Complementarity and Coherence: Physics with LHC and LC

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DESY 11/2003

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

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

1. Introduction

- Large Hadron Collider (LHC): pp collider with $E_{\rm CM} \approx 14$ TeV

  $\gtrsim 2007$, expected to run for $\mathcal{O}(20)$ years

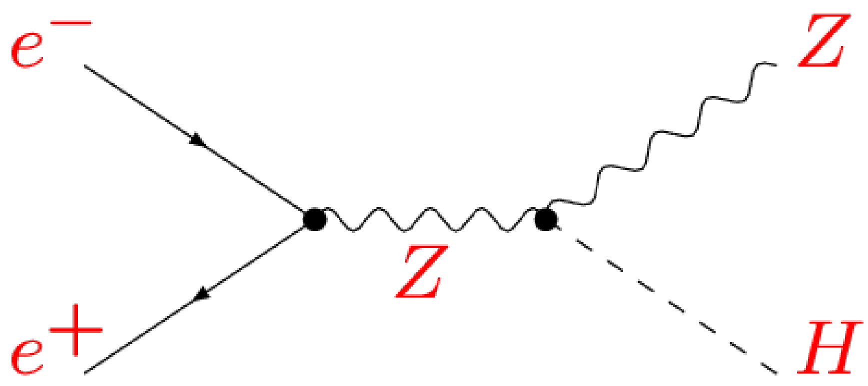
- Linear Collider (LC): e^+e^- collider with $E_{\rm CM} \approx 500$ GeV–1 TeV

  $\gtrsim 2015$?

LC physics

LC: clean experimental environment

$\Rightarrow$ high-precision physics



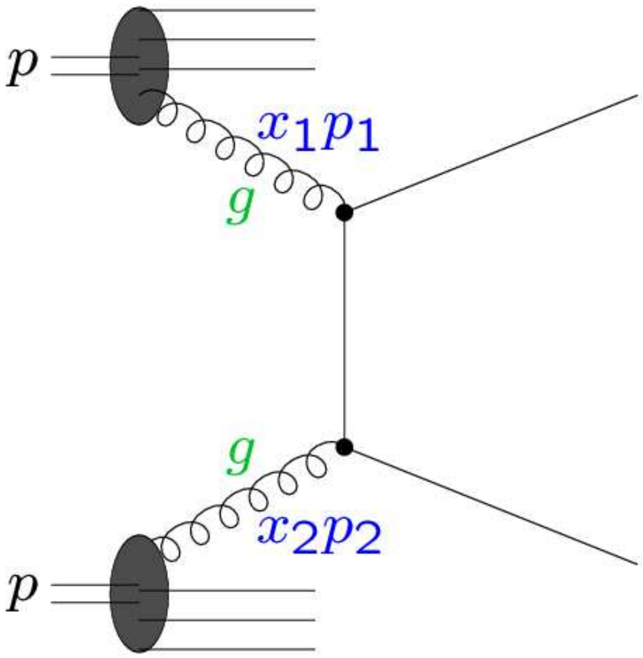
well-defined initial state, beam polarization, . . .

Lepton collider kinematics:

momentum conservation can be used to analyze decay products

LHC physics

pp scattering contains "hard" collision process of partons q, $\bar{q}$, g, e.g.:



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

LHC physics

LHC has in general bigger mass reach for direct discovery

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

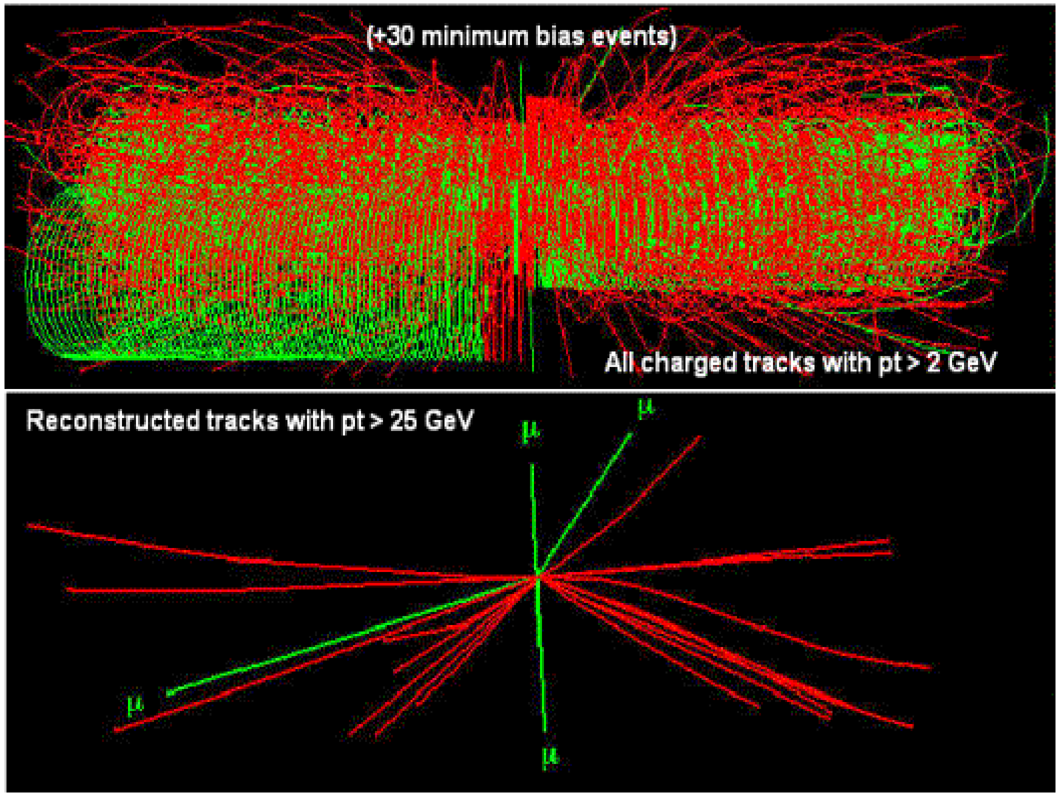
Strongly interacting particles in initial state (mostly gluons)

$\Rightarrow$ 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

Prof. Dr. Stefan Schael, RWTH Aachen — Vorlesung 1, Maria-Laach, September 2001 — 25

Example for new physics searches: Supersymmetry (SUSY)

The Minimal Supersymmetric Standard Model:

Superpartners for Standard Model particles:

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^\pm, H^\pm} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin } 1 \text{ / Spin } 0$$

$$\tilde{g} \quad \tilde{\chi}^\pm_{1,2} \quad \tilde{\chi}^0_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: two Higgs doublets, physical states:
$h^0, H^0, A^0, H^\pm$

SUSY searches at the LHC

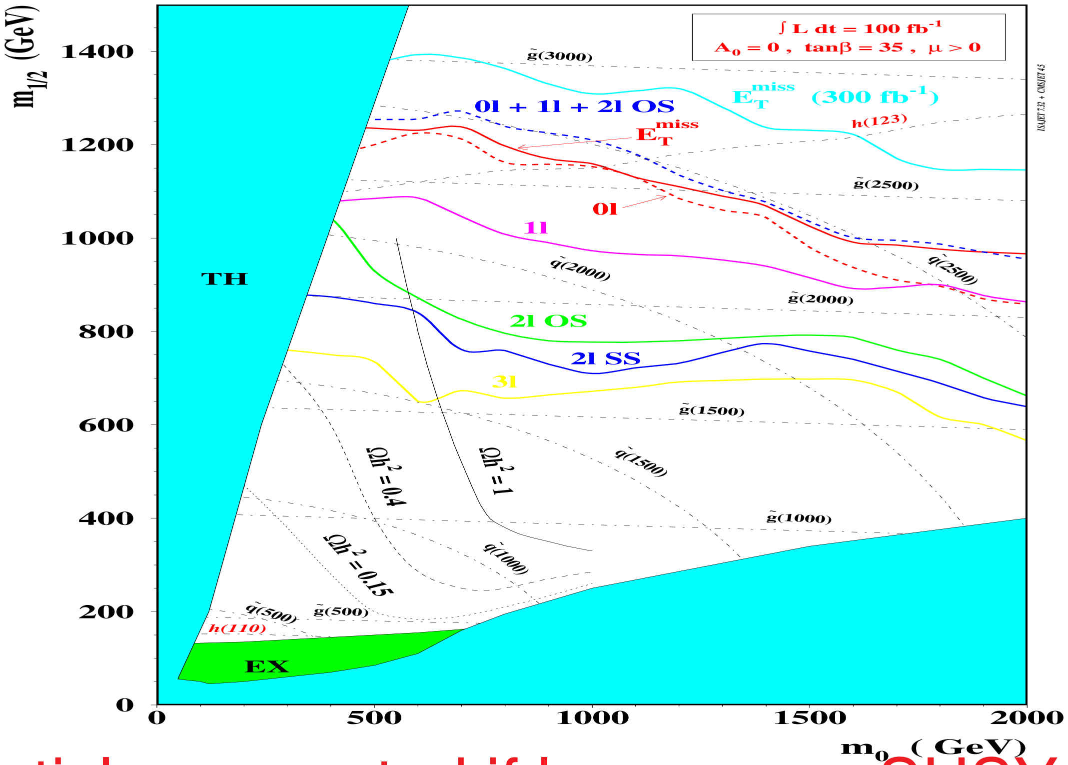
Dominated by production of colored particles: gluinos, squarks

Very large mass range in the searches for jets $+$ missing energy

$\Rightarrow$ gluino, squarks accessible up to 2–3 TeV

Discovery reach contours in m_0–$m_{1/2}$ plane (mSUGRA scenario) for various final states with 100 fb^{-1}:

[*CMS '99*]



$\Rightarrow$ discovery of SUSY particles 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
- $\ldots$

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

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

Comparison: LHC – LC

Production of SUSY particles at LHC $\Rightarrow$ complicated final states,

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

Production of uncolored particles via cascade decays often dominates over direct production

