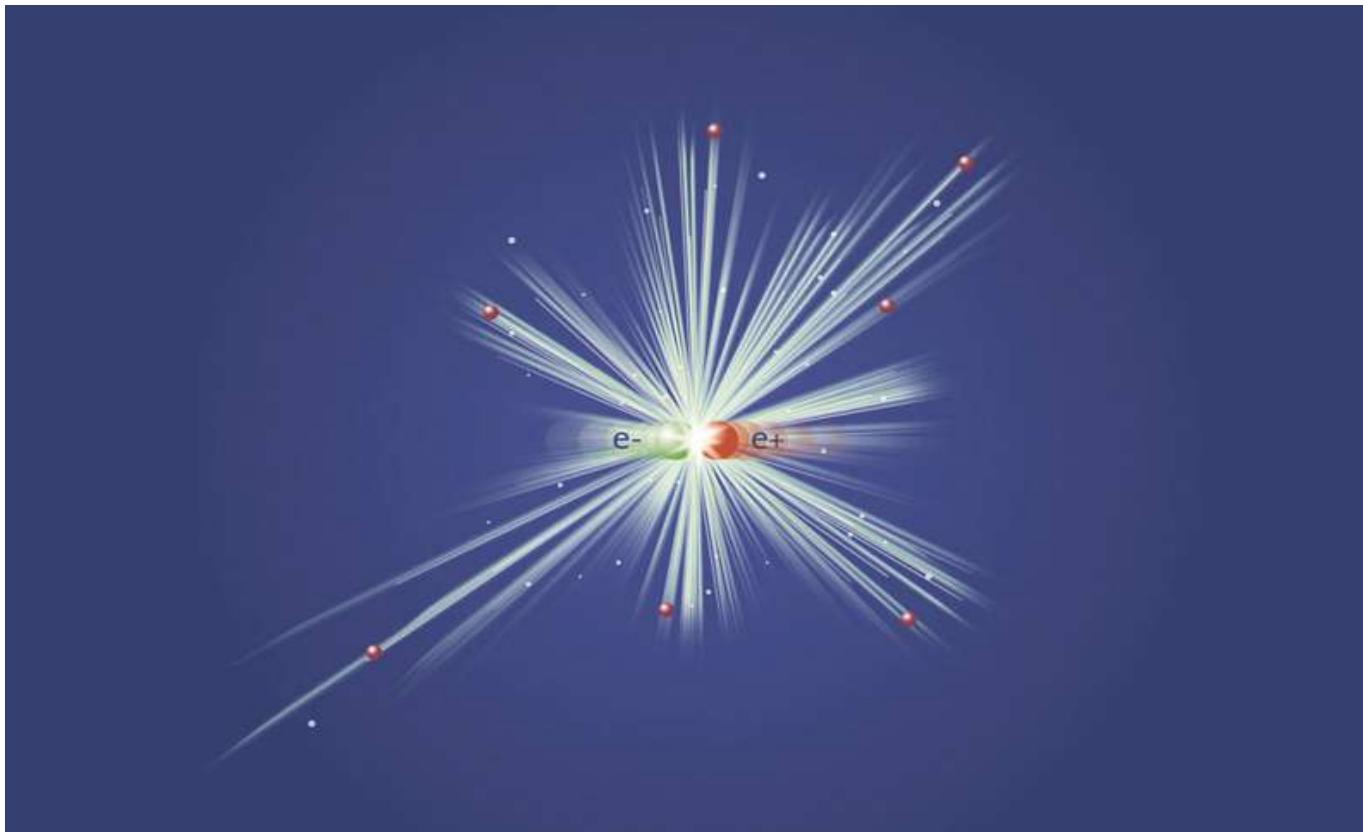
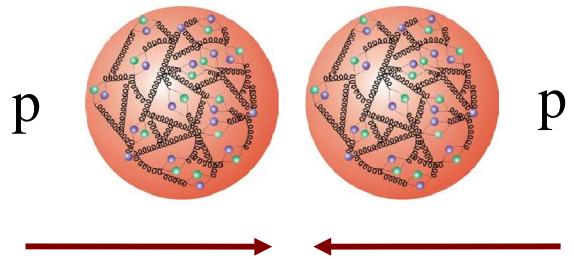


# ILC Physics Prospects



*Alexei Raspereza, MPI for Physics, Munich  
DIS'07 Conference 18/04/2007 Munich*

# Complementarity of Hadron and Lepton Colliders



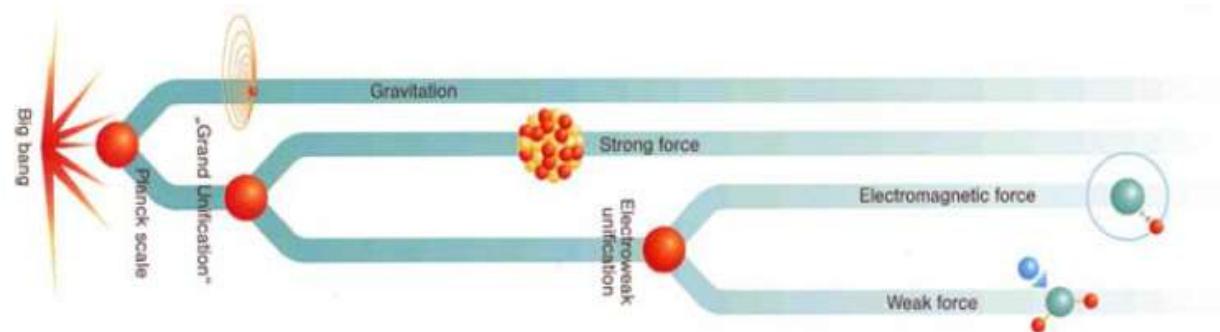
- Higher energy reach
- $p$  = composite particle:  
unknown  $\sqrt{s}$  of IS partons,  
no polarization of IS partons,  
parasitic collisions
- $p$  = strongly interacting:  
→ huge QCD backgrounds,  
highly selective trigger needed,  
radiation hard detectors needed
- **“Discovery” machine (LHC)**



- Limited energy reach (synchrotron radiation, limited length of LC)
- $e$  = pointlike particle:  
known and tunable  $\sqrt{s}$  of IS particles,  
polarization of IS particles possible,  
kinematic constraints can be used
- $e$  = electroweakly interacting  
low SM backgrounds,  
no trigger needed,  
detector design driven by precision
- **Machine of „model validation & indirect prediction“ (sub-TeV ILC)**

# Future Program of HEP

- Key question: mechanism of EWSB (origin of mass)
  - Conventional Higgs mechanism
  - Structure of Higgs Sector (single doublet, 2HDM)
  - Alternatives (dynamical symmetry breaking, composite models, strong EWSB)
- Hierarchy problem, unification of gauge interactions, gravity as QFT  $\Rightarrow$  New physics
  - SUSY
  - Extra Dimensions
  - Little Higgs models
  - Extended Gauge Theories  $\Rightarrow$  GUT's

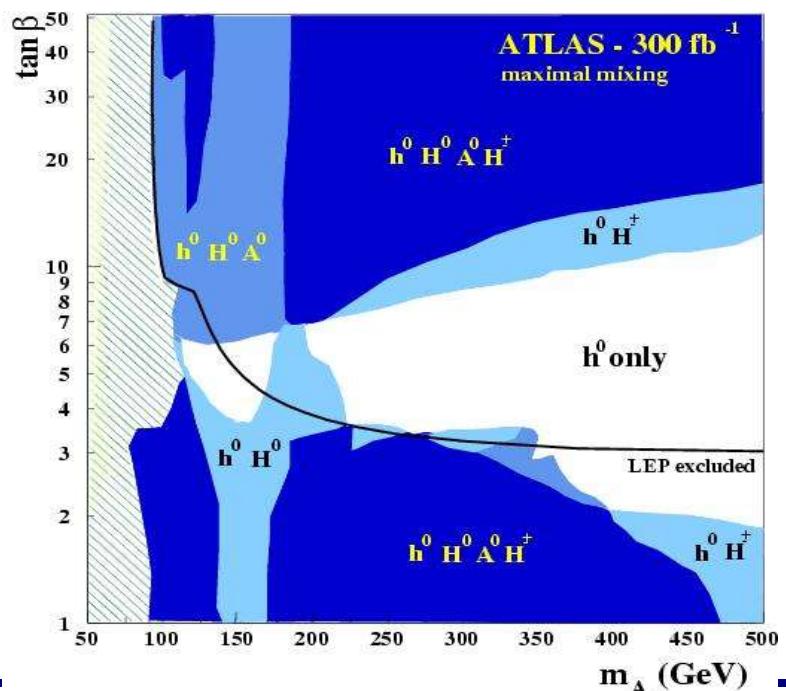
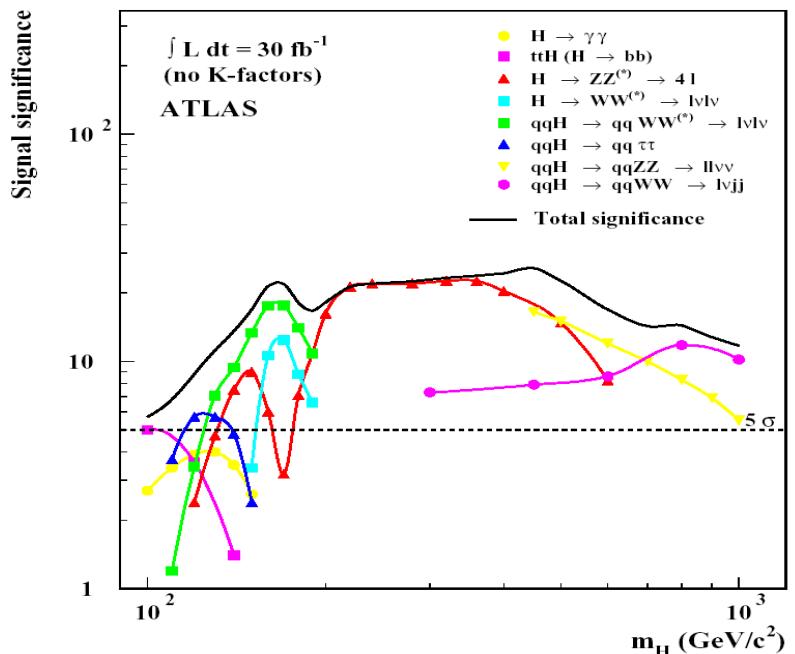


