Can CP violation be observed in $\tilde{\chi}_2^0$ production and decay?

Based on

J.A.A.-S. PLB 596, 247 (2004)

J.A.A.-S. NPB 697, 207 (2004)

★ Short answer: "yes" ☺

★ Not-so-short answer:

- Two processes:

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

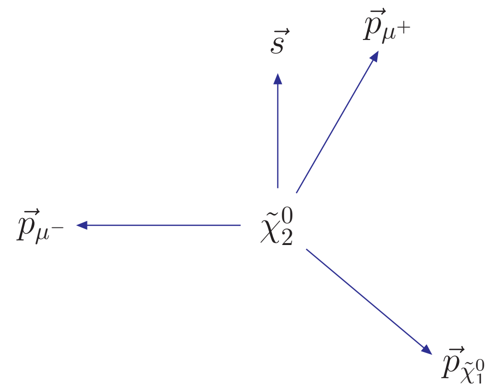
$$e^+e^- \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ell^+ \ell^-$$

- Define CP-violating asymmetries
- Observability depends on SUSY scenario
- Important backgrounds

Processes:

★ Selectron cascade decays

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

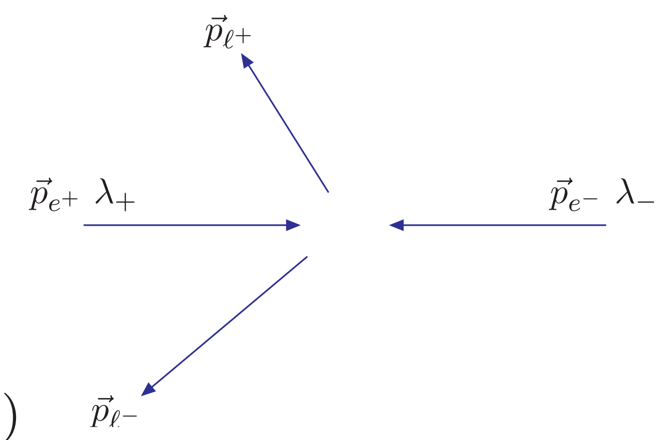


CP-odd, T-odd product $Q_1 = \vec{s} \cdot (\vec{p}_{\mu^-} \times \vec{p}_{\mu^+})$

also: CP-odd T-even product $Q_2 = \vec{s} \cdot (\vec{p}_{\mu^-} + \vec{p}_{\mu^+})$

★ $\tilde{\chi}_1^0\tilde{\chi}_2^0$ production

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



CP-odd, T-odd product $Q_1 = \vec{p}_{e+} \cdot (\vec{p}_{\ell-} \times \vec{p}_{\ell+})$

also: CP-odd T-even product $Q_2 = \vec{p}_{e+} \cdot (\vec{p}_{\ell-} + \vec{p}_{\ell+})$

CP asymmetries

$$Q_1 = \begin{cases} \vec{s} \cdot (\vec{p}_{\mu^-} \times \vec{p}_{\mu^+}) & \tilde{e}_L \text{ decays} \\ \vec{p}_{e^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}) & \tilde{\chi}_1^0 \tilde{\chi}_2^0 \text{ prod.} \end{cases}$$

Asymmetries based on Q_2 require absorptive parts

★ Without background:

$$A_1 = \frac{N(Q>0) - N(Q<0)}{N(Q>0) + N(Q<0)}$$

$$\Delta A_1 = \sqrt{\frac{1 - A^2}{N}}$$

with N = number of (signal) events

★ With background:

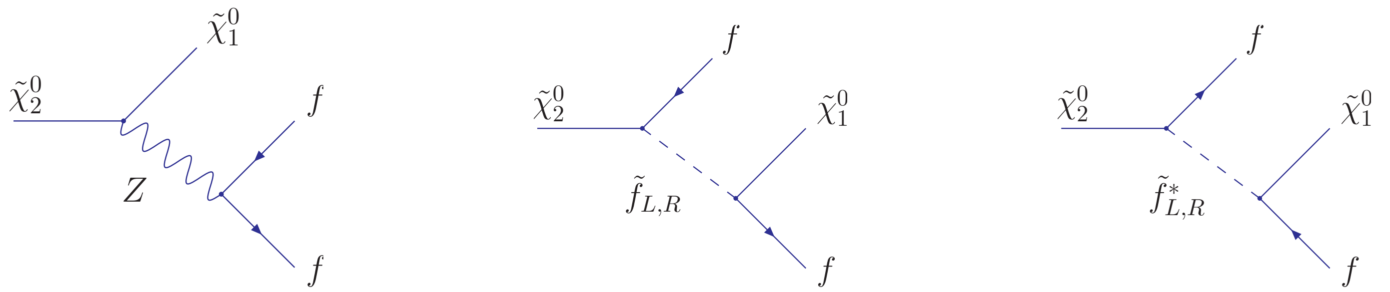
$N = S$ (signal) $+B$ (background)

In case $B(Q>0) = B(Q<0)$

$$r \equiv \frac{S}{S+B} \quad \longrightarrow \quad \begin{array}{l} A_1^{\text{eff}} = r\, A_1 \\ \\ \Delta A_1^{\text{eff}} \simeq \sqrt{r}\, \Delta A_1 \end{array}$$

☞ $$(A_1^{\text{eff}} / \Delta A_1^{\text{eff}}) = \sqrt{r}\, (A_1 / \Delta A_1)$$

$\tilde{\chi}_2^0$ decay



SUSY scenarios vs CP asymmetry

	$\tilde{\chi}_2^0$ decay mode			
Process	Three-body	$\tilde{\chi}_2^0 \to \ell^\pm \, \tilde{\ell}_R^\mp$	$\tilde{\chi}_2^0 \to \ell^\pm \, \tilde{\ell}_L^\mp$	$\tilde{\chi}_2^0 \to Z \tilde{\chi}_1^0$
$\tilde{e}_L$ decay	☺	☹	✗	☹
$\tilde{\chi}_1^0 \tilde{\chi}_2^0$ prod.	☺	☺	☺	☹

We choose:

- One scenario with $\tilde{\chi}_2^0 \to \ell^\pm \, \tilde{\ell}_R^\mp$
- One scenario with $\tilde{\chi}_2^0$ 3-body decays

☞ Survey of scenarios ($\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production):

Bartl et al., PRD 69, 035007 (2004)
Bartl et al., EPJC 36, 233 (2004)
Bartl et al., hep-ph/0406190

Parameter	Scenario 1	Scenario 2
M_1	$101.8\ e^{i\phi_1}$	$102.0\ e^{i\phi_1}$
M_2	191.8	192.0
μ	$358.5\ e^{i\phi_\mu}$	$377.5\ e^{i\phi_\mu}$
$\tan\beta$	10	10
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	142.5	224.0
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	200.7	264.5
$m_{\tilde{\chi}_1^0}$	98.7	99.1
$m_{\tilde{\chi}_2^0}$	176.4	178.1

