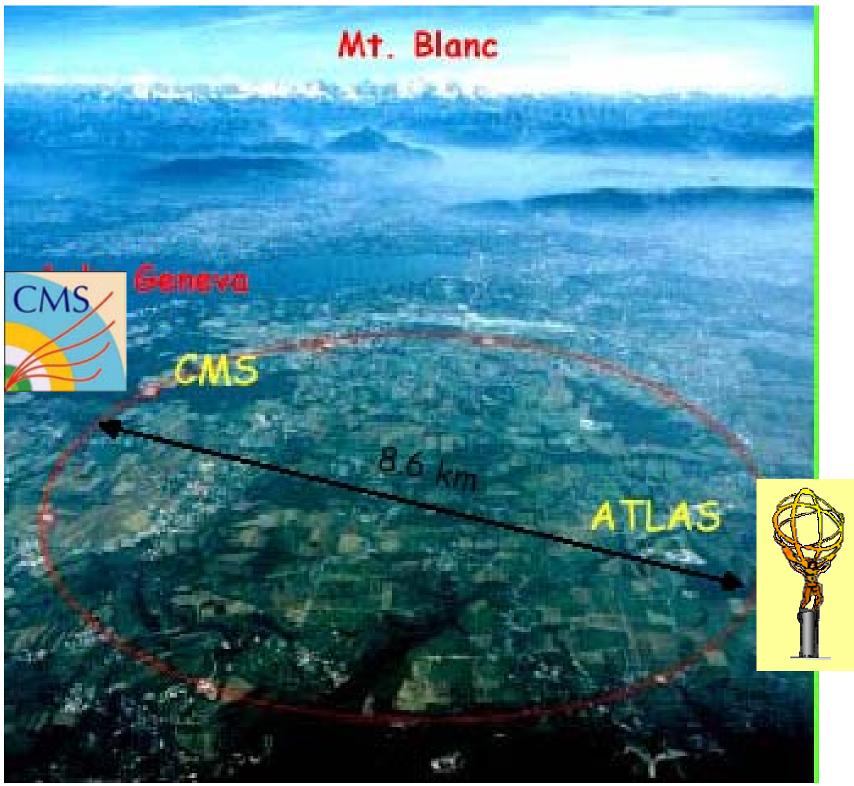
Interplay Between the LHC and a Linear Collider

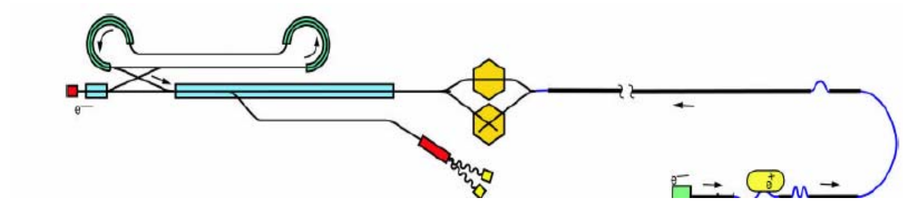
Albert De Roeck CERN

Ecole de Gif 2004

Le Future de la Physique des Hautes Energies



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



Contents

- Introduction: LHC↔ LC
- Examples of complimentarity
  - Supersymmetry
  - Higgs
  - Z′ bosons
  - Extra dimensions
- Conclusion

High Energy Frontier in HEP

Next projects on the HEP roadmap

- Large Hadron Collider LHC at CERN → G. Unal
  - Approved, budget in place and under construction
  - Expected turn on in middle of 2007
- Linear Collider (LC) ? → H. Videau
  - Strong world-wide effort to start construction around 2009/2010, if approved and budget established
  - Expected turn on 2015(+)
  - Study groups in Europe, Americas and Asia (+World Wide Study)
- Physics case for both machines separately is well established
- In Europe: up to LHC/LC study little contact between -experimental- the two communities (→"miss understandings"…)

  ⇒Initiative to form a LHC/LC common study group in 2002

The LHC/LC study group

Aim of the LHC/LC Study group: investigate how the analyses at the LHC could profit from results obtained at the LC and vice versa – maybe even affect LHC running or triggers --

- Started in summer 2002 as a world wide effort
- Collaborative effort of the LHC and linear collider community.
- Study group which has been officially recognized by international linear collider steering committee (ILCSC)
- Current about 190 (interested) working group members from ATLAS, CMS, LC working groups + Tevatron contact person
- Working group coordinators: R. Godbole, G. Weiglein
- Web page `www.ippp.dur.ac.uk/~georg/lhclc`

- First document with results is being finalized

LHC/LC study group

LHC / LC Study Group Working Document

ALL AUTHORS

[1] Institute 1

[2] Institute 2

Expect to finalize by fall 2004

Abstract

The LHC / LC Study Group investigates the possible interplay between the LHC and a future e^+e^- Linear Collider in testing the Standard Model and in searches for new physics. It is studied in particular to what extent analyses carried out at one of the machines can profit from results obtained at the other machine. Mutual benefits can occur both at the level of a combined interpretation of Hadron Collider and Linear Collider data and at the level of combined analyses of the data, where results obtained at one machine can directly influence the way analyses are carried out at the other machine. Topics under study comprise the physics of weak and strong electroweak symmetry breaking, Supersymmetric models, new gauge theories, models with extra dimensions, and electroweak and QCD precision physics. The present report summarizes the status of the work that has been carried out within the LHC / LC Study Group so far. Possible topics for future studies are outlined.

Contains work discussed at ~ 5 meetings, in particular around/during Les Houches 2003 (May 2003)

LES HOUCHES
centre de physique

⇒ Over 500 Pages already !?!

⇒ Mostly comparison studies between the two machines

But a number of true complementarity studies…several are still ongoing

⇒ Not the final word

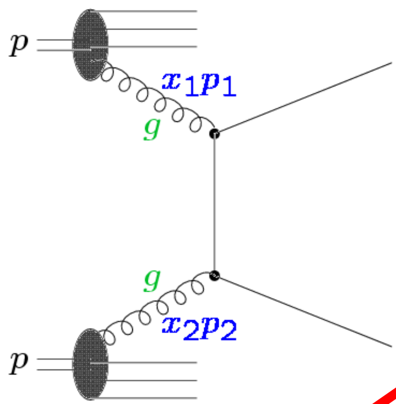
Will give several examples in the following

LHC/LC studies

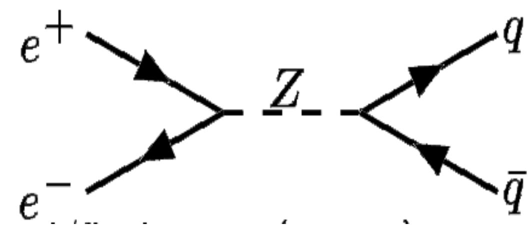
- Electroweak Symmetry breaking (weakly)
  H. Haber, R. Godbole, G. Weiglein, ADR (*)
- Strong Electroweak Symmetry breaking
  T. Barklow, K. Moenig
- Supersymmetric Models
  K. Desch K. Kawagoe, M. Nijori, F. Paige, G. Polleselo
- New Gauge Theories
  S. Riemann
- Models with Extra Dimensions
  J. Hewett
- Exotics
  J. Gunion
- Electroweak and QCD precision tests
  E. Boos, S. Heinemeyer, J. Stirling, ADR

(*) = main chapter editors/organizers

LHC/LC



Different characteristics of the two machines
⇒Different capabilities & virtues



LHC pp collisions √s = at 14 TeV

⇒ Strong point: larger mass reach for direct discoveries

- Kinematics: can use conservation of p
- Composite nature of colliding protons ⇒underlying event
- √s of the hard interaction not fixed
- Strongly interacting particles ⇒ huge QCD cross sec. (background)

e+e- collisions at √s = 0.5-1.0 TeV

⇒Strong point: high precision physics

- Kinematics: mom. conservation used to analyze the decays,…
- Well defined initial state, beam polarization, √s,…
- Backgrounds smaller than LHC
- Options: γγ, eγ, e-e- colliders.

The LHC/LC study

- Physics case well established for the LHC and LC
  - Not the aim to see who is better (always tempting of course…)
  - One of the purposes is to make both communities aware when designing there analyses on what kind of additional information they might get when a LC kicks in

- Interplay between LHC and a LC can happen at different levels
  - Combined interpretation of LHC/LC data

    ⇒In particular to reduce possible model dependencies

    $$\mathbf{LHC} \oplus \mathbf{LC} > \mathbf{LHC} + \mathbf{LC}$$

  - Combined analyses of LHC and LC (simultaneous running)

    $$\mathbf{LHC} \otimes \mathbf{LC} > \mathbf{LHC} \oplus \mathbf{LC}$$

- If a LC gets into operation in time, could even influence detector/trigger choices at LHC upgrades (time-of-flight, softer scales, particle ID,….)

  ⇒ Can help to make the case for concurrent running of LHC and a LC

Linear Collider Time Scales

R. Heuer LCWS04

ILCSC Road Map

2004 technology recommendation (confirmed by ITRP)

Establish Global Design Initiative / Effort (GDI/E)

2005 CDR for Collider (incl. first cost estimate)

2007 TDR for Collider

2008 site selection

2009/2010 construction could start (if budget approved)

→ First collisions in 2015?

Certainly a challenge

LC the first real "global machine" in HEP?

A LC Collider

International LC scope document

- 500 GeV, and upgradeable to ~1 TeV,
- 500 fb^{-1} in 4 years at 500 GeV
- 2 interaction regions,
- 80% electron polarization
- Energy flexibility between $\sqrt{s}$ = 90-500 GeV
- Future: possibility of γγ, e-e-, e+ polarization, Giga -Z

⇒ TeV e+e- Linear Collider

LHC Status/plans

- Date for first beams/collisions: $\Rightarrow$ **Spring 2007**
- Initial physics run starts in summer/fall 2007
  - $\Rightarrow$ collect ~10 fb^{-1} /exp ($2.10^{33} cm^{-2} s^{-1}$) by early 2008
- Depending on the evolution of the machine…
  - $\Rightarrow$ collect 200-300 fb^{-1} /exp ($3.4\text{-}10.10^{33} cm^{-2} s^{-1}$) in 5-6 years time

Already time to think of upgrading the machine

Two options presently discussed/studied

•Higher luminosity ~$10^{35} cm^{-2} s^{-1}$ (SLHC)

–Needs changes in machine and and particularly in the detectors

$\Rightarrow$ Start change to SLHC mode some time 2013-2016

$\Rightarrow$ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.

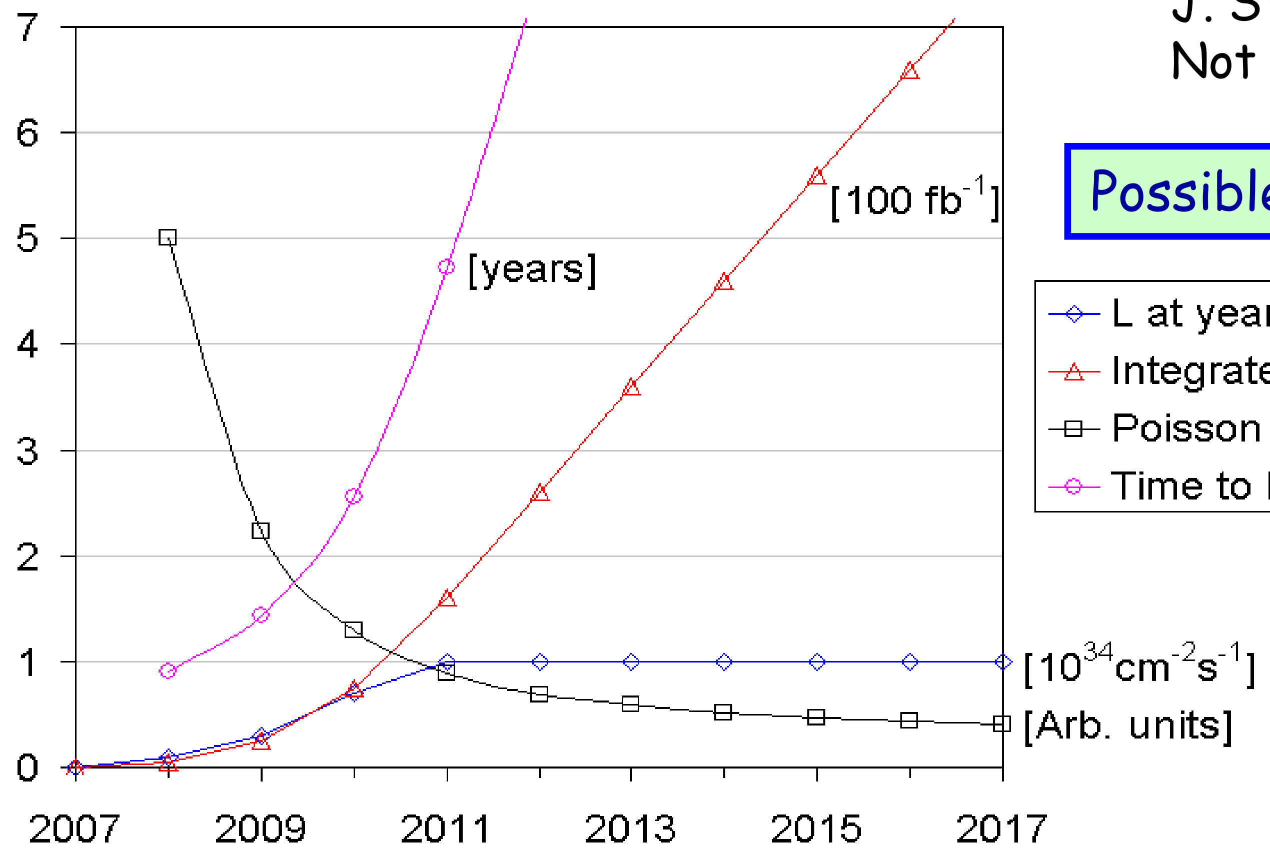
•Higher energy?

–LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)

–$\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets $\Rightarrow$ R&D needed!

Upgrades of the LHC

J. Strait exercise:
Not an "official" LHC plot



Possible lumi scenario

If startup is as smooth as assumed here:
⇒Around 2013: simple continuation becomes less exciting
⇒Time for an upgrade?

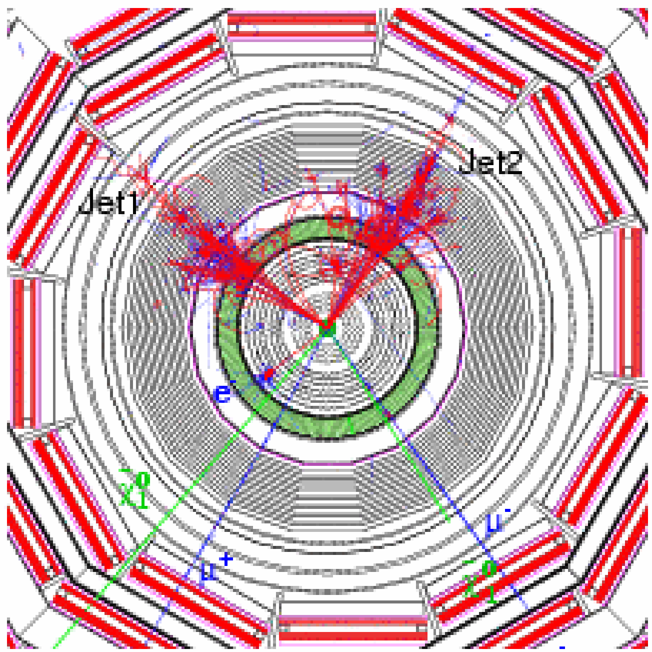
By the Time the LC Turns on...

- The LHC luminosity upgrade complete or nearing completion
  - ⇒ ~ 300 fb^{-1}/experiment accumulated
  - ⇒ LHC luminosity = $10^{35}/cm^{-2}s^{-1}$
- Physics is focused on
  - Improvements in determination of SM parameters (Higgs & gauge boson couplings)
  - Improvements of acuracy of new physics parameters (sparticle spectroscopy, tanβ measurements)
  - Extension of the high mass discovery reach
  - Extension of the sensitivity to rare processes (FCNC top decays, Higgs pair production...)

The hard stuff

Discovery Physics → Spectroscopy

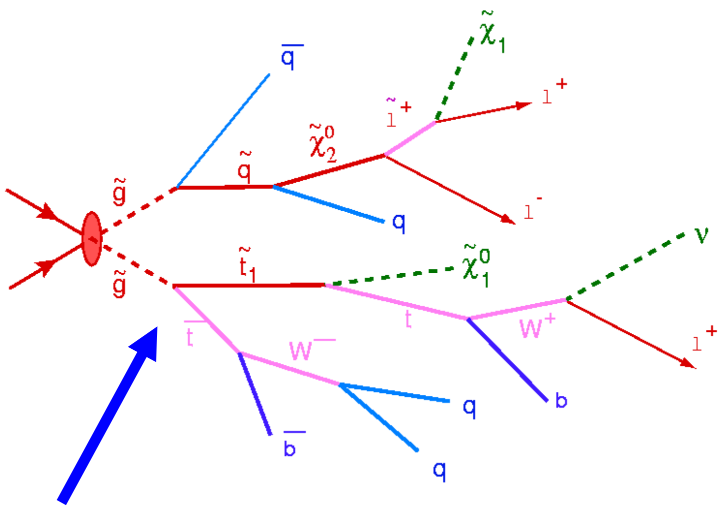
1. Supersymmetry



Supersymmetry

Supersymmetry (SUSY) → assumes a new hidden symmetry between the bosons (particles with integer spin) and fermions (particles with half integer spin) to stabelize the Higgs mass up to the Planck scale

⇒Lots of new particles (squarks, sleptons,…) predicted with masses in the range from 10's of GeV's up to several TeV range



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

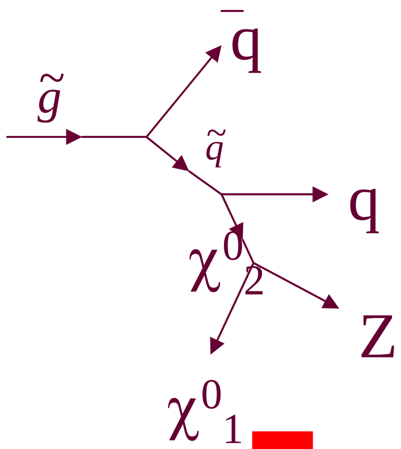
Should SUSY be realized, we have a lot to do

- Is it really SUSY?
- How is it realized?
  (particle content) MSSM NMSSM,…
- How is it broken?
  Measure as many of the ~100 low energy parameters as possible
  Measure them precisely as possible
  → Extrapolation to high scale

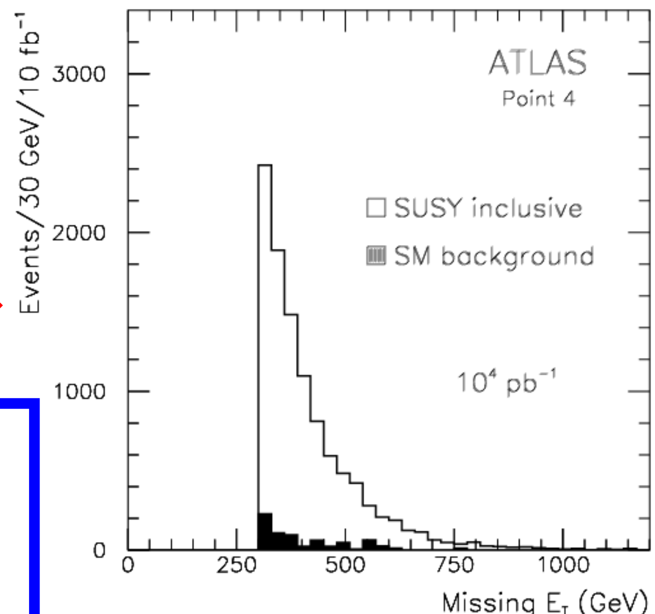
Lightest SUSY particle stable: dark matter candidate ?

