LHC/ILC interplay in focuspoint inspired scenarios
(work in progress)

Gudrid Moortgat-Pick

in collaboration with: *K. Desch, J. Kalinowski, G. Polesello, K. Rolbiecki, J. Stirling*

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1. Introduction, motivation
   → *general remarks about spin correlations, angular and energy distributions*
2. Chosen scenario – focuspoint/split-Susy inspired
   → masses, cross sections
3. Energy and invariant mass distributions
4. Forward-backward asymmetries
   → *determination of* $m_{\tilde{\nu}}$, $m_{\tilde{q}}$ *far beyond the kinematical limit*
5. Fit results for parameter determination
6. Conclusions

Motivation

⇒ Revealing the structure of the underlying physics

- MSSM has 105 new parameters — how to constrain the parameter space?
  → constraints on parameters from e, n, Hg dipole moments,
  → exclusion bounds from LEP, Tevatron
  → constraints from low-energy experiments $b \to s\gamma$, $g_\mu - 2$
  → constraints from dark matter searches, etc.

Ibrahim ea '99, Barger ea. '01, Abel ea.'01, Belanger'04, Olive ea. '05,...

- Soon LHC data and maybe also first ILC data
  → suitable observables: cross sections, masses, BR's, ...

- possible problem: only a few particles directly accessible
  → possible to determine the model with only a few data?
  → today: challenging 'focuspoint-inspired' scenario
  → suitable observable: forward-backward asymmetries

⇒ LHC/ILC interplay essential: covers a large range of the parameter space

Spin correlations

Processes: $a + b \longrightarrow f_1 + f_2$, $f_1 \rightarrow 123$ and $f_2 \rightarrow 456$

- study of properties of f_1, f_2

$\rightarrow$ 'split' process in production$\times$decay in narrow width approximation

ok., since here $m_{\tilde{\chi}} \gg \Gamma_{\tilde{\chi}}$

$\rightarrow$ however take into account full spin correlations of f_1, f_2

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

$\Rightarrow$ production and decay process are coupled by interference terms between various polarization states of the fermions!

Amplitude squared of production $\times$ decay:

$$|T|^2 \sim \mathcal{P}(p_{f_1}, \overbrace{s_{f_1}, p_{f_2}, \underbrace{s_{f_2}) \mathcal{D}(p_{f_2}, s_{f_2}}_{\text{spin correlations}}) \otimes \mathcal{D}(p_{f_1}, s_{f_1}}^{\text{spin correlations}})$$

spin vectors $s_f \Rightarrow S^L(f_i)$ longitudinal and $S^{T_x}(f_i)$, $S^{T_y}(f_i)$: transverse polarizations of f_i

Spin correlations, cont.

Processes: $a + b \longrightarrow f_1 + f_2$, $f_1 \to 123$ and $f_2 \to 456$

$\Rightarrow$ Decay particles '$1, 2, 3'$ and '$4, 5, 6'$ depend on polarization of f_1, f_2.

- Which observables depend on spin correlations?

$\Rightarrow$ depends on Majorana↔Dirac character of fermions f_1, f_2

Petkov'84, Bilenky et al. '85,'86, GMP et al., '97, '98, '99, '00, '02

Decay	Dirac CP	Dirac $\not{CP}$	Majorana CP	Majorana $\not{CP}$
energy distrib. of particle '1'	$S^L(f_i)$	$S^L(f_i)$	–	$S^L(f_i)$
opening angle of particles '1' and '2'	$S^L(f_i)$	$S^L(f_i)$	–	$S^L(f_i)$
angular distrib. of particle '1'	all	all	all	all
opening angle of particles '1' and '4'	all	all	all	all

GMP, Fraas '00

In Dirac case:

$\rightarrow$ effects in shape of $d\sigma/dE_f$!

Remark: invariant mass distrib. ('12') are independent of spin correlations!

