CP violation in the neutralino/chargino sector with transverse beam polarization

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Outline

Introduction

→ MSSM with complex parameters

→ neutralino/chargino mixing in complex MSSM

CP violation in neutralino production and decay

CP sensitive observables in chargino production and decay

Conclusion

Introduction

Minimal Supersymmetric Standard Model (MSSM)

$\rightarrow$ minimal extension of Standard Model (SM)

$\rightarrow$ SM gauge group

$\rightarrow$ minimal Higgs sector: 2 doublets

MSSM with complex parameters

General MSSM:

Complex parameters in Higgs potential and soft SUSY breaking terms

$\rightarrow$ Introduction of CP violation

- $\rightarrow$ may help to explain baryon asymmetry of universe
- $\rightarrow$ constraints from electric dipole moments (EDMs)

  of e, n, Hg, Tl

Neutralino and chargino mixing

Neutralino mass matrix:

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

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

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

μ : Higgs-higgsino mass parameter $\rightarrow$ complex

M_1 : U(1) gaugino mass parameter $\rightarrow$ complex

M_2 : SU(2) gaugino mass parameter

CP violation in the neutralino sector with transverse beam polarization

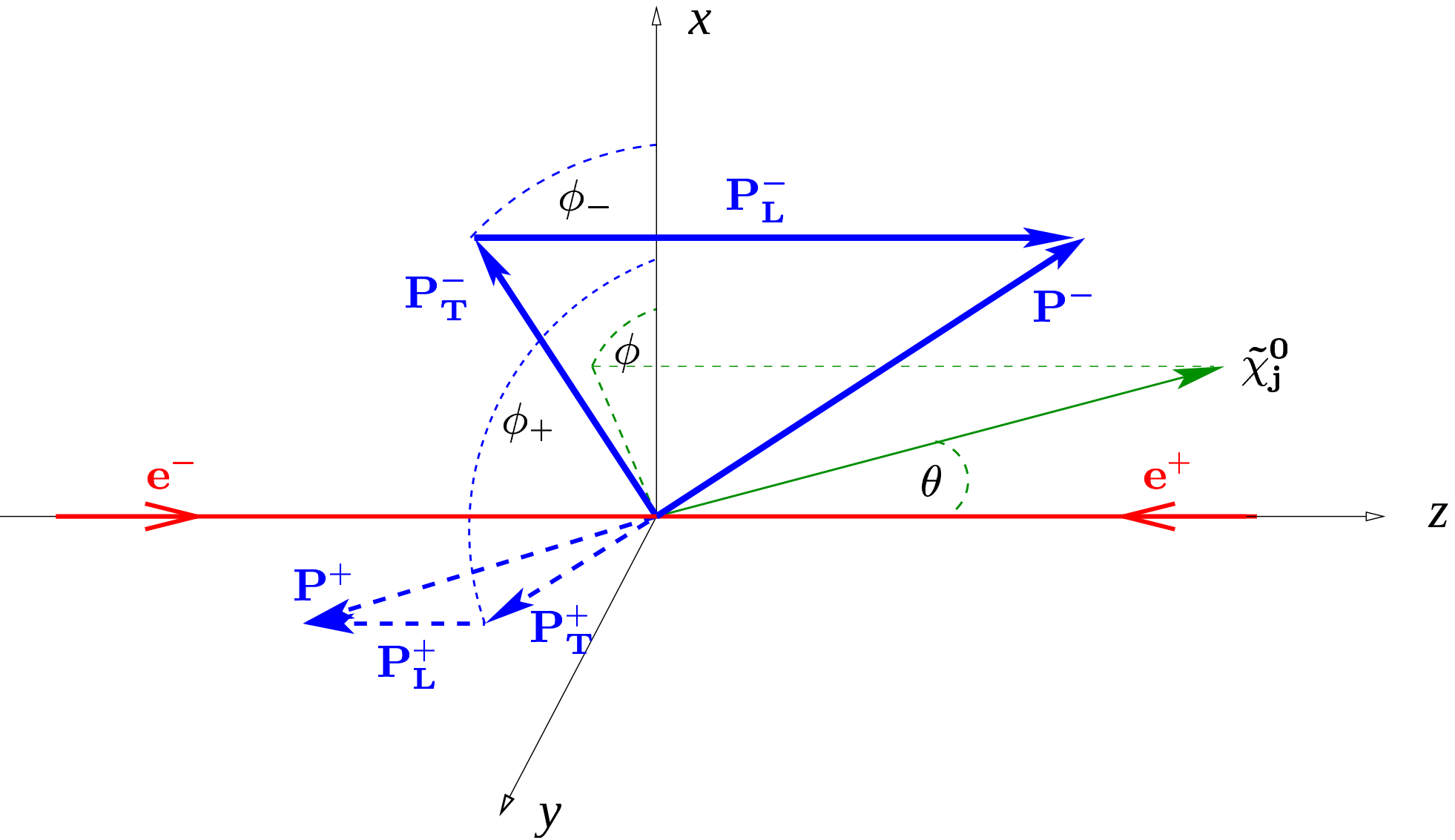
neutralino production

$$e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0 \,, \qquad i,j = 1,\ldots,4$$

and subsequent two-body decay processes

$$\tilde{\chi}_j^0 \to \ell^\pm \tilde{\ell}_n^\mp \to \ell^\pm \ell^\mp \tilde{\chi}_1^0 \,, \qquad n = 1,2$$

$\to$ with spin correlation between production and decay


x
ϕ_-
$\mathbf{P_L^-}$
$\mathbf{P_T^-}$
$\mathbf{P^-}$
ϕ
$\tilde{\chi}_\mathbf{j}^\mathbf{0}$
ϕ_+
$\mathbf{e^-}$
θ
$\mathbf{e^+}$
z
$\mathbf{P^+}$
$\mathbf{P_T^+}$
$\mathbf{P_L^+}$
y

CP asymmetries in neutralino production

→ production cross section

$$\mathrm{d}\sigma = \frac{1}{2(2\pi)^2}\frac{q}{s^{3/2}}\, P(\tilde{\chi}_i^0\tilde{\chi}_j^0)\, \mathrm{d}\cos\theta\, \mathrm{d}\phi$$

→ contributions dependent on transverse beam polarization

$$P_T = \mathcal{P}_T^- \mathcal{P}_T^+ \Big(\underbrace{\mathrm{Re}\{a\, \cos(\eta - 2\phi)\}}_{\text{CP-even}} + \underbrace{\mathrm{Im}\{b\, \sin(\eta - 2\phi)\}}_{\text{CP-odd}} \Big)$$

$(\eta = \phi_- + \phi_+)$

→ extraction of the CP violating contributions

$$A_{CP}(\theta) = \frac{\mathrm{N}[\sin(\eta-2\phi)>0;\theta] - \mathrm{N}[\sin(\eta-2\phi)<0;\theta]}{\mathrm{N}[\sin(\eta-2\phi)>0;\theta] + \mathrm{N}[\sin(\eta-2\phi)<0;\theta]}$$

