CP Violation in e^+e^- Collisions: Production of Neutralinos and Charginos

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CP violation in e^+e^- collisions: production of neutralinos and charginos

- Introduction: CP violation and Supersymmetry
- Constructing CP observables: triple products
- Results for e^+e^- collisions:
  - neutralino production
  - chargino production
- Summary and conclusions

Motivation

History of CP violation:

- Experiment: $K^0/\bar{K}^0$ mesons 1964
- Theory: prediction of third generation (t,b quarks) in 1972!

Importance of CP violation today:

- Experiments with B mesons verify one CP phase of Standard Model
- Cosmology: need more CP phases to explain baryon asymmetry!

In addition:

- Physics beyond Standard Model is needed: solve hierarchy problem, dark matter candidate, include gravity, ... SUSY !

the relevant parameters of the Minimal Supersymmetric Standard Model

chargino sector

$\mu = |\mu| \exp(i\,\varphi_\mu)$ Higgsino mass parameter

M_2 SU(2) gaugino mass parameter

$\tan\beta = \frac{v_2}{v_1}$ ratio of the neutral Higgs VEVs

neutralino sector

$M_1 = |M_1| \exp(i\,\varphi_{M1})$ U(1) gaugino mass parameter

stau sector

$A_\tau = |A_\tau|\ exp(i\,\varphi_{A_\tau})$ trilinear scalar coupling parameter

phases φ_μ, φ_{M1}, φ_{A_τ} $\rightarrow$ CP violation

Impact of complex parameters

- couplings become complex
- masses, cross sections, distributions, etc. change their value

Are there observables A which are

CP-sensitive $\Leftrightarrow$ $A = 0$ if CP is conserved

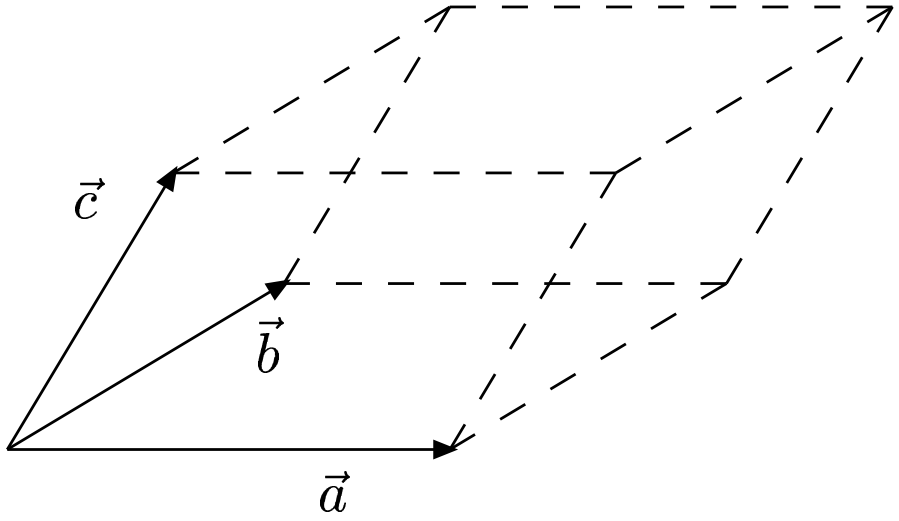
$A \neq 0$ if CP is violated

How to construct them? $\Rightarrow$ triple products

Triple products

$$[\vec{a},\vec{b},\vec{c}] \;=\; (\vec{a}\times\vec{b})\cdot\vec{c}$$

spins or momenta



- time reversal $T(t\to -t)$: $T[\vec{a},\vec{b},\vec{c}] = -[\vec{a},\vec{b},\vec{c}] \Rightarrow$ T-odd
  CPT-theorem: T-odd observables are also CP-odd

- source: $\mathcal{T}r\{\gamma_5\ \not{a}\ \not{b}\ \not{c}\ \not{d}\} = 4\,i\,\epsilon_{\mu\nu\rho\sigma}a^\mu b^\nu c^\rho d^\sigma$
  interference with complex parameters

T odd asymmetry

$$A := \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}$$

- triple product: $\mathcal{T} = (\vec{p}_a \times \vec{p}_b) \cdot \vec{p}_c$
- cross section: σ

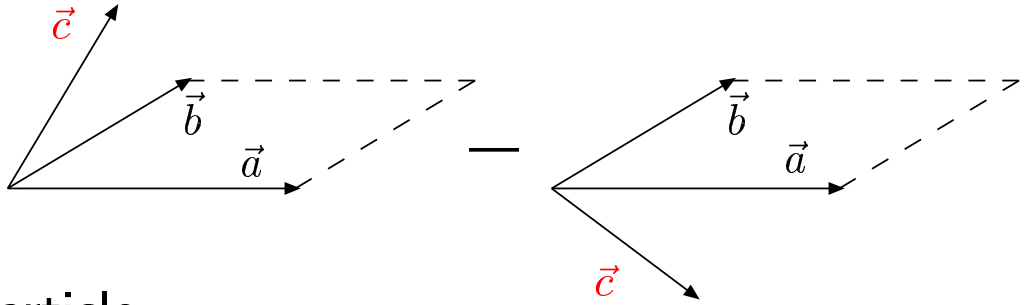
$$\Rightarrow A = \frac{\int Sign[\mathcal{T}]\, |T|^2\, d\mathrm{Lips}}{\int |T|^2\, d\mathrm{Lips}}$$

- Amplitude: $|T|^2$
- Lorentz-invariant phase space: Lips

Geometrical interpretation

- Asymmetry A is an angular distribution:

$$A = \frac{N_+ - N_-}{N_+ + N_-} \quad \Leftrightarrow$$



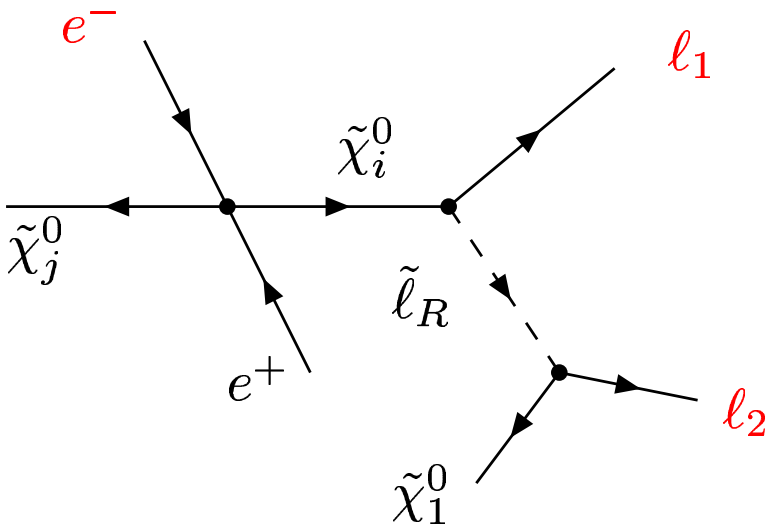
- $N_+(N_-)$: events with particle c
  above (below) plane spanned by $\vec{p}_a \times \vec{p}_b$

Remember: A is CP-sensitive $\Rightarrow$ CP violation can be tested directly!

