Towards a first LHC / LC working group document

The LHC / LC Study Group

Georg Weiglein

IPPP Durham

Les Houches, 06/2003

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

1. Introduction

Aim of the LHC / LC Study Group: investigate how analyses at the LHC could profit from results obtained at a LC and vice versa

- Started in spring 2002, truly world-wide effort
- Collaborative effort of Hadron Collider (HC) and Linear Collider (LC) community
- Study Group meanwhile officially recognized by International Linear Collider Steering Committee (ILCSC)
- Currently about 190 working group members from ATLAS, CMS, LC working groups, theory + Tevatron contact person
- Working group coordination: R. Godbole, F. Paige, G. W.
- Web page: `www.ippp.dur.ac.uk/~georg/lhclc`

What is it about?

- Physics case well established for LHC and LC:

  different characteristics of the two machines give rise to different virtues

- It is not the aim of the LHC / LC Study Group to compare (or even fight about) which collider can do what better

- One of the purposes of this study is to make LHC experimentalists aware when designing their analyses of what kind of additional informations they might get once the LC kicks in

- Interplay between HC and LC can happen at different levels:

  Combined interpretation of HC and LC data:

$$\mathrm{HC} \oplus \mathrm{LC} > \mathrm{HC} + \mathrm{LC}$$

  Combined analyses of HC and LC data:

$$\mathrm{HC} \otimes \mathrm{LC} > \mathrm{HC} \oplus \mathrm{LC}$$

Status of the first working group document

Nearly all promised contributions have been submitted or are about to be submitted

Contributions are with the editors responsible for the different sections: some iterations, merging, rewriting going on

Detailed Introduction section ("synopsis") under way

First complete draft to be finished soon after Les Houches

Report should appear on hep-ph/hep-ex,
'hybrid' CERN/DESY/Fermilab/KEK/SLAC . . . report?

Editors for different parts of the document:

1. Introduction:

Experimental aspects of LHC / LC, interplay of particle physics and cosmology, . . .
Daniel Denegri, Fabiola Gianotti, Francois Richard, Heidi Schellman

Aim of Study Group, summary of main results
All

2. Electroweak Symmetry Breaking (Weakly)

Albert De Roeck, Howie Haber, Rohini Godbole, G. W.

3. Strong Electroweak Symmetry Breaking

Tim Barklow, Klaus Mönig

4. Supersymmetric Models

Klaus Desch, Kiyotomo Kawagoe, Frank Paige, Giacomo Polesello

5. New Gauge Theories

Francois Richard, Sabine Riemann

6. Models with Extra Dimensions

JoAnne Hewett

7. Exotics

Jack Gunion

8. Electroweak and QCD Precision Physics

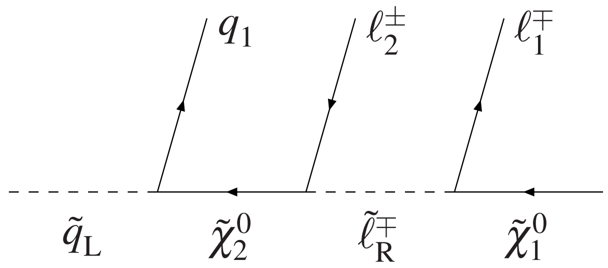
Edward Boos, Sven Heinemeyer, James Stirling

2. SUSY parameters at LHC and LC

Reconstruction of sparticle masses at the LHC

[*B. Gjelsten, E. Lytken, D. Miller, P. Osland, G. Polesello, M. Chiorboli, A. Tricomi*]

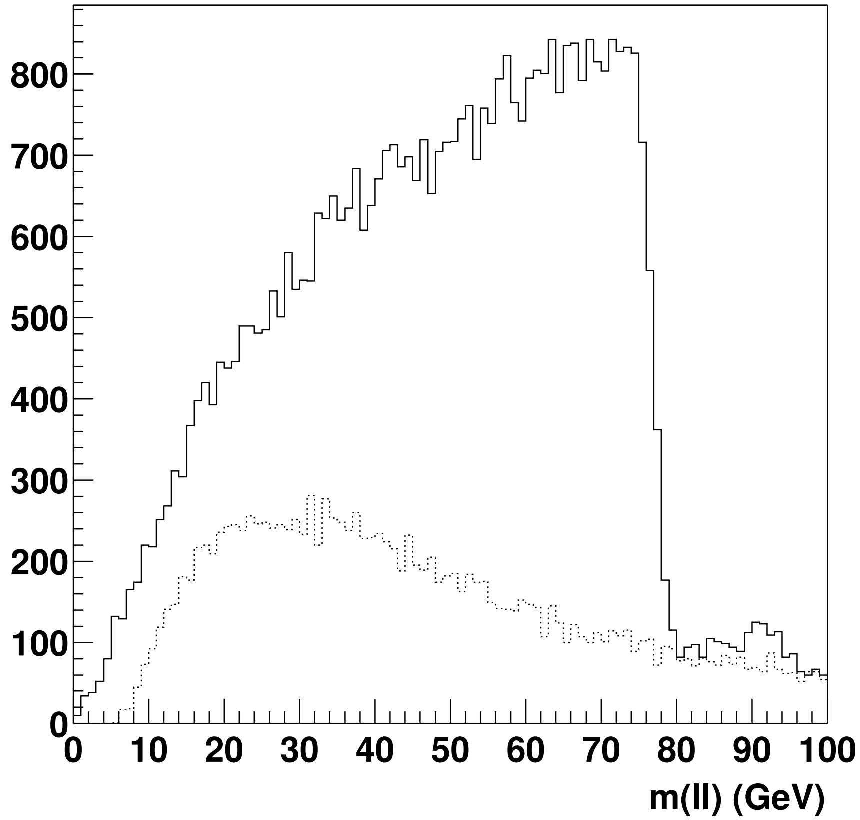
Complicated decay chains for squarks and gluinos

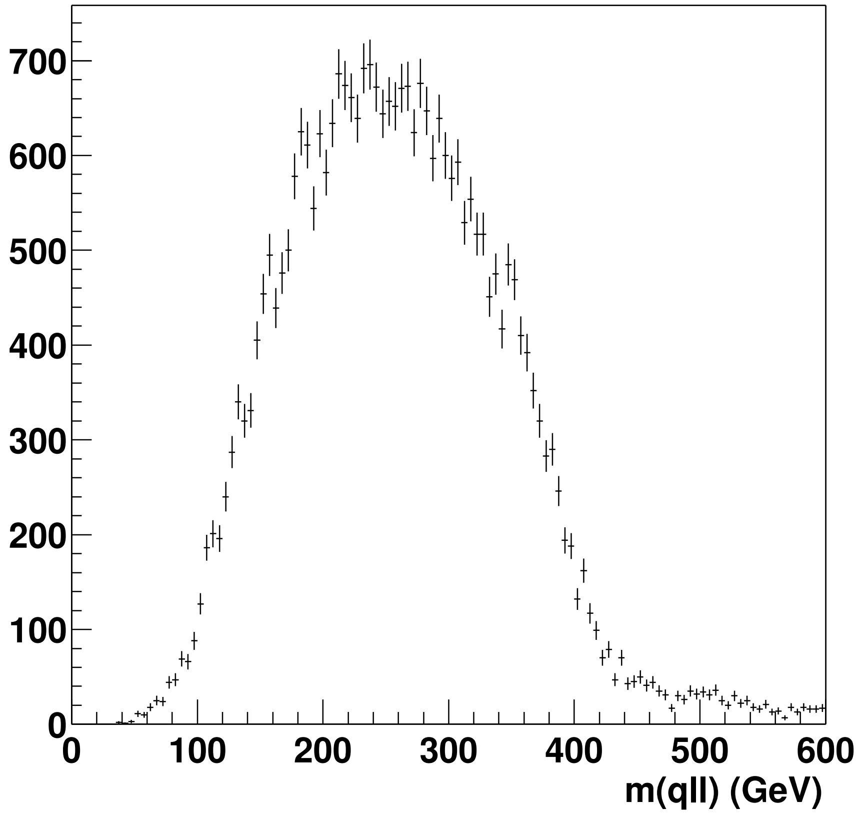


Examples worked out for SPS1a from ATLAS and CMS
main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$

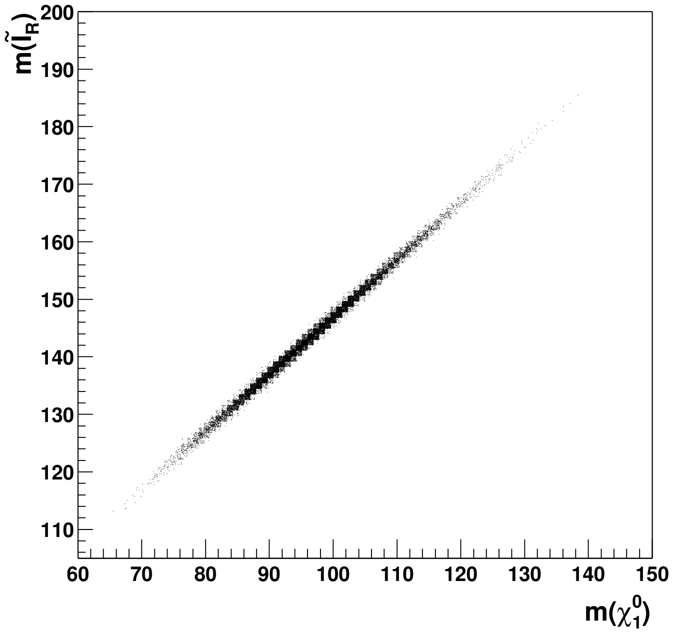
Sbottom/squark and gluino reconstruction:

