Probing SUSY CP phases at colliders

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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

- 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:

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

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

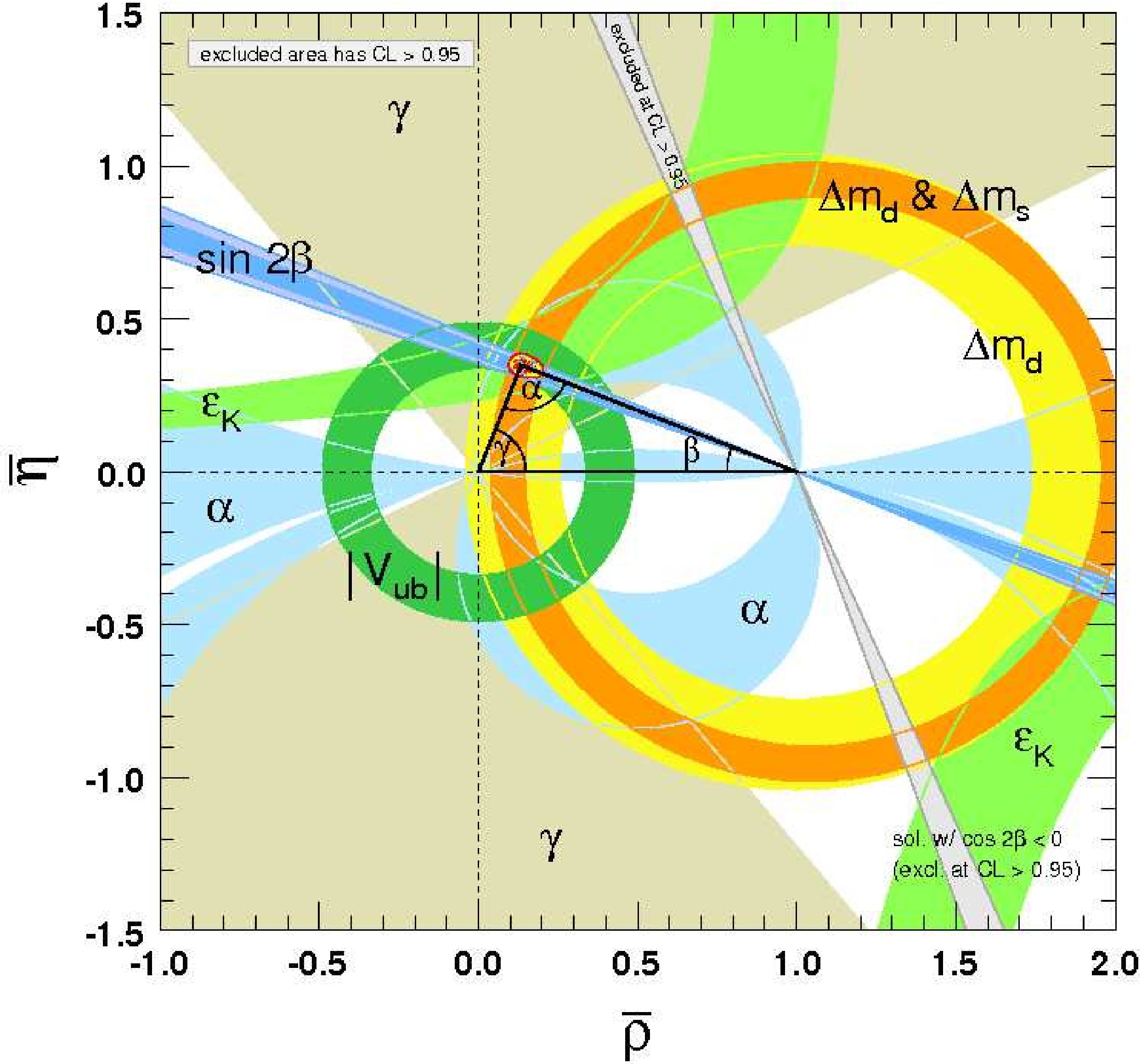
quark mixing: 3 mixing angles $\theta_{12,\,13,\,23}$, and 1 CP phase δ

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

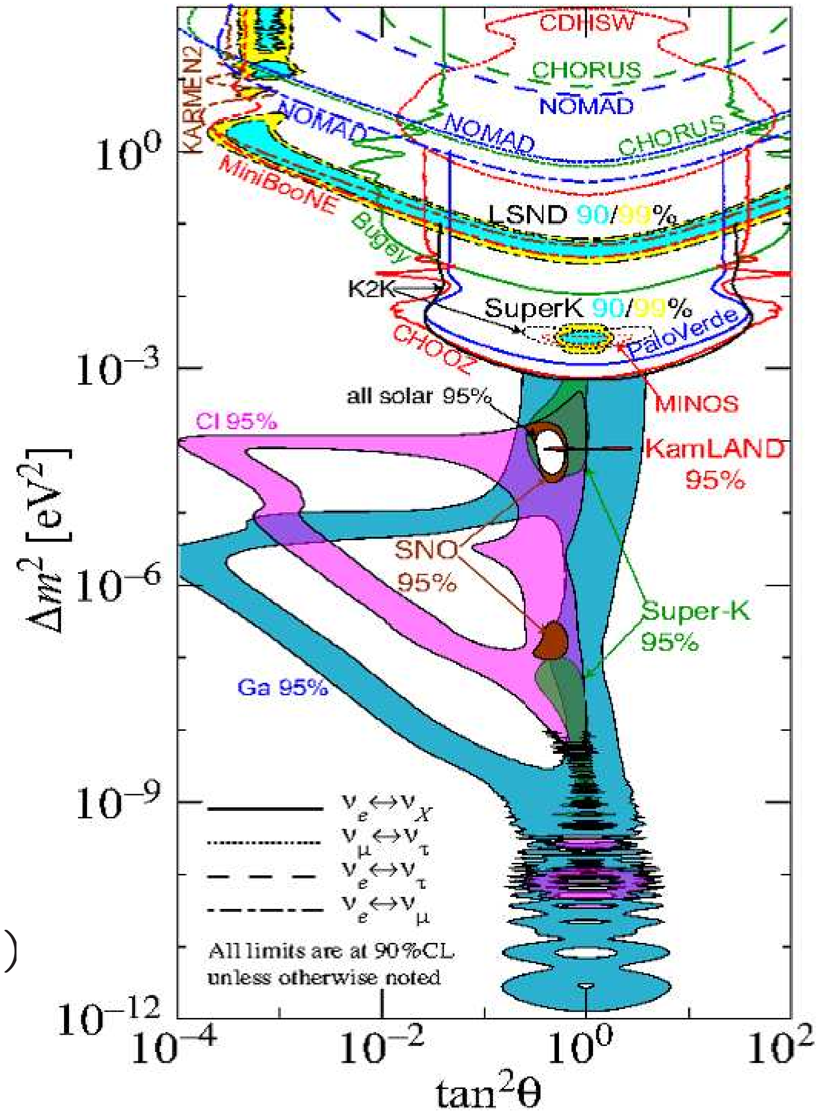
(V in the CKM form)

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

3 CP phases:

- 1 Dirac phase δ, and
- 2 Majorana phases ϕ_{ij} (measurement pending)

[PDG]



CP violation in Cosmology

- CP phases needed for baryon asymmetry of the universe (baryo/leptogenesis)

