SUSY CP phases and asymmetries at colliders

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Outline

- Introduction: the MSSM and its complex parameters

- CP observables: asymmetries of triple products

- Results and examples:
  - neutralino and chargino production at the ILC and LHC
  - squark decays at the LHC

- Summary and conclusions

1 Introduction

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 in the SM
- Cosmology: need more CP phases to explain baryon asymmetry!

In addition:

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

The chargino mass matrix $\mathcal{M}_\pm$

- Charginos $\tilde{\chi}_i^\pm$ are a mixture of charged winos $\tilde{W}^\pm$ and higgsinos $\tilde{H}^\pm$.

$$\mathcal{M}_\pm = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin(\beta) \\ \sqrt{2} M_W \cos(\beta) & \mu \end{pmatrix}$$

- Parameters:

  M_2: wino mass, soft supersymmetry breaking parameter

  μ: Higgs mixing parameter

  $\tan\beta$: ratio of vacuum expectation values of the two neutral, CP-even Higgs fields

- $|\text{eigenvalues}|$ of $\mathcal{M}_\pm$ = chargino masses $m_{\tilde{\chi}^\pm_{i=1,2}}$
- diagonalization matrix determines the chargino couplings

The neutralino mass matrix $\mathcal{M}_0$

- Neutralinos $\tilde{\chi}_i^0$ are a mixture of the neutral gauginos ($\tilde{B}$, $\tilde{W}^3$) and higgsinos ($\tilde{H}_u$, $\tilde{H}_d$).

$$\mathcal{M}_0 = \begin{pmatrix} M_1 & 0 & -m_Z \sin(\theta_W)\cos(\beta) & m_Z \sin(\theta_W)\sin(\beta) \\ 0 & M_2 & m_Z \cos(\theta_W)\cos(\beta) & -m_Z \cos(\theta_W)\sin(\beta) \\ -m_Z \sin(\theta_W)\cos(\beta) & m_Z \cos(\theta_W)\cos(\beta) & 0 & -\mu \\ m_Z \sin(\theta_W)\sin(\beta) & -m_Z \cos(\theta_W)\sin(\beta) & -\mu & 0 \end{pmatrix}$$

- M_1: bino mass, soft supersymmetry breaking parameter

- |eigenvalues| of $\mathcal{M}_0$ = neutralino masses $m_{\tilde{\chi}^0_{i=1,2,3,4}}$

- diagonalization matrix determines the neutralino couplings

The sfermion mass matrix $\mathcal{M}_{\tilde{f}}$

- Sfermions $\tilde{f}_n$ are a mixture of right and left sfermions.

$$\mathcal{M}_{\tilde{f}} = \begin{pmatrix} M^2_{\tilde{f}\,L} & m_f \left[A_f - \mu^* (\cot\beta)^{(2I^f)} \right] \\ m_f \, [\ldots]^* & M^2_{\tilde{f}\,R} \end{pmatrix}$$

- Parameters:

I^f : third isospin component of fermion

$M_{\tilde{f}\,L(R)}$: left (right) sfermion mass (soft SUSY breaking)

A_f: trilinear scalar coupling parameter (soft SUSY breaking)

- |eigenvalues| of $\mathcal{M}_{\tilde{f}}$ = sfermion masses $m_{\tilde{f}_{n=1,2}}$
- diagonalization matrix determines the sfermion couplings

Summary of the relevant MSSM parameters

neutralino sector

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

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

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

chargino sector

M_2 SU(2) gaugino mass parameter

sfermion sector

$A_f = |A_f|\ exp(i\,\varphi_A)$ trilinear scalar coupling parameter

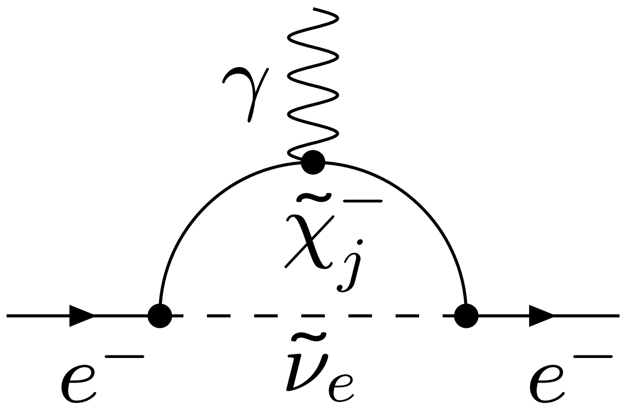
constraints on phases from electric dipole moments (EDM)