Approximately:

$$m_{1/2} = 250 \text{ GeV}$$

$$m_0 = 100, 200 \text{ GeV}$$

$$A_0 = -100, -200 \text{ GeV}$$

$$\tan\beta = 10$$

$+$ phases in M_1, μ

Checked that electron EDM within experimental limits

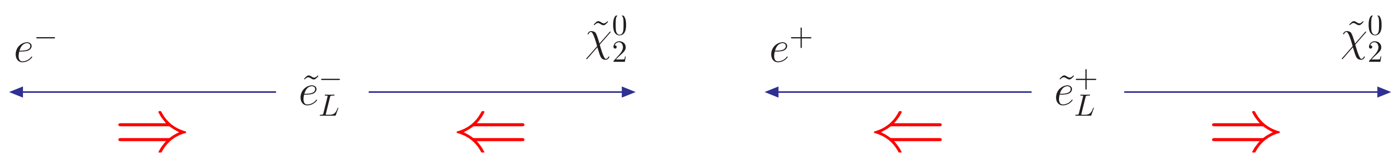
$$\text{For } 0 \leq \phi_1 \leq 2\pi \begin{cases} |\phi_\mu| \leq 0.08 & \text{Scenario 1} \\ |\phi_\mu| \leq 0.12 & \text{Scenario 2} \end{cases}$$

☞ Take $\phi_\mu = 0$

CP asymmetry in $\tilde{e}_L$ cascade decays

$\tilde{e}_L$ decays $\tilde{e}_L \to e\tilde{\chi}_2^0 \to e\tilde{\chi}_1^0 \mu^+\mu^-$ used as a source of polarised $\tilde{\chi}_2^0$

$$\mathcal{L} = a_L \; \tilde{e}_L^* \, \overline{\tilde{\chi}_2^0} P_L \, e + a_L^* \; \tilde{e}_L \, \bar{e} \, P_R \, \tilde{\chi}_2^0$$

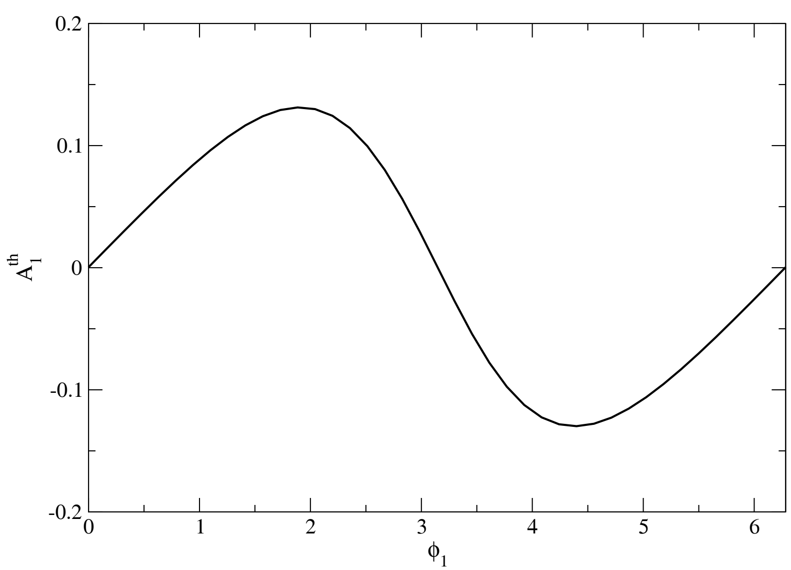


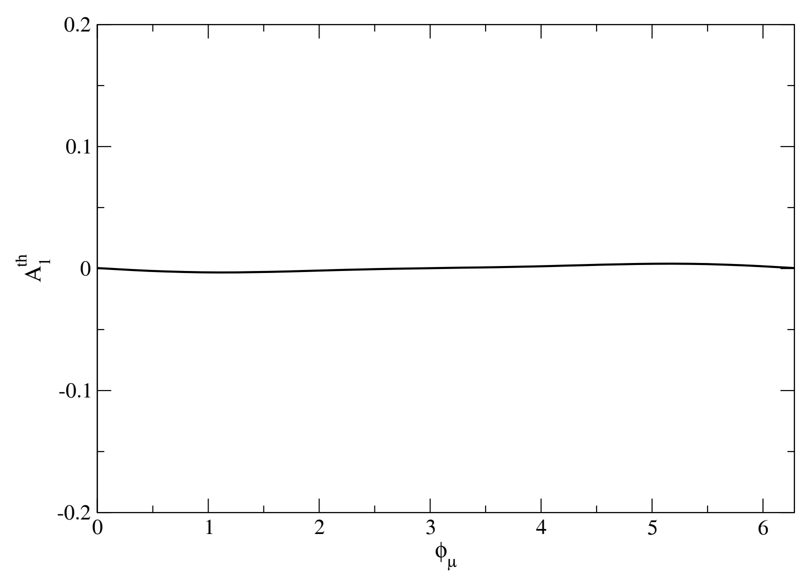
$\tilde{\chi}_2^0$ fixed helicity in $\tilde{e}_L$ rest frame: Reconstruction required

$Q_1 = \vec{s} \cdot (\vec{p}_{\mu^-} \times \vec{p}_{\mu^+}) \longrightarrow A_1$ ☞ Indep. of $\tilde{e}_L$ production process

- $\tilde{e}_R$ decays not considered: $\mathrm{Br}(\tilde{e}_R \to e\tilde{\chi}_2^0)$ small
- $\tilde{\chi}_2^0 \to e^+e^-\tilde{\chi}_1^0, \tau^+\tau^-\tilde{\chi}_1^0$ not considered: Reconstruction not possible
- Asymmetry nonnegligible only in Scenario 2 (with $\tilde{\chi}_2^0$ 3-body decays)

Theoretical values in Scenario 2





Processes:

$$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^- \to e^+\tilde{\chi}_1^0\, e^-\tilde{\chi}_2^0 \to e^+\tilde{\chi}_1^0\; e^-\tilde{\chi}_1^0\mu^+\mu^-$$

$$e^+e^- \to \tilde{e}_L^+\tilde{e}_L^- \to e^+\tilde{\chi}_2^0\, e^-\tilde{\chi}_1^0 \to e^+\tilde{\chi}_1^0\mu^+\mu^-\; e^-\tilde{\chi}_1^0$$

$$e^+e^- \to \tilde{e}_R^+\tilde{e}_L^- \to e^+\tilde{\chi}_1^0\, e^-\tilde{\chi}_2^0 \to e^+\tilde{\chi}_1^0\; e^-\tilde{\chi}_1^0\mu^+\mu^-$$

$$e^+e^- \to \tilde{e}_R^-\tilde{e}_L^+ \to e^-\tilde{\chi}_1^0\, e^+\tilde{\chi}_2^0 \to e^-\tilde{\chi}_1^0\; e^+\tilde{\chi}_1^0\mu^+\mu^-$$

