

# CP-violating effects in SUSY

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# Outline

- Introduction: the SM, the MSSM, and their complex parameters
- CP observables: asymmetries of triple/epsilon products
- Results and examples
  - neutralino/chargino production at the ILC/LHC
  - squark decays at the LHC
  - current experimental ILC study  
(with Moortgat-Pick, Rolbiecki, Schade, Tattersall, Terwort)
- Summary

# The history of CP violation

- first evidence in the neutral  $K^0/\bar{K}^0$  system in 1964
- theory: prediction of a third generation of quarks in 1972!
- mixing of three quark families allows **one CP phase** in the CKM matrix:

$$V_{CKM} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

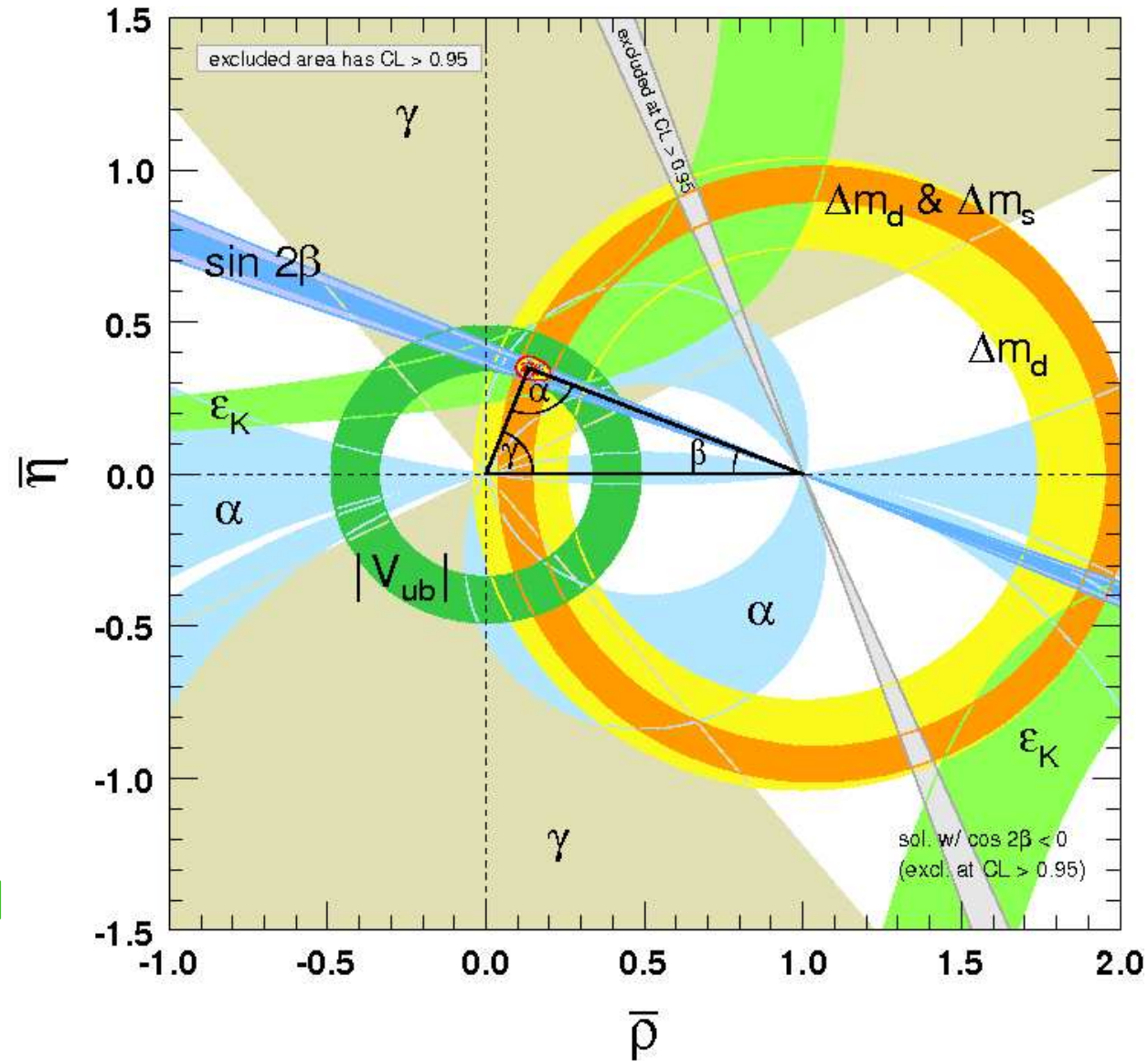
$$s_{ij} = \sin \theta_{ij}, \quad c_{ij} = \cos \theta_{ij}$$

quark mixing: 3 mixing angles  $\theta_{12, 13, 23}$ , and 1 CP phase  $\delta$

# CP violation in the quark sector today

- Experiments with B-mesons verify one CP phase
- Goal: to systematically over-constrain the CKM elements with experiments

[PDG]



# Neutrino mixings also allow for CP phases

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\text{mass}} = \begin{pmatrix} U \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_{\text{flavor}}$$

mixing matrix:  $U = V \cdot \text{diag}(1, e^{i\frac{\phi_{12}}{2}}, e^{i\frac{\phi_{23}}{2}})$

( $V$  in the CKM form)

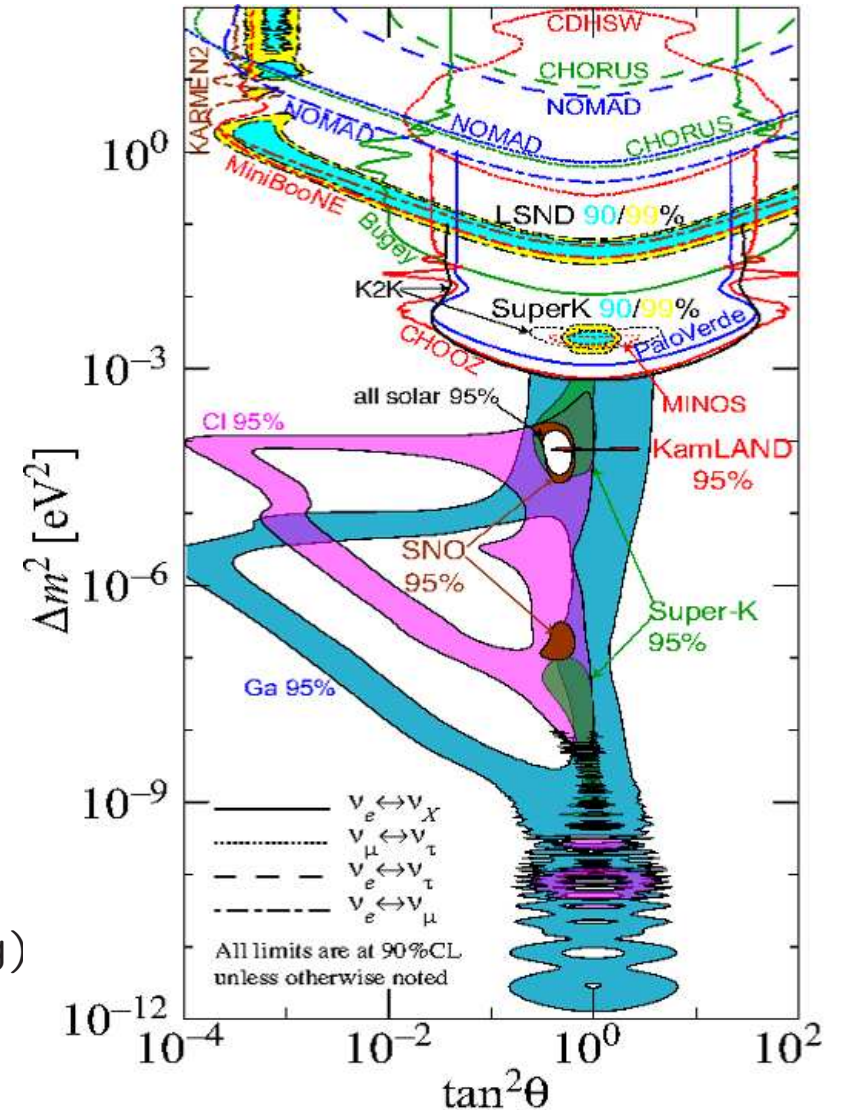
3 mixing angles:  $\theta_{12}, \theta_{13}, \theta_{23}$

3 CP phases:

1 Dirac phase  $\delta$ , and

2 Majorana phases  $\phi_{ij}$  (measurement pending)

[PDG]



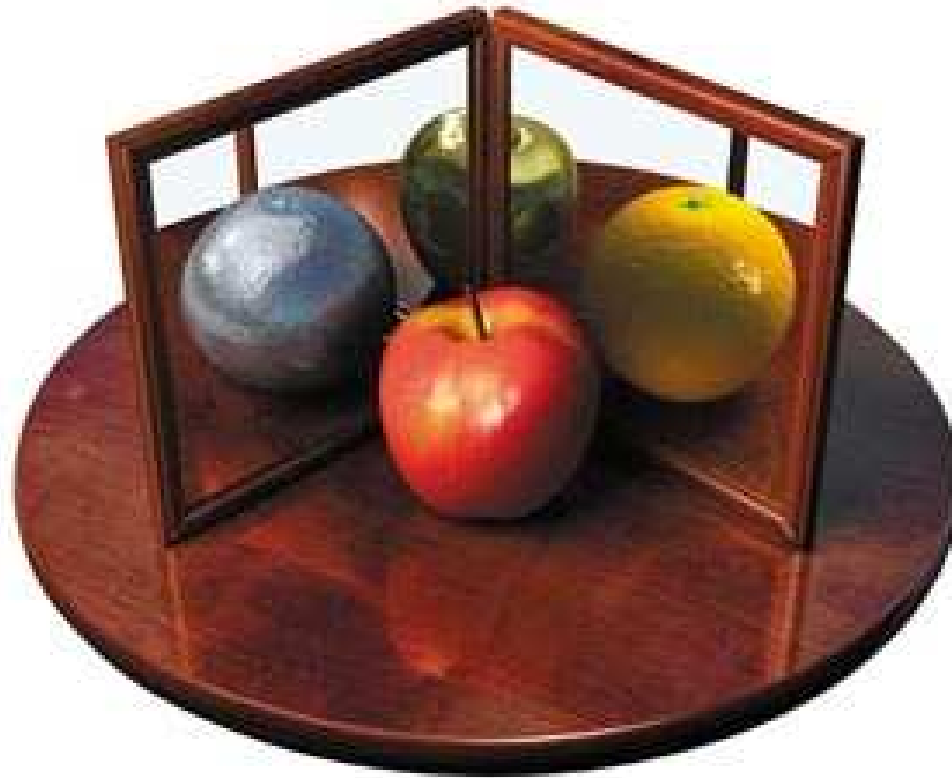
# CP violation in Cosmology

- CP phases needed for baryon asymmetry of the universe (baryo/leptogenesis)
- However:  
CP phase of the quark sector is not enough!
- CP phases beyond the Standard Model are needed!



