CP-odd and T-odd Asymmetries in Chargino and Neutralino Production and Decay

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based on

Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, JHEP **0408** (2004) 038 [hep-ph/0406190]

Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, in preparation

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Outline

- Introduction
  - MSSM with complex parameters
  - Complex parameters in chargino/neutralino sectors
- Parameter determination in chargino/neutralino sectors
- T-odd triple product asymmetries
- CP-odd and T-odd asymmetries using transverse beam polarization
- Summary and outlook

Introduction
MSSM with complex parameters

- General MSSM:
  Complex parameters in Higgs potential and soft SUSY breaking terms
- Physical phases of the parameters
  M_1 : U(1) gaugino mass parameter
  μ : Higgs-higgsino mass parameter
  A_f : trilinear couplings of sfermions
  $m_{\tilde{g}}$: gluino mass
- Introduction of CP violation
  - May help to explain baryon asymmetry of universe
  - Constraints from electric dipole moments (EDMs) of e, n, Hg, Tl
    [Ibrahim, Nath, '99; Barger, Falk, Han, Jiang, Li, Plehn, '01; Abel, Khalil, Lebedev, '01]
    [Oshimo, Nihei, Fujita, '05; Pospelov, Ritz, '05; Olive, Pospelov, Ritz, Santoso, '05]
- Aim: analysis the CP structure of theory and determination of phases

Introduction

Complex parameters in $\tilde{\chi}^{\pm,0}$ sectors

- Chargino mass matrix: $$X = \begin{pmatrix} M_2 & \sqrt{2}\, m_W s_\beta \\ \sqrt{2}\, m_W c_\beta & \mu \end{pmatrix}$$
- Neutralino mass matrix:

$$Y = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & 0 & -\mu \\ m_Z c_W c_\beta & -m_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$s_\beta \equiv \sin\beta$, $c_\beta \equiv \cos\beta$

μ : Higgs-higgsino mass parameter $\longrightarrow$ $|\mu|$, φ_μ

M_1 : U(1) gaugino mass parameter $\longrightarrow$ $|M_1|$, φ_{M_1}

M_2 : SU(2) gaugino mass parameter

- Diagonalization $\Rightarrow$ complex mixing matrices $\longrightarrow$ enter $\tilde{\chi}^\pm$, $\tilde{\chi}^0$ couplings

Parameter determination

- CP-even observables: cross sections, masses, ...

[Choi, Djouadi, Song, Zerwas, hep-ph/9812236]
[Kneur, Moultaka, hep-ph/9907360, hep-ph/9910267]
[Barger, Han, Li, Plehn, hep-ph/9907425]
[Choi, Guchait, Kalinowski, Zerwas, hep-ph/0001175]
[Choi, Djouadi, Guchait, Kalinowski, Song, Zerwas, hep-ph/0002033]
[Choi, Kalinowski, Moortgat-Pick, Zerwas, hep-ph/0108117, hep-ph/0202039]
[Gounaris, Mouël, hep-ph/0204152]
[Choi, Drees, Gaissmaier, hep-ph/0403054]

$\longrightarrow$ Determination of $|\mu|$, φ_μ, $|M_1|$, φ_{M_1}, M_2, $\tan\beta$ in principle possible

However: ambiguities for phases remain

- CP-odd/T-odd observables needed

recent studies e.g. [Choi, Kim, hep-ph/0311037]
[Choi, hep-ph/0308060, hep-ph/0409050]
[Aguilar-Saavedra, hep-ph/0403243, hep-ph/0404104, hep-ph/0410068]
[Eberl, Gajdosik, Majerotto, Schraußer, hep-ph/0502112]
[Choi, Chung, Kalinowski, Kim, Rolbiecki, hep-ph/0504122]
[Frank, Turan, de la Cruz do Oña, hep-ph/0508130]

Parameter determination

Comparison of real and complex scenarios

Scenario	$\lvert M_1 \rvert$	ϕ_{M_1}	M_2	μ	ϕ_μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
real	180	0	300	335	0	3	300	180
complex	181	0.04π	305	328	1.91π	3.2	297	181

- CP-even observables at $\sqrt{s}$ = 500 GeV ILC:

Scenario	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ for $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ =		
			(0, 0)	(−80%, +60%)	(+80%, −60%)
real	170.0	254.2	18.3	20.2	34.0
complex	169.1	252.3	18.2	19.7	34.1

- CP-odd observables:

  real: all CP-odd/T-odd asymmetries = 0

  complex: A_T = 5.2% for $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+})$ = (−80%, +60%)

  A_{CP} = 4.1% (with transverse polarization)

T-odd triple product asymmetries

Chargino/neutralino production with subsequent three-body decays

$$e^+e^- \longrightarrow \tilde{\chi}_i + \tilde{\chi}_j \longrightarrow \tilde{\chi}_i + \tilde{\chi}_1^0 f \bar{f}^{(\prime)}$$

- Full spin correlation between production and decay

  [Moortgat-Pick, Fraas, '97; Moortgat-Pick, Fraas, Bartl, Majerotto, '98, '99; Choi, Song, Song, '99]

