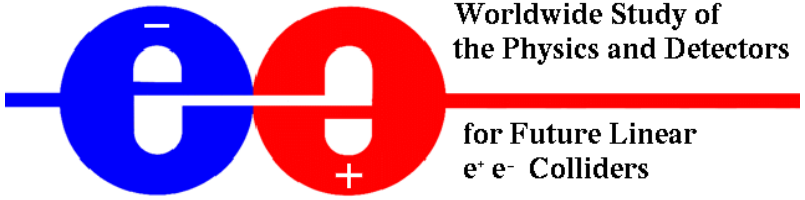
Interplay between LHC and LC

Georg Weiglein

IPPP Durham

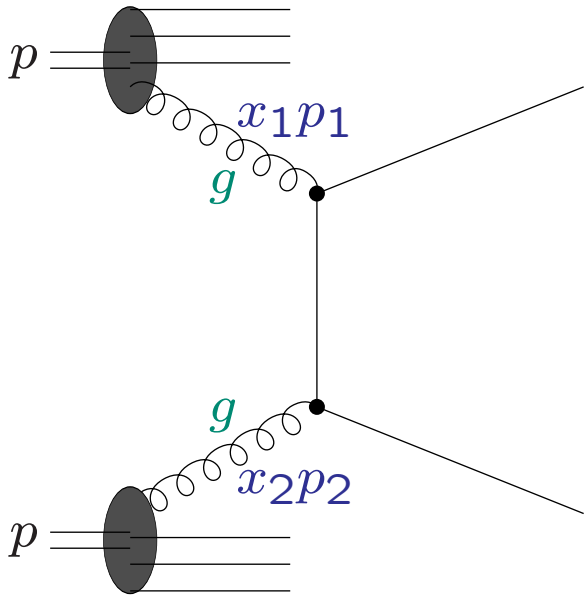
Ambleside, 08/2003



1. Introduction

LHC: pp collider with $E_{\mathrm{CM}} \approx 14$ TeV

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



Available (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: cleaner 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: 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

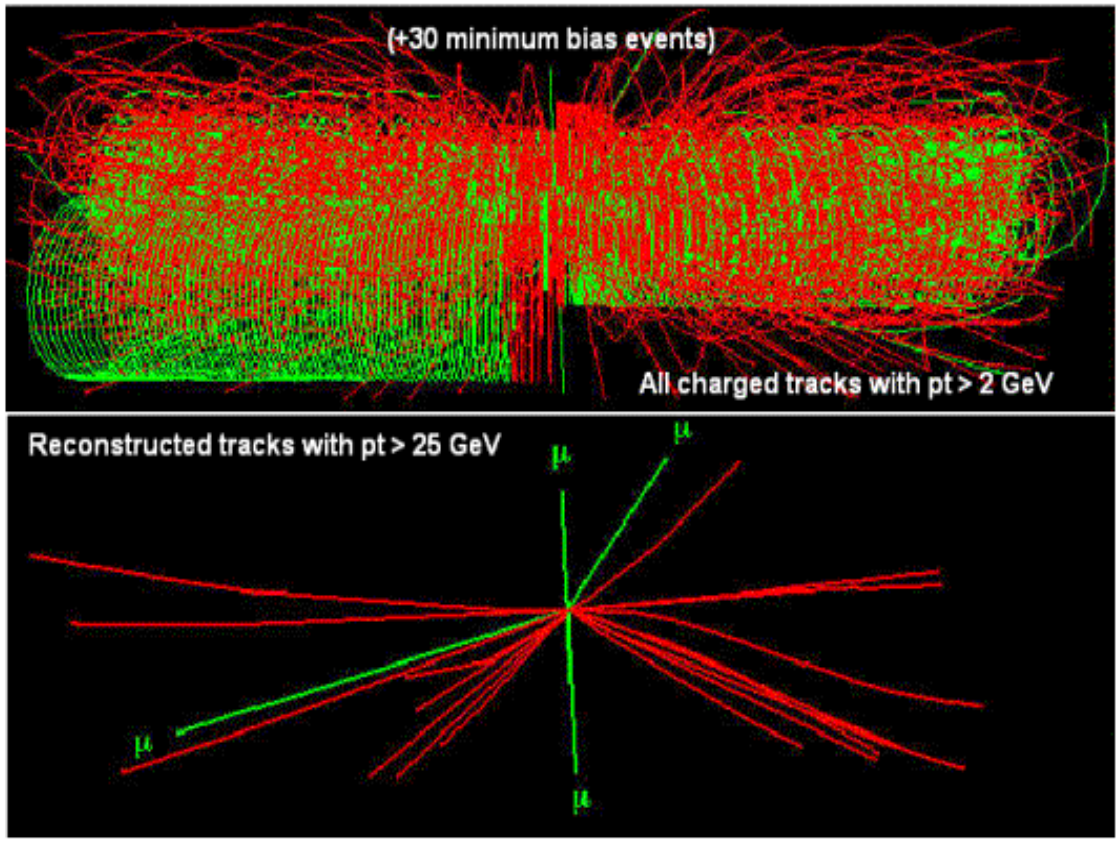
Strongly interacting particles in initial state (mostly gluons)

$\Rightarrow$ 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

SUSY searches at the LHC:

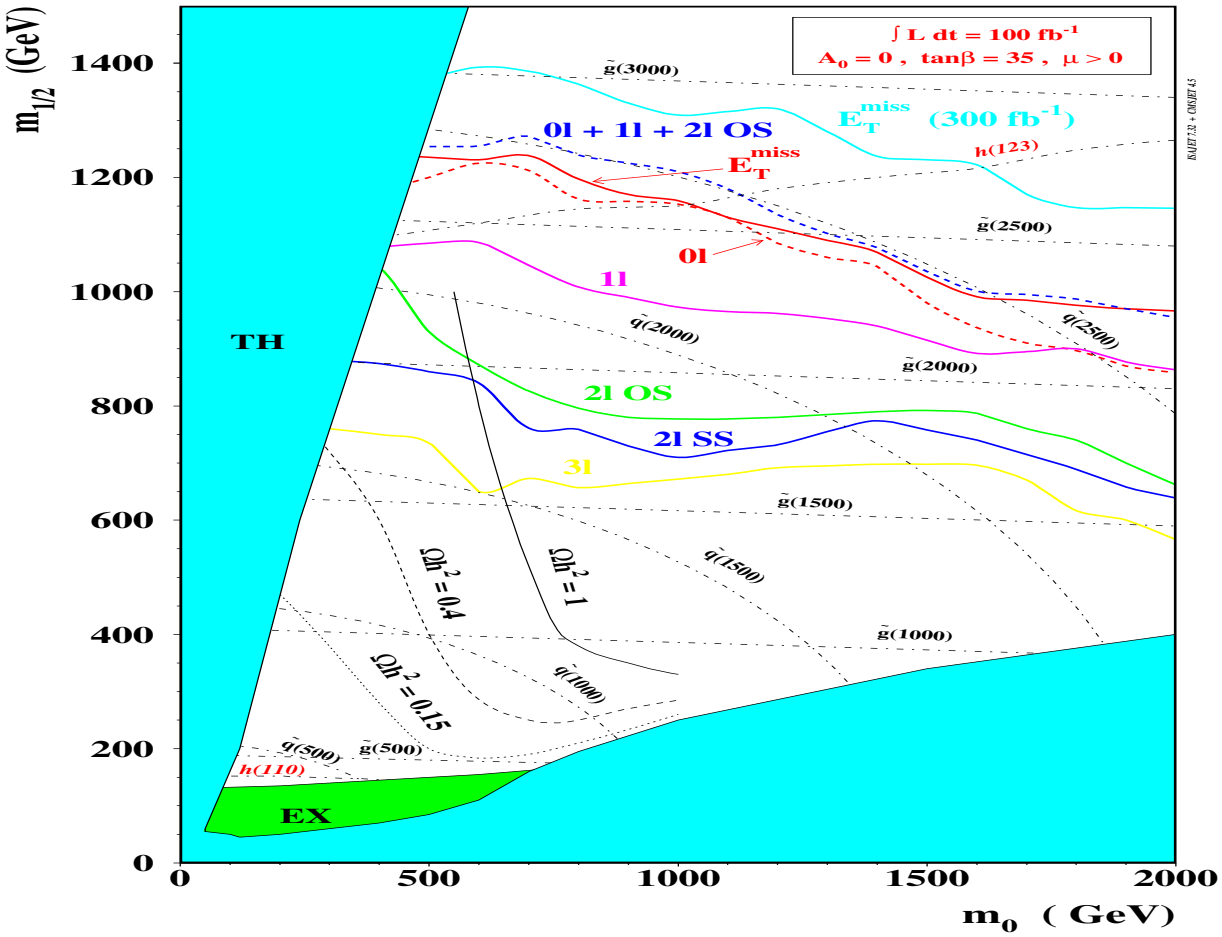
Dominated by production of colored particles: gluinos, squarks

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

...

