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CP Violation at the ILC: Production of Neutralinos and Charginos

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Motivation

What about CP violating phases at the linear collider (ILC) ?

- MSSM may have several phases: $\varphi_\mu, \varphi_{M_1}, \varphi_{A_\tau}, \ldots$ (and many more)
- how to measure them? $\to$ find sensitive observables and processes

Low-energy restrictions of the phases?

- measurements of electric dipole moments impose strong constraints.
- however: cancellations of loop contributions to EDMs,
  or other models (e.g. with flavor violation) may weaken constraints
- $\to$ ILC could provide independent measurements of phases!

CP violation at the ILC: production of neutralinos and charginos

- Constructing CP observables: triple products
- Results for e^+e^- linear collider:
  - neutralino production
  - chargino production
- Summary and conclusions

Impact of complex parameters

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

Are there observables A which are

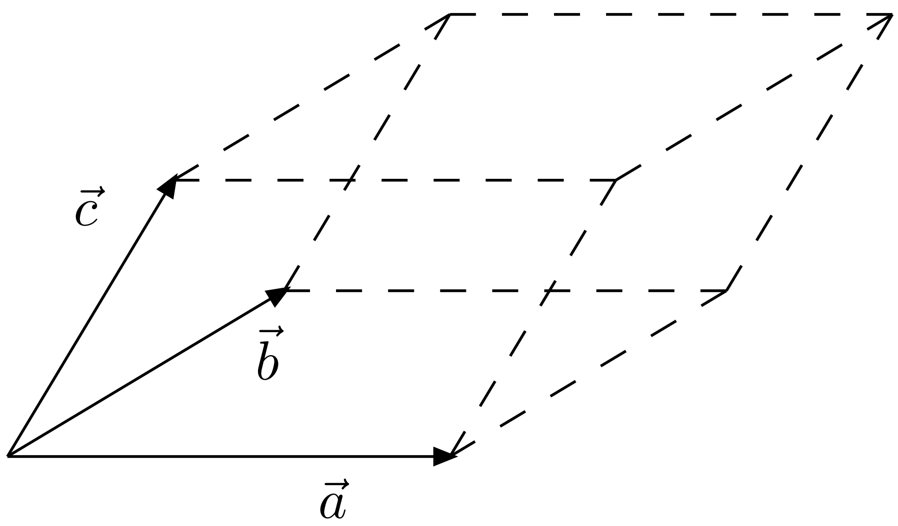
$$\text{CP-sensitive} \Leftrightarrow \begin{array}{ll} A = 0 & \text{if CP is conserved} \\ A \neq 0 & \text{if CP is violated} \end{array}$$

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

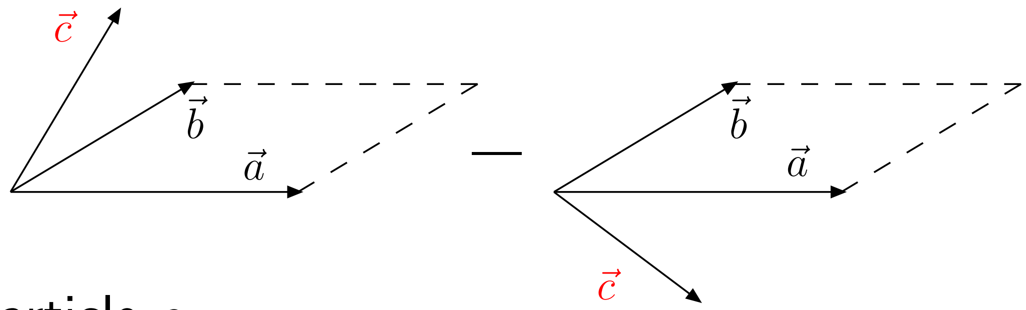
$$\Rightarrow A = \frac{\int Sign[\mathcal{T}]\ |T|^2\, d\text{Lips}}{\int |T|^2\, d\text{Lips}}$$

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

Geometrical interpretation

- Asymmetry A is an angular distribution:

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



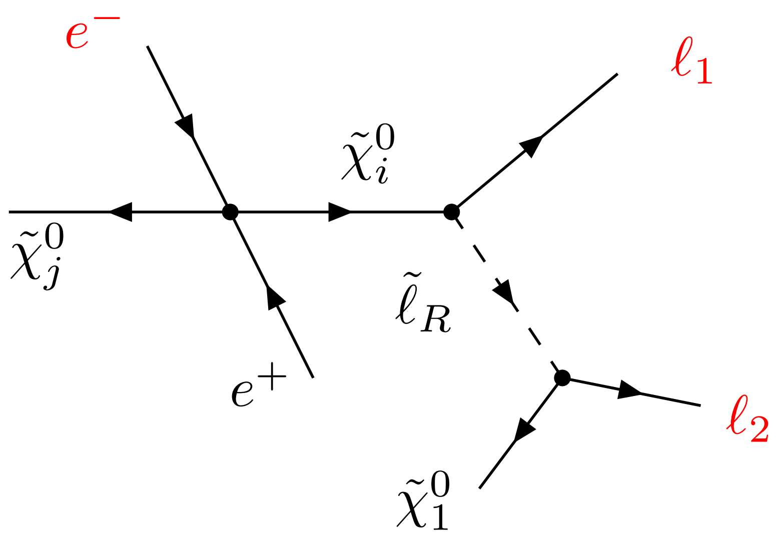
- $N_+(N_-)$: events with particle c above (below) plane spanned by $\vec{p}_a \times \vec{p}_b$