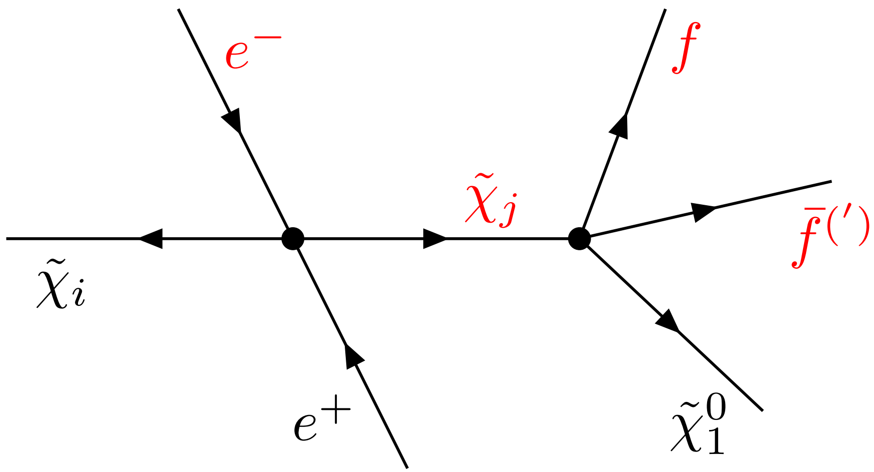
- Amplitude squared $|T|^2 = PD + \Sigma_P^a \Sigma_D^a$
- In Σ_P^a and Σ_D^a: products like $\boxed{i\epsilon_{\mu\nu\rho\sigma} p_i^\mu p_j^\nu p_k^\rho p_l^\sigma}$

  $\Rightarrow$ with complex couplings: real contributions to observables

  $\Rightarrow$ CP violation at tree level

T-odd triple product asymmetries

Triple products: $\boxed{\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_f \times \vec{p}_{\bar{f}^{(\prime)}})}$ or $\boxed{\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_j} \times \vec{p}_f)}$



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

$\longrightarrow$ CP-odd, if final state interactions and finite-widths effects can be neglected

T-odd asymmetry in $\tilde{\chi}^0$ sector

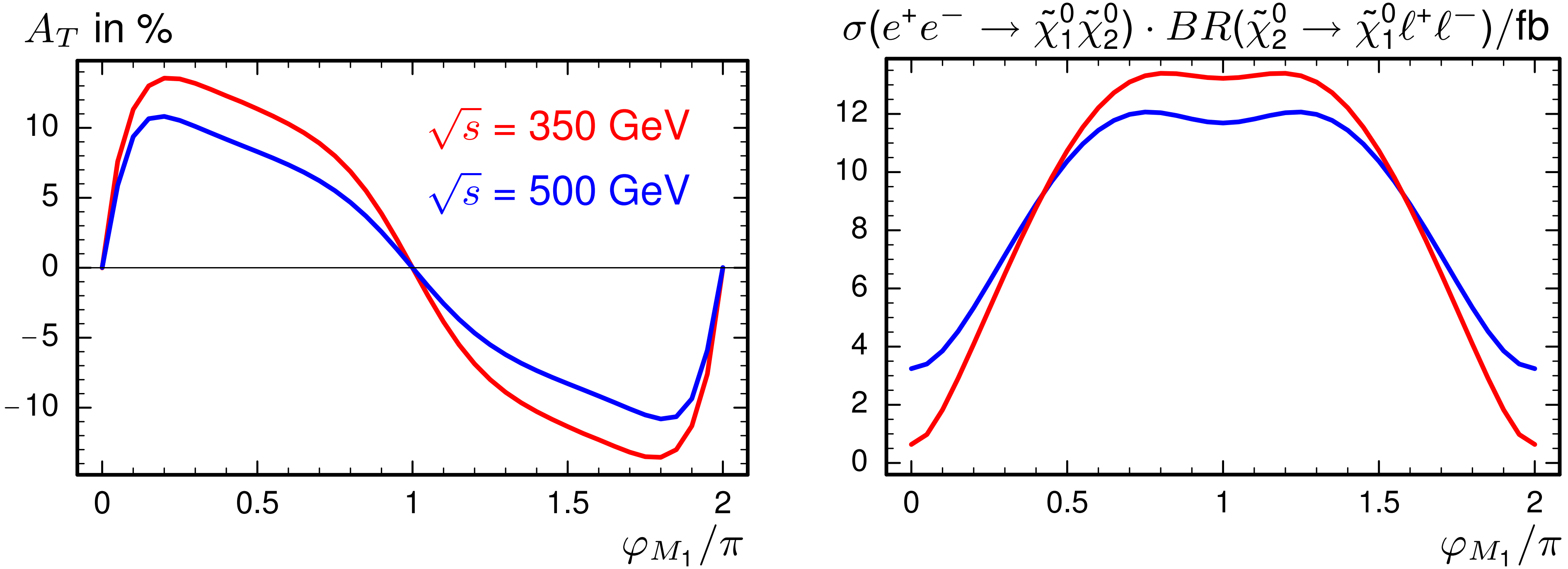
Asymmetry A_T for $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\ell^+} \times \vec{p}_{\ell^-})$

[Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, hep-ph/0406190]

- φ_{M_1} dependence

  $\tan\beta = 10$, $M_2 = 300$ GeV, $|M_1| = 150$ GeV, $|\mu| = 200$ GeV, $\varphi_\mu = 0$

