CRACOW EPIPHANY CONFERENCE
ON LHC PHYSICS
4 - 6 January 2008, Cracow, Poland

CP violation in the chargino/neutralino sector of the MSSM

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Outline

- Introduction
- MSSM charginos and neutralinos

  tree level: basic properties, parameter determination,

  CP violation
- CP in chargino production at one loop
- Summary

Introduction

SUSY is now more than 35 years old !

But remember:
- it took more than 40 years to build the Standard Model
- it took some 20 years from bottom to top quark (which was expected)

The required scale to study the EW theory (since Fermi) is TeV

After 70 years we are finally getting there!

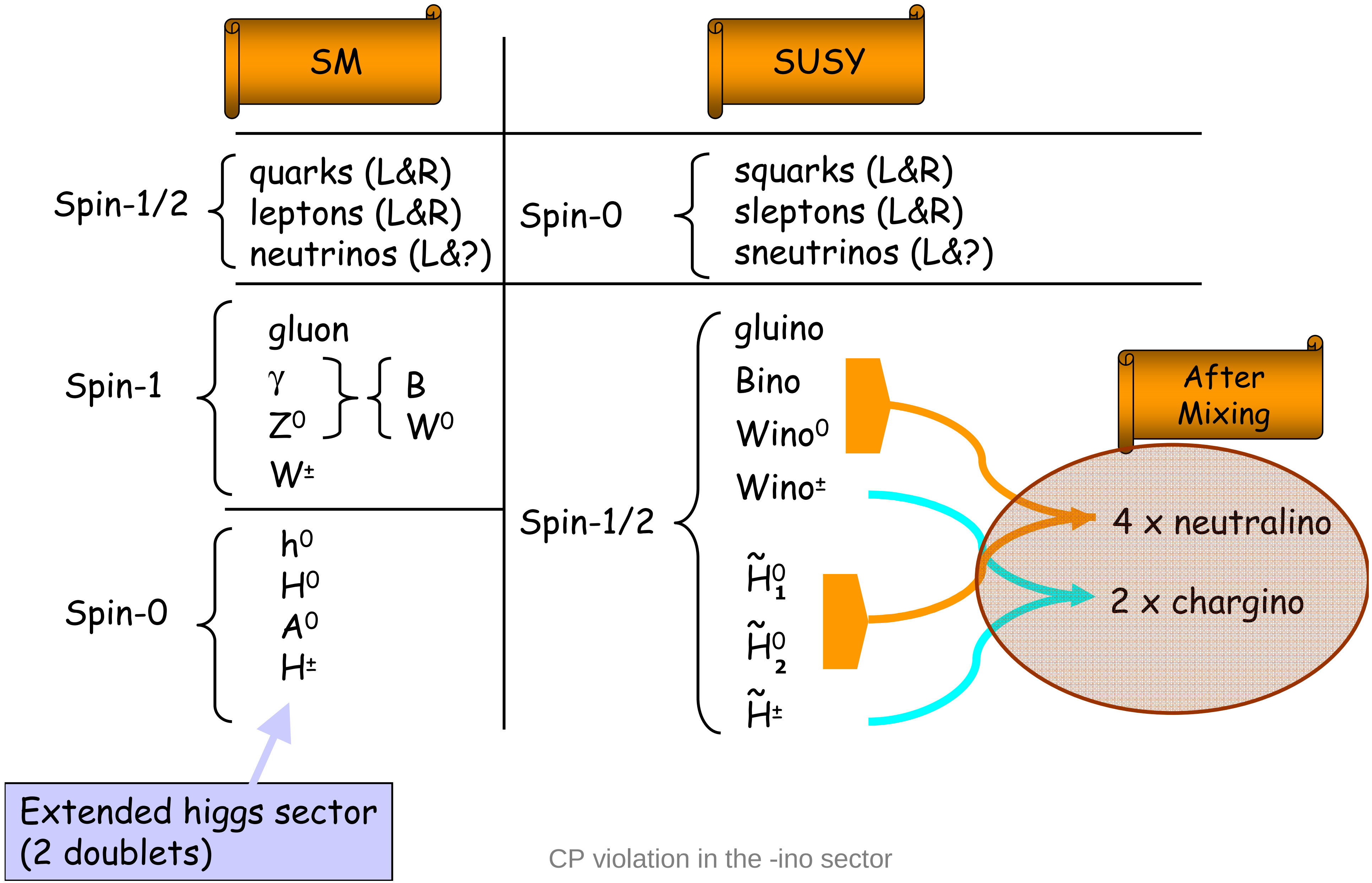
LHC experiments

- the outcome far more important than any other in the past
- all future projects: ILC, superB, super..., depend on LHC discovery
- huge responsibility to provide quick and reliable answers

Motivation for (weak-scale) SUSY

- Naturalness => new TeV scale that cuts off quadratically divergent contributions from SM particles
- predicts a light Higgs M_h< 130 GeV
  as suggested by data M_h< 200 GeV @ 95%
- predicts gauge coupling unification
- dark matter candidate: neutralino, sneutrino, ..
- new sources of CP violation
- consistent with EW data

MSSM: particles and sparticles

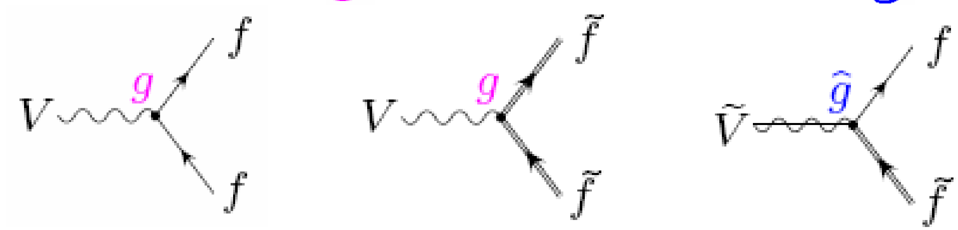


Exact SUSY

Exact SUSY => no new parameters

SUSY implies relations between masses and couplings:

- gauge coupling g = Yukawa coupling $\hat{g}$



crucial for hierarchy problem

- scalars and fermions from the same multiplet have equal masses

⇒ **SUSY must be broken**

Top-down: **or From Strings to LHC**

Derive SUSY breaking from high-scale physics

Unconstrained MSSM

No particular SUSY breaking mechanism assumed

L. Girardello, M. Grisaru '82

$$
\begin{aligned}
\mathcal{L}_{\rm soft} \;=\; & -\frac{1}{2}\Big(M_1\widetilde{B}\widetilde{B} + M_2\widetilde{W}\widetilde{W} + M_3\tilde{g}\tilde{g}\Big) + \text{h.c.} \\
& - m^2_{H_u}H_u^\dagger H_u - m^2_{H_d}H_d^\dagger H_d - (bH_uH_d + \text{h.c.}) \\
& - \Big(\tilde{u}_R\mathbf{a_u}\widetilde{Q}H_u - \tilde{d}_R\mathbf{a_d}\widetilde{Q}H_d - \tilde{e}_R\mathbf{a_e}\widetilde{L}H_d\Big) + \text{h.c.} \\
& - \widetilde{Q}^\dagger\mathbf{m^2_Q}\widetilde{Q} - \widetilde{L}^\dagger\mathbf{m^2_L}\widetilde{L} - \tilde{u}_R\mathbf{m^2_u}\tilde{u}^*_R - \tilde{d}_R\mathbf{m^2_d}\tilde{d}^*_R - \tilde{e}_R\mathbf{m^2_e}\tilde{e}^*_R
\end{aligned}
$$

- Most general case: 105 new parameter – masses, mixing angles, **CP phases**
- Good phenomenological description if universal breaking terms

- Experimental determination of SUSY parameters

=> patterns of SUSY breaking

MSSM charginos and neutralinos

Mass matrices

charginos

in $(\tilde{W}^-, \tilde{H}^-)$ basis

$$\begin{pmatrix} M_2 & \sqrt{2} m_W c_\beta \\ \sqrt{2} m_W s_\beta & \mu \end{pmatrix}$$

neutralinos

in $(\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

$$M_2 \text{ real}, \qquad M_1 = |M_1| e^{i\Phi_1}, \qquad \mu = |\mu| e^{i\Phi_\mu}$$