SUSY at the LHC

Discovery should be 'easy' for squark masses < ~2 TeV



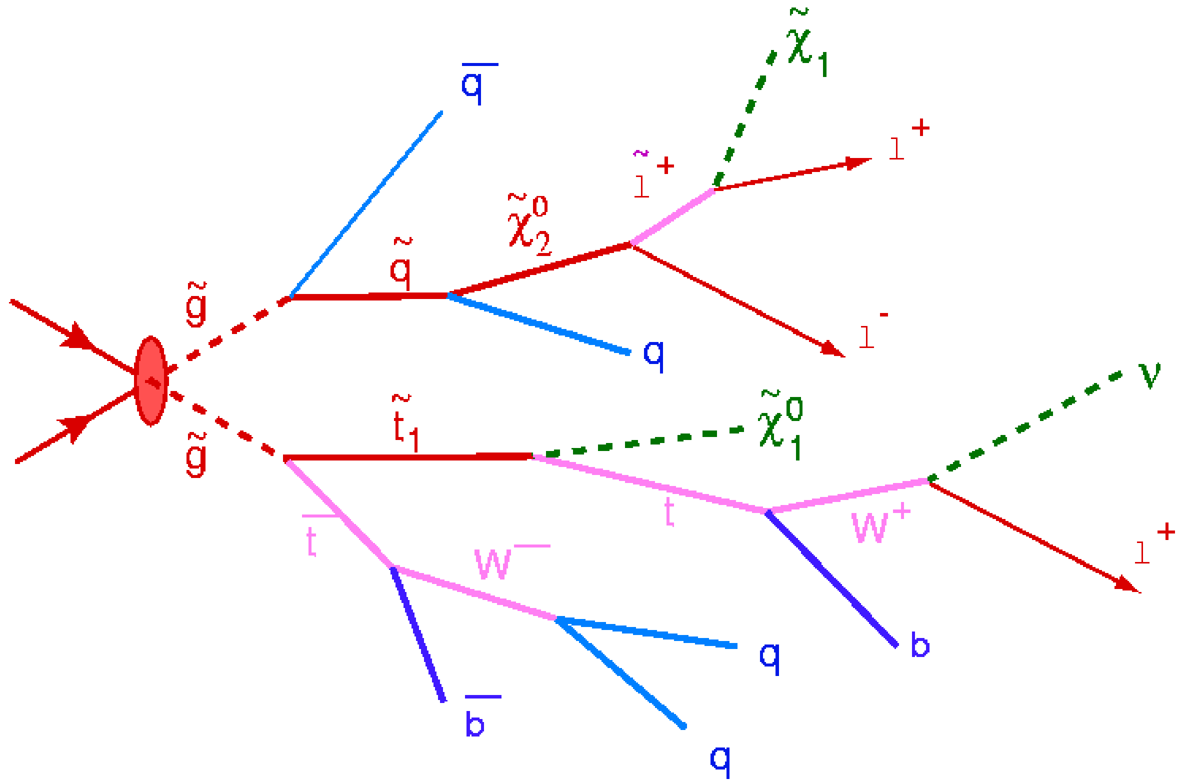
E.G. 900 GeV squarks
E_t^{miss} > 300GeV
+ 4 jets



DISCOVERY

SUSY SPECTROSCOPY?

SUSY at the LHC



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_t^{miss}

But exclusive reconstruction often difficult

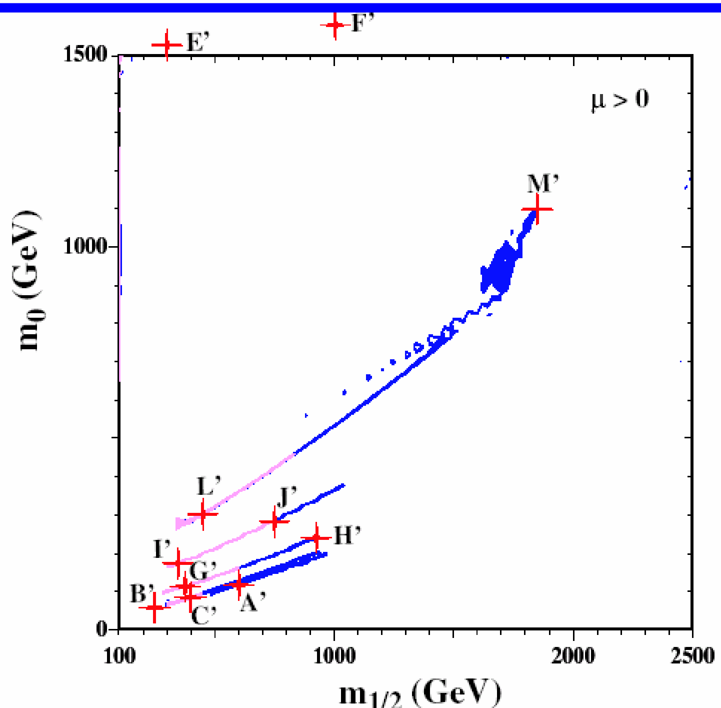
Sparticle discoveries

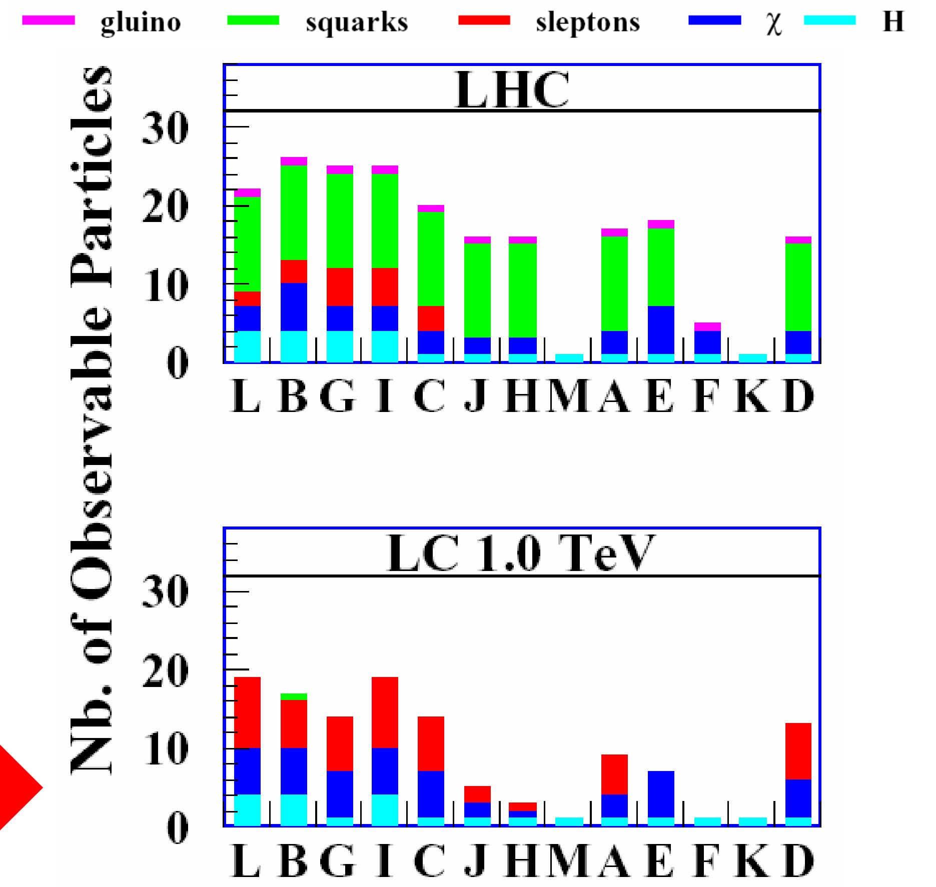
- A number of SUSY (msugra) benchmark points to study LHC/LC sensitivity

(Battaglia, ADR, Ellis, Gianotti, Olive, Pape)

- Take into account direct searches at LEP and Tevatron, BR ($b \to s\gamma$), g_μ-2 (E821), Cosmology: $0.09 \leq \Omega_\chi h^2 \leq 0.13$

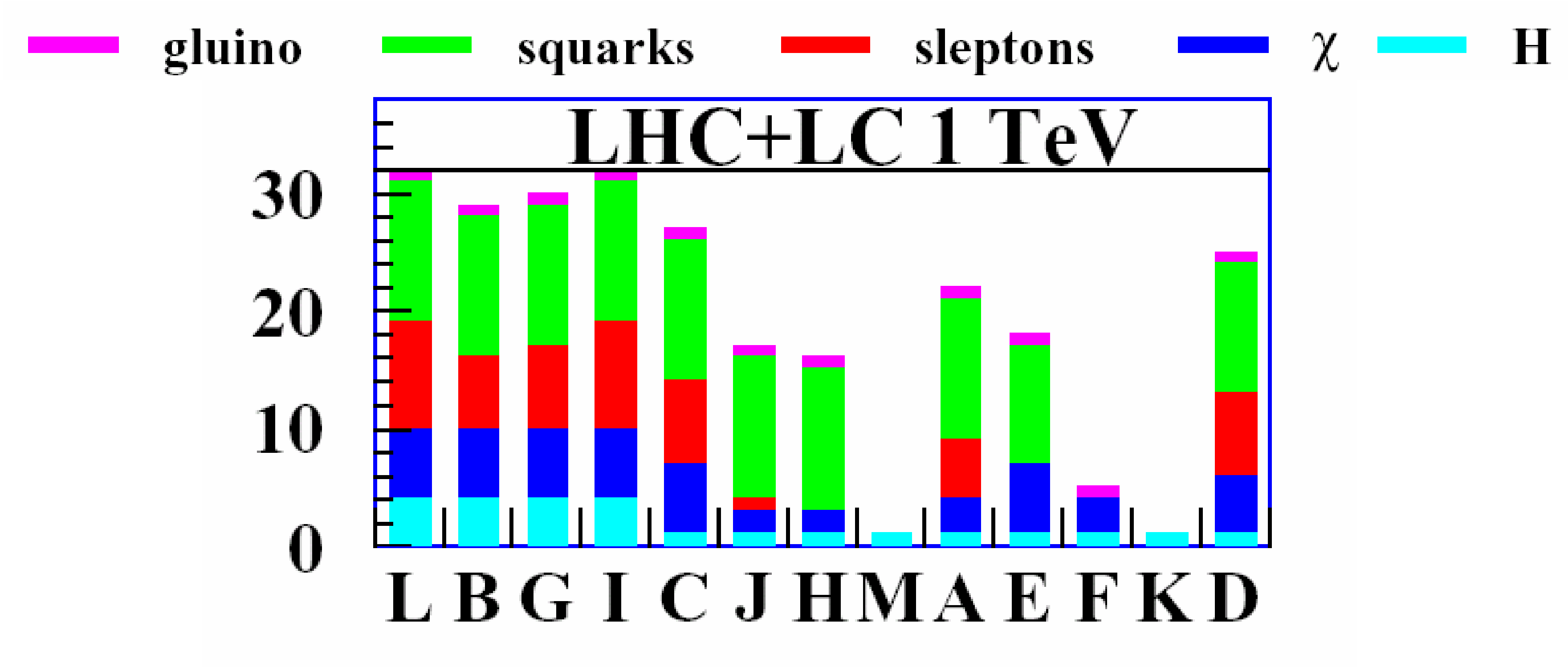
Allowed regions in the M_0-$M_{1/2}$ plane





Complementarity in sparticle reach
LHC: mostly squarks/gluinos
LC: mostly gauginos, sleptons

LHC⊕LC



For several of these scenarios (almost) all particles can be detected

Just an example... there are many more (also non-msugra) scenarios in use..

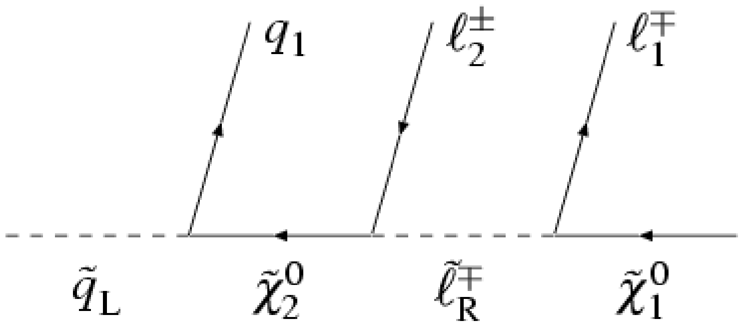
For the LHC/LC study: Choose point B (SPS1a)
Favorable point for LHC/LC!! Maybe Nature will be less kind...

1.Measurement of Sparticle Masses

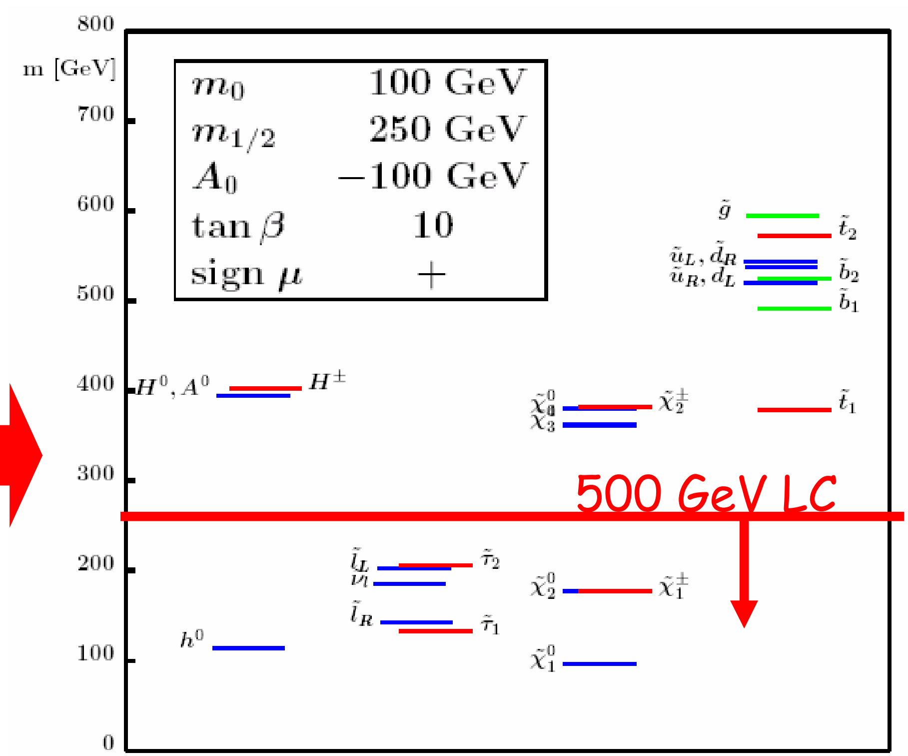
Gjelsten,Lytken,Miller,Osland,Polesello,Chiorboli,Tricomi,ADR

To understand SUSY breaking we will need to measure as many parameters as possible, e.g. sparticle masses

LHC: complicated by decay chains for squarks and gluons



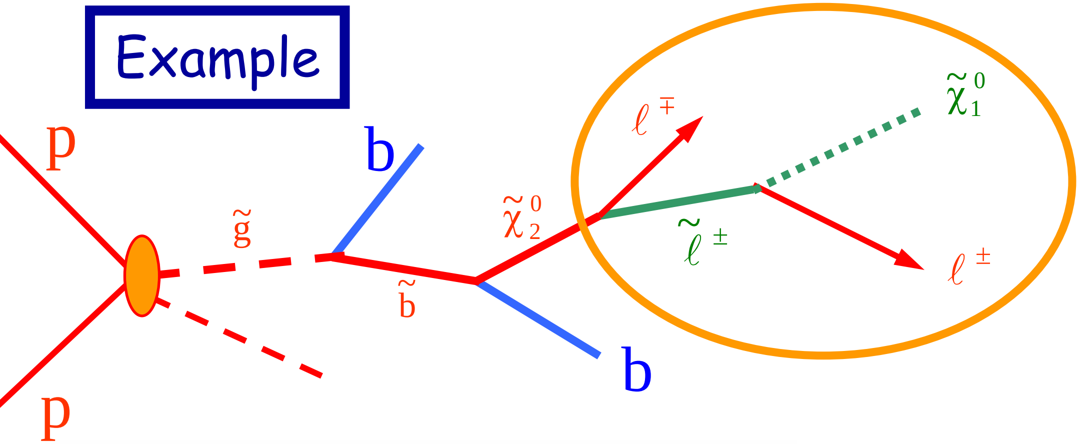
Examples worked out for SPS1a (point B) in ATLAS/CMS

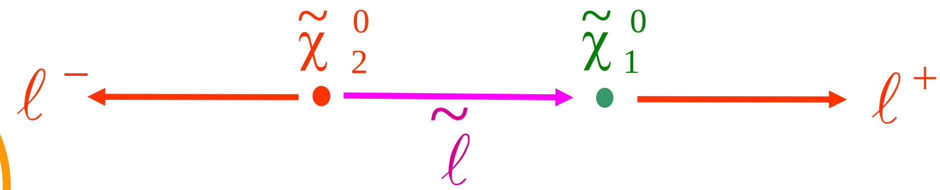


LHC will see all squarks, H,A and may see most gauginos

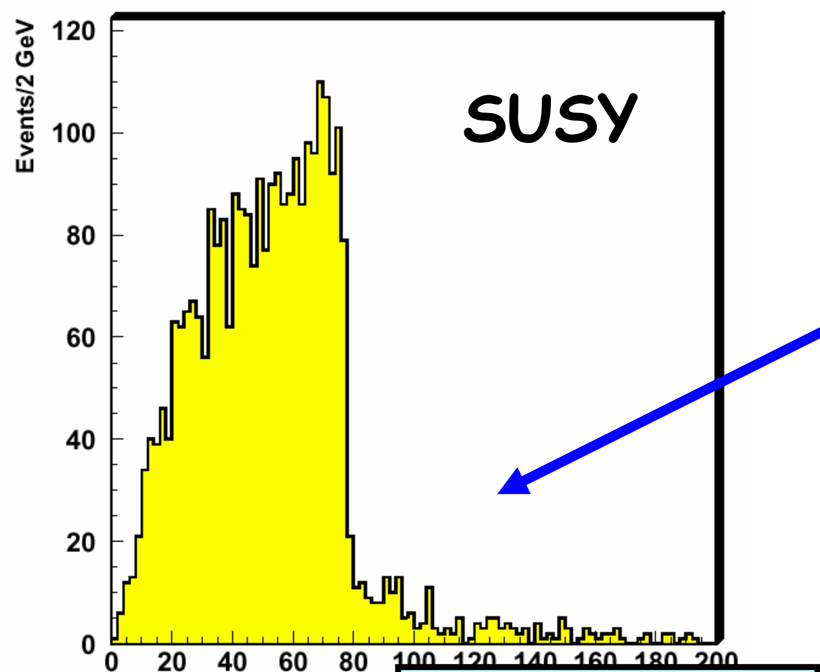
LHC Sparticle Reconstruction

Example





Problem χ_1^0 measurement!
It escapes detection like a neutrino!
Use kinematic formulae...