Dicus, Sudarshan, Tata '85

- What are we doing today? some applications; pure analytical approach for phase space and spin-density matrix

- Which generators could also simulate these effects?

  $\longrightarrow$ SUSYGEN (Ghodbane '99), HERWIG (Richardson '01)

Chosen scenario – focuspoint-inspired scenario

- Motivation: what to do if only very few particles accessible at LHC/ILC?

- case study – focuspoint inspired mSUGRA scenario (Desch, Kalinowski, GMP, Rolbiecki, Stirling):

  $\rightarrow$ challenging in general at LHC as well as at ILC!

  $\rightarrow$ assume: LHC + first stage of $\mathrm{ILC}_{500\mathrm{GeV}}$, later $\mathrm{ILC}_{1\mathrm{TeV}}$(but not today!)

- chosen scenario: $M_1 = 60$GeV, $M_2 = 121$GeV, $\mu = 540$GeV, $\tan\beta = 20$

  $\rightarrow m_h = 120$GeV, $m_{A,H,H^\pm} \sim 2$TeV

  $\rightarrow m_{\tilde{g}} = 416$GeV, $m_{\tilde{q}} \sim 2$TeV, $m_{\tilde{t}_{1,2}} \sim (1100, 1600)$GeV

  $\rightarrow m_{\tilde{\chi}^0_i} = (59, 117, 546, 550)$GeV, $m_{\tilde{\chi}^+_j} = (117, 553)$GeV, $m_{\tilde{e}_{L,R},\tilde{\nu}} \sim 2$TeV
- at LHC: $\tilde{g}$ and its chains accessible, mainly $\tilde{g} \rightarrow \tilde{\chi}^0_2 b\bar{b}$
- at ILC: $m_{\tilde{\chi}^0_{1,2}}$, $m_{\tilde{\chi}^\pm_1}$ kinematically acessible

$$\sigma(e^+e^- \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1) \sim 2 \text{ pb, but } \sigma(e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_2) < 1 \text{ fb!}$$

$\Rightarrow$ Life may be tough: what could one do with LHC+ILC_{500}?
Could one get any constraints on heavy scalar particles?

Parameter determination – input data

- in the ff: use A_{FB} of final decay ℓ! GMP ea '99

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+\nu_e$ or $\to \tilde{\chi}_1^0\bar{s}c$

Cross sections of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ at $\sqrt{s}=$ 350, 500 GeV:

$BR = BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 q_u\bar{q}_d) \times BR(\tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell^-\bar{\nu}_\ell) + BR(\tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell^-\bar{\nu}_\ell)^2 \sim$ 0.34