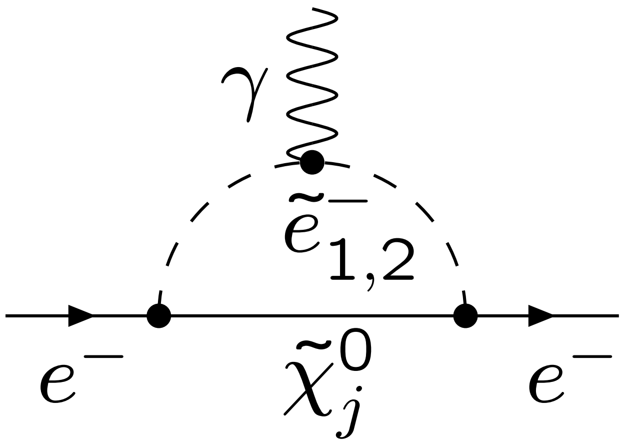
experimental bounds for electron and neutron EDM

$$d^e_{exp} < 4.3 \times 10^{-27}\, e\, cm$$

$$d^n_{exp} < 6.3 \times 10^{-26}\, e\, cm$$

MSSM contributions to e^- EDM $\Rightarrow$ φ_1, φ_μ small (esp. $\varphi_\mu < \pi/10$)





The SUSY CP problem

The strong exp. bounds from the EDMs suggest that:

- SUSY CP phases are severely suppressed ($\approx 10^{-2}$, es. μ), or
- SUSY particles are very heavy (>10 TeV), or
- different loop-contributions to EDMs cancel

the problem: all solutions require fine-tuning/ are unnatural

$\Rightarrow$ solution: measure/constrain CP phases independently at colliders

Goal:

- to analyze the impact of CP-violating phases
- to define and calculate CP-sensitive observables

Frame:

- MSSM with complex parameters μ, M_1, A_f
- neutralino/chargino/squark production at ILC and LHC
- tree level, polarizations + spin correlations

What is the impact of complex parameters?

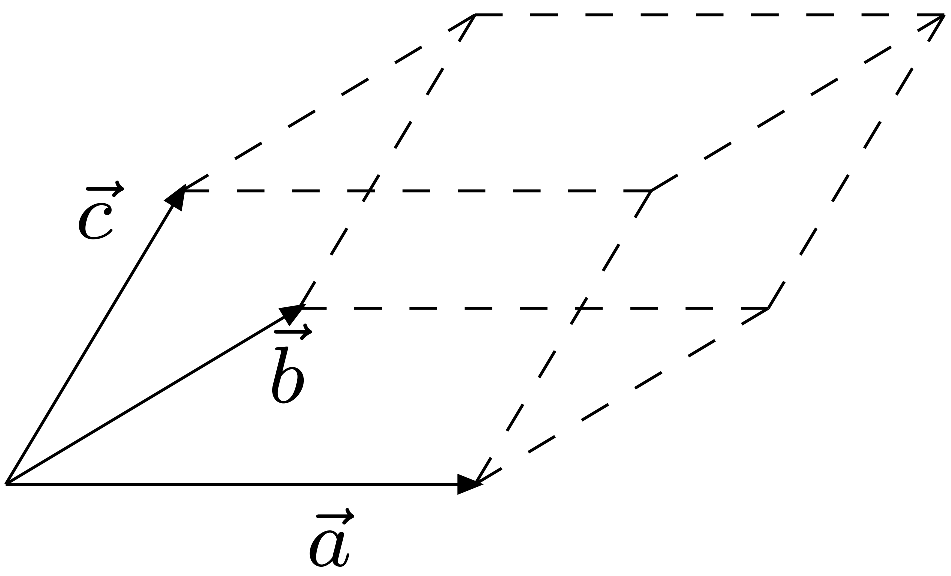
- couplings become complex

- 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
such that CP could be tested directly?

How to construct them? $\Rightarrow$ triple-products

2 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

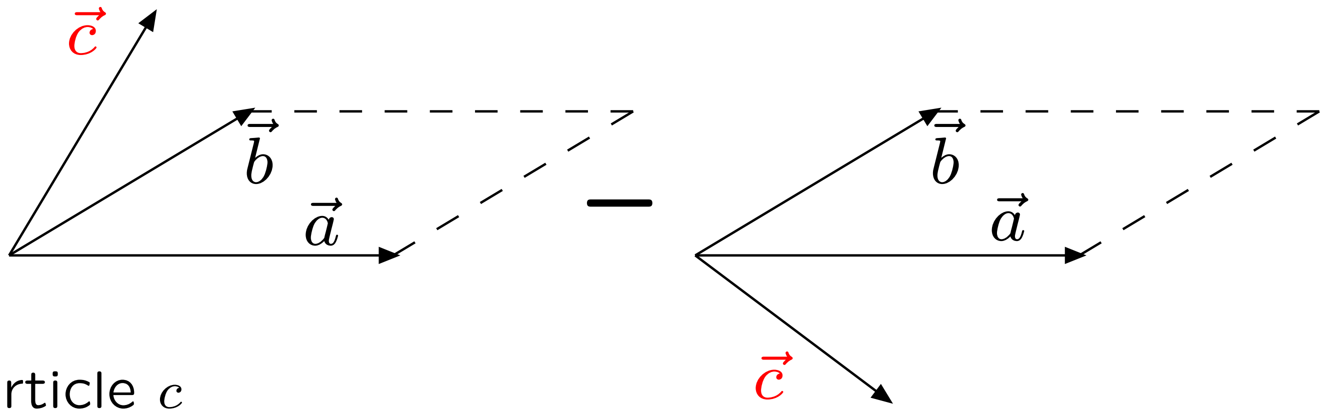
$$\Rightarrow A = \frac{\int Sign[\mathcal{T}]\ |T|^2\, d\mathrm{Lips}}{\int |T|^2\, d\mathrm{Lips}}$$