At tree level:

charginos $M_2, \mu, \tan\beta$

neutralinos $+M_1$

Expected to be among the lightest sparticles

Φ_μ, Φ_1

CP phases

→ **A good starting point towards SUSY parameter determination**

Charginos

Chargino mass matrix diagonalized by two unitary matrices $U_R^* M_C U_L^\dagger$

$$U_L = \begin{pmatrix} c_L & s_L^* \\ -s_L & c_L \end{pmatrix} \qquad U_R = \begin{pmatrix} e^{i\gamma_1} & 0 \\ 0 & e^{i\gamma_2} \end{pmatrix} \begin{pmatrix} c_R & s_R^* \\ -s_R & c_R \end{pmatrix}$$

$$c_{L,R} = \cos\phi_{L,R}, \qquad s_{L,R} = e^{i\beta_{L,R}} \sin\phi_{L,R}$$

$$m^2_{\tilde{\chi}^\pm_{1,2}} = \frac{1}{2}\left[M_2^2 + |\mu|^2 + 2m_W^2 \mp \Delta_C\right]$$

$$\cos 2\phi_{L,R} = -\left[M_2^2 - |\mu|^2 \mp 2m_W^2 \cos 2\beta\right] / \Delta_C$$

$$\sin 2\phi_{L,R} = -2m_W \left[M_2^2 + |\mu|^2 \pm (M_2^2 - |\mu|^2)\cos 2\beta + 2M_2|\mu| \sin 2\beta \cos\Phi_\mu\right]^{1/2} / \Delta_C$$

$$\tan\beta_L = -\frac{\sin\Phi_\mu}{\cos\Phi_\mu + \frac{M_2}{|\mu|}\cot\beta} \qquad \tan\beta_R = +\frac{\sin\Phi_\mu}{\cos\Phi_\mu + \frac{M_2}{|\mu|}\tan\beta}$$

$$\tan\gamma_1 = +\frac{\sin\Phi_\mu}{\cos\Phi_\mu + \frac{M_2[m^2(\tilde{\chi}_1^\pm) - |\mu|^2]}{|\mu| m_W^2 \sin 2\beta}} \qquad \tan\gamma_2 = -\frac{\sin\Phi_\mu}{\cos\Phi_\mu + \frac{M_2 m_W^2 \sin 2\beta}{|\mu|[m^2(\tilde{\chi}_2^\pm) - M_2^2]}}$$

$$\Delta_C = \left[(M_2^2 - |\mu|^2)^2 + 4m_W^4 \cos^2 2\beta + 4m_W^2(M_2^2 + |\mu|^2) + 8m_W^2 M_2|\mu| \sin 2\beta \cos\Phi_\mu\right]^{1/2}$$

Neutralinos

Neutralino mass matrix diagonalized by a unitary matrix $N^* M_N N^{-1}$

$$N = \mathrm{diag}\left\{ \mathrm{e}^{i\alpha_1}, \mathrm{e}^{i\alpha_2}, \mathrm{e}^{i\alpha_3}, \mathrm{e}^{i\alpha_4} \right\} \mathrm{R}_{34}\, \mathrm{R}_{24}\, \mathrm{R}_{14}\, \mathrm{R}_{23}\, \mathrm{R}_{13}\, \mathrm{R}_{12}$$

Can be solved analytically

$$\mathrm{R}_{12} = \begin{pmatrix} c_{12} & s_{12}^* & 0 & 0 \\ -s_{12} & c_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Unitarity constraints – two types of unitarity quadrangles

Two rows: $M_{ij} = N_{i1} N_{j1}^* + N_{i2} N_{j2}^* + N_{i3} N_{j3}^* + N_{i4} N_{j4}^*$

Two columns $D_{ij} = N_{1i} N_{1j}^* + N_{2i} N_{2j}^* + N_{3i} N_{3j}^* + N_{4i} N_{4j}^*$

CKMZ '01

$$\begin{aligned} \mathrm{area}[M_{ij}] &= (|J_{ij}^{12}| + |J_{ij}^{23}| + |J_{ij}^{34}| + |J_{ij}^{41}|)/4 \\ \mathrm{area}[D_{ij}] &= (|J_{12}^{ij}| + |J_{23}^{ij}| + |J_{34}^{ij}| + |J_{41}^{ij}|)/4 \end{aligned}$$

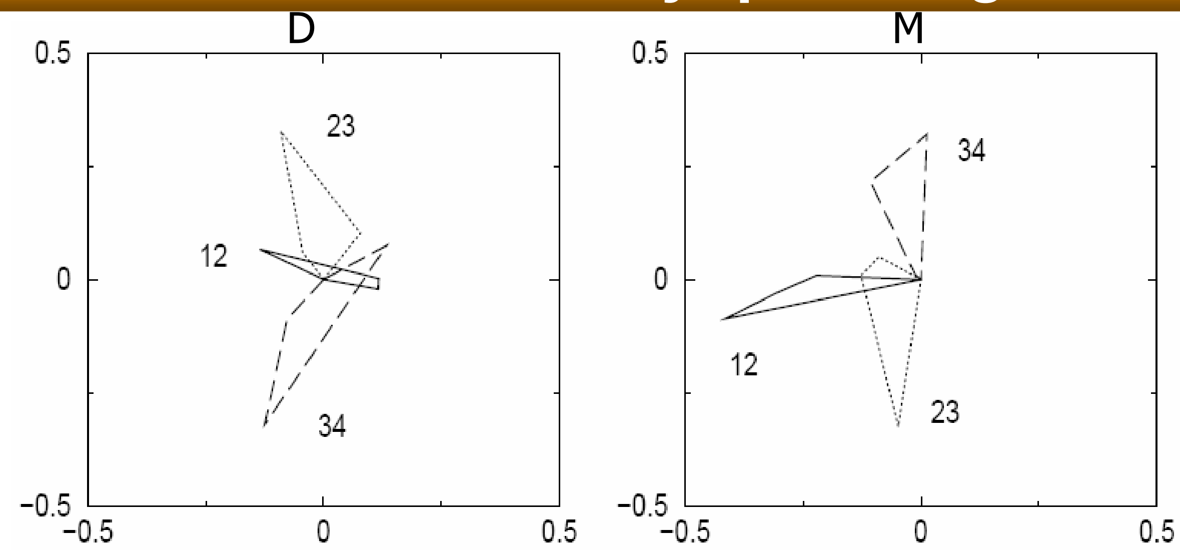
$$J_{ij}^{kl} = Im\, N_{ik} N_{jl} N_{jk}^* N_{il}^*$$

Unlike in CKM or MNS, the orientation of all quadrangles is physical

CP is conserved if all quadrangles collaps to lines parallel to either Re or Im axis

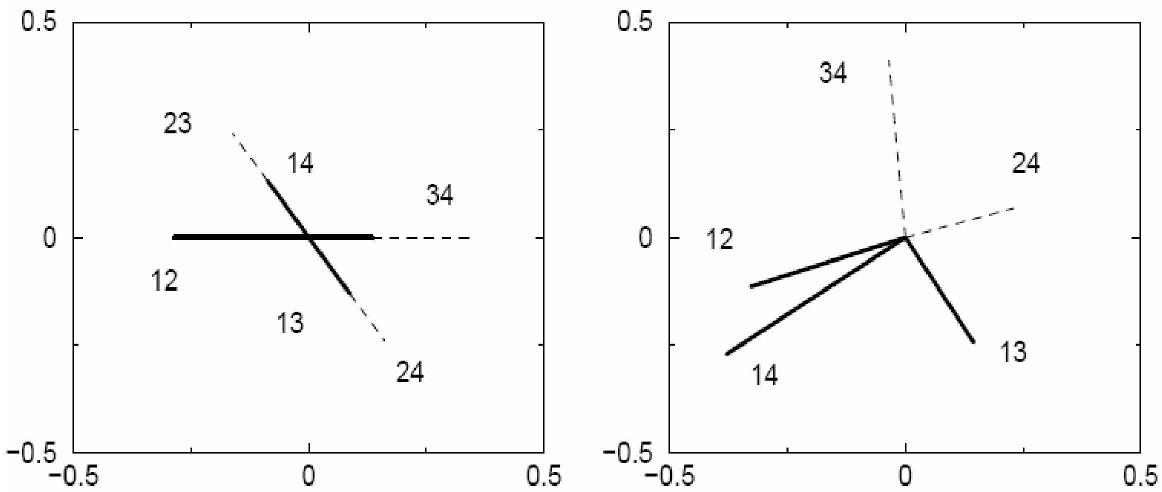
Unitarity quadrangles

Choi, JK, Moortgat-Pick, Zerwas



$\Phi_\mu = \pi/2$

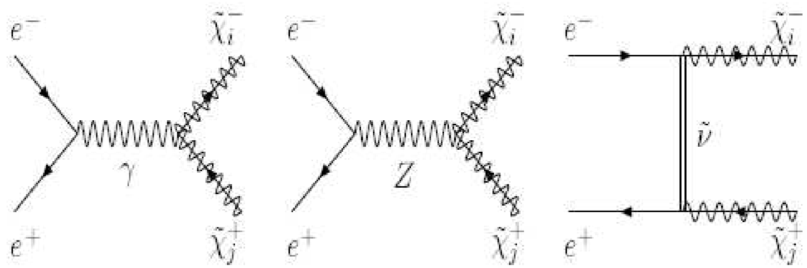
$\tan\beta = 3,\ |M_1| = 100\ GeV,\ \Phi_1 = 0,\ M_2 = 150\ GeV,\ |\mu| = 200\ GeV$



$\tan\beta = 1\ and\ M_1 = M_2 = 100\ GeV,\ and\ |\mu| = 150\ GeV,$

All phases determined by two phases of M1 and mu parameters – many consistency checks

Chargino production in e+e-



after Fierz-ing

$$T[e^+e^- \to \tilde{\chi}_i^- \tilde{\chi}_j^+] = \frac{e^2}{s} Q_{\alpha\beta} \left[\bar{v}(e^+)\gamma_\mu P_\alpha u(e^-)\right] \left[\bar{u}(\tilde{\chi}_i)\gamma^\mu P_\beta v(\tilde{\chi}_j)\right]$$

For diagonal pairs (11)/(22)

$$Q_{LL} = D_L \mp F_L \cos 2\phi_L$$
$$Q_{LR} = D'_L \mp F'_L \cos 2\phi_R$$
$$Q_{RL} = D_R \mp F_R \cos 2\phi_L$$
$$Q_{RR} = D_R \mp F_R \cos 2\phi_R$$