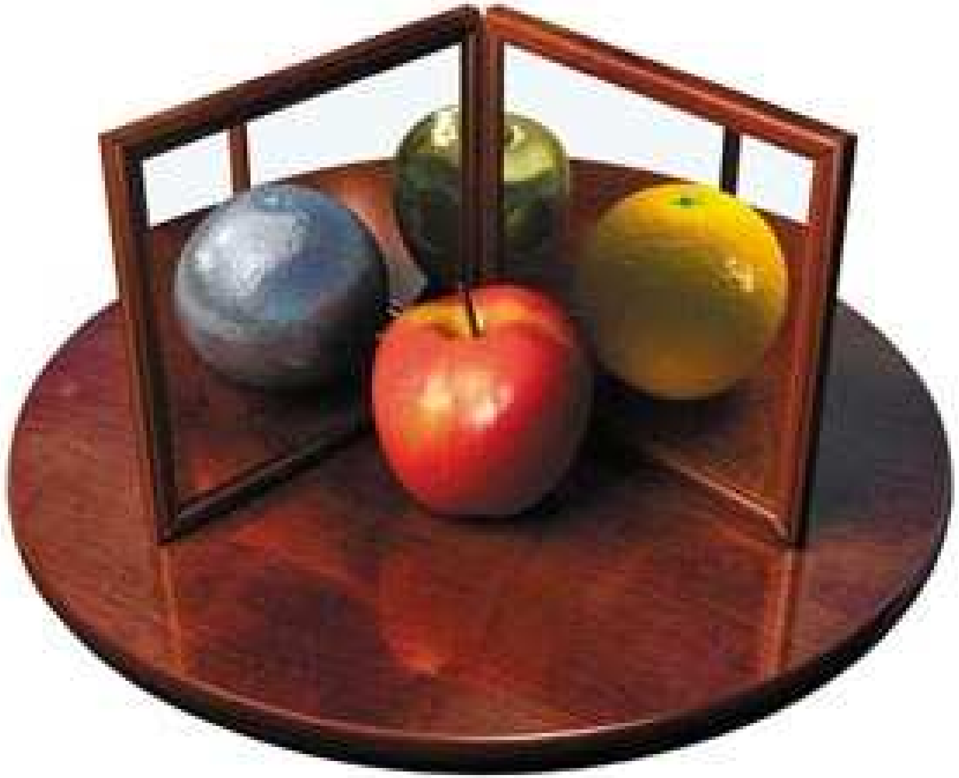
- However:
  CP phase of the quark sector is not enough!

- 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 (≈ 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

  μ: Higgs mixing parameter

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

- |eigenvalues| of $\mathcal{M}_{\pm}$ = chargino masses $m_{\tilde{\chi}^{\pm}_{i=1,2}}$
- 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

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

- diagonalization matrix determines the neutralino couplings

Scalar particles: sfermions

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

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

- 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

chargino sector

$\mu = \lvert\mu\rvert exp(i\,\varphi_\mu)$	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

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

sfermion sector

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

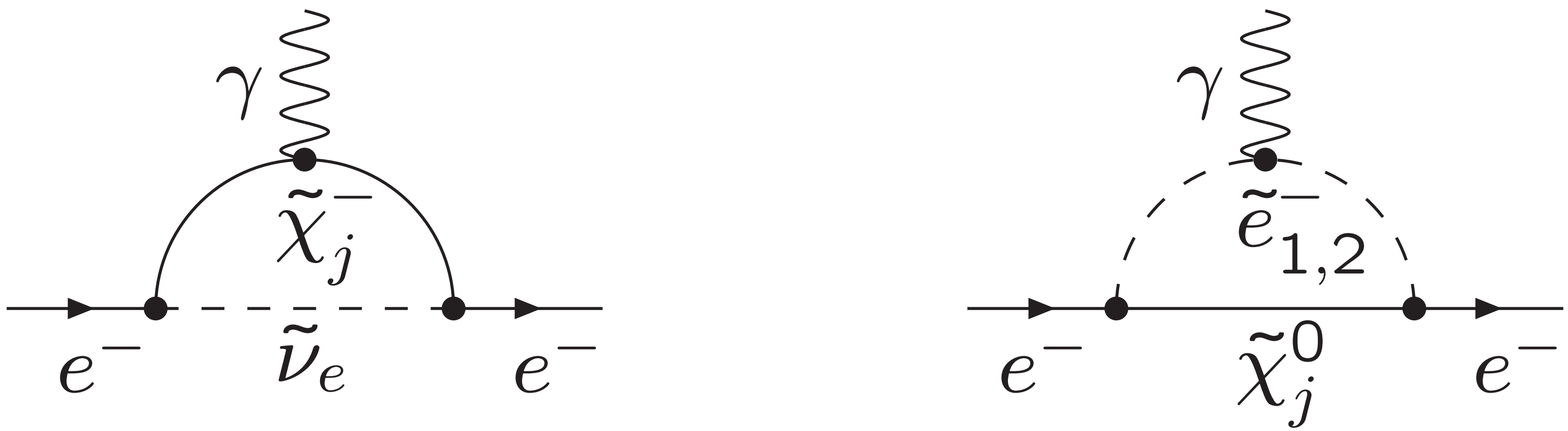
constraints on phases from electric dipole moments (EDM)

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

$$d^e_{exp} < 4 \times 10^{-27}\, e\, cm$$

$$d^n_{exp} < 3 \times 10^{-26}\, e\, cm$$

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



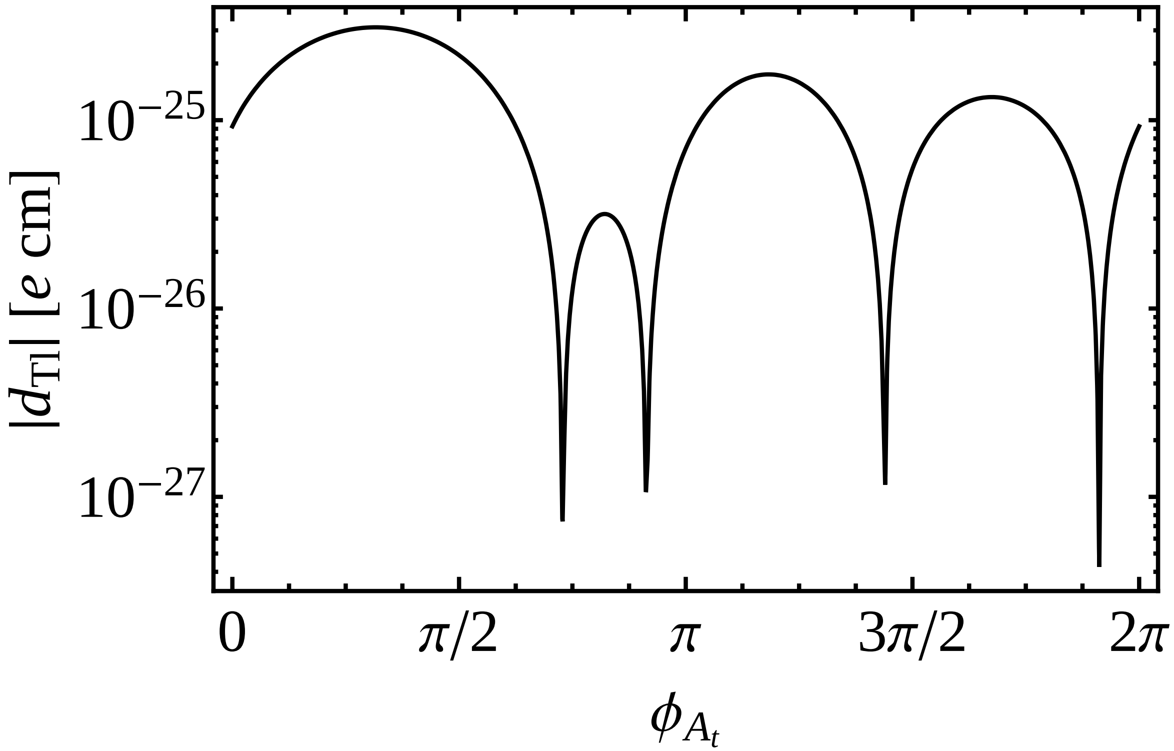
The SUSY CP problem

The strong exp. constraints on the EDMs require:

- the SUSY phases are sufficiently small ($\approx 10^{-2}$, in part. μ), 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: $d_{Tl} < 9 \times 10^{-25} e$ cm



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

$\phi_{A_b} = \frac{2}{9}\pi$, $\phi_{A_\tau} = \frac{1}{180}\pi$, $\phi_{M_3} = \frac{1}{18}\pi$, $\phi_\mu = \phi_{M_1} = 0$. [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?