Asymmetry for neutralino production

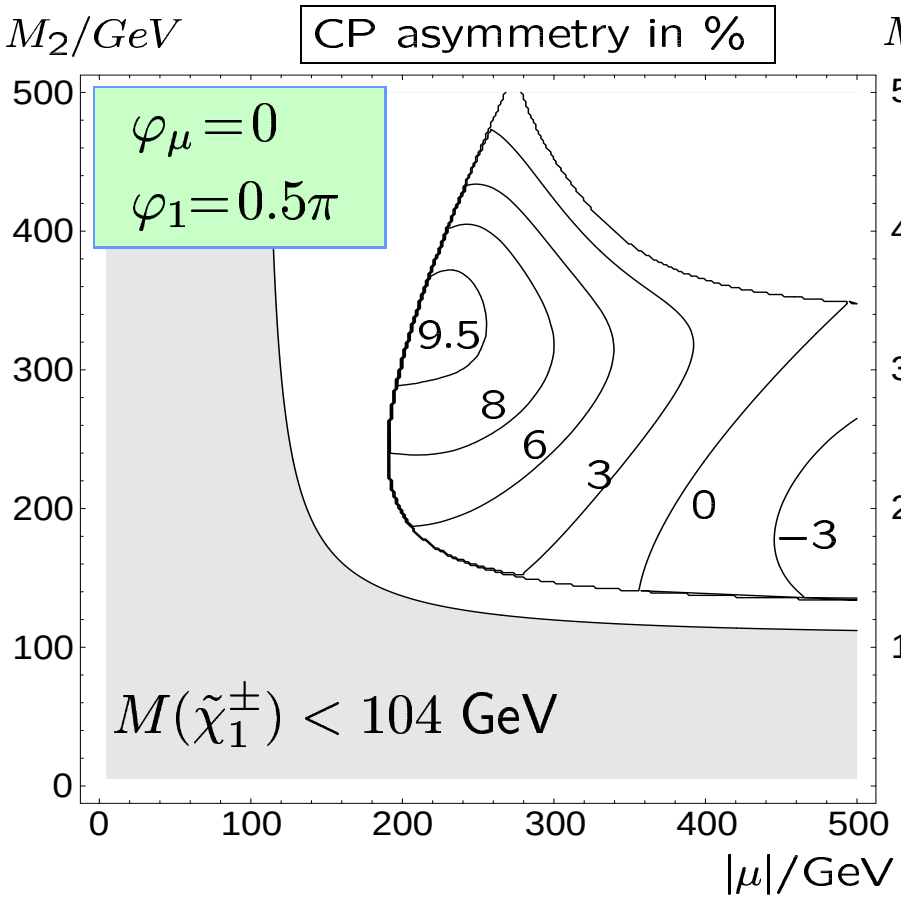
$$A = \frac{\sigma(\mathcal{T}>0)-\sigma(\mathcal{T}<0)}{\sigma(\mathcal{T}>0)+\sigma(\mathcal{T}<0)}$$

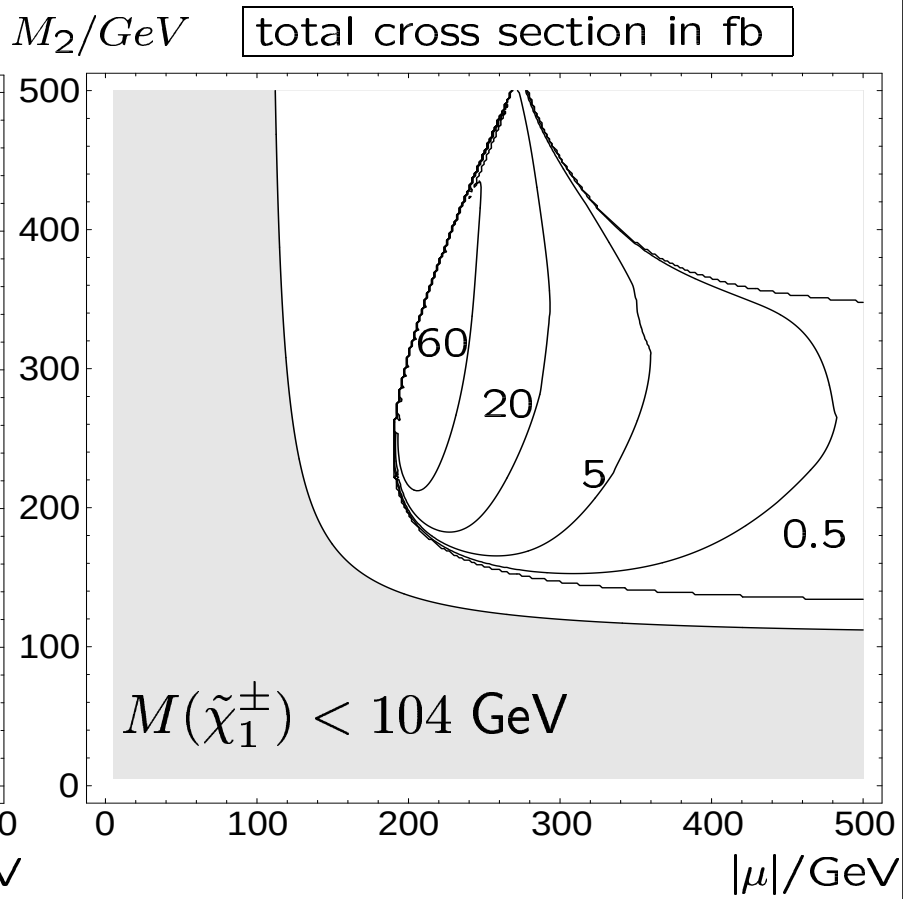
$$\mathcal{T} = [\vec{p}(e^-)\times\vec{p}(\ell_1)]\cdot\vec{p}(\ell_2)$$