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

  - establishing SUSY experimentally
  - disentangling patterns of SUSY breaking

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

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

SUSY searches at the 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

Complementarity of LHC and LC:

⇒ Results obtained at one collider can be used for improving experimental analyses at the other

⇒ investigated in "LHC / LC Study Group"

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

Collaborative effort of Hadron Collider (HC) and LC community

Started in spring 2002, currently about 190 working group members from ATLAS, CMS, LC working groups, theory + Tevatron contact person

Interplay between HC and LC can happen at different levels:

Combined interpretation of HC and LC data:

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

Combined analyses of HC and LC data:

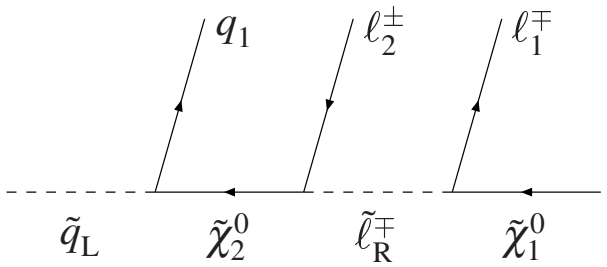
$$\text{HC} \otimes \text{LC} > \text{HC} \oplus \text{LC}$$

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*]

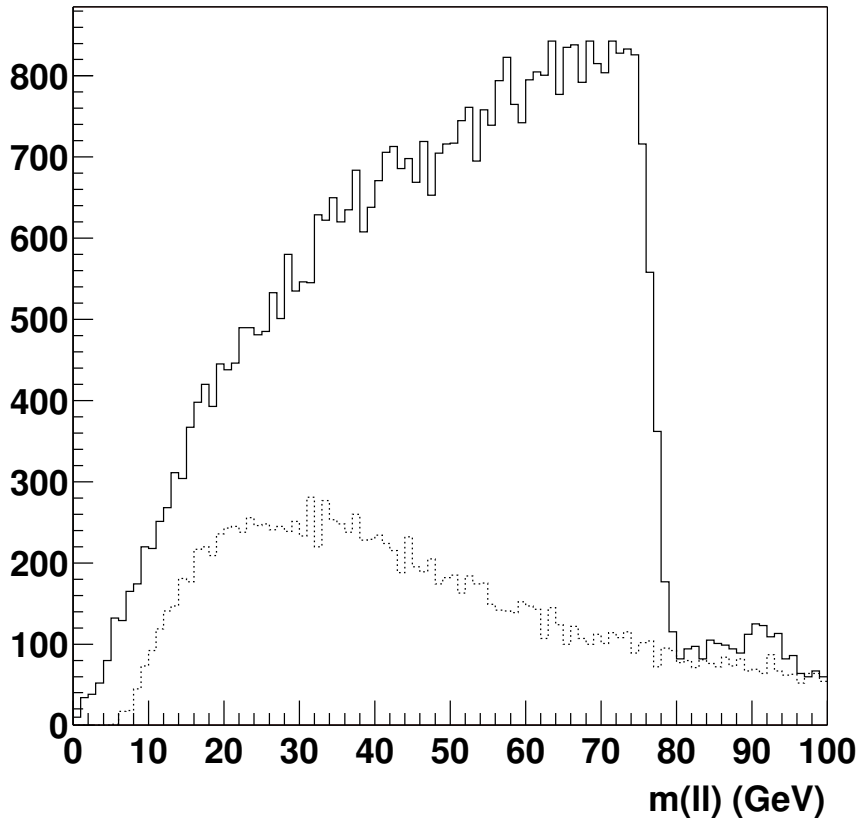
Cascade decays: complicated decay chains for squarks and gluinos

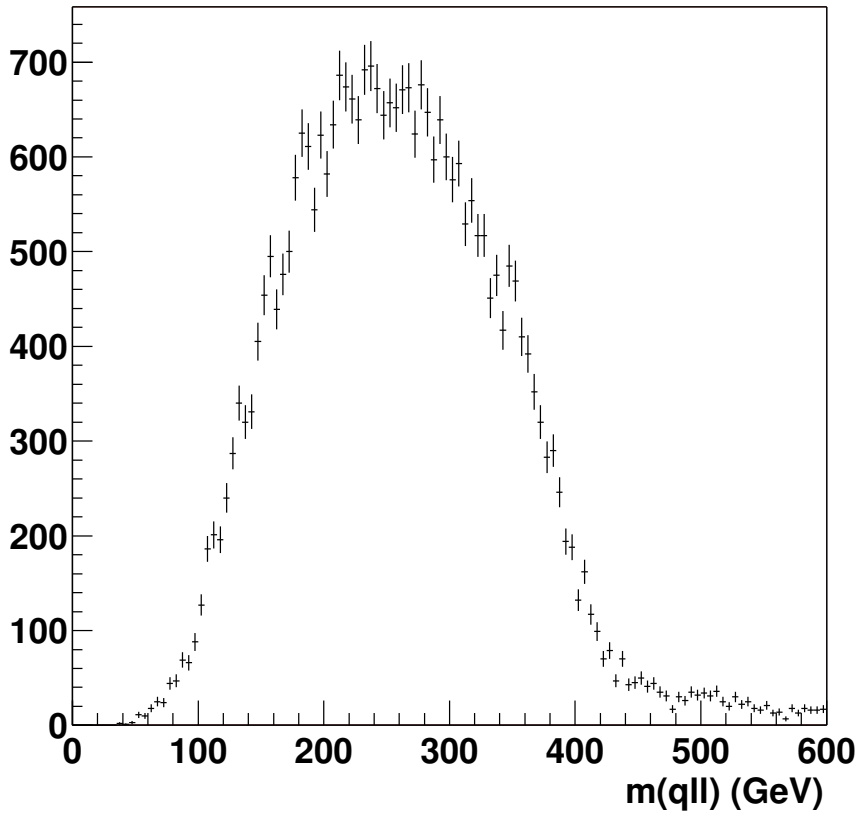


Examples worked out for SPS1a from ATLAS and CMS
main tool: dilepton "edge" from $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$

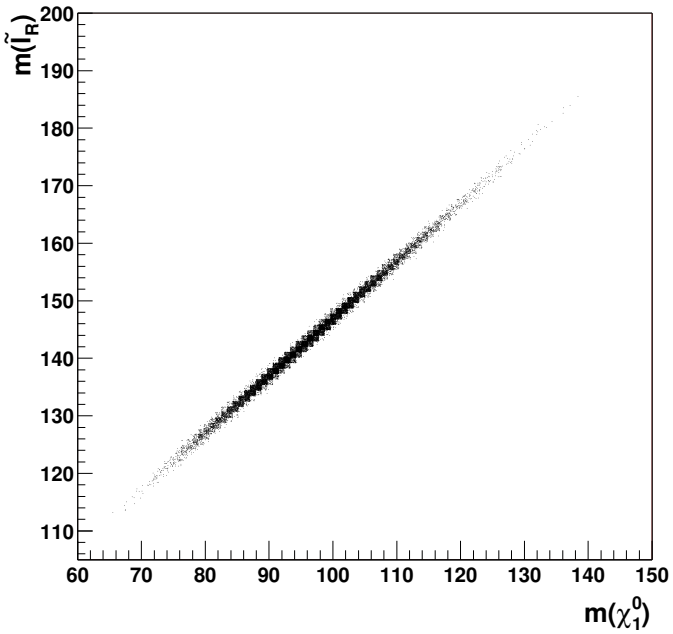
Sbottom/squark and gluino reconstruction:

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:



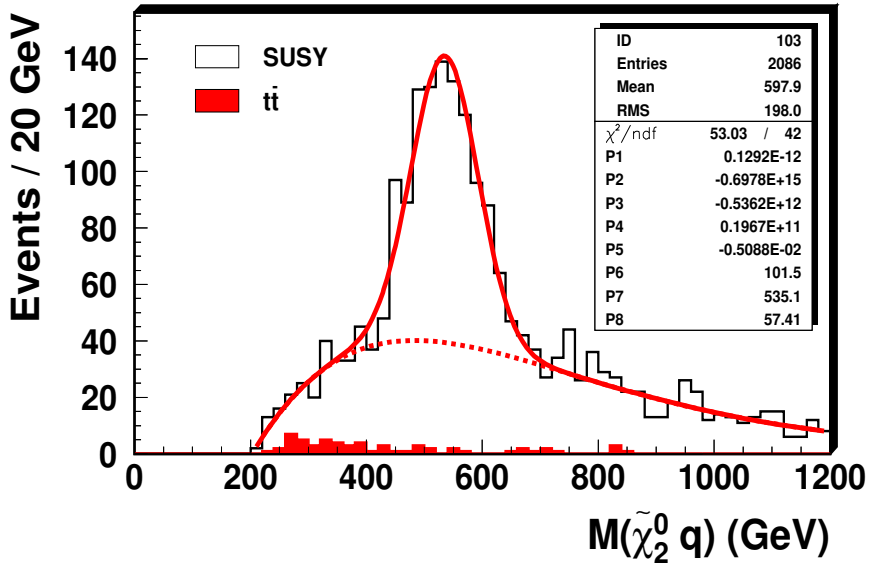
$\Rightarrow$ Take LSP mass as input from LC

