Tools for constraining heavy particles (work in progress)

Gudrid Moortgat-Pick (CERN Theory)

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

SUSY WG

Snowmass, 22/08/2005

1. Introduction
   → *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. First results for parameter determination
6. Conclusions

Motivation

Processes: fermion production with subsequent decay(s)

- Problem for today:
  determination of heavy virtual particles

- 105 new parameters in the general MSSM
  $\rightarrow$ constraints on parameters from e, n, Hg dipole moments, LEP, Tevatron, $b \rightarrow s\gamma$, $g_\mu - 2$, dark matter searches, etc.

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

- Suitable observables: cross sections, masses, BR's, ...
  $\rightarrow$ what else could one use?

- Energy and angular distributions, different kinds of asymmetries
  $\rightarrow$ some observables depend strongly on spin correlations

1. Introduction: spin correlations

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

- 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

Introduction: 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$\leftrightarrow$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 $\not{C}\not{P}$	Majorana CP	Majorana $\not{C}\not{P}$
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:

$\to$ 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)

2. Forward-backward asymmetries: access to heavy $m_{\tilde{q},\tilde{\ell}}$?

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

- case study – focuspoint inspired 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: $M_1 = 60\mathrm{GeV}$, $M_2 = 121\mathrm{GeV}$, $\mu = 540\mathrm{GeV}$, $\tan\beta = 20$
  $\rightarrow m_h = 120\mathrm{GeV}$, $m_{A,H,H^\pm} \sim 2\mathrm{TeV}$
  $\rightarrow m_{\tilde{g}} = 416\mathrm{GeV}$, $m_{\tilde{q}} \sim 2\mathrm{TeV}$, $m_{\tilde{t}_{1,2}} \sim (1100, 1600)\mathrm{GeV}$
  $\rightarrow m_{\tilde{\chi}^0_i} = (59, 117, 546, 550)\mathrm{GeV}$, $m_{\tilde{\chi}^+_j} = (117, 553)\mathrm{GeV}$, $m_{\tilde{e}_{L,R},\tilde{\nu}} \sim 2\mathrm{TeV}$
- 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?

How to get the masses?

- here other method needed: use A_{FB} of final decay ℓ! GMP ea '99

Processes: $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e$ 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 $\sqrt{s} = 400$, 500 GeV:

$BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 e^+ \nu_e) \sim 11\%$ and $BR(\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \bar{s} c) \sim 33\%$

→ excellent $\tilde{\chi}_1^\pm$!

→ $\tilde{\chi}_{1,2}^0$ rates challenging!

Today: take $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ only!

