Combined LHC/ILC analysis -- case of heavy sfermions

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Outline

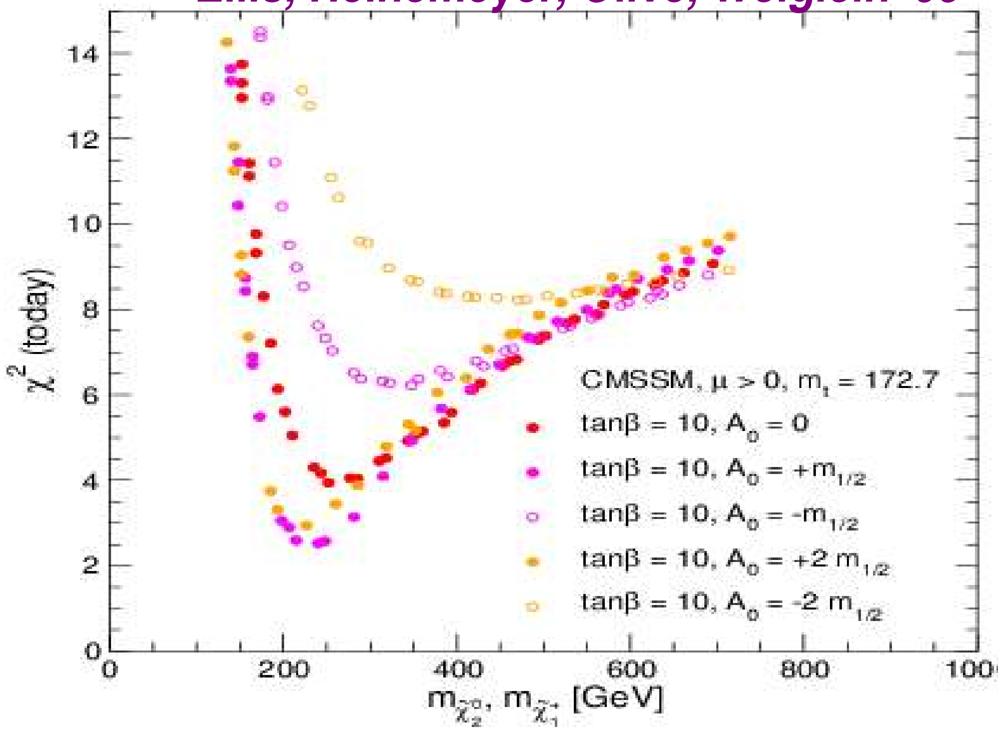
- Introduction: 'warm-up'
- Case study: chosen scenario with heavy sfermions
- Numerical results: expectations for LHC
- Numerical results: ILC strategy and LHC/ILC interplay
- Conclusions

Supersymmetry

- **One of the most promising candidates for physics beyond the Standard Model (SM) is Supersymmetry (SUSY)**
  - **high predictive power, solves hierarchy, unification, dark matter problem etc.**
  - **every SM particle gets a SUSY partner with the same quantum numbers**
  - **all these assumptions have to be checked experimentally model-independently!**

Ellis, Heinemeyer, Olive, Weiglein '05

- **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**



Warm-up: SUSY challenge

- Problem: number of new parameters
  - even in the MSSM 105 !
- We have only
  - constraints on parameters from e,n, Hg, etc. dipole moments
  - exclusion bounds from LEP and Tevatron
  - constraints from low-energy experiments $b \rightarrow s\gamma$, g_μ-2
  - constraints from dark matter searches
- 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 !

Tricky case with heavy sfermions

- Feature of, for instance, Split-SUSY or 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 in that case the right machine ?
  - some analysis done at LHC, but within mSUGRA and still very difficult
- Our approach: take a focuspoint-inspired scenario, but do not impose any assumption on the SUSY breaking mechanism and apply LHC / ILC analysis
  - implies a rather large model-independence
- How well is it possible to
  - determine the underlying fundamental parameters?
  - check some SUSY implications?
  - predict masses of heavier states? (-> input for the second stage of the ILC?)