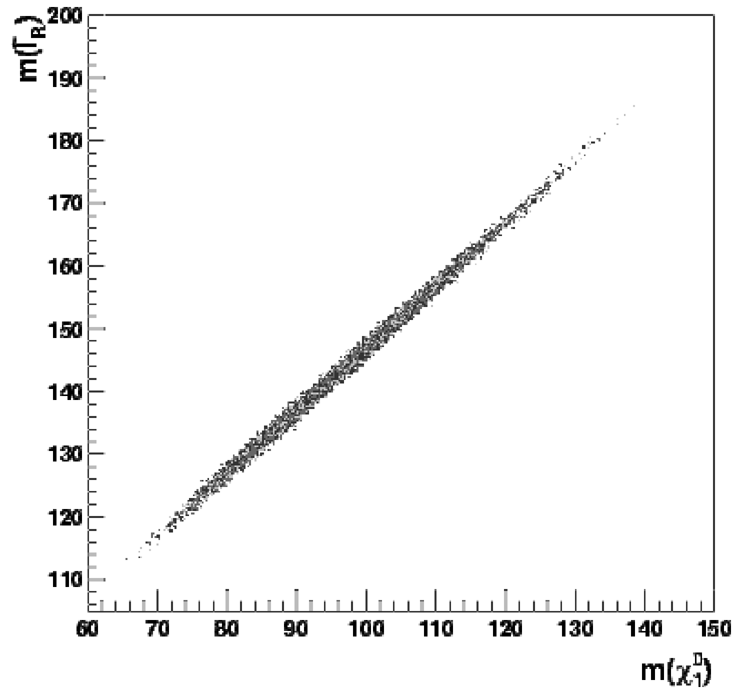
$M(e^+e^-) + M(\mu^+\mu^-)$

$$M^{max}_{\ell^+\ell^-} = \frac{\sqrt{(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}})(M^2_{\tilde{\ell}} - M^2_{\tilde{\chi}^0_1})}}{M_{\tilde{\ell}}}$$

Strategy:
- Study many decay modes & fit "kinematic end points"
- Assume 'model' for χ^0_1 & reconstruct masses

Mass Correlations

Masses of the measured particles are strongly correlated with the mass of the lightest neutralino



However LHC can do better analyzing many edges simultaneously

… but correlations between masses will remain

General "Edge" Analysis

Analyse many edges of distributions:

$$(m^2_{ll})^{\rm edge} = \frac{(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

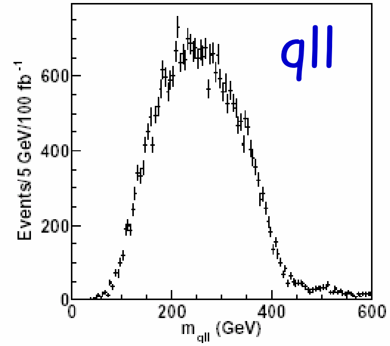
$$(m^2_{qll})^{\rm edge} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde\chi^0_2}}$$

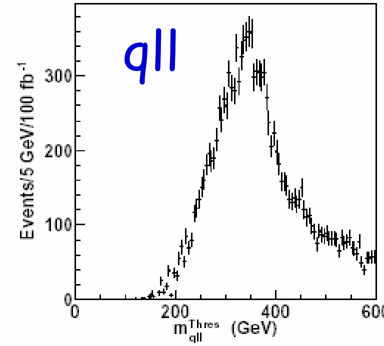
$$(m^2_{ql})^{\rm edge}_{\rm min} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})}{m^2_{\tilde\chi^0_2}}$$

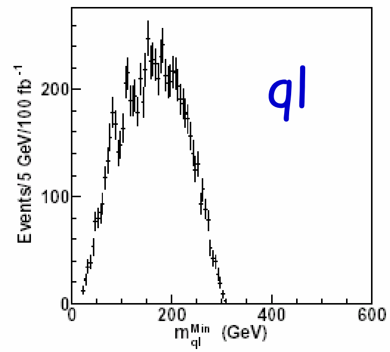
$$(m^2_{ql})^{\rm edge}_{\rm max} = \frac{(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1})}{m^2_{\tilde l_R}}$$

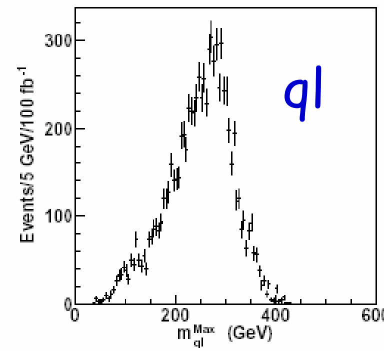
$$(m^2_{qll})^{\rm thres} = [(m^2_{\tilde q_L} + m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde l_R})(m^2_{\tilde l_R} - m^2_{\tilde\chi^0_1}) - (m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})\sqrt{(m^2_{\tilde\chi^0_2} + m^2_{\tilde l_R})^2(m^2_{\tilde l_R} + m^2_{\tilde\chi^0_1})^2 - 16 m^2_{\tilde\chi^0_2} m^4_{\tilde l_R} m^2_{\tilde\chi^0_1}} + 2m^2_{\tilde l_R}(m^2_{\tilde q_L} - m^2_{\tilde\chi^0_2})(m^2_{\tilde\chi^0_2} - m^2_{\tilde\chi^0_1})]/(4m^2_{\tilde l_R} m^2_{\tilde\chi^0_2})$$

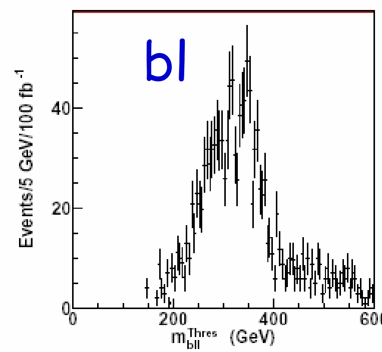
SPS1a











Min,max refer to choice of lepton

Solve numerically equations ⇒ derive masses

Extracted Edge Values

SPS1a 300 fb^{-1}
Includes 1% energy-scale systematics

Variable	Value (GeV)	Errors: Stat. (GeV)	Errors: Scale (GeV)	Errors: Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

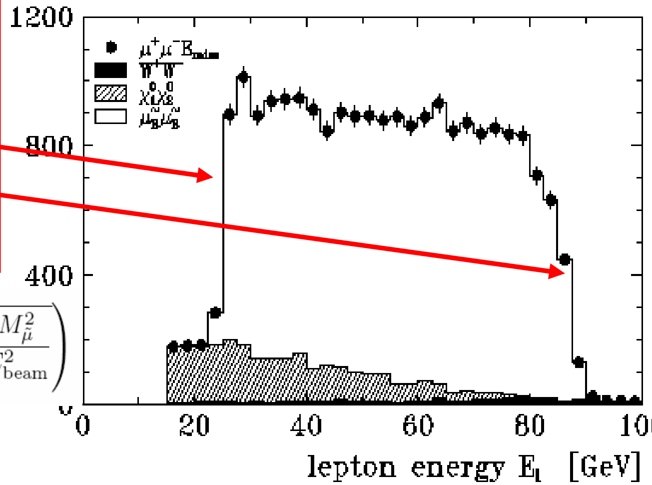
Supersymmetry at a LC

Measure single muons

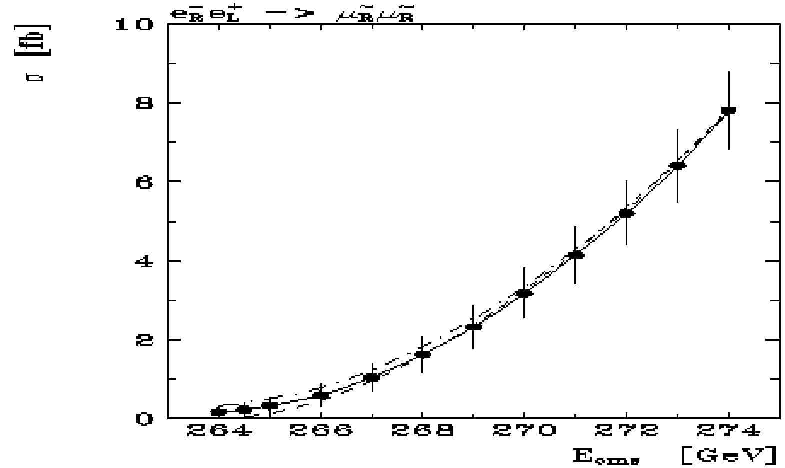
Kinematics: end-points allows to measure sparticle masses precisely

$$E_{\rm max/min} = \frac{M_{\tilde\mu}}{2}\left(1-\frac{M^2_{\tilde\chi^0_1}}{M^2_{\tilde\mu}}\right)\times\left(1\pm\sqrt{1-\frac{M^2_{\tilde\mu}}{E^2_{\rm beam}}}\right)$$

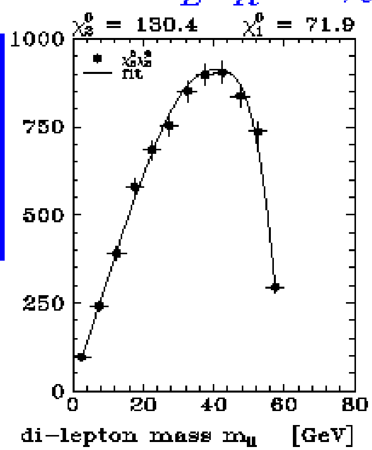
$e^-_L e^+_R \to \tilde\mu_L \tilde\mu_R \to \mu \tilde\chi^0_2$

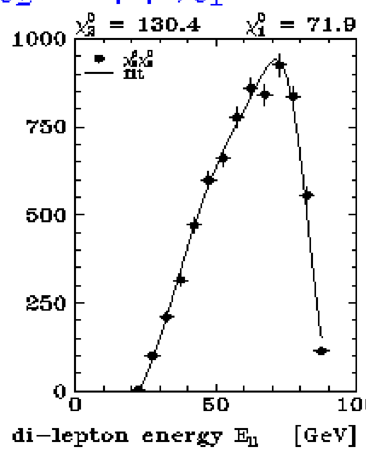


$\tilde\mu$ Threshold Scan

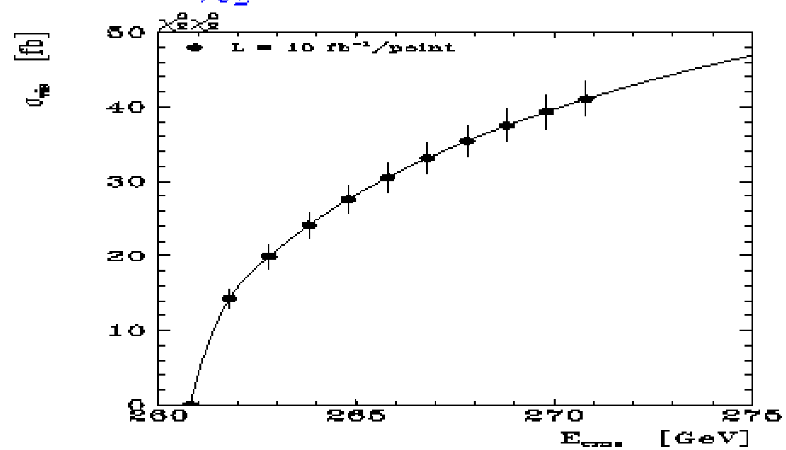


$e^-_L e^+_R \to \tilde\chi^0_2 \tilde\chi^0_2 \to \mu\mu\tilde\chi^0_1$





χ^0_2 Threshold Scan



Precision on masses of order 0.5-0.1%

SUSY Sparticle Mass Precision at a LC

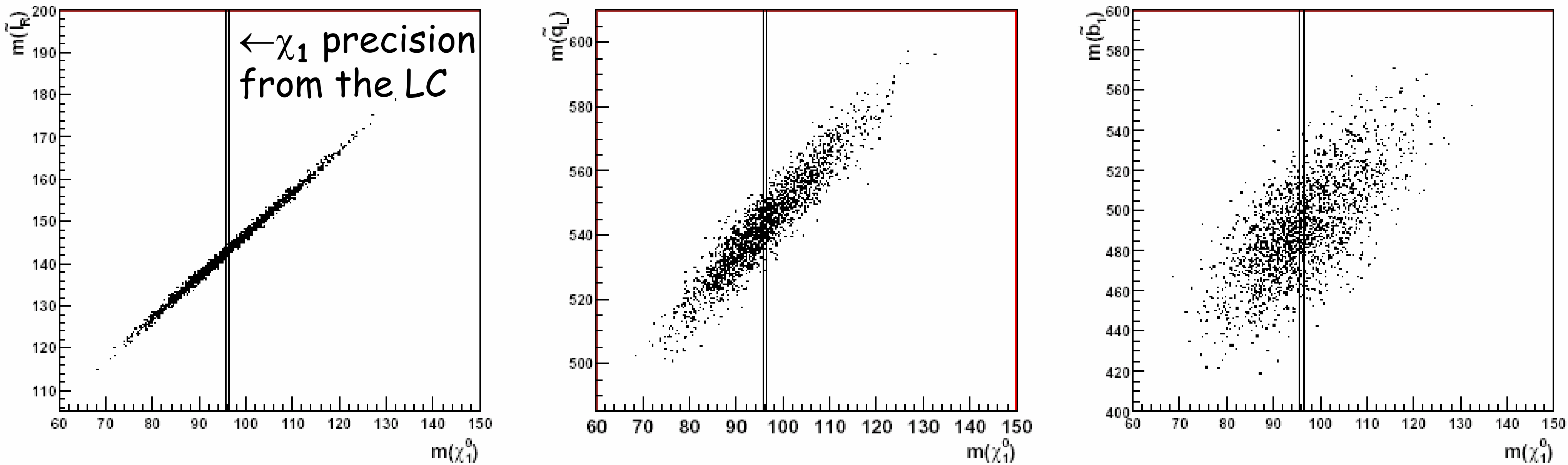
	m [GeV]	Δm [GeV]	Comments
$\tilde{\chi}_1^\pm$	176.4	0.55	simulation threshold scan , 100 fb^{-1}
$\tilde{\chi}_2^\pm$	378.2	3	estimate $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$, spectra $\tilde{\chi}_2^\pm \to Z\tilde{\chi}_1^\pm$, $W\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$	96.1	0.05	combination of all methods
$\tilde{\chi}_2^0$	176.8	1.2	simulation threshold scan $\tilde{\chi}_2^0\tilde{\chi}_2^0$, 100 fb^{-1}
$\tilde{\chi}_3^0$	358.8	$3-5$	spectra $\tilde{\chi}_3^0 \to Z\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{\chi}_4^0$	377.8	$3-5$	spectra $\tilde{\chi}_4^0 \to W\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\tilde{\chi}_4^0$, $\tilde{\chi}_3^0\tilde{\chi}_4^0$, 750 GeV, $>$ 1000 fb^{-1}
$\tilde{e}_R$	143.0	0.05	e^-e^- threshold scan, 10 fb^{-1}
$\tilde{e}_L$	202.1	0.2	e^-e^- threshold scan 20 fb^{-1}
$\tilde{\nu}_e$	186.0	1.2	simulation energy spectrum, 500 GeV, 500 fb^{-1}
$\tilde{\mu}_R$	143.0	0.2	simulation energy spectrum, 400 GeV, 200 fb^{-1}
$\tilde{\mu}_L$	202.1	0.5	estimate threshold scan, 100 fb^{-1} [36]
$\tilde{\tau}_1$	133.2	0.3	simulation energy spectra, 400 GeV, 200 fb^{-1}
$\tilde{\tau}_2$	206.1	1.1	estimate threshold scan, 60 fb^{-1} [36]
$\tilde{t}_1$	379.1	2	estimate b-jet spectrum, $m_{\min}()$, 1TeV, 1000 fb^{-1}

Table 5.12: Sparticle masses and their expected precisions in Linear Collider experiments, SPS 1a mSUGRA scenario

Mass Determinations including LC data

Improvement of measured particle masses at LHC when the mass of the lightest neutralino is known from the LC

slepton squark sbottom



Significant improvements & reduction of correlations

... but correlations between masses will remain

Combining the LC/LHC Data

300 fb^{-1}@LHC

Takes into account 1% energy scale uncertainties

ΔM values in GeV

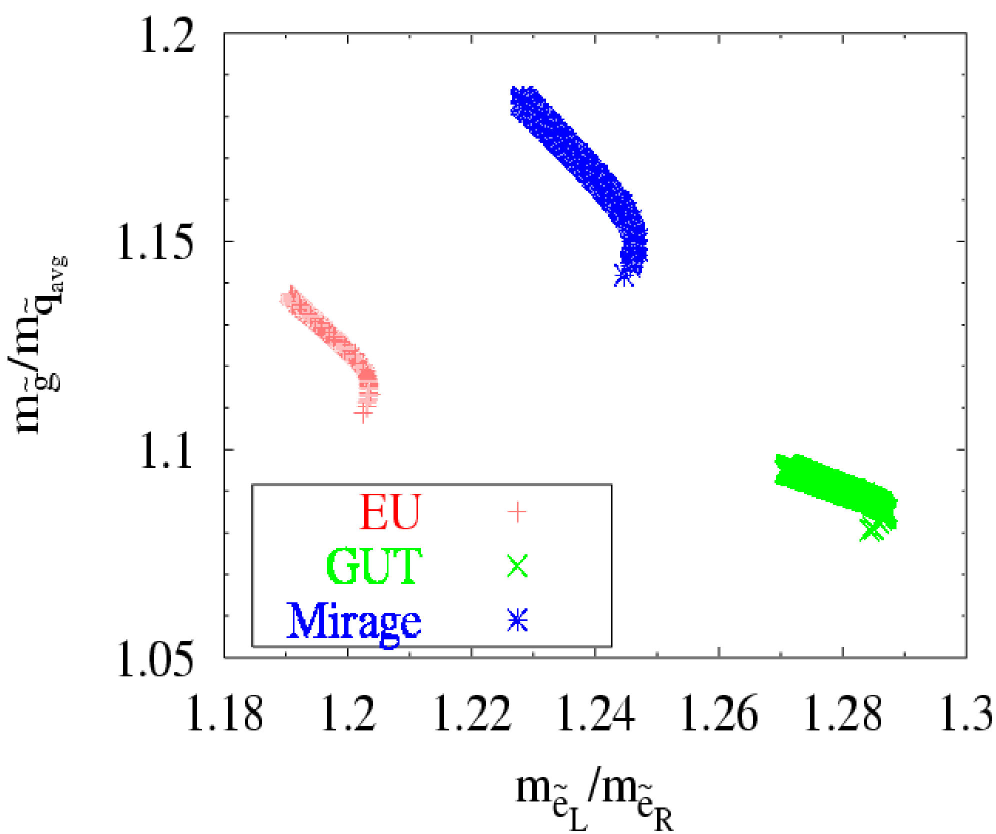
	LHC	LHC+LC
$\Delta m_{\tilde{\chi}_1^0}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\chi}_2^0}$	4.7	0.08
$\Delta m_{\tilde{\chi}_4^0}$	5.1	2.23
$\Delta m_{\tilde{l}_R}$	4.8	0.05 (LC input)
$\Delta m_{\tilde{\ell}_L}$	5.0	0.2 (LC input)
$\Delta m_{\tilde{\tau}_1}$	5-8	0.3 (LC input)
$\Delta m_{\tilde{q}_L}$	8.7	4.9
$\Delta m_{\tilde{q}_R}$	7-12	5-11
$\Delta m_{\tilde{b}_1}$	7.5	5.7
$\Delta m_{\tilde{b}_2}$	7.9	6.2
$\Delta m_{\tilde{g}}$	8.0	6.5

Significant improvements with an LC/LHC combined data

Why do we want % precision on masses?

