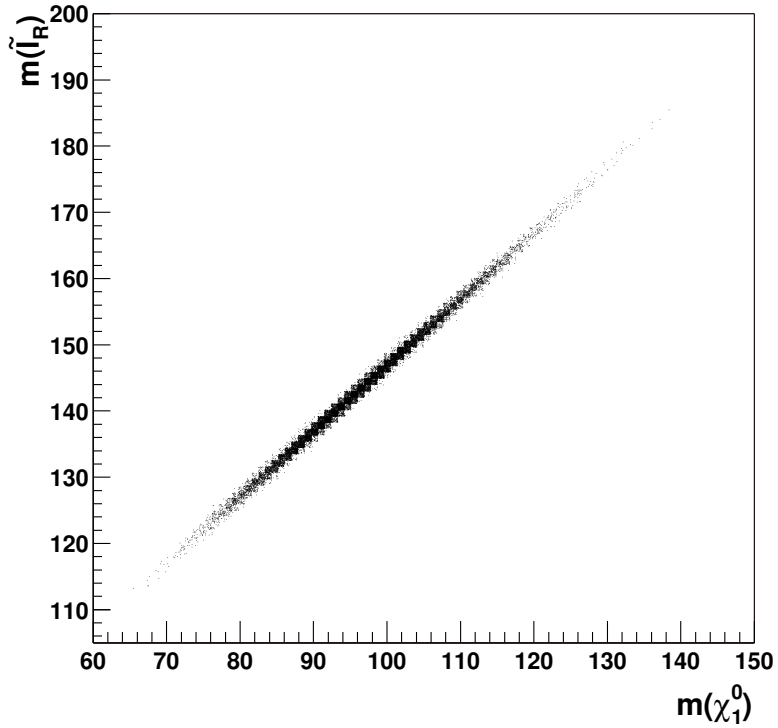
Main tool: dilepton "edge" from

$\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$



LHC analysis with LC input: mass of lightest SUSY particle (LSP)

Reconstruction of the states in decay chain requires precise knowledge of LSP mass



$\Rightarrow$ Precision measurement of m_{LSP} at LC leads to significant improvement in determination of slepton, squark and gluino masses at the LHC

Detailed analysis for SPS1a benchmark scenario: potential of LHC (300 fb^{-1}) alone and LHC + LC

	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (input)
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	11.8	10.9
$\Delta m_{\tilde{g}}$	8.0	6.4
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{l}_L}$	5.0	0.2 (input)
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23

LHC+LC accuracy limited by LHC jet energy scale resolution

SPS 1a benchmark scenario:

favorable scenario for both LHC and LC

$\Rightarrow$ LC input improves accuracy significantly

Search for the heaviest neutralino at LHC following the prediction from LC

[*K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03*]

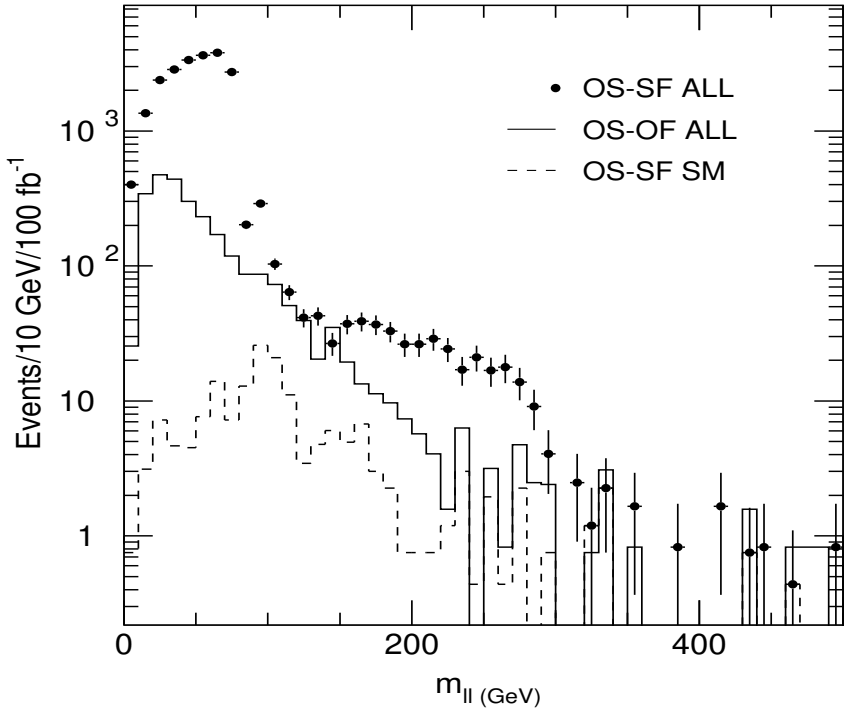
Assumption: lightest neutralino and chargino states $(\chi_1^0, \chi_2^0, \chi_1^\pm)$ accessible at LC