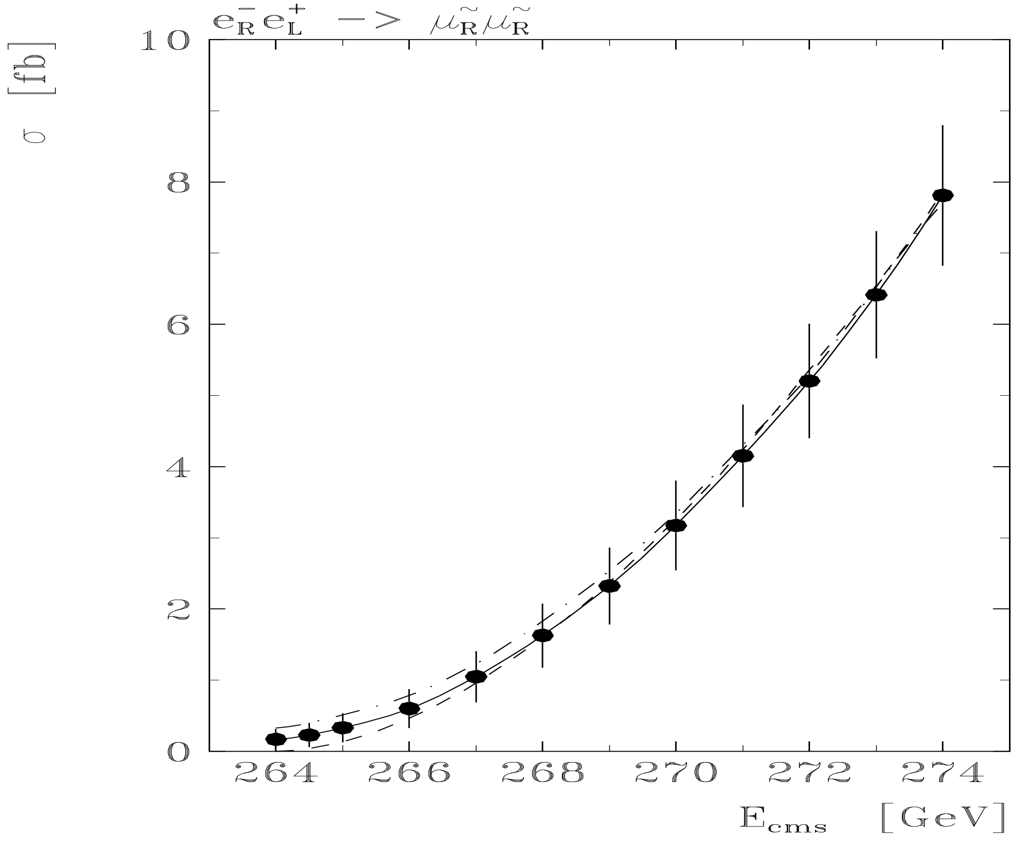
Many states are produced at once

Comparison: LHC – LC

SUSY searches at the LC:

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

[*TESLA TDR '01*]



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

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

Comparison: LHC – LC

LC: Clean signatures, small backgrounds

Thresholds for pair production of SUSY particles

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

Limited by kinematic reach

Good prospects for production of uncolored particles

$\Rightarrow$ LHC / LC complementarity

LHC / LC Study Group

$\Rightarrow$ Results obtained at one collider can be used for improving experimental analyses at the other

$\Rightarrow$ investigated in "LHC / LC Study Group"

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

- LHC / LC interplay: investigate how analyses at the LHC could profit from results obtained at a LC and vice versa

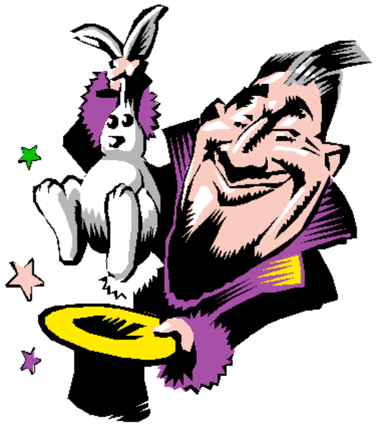
  $\Rightarrow$ mutual benefits for physics program at both machines

- Started in spring 2002 as a world-wide working group
- 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

- Make LHC community aware of what kind of additional information might become available once the LC kicks in
- Transfer of knowledge, strategies for parameter determinations, etc. in both directions
- If LC gets in operation in time, LC results could influence detector, trigger, . . . choices at LHC upgrades

How far are we?

- We had six working group meetings so far (most at CERN)
- Draft of first working group report exists:

  $\approx$ 400 pages, $\approx$ 40 individual contributions, 107 authors
- Currently going through editorial process

  Editors: T. Barklow, E. Boos, A. De Roeck, D. Denegri, K. Desch, H. Haber, F. Gianotti, R. Godbole, J. Gunion, S. Heinemeyer, J. Hewett, K. Kawagoe, K. Mönig, M. Nojiri, F. Paige, G. Polesello, F. Richard, S. Riemann, H. Schellman, W.J. Stirling P. Zerwas, G. W.
- Next meeting: early next year, CERN

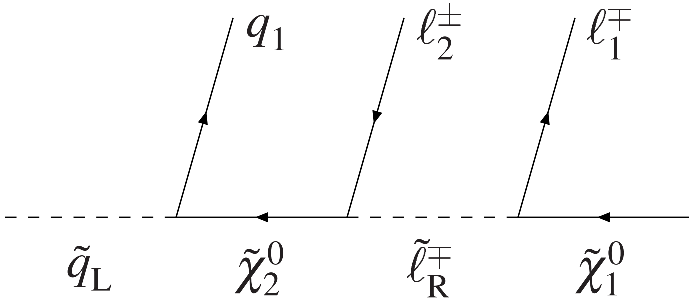
  see `www.ippp.dur.ac.uk/~georg/lhclc`

2. Determination of SUSY parameters at LHC / LC

Reconstruction of sparticle masses at the LHC

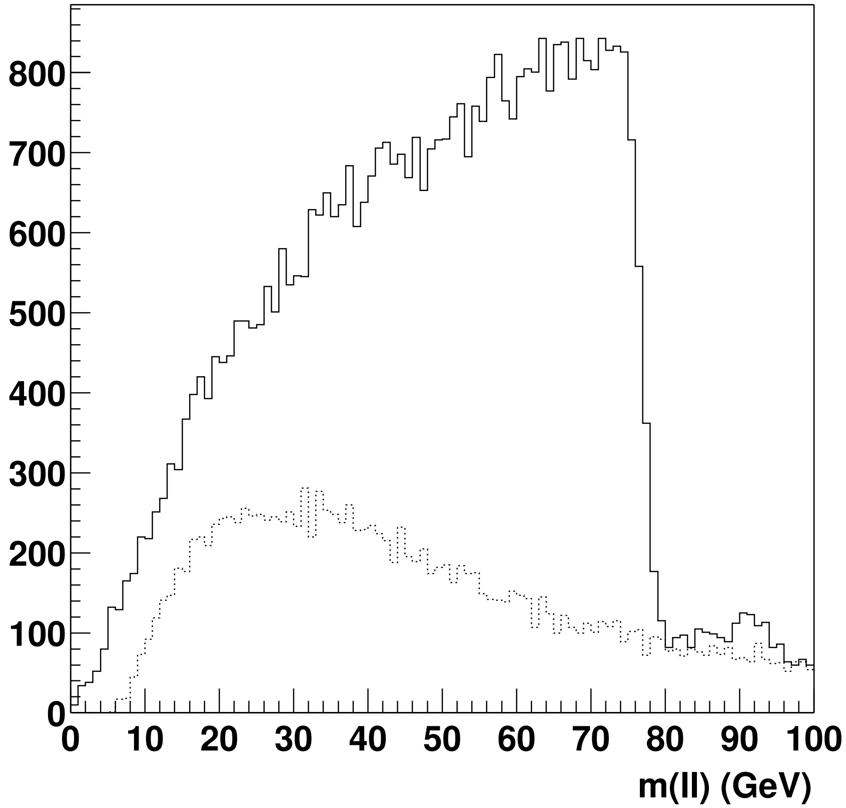
[M. Chiorboli, B.K. Gjelsten, J. Hisano, K. Kawagoe, E. Lytken, U. Martyn, D. Miller, M. Nojiri, P. Osland, G. Polesello, A. Tricomi '03]

Cascade decays: complicated decay chains for squarks and gluinos



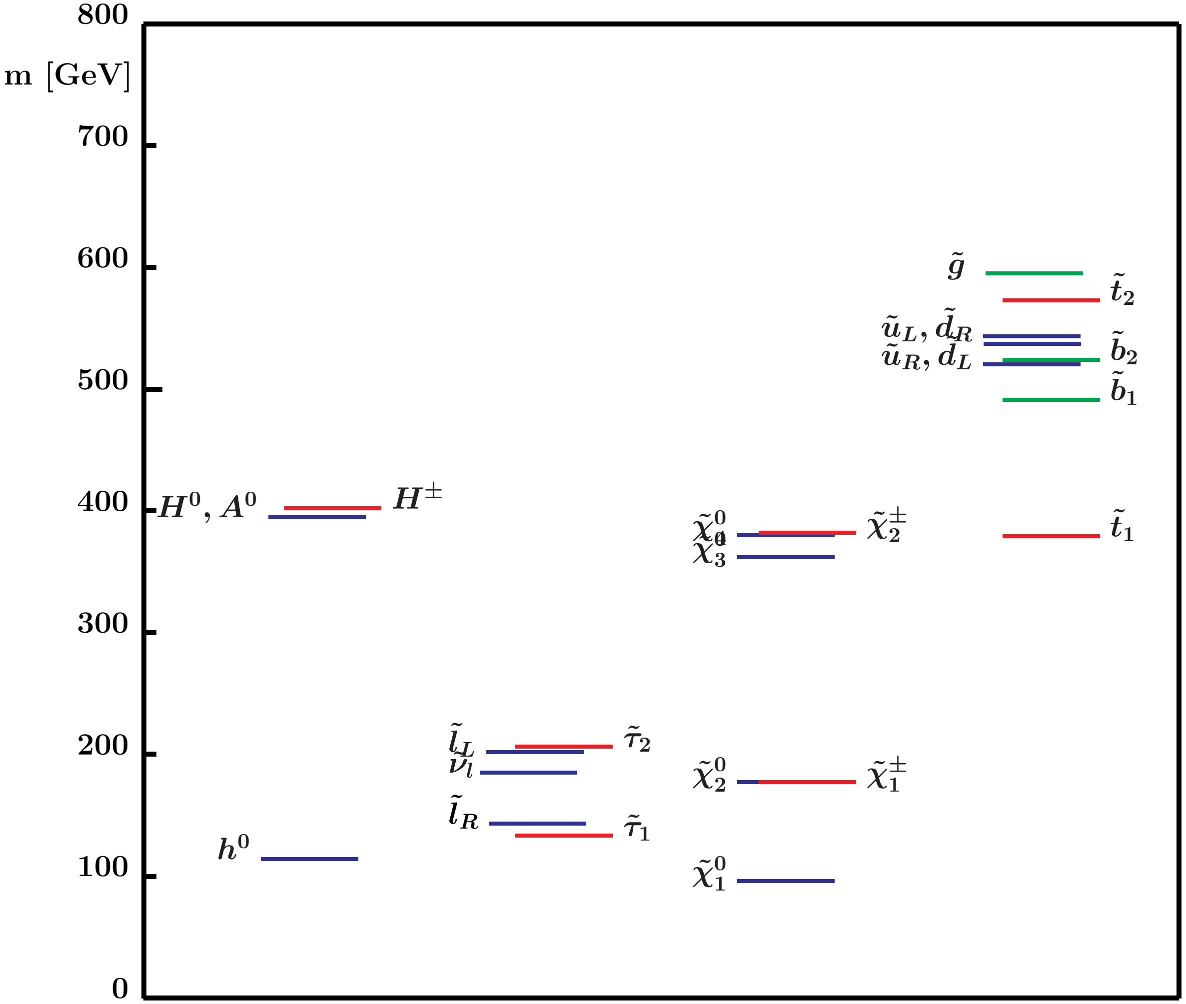
Reconstruction of sparticle masses at the LHC

Main tool: dilepton "edge"
from $\tilde{\chi}_2^0 \to \ell^+ \ell^- \tilde{\chi}_1^0$