Allanach, Grellscheid, Quevedo

Discrimination between different SUSY-breaking scenarios



Need information of both the squark and slepton sector
Need % level accuracy to distinguish between different models

2.Predict Sparticle Masses from LC→LHC

Kalinowski,Moortgat-pick,Nojiri, Polesello

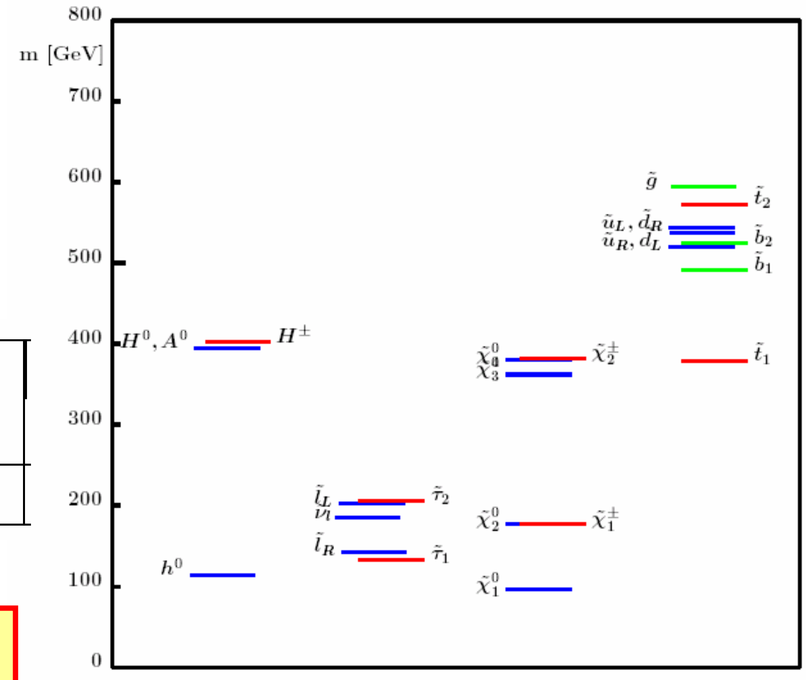
A step further: predicting sparticles masses from LC data.
LC can measure neutral χ_1, χ_2 and charged χ_1 precisely

⇒Measurements of masses, cross sections and the mixing angles (using polarized beams)

⇒Determine the SUSY parameters
M_1, M_2 (U(2) and SU(2) gaugino masses)
μ (higgsino mixing parameter)
and $\tan\beta$

SUSY Parameters			
M_1	M_2	μ	$\tan\beta$
99.1 ± 0.2	192.7 ± 0.5	352.4 ± 4.5	10.2 ± 0.9

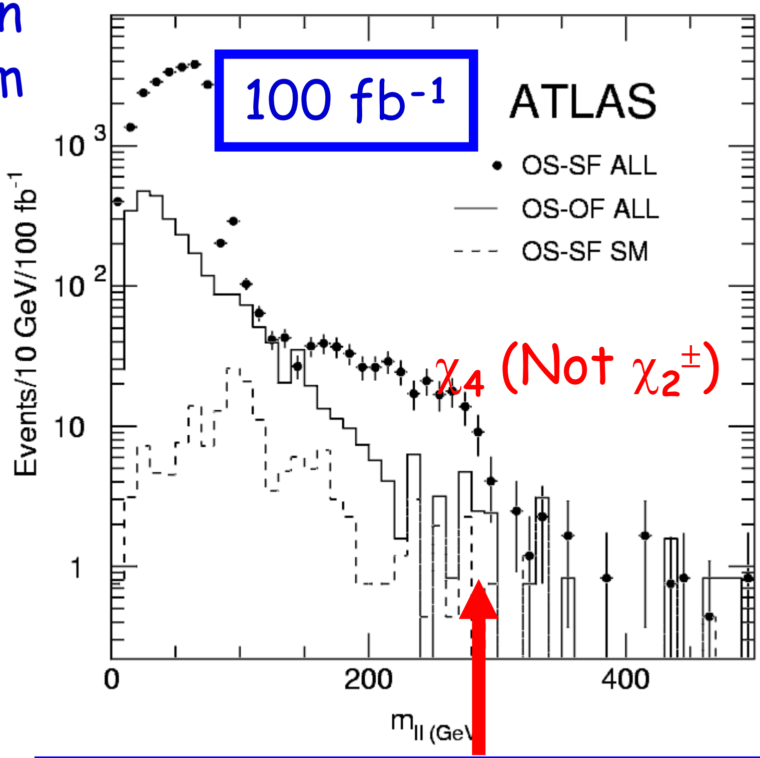
Predicts: $m(\chi_4)=378.3 \pm 8.8$ GeV

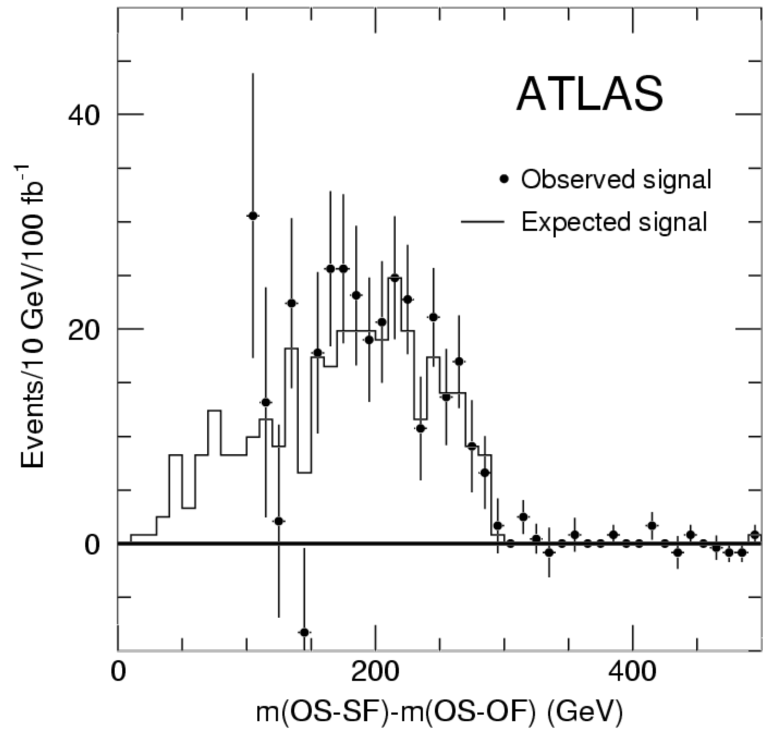


Finding χ_4 in the LHC Data…

⇒This helps to interprete the LHC data
⇒Marginal edge for χ_4 at the LHC found with LC input!

Di-lepton spectrum



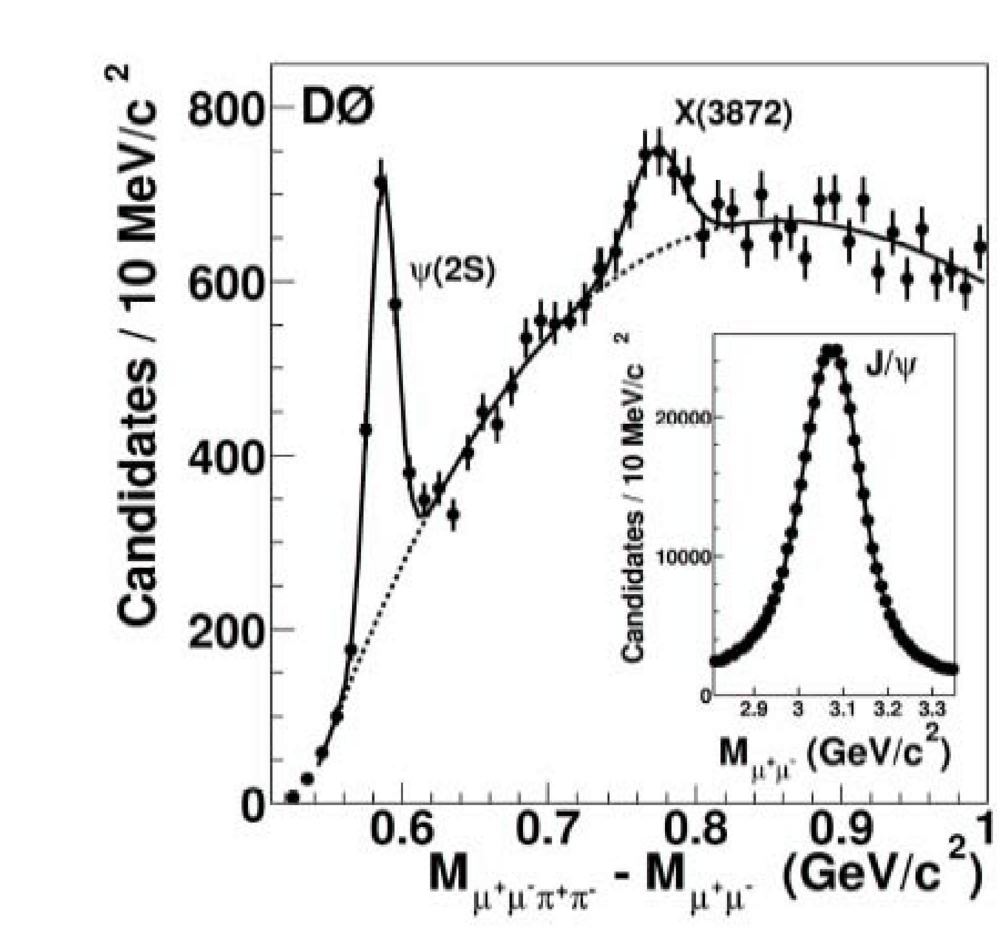


With a taylored analysis can measure ⇒m(χ_4) to ~ 5 GeV
When m(χ_1) is known from the LC then ⇒ m(χ_4) to 2.2 GeV

Requires machines to run at the same time

Not a precedent…

2003: Belle (e+e-) finds X(3872) → D0 and CDF search and find it

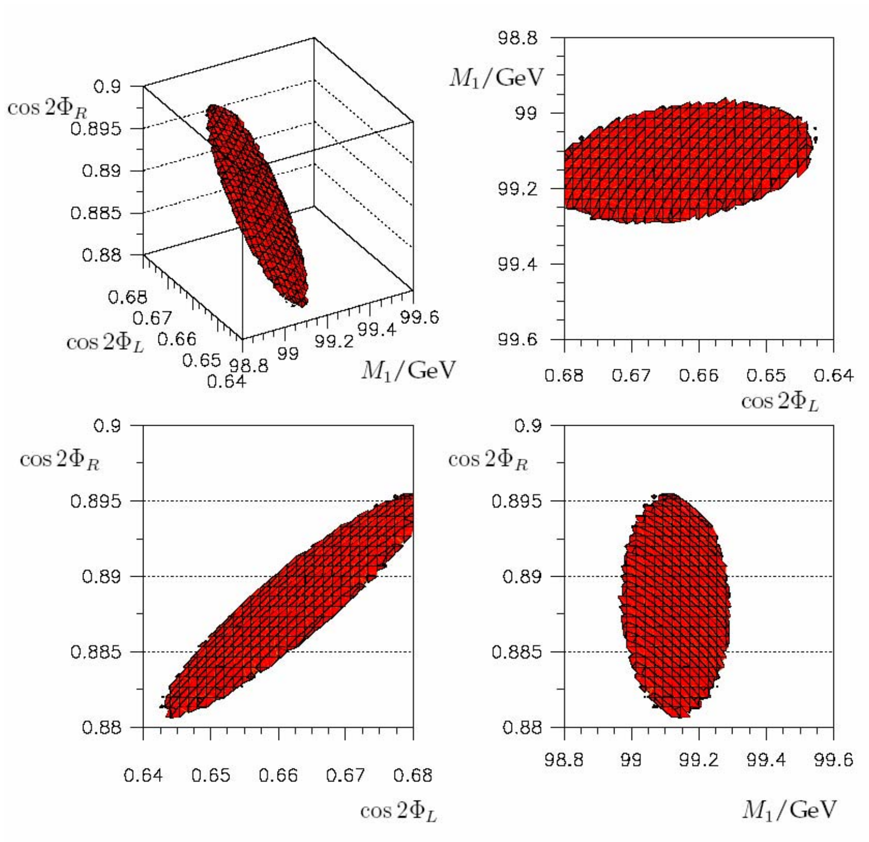


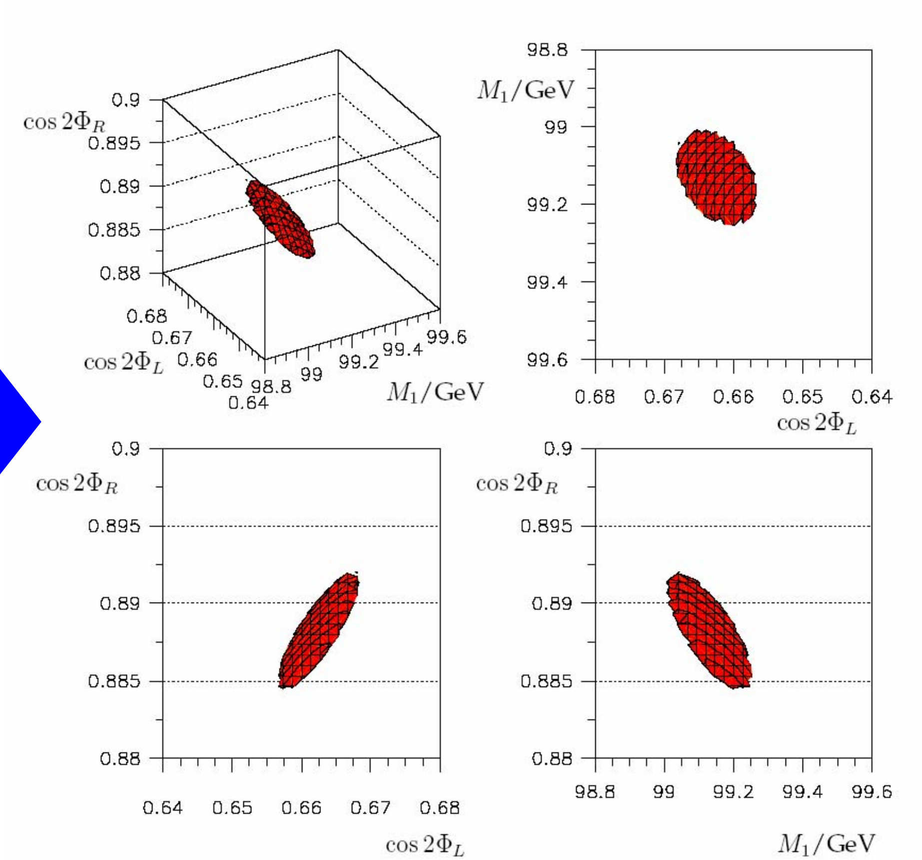
…and now.. ⇒use χ_4 for LC data!

LC information alone

$\Delta\chi^2=6$ curves

LHC+LC information





SUSY Parameters			
M_1	M_2	μ	$\tan\beta$
99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6

Significant improvement of the precision

Some Comments

- LC prediction for $M(\chi_4)$ increases the statistical significance of the LHC: testing only one mass hypothesis rather than many hypotheses.
- A mismatch between LC prediction and LHC measurement can imply (N)MSSM or something entirely different. So it will be important anyway
- Prototype example of LHC/LC synergy:
  - A signal with small statistical significance seen at the LHC after LC predicts it, calls for higher luminosity, improved analyses, cuts, perhaps trigger upgrades etc.
  - In such case overlap in LHC/LC running will be very important

3.Full Reconstruction of the stop/bottom Parameters with LHC $\otimes$ LC

Hisano, Kawagoe, Nojiri

- Take the set of electroweak SUSY parameters determined by the LC and LHC data.
- Take branching ratios of bottom (stop) measured by the LHC
- Take m_{b1} and m_{b2} from edge study (+ neutralino from the LC)

- Measure

-tb invariant mass distribution

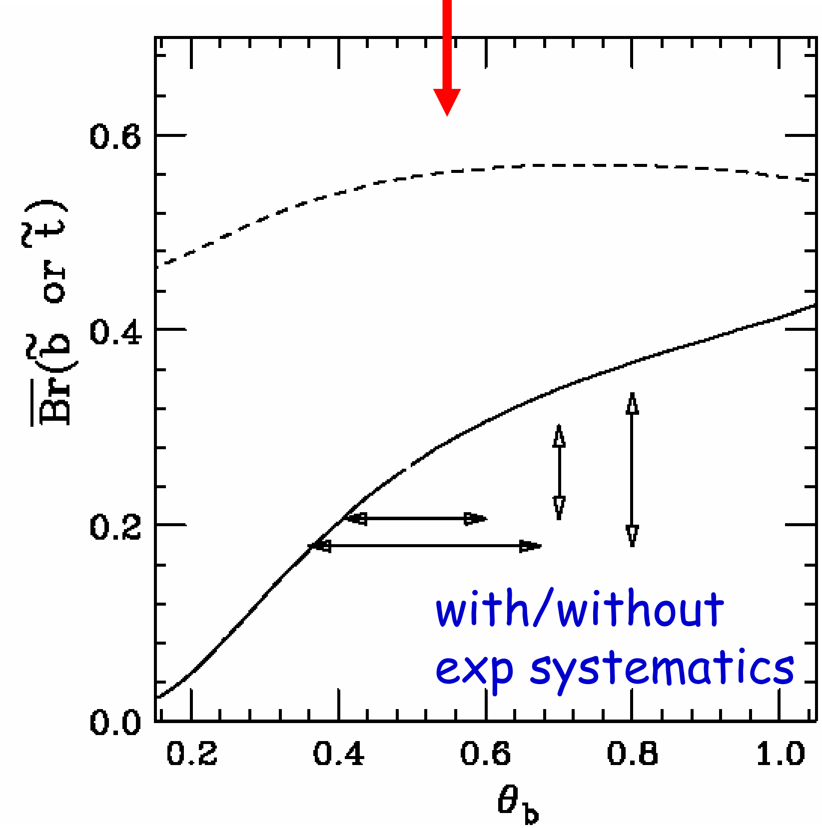
-rate of "edge events" in m_{tb} distribution (chargino chain)

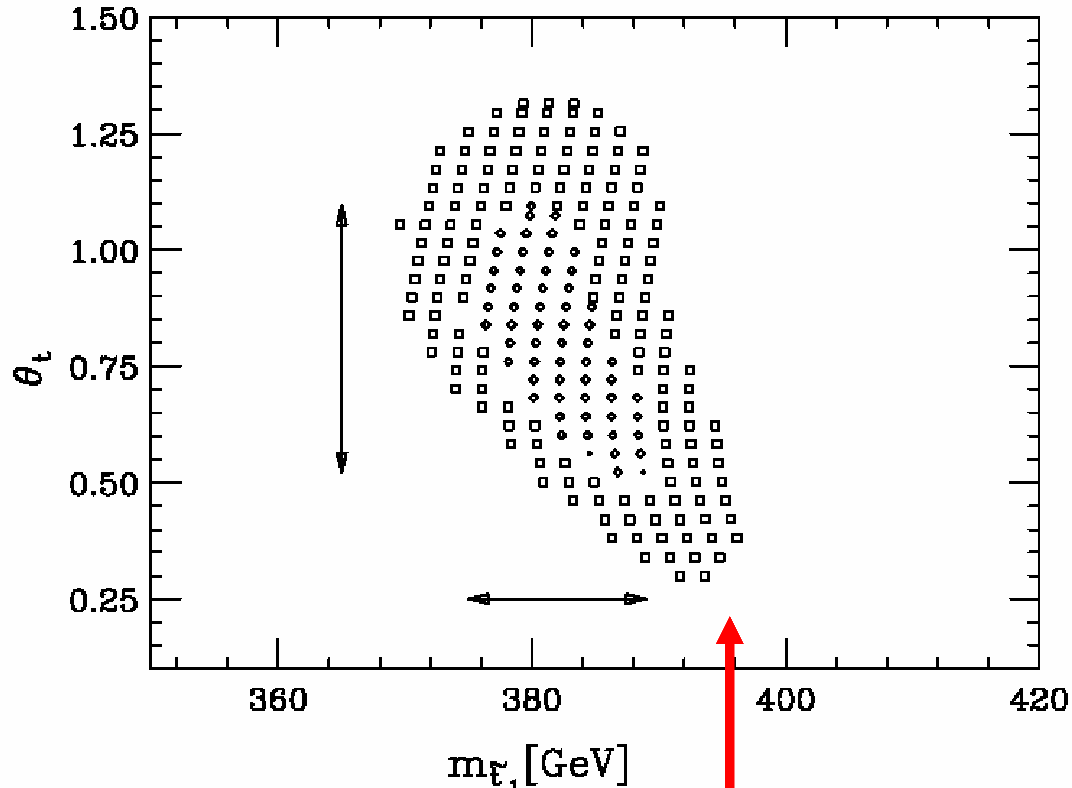
-rate of events in the 2 leton+b distribution (neutralino-2 chain)

$\Rightarrow$ extract sbottom and stop mixing parameters

Stop/Sbottom mixing angles

Determination of θ_b from $\mathrm{BR}(\tilde{g} \to b\tilde{b}_2 \to bb\tilde{\chi}_2^0)/\mathrm{BR}(\tilde{g} \to b\tilde{b}_1 \to bb\tilde{\chi}_2^0)$





Determination of θ_{stop},m_{stop} when θ_b is known

4. Determine the Pattern of SUSY Breaking

	Mass, ideal	"LHC"	"LC"	"LHC+LC"
$\tilde{\chi}_1^\pm$	179.7		0.55	0.55
$\tilde{\chi}_2^\pm$	382.3	–	3.0	3.0
$\tilde{\chi}_1^0$	97.2	4.8	0.05	0.05
$\tilde{\chi}_2^0$	180.7	4.7	1.2	0.08
$\tilde{\chi}_3^0$	364.7		3-5	3-5
$\tilde{\chi}_4^0$	381.9	5.1	3-5	2.23
$\tilde{e}_R$	143.9	4.8	0.05	0.05
$\tilde{e}_L$	207.1	5.0	0.2	0.2
$\tilde{\nu}_e$	191.3	–	1.2	1.2
$\tilde{\mu}_R$	143.9	4.8	0.2	0.2
$\tilde{\mu}_L$	207.1	5.0	0.5	0.5
$\tilde{\nu}_\mu$	191.3	–		
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	–	1.1	1.1
$\tilde{\nu}_\tau$	190.4	–	–	–
$\tilde{q}_R$	547.6	7-12	–	5-11
$\tilde{q}_L$	570.6	8.7	–	4.9
$\tilde{t}_1$	399.5		2.0	2.0
$\tilde{t}_2$	586.3		–	
$\tilde{b}_1$	515.1	7.5	–	5.7
$\tilde{b}_2$	547.1	7.9	–	6.2
$\tilde{g}$	604.0	8.0	–	6.5
h^0	110.8	0.25	0.05	0.05
H^0	399.8		1.5	1.5
A^0	399.4		1.5	1.5
$H^\pm$	407.7	–	1.5	1.5