For non-diagonal pairs (12)/(21)

$$Q_{LL} = F_L\, e^{\mp i\beta_L} \sin 2\phi_L$$
$$Q_{LR} = F'_L\, e^{\mp i(\beta_R - \gamma_1 + \gamma_2)} \sin 2\phi_R$$
$$Q_{RL} = F_R\, e^{\mp i\beta_L} \sin 2\phi_L$$
$$Q_{RR} = F_R\, e^{\mp i(\beta_R - \gamma_1 + \gamma_2)} \sin 2\phi_R$$

$$D_L = 1 + \frac{D_Z}{s_W^2 c_W^2}(s_W^2 - \frac{1}{2})(s_W^2 - \frac{3}{4}) \qquad F_L = \frac{D_Z}{4 s_W^2 c_W^2}(s_W^2 - \frac{1}{2})$$

$$D_R = 1 + \frac{D_Z}{c_W^2}(s_W^2 - \frac{3}{4}) \qquad F_R = \frac{D_Z}{4 c_W^2}$$

$$D'_L = D_L + \left(\frac{g_{\tilde{W}}}{g_W}\right)^2 \frac{D_{\tilde{\nu}}}{4 s_W^2} \qquad F'_L = F_L - \left(\frac{g_{\tilde{W}}}{g_W}\right)^2 \frac{D_{\tilde{\nu}}}{4 s_W^2}$$

$$D_Z = s/(s - m_Z^2 + i m_Z \Gamma_Z)$$
$$D_{\tilde{\nu}} = s/(t - m_{\tilde{\nu}}^2)$$

- linear in $\cos 2\phi_{L,R}, \sin 2\phi_{L,R}$
- CP phases enter only (12)/(21)
- sneutrino only in LR amplitude breaks L-R symmetry

Choi, Djouadi, Guchait, JK, Song, Zerwas

Chargino production in e+e-

With polarized beams $P=(P_T,0,P_L)$, $\bar{P}=(\bar{P}_T\cos\eta, \bar{P}_T\sin\eta, -\bar{P}_L)$ summing chargino polarizations

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{16s}\lambda^{1/2}\Big[(1-P_L\bar{P}_L)\,\Sigma_{\rm unp} + (P_L-\bar{P}_L)\,\Sigma_{LL} + P_T\bar{P}_T\cos(2\Phi-\eta)\,\Sigma_{TT}\Big]$$

$$\begin{aligned}
\Sigma_{\rm unp} &= 4\Big\{\Big[1-(\mu_i^2-\mu_j^2)^2+\lambda\cos^2\Theta\Big]Q_1 + 4\mu_i\mu_j Q_2 + 2\lambda^{1/2}Q_3\cos\Theta\Big\}\\
\Sigma_{LL} &= 4\Big\{\Big[1-(\mu_i^2-\mu_j^2)^2+\lambda\cos^2\Theta\Big]Q_1' + 4\mu_i\mu_j Q_2' + 2\lambda^{1/2}Q_3'\cos\Theta\Big\}\\
\Sigma_{TT} &= -4\lambda\sin^2\Theta\; Q_5
\end{aligned}$$

P	CP	Quartic charges
even	even	$Q_1 = \frac{1}{4}\left[\lvert Q_{RR}\rvert^2 + \lvert Q_{LL}\rvert^2 + \lvert Q_{RL}\rvert^2 + \lvert Q_{LR}\rvert^2\right]$
		$Q_2 = \frac{1}{2}\mathrm{Re}\left[Q_{RR}Q_{RL}^* + Q_{LL}Q_{LR}^*\right]$
		$Q_3 = \frac{1}{4}\left[\lvert Q_{RR}\rvert^2 + \lvert Q_{LL}\rvert^2 - \lvert Q_{RL}\rvert^2 - \lvert Q_{LR}\rvert^2\right]$
		$Q_5 = \frac{1}{2}\mathrm{Re}\left[Q_{LR}Q_{RR}^* + Q_{LL}Q_{RL}^*\right]$
	odd	$Q_4 = \frac{1}{2}\mathrm{Im}\left[Q_{RR}Q_{RL}^* + Q_{LL}Q_{LR}^*\right]$

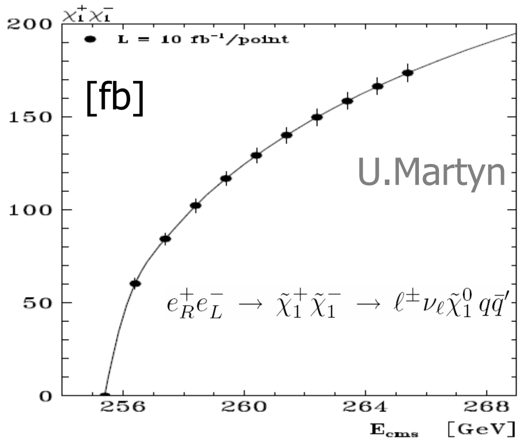
Polarized beams not sufficient to probe
CP from cross-section measurements alone

Only Q4 changes sign under CP

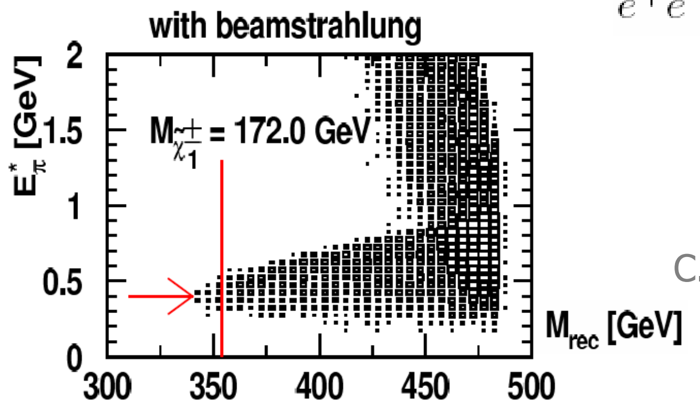
- determines the normal component of the polarization vector of produced chargino
- vanishes if produced charginos are of equal mass

Determining masses and mixings

Masses: from threshold or in continuum

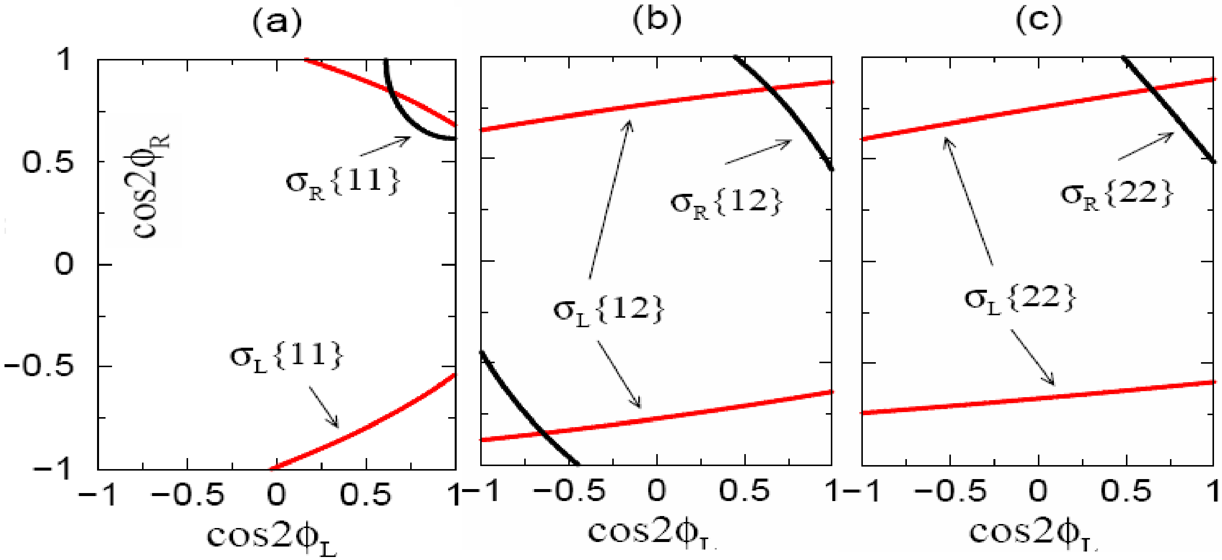


If $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$ mass splitting small, exploit $e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-\gamma$



C.Hensel

Mixing angles: from polarized cross sections



Choi Guchait, JK, Zerwas.