- Amplitude squared: $|T|^2$
- 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

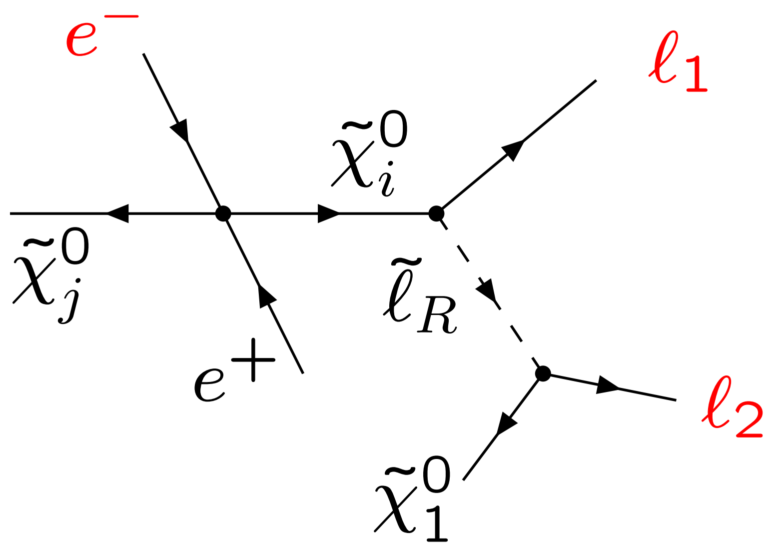
  above (below) plane spanned by $\vec{p}_a \times \vec{p}_b$

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

3 Results: Asymmetry in neutralino production

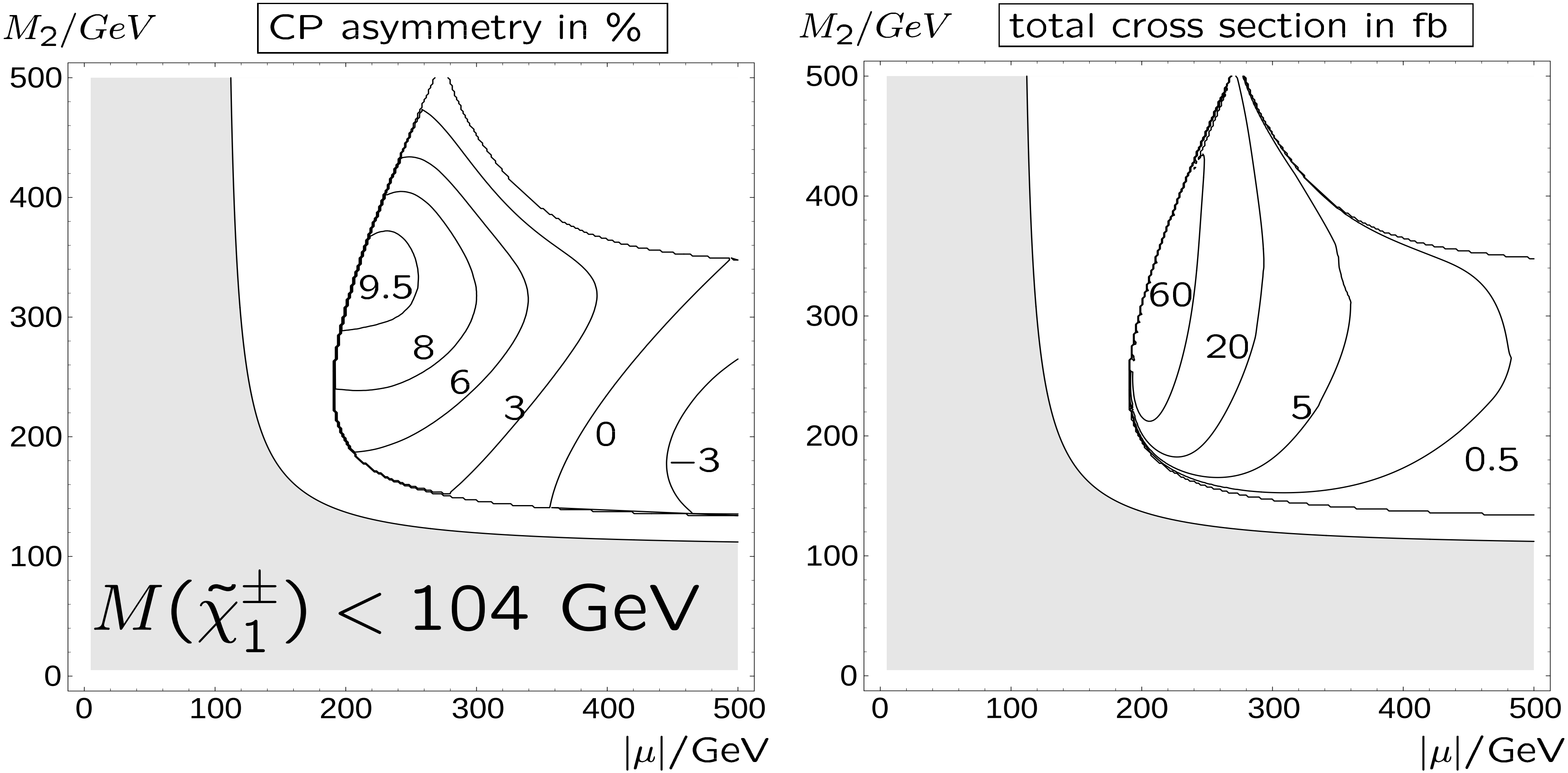
$$A = \frac{\sigma(\mathcal{T} > 0) - \sigma(\mathcal{T} < 0)}{\sigma(\mathcal{T} > 0) + \sigma(\mathcal{T} < 0)}$$

