# Resonant Higgs boson interference in chargino production at the Muon Collider

Olaf Kittel

University of Granada, Spain

in collaboration with: Federico von der Pahlen

Muon Collider Workshop, Fermilab, November 10-12, 2009

# Resonant Higgs boson interference in chargino production

- Introduction
  - Supersymmetry and the MSSM
  - Process: $\mu^+\mu^- \to A, H \to$ charginos, neutralinos
- Correlation of initial and final longitudinal polarizations
- Energy distributions and asymmetries of decay leptons
- Asymmetries of production cross section
- Summary and conclusions

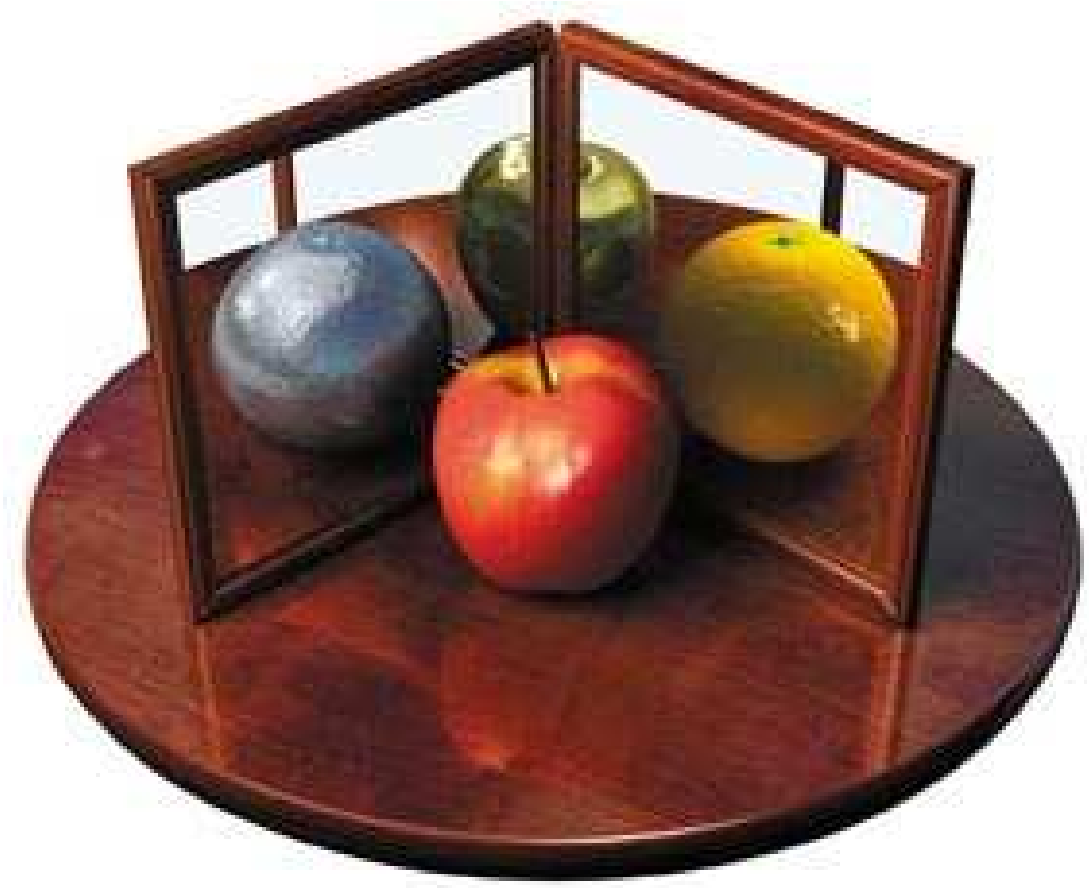
# Introduction: Supersymmetry (SUSY)

$$Q\,|\text{Fermion}\rangle \;\rightarrow\; |\text{Boson}\rangle$$
$$Q\,|\text{Boson}\rangle \;\rightarrow\; |\text{Fermion}\rangle$$

## Why SUSY?

- Solves hierarchy problem: light Higgs boson naturally obtained
- Provides most famous dark matter candidate:
  lightest neutralino (WIMP miracle: right mass + coupling)
- Unification of gauge couplings
- Window to gravity (local SUSY)

# Introduction: SUSY particle spectrum



$\Rightarrow$ Let's have a closer look at the SUSY particle spectrum

# Introduction: MSSM particle spectrum

Minimal supersymmetric extension of the Standard Model:

- For each Standard Model fermion there is a SUSY partner

$$\begin{array}{rcccl} \text{electron} & e\ (\mathrm{S}=\frac{1}{2}) & \longleftrightarrow & \tilde{e}\ (\mathrm{S}=0) & \text{selectron} \\ \text{neutrino} & \nu\ (\mathrm{S}=\frac{1}{2}) & \longleftrightarrow & \tilde{\nu}\ (\mathrm{S}=0) & \text{sneutrino} \\ \text{quark} & q\ (\mathrm{S}=\frac{1}{2}) & \longleftrightarrow & \tilde{q}\ (\mathrm{S}=0) & \text{squark} \end{array}$$

# Introduction: MSSM particle spectrum cont.

- Similarly for the Standard Model gauge bosons

| | | | | | | |
|---|---|---|---|---|---|---|
| $U(1)_Y$ | $B_\mu$ | (S = 1) | $\longleftrightarrow$ | $\tilde{B}$ | (S = $\frac{1}{2}$) | bino |
| $SU(2)_L$ | $W^3_\mu,\, W^\pm_\mu$ | (S = 1) | $\longleftrightarrow$ | $\tilde{W}^3,\, \tilde{W}^\pm$ | (S = $\frac{1}{2}$) | wino |
| $SU(3)_C$ | $\mathcal{G}_\mu$ | (S = 1) | $\longleftrightarrow$ | $\tilde{g}$ | (S = $\frac{1}{2}$) | gluino |
| Higgs | $H_1,\, H_2$ | (S = 0) | $\longleftrightarrow$ | $\tilde{H}_1,\, \tilde{H}_2$ | (S = $\frac{1}{2}$) | higgsino |

# Introduction: charginos

charginos $\tilde{\chi}_i^{\pm}$: mixture of charged winos $\tilde{W}^{\pm}$ and higgsinos $\tilde{H}^{\pm}$.

