Angular distributions and CP-sensitive observables in the MSSM

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1. Introduction
   → *general remarks about spin correlations, angular and energy distributions*

2. Forward-backward asymmetries
   → *determination of* $m_{\tilde{\nu}}$ *far beyond the kinematical limit* (work in progress)

3. Triple-product correlations
   → *sensitivity to CP-violating phases*

4. Azimuthal asymmetries and transverse beam polarization
   → *CP-violating phases of Majorana fermions* (work in progress)

5. Conclusions

Motivation

Processes: fermion production with subsequent decay(s)

- Problems for today:
  a) determination of heavy virtual particles
  b) access to CP-violating phases

- 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↔Dirac character of fermions f_1, f_2

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

	Dirac		Majorana	
Decay	CP	$\not{C}\not{P}$	CP	$\not{C}\not{P}$
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 $\text{ILC}_{500\text{GeV}}$, later $\text{ILC}_{1\text{TeV}}$

- 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?

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

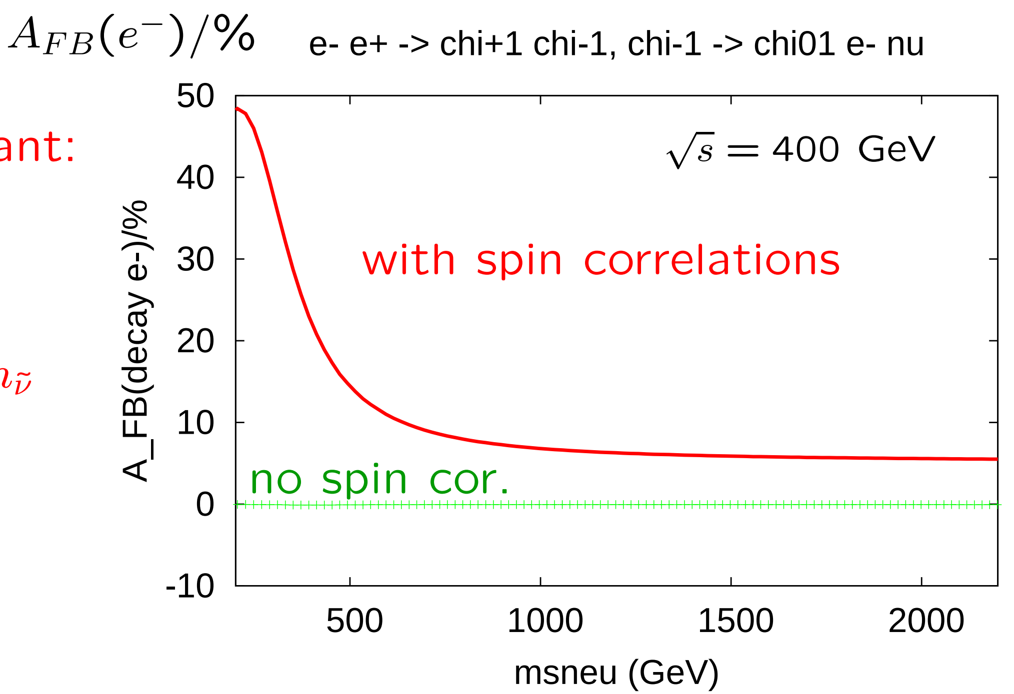
Processes: $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^- \to \tilde{\chi}_1^0 e^-\bar{\nu}$

- spin correlations important:

  $\Rightarrow$ huge effect!

- strong dependence on $m_{\tilde{\nu}}$

  $\Rightarrow$ useful for heavy $m_{\tilde{\nu}}$?



$\Rightarrow$ Precise A_{FB} useful for parameters in our case?
And what about other parameters?

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

(work in progress with Desch, Kalinowski, Rolbiecki, Stirling)

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 P. Wenemann, however fixed $\tan\beta$ – so far)

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 $\tan\beta$)

$\Rightarrow$ A_{FB} very suitable for constraining heavy $m_{\tilde{\ell},\tilde{q}}$
$\Rightarrow$ rather accurate parameter determination although tricky scenario!

