Combined LHC/ILC analysis -- case of heavy sfermions

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Outline

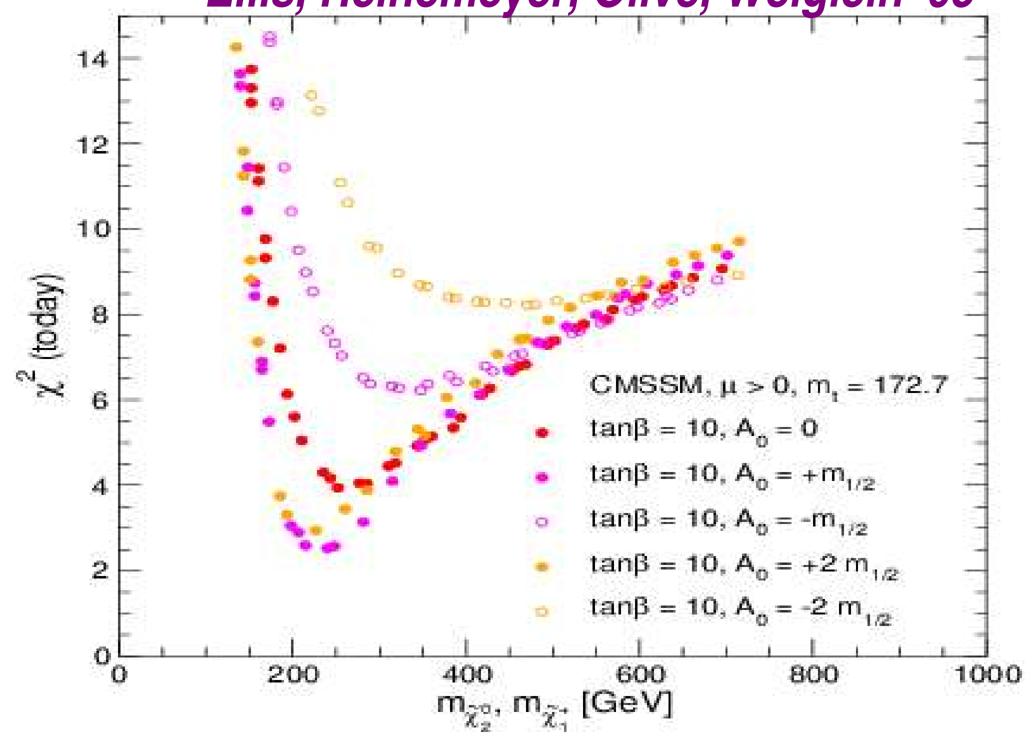
- Introduction: SUSY parameter determination and LHC/ILC interplay
- Case study: chosen scenario with heavy sfermions
- Numerical results: expectations for LHC
- Numerical results: ILC strategy and LHC/ILC interplay
- Conclusions

Supersymmetry

- **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

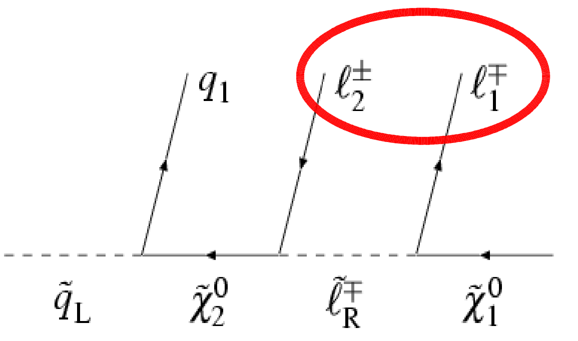


SUSY parameter determination

- 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 $b \to s\gamma$, 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 !

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 $m_{\tilde{\chi}} < 250$ GeV
    b) via cascade decay chains