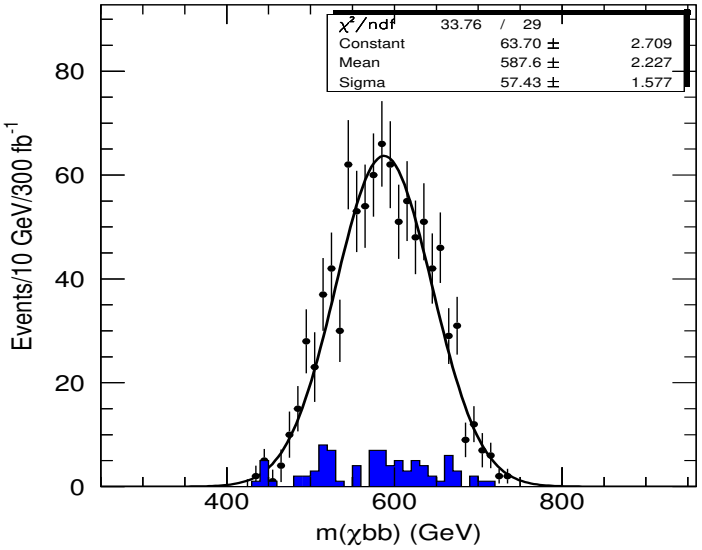
Select events close to the edge and combine with b-jet / q-jet

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

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

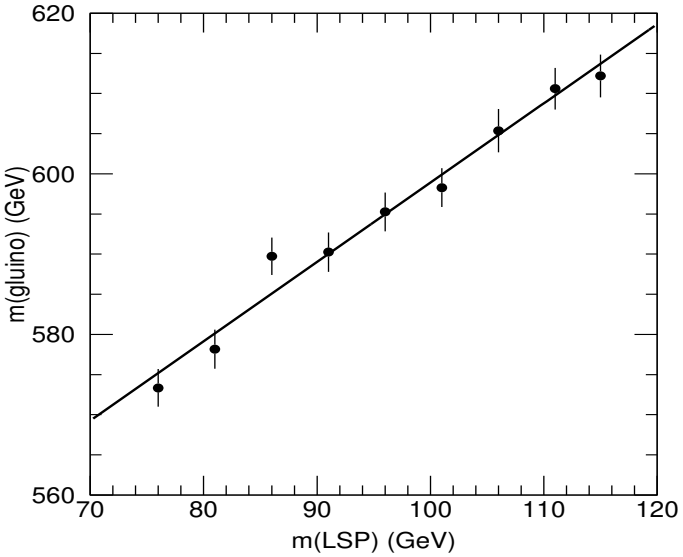
Squark peak (left) and gluino reconstruction from $(\chi_2^0 bb)$ invariant mass distribution (right):





$m_{\tilde{g}}$ 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:

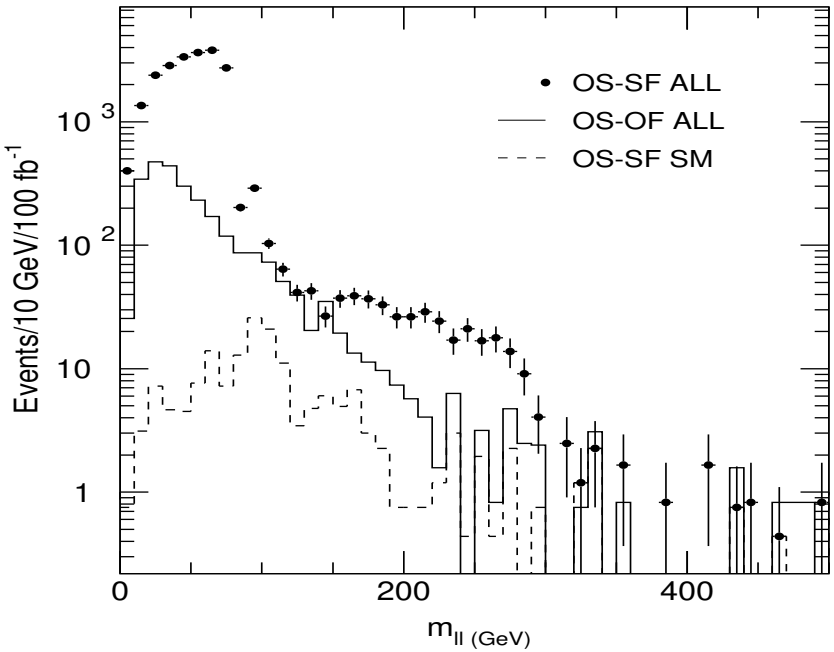
	LHC	LHC+LC (0.2%)	LHC+LC (1.0%)
$\Delta m_{\tilde{\chi}_1^0}$	9.2	0.2	1.0
$\Delta m_{\tilde{l}_R}$	9.2	0.5	1.0
$\Delta m_{\tilde{\chi}_2^0}$	9.0	0.3	1.0
$\Delta m_{\tilde{b}_1}$	23.1	16.9	17.0
$\Delta m_{\tilde{q}_L}$	15.0	5.1	5.3

$\Rightarrow$ 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*]



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

$\Rightarrow$ Feeding $m(\tilde{\chi}_4^0)$ 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

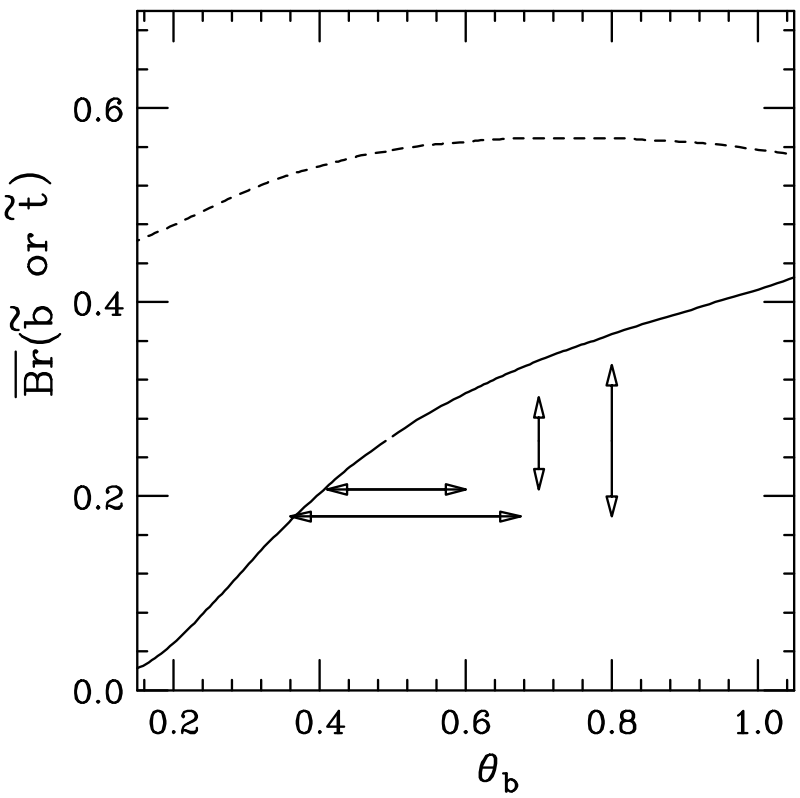
Stop/sbottom sector determined by 5 parameters, e.g. $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$, $m_{\tilde{t}_1}$, $\theta_{\tilde{b}}$, $\theta_{\tilde{t}}$