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



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

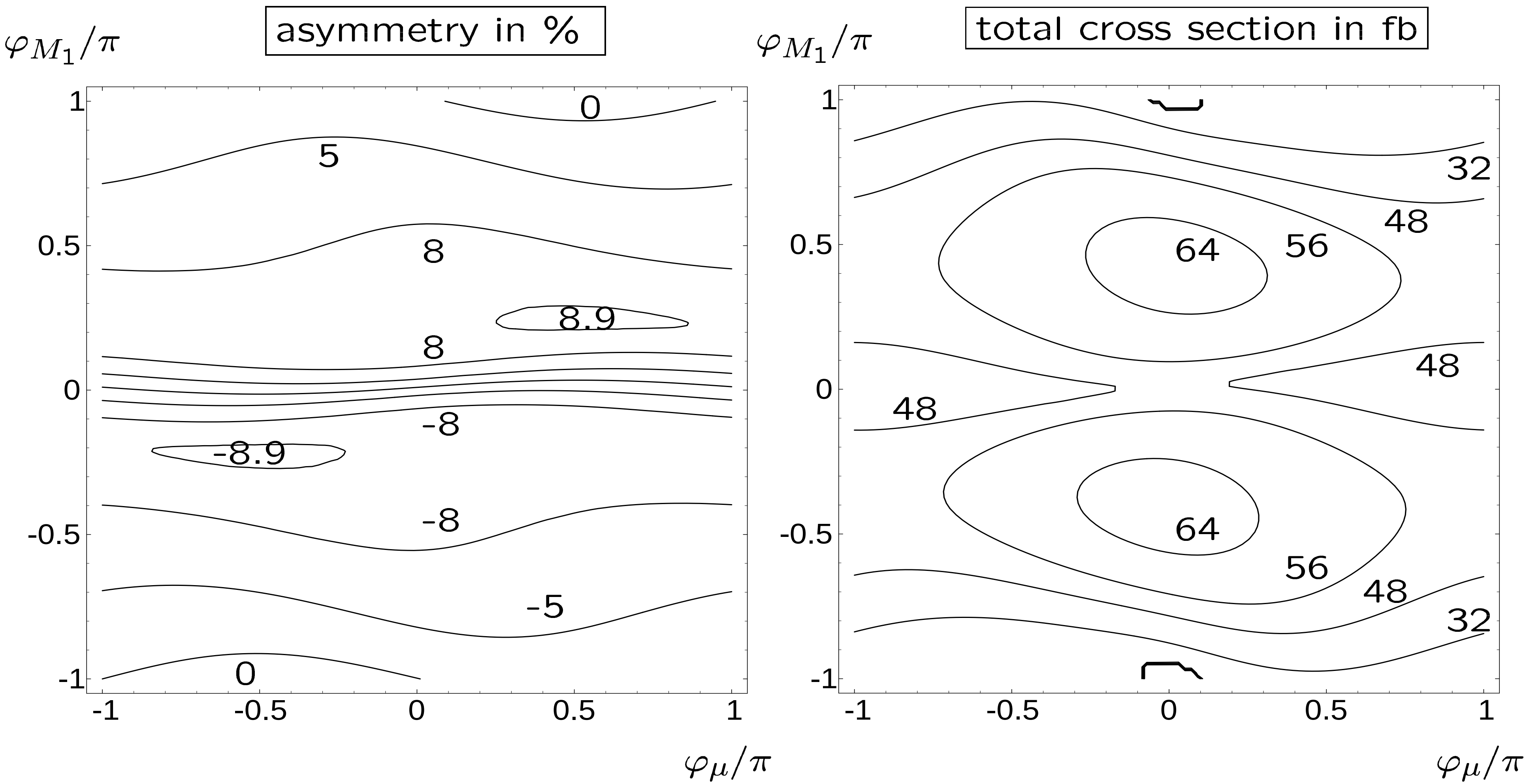
$\varphi_1 = 0.5\pi$; $\tan\beta = 10$; $m_0 = 100$ GeV; $P(e^-|e^+) = (0.8|-0.6)$