Edge in same flavour-opposite sign lepton distribution (left), invariant mass distributions with kinematical endpoints (right)





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



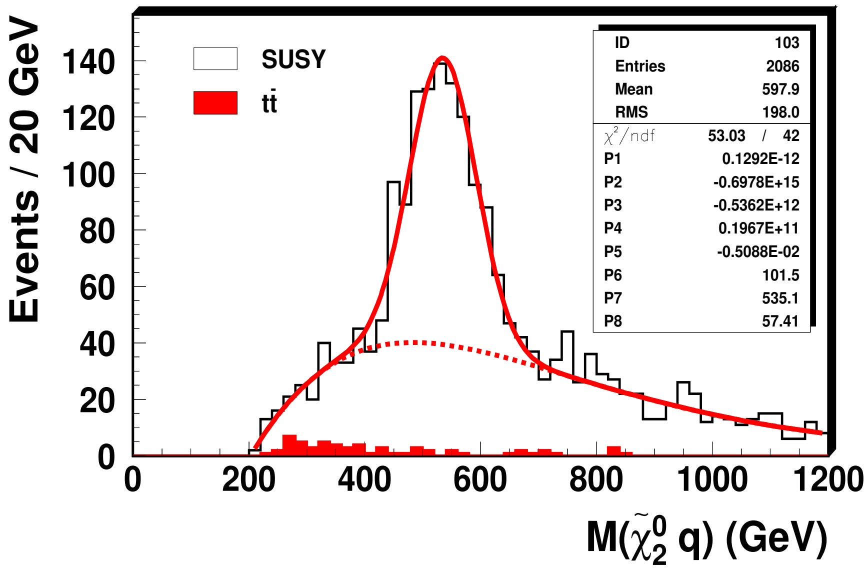
$\Rightarrow$ Take LSP mass as input from LC

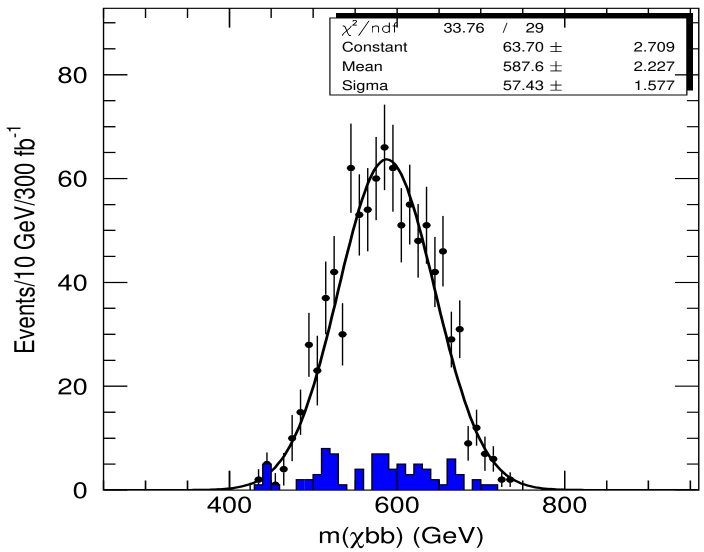
Select events close to the edge and combine with b-jet / q-jet

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

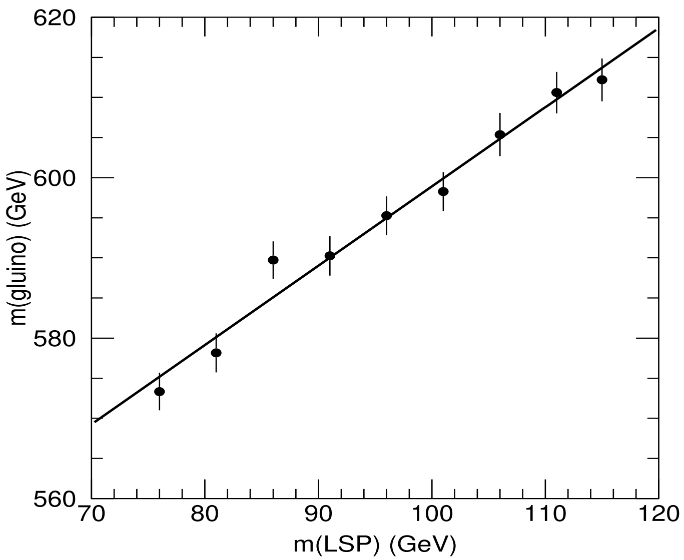
$\Rightarrow$ Get sbottom/squark mass if LSP mass is known

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





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



$\Rightarrow\ \Delta m_{\tilde{g}} \approx \Delta m_{\mathrm{LSP}}$

Accuracies for the case of the LHC alone (left) and with the LC measurement of the LSP mass with 0.2% accuracy (middle) and 1.0% accuracy (right column) in GeV:

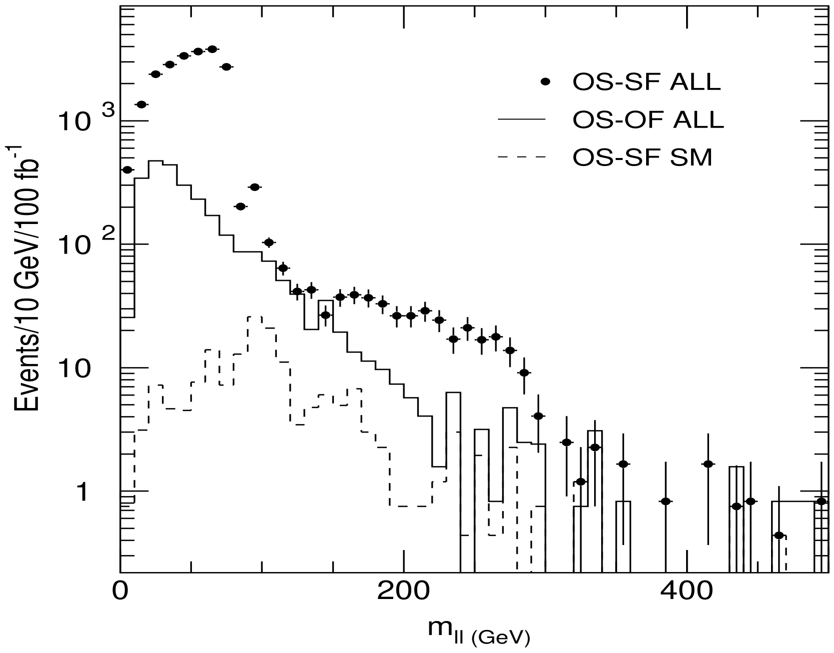
	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{\chi}_1^0}$	9.2	0.2	1.0
$\Delta m_{\tilde{l}_R}$	9.2	0.5	1.0
$\Delta m_{\tilde{\chi}_2^0}$	9.0	0.3	1.0
$\Delta m_{\tilde{b}_1}$	23.1	16.9	17.0
$\Delta m_{\tilde{q}_L}$	15.0	5.1	5.3

$\Rightarrow$ LC input improves accuracy significantly

One step further:

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

[*J. Kalinowski, G. Moortgat-Pick, M. Nojiri, G. Polesello*]



⇒ Need besides LSP mass also masses of sleptons and charginos from LC in order to correctly identify $\tilde{\chi}^0_4$

⇒ Feeding $m(\tilde{\chi}^0_4)$ back into LC analysis improves accuracy of parameter determination at the LC

Even further:

Full reconstruction of stop/sbottom parameters with LHC $\otimes$ LC

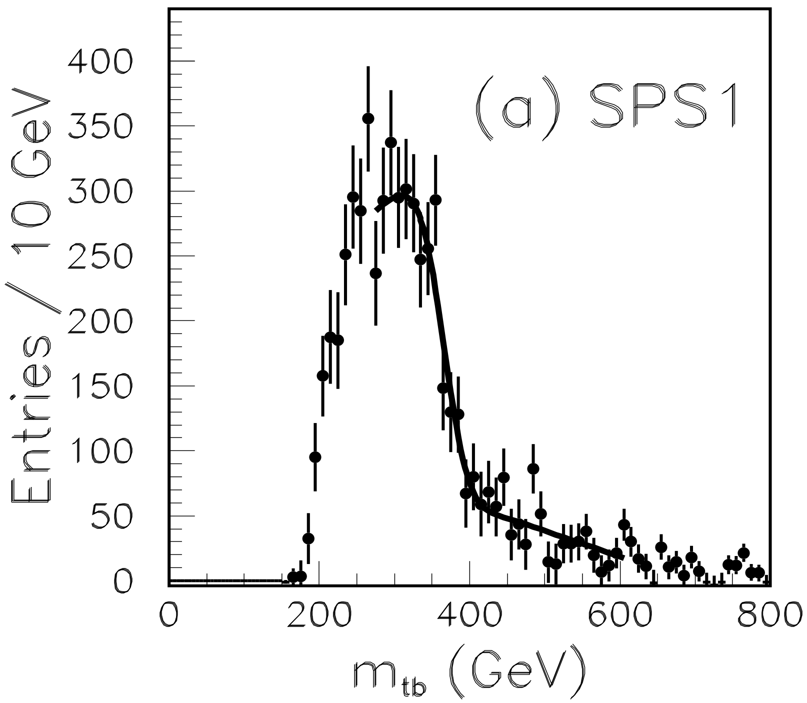
[*J. Hisano, K. Kawagoe, M. Nojiri*]