# Importance of SUSY CP phases

- Supersymmetry (SUSY) yields new sources of CP violation
- SUSY CP phases might change the relic-density of neutralinos (dark matter)
- SUSY CP phases allow a mixing of CP-even and CP-odd neutral Higgs bosons  $\Rightarrow$  a light Higgs boson ( $\approx 45$  GeV) might not have been discovered at LEP
- SUSY is attractive also due to other reasons:  
dark matter candidates, unification of forces,  
solution to hierarchy problem, window to include gravity



⇒ Enough motivation to take a closer look at the SUSY particles and their CP phases!



## Charged fermions: the charginos

- 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

$\mu$ : Higgs mixing parameter

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

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

## Neutral fermions: the neutralinos

- 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
- $\sqrt{\text{eigenvalues of } \mathcal{M}_0 \mathcal{M}_0^\dagger} = \text{neutralino masses } m_{\tilde{\chi}_{i=1,2,3,4}^0}$
- diagonalization matrix determines the neutralino couplings

## Scalar particles: sfermions

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

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

- 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

## 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

## sfermion sector

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

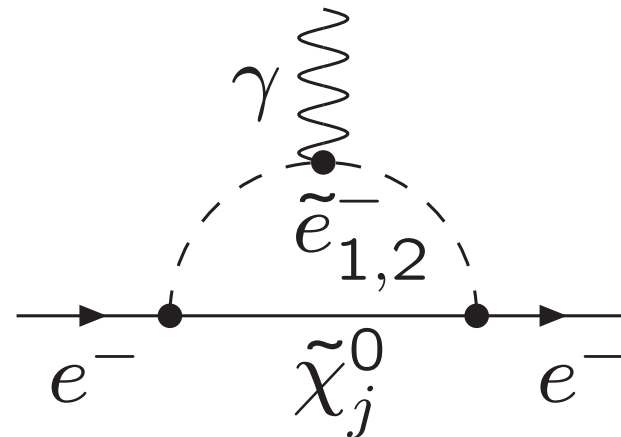
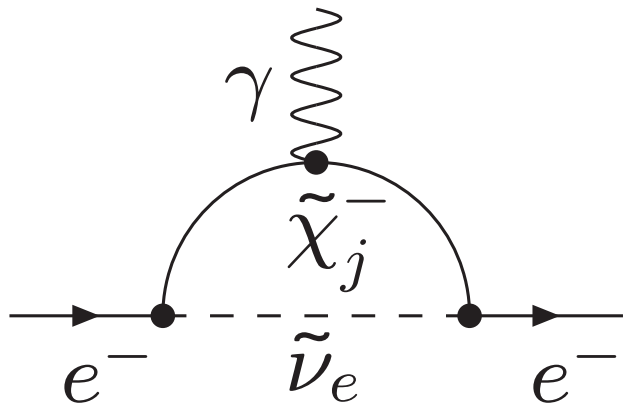
# constraints on phases from electric dipole moments (EDM)

e.g., experimental bounds for electron and neutron EDM

$$d_{exp}^e < 4 \times 10^{-27} \text{ e cm}$$

$$d_{exp}^n < 3 \times 10^{-26} \text{ e cm}$$

(future experiments better by two orders of magnitude and more!)



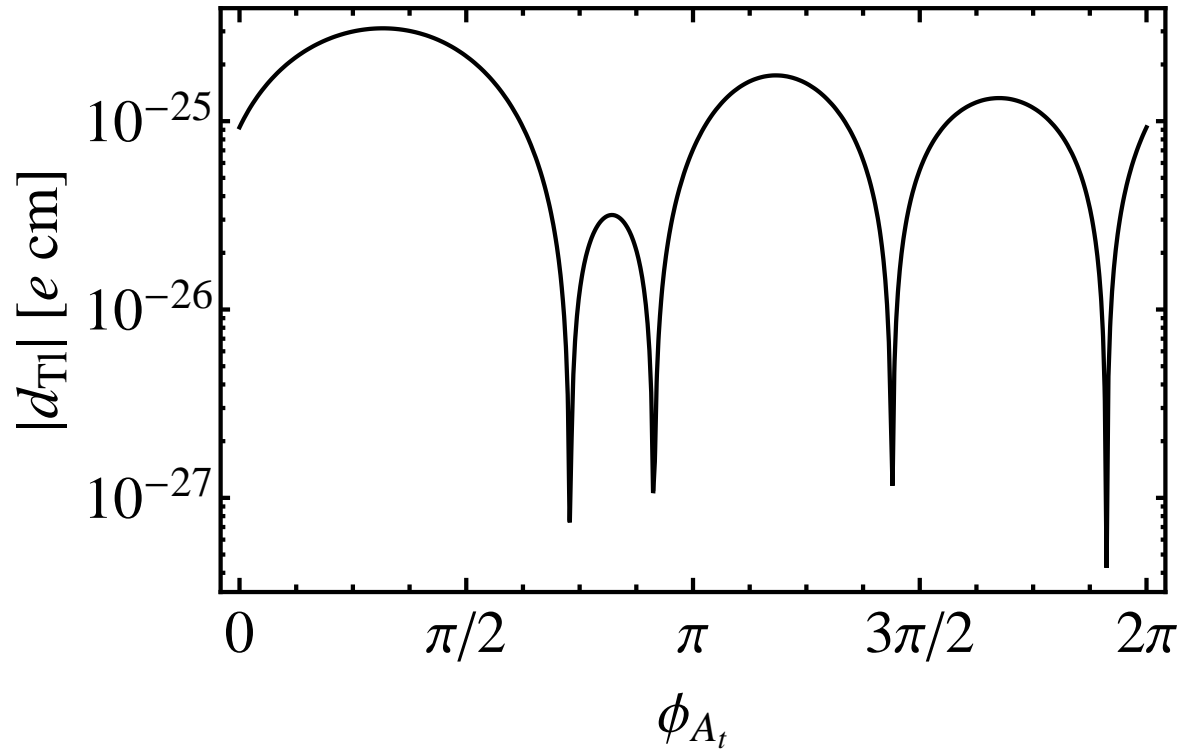
## The SUSY CP problem

The strong exp. constraints on the EDMs require:

- the SUSY phases are sufficiently small ( $\approx 10^{-2}$ , in part.  $\mu$ ), or
- the SUSY particles are sufficiently heavy ( $> 10$  TeV), or
- there are cancellations of different loop contributions to the EDMs.

The problem: all solutions require a fine-tuning, or are unnatural!

Cancellations in EDM of Thallium. experiment:  $d_{Tl} < 9 \times 10^{-25} e \text{ cm}$



$$A_0 = 500 \text{ GeV}, m_{1/2} = 270 \text{ GeV}, m_0 = 70 \text{ GeV}, \tan \beta = 5$$

$$\phi_{A_b} = \frac{2}{9} \pi, \phi_{A_\tau} = \frac{1}{180} \pi, \phi_{M_3} = \frac{1}{18} \pi, \phi_\mu = \phi_{M_1} = 0. \quad [\text{Deppisch, OK, 09}]$$

# The goal

independent measurements of the SUSY phases at colliders.

## Questions:

- What are the appropriate observables?
- What are the appropriate processes?
- How big are the effects of the SUSY CP phases?
- Can we measure these CP effects at all? (ILC needed?)



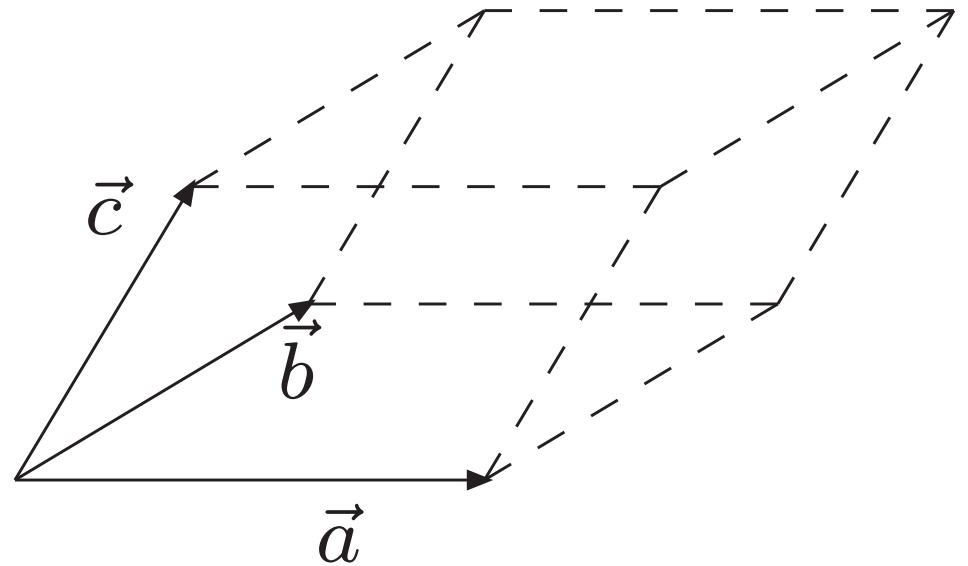
# What is the impact of complex SUSY parameters

- couplings become **complex**
- masses, branching ratios, cross sections, etc, change their values
- Are there also CP-sensitive observables?  
( $A = 0$  if CP is conserved,  $A \neq 0$  if CP is violated)
- How to define such CP asymmetries?  $\Rightarrow$  **triple products**