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

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

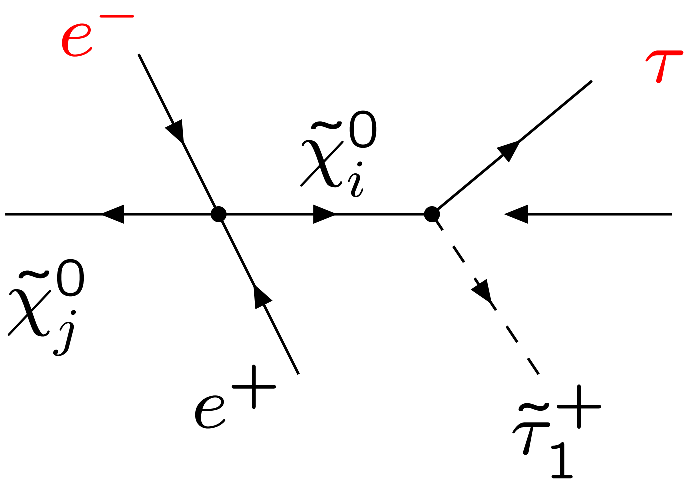
dependence on the phases



Tau polarization asymmetry

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

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

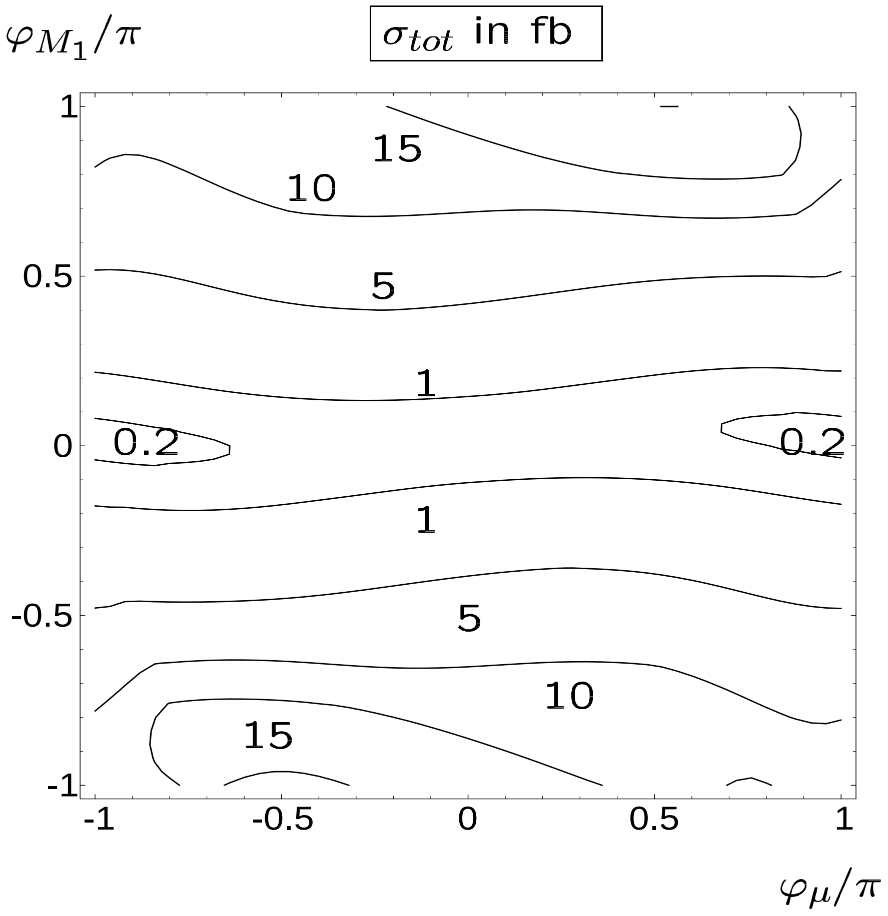


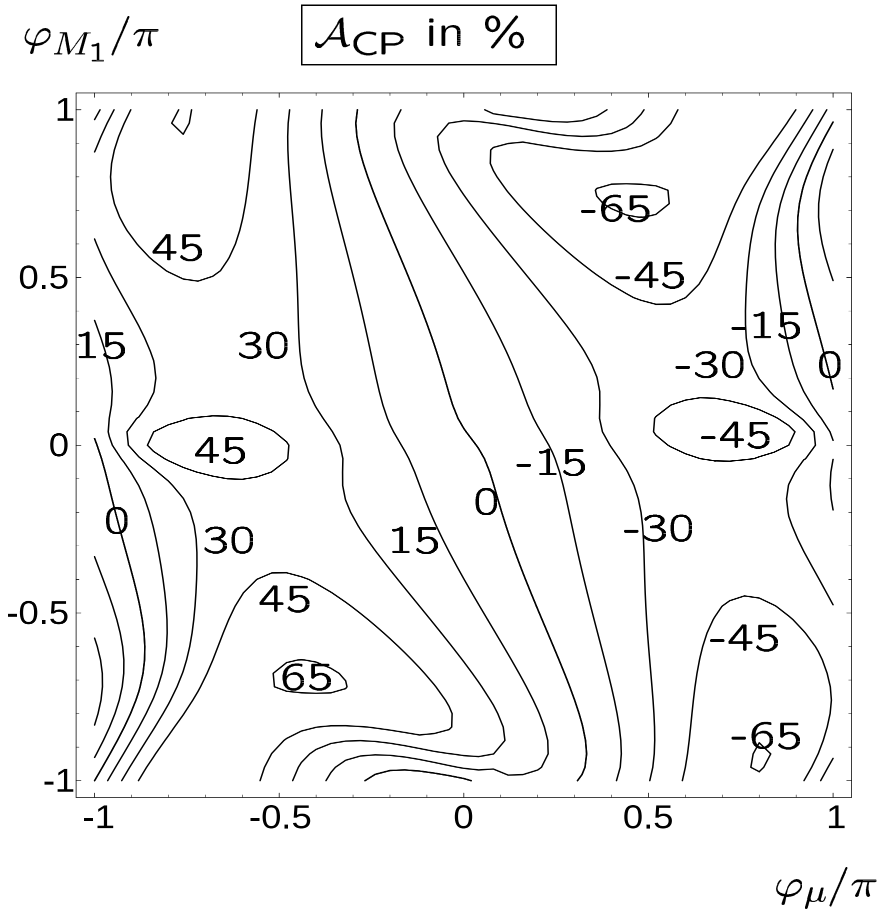
sensitivity to A_τ

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

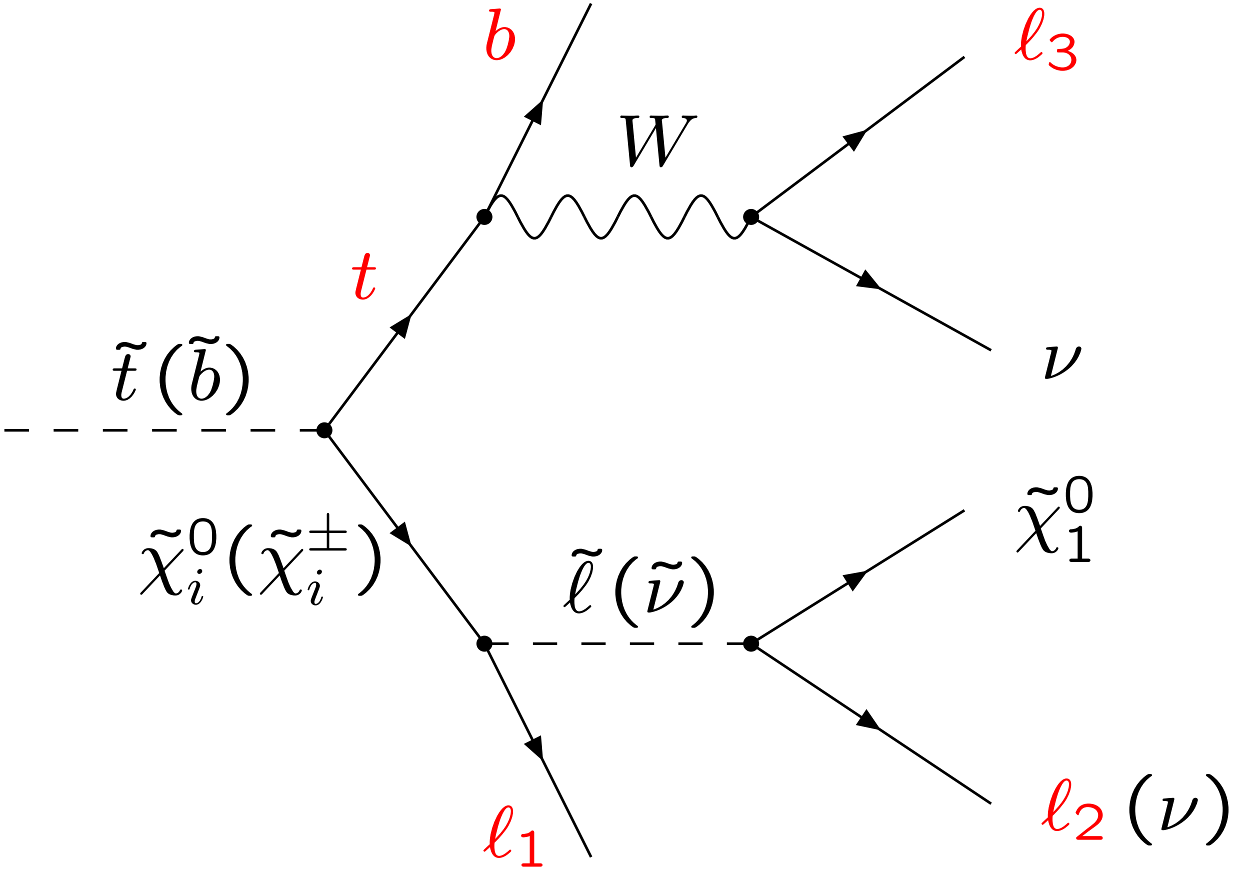
$$A_\tau = 250 \text{ GeV};\ \tan\beta = 5;\ m_0 = 100 \text{ GeV};\ P(e^-|e^+) = (-0.8|0.6)$$