$e^+e^- \longrightarrow \tilde{\chi}^0_1\tilde{\chi}^0_2;\ \ \tilde{\chi}^0_2 \longrightarrow \tilde{\ell}_R\,\ell_1;\ \ \tilde{\ell}_R \longrightarrow \tilde{\chi}^0_1\,\ell_2$ at $\sqrt{s} = 500$ GeV;

$\tan\beta = 10$; $m_0 = 100$ GeV; $P(e^-|e^+) = (0.8|-0.6)$



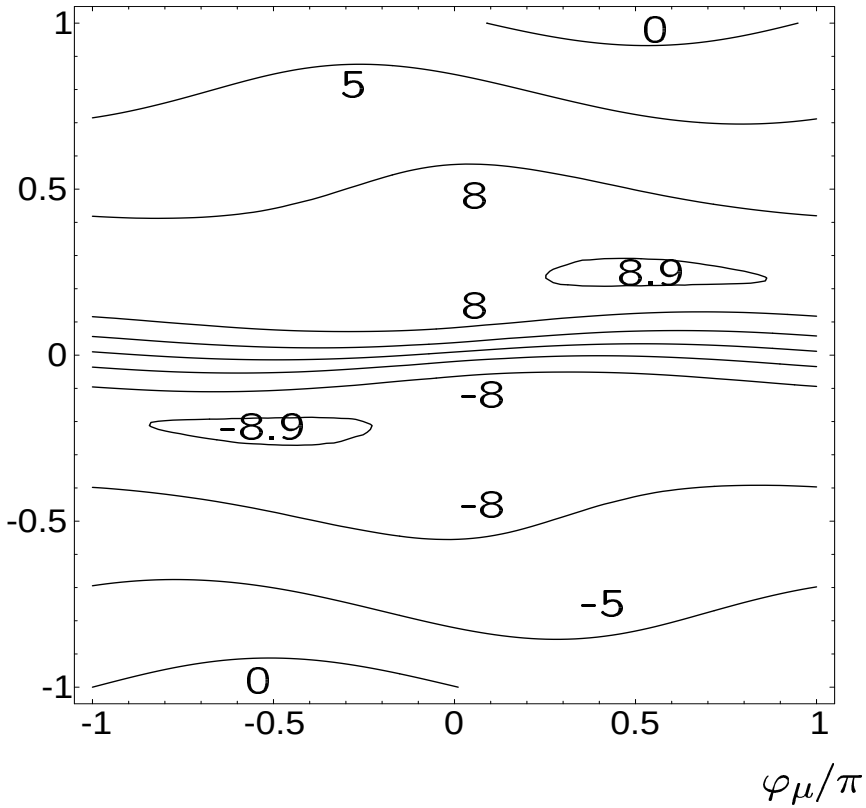


$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0;\ \ \tilde{\chi}_2^0 \longrightarrow \tilde{\ell}_R\,\ell_1;\ \ \tilde{\ell}_R \longrightarrow \tilde{\chi}_1^0\,\ell_2$

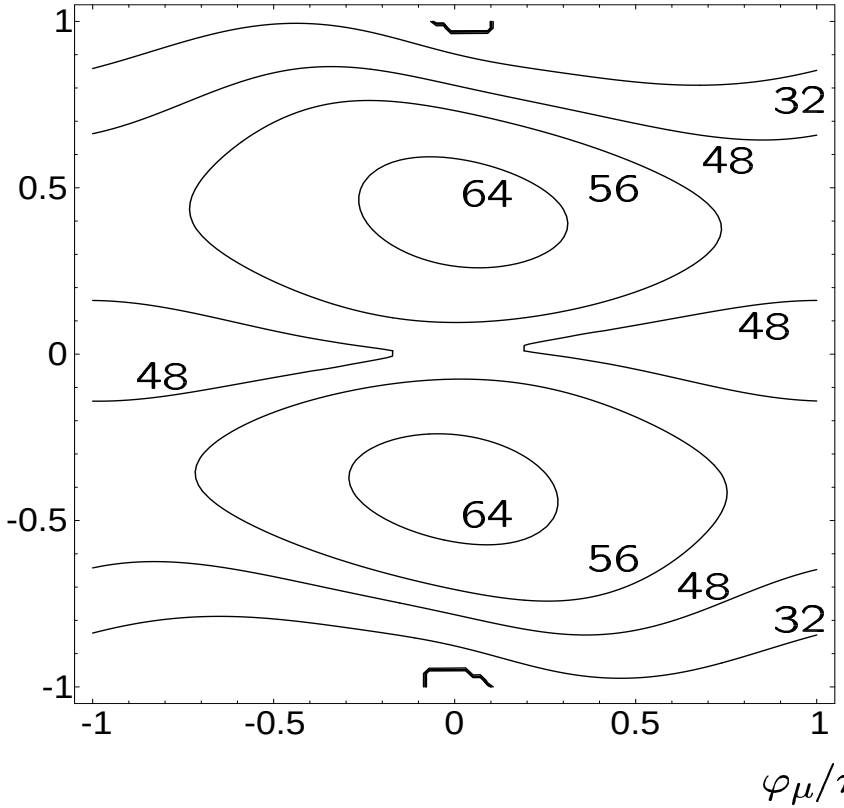
$|\mu| = 240$ GeV; $M_2 = 400$ GeV

dependence on the phases

asymmetry in %



total cross section in fb



$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0;\ \ \tilde{\chi}_2^0 \longrightarrow \tilde{\ell}_R\,\ell_1;\ \ \tilde{\ell}_R \longrightarrow \tilde{\chi}_1^0\,\ell_2$