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

Asymmetry for neutralino production

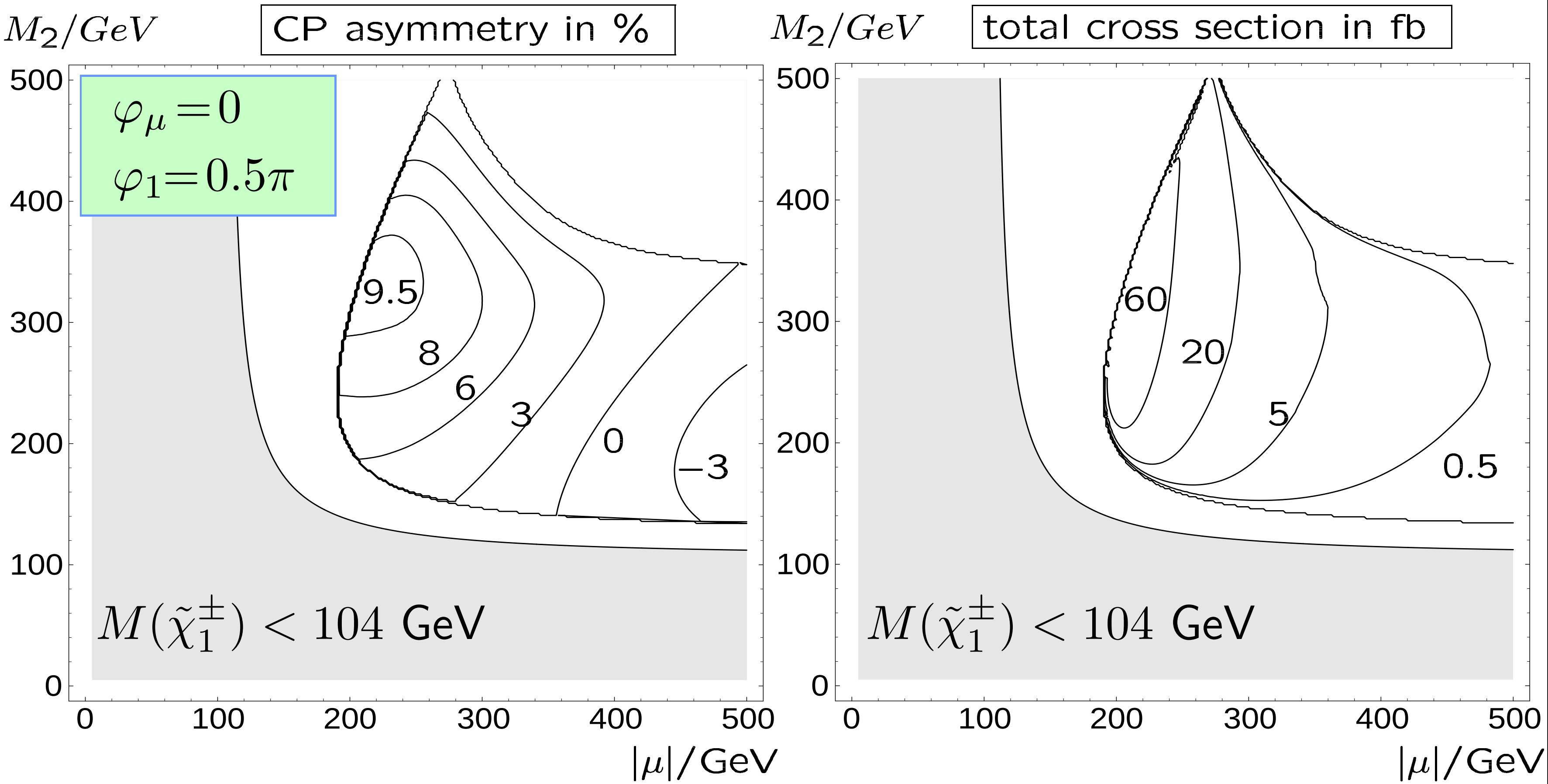
$$A = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}$$

