

LHC/ILC analysis for SUSY scenarios with heavy sfermions

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

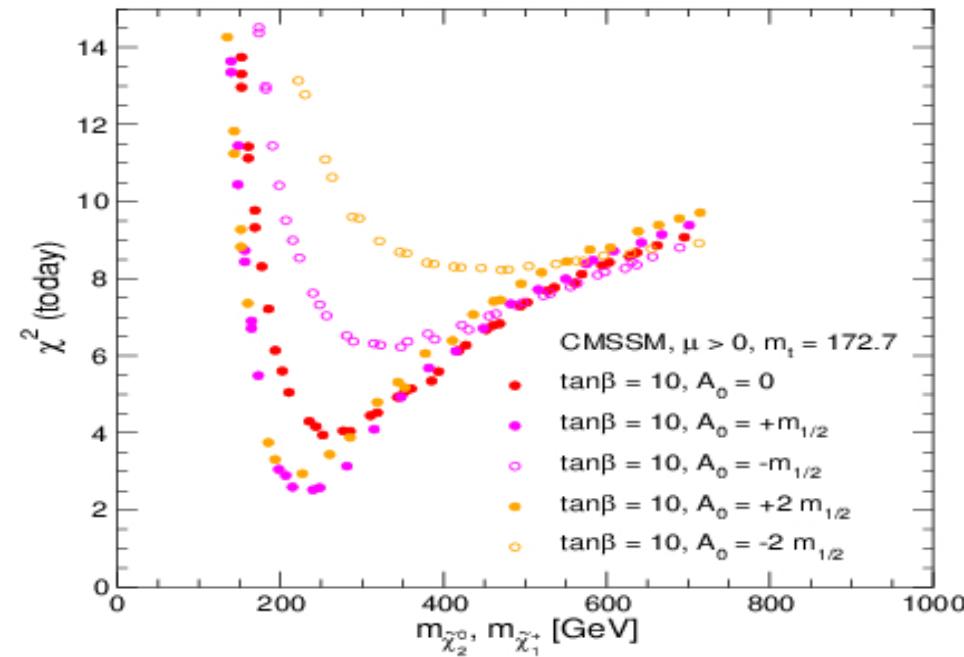
Outline

- Introduction: 'warm-up'
- 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
- 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 !

Ellis, Heinemeyer, Olive, Weiglein '05



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:**

$M_1 = 60 \text{ GeV}$, $M_2 = 121 \text{ GeV}$, $M_3 = 322 \text{ GeV}$, $\mu = 540 \text{ GeV}$, $\tan\beta = 20$

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

- clear dilepton edge from neutralino decay $\delta(m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}) \sim 0.5$ 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

$\sigma(\tilde{\chi}_i \tilde{\chi}_j)/\text{fb}$	$\sqrt{s} = 350 \text{ GeV}$		$\sqrt{s} = 500 \text{ GeV}$		$\sqrt{s} = 800 \text{ GeV}$		$\sqrt{s} = 1300 \text{ GeV}$	
	(-, +)	(+, -)	(-, +)	(+, -)	(-, +)	(+, -)	(-, +)	(+, -)
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	0.58	0.08	0.93	0.07	1.76	0.07	3.14	0.08
$\tilde{\chi}_1^0 \tilde{\chi}_3^0$	—	—	—	—	0.24	0.27	0.13	0.28
$\tilde{\chi}_1^0 \tilde{\chi}_4^0$	—	—	—	—	0.05	0.11	0.02	0.20
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.06	0.05	0.49	0.05	2.06	0.05	4.91	0.07
$\tilde{\chi}_2^0 \tilde{\chi}_3^0$	—	—	—	—	1.44	0.79	1.18	0.53
$\tilde{\chi}_2^0 \tilde{\chi}_4^0$	—	—	—	—	0.23	0.09	0.55	0.13
$\tilde{\chi}_3^0 \tilde{\chi}_3^0$	—	—	—	—	—	—	< 0.001	< 0.001
$\tilde{\chi}_3^0 \tilde{\chi}_4^0$	—	—	—	—	—	—	38.53	24.97
$\tilde{\chi}_4^0 \tilde{\chi}_4^0$	—	—	—	—	—	—	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 $\tilde{\chi}_1^0 \sim \tilde{B}$, $\tilde{\chi}_2^0 \sim \tilde{W}$: production suppressed by heavy \tilde{e}_L, \tilde{e}_R exchange
- heavier $\tilde{\chi}_3^0, \tilde{\chi}_4^0 \sim \tilde{H}$ with specific CP-phases: rather high rates!
- heavy pair $\tilde{\chi}_2^+ \tilde{\chi}_2^- \sim \tilde{H}$: 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: $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 e^- \bar{\nu}_e$, $\tilde{\chi}_1^0 \mu^- \bar{\nu}_\mu$, $\tilde{\chi}_1^0 d \bar{u}$ $\tilde{\chi}_1^0 s \bar{c}$
- Due to very limited information, use two energies and polarized beams!

