Interference of Higgs bosons in neutralino/chargino production at the muon collider

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Outline

- Introduction
- Correlation of initial and final longitudinal polarizations
- H–A interference in chargino and neutralino pair production
- Summary and conclusions

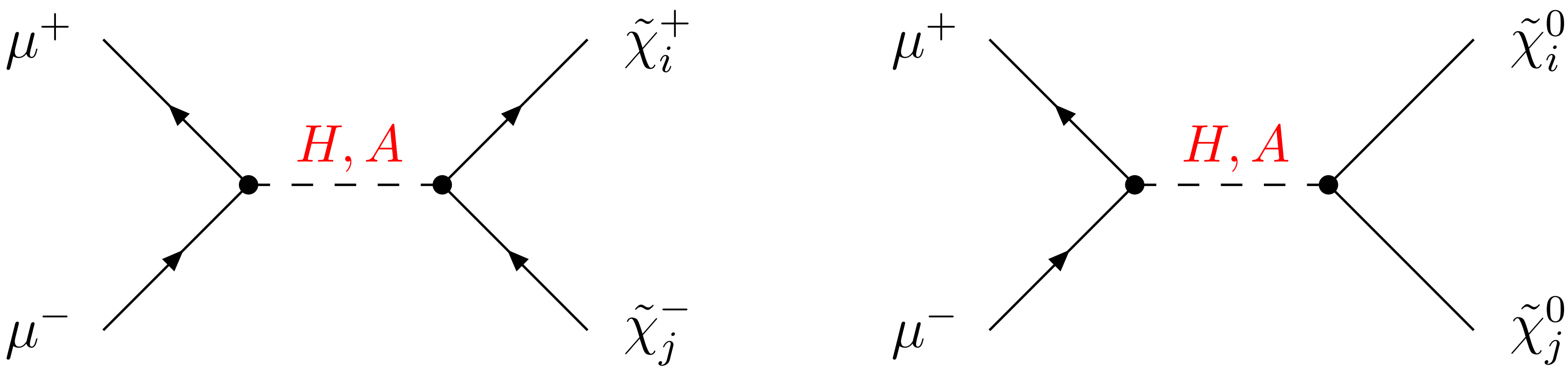
Why do we need a $\mu^+\mu^-$ collider at $\sqrt{s} \approx m_\phi$?

- Higgs bosons are produced in s-channel $\Rightarrow$ Higgs factory
- Precise knowledge of the beam parameters
- Lepton colliders are precision machines

Why chargino and neutralino production?

- Large branching ratios of H and A into charginos and neutralinos (e.g. for intermediate $\tan\beta$)
- Test Higgs-chargino/neutralino interaction!

Production channels: Higgs exchange (MSSM)