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



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

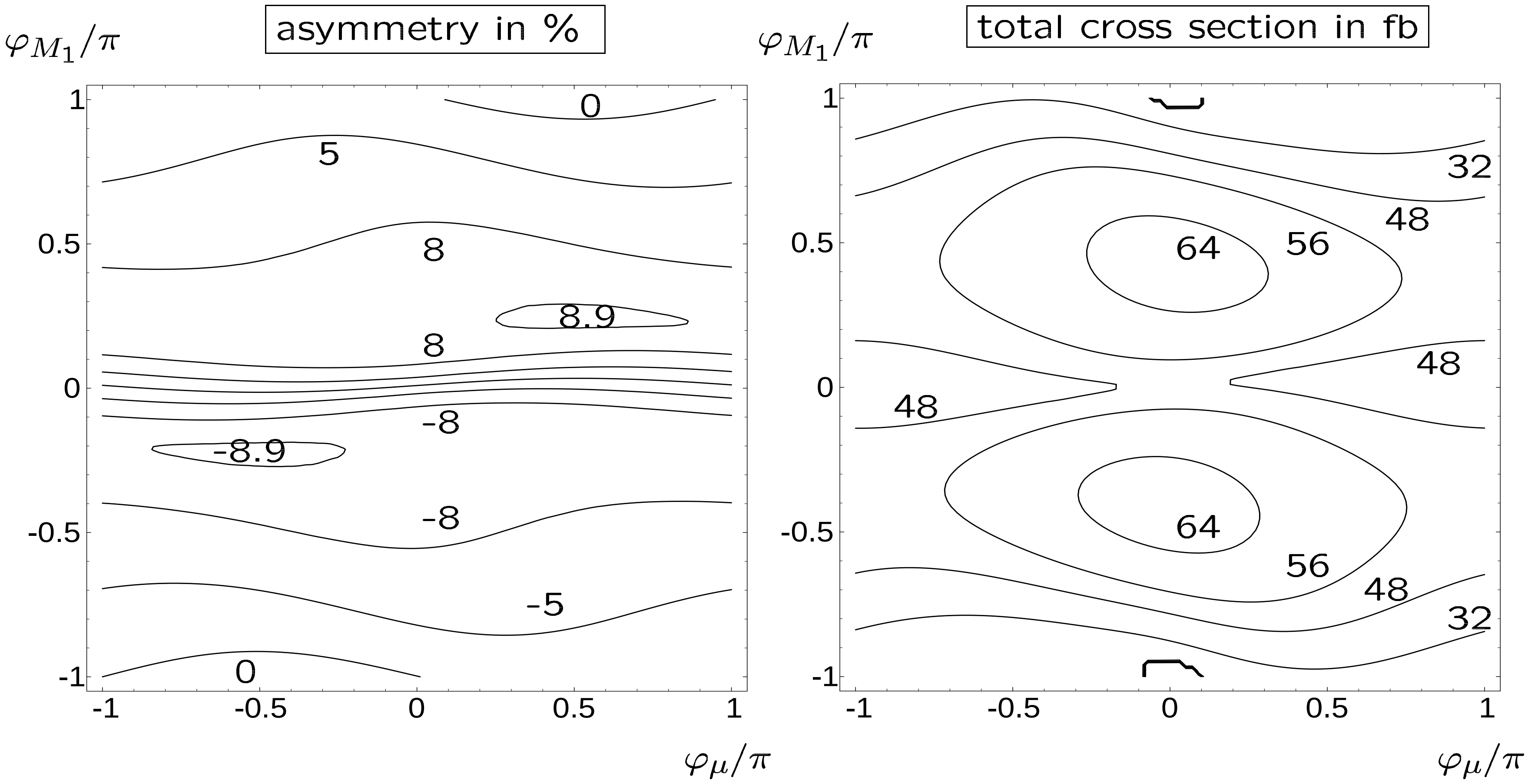
$\tan\beta = 10$; $m_0 = 100$ GeV; $P(e^-|e^+) = (0.8|-0.6)$



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

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

dependence on the phases



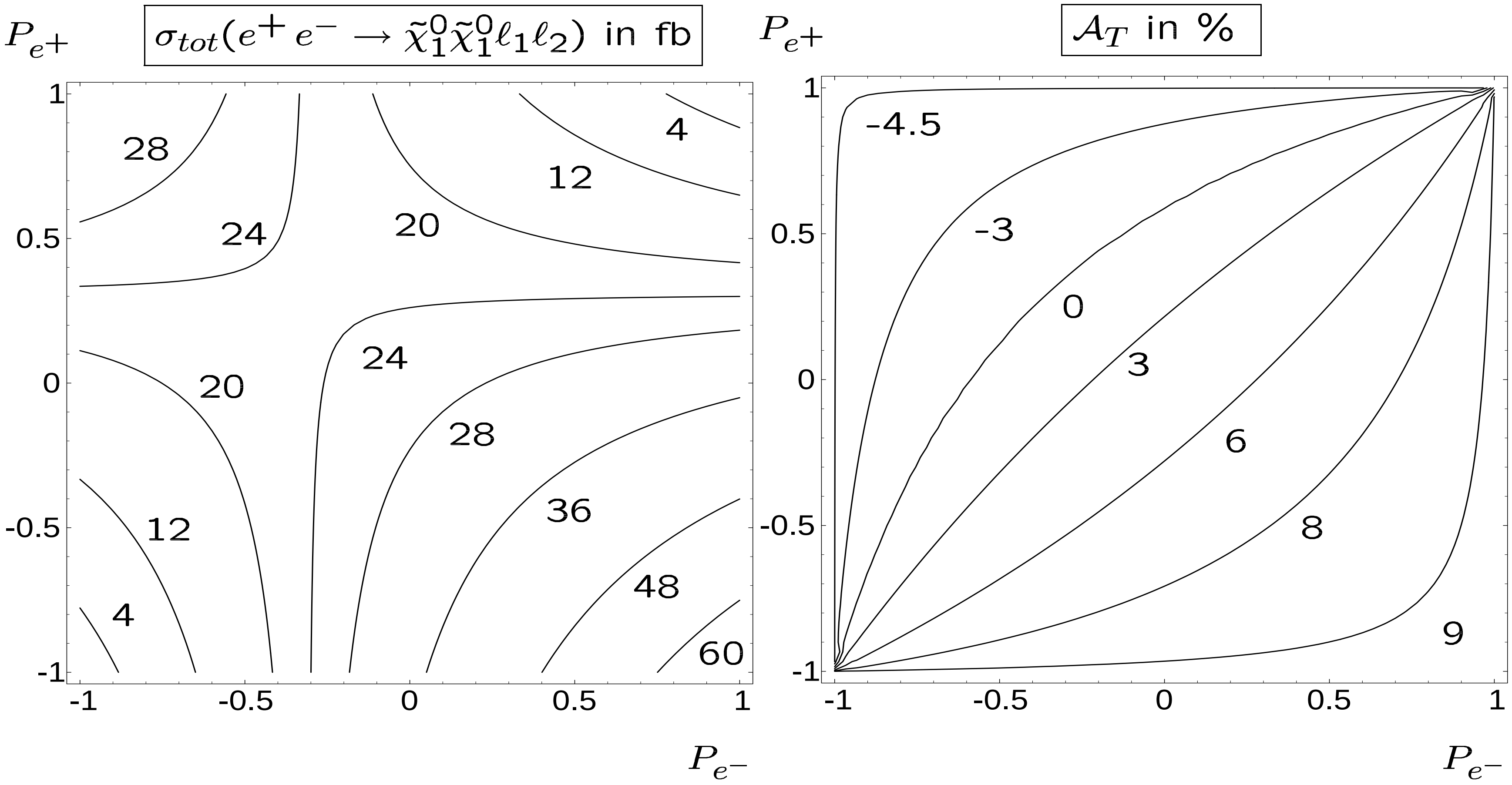
$$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0;\;\; \tilde{\chi}_2^0 \longrightarrow \tilde{\ell}_R\,\ell_1;\;\; \tilde{\ell}_R \longrightarrow \tilde{\chi}_1^0\,\ell_2$$