Reconstruction of $\tilde{\chi}_1^0$ momenta possible $\longrightarrow$ It allows for

- Discrimination of $\tilde{e}_L\,\tilde{e}_L\,,\tilde{e}_R\,\tilde{e}_L$ production
- Identification of $\tilde{e}_L^+\,,\tilde{e}_L^-$ decay modes
- Determination of $\tilde{e}$ rest frames
- Background rejection

Backgrounds

$$e^+e^- \to \tilde\nu_e^* \tilde\nu_e \to e^+ \tilde\chi_1^- \; e^- \tilde\chi_1^+ \to e^+ \tilde\chi_1^0 \mu^- \bar\nu_\mu \; e^- \tilde\chi_1^0 \mu^+ \nu_\mu$$

$$e^+e^- \to \tilde\nu_e^* \tilde\nu_e \to e^+ \tilde\chi_1^- \; \nu_e \, \tilde\chi_2^0 \to e^+ \tilde\chi_1^0 e^- \bar\nu_e \; \nu_e \, \tilde\chi_1^0 \mu^+ \mu^-$$

$$e^+e^- \to \tilde\chi_2^0 \tilde\chi_2^0 \to \tilde\chi_1^0 e^+ e^- \; \tilde\chi_1^0 \mu^+ \mu^-$$

5 times larger than the signals

The calculation

- Including finite width and spin effects
- Including ISR, beamstrahlung and beam energy spread
- Detector simulation with Gaussian smearing of energies

CM energy: 800 GeV

$P_{e^+} = 0.6$, $P_{e^-} = -0.8$

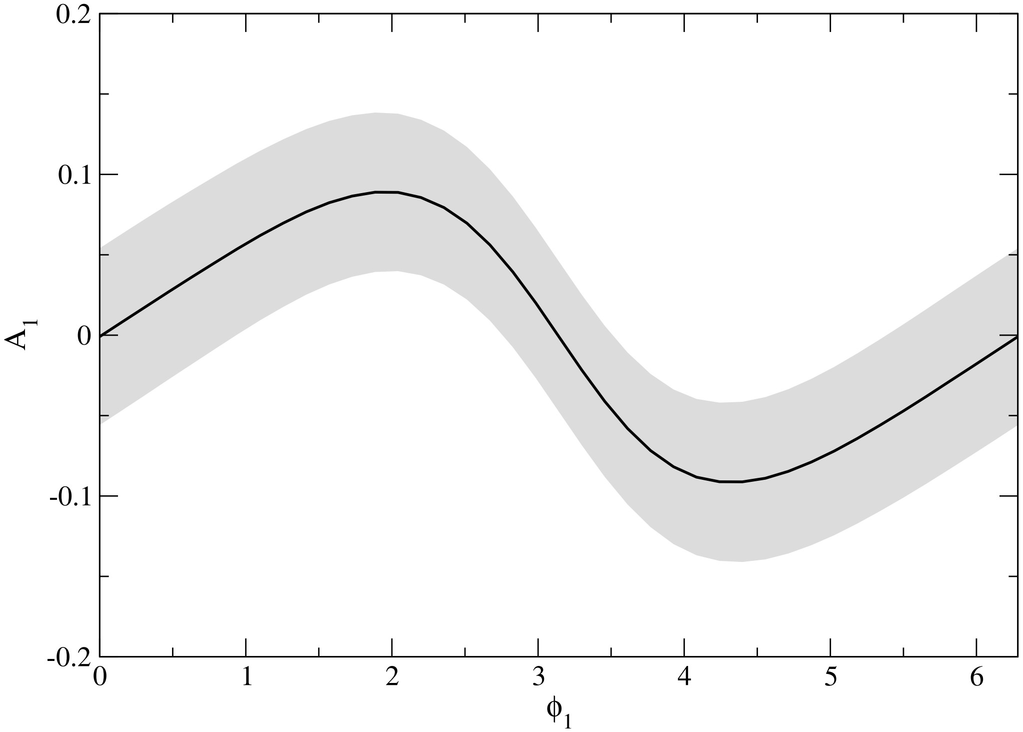
For $\phi_1 = 0$:	$\sigma(\tilde{e}_L^+ \tilde{e}_L^-)$	92 fb	$\mathrm{Br}(\tilde{e}_L \to e \tilde{\chi}_1^0)$	0.18
	$\sigma(\tilde{e}_R^+ \tilde{e}_L^-)$	9.5 fb	$\mathrm{Br}(\tilde{e}_L \to e \tilde{\chi}_2^0)$	0.30
	$\sigma(\tilde{e}_R^- \tilde{e}_L^+)$	4.2 fb	$\mathrm{Br}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \mu^+ \mu^-)$	0.035

Signal small but visible

Back. reduced with reconstruction

	Before	After	
$\tilde{e}_L^+ \tilde{e}_L^-$	0.21	0.18	
$\tilde{e}_R^+ \tilde{e}_L^-$	0.061	0.046	
$\tilde{e}_L^+ \tilde{e}_R^-$	0.027	0.021	
$\tilde{\nu}^* \tilde{\nu}$ $(\tilde{\chi}_1^- \tilde{\chi}_1^+)$	0.99	0.039	☺
$\tilde{\nu}^* \tilde{\nu}$ $(\tilde{\chi}_1^- \tilde{\chi}_2^0)$	0.24	0.011	☺
$\tilde{\chi}_2^0 \tilde{\chi}_2^0$	0.11	0.0081	