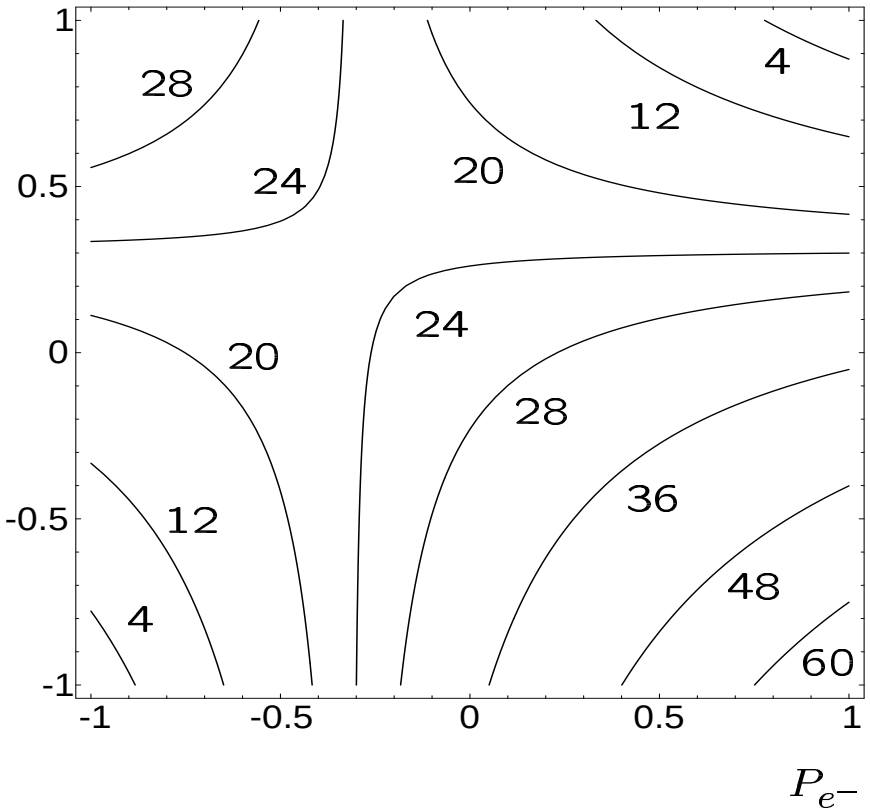
$|\mu| = 240$ GeV; $M_2 = 400$ GeV

$\varphi_\mu = 0$

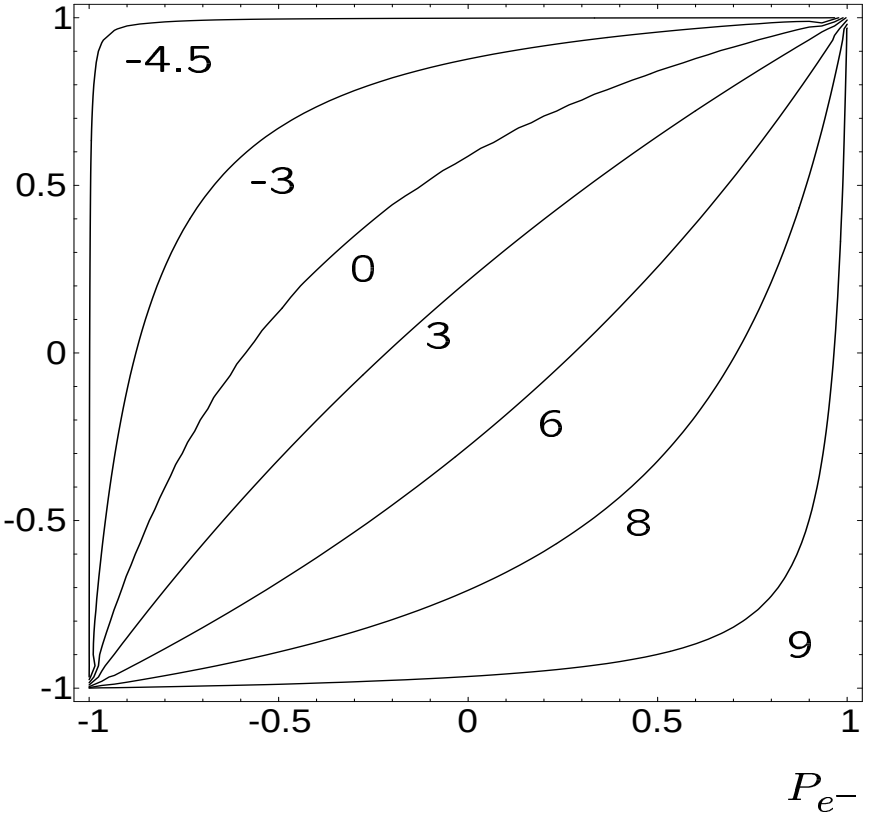
$\varphi_1 = 0.2\pi$

beam polarization dependence

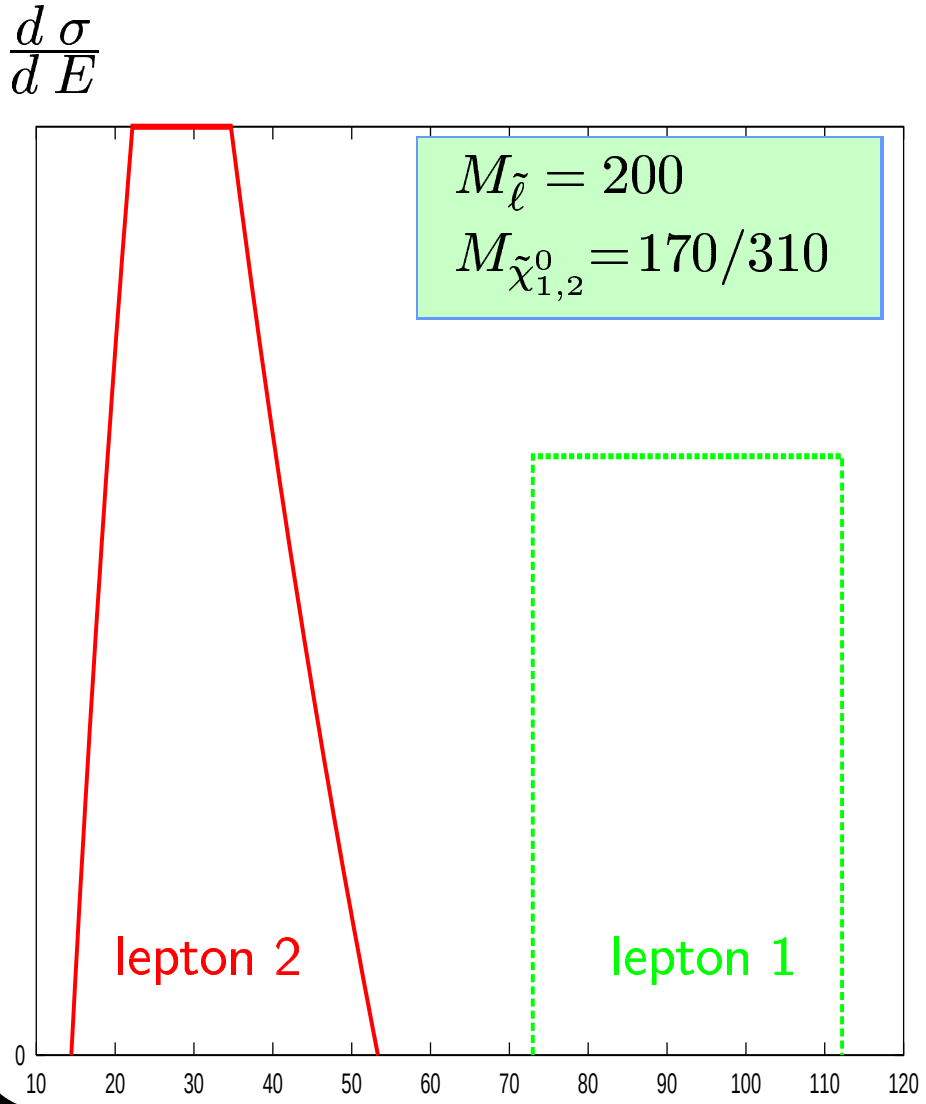
$\sigma_{tot}(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell_1\ell_2)$ in fb