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

$\varphi_\mu = 0$

$\varphi_1 = 0.2\pi$

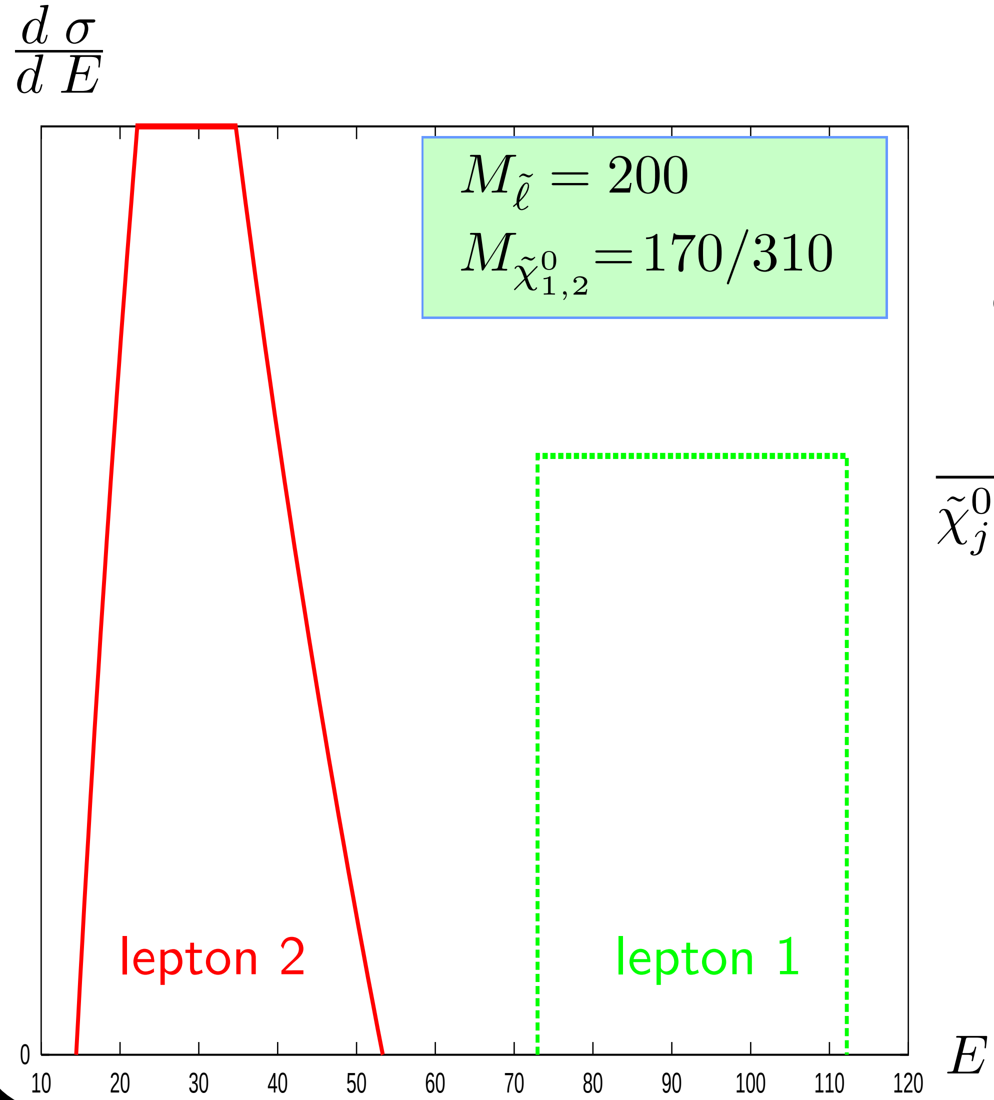
beam polarization dependence

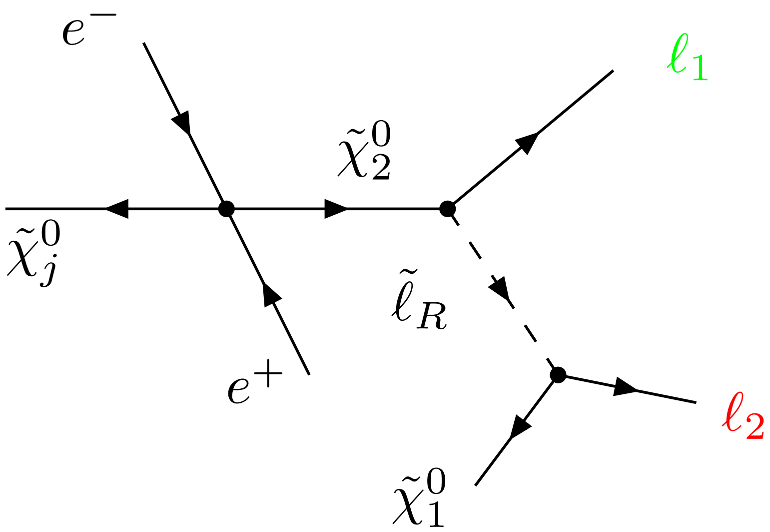


A bit of statistics

- How many events $N = \mathfrak{L} \times \sigma$ are needed to measure the CP-asymmetry A ?
- Statistical significance is given by: $S = A\,\sqrt{N}$
- An example: asymmetry of $A = 5\%$ and cross section $\sigma = 20$ fb would yield a CL of 5 (luminosity $\mathfrak{L} = 500$ fb^{-1}).