$\Rightarrow$ Determination of all parameters in neutralino/chargino sector possible

$\Rightarrow$ Prediction of masses and decay properties of all neutralinos and charginos, e.g. $m_{\tilde{\chi}_4^0} = 378.3 \pm 8.8$ GeV

$\Rightarrow$ With this information the heaviest neutralino can be identified at the LHC using a dilepton "edge"

Search for the heaviest neutralino at LHC following the prediction from LC



$\Rightarrow$ Determination of $m(\tilde{\chi}_4^0)$ at LHC with high precision

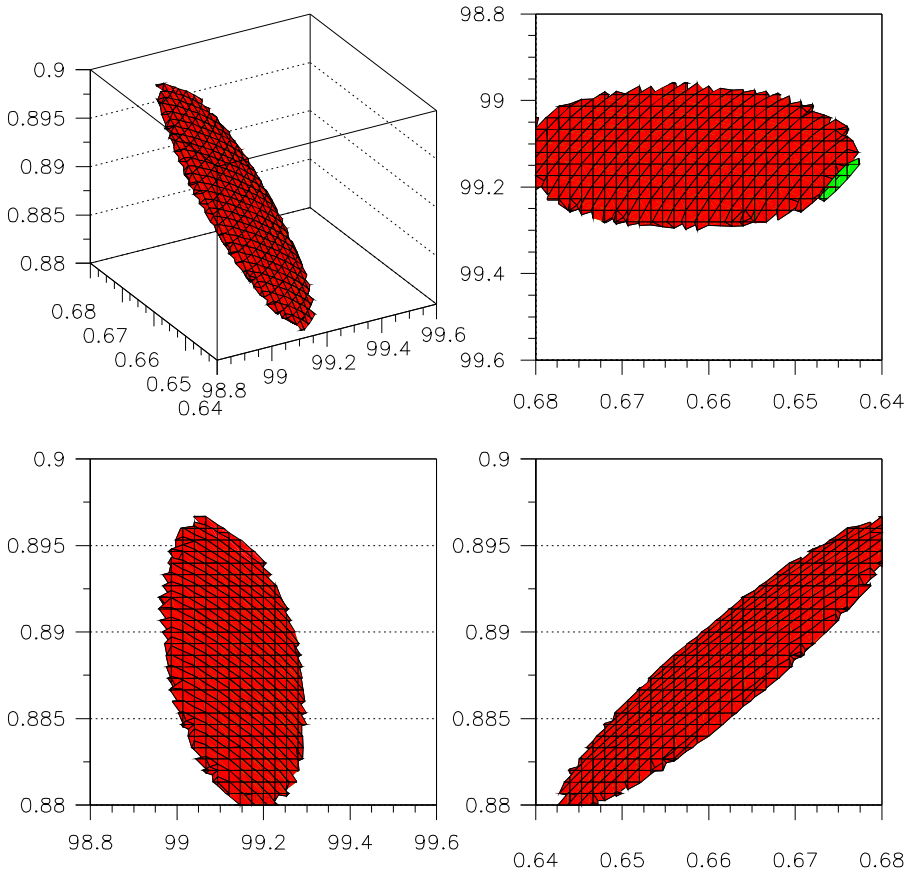
$\Rightarrow$ Feeding $m(\tilde{\chi}_4^0)$ back into LC analysis provides additional information