  $m_{\tilde{e}_L} = 267.6$ GeV, $m_{\tilde{e}_R} = 224.4$ GeV, $\mathcal{P}_{e^-} = -0.8$, $\mathcal{P}_{e^+} = +0.6$



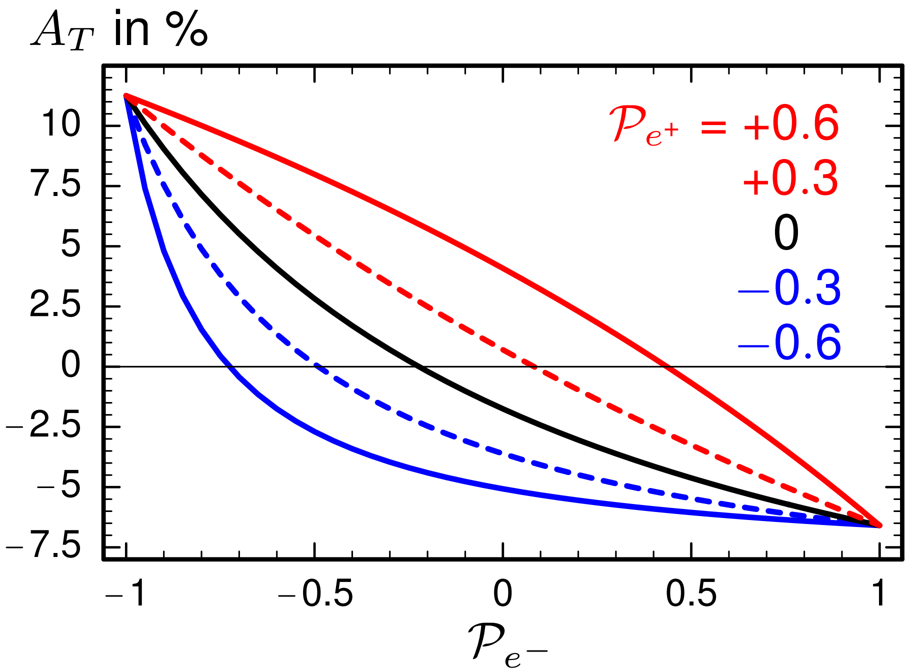
$\longrightarrow$ A_T larger closer to threshold (spin correlations)

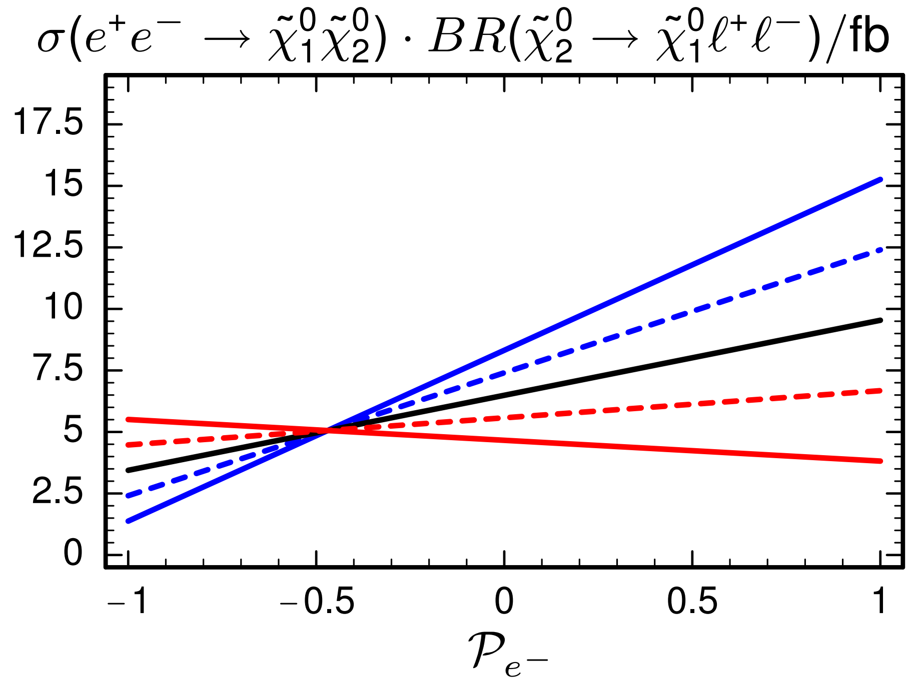
T-odd asymmetry in $\tilde{\chi}^0$ sector

- Polarization dependence [POWER report, hep-ph/0507011]

$\tan\beta$ = 10, M_2 = 300 GeV, $|M_1|$ = 150 GeV, $|\mu|$ = 200 GeV, φ_μ = 0

$m_{\tilde{e}_L}$ = 267.6 GeV, $m_{\tilde{e}_R}$ = 224.4 GeV, $\sqrt{s}$ = 500 GeV





$\longrightarrow$ e^- polarization considerably enhances A_T

$\longrightarrow$ e^+ polarization enhances rate

T-odd asymmetry in $\tilde{\chi}^0$ sector

Asymmetry A_T for $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1 q\bar{q}$, $q = c, b$, $\quad \mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_q \times \vec{p}_{\bar{q}})$