# Anticipated Nearest Future of HEP

- ◆ One of possible scenarios
  - EWSB is realised through Higgs mechanism;
  - Low energy SUSY as a bridge to New Physics
- ◆ LHC
  - Discovers Higgs and explores strongly interacting SUSY sector (squarks, gluinos); performs moderate precision (in many cases model-dependent) measurements
- ◆ ILC
  - high precision measurements in the Higgs sector    complete establishment of EWSB; detailed exploration of EW-interacting SUSY sector (sleptons, gauginos); possible discoveries in those regions of parameter space where LHC is „blind“
- ◆ ILC+LHC
  - Joint reconstruction of SUSY Lagrangian, constraints on New Physics

**But... Nature may be much reacher than our imagination!**

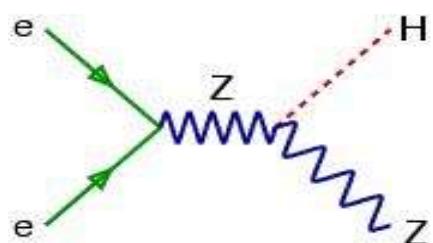
# Higgs Mechanism of EWSB Breaking (LHC Corner)



- Detection of Higgs in various channels, discovery potential over the entire mass range
  - At least one Higgs boson (light SM-like state) will be detected provided that relevant signal channels are combined
- First measurements of Higgs boson properties
  - ✓ moderate precision
  - ✓ model dependence
- Incomplete probe of Higgs mechanism
- Exploration of extended Higgs sector (SUSY)
  - more than one physical state
  - ✓ Domains in parameter space, where additional Higgs particles may escape detection : „wedge“ region in  $(m_A, \tan\beta)$  plane

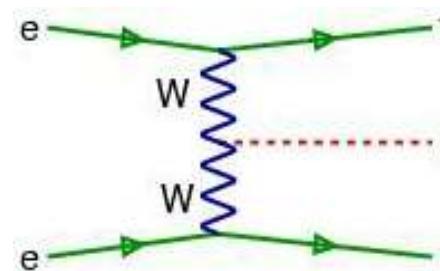
⇒ ILC is needed!

# Higgs Production at ILC

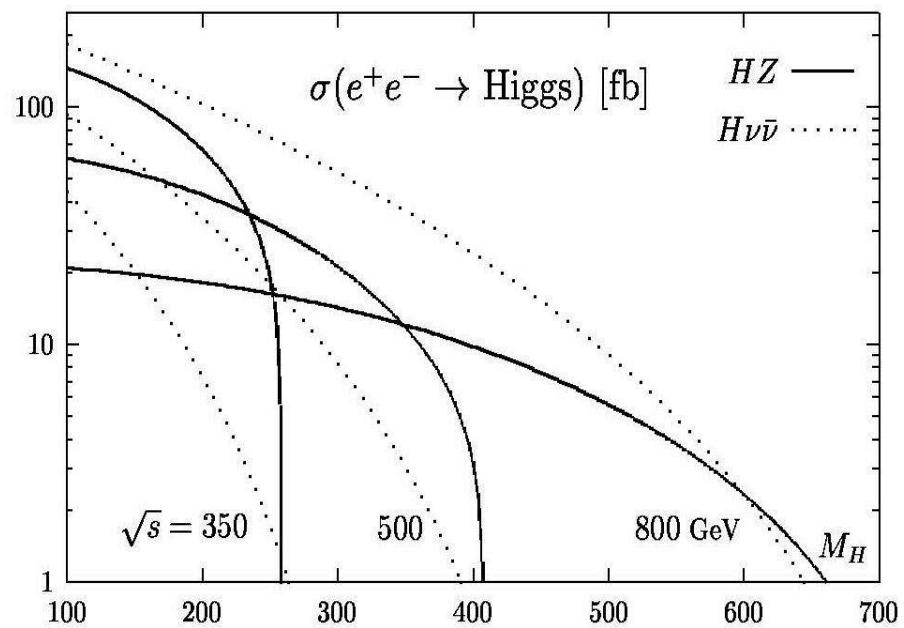


$$\sigma \propto \sim 1/s$$

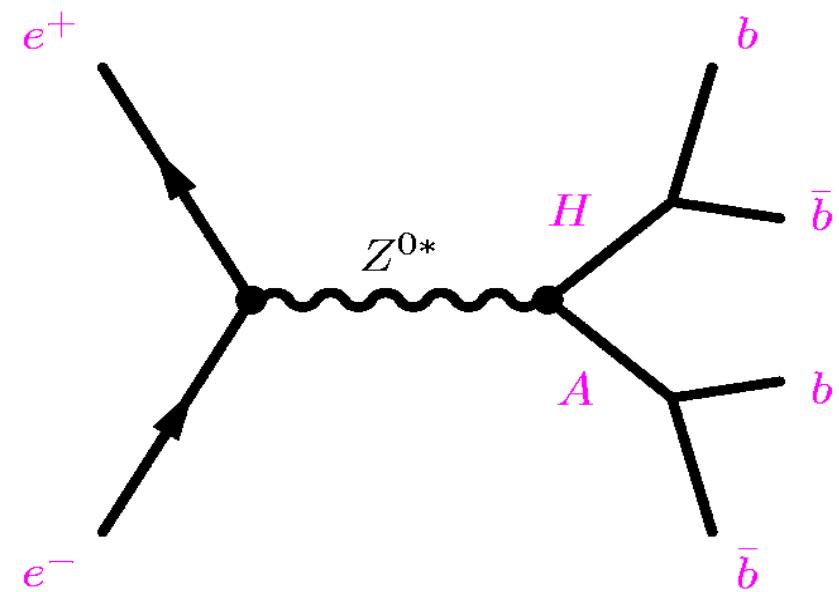
Higgs-strahlung



WW fusion



**Access to heavy SUSY  
Higgs particles**



# Decay Independent Higgs Detection

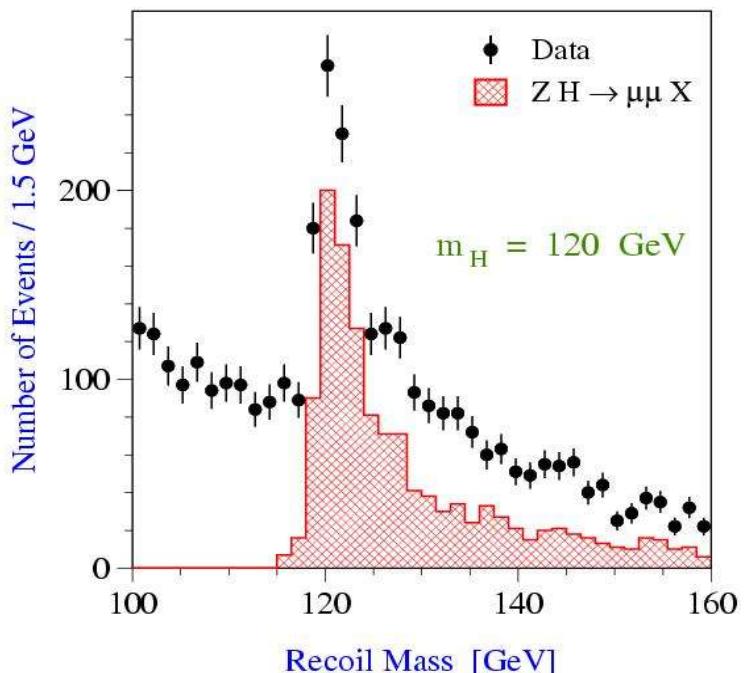
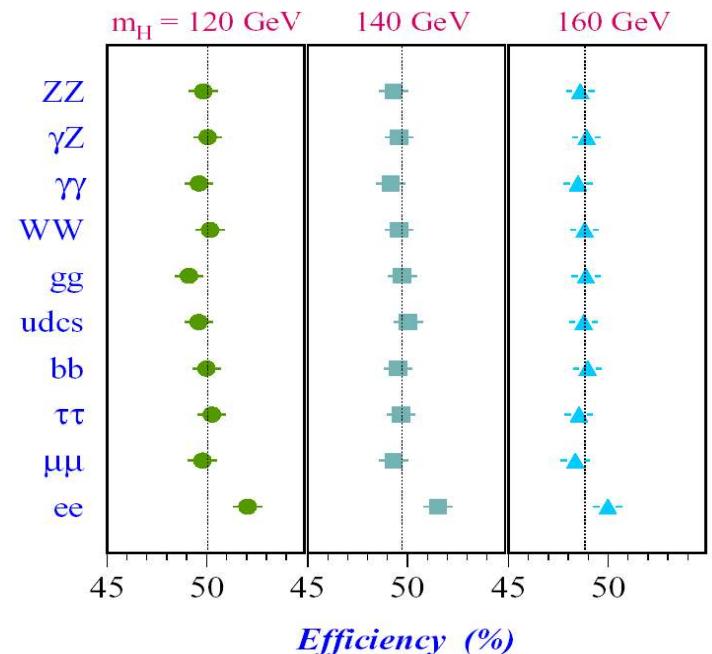
At ILC Higgs boson can be detected independent of its decay mode, even if it decays into invisible particles  $H \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$

*ILC „golden“ channel :  $ZH \rightarrow (ee, \mu\mu)X$*

*Peak in  $(ee, \mu\mu)$  recoil mass spectrum*

⇒ model independent extraction  
of  $ZHH$  coupling     $\sigma(ZH) \propto g_{HZZ}^2$

- ◆  $\sqrt{s} = 350 \text{ GeV}, L=500 \text{ fb}^{-1}$
- ⇒  $\delta\sigma/\sigma = 2.6(3.1)\% \quad m_H = 120(160) \text{ GeV}$   
*combining  $Z \rightarrow ee$  and  $Z \rightarrow \mu\mu$*



# Higgs Mass

**Exploited channel  $e^+e^- \rightarrow ZH$**

$Z \rightarrow e^+e^-, \mu^+\mu^-, qq$

*use of kinematic fits*

→ 4C fit : 4P ( $Z \rightarrow e^+e^-, \mu^+\mu^-$ )

→ 5C fit : 4P +  $m_Z$  ( $Z \rightarrow qq$ )