$\Rightarrow$ Improved accuracy of parameter determination at LC

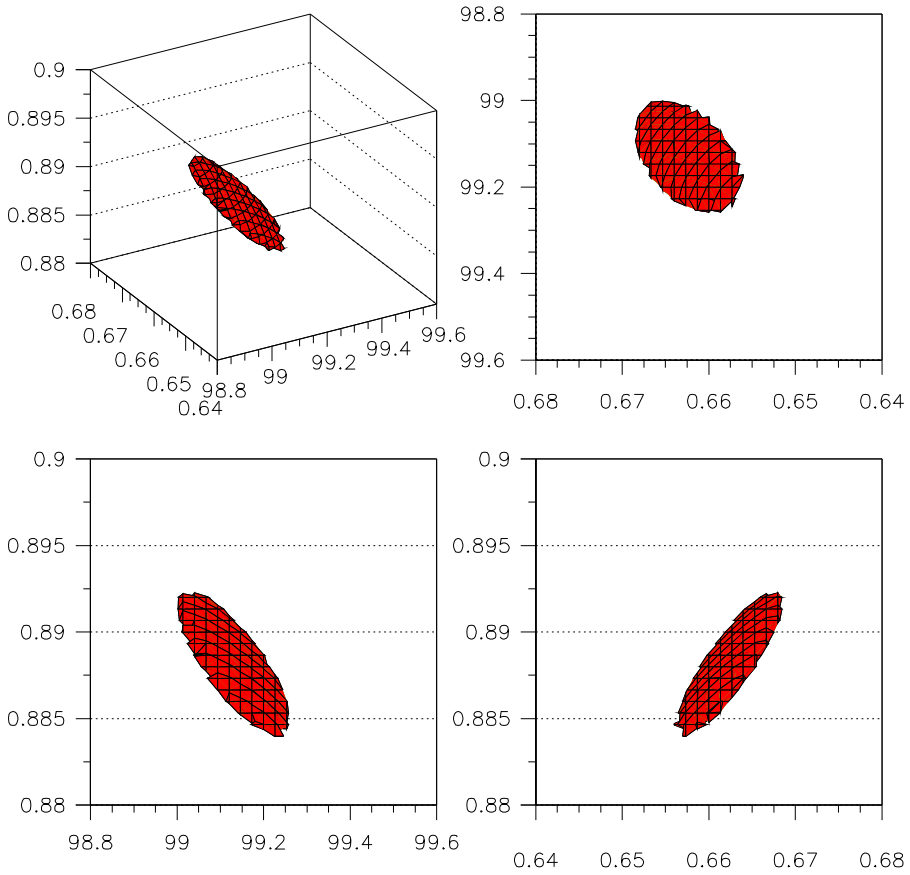
LC analysis with LHC input

Determination of neutralino parameter M_1 and chargino mixing angles $\cos\phi_{\rm L}$, $\cos\phi_{\rm R}$:

LC information alone



LHC + LC information



LHC / LC synergy

Search for heaviest neutralino at LHC is typical example for possible LHC / LC synergy effects:

If statistically marginal signal appears at the LHC right where it was predicted from LC information

$\Rightarrow$ LC input can be crucial for optimised searches and possible upgrades at the LHC

- LC prediction leads to increase of LHC statistical sensitivity!
- Improved cuts, modified triggers
- Call for higher luminosity
- . . .

Global Fit in the MSSM

Prospects for SUSY parameter determination at LHC and LC investigated in detail for SPS 1a benchmark scenario

(favorable scenario for LHC and LC)

[*LHC / LC Study Group '04*]

Most observables depend on variety of SUSY parameters

$\Rightarrow$ Need global fit to large set of observables

[*R. Lafaye, T. Plehn and D. Zerwas '04*]

[*P. Bechtle, K. Desch and P. Wienemann '04*]

$\Rightarrow$ Reliable determination of SUSY parameters only possible from combined LHC + LC data, global fit doesn't converge if LHC or LC data are taken alone

4. New gauge theories and extra dimensions

[*D. Bourilkov, M. Dittmar, A. Djouadi, S. Godfrey, A. Nicollerat, F. Richard, S. Riemann, T. Rizzo*]