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

→ CP-odd observable

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

CP asymmetries in neutralino production and decay

$\rightarrow$ amplitude squared for production and decay

$$|T|^2 = PD + \Sigma_P^a \Sigma_D^a$$

$\rightarrow$ contributions dependent on transverse beam polarization

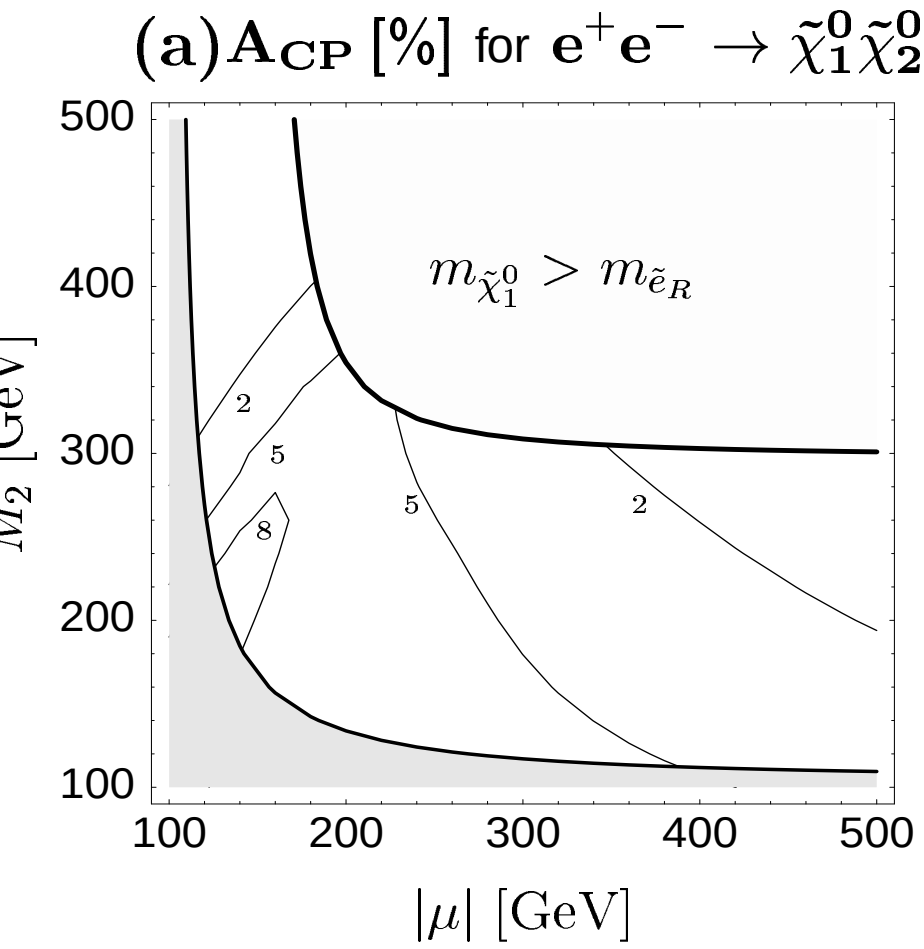
$$\Sigma_{P,T}^a = \mathcal{P}_T^- \mathcal{P}_T^+ \Big(\underbrace{\mathsf{Re}\{A\ \mathsf{cos}(\eta - 2\phi_\ell)\}}_{\text{CP-even}} + \underbrace{\mathsf{Im}\{B\ \mathsf{sin}(\eta - 2\phi_\ell)\}}_{\text{CP-odd}} \Big)$$