⇒ *improved mass resolution*

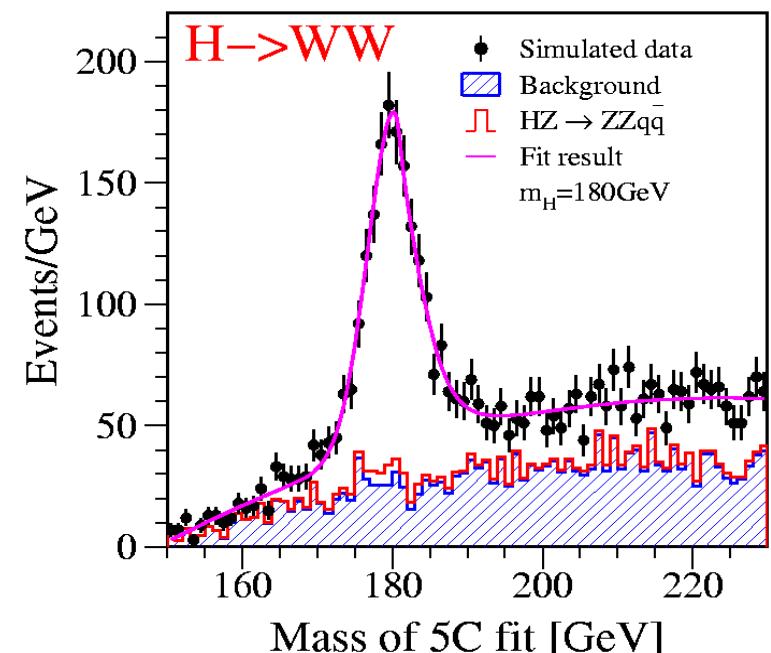
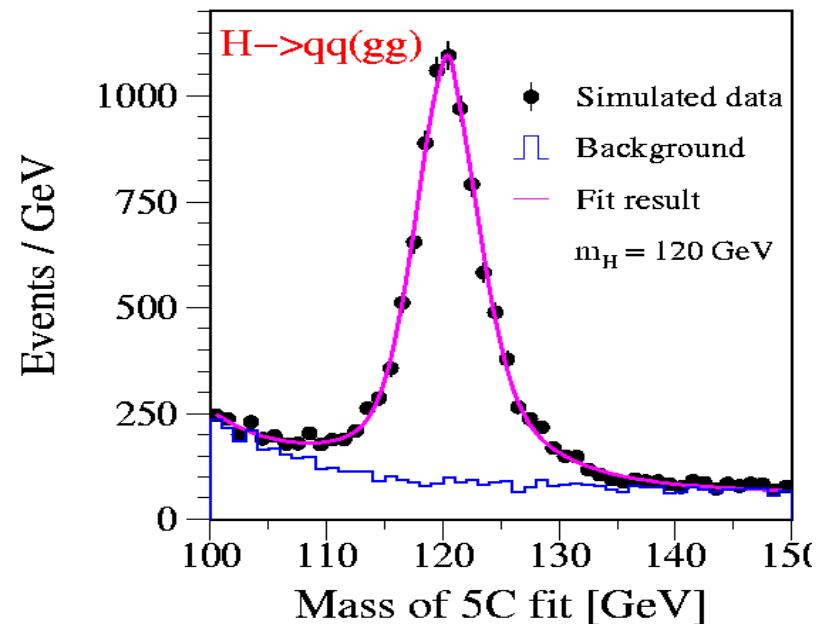
$\sqrt{s}=350\text{GeV}, 500\text{ fb}^{-1}$

◆  $m_H=120\text{GeV}, H \rightarrow bb$

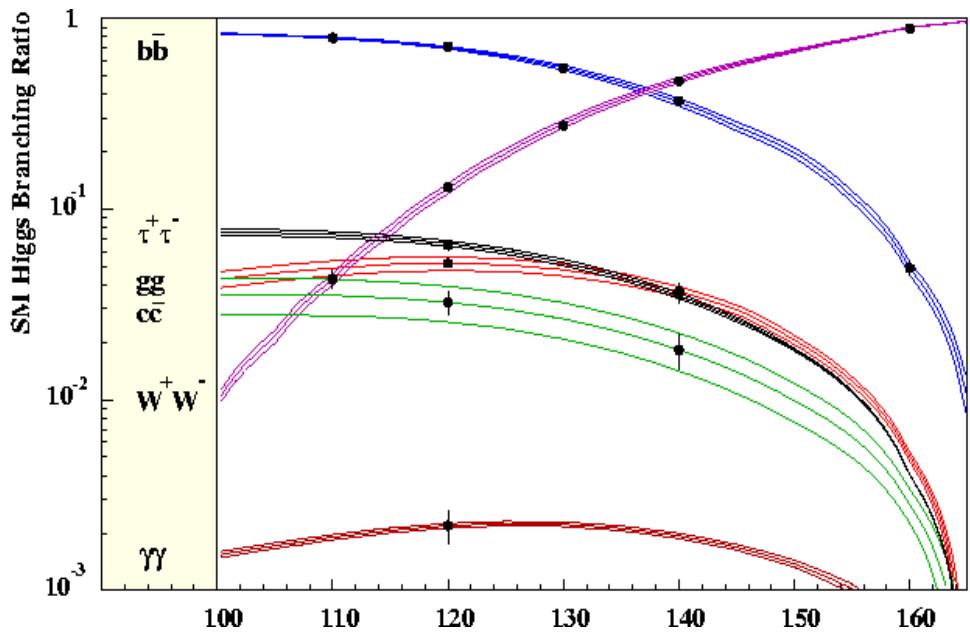
→  $\delta(m_H)=40\text{MeV}$

◆  $m_H=180\text{GeV}, H \rightarrow WW \rightarrow 4\text{jets}$

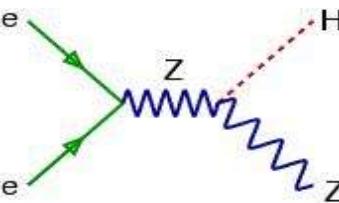
→  $\delta(m_H)=70\text{MeV}$



# Higgs Couplings to SM Particles

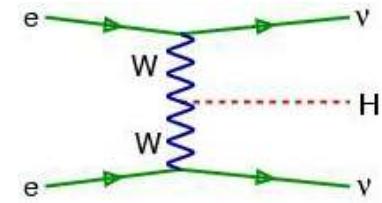


*Couplings to weak bosons through production rates*



$$\sigma(ZH) \propto g_{HZZ}^2$$

$$\Gamma_{ZZ}$$



$$\sigma(H\nu\nu) \propto g_{HWW}^2$$

$$\Gamma_{WW}$$

$\Delta BR/BR$
$bb$ 1.0%
$cc$ 12.3%
$gg$ 8.3%
$\tau\tau$ 5.0%
$WW$ 4.2%
$\gamma\gamma$ 26%