3. Triple product correlations
now: study of neutralino production and decay

- MSSM with complex parameters

→ masses, cross sections, angular distributions, etc. depend on phases

→ CP-sensitive observables needed

- If only CP-even observables used (and not full spectrum accessible): similar m, σ's with CP-conserving as well as CP-violating scenario

→ example: $m_{\tilde{\chi}^0_{1,2}} = (196, 258)$, $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2) = 43, 115, 19$ fb

at $\sqrt{s} = 500$ GeV and $(P_{e^-}, P_{e^+}) = (0,0), (\pm 90\%, \mp 60\%)$

These values within 1σ uncertainty could be obtained with:

$(|M_1|, \phi_{M_1}, M_2, \mu, \tan\beta) = (200, 0.7\pi, 320, 330, 3) \Rightarrow$ CP-phase ϕ_{M_1}

as well as $(|M_1|, \phi_{M_1}, M_2, \mu, \tan\beta) = (196, 0, 324, 330, 3) \Rightarrow$ no CP-phase!

Bartl, Fraas, Hesselbach, Hohenwarter-Sodek, Kernreiter, GMP

- other methods?

→ study threshold behaviour of $\tilde{\chi}^0_i\tilde{\chi}^0_j$,e.g. $(i,j) = (1,2), (1,3), (2,3)$ Choi ea '01

may be kinematically closed...

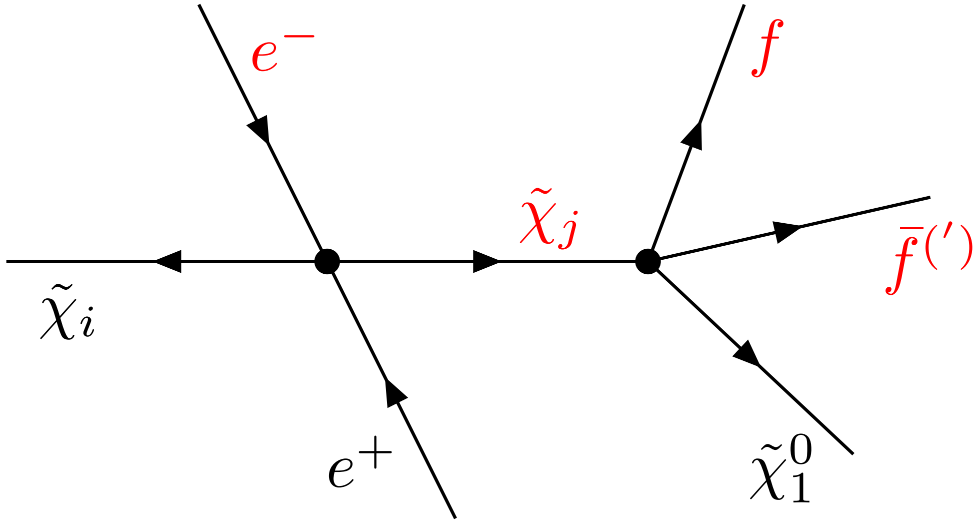
- study T-odd observables: triple products of initial and final state momenta

Bartl ea '03, '04, Hesselbach'04, Aguilar-Saavedra'04

Triple product correlations, cont.

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

Suitable triple product: $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{\bar{f}})$ (also $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_{\bar{f}})$ but reconstruction of $\vec{p}_{\tilde{\chi}_j}$ difficult)



$\Rightarrow$ T-odd asymmetry: $A_T = \frac{\sigma(\mathcal{T}>0)-\sigma(\mathcal{T}<0)}{\sigma(\mathcal{T}>0)+\sigma(\mathcal{T}<0)} = \frac{\int \text{sign}(\mathcal{T})|T|^2 d\text{lips}}{\int |T|^2 d\text{lips}}$