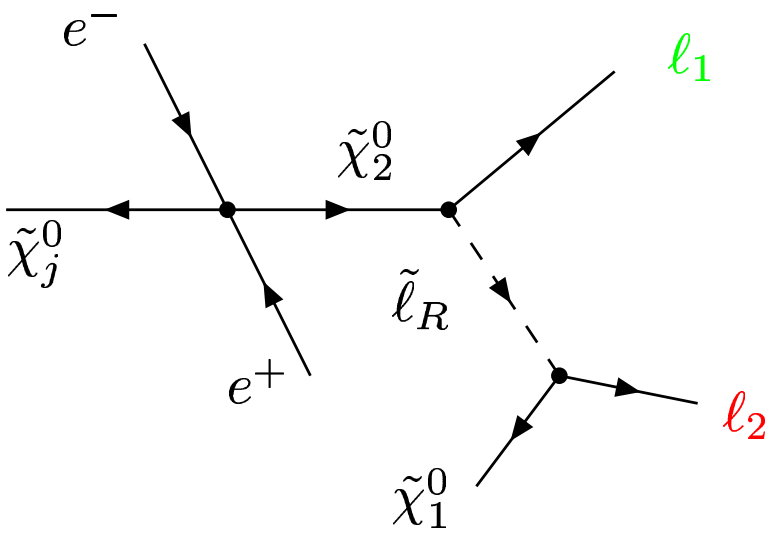


$\mathcal{A}_T$ in %



Distinguish the leptons by energy distributions

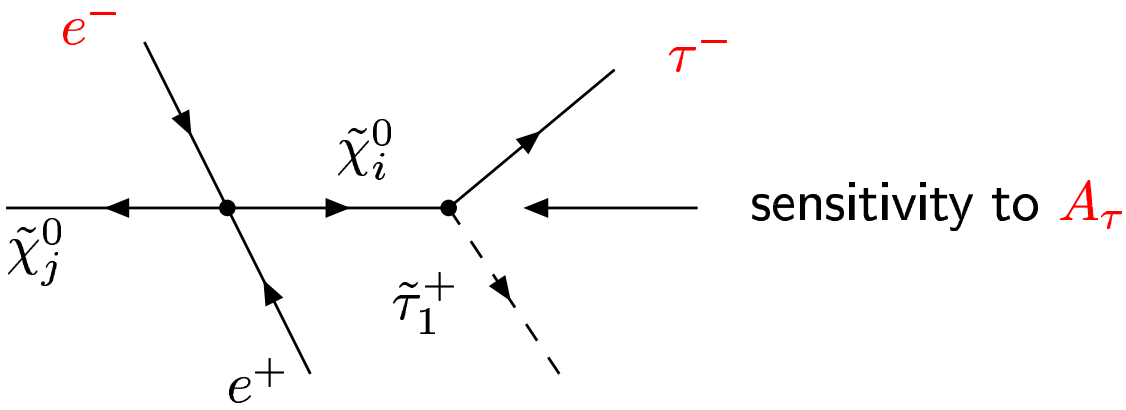




Tau polarization asymmetry

$$\boxed{A = P_2 = \frac{\mathrm{Tr}(\sigma_2 \varrho_{\tau^-})}{\mathrm{Tr}(\varrho_{\tau^-})}}$$

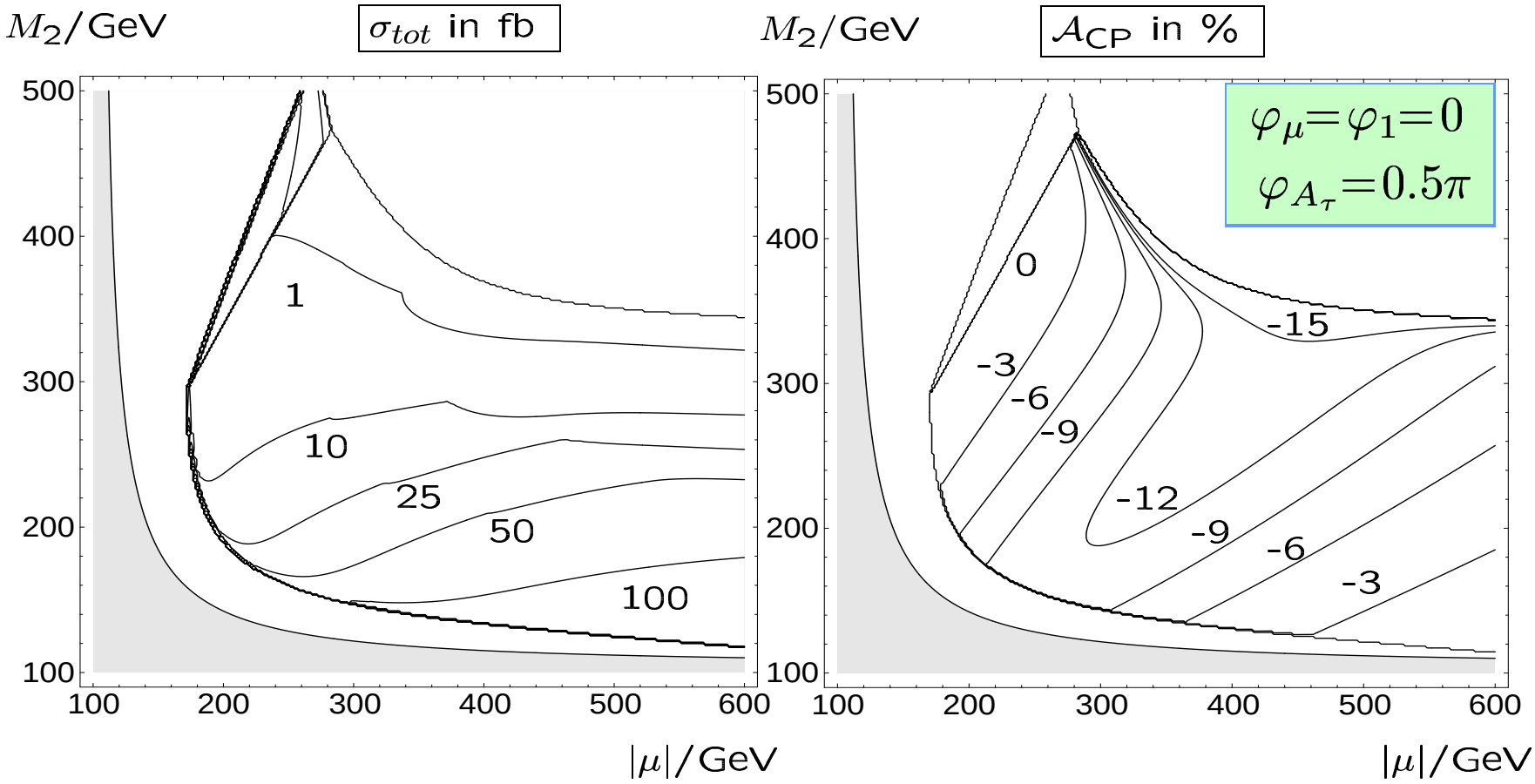
$$\mathcal{T} = [\vec{p}(e^-) \times \vec{p}(\tau)] \cdot \vec{P}_2$$