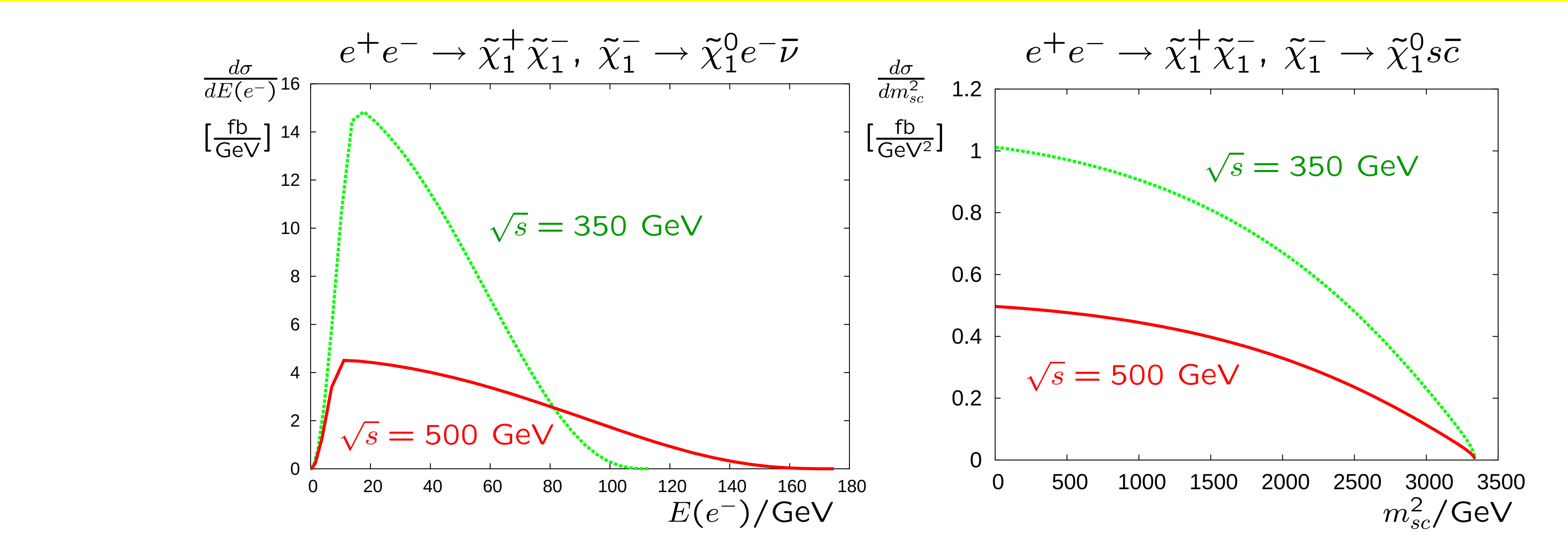
$\to$ excellent $\tilde{\chi}_1^\pm$ with with 50% effi. 1σ stat. error $\Delta P_{e^\pm}/P_{e^\pm} =$ 0.5% $\mathcal{L} =$ 200 fb^{-1}/Pol.

$\to$ $\tilde{\chi}_{1,2}^0 <$ 1 fb not used, challenging!

$\sqrt{s}$/GeV	(P_{e^-}, P_{e^+})	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$/fb	$\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-) \times BR$/fb	$A_{FB}(e^-)$/%
350	(−90%, +60%)	6195.5±7.9	2127.9±4.0	4.49±0.32
	(0, 0)	2039.1±4.5	700.3±2.7	4.5±0.5
	(+90%, −60%)	85.0±0.9	29.2±0.7	4.7±2.7
500	(−90%, +60%)	3041.5±5.5	1044.6±2.3	4.69±0.45
	(0, 0)	1000.6±3.2	343.7±1.7	4.7±0.8
	(+90%, −60%)	40.3±0.4	13.8±0.4	5.0±3.9

How to measure the masses at LHC and ILC?

- LHC: from $\tilde{g}$ decay chain: $m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}$
- ILC: masses of $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ from a) a threshold scan and from b) lepton energy distribution and c) hadronic invariant mass distribution