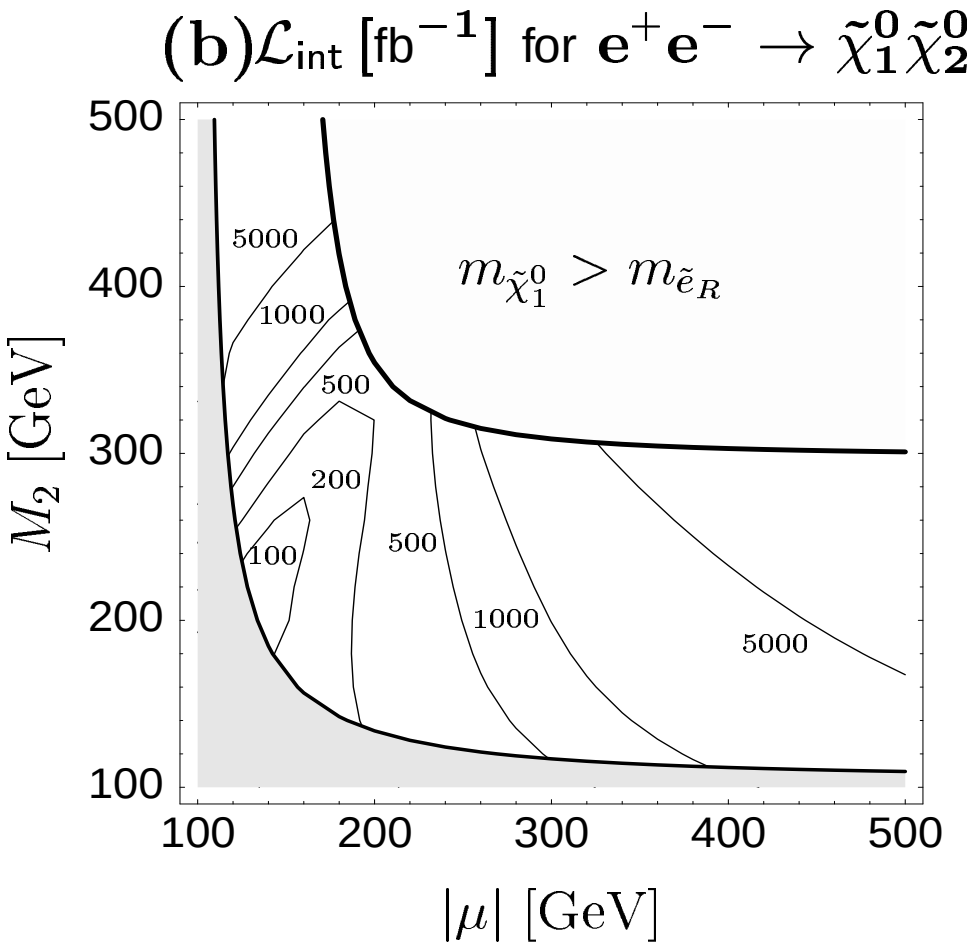
CP-odd asymmetry for $e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0$ and $\tilde{\chi}_j^0 \to \ell_1^- \tilde{\ell}^+$:

$$A_1^- = \frac{\mathsf{N}[\sin(\eta - 2\phi_{\ell_1}) > 0] - \mathsf{N}[\sin(\eta - 2\phi_{\ell_1}) < 0]}{\mathsf{N}[\sin(\eta - 2\phi_{\ell_1}) > 0] + \mathsf{N}[\sin(\eta - 2\phi_{\ell_1}) < 0]}$$

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

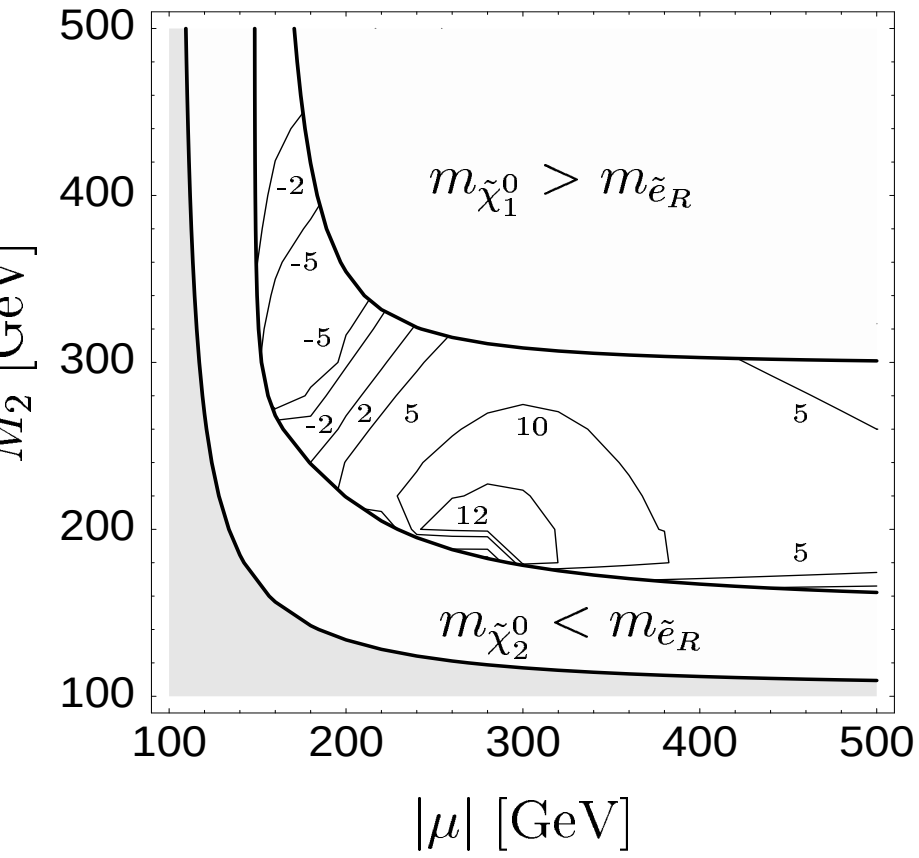
$$(\sigma_1 = \sigma(e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_j^0) \times B(\tilde{\chi}_j^0 \to \tilde{\ell}^+ \ell_1^-))$$