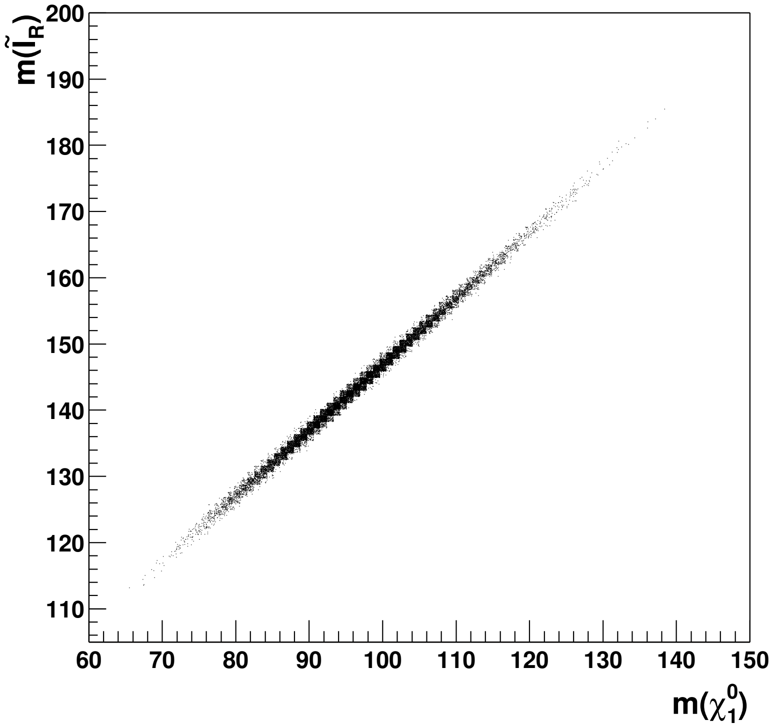
Examples worked out for SPS1a from ATLAS and CMS

Mass spectrum in SPS1a scenario



$\Rightarrow$ Favourable scenario for both LHC and LC

Strong correlation between slepton mass and LSP mass,
LSP mass can be constrained at LHC at the 10% level only:



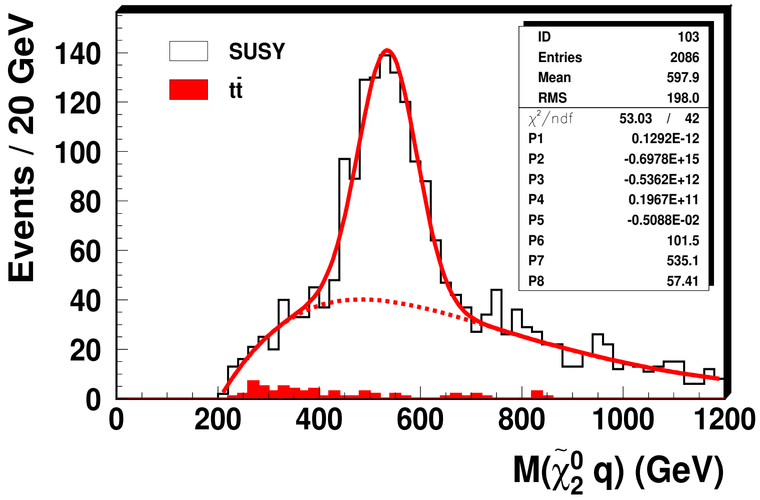
$\Rightarrow$ Take LSP mass as input from LC

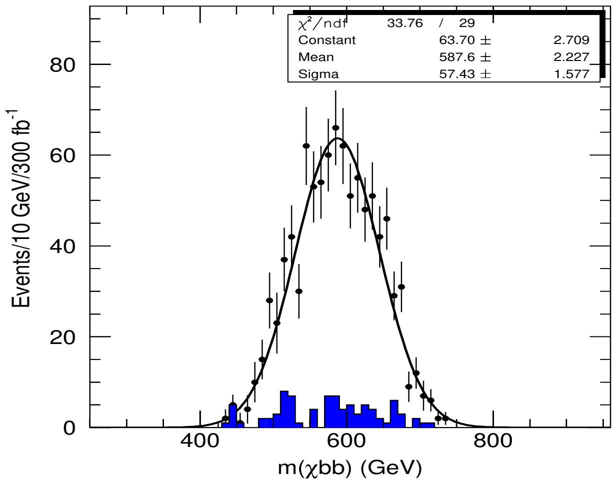
$$\vec{p}(\tilde{\chi}_2^0) = \left(1 - \frac{m(\tilde{\chi}_1^0)}{m(\ell\ell)}\right) \vec{p}_{\ell\ell}$$

$\Rightarrow$ Get sbottom/squark mass if LSP mass is known

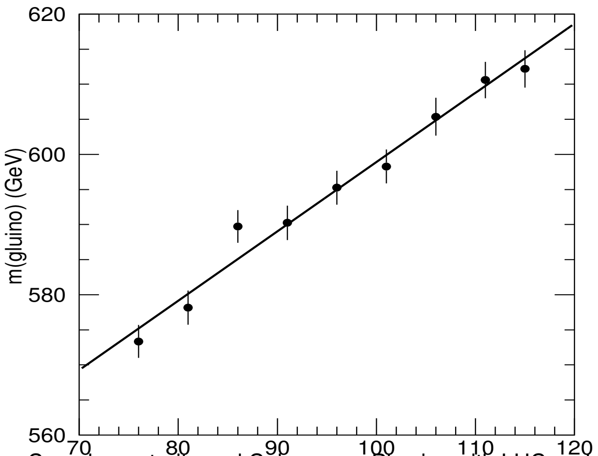
Squark and gluino reconstruction

Squark peak (left) and gluino reconstruction from $(\chi_2^0 bb)$ invariant mass distribution (right):



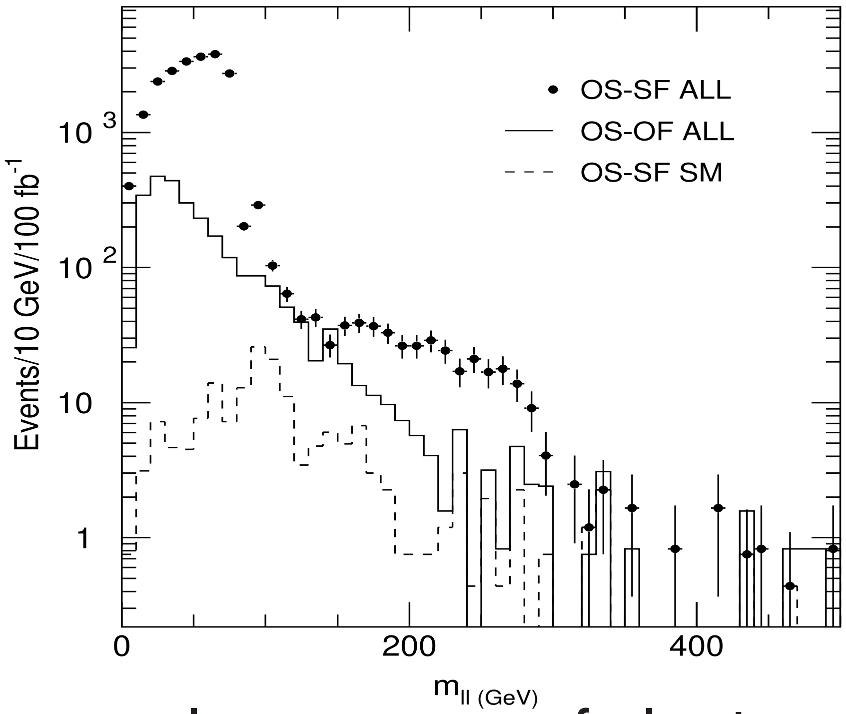


$m_{\tilde{g}}$ as function of the LSP mass:



Determination of the mass of the heaviest neutralino at the LHC using LC input from the neutralino/chargino sector

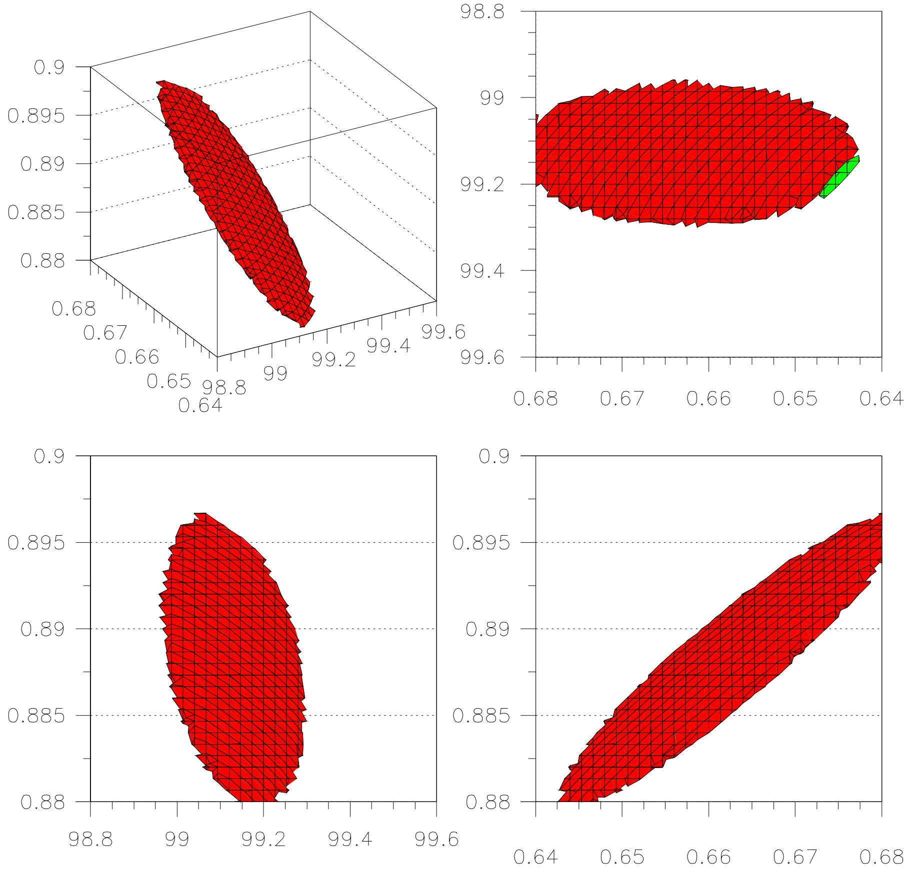
[*K. Desch, J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello '03*]