- However, since A and σ vary a lot over the MSSM parameter space, it is difficult to make global statements, whether phases could be measured or not.

Distinguish the leptons by energy distributions

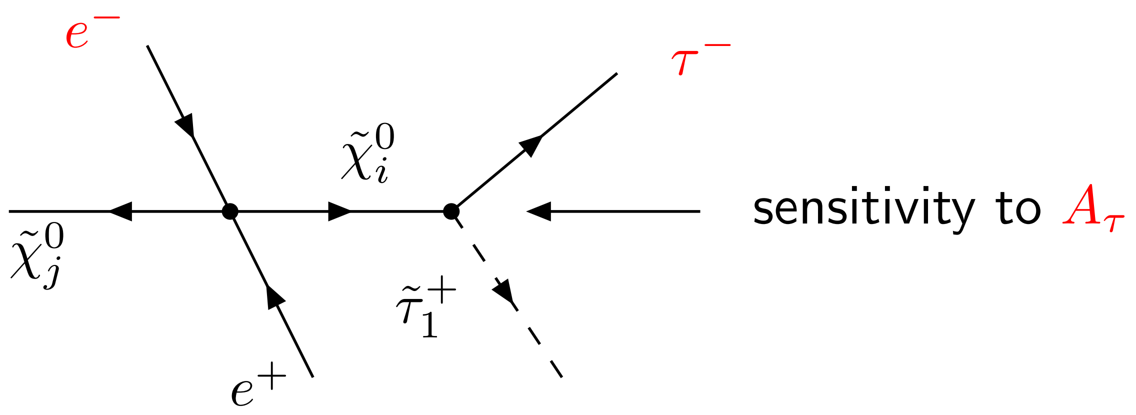




Transverse tau polarization as CP-asymmetry

$$A = P_\perp = \tau\text{−polarization} \perp \vec{p}(e^-), \vec{p}(\tau)$$

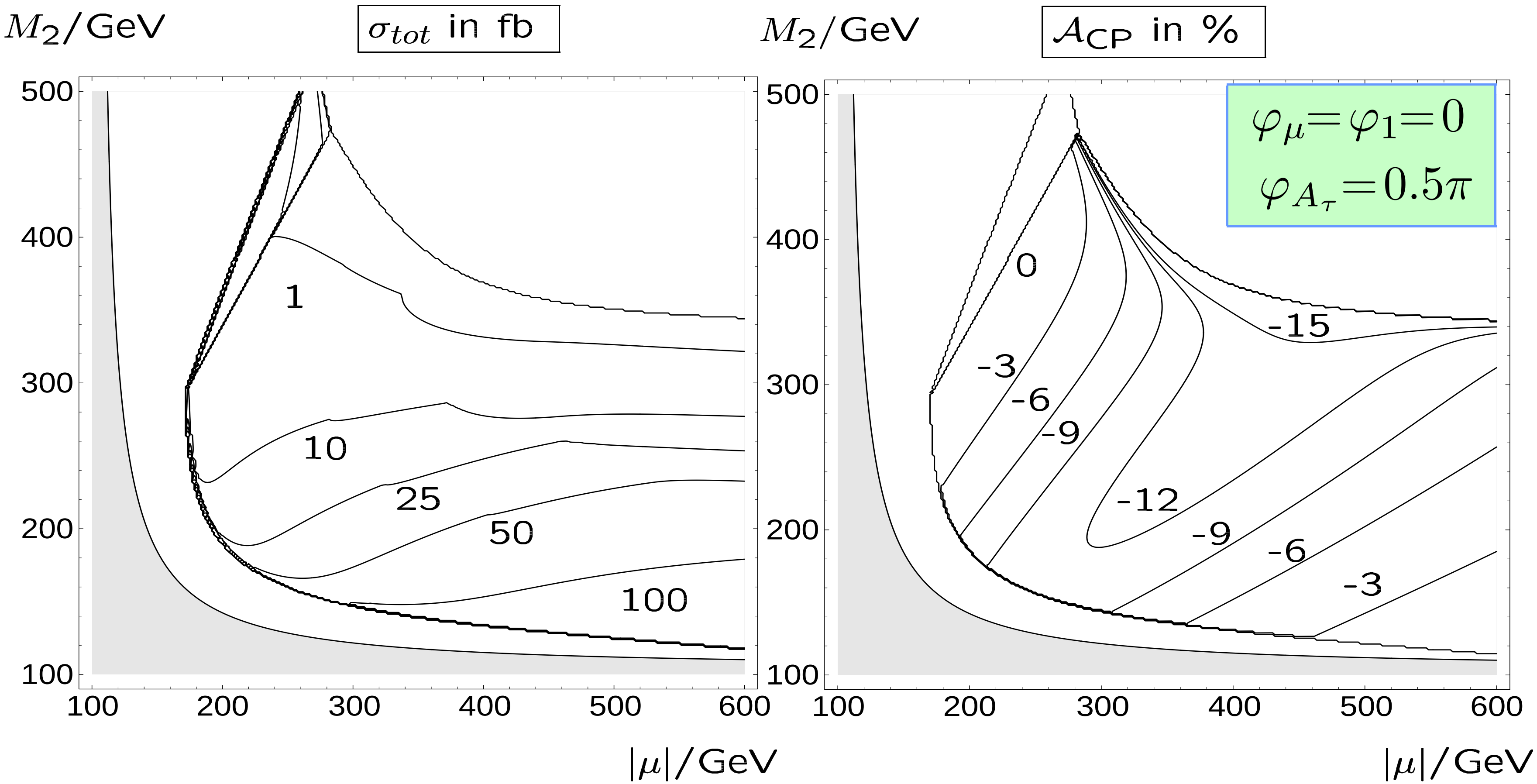
triple product: $\mathcal{T} \;=\; [\vec{p}(e^-) \times \vec{p}(\tau)] \cdot \vec{P}_\perp$