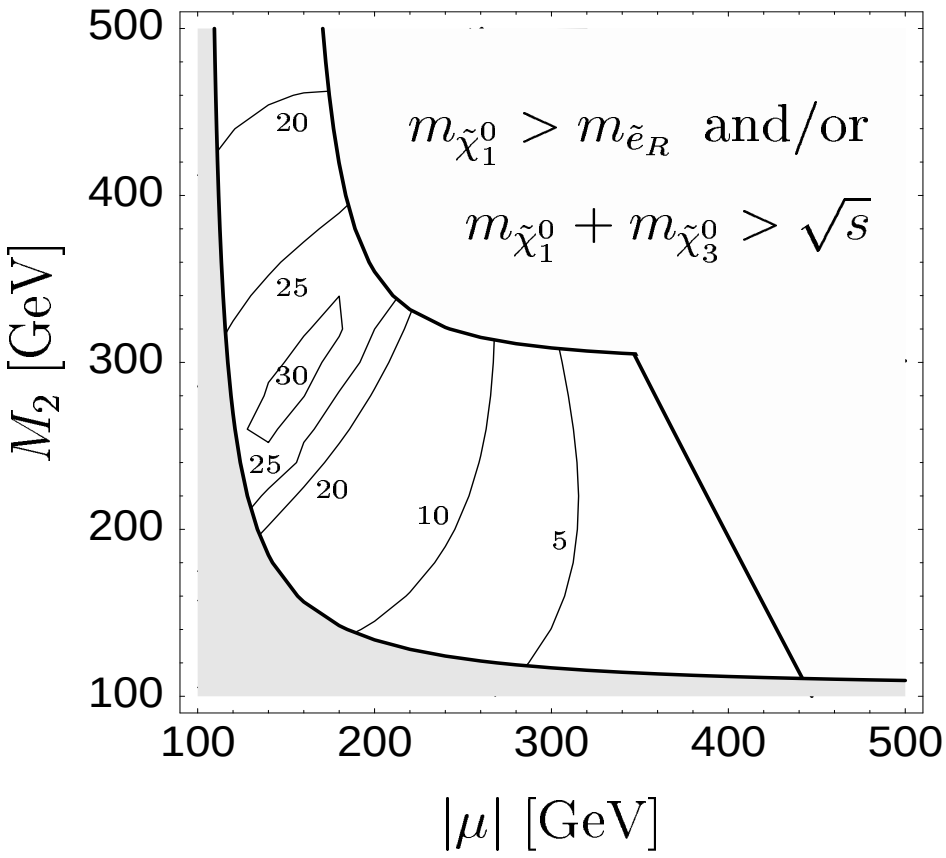


ϕ_{M_1}	ϕ_μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
0.5π	0	3	400	120

$\mathbf{A_1^+}$ [%] for
$\mathbf{(a) e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\ell}_R^- \ell_1^+}$



$\mathbf{A_1^+}$ [%] for
$\mathbf{(b) e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_3^0 \to \tilde{\chi}_1^0 \tilde{\ell}_R^- \ell_1^+}$