# 1 Triple products

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

spins or momenta



- time reversal  $T(t \rightarrow -t)$ :  $T[\vec{a}, \vec{b}, \vec{c}] = -[\vec{a}, \vec{b}, \vec{c}] \Rightarrow$  T-odd

CPT-theorem: T-odd observables are also CP-odd

- source:  $\text{Tr}\{\gamma_5 \not{a} \not{b} \not{c} \not{d}\} = 4i \epsilon_{\mu\nu\rho\sigma} a^\mu b^\nu c^\rho d^\sigma$

interference with complex SUSY couplings

## 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:  $\sigma$

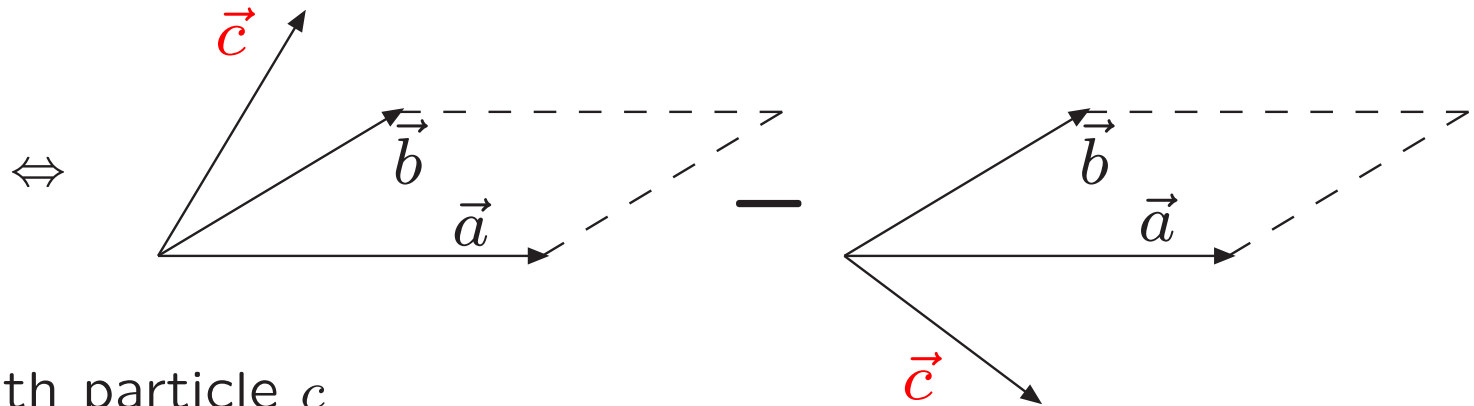
$$\Rightarrow A = \frac{\int \text{Sign}[\mathcal{T}] |M|^2 d\text{Lips}}{\int |M|^2 d\text{Lips}}$$

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

# Geometrical interpretation

- Asymmetry  $A$  is an **angular distribution**:

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



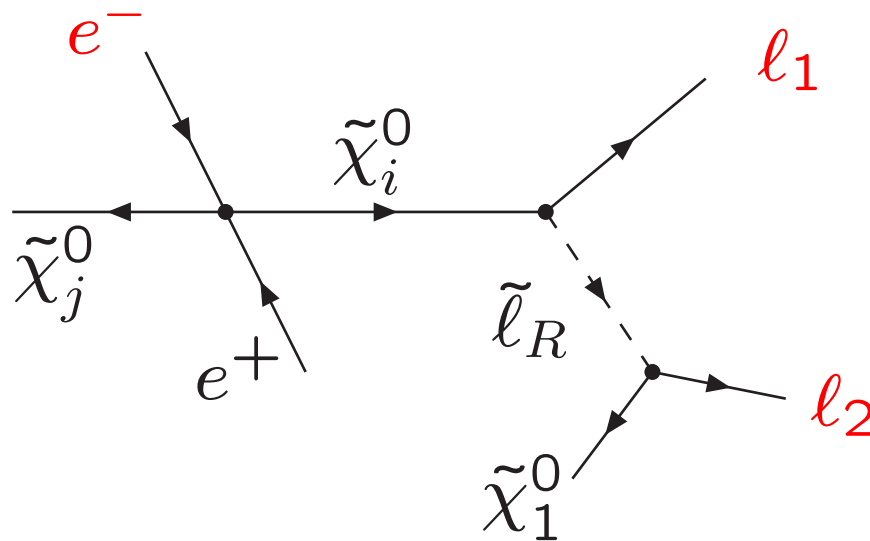
- $N_+$  ( $N_-$ ): events with particle  $c$   
above (below) plane spanned by  $\vec{p}_a \times \vec{p}_b$

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

## 2 Results: Asymmetry in neutralino production

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

$$\mathcal{T} = [\vec{p}(e^-) \times \vec{p}(l_1)] \cdot \vec{p}(l_2)$$

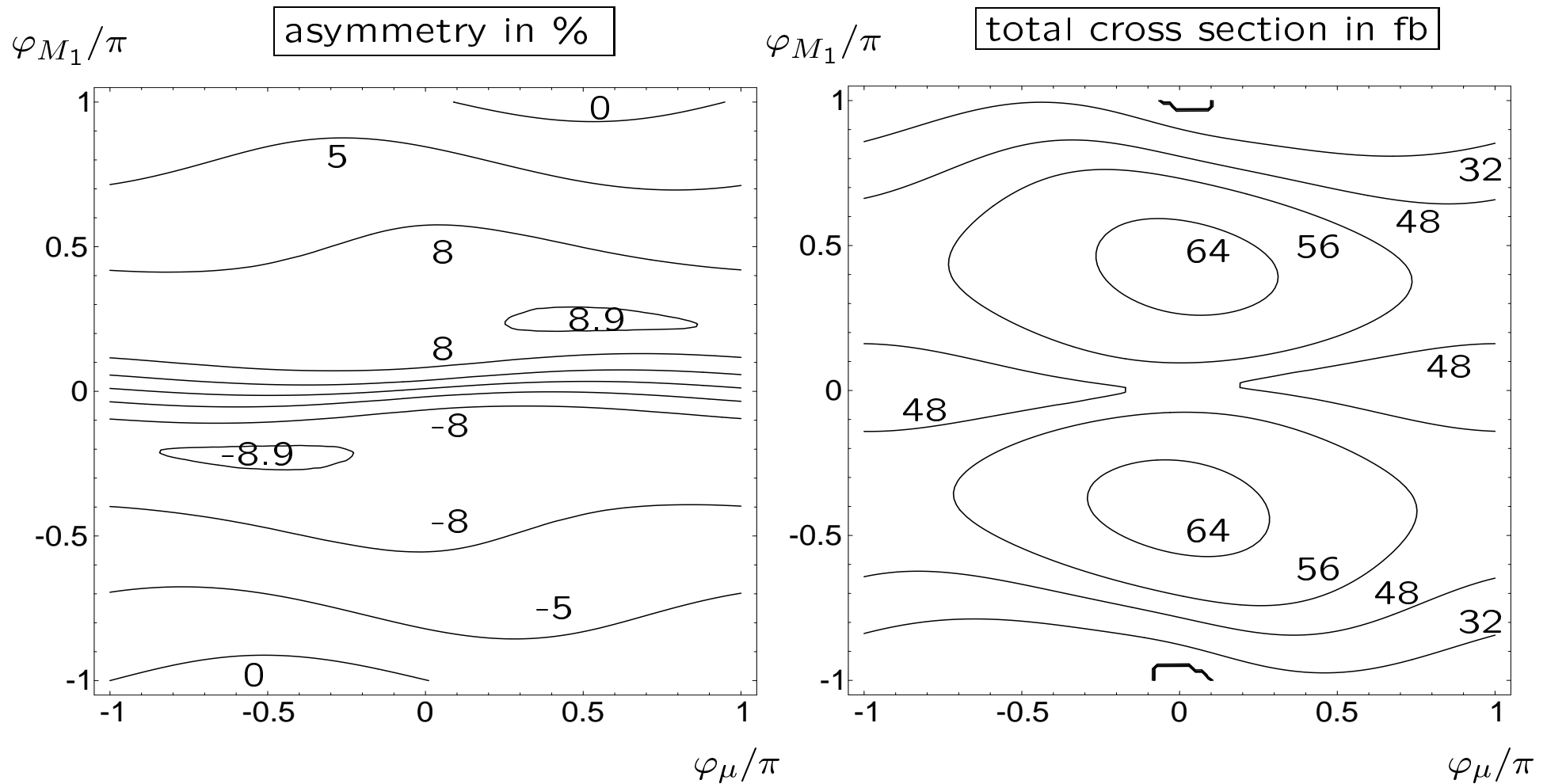


[Bartl, Fraas, OK, Majerotto, 03]

$$e^+e^- \longrightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0; \quad \tilde{\chi}_2^0 \longrightarrow \tilde{\ell}_R l_1; \quad \tilde{\ell}_R \longrightarrow \tilde{\chi}_1^0 l_2 \quad \text{at } \sqrt{s} = 500 \text{ GeV};$$

$$|\mu| = 240 \text{ GeV}, \quad \tan\beta = 10, \quad M_2 = 2M_1 = 4m_0 = 400 \text{ GeV}; \quad P(e^-|e^+) = (0.8|-0.6)$$

