LHC / ILC interplay in SUSY searches

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(K Desch, J Kalinowski, GMP, K Rolbiecki, WJ Stirling, JHEP 0612:007, 2006)

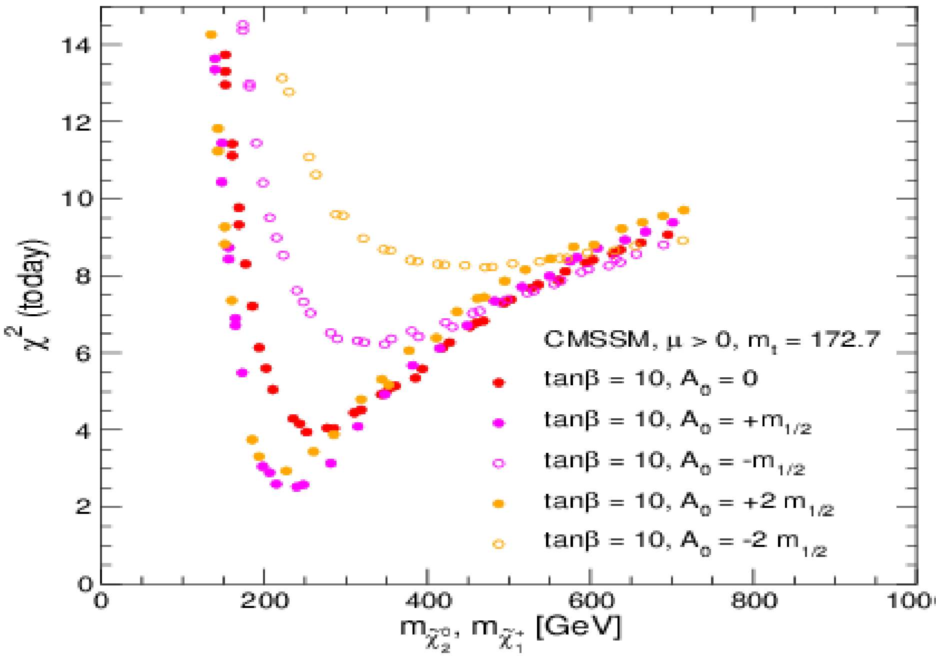
Outline

- SUSY parameter determination and LHC/ILC interplay
- Case study: chosen scenario with heavy sfermions
- Numerical results: expectations for LHC
- Numerical results: ILC strategy and LHC/ILC interplay
- Conclusions

Supersymmetry

- In which range do we expect SUSY?
  - at least some light particles should be accessible at 500 GeV
  - best possible tools needed to get maximal information out of only the part of the spectrum

Ellis, Heinemeyer, Olive, Weber, Weiglein '07

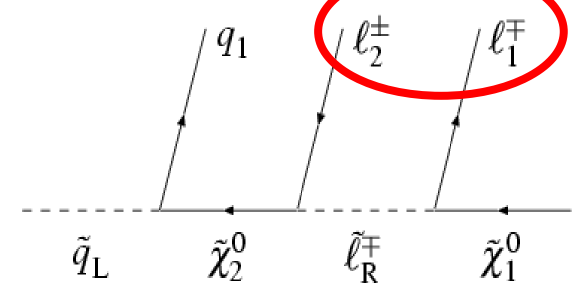


- To reveal the structure of the underlying physics, it is important to determine the parameters in a model-independent way and test all model assumptions experimentally

- Soon we will have LHC data, but LHC/ILC interplay will be essential and both machines cover a large range of the parameter space !

Discovery of SUSY

- **Expectations at the LHC:**
  - Coloured SUSY partners: discovery reach $m_{\tilde{q},\tilde{g}} < 2\text{-}2.5$ TeV
  - Non-coloured partners:
    a) via Drell-Yan $m_\chi < 250$ GeV
    b) via cascade decay chains

