

# Complementarity of LHC and ILC

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Complement  
: to provide what  
the partner lacks  
and lack what the  
partner provides

Standard Model

$\beta$

SUSY/Extra Dimensions/Strong Dynamics

Targets of LHC and ILC (for SUSY)  
LHC/ILC Complementarity  $\oplus$  Implications

Summary

LHC/LC Study WG, Weiglein et al.  
Zerwas' LCWS07 talk  
ILC RDR document  
M

SUSY07, July 30 @ Karlsruhe, Germany

## Central Problems in Particle Physics

Electroweak symmetry breaking  
Unification of forces  
Microscopic spacetime structure  
Connection with cosmology



## Supersymmetry = SUSY

Impact across all microscopic scales  $\oplus$  cosmology



Generating and stabilizing light Higgs boson at Terascale  
Leading to unification of gauge couplings and paving path to gravity  
Providing candidate particle for cold dark matter

M

## Targets of LHC and ILC on SUSY

Model- independent and high- resolution SUSY picture at Terascale

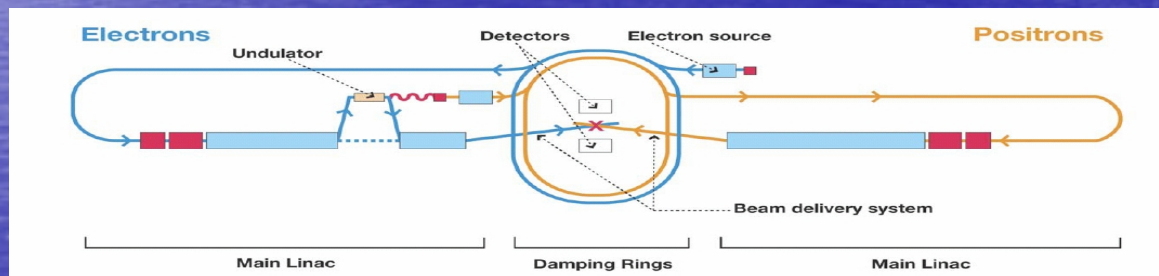


Unification of matter and interactions



ILC = International  $e^+e^-$  linear collider  $\oplus$  LHC

[<http://www.linearcollider.org/>]



### Characteristics

0.5 to 1 TeV to CLIC w/ 3 TeV  
300 fb<sup>-1</sup>/y ) 1 ab<sup>-1</sup> in total  
90/60% e<sup>-</sup> /<sup>+</sup> polarization

### Satellite modes

GigaZ: 10<sup>9</sup> Z bosons  
e<sup>-</sup> e<sup>-</sup> w/ same E / reduced L  
ge/gg via Compton backscattering

## SUSY Path

[ILC RDR]

**Measure the masses and mixings of the newly produced particles, their decay widths and branching ratios, their production cross sections, etc.**



**Verify that there are indeed the super-partners of the SM particles by determining their spin and parity, gauge quantum #'s and their couplings.**



**Reconstruct the low-E Lagrangian parameters with the smallest number of assumptions, i.e. as model-independently as possible.**



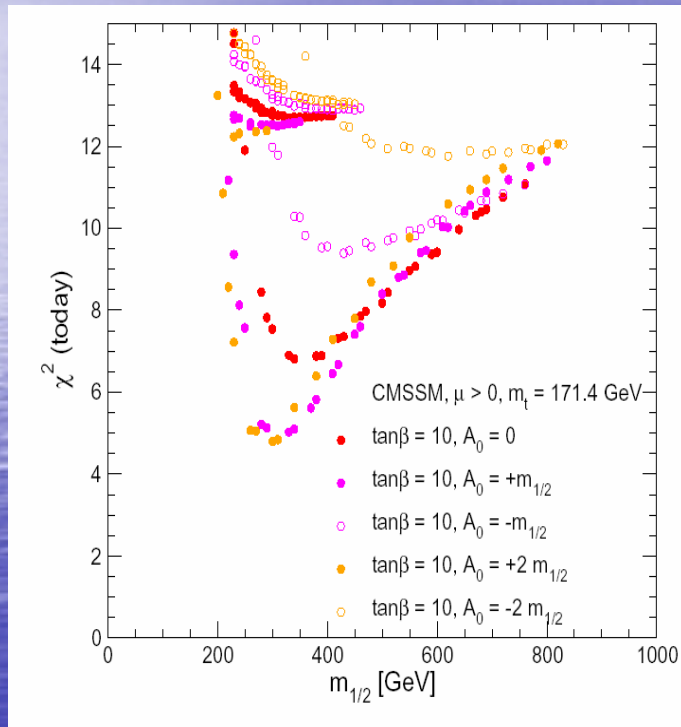
**Unravel the fundamental SUSY breaking mechanism and shed light on the physics at the very high energy (GUT or Planck) scale.**

# SUSY Mass Scale

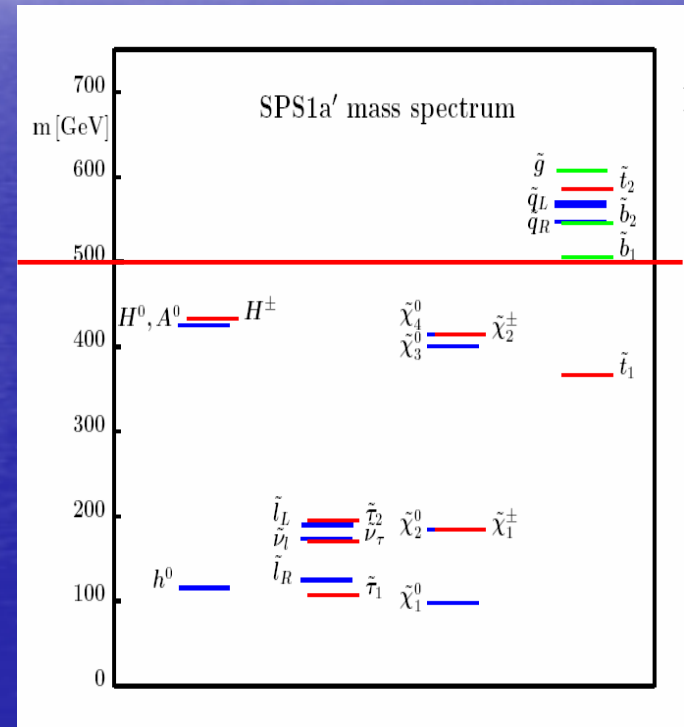
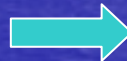
[no firm prediction]

Low- E data + CDM w/ mod. tanb

[SPS1a<sup>0</sup>]



ILC1000



[Ellis et al.] Weiglein's talk on 31.7

H

S

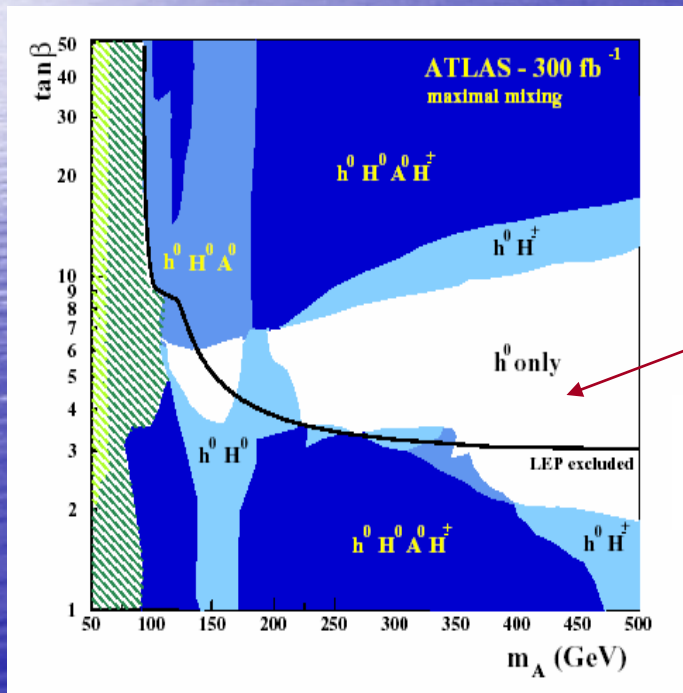
A favorable scenario: all non- colored SUSY particles produced at ILC1000

# MSSM Higgs Bosons

[Djouadi and Jacobs' talks]

2 doublets  $\rightarrow$  5 physical states  
 $h$  light  $\leq 140$  GeV  
 $H, A, H^\pm$  typically  $\sim$  to 1 TeV