$$|\mu| = 240 \text{ GeV};\ M_2 = 400 \text{ GeV}$$





Squark decays at the LHC



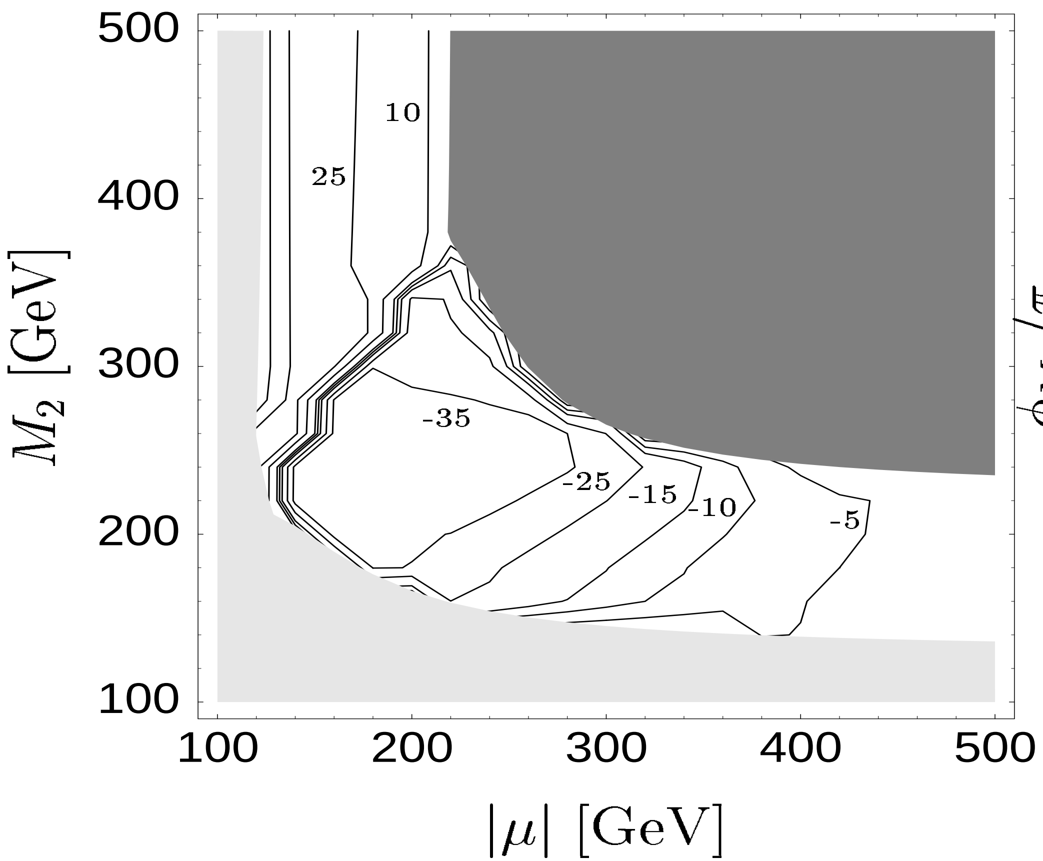
[Bartl et al., hep-ph/0409060, hep-ph/0610234]

$\tilde{t}_1 \to t\tilde{\chi}_2^0 \to bW\tilde{\ell}\ell_1 \to \tilde{\ell}\ell_1\ell_3\nu$ [hep-ph/0409060]

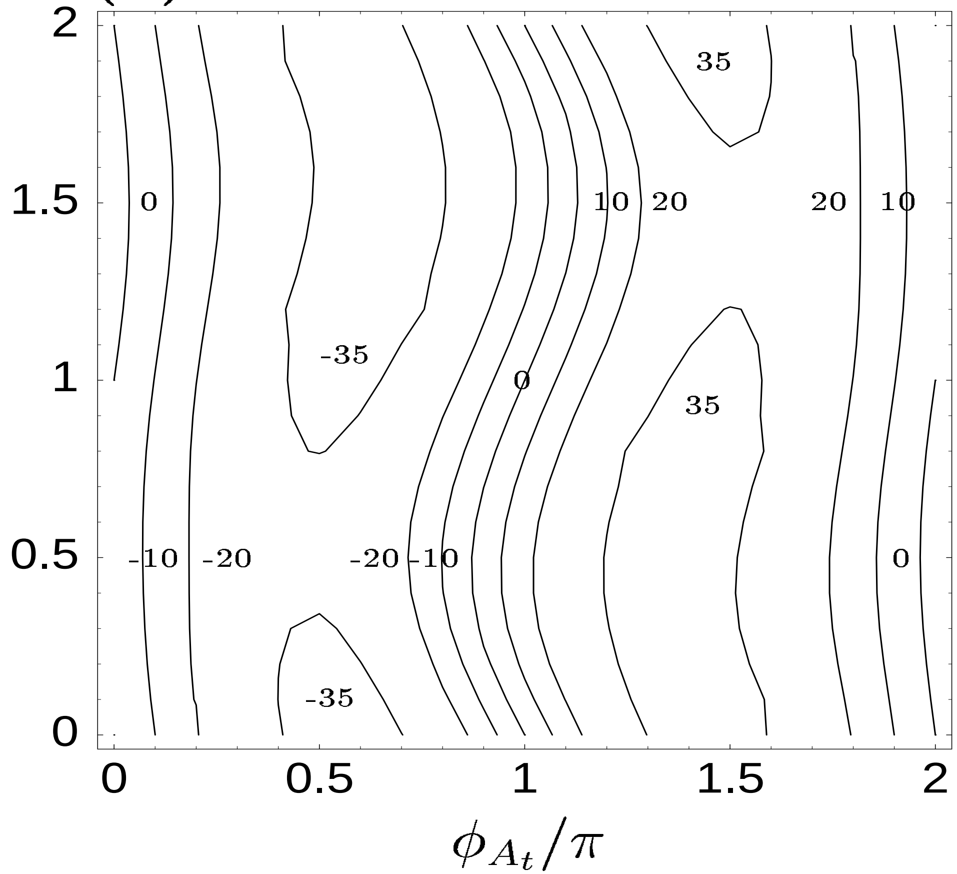
$A_t = 1.2$ TeV; $\Phi_{A_t} = \pi/2$; $\tan\beta = 10$; $m_{\tilde{t}_1} = 400$ GeV;