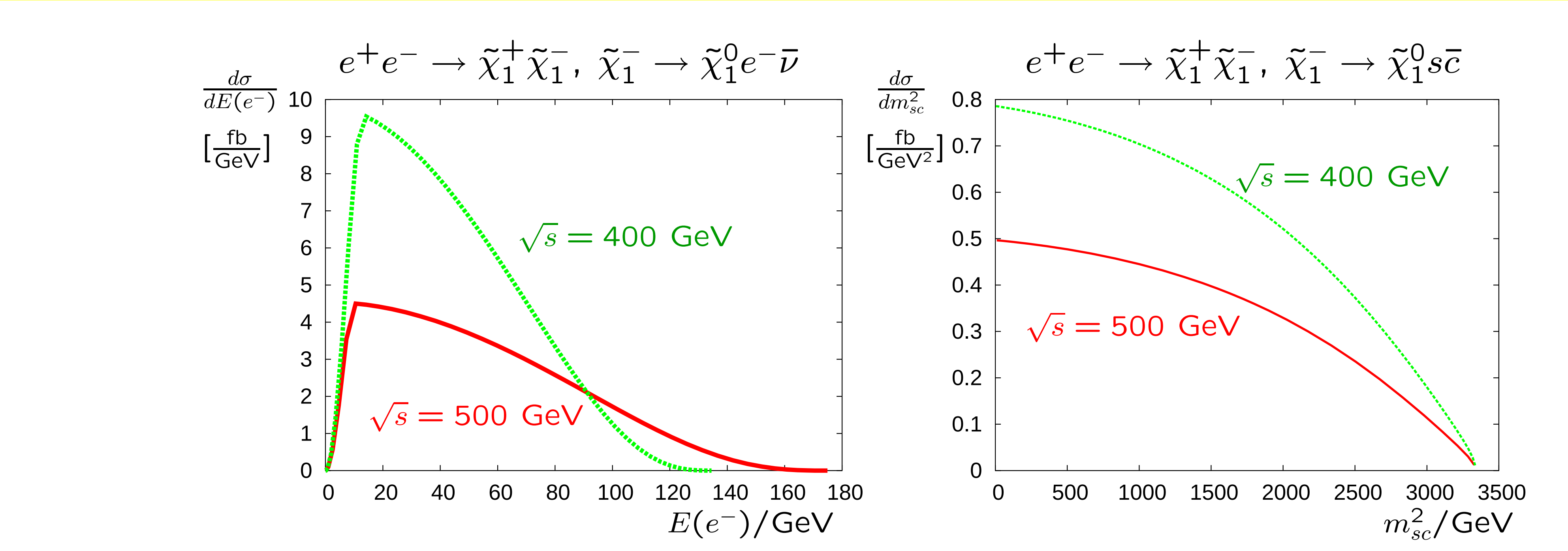
$\sqrt{s}$/GeV	(P_{e^-}, P_{e^+})	$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)$/fb	$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_2^0)$/fb	$\sigma(\tilde{\chi}_2^0 \tilde{\chi}_2^0)$/fb
400	$(-90\%, +60\%)$	4811.3 ± 6.9	0.7 ± 0.1	0.2 ± 0.0
	$(0, 0)$	1583.1 ± 4.0	0.3 ± 0.1	< 0.1
	$(+90\%, -60\%)$	64.7 ± 0.8	< 0.1	< 0.1
500	$(-90\%, +60\%)$	3041.7 ± 5.5	1.0 ± 0.1	0.5 ± 0.1
	$(0, 0)$	1000.6 ± 3.2	0.3 ± 0.1	< 0.1