## LHC coverage

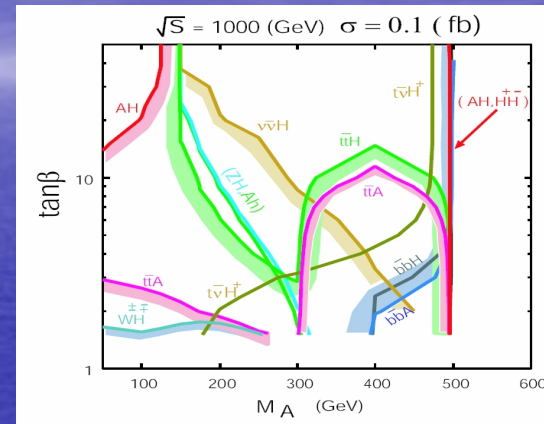


[Heinemeyer's talk on 26.7]

## ILC

Pairs with mass up to  $E_{cm}/2$

$e^+e^- \rightarrow AH, H^+H^-$



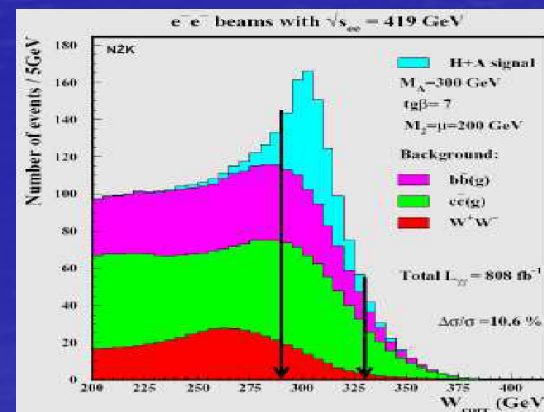
[Kiyoura ea]

ILC1000  
 PLC800

completely covered!

## Photon Linear Collider

$gg \rightarrow H/A + 50\%$

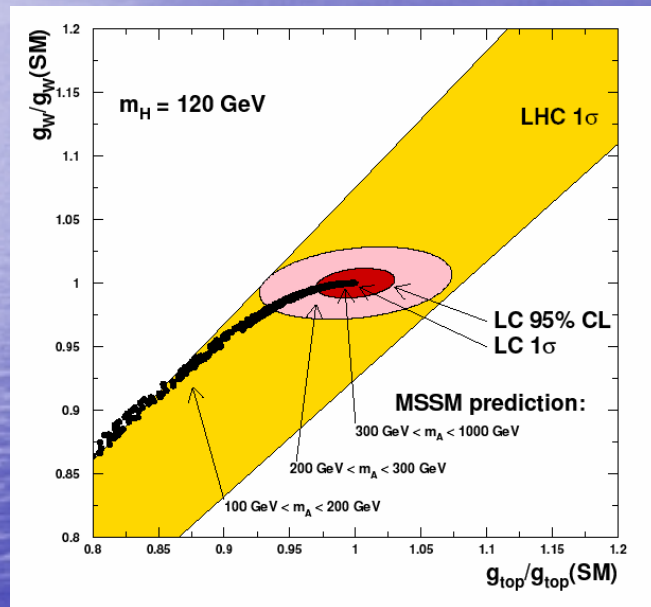


[Mühlleitner ea]  
 [Gunion ea]  
 [Niezurawski ea]

# Higgs Couplings and Masses

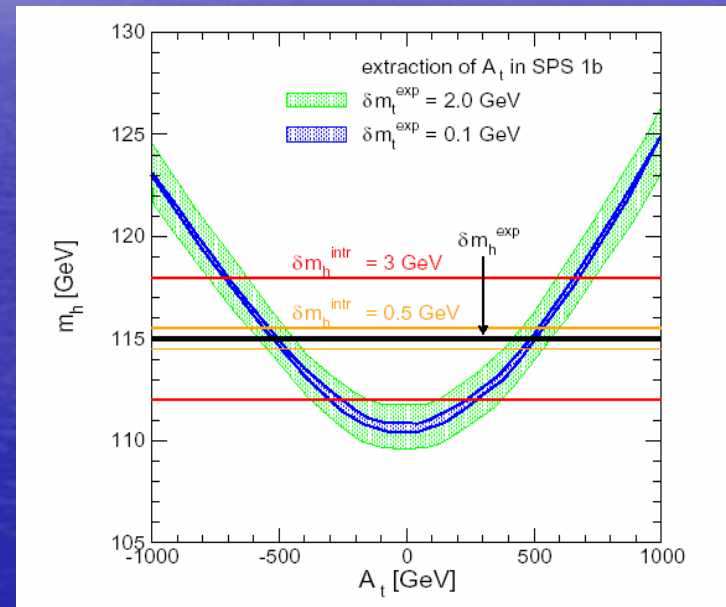
Model-independent and precise “coupling” and “mass” measurements

[ECFA/DESY LC Physics WG]



Precision ) ILC reach  
far beyond LHC reach

[Heinemeyer, Hollik, Weiglein]

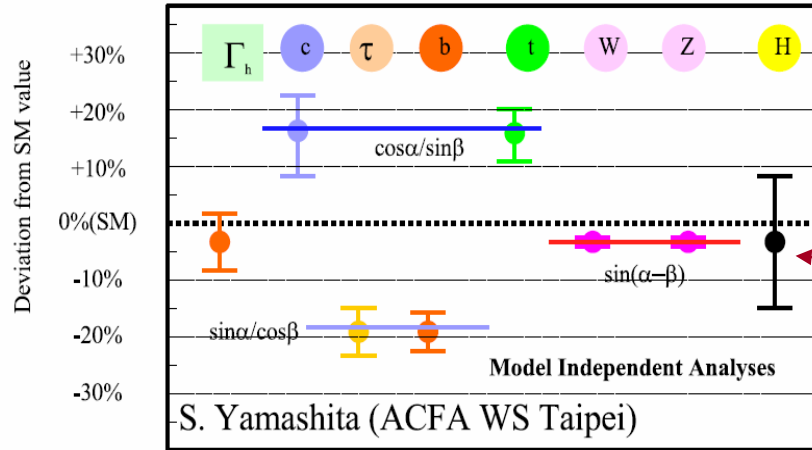


Reduced theoretical uncertainty  
⊕ precise  $m_t$  measurement at ILC  
) reliable  $A_t$  determination

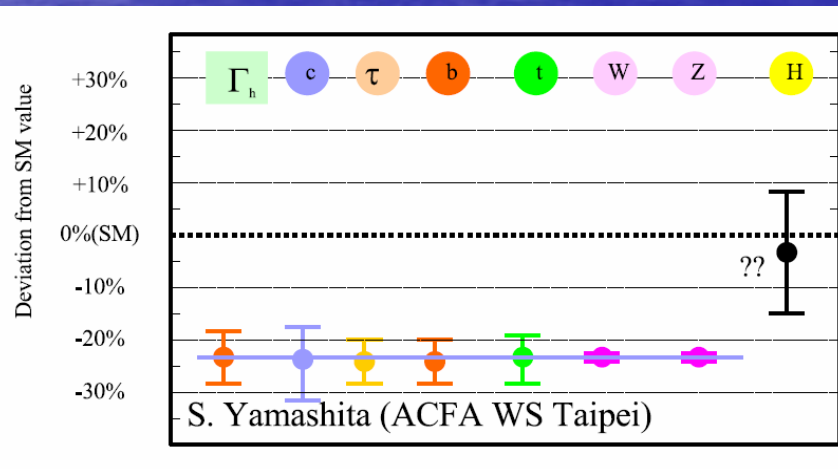
Different BSM models ) different deviation patterns