$$\Gamma = \Gamma_{WW} / Br_{H \rightarrow WW}$$

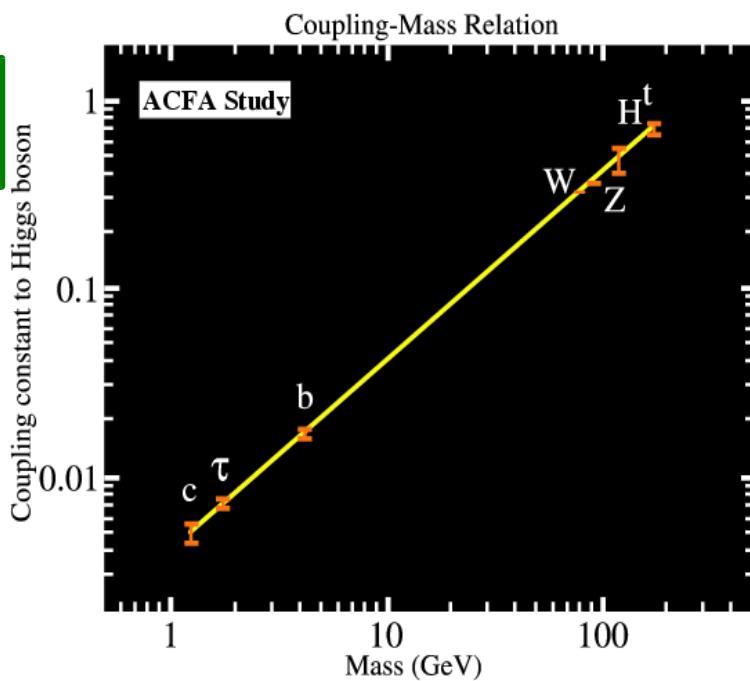
$$Br_{H \rightarrow X}$$

$$e^+ e^- \rightarrow ZH$$

$$\sqrt{s} = 350 \text{ GeV}$$

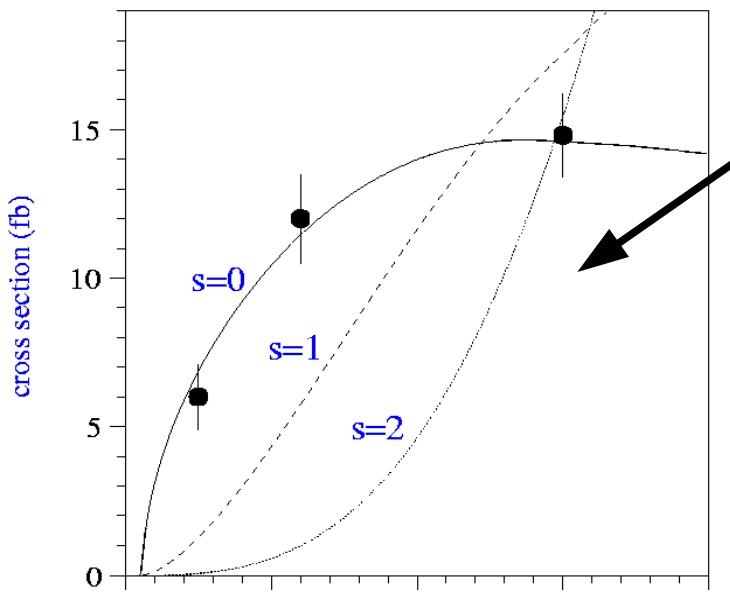
$$L = 500 \text{ fb}^{-1}$$

$$m_H = 120 \text{ GeV}$$

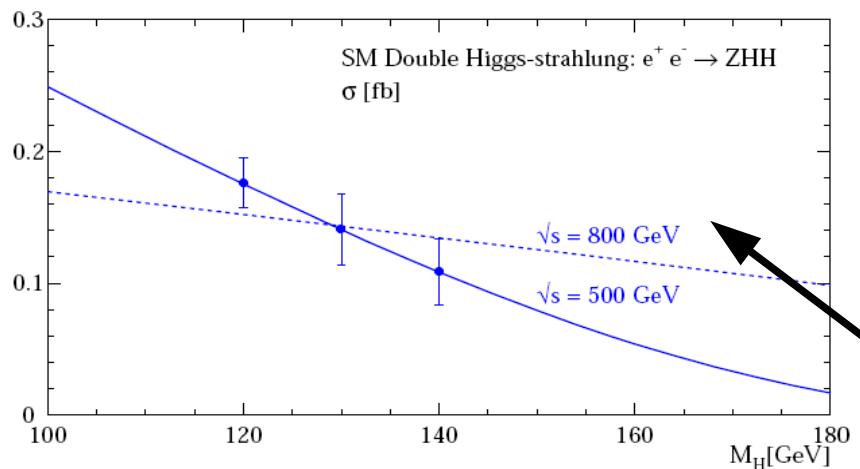
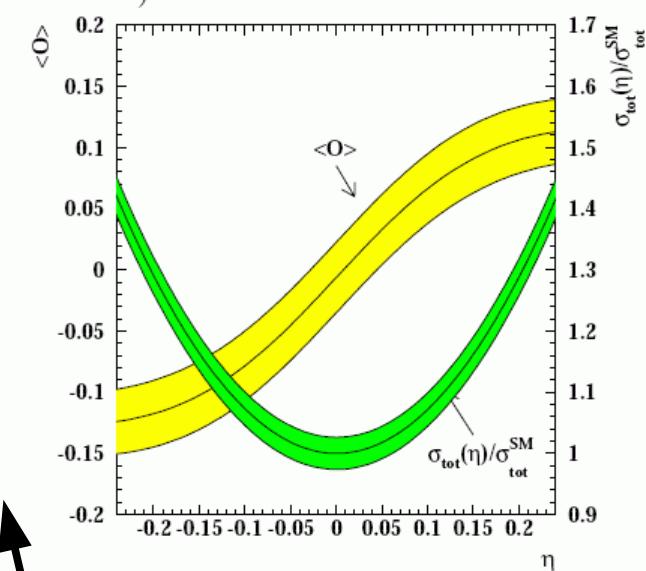
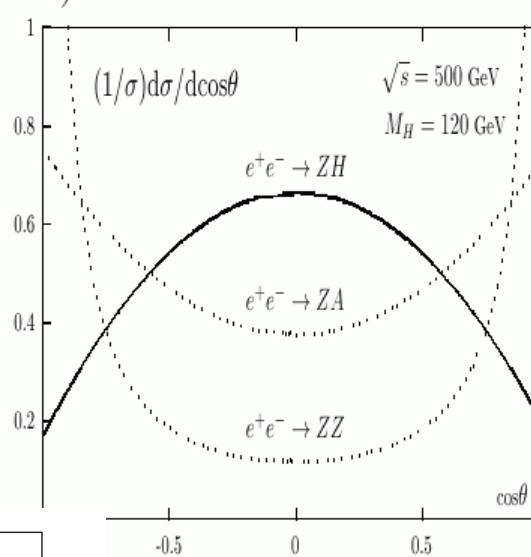


# Higgs Quantum Numbers & Self-Coupling

$\Rightarrow$ complete establishment of Higgs mechanism



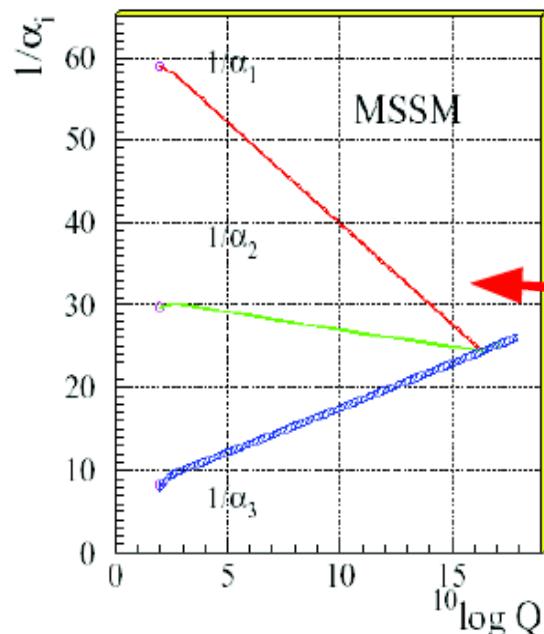
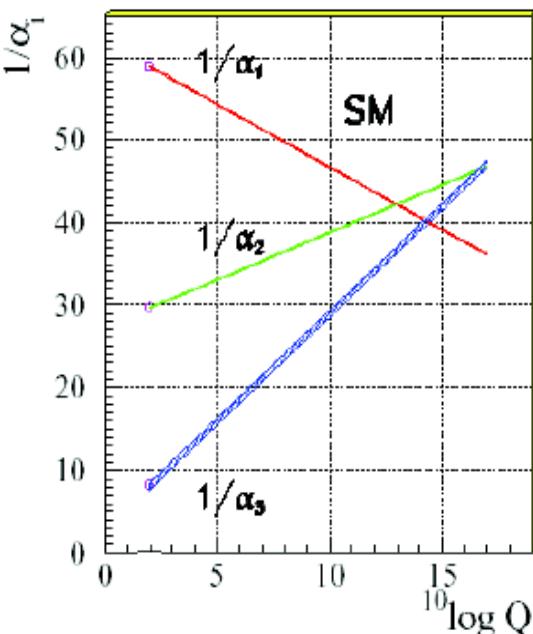
Higgs spin through  $ZH$  threshold scan



Higgs parity from  $ZH$  x-sec & angular distributions

Higgs self-couplings from  $ZHH$  &  $\nu\nu HH$

# Supersymmetry



## MSSM

- Each SM particle has SUSY partner ( $\Delta s=1/2$ )
- $R=(-1)^{L+3B+2S}$  is conserved
  - Proton decay is forbidden
  - LSP is stable (candidate for dark matter in universe)
  - Experimental signatures : large missing E

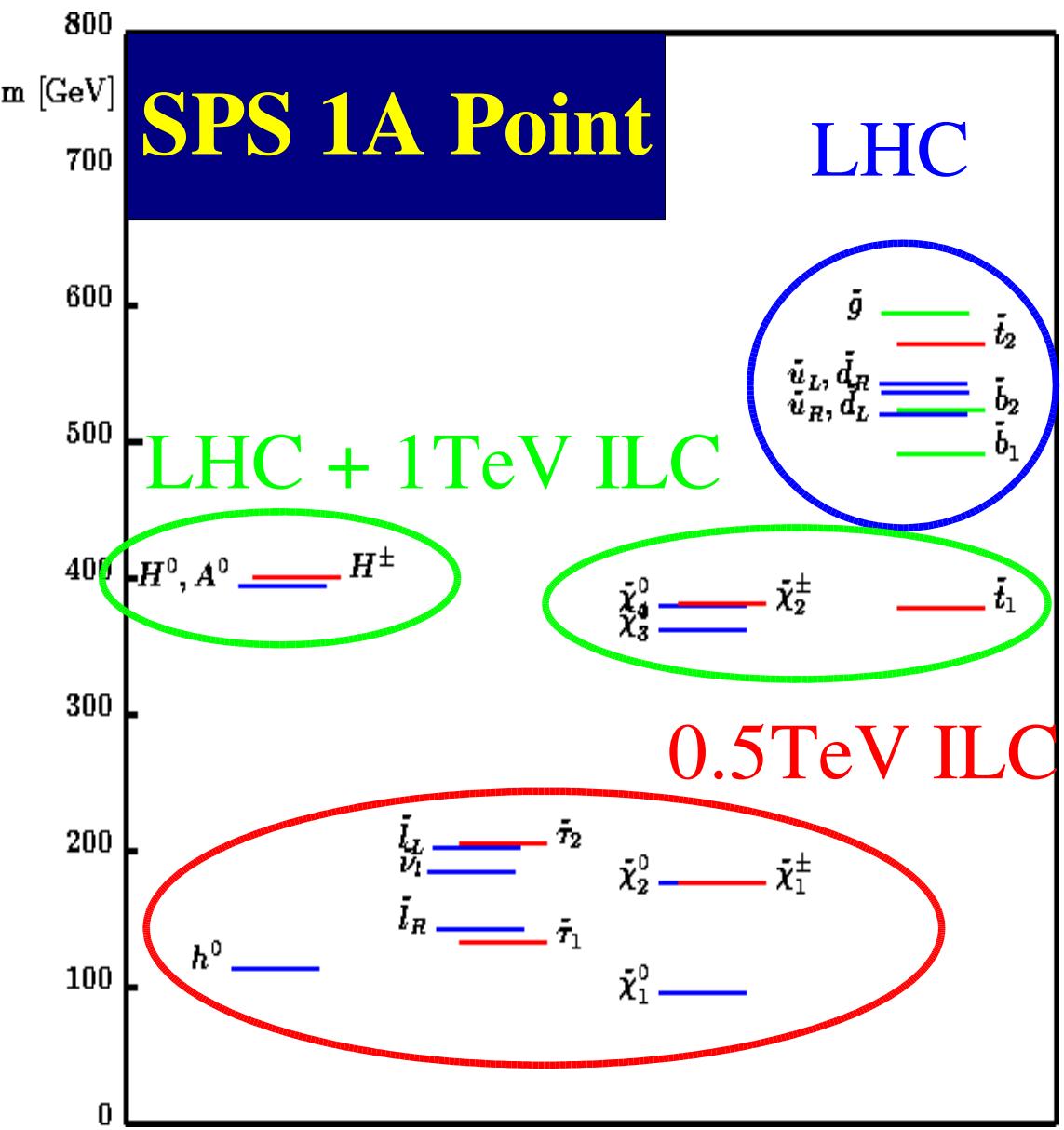
*SUSY – excellent candidate for new physics*

- Accomodates gravity as QFT
- Solves hierarchy problems
- Clear Path to Grand Unification
- EWSB is natural result of RGE  
(SUSY Lagrangian evolved down to TeV scale contains minimum at non-zero Higgs fields values)

Spin	Standardparticle	Superpartner	Spin
1/2	Leptons ( $e, \nu_e, \dots$ ) Quarks ( $u, d, \dots$ )	Sleptons ( $\tilde{e}, \tilde{\nu}_e, \dots$ ) Squarks ( $\tilde{u}, \tilde{d}, \dots$ )	0
1	Gluons $W^\pm$ $Z^0$ Photon ( $\gamma$ )	Gluinos Wino Zino Photino ( $\tilde{\gamma}$ )	1/2
0	Higgs	Higgsino	1/2
2	Graviton	Gravitino	3/2