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 from 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 about 50 GeV

    (but that's not crucial for our further procedure)
- **Production of light gluino: perfect for LHC** (high rates, several decays)

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

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

$\sigma(\tilde{\chi}_i\tilde{\chi}_j)/\text{fb}$	$\sqrt{s} = 350$ GeV		$\sqrt{s} = 500$ GeV		$\sqrt{s} = 800$ GeV		$\sqrt{s} = 1300$ 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:** $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}_e,\ \tilde{\chi}_1^0 \mu^- \bar{\nu}_\mu,\ \tilde{\chi}_1^0 d\bar{u}$, $\tilde{\chi}_1^0 s\bar{c}$
- **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:

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

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

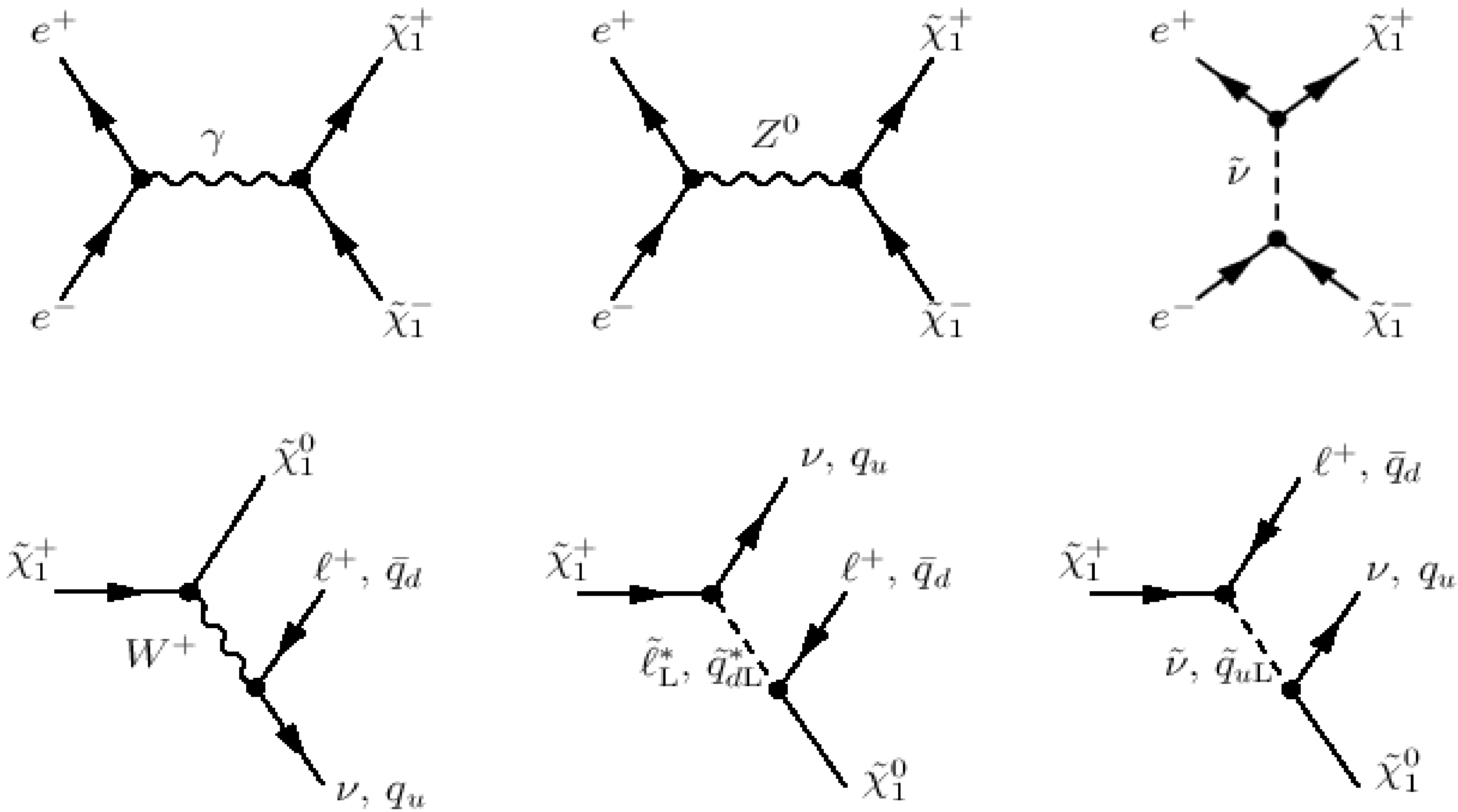
$$m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2 \text{ GeV}$$