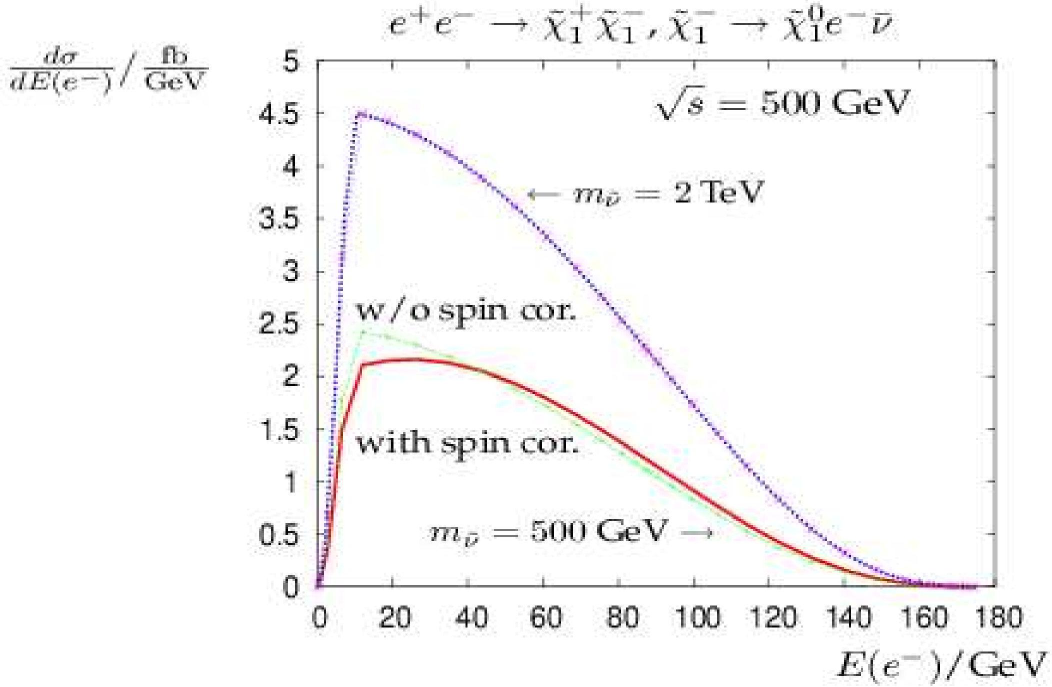
$\Rightarrow$ Both distributions are suitable (together with threshold scan) we assume $m_{\tilde{\chi}^0_1} \sim 0.2$ GeV, $m_{\tilde{\chi}^{\pm}_1} \sim 0.1$ GeV

$\Rightarrow$ together with LHC: $m_{\tilde{\chi}^0_2} = 0.2$ GeV

Short intermezzo

- Dependence of decay energy distribution on spin correlations:

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}$



$\Rightarrow$ Shape depends on spin correlations

$\Rightarrow$ today: we are using only the kinematical endpoints

Parameter determination – preliminary

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 e^- \bar{\nu}, s\bar{c}$ in our scenario...

Methods to get parameters: Feng ea '94, Tsukamoto ea '95, Baer ea '96, Kneur ea. '99, GMP'98,'00, Choi'98,'00,'01, ...

Assumptions: ILC: $\delta m_{\tilde{\chi}_1^\pm} \sim 0.1$ GeV (threshold scan) and $\delta m_{\tilde{\chi}_1^0} \sim 0.2$ GeV

LHC: $\delta m_{\tilde{\chi}_2^0} \sim 0.2$ GeV

ILC: δ(pol. cross sections$\times$BR): 1σ stat., $\epsilon = 50\%$, $\Delta P/P = 0.5\%$

fit-results wo A_{FB} of e^-: M_1/GeV$\sim 60.0 \pm 0.23$, M_2/GeV$\sim 121.0 \pm 0.7$,

μ/GeV$= 540 \pm 50$, $m_{\tilde{\nu}}$/GeV$= 2000 \pm 100$

fixed $\tan\beta = 20$ – so far)

- gaugino parameters M_1, M_2 rather well determined: relative error $\sim 0.5\%$

$\Rightarrow$ but μ very weak, about $\pm 10\%$ — clear, $\tilde{\chi}_1^\pm$ only gaugino–like