# Higgs Boson in SUSY or Extra-D? ) Model-independent analysis!

## Coupling measurements



Only ILC

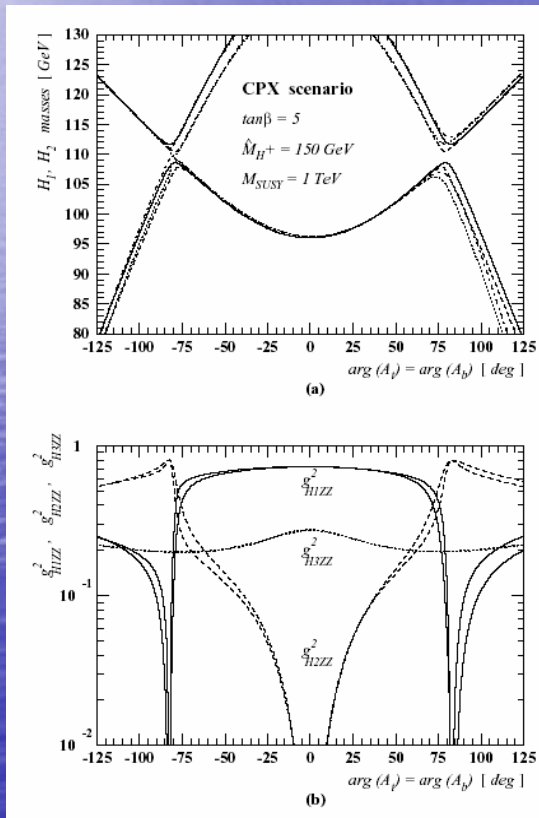


Same branching fractions as SM, but different widths

# MSSM Higgs Sector with CP Violation

Loop corrections )  $h, H$  are mixed with  $A$  )  $H_1, H_2, H_3$

## Masses and couplings



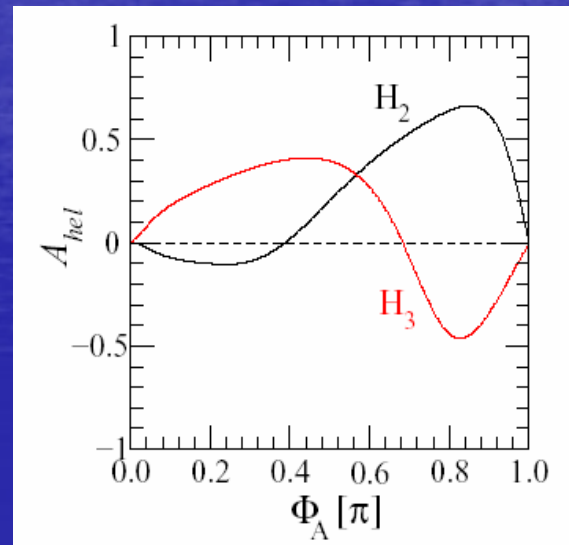
[Carena ea]



Large effects in decoupling regime  
due to degenerate  $H$  and  $A$

- shift in complex masses w/widths
- gg !  $H_2, H_3$  with polarized photons

## Circular asymmetry [(++) - (--)]



[SYC ea]

Codes: CPsuperH [J.S. Lee ea]

FeynHiggs [Heinemeyer ea] ) Hahn's talk

CPnSH report ) Kraml's talk

# Extended Higgs Sector: NMSSM, USSM etc

Two doublets  $H_1, H_2 \oplus$  one isosinglet  $S$

## NMSSM

$h, H \oplus H^0 \rightarrow H_1, H_2, H_3$   
 $A \oplus A^0 \rightarrow A_1, A_2$   
 $H^\pm$

$H_1 ! A_1 A_1 ! bbbb$   
 [difficult to observe at LHC]

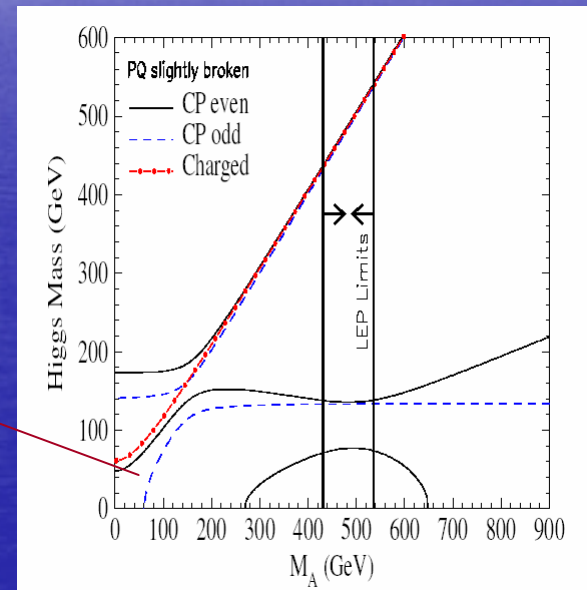
Higgs Search in NMSSM ) Gunion ea

## USSM: $SM \otimes U(1)$

One CP-odd state eaten by  $U(1)$   
 $Z^0$  boson  $\rightarrow H_1, H_2, H_3 \oplus A \oplus H^\pm$

Distinct  $Z^0$  couplings to fermions

## typical mass spectrum

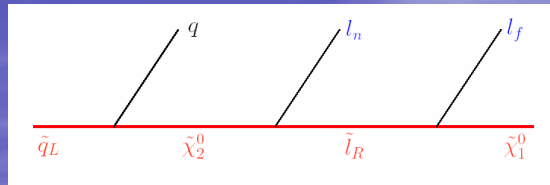


[Miller, Nevzorov, Zerwas]

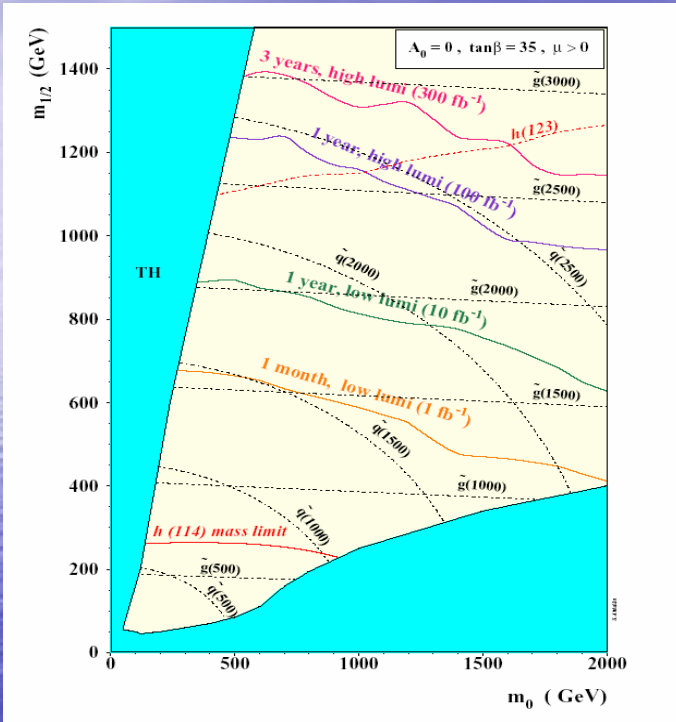
## SUSY Particle Masses at LHC

## [Dutta, Spiropulu and Ozturk's talks]

## Cascade decays

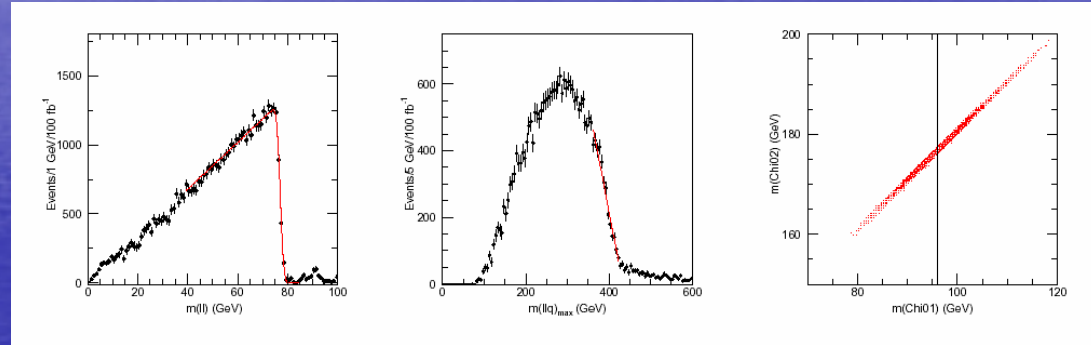


## SUSY mass reach at LHC



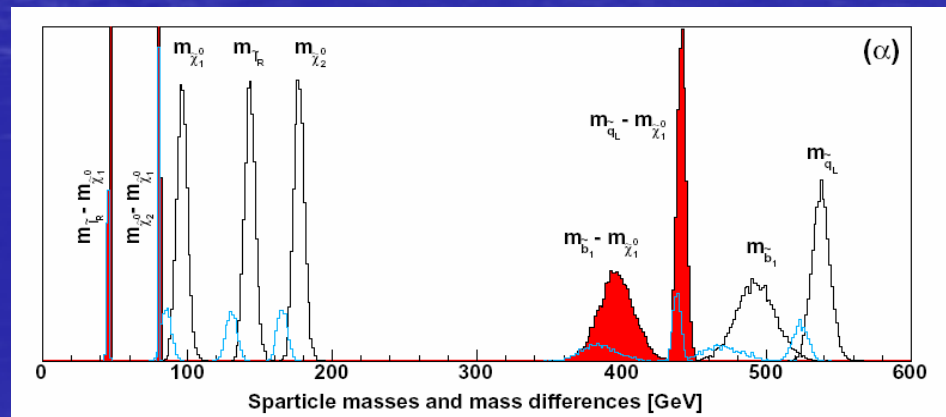
[CMS]