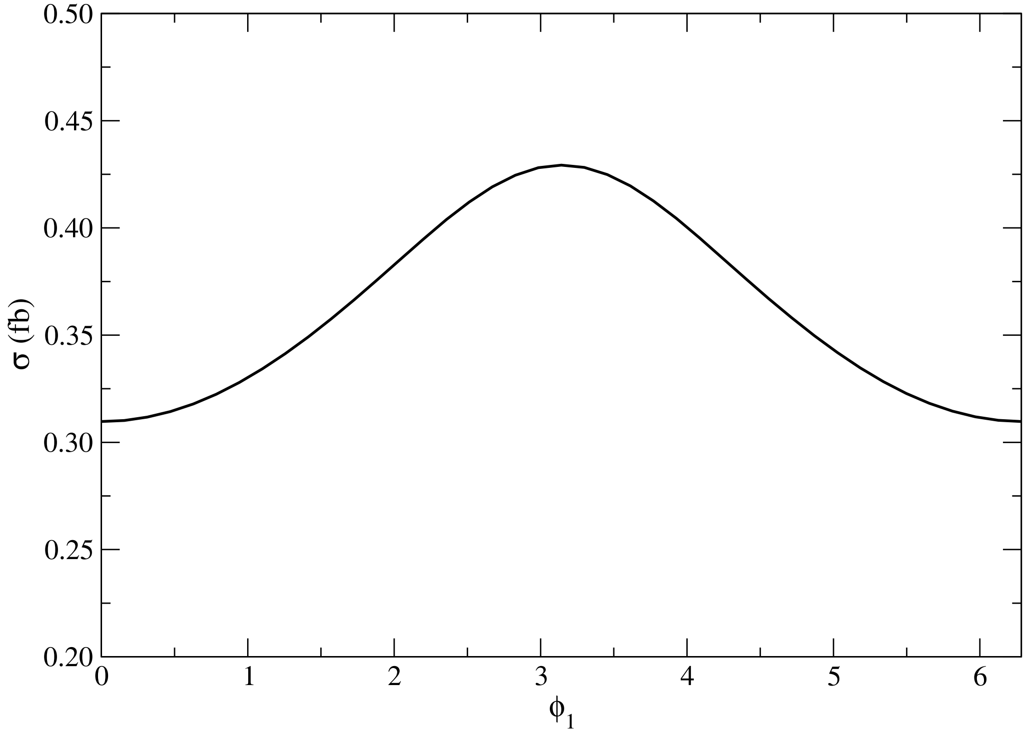
CP asymmetry



- Including ISR, etc.
- Summing all contributions
- Including backgrounds

- Statistical error for 2 years of running
- Maximum: $1.8\,\sigma$

Total cross section



☞ Difficult to extract information on ϕ_1

CP asymmetry in $\tilde{\chi}_1^0 \tilde{\chi}_2^0$ production

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

$Q_1 = \vec{p}_{e^+} \cdot (\vec{p}_{\ell^-} \times \vec{p}_{\ell^+}) \longrightarrow A_1$ ☞ Depends on { beam polarisation; CM energy }

Problem: large backgrounds

$$e^+e^- \to W^+W^- \to \ell^+ \nu_\ell \, \ell^- \bar{\nu}_\ell$$

$$e^+e^- \to \tilde{\ell}^+_{R,L} \, \tilde{\ell}^-_{R,L} \to \ell^+ \tilde{\chi}_1^0 \, \ell^- \tilde{\chi}_1^0$$

$$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to \ell^+ \nu_\ell \tilde{\chi}_1^0 \, \ell^- \bar{\nu}_\ell \tilde{\chi}_1^0$$

In general:

P_{e^+}	$+$	$\longrightarrow$	Increases W^+W^- (and $\tilde{\ell}_L^+\tilde{\ell}_L^-$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$)
P_{e^-}	$-$		Reduces $\tilde{\ell}_R^+\tilde{\ell}_R^-$
P_{e^+}	$-$	$\longrightarrow$	Reduces W^+W^- (and $\tilde{\ell}_L^+\tilde{\ell}_L^-$, $\tilde{\chi}_1^+\tilde{\chi}_1^-$)
P_{e^-}	$+$		Increases $\tilde{\ell}_R^+\tilde{\ell}_R^-$

Backgrounds large for any P_{e^+}, P_{e^-}

We study:

★ Scenario 1: with $\tilde{\chi}_2^0 \to \ell^\pm \, \tilde{\ell}_R^\mp$ (scenario with $\tilde{\chi}_2^0 \to \ell^\pm \, \tilde{\ell}_L^\mp$ is similar)

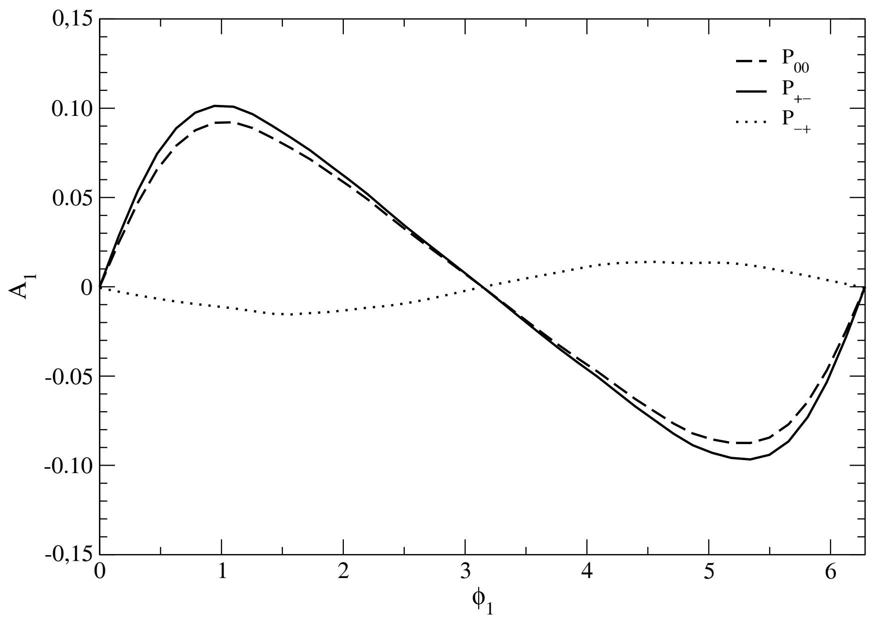
★ Scenario 2: with $\tilde{\chi}_2^0$ 3-body decays

CM energy: 500 GeV

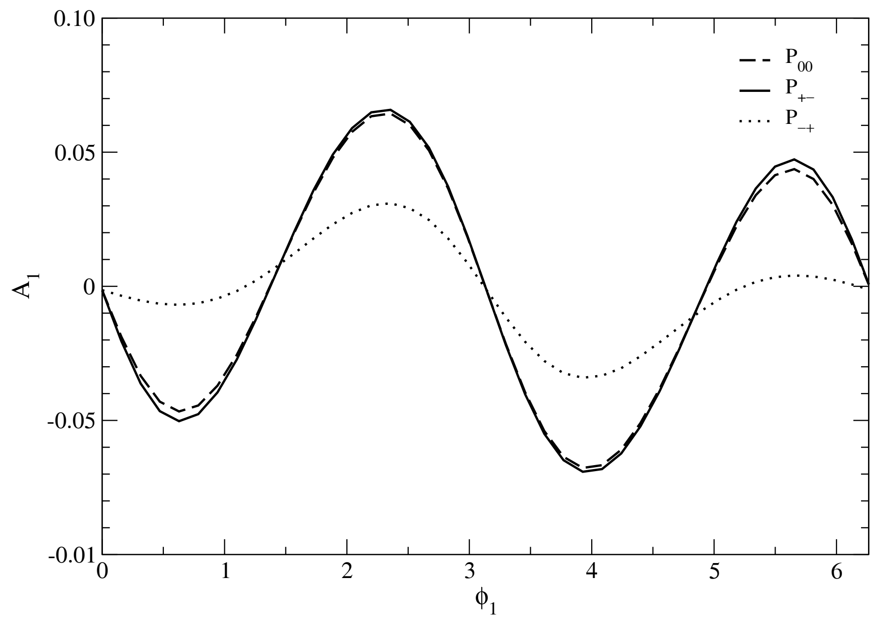
In both cases $P_{e^+} = 0.6$, $P_{e^-} = -0.8$ enhance CP asymmetry (and signal cross section)