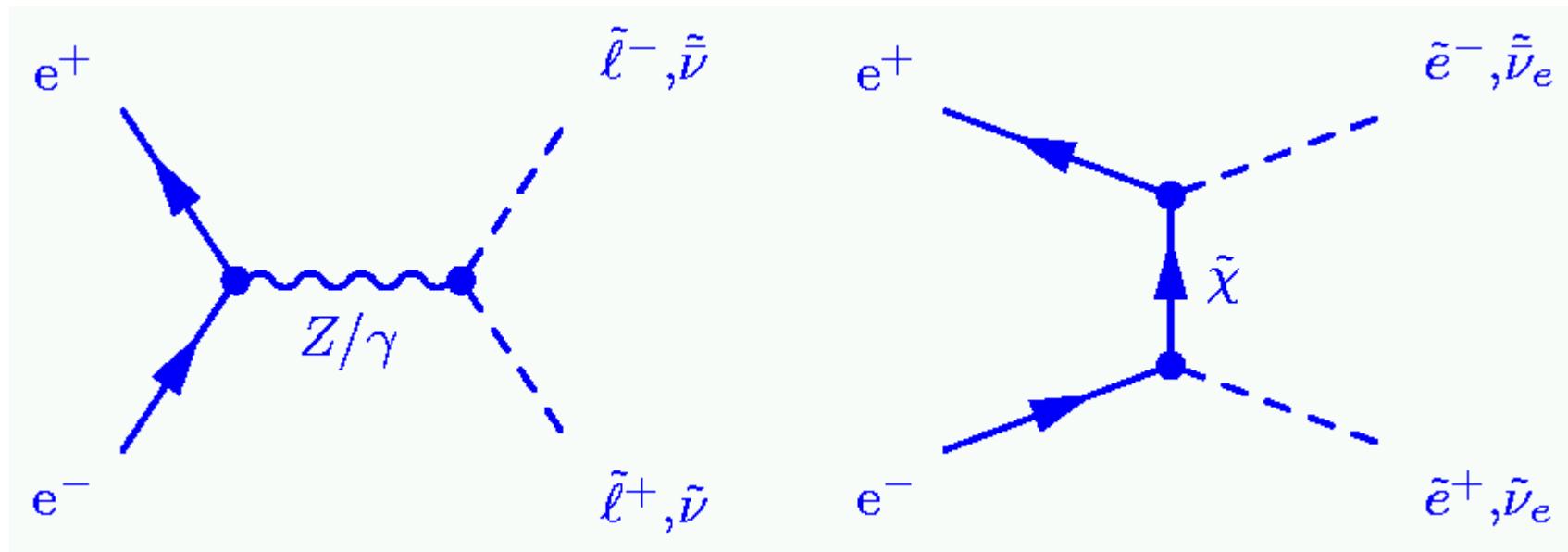
# Exploring SUSY

## Complementarity of LHC & ILC



- LHC explores in detail strongly interacting SUSY sector (squarks, gluinos)
- Most of other SUSY particles are within reach of sub-TeV ILC
  - \* Big chance to observe SUSY particles at early stage of ILC operation ( $\sqrt{s}=500$  GeV)
  - \* Clean signatures, low backgrounds precise SUSY spectroscopy (EW-interacting sector)
- From physical observables to SUSY Lagrangian
  - $M_1, M_2, M_3, \tan\beta, \mu, m_0 \dots$  etc (Joint LHC & LC effort)

# Sleptons. Production & Decays



$\tilde{l}^- \rightarrow \tilde{\chi}^0 l^-$	$m_{\tilde{l}} > m_{\tilde{\chi}^0}$
$\tilde{l}^- \rightarrow \tilde{\chi}^- \nu$	$m_{\tilde{l}} > m_{\tilde{\chi}^-}$
$\tilde{\nu} \rightarrow \tilde{\chi}^0 \nu$	$m_{\tilde{\nu}} > m_{\tilde{\chi}^0}$
$\tilde{\nu} \rightarrow \tilde{\chi}^- l^+$	$m_{\tilde{\nu}} > m_{\tilde{\chi}^-}$

## Most favored decay

slepton  $\Rightarrow$  lightest neutralino (LSP) + lepton

## Main signatures

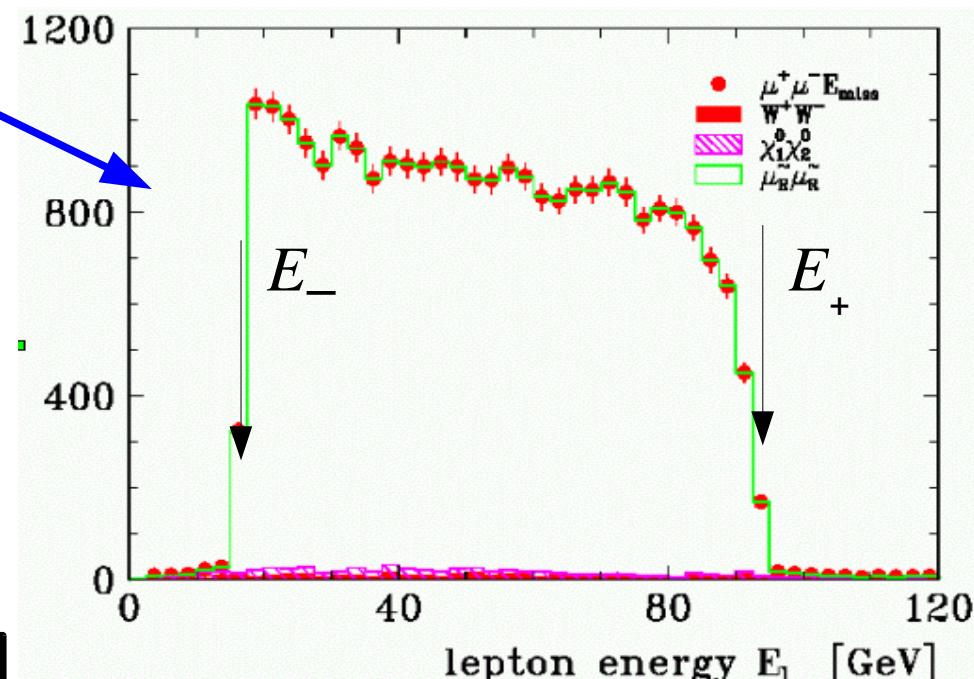
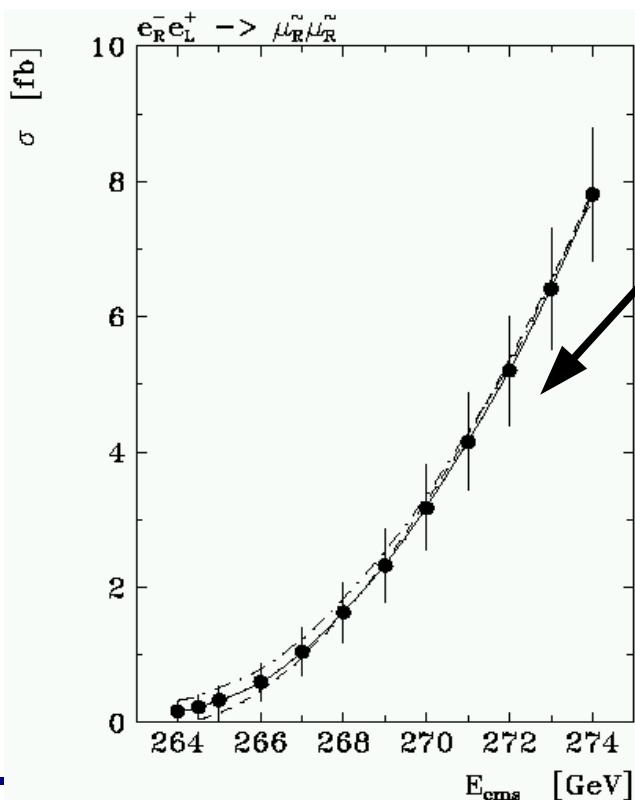
- 1) two leptons + missing E
- 2) two narrow jets ( $\tau$ 's) + missing E

# Sleptons. Mass Determination

Masses of  $\tilde{\chi}_1^0$  and  $\tilde{\mu}$  from kinematic edges

$$m_{\tilde{t}} = \frac{\sqrt{s}}{E_- + E_+} \sqrt{E_- E_+}$$

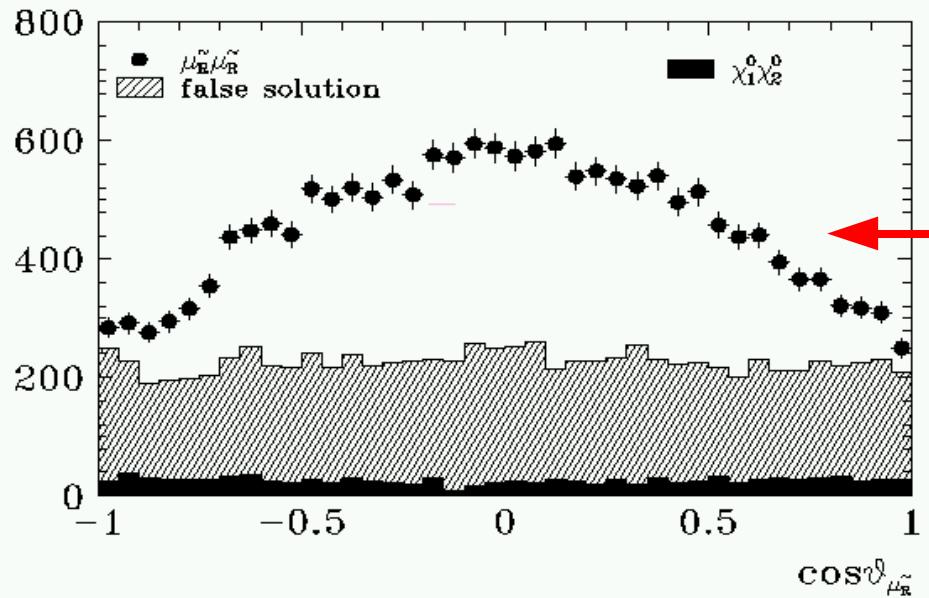
$$m_{\tilde{\chi}} = m_{\tilde{t}} \sqrt{1 - \frac{E_- + E_+}{\sqrt{s}/2}}$$



## Slepton masses in mSUGRA SPS 1A

	$m$ , GeV	$\delta_m$ , GeV		$m$ , GeV	$\delta_m$ , GeV
$\tilde{e}_R$	143.0	0.05	$\tilde{\mu}_R$	143.0	0.2
$\tilde{e}_L$	202.1	0.2	$\tilde{\mu}_L$	202.1	0.5
$\tilde{\nu}_e$	186.0	1.2	$\tilde{\tau}_1$	133.2	0.3
$\tilde{\nu}_{\mu,\tau}$	inaccessible		$\tilde{\tau}_2$	133.2	1.1