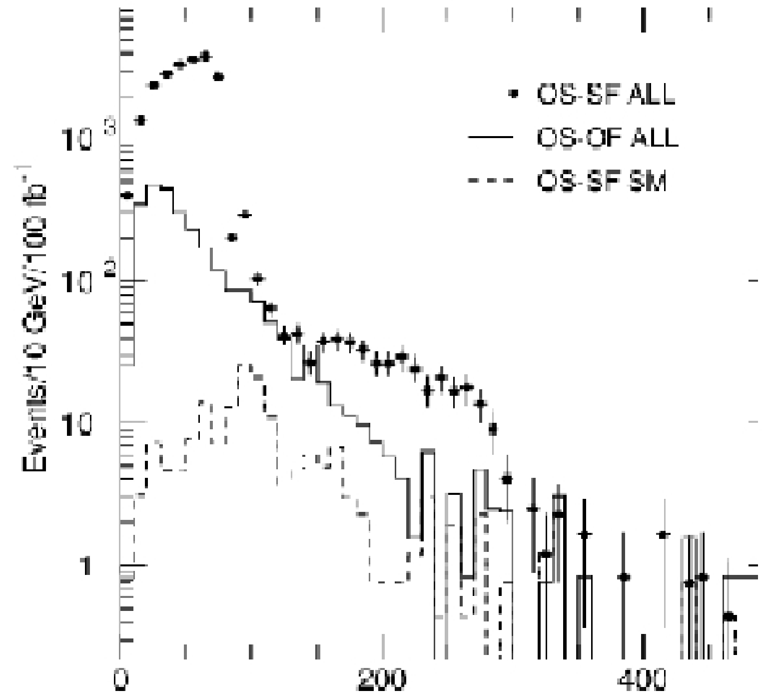


  - Parameter determinations: in specific SUSY breaking models
- **At the ILC:**
  - direct production of all kind of SUSY particles up to kinematical limit $\sqrt{s}/2$
  - indirect mass bounds due to high precision
  - precise model-independent parameter determination
- **Particularly promising field 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 and distinction between e.g. MSSM vs. NMSSM model!



	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 LHC/ILC interplay!

NMSSM versus MSSM

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

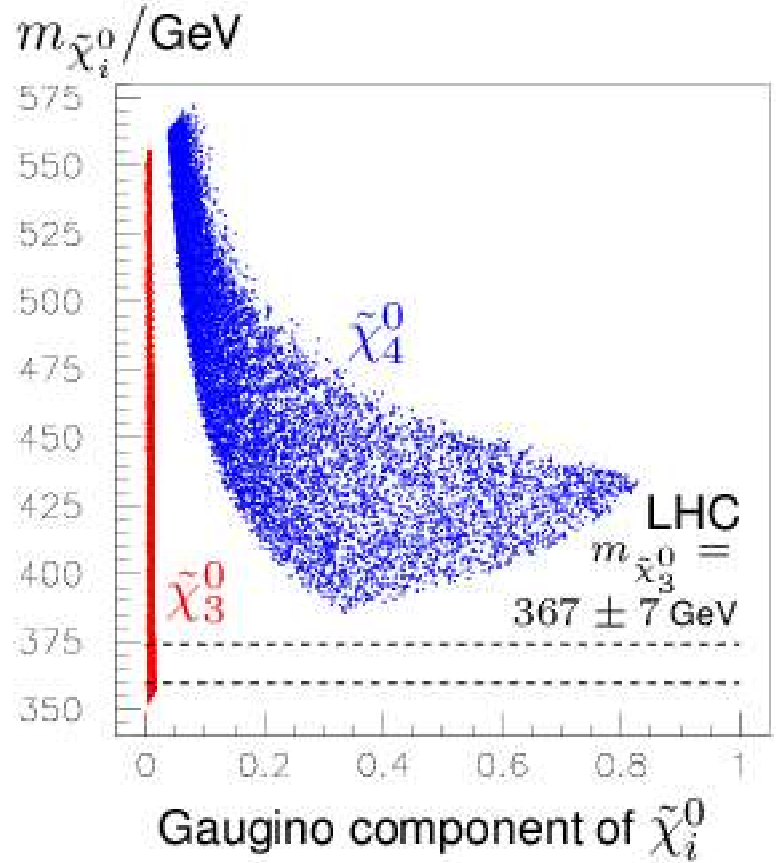
  → **Consistent within MSSM-analysis:**

  M1, M2, μ, tanβ

  → **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

- **Model inconsistency determined via LHC/ILC**
  - motivation for further analysis

Today: heavy sfermions

- **Tricky case: e.g. 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**
  - to impose even more difficult conditions: only use the ILC(500) !

- **How well is it possible to**
  - determine the underlying fundamental parameters
  - check some SUSY implications

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 about 50 GeV

    (but that's not important for our further procedure)
- Production of light gluino: perfect for LHC
  - excellent for LHC: high rates and interesting 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%

  - dilepton edge clearly visible:

$$\delta(m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}) \sim 0.5 \text{ GeV}$$

What is expected at the ILC (500) ?