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

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

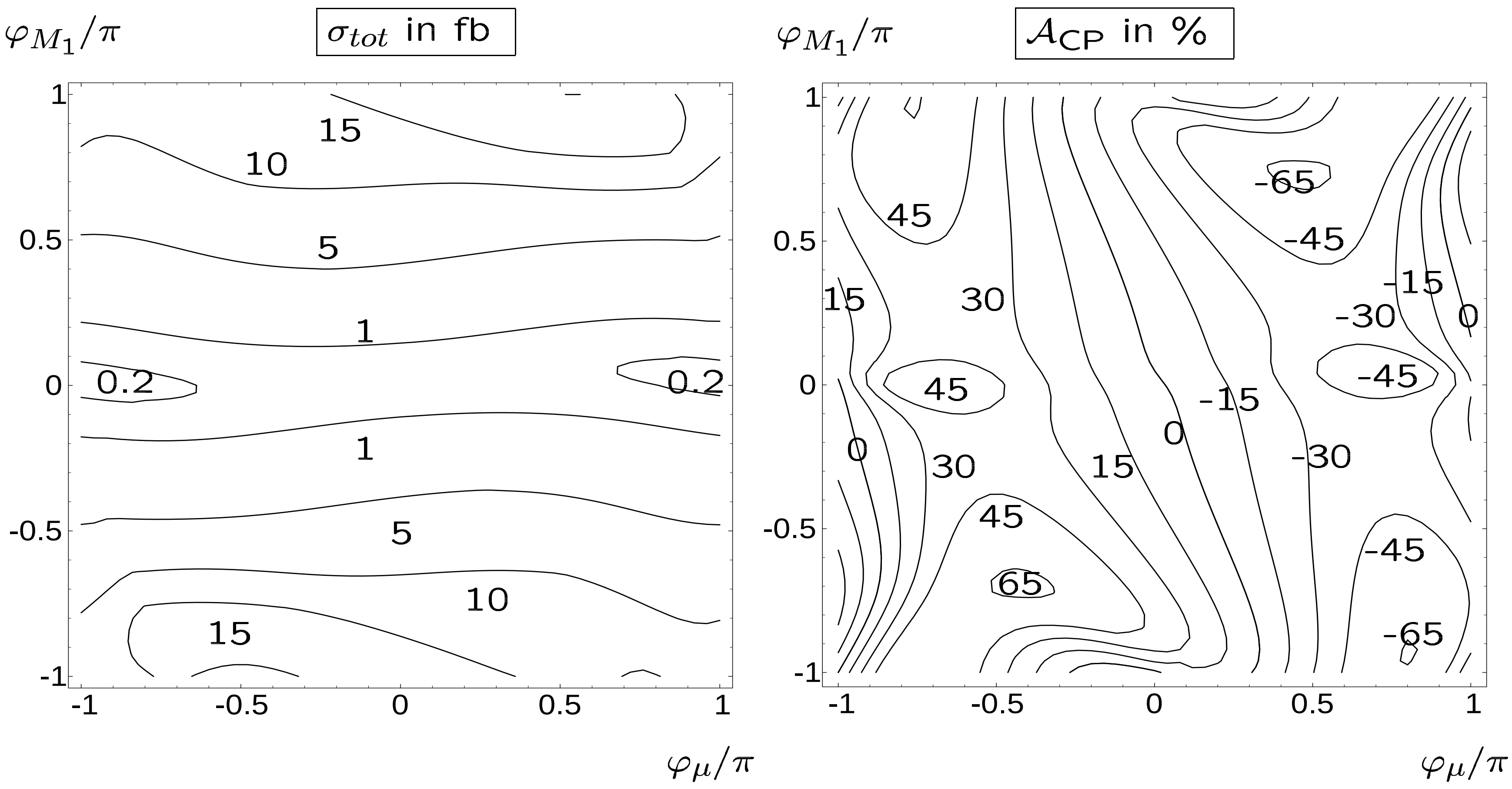
gray shaded area: $M(\tilde{\chi}^\pm_1) < 104$ GeV