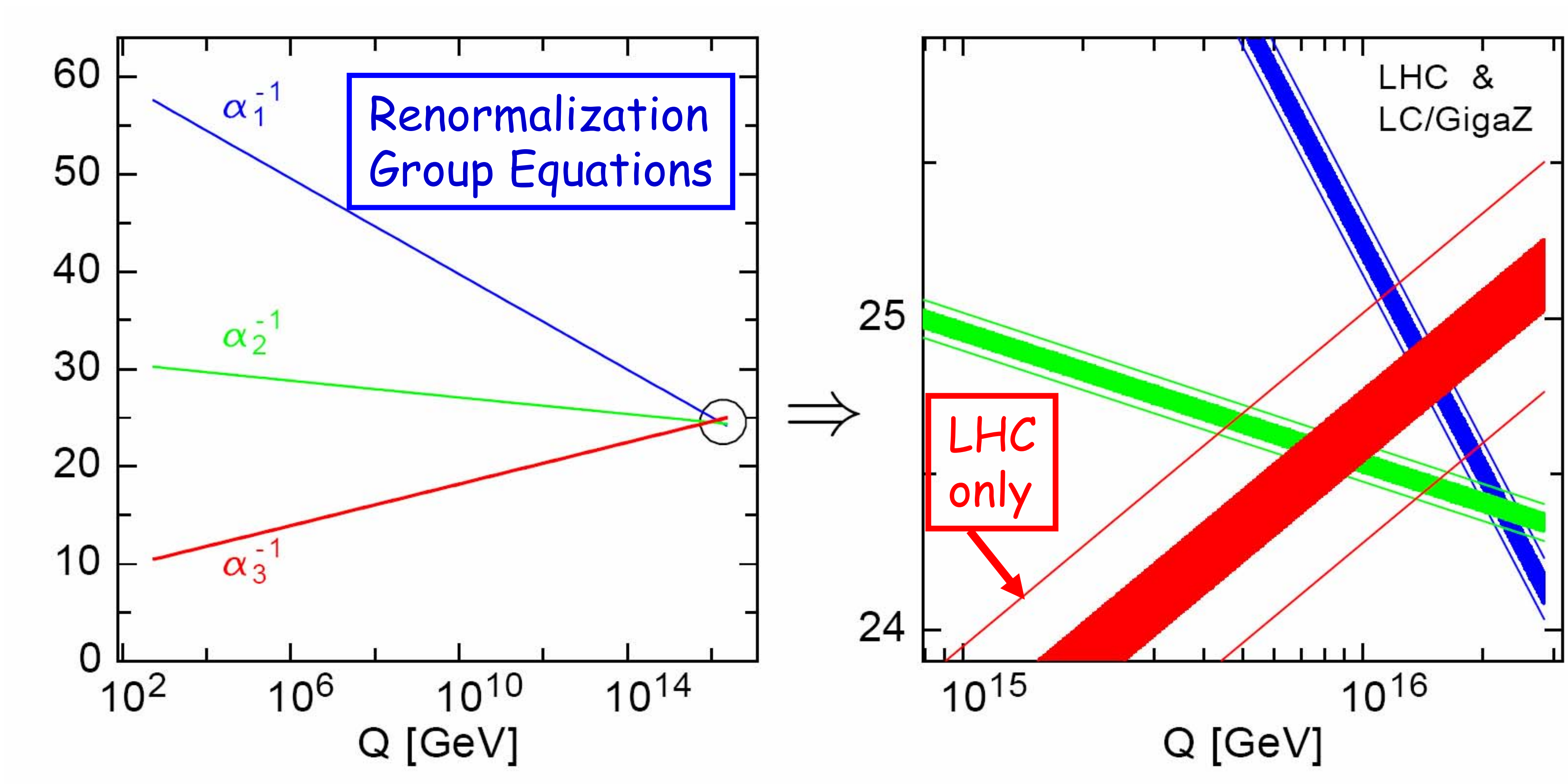
With all LC/LHC information $\Rightarrow$
Determine the SUSY Parameters

Low energy SUSY parameters

	Parameter, ideal	"LHC+LC" errors
M_1	101.66	0.08
M_2	191.76	0.25
M_3	584.9	3.9
μ	357.4	1.3
$M^2_{\tilde{L}_1}$	$3.8191 \cdot 10^4$	82.
$M^2_{\tilde{E}_1}$	$1.8441 \cdot 10^4$	15.
$M^2_{\tilde{Q}_1}$	$29.67 \cdot 10^4$	$0.32 \cdot 10^4$
$M^2_{\tilde{U}_1}$	$27.67 \cdot 10^4$	$0.86 \cdot 10^4$
$M^2_{\tilde{D}_1}$	$27.45 \cdot 10^4$	$0.80 \cdot 10^4$
$M^2_{\tilde{L}_3}$	$3.7870 \cdot 10^4$	360.
$M^2_{\tilde{E}_3}$	$1.7788 \cdot 10^4$	95.
$M^2_{\tilde{Q}_3}$	$24.60 \cdot 10^4$	$0.16 \cdot 10^4$
$M^2_{\tilde{U}_3}$	$17.61 \cdot 10^4$	$0.12 \cdot 10^4$
$M^2_{\tilde{D}_3}$	$27.11 \cdot 10^4$	$0.66 \cdot 10^4$
$M^2_{\tilde{H}_1}$	$3.25 \cdot 10^4$	$0.12 \cdot 10^4$
$M^2_{\tilde{H}_2}$	$-12.78 \cdot 10^4$	$0.11 \cdot 10^4$
A_t	$-497.$	9.
$\tan\beta$	10.0	0.4

Check the Unification of the Couplings

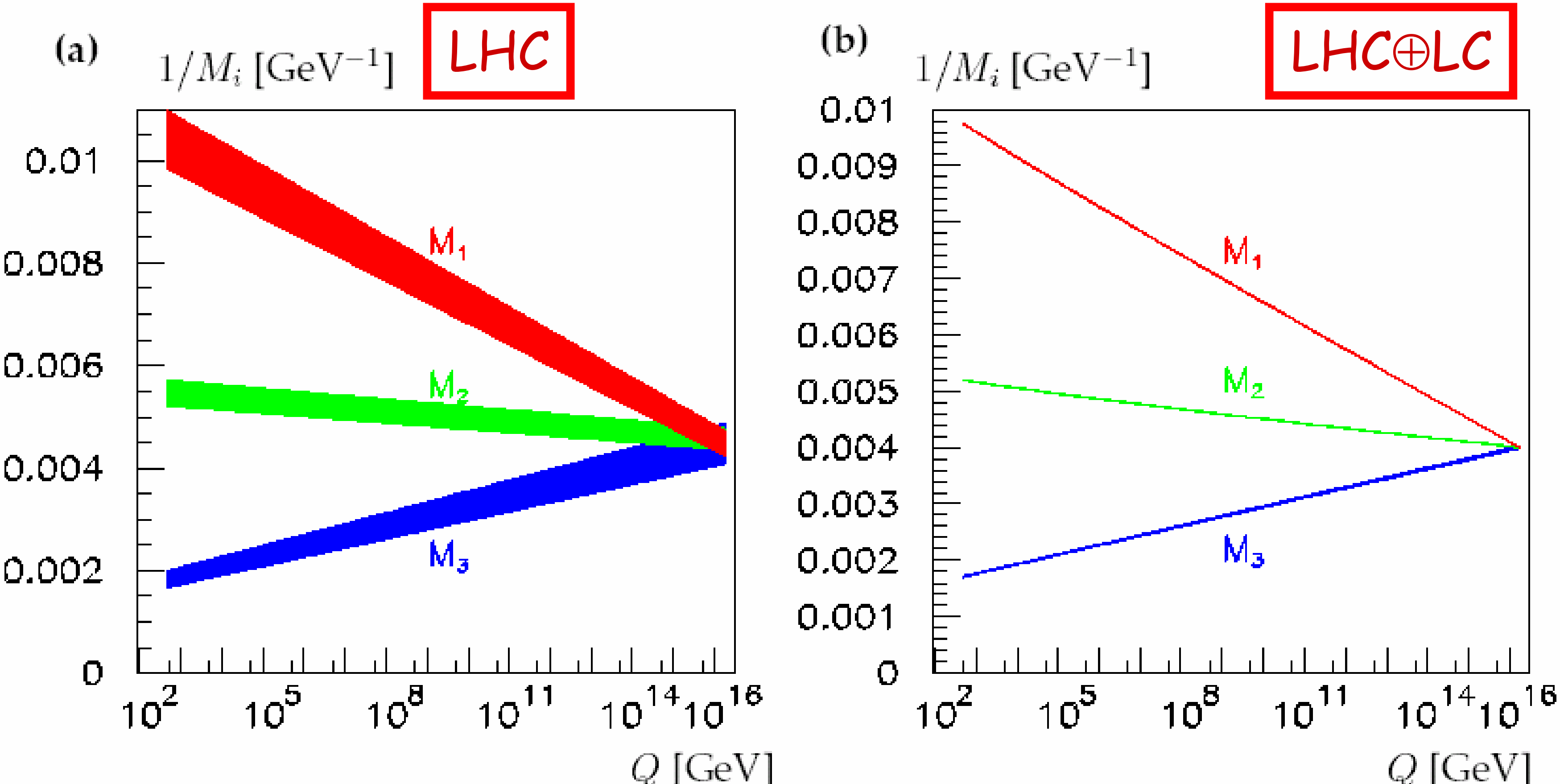
Input SUSY spectrum parameters and + present data on α,α_s,$\sin^2\theta$...



Extrapolation to Physics at High Scales

Blair, Martyn, Polesello, Porod, Zerwas

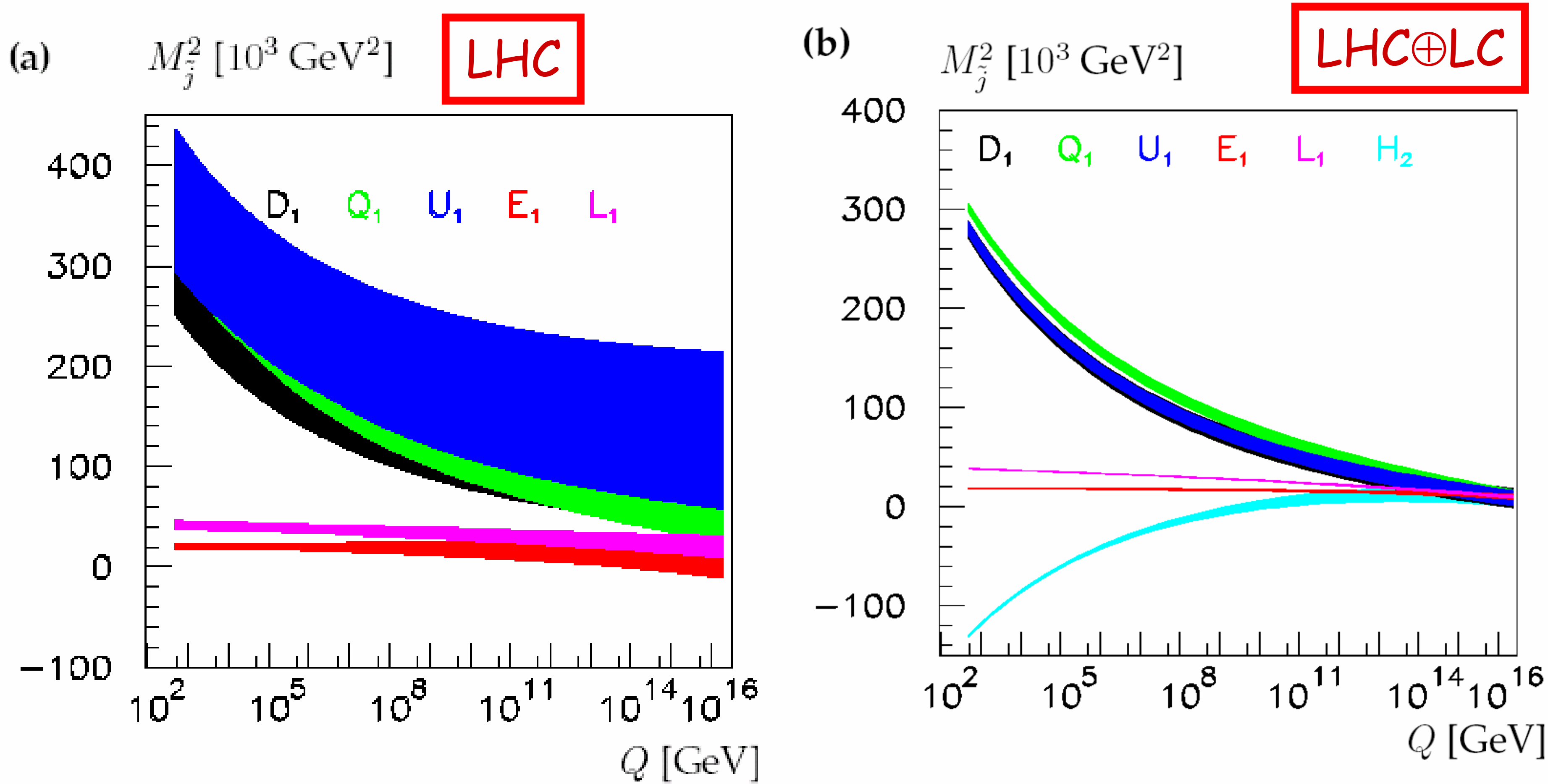
From a combination of LHC and LC results, precise measurements of masses of SUSY particles, couplings: Evolution of gaugino mass parameters



Model independent bottom-up approach: combined information on low-energy SUSY parameters as input to the Renormalization Group Equation evolution

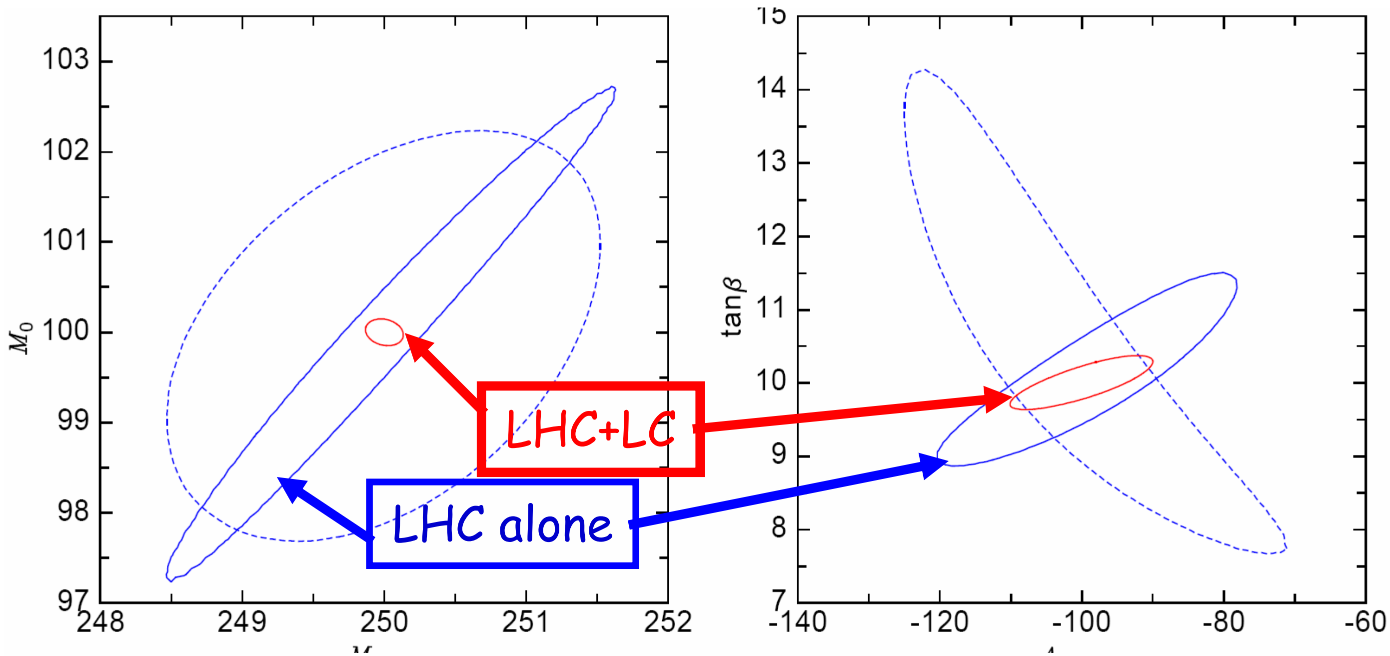
Extrapolation to Physics at High Scales

From a combination of LHC and LC results, precise measurements of masses of SUSY particles, couplings: Evolution of sfermion mass parameters



Precision on MSUGRA Parameters

M_0, $M_{1/2}$, tanβ, A_0, sign(μ) are the MSUGRA parameters



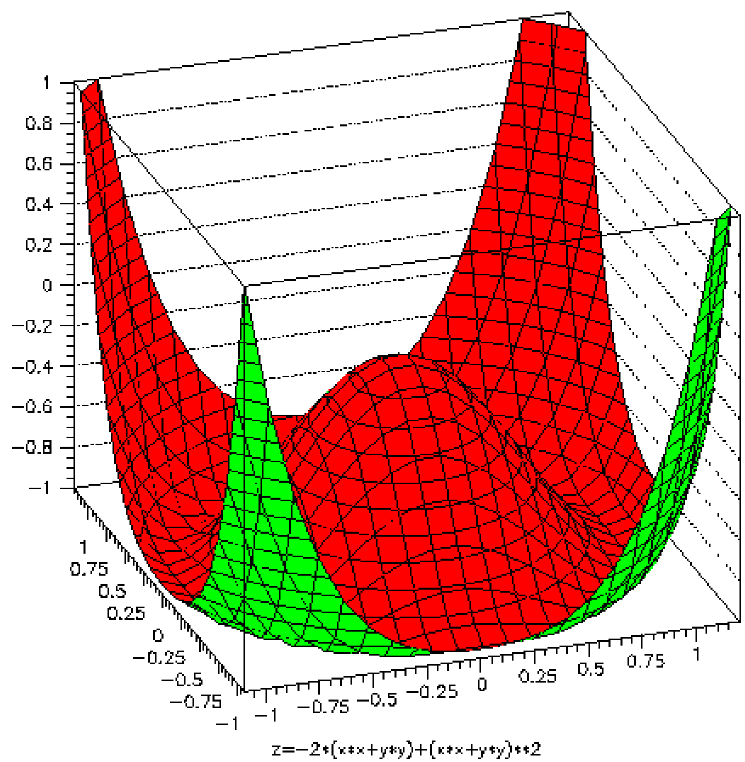
	"LHC"	"LC"	"LHC+LC"
$M_{1/2}$	250.0 ± 2.1	250.0 ± 0.4	250.0 ± 0.2
M_0	100.0 ± 2.8	100.0 ± 0.2	100.0 ± 0.2
A_0	-100.0 ± 34	-100.0 ± 27	-100.0 ± 14
$\tan\beta$	10.0 ± 1.8	10.0 ± 0.6	10.0 ± 0.4

Few Remarks on these SUSY Studies

- All studies done (coherently) for SPS1a!
- In future we need to study also less favorable points.