- Kinematically only two light neutralinos and light chargino accessible
  - in reality: neutralino production below 1 fb .... not impossible, but not used today
  - only chargino production has 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^+})	$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)$/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, $\Delta P / P = 0.5\%$
  - background WW: in semileptonic 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 $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 q_d \bar{q}_u$

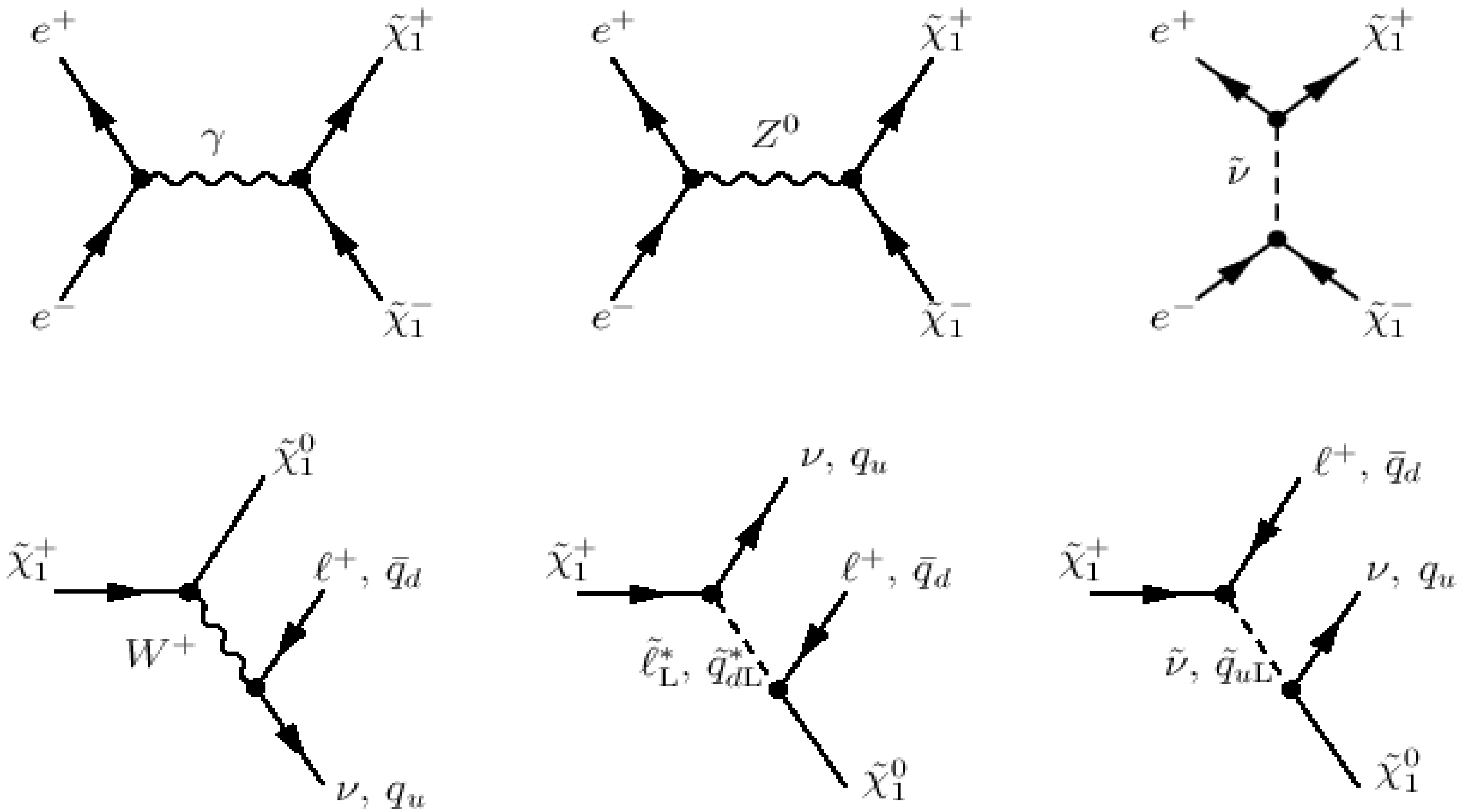
$$m_{\tilde{\chi}_1^0} = 59.2 \pm 0.2 \text{ GeV}$$

  - 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 tanβ (took several values) to get convergence of fit !
- Results:
  - contradiction to theory for tan β < 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_ν rather weak (~16%) due to limited information