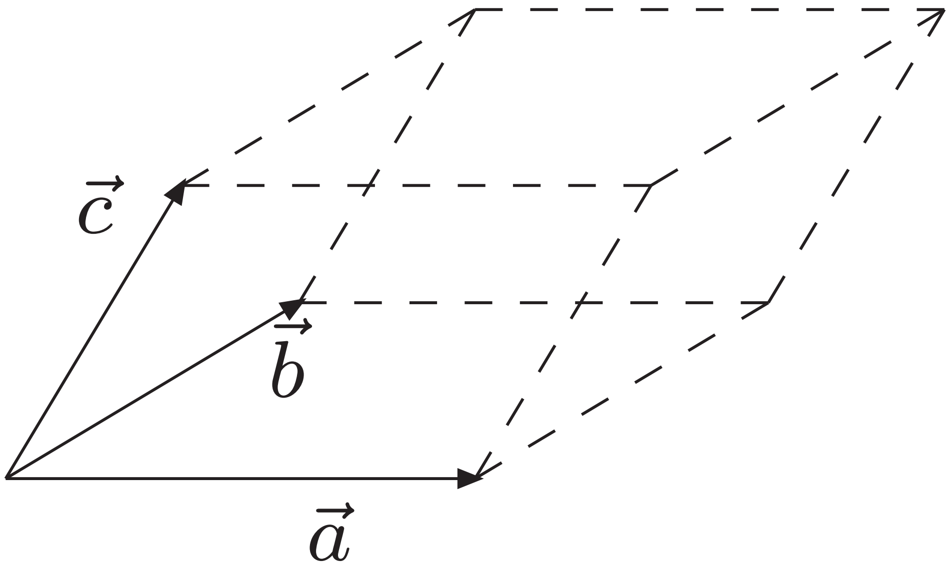
  ($A = 0$ if CP is conserved, $A \neq 0$ if CP is violated)

- 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 $T(t \to -t)$: $T[\vec{a}, \vec{b}, \vec{c}] = -[\vec{a}, \vec{b}, \vec{c}] \Rightarrow$ 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 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: σ

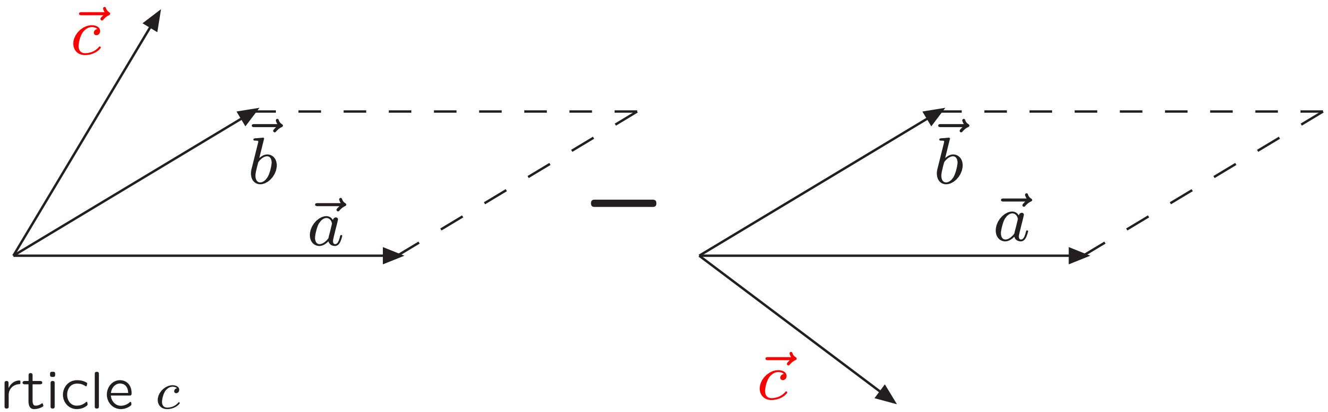
$$\Rightarrow A = \frac{\int Sign[\mathcal{T}]\, |M|^2 \, d\text{Lips}}{\int |M|^2 \, d\text{Lips}}$$

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

Geometrical interpretation

- Asymmetry A is an angular distribution:

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



- $N_+(N_-)$: events with particle c

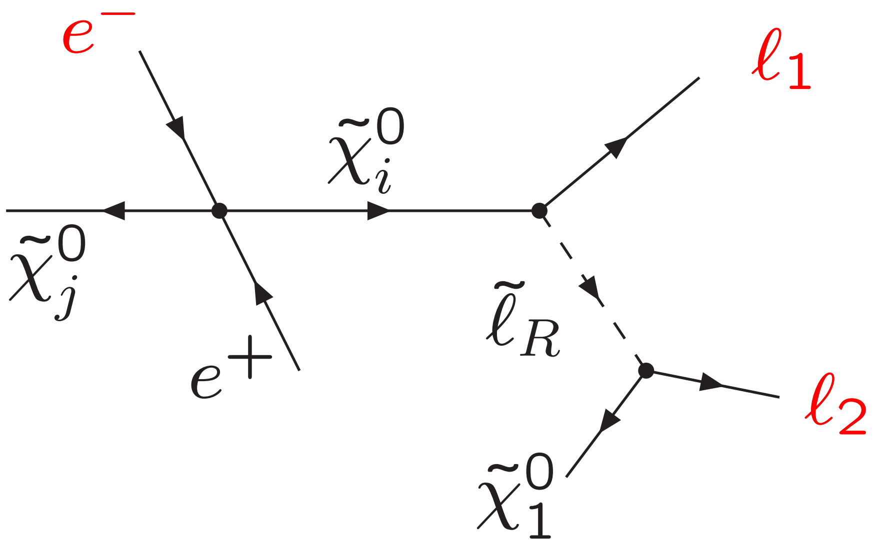
  above (below) plane spanned by $\vec{p}_a \times \vec{p}_b$