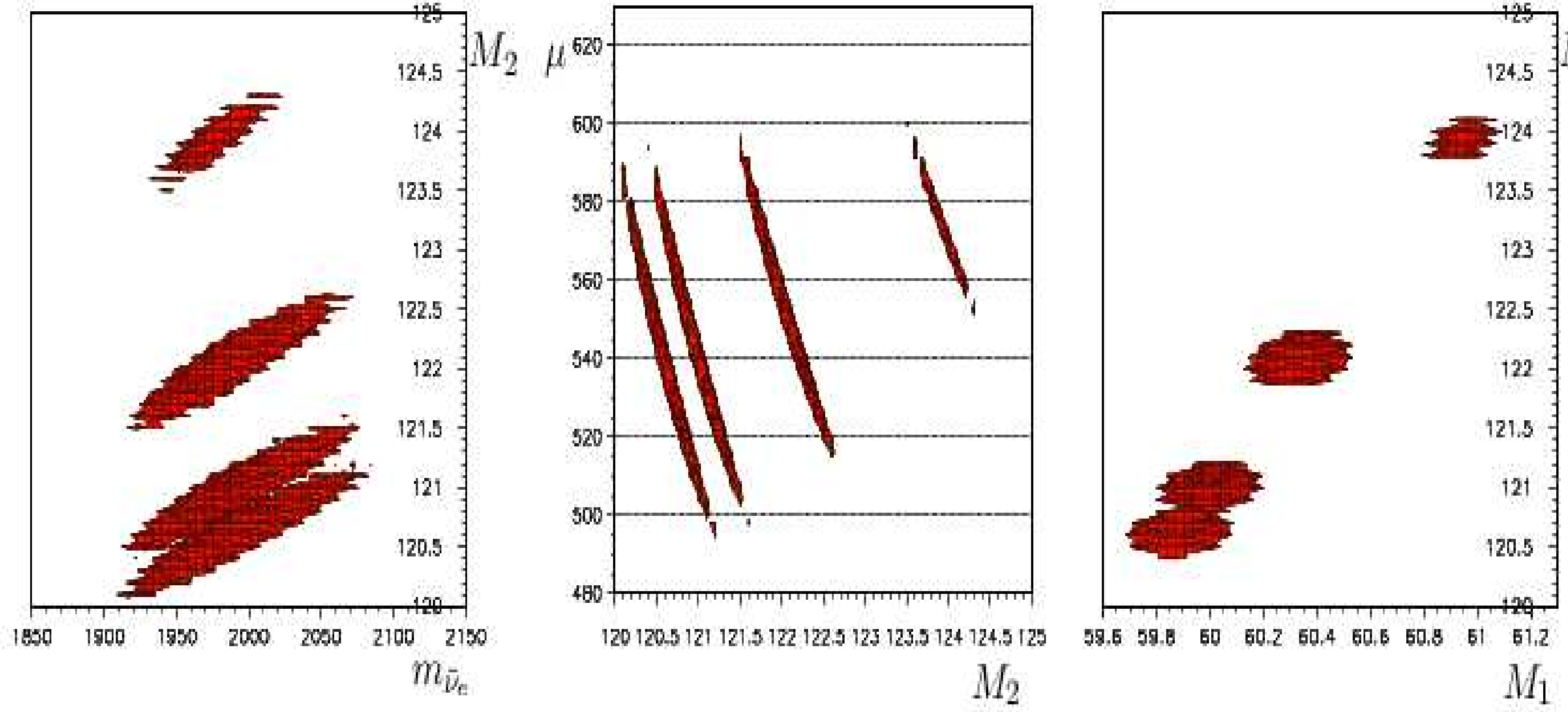
$\Rightarrow$ also $m_{\tilde{\nu}}$ very inaccurate, about $\pm 5\%$ — also clear, since very heavy

$\to$ kinematically suppressed

- how do allowed parameter ranges change with different $\tan\beta$?

Impact of fixed $\tan\beta$ in fit without using A_{FB}

- Fitted central values depend on $\tan\beta$:



- Varying $\tan\beta$ between 5 and 30

$\Rightarrow$ shift in M_1 by about 1 GeV

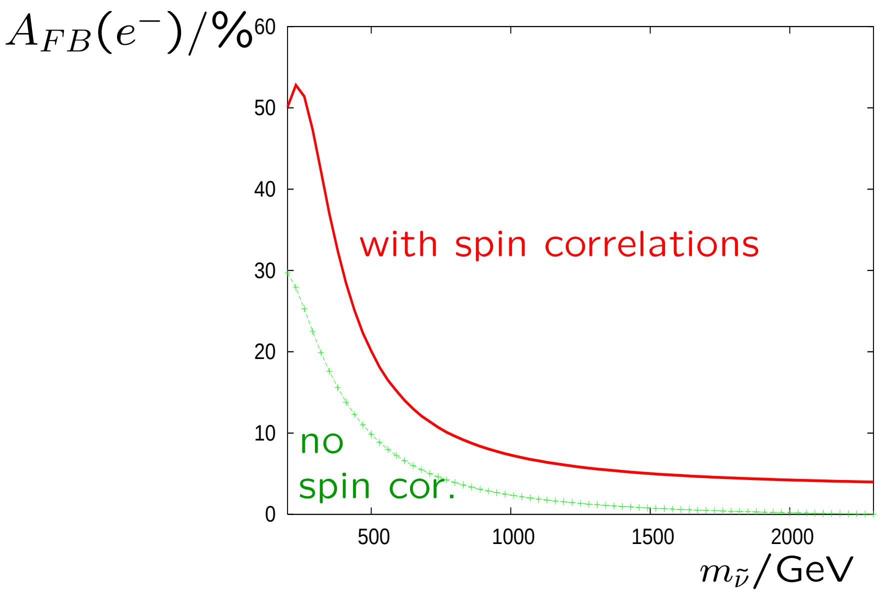
$\Rightarrow$ shift in M_2 by about 3.5 GeV

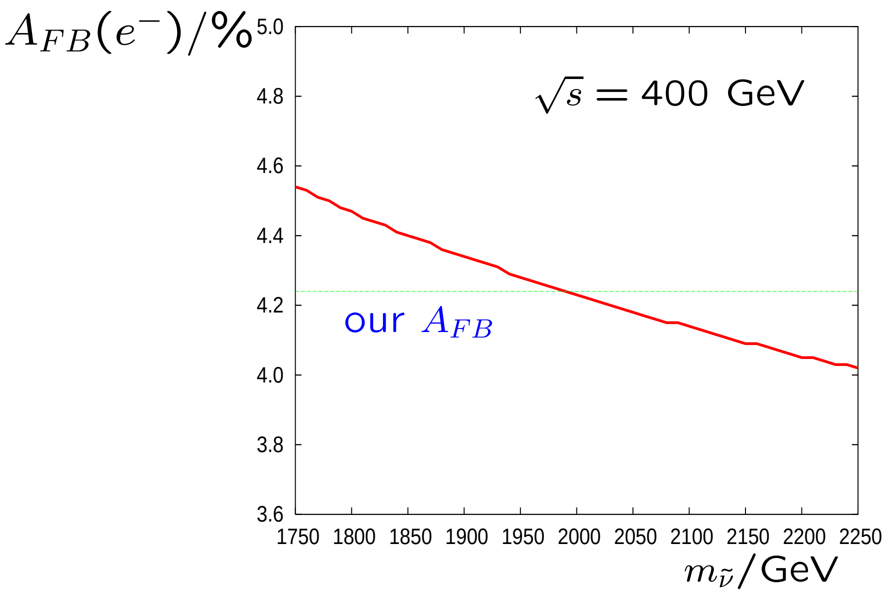
$\Rightarrow$ shift in μ and $m_{\tilde{\nu}}$ much weaker

A_{FB} of decay f: chargino production and decay

- known proposals: $m_{\tilde{\nu}}$ from $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ production only — Baer et al. '95
- here other method needed: use A_{FB} of final decay ℓ! — GMP ea '99

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}$





- spin correlations important: large effect!

- strong dependence on $m_{\tilde{\nu}}$
  - $\Rightarrow$ since $\Delta(A_{FB}) \sim 0.1\%$ $\to$ seems to be useful for heavy $m_{\tilde{\nu}}$

$\Rightarrow$ redo the fit including A_{FB}

Constraining of $m_{\tilde{\nu}}$ with A_{FB} of e^-: some results

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^- \bar{\nu}$ in our scenario...