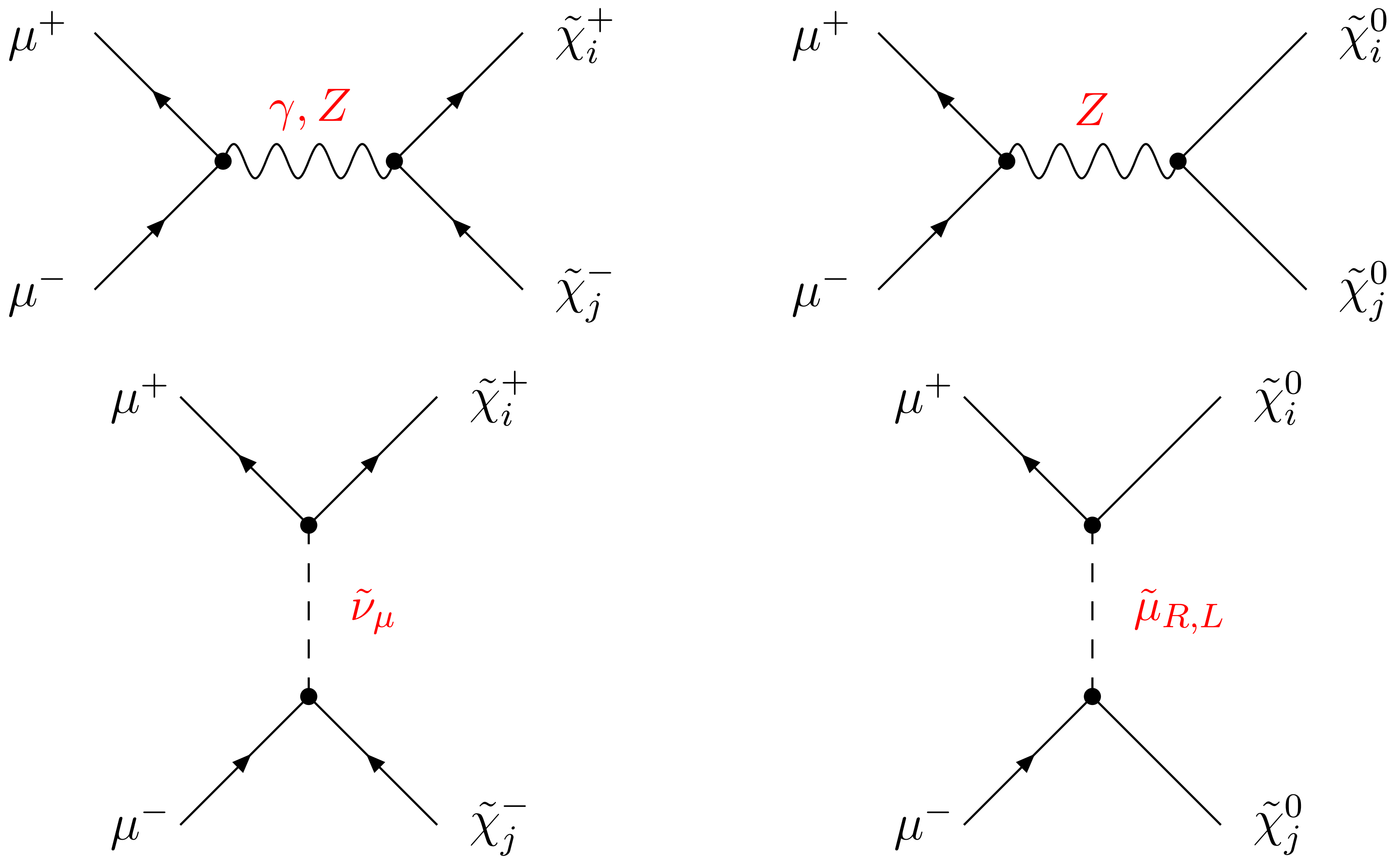
$$\begin{aligned} \mathcal{L}_{\tilde{\chi}\tilde{\chi}\phi} &= g\bar{\tilde{\chi}}_i\,(c_{ij}^{\phi} P_R + c_{ji}^{\phi\,*} P_L)\tilde{\chi}_j\phi, \quad \phi = H, A \\ \mathcal{L}_{\mu\mu\phi} &= g c^{\phi\mu}\bar{\mu}\,\Gamma^{(\phi)}\mu\phi, \quad \Gamma^{(H)} = 1,\ \Gamma^{(A)} = i\gamma^5 \end{aligned}$$

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

However at $\sqrt{s} \approx m_\phi$: Breit-Wigner enhancement $\Rightarrow$

$c^{\phi\mu}\frac{m_\phi}{\Gamma_\phi} \sim \mathcal{O}(1)$

Production channels: continuum



continuum well studied at e^+e^- colliders

(assuming unification of the first two slepton families)

CP properties of a two-fermion system

Dirac $f\bar{f}$ pair:

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

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Longitudinal beam polarizations:

Initial states $|S, S_z\rangle = |0,0\rangle, |1,0\rangle$ interact with the Higgs bosons:

$|0,0\rangle = \frac{1}{\sqrt{2}}[|++\rangle - |--\rangle]$ $(CP$-odd $A)$

$|1,0\rangle = \frac{1}{\sqrt{2}}[|++\rangle + |--\rangle]$ $(CP$-even $H)$

equal longitudinal beam polarizations $\Rightarrow$ no state with definite CP

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Chargino longitudinal polarizations:

Linear combination of CP-even and CP-odd chargino pair states

$\Rightarrow$ Depend on longitudinal beam polarizations
and the relative sign of H and A couplings to $\mu^{\pm}$ and $\tilde{\chi}^{\pm}$

Correlation between

beam and chargino longitudinal polarizations:

sensitive to relative phases of Higgs couplings

Due to the interference of Higgs bosons with different CP phases

CP properties of a two-fermion system

Dirac $f\bar{f}$ pair:

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

Majorana $f_i f_j$ pair:

$$CP = \eta_i \eta_j (-1)^{S+2L+1}, \quad |\eta_i|, |\eta_j| = 1$$

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beam $\leftrightarrow$ chargino/neutralino longitudinal polarizations
$\Rightarrow$ interference of Higgs bosons with different CP phases

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$\Rightarrow$ interference of Higgs bosons with different CP phases

chargino/neutralino longitudinal polarization: parity violating decays

$\Rightarrow$ ideally 2-body decays with maximal $\not{P}$

$$\tilde{\chi}_i^+ \to \ell^+ \tilde{\nu}_\ell, \quad \tilde{\chi}_i^0 \to \ell^+ \tilde{\ell}^-_{L,R}$$

Chargino production and decay

$$\mu^+\mu^- \to \tilde{\chi}_i^{\pm}\tilde{\chi}_j^{\mp}, \qquad \tilde{\chi}_i^{\pm} \to \ell^{\pm}\tilde{\nu}_\ell^{(*)}, \quad (\tilde{\chi}_i^{\pm} \to W^{\pm}\tilde{\chi}_k^0)$$

Energy distribution of decay lepton $\ell = e, \mu, \tau$:

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

$\eta_{\ell^\pm} = \pm 1$: measure of $\not{P}$ in decay

$\mathcal{P}_\chi$: average chargino longitudinal polarization

$E_\ell^{\max/\min} = \bar{E}_\ell \pm \Delta_\ell$: kinematical end points

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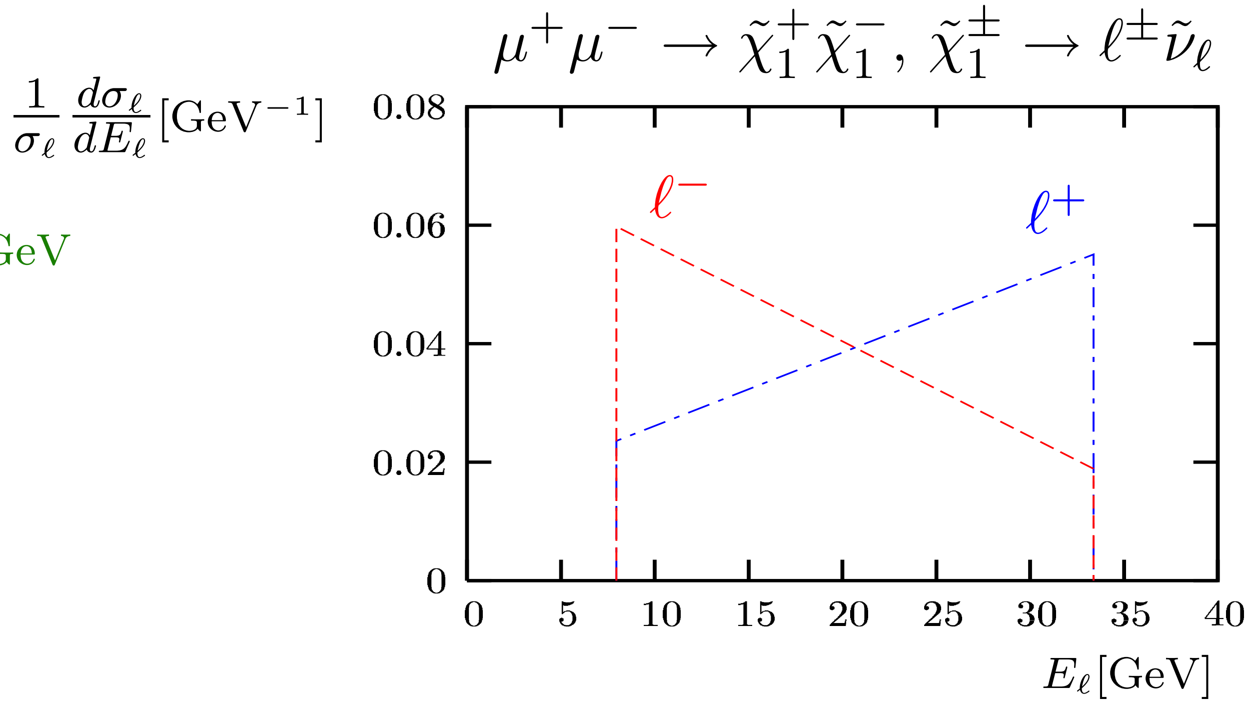