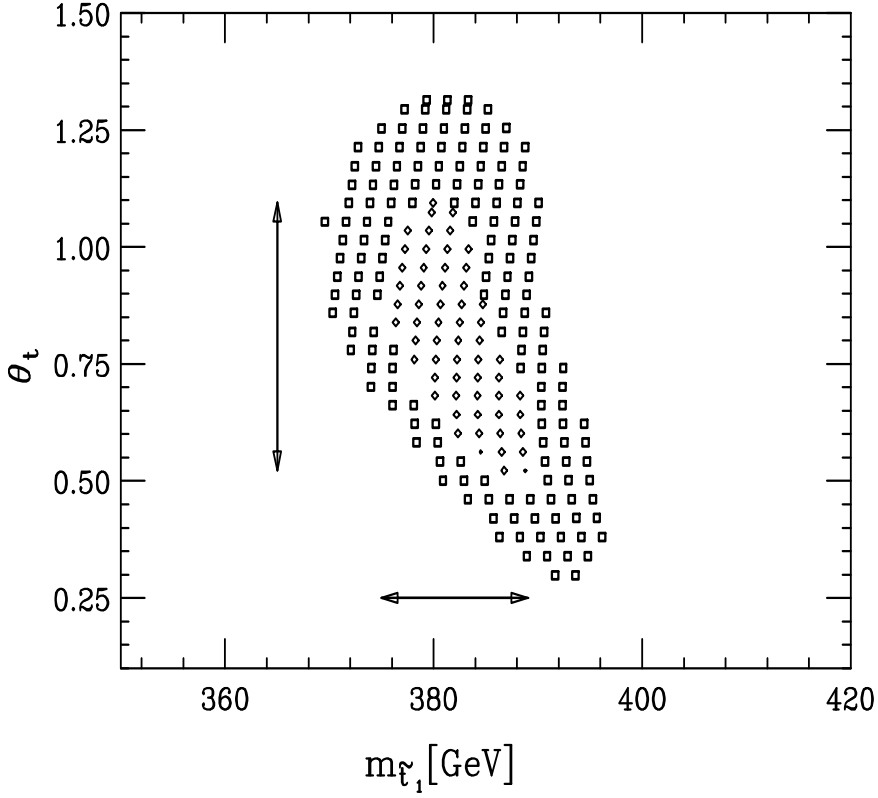
- Take $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ from previous study
- $\Rightarrow$ need three more observables:
  - tb invariant mass distribution
  - rate of "edge-events" in m_{tb} distribution (chargino chain)
  - rate of events in $\ell\ell b$ distribution ($\tilde{\chi}_2^0$ chain)

$\Rightarrow$ 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)

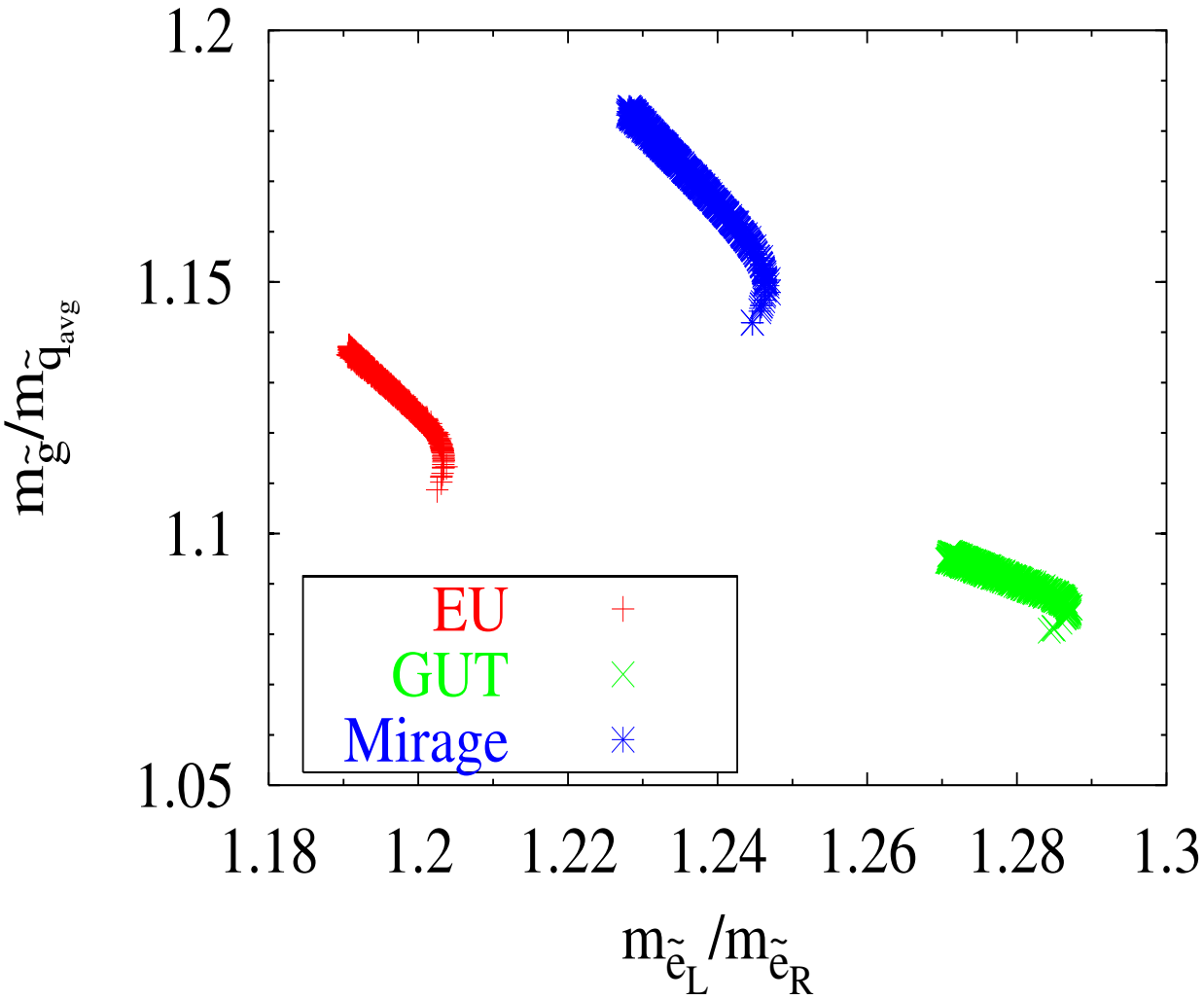




$\Rightarrow \mathcal{O}(50\%)$ determination of mixing angles, $\Delta m_{\tilde{t}_1}/m_{\tilde{t}_1} < 5\%$