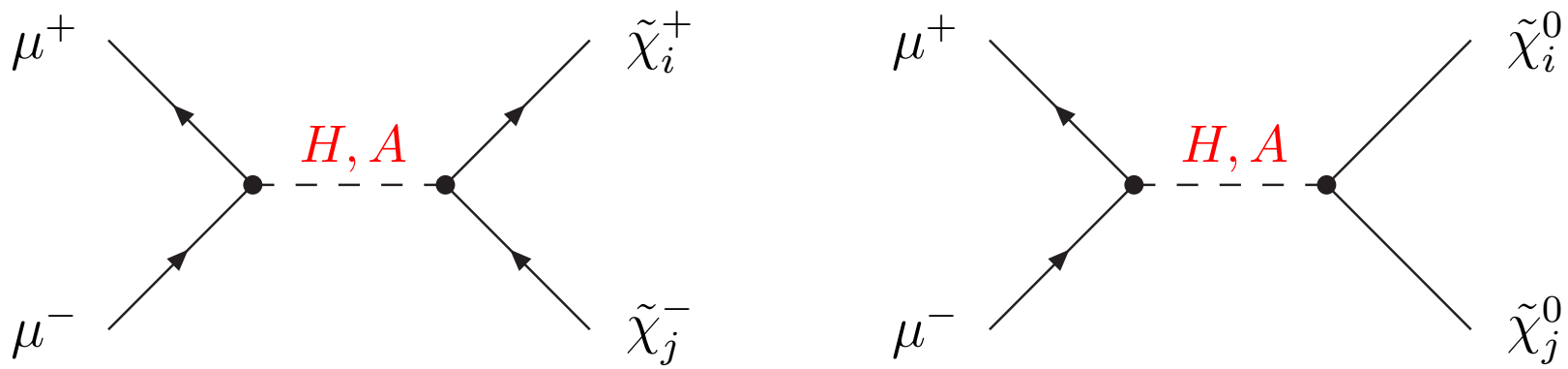
$$\mathcal{M}_{\pm} = \begin{pmatrix} M_2 & \sqrt{2} M_W \sin(\beta) \\ \sqrt{2} M_W \cos(\beta) & \mu \end{pmatrix}$$

parameters:

- $M_2$: wino mass, soft SUSY breaking parameter
- $\mu$: Higgs mixing parameter
- $\tan\beta$: ratio of VEVs 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

# Process: Higgs exchange




$$\mathcal{L}_{\tilde{\chi}\tilde{\chi}\phi} = g\bar{\tilde{\chi}}_i\,(c_{ij}^{\phi}P_R + c_{ji}^{\phi\,*}P_L)\tilde{\chi}_j\phi, \quad \phi = H, A$$

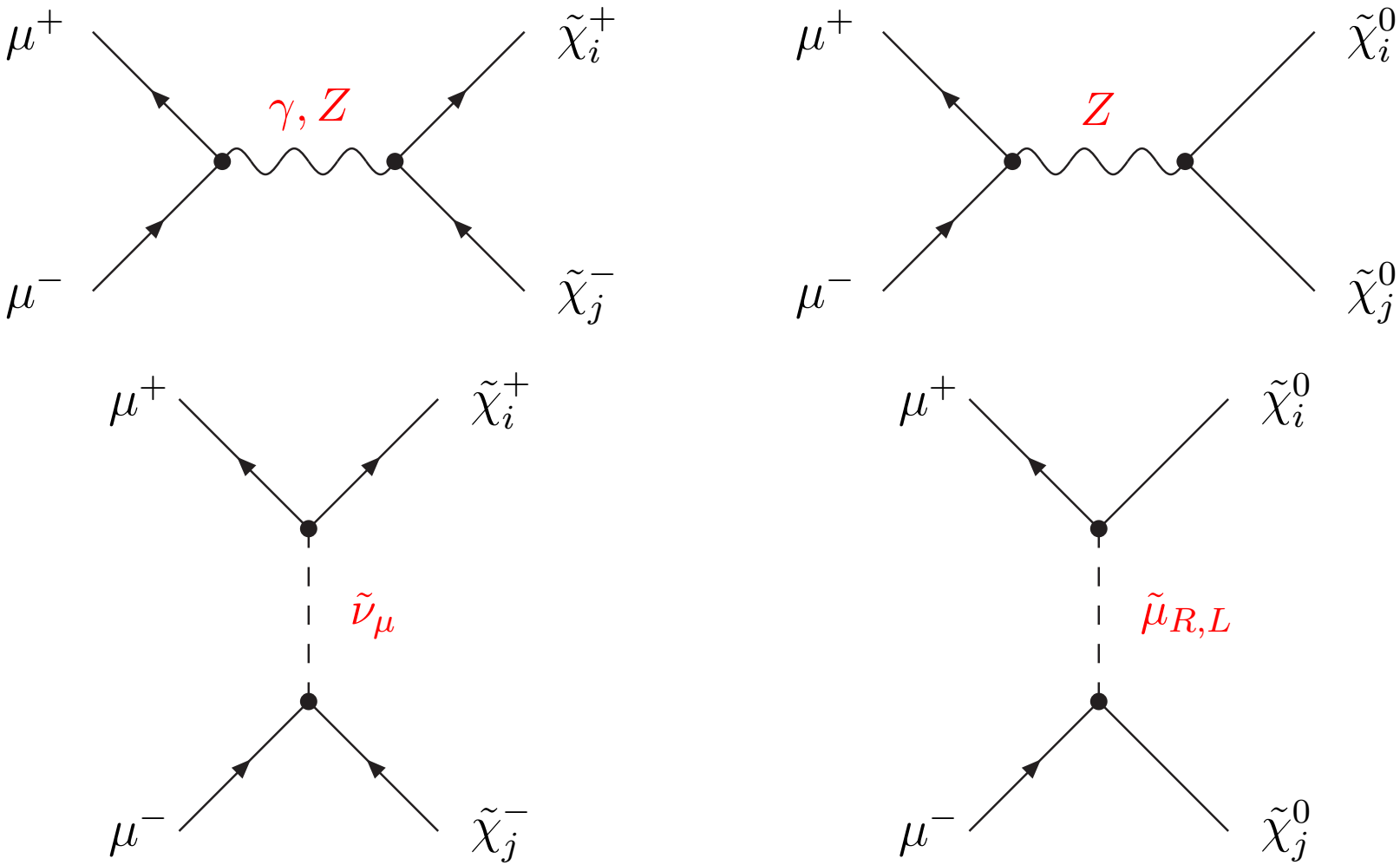
$$\mathcal{L}_{\mu\mu\phi} = g c^{\phi\mu}\bar{\mu}\,\Gamma^{(\phi)}\mu\phi, \quad \Gamma^{(H)} = 1,\ \Gamma^{(A)} = i\gamma^5$$