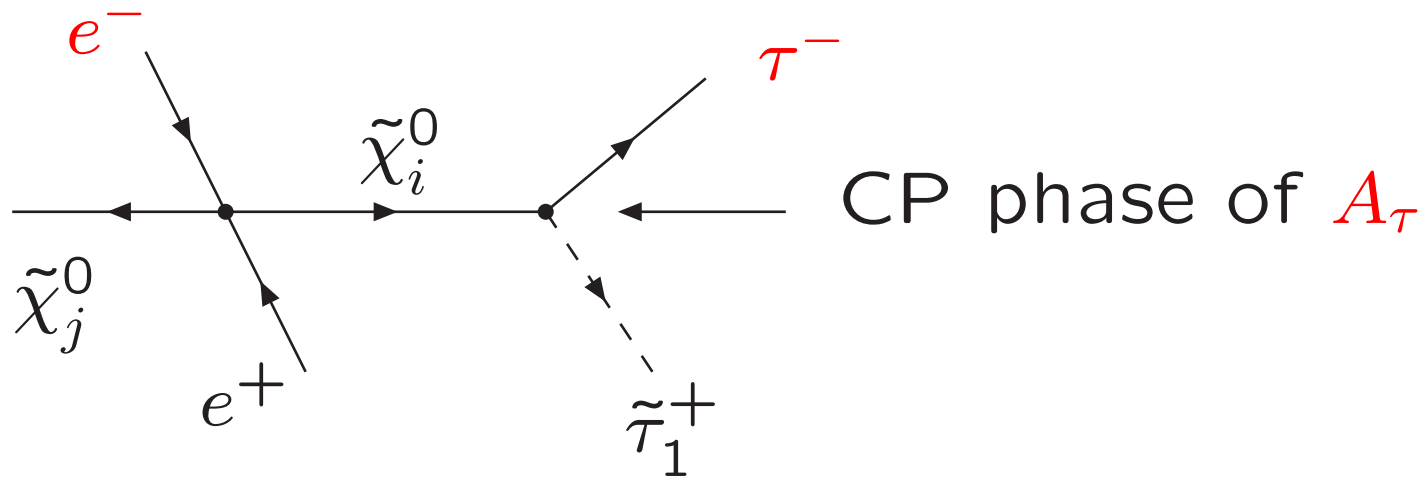
impact of the CP phases of  $\mu$  und  $M_1$



# Tau polarization asymmetry: neutralinos

$$A = P_{\perp} = \frac{N(s\uparrow) - N(s\downarrow)}{N(s\uparrow) + N(s\downarrow)}$$

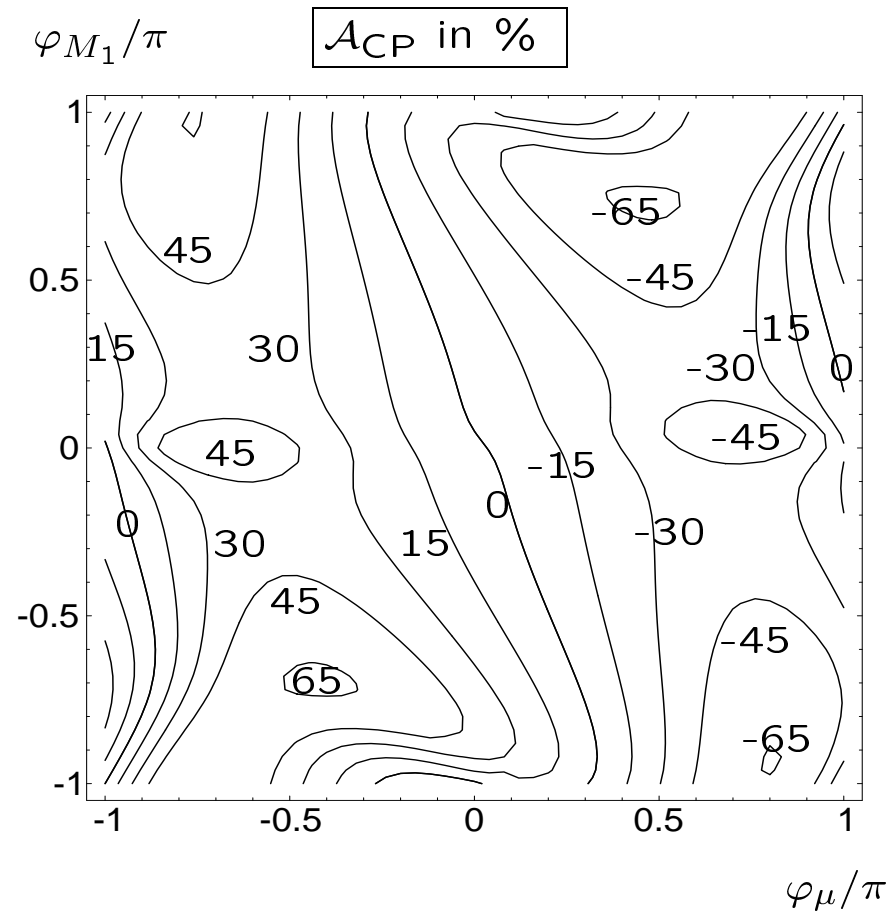
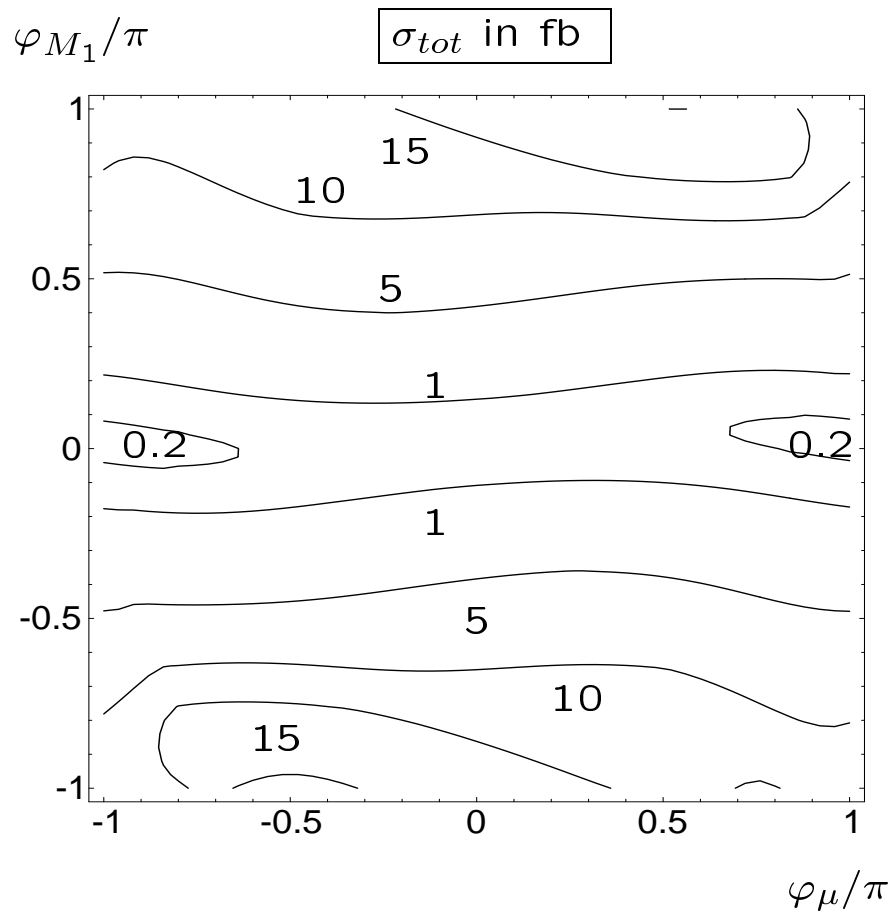
$$\mathcal{T} = [\vec{p}(e^{-}) \times \vec{p}(\tau^{-})] \cdot \vec{s}(\tau)$$



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

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

$$|\mu| = 240 \text{ GeV}; \quad M_2 = 2M_1 = 400 \text{ GeV}$$

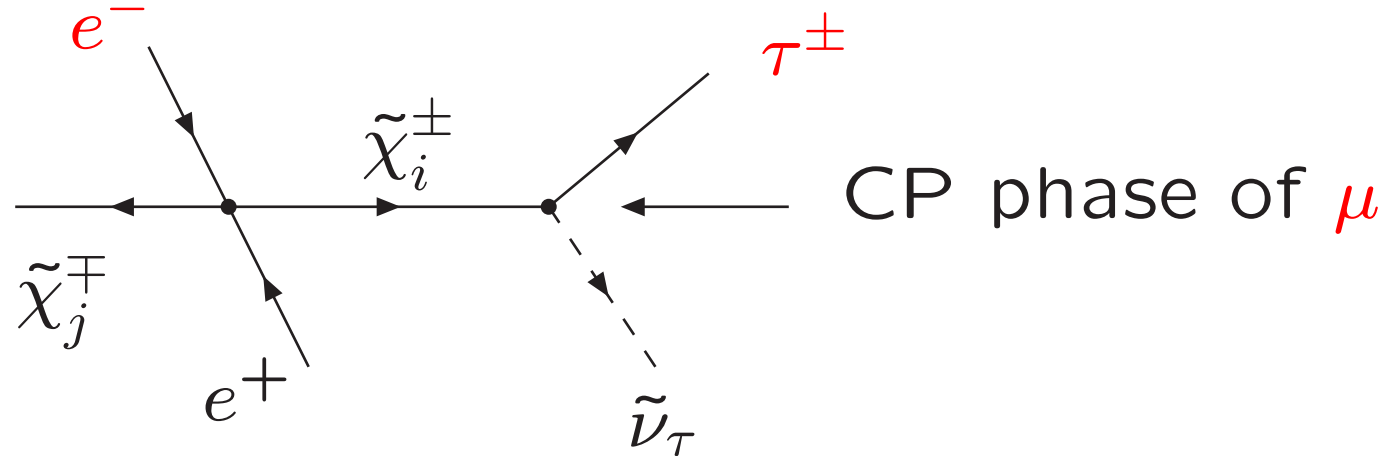




# Tau polarization asymmetry: charginos

$$A = P_{\perp} = \frac{N(s\uparrow) - N(s\downarrow)}{N(s\uparrow) + N(s\downarrow)}$$