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

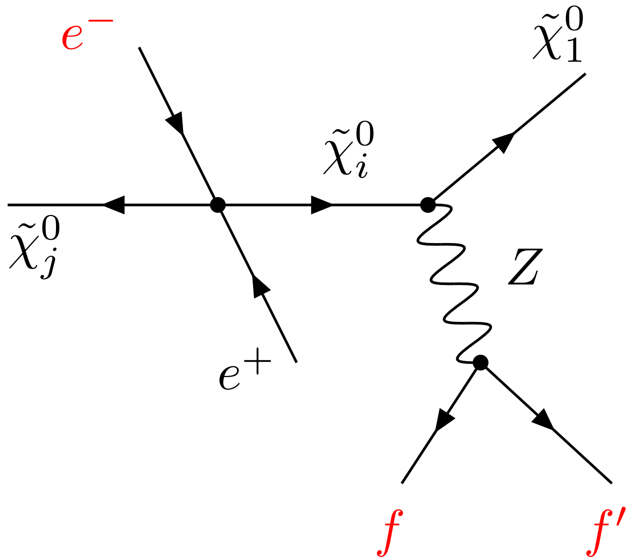
$A_\tau = 250$ GeV; $\tan\beta = 5$; $m_0 = 100$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

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



Asymmetry for neutralino decay into Z

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

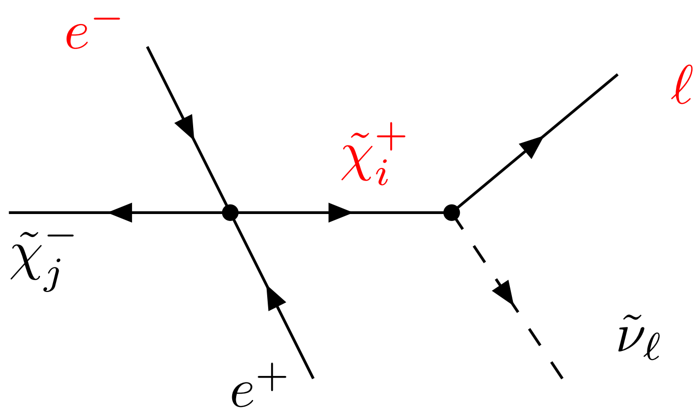


- also CP contributions to A from decay $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z$
- $A \propto \frac{|L|^2-|R|^2}{|L|^2+|R|^2} = 0.15(0.94)$ for $Z \to \ell^+\ell^-(b\,\bar{b})$ $\Rightarrow A \approx 3\%(18\%)$ for leptonic (hadronic) decays
- CP sensitive matrix elements of Z spin matrix

Asymmetry for chargino production

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

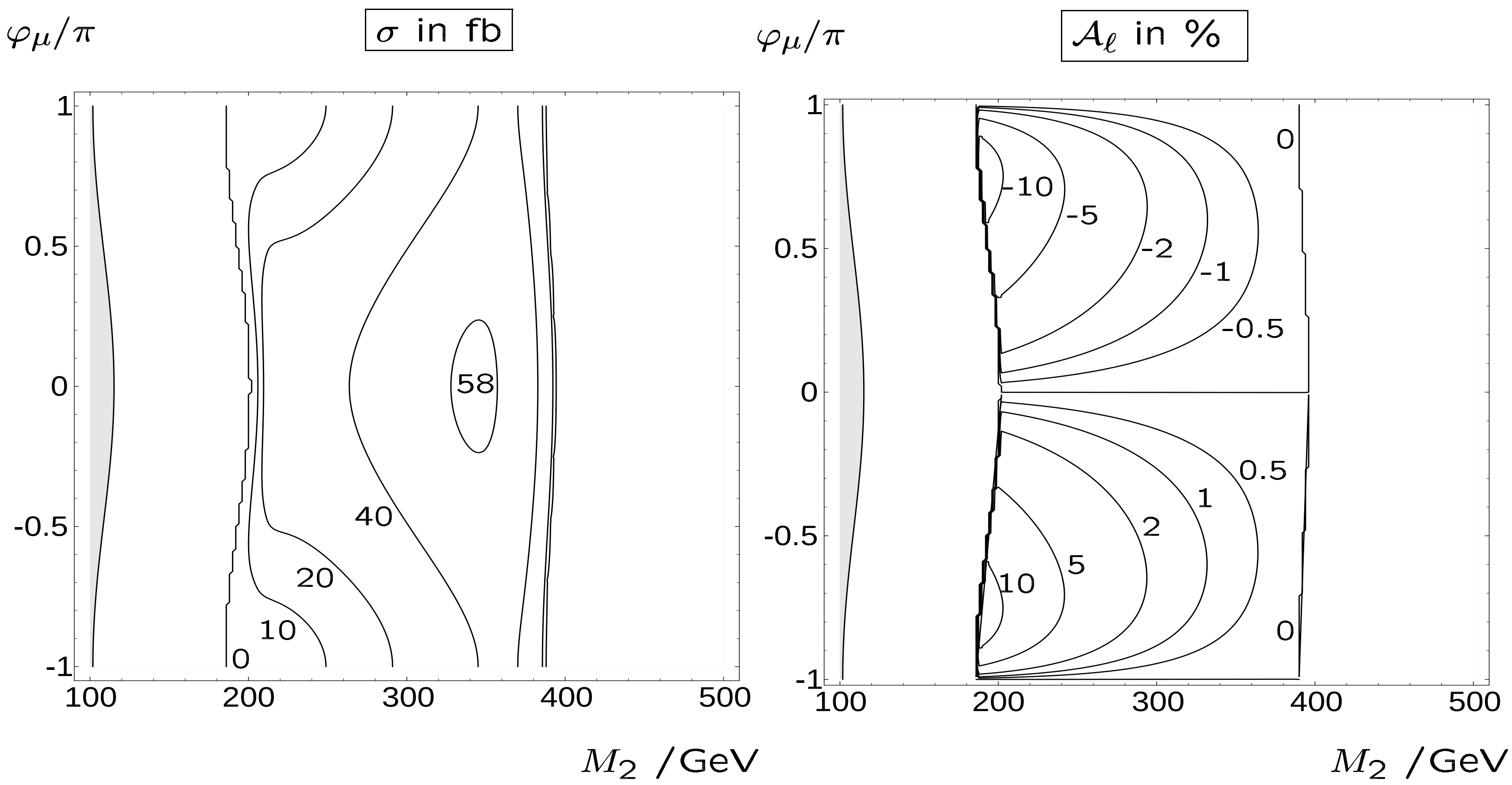
$$\mathcal{T} = [\vec{p}(e^-) \times \vec{p}(\tilde{\chi}_i^+)] \cdot \vec{p}(\ell)$$