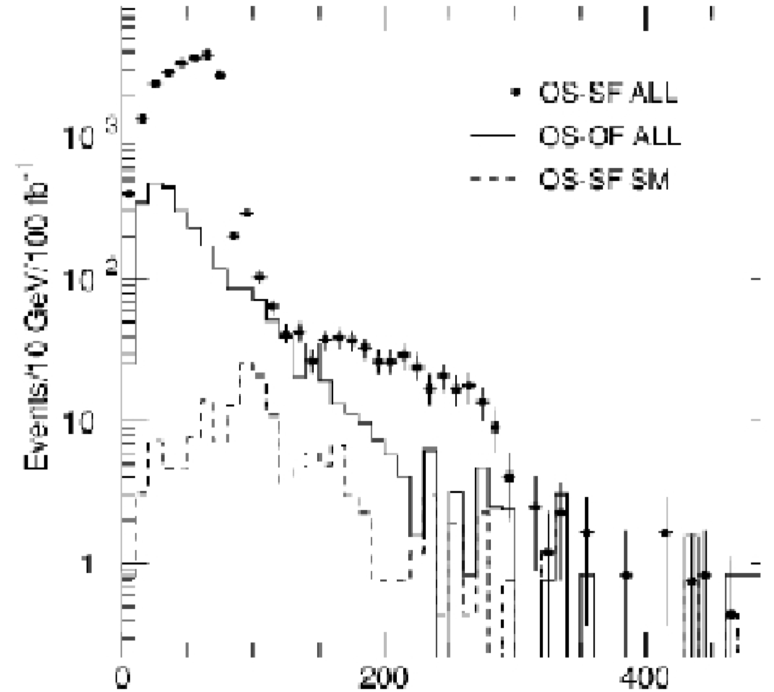


  - Parameter determinations: in specific SUSY breaking models
- **At the ILC:**
  - direct production of all kind of SUSY particles up to kinematical limit $\sqrt{s}/2$
  - indirect mass bounds due to high precision
  - precise model-independent parameter determination
- **Particularly promising field for LHC/ILC interplay studies !**

LHC / ILC interplay

- **If fundamental parameters determined: allows mass predictions for heavier particles**
  - **significant increase of sensitivity for searches at the LHC and unique identification of particles in decay chain**
  - ***Powerful test of the model***

K. Desch, K. Kalinowski, GMP, M. Nojiri, G. Polesello, JHEP 2004



	M_1	M_2	μ	$\tan\beta$
input	99.1	192.7	352.4	10
LC_{500}	99.1 ± 0.2	192.7 ± 0.6	352.8 ± 8.9	10.3 ± 1.5
$LHC+LC_{500}$	99.1 ± 0.1	192.7 ± 0.3	352.4 ± 2.1	10.2 ± 0.6

- **strong improvement in parameter determination via interplay!**

NMSSM versus MSSM

- **SUSY scenario in the NMSSM: Higgs and light particle sector (neutralino / chargino) show no hints for model distinction**
- **measured at ILC (500 GeV):** $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_{1,2}^0}, \sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^0\tilde{\chi}_2^0)$
  - **Consistent within MSSM-analysis**
  - **Predictions:**

$m_{\tilde{\chi}_3^0} = [352, 555]$ GeV $\longrightarrow$ pure higgsino

$m_{\tilde{\chi}_4^0} = [386, 573]$ GeV $\longrightarrow$ larger gaugino comp.

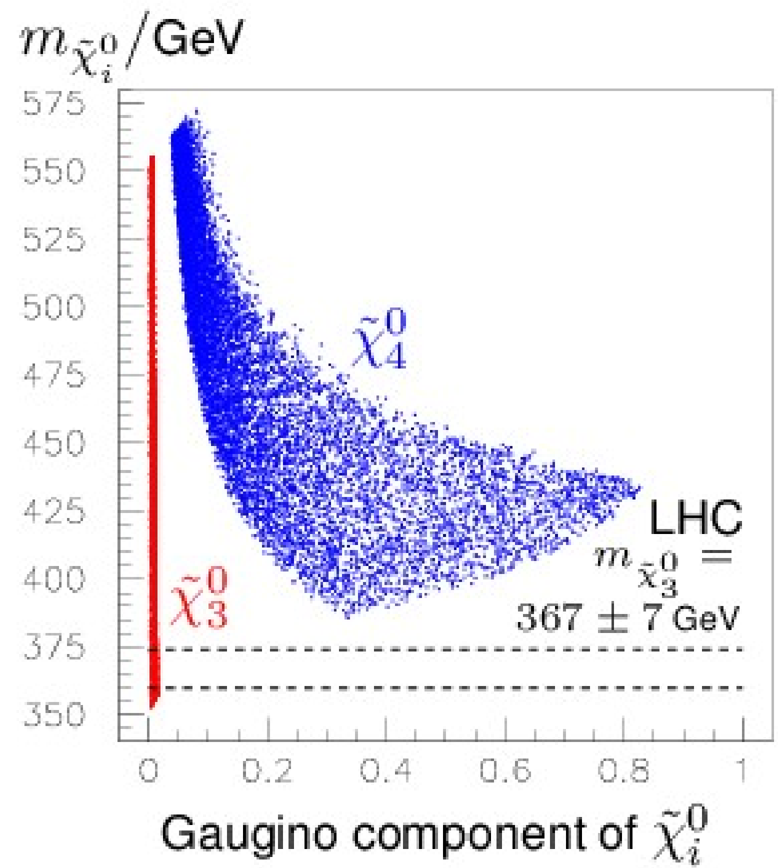
$m_{\tilde{\chi}_2^\pm} = [450, 600]$ GeV