$c^{\phi\mu} \propto \frac{m_\mu}{m_W}\tan\beta \ll 1$

At $\sqrt{s} \approx m_\phi$: Breit-Wigner enhancement $\Rightarrow c^{\phi\mu}\frac{m_\phi}{\Gamma_\phi} \sim \mathcal{O}(1)$

For $5 \lesssim \tan\beta \lesssim 15$ large BR into charginos/neutralinos

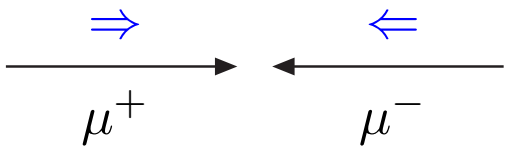
# Process: continuum




continuum can be well studied at $e^+e^-$ colliders!
(assuming unification of the first two slepton families)

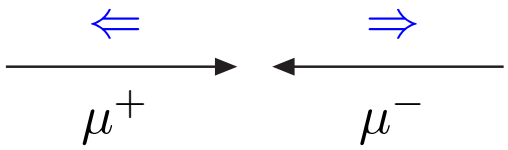
# Polarization dependence: initial muons

**Higgs exchange:** $J = 0,\ L_z = 0 \Rightarrow S_z = J_z = 0$




$|RR\rangle$

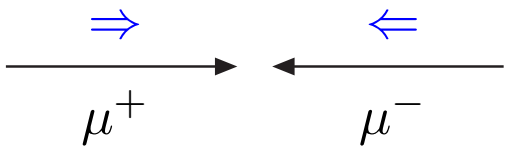
chirality violating couplings




$|LL\rangle$

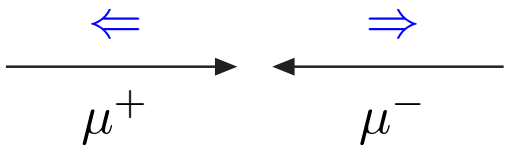
# Polarization dependence: initial muons

**Higgs exchange:** $J = 0,\ L_z = 0 \Rightarrow S_z = J_z = 0$




$|RR\rangle$

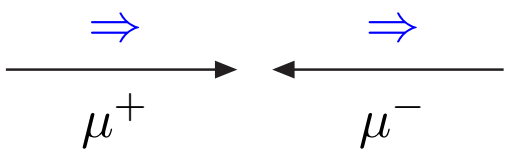
chirality violating couplings




$|LL\rangle$

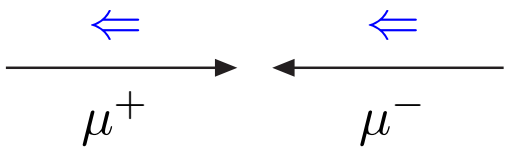
Higgs–continuum interference negligible

**Continuum:** $S_z = \pm 1$




$|RL\rangle$

chirality conserving couplings




$|LR\rangle$

# Two-fermion systems: CP properties

For a dirac $f\bar{f}$ pair

$$CP = (-1)^{S+2L+1}$$

Spin $S$ and $CP$ quantum numbers are related

$$CP \leftrightarrow S = |\vec{S}_f + \vec{S}_{f'}|$$

$$|S, S_z\rangle = |1, 0\rangle = \frac{1}{\sqrt{2}}\left[|RR\rangle + |LL\rangle\right]_{(\mu^+\mu^-)} \qquad (|CP+\rangle)$$

$$|S, S_z\rangle = |0, 0\rangle = \frac{1}{\sqrt{2}}\left[|RR\rangle - |LL\rangle\right]_{(\mu^+\mu^-)} \qquad (-i|CP-\rangle)$$

# Two-fermion systems: CP properties

For a dirac $f\bar{f}$ pair

$$CP = (-1)^{S+2L+1}$$

Spin $S$ and $CP$ quantum numbers are related

$$CP \leftrightarrow S = |\vec{S}_f + \vec{S}_{f'}|$$

$$|S, S_z\rangle = |1, 0\rangle = \frac{1}{\sqrt{2}}\left[|RR\rangle + |LL\rangle\right]_{(\mu^+\mu^-)} \qquad (|CP+\rangle)$$

$$|S, S_z\rangle = |0, 0\rangle = \frac{1}{\sqrt{2}}\left[|RR\rangle - |LL\rangle\right]_{(\mu^+\mu^-)} \qquad (-i|CP-\rangle)$$