Discrimination between different SUSY-breaking scenarios

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



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

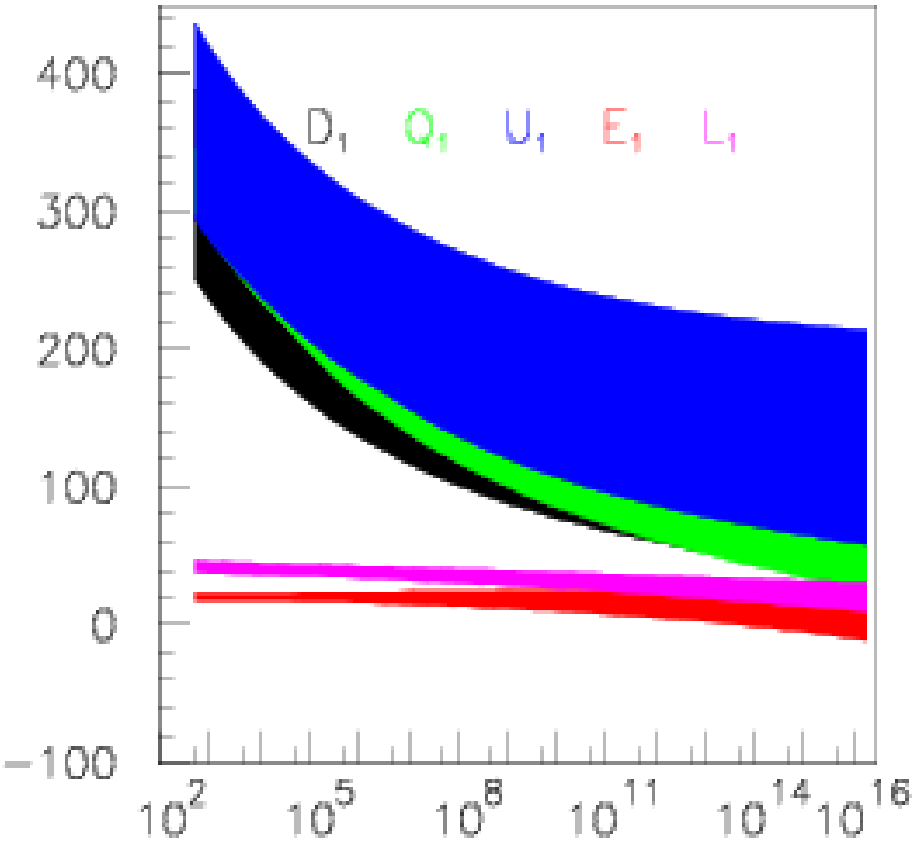
Extrapolation to physics at high scales

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

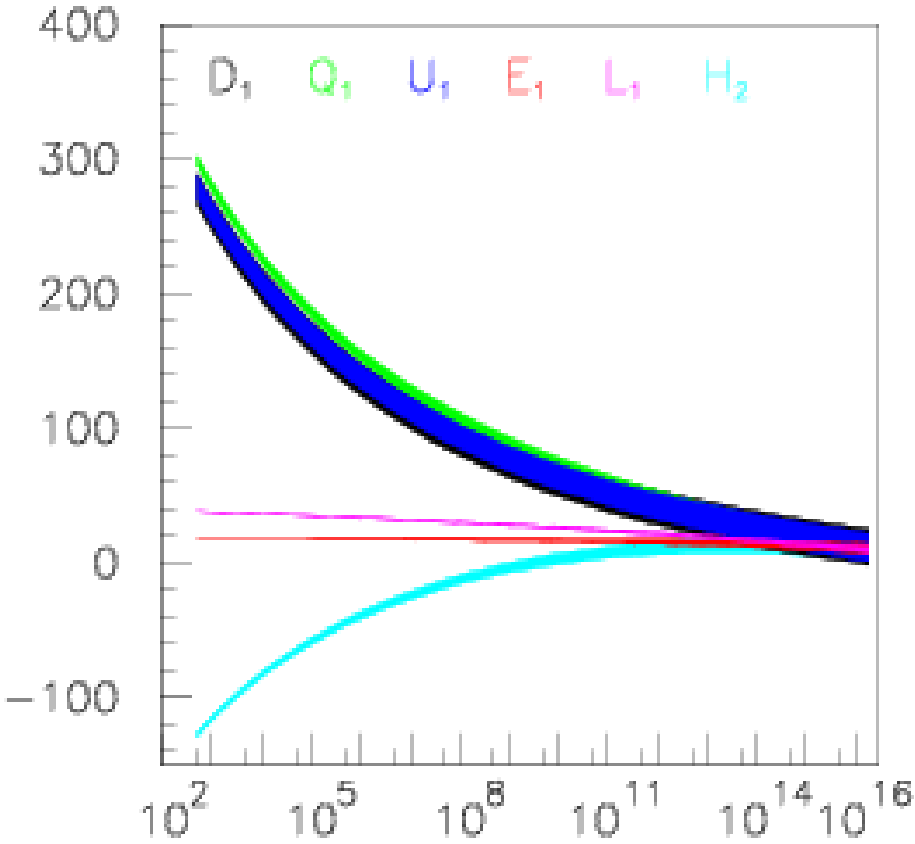
from combination of LHC and LC results, precise measurement of masses of SUSY particles, couplings

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

LHC



LHC ⊕ LC



3. Higgs physics

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

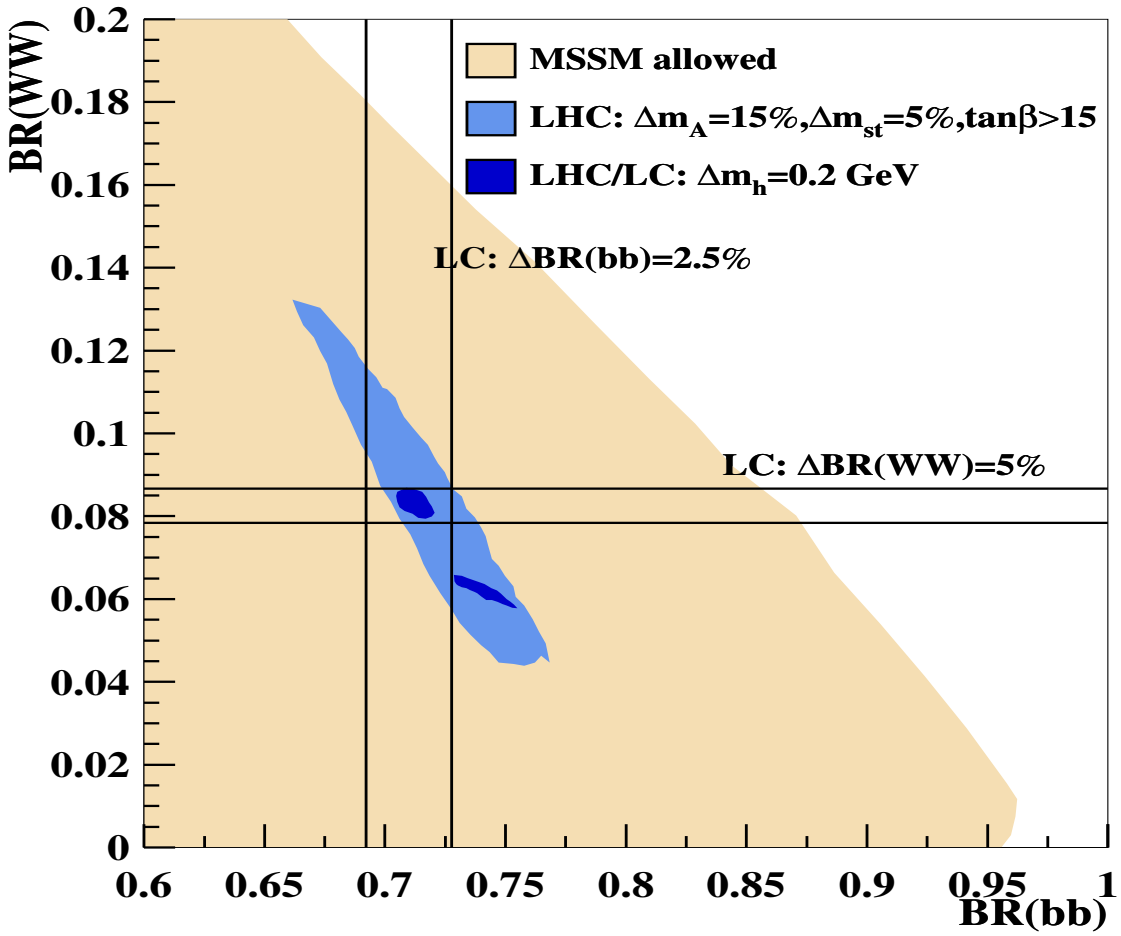
[*K. Desch, S. Heinemeyer, G.W.*]

Assume:

LHC information on M_A, $\tan\beta$

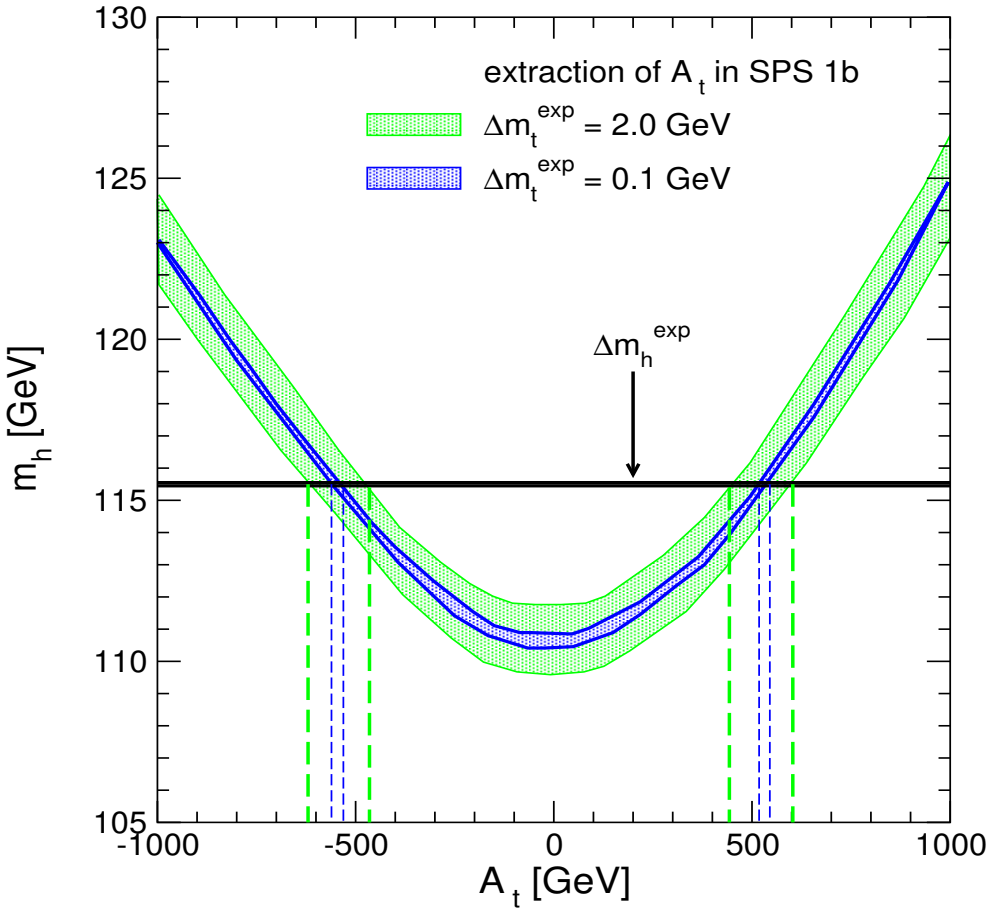
$\oplus$ (LHC $\otimes$ LC) information on stop/sbottom masses