Complete set of electroweak SUSY parameters (from LC) and branching ratios used to exploit LHC rate measurements

Stop/sbottom sector determined by 5 parameters, e.g. $m_{\tilde{\mathrm{b}}_1}$, $m_{\tilde{\mathrm{b}}_2}$, $m_{\tilde{\mathrm{t}}_1}$, $\theta_{\tilde{\mathrm{b}}}$, $\theta_{\tilde{\mathrm{t}}}$

- Take $m_{\tilde{\mathrm{b}}_1}$, $m_{\tilde{\mathrm{b}}_2}$ from previous study
- $\Rightarrow$ need three more observables:
  - tb invariant mass distribution
  - rate of "edge-events" in m_{tb} distribution (chargino chain)
  - rate of events in $\ell\ell b$ distribution ($\tilde{\chi}_2^0$ chain)

m_{tb} distribution for SPS1a:

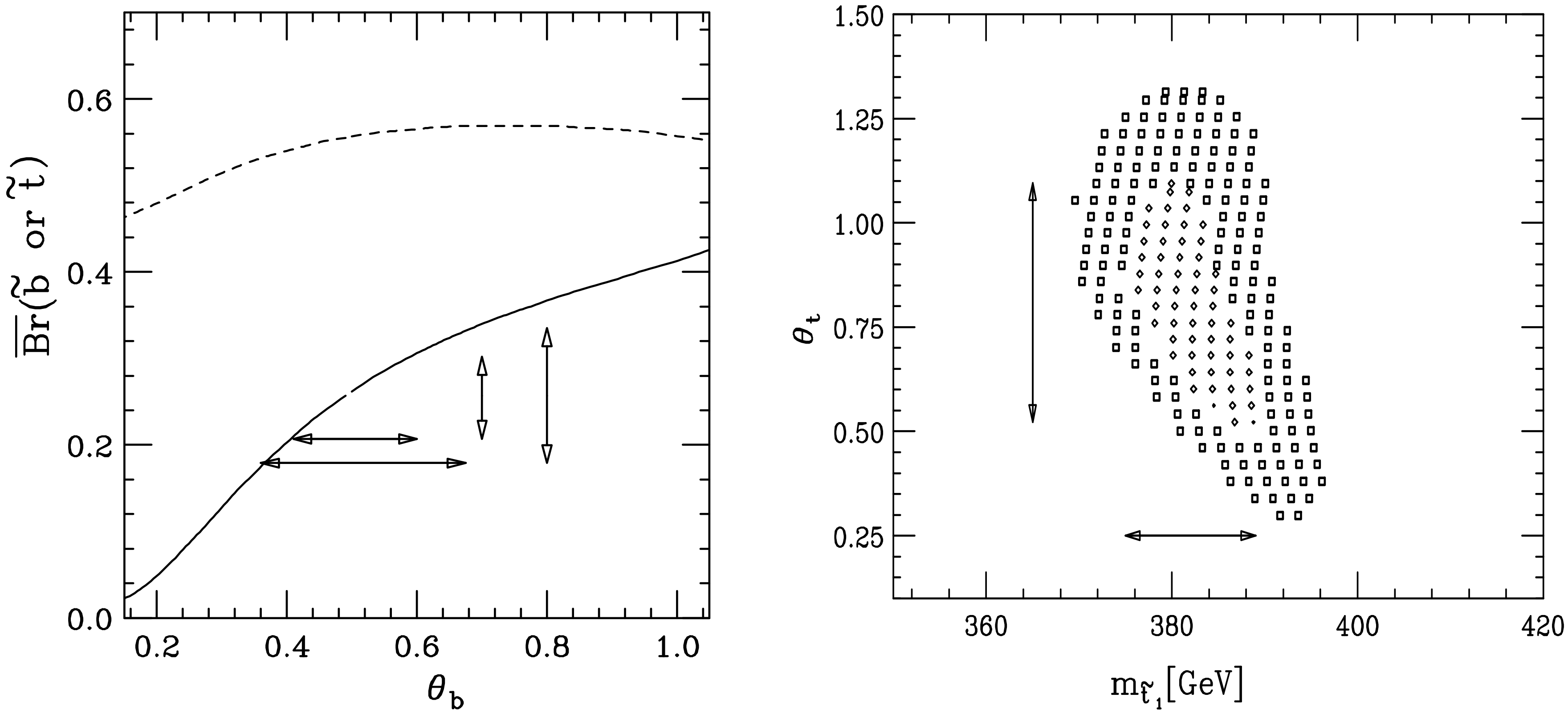


Involved couplings are stop–sbottom–W, top–sbottom–chargino and stop–bottom–chargino

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

Determination of $\theta_{\tilde{b}}$ from $\mathrm{BR}(\tilde{g} \to b\tilde{b}_2 \to bb\tilde{\chi}_2^0)/\mathrm{BR}(\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0)$ in SPS1a, sbottom masses and parameters of chargino/neutralino sector are assumed to be known (left)

Determination of $m_{\tilde{t}_1}$, $\theta_{\tilde{t}}$ assuming also $\theta_{\tilde{b}}$ is known (right)



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

Results used for:

mSUGRA fit to LHC $\oplus$ LC data in SPS1a

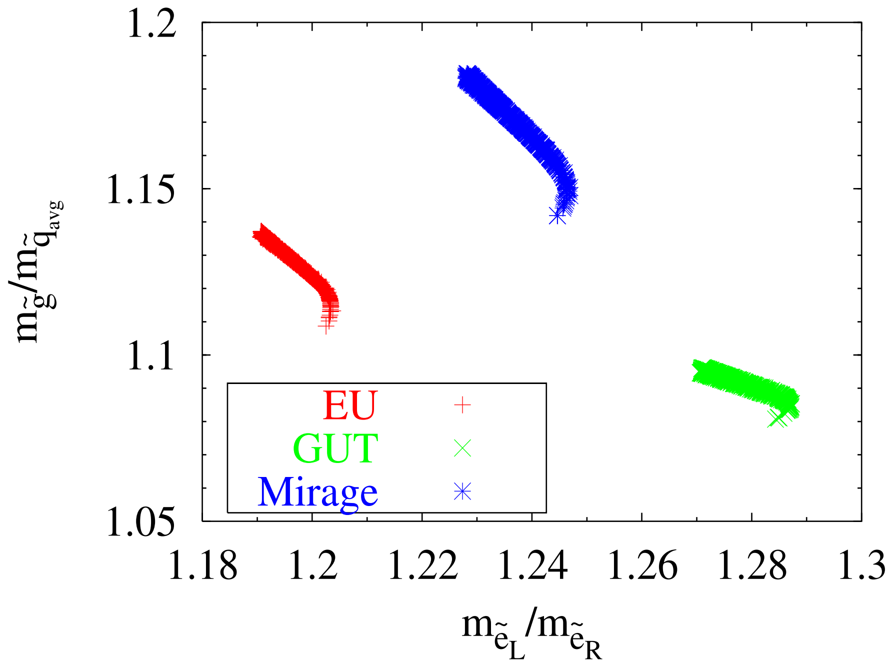
[*B. Allanach, S. Kraml, W. Porod*]

LHC / LC complementarity in mSUGRA fits

[*D. Tovey*]

Discrimination between different SUSY-breaking scenarios

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



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

Extrapolation to physics at high scales

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

3. Higgs physics

$\tan\beta$ determination at LHC $\oplus$ LC

[*J. Gunion, T. Han, J. Jiang, A. Sopczak*]