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

2 Results: Asymmetry in neutralino production

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

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

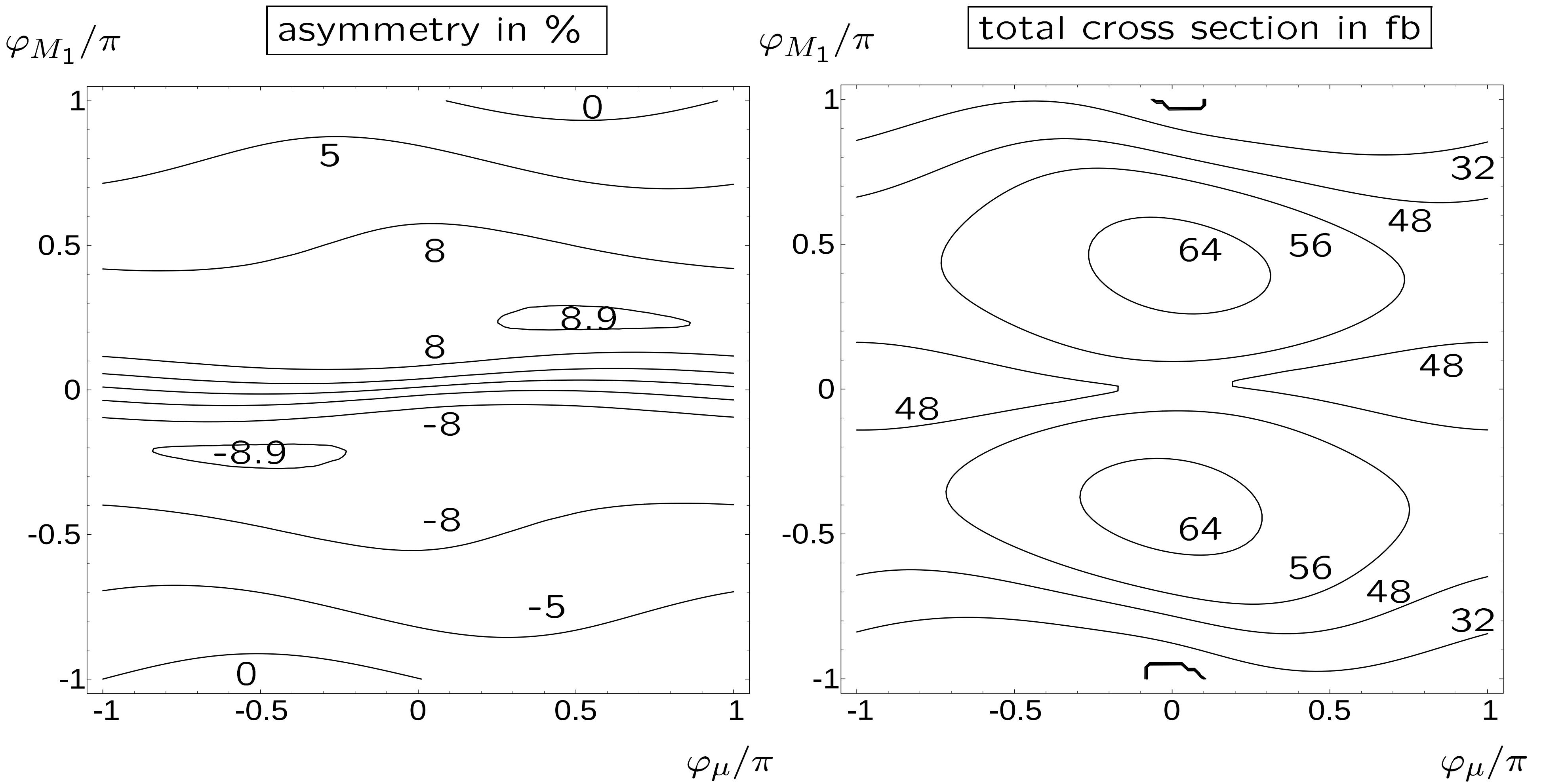


[Bartl, Fraas, OK, Majerotto, 03]

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

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

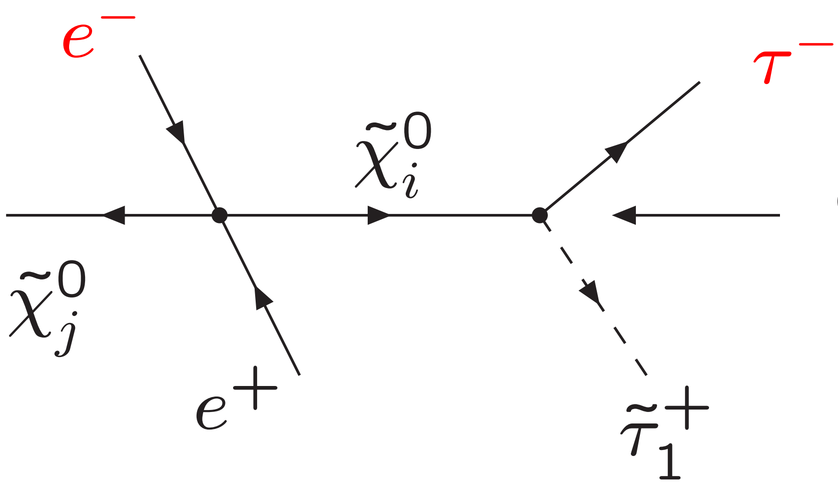
impact of the CP phases of μ und M_1



Tau polarization asymmetry: neutralinos

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

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



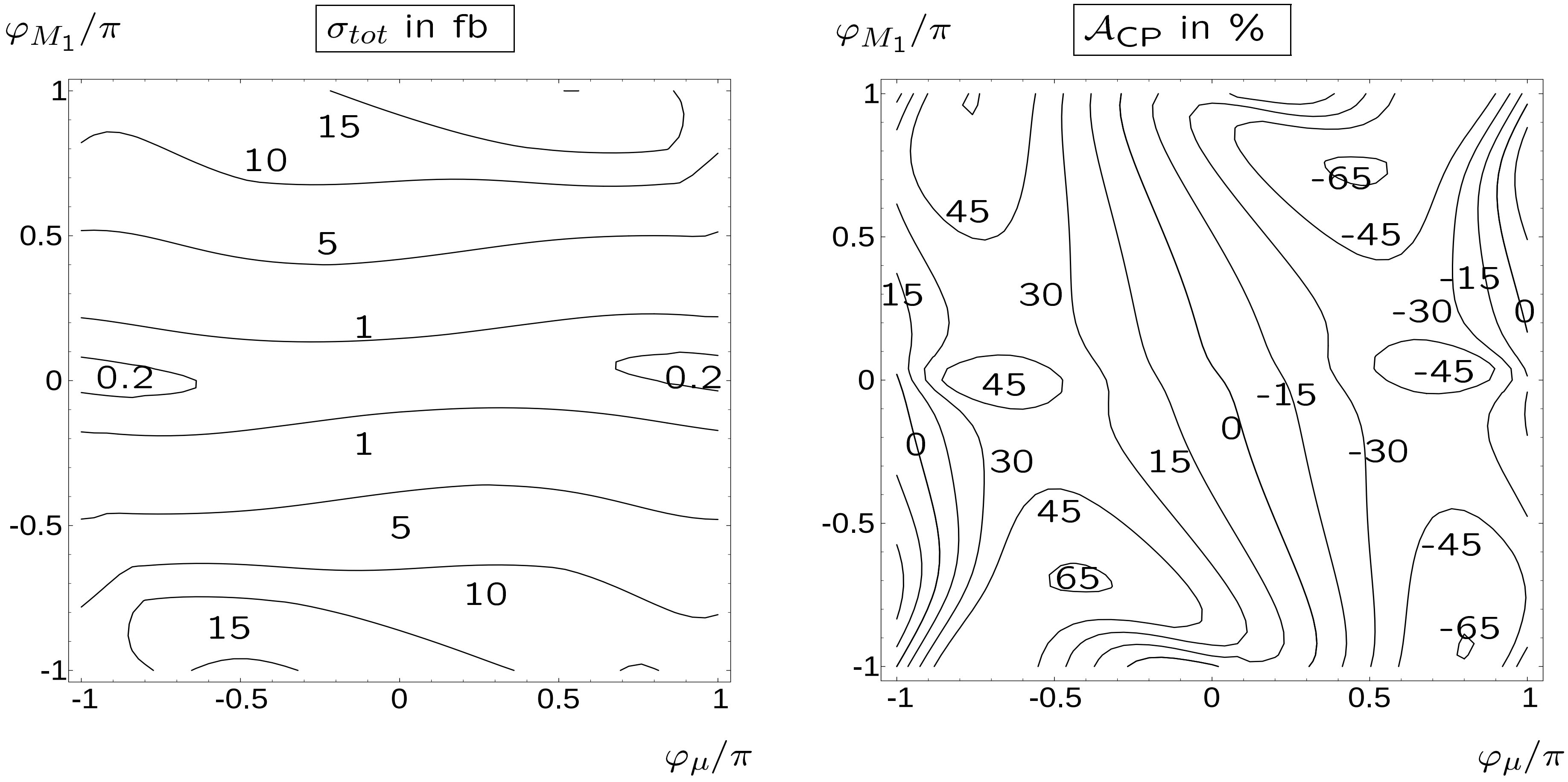
CP phase of A_τ

[Bartl, Kernreiter, OK, 03]