$\Rightarrow$ $\tilde{\chi}_3^0$ not accessible at LHC

However: $\tilde{\chi}_3^0$ in underlying NMSSM scenario has large gaugino component

$\longrightarrow$ visible at LHC $\longrightarrow$ inconsistency

S Hesselbach, GMP, F Franke, H Fraas, 2005



- **Model inconsistency determined via LHC/ILC**

Tricky case with heavy sfermions

- Feature of, for instance, focuspoint - inspired scenarios
  - features: very heavy squarks, sleptons, heavy H, A but light SM-like h and light gluino and light charginos / neutralinos
  - challenging for the LHC……but is the ILC then the right machine ?
  - some analysis done at LHC, but within mSUGRA and still difficult
- Our approach: take a focuspoint-inspired scenario, but do not impose any assumption on the SUSY breaking mechanism and apply LHC / ILC analysis
- How well is it possible to
  - determine the underlying fundamental parameters?
  - predict masses of heavier states?

Chosen scenario

- **MSSM parameters:**

  M_1 = 60 GeV, M_2 = 121GeV, M_3 = 322 GeV, μ = 540 GeV, tanβ = 20

- **Resulting masses:**

$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{g}}$
117	552	59	117	545	550	416

m_h	$m_{H,A}$	$m_{H^\pm}$
119	1934	1935

→ **light gauginos/higgsinos, light gluino, light h but heavy H's, A**

$m_{\tilde{\nu}}$	$m_{\tilde{e}_R}$	$m_{\tilde{e}_L}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{q}_R}$	$m_{\tilde{q}_L}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$
1994	1996	1998	1930	1963	2002	2008	1093	1584

→ **heavy squarks and sleptons in the multi-TeV range**

What is expected that LHC could do ?

- **In principle: all squarks should be kinematically accessible**
  - **stops:** $BR(\tilde{t}_{1,2} \to \tilde{g} t) \sim 66\%$
    background t large, no new interesting channels open in decays
  - **other quarks: decay mainly via gluino and q, but reconstruction of heavy squarks at 2 TeV difficult**
  - **assume: mass resolution of squarks with uncertainty of ~50 GeV**
- **Light gluino: perfect for LHC (high rates, several decays)**

Mode	$\tilde{g} \to \tilde{\chi}^0_2 b\bar{b}$	$\tilde{g} \to \tilde{\chi}^-_1 q_u \bar{q}_d$	$\tilde{\chi}^+_1 \to \tilde{\chi}^0_1 \bar{q}_d q_u$	$\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^+ \ell^-$	$\tilde{t}_{1,2} \to \tilde{g} t$	$\tilde{\chi}^-_1 \to \tilde{\chi}^0_1 \ell^- \bar{\nu}_\ell$
BR	14.4%	10.8%	33.5%	3.0%	66%	11.0%

  - **clear dilepton edge from neutralino decay** $\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}) \sim 0.5$ GeV
  - **decay via chargino less promising (escaping ν, 3-body decay)**

What is expected at the ILC (500) ?