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

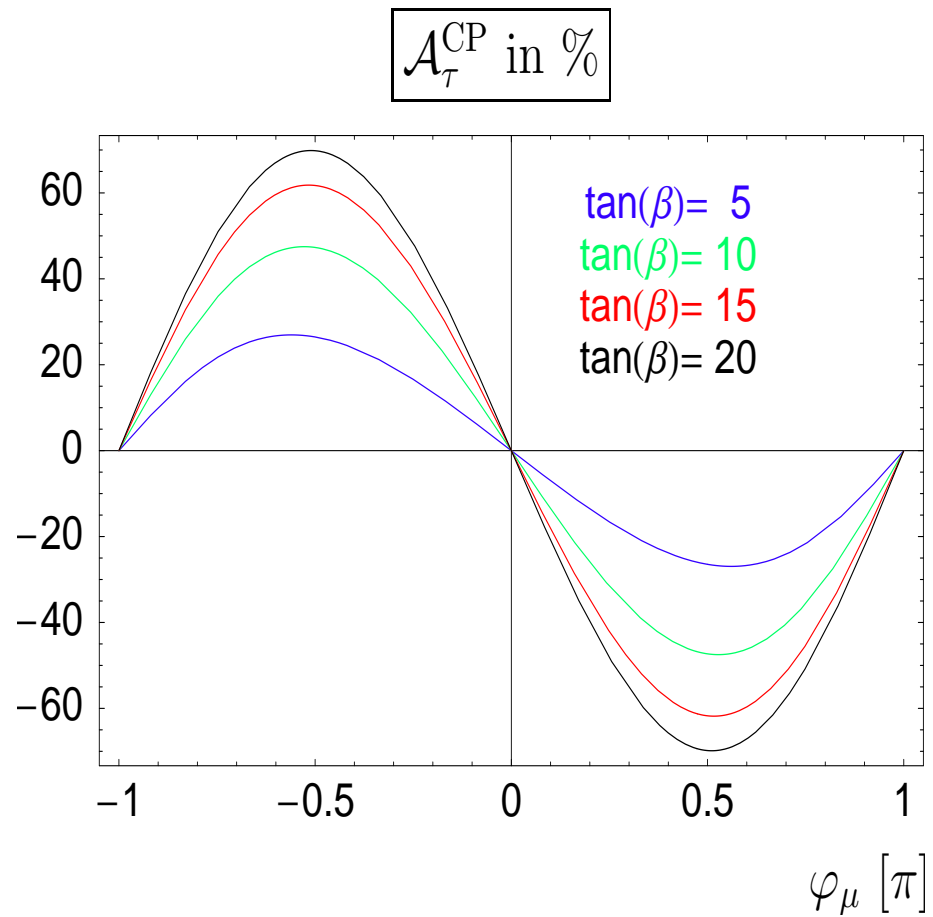
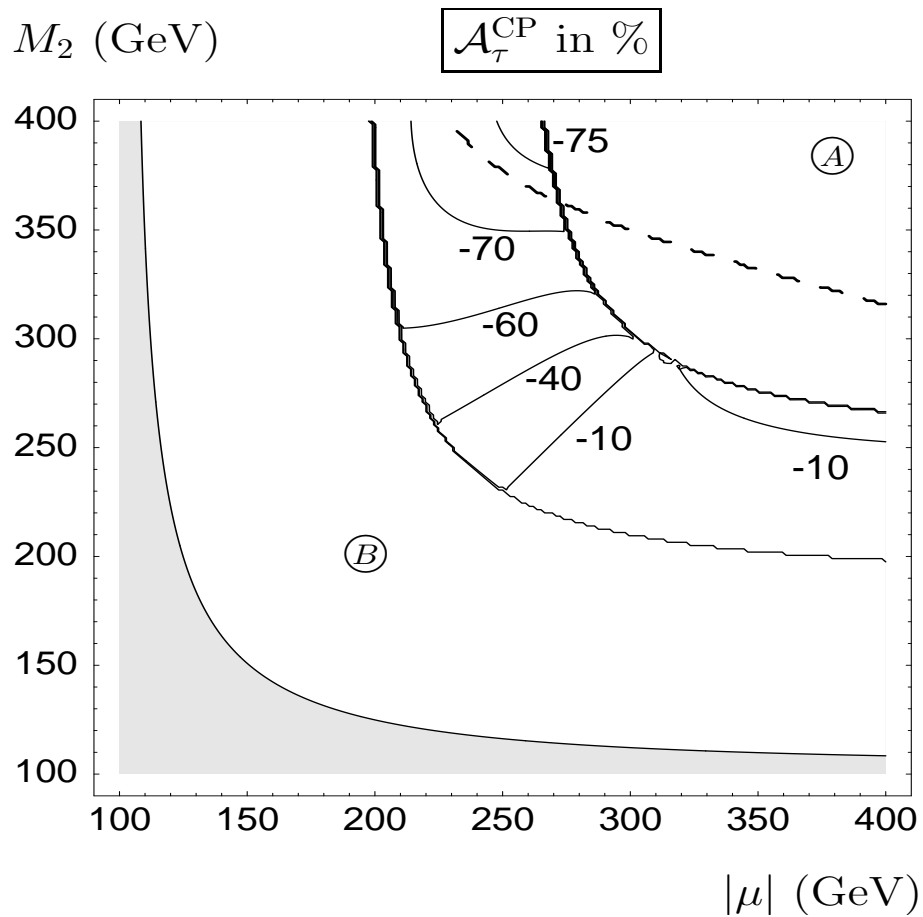


[Dreiner, OK, Marold, 10]

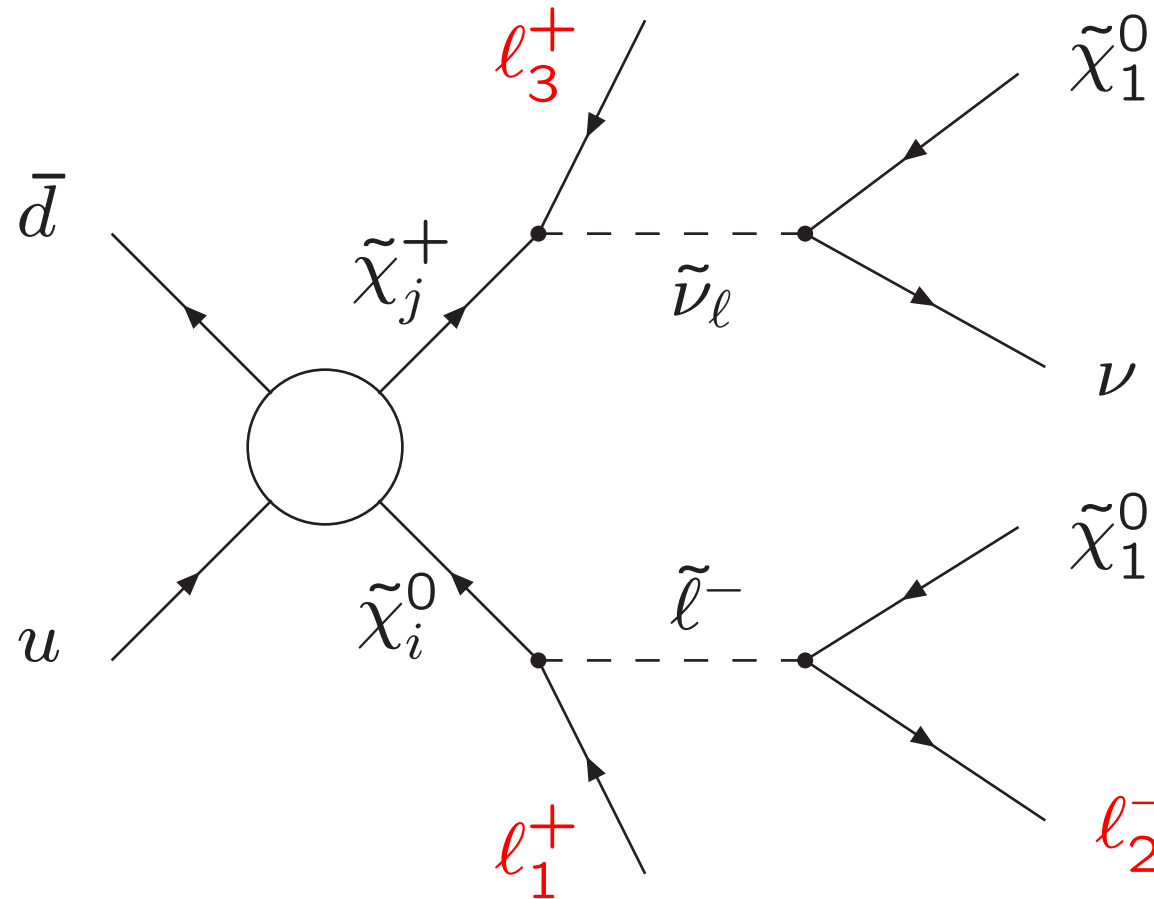
$$e^+e^- \longrightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-; \tilde{\chi}_1^\pm \longrightarrow \tilde{\nu}_\tau \tau \quad \text{at } \sqrt{s} = 500 \text{ GeV};$$

$$\tan \beta = 25; M_{\tilde{E}} = M_{\tilde{L}} = 200 \text{ GeV}; P(e^-|e^+) = (-0.8|0.6)$$