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

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

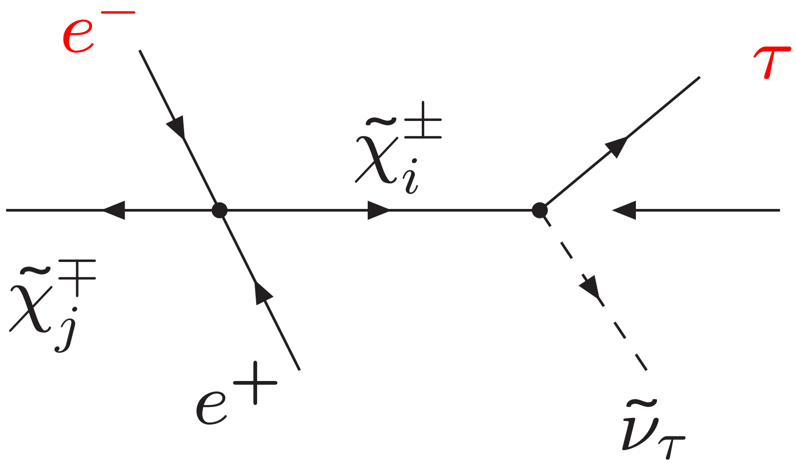
$$|\mu| = 240 \text{ GeV}; \; M_2 = 2M_1 = 400 \text{ GeV}$$



Tau polarization asymmetry: charginos

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

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



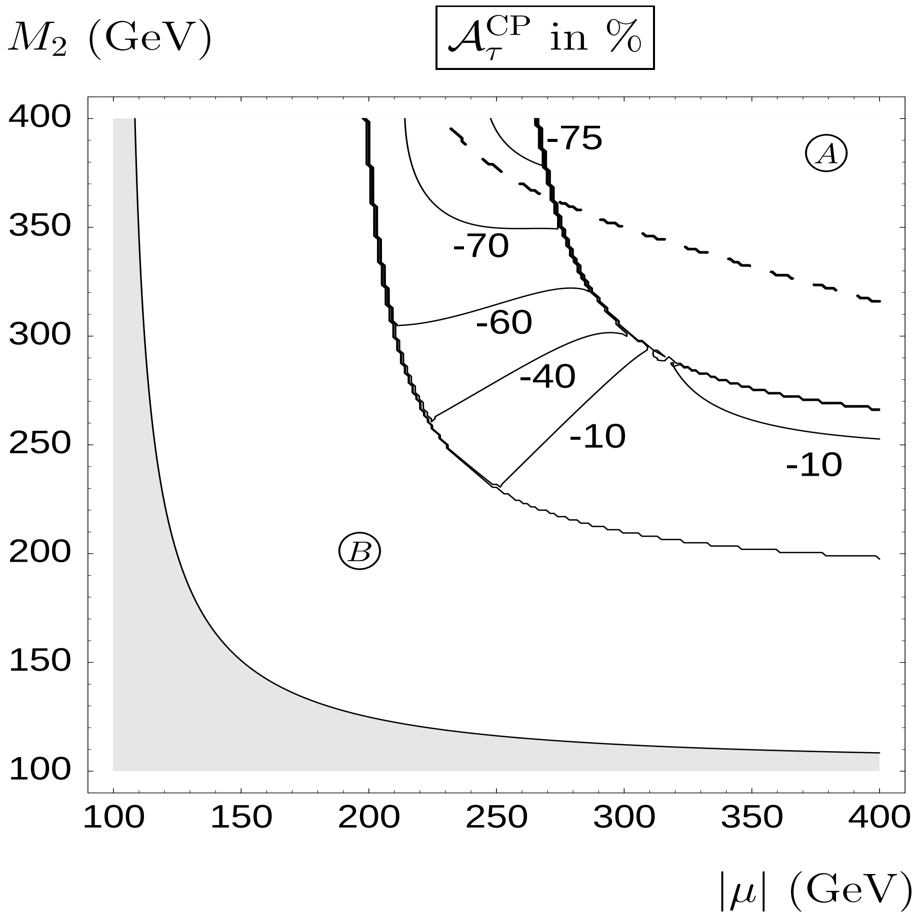
CP phase of μ

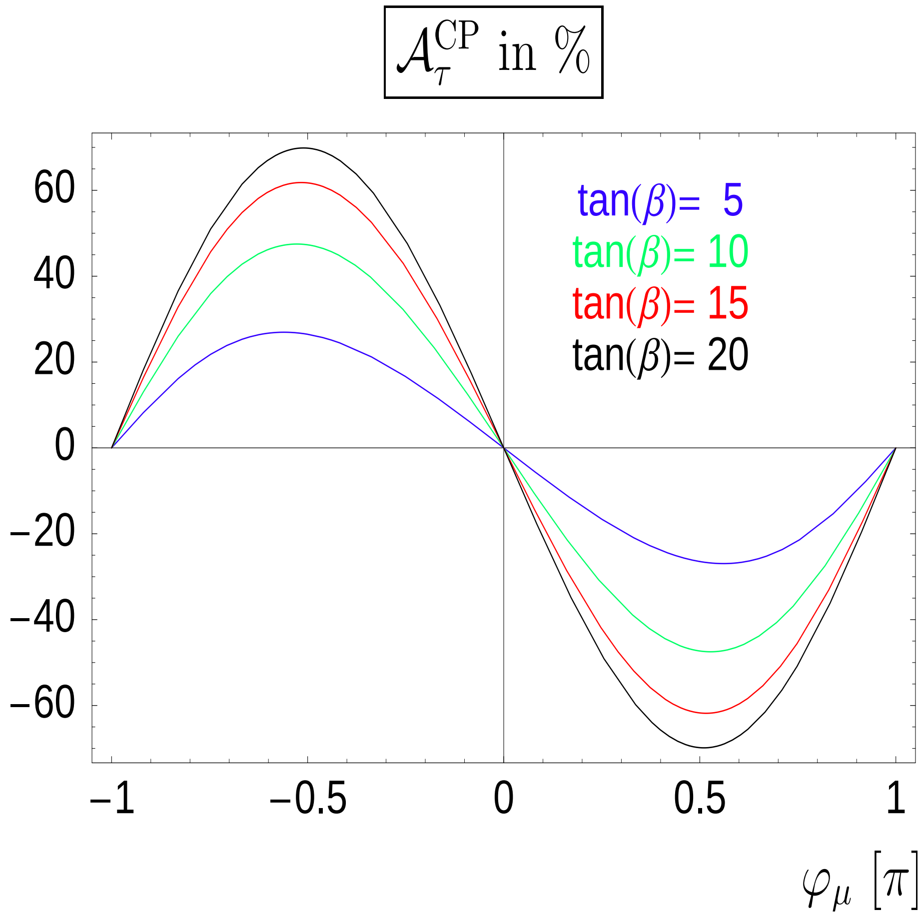
[Dreiner, OK, Marold, 10]