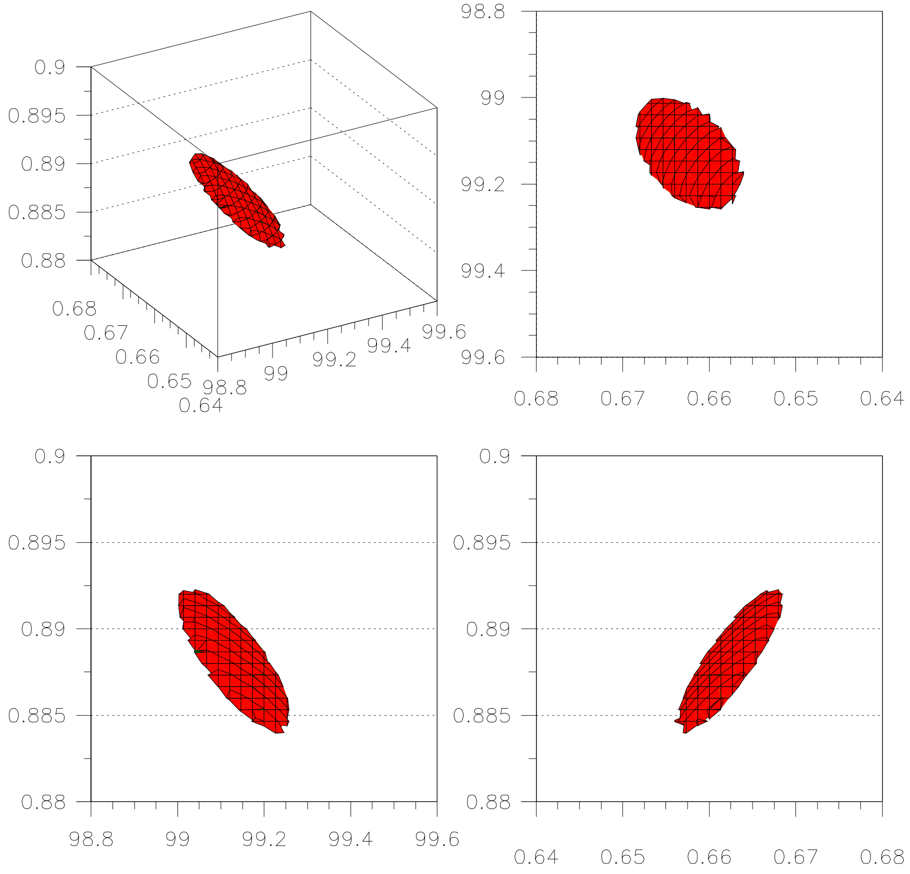
$\Rightarrow$ Need besides m_{LSP} also masses of sleptons, charginos from LC to correctly identify $\tilde{\chi}_4^0$; LC prediction: $m_{\tilde{\chi}_4^0} = 378.3 \pm 8.8$ GeV

Determination of neutralino parameter M_1 *and chargino mixing angles* $\cos\phi_{\rm L}$, $\cos\phi_{\rm R}$ *(*$\Delta\chi^2 = 6$ *contours)*

LC information alone



LHC + LC information



Dedicated effort: detailed analysis for SPS1a on 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

$\Rightarrow$ LC input improves accuracy significantly

Full reconstruction of stop/sbottom parameters using LHC / LC interplay

[*J. Hisano, K. Kawagoe, M. Nojiri '03*]

- Take the set of electroweak SUSY parameters determined by the LC and LHC data
- Take ratios of branching ratios of $\tilde{\mathrm{b}}$ / $\tilde{\mathrm{t}}$ measured at the LHC
- Take $m_{\tilde{\mathrm{b}}_1}$, $m_{\tilde{\mathrm{b}}_2}$ from edge study (using LC input on LSP mass)

Measure:

– tb invariant mass distribution

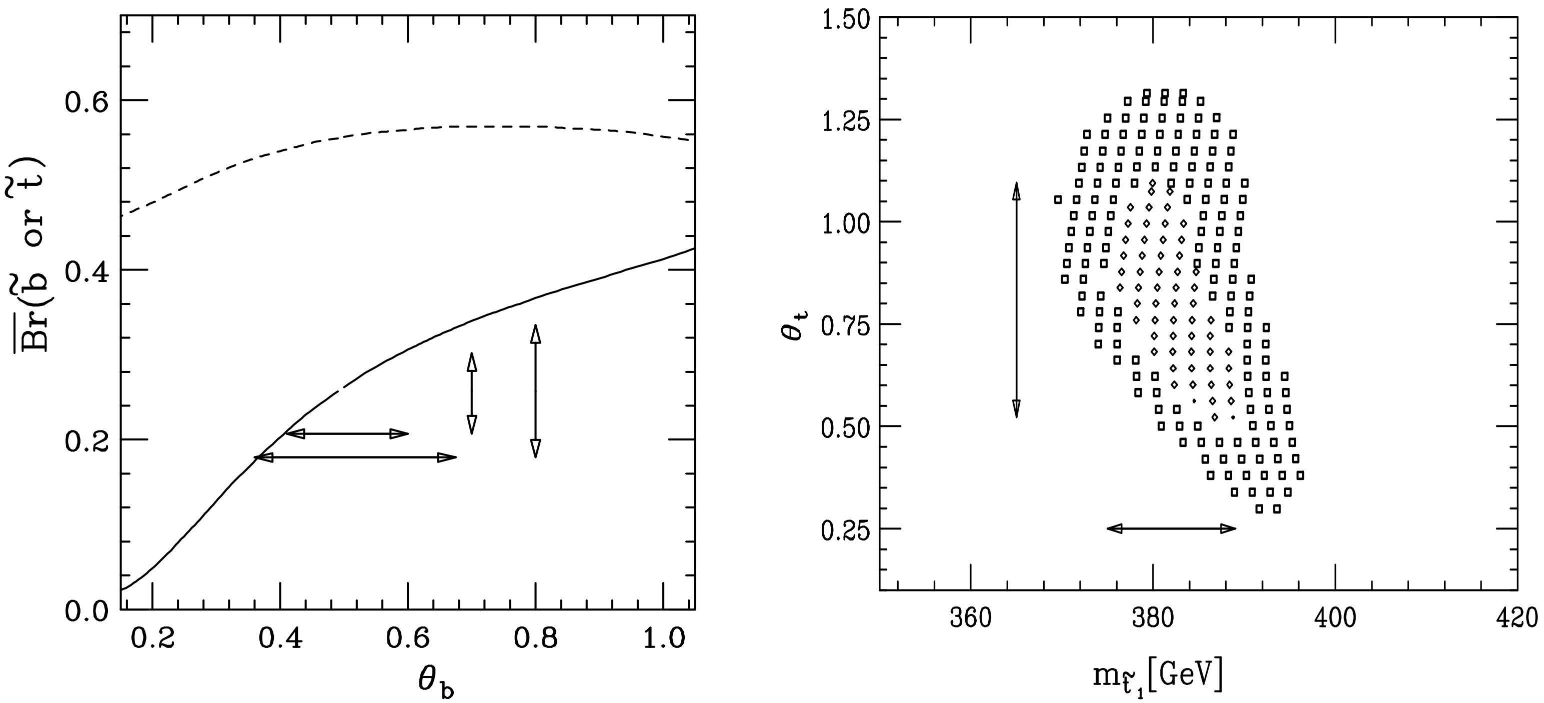
– rate of “edge-events” in m_{tb} distribution (chargino chain)

– rate of events in $\ell\ell b$ distribution ($\tilde{\chi}^0_2$ chain)

$\Rightarrow$ If chargino couplings $+$ BR's are known then observed rates are sensitive to sbottom/stop mixing parameters

Determination of $\theta_{\tilde{b}}$, $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ in SPS1a

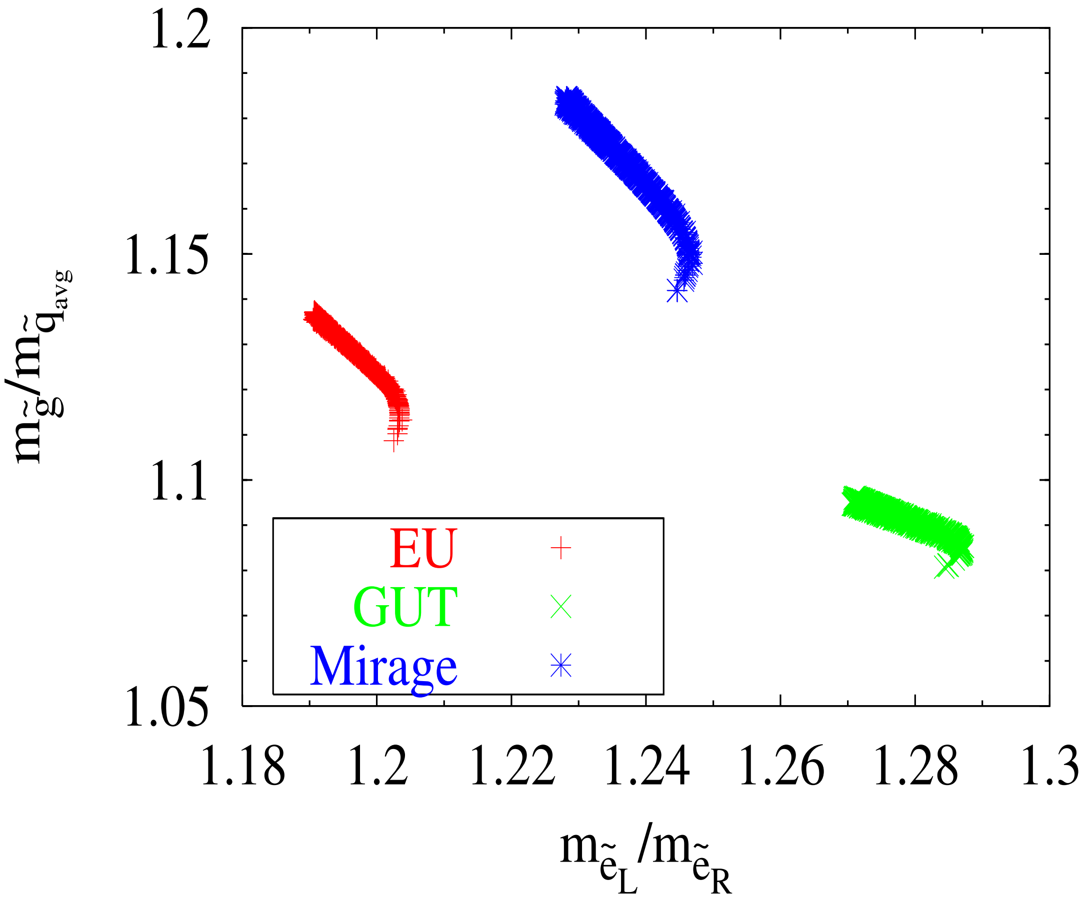
- Det. of $\theta_{\tilde{b}}$ from $\mathrm{BR}(\tilde{g} \to b\tilde{b}_2 \to bb\tilde{\chi}_2^0)/\mathrm{BR}(\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0)$ (left)
- Det. of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ assuming also $\theta_{\tilde{b}}$ is known (right)



$\Rightarrow \mathcal{O}(50\%)$ determination of mixing angles, $\Delta m_{\tilde{t}_1}/m_{\tilde{t}_1} < 5\%$

Discrimination between different SUSY-breaking scenarios

[*B. Allanach, D. Grellscheid, F. Quevedo '03*]