ϕ_{M_1}	ϕ_μ	$\tan\beta$	$m_{\tilde{e}_L}$	$m_{\tilde{e}_R}$
0.5π	0	3	400	150

CP violation in the chargino sector with transverse beam polarization

chargino production

$$e^+e^- \to \tilde{\chi}_i^+ \tilde{\chi}_j^- \ , \qquad i,j = 1,2$$

and subsequent two-body decay processes

$$\tilde{\chi}_j^- \to \tilde{\nu}_\ell \ell^- \quad \text{and} \quad \tilde{\chi}_j^- \to W^- \tilde{\chi}_1^0$$

$\to$ with spin correlation between production and decay

→ contributions dependent on transverse beam polarization

$$P_T = \mathcal{P}_T^- \mathcal{P}_T^+ \Big(\underbrace{\mathrm{Re}\{a\ \cos(\eta - 2\phi)\}}_{\mathrm{CP-even}} + \underbrace{\mathrm{Im}\{b\ \sin(\eta - 2\phi)\}}_{0} \Big)$$

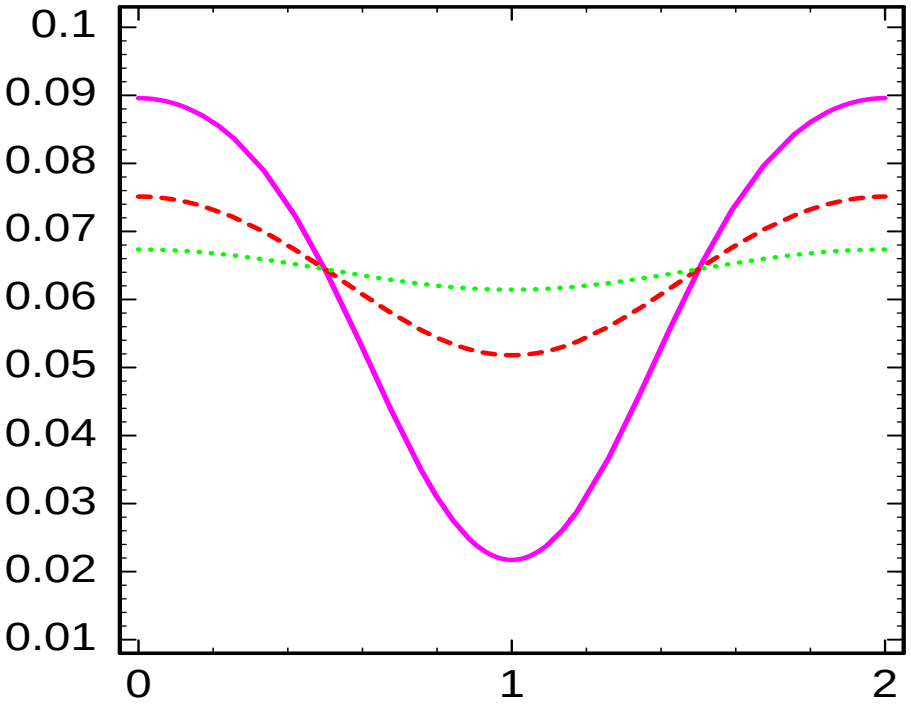
$$\Sigma^a_{P,T} = \mathcal{P}_T^- \mathcal{P}_T^+ \Big(\underbrace{\mathrm{Re}\{A\ \cos(\eta - 2\phi_\ell)\}}_{\mathrm{CP-even}} + \underbrace{\mathrm{Im}\{B\ \sin(\eta - 2\phi_\ell)\}}_{0} \Big)$$