$$|\mu| = 240 \text{ GeV}; \varphi_\mu = 0.5\pi; M_2 = 2M_1 = 380 \text{ GeV}$$



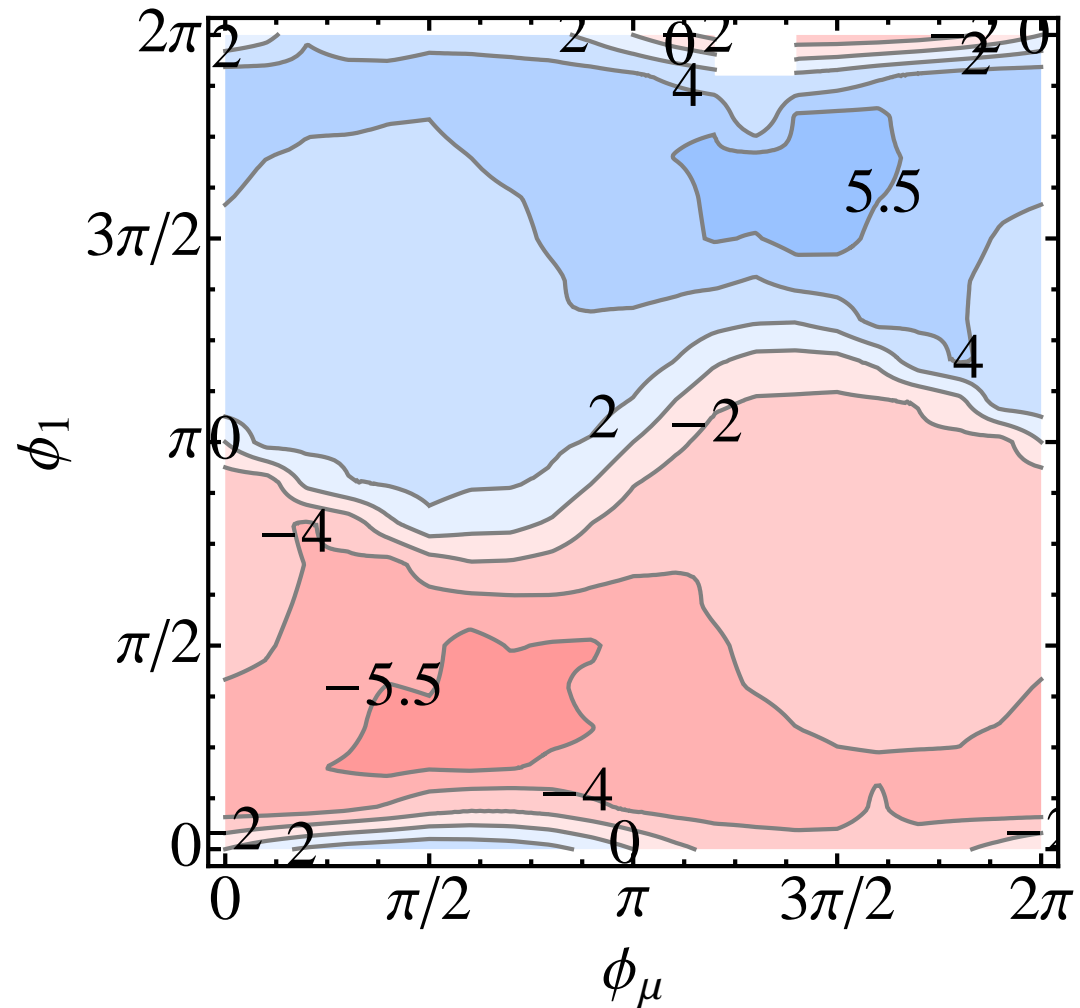
# Trilepton signal at the LHC: CP phases of $\mu, M_1$



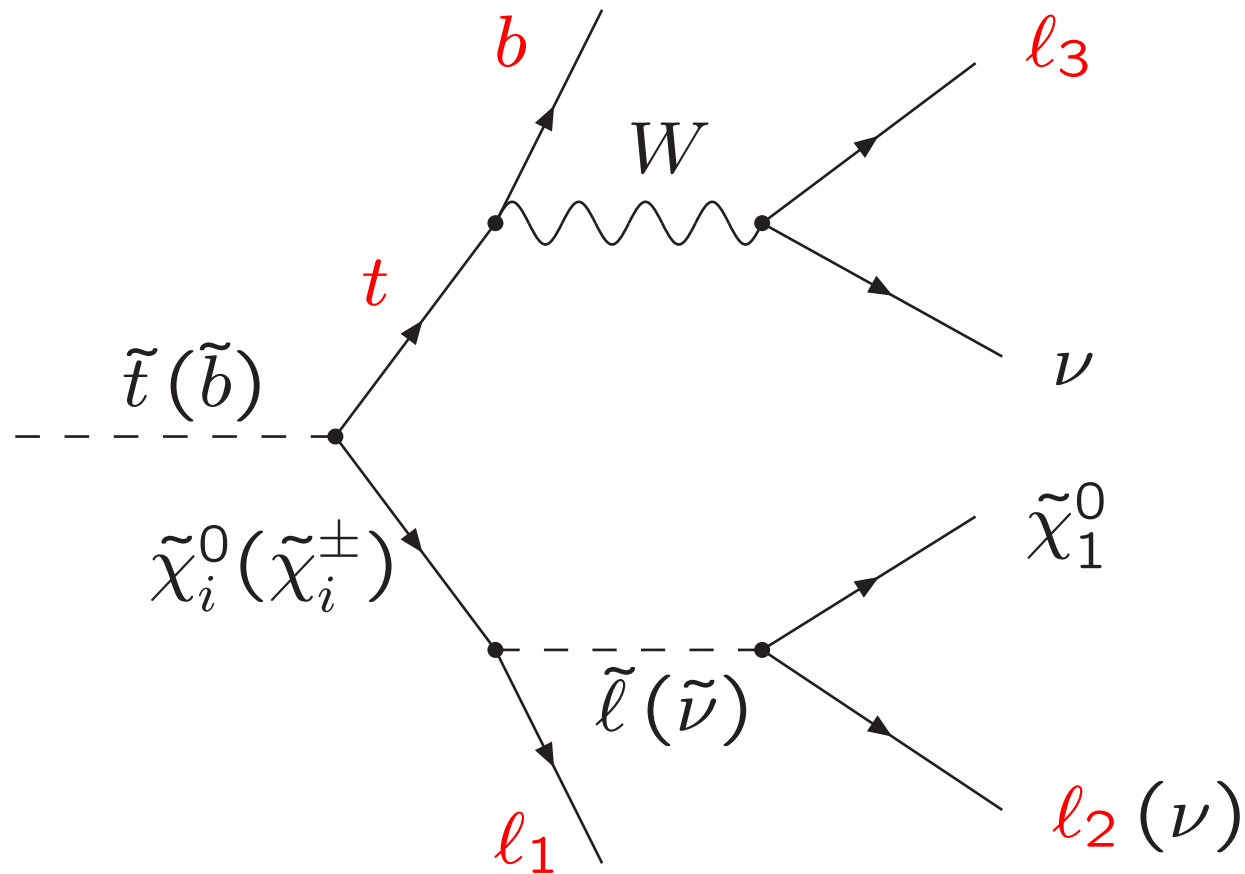
[Tevatron: Choi et al.,00]

[LHC: Drees, Dreiner, Éboli, OK, in prep.]

$M_2 = 240$  GeV,  $\mu = 150$  GeV,  $\tan \beta = 5$ ;  $M_{\tilde{R}(\tilde{L})}^{\tilde{\ell}} = 110(150)$  GeV,  
 $m_{\tilde{q}} = 400$  GeV, triple product asymmetry  $\mathcal{A}(\ell_1, \ell_2, \ell_3)$  in %



# Squark decays at the LHC: CP phases of $A_{t(b)}$



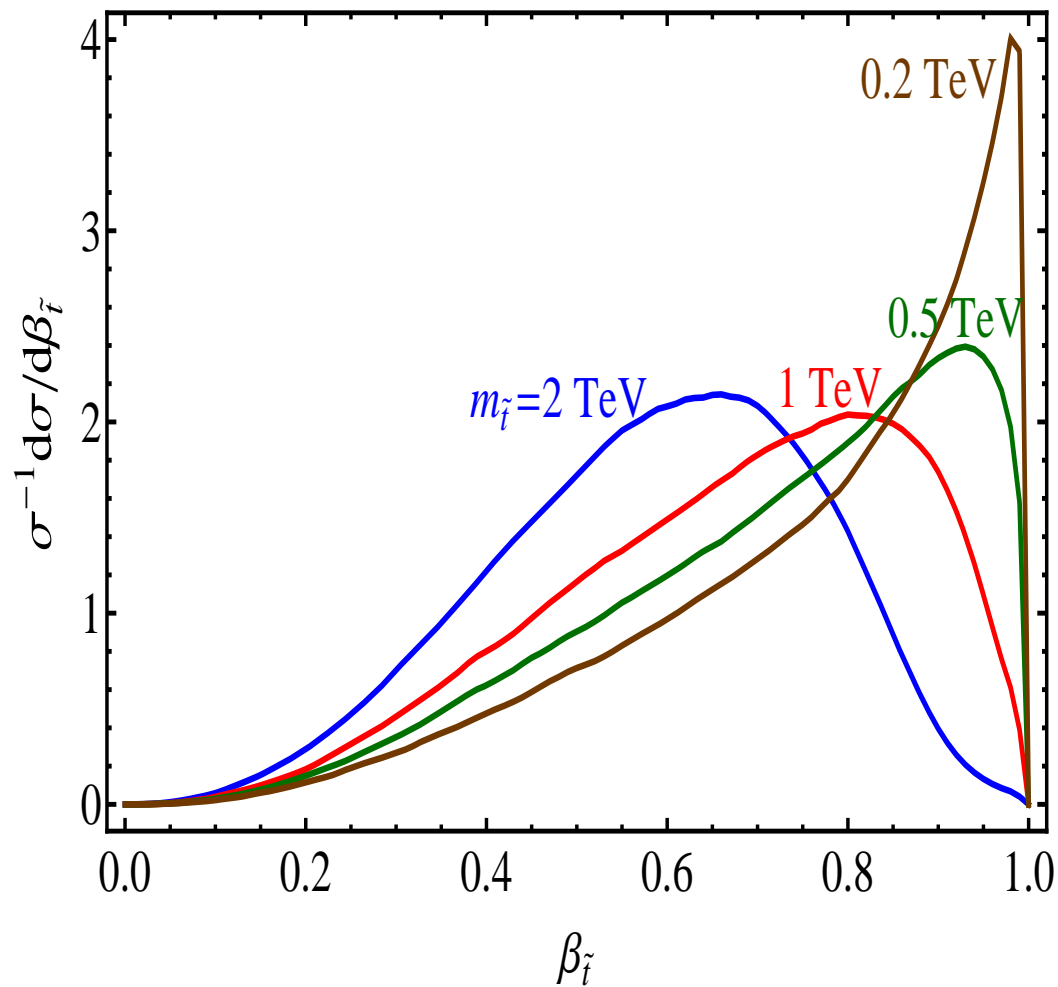
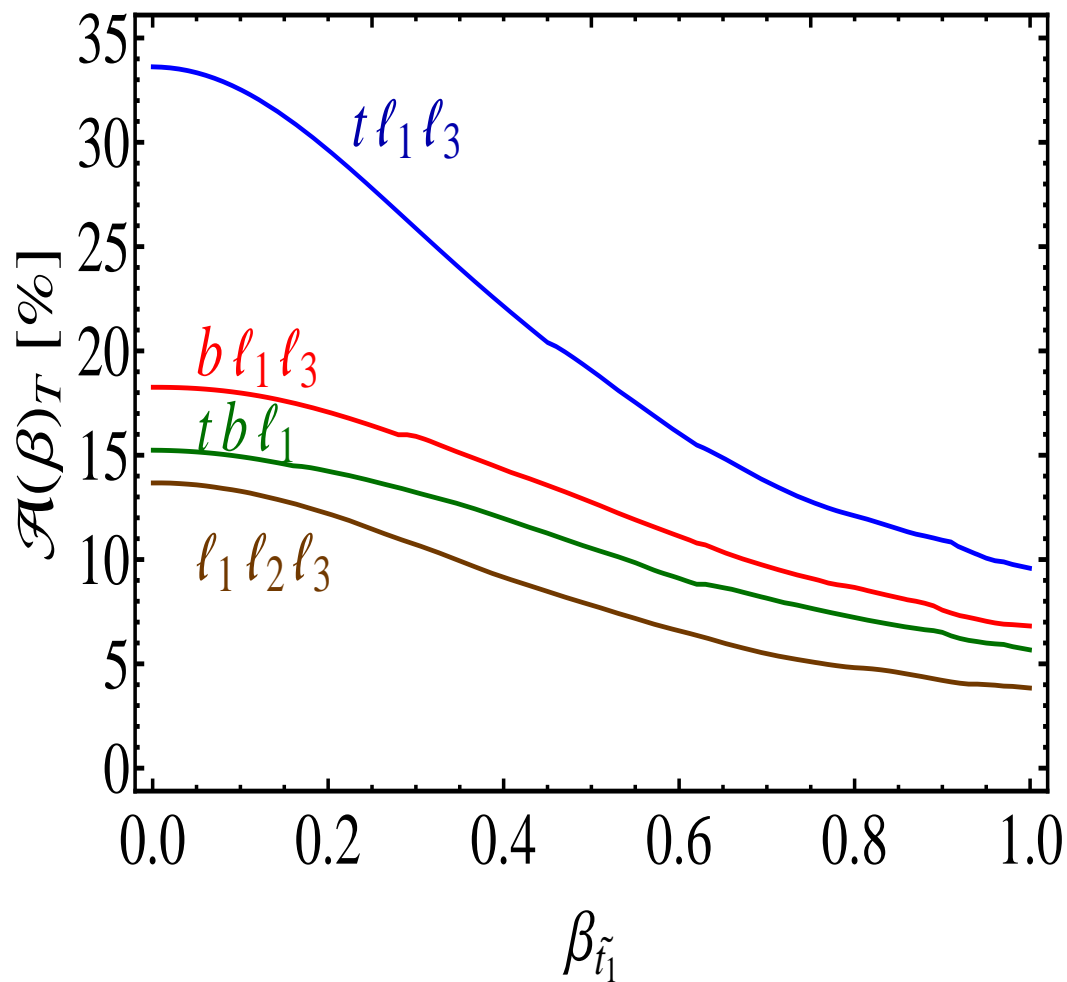
[Deppisch,OK,09,10]