Assumptions – again: ILC: $\delta m_{\tilde{\chi}_1^\pm} \sim 0.1$ GeV (threshold scan) and $\delta m_{\tilde{\chi}_1^0} \sim 0.2$ GeV

LHC: $\delta m_{\tilde{\chi}_2^0} \sim 0.2$ GeV

ILC: δ(pol. cross sections$\times$BR): 1σ stat., $\Delta P/P = 0.5\%$

fit-results wo A_{FB} of e^-: M_1/GeV$\sim 60.0 \pm 0.23$, M_2/GeV$\sim 121.0 \pm 0.7$,

μ/GeV$\sim 540 \pm 50$, $m_{\tilde{\nu}}$/GeV$= 2000 \pm 100$

but now:

fit-results w A_{FB} of e^-: μ/GeV$\sim 533 \pm 6.5$, $m_{\tilde{\nu}}$/GeV$= 1992 \pm 17$!

fit-results w A_{FB} of e^- and variable $\tan\beta$:

M_1/GeV$\sim 60.0 \pm 0.4$, M_2/GeV$\sim 121.0 \pm 1.5$,

μ/GeV$\sim 540 \pm 50$, $m_{\tilde{\nu}}$/GeV$= 1995 \pm 60$

$\Rightarrow$ A_{FB} very suitable for constraining heavy $m_{\tilde{\ell},\tilde{q}}$

$\Rightarrow$ rather accurate parameter determination although tricky scenario!

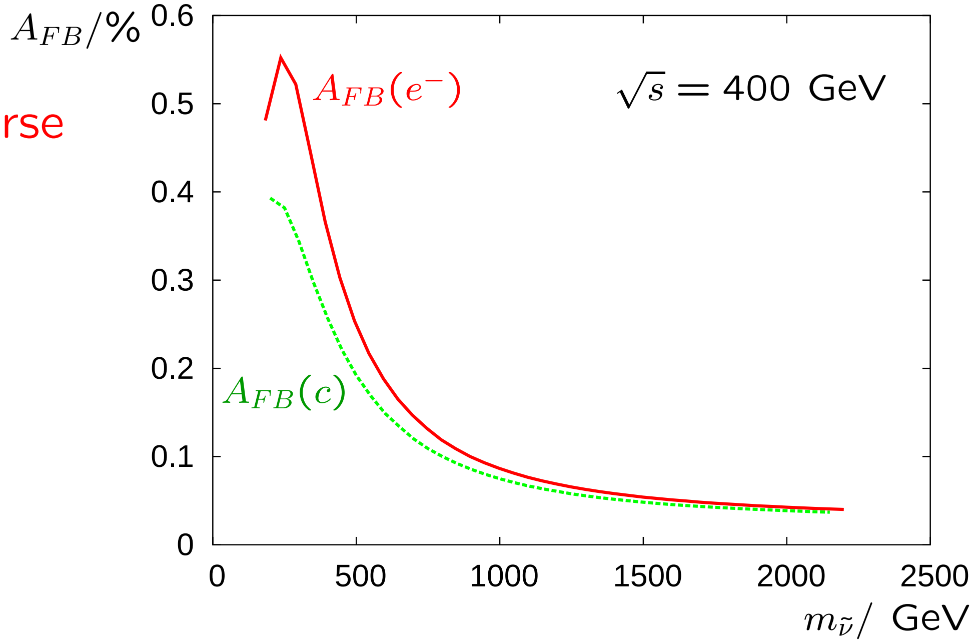
A_{FB} of decay f: chargino production and decay

- what's about hadronic decay?
- $m_{\tilde{\nu}}$ appears only in production: A_{FB} still sensitive?