# Slepton Properties

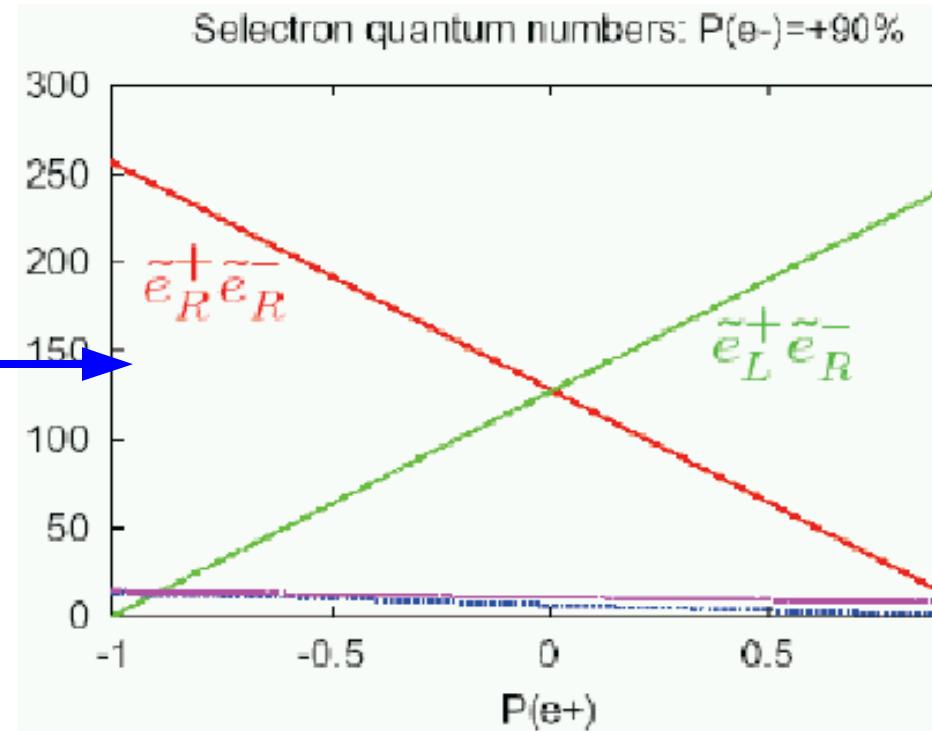
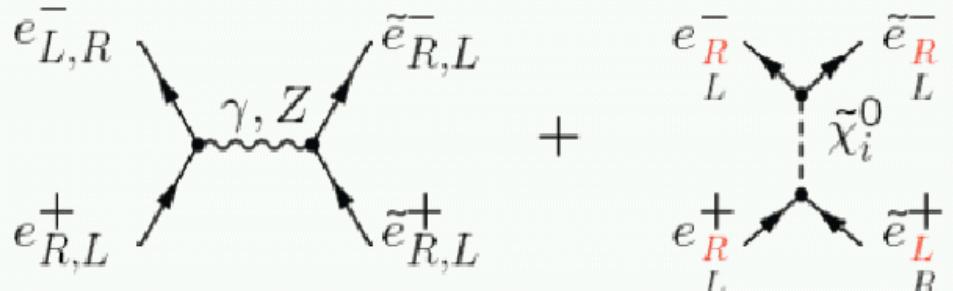


## SPIN (in s-channel)

- $S=0$  :  $\sigma \propto \beta^3$  ;  $d\sigma/d\cos\theta \propto \sin^2\theta$
- *Threshold scan*
- *Angular distribution*

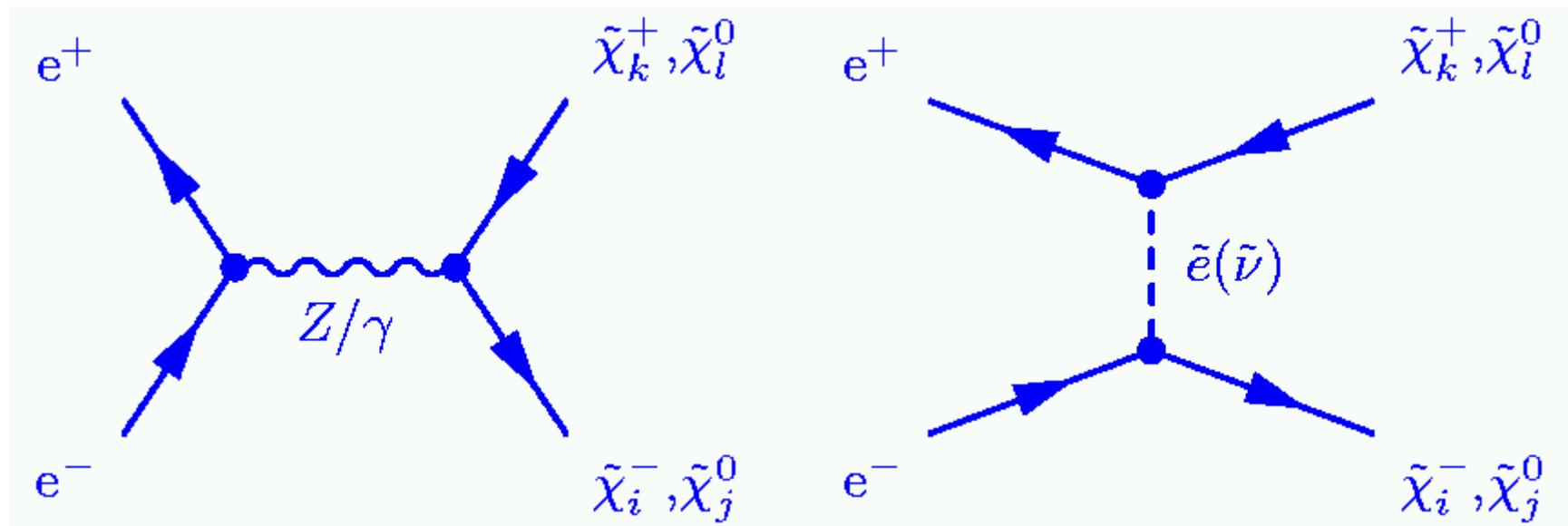
$(\tilde{\ell}_L, \ell_L)$  and  $(\tilde{\ell}_R, \ell_R)$  association

⇒  $\sigma(\tilde{\ell}^+ \tilde{\ell}^-)$  as a function  
of  $P(e^+)$  and  $P(e^-)$



# Gaugino Production and Decays

*Gauginos = mixture of winos, bino and higgsinos*  
*⇒ 6 physical (mass) states : 2 charginos + 4 neutralinos*  
*Lightest neutralino – good candidate for LSP*



$\tilde{\chi}_i$	$\rightarrow Z/W \tilde{\chi}_j$	$\rightarrow f\bar{f} \tilde{\chi}_j$
$\tilde{\chi}_1^+$	$\rightarrow \tilde{\tau}_1^+ \nu_\tau$	$\rightarrow \tau^+ \nu_\tau \tilde{\chi}_1^0$
$\tilde{\chi}_2^0$	$\rightarrow \ell\bar{\ell}$	$\rightarrow \ell\bar{\ell} \tilde{\chi}_1^0$

## Variety of signatures

**from 2 to 4 observable fermions  
 (leptons or jets) + missing E**

# Gaugino Masses

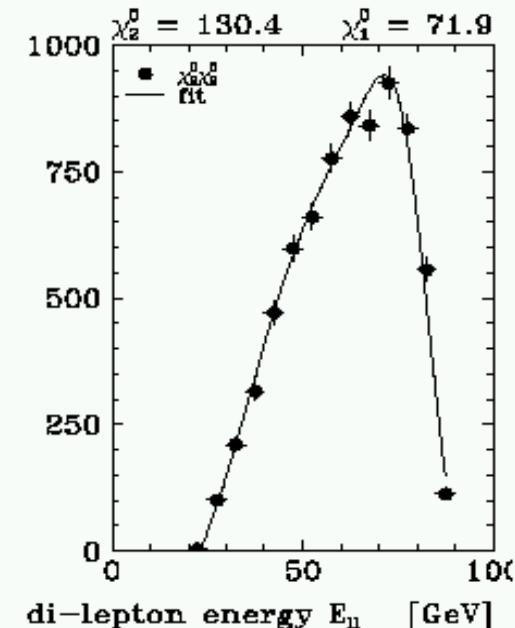
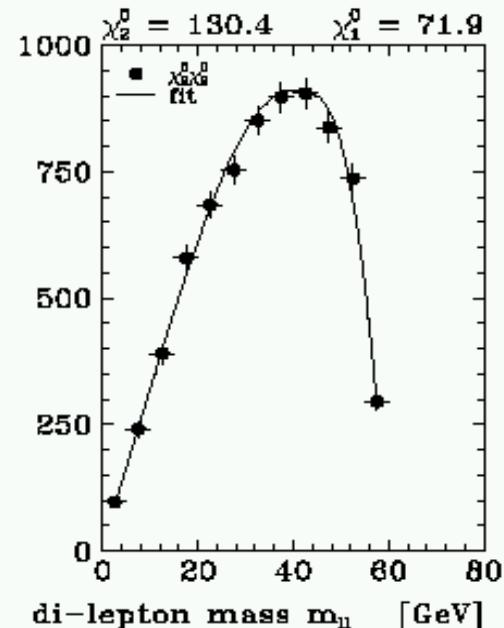
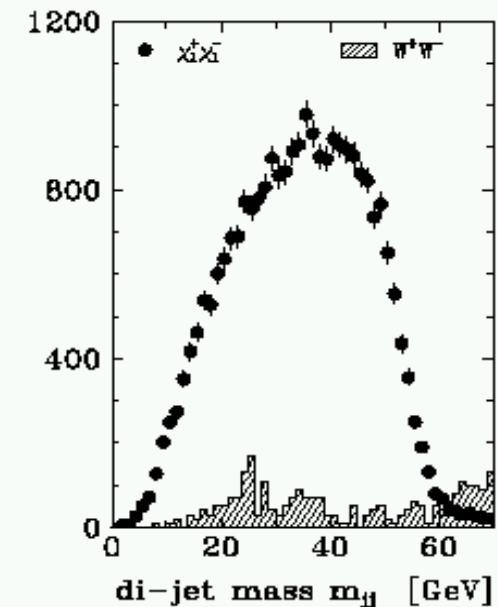
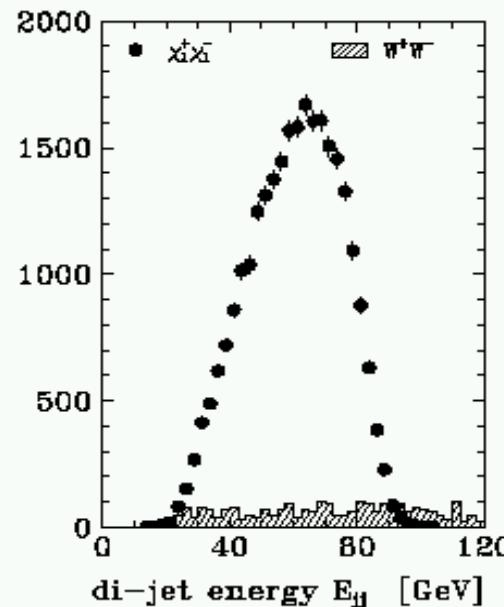
Exploit sensitivity of dijet & dilepton energy and mass spectra to gaugino masses