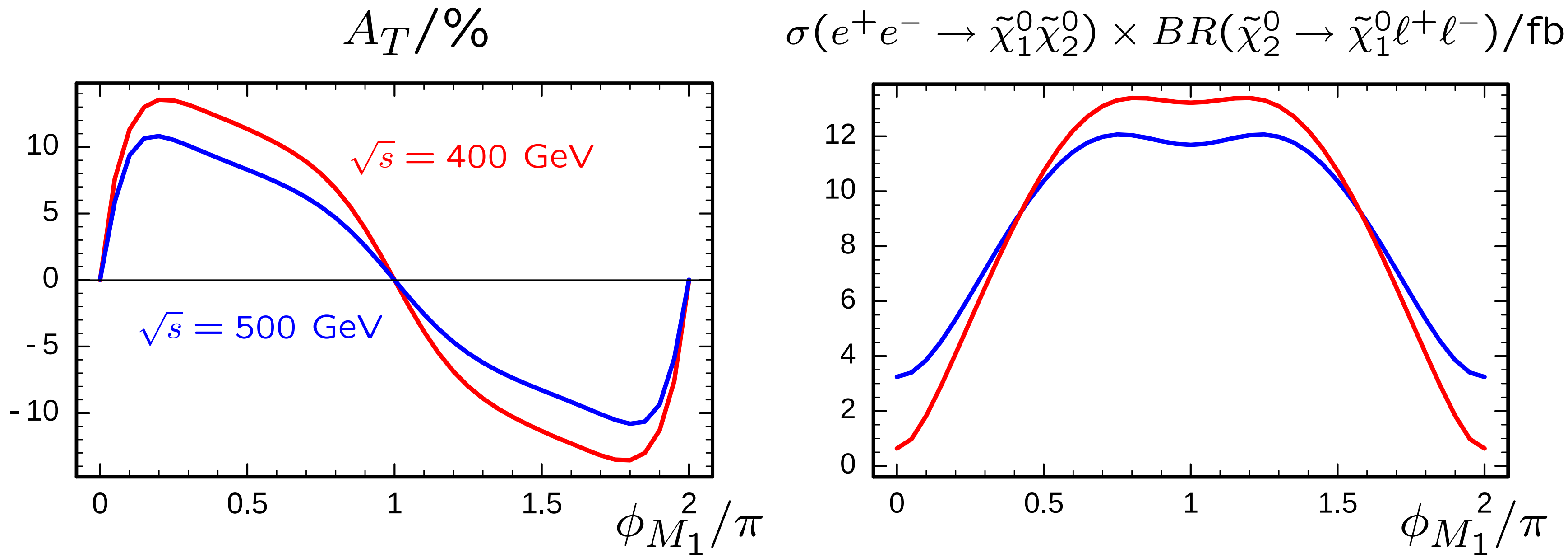
'$A_T \equiv 0$ if no spin correlations are taken into account!'

$\Rightarrow$ With CPT$_N$ $A_T \equiv$ CP-odd asymmetry (neglecting FSI effects!)

$\Rightarrow$ Are these asymmetries large enough to be significant for CPV?

Example: neutralino production and leptonic decay

Processes: $e^+e^- \to \tilde{\chi}_j^0 \tilde{\chi}_j^0, \tilde{\chi}_j^0 \to \tilde{\chi}_1^0 f \bar{f}$ Studied: $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$



(Bartl, Fraas, Hesselbach, Hohenwarter-Sodek, GMP, JHEP 0408 (2004) 038)