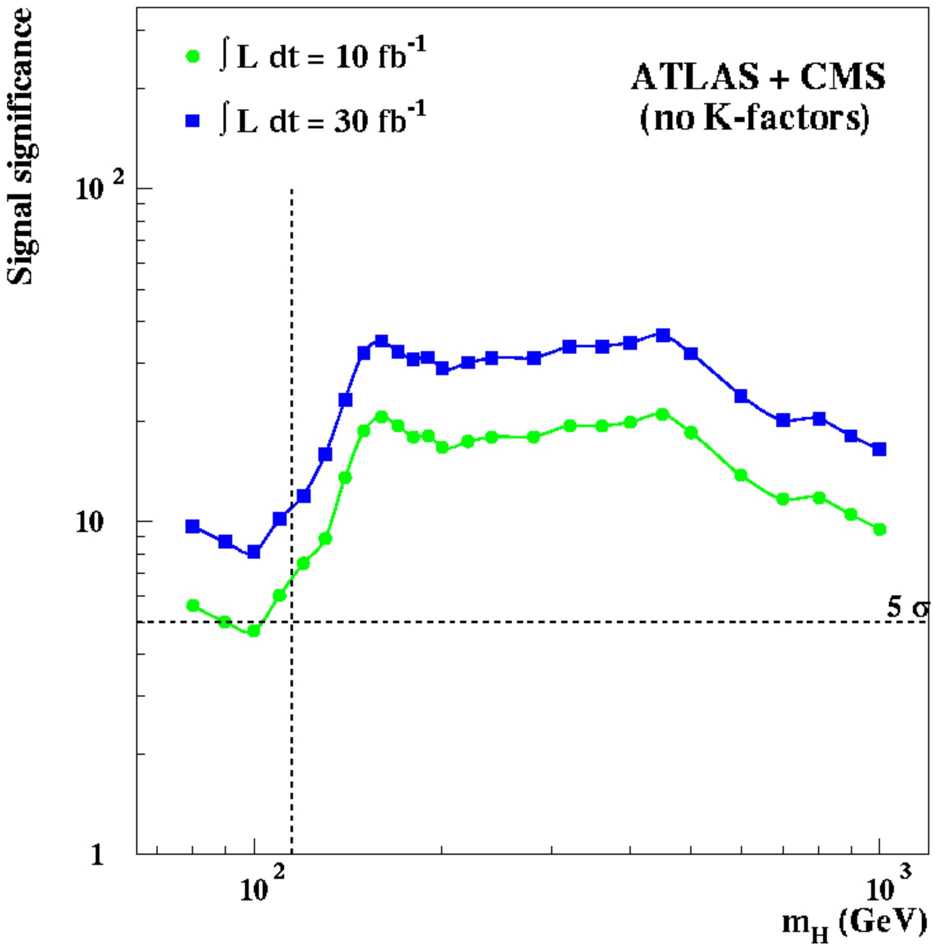
⇒The impact of a LC/LHC synergy may be even larger for "less favorable" SUSY points, e.g. points at large tan β
  - lots of decays into τ leptons
  - more difficult at the LHC

2. Higgs Physics



Higgs Measurement Prospects

Discovery in full range with 10 fb^{-1}



LHC

- $\Delta M/M$ = 0.1-1% large region
- $\Delta\Gamma/\Gamma$ = 5-8% ($M_H > 2M_Z$)
  = ~20% ($M_H < 2M_Z$)
- Ratios of couplings: 10-20%

LC

- $\Delta M/M$ = 0.03%
- Total width
- Invisible width ($ee \to ZH$)
- Absolute couplings: few %
- Higgs self coupling 20 %
- …

1. Combine LHC Data on Heavy Higgs with LC Data on the Light Higgs

Desch, Gross, Heinemeyer, Weiglein

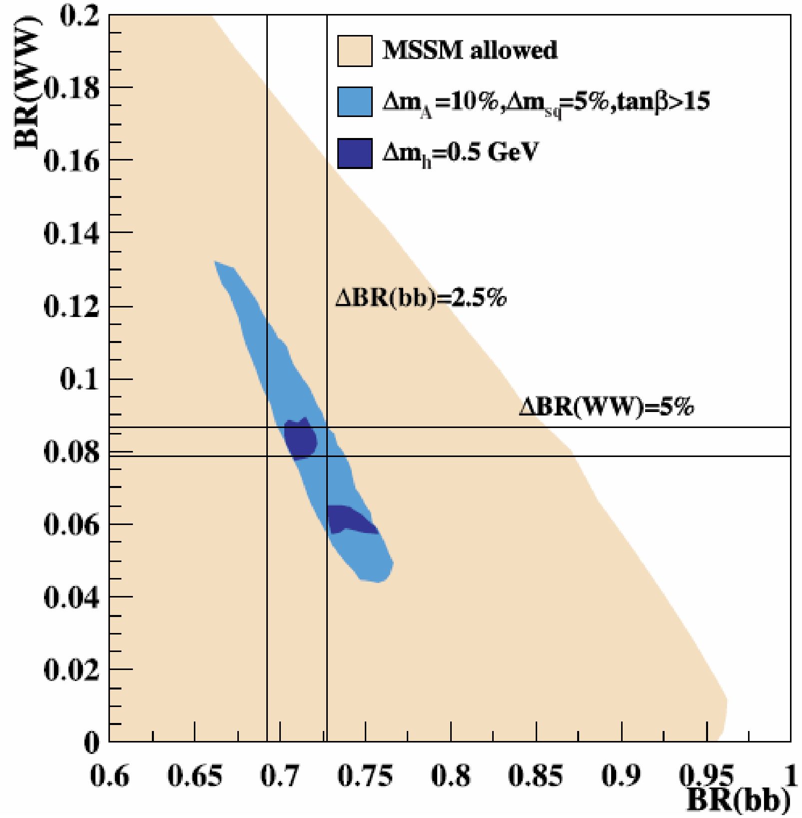
SPS1b tanβ=30

Assume:
LHC information on M_A and tan β

⊕ (LHC⊗LC) information on stop/bottom masses

⊕ LHC/LC measurement of m_H

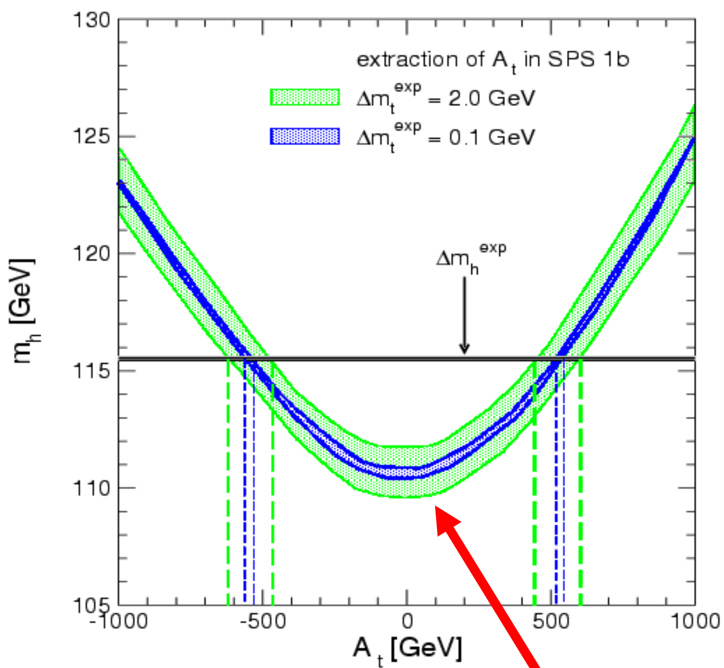
⊕ LC information on m_{top} ~0.1 GeV

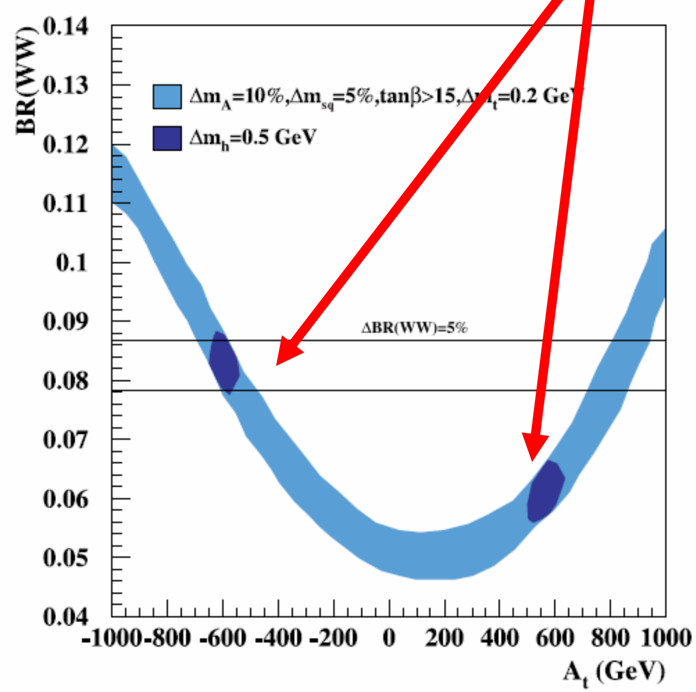


Comparison of MSSM predictions based on LHC data with BR's measured at the LC leads to very sensitive tests.

Trilinear Coupling A_t

If m_{stop} and m_{bottom} measured
$\Rightarrow$ m_H allows for an indirect determination of A_t (up to a sign)

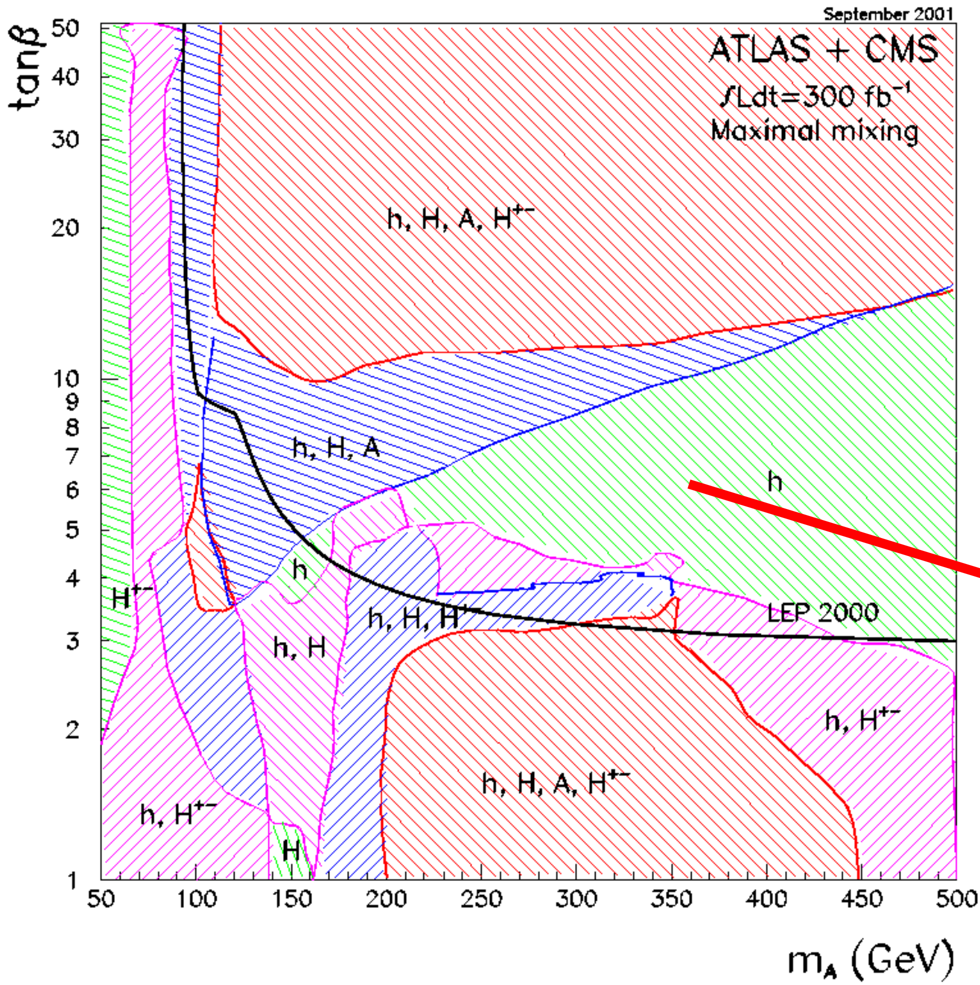




Precise measurement of m_t at the LC crucial: $\Delta m_t \sim 100$ MeV
$\Rightarrow$ Δm_t^{LC} vs Δm_t^{LHC} $\Rightarrow$ accuracy of A_t determination improved by factor 3

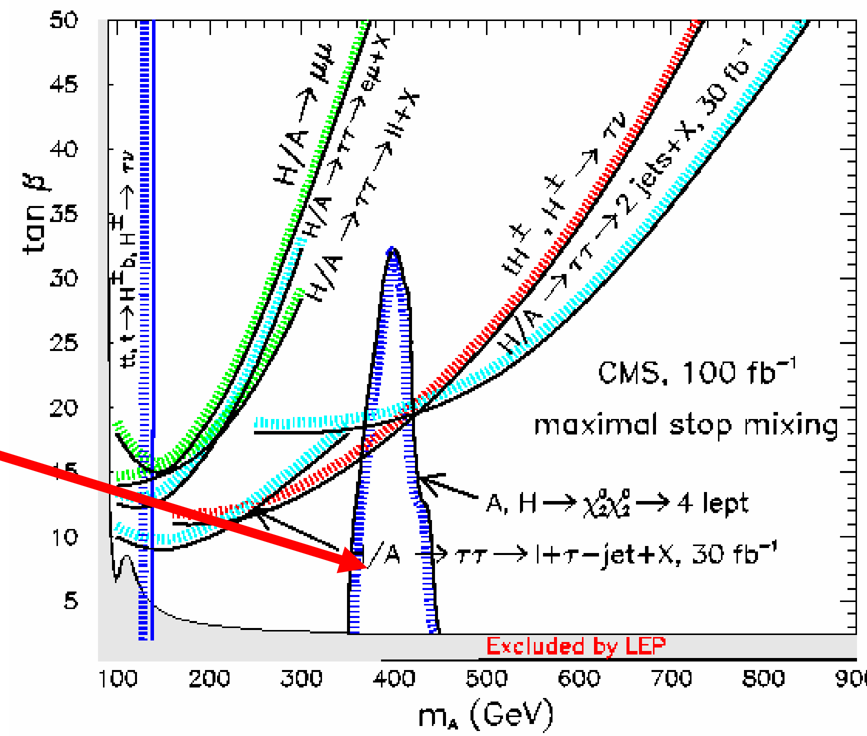
2. Heavy MSSM Higgs

Plot for 5 σ discovery



At low tan β, we may exploit the sparticle decay modes:

$A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + E_T^{miss}$

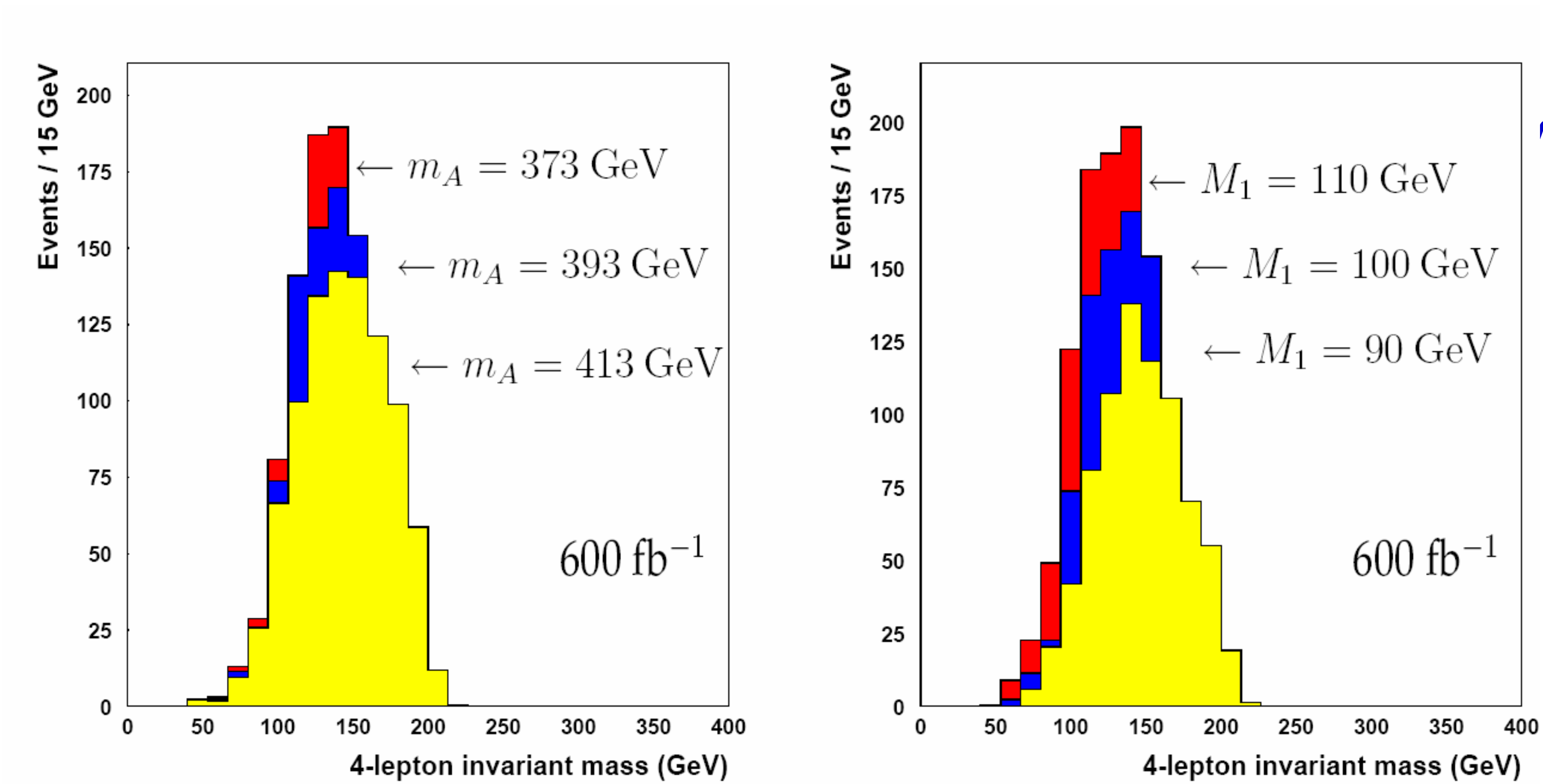


Reconstruct M_A

Moortgat

$H, A \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$ $\rightarrow$ 4 leptons and missing E_T

Get mass from sensitivity to the four lepton invariant mass



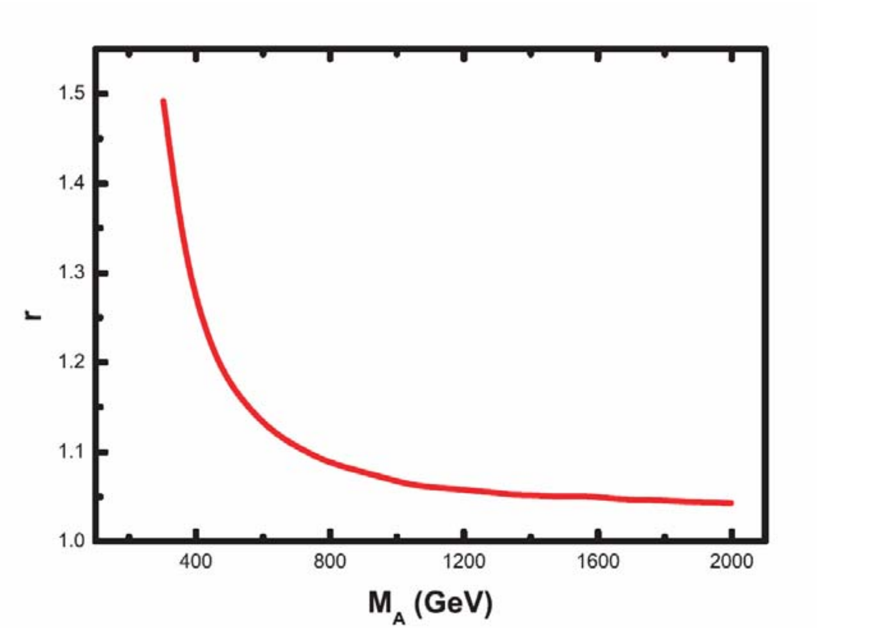
LHC: Sensitivity dominated by uncertainty at the LSP mass knowledge
LHC⊗LC : Sensitive to M_A ~3% if mass of LSP known to better than 1%