$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \longrightarrow \tilde{\tau}_1\,\tau$ at $\sqrt{s} = 500$ GeV;

$A_\tau = 1$ TeV; $\tan\beta = 5$; $m_0 = 100$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

gray shaded area: $M(\tilde{\chi}_1^\pm) < 104$ GeV

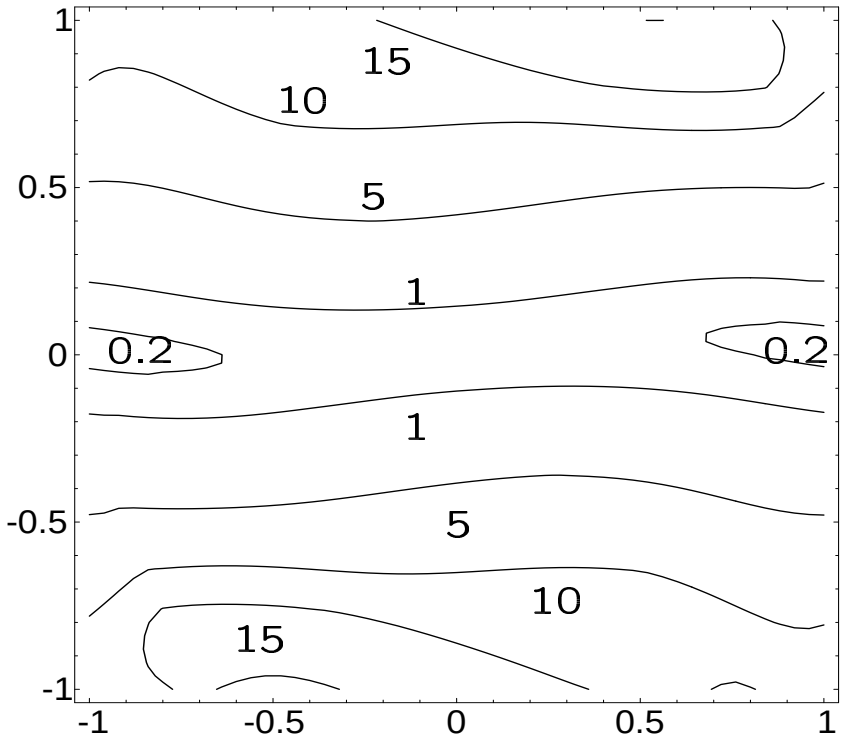


$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$; $\tilde{\chi}_2^0 \longrightarrow \tilde{\tau}_1\,\tau$ at $\sqrt{s} = 500$ GeV;

$A_\tau = 250$ GeV; $\tan\beta = 5$; $m_0 = 100$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