$\Rightarrow$ Rather high asymmetries reachable

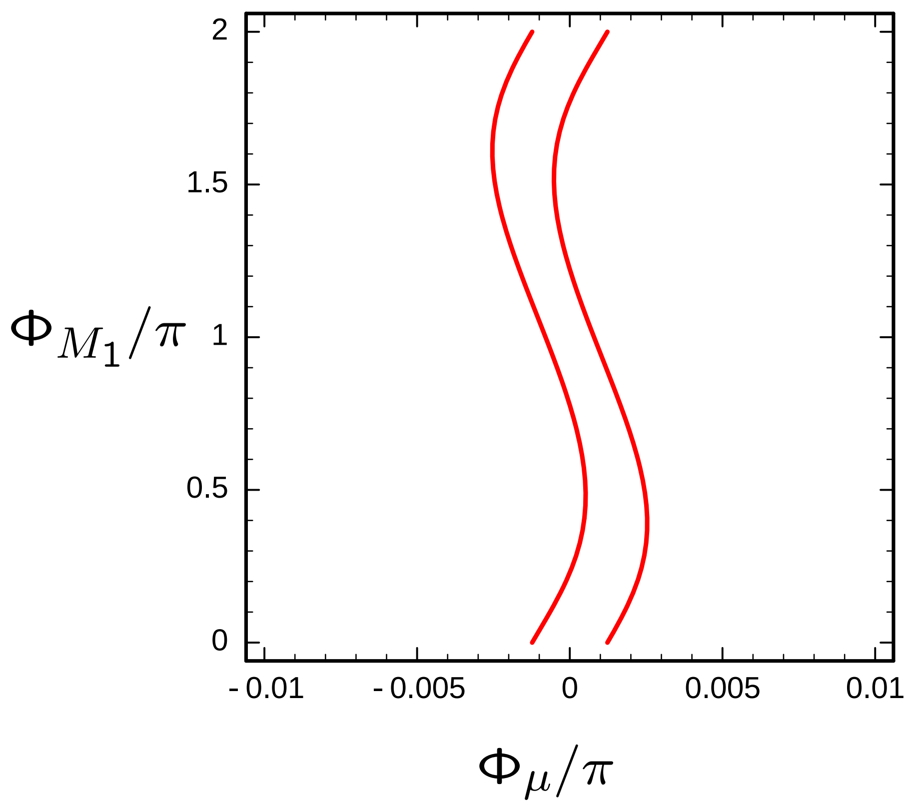
Assume 1σ error in cross sections, $\Delta A_T \sim 1/\sqrt{N}$: $A_T = (10 \pm 2)\%$ ($\mathcal{L} = 300$ fb^{-1})

$\Rightarrow$ $A_T \equiv 0$ for $\Phi_{M_1} = 0, \pi, 2\pi$ (since $A_T \neq 0$ only if CP-violation)

$\Rightarrow$ A_T together with CP-even observables are suitable tools to determine ϕ_{M_1} and its sign!

Only small phases allowed?

Bounds from e EDM for chosen scenario:



$\Rightarrow$ in our example: rather large Φ_{M_1} not excluded by e EDM!
$\Rightarrow$ has to check every point separately!

Neutralino production and hadronic decay

Processes: $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2,\ \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 c\bar{c}$ Studied: $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\bar{c}} \times \vec{p}_c)$

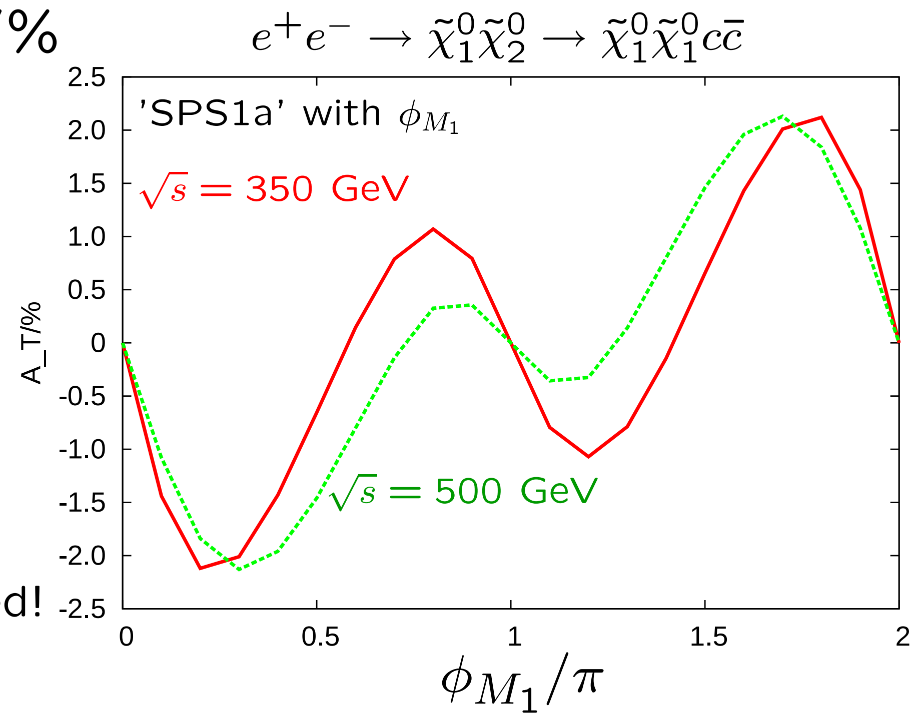
$\Rightarrow$ small (in SPS1a!)