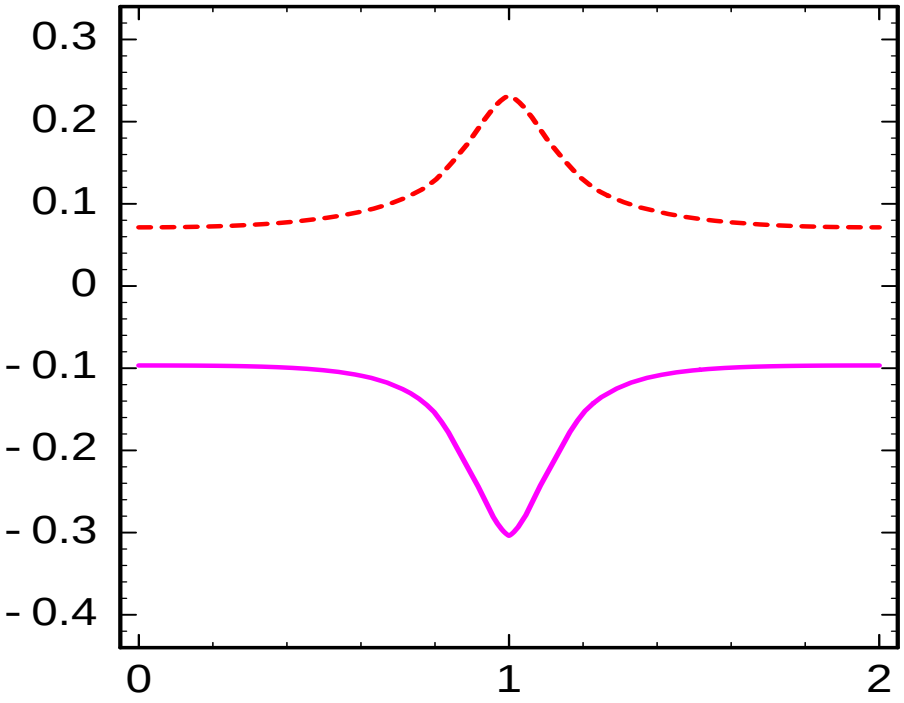
→ the coupling $V_{i1}^* V_{j1} O'^L_{ij}$ is real

CP-even observable

$$A_\phi = \frac{\mathrm{N}[\cos(\eta - 2\phi) > 0] - \mathrm{N}[\cos(\eta - 2\phi) < 0]}{\mathrm{N}[\cos(\eta - 2\phi) > 0] + \mathrm{N}[\cos(\eta - 2\phi) < 0]}$$

$$= \frac{1}{\sigma}\left[-\int_{\frac{\pi}{4}+\frac{\eta}{2}}^{\frac{3\pi}{4}+\frac{\eta}{2}} + \int_{\frac{3\pi}{4}+\frac{\eta}{2}}^{\frac{5\pi}{4}+\frac{\eta}{2}} - \int_{\frac{5\pi}{4}+\frac{\eta}{2}}^{\frac{7\pi}{4}+\frac{\eta}{2}} + \int_{\frac{7\pi}{4}+\frac{\eta}{2}}^{\frac{9\pi}{4}+\frac{\eta}{2}} \right] \frac{\mathrm{d}\sigma}{\mathrm{d}\phi}\,\mathrm{d}\phi$$





$\rightarrow$ Figure a: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^- \rightarrow \tilde{\nu}_\ell \ell^-$

$|\mu| = 300$ GeV, $M_2 = 200$ GeV, $m_{\tilde{\nu}} = 150$ GeV, $\sqrt{s} = 500$ GeV,

$\tan\beta = 3, 10, 40$, $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-) \approx 200$ fb

$\rightarrow$ Figure b: $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_2^-$, $\tilde{\chi}_2^- \rightarrow \tilde{\nu}_\ell \ell^-$ und $\tilde{\chi}_2^- \rightarrow W^-\tilde{\chi}_1^0$

$|\mu| = 400$ GeV, $M_2 = 200$ GeV, $m_{\tilde{\nu}} = 150$ GeV, $\sqrt{s} = 800$ GeV,

$\tan\beta = 3$

Conclusion

Transverse beam polarization in neutralino production and decay:

$\rightarrow e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$

$\rightarrow$ construction of CP-even and CP-odd observables

$\rightarrow$ CP-odd asymmetries of the order of 10%

$\rightarrow$ measurable in a broad range of the parameter space

Transverse beam polarization in chargino production and decay:

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

$\rightarrow$ construction of CP-even observables