- Asymmetry A_T of same order of magnitude as for $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 e^+e^-$
- Cross section $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1 q\bar{q})$ can be a factor 5–10 larger
- However:
  - Distinction of b and $\bar{b}$ or c and $\bar{c}$ required
  - Resolution of jet momenta worse than for leptonic decays

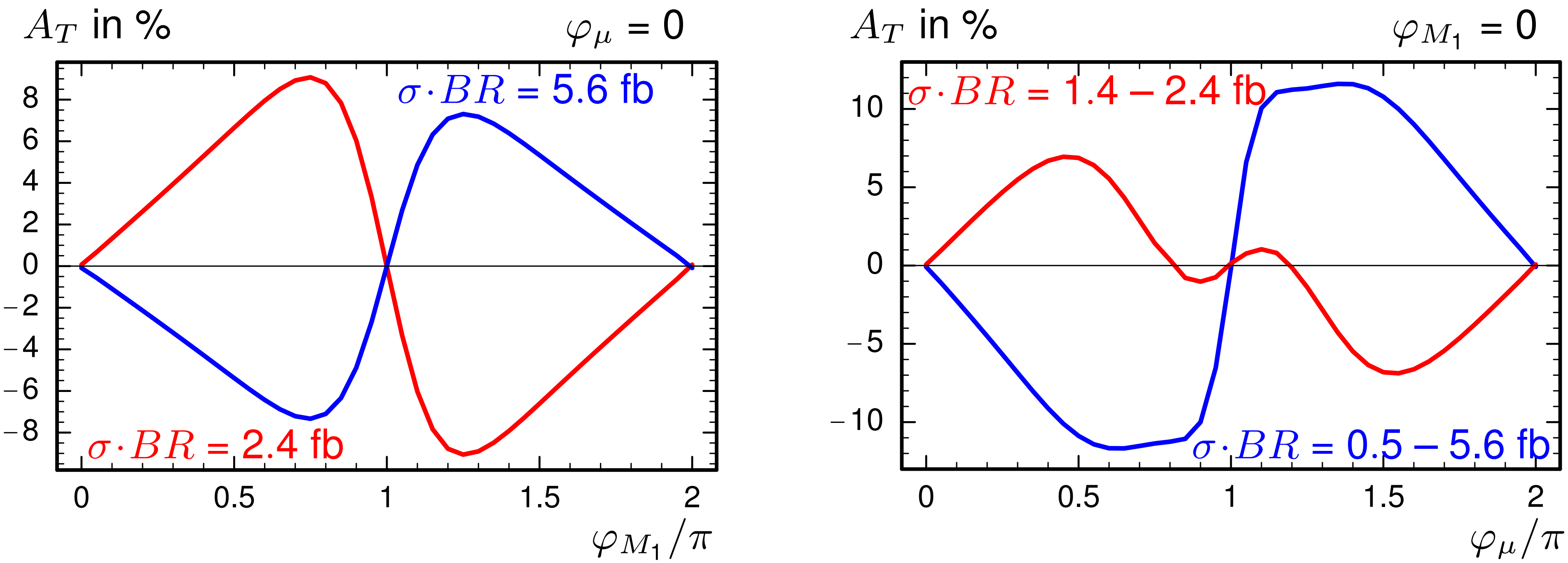
T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

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

[Bartl, Fraas, SH, Hohenwarter-Sodek, Moortgat-Pick, in preparation]

$\longrightarrow$ tagging of c jet important

$\tan\beta = 5$, $M_2 = 150$ GeV, $|M_1| = M_2\, 5/3 \tan^2\theta_W$, $|\mu| = 320$ GeV, $m_{\tilde{\nu}} = 250$ GeV, $m_{\tilde{u}_L} = 500$ GeV
$\sqrt{s} = 500$ GeV, $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (-0.8, +0.6)$, $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (+0.8, -0.6)$