T-odd asymmetries

but higher rates!

$*$ However $c \leftrightarrow \bar{c}$ distinction required!*

$\Rightarrow$ excellent c-tagging needed!



If no spins:

$A_T \equiv 0!$

$\Rightarrow$ $c \leftrightarrow \bar{c}$ distinction under discussion and feasible for ILC vertex detector

(see talk by Chris Damerell at LCWS'05, SLAC, March 2005)

$\Rightarrow$ T-odd asymmetries in hadronic decays need $c \leftrightarrow \bar{c}$, $b \leftrightarrow \bar{b}$ distinction!

4. Azimuthal asymmetries with trans. e^+ and e^- polarization CP-odd observables in neutralino production

- Cross sections: $\sigma^T \sim P^T_{e^-} P^T_{e^+} \int d\phi Re f_1 \cos(\eta - 2\phi) + Im f_2 \sin(\eta - 2\phi)$

(η gives azimuthal orientation of transverse beams w.r.t. to fixed reference frame)

$\Rightarrow$ both beams have to polarized, otherwise no contribution ($m_e \to 0!$)

** further details about beam polarization, see POWER report hep-ph/0507011,
$\Rightarrow$ Physics case for polarized e^+ made $\to$ under discussion for baseline design!**

- CP-odd terms are $\sim \sin(\eta - 2\phi)$

$\to$ Dirac case: in $\tilde{\chi}^+_i \tilde{\chi}^-_j$ production CP-odd terms$\sim \sin(\eta - 2\phi)$ vanish! Bartl ea '04

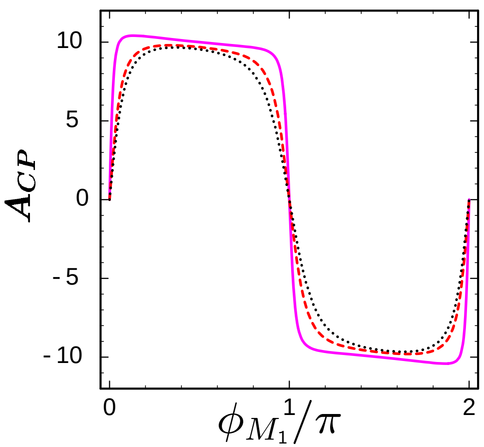
$\to$ Majorana case: in $\tilde{\chi}^0_i \tilde{\chi}^0_j$ production CP-odd terms$\sim \sin(\eta - 2\phi)$ contribute!

(because of t, u channel)

$e^+e^- \to \tilde{\chi}^0_1 \tilde{\chi}^0_2$:

at $\sqrt{s} = 500$ GeV

for $\tan\beta = 3, 10, 30$



(work in progress with Bartl, Fraas, Hesselbach, Hohenwarter-Sodek, Kernreiter)

$A_{CP} = [\int_0^{\pi/2} - \int_{\pi/2}^{\pi}] A_{CP}(\theta) d\theta$

$A_{CP}(\theta) \sim [\int_1 \pm \int_2 \mp \dots \int_4] d\phi d^2\sigma/(d\phi d\theta)$

$\to$ reconstruction of scattering plane!

$\Rightarrow$ Rather large A_{CP} expected, even for small CP-phases!