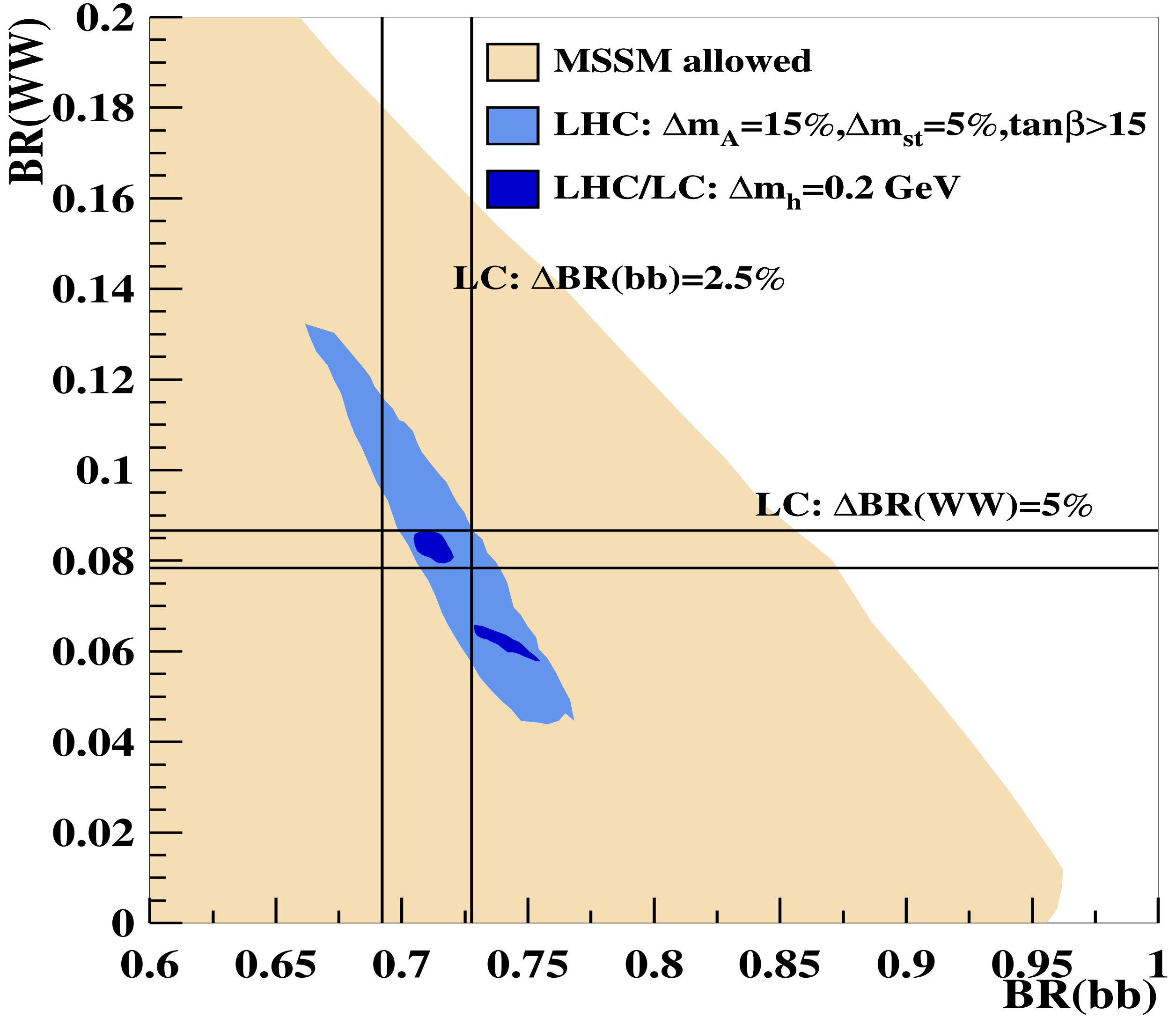
Combination of LHC data on heavy Higgs states with LC data on the light $\mathcal{CP}$-even Higgs

[*K. Desch, S. Heinemeyer, G.W.*]

Assume: LHC information on M_A, $\tan\beta$ $\oplus$ (LHC $\otimes$ LC) information on stop/sbottom masses $\oplus$ LHC / LC measurement of m_h:

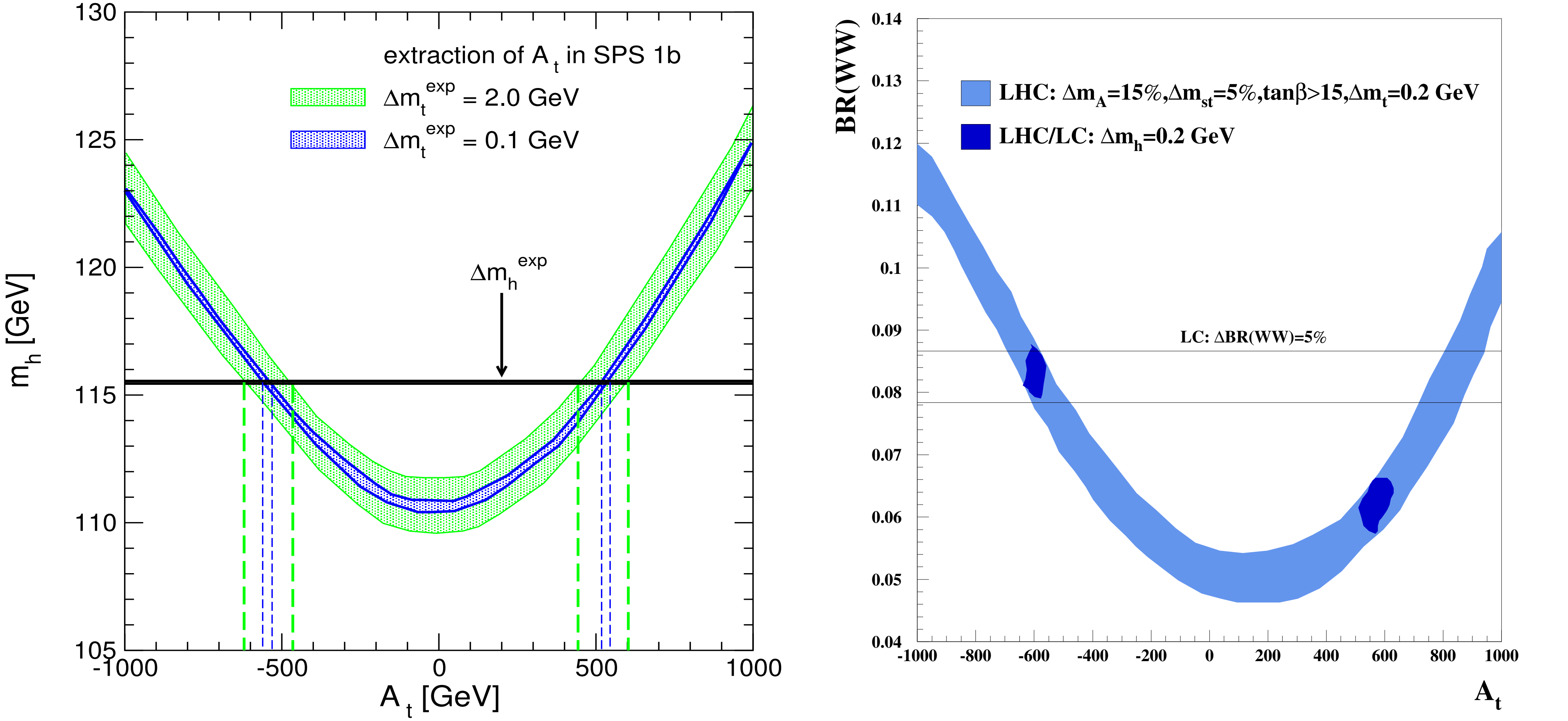
M_A: 15% accuracy, $m_{\tilde{\mathrm{t}}_1}, m_{\tilde{\mathrm{t}}_2}, m_{\tilde{\mathrm{b}}_1}, m_{\tilde{\mathrm{b}}_2}$: 5% accuracy, $\tan\beta > 15$

BR($h \to b\bar{b}$): 2.5% accuracy, BR($h \to WW^*$): 5% accuracy



⇒ Comparison of MSSM prediction based on assumed inputs with BR's measured at the LC yields very sensitive test of the model

$\Rightarrow$ Indirect determination of trilinear coupling A_t:



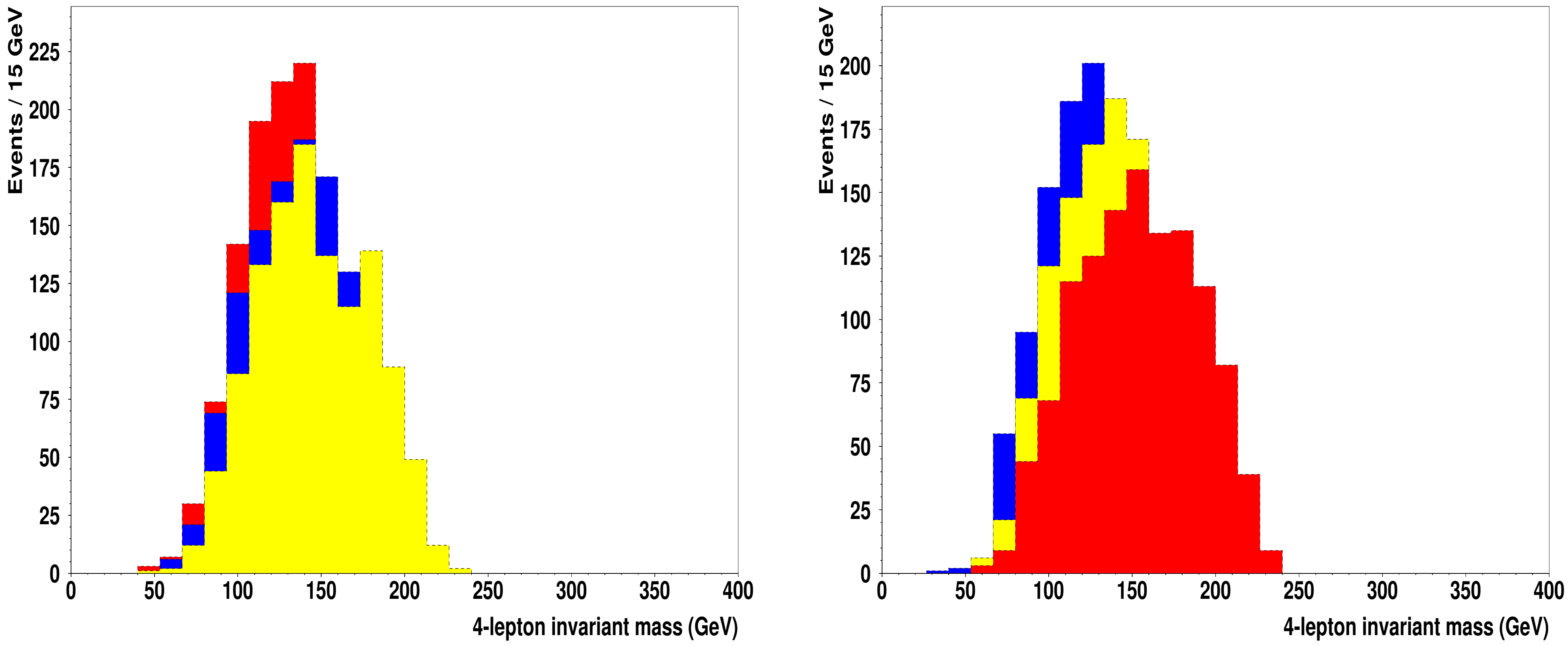
Precise measurement of m_t at the LC crucial, $\delta m_t \lesssim 100$ MeV