If only light chargino measured, reconstruction possible with help from neutralinos

Derive SUSY parameterss

$$M_2 = m_W\sqrt{\Sigma - \Delta\,(c_{2L} + c_{2R})}$$

$$|\mu| = m_W\sqrt{\Sigma + \Delta\,(c_{2L} + c_{2R})}$$

$$\cos\Phi_\mu = \frac{\Delta^2(2 - c_{2L}^2 - c_{2R}^2) - \Sigma}{\sqrt{[1 - \Delta^2(c_{2L} - c_{2R})^2]\,[\Sigma^2 - \Delta^2(c_{2L} + c_{2R})^2]}}$$

$$\tan\beta = \sqrt{\frac{1 - \Delta(c_{2L} - c_{2R})}{1 + \Delta(c_{2L} - c_{2R})}}$$

Choi ea., Kneur & Moultaka

$$\Sigma = \left[m^2_{\tilde\chi_2^\pm} + m^2_{\tilde\chi_1^\pm} - 2m^2_W\right]/2m^2_W$$

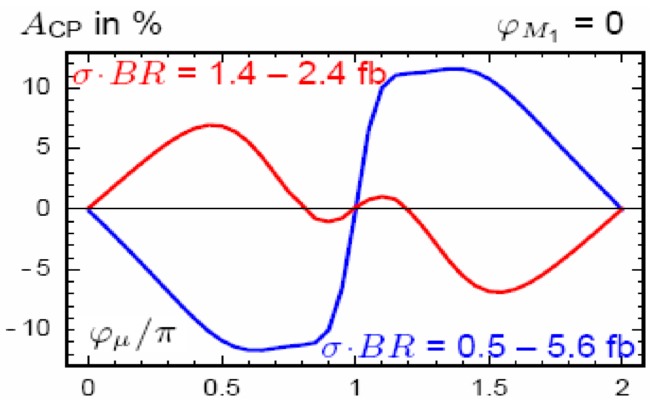
$$\Delta = \left[m^2_{\tilde\chi_2^\pm} - m^2_{\tilde\chi_1^\pm}\right]/4m^2_W$$

Two-fold ambiguity in $\Phi_\mu \leftrightarrow 2\pi - \Phi_\mu$ resolved from

- chargino spin
- or CP-asymmetries in production+decay, e.g.

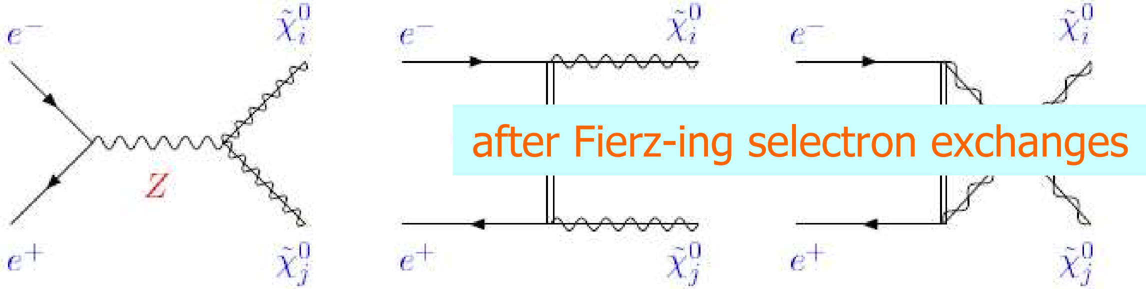
$$e^+e^- \to \tilde\chi_2^-\tilde\chi_1^+ \to \tilde\chi_2^-\tilde\chi_1^0 c\bar{s}, \qquad \mathcal{T} = \vec{p}_{e^-}\cdot(\vec{p}_{\bar{s}} \times \vec{p}_c)$$

Bartl ea., hep-ph/0608065



$P_{e^-} = -0.8$, $P_{e^+} = +0.6$, $P_{e^-} = +0.8$, $P_{e^+} = -0.6$

Neutralino production



For polarized beams and summing neutralino polarizations

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\{ij\} = \frac{\alpha^2}{16\, s}\lambda^{1/2}\big[(1-P_L\bar{P}_L)\,\Sigma_U + (P_L-\bar{P}_L)\,\Sigma_L + P_T\bar{P}_T\cos(2\Phi-\eta)\,\Sigma_T + P_T\bar{P}_T\sin(2\Phi-\eta)\,\Sigma_N\big]$$

Majorana nature => new term $\Sigma_N = 4\lambda\, Q'_6 \sin^2\Theta$

$$Q'_6 = \tfrac{1}{2} Im\left[Q_{RR}Q^*_{LR} - Q_{LL}Q^*_{RL}\right]$$

non-vanishing only if CP violated and neutralinos of different mass

$$Q'_6\{ij\} = \frac{D_Z}{2s^2_W c^2_W}\left[s^2_W(D_{tL}-D_{uL})\,\Im\mathrm{m}(\mathcal{Z}_{ij}g^*_{Lij}) - \left(s^2_W-\tfrac{1}{2}\right)(D_{tR}-D_{uR})\,\Im\mathrm{m}(\mathcal{Z}_{ij}g^*_{Rij})\right] + \frac{1}{2}(D_{tL}D_{uR}-D_{tR}D_{uL})\,\Im\mathrm{m}(g_{Lij}g^*_{Rij})$$

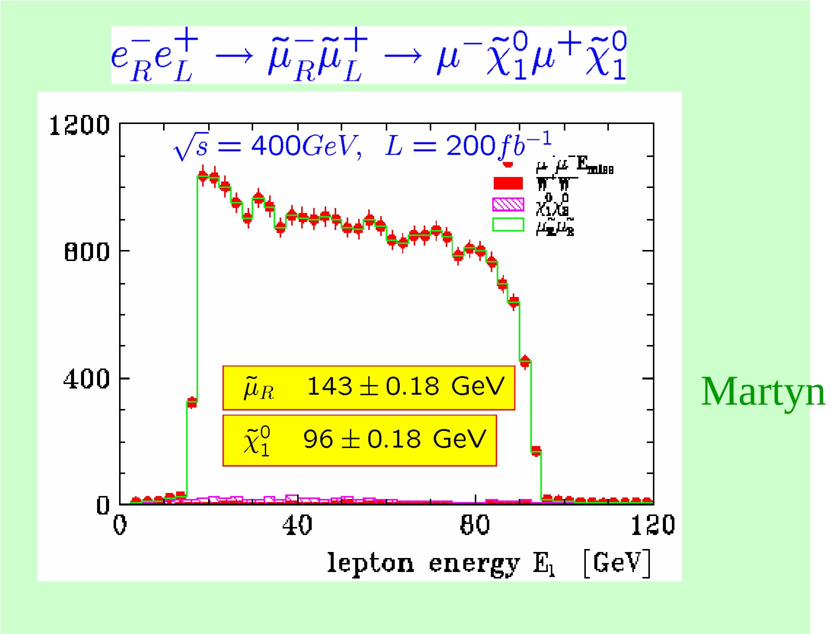
where e.g.

$$\Im\mathrm{m}(\mathcal{Z}_{ij}g^*_{Rij}) = \frac{1}{2c^2_W}\left[\Im\mathrm{m}(N_{i3}N^*_{j3}N^*_{i1}N_{j1}) - \Im\mathrm{m}(N_{i4}N^*_{j4}N^*_{i1}N_{j1})\right]$$

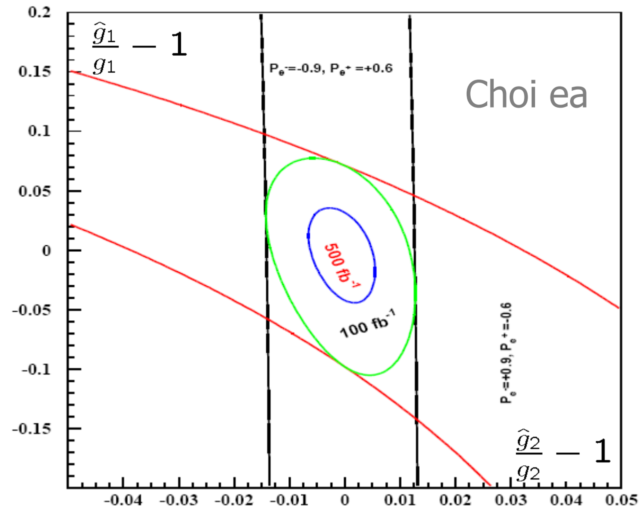
Transverse beam polarization useful to probe CP in non-diagonal neutralino pairs

Neutralino masses, couplings

Masses from threshold or in continuum



Couplings: gauge=Yukawa



If only the lightest accessible, exploit $e^+e^- \to \tilde{\chi}^0_1 \tilde{\chi}^0_1 \gamma$

Ambrosanio, Mele

$m_{\tilde{\chi}^0_1} = 180$ GeV

$\sqrt{s} = 500$ GeV

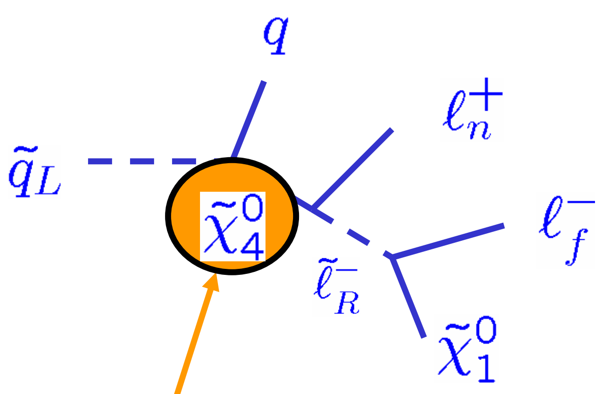
$\mathcal{L} = 500$ fb^{-1}

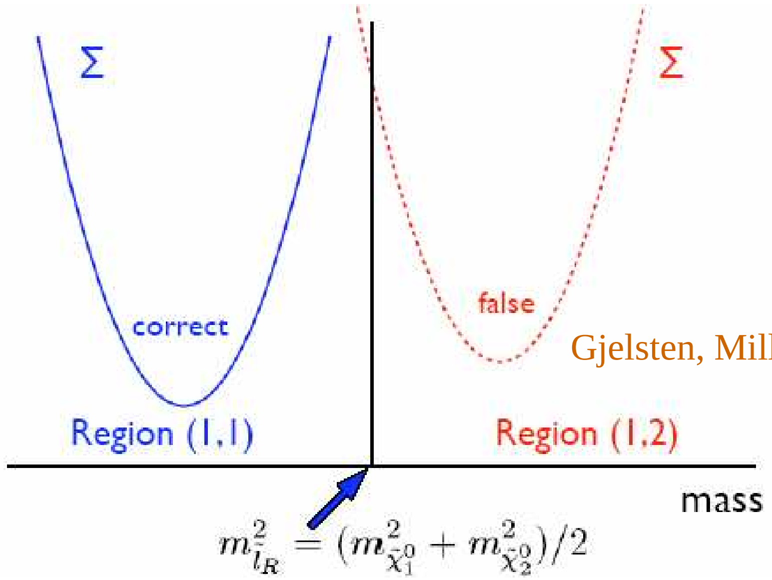
(P_{e^+}, P_{e^-})	$(0\|0)$	$(-0.6\|0.8)$
$\sigma(\tilde{\chi}^0_1 \tilde{\chi}^0_1 \gamma)$	4.7 fb	13 fb
$\sigma_B(\nu\bar{\nu}\gamma)$	3354 fb	301 fb
S	1.8	17
$R = \sigma/\sigma_B$	0.1%	4.4%