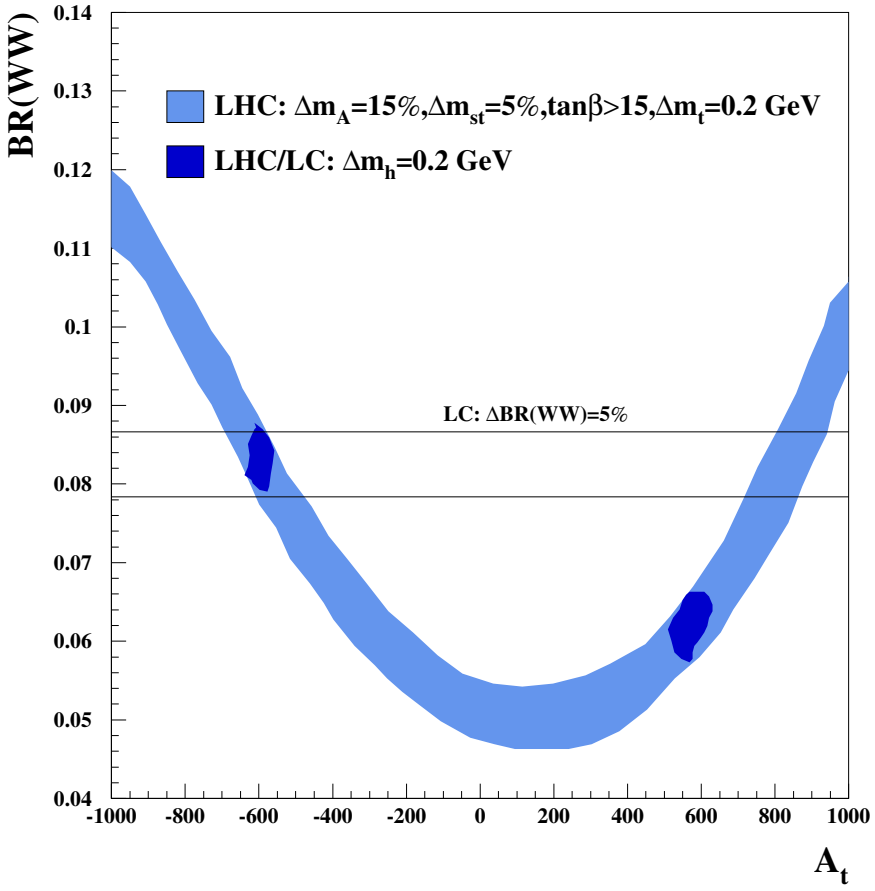
$\oplus$ LHC / LC measurement of m_h:



⇒ 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:





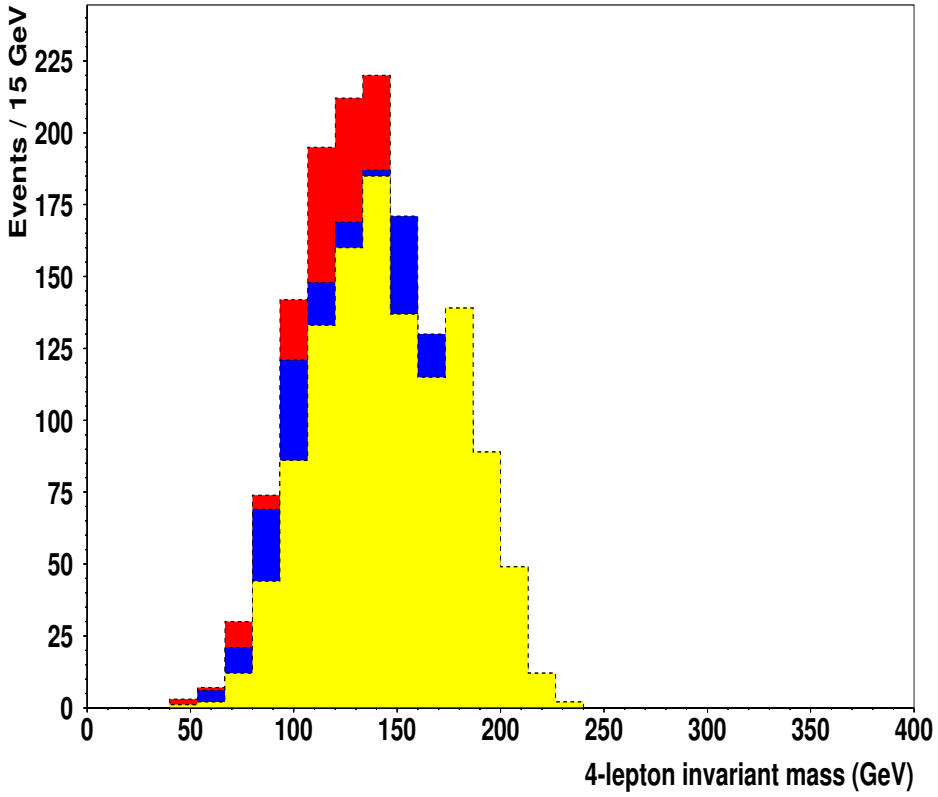
Precise measurement of m_t at the LC crucial, $\delta m_t \lesssim 100$ MeV

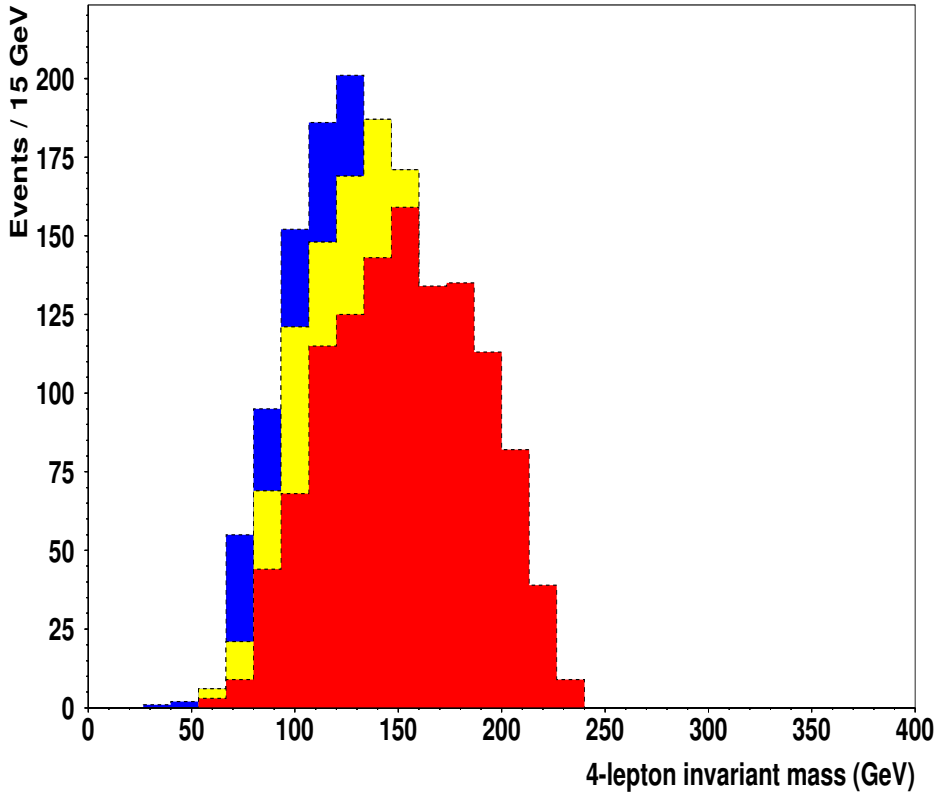
Δm_t^{LC} vs. $\Delta m_t^{LHC} \Rightarrow$ accuracy of A_t determination improved by factor 3

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}

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

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.*]