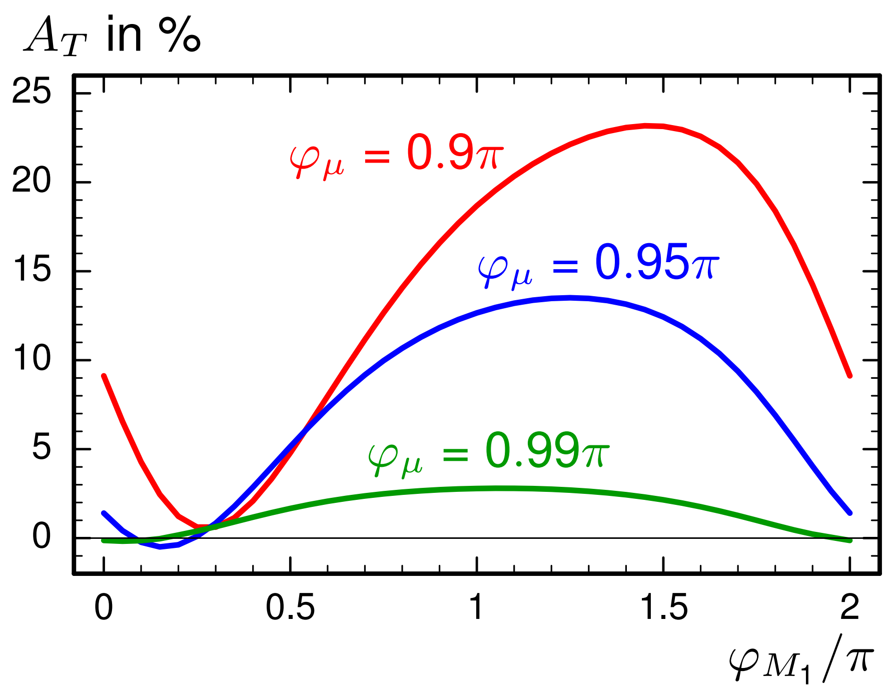


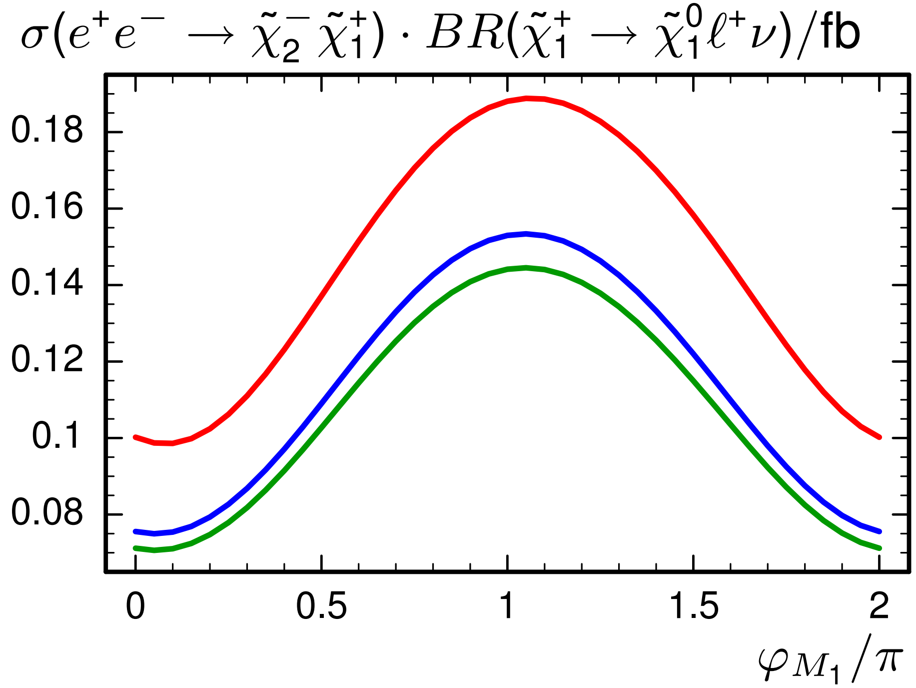
T-odd asymmetry in $\tilde{\chi}^{\pm}$ sector

Asymmetry A_T for $e^+e^- \to \tilde{\chi}_2^- \tilde{\chi}_1^+ \to \tilde{\chi}_2^- \tilde{\chi}_1^0 \ell^+ \nu$, $\mathcal{T} = \vec{p}_{e^-} \cdot (\vec{p}_{\tilde{\chi}_1^+} \times \vec{p}_{\ell^+})$

$\longrightarrow$ reconstruction of $\vec{p}_{\tilde{\chi}_1^+}$ with information from $\tilde{\chi}_2^-$ decay

$\tan\beta = 5$, $M_2 = 120$ GeV, $|M_1| = M_2\, 5/3 \tan^2\theta_W$, $|\mu| = 320$ GeV, $m_{\tilde{\nu}} = 250$ GeV,
$m_{\tilde{u}_L} = 500$ GeV, $\sqrt{s} = 500$ GeV, $P_{e^-} = -0.8$, $P_{e^+} = +0.6$





T-odd asymmetries for two-body decays

Chargino/neutralino production with subsequent two-body decays

- Leptonic decays:

$$e^+e^- \to \tilde{\chi}^0_1 + \tilde{\chi}^0_2 \to \tilde{\chi}^0_1 + \tilde{\ell}\ell_1, \quad \tilde{\ell} \to \tilde{\chi}^0_1 \ell_2 \qquad (\ell = e, \mu, \tau)$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0308141, hep-ph/0308143]

[Bartl, Fraas, Kernreiter, Kittel, W. Majerotto, hep-ph/0310011]

$$e^+e^- \to \tilde{\chi}^-_i + \tilde{\chi}^+_j \to \tilde{\chi}^-_i + \tilde{\nu}\ell^+$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0406309]

- Decays into Z and W:

$$e^+e^- \to \tilde{\chi}^0_i + \tilde{\chi}^0_j \to \tilde{\chi}^0_i + \tilde{\chi}^0_n Z, \quad Z \to \ell\bar{\ell}, q\bar{q}$$

[Bartl, Fraas, Kittel, Majerotto, hep-ph/0402016]

$$e^+e^- \to \tilde{\chi}^-_i + \tilde{\chi}^+_j \to \tilde{\chi}^-_i + \tilde{\chi}^0_n W^+, \quad W^+ \to c\bar{s}$$

[Bartl, Fraas, Kernreiter, Kittel, Majerotto, hep-ph/0410054]