[Moortgat-Pick,Rolbiecki,Tattersall,Wienemann,08-10]

$A_0 = 500$  GeV,  $m_{1/2} = 270$  GeV,  $m_0 = 70$  GeV;  $\tan \beta = 5$ ;  $\phi_{A_t} = \frac{3}{4}\pi$

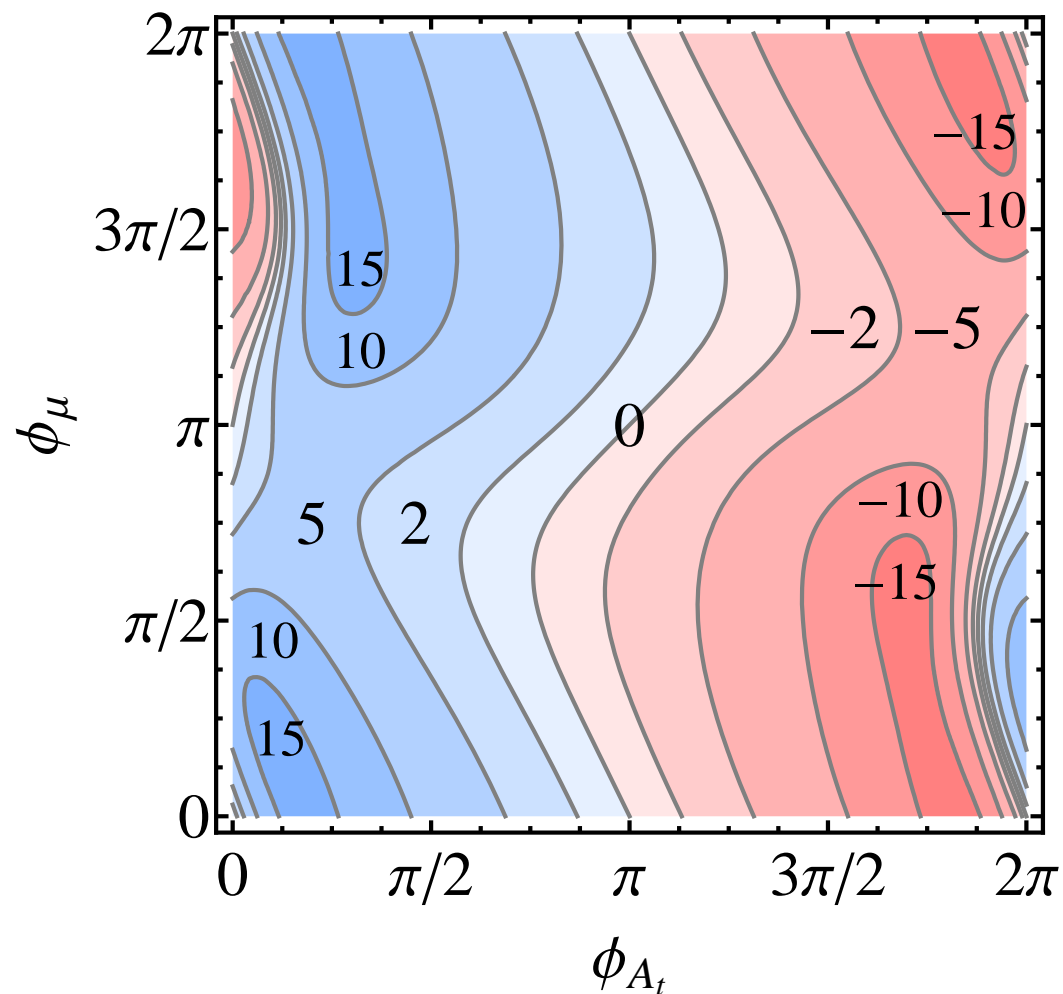
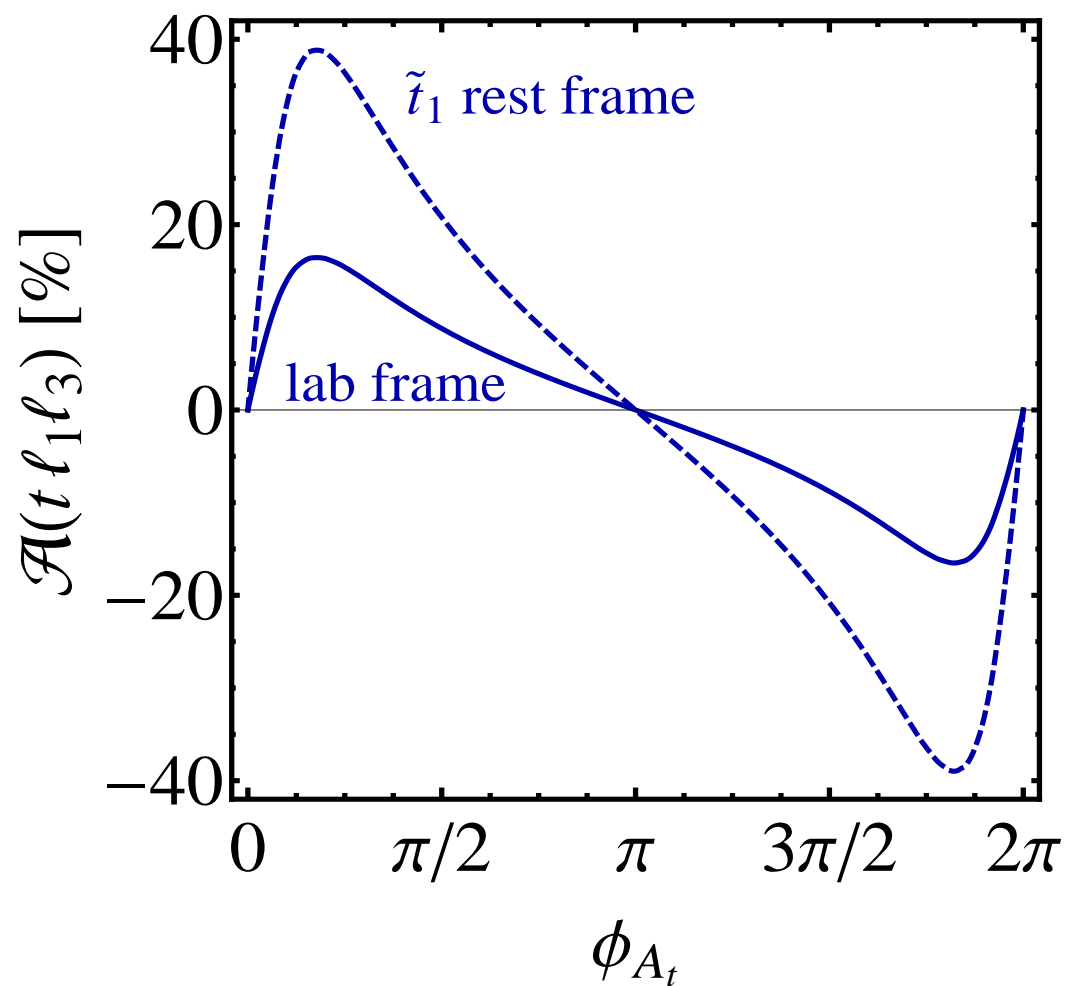
boost dependence of asymmetries

stop boost distributions



$A_0 = 500 \text{ GeV}$ ,  $m_{1/2} = 270 \text{ GeV}$ ,  $m_0 = 70 \text{ GeV}$ ;  $\tan \beta = 5$