$\Rightarrow$ Need %-level accuracy to distinguish between different models

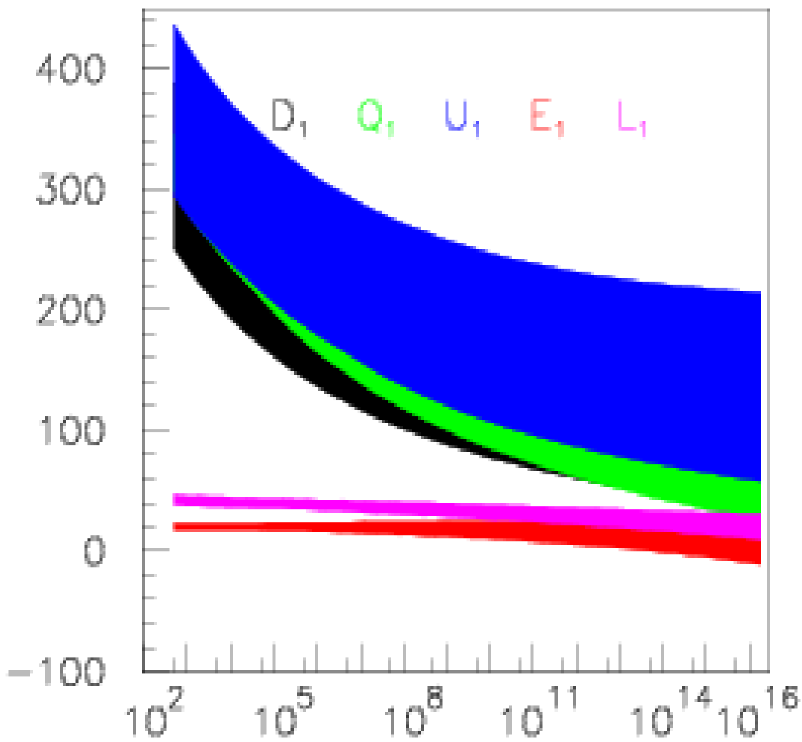
Extrapolation to physics at high scales

[*G. Blair, U. Martyn, G. Polesello, W. Porod, P. Zerwas '03*]

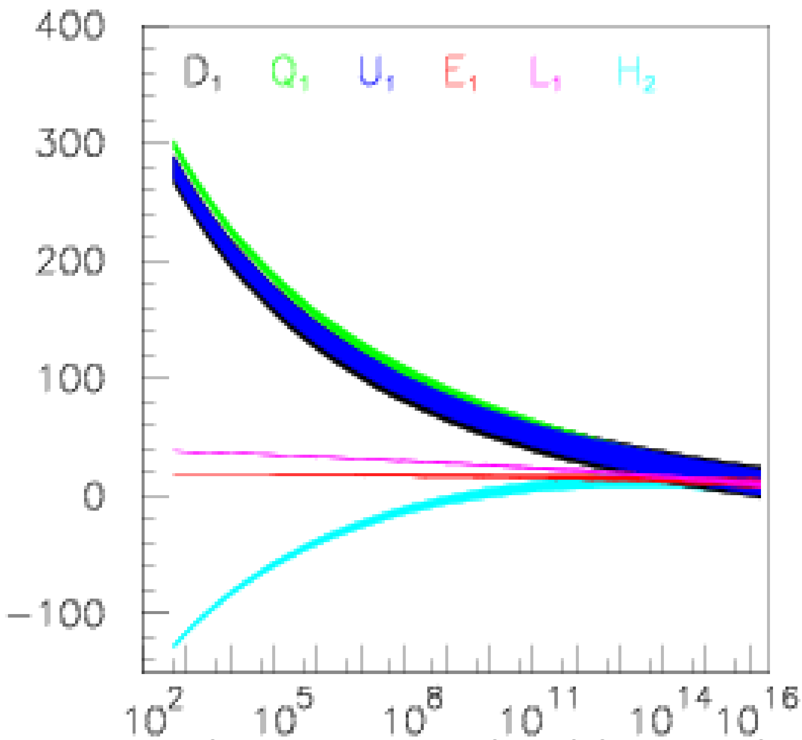
from combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings

E.g.: evolution of first-gen. sfermion and Higgs mass parameters

LHC



LHC $\oplus$ LC



Some open issues

- What is the theoretical uncertainty of Monte Carlo simulation of distributions, edges, etc.?

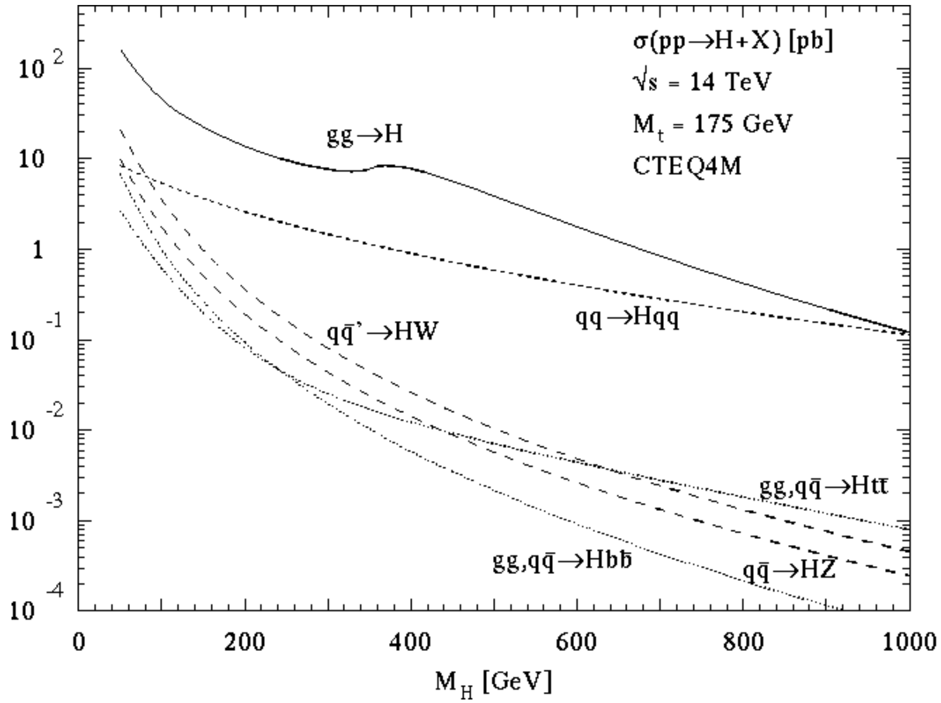
  Effects of initial / final state radiation?

- SPS1a is a rather favourable scenario both for LHC and LC

  What is the LHC / LC mutual benefit in a more difficult scenario?

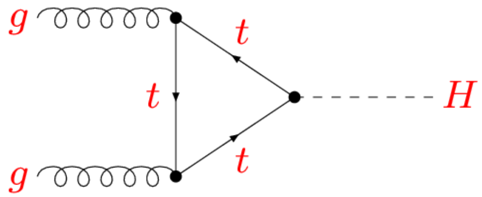
3. Higgs physics

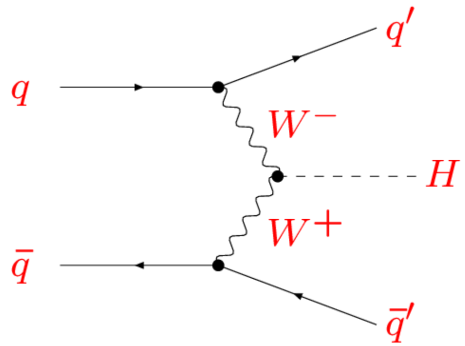
SM Higgs production at the LHC:



Dominant production processes:

gluon fusion $gg \to H$, weak boson fusion (WBF) $q\bar{q} \to q'\bar{q}'H$:

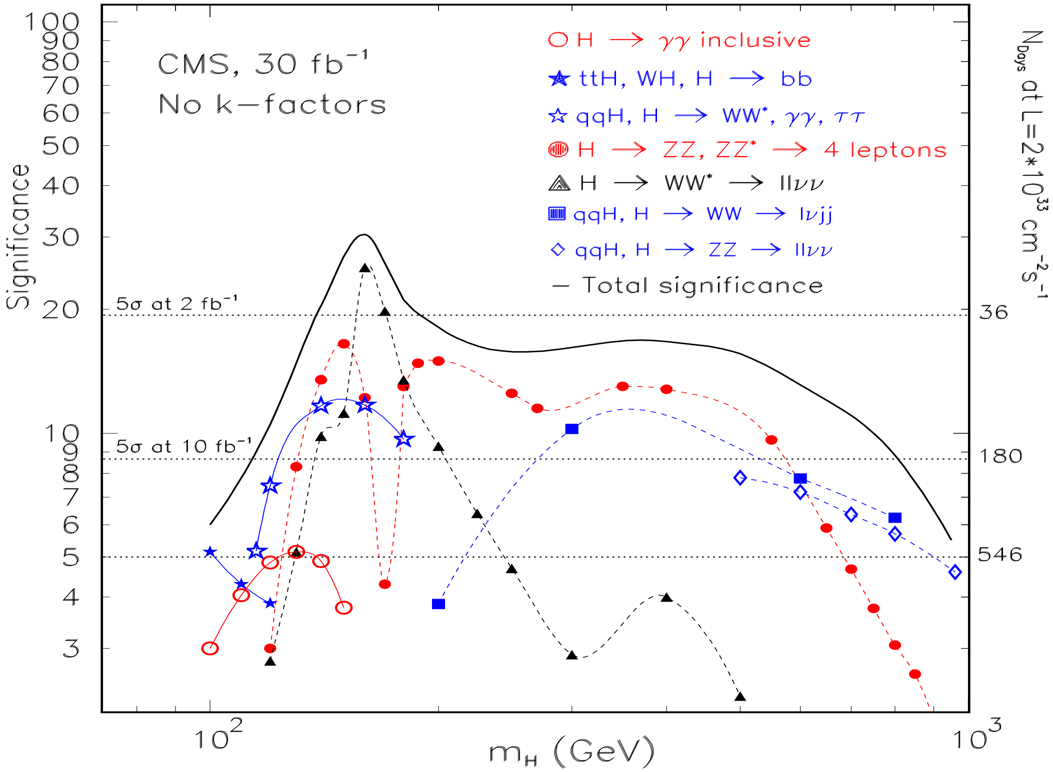




SM Higgs at the LHC

The LHC will discover a SM-like Higgs, covers whole range

$M_{\mathrm{H}} \lesssim 1$ TeV



[CMS ’03]

For light SM-like Higgs, $H \to \gamma\gamma$ decay mode:

$\Rightarrow$ LHC can do first precision measurement in Higgs sector:

$$\delta M_{\mathrm{H}}^{\mathrm{exp}} \approx 0.2 \text{ GeV}$$

Higgs physics at the LC

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

Higgs discovery possible independent of decay modes

(from recoil against Z boson)

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

LC is a "Higgs factory"

e.g.: $E_{\mathrm{CM}} = 800$ GeV, 1000 fb^{-1}, $M_{\mathrm{H}} = 120$ GeV:

$\Rightarrow$ ≈ 160000 Higgs events in "clean" experimental environment

$\Rightarrow$ Precise measurement of Higgs mass ($\approx 4 \times 10^{-4}$) and couplings, determination of Higgs spin and quantum numbers, ...