$\Rightarrow$ Initial $\mu^+\mu^-$ pol. states couple to both H ($CP+$) and A ($CP-$)

$$|RR\rangle = \frac{1}{\sqrt{2}}\left[|CP+\rangle - i|CP-\rangle\right]$$

$$|LL\rangle = \frac{1}{\sqrt{2}}\left[|CP+\rangle + i|CP-\rangle\right]$$

# Two-fermion systems: initial-final spin correlations

Longitudinal beam polarizations:

$|RR\rangle_{(\mu^+\mu^-)}$ & $|LL\rangle_{(\mu^+\mu^-)}$ interact with the Higgs bosons ($S_z = 0$):

$$
\begin{aligned}
|RR\rangle_{(\mu^+\mu^-)} &= \frac{1}{\sqrt{2}}\big[|CP+\rangle - i|CP-\rangle\big]_{(\mu^+\mu^-)} \\
&\to \big[a|CP+\rangle - ib|CP-\rangle\big]_{(\mathrm{Higgs})} \\
&\to \big[\alpha|CP+\rangle - i\beta|CP-\rangle\big]_{(\chi\chi)} \\
&= \frac{1}{\sqrt{2}}\big[(\alpha+\beta)|RR\rangle + (\alpha-\beta)|LL\rangle\big]_{(\chi\chi)}
\end{aligned}
$$

# Two-fermion systems: initial-final spin correlations

Longitudinal beam polarizations:

$|RR\rangle_{(\mu^+\mu^-)}$ & $|LL\rangle_{(\mu^+\mu^-)}$ interact with the Higgs bosons ($S_z = 0$):

$$
\begin{aligned}
|RR\rangle_{(\mu^+\mu^-)} &= \tfrac{1}{\sqrt{2}}\big[|CP+\rangle - i|CP-\rangle\big]_{(\mu^+\mu^-)} \\
&\to \big[a|CP+\rangle - ib|CP-\rangle\big]_{(\mathrm{Higgs})} \\
&\to \big[\alpha|CP+\rangle - i\beta|CP-\rangle\big]_{(\chi\chi)} \\
&= \tfrac{1}{\sqrt{2}}\big[(\alpha+\beta)|RR\rangle + (\alpha-\beta)|LL\rangle\big]_{(\chi\chi)}
\end{aligned}
$$

$\Rightarrow$ $\tilde{\chi}\tilde{\chi}$ longitudinal polarizations ($\sim \mathrm{Re}\{\alpha\beta^*\}$) depend on

- beam polarizations
- relative sign of $H$ and $A$ couplings (here $\alpha$ and $\beta$)

**interference of Higgs bosons with different CP parities**

# Two-fermion systems: initial-final spin correlations

How to determine the polarizations of the initial and final fermions?

Analyze their decays!

- muons: decay angle $\rightarrow$ beam parameters
- charginos (and also neutralinos): need parity violating decays
  longitudinal polarization $\leftrightarrow$ energy distrib. of decay products

ideally 2-body decays with maximal $P$ violation

$$\tilde{\chi}_i^{\pm} \rightarrow \ell^{\pm} + \tilde{\nu}_{\ell}, \quad \ell = e, \mu, \tau$$