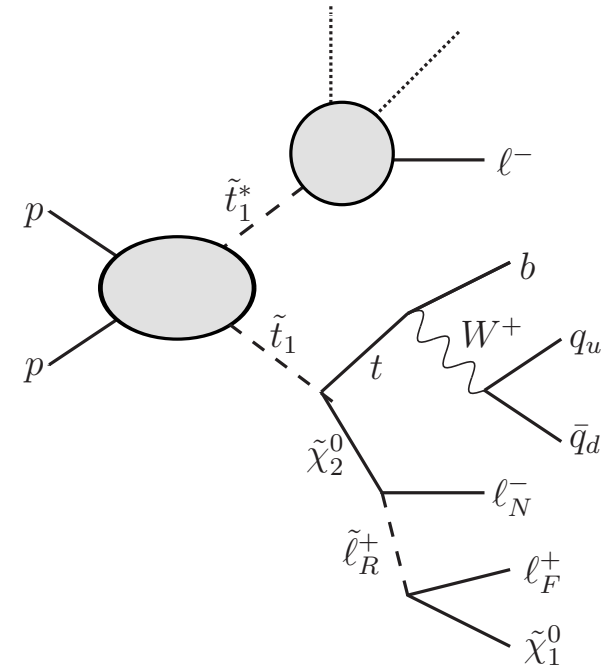
phase dependence lab-frame [Deppisch,OK,09]



# Reconstruction of $\tilde{t}$ events at the LHC

test mass conditions for each event:

$$\begin{aligned}
 m_{\tilde{t}_1}^2 &= (p_{\tilde{\chi}_2^0} + p_t)^2 \\
 m_{\tilde{\chi}_2^0}^2 &= (p_{\tilde{\ell}_R} + p_{\ell_N})^2 \\
 m_{\tilde{\ell}}^2 &= (p_{\tilde{\chi}_1^0} + p_{\ell_F})^2 \\
 m_{\tilde{\chi}_1^0}^2 &= p_{\tilde{\chi}_1^0}^2
 \end{aligned}$$



- More signal- than background events pass this test:
    - Signal ( $\tilde{t}\tilde{t}$  [3.5 pb] + decay): 27 fb  $\rightarrow$   $\sim$  2 fb
    - SUSY QCD background ( $\tilde{q}\tilde{q}, \tilde{g}\tilde{q}$ ): 80 pb  $\rightarrow$   $\sim$  2 fb
  - Topology  $3\ell, 2j, 1b$ -jet eliminates SM ( $t\bar{t}Z$ , gauge boson prod., etc)
  - $\tilde{t}$  rest frame: CP Asymmetry  $\mathcal{A}(p_{\ell_N}, p_W, p_b)$  enhanced: 5%  $\rightarrow$  15%.
- $\Rightarrow$  one achieves  $\sim 3\sigma$  significance @500fb $^{-1}$ . [Moortgat-Pick, Rolbiecki, Tattersall, 10]



## Study for the ILC (work in progress)

process:  $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_i^0$ ; 2-body decay  $\tilde{\chi}_i^0 \rightarrow l\tilde{l}_R$ ;  $\tilde{l}_R \rightarrow l\tilde{\chi}_1^0$

$\sigma(\tilde{\chi}_1^0\tilde{\chi}_{2,3}^0) = 135(95)\text{fb}$ ;  $\text{BR}(\tilde{\chi}_{2,3}^0 \rightarrow l\tilde{l}_R) = 55\%, 64\%$ ;  $\tan\beta = 10$

$m(\tilde{\chi}_1^0, \tilde{l}_R, \tilde{\chi}_2^0, \tilde{\chi}_3^0) = (118, 166, 169, 181)\text{ GeV}$ ;  $\mu, M_2, M_1 = (165, 300, 150)\text{ GeV}$

process	(# events for $100\text{fb}^{-1}$ )	events, that ONLY solve $\tilde{\chi}_1^0\tilde{\chi}_2^0$ cond.	events, that ONLY solve $\tilde{\chi}_1^0\tilde{\chi}_3^0$ cond.
$e^+e^- \rightarrow W^+W^-$	(17.5k)	0.03% (6)	0.01% (17)
$e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^-$	(11.6k)	0.3% (32)	1.4% (165)
$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^-$	(4.2k)	0.02% (1)	1% (41)
$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0$	(8.1k)	<b>82%</b> (6.7k)	0.1% (8)
$e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_3^0$	(6k)	0.05% (3)	<b>40%</b> (2.3k)

$\sim 80\%$  of  $\tilde{\chi}_1^0\tilde{\chi}_2^0$  remain, with  $< 1\%$  background admixture

$\sim 40\%$  of  $\tilde{\chi}_1^0\tilde{\chi}_3^0$  remain, with  $\sim 10\%$  background admixture

# Summary and conclusions

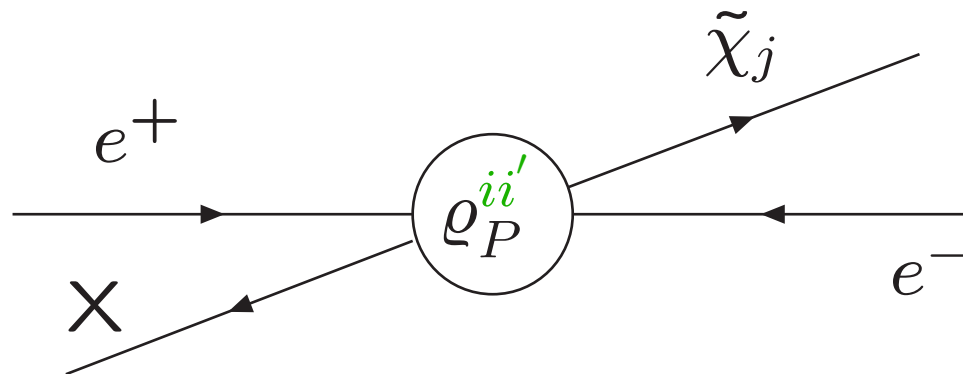
- There are new sources of CP violation in supersymmetric theories.
- SUSY CP phases have impact on the production and the decay of neutralinos, charginos, and squarks.
- There are CP-sensitive observables:  
triple/epsilon products lead to CP asymmetries.
- CP asymmetries are typically of the order of 10% (and more!).  
→ should motivate experimental studies. ILC study ongoing!  
→ can phases be constrained/measured at future colliders?

# Spin density matrix formalism

production of a spin  $\frac{1}{2}$  fermion ensemble:  $\tilde{\chi}_j$

$$\text{density matrix: } \rho_P^{ii'} = P \delta^{ii'} + \vec{\Sigma}_P \vec{\sigma}^{ii'}$$

- straight forward expansion of a hermitian  $2 \times 2$  matrix
- real coefficients:  $P \sim$  cross section  
 $\Sigma_P^a \sim$  three polarizations of  $\tilde{\chi}_j$ ,  $a = 1, 2, 3$



## Origin of $\delta, \sigma$ from Feynman calculus

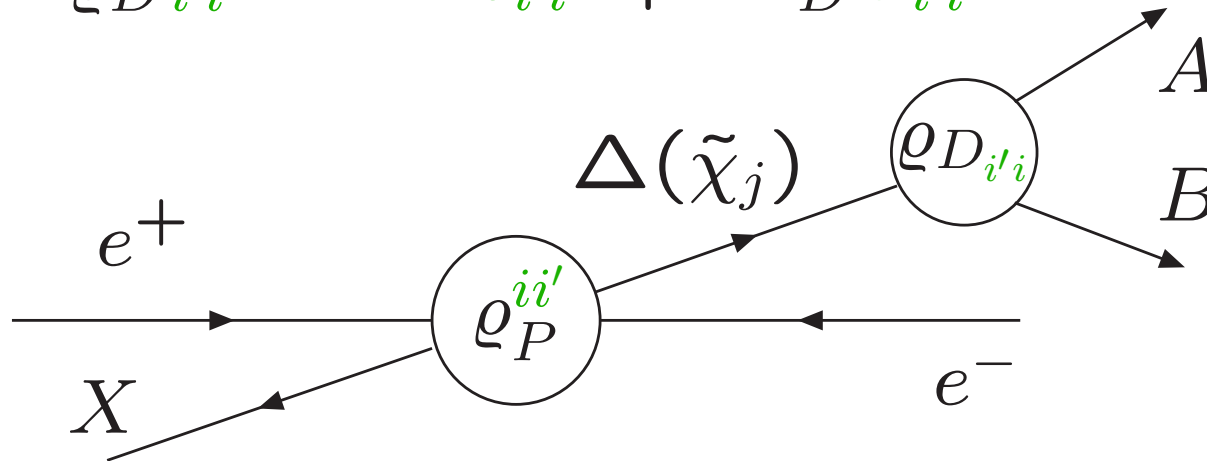
Bouchiat-Michel-Formula:

$$u(\lambda', p) \bar{u}(\lambda, p) = \frac{1}{2} \left[ \delta_{\lambda\lambda'} + \gamma_5 \not{s}^a \sigma_{\lambda\lambda'}^a \right] (\not{p} + m)$$

$s^a$ : spin vector basis

## Production and decay

$$\rho_{D i' i} = D \delta_{i' i} + \vec{\Sigma}_D \vec{\sigma}_{i' i}$$



Feynman amplitude squared:

$$\begin{aligned} |T|^2 &= |\Delta(\tilde{\chi}_j)|^2 \text{Tr}\{\rho_P \cdot \rho_D\} \\ &= 2 |\Delta(\tilde{\chi}_j)|^2 (P D + \vec{\Sigma}_P \vec{\Sigma}_D) \end{aligned}$$

$$\Delta(\tilde{\chi}_j) = \frac{i}{s - m^2 + im\Gamma}$$

$\sim \sigma \times \text{BR}$

spin correlations