CP asymmetry (Including ISR, beamstrahlung, etc. but not backgrounds)

Scenario 1



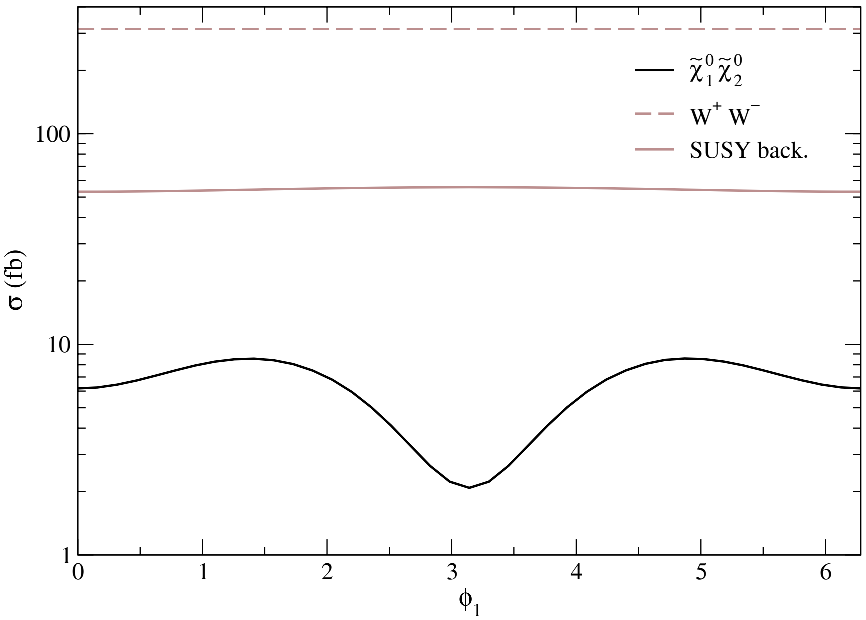
Scenario 2



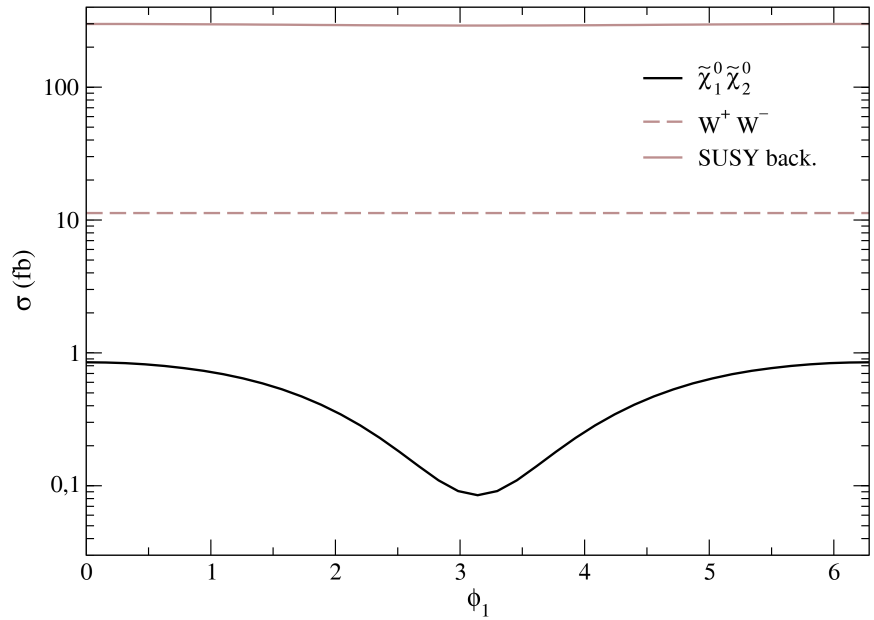
☞ best results for $P_{e^+} = 0.6$, $P_{e^-} = -0.8$