## Invariant masses



## Discovery of colored gluino/squarks with mass up to 2.5 to 3 TeV

**“Precise” differences, but  
“Crude” absolute masses**



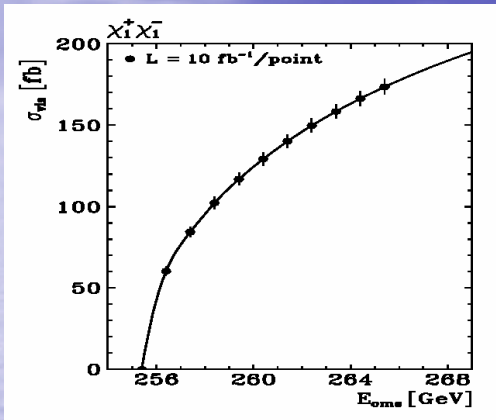
[Gjelsten, Miller, Osland]

## 1) Gunion's talk

# SUSY Particle Masses at ILC

filling voids  
accuracy increased  
by one to two orders

## Threshold excitations

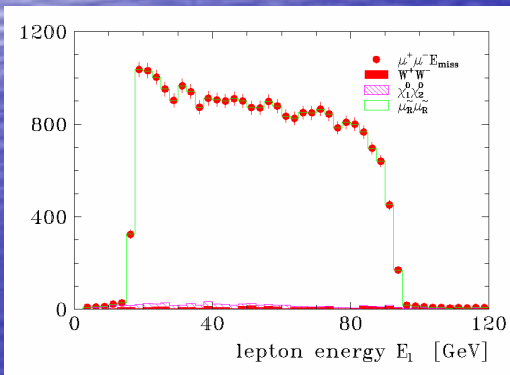


[LHC/ILC Study WG, Weiglein et al.]



	Mass, ideal	“LHC”	“ILC”	“LHC+ILC”
$\tilde{\chi}_1^\pm$	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
$\tilde{e}_R$	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
$\tilde{\tau}_1$	134.8	5-8	0.3	0.3
$\tilde{\tau}_2$	210.7	—	1.1	1.1
$\tilde{q}_L$	570.6	8.7	—	4.9
$\tilde{t}_1$	399.5	—	2.0	2.0
$\tilde{t}_2$	586.3	—	—	—
$\tilde{g}$	604.0	8.0	—	6.5
$h^0$	110.8	0.25	0.05	0.05
$A^0$	399.4	—	1.5	1.5

## Decay edges



[Martyn]

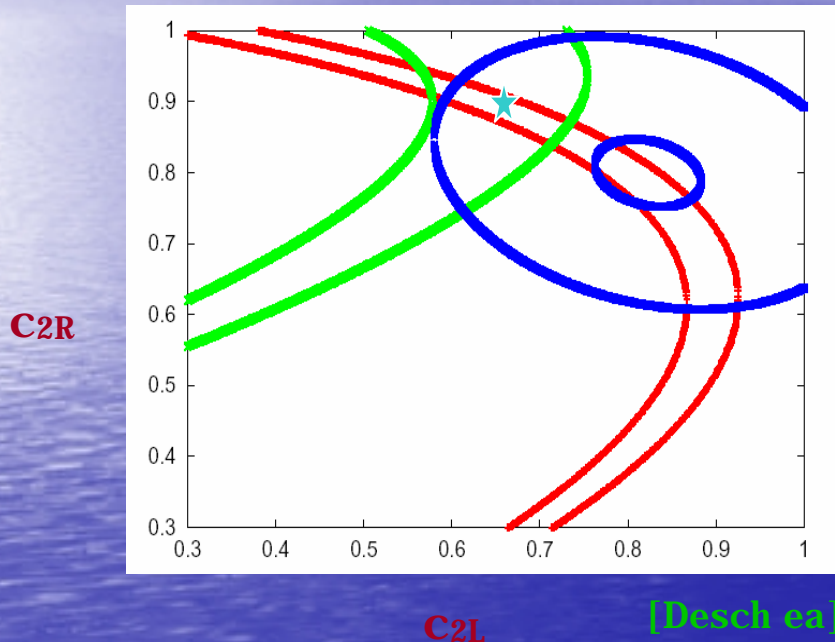
“Absolute” mass determination

voids in spectrum  
percent accuracy  
mass diff permille

Coherent LHC  $\otimes$  ILC )  
comprehensive and high  
resolution SUSY picture

# Mixing Parameter Determination

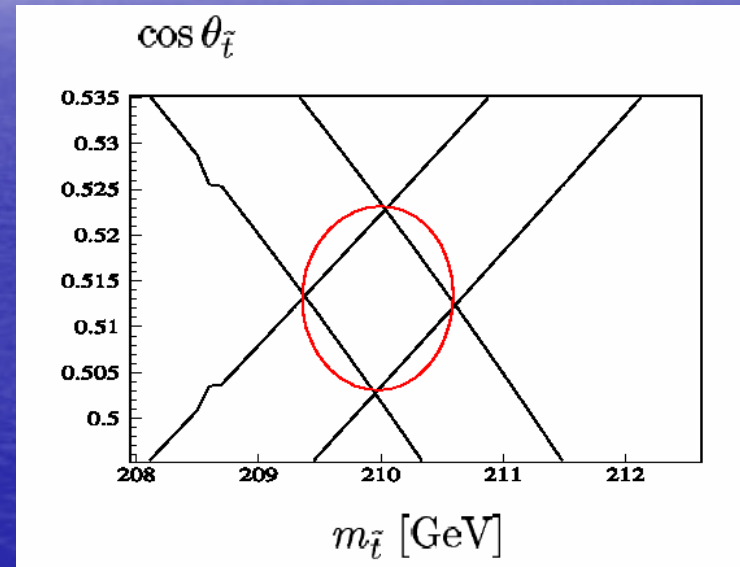
## Gaugino- higgsino mixing



R/G for  $L^\pm$  [11] and B for  $R^\pm$  [11]

Similar studies at LHC??

## Top squark mixing



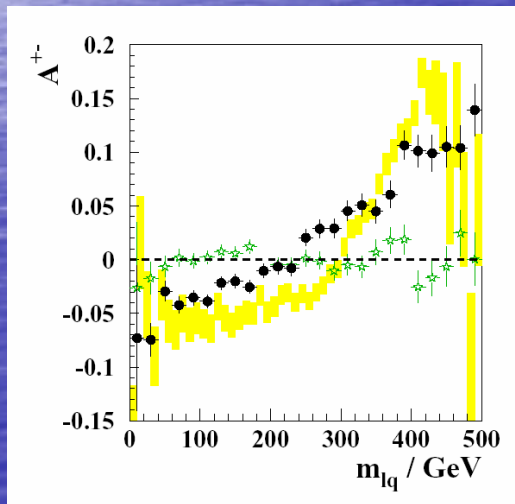
Analogously for staus and sbottoms

## LHC

$$\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow q\ell^+\tilde{\ell}^- \rightarrow q\ell^+\ell^-\tilde{\chi}_1^0 \rightarrow q\ell^+\ell^- E_{miss}$$

[q, l<sup>+</sup>, l<sup>-</sup>] invariant masses  
affected by Intermediate spins

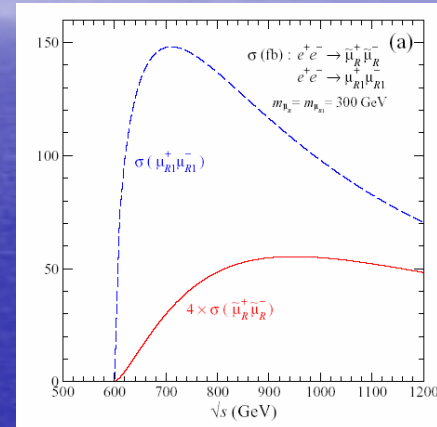
Charge asymmetry in [ql<sup>+</sup>] and [ql<sup>-</sup>]



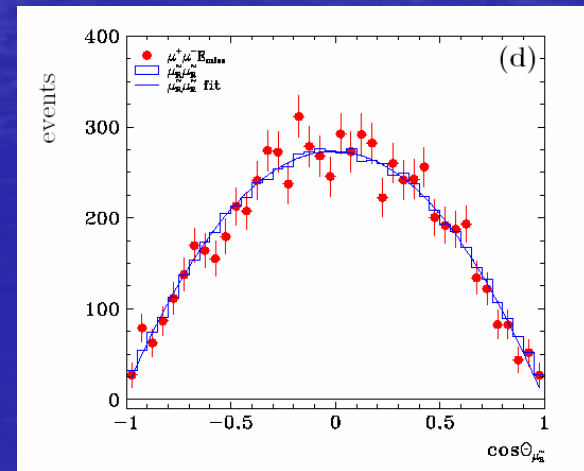
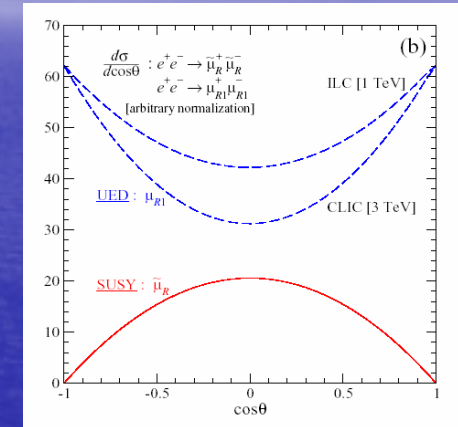
[Bar] ) Ozturk's talk