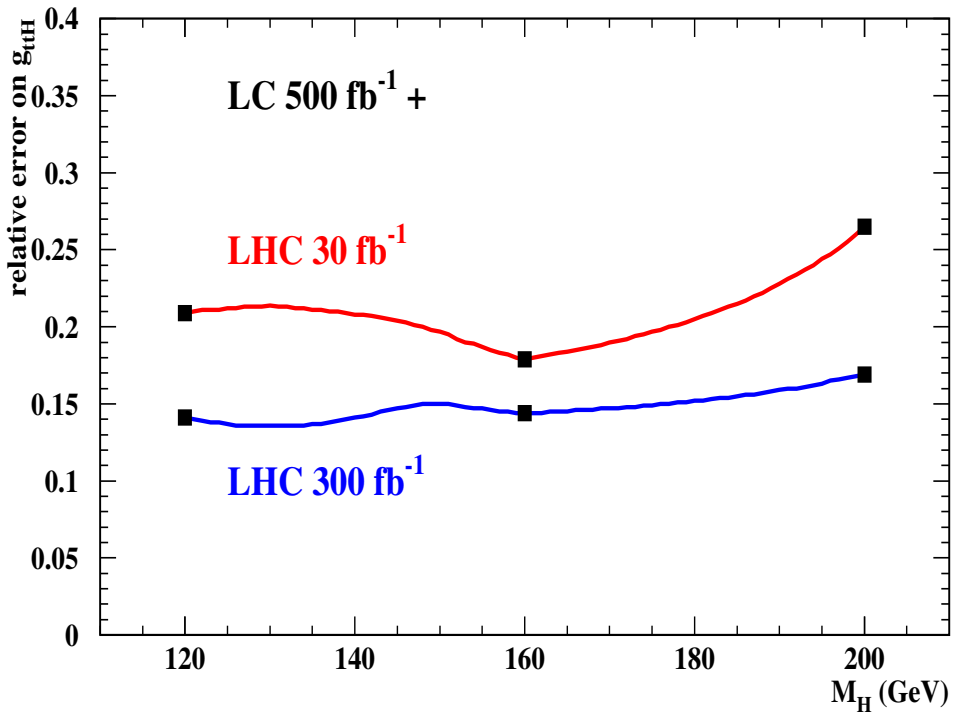
Only preliminary measurement of tth coupling at 500 GeV LC for light Higgs

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:

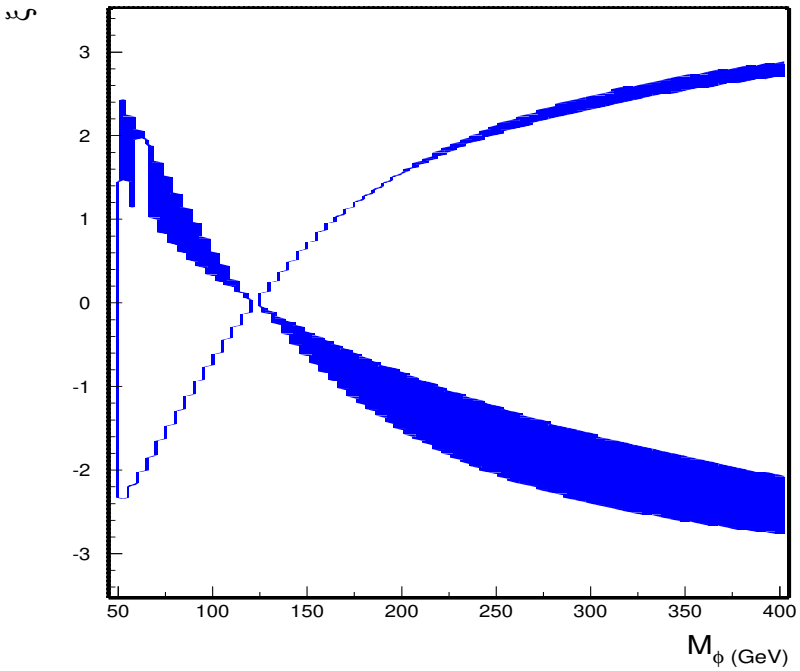


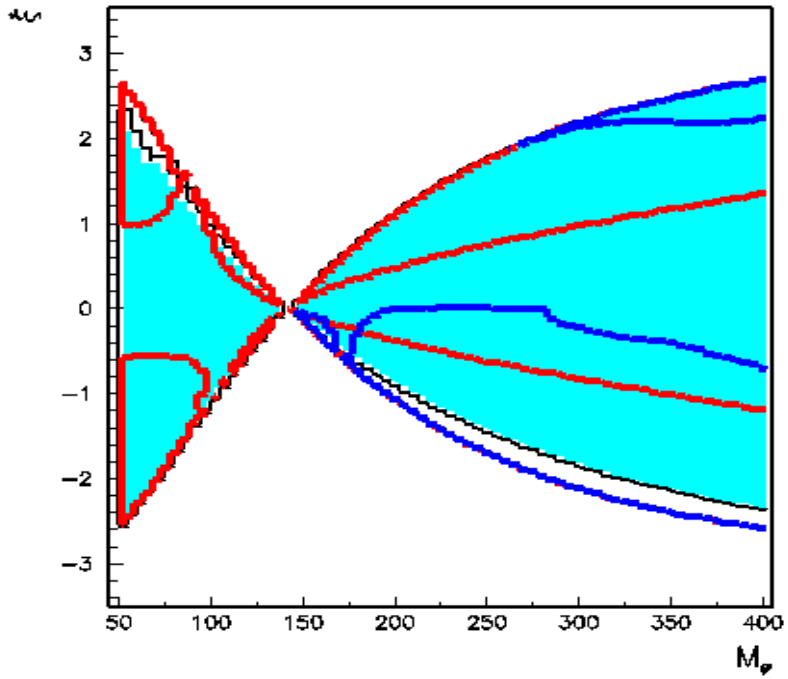
Higgs and radion searches at LHC and LC:

[*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 100 fb^{-}1 (left), regions where the precise measurements of the $h b\bar{b}$ 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*]

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 $1/16\pi^2$

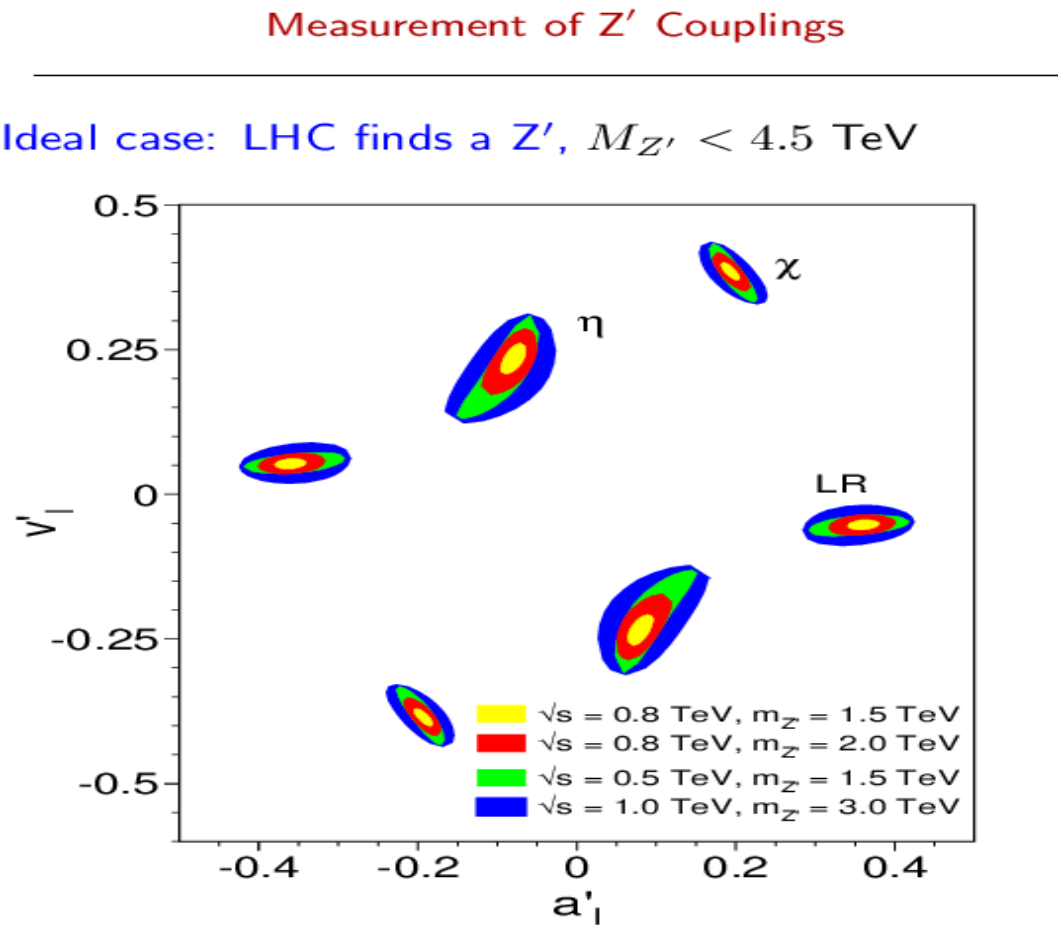
Resonances at high energy only directly accessible at the LHC; combination with sub-TeV data of LC on cross-section rise essential for disentangling new states