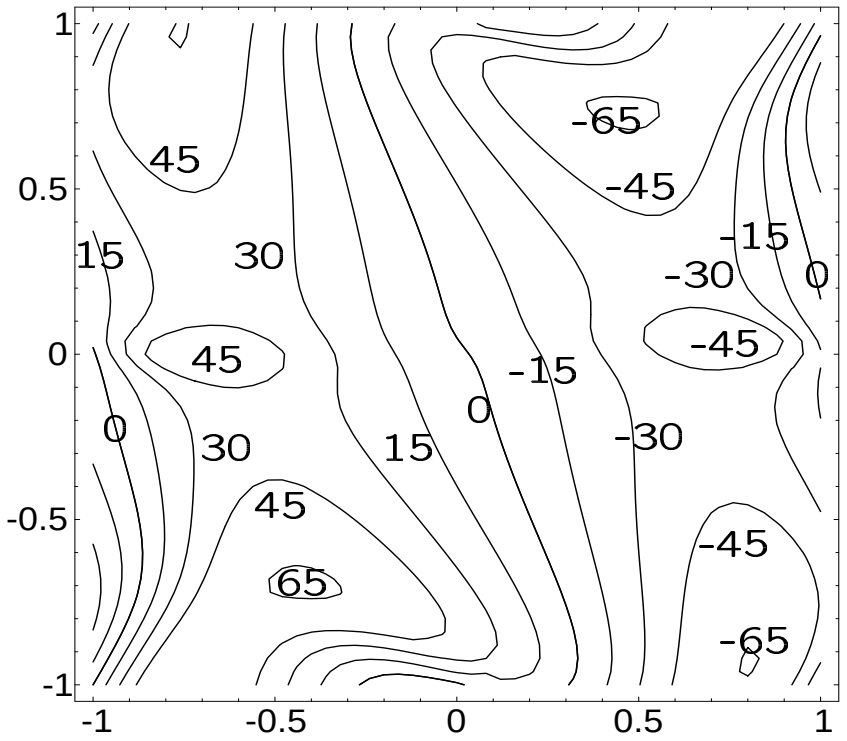
$|\mu| = 240$ GeV; $M_2 = 400$ GeV

φ_{M_1}/π σ_{tot} in fb



φ_μ/π

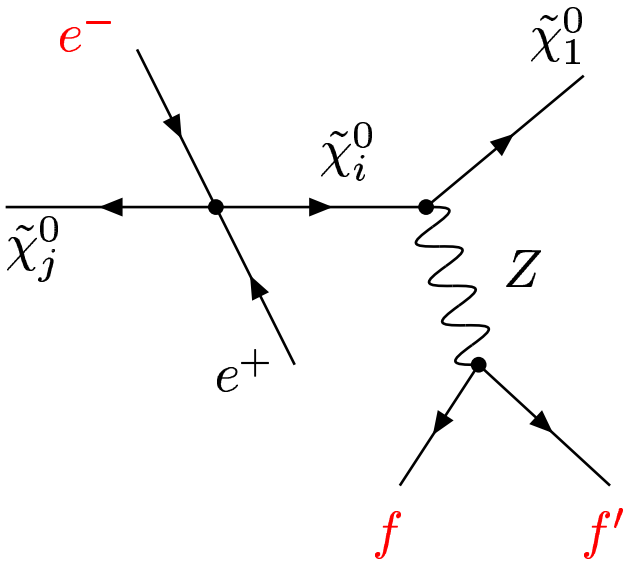
φ_{M_1}/π $\mathcal{A}_{CP}$ in %



φ_μ/π

Asymmetry for neutralino decay into Z

$$A = \frac{\sigma(\mathcal{T}>0)-\sigma(\mathcal{T}<0)}{\sigma(\mathcal{T}>0)+\sigma(\mathcal{T}<0)}; \qquad \mathcal{T} = [\vec{p}(e^-)\times\vec{p}(f)]\cdot\vec{p}(f')$$

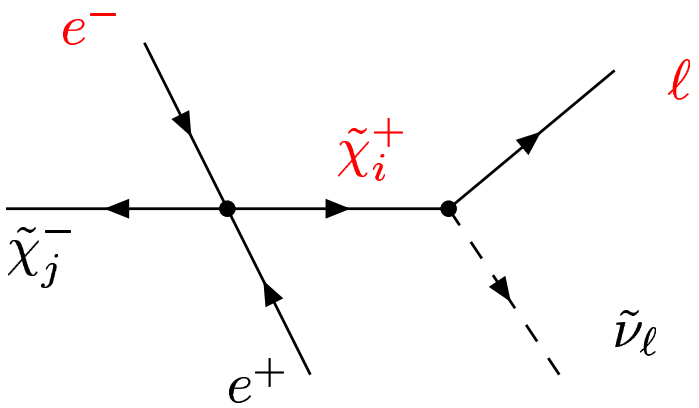


- also CP contributions to A from decay $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z$
- $A \propto \frac{|L|^2-|R|^2}{|L|^2+|R|^2} = 0.15(0.94)$ for $Z \to \ell^+\ell^-(b\,\bar{b})$
  $\Rightarrow A \approx 3\%(18\%)$ for leptonic (hadronic) decays
- CP sensitive matrix elements of Z spin matrix

Asymmetry for chargino production

$$A = \frac{\sigma(\mathcal{T}>0)-\sigma(\mathcal{T}<0)}{\sigma(\mathcal{T}>0)+\sigma(\mathcal{T}<0)}$$

$$\mathcal{T} = [\vec{p}(e^-)\times\vec{p}(\tilde{\chi}_i^+)]\cdot\vec{p}(\ell)$$

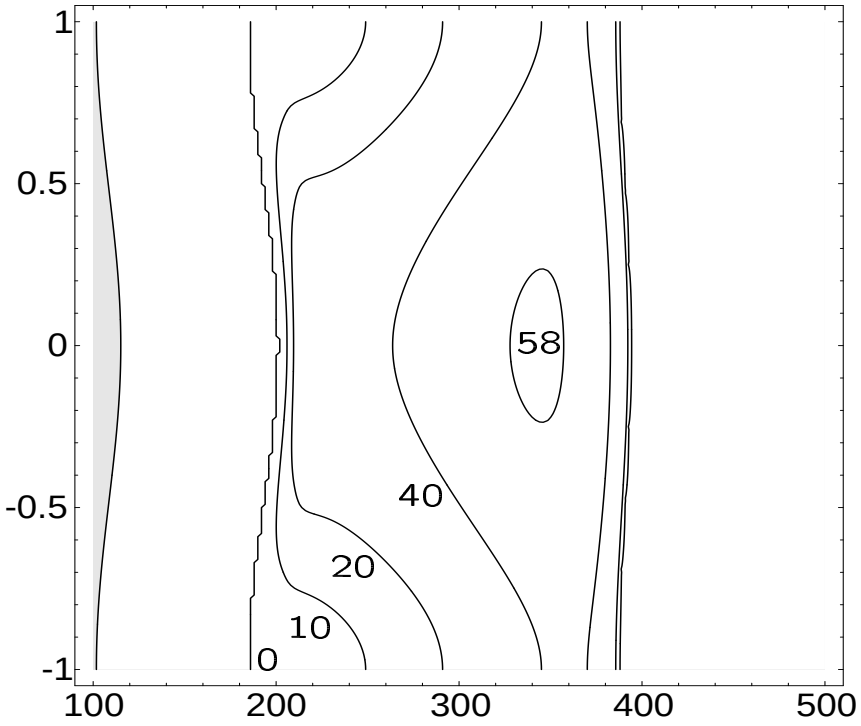


$e^+e^- \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_2^-$; $\tilde{\chi}_1^+ \longrightarrow \tilde{\nu}_\ell\,\ell^+$ at $\sqrt{s} = 800$ GeV;

$|\mu| = 400$ GeV; $\tan\beta = 5$; $m_{\tilde{\nu}} = 185$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