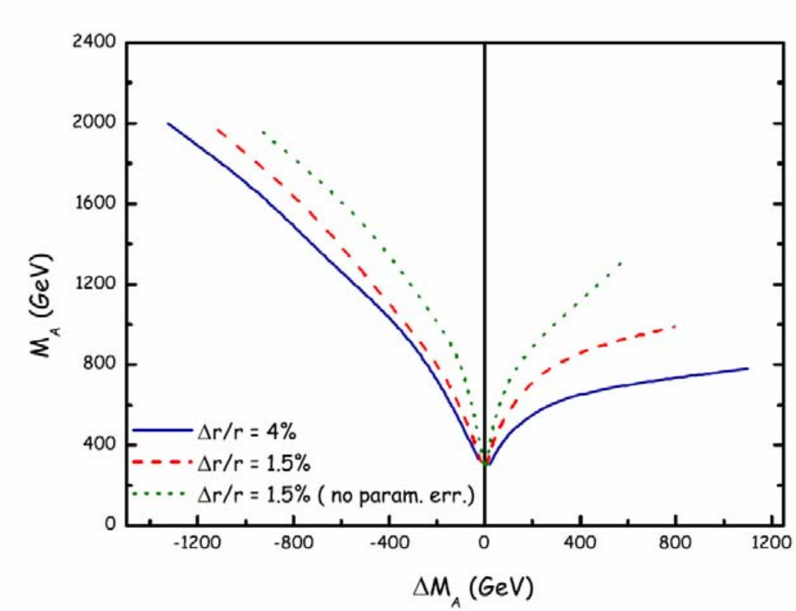
3. Constraining M_A from LHC and LC Measurements

- Suppose LHC sees only one Higgs and some SUSY particles, but not the A/H Higgses (SPS1a, but M_A as a free parameter)
- Use information from the measured SUSY spectrum at LC & LHC and from measured BR of the Higgs measured at LC to predict mass of M_A (mass of the gluino, sbottom quarks, light stop, Higgs and tan β)
- Compare :

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

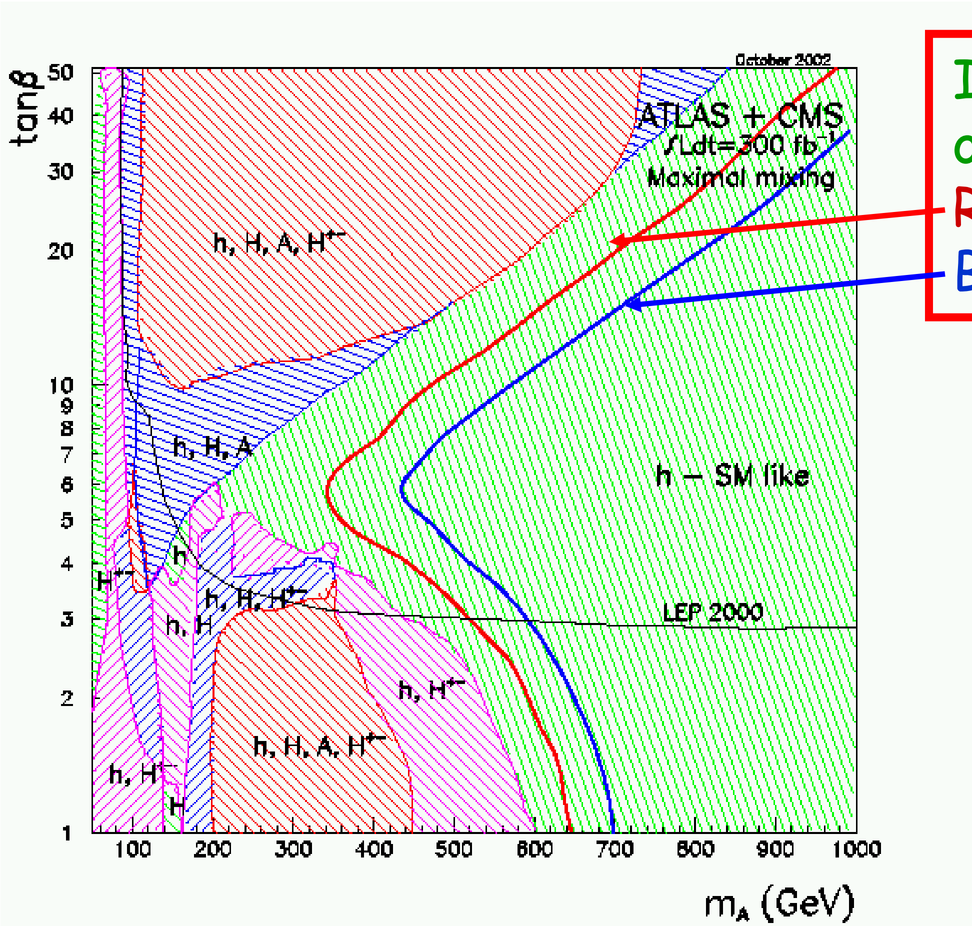
Determine M_A with 20-30% for M_A 600-800 GeV





l)

MSSM Higgs search with a LHC upgrade



In the green region only SM-like h observable with 300 fb^{-1}/exp

Red line: extension with 3000 fb^{-1}/exp

Blue line: 95% excl. with 3000 fb^{-1}/exp

Factor 10 increase in luminosity: Heavy Higgs observable region increases by ~100 GeV.

If LC predicts e.g M_A ~ 600 GeV (for tanβ = 15) then the *A* boson within reach of the LHC with sufficient luminosity

4. Top Yukawa Coupling

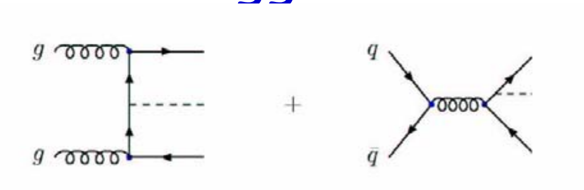
Dawson, Desch, Juste, Rainwater, Reina, Schumacher, Wackeroth

Assume a light Higgs < $2m_t$

Production processes

LC: e+e- → ttH No precise measurement at 350-500 GeV LC

LHC: gg → ttH measures σ•BR



studied for ttbb and ttWW final states

depends on $g^2_{ttH}\, g^2_{bbH}$ and $g^2_{ttH}\, g^2_{WWH}$

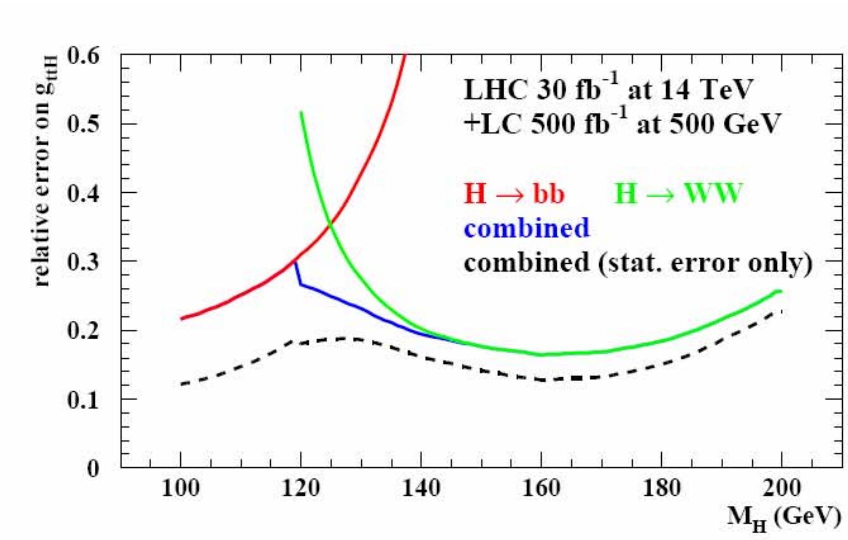
g^2_{bbH} and g^2_{WWH} can be measured precisely in a model independent way at a LC (few %)

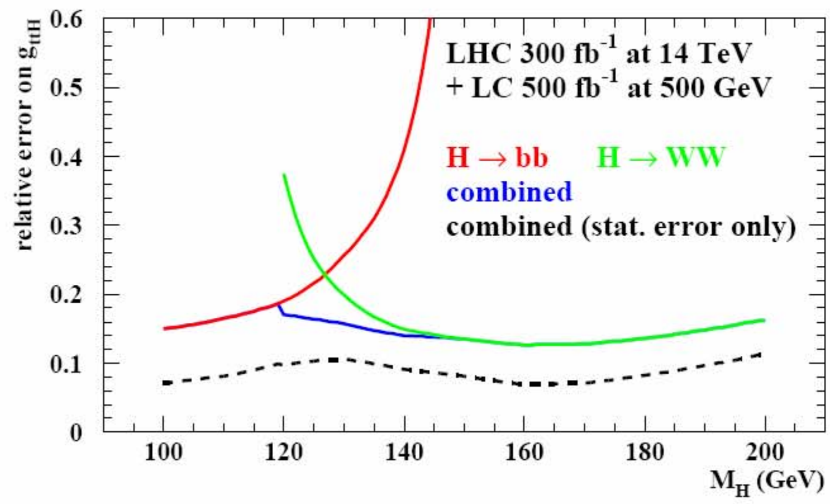
m_H (GeV)	$\Delta BR(b\bar{b})/BR(b\bar{b})$	$\Delta BR(WW)/BR(WW)$
100	0.024	
120	0.024	0.051
140	0.026	0.025
160	0.065	0.021
200		0.021

LC
350 GeV
500 fb^{-1}

⇒ can determine g^2_{ttH} without any model assumptions

Top Yukawa Coupling



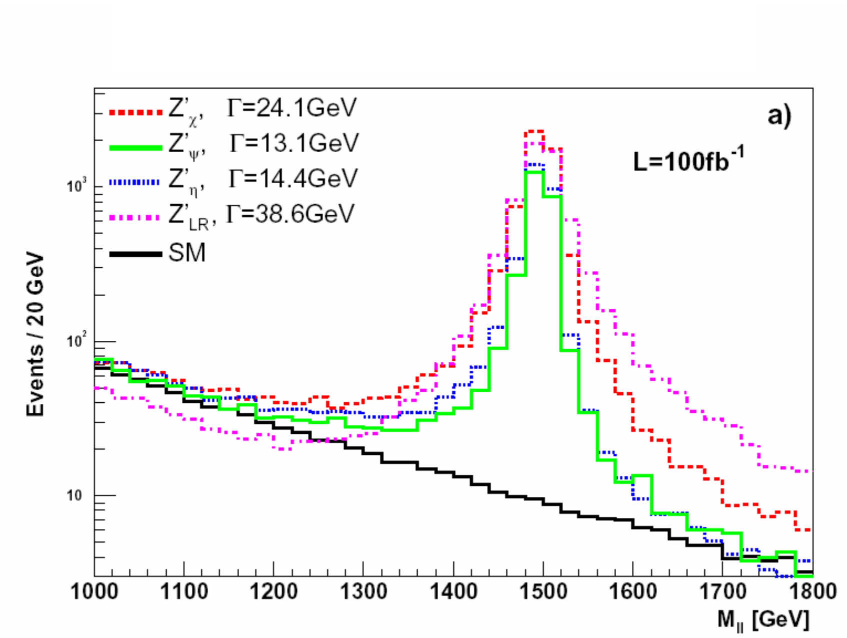


Precision of the top Yukawa coupling

m_H	30 fb^{-1}			300 fb^{-1}		
(GeV)	bb	WW	bb+WW	bb	WW	bb + WW
100	0.22(0.12)			0.15(0.07)		
110	0.25(0.15)			0.17(0.08)		
120	0.31(0.19)	0.52(0.49)	0.27(0.18)	0.19(0.10)	0.38(0.31)	0.17(0.10)
130	0.43(0.28)	0.28(0.25)	0.23(0.19)	0.26(0.15)	0.20(0.15)	0.16(0.11)
140	0.72(0.50)	0.20(0.17)	0.19(0.16))	0.41(0.26)	0.15(0.10)	0.14(0.09)
150		0.18(0.14)		1.88(1.21)	0.14(0.08)	0.14(0.08)
160		0.16(0.13)			0.13(0.07)	
170		0.17(0.13)			0.13(0.07)	
180		0.18(0.15)			0.14(0.08)	
190		0.22(0.19)			0.15(0.10)	
200		0.26(0.23)			0.16(0.11)	

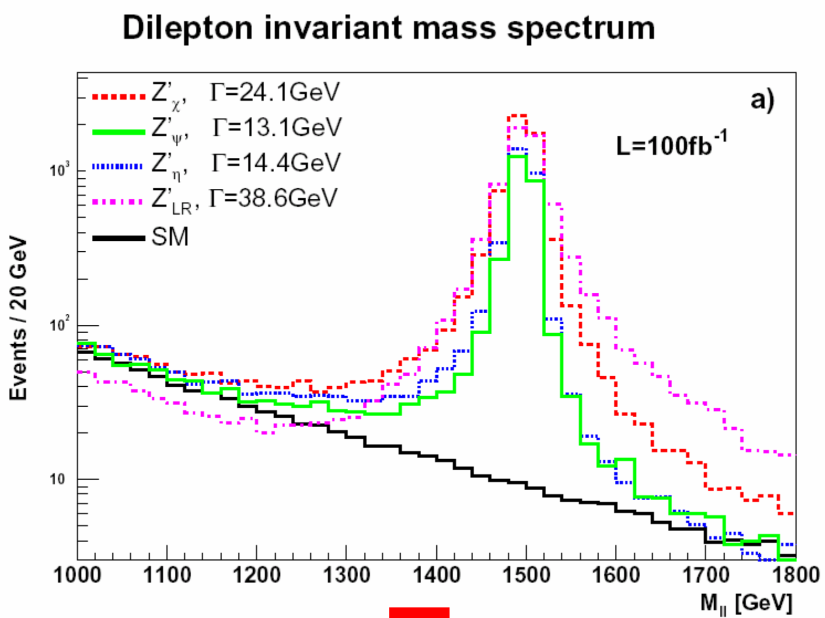
~15%

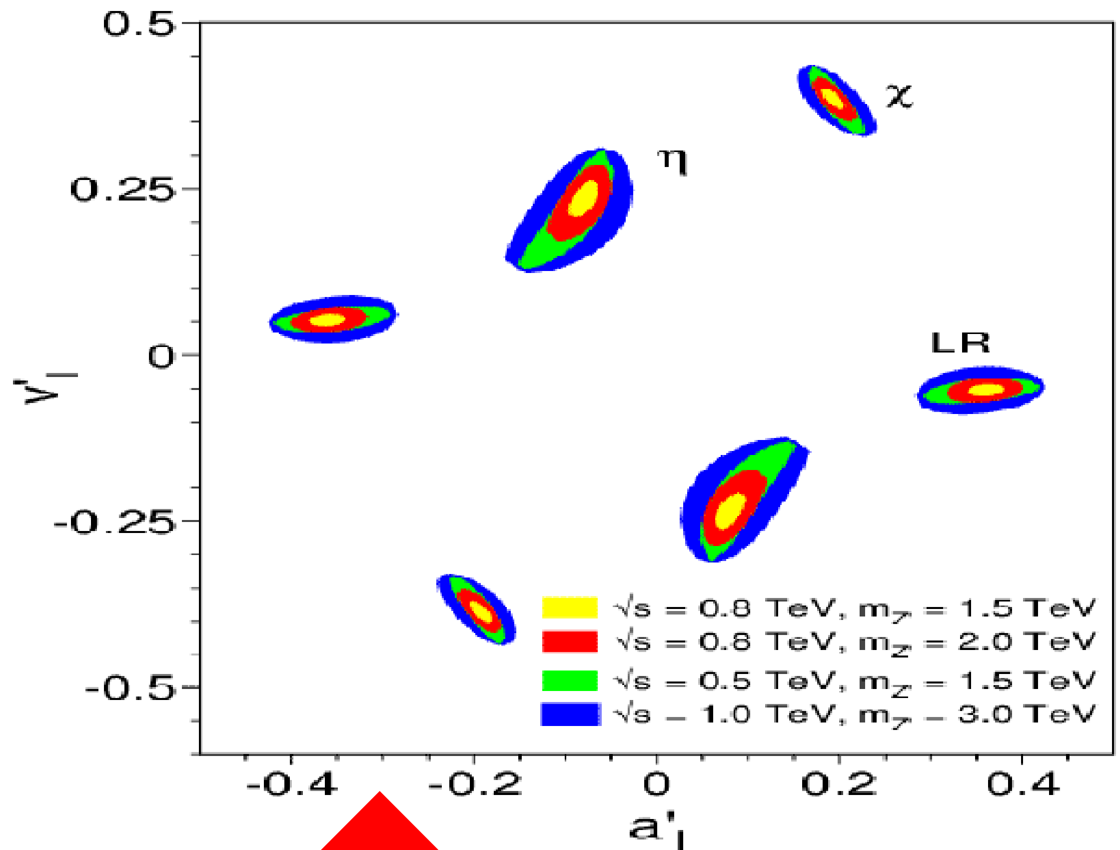
3. New Gauge Theories



New Gauge Theories

Bourlikov, Godfrey, Hewett, Richard, Riemann, Rizzo



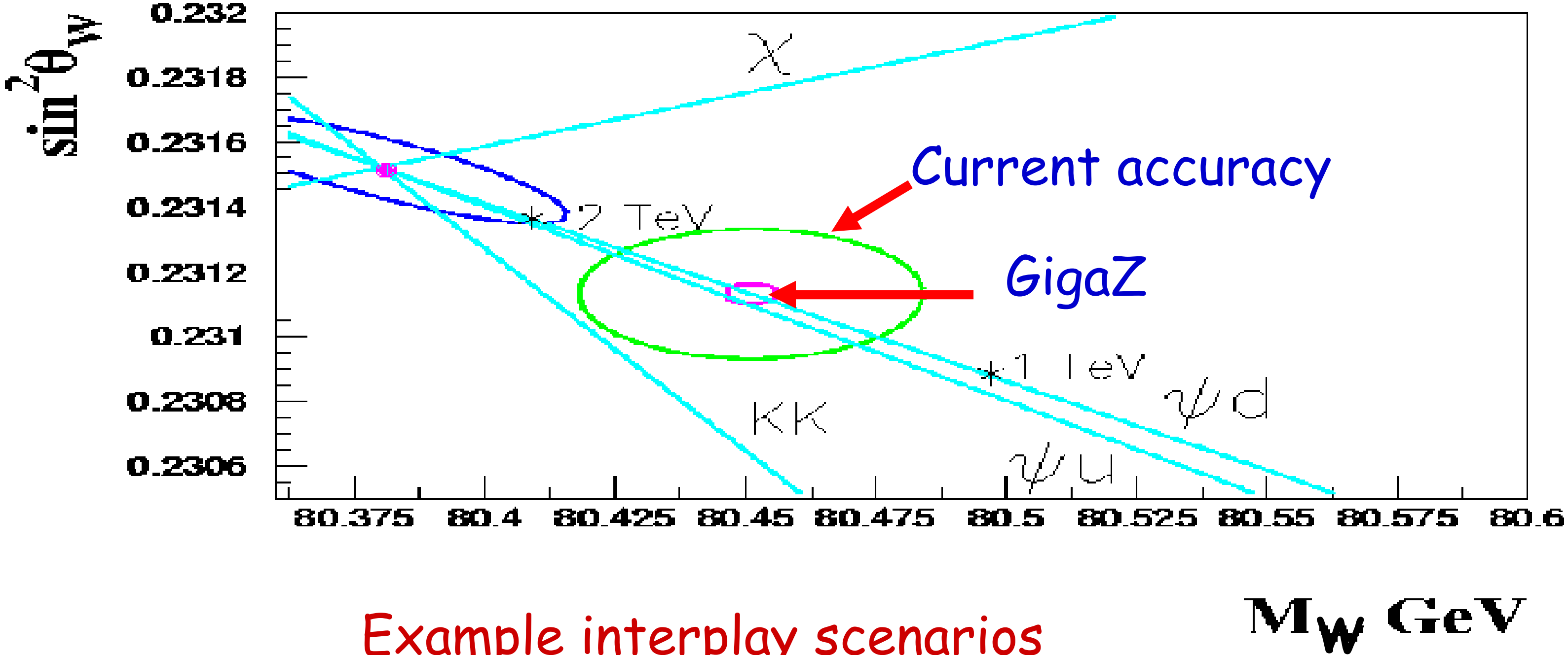


Discover of an extra gauge boson at the LHC⇒ measure the mass

LC is sensitive to $g/M_{Z'}$
Mass at LHC + precision LC measurements allows to determine the couplings and distinguish between different scenarios

Precision measurements

Assume no Z' etc. detected directly at the LHC
Revisit the Z with a Z- factory (Giga-Z: 10^9 Zs!)