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

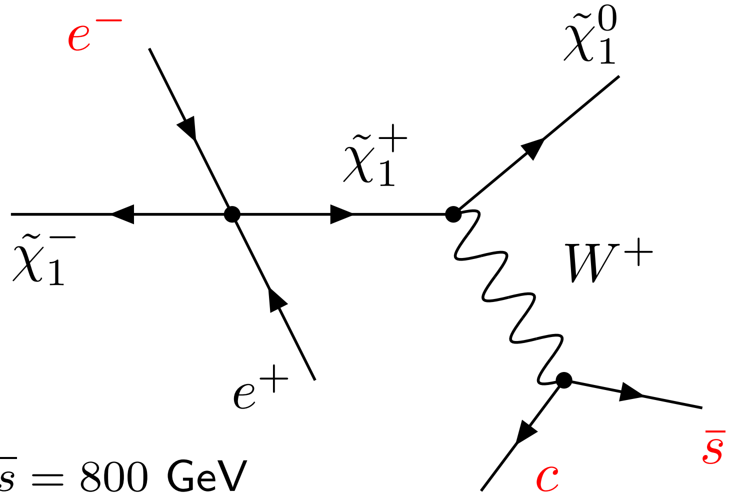
$|\mu| = 400$ GeV; $\tan\beta = 5$; $m_{\tilde{\nu}} = 185$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

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



Asymmetry for chargino decay into W

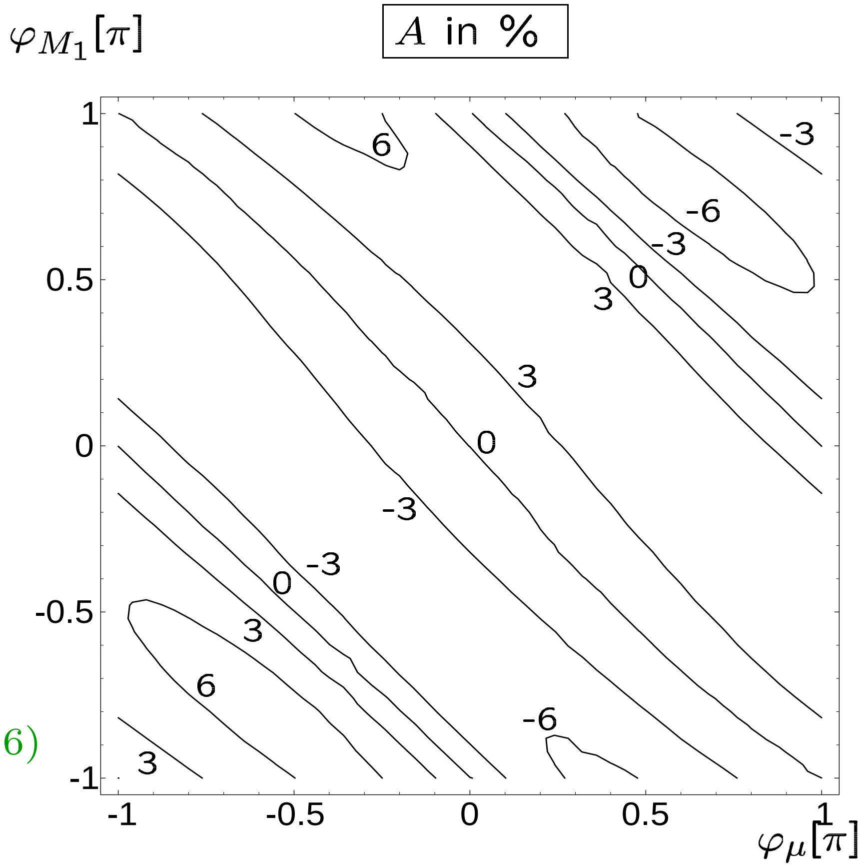
$$A = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}; \quad \mathcal{T} = [\vec{p}(e^-) \times \vec{p}(c)] \cdot \vec{p}(\bar{s})$$



$\sqrt{s} = 800$ 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 MSSM parameters (here phases of μ, M_1, A_τ) have impact on the production and the decay 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 (ILC).