	$(+90\%, -60\%)$	40.3 ± 0.6	< 0.1	< 0.1

⇒ Which observables could be used?
How to get the fundamental SUSY parameters?

How to get the masses?

- exploit lepton energy distribution or hadronic invariant mass distribution

Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ and decays



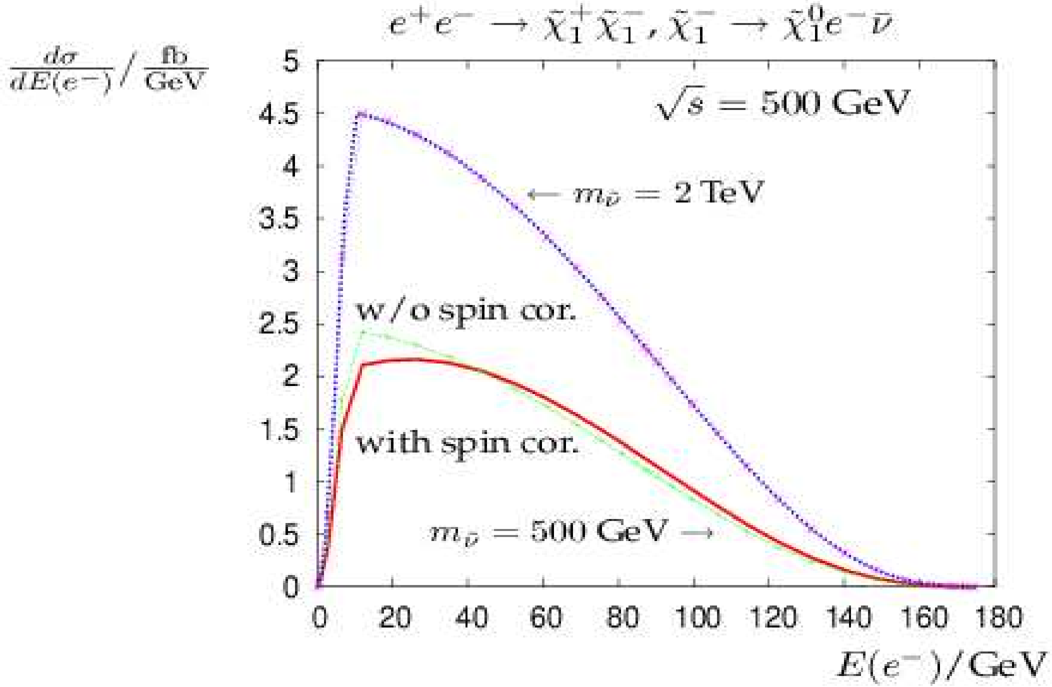
⇒ Both distributions are suitable (together with threshold scan)
we assume $m_{\tilde{\chi}_1^0} \sim 0.5$ GeV, $m_{\tilde{\chi}_1^\pm} \sim 0.2$ GeV