Example interplay scenarios

Little Higgs: assume LHC sees Higgs at 300 GeV

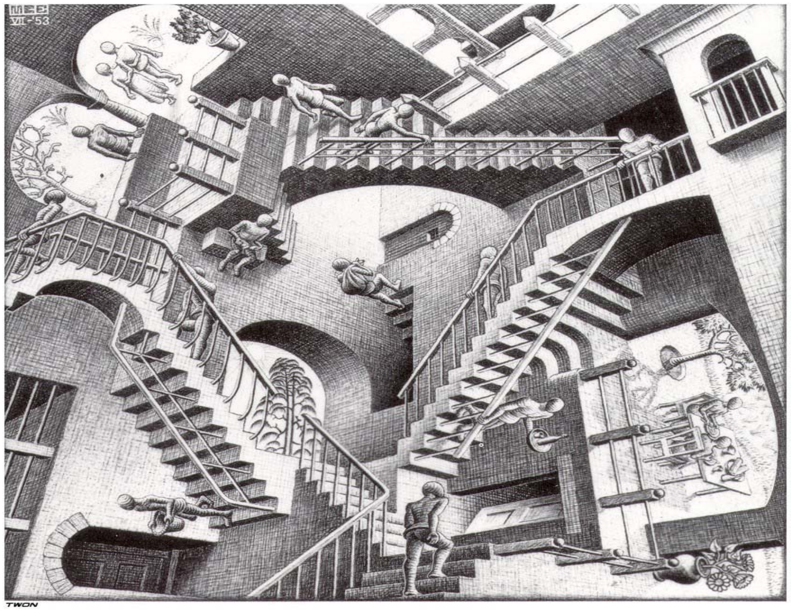
⇒ Giga-Z can estimate the mass of the Z' (U(1) singlet), say 5 GeV

Universal extra dimensions: assume LHC sees a light Higgs only.

⇒ Giga-Z demonstrates that direct and indirect Higgs mass meas. disagree

Improve search strategy or increase energy of LHC (a little)

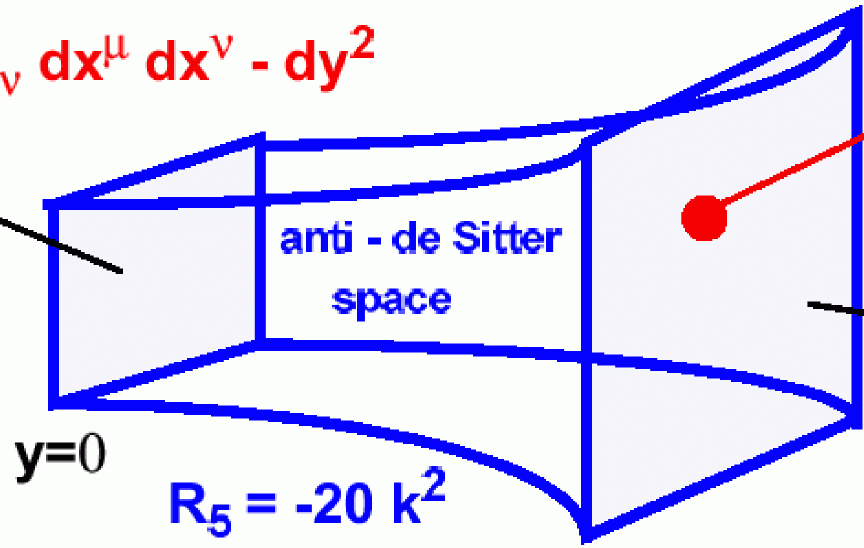
4. Extra Dimensions



Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

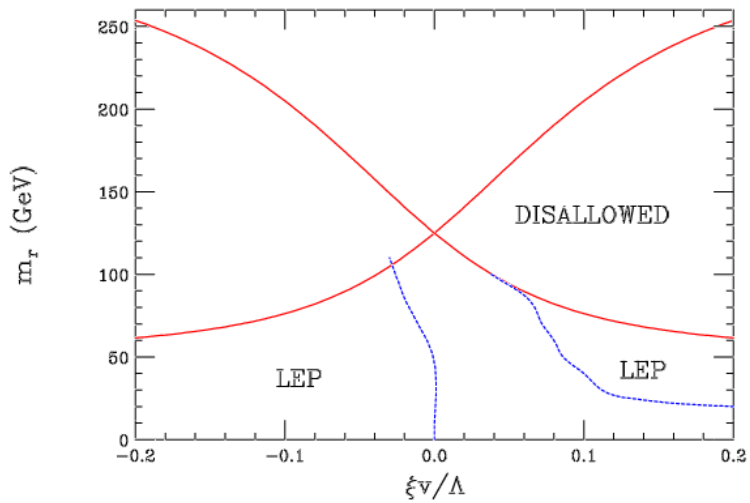
$ds^2 = e^{-2k|y|} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$

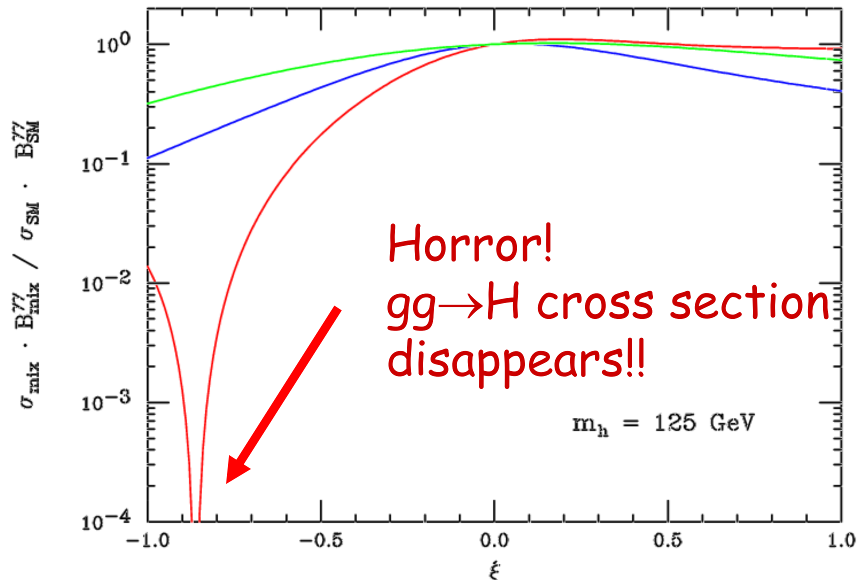


- Gravity strong at y=0 and falls like exp(-ky)
- Gravity scale $\Lambda_\pi = M_{Planck} \exp(-k\pi r_c)$ ~ TeV — no hierarchy
- Graviton resonances $m_n = x_n\ k \exp(-k\pi r_c)$, $J_1(x_n)=0$
- $M_{Planck}/M_{electroweak} \Rightarrow kr_c \sim 11\text{-}12$
- Newton's law $\Rightarrow |R_5| < M_{5D}^2 \Rightarrow$ coupling $c < 0.1$

Radions!

- Models with 3-branes in extra dimensions predict radions
- Quantum excitations of brane distance in RS theories





✧ Radion Couplings to Gauge Bosons and Fermions similar to SM H^0;

✧ ϕ Mixing to H ξ cause shift in g_{HVV} and g_{Hff} couplings

Three Fundamental Parameters :

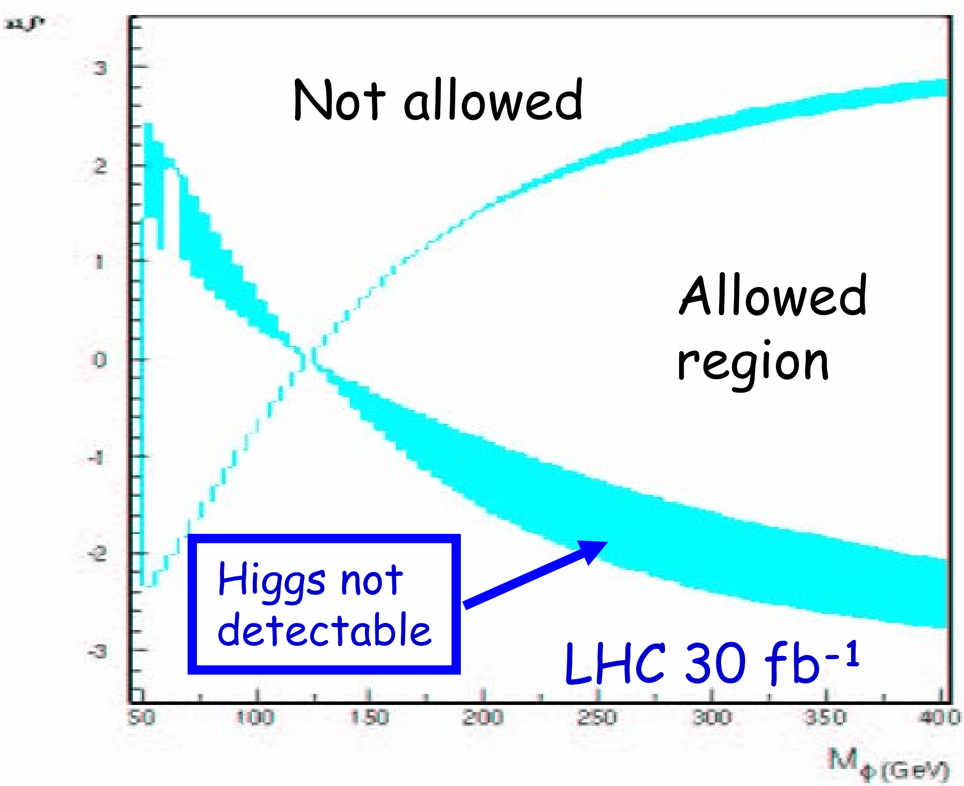
m_r $\quad \xi \quad$ v/Λ

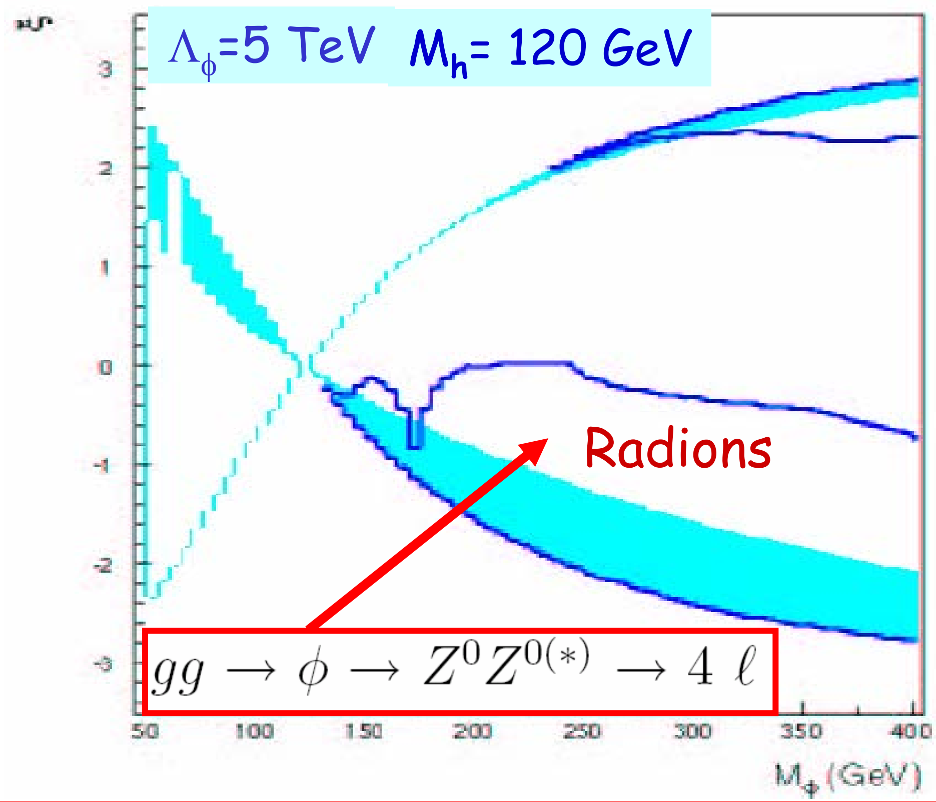
Can change things a lot for the LHC

Higgs and Radion Searches

Battaglia, ADR, DeCurtis, Dominici, Gunion

Detectability at the LHC versus mixing ξ and mass of the radion $M\phi$





LHC has regions from the parameters space where it cannot find the Higgs
However in most of these regions LHC will observe a Radion
$\Rightarrow$ LHC will essentially always see a scalar particle.

Higgs or Radion?

- At LHC mostly ratios of couplings are determined
- Radions: same fermions/WW,ZZ coupling ratio as for SM Higgs
- Couplings to $\gamma\gamma$ and gg receive anomalous contributions $\rightarrow$e.g. $g_{h\gamma\gamma}/g_{hWW}$

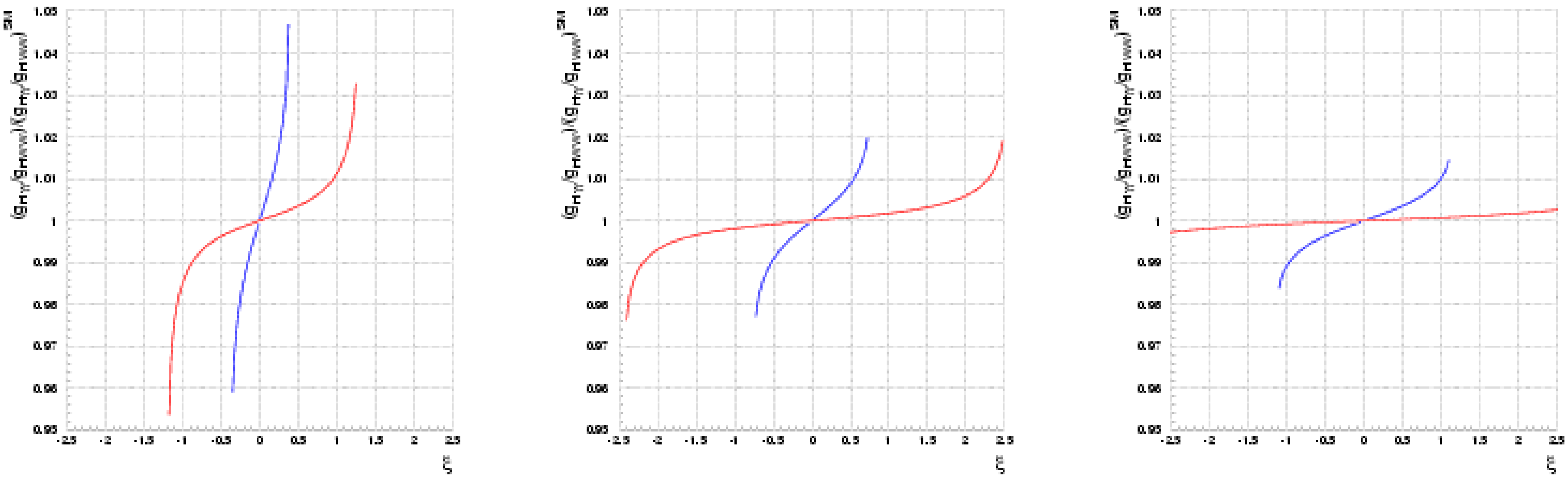
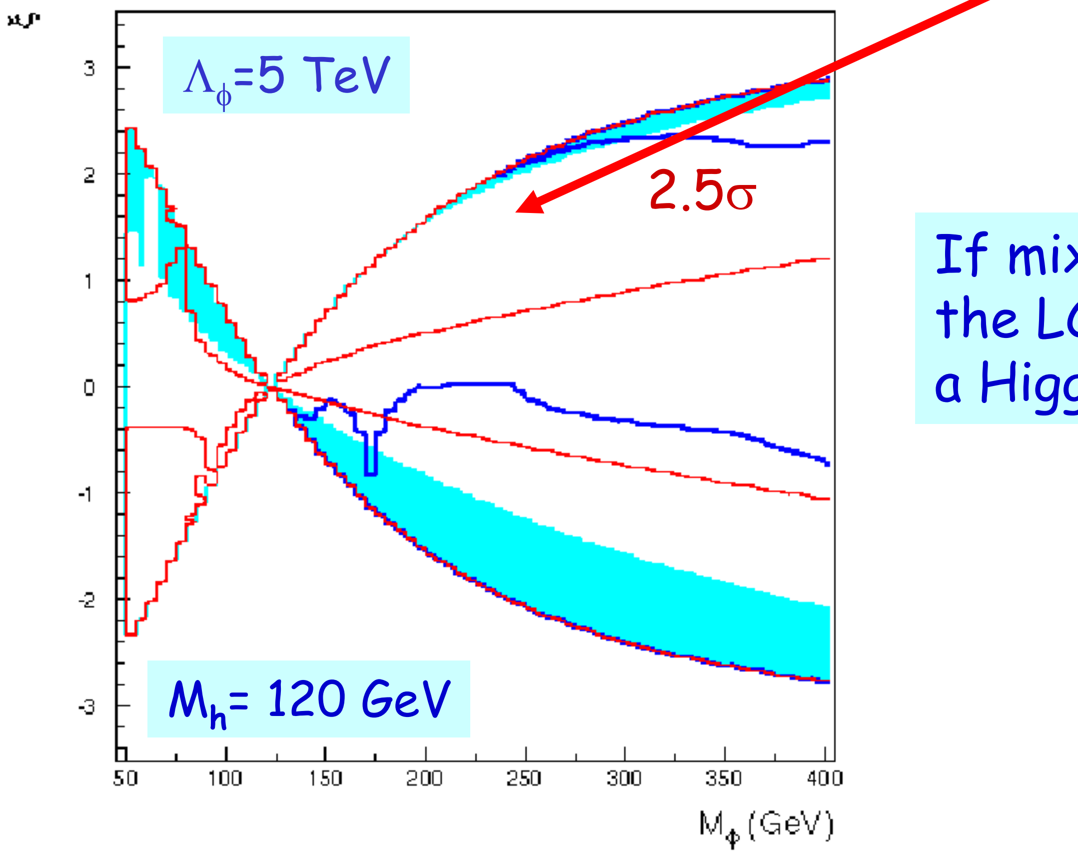


Figure 4: *Ratio of couplings $g^{effective}_{H\gamma\gamma}/g_{HWW}$ normalised to the SM prediction as function of ξ. Results are obtained for M_H=120 GeV and Λ= 2.5 TeV (left), 5.0 TeV (center) and 7.5 TeV (right). The darker (blue) curves refer to M_ϕ = 150 GeV and the lighter (red) to M_ϕ = 300 GeV.*

Effects are ~1-5%: Difficult to establish at LHC
Some absolute rates go down up to factor 2 for mϕ> 2mh and $\xi \neq 0$

Radions @ a Linear Collider

- Nature (h or ϕ) can be determined at LC since it measures absolute coupling strengths with a few % accuracy: e.g. using couplings to bb and WW



If mixing is strong enough the LC can easily distinguish a Higgs from a Radion

…more…

- Lots more on
  - Electroweak physics
  - QCD
  - Top physics
  - ADD extra dimensions
  - CP studies in the Higgs sector
  - Higgs potential
  - NMSSM studies
  - Little Higgs studies
  - 'Invisible' Higgs
  - Contact interactions
  - etc… etc.

Summary

- Topics covered here just a small survey.

  Expect the first document to be a basis for future work, summarize where we are and give guidance for future studies
  - Several studies still need to be worked out quantitatively
  - Certainly more ideas will come when we think a bit harder.

  If you have any, please do join us.
- Combined information from LHC& LC better than the sum of both separately.

  Not surprising, but quantified in coherent examples
- Need to Run the machines at the same time:

  A few concrete examples studies.
- Impact of LC data on analyses strategy, luminosity/detector upgrades, triggering etc. at LHC started but needs more work

  Ideas exist, e.g. stable gluinos in split SUSY, metastable Staus in models with gravitino LSP, decays of massive particles in many soft particles…

Positive outcome is good synergy between LHC and LC enthousiasts