## ILC ) various methods

### Thres. excitation



### Ang distr

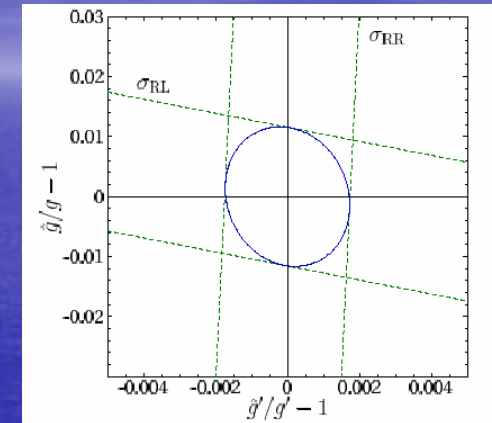
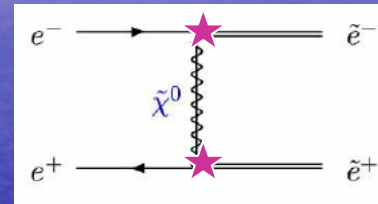
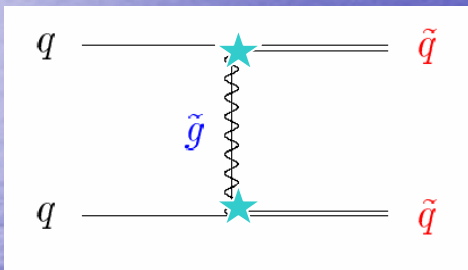


[SYC ea] ) Zerwas' talk

# Yukawa=Gauge

LHC )  $SU(3)_C$

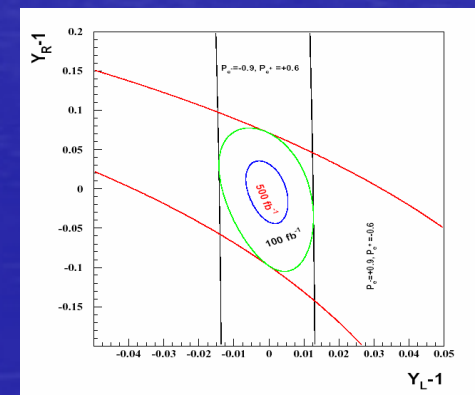
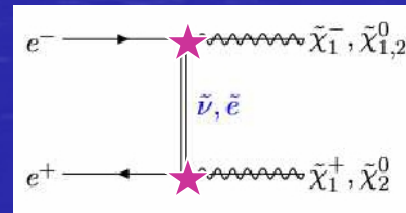
$$\hat{g}_s(q\tilde{q}\tilde{g}) = g_s(qqg)$$



[Freitas, von Manteuffel, Zerwas]

Test in cross section for  
like- sign di- lepton pairs  
) accuracy  $\sim 5\%$

[Freitas et al.] ) Freitas' talk



[SYC et al.]

# Extracting SUSY Parameters at Terascale

Gaugino, higgsino, scalar mass parameters, trilinear couplings, etc

## SPA Project

[<http://spa.desy.de/spa/>]

Well- defined theoretical  
scheme and conventions  
for multi- loop LHC and  
ILC analyses

SFitter [Lafaye, Plehn, D. Zerwas]  
) Rauch's talk

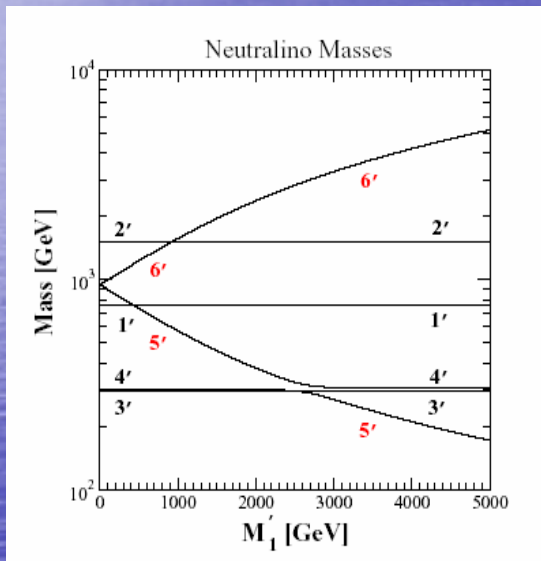
Fittino [Bechtle, Desch, Weinmann]  
) Bechtle's talk  
[Allanach's talk]

EXC	LHC	LC	LHC+LC	SPS1a
$M_1$	$102.5 \pm 5.3$	$102.3 \pm 0.1$	$102.2 \pm 0.1$	102.2
$M_2$	$191.8 \pm 7.3$	$192.5 \pm 0.7$	$191.8 \pm 0.2$	191.8
$M_3$	$578. \pm 15.$	$\rightarrow$	$588. \pm 11.$	589.4
$M_{\tilde{e}_L}$	$198.7 \pm 5.1$	$198.7 \pm 0.2$	$198.7 \pm 0.2$	198.7
$M_{\tilde{e}_R}$	$138.2 \pm 5.0$	$138.2 \pm 0.05$	$138.2 \pm 0.05$	138.2
$M_{\tilde{q}_L}$	$550. \pm 13.$	$\rightarrow$	$553.3 \pm 6.5$	553.7
$M_{\tilde{u}_R}$	$529. \pm 20.$	$\rightarrow$	$532. \pm 15.$	532.1
$M_{\tilde{d}_R}$	$526. \pm 20.$	$\rightarrow$	$529. \pm 15.$	529.3
$A_t$	$-507. \pm 91.$	$-501.9 \pm 2.7$	$-505.2 \pm 3.3$	-504.9
$\mu$	$345.2 \pm 7.3$	$344.3 \pm 2.3$	$344.4 \pm 1.0$	344.3
$\tan \beta$	$10.2 \pm 9.1$	$10.3 \pm 0.3$	$10.06 \pm 0.2$	10

## Extended SUSY Models: USSM = MSSM $\otimes$ U(1) etc

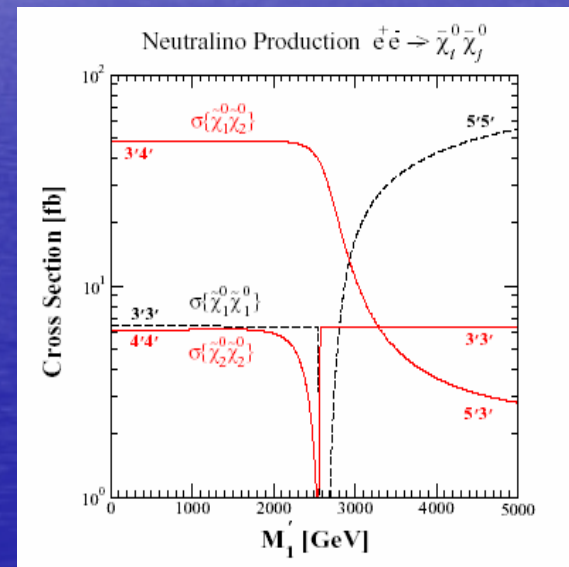
6 neutralinos: 4 MSSM states  $\oplus$  singlino and U(1) gaugino  
[identical chargino spectrum]

### Mass



[SYC ea]