$|\mu| = 200$ GeV; $M_2 = 400$ GeV

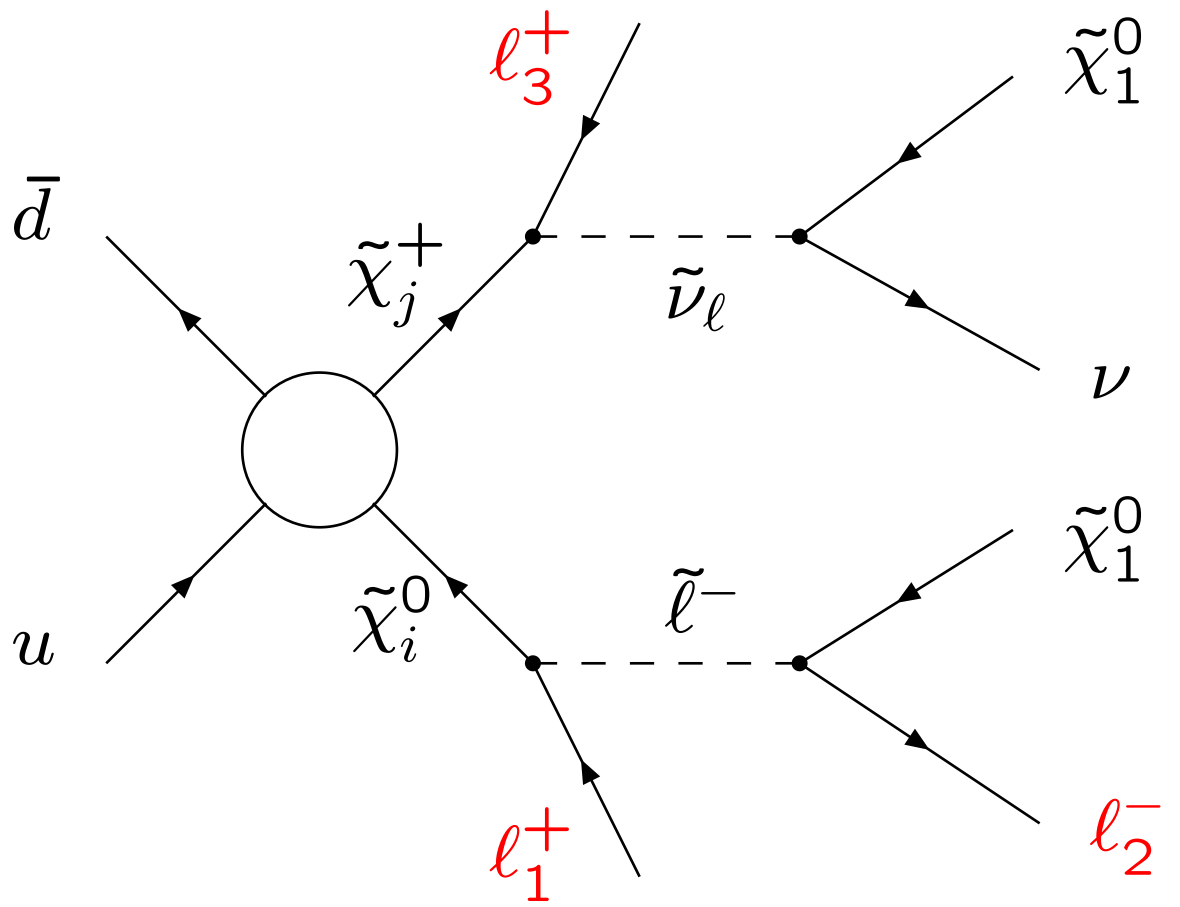
(a)



(a)



Chargino/Neutralino production at the LHC



[Tevatron: Choi et al., hep-ph/0007276]

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, charginos and squarks.

- 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 colliders.