\sqrt{s}/GeV	(P_{e^-}, P_{e^+})	$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)/\text{fb}$	$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-) B_{slc} e_{slc}/\text{fb}$
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:

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

- **Neutralino mass resolution:**

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

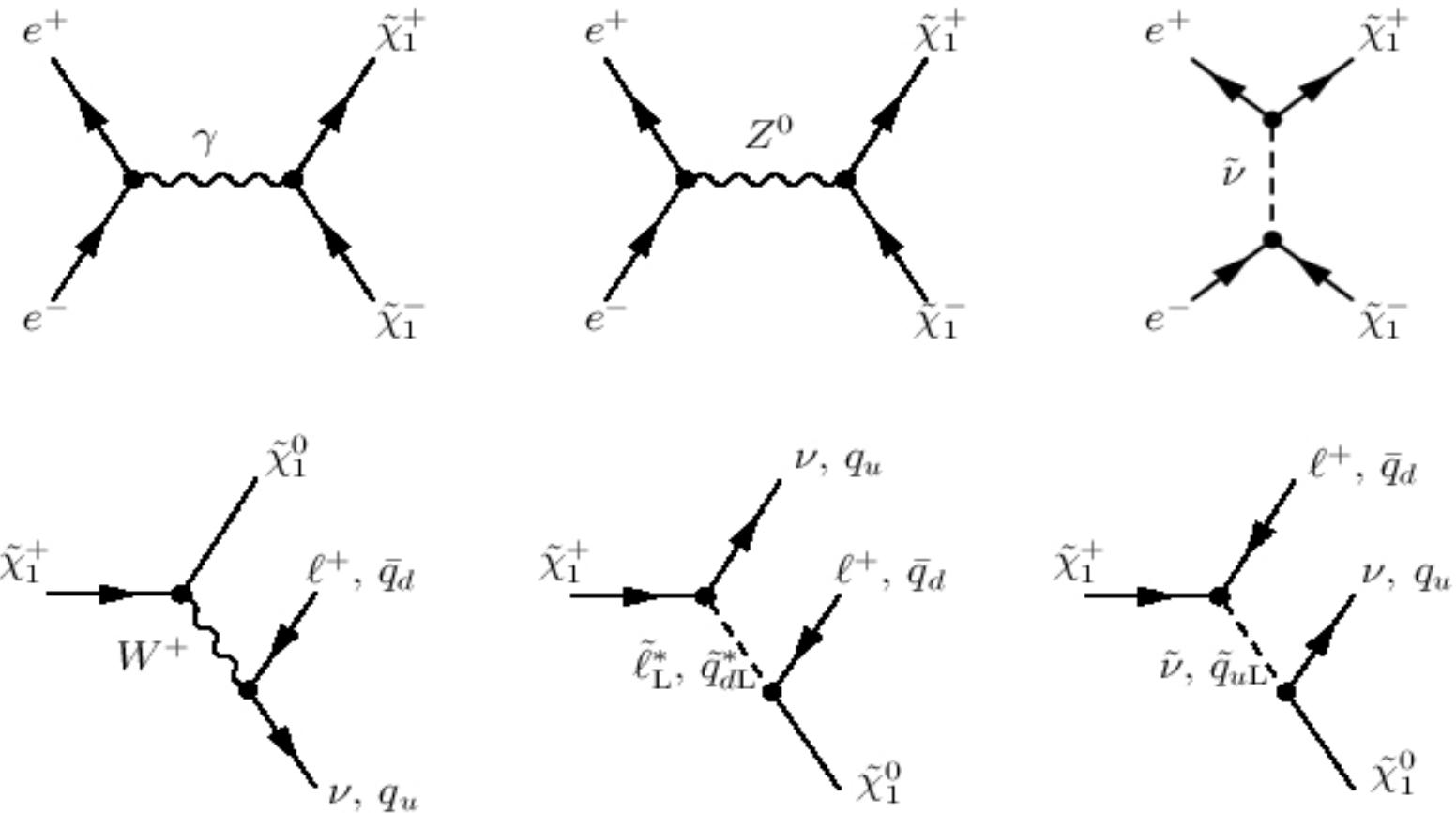
$$m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2 \text{ GeV}$$

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

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

Determine fundamental parameters

- On which parameters depend the process?