### Production



Patterns very different from MSSM



Crucial to have high-precision data for model identification

# RGE Extrapolation to GUT/Planck Scale

Reconstruction of  
fundamental theory  $\sim L$

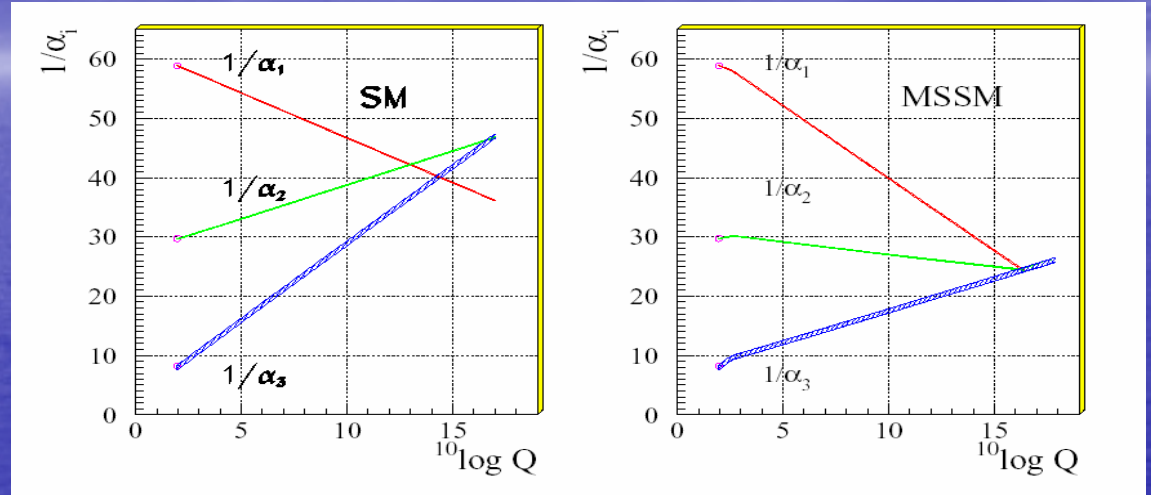
Exploration of  
microscopic SUSY  
breaking

Symmetries/universal  
behavior at  $L$  ?

Impact of high- scale  
physics?

Crucial to have reliable RGE programs

## Gauge couplings



LHC  $\oplus$  ILC era

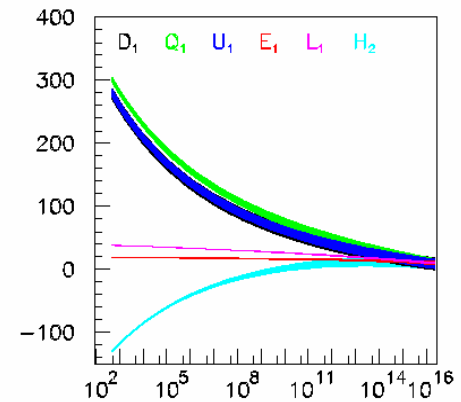
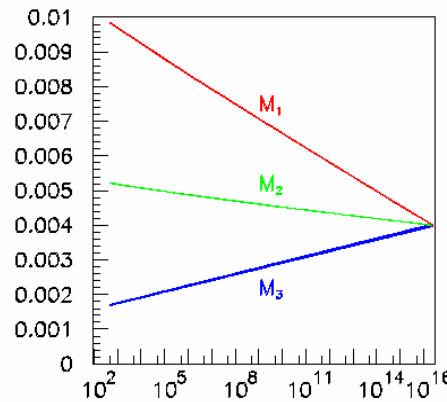
[Amaldi, de Boer, Fürstenau]  
[Ellis, Kelly, Nanopoulos]  
[Giunti, C. W. Kim, U. Lee]  
[Langacker, Luo]

	Present/"LHC"	GigaZ/"LHC+LC"
$M_U$	$(2.36 \pm 0.06) \cdot 10^{16} \text{ GeV}$	$(2.360 \pm 0.016) \cdot 10^{16} \text{ GeV}$
$\alpha_U^{-1}$	$24.19 \pm 0.10$	$24.19 \pm 0.05$
$\alpha_3^{-1} - \alpha_U^{-1}$	$0.97 \pm 0.45$	$0.95 \pm 0.12$

# RGE Extrapolation to GUT/Planck Scale

[Blair, Porod, Zerwas]

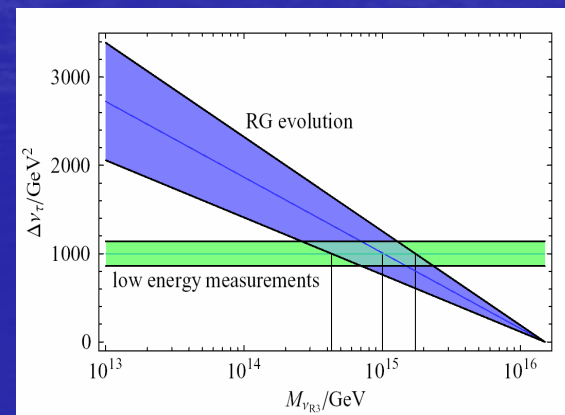
**mSUGRA**  
Universal gaugino  
and scalar masses



**Leptogenesis:** heavy  $n_R \oplus$  CP violation in  $n$  sector  
) See-saw scale  $M[n_R] \sim 10^{10}$  to  $10^{15}$  GeV

[Freitas, Porod, Zerwas]

See-saw affects evolution  
of  $t$  slepton and sneutrino  
masses, but not of 1<sup>st</sup>/2<sup>nd</sup>  
generation masses

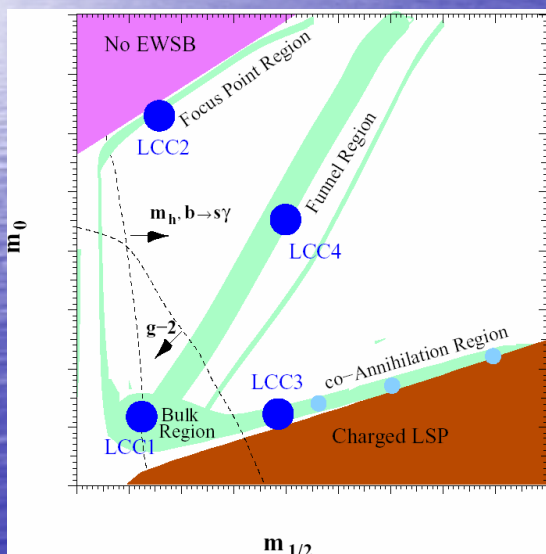


Other SUSY breaking scenarios  $\Rightarrow$  [Blair, Porod, P. Zerwas]

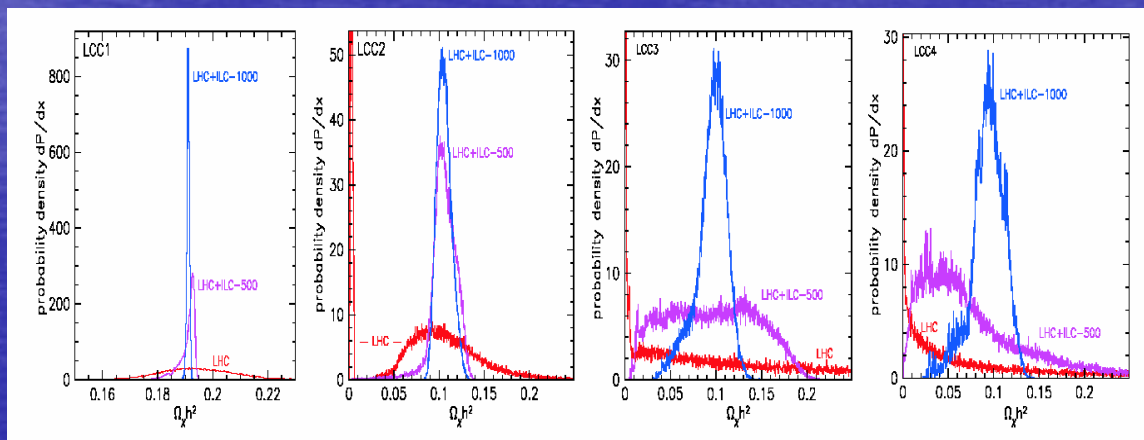
# LHC $\oplus$ ILC $\delta$ Neutralino CDM

[WMAP] :  $\Omega h^2 = 0.104^{+0.007}_{-0.013} \sim 10\% \Rightarrow 1.4\%$  [PLANCK]

	character	channel	sensitivity	LHC	(500)	(1000)
SPS1a'	buck/co-an	$\tilde{\chi}\tilde{\chi} \rightarrow \tau\tau, bb$ / co-an	$\tilde{\tau}, \tilde{b}$	10%	3%	2%
LCC2	focus point	$\tilde{\chi}\tilde{\chi} \rightarrow WW, ZZ$	$\tilde{V}\tilde{H}$ mix	80%	14%	8%
LCC3	$\tilde{\tau}\tilde{\chi}$ co-ann.	$\tilde{\tau}\tilde{\chi} \rightarrow \tau\gamma$	$M[\tilde{\tau} - \tilde{\chi}_1^0]$	176%	50%	18%
LCC4	A funnel	$\tilde{\chi}\tilde{\chi} \rightarrow A$	$M_A, \Gamma_A$	405%	85%	19%



[Battaglia]



LCC [Baltz ea] / SPA [Bélanger ea]

Similar to SPS1a<sup>0</sup>

Significant improvement if over- all picture under better control

## Summary

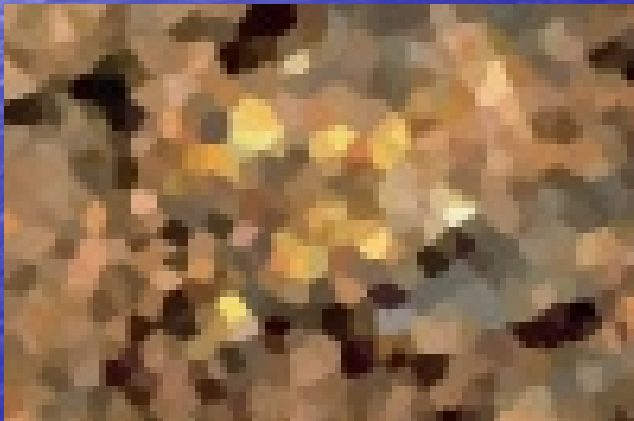
LHC and ILC can contribute coherently and complementarily to solutions of key questions in particle physics and cosmology.