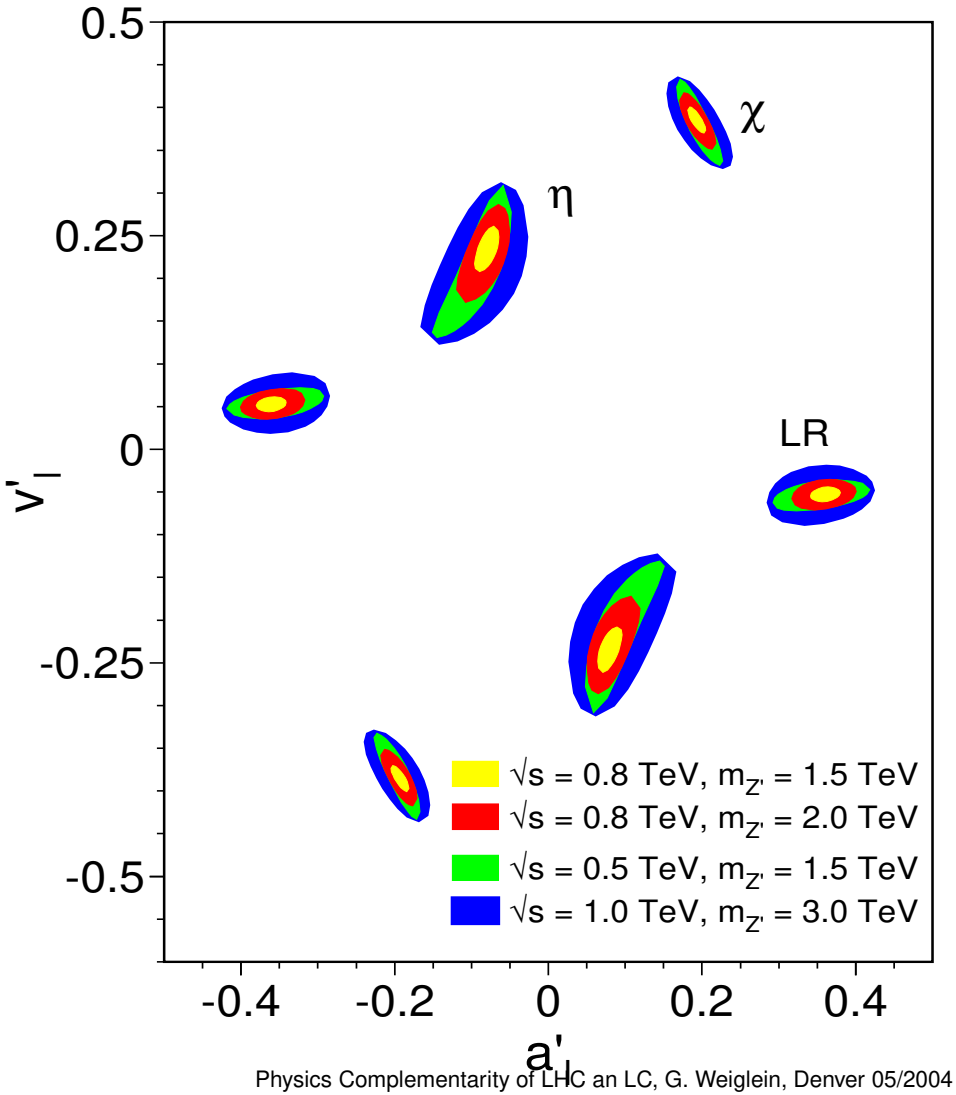
Discovery of extra gauge bosons at LHC

+ large indirect reach of LC

⇒ Mass measurement at LHC as input for determining couplings at LC

Precision measurements at LC

⇒ Distinction between Z' and KK excitation



Extra spatial dimensions:

[*D. Bourilkov, H. Davoudiasl, J.L. Hewett, T.G. Rizzo, M. Spiropulu, T. Tait*]

LC: sensitivity to direct production and indirect effects of Kaluza-Klein excitations of the graviton and SM particles

Graviton resonances often very narrow, may be missed in general search at the LHC

$\Rightarrow$ LC searches for narrow resonances via radiative return; if discovered can tell LHC where to look

5. Conclusions

- LHC / LC interplay is a very rich field

  LHC / LC synergy extends physics potential of both machines

  With LC results $\Rightarrow$ new questions to the LHC

  Topics covered in this talk are just a small survey

- In order to investigate the interplay, we need detailed information about how well LHC and LC can measure a wide variety of observables in different scenarios

  $\Rightarrow$ need to stay tuned for input from LHC and LC simulations

- First LHC / LC Study Group report is close to completion

- Work doesn't stop with the completion of the present working group report – we have just scratched the surface so far