Charginos:

e.g.  $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$   
 $\rightarrow 2\text{jets} + \ell\nu + \tilde{\chi}_1^0 \tilde{\chi}_1^0$

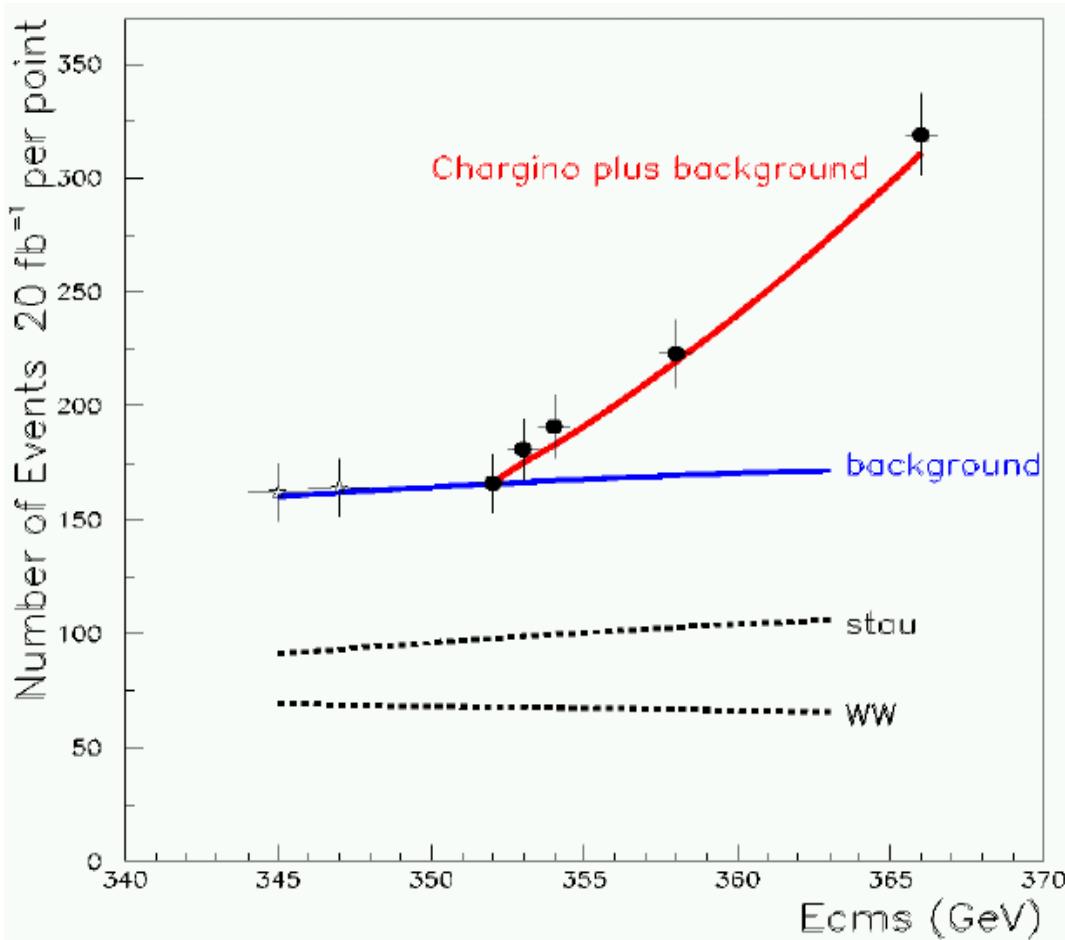
Neutralinos:

e.g.  $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0$   
 $\rightarrow 4\ell + \tilde{\chi}_1^0 \tilde{\chi}_1^0$



# Gaugino Masses

*Traditional threshold scan technique*



Gaugino masses  
(mSUGRA SPS 1A point)

	$m$ , GeV	$\delta_m$ , GeV
$\tilde{\chi}_1^\pm$	176.4	0.55
$\tilde{\chi}_2^\pm$	378.2	3
$\tilde{\chi}_1^0$	96.1	0.05
$\tilde{\chi}_2^0$	176.8	1.2
$\tilde{\chi}_3^0$	358.8	3–5
$\tilde{\chi}_4^0$	377.8	3–5

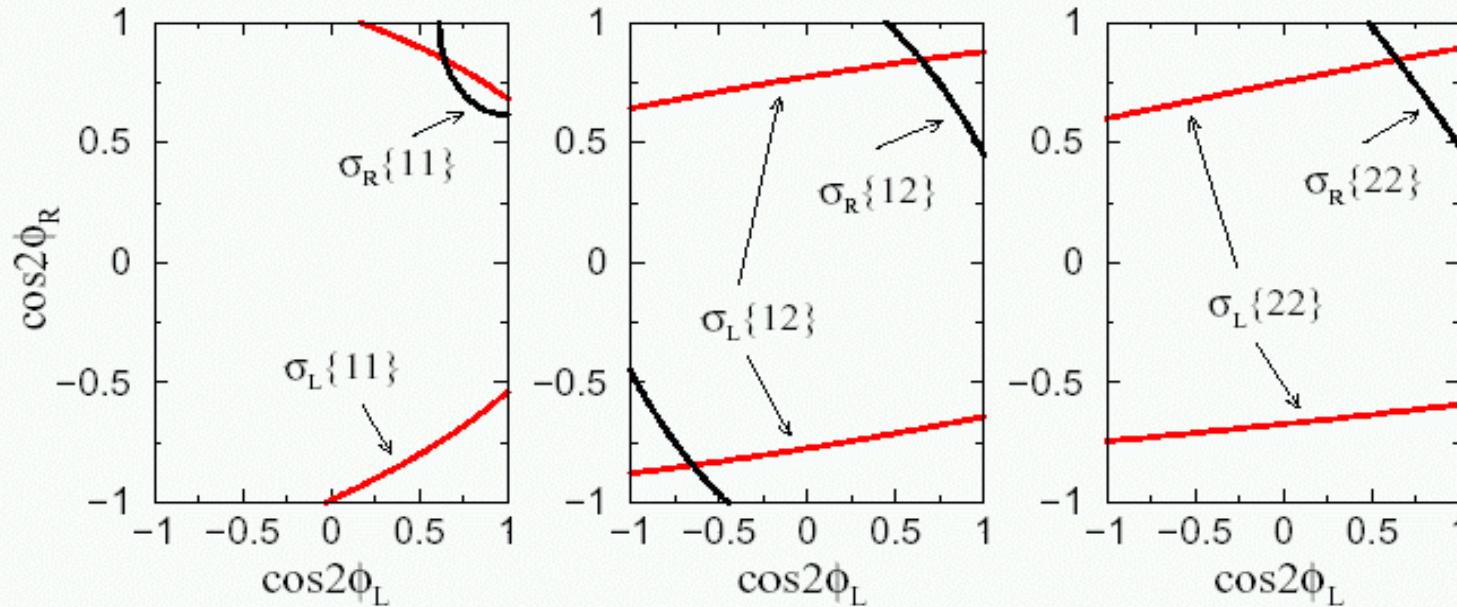
Threshold scan of  $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tau^+ \nu_\tau \tilde{\chi}_1^0 \tau^- \bar{\nu}_\tau \tilde{\chi}_1^0$

# Charginos - Properties

Disentangle Wino/Higgsino admixture of Charginos:

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \sqrt{2}m_W \cos\beta \\ \sqrt{2}m_W \sin\beta & \mu \end{pmatrix} \Rightarrow 2 \text{ mixing angles } \Phi_R, \Phi_L$$

$\mu$ ,  $M_2$  and (moderate)  $\tan\beta$  can be uniquely determined with polarisation:



	input 1	fit	input 2	fit
$M_2$	152 GeV	$152 \pm 1.8$ GeV	150 GeV	$150 \pm 1.2$ GeV
$\mu$	316 GeV	$316 \pm 0.9$ GeV	263 GeV	$263 \pm 0.7$ GeV
$\tan\beta$	3	$3 \pm 0.7$	30	$> 20$

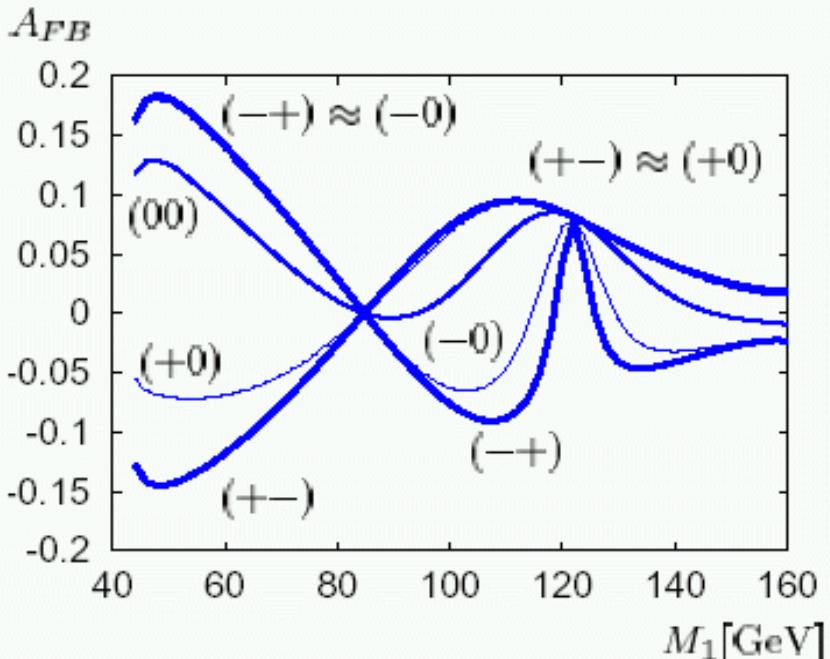
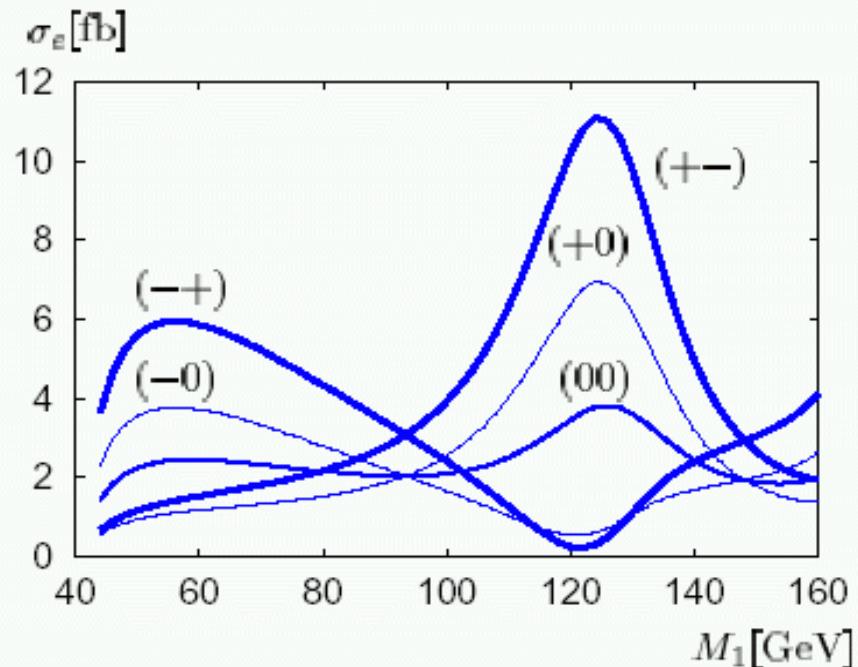
# Neutralino - Properties