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

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

Strategy to determine fundamental parameters

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



→ **Parameters in the gaugino/higgsino: M_1, M_2, μ, $\tan\beta$**

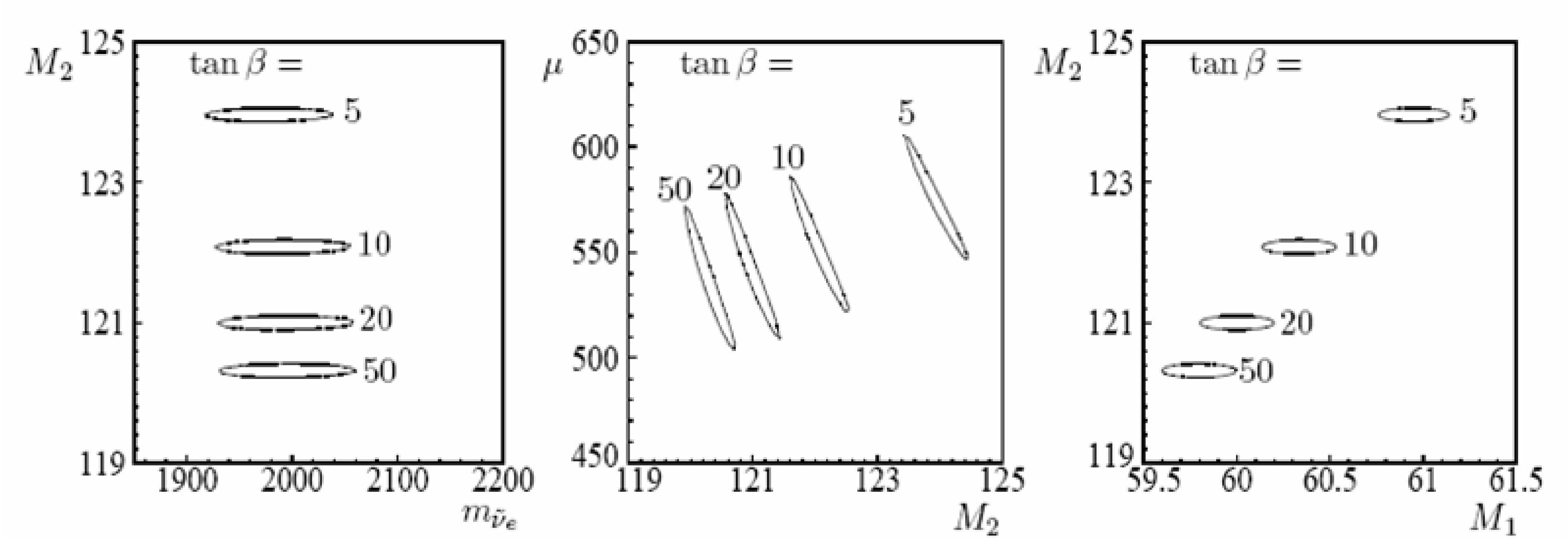
→ **But heavy virtual particles: $m_{\tilde{\nu}}$, $m_{\tilde{l}}$, $m_{\tilde{q}L}$, $m_{\tilde{q}R}$**

Strategy, 1st step

- Use measured masses and polarized cross sections
- Convert them analytically and derive / fit the parameters within uncertainties
  - 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 ! (because of strong correlations among parameters ...)
- Results:
  - contradiction to theory for $\tan\beta < 1.7$
  - $$59.4 \leq M_1 \leq 62.2 \text{ GeV}, \quad 118.7 \leq M_2 \leq 127.5 \text{ GeV},$$ $$450 \leq \mu \leq 750 \text{ GeV}, \quad 1800 \leq m_{\tilde{\nu}_e} \leq 2210 \text{ GeV}$$
  - M_1, M_2 good (~5%), but μ and $m_{\tilde{\nu}}$ rather weak (~16%) due to limited information