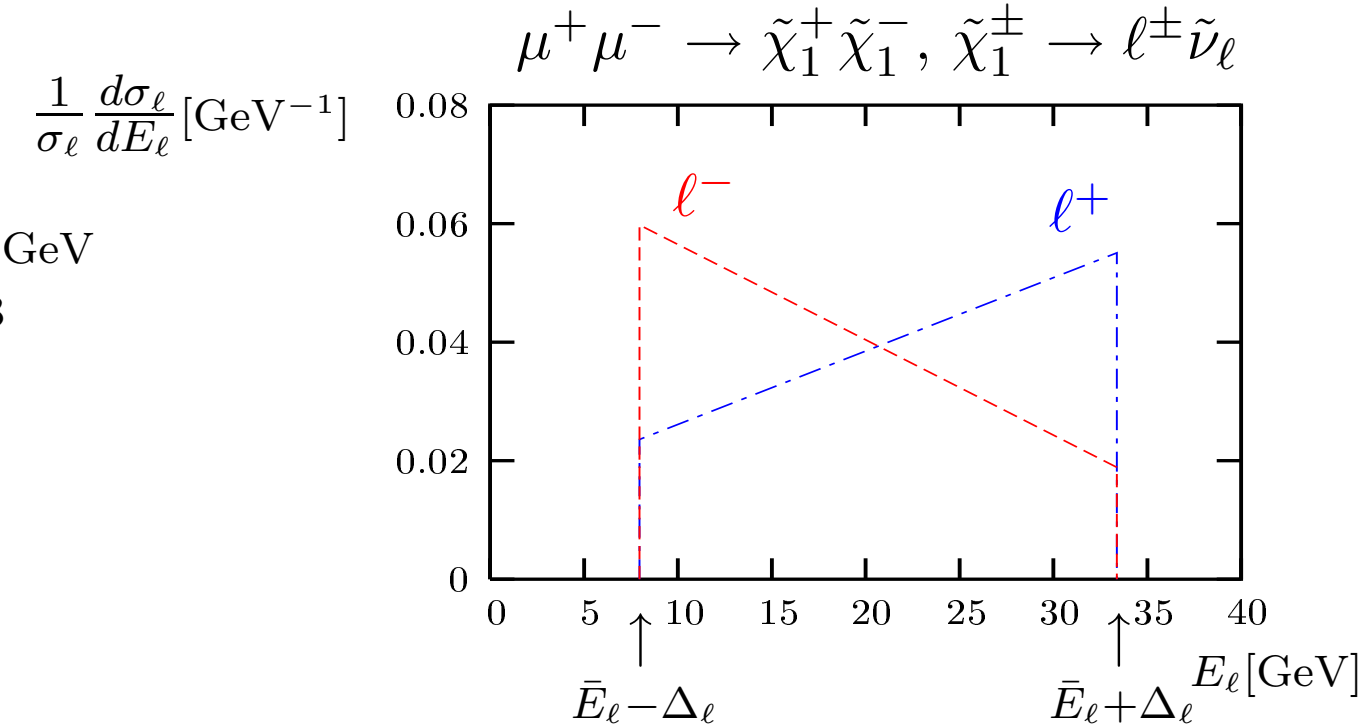
similar for neutralinos, e.g.,

$$\tilde{\chi}_i^{0} \rightarrow \ell^{\pm} + \tilde{\ell}_{L,R}^{\mp}.$$

# Chargino production and decay: lepton energy distribution

$$\frac{d\sigma_{\ell^\pm}}{dE_\ell} = \frac{\sigma_\ell}{2\Delta_\ell}\left[1 + \eta_{\ell^\pm}\mathcal{P}_\chi \frac{(E_\ell - \bar{E}_\ell)}{\Delta_\ell}\right], \quad \ell = e, \mu; \quad \eta_{\ell^\pm} = \pm 1$$

$\sqrt{s}=m_A=500$ GeV
$\mathcal{P}^L_-=\mathcal{P}^L_+=-0.3$
$\tan\beta=10$
$\mu=-500$ GeV
$M_2=200$ GeV
$m_0=70$ GeV




average longitudinal chargino polarization: $\mathcal{P}_\chi$ [OK,Pahlen,05]

# Energy distribution asymmetries ($\tilde{\chi}^{\pm}$)

Energy distribution asymmetry $\leftrightarrow$ average chargino polarization $\mathcal{P}_\chi$

$$\mathcal{A}_{\ell^\pm} = \frac{\sigma_{\ell^\pm}(E_\ell > \bar{E}_\ell) - \sigma_{\ell^\pm}(E_\ell < \bar{E}_\ell)}{\sigma_{\ell^\pm}(E_\ell > \bar{E}_\ell) + \sigma_{\ell^\pm}(E_\ell < \bar{E}_\ell)} = \frac{1}{2}\eta_{\ell^\pm}\mathcal{P}_\chi$$

$$\mathcal{P}_\chi \;=\; \mathcal{P}_\chi^{HA} \;+\; \mathcal{P}_\chi^{\rm cont}$$

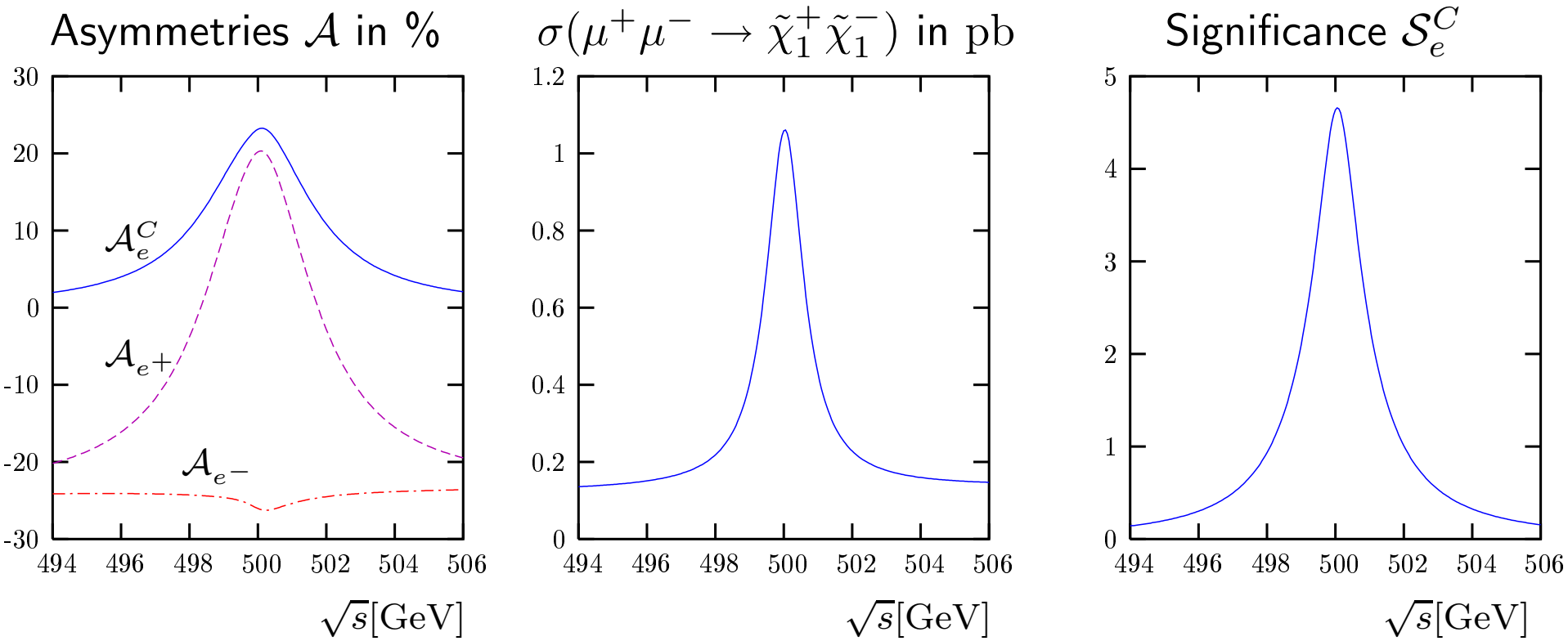
Charge asymmetry (equal charginos), to eliminate continuum

$$\mathcal{A}_\ell^C = \frac{1}{2}[\mathcal{A}_{\ell^+} - \mathcal{A}_{\ell^-}] = \frac{1}{2}\eta_{\ell^+}\mathcal{P}_\chi^{HA}$$

$\mathcal{P}_\chi^{HA}$: function of Higgs couplings and line-shape parameters
sensitive to relative signs