- **Kinematically only two light neutralinos and light chargino accessible**

  → **in reality: light neutralino production below 1 fb ....**

$\sigma(\tilde{\chi}_i\tilde{\chi}_j)$/fb	$\sqrt{s} = 350$ GeV		$\sqrt{s} = 500$ GeV		$\sqrt{s} = 800$ GeV		$\sqrt{s} = 1300$ GeV	
	$(-,+)$	$(+,-)$	$(-,+)$	$(+,-)$	$(-,+)$	$(+,-)$	$(-,+)$	$(+,-)$
$\tilde{\chi}^0_1\tilde{\chi}^0_2$	0.58	0.08	0.93	0.07	1.76	0.07	3.14	0.08
$\tilde{\chi}^0_1\tilde{\chi}^0_3$	–	–	–	–	0.24	0.27	0.13	0.28
$\tilde{\chi}^0_1\tilde{\chi}^0_4$	–	–	–	–	0.05	0.11	0.02	0.20
$\tilde{\chi}^0_2\tilde{\chi}^0_2$	0.06	0.05	0.49	0.05	2.06	0.05	4.91	0.07
$\tilde{\chi}^0_2\tilde{\chi}^0_3$	–	–	–	–	1.44	0.79	1.18	0.53
$\tilde{\chi}^0_2\tilde{\chi}^0_4$	–	–	–	–	0.23	0.09	0.55	0.13
$\tilde{\chi}^0_3\tilde{\chi}^0_3$	–	–	–	–	–	–	< 0.001	< 0.001
$\tilde{\chi}^0_3\tilde{\chi}^0_4$	–	–	–	–	–	–	38.53	24.97
$\tilde{\chi}^0_4\tilde{\chi}^0_4$	–	–	–	–	–	–	0.002	0.001
$\tilde{\chi}^+_1\tilde{\chi}^-_2$	–	–	–	–	1.36	0.88	1.05	0.68
$\tilde{\chi}^+_2\tilde{\chi}^-_2$	–	–	–	–	–	–	143.23	25.95

→ **light pure $\tilde{\chi}_1^0$~$\tilde{B}$, $\tilde{\chi}_2^0$~$\tilde{W}$: production suppressed by heavy $\tilde{e}_L$,$\tilde{e}_R$ exchange**

→ **heavier $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$~$\tilde{H}$ with specific CP-phases: rather high rates!**

→ **heavy pair $\tilde{\chi}_2^+\tilde{\chi}_2^-$~$\tilde{H}$: also high rates !**

Promising channel: light chargino

- So forget light neutralino production at ILC(500) for today ...
- Use only (light) chargino production, provides high rates
  - subsequent decays: $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}_e,\ \tilde{\chi}_1^0 \mu^- \bar{\nu}_\mu,\ \tilde{\chi}_1^0 d\bar{u}\ \ \tilde{\chi}_1^0 s\bar{c}$
- Due to very limited information, use two energies and polarized beams!

$\sqrt{s}$/GeV	(P_{e^-}, P_{e^+})	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$/fb	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)\, B_{slc}\, e_{slc}$/fb
350	$(-90\%, +60\%)$	6195.5	1062.5 ± 4.0
	$(+90\%, -60\%)$	85.0	14.6 ± 0.7
500	$(-90\%, +60\%)$	3041.5	521.6 ± 2.3
	$(+90\%, -60\%)$	40.3	6.9 ± 0.4

uncertainties: efficiency 50%, 1σ stat. uncertainties, $\Delta P / P = 0.5\%$

- to separate background WW: use semileptonic chargino decay channel, since mass constraints applicable

Mass measurements at LHC+ILC

- **Expected chargino mass resolution:**
  - in the continuum: up to 0.5 GeV
  - threshold scan:

$$m_{\tilde{\chi}_1^\pm} = 117.1 \pm 0.1\ \mathrm{GeV}$$

- **Neutralino mass resolution:**
  - use either energy $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell$ or invariant mass distribution $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 q_d \bar{q}_u$