Δm_t^{LC} vs. Δm_t^{LHC} $\Rightarrow$ accuracy of A_t determination improved by factor 3

Heavy Higgs decays into SUSY particles at the LHC with LC input on LSP mass

[*F. Moortgat*]

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



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

$\mathcal{CP}$ studies in the Higgs sector:

[*R. Godbole, S. Kraml, M. Krawczyk, D.Miller*]

So far only few studies of $\mathcal{CP}$-violating Higgs phenomenology at LHC, LC

LHC / LC document summarises status of current studies pointing out what analyses are required to address the LHC $\otimes$ LC issue

Two aspects:

– Establishing $\mathcal{CP}$ nature of $\mathcal{CP}$-even/odd states

– Higgs sector phenomenology with mixing between $\mathcal{CP}$-eigenstates

$\Rightarrow$ More experimental simulations needed

$\mathcal{CP}$-violating effects depend on sparticle spectra $\Rightarrow$ need correlated study of sparticle phenomenology and $\mathcal{CP}$-violating Higgs effects in context of LHC / LC interplay

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
[*F. Moortgat*]

Fermiophobic Higgs:

[*A. Akeroyd, M. Diaz*]

Fermiophobic Higgs, also VVh coupling can be suppressed in general 2HDM

$\Rightarrow$ Production both at LHC and LC in associated production:
$pp \to H^{\pm}h, Ah,\ e^{+}e^{-} \to Ah$

Higgs physics in the NMSSM:

[*U. Ellwanger, J. Gunion, C. Hugonie, S. Moretti*]

Situation where the only light non-singlet Higgs decays into two $\mathcal{CP}$-odd scalars

⇒ The channel $WW \to h \to AA$ increases the discovery range for the NMSSM Higgs at the LHC

⇒ Establish the signal also at the LC: $e^+e^- \to \nu\nu WW \to \nu\nu h \to \nu\nu AA$

Higgs coupling measurements

Higgs self couplings:
[*U. Baur, T. Plehn, D. Rainwater*]

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

Top Yukawa coupling:

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

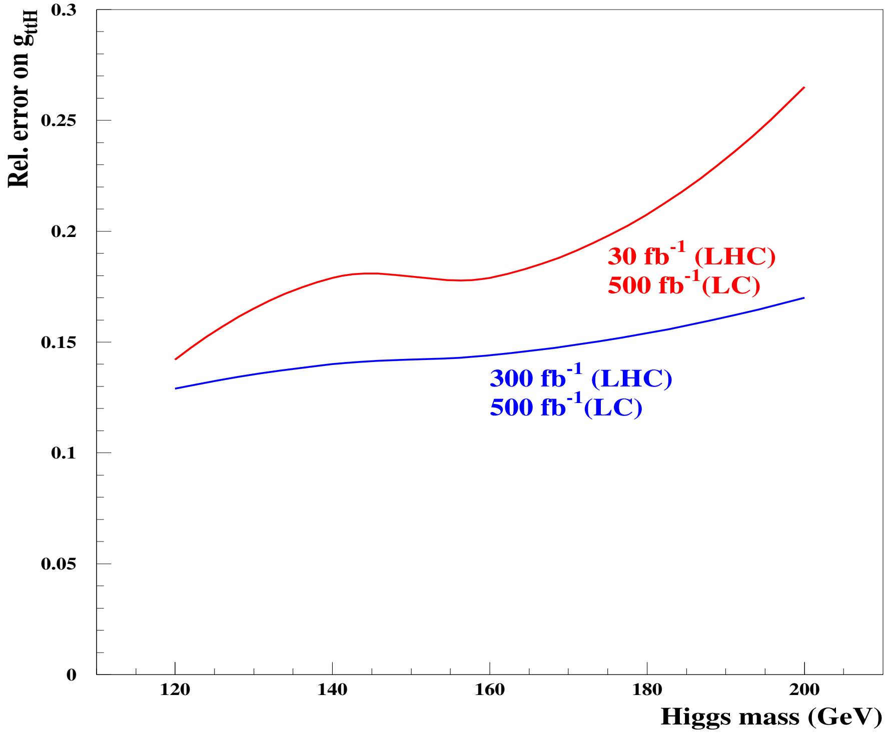
Only preliminary measurement of tth coupling at 500 GeV LC for light Higgs

Precision measurement requires LC with 800-1000 GeV

LHC measures ($\sigma \times$ BR)

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

Combination of measurements at LHC and a LC running at $\sqrt{s} = 350$ GeV:

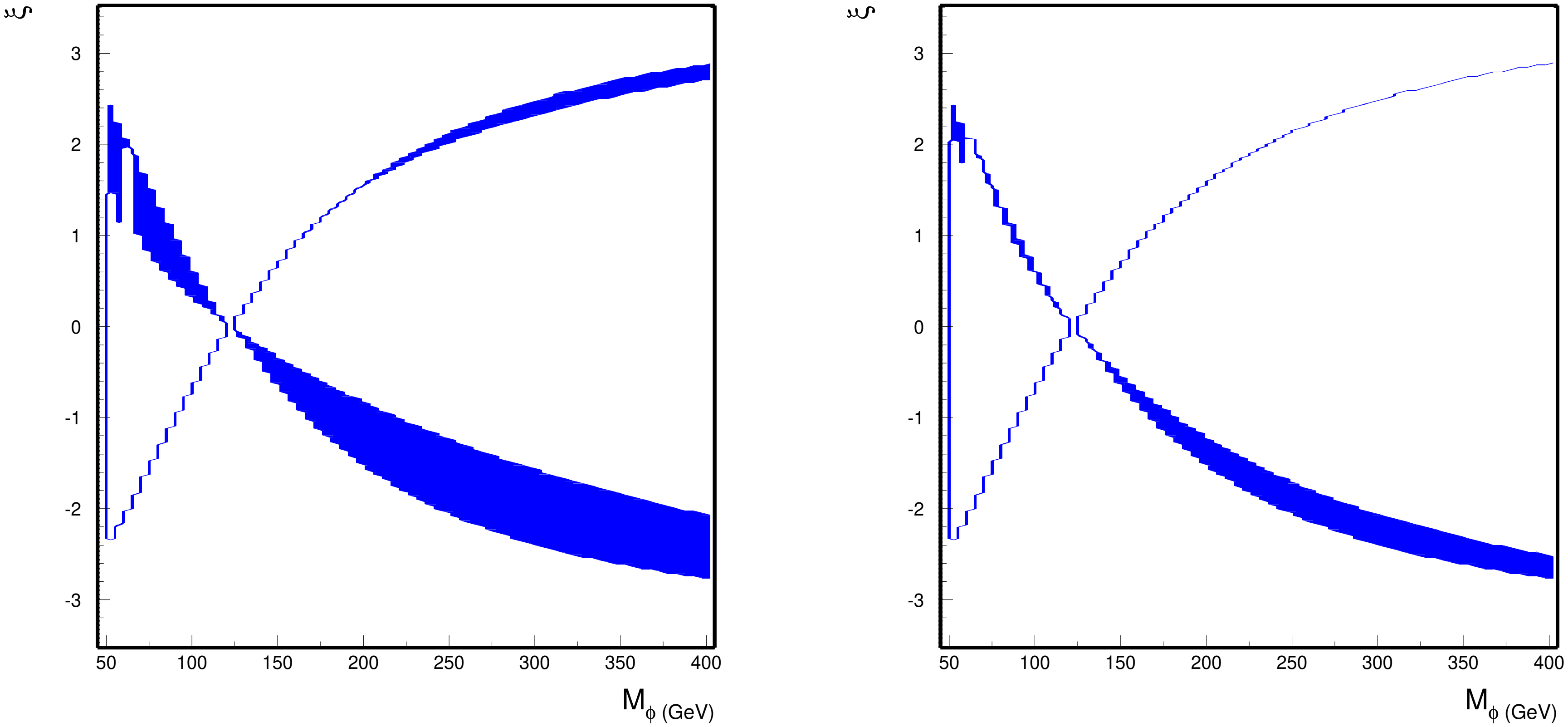


Higgs and radion searches at LHC and LC:

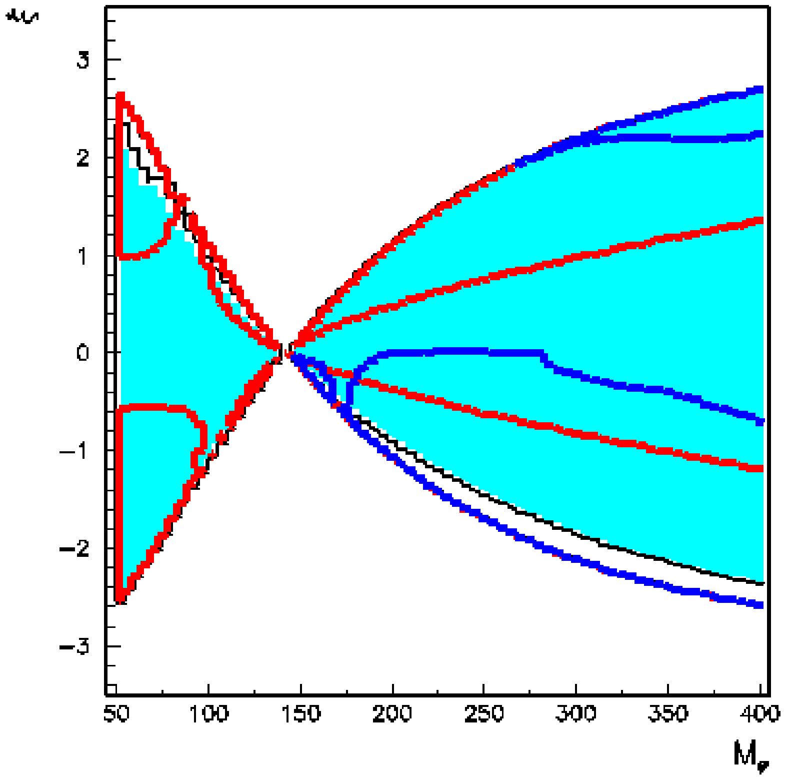
[*M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici, J. Gunion*]

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

Parameter regions where Higgs significance is below 5σ at the LHC with 30 fb^{-}1 (left) and 100 fb^{-}1 (right):



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:



Hidden Higgs in extra-dimensional Models

[*A. Aranda, C. Balázs, J.L. Díaz-Cruz*]

Scenario in TeV^{-}1 size extra-dimensional model where Higgs production at LEP and Tevatron is suppressed but greatly enhanced at LHC and LC

4. Strong electroweak symmetry breaking

[*M. Arneodo, T. Barklow, S. Boogert, G. Cerminara, W. Kilian, C. Mariotti, K. Mönig, A.F. Osorio, G. Passarino*]

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 $1/16\pi^2$

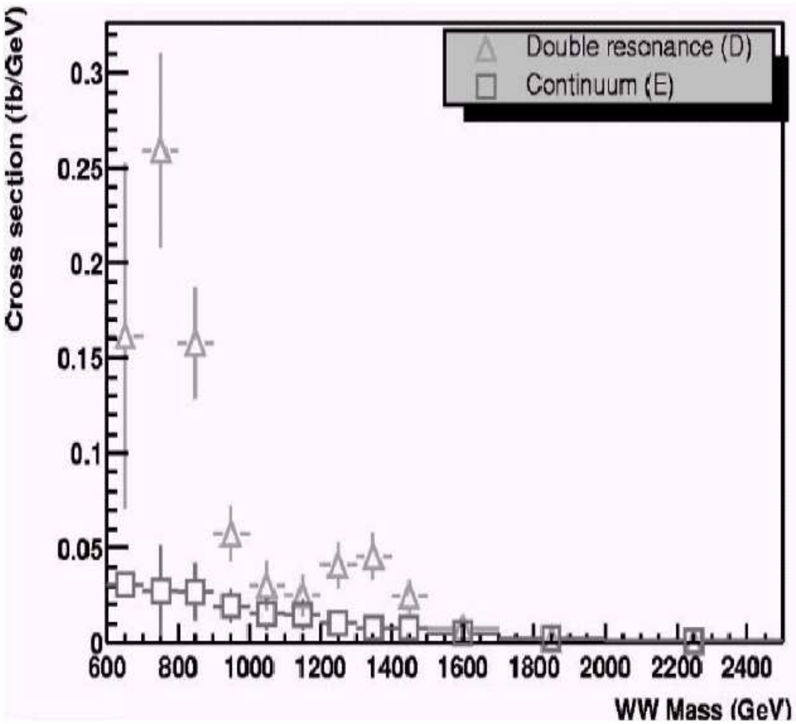
Resonances at high energy only directly accessible at the LHC; combination with sub-TeV data of LC on cross-section rise essential for disentangling new states