- Parameters in the gaugino/higgsino: $M_1, M_2, \mu, \tan \beta$
- But heavy virtual particles: $\tilde{m}_\nu, \tilde{m}_l, \tilde{m}_{qL}, \tilde{m}_{qR}$

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 $\tan\beta$ (took several values) to get convergence of fit ! (strong correlations among parameters)

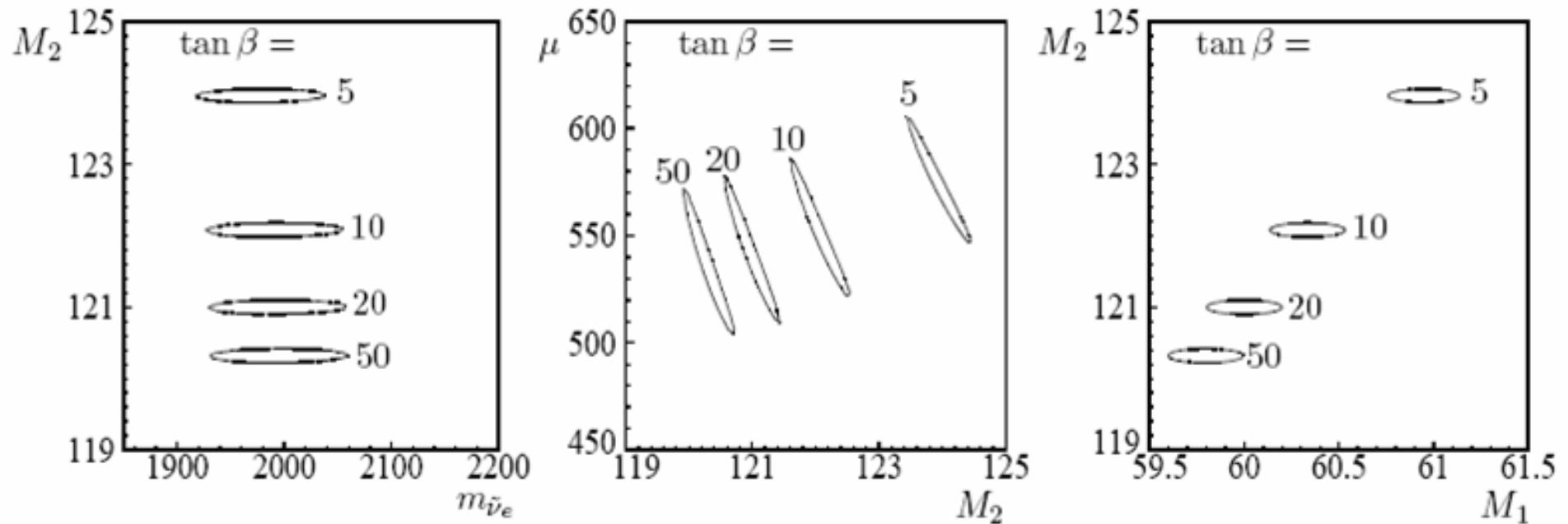
● Results:

- contradiction to theory for $\tan \beta < 1.7$
- $450 \leq \mu \leq 750 \text{ GeV}, \quad 1800 \leq m_{\tilde{\nu}_e} \leq 2210 \text{ GeV}$
 $59.4 \leq M_1 \leq 62.2 \text{ GeV}, \quad 118.7 \leq M_2 \leq 127.5 \text{ GeV},$

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 $\tan \beta$



- 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: $e^- + e^+ \rightarrow \tilde{\chi}_1^+ + \tilde{\chi}_1^-$ and $\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0 + \ell^- + \bar{\nu}$