$\Rightarrow$ Verification of Higgs mechanism

Higgs coupling measurements at LHC and LC

Top Yukawa coupling:

[*S. Dawson, A. Juste, L. Reina, D. Wackeroth, K. Desch, M. Schumacher; D. Rainwater et al.*]

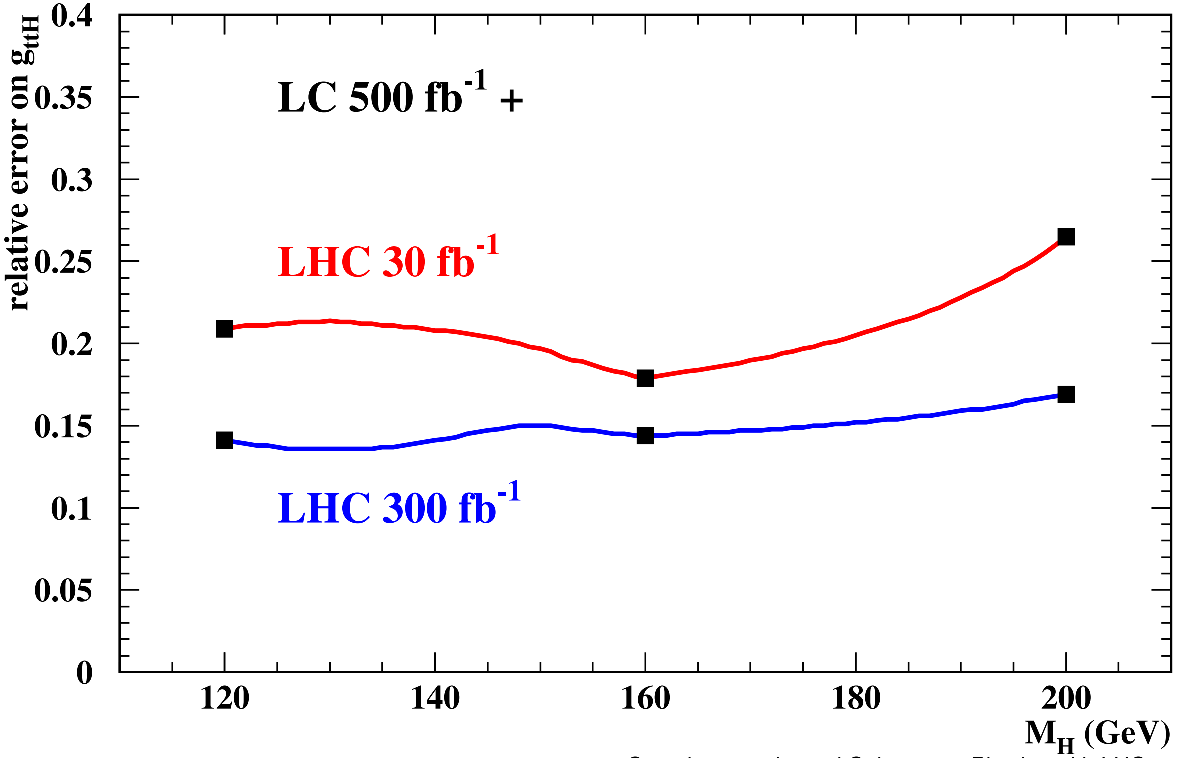
Only preliminary measurement of tth coupling at 500 GeV LC for light Higgs

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 / LC running at $\sqrt{s} = 350$ GeV:



Higgs self couplings:

[*U. Baur, T. Plehn, D. Rainwater '03*]

Better prospects for measuring Higgs self-coupling at LC for $m_H < 140$ GeV; better prospects at LHC for $m_H > 140$ GeV

Measurement at LHC requires input from LC on Higgs properties: top Yukawa coupling, HWW coupling, total Higgs width

Invisible Higgs

[*G. Belanger, F. Boudjema, R. Godbole*]

Higgs can have large invisible BR, e.g. for non-universal gaugino masses

$\Rightarrow$ difficult at the LHC ($pp \to pph$, $pp \to Zh$)

$\Rightarrow$ Nature of invisible Higgs can be established at the LC;

look for corresponding sparticle phenomenology at the LHC

E.g. production of h in decays of heavier neutralinos can be possible at LHC

SUSY Higgs

MSSM Higgs potential contains two Higgs doublets:

$$
\begin{aligned}
V \quad = \quad & m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
& + \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

Five physical states: $h^0, H^0, A^0, H^{\pm}$

Input parameters: $\tan\beta = \frac{v_2}{v_1}$, M_A

$\Rightarrow m_\mathrm{h}$, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters

Higgs mass bound in the MSSM:

Tree-level result for m_{h}, m_{H}:

$$m^2_{\mathrm{H,h}} = \frac{1}{2}\left[M_{\mathrm{A}}^2 + M_{\mathrm{Z}}^2 \pm \sqrt{(M_{\mathrm{A}}^2 + M_{\mathrm{Z}}^2)^2 - 4M_{\mathrm{Z}}^2 M_{\mathrm{A}}^2 \cos^2 2\beta}\right]$$

$\Rightarrow m_{\mathrm{h}} \leq M_{\mathrm{Z}}$ at tree level

MSSM tree-level bound (gauge sector): excluded by LEP!

Large radiative corrections (Yukawa sector, . . .):

Yukawa couplings: $\frac{e\, m_{\mathrm{t}}}{2M_{\mathrm{W}} s_{\mathrm{W}}}$, $\frac{e\, m_{\mathrm{t}}^2}{M_{\mathrm{W}} s_{\mathrm{W}}}$, . . .

$\Rightarrow$ Dominant one-loop corrections: $G_\mu m_{\mathrm{t}}^4 \ln\left(\frac{m_{\tilde{\mathrm{t}}_1} m_{\tilde{\mathrm{t}}_2}}{m_{\mathrm{t}}^2}\right)$, $\quad \mathcal{O}(100\%)$!

Higgs mass bound in the MSSM:

Present status of m_{h} prediction in the MSSM:

Complete one-loop $+$ "almost complete" two-loop result available

Upper bound on m_{h}:

"Unconstrained MSSM": M_{A}, $\tan\beta$, 5 parameters in $\tilde{\mathrm{t}}$–$\tilde{\mathrm{b}}$ sector, μ, $m_{\tilde{\mathrm{g}}}$, M_2

$$m_{\mathrm{h}} \lesssim 135\,\mathrm{GeV}$$

[*S. Heinemeyer, W. Hollik, G. W. '99*], [*M. Frank, S. Heinemeyer, W. Hollik, G. W. '02*] [*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

for $m_{\mathrm{t}} = 175\,\mathrm{GeV}$, no theoretical uncertainties included

Remaining theoretical uncertainties in prediction for $m_{\rm h}$:

[*G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich, G. W. '02*]

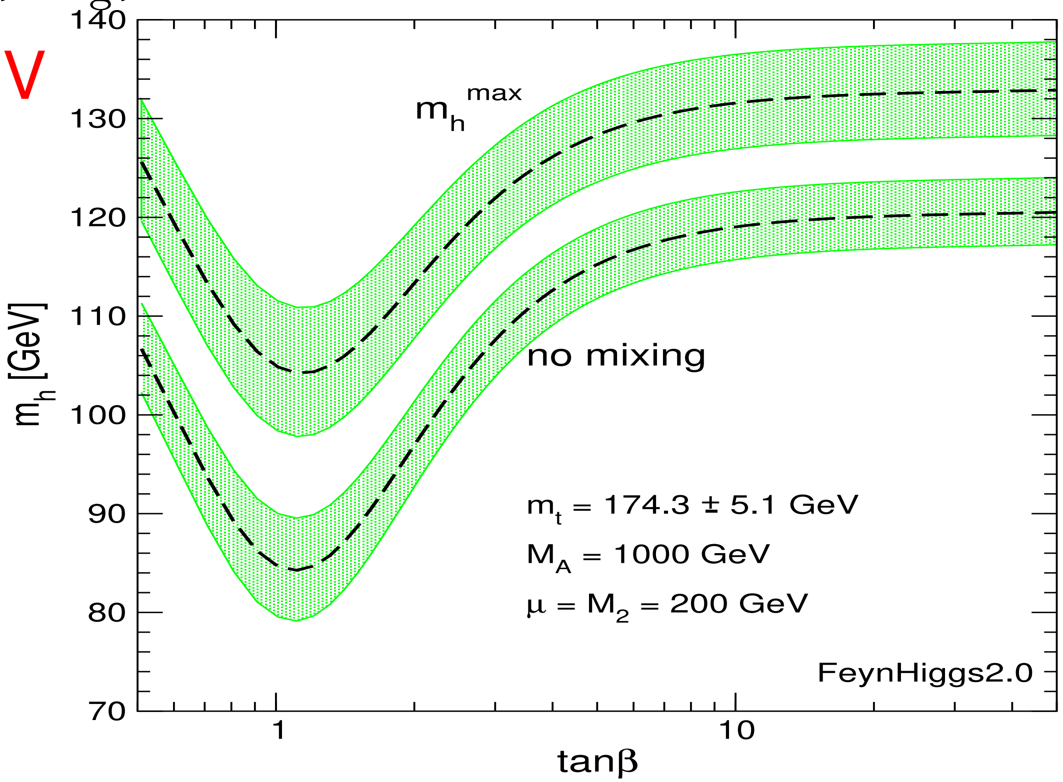
– From unknown higher-order corrections: $\Rightarrow \Delta m_{\rm h} \approx 3$ GeV

(in region where $\tilde{\rm b}$ sector corrections are under control)

– From uncertainties in input parameters

$m_{\rm t}, \ldots, M_{\rm A}, \tan\beta, m_{\tilde{\rm t}_1}, m_{\tilde{\rm t}_2}, \theta_{\tilde{\rm t}}, m_{\tilde{\rm g}}, \ldots$:

$\Delta m_{\rm t} \approx 5$ GeV $\Rightarrow \Delta m_{\rm h} \approx 5$ GeV



Upper bound on $m_{\rm h}$ saturated for large $M_{\rm A}$, large $\tan\beta$, significant mixing in $\tilde{\rm t}$ sector

Complementarity example:

Necessary improvements in accuracy of theoretical prediction in order to match experimental precision at LHC, $\delta m_{\mathrm{h}}^{\mathrm{exp}} \approx 0.2$ GeV:

- Uncertainty from experimental errors of input parameters:

  $\Rightarrow$ In order to match

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

  need

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

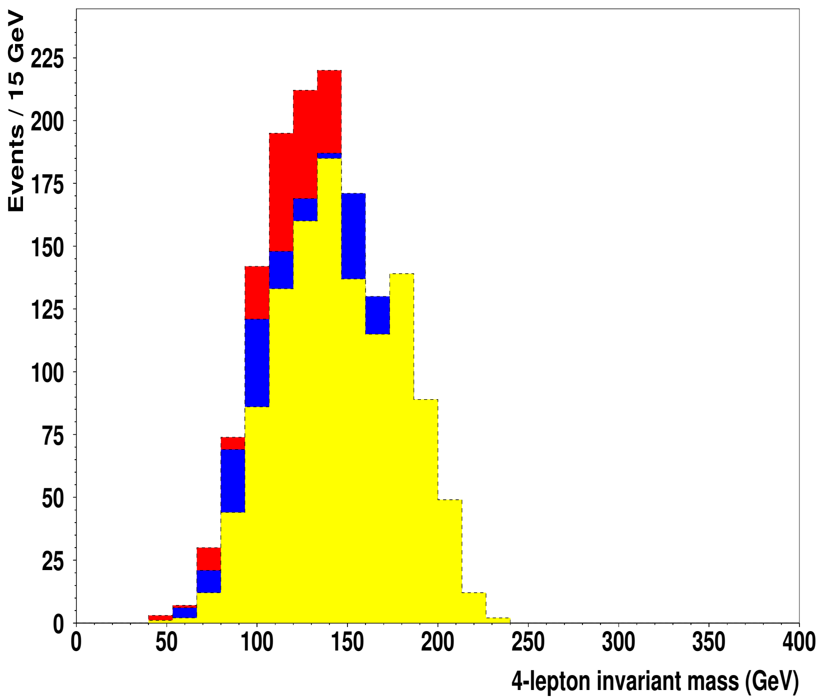
- Uncertainty from unknown higher-order corrections:

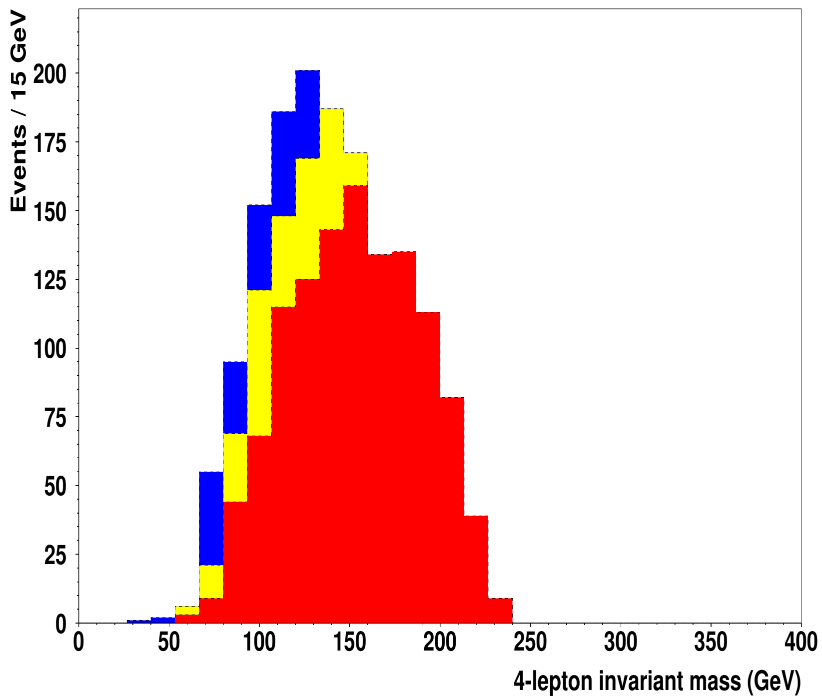
  $\Rightarrow$ Need improvement by more than a factor 10!

Determination of $M_{\rm A}$ from heavy Higgs decays into SUSY particles at the LHC

[*F. Moortgat '03*]

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





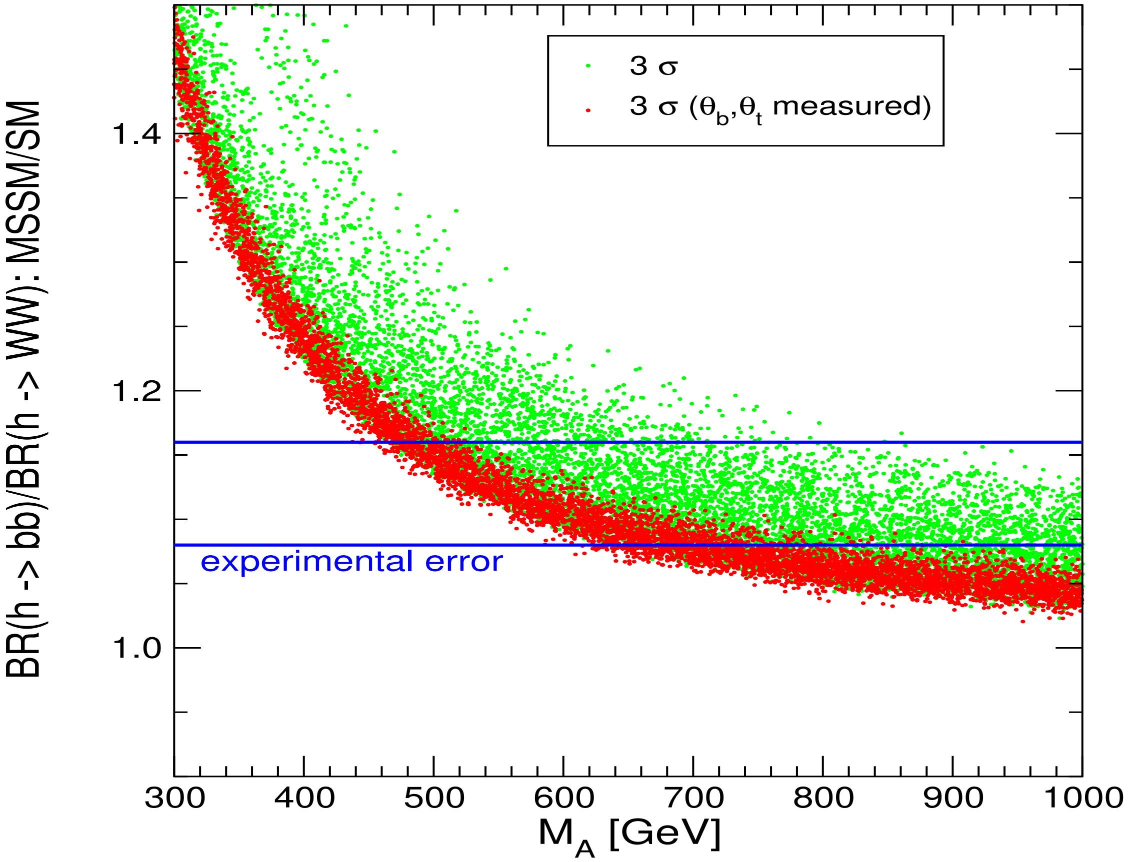
$\Rightarrow$ Precise knowledge of LSP mass from LC crucial for determination of $M_{\rm A}$

Indirect constraints on $M_{\rm A}$ from Higgs BR measurements at the LC using LHC / LC input

[*K. Desch, E. Gross, S. Heinemeyer, G.W., L. Zivkovic '03*]

LC measurement of

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



Higgs BRs from LC measurements

Parameters of $\tilde{\rm t}$ / $\tilde{\rm b}$ sector from LHC / LC analysis

Comparison:

no experimental information on $\theta_{\tilde{\rm b}}$, $\theta_{\tilde{\rm t}}$

$\Delta\theta_{\tilde{\rm b}} = 20\%$, $\Delta\theta_{\tilde{\rm t}} = 10\%$

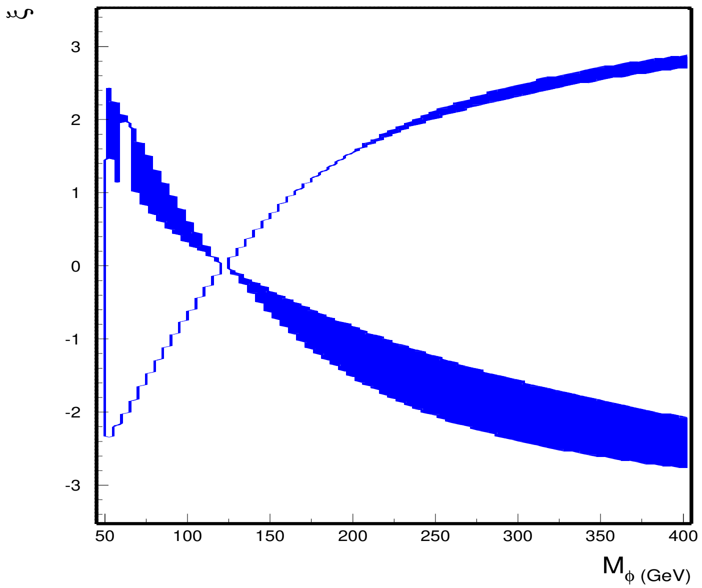
$\Rightarrow$ Knowledge of $\tilde{\rm t}$ / $\tilde{\rm b}$ sector parameters is crucial

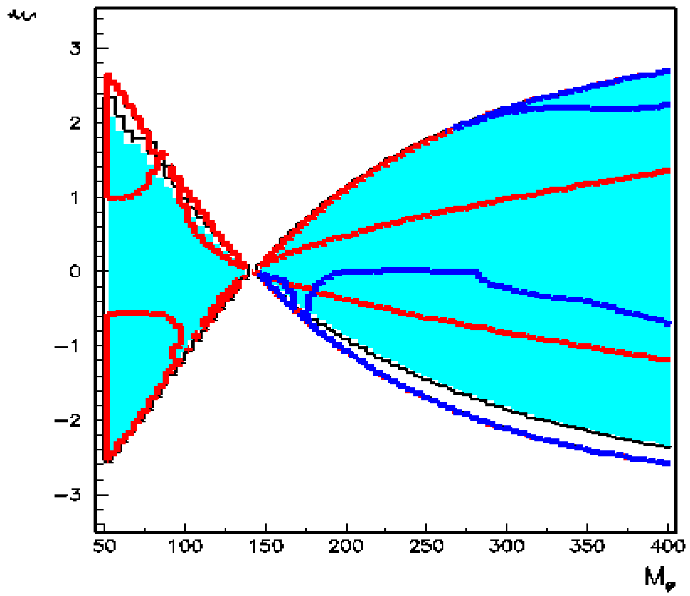
Higgs and radion searches at LHC and LC

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

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

Parameter regions where Higgs significance is below 5σ at the LHC with 100 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):





4. Strong electroweak symmetry breaking

[*M. Arneodo, T. Barklow, S. Boogert, G. Cerminara, W. Kilian, C. Mariotti, K. Mönig, A.F. Osorio, G. Passarino '03*]

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

Detailed measurements of cross sections and angular distributions at the LC will be crucial for making full use of the LHC data

Measurement of anomalous couplings at the LC down to natural scale $1/16\pi^2$

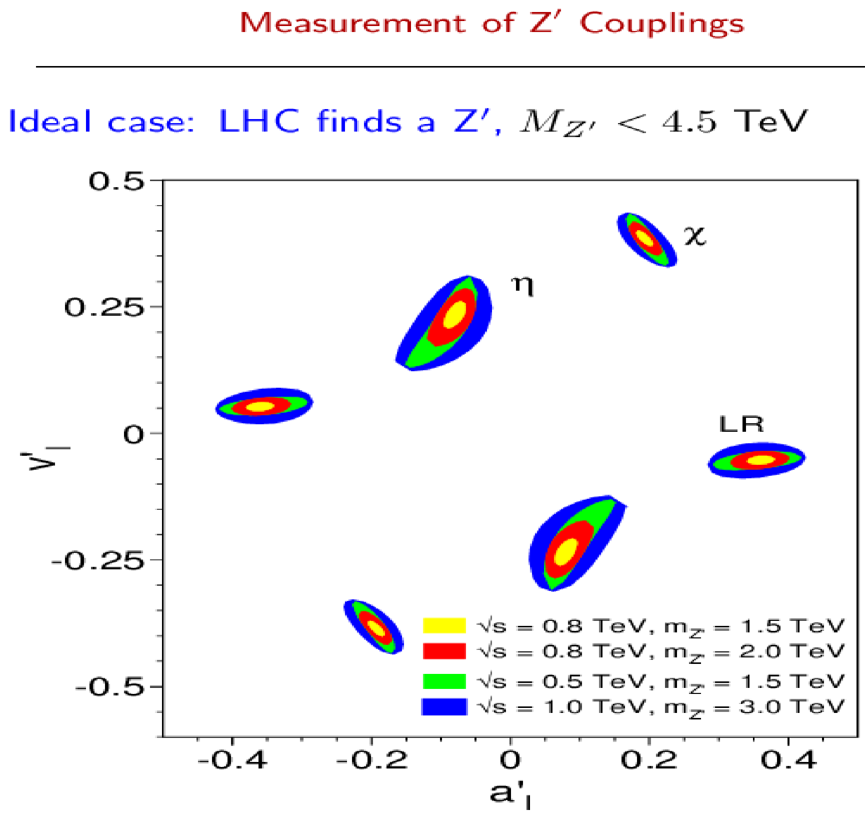
Resonances at high energy only directly accessible at the LHC; combination with sub-TeV data of LC on cross-section rise essential for disentangling new states