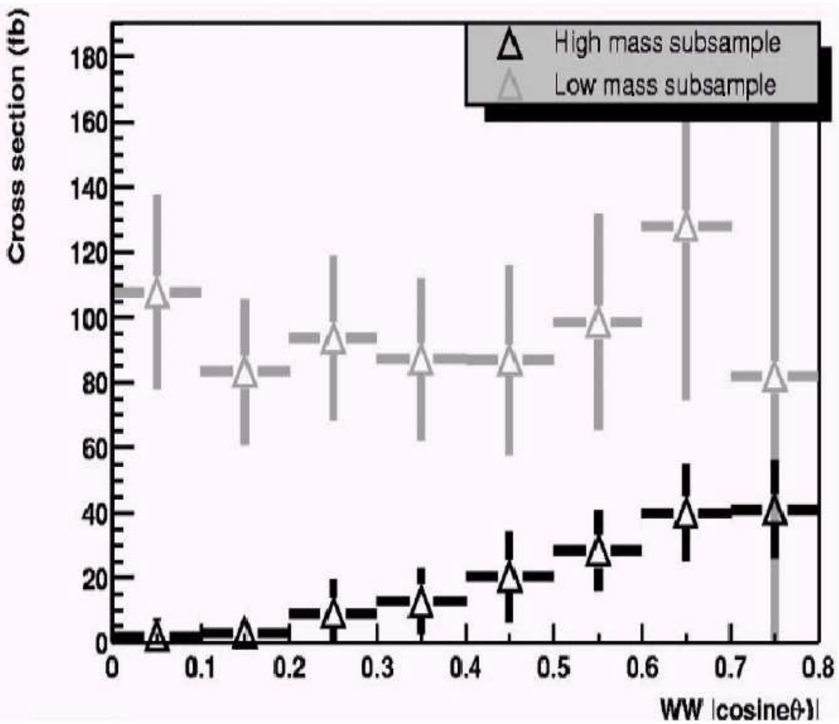
LHC $WW \to jjl\nu$ $L = 100\ fb^{-1}$

Differential Cross Section Measurements

Double resonance (D) : 0.8 TeV Scalar & 1.4 TeV Vector Resonances

Continuum (E): Non-resonant strong WW scattering



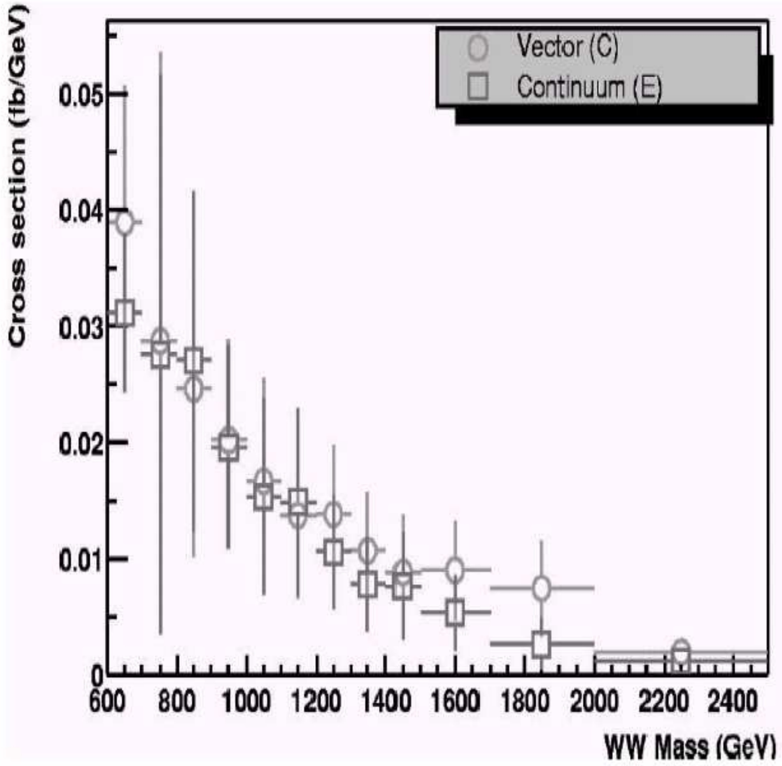


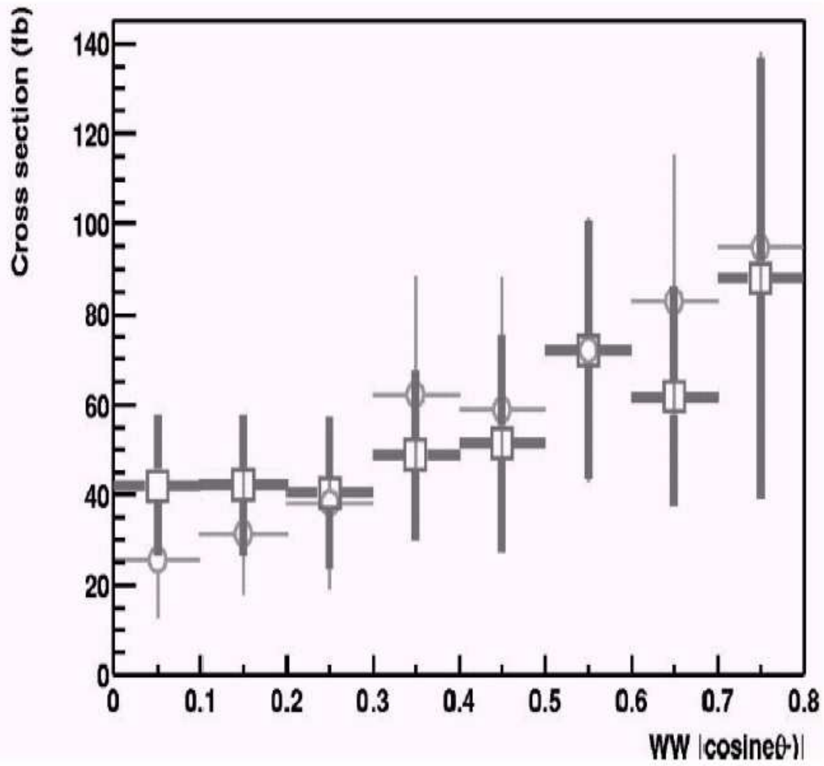
LHC $WW \to jjl\nu$ $L = 100\ fb^{-1}$

Differential Cross Section Measurements

Vector (C): 1.9 TeV Vector Resonance

Continuum (E): Non-resonant strong WW scattering





LC $e^+e^- \to W^+W^-$ $\sqrt{s} = 500\,GeV$ $L = 500\,fb^{-1}$

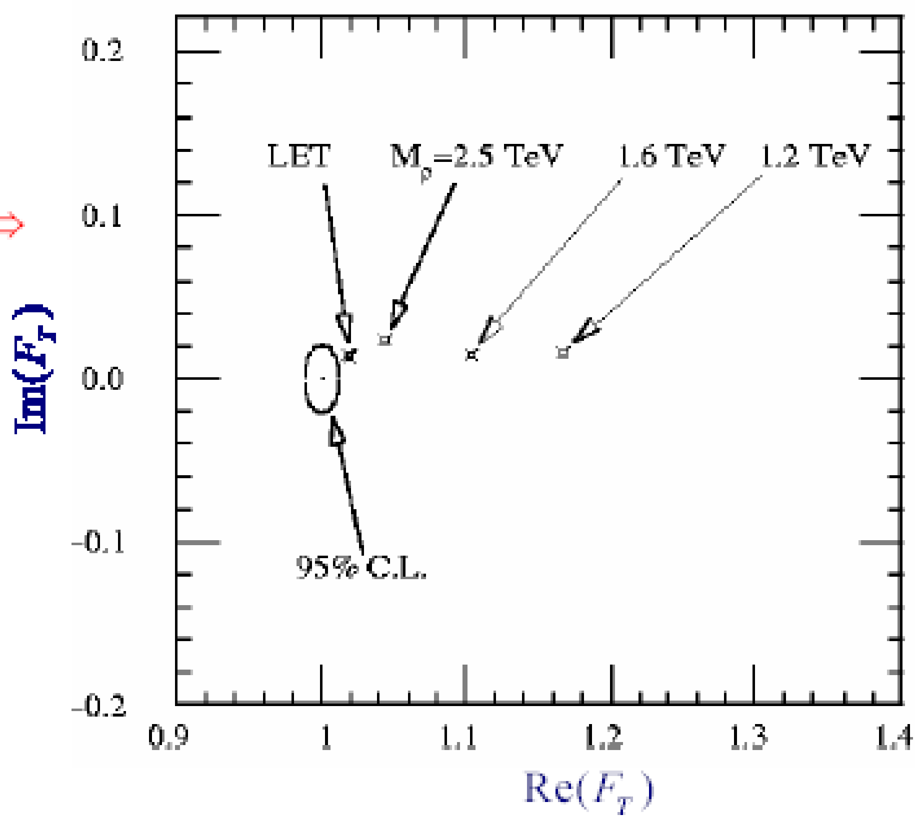
Form Factor for Vector Resonance Enhancement of $e^+e^- \to W_L^+W_L^-$

$$F_T = \frac{M_\rho^2 - i\Gamma_\rho M_\rho}{M_\rho^2 - s - i\Gamma_\rho M_\rho}$$

17σ signal for 1.9 TeV vector resonance $\Rightarrow$

4σ LET signal if resonance is a scalar

$M_\rho (TeV)$	$\frac{\Delta M_\rho}{M_\rho}(\%)$	$\frac{\Delta \Gamma_\rho}{\Gamma_\rho}(\%)$
1.0	0.58	1.90
1.5	1.84	6.00



5. New gauge theories

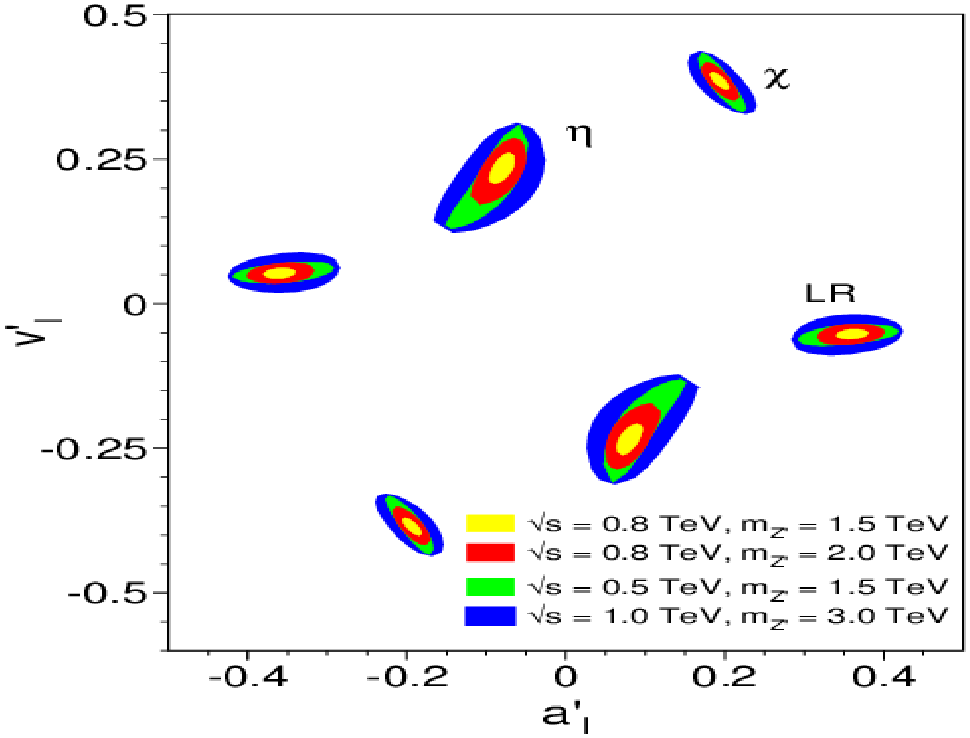
[*D. Bourilkov, S. Godfrey, J. Hewett, F. Richard, S. Riemann, T. Rizzo*]