O.Kittel, LCWS'07

Possible with
high luminosity
+ polarization

LHC/ILC interplay

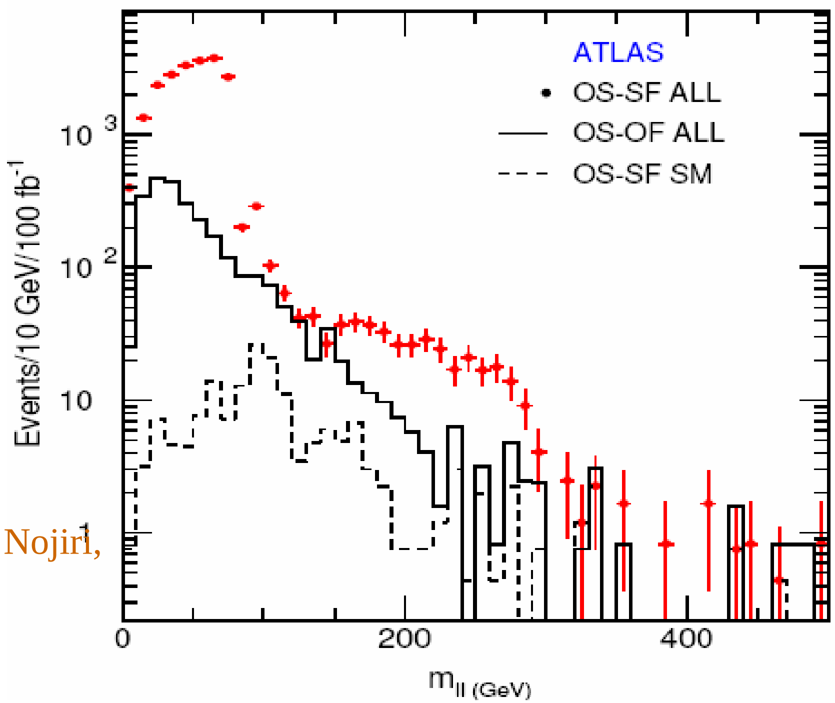




Gjelsten, Miller, Osland

- false solutions may occur
  ILC would help to eliminate them

- heavy gauginos in cascade decays
  ILC would help to identify edges of beyond-ILC states



Desch, JK, Moortgat-Pick, Nojiri, Polesello

Majorana and CP of neutralinos

Can be probed in many ways

1. Production at threshold

If CP conserved, in non-relat. limit

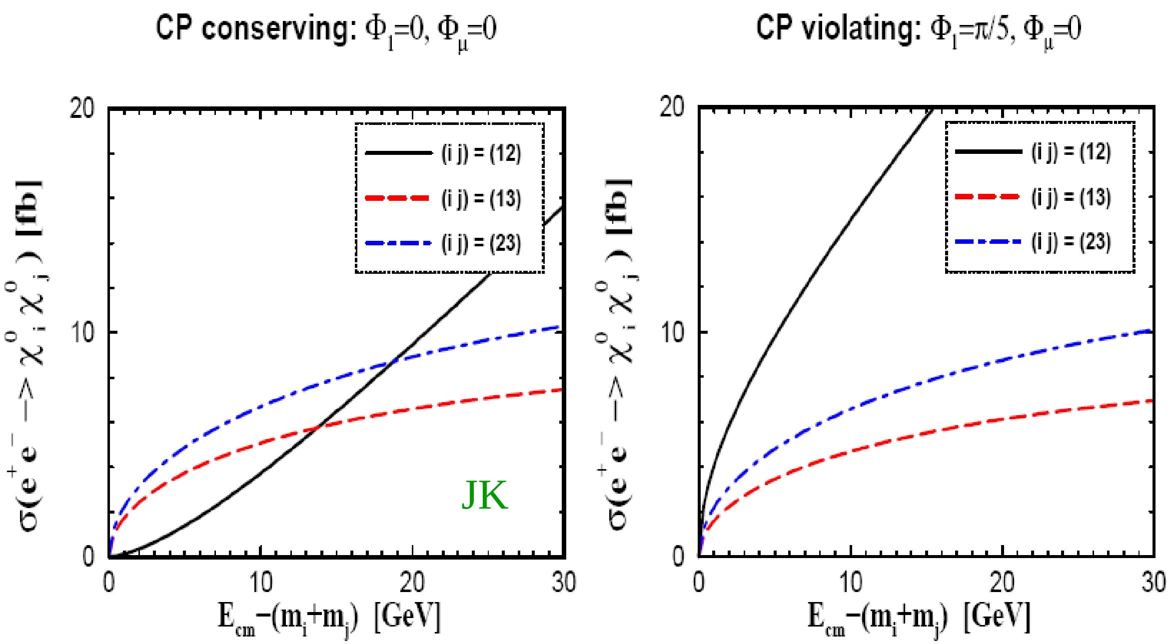
$$1 = \eta_i \eta_j (-1)^L$$

($\eta_i = \pm i$ intrinsic CP)

- if $\eta_i = \eta_j$ => P-wave
- if $\eta_i = -\eta_j$ => S-wave

CPC: if (13) and (23) in S-wave
(12) must be in P-wave

otherwise CP violated



Majorana and CP of neutralinos

2. neutralino decay spectrum near the end-point

Production: $T(e^+e^- \to \tilde{\chi}_i^0 \tilde{\chi}_j^0) = \sum_{\alpha,\beta=L,R} Q_{\alpha\beta} \left[\bar{v}(e^+)\gamma_\mu P_\alpha u(e^-)\right] \left[\bar{u}(\tilde{\chi}_i^0)\gamma^\mu P_\beta\, v(\tilde{\chi}_j^0)\right]$

Decay: $D(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 f \bar{f}) = \sum_{\alpha,\beta=L,R} Q'_{\alpha\beta} \left[\bar{u}(f)\gamma^\mu P_\alpha\, v(\bar{f})\right] \left[\bar{u}(\tilde{\chi}_j^0)\gamma_\mu P_\beta\, u(\tilde{\chi}_i^0)\right]$

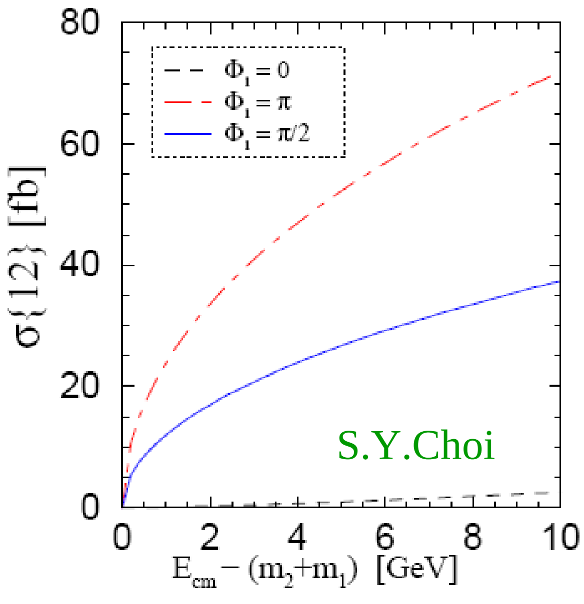
$1 = \eta_i \eta_j (-1)^L$ for production

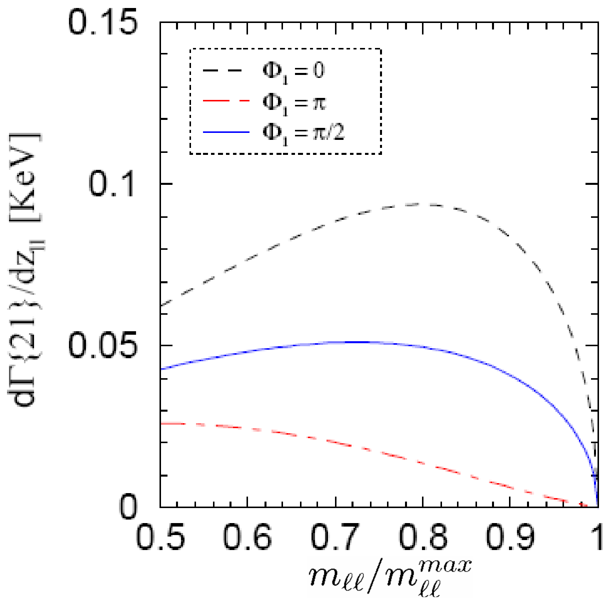
$1 = -\eta_i \eta_j (-1)^L$ for decay

Compare production of (12) with decay of 2->1

CPC: if production in S-wave
decay must be in P-wave

otherwise CP violated





Majorana and CP of neutralinos

3. neutralino production and decay

Consider the process $e^+e^- \to \tilde{e}_L^+\tilde{e}_L^- \to (e^+\tilde{\chi}_1^0)(e^-\tilde{\chi}_1^0\mu^+\mu^-)$ + c.c.