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

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

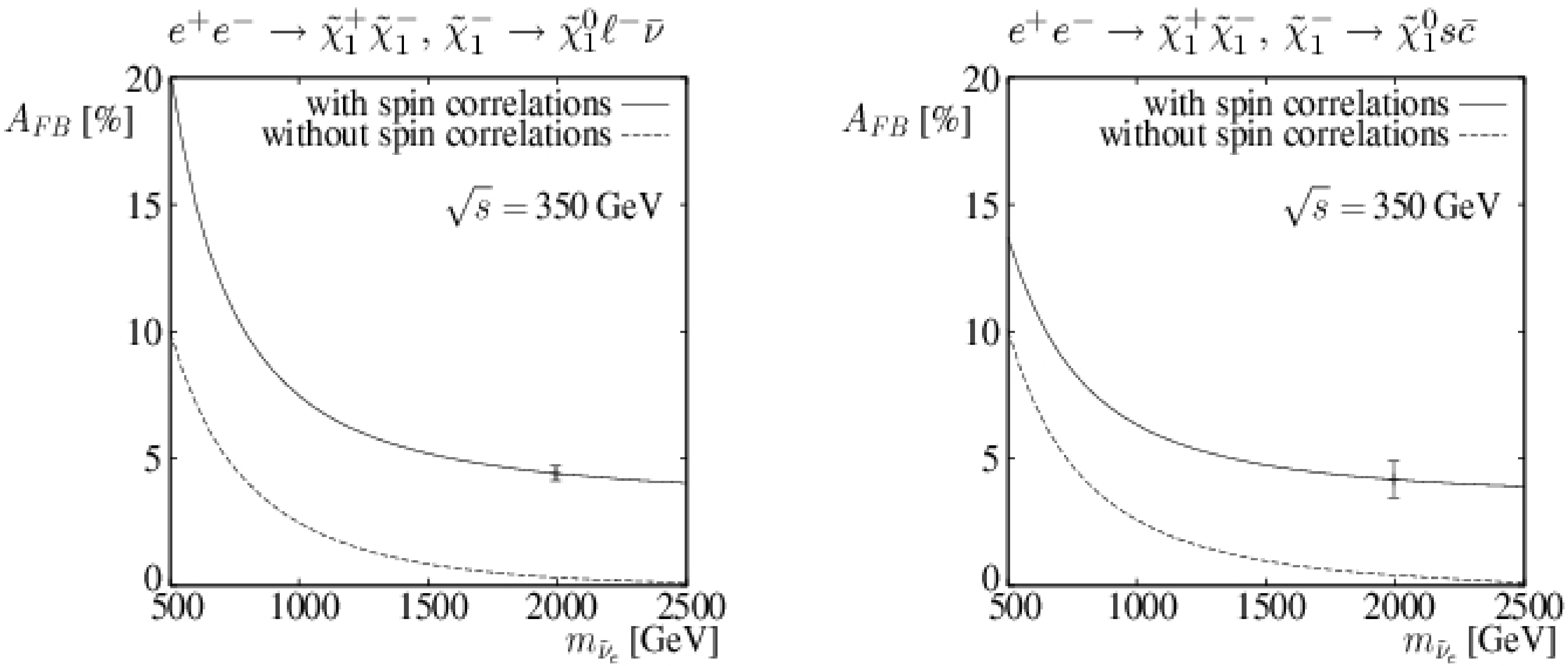
$$\longrightarrow \quad |T|^2 \sim P D_i D_j + \Sigma_a^P \Sigma_a^D D_j + \Sigma_b^P \Sigma_b^D D_i + \Sigma_{ab}^P \Sigma_a^D \Sigma_b^D$$

cross section | **$A_{fb}(l^-)$** | **$A_{fb}(l^+)$** | **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 (in the MSSM without assumption on the SUSY breaking scheme)
  - $$506 < m_{\tilde{\chi}^0_3} < 615\,GeV$$
    $$512 < m_{\tilde{\chi}^0_4} < 619\,GeV$$
    $$514 < m_{\tilde{\chi}^\pm_2} < 621\,GeV$$
  - Obviously 1 TeV as 2nd ILC energy stage would not be sufficient ...
    but 1.1-1.3~TeV !!!
- **Rather precise parameter determination important and possible at 500 GeV (even in such tricky scenarios with limited information only)**
  - enables to provide important input for future upgrade strategies ...

Strategy, 3[rd] 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 sneutrino mass
  - no upper bound for selectron mass, but consistent with SU(2) relation !

Conclusions

- Tricky case of SUSY: multi-TeV sleptons and squarks
  - only few particles kinematically accessible at the ILC with 500 GeV
- Study done even without assuming a specific 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!
- Also rather accurate parameter determination possible with A_{fb}
  - allows to predict masses of heavier charginos/neutralinos
  - important input to outline needed energy scale for the 2^{nd} stage of the ILC .... !

- LHC / ILC(500): neither of these colliders alone can provide sufficient information to solve such a challenging scenario with multi-TeV squarks and sleptons --> LHC / ILC(500) interplay crucial !