5. New gauge theories

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

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



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

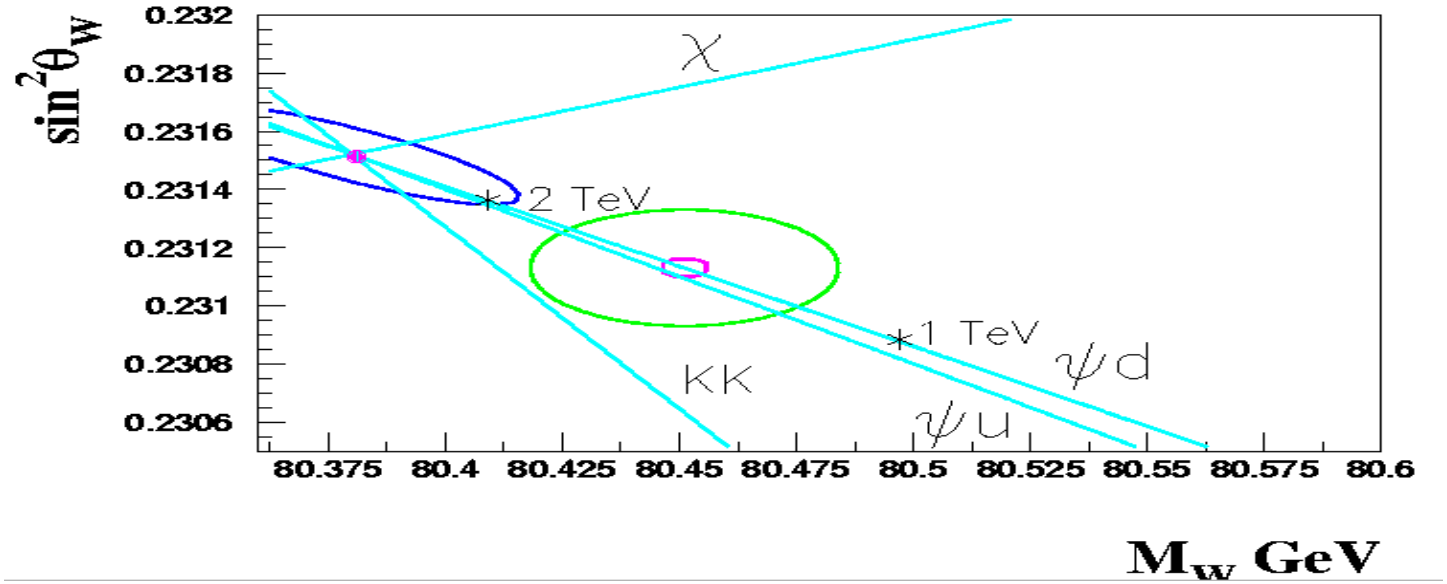
Distinction between Z' and KK excitation:

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



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)

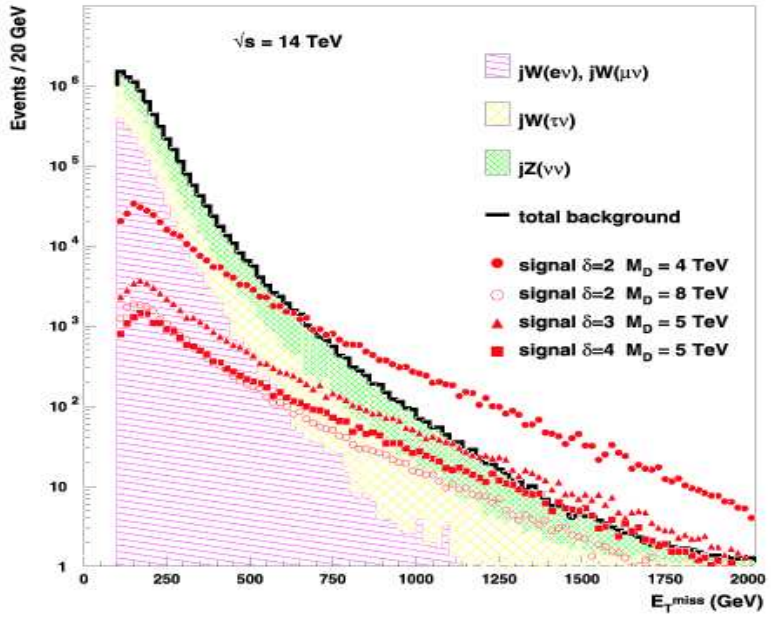
$e^+e^- \to \gamma + G_n$		2	4	6
LC	$P_{-,+} = 0$	5.9	3.5	2.5
LC	$P_- = 0.8$	8.3	4.4	2.9
LC	$P_- = 0.8,\ P_+ = 0.6$	10.4	5.1	3.3
$pp \to g + G_n$		2	3	4
LHC		$4 - 8.9$	$4.5 - 6.8$	$5.0 - 5.8$

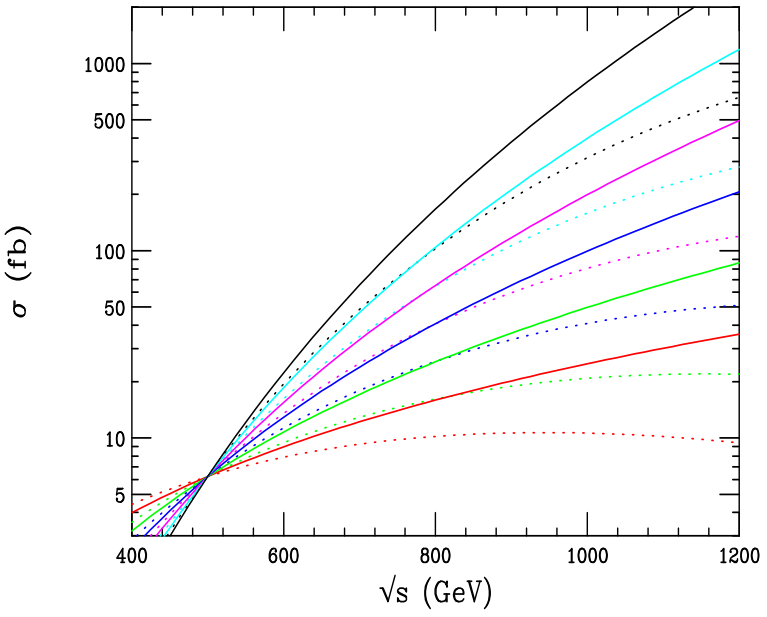
Model parameters: fundamental Planck scale M_D, number of extra dimensions δ, brane tension Δ

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 $\mathcal{O}(10^{-6})$

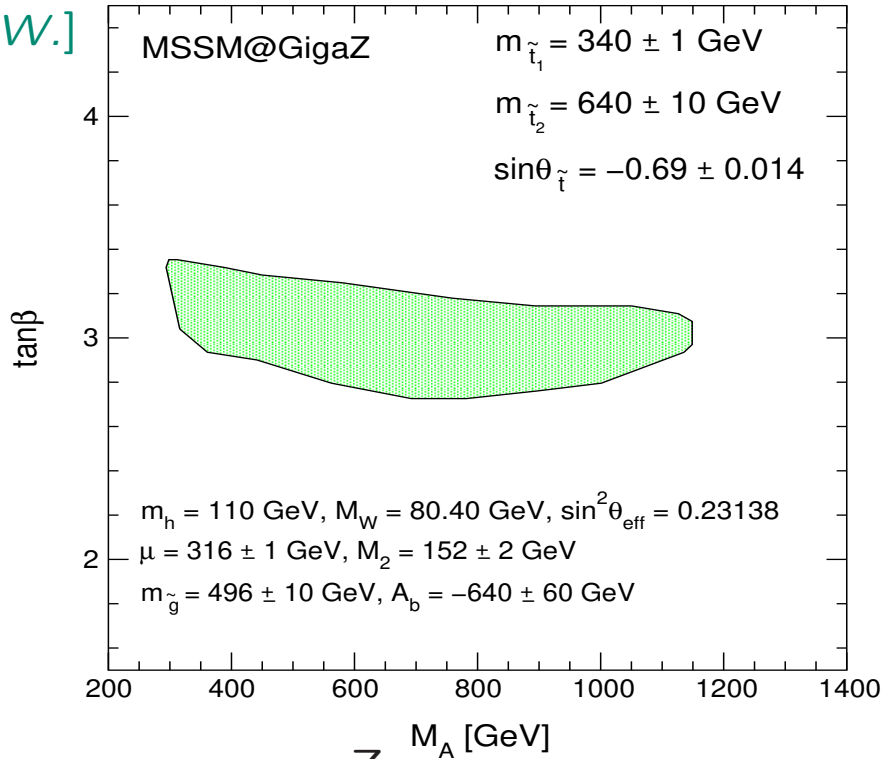
Prospective sensitivity to FCNC interactions:

	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

- Topics covered in this lecture 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 only recently – we have just scratched the surface so far

  A first working group document is currently being compiled

  $\Rightarrow$ 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!