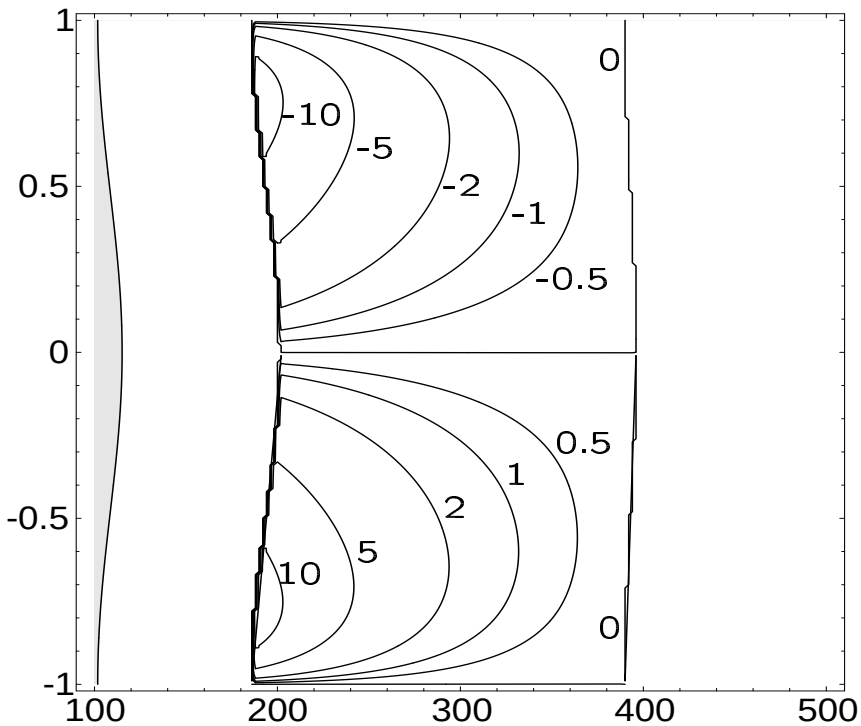
gray shaded area: $M(\tilde{\chi}_1^\pm) < 104$ GeV

φ_μ/π σ in fb



M_2 /GeV

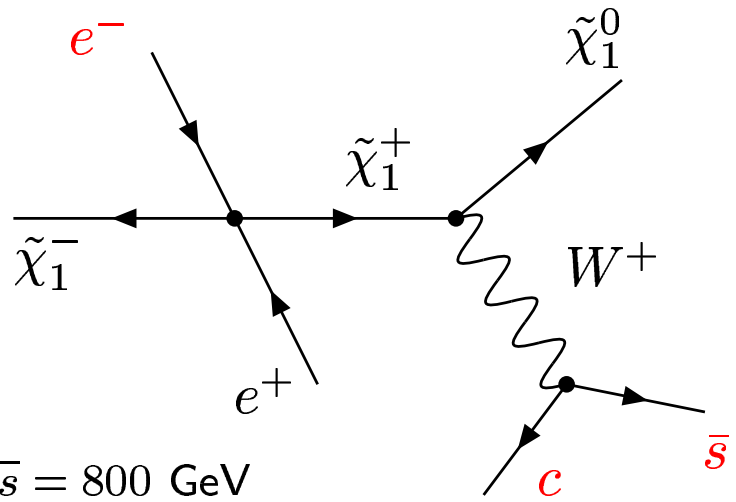
φ_μ/π $\mathcal{A}_\ell$ in %



M_2 /GeV

Asymmetry for chargino decay into W

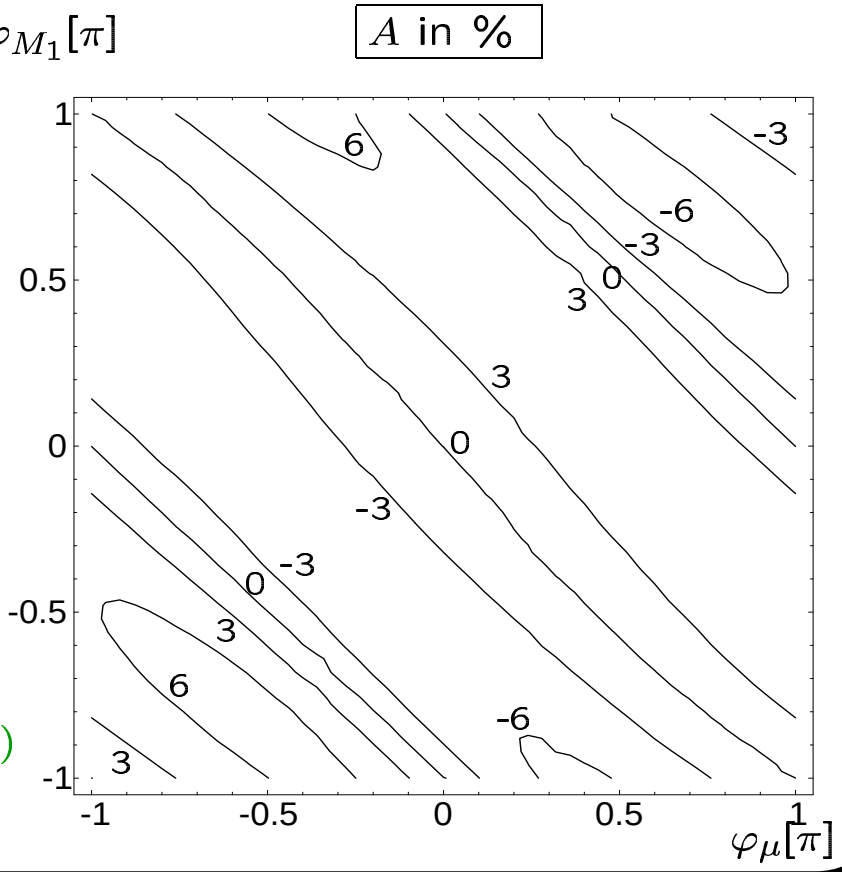
$$A = \frac{\sigma(\mathcal{T}>0)-\sigma(\mathcal{T}<0)}{\sigma(\mathcal{T}>0)+\sigma(\mathcal{T}<0)}; \quad \mathcal{T} = [\vec{p}(e^-)\times\vec{p}(c)]\cdot\vec{p}(\bar{s})$$



$\sqrt{s} = 800$ GeV

$|\mu| = 350$ GeV; $M_2 = 400$ GeV;

$\tan\beta = 5$; $m_0 = 300$ GeV; $P(e^-|e^+) = (-.8|.6)$



Summary and conclusions

- There are new sources of CP violation
  in supersymmetric theories.
- Complex parameters have impact on the production
  and the decay characteristics of neutralinos and charginos.
- There are CP-sensitive observables:
  triple products lead to CP-asymmetries.
- The CP-violating effects are of the order of 10%.
  $\rightarrow$ phases can be constrained/measured at future collider.