Processes: $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^- \to \tilde{\chi}_1^0 s\bar{c}$

- spin correlations important, of course
- also $c \leftrightarrow \bar{c}$ assumed
- still strong dependence on $m_{\tilde{\nu}}$

  $\Rightarrow$ about same accuracy for $\Delta m_{\tilde{\nu}}$ from $A_{FB}(c)$ as from $A_{FB}(e^-)$



$\Rightarrow$ unknown parameters at ILC: $m_{\tilde{\nu}_e}$, $m_{\tilde{s}}$, $m_{\tilde{c}}$
in progress: study with $m_{\tilde{q}}$ from LHC!

Further possible interplay with LHC

- Strategy: $m_{\tilde{q}}$ known from LHC with about $\Delta m_{\tilde{q}} \sim 5\%$?
- Could we use $A_{FB}(c)$ at the ILC, derive $m_{\tilde{\nu}}$ and use $A_{FB}(e^-)$ for $m_{\tilde{e}_L}$?

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^- \bar{\nu}$

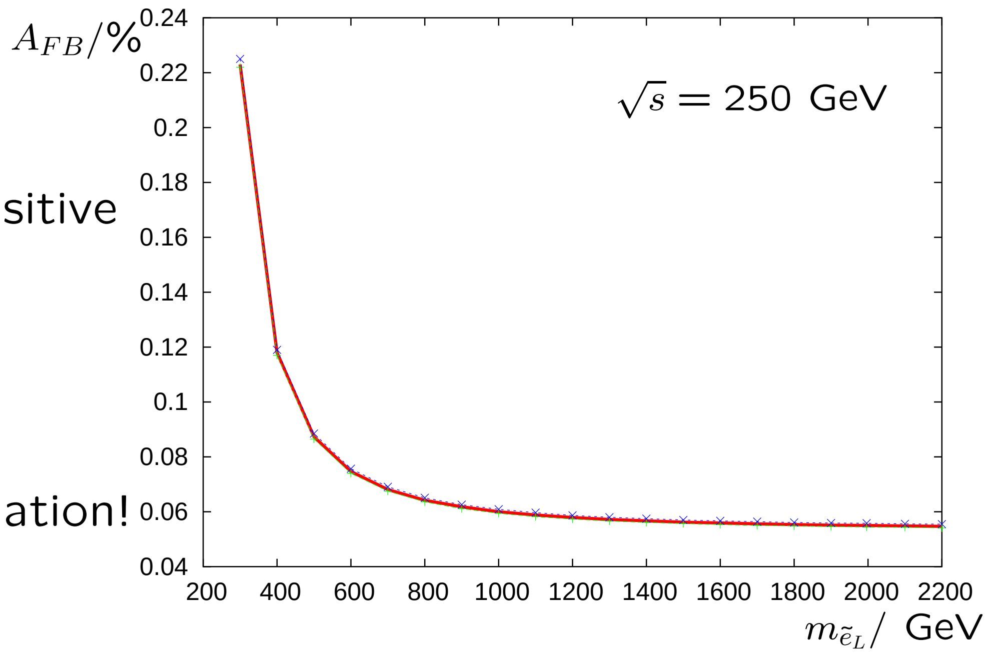
- $m_{\tilde{e}_L}$ contributes only in decay!

  $\Rightarrow$ go closer to threshold to be sensitive

- strong dependence also on $m_{\tilde{e}_L}$

  $\Rightarrow$ even for high $m_{\tilde{e}_L}$ constraints

  e.g. testing the SU(2) $m_{\tilde{e}_L}/m_{\tilde{\nu}}$ relation!



$\Rightarrow$ Precise A_{FB} measurements leads to powerful constraints far beyond kinematical limit!

Conclusions and Outlook

- Angular distributions are powerful observables
  - ⋆ spin correlations very important!
    - $\longrightarrow$ if MC studies: please use corresponding program!

- With forward-backward asymmetries: excellent constraints on heavy masses rather accurate parameter determination
  - $\longrightarrow$ possible, even in challenging scenarios!

- Do not be afraid for heavy sleptons, squarks

- Excellent potential for further promising LHC/ILC interplay
  - $\longrightarrow$ inclusion of squark masses etc. (stay tuned)