- CP asymmetries using tau polarization for $\ell = \tau$

[Bartl, Kernreiter, Kittel, hep-ph/0309340; Choi, Drees, Gaissmaier, Song, hep-ph/0310284]

Transverse beam polarization

Chargino/neutralino production

$$e^+e^- \longrightarrow \tilde{\chi}_i + \tilde{\chi}_j$$

with transverse beam polarization (4-vector $t^\mu_\pm$, polarization degree $\mathcal{P}^T_{e^\pm}$)

- Terms in amplitude squared $|T|^2 = P$ depending on $\mathcal{P}^T_{e^\pm}$:

  $P_T \sim \mathcal{P}^T_{e^-}\mathcal{P}^T_{e^+}\,[f_1\Delta_1 r_1 + f_2\Delta_2 r_2]$

  f_i: couplings; Δ_i: propagators; r_i: products of $t_\pm$ and momenta

  $\Rightarrow$ both beams have to be polarized (in limit $m_e = 0$!)

  [POWER report, hep-ph/0507011]

- r_1 is real; r_2 is imaginary, consisting of products like $\boxed{i\epsilon_{\mu\nu\rho\sigma}t^\mu_\pm p^\nu_i p^\rho_j p^\sigma_k}$

  $\Rightarrow$ with complex couplings f_2: real contributions to observables

  $\Rightarrow$ CP-odd terms $\sim$ Im$(f_2\Delta_2)$Im(r_2) at tree level

Transverse beam polarization

- Chargino production:

  Dirac particles: couplings $f_2\Delta_2$ have to be real (CPT invariance)

  $\Rightarrow$ CP-odd terms $f_2\Delta_2 r_2$ vanish

  [Bartl, Hohenwarter-Sodek, Kernreiter, Rud, hep-ph/0403265]

  $\rightarrow$ CP-even asymmetries can be defined with help of $f_1\Delta_1 r_1$

- Neutralino production:

  Majorana particles: t and u channels contribute

  $\Rightarrow$ CP-odd terms $f_2\Delta_2 r_2 \neq 0$ allowed

  $\Rightarrow$ CP-odd observables can be defined

Transverse beam polarization

- $f_2 \Delta_2 r_2 \sim \sin(\eta - 2\phi)$

  with ϕ: azimuthal angle of scattering plane; η: orientation of transverse polarizations

- CP-odd asymmetry

  - ϕ integration:

$$\boxed{A_{CP}(\theta) = \frac{1}{\sigma}\left[\int_{\frac{\eta}{2}}^{\frac{\pi}{2}+\frac{\eta}{2}} - \int_{\frac{\pi}{2}+\frac{\eta}{2}}^{\pi+\frac{\eta}{2}} + \int_{\pi+\frac{\eta}{2}}^{\frac{3\pi}{2}+\frac{\eta}{2}} - \int_{\frac{3\pi}{2}+\frac{\eta}{2}}^{2\pi+\frac{\eta}{2}}\right] \frac{d^2\sigma}{d\phi\, d\theta} d\phi}$$

  - θ integration:

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

$\longrightarrow$ 8 sectors with alternating sign

Transverse beam polarization

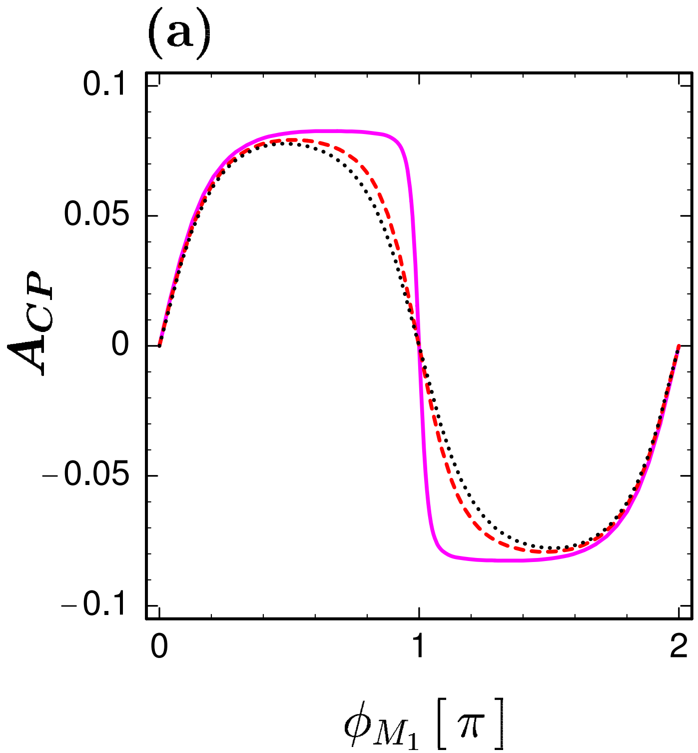
Asymmetry A_{CP} for $e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0$