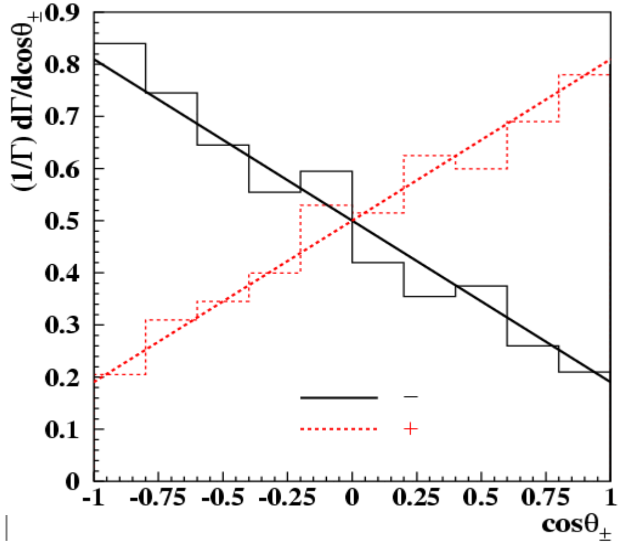
Aguilar-Saavedra

- Kinematics fully reconstructable
- Neutralino coming from selectron fully polarized
  - left-handed in $\tilde{e}_L^- \to e^-\tilde{\chi}_2^0$
  - right-handed in $\tilde{e}_L^+ \to e^+\tilde{\chi}_2^0$

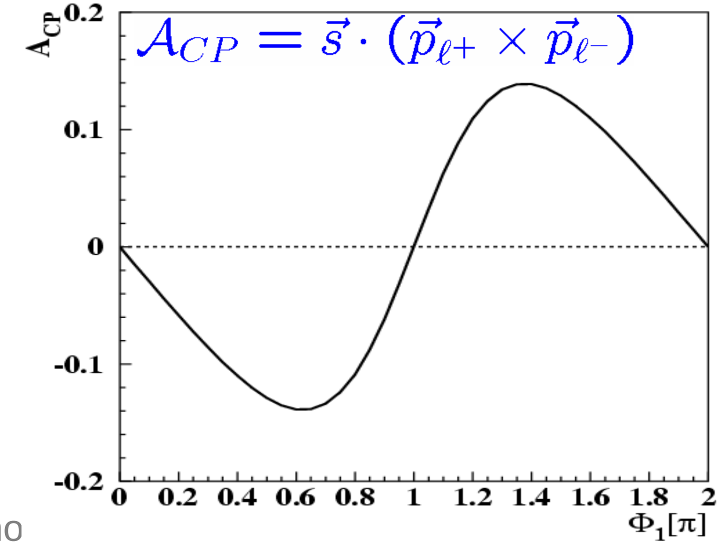
One can have a sample of fully polarized neutralinos and analyze their decay $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\mu^+\mu^-$ in the rest frame!

❖ lepton angular distribution w.r.t. neutralino spin: slopes equal irresp. CP

❖ CP-odd asymmetry



Choi, Chung, Kim, JK, Rolbiecki



CP in chargino production

- S matrix element for chargino production

$$\langle \tilde{\chi}_i^+(\mathbf{k}_1), \tilde{\chi}_j^-(\mathbf{k}_2)|S|e^+(\mathbf{p}_1), e^-(\mathbf{p}_2)\rangle$$

- P transformation: $\mathbf{p}_{1,2} \leftrightarrow -\mathbf{p}_{1,2}$, $\mathbf{k}_{1,2} \leftrightarrow -\mathbf{k}_{1,2}$

$$\langle \tilde{\chi}_i^+(-\mathbf{k}_1), \tilde{\chi}_j^-(-\mathbf{k}_2)|S|e^+(-\mathbf{p}_1), e^-(-\mathbf{p}_2)\rangle$$

- C transformation

$$\langle \tilde{\chi}_i^-(\mathbf{k}_1), \tilde{\chi}_j^+(\mathbf{k}_2)|S|e^-(\mathbf{p}_1), e^+(\mathbf{p}_2)\rangle$$

- CP transformation

$$\langle \tilde{\chi}_j^+(-\mathbf{k}_2), \tilde{\chi}_i^-(-\mathbf{k}_1)|S|e^+(-\mathbf{p}_2), e^-(-\mathbf{p}_1)\rangle$$

- in center of mass frame: $\mathbf{p}_1 = -\mathbf{p}_2$ i $\mathbf{k}_1 = -\mathbf{k}_2$

$$\langle \tilde{\chi}_j^+(\mathbf{k}_1), \tilde{\chi}_i^-(\mathbf{k}_2)|S|e^+(\mathbf{p}_1), e^-(\mathbf{p}_2)\rangle$$

→ **no CP violation in** $\chi_i^+ \chi_i^-$

For non-diagonal pairs

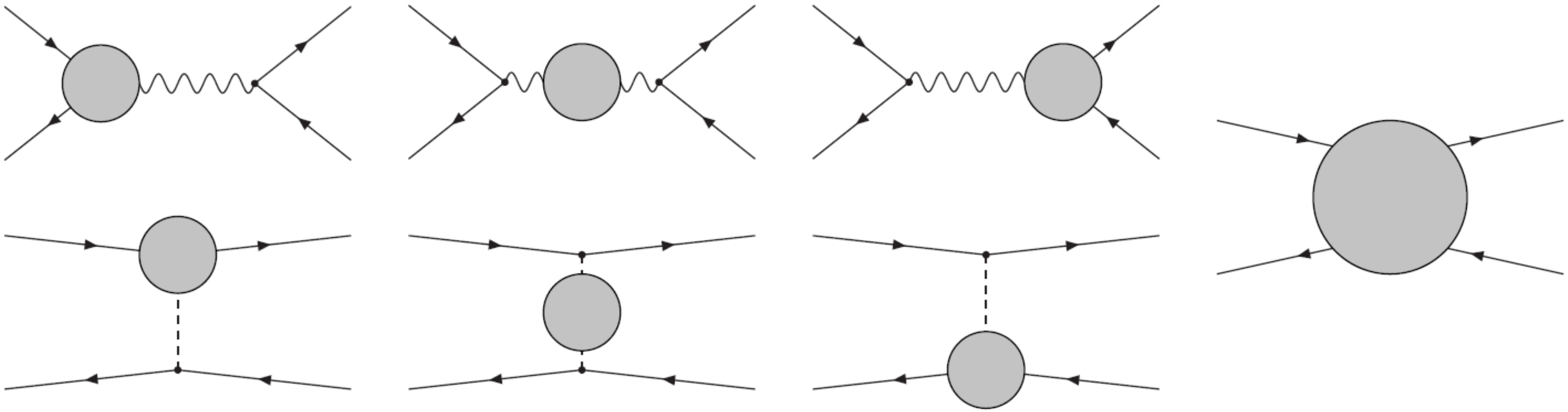
- at tree level $\sigma(\tilde{\chi}_1^- \tilde{\chi}_2^+) - \sigma(\tilde{\chi}_1^+ \tilde{\chi}_2^-) = 0$
- beyond tree level no reason to expect

→ Possibility to construct the CP asymmetry without polarization measurements

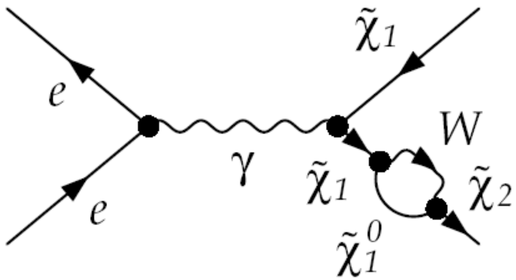
Osland, Vereshagin '07

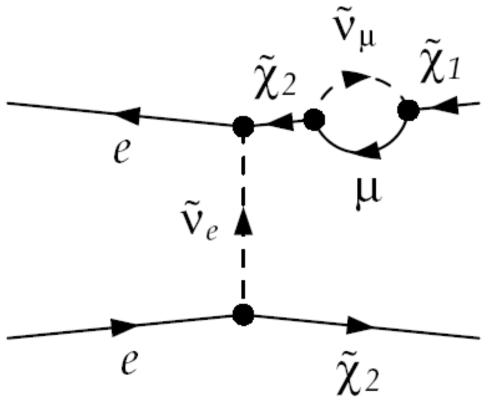
Full one-loop calculations: Rolbiecki & JK, PRD76, 115006 (2007)

Loop corrections



- three types of one-loop contributions: vertex diagrams, self-energy diagrams and box diagrams ⇒ use *FeynArts/FormCalc/LoopTools*
- inclusion of corrections on external chargino lines necessary