Azimuthal asymmetries with transv. e^+ and e^- polarization
T-odd observables in neutralino production×decay

Process: $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \ell^\mp_1 \tilde{\ell}^\pm_R \to \tilde{\chi}^0_1 \ell^\mp_1 \ell^\pm_2 \tilde{\chi}^0_1$

- define several T-odd A_i:

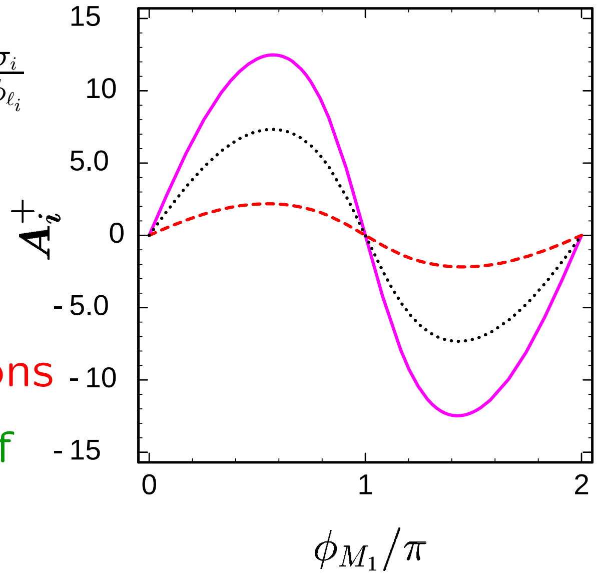
$$A_i^+ \sim [\int_1 - \int_2 \pm \ldots \int_4] d\phi_{\ell_i} \frac{d\sigma_i}{d\phi_{\ell_i}}$$

$\Rightarrow$ rather high asymmetries and cross sections!

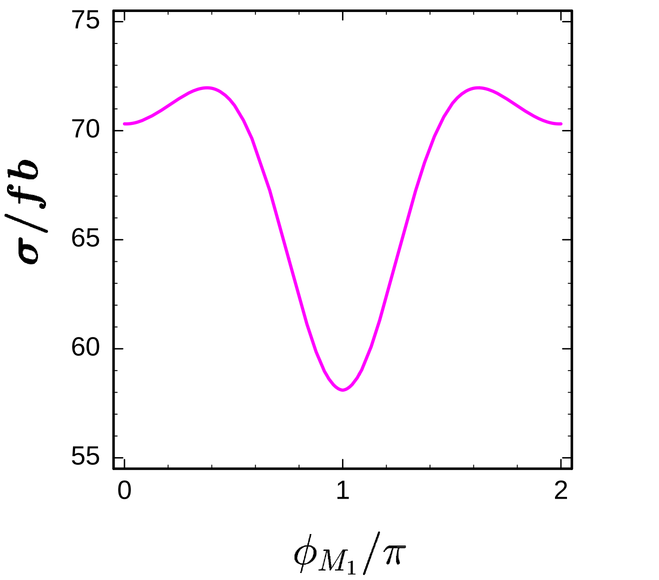
- depends on spin correlations

$\rightarrow$ but no reconstruction of scattering plane needed!

T-odd $A_i^+/\%$



$\sigma(e^-e^+ \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tilde{\ell}_R \ell_1)$/fb



(work in progress with Bartl, Fraas, Hesselbach, Hohenwarter-Sodek, Kernreiter)

$\Rightarrow$ with transversely polarized beams definition of several suitable T-odd asymmetries A_i possible!

5. Conclusions

- Angular distributions –polar or azimuthal– are powerful observables
  - ⋆ spin correlations very important!
    - → if MC studies: please use corresponding program!
- With forward-backward asymmetries: excellent constraints on heavy masses
  → possible, even in challenging scenarios!
- Triple-products between intial+final state momenta: T-odd observables
  → unique access to even small CP phases (here Φ_{M_1})
  → hadronic decays: $c \leftrightarrow \bar{c}$, $b \leftrightarrow \bar{b}$ distinction needed
- If transverse e^- and e^+ beam polarization available at the ILC:
  → Majorana case: A_{CP} of only production available!
  → different azimuthal asymmetries: access to CP-phases
- To-do list: detailed case studies for the shown observables
  some more physics examples for $c \leftrightarrow \bar{c}$, $b \leftrightarrow \bar{b}$ needed
  extension to observables at LHC (cf. also Barr'04, Smillie, Webber'05)
  (under work in the context of the Les Houches working group)