Cross sections for Scenario 1

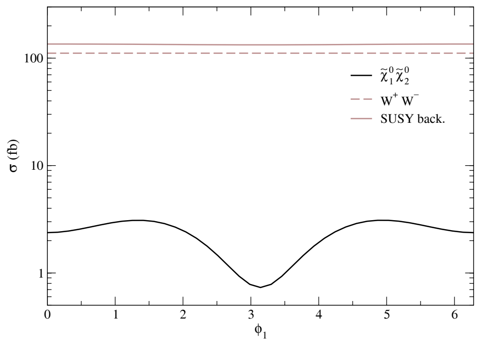
$P_{e^+} = 0.6,\ P_{e^-} = -0.8$



$P_{e^+} = -0.6,\ P_{e^-} = 0.8$

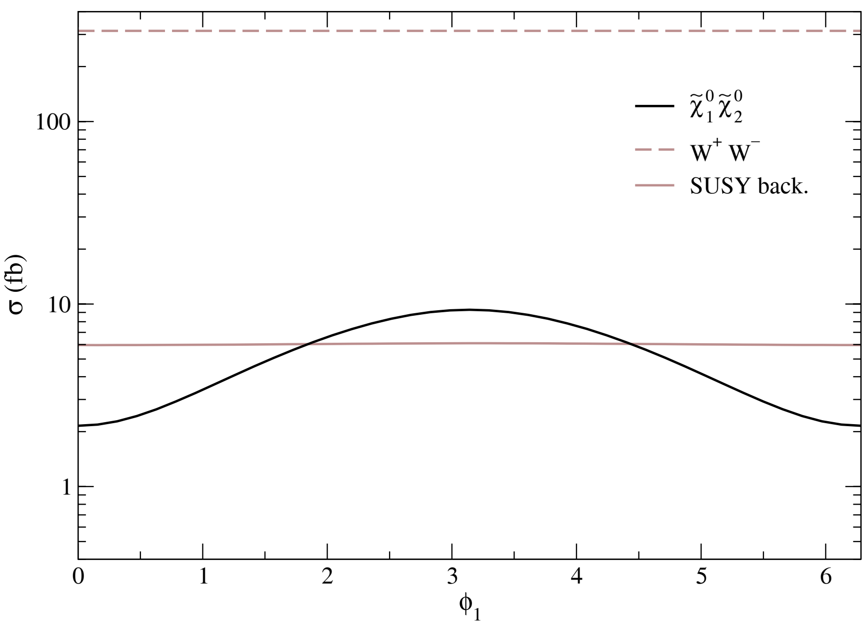


Unpolarised

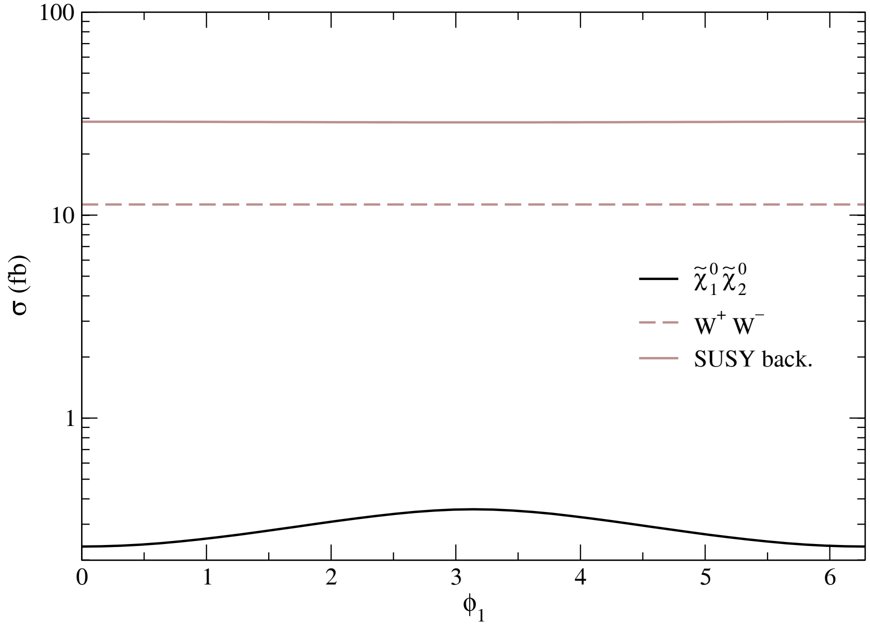


Cross sections for Scenario 2

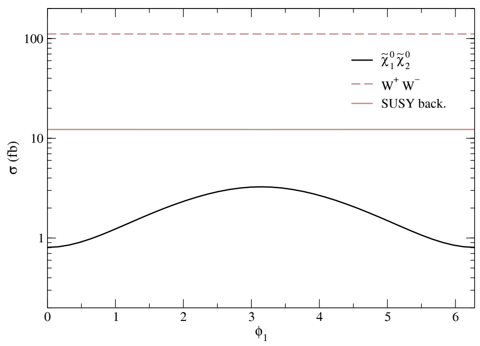
$P_{e^+} = 0.6,\ P_{e^-} = -0.8$



$P_{e^+} = -0.6,\ P_{e^-} = 0.8$



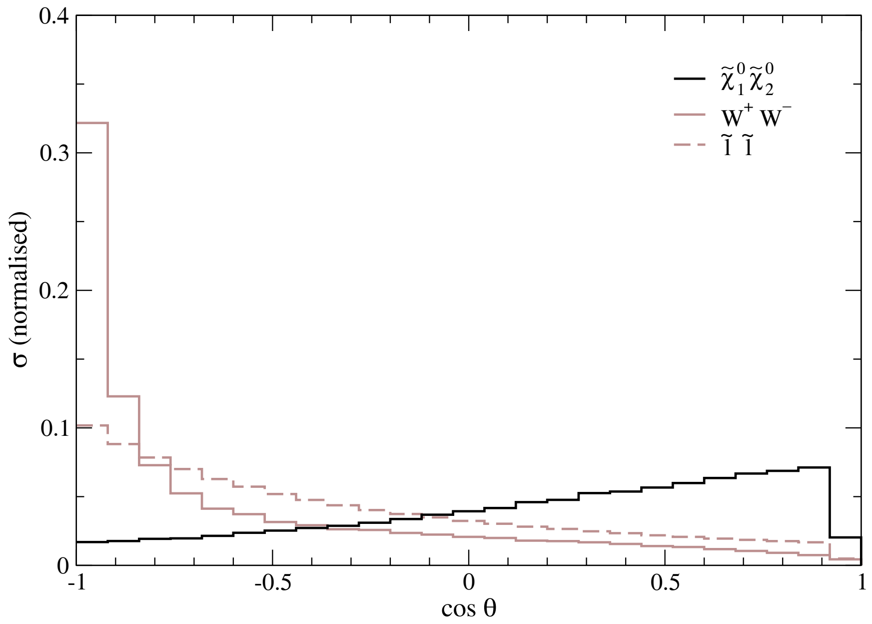
Unpolarised



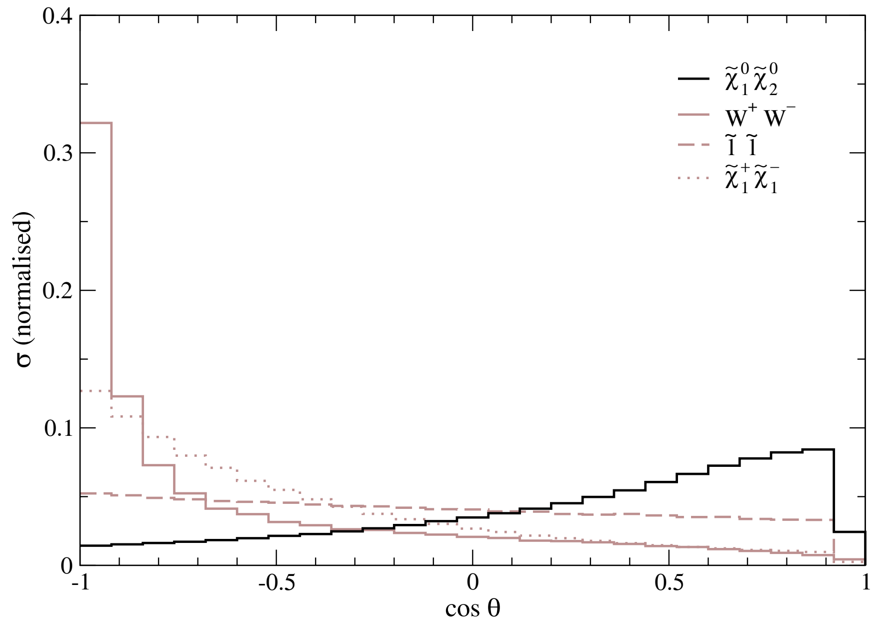
Backgrounds can be reduced

$\theta \quad \longrightarrow \quad$ angle between ℓ^+ , ℓ^-

Scenario 1