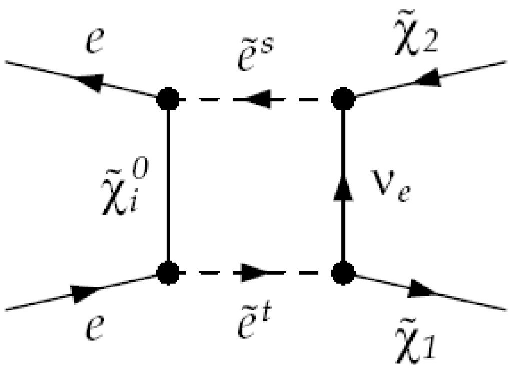


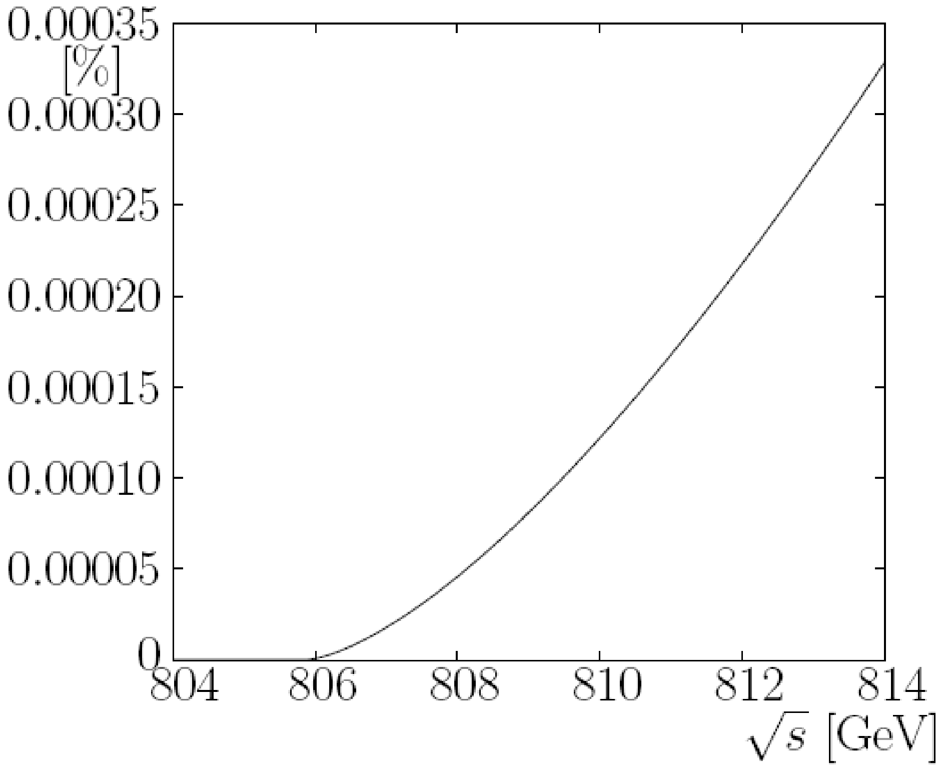


Source of CP asymmetry

$$|\mathcal{M}_{\rm loop}|^2 = |\mathcal{M}_{\rm tree}|^2 + 2\,{\rm Re}(\mathcal{M}^*_{\rm tree}\mathcal{M}_{\rm loop})$$

- CP violating effects appear due to interference between complex couplings and absorptive parts of loop integrals
- example: box diagram with selectron exchange
- asymmetry appears above selectron production threshold





CP asymmetry in $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$

- matrix element squared at one loop

$$|\mathcal{M}_{\rm loop}|^2 = |\mathcal{M}_{\rm tree}|^2 + 2\,{\rm Re}(\mathcal{M}^*_{\rm tree}\mathcal{M}_{\rm loop})$$

- asymmetry in production cross section of non-diagonal chargino pairs induced by radiative corrections

$$A_{12} = \frac{\sigma^{\rm loop}(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) - \sigma^{\rm loop}(e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_1^-)}{\sigma^{\rm tree}(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_2^-) + \sigma^{\rm tree}(e^+e^- \to \tilde{\chi}_2^+\tilde{\chi}_1^-)}$$

- asymmetry vanishes at the tree level $\Rightarrow$ it is finite at one loop
- soft and hard QED corrections cancel in the numerator
- A_{12} can be sensitive to the phases of μ, A_t, M_1, A_b, A_τ

Chosen parameters

- gaugino mass parametrs

$$|M_1| = 100 \text{ GeV}, \; M_2 = 200 \text{ GeV}, \; |\mu| = 400 \text{ GeV}, \; \tan\beta = 10$$

- sfermion parameters

$$m_{\tilde{q}} \equiv M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}} = 450 \text{ GeV}$$

$$M_{\tilde{Q}} \equiv M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = 300 \text{ GeV}$$

$$m_{\tilde{l}} \equiv M_{\tilde{L}_{1,2,3}} = M_{\tilde{E}_{1,2,3}} = 150 \text{ GeV}$$

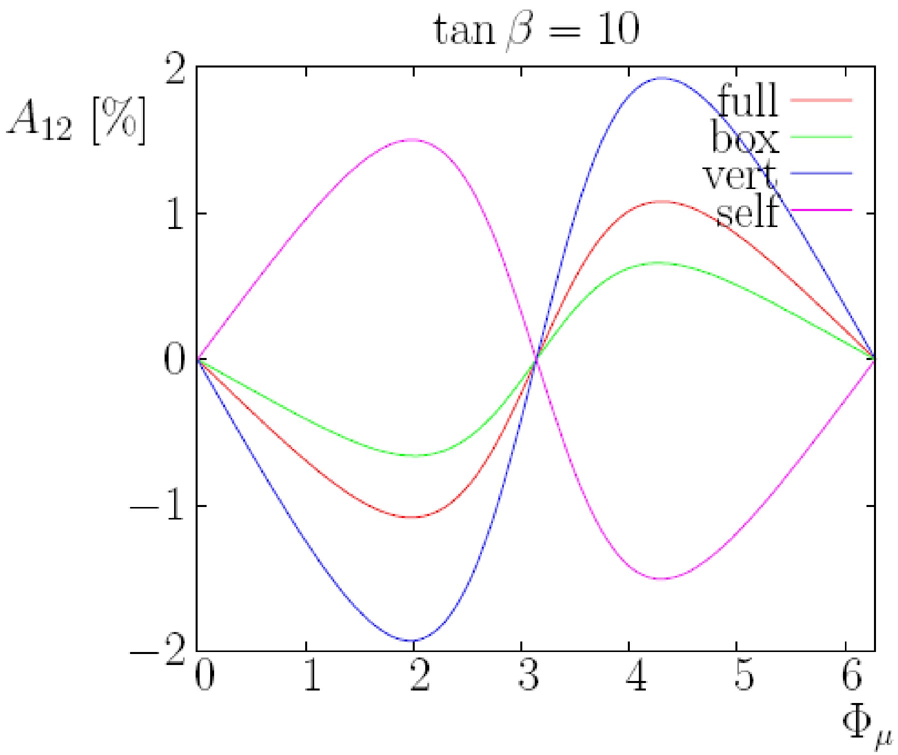
$$A \equiv |A_t| = -A_b = -A_\tau = 400 \text{ GeV}$$

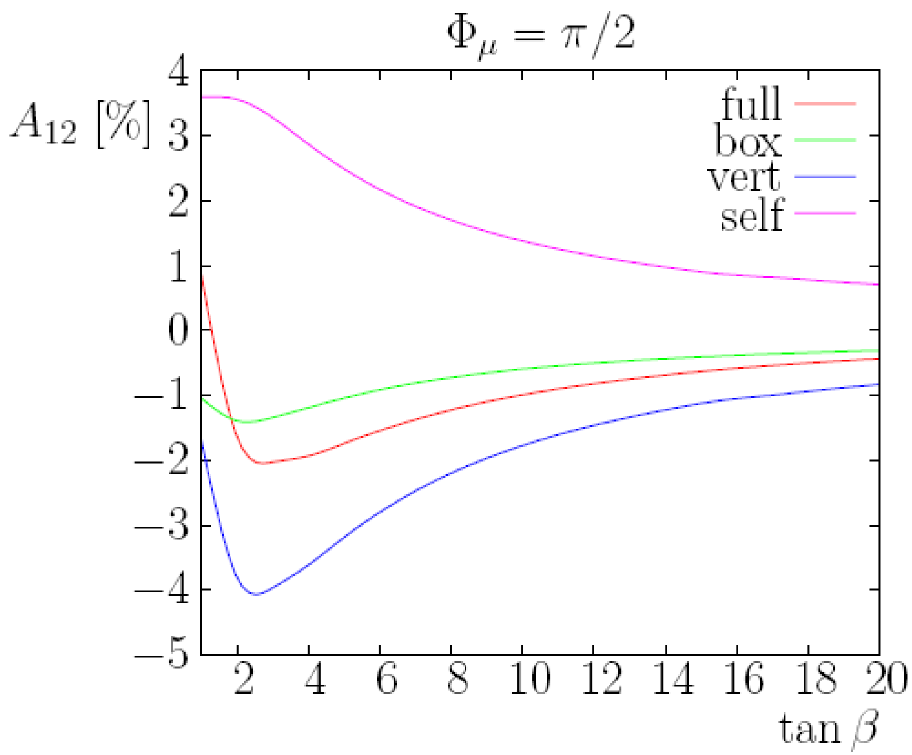
- resulting masses:

$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$
186.7	421.8	97.5	187.0	405.8	421.2	204.9	438.6

Asymmetry for Φ_μ

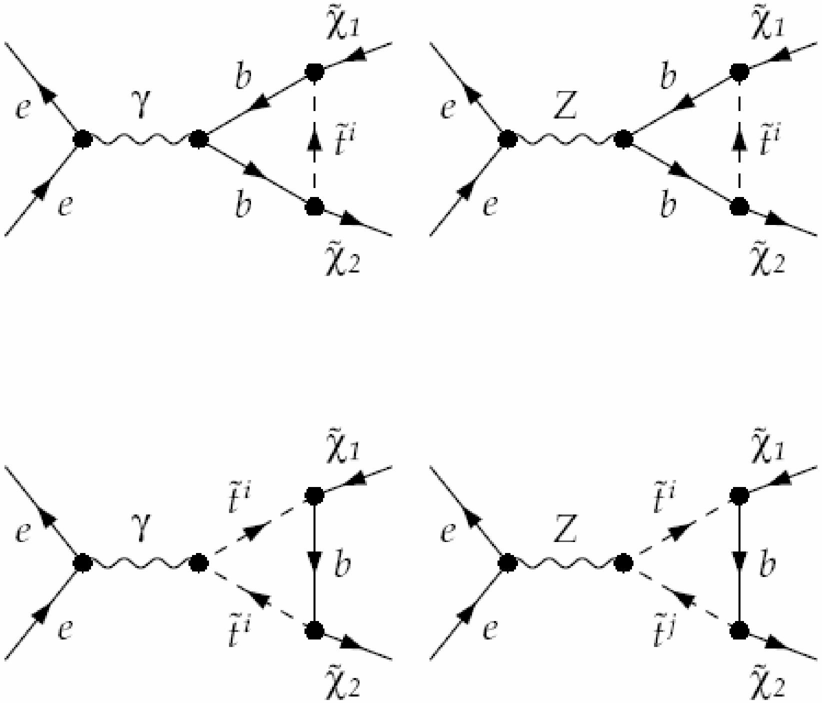
- dependence of asymmetry on the phase of μ parameter
- large cancelations between different contributions
- for low $\tan\beta$ small asymmetry due to small value of imaginary parts of couplings

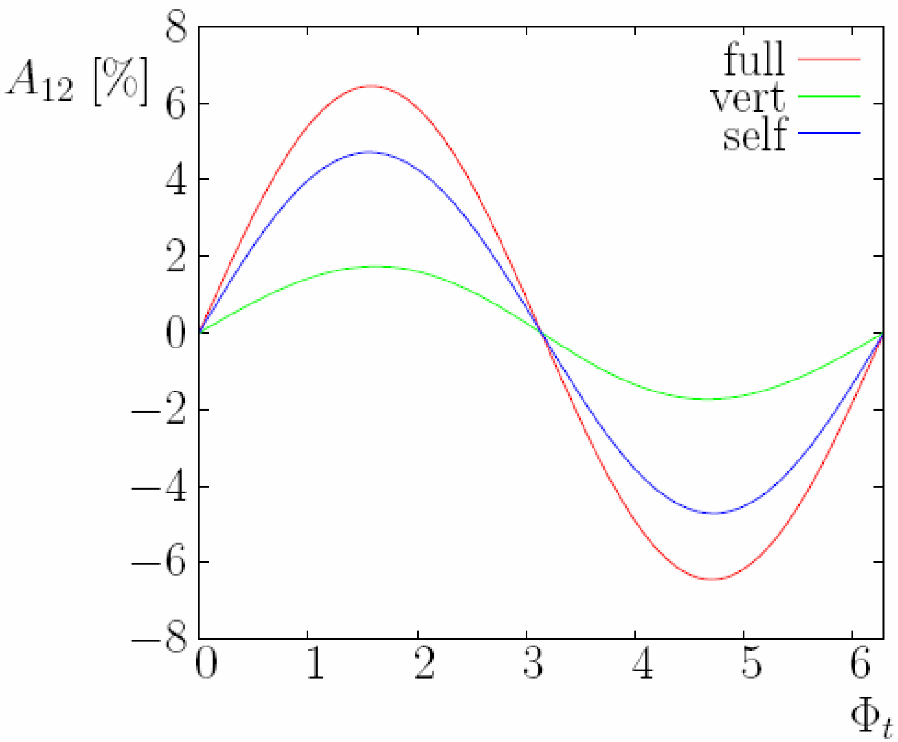




Asymmetry for A_t

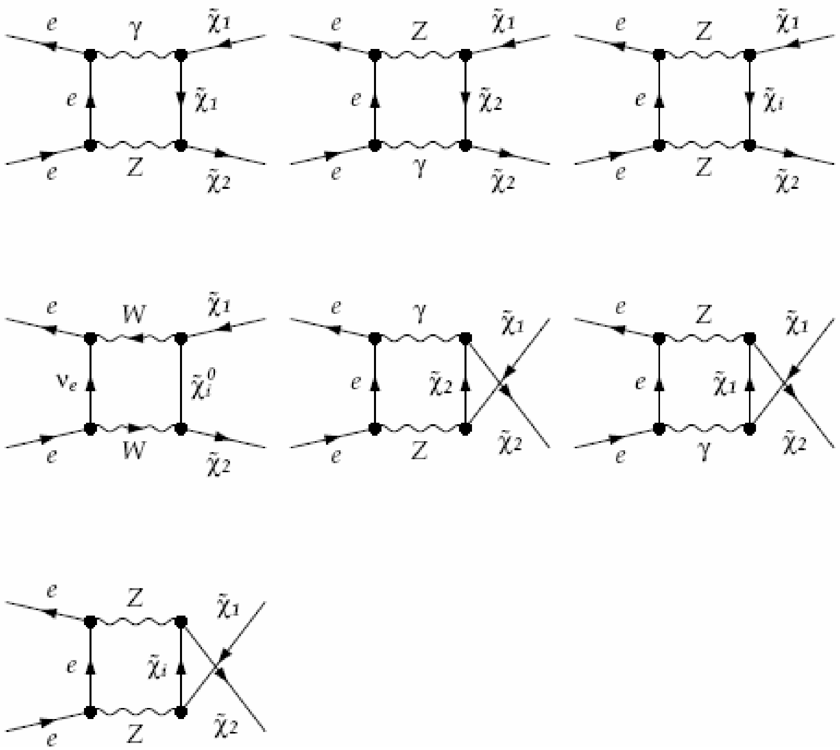
- only contributions from diagrams with stop exchange enter
- asymmetry can reach 6%
- gives access to CP violation in stop sector

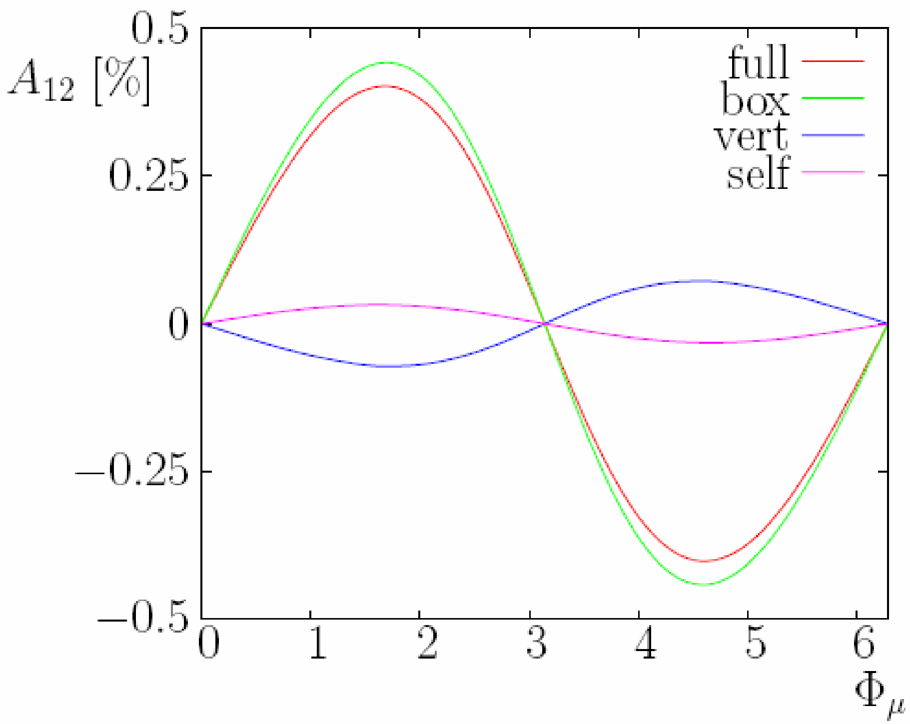




Case of heavy sfermions

- take heavy sfermions with masses 10 TeV - sfermion contributions can be neglected
- only gauge boson exchange contributes to asymmetry
- asymmetry significantly smaller $\sim$ 0.5%





Summary

- Susy - best scenario for physics beyond SM
- Charginos and neutralinos can be among light sparticles
- LHC –gross feature can be seen
- ILC – ideal place, in particular for studying CP violation
  - Neutralino sector
    - Unitarity quadrangles
    - Threshold behavior in production and decay
  - Chargino sector
    - CP asymmetry at one-loop

- Outlook: full analysis of production+decay beyond tree level required for precision physics.