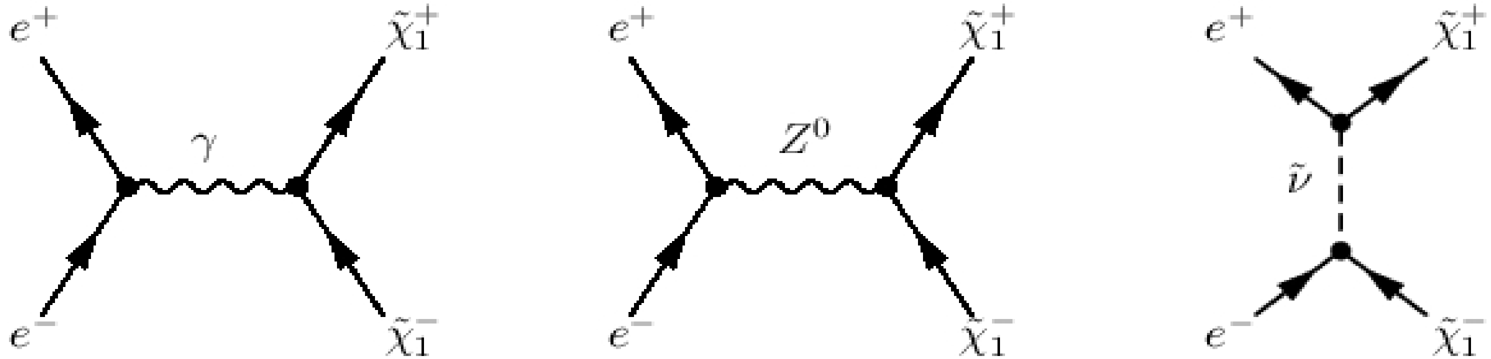
$$m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2\ \mathrm{GeV}$$

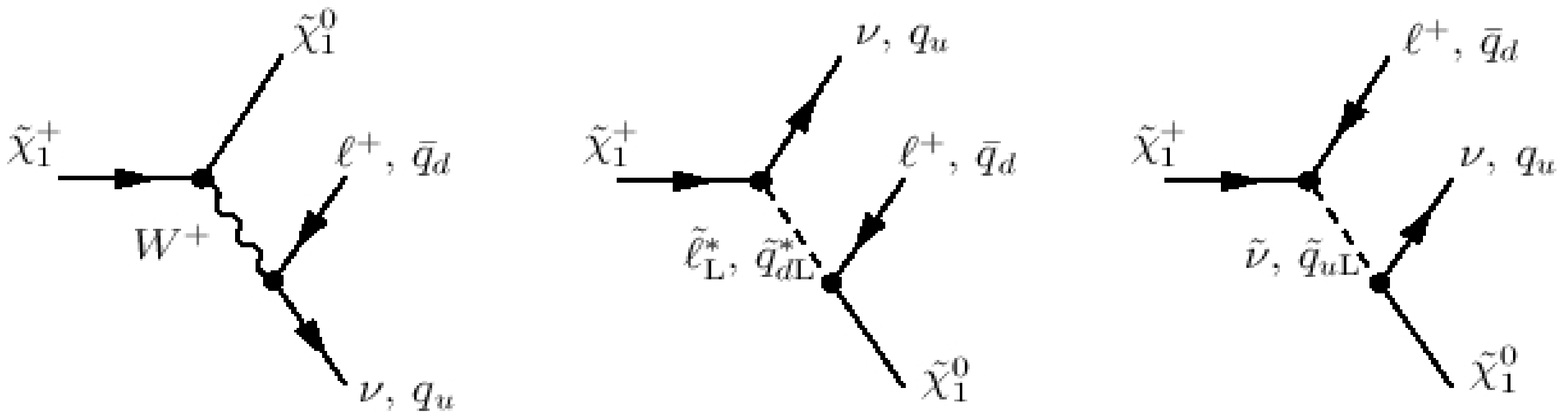
  - together with LHC mass information ($\delta(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) \sim 0.5\ \mathrm{GeV}$) :

$$m_{\tilde{\chi}_2^0} = 117.1 \pm 0.5\ \mathrm{GeV}$$

Determine fundamental parameters

- **On which parameters depend the process?**





→ **Parameters in the gaugino/higgsino: M_1, M_2, μ, tan β**

→ **But heavy virtual particles: $m_{\tilde{\nu}}$, $m_{\tilde{l}}$, $m_{\tilde{q}L}$, $m_{\tilde{q}R}$**