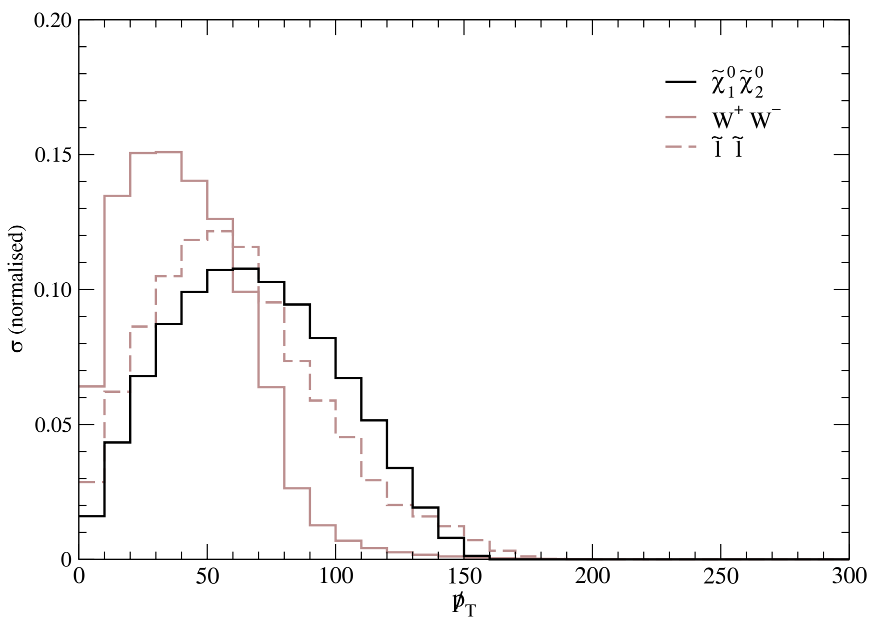


Scenario 2

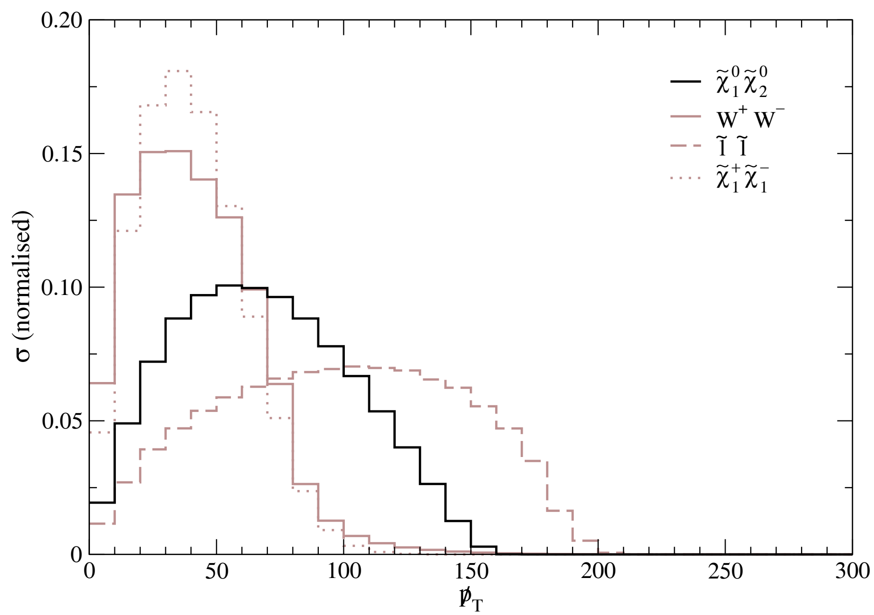


Missing transverse momentum is not useful to separate signal

Scenario 1



Scenario 2



Require $\cos\theta \geq 0.5$

Scenario 1: $\phi_1 = \pi/3$; Scenario 2: $\phi_1 = 3\pi/4$

	Scenario 1		Scenario 2	
	before	after	before	after
$\sigma(\tilde{\chi}_1^0 \tilde{\chi}_2^0)$	8.18	5.49	7.83	6.01
$\sigma(W^+ W^-)$	318.0	54.3	318.0	54.3
$\sigma(\tilde{\ell}^+ \tilde{\ell}^-)$	53.1	14.2	3.11	1.33
$\sigma(\tilde{\chi}_1^+ \tilde{\chi}_1^-)$	$\sim 10^{-3}$		2.96	0.56
r	0.022	0.074	0.024	0.097