(can also construct polarization asymmetry to eliminate continuum)

# Energy distribution asymmetries ($\tilde{\chi}^{\pm}$)




$\tan\beta$=10, $\mu$=−500 GeV, $M_2$=200 GeV, $m_0$=70 GeV

$\mathcal{P}_-^L=\mathcal{P}_+^L=-0.3$, $\mathcal{L}_{\rm eff}$=1 fb$^{-1}$

$$\mathcal{S}_e^C=|\mathcal{A}_e^C|\sqrt{2\,\sigma(\mu^+\mu^-\to\tilde{\chi}_i^-\tilde{\chi}_j^+)\mathrm{BR}(\tilde{\chi}_j^+\to e^+\tilde{\nu}_e)\mathcal{L}_{\rm eff}}$$

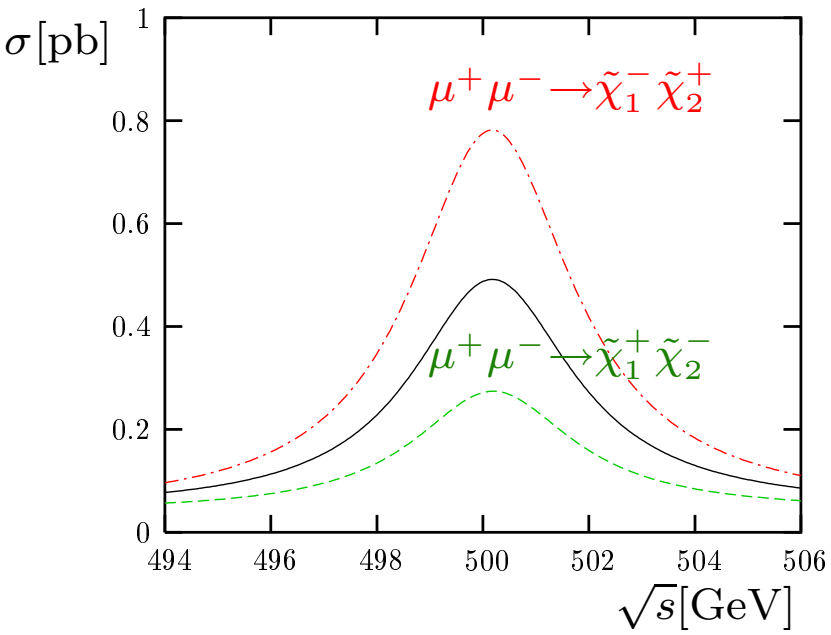
[OK,Pahlen,05]

# Charge symmetries for the cross section in $\tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$ production

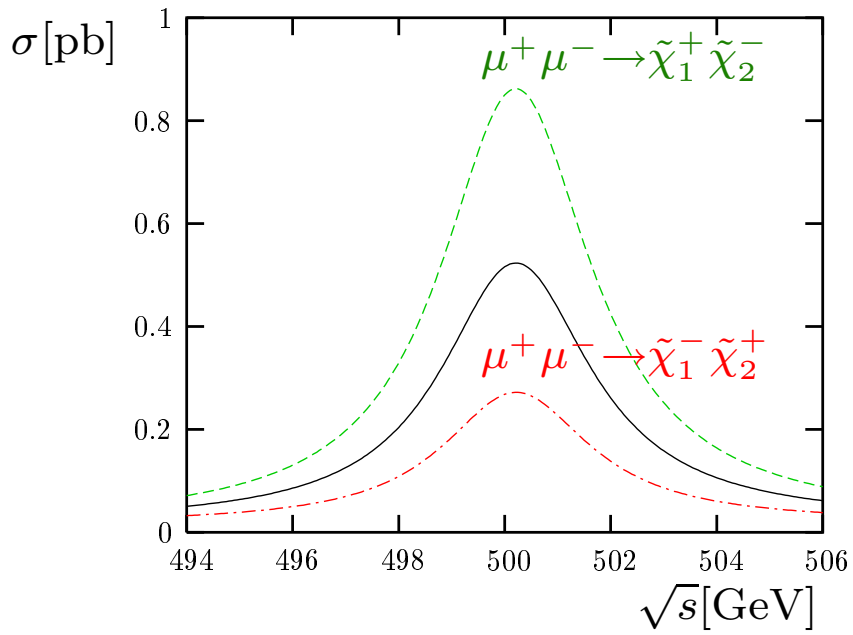
H-A interference in production cross section: [OK,Pahlen,05]

$$\mathcal{A}^C_{\rm prod} = \frac{\sigma(\tilde{\chi}_1^+\tilde{\chi}_2^-) - \sigma(\tilde{\chi}_1^-\tilde{\chi}_2^+)}{\sigma(\tilde{\chi}_1^+\tilde{\chi}_2^-) + \sigma(\tilde{\chi}_1^-\tilde{\chi}_2^+)} \propto \frac{\mathcal{P}_+ + \mathcal{P}_-}{1 + \mathcal{P}_+\mathcal{P}_-}$$

$\tilde{\chi}_1^\pm$ gaugino, $\mathcal{A}^C_{\rm prod} = -48\%$




$\tilde{\chi}_1^\pm$ higgsino, $\mathcal{A}^C_{\rm prod} = +45\%$




$\mathcal{P}_\pm = -0.3$, $M_A = 500$ GeV, $\tan\beta = 10$, $\{\mu, M_2\}/\text{GeV} = \{-250, 150\}, \{-110, 300\}$

# Summary and conclusions

- Muon Collider:
  - ideal to test Higgs-chargino interaction [OK,Pahlen 05]
  - also Higgs-neutralino [Fraas,Pahlen,Sachse 04]
- unique interference of CP-even and CP-odd Higgs bosons:
  - correlation of initial and final longitudinal polarizations
  - decay asymmetries to probe chargino polarizations
  - production asymmetries of the cross section
  - probe Higgs-chargino couplings, and their relative sign: test the Higgs-SUSY sector!
- Numerical results:
  - asymmetries are proportional to beam polarizations: $(\mathcal{P}_{\mu^+} + \mathcal{P}_{\mu^-})/(1 + \mathcal{P}_{\mu^+}\mathcal{P}_{\mu^-})$
  - maximal asymmetries
    production: 50%, decay: 25%, for $\mathcal{P}_\mu = 0.3$