Need to be demonstrated!

Comprehensive and high-resolution picture of (not only) SUSY (but also alternatives)  
 ) Telescope to unification of interactions and connection of particle physics to cosmology

LHC



?

LHC  $\oplus$  ILC



Toad!

# Back- up Slides

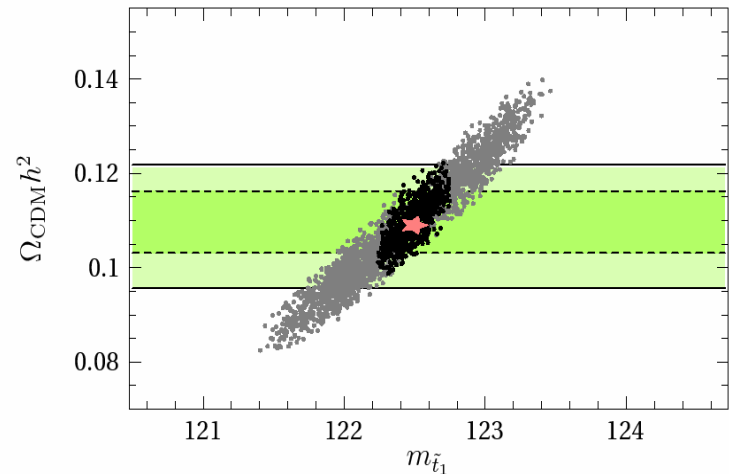
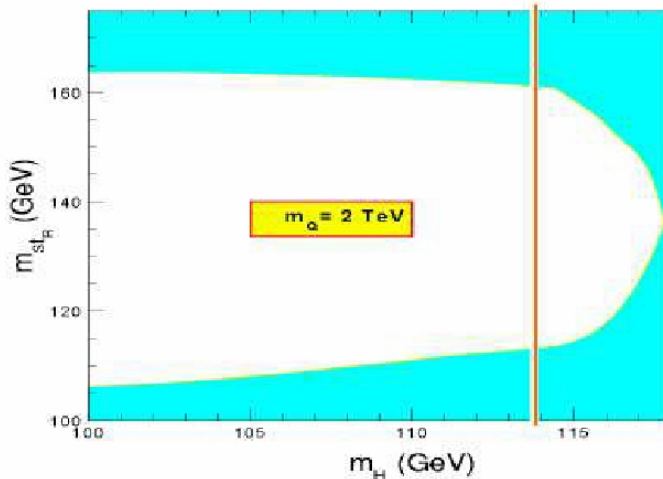
# EW Baryogenesis $\sigma$ CDM

Can we get two rabbits with one stone?

EW baryogenesis

MSSM

CDM relic density



1<sup>st</sup> PT: light R-stop  
Large CP phase [c]  
Degenerate R-stop/LSP

Stop-LSP co-annihilation

ILC

# Alternative: Strong EWSB

[Cheng's talk]

## Little Higgs Models

Large global symmetry group  
Rich spectrum of TeV particles  
 $\oplus$  light Higgs sector

**Pseudoscalar  $h$ :**  $e^+e^- \rightarrow t\bar{t}\eta \mid \eta \rightarrow b\bar{b}$

**Parameters almost completely covered.**

## Minimal Strong Theory

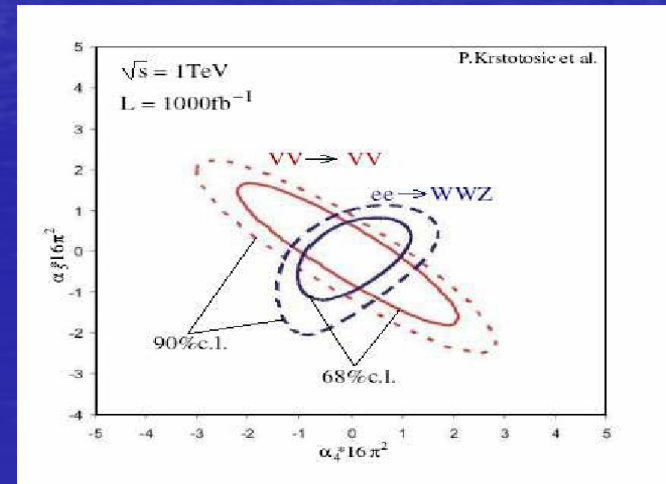
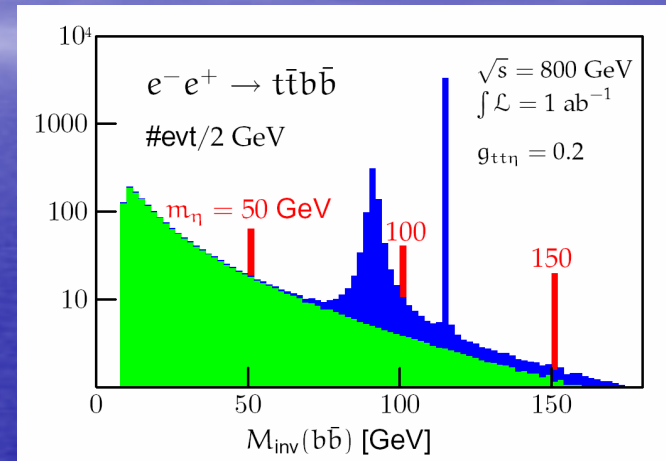
No light states but [WW] with mass  $\sim 1$  TeV  
in  $0^+$ ,  $1^-$ ... observed in WW scattering

$$e^+e^- \rightarrow \bar{\nu}\nu WW$$

$$e^+e^- \rightarrow WWZ$$

**Sensitivity:**  $L_* < 4\text{pv} \sim 3\text{ TeV}$

[Reuter ea] ) Reuter's talk



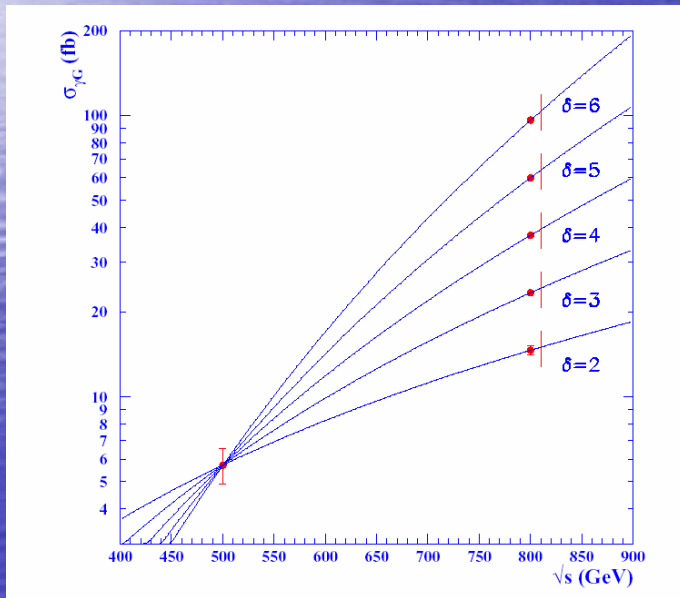
[Krstotic, Beyer ea]

# Extra Space Dimensions

Gravity extends to higher flat/warped dimensions.