Neutralino system depends also on  $M_1$  (in addition to  $M_2, \mu, \tan \beta$ )

Exploit spin correlation in two lepton final state from

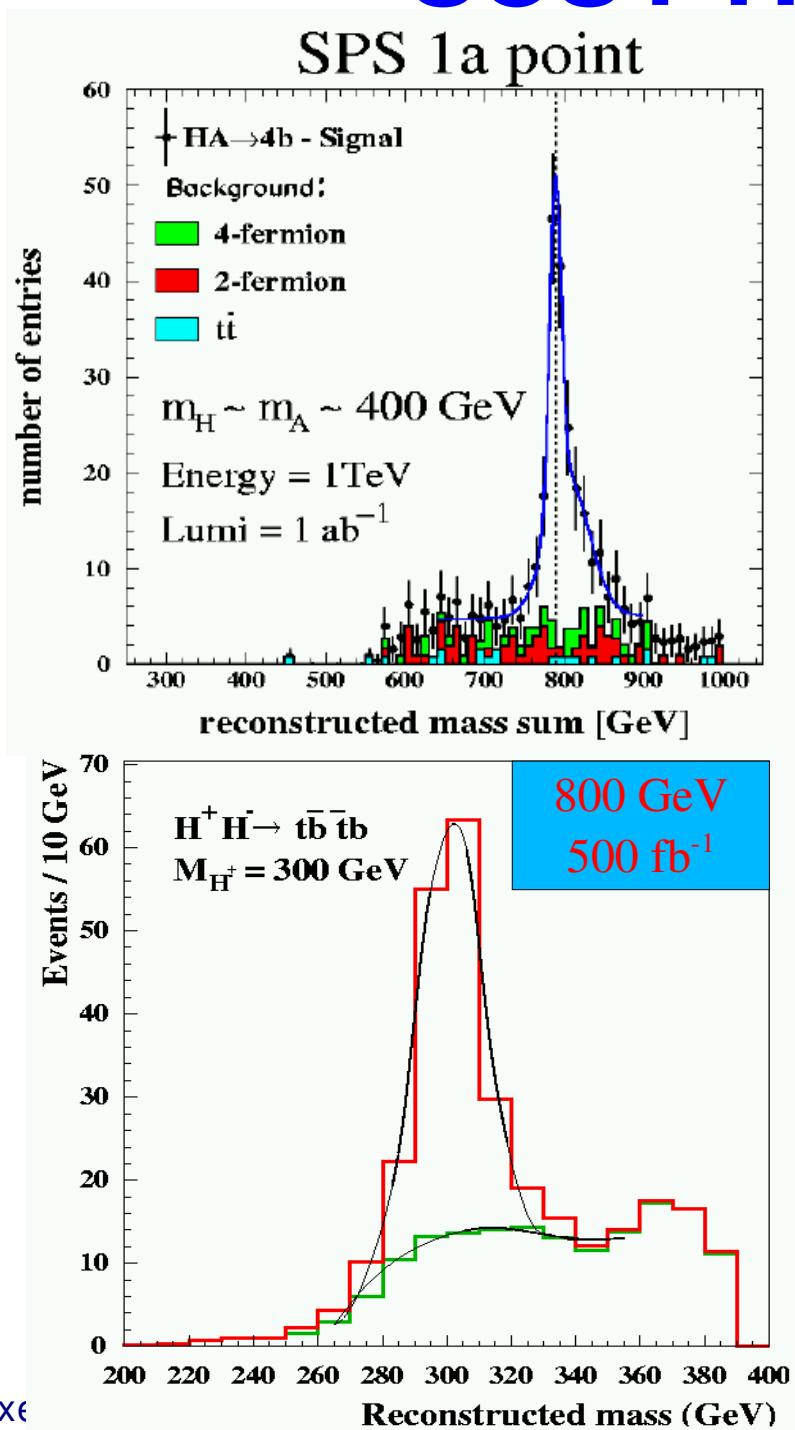
$$e^+ e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

beam polarisation essential!



	input 1	fit	input 2	fit
$M_1$	78.7 GeV	$78.7 \pm 0.7$ GeV	78.0 GeV	$78.0 \pm 0.4$ GeV

# SUSY Higgs Bosons



*Two doublets  $\Rightarrow$  5 physical states*

$h^0 (m_{h0} \leq 135 \text{ GeV}), H^0, A^0, H^\pm$

Decoupling limit in neutral sector  
 $h^0$  approaches SM Higgs properties  
 $H^0$  &  $A^0$  are heavy,  $m_{H^0} \approx m_{A^0}$

## Main Channels

- $e^+ e^- \rightarrow H^0 A^0 \rightarrow b\bar{b} b\bar{b}, b\bar{b} \tau^+ \tau^-$
- $e^+ e^- \rightarrow H^+ H^- \rightarrow t\bar{b} t\bar{b} \text{ (8 jets!)}$

*1TeV-ILC surpasses sensitivity of LHC for heavy Higgs states (coverage of „wedge“ region!)*

# Probing SUSY Breaking Models

- ♦ Key steps towards revealing mechanism of SUSY breaking and understanding more fundamental theories

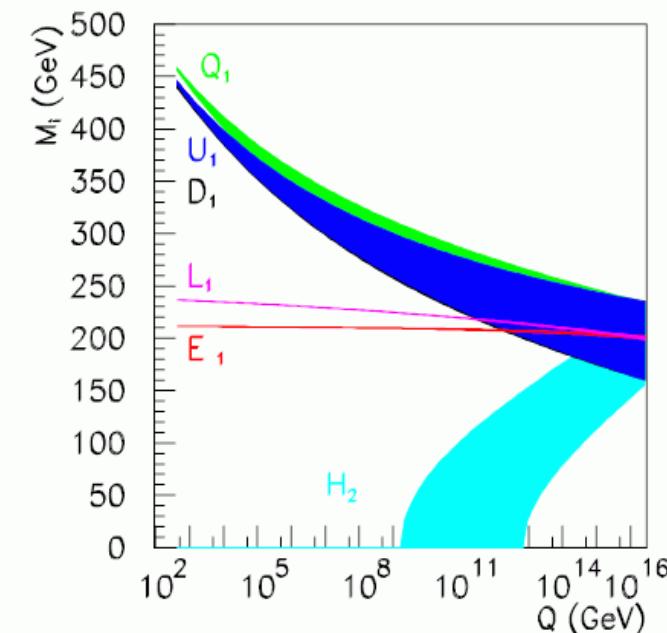
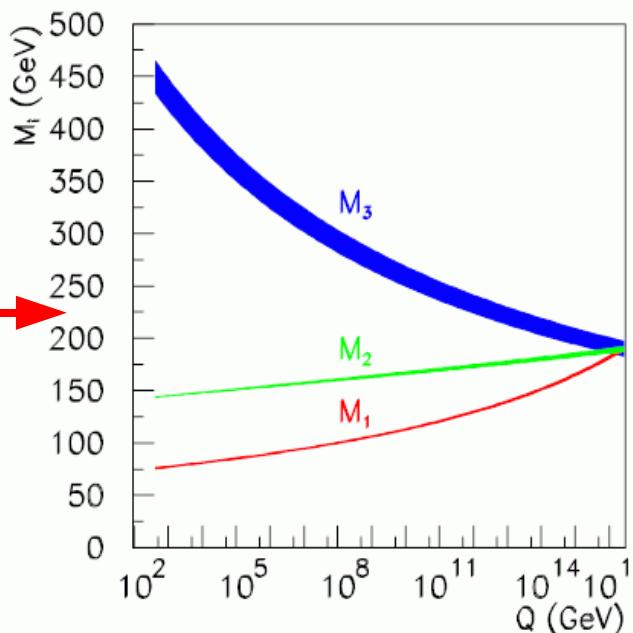
- Reconstruction of MSSM Lagrangian & TeV scale from physical observables
- Extrapolating Lagrangian parameters to higher scales (e.g. GUT scale)
- Probing different SUSY breaking models (SUGRA, GMSB, AMSB, ...)

- ♦ Joint effort of LHC & ILC

- Complementarity in the study of SUSY: strongly interacting sector (squarks, gluinos) & LHC, electroweakly interacting sector (sleptons, gauginos) @ ILC
- Combined measurements (e.g.  $Htt$  coupling) ⇒ more information, better precision, higher level of understanding

**Example: mSUGRA**  
**Parameters @  $Q=10^{16}$  GeV**

$m_0 = 200\text{GeV}$   
 $m_{1/2} = 190\text{GeV}$   
 $A_0 = 550\text{GeV}$   
 $\tan\beta = 30$   
 $\text{sign}(\mu) < 0$



# Uncovered Topics

- ◆ Alternative models of EWSB (strong EWSB, composite models)
  - ◆ Extra dimensions
  - ◆ Theories with extended gauge sector
  - ◆ QCD & top physics
  - ◆ CP-violation in EW, SUSY, Higgs sectors
  - ◆ R-parity violating SUSY
  - ◆ Lepton flavour violation
  - ◆ High precision EW physics & giga-Z (high luminosity run @ 91.2GeV)
  - ◆ ...
- 
- ✓ Many topics still need to be scrutinized
  - ✓ Any interesting topic for you?
  - ✓ Expertise is needed, volunteers are searched

# Summary

- International Linear  $e^+e^-$  collider – next large experimental facility after LHC
- Fascinating physics is anticipated
  - Elucidating mechanism of EWSB
  - Probing New Physics (SUSY, Extra Dimensions, Extended Gauge Theories)
- Complements LHC data
- Universality of detector (from hardware side) and universality of thinking (from human side) is needed to embrace all expected and unexpected scenarios
- ILC project is global (inter-regional) effort  $\Rightarrow$  high chances for success
- Interested, intrigued? Joins us!