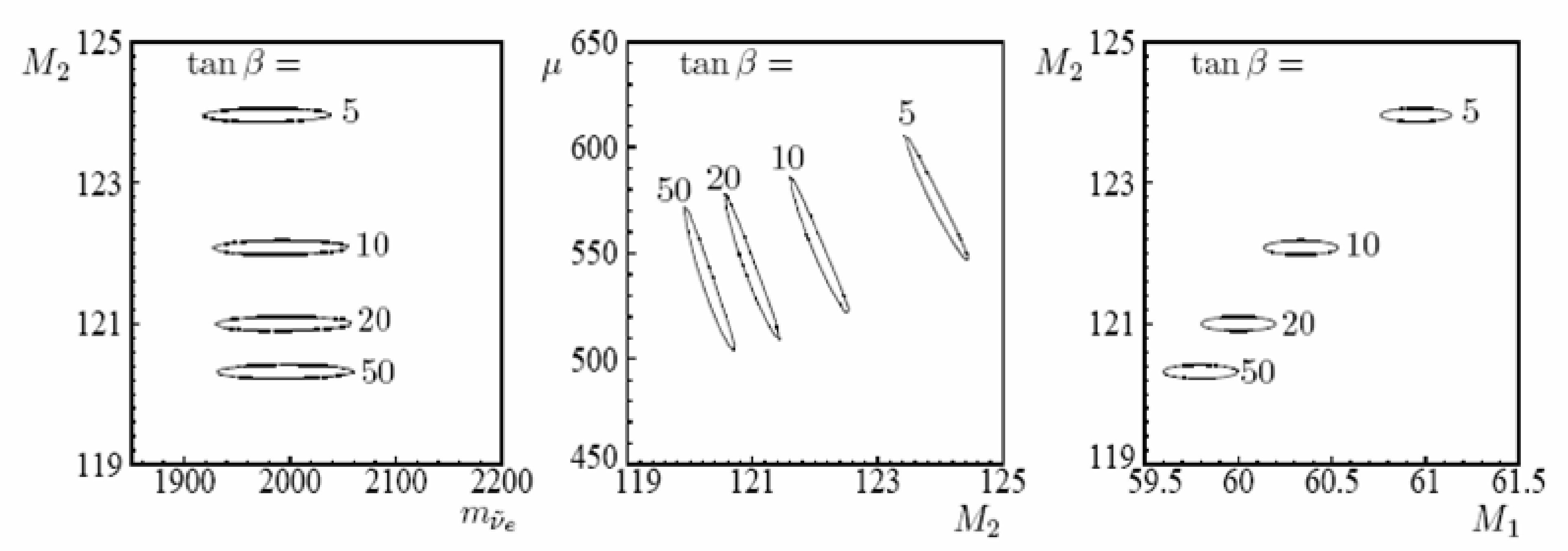
Strategy, 1st step

- Use measured masses and polarized cross sections
- Analytical conversion and derive / fit parameters
  - do χ^2 test for M_1, M_2, μ and $m_{\tilde{\nu}}$
  - BR not sensitive to heavy slepton masses
  - was necessary to fix tanβ (took several values) to get convergence of fit ! (strong correlations among parameters)
- Results:
  - contradiction to theory for tan β < 1.7
  - $$450 \le \mu \le 750 \text{ GeV}, \quad 1800 \le m_{\tilde{\nu}_e} \le 2210 \text{ GeV}$$
    $$59.4 \le M_1 \le 62.2 \text{ GeV}, \quad 118.7 \le M_2 \le 127.5 \text{ GeV},$$

M_1, M_2 good (~5%), but μ and $m_{\tilde{\nu}}$ rather weak (~16%) (limited info)

Strategy, 1st step

- **Masses and cross sections are not enough to constrain five parameter space due to strong correlations**
- **Allowed ranges migrate with change of tan β**



- **Need another observable to get better constraints**

Strategy, 2nd step -- spin correlations

- **Which further observable could be used?**
  - **Forward-backward asymmetry of the final lepton / quark**

    (angle between incoming beam and final lepton or quark)

- **Dependent on spin correlations of decaying chargino:**
  - **amplitude squared:** $e^- + e^+ \to \tilde{\chi}_1^+ + \tilde{\chi}_1^-$ **and** $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 + \ell^- + \bar{\nu}$

$$|T|^2 = |\Delta_{f_1}|^2 |\Delta_{f_2}|^2 \sum_{fin.sp.} \overbrace{(P^{\lambda_{f_1}\lambda_{f_2}} P^{*\lambda'_{f_1}\lambda'_{f_2}})}^{\text{spin-density matrix}} \times \overbrace{(Z_{\lambda_{f_1}} Z^*_{\lambda'_{f_1}})}^{\text{decay matrix}} \times \overbrace{(Z_{\lambda_{f_2}} Z^*_{\lambda'_{f_2}})}^{\text{decay matrix}}$$