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

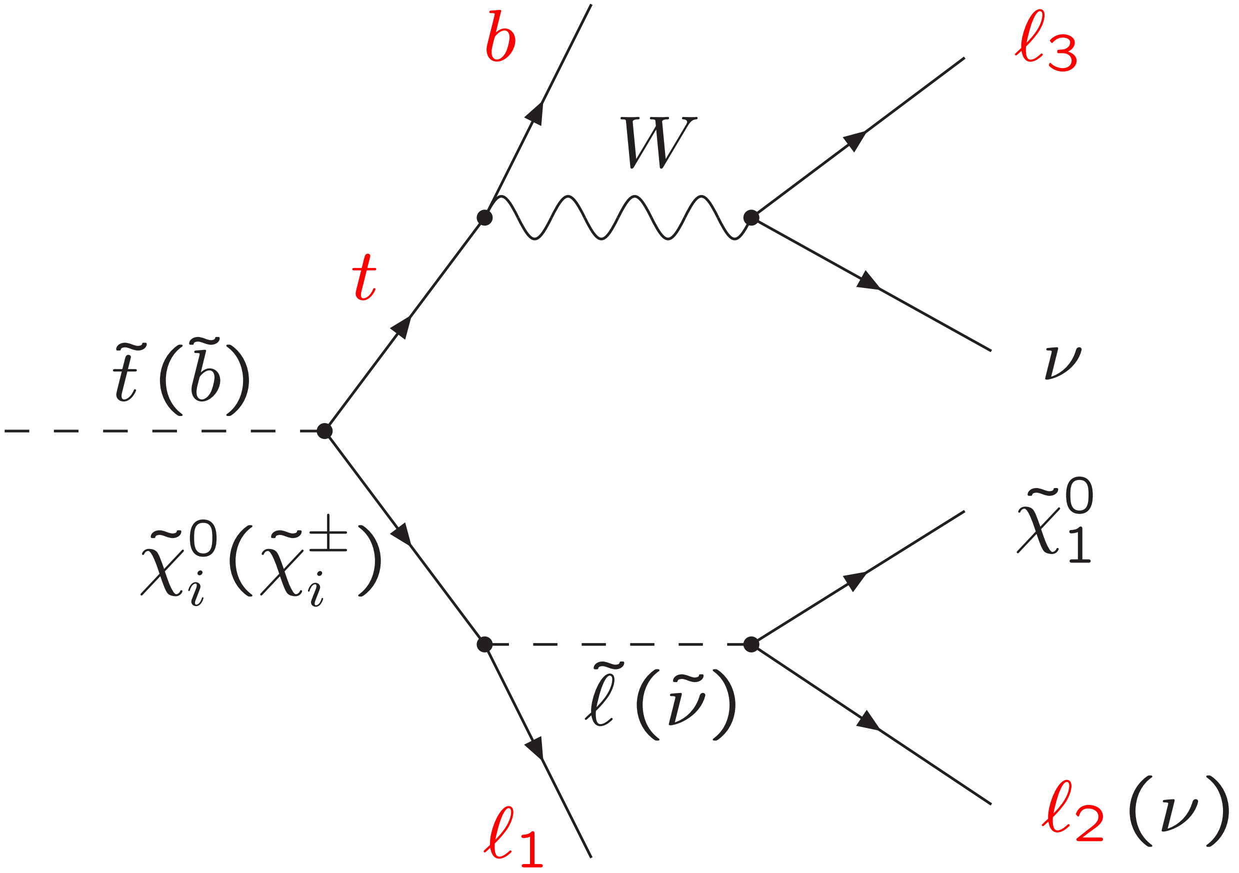
$\tan\beta = 25$; $M_{\tilde{E}} = M_{\tilde{L}} = 200$ GeV; $P(e^-|e^+) = (-0.8|0.6)$

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





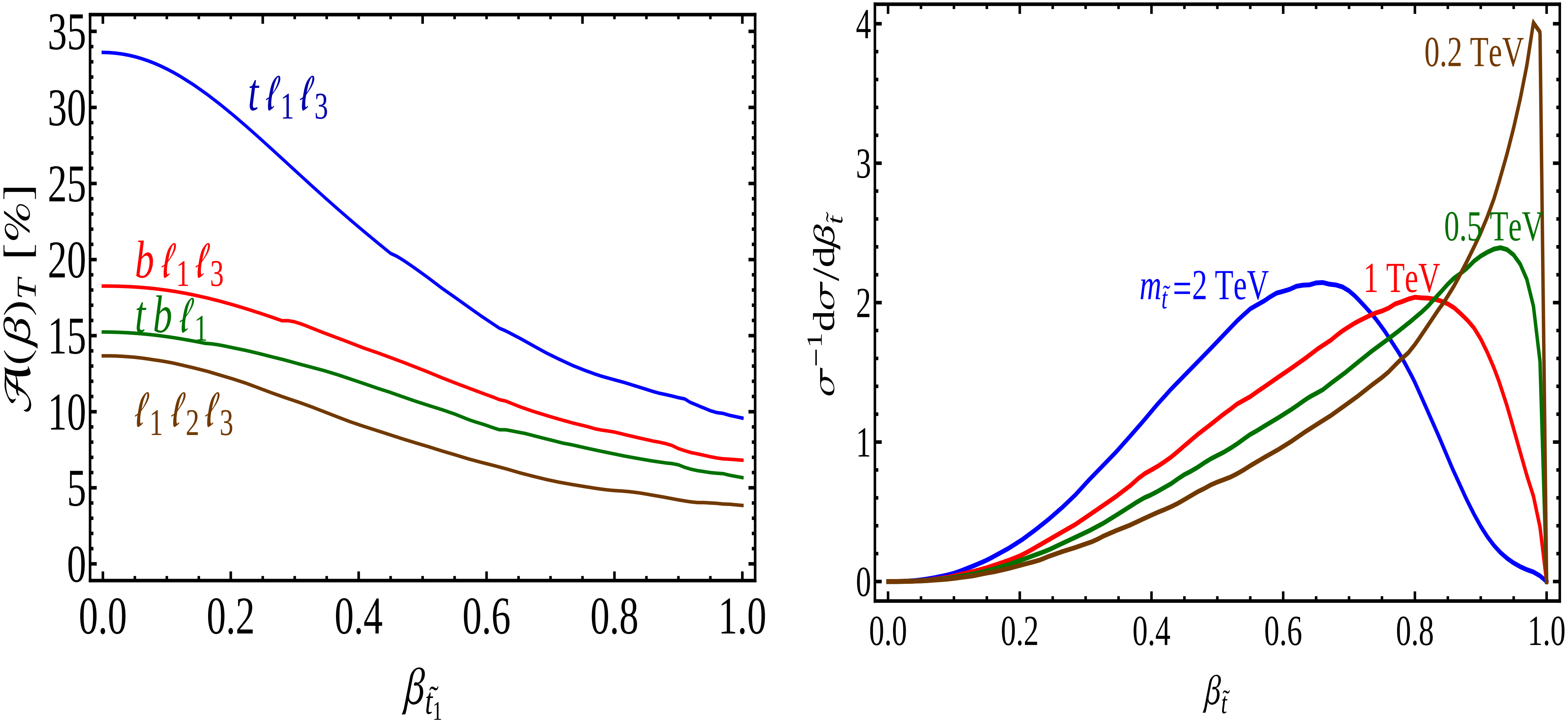
Squark decays at the LHC: CP phases of $A_{t(b)}$



[Deppisch, OK, 09, 10] [Moortgat-Pick, Rolbiecki, Tattersall, 09, 10]