5. New gauge theories

[D. Bourilkov, S. Godfrey, J. Hewett, F. Richard, S. Riemann, T. Rizzo '03]

Discovery of extra gauge bosons at LHC $+$ large indirect reach of LC

$\Rightarrow$ Mass measurement at LHC as input for determining couplings at LC



Sensitivity to contact interactions and extra dimensions at LHC + LC

Distinction between Z' and KK excitation from ew precision data:

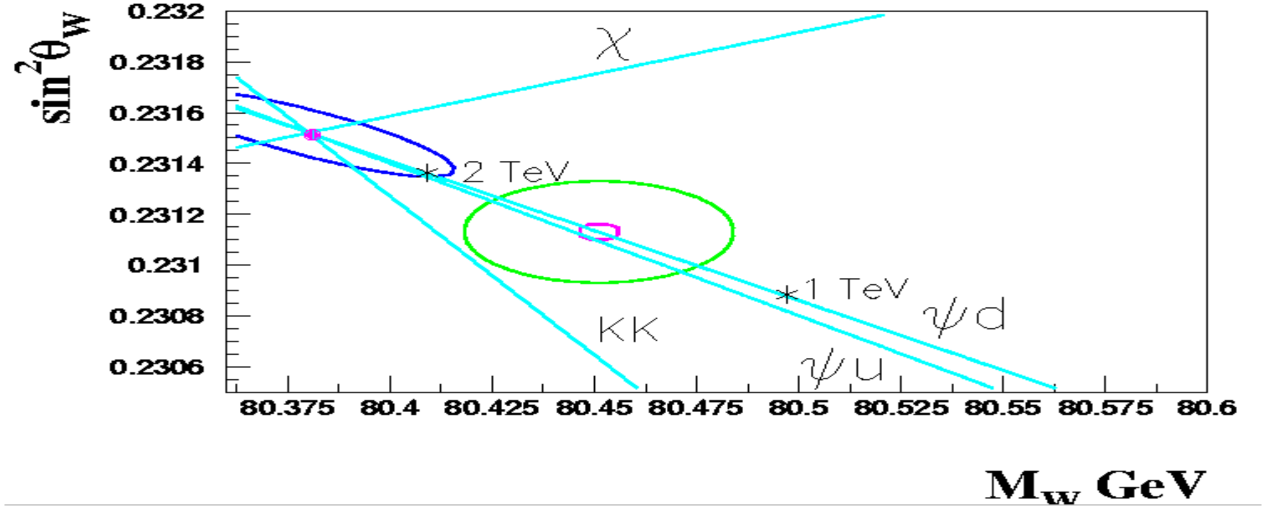
LHC sees new Drell-Yan resonance: measures mass

LC: uses LHC mass determination as input

$\Rightarrow$ determines couplings via $e^+e^- \to f\bar{f}$

Sensitivity of precision measurements of M_W, $\sin^2\theta_{\text{eff}}$ at GigaZ to predictions of different models: E6 vs. KK

GigaZ vs. current accuracy



6. Large extra dimensions

[*C. Balázs, D. Bourilkov, H. Davoudiasl, A. De Roeck, J. Hewett, B. La Forge, T. Rizzo '03*]

Graviton emission: $pp \to gG^{(n)}$, $e^+e^- \to \gamma G^{(n)}$

LHC / LC have comparable search reach:

95% CL sensitivity to the fundamental scale M_D in TeV for different values of δ (number of extra dim.) at LHC / LC
(note that the LHC only probes M_D within the stated range)

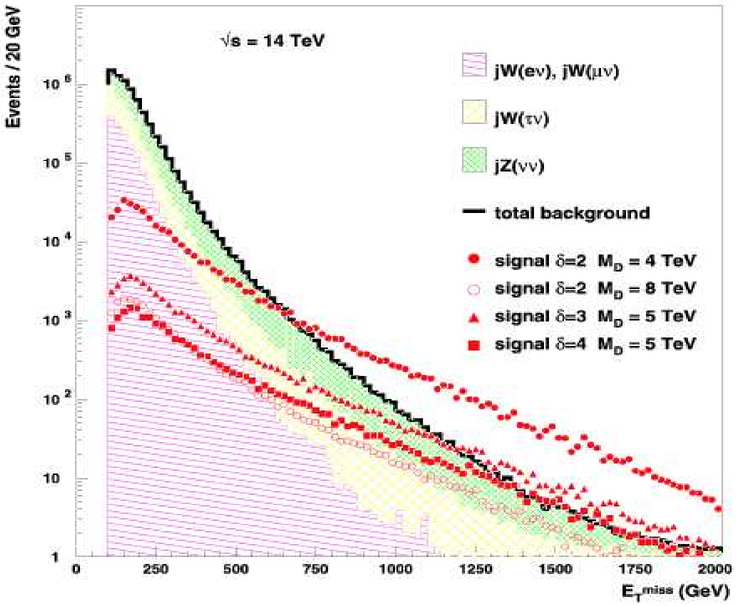
$e^+e^- \to \gamma + G_n$		2	4	6
LC	$P_{-,+} = 0$	5.9	3.5	2.5
LC	$P_- = 0.8$	8.3	4.4	2.9
LC	$P_- = 0.8$, $P_+ = 0.6$	10.4	5.1	3.3

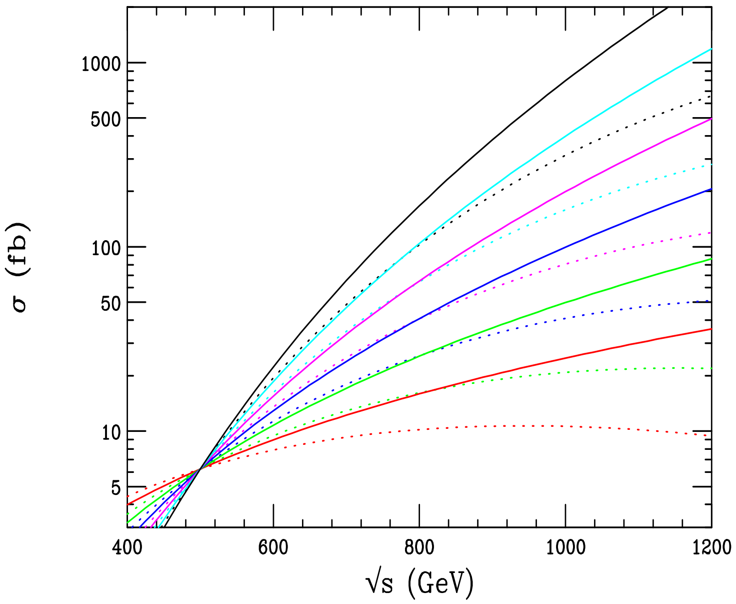
$pp \to g + G_n$		2	3	4
LHC		$4 - 8.9$	$4.5 - 6.8$	$5.0 - 5.8$

Determination of model parameters: fundamental Planck scale M_D, number of extra dimensions δ, brane tension Δ

from energy dependence of cross section, requires LC running at 3 widely separated values of $\sqrt{s}$ or accurate determination of missing E_T spectrum at LHC $+$ one LC point for normalisation

LHC mono-jet signal for graviton emission (left), energy dependence of cross section for graviton production at LC (right)





Randall Sundrum model with brane curvature terms

Brane quantum effects generate Brane Localised Kinetic Terms (BLKT)

BLKT are present in gravitation action and modify graviton KK spectrum and couplings

$\Rightarrow$ graviton resonances can become very narrow and may be missed in a general search at the LHC

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

7. Electroweak and QCD precision physics

Top physics

[*E. Boos, A. Sherstnev, S. Slabospitsky, Z. Sullivan, S. Weinzierl '03*]

Single top at LHC and LC (at LC particularly important in $e\gamma$ mode):

$\Rightarrow$ measure both $|V_{tb}|^2$

Precise measurement at LC $\Rightarrow$ input at LHC for $qb \to q't$

$\Rightarrow$ measurement of b-quark distribution function of the proton

Rare top decays: better statistics at the LHC, smaller backgrounds at LC, sensitivity to BR's of $\mathcal{O}(10^{-6})$

Prospective sensitivity to FCNC interactions:

$t \to$	Tevatron Run II	LHC decay	LHC production	e^+e^- $\sqrt{s} > 500$ GeV
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

QCD

[*T. Binoth, A. De Roeck, L. Orr, W. Stirling '03*]

Measurement of $\alpha_{\rm s}$

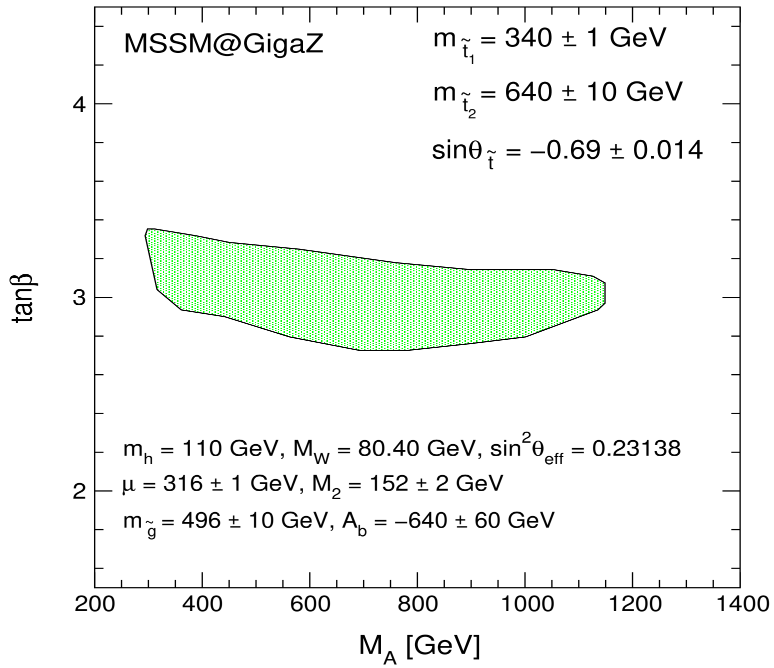
BFKL physics

Improving the $H \to \gamma\gamma$ background by using combined collider data

Electroweak physics

[*U. Baur, S. Heinemeyer, S. Kraml, W. Porod, G. W. '03*]

Constraints on $\tan\beta$ and M_A from measurements of SUSY particles at LHC and LC, m_h, and GigaZ measurements



Triple gauge-boson couplings: anomalous coupling Δg_1^Z can be measured independently at LHC and LC with similar precision

8. Conclusions

- Topics covered in this talk are just a small survey, there are many more examples where LHC and LC can successfully work hand in hand
- LHC / LC Study Group has started last year

  A first working group document is currently being compiled
- Work does not stop here – we have just scratched the surface so far; certainly more ideas will come when we dig a bit deeper
- LHC / LC interplay is a very rich field – and a lot of fun