⇒ apply now 'usual' parameter stategy with masses and cross sections

Short intermezzo

- Dependence of decay energy distribution on spin correlations:

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



⇒ Shape depends on spin correlations

⇒ today: we are using only the kinematical endpoints

Parameter determination – preliminary

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: ILC: $\delta m_{\tilde{\chi}_1^\pm} \sim 0.2$ GeV (threshold scan) and $\delta m_{\tilde{\chi}_1^0} \sim 0.5$ GeV

LHC: $\delta m_{\tilde{\chi}_2^0} \sim 0.5$ GeV

ILC: δ(pol. cross sections$\times$BR) up to 0.5 fb

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

fit-results wo A_{FB} of e^-: M_1/GeV$\sim 60.0 \pm 0.6$, M_2/GeV$\sim 121 \pm 2$,

μ/GeV$\sim [440, 800]$, $m_{\tilde{\nu}}$/GeV$= 2000 \pm 250$

(used modified fittino see talk Philip Bechtle, however fixed $\tan\beta$ – so far)

- gaugino parameters M_1, M_2 rather well determined

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

⇒ also $m_{\tilde{\nu}}$ very inaccurate — also clear, since very heavy

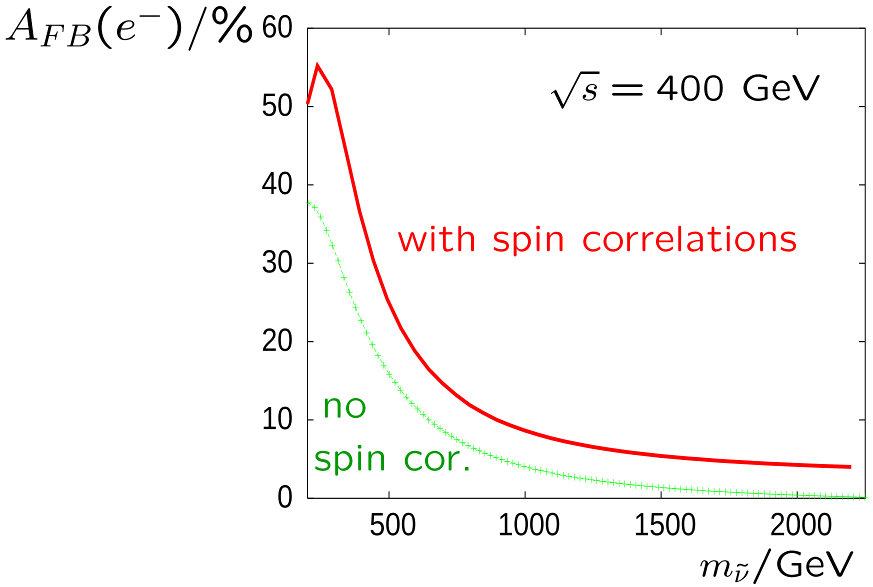
$\to$ kinematically suppressed

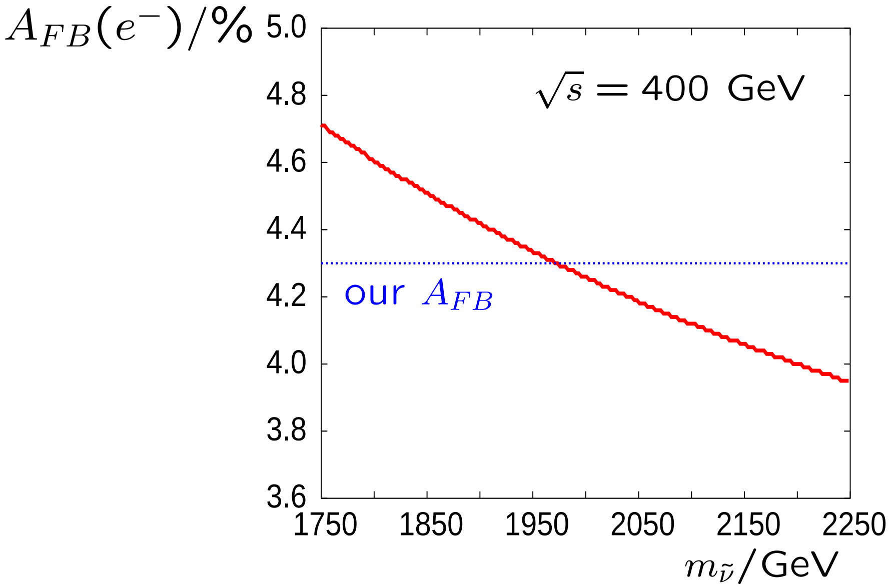
- Which other observable could be useful?

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 $\Delta(A_{FB}) \sim 0.2\% \to$ 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: $\delta m_{\tilde{\chi}_1^\pm} \sim 0.2$ GeV (threshold scan) and $\delta m_{\tilde{\chi}_1^0} \sim 0.5$ GeV

LHC: $\delta m_{\tilde{\chi}_2^0} \sim 0.5$ GeV

ILC: δ(pol. cross sections$\times$BR) up to 0.5 fb

fit-results wo A_{FB} of e^-: M_1/GeV$\sim 60.0 \pm 0.6$, M_2/GeV$\sim 121 \pm 2$,

μ/GeV$\sim [440, 800]$, $m_{\tilde{\nu}}$/GeV$= 2000 \pm 250$

but now:

fit-results w A_{FB} of e^-: M_1/GeV$\sim 60.0 \pm 0.5$, M_2/GeV$\sim 121 \pm 0.3$,

μ/GeV$\sim 533 \pm 6.5$, $m_{\tilde{\nu}}$/GeV$= 1992 \pm 17$!

next step a): fit with $\tan\beta \to$ preliminary results, but w.r.t. $m_{\tilde{\nu}} \approx$ the same result

next step b): $\sqrt{s} = 1$ TeV $\to \tilde{\chi}_1^+\tilde{\chi}_2^-$ $\sim$few fb only!