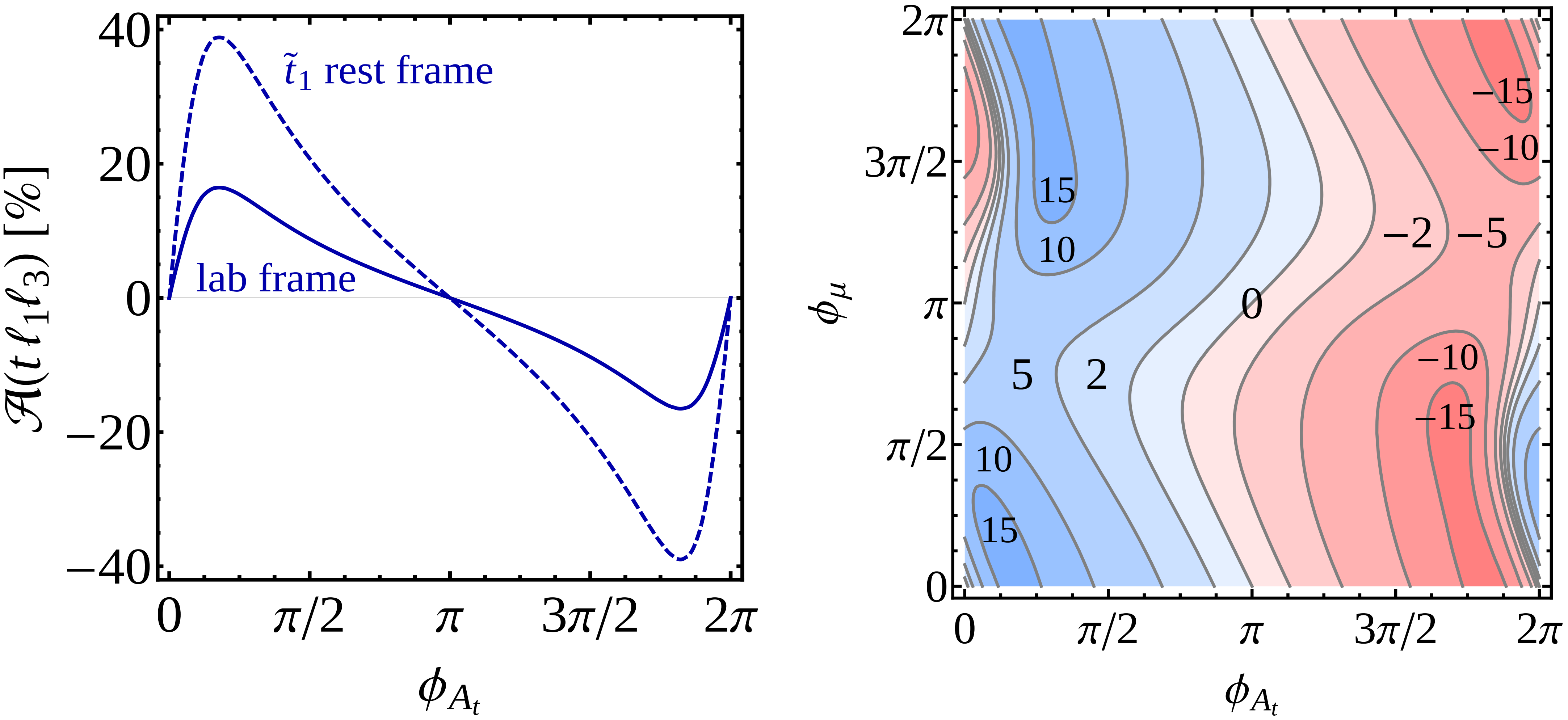
$A_0 = 500$ GeV, $m_{1/2} = 270$ GeV, $m_0 = 70$ GeV; $\tan\beta = 5$; $\phi_{A_t} = \frac{3}{4}\pi$