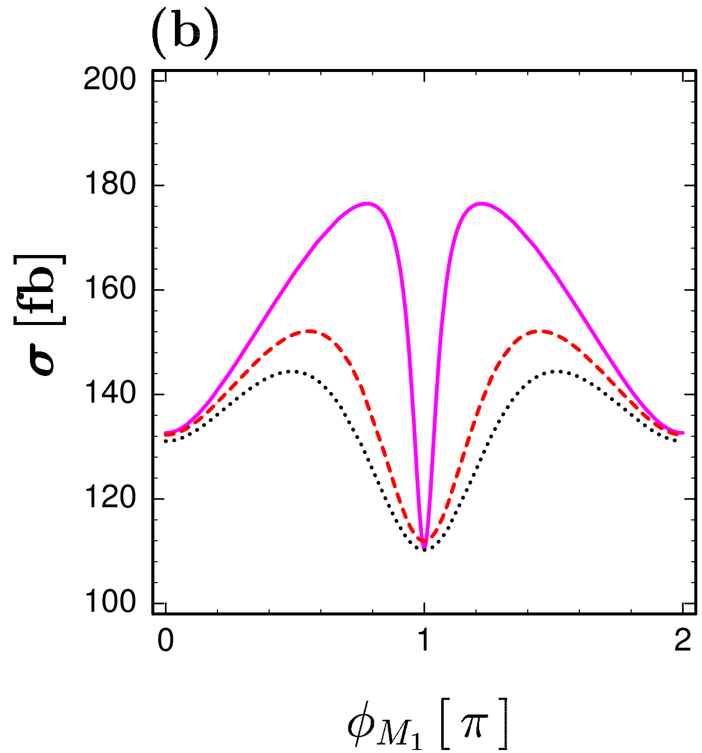
[Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, in preparation]

M_2 = 245 GeV, $|M_1|$ = 123.3 GeV, $|\mu|$ = 160 GeV, ϕ_μ = 0, $m_{\tilde{e}_L}$ = 400 GeV, $m_{\tilde{e}_R}$ = 150 GeV

$\sqrt{s}$ = 500 GeV, $(\mathcal{P}^T_{e^-}, \mathcal{P}^T_{e^+})$ = (100%, 100%)

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





Transverse beam polarization

Asymmetries including neutralino decay

$$e^+e^- \longrightarrow \tilde{\chi}_i^0 + \tilde{\chi}_j^0 \longrightarrow \tilde{\chi}_i^0 + \tilde{\ell}^{\pm}_{L,R}\ell_1^{\mp} \longrightarrow \tilde{\chi}_i^0 + \tilde{\chi}_1^0 \ell_1^{\mp}\ell_2^{\pm}$$

- $A_1^{\mp} = \frac{1}{\sigma_1}\left[\int_{\frac{\eta}{2}}^{\frac{\pi}{2}+\frac{\eta}{2}} - \int_{\frac{\pi}{2}+\frac{\eta}{2}}^{\pi+\frac{\eta}{2}} + \int_{\pi+\frac{\eta}{2}}^{\frac{3\pi}{2}+\frac{\eta}{2}} - \int_{\frac{3\pi}{2}+\frac{\eta}{2}}^{2\pi+\frac{\eta}{2}}\right]\frac{\mathrm{d}\sigma_1}{\mathrm{d}\phi_{\ell_1^{\mp}}}\mathrm{d}\phi_{\ell_1^{\mp}}$

  with $\sigma_1 = \sigma(e^+e^- \longrightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0) \times BR(\tilde{\chi}_j^0 \longrightarrow \tilde{\ell}\ell_1)$

- $A_2^{\pm} = \frac{1}{\sigma_2}\left[\int_{\frac{\eta}{2}}^{\frac{\pi}{2}+\frac{\eta}{2}} - \int_{\frac{\pi}{2}+\frac{\eta}{2}}^{\pi+\frac{\eta}{2}} + \int_{\pi+\frac{\eta}{2}}^{\frac{3\pi}{2}+\frac{\eta}{2}} - \int_{\frac{3\pi}{2}+\frac{\eta}{2}}^{2\pi+\frac{\eta}{2}}\right]\frac{\mathrm{d}\sigma_2}{\mathrm{d}\phi_{\ell_2^{\pm}}}\mathrm{d}\phi_{\ell_2^{\pm}}$

  with $\sigma_1 = \sigma(e^+e^- \longrightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0) \times BR(\tilde{\chi}_j^0 \longrightarrow \tilde{\ell}\ell_1) \times BR(\tilde{\ell} \longrightarrow \tilde{\chi}_1^0\ell_2)$

$\longrightarrow$ Distinguishing of ℓ_1 and ℓ_2 necessary (energy/angular distributions)

$\longrightarrow$ $A_i^- = -A_i^+$

Transverse beam polarization

Asymmetries including neutralino decay

- $$A'^{-} = \frac{(\int^{+} - \int^{-})(\frac{d\sigma_1}{d\phi_{\ell_1}} d\phi_{\ell_1} + \frac{d\sigma_2}{d\phi_{\ell_2}} d\phi_{\ell_2})}{\int_0^{2\pi}(\frac{d\sigma_1}{d\phi_{\ell_1}} d\phi_{\ell_1} + \frac{d\sigma_2}{d\phi_{\ell_2}} d\phi_{\ell_2})} = \frac{A_1^{-} + A_2^{-}\, BR(\tilde{\ell} \to \ell\tilde{\chi}_1^0)}{1 + BR(\tilde{\ell} \to \ell\tilde{\chi}_1^0)}$$

  $\int^{\pm}$: integration over regions where $\sin(\eta - 2\phi_{1,2})$ is positive/negative