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

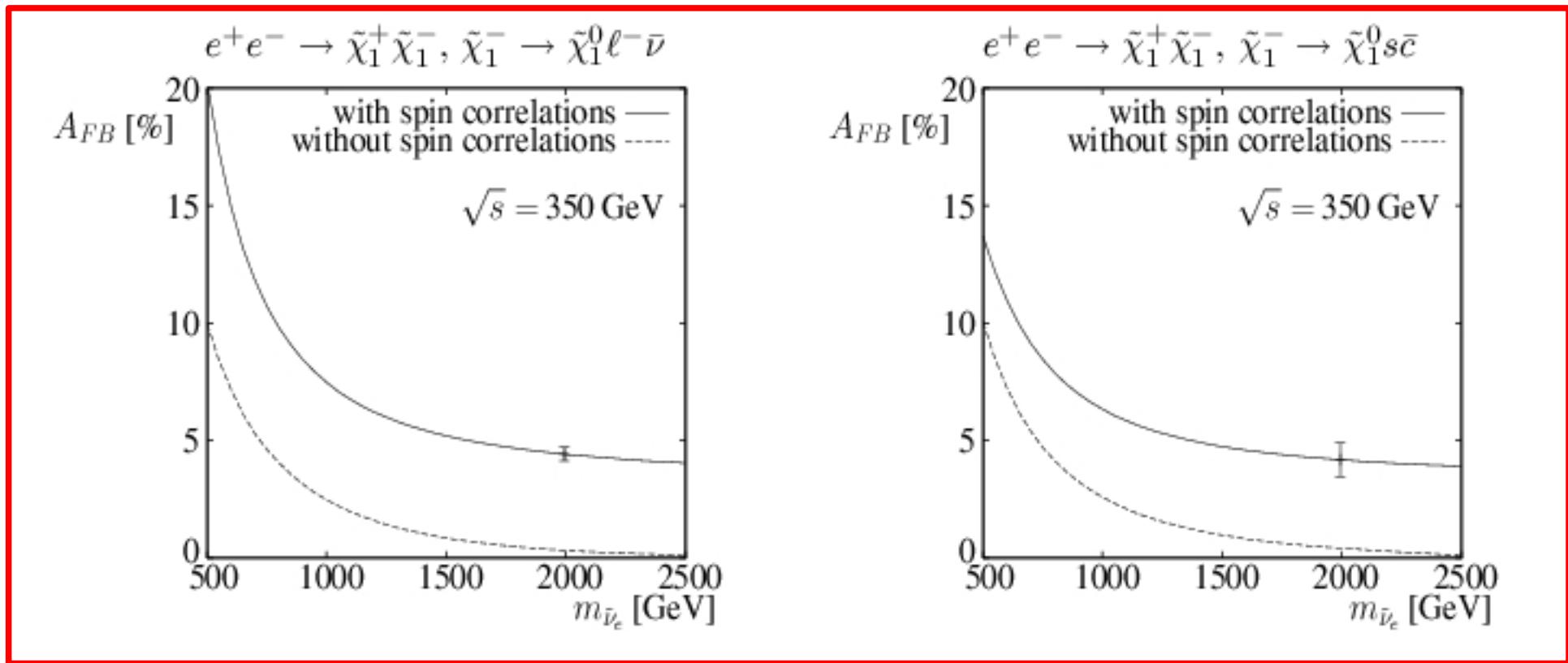
→ $|T|^2 \sim PD_i D_j + \Sigma_a^P \Sigma_a^D D_j + \Sigma_b^P \Sigma_b^D D_i + \Sigma_{ab}^P \Sigma_a^D \Sigma_b^D$

↓ ↓ ↓ ↓

cross section $A_{fb}(\Gamma)$ $A_{fb}(\Gamma^+)$ 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:

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

- 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:

$$\chi_{A_{\text{FB}}}^2 = \chi^2 + \sum_i \left(\frac{A_{\text{FB}}(i) - A_{\text{FB}}(i)^{\text{th}}}{\Delta A_{\text{FB}}(i)} \right)^2$$

→ **not necessary to fix $\tan\beta$ any more !!!**

→ $59.7 \leq M_1 \leq 60.35 \text{ GeV}, \quad 119.9 \leq M_2 \leq 122.0 \text{ GeV},$
 $500 \leq \mu \leq 610 \text{ GeV}, \quad 14 \leq \tan\beta \leq 31$
 $1900 \leq m_{\tilde{\nu}_e} \leq 2100 \text{ GeV}$

• **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 $\tan\beta$ 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**
 - - $506 < m_{\tilde{\chi}_3^0} < 615 \text{ GeV}$
 - $512 < m_{\tilde{\chi}_4^0} < 619 \text{ GeV}$
 - $514 < m_{\tilde{\chi}_2^\pm} < 621 \text{ GeV}$
 - 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) :

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

 - 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 !