boost dependence of asymmetries | stop boost distributions

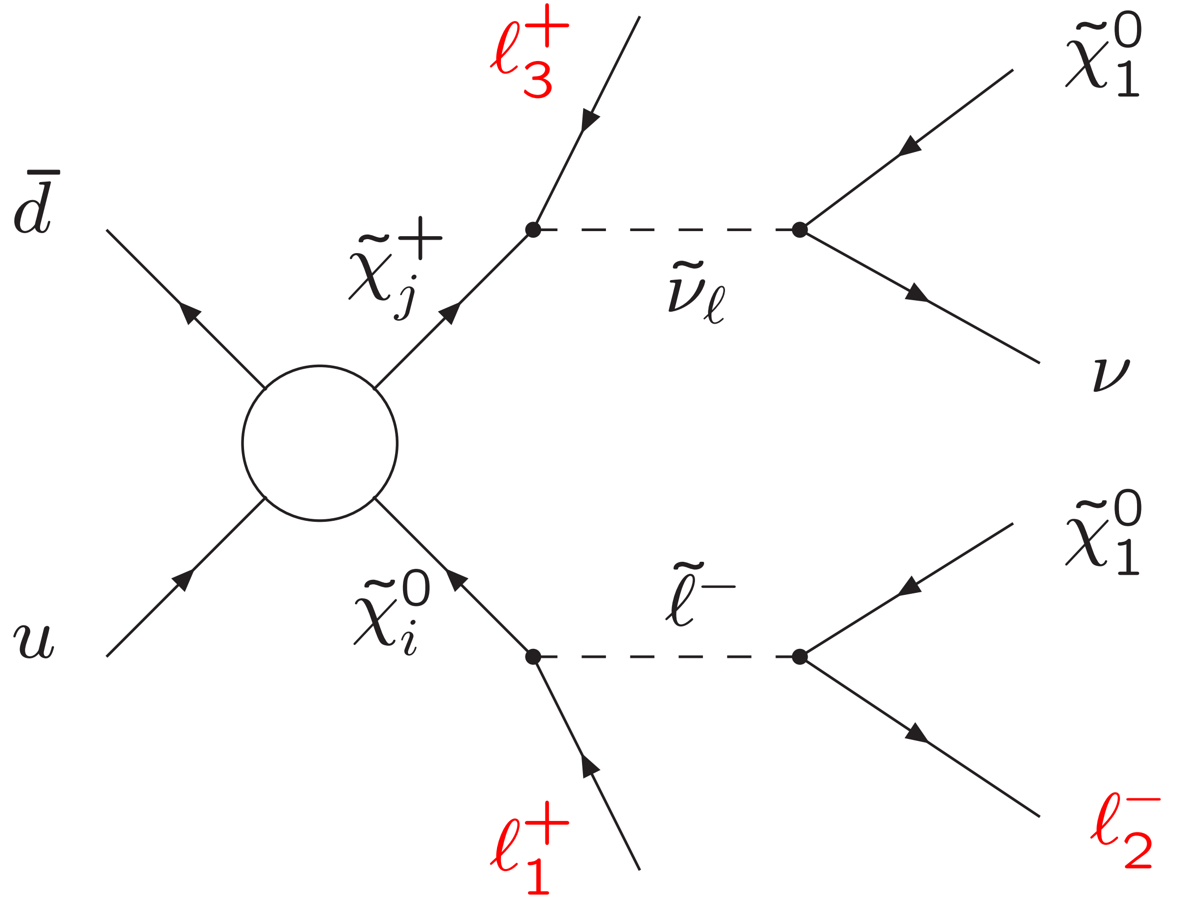


$A_0 = 500$ GeV, $m_{1/2} = 270$ GeV, $m_0 = 70$ GeV; $\tan\beta = 5$

phase dependence



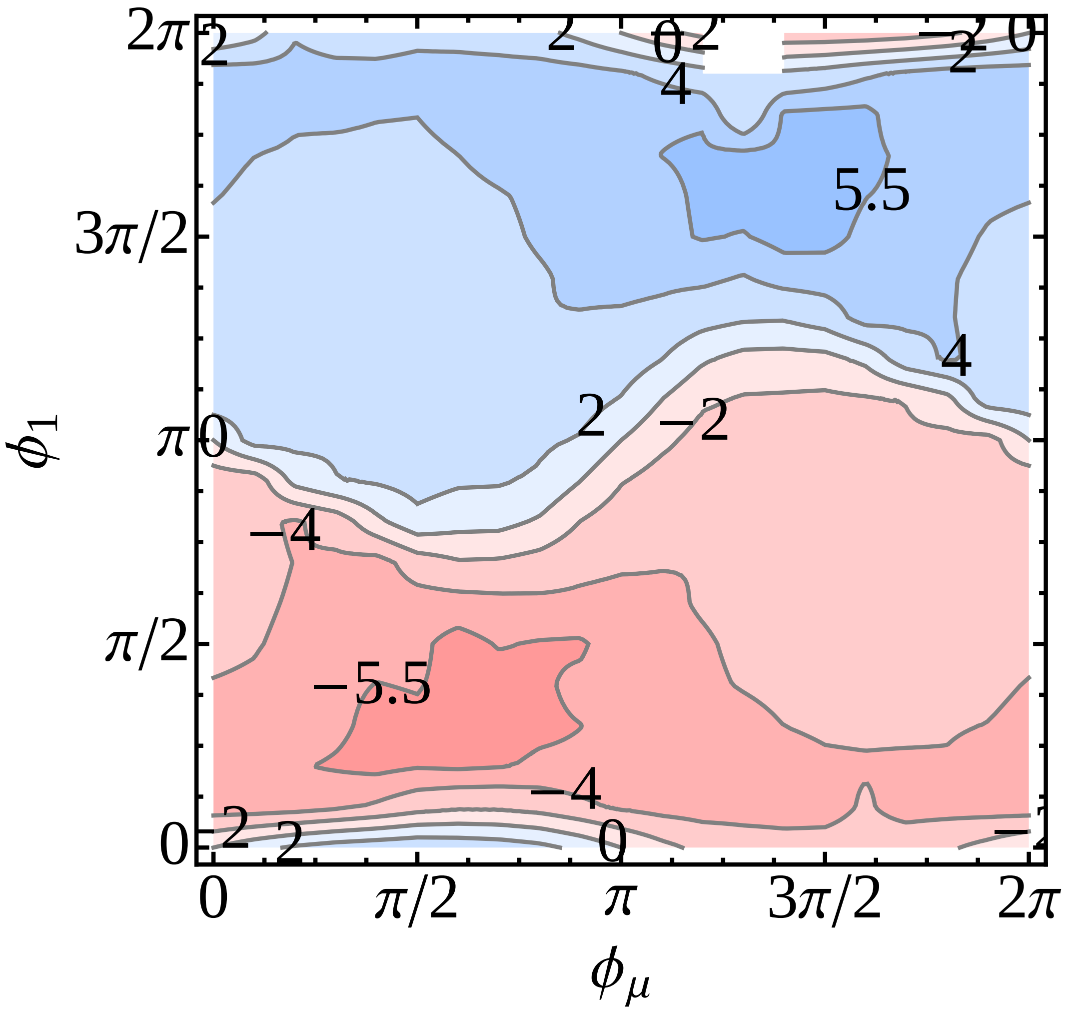
Trilepton signal at the LHC: CP phases of μ, M_1



[Tevatron: Choi et al.,00]

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

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



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.

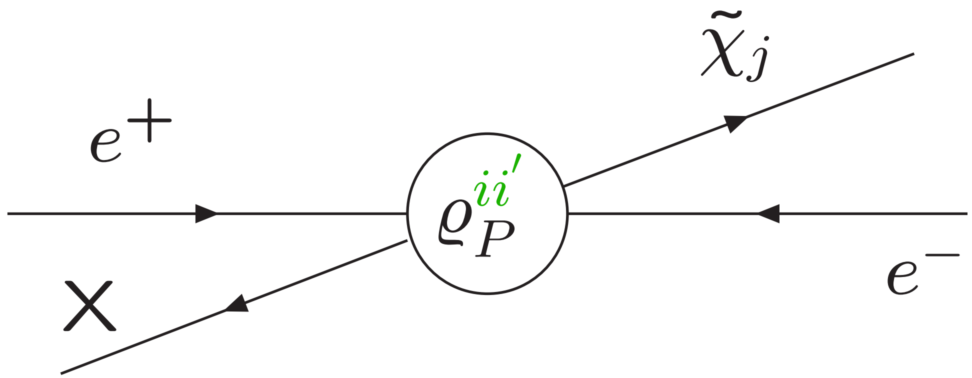
- CP asymmetries are typically of the order of 10% (and more!).
  $\longrightarrow$ should motivate experimental studies.
  $\longrightarrow$ can phases be constrained/measured at future colliders?

Spin density matrix formalism

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

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

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



Origin of δ, σ from Feynman calculus

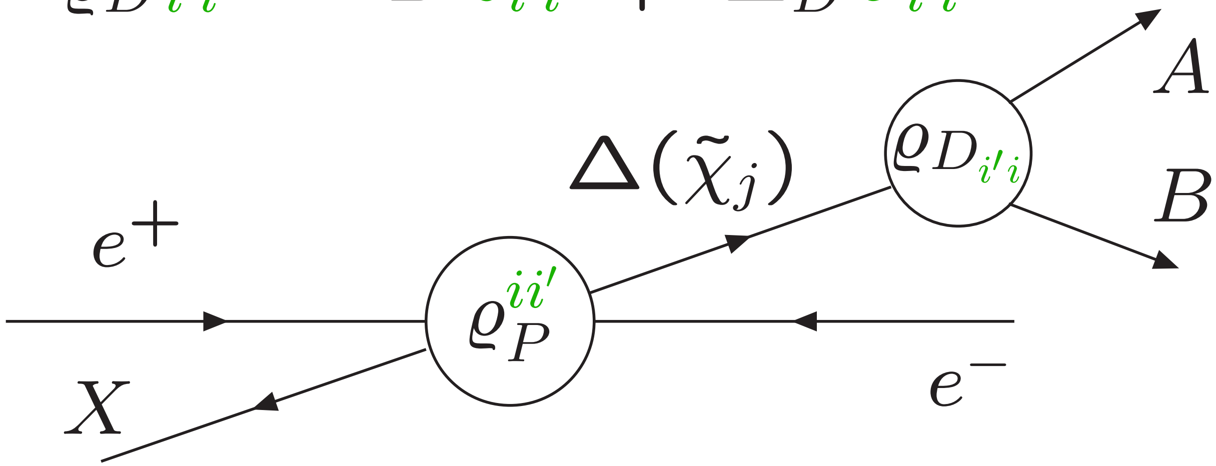
Bouchiat-Michel-Formula:

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

s^a: spin vector basis

Production and decay

$$\varrho_{D\,i'i} \;=\; D\,\delta_{i'i} \;+\; \vec{\Sigma}_D\,\vec{\sigma}_{i'i}$$



Feynman amplitude squared:

$$|T|^2 \;=\; |\Delta(\tilde{\chi}_j)|^2\, Tr\{\varrho_P \cdot \varrho_D\}$$

$$\;=\; 2\,|\Delta(\tilde{\chi}_j)|^2\,(P\,D + \vec{\Sigma}_P \vec{\Sigma}_D)$$

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

spin correlations

$\sim \sigma \times$ BR