**ADD**

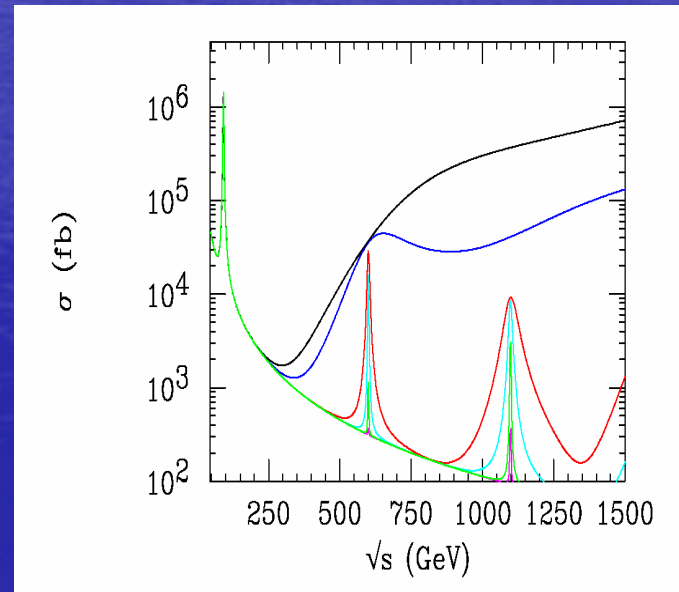
$e^+e^- \rightarrow S, G_{KK}, g$



[Wilson]

**RS**

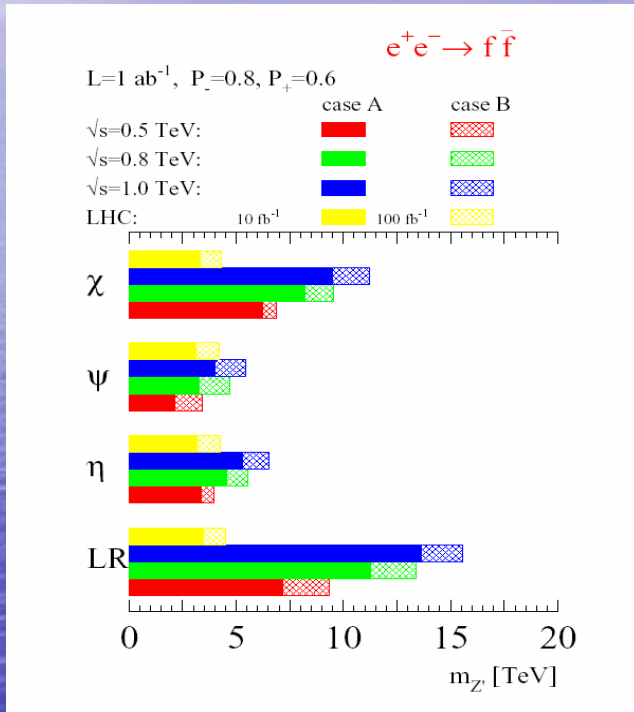
Excitation of KK graviton towers



[Hewett et al.]

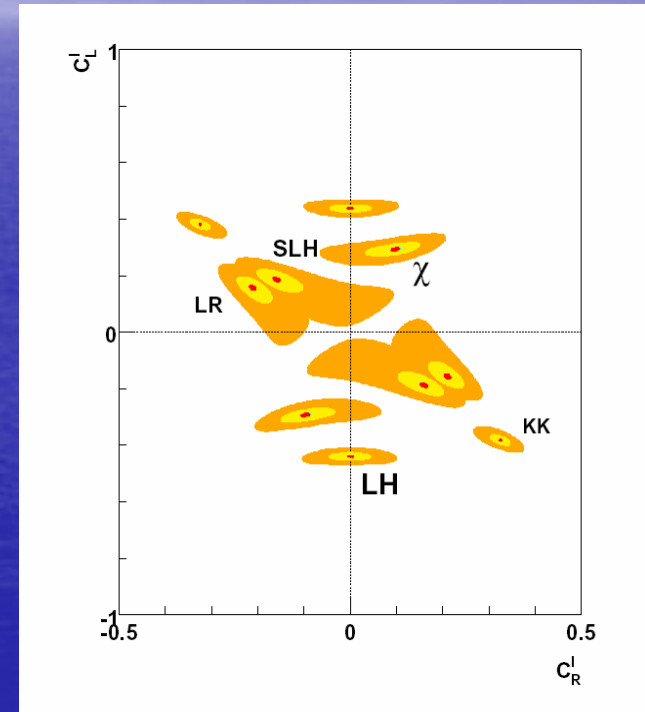
# Intermediate Scale: $Z^0$

Heavy  $Z'$  motivated by TeV scale remnants of GUTs and string theories, extended Higgs and extra-dim models, etc



[Riemann]

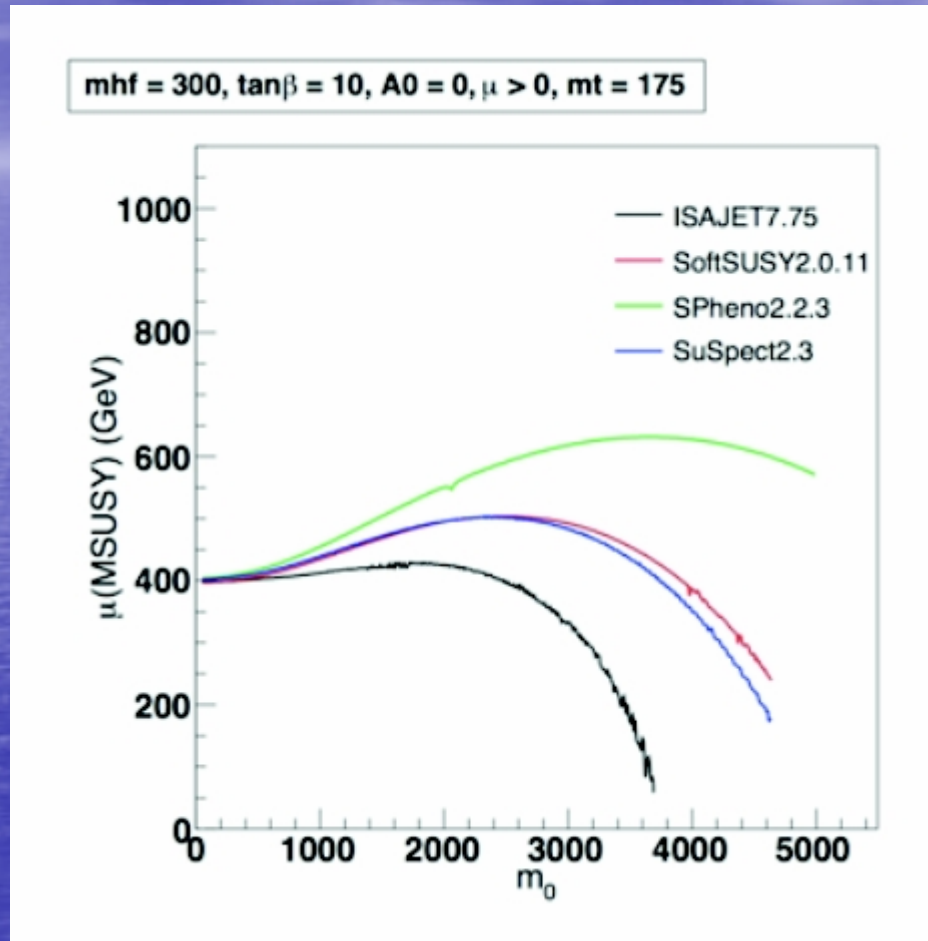
Virtual extension to 15 TeV



[Godfrey ea]

$Z^0$  couplings distinguishing models

## Which are/is most reliable?



From Spiropulu's talk

## Summary

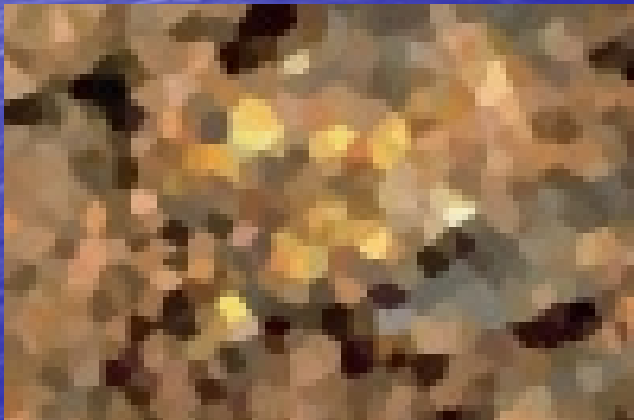
LHC and ILC can contribute coherently and complementarily to solutions of key questions in particle physics and cosmology.



Need to be demonstrated!

Comprehensive and high-resolution picture of not only SUSY but also alternatives  
)  
Telescope to unification of interactions and connection of particle physics to cosmology

LHC



LHC  $\oplus$  ILC