$\longrightarrow$ Only measurement of charges of ℓ_1 and ℓ_2 necessary
(no distinguishing of ℓ_1 and ℓ_2 required)

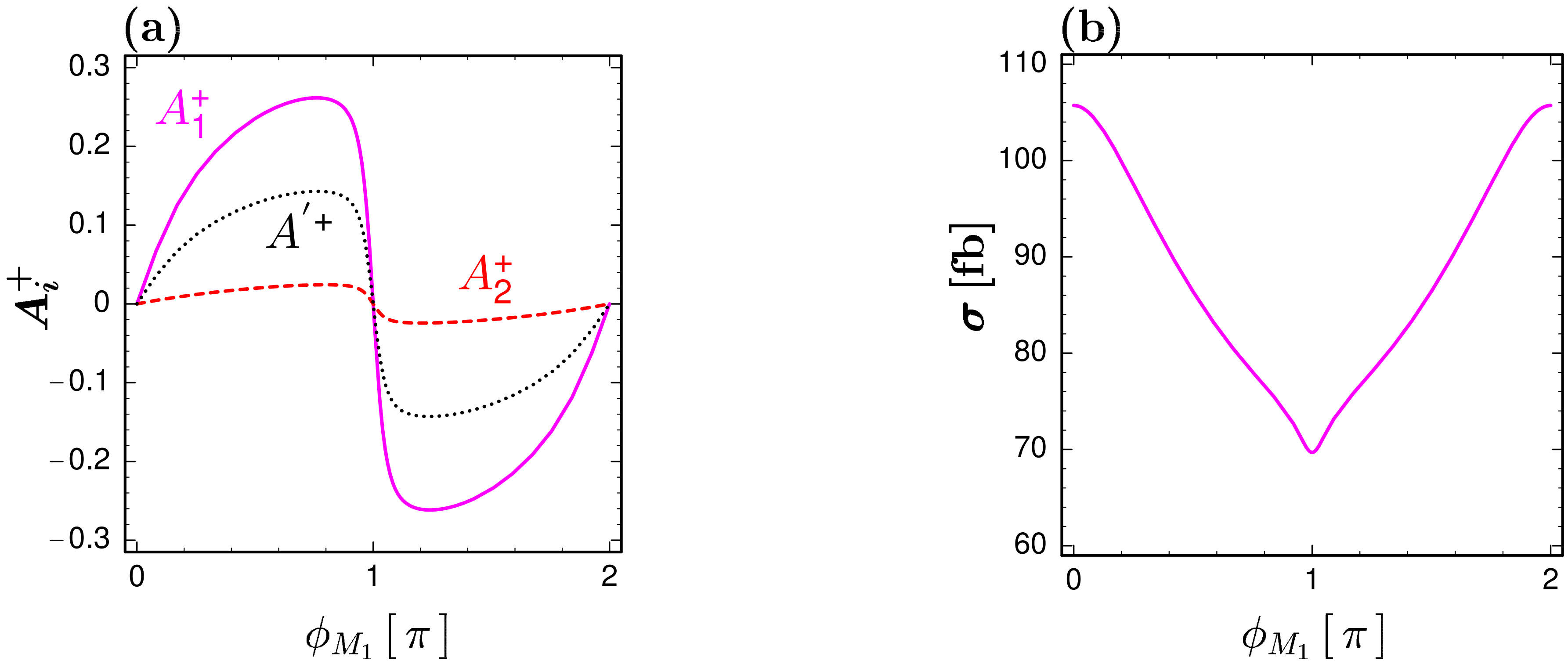
Transverse beam polarization

Asymmetries A_1^+, A_2^+, A'^+ for $e^+e^- \to \tilde{\chi}_1^0 + \tilde{\chi}_3^0 \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0 \ell_1^\mp \ell_2^\pm$

[Bartl, Fraas, SH, Hohenwarter-Sodek, Kernreiter, Moortgat-Pick, in preparation]

M_2 = 245 GeV, $|M_1|$ = 123.3 GeV, $|\mu|$ = 160 GeV, ϕ_μ = 0, tan β = 3

$m_{\tilde{e}_L}$ = 400 GeV, $m_{\tilde{e}_R}$ = 150 GeV; $\sqrt{s}$ = 500 GeV, $(\mathcal{P}^T_{e^-}, \mathcal{P}^T_{e^+})$ = (100%, 100%)



Conclusions

- T-odd/CP-odd asymmetries in chargino/neutralino production + decay
- T-odd triple product asymmetries
  $\longrightarrow$ full spin correlations between production and decay necessary
- CP-odd asymmetries with transverse beam polarization
  $\longrightarrow$ both beams have to be polarized
- Charginos: leptonic decays: reconstruction of $p(\tilde{\chi}^+)$
  hadronic decays: discrimination of $c \leftrightarrow s$ jets
- Neutralinos: hadronic decays: discrimination of $c \leftrightarrow \bar{c}$ or $b \leftrightarrow \bar{b}$
- Beam polarization is important
- Asymmetries of $\mathcal{O}(20\,\%)$ possible
  $\Rightarrow$ important tool for $\longrightarrow$ search for CP violation in SUSY
  $\longrightarrow$ unambiguous determination of SUSY phases