$\to$ strong improvement in μ (and $\tan\beta$) expected

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

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

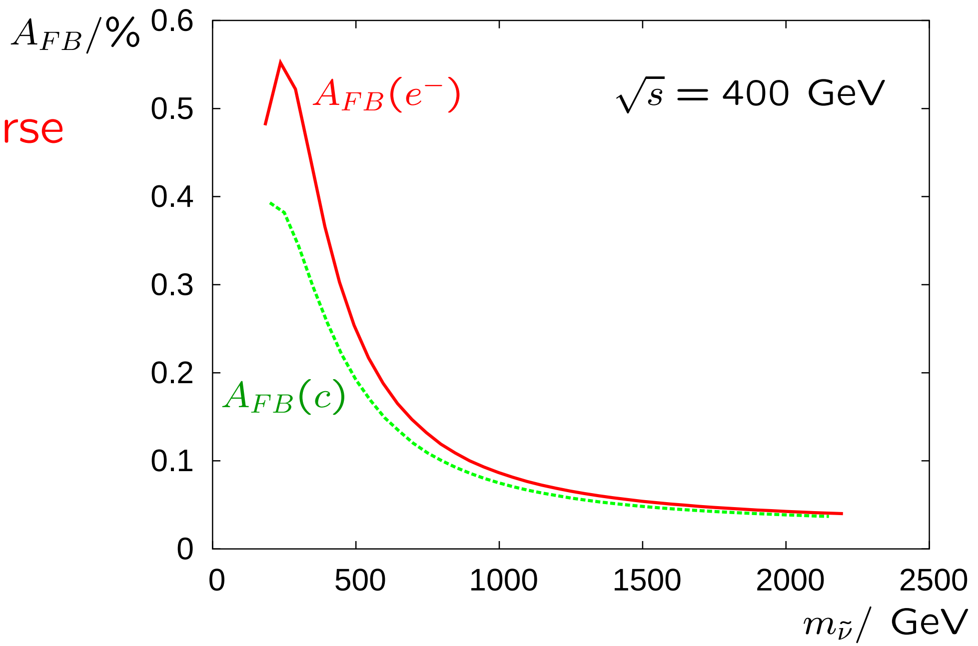
A_{FB} of decay f: chargino production and decay

- 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: $m_{\tilde{\nu}_e}$, $m_{\tilde{s}}$, $m_{\tilde{c}}$
Maybe combined study with LHC?

Possible interplay with LHC (very preliminary – wait for next week)

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

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

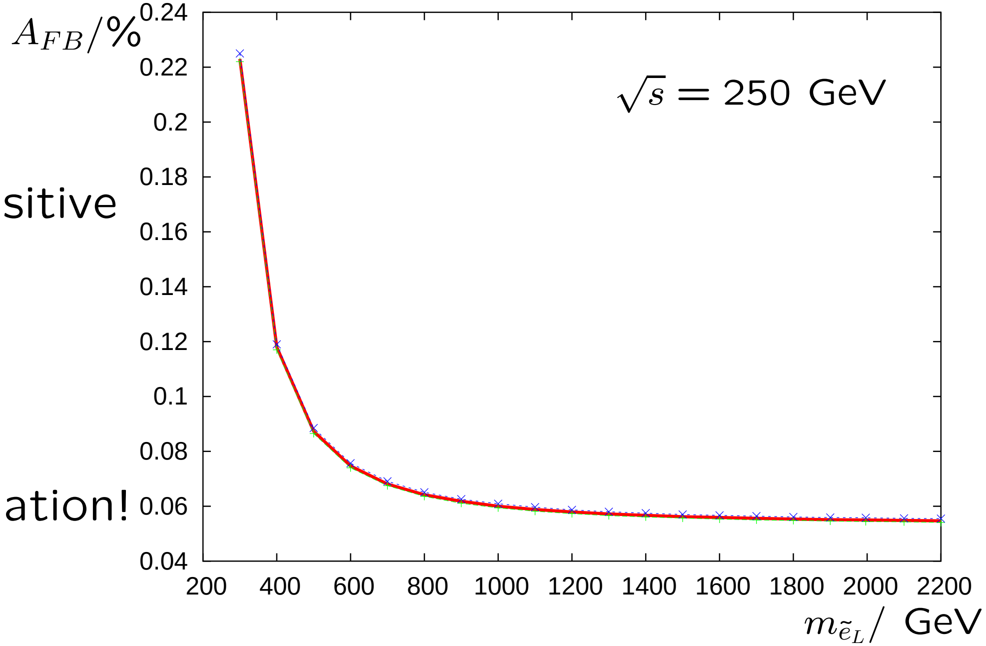
- $m_{\tilde{e}_L}$ contributes only in decay!

  $\Rightarrow$ 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

- 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
  - $\longrightarrow$ possible, even in challenging scenarios!

- Do not be afraid for heavy sleptons, suarks at the ILC!

- To-do list: detailed case studies for the shown observables
  finish the fit, also for $\tan\beta$
  extension to observables at LHC (cf. also Barr'04, Smillie, Webber'05)
  (under work in the context of the Les Houches working group)