Discovery of extra gauge bosons at LHC $\oplus$ large indirect reach of the LC

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

Measurement of Z' Couplings

Ideal case: LHC finds a Z', $M_{Z'} < 4.5$ TeV



Sensitivity to contact interactions and extra dimensions at LHC $\oplus$ LC

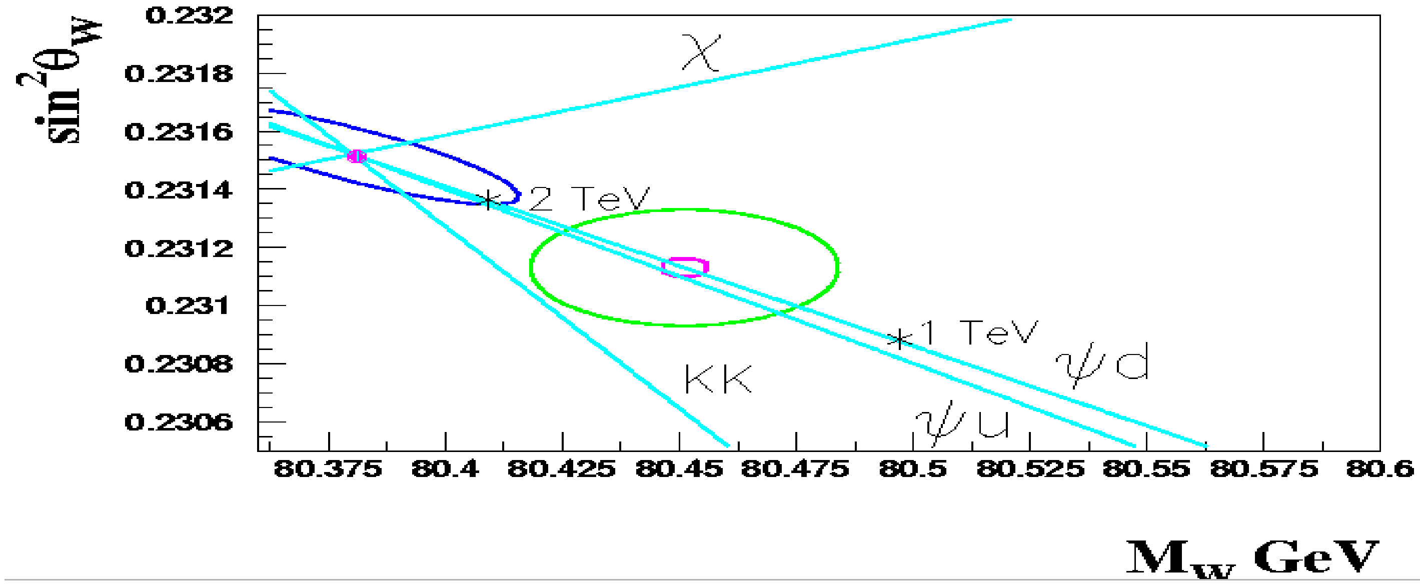
Distinction between Z' and KK excitation:

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}, $\sin^2\theta_{\mathrm{eff}}$ at GigaZ to predictions of different models: E6 vs. KK

GigaZ vs. current accuracy



Little Higgs scenario:

LH Scenario at LHC/FLC

- 'A Higgs with mH> 300 GeV has been seen at LHC and nothing else' (Bh and Zh too heavy)

- 'LEP/SLD inconsistent with SM'

- MSSM or standard Z' cannot help

7. Within LH, GigaZ can predict the mass of Bh and tell if it can be reached at LHC with increased Luminosity

$\Longrightarrow$ Synergy LHC-LC

6. Large extra dimensions

[*C. Balázs, D. Bourilkov, H. Davoudiasl, A. De Roeck, J. Hewett, B. La Forge, T. Rizzo*]

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)

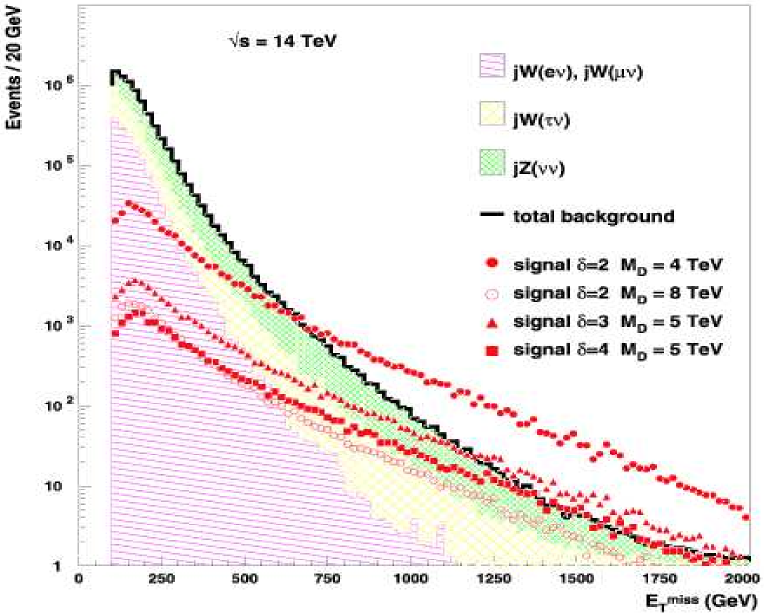
$e^+e^- \to \gamma + G_n$		2	4	6
LC	$P_{-,+} = 0$	5.9	3.5	2.5
LC	$P_- = 0.8$	8.3	4.4	2.9
LC	$P_- = 0.8,\ P_+ = 0.6$	10.4	5.1	3.3
$pp \to g + G_n$		2	3	4
LHC		4 – 8.9	4.5 – 6.8	5.0 – 5.8

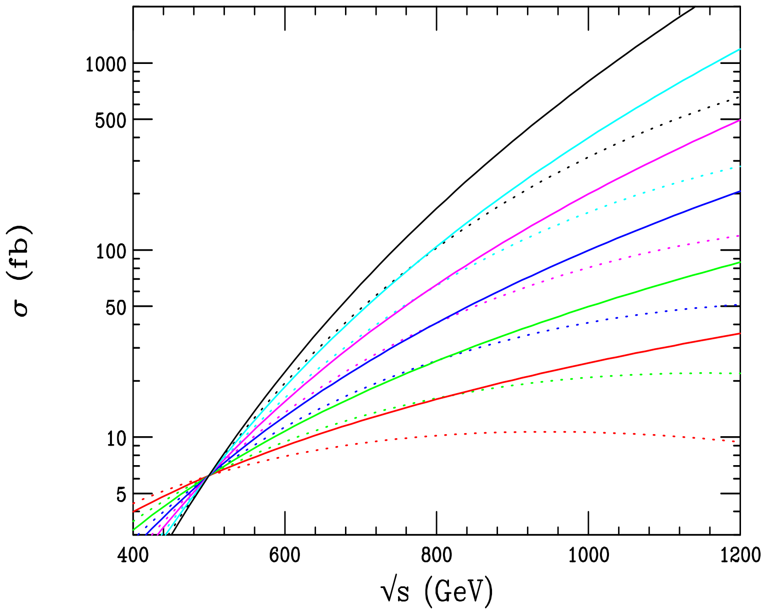
Model parameters: fundamental Planck scale M_D, number of extra dimensions δ, brane tension Δ

determined 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 $\oplus$ one LC point for normalisation

LHC mono-jet signal for graviton emission (left), energy dependence of cross section for graviton production at the 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*]

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

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

Precise measurement at LC can be used as input at LHC for $qb \to q't$

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

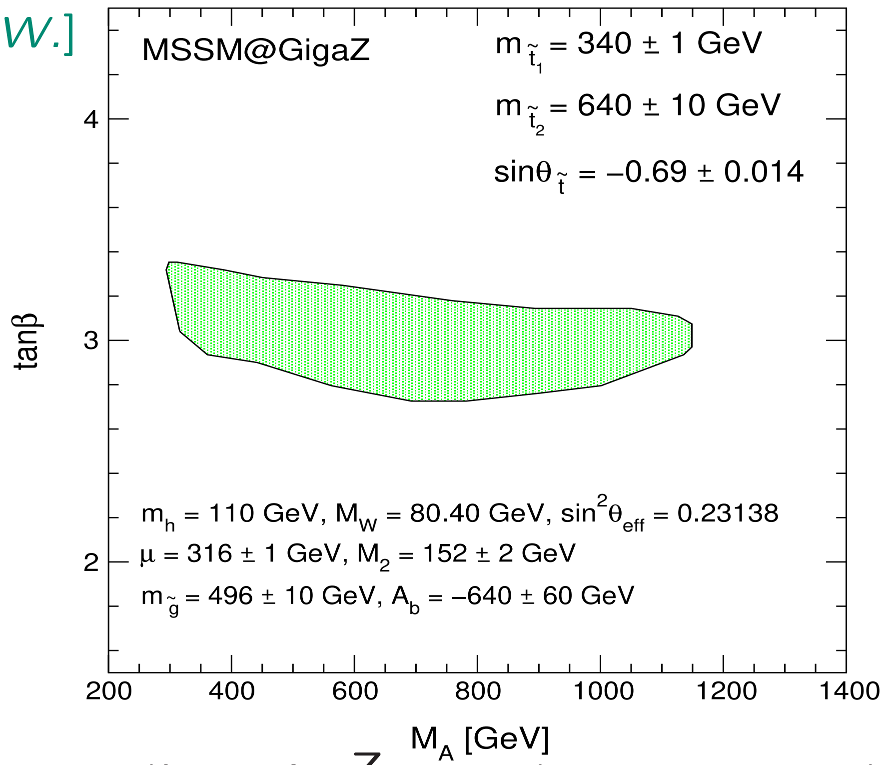
Rare top decays: better statistics at the LHC, smaller backgrounds at LC, sensitivity to BR's of $\mathcal{O}(10^{-6})$

Prospective sensitivity to FCNC interactions:

	Tevatron	LHC		e^+e^-
$t \to$	Run II	decay	production	$\sqrt{s} > 500$ 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}

Electroweak physics

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



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

QCD

[*T. Binoth, D. Bourilkov*]

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

Study of parton density uncertainties

8. Conclusions

- Apologies for the many nice results that I couldn't discuss

- First working group document is on a good way, still a lot of work needed

- The present document is just a first step – we have only scratched the surface so far

  $\Rightarrow$ basis for future work, summarize where we are, give some guidance for future studies

- LHC / LC interplay is a very rich field

Let's further explore it!