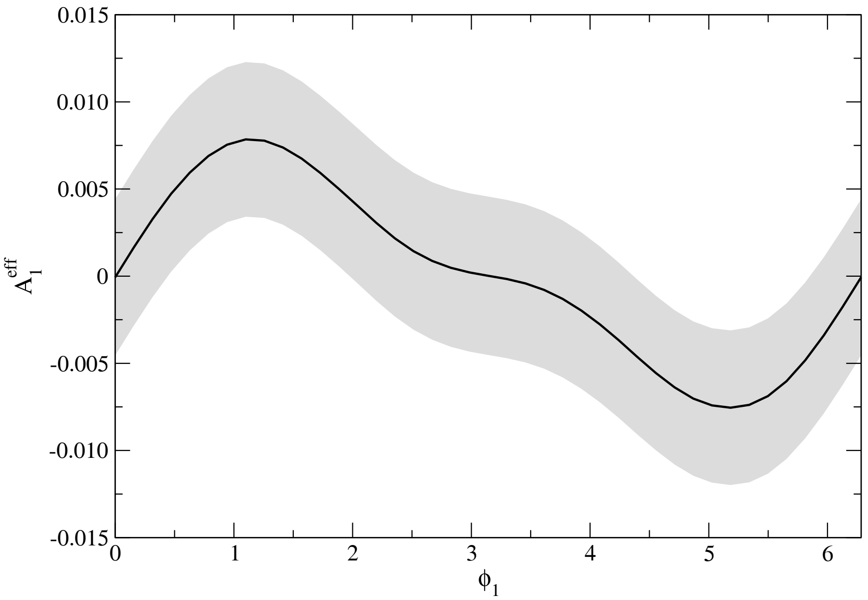
☞

Scenario 1: $A_1 = 0.108$ $A_1^{\text{eff}} = 0.0080$

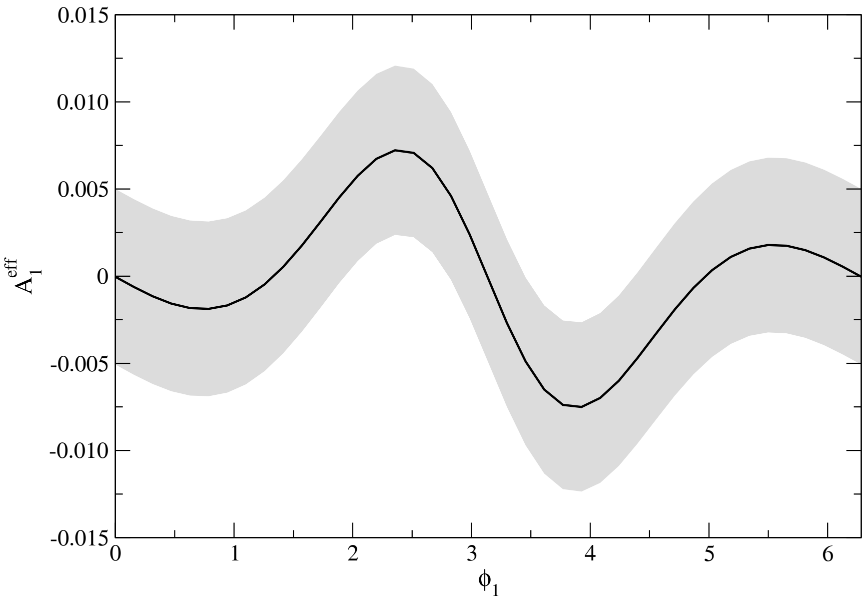
Scenario 2: $A_1 = 0.074$ $A_1^{\text{eff}} = 0.0072$

Observed CP asymmetry

Scenario 1



Scenario 2



- Including ISR, etc.
- Including backgrounds
- Statistical error for 2 years
- Maximum: $1.8\,\sigma$, $1.5\,\sigma$

Summary

★ $\tilde{e}_L \to e\tilde{\chi}_2^0 \to e\tilde{\chi}_1^0\mu^+\mu^-$

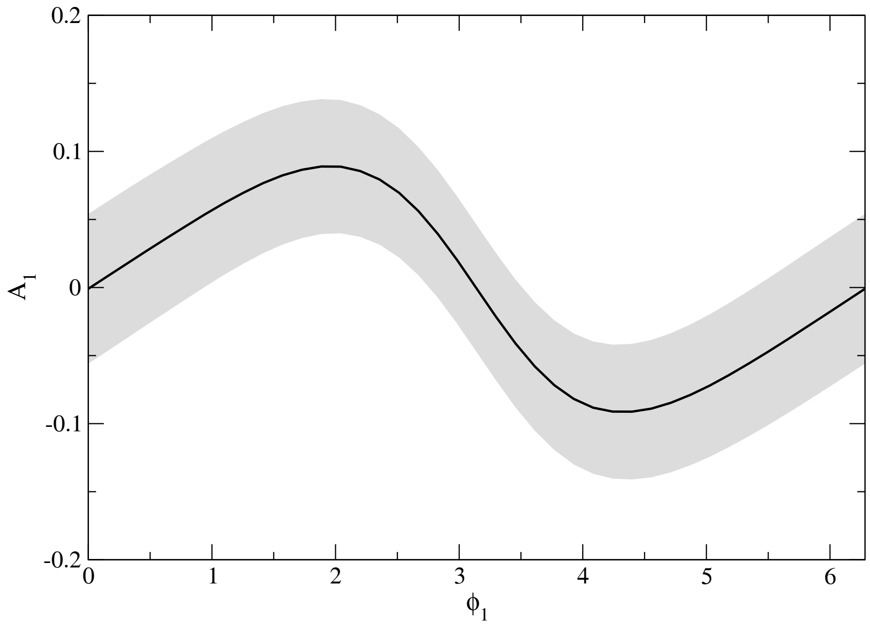
- ➤ Small cross section
- ➤ Small backgrounds which can be further reduced
- ➤ Negligible asymmetry in Sc. 1
  Asymmetry $O(0.1)$ in Sc. 2
- ➤ $\tilde{e}_L$ must be produced on shell: higher CM energy required

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

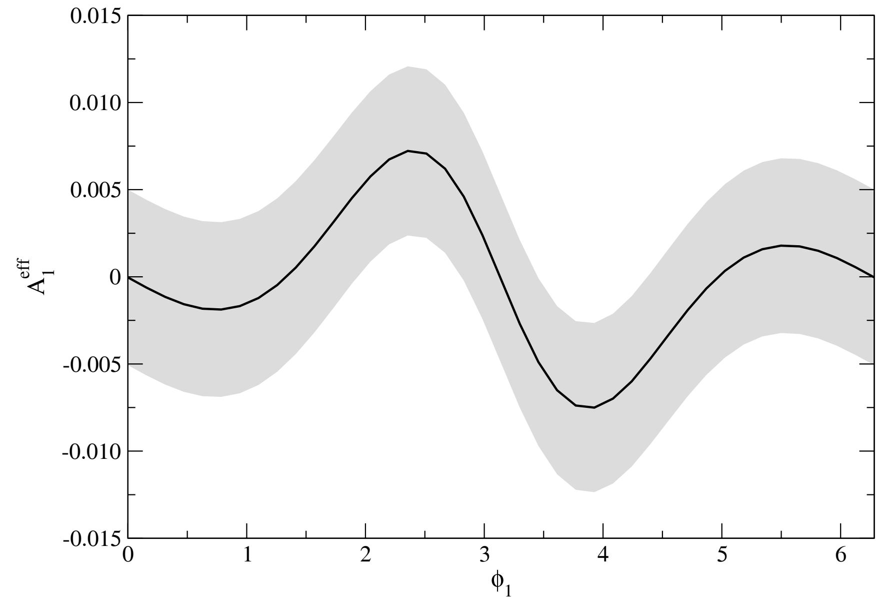
- ➤ Large cross section
- ➤ Huge backgrounds
- ➤ $A_1 \sim O(0.1)$ in both scenarios but $A_1^{\text{eff}} \sim O(0.01)$
- ➤ Process possible at lower CM energies

Scenario 2: comparison

$\tilde{e}_L$ decays



$\tilde{\chi}^0_1 \tilde{\chi}^0_2$ production



- Different dependence on ϕ_1
- For $\phi_1 \simeq \pi/2$
  In $\tilde{e}_L$ decays $A_1 \simeq 0.082$ $(1.6\,\sigma)$
  In $\tilde{\chi}^0_1 \tilde{\chi}^0_2$ prod. $A_1 \simeq 0$