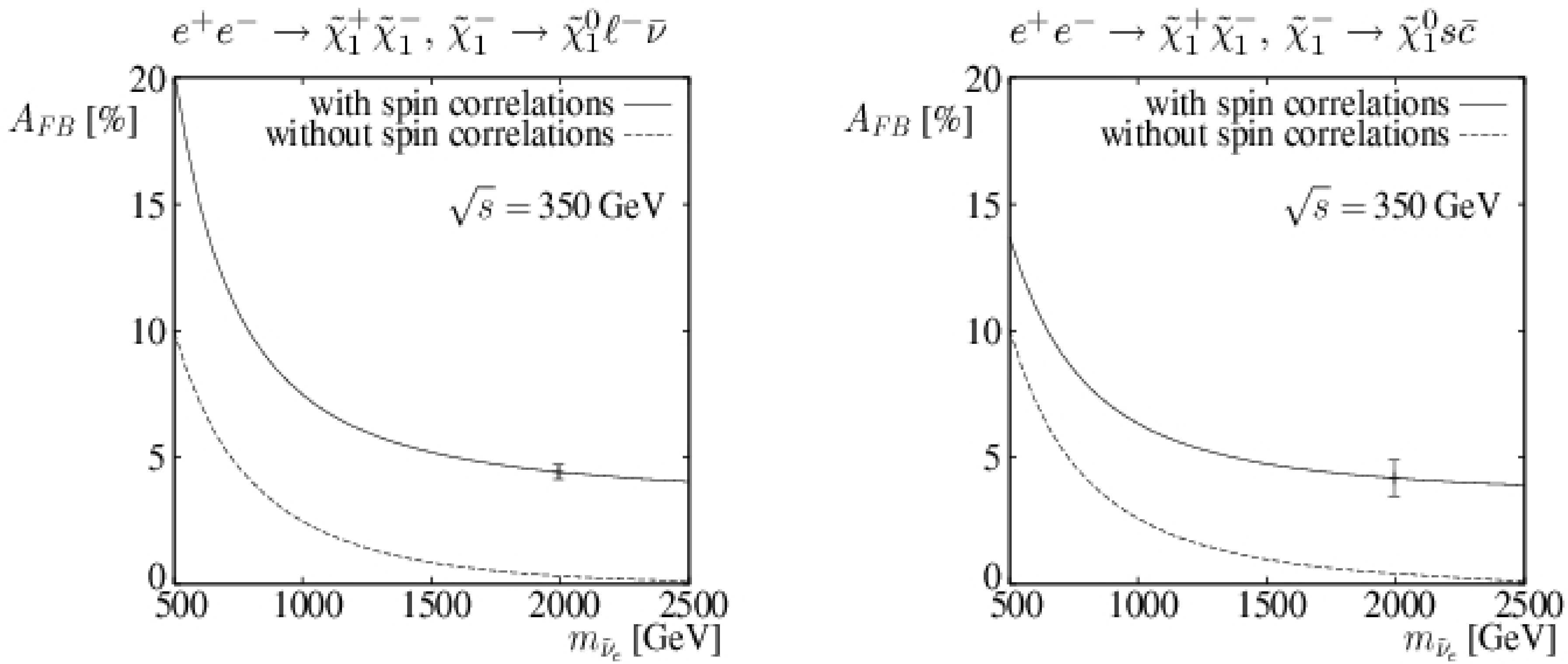
$$\longrightarrow \quad |T|^2 \sim P D_i D_j + \Sigma^P_a \Sigma^D_a D_j + \Sigma^P_b \Sigma^D_b D_i + \Sigma^P_{ab} \Sigma^D_a \Sigma^D_b$$

↓ **cross section** ↓ $\mathbf{A_{fb}(l^-)}$ ↓ $\mathbf{A_{fb}\ (l^+)}$ ↓ **not needed here**

'new contributions'

How important are spin correlations?