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

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

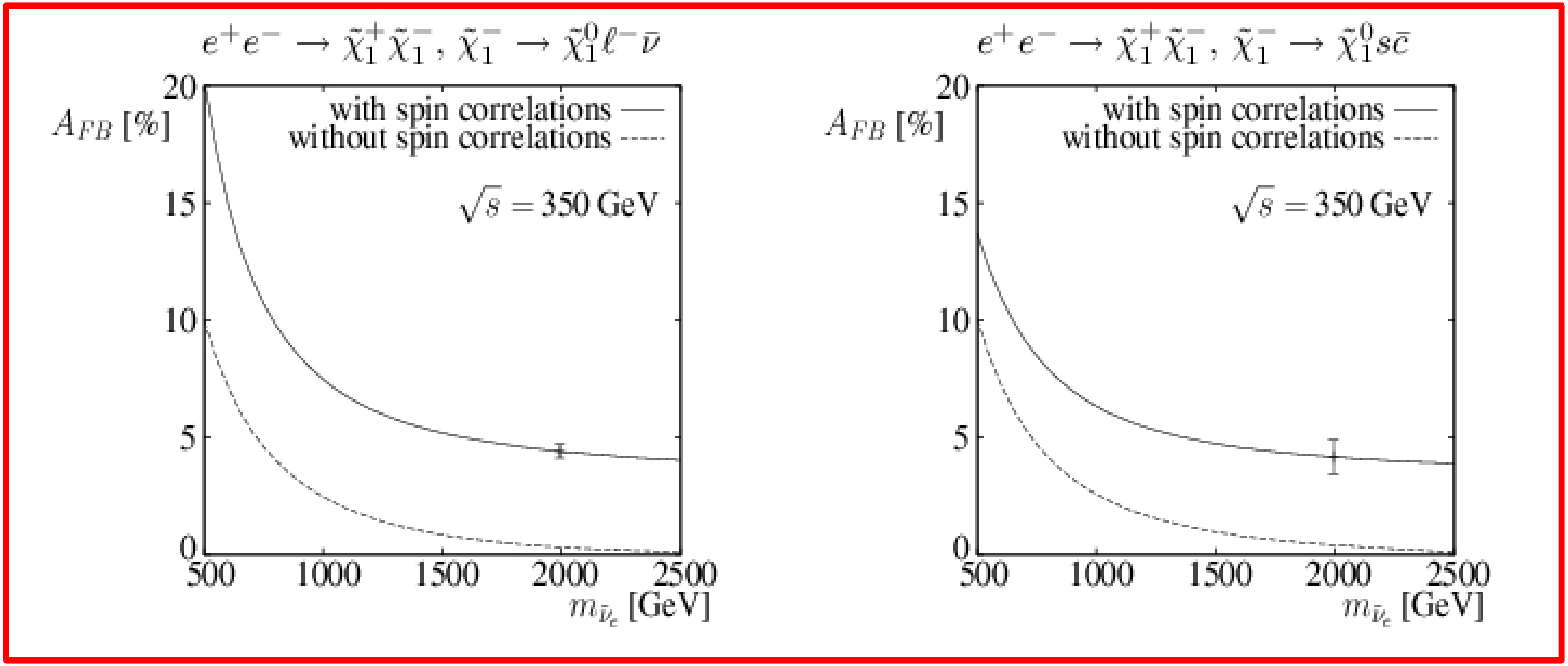
$$\longrightarrow \quad |T|^2 \sim P D_i D_j + \Sigma_a^P \Sigma_a^D D_j + \Sigma_b^P \Sigma_b^D D_i + \Sigma_{ab}^P \Sigma_a^D \Sigma_b^D$$

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%]**

→ **still sensitivity to heavy sneutrino mass !**

Strategy, 2nd step -- with 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 for M_1, M_2, μ , m_ν and $\tan\beta$
  - **not necessary to fix $\tan\beta$**
  - $$59.7 \le M_1 \le 60.35 \text{ GeV}, \quad 119.9 \le M_2 \le 122.0 \text{ GeV},$$
    $$500 \le \mu \le 610 \text{ GeV}, \quad 14 \le \tan\beta \le 31$$
    $$1900 \le m_{\tilde{\nu}_e} \le 2100 \text{ GeV}$$

- **Improvements:**
  - **prediction of sneutrino mass by factor 2**
  - **accuracy of M_1, M_2 by factor 5**
  - **accuracy of μ by factor 1.6 and $\tan\beta$ now included!**

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

- **Include also A_{fb} from hadronic distribution:**
  - no SU(2) assumption necessary, since squark masses known from LHC!
  - charm identification needed : assume c-tag efficiency of 40% for selection efficiency of 50%

- **Results:**

$$59.45 \le M_1 \le 60.80 \text{ GeV}, \quad 118.6 \le M_2 \le 124.2 \text{ GeV}, \quad 420 \le \mu \le 770 \text{ GeV}$$

$$1900 \le m_{\tilde{\nu}_e} \le 2120 \text{ GeV}, \quad m_{\tilde{e}_L} \ge 1500 \text{ GeV}, \quad 11 \le \tan\beta \le 60.$$

  - most significant improvement: factor 2 for sneutrino mass prediction
  - no upper bound for selectron mass, but consistent with SU(2) relation

Conclusions

- **Angular distibutions very powerful observables**
  - contain 'new' contributions (the spin correlations)
- **With forward-backward asymmetries sensitive to heavy virtual particles**
  - even in multi-TeV range far beyond kinematical limit
  - rather accurate parameter determination possible
  - possible even in challenging scenarios !
  - high model-independence
- **LHC / ILC interplay crucial**
  - further examples coming up

Do not be afraid for heavy sleptons and squarks at LHC and ILC (500) !