# Production of equal charginos: beam energy spread

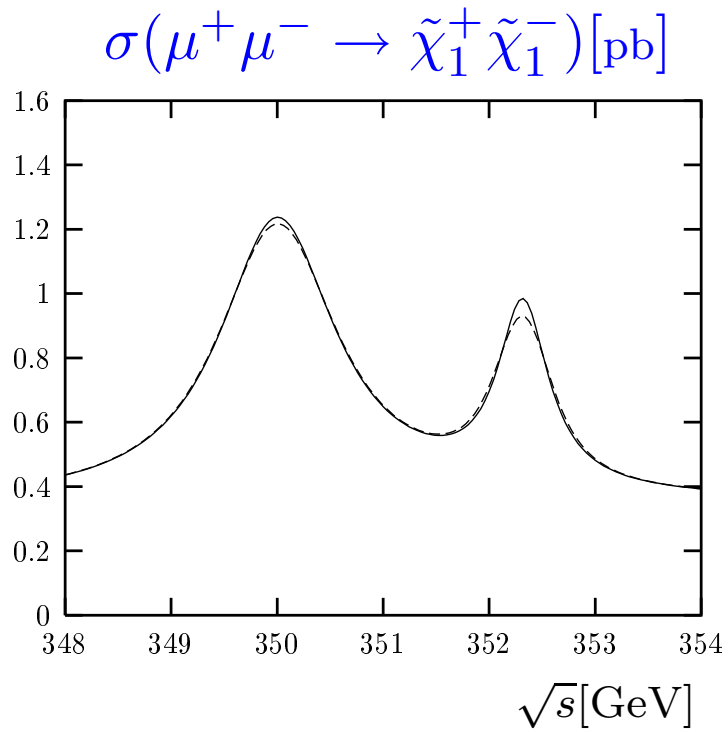
$M_A$=350 GeV

$\mu$=$M_2$, $m_{\chi_1^\pm}$=155 GeV

$\tan\beta$=5

Beam energy resolution

$R$=0.06 % (dashed)



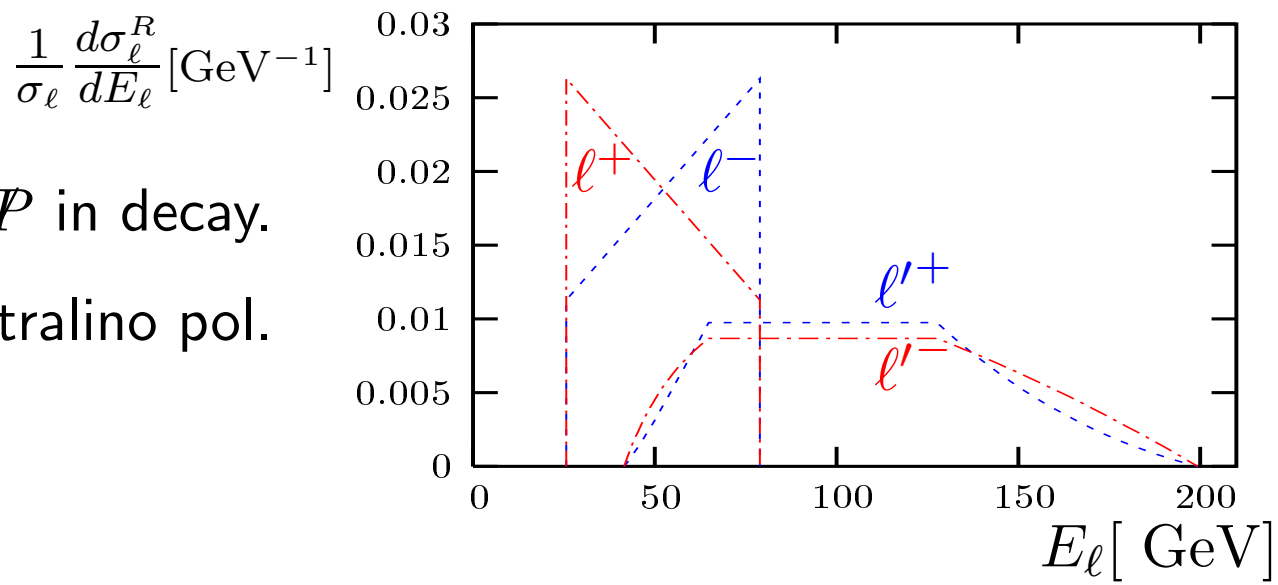

$\Rightarrow$ Estimate continuum from $\sigma^{ii}$ above and below the resonances

If resonances can be separated, determination of $|c^{(\phi\mu)}||c_{ii}^{(\phi)}|$

# Neutralino production and decay: lepton energy distribution

$$\frac{d\sigma_{\ell^\pm}}{dE_\ell} = \frac{\sigma_\ell}{2\Delta_\ell}\left[1 + \eta^n_{\ell^\pm}\mathcal{P}_\chi \frac{(E_\ell - \bar{E}_\ell)}{\Delta_\ell}\right], \qquad \ell = e, \mu$$

$\tilde{\chi}^0_i \to \ell\tilde{\ell}_R, \quad \tilde{\ell}_R \to \ell'\tilde{\chi}^0$




$\eta^n_{\ell^\pm}$: measure of $\not{P}$ in decay.

$\mathcal{P}_\chi$ : average neutralino pol.