- **Impact of the 'new contributions' on A_{fb}:**



→ **strong influence of spin correlations: A_{fb} within [5%, 20%]**

→ **and also sensitivity to heavy sneutrino mass !**

Strategy, 2nd step -- leptonic A_{fb}

- use measured masses, cross sections and leptonic A_{fb}
- since decay also depends on unknown left slepton mass, use SU(2) relation:

$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_e} + m^2_Z \cos(2\beta)(-1 + \sin^2\theta_W)$$

- include also statistical and polarization uncertainty for A_{fb} :

$\sqrt{s}$/GeV	(P_{e^-}, P_{e^+})	$A_{FB}(\ell^-)/\%$	$A_{FB}(\bar{c})/\%$
350	$(-90\%, +60\%)$	4.42 ± 0.29	4.18 ± 0.74
	$(+90\%, -60\%)$	–	–
500	$(-90\%, +60\%)$	4.62 ± 0.41	4.48 ± 1.05
	$(+90\%, -60\%)$	–	–

- use only (- +) values due to statistical uncertainty

Strategy, 2nd step -- results

- **Results:**
  - do χ^2 test: $$\chi^2_{A_{\rm FB}} = \chi^2 + \sum_i \left(\frac{A_{\rm FB}(i) - A_{\rm FB}(i)^{\rm th}}{\Delta A_{\rm FB}(i)}\right)^2$$
  - **not necessary to fix tanβ any more !!!**
  - $$59.7 \le M_1 \le 60.35 \text{ GeV}, \quad 119.9 \le M_2 \le 122.0 \text{ GeV},$$ $$500 \le \mu \le 610 \text{ GeV}, \quad 14 \le \tan\beta \le 31$$ $$1900 \le m_{\tilde{\nu}_e} \le 2100 \text{ GeV}$$

- **Improvements:**
  - constraints for multi-TeV sneutrino mass by factor 2, up to 5% accuracy !
  - accuracy of M_1, M_2 by factor 5
  - accuracy of μ by factor 1.6 and tan β now included!

Strategy, 2nd step -- mass predictions

- **Due to rather precise parameter determination:**
  - use these allowed parameters and predict, for instance, the possible ranges for the masses of the heavier chargino and neutralino states
  - $$506 < m_{\tilde{\chi}^0_3} < 615\,GeV$$
    $$512 < m_{\tilde{\chi}^0_4} < 619\,GeV$$
    $$514 < m_{\tilde{\chi}^\pm_2} < 621\,GeV$$
  - Obviously 1.3 TeV as 2nd ILC energy stage would be sufficient
- **Rather precise parameter determination important and possible at 500 GeV (even in such tricky scenarios with limited information only)**
  - important input for future upgrade strategies

Strategy, 3rd step -- also hadronic A_{fb}

- Redo analysis without assuming SU(2) relation between slepton masses
  - squark masses constrained from LHC
  - strategy as before: use masses, cross sections, leptonic A_{fb}
- Include also A_{fb} from hadronic distribution:
  - charm identification needed : assume c-tag efficiency of 40% for selection efficiency of 50%
- Results (without using SU(2) relation) :

$$59.45 \le M_1 \le 60.80 \text{ GeV}, \quad 118.6 \le M_2 \le 124.2 \text{ GeV}, \quad 420 \le \mu \le 770 \text{ GeV}$$
$$1900 \le m_{\tilde{\nu}_e} \le 2120 \text{ GeV}, \quad m_{\tilde{e}_L} \ge 1500 \text{ GeV}, \quad 11 \le \tan\beta \le 60.$$

  - again precise parameter determination and constraints for msn
  - no upper bound for msel, but consistent with SU(2) relation !

Conclusions

- Tricky case of SUSY: multi-TeV sleptons and squarks
  - ➔ only few particles kinematically accessible at ILC with 500 GeV
- Study done without assuming a SUSY breaking scheme!
- Forward-backward asymmetries of the final leptons/quarks: sensitivity to heavy virtual particles
  - ➔ get tight constraints even for masses in the multi-TeV range!
- Rather accurate parameter determination possible with A_{fb}
  - ➔ allows to predict masses of heavier charginos/neutralinos
- LHC / ILC(500): neither of these colliders alone can resolve such a challenging scenario with multi-TeV squarks and sleptons --> both LHC and ILC required !