[Fraas,FP,Sachse 04]

# Energy distribution asymmetries ($\tilde{\chi}^0$)

Energy distribution asymmetry

$$\mathcal{A}^n_{\lambda^\pm} = \frac{\sigma_{\lambda^\pm}(E_\lambda > \bar{E}_\lambda) - \sigma_{\lambda^\pm}(E_\lambda < \bar{E}_\lambda)}{\sigma_{\lambda^\pm}(E_\lambda > \bar{E}_\lambda) + \sigma_{\lambda^\pm}(E_\lambda < \bar{E}_\lambda)} = \frac{1}{2}\eta^n_{\lambda^\pm}\mathcal{P}_\chi$$

Majorana character of neutralinos:

$\Rightarrow$ continuum contribution to polarization vanishes

# Energy distribution asymmetries ($\tilde{\chi}^0$)

Energy distribution asymmetry

$$\mathcal{A}^n_{\lambda^\pm} = \frac{\sigma_{\lambda^\pm}(E_\lambda > \bar{E}_\lambda) - \sigma_{\lambda^\pm}(E_\lambda < \bar{E}_\lambda)}{\sigma_{\lambda^\pm}(E_\lambda > \bar{E}_\lambda) + \sigma_{\lambda^\pm}(E_\lambda < \bar{E}_\lambda)} = \frac{1}{2}\eta^n_{\lambda^\pm}\mathcal{P}_\chi$$

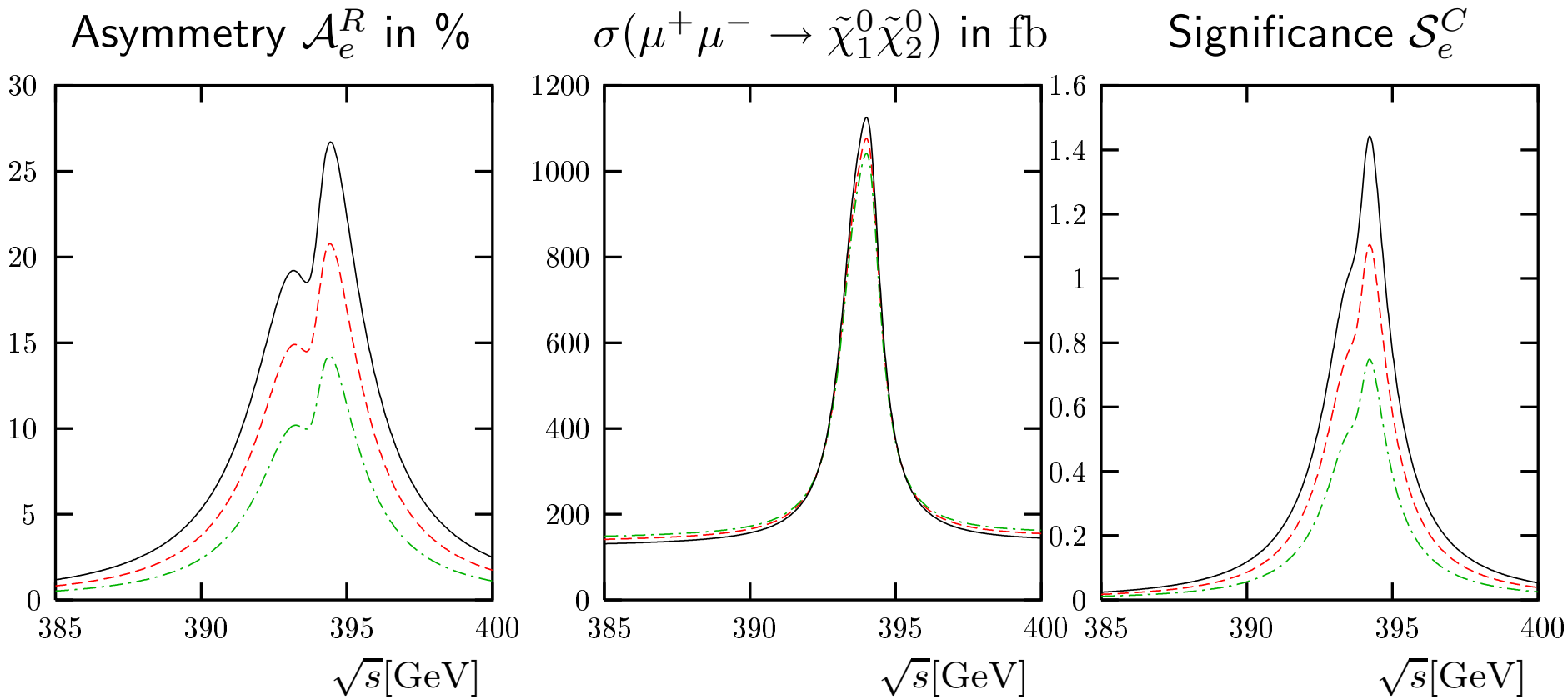
Majorana character of neutralinos:
$\Rightarrow$ continuum contribution to polarization vanishes

Charge distribution asymmetry

$$\mathcal{A}^{nC}_\lambda = \frac{1}{2}[\mathcal{A}^n_{\lambda^+} - \mathcal{A}^n_{\lambda^-}] = \frac{1}{2}\eta^n_{\lambda^+}\mathcal{P}_\chi$$

Formally $\mathcal{A}^{nC}_\lambda = \mathcal{A}^n_{\lambda^+}$
background from secondary leptons is reduced

# Energy distribution asymmetries ($\tilde{\chi}^0$)




Longitudinal beam polarization $\mathcal{P}_+ = \mathcal{P}_- = -0.4, -0.3, -0.2$

Luminosity $\mathcal{L}_{\rm eff} = 1\ {\rm fb}^{-1}$

SPS1a: $\tan\beta = 10,\ \mu = 352.4\ {\rm GeV},\ {\rm M}_2 = 192.7\ {\rm GeV},\ {\rm m}_0 = 100\ {\rm GeV}$

[Fraas,FP,Sachse 04]