$\sqrt{s}=m_A=500$ GeV
$\mathcal{P}_-^L=\mathcal{P}_+^L=-0.3$
$\tan\beta=10$
$\mu=-500$ GeV
$M_2=200$ GeV
$m_0=70$ GeV

Energy distribution asymmetries

Energy distribution asymmetry $\leftrightarrow$ average chargino polarization

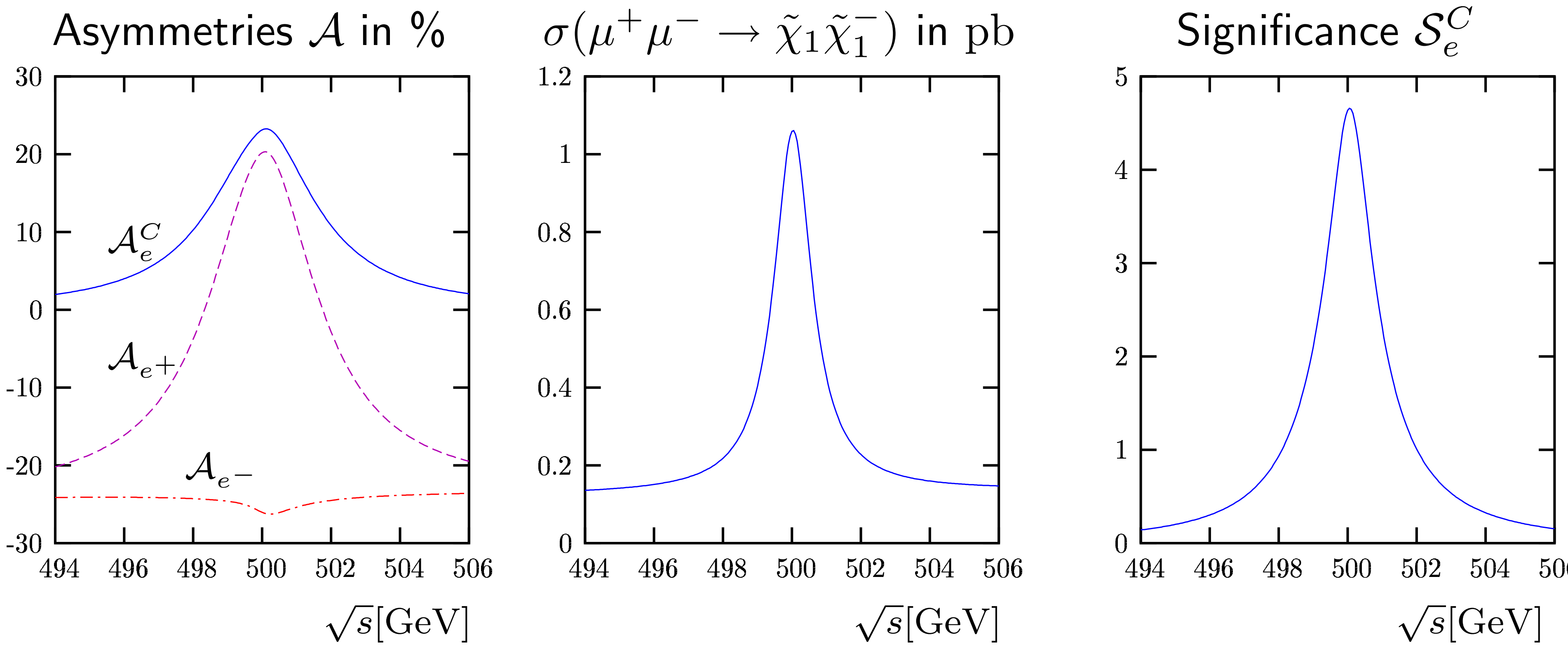
$$\mathcal{A}_{\ell^\pm} = \frac{\sigma_{\ell^\pm}(E_\ell > \bar{E}_\ell) - \sigma_{\ell^\pm}(E_\ell < \bar{E}_\ell)}{\sigma_{\ell^\pm}(E_\ell > \bar{E}_\ell) + \sigma_{\ell^\pm}(E_\ell < \bar{E}_\ell)} = \frac{1}{2}\eta_{\ell^\pm}\mathcal{P}_\chi$$

Charge asymmetry (equal charginos)

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

$\mathcal{P}'_\chi$: continuum contribution to polarization cancels out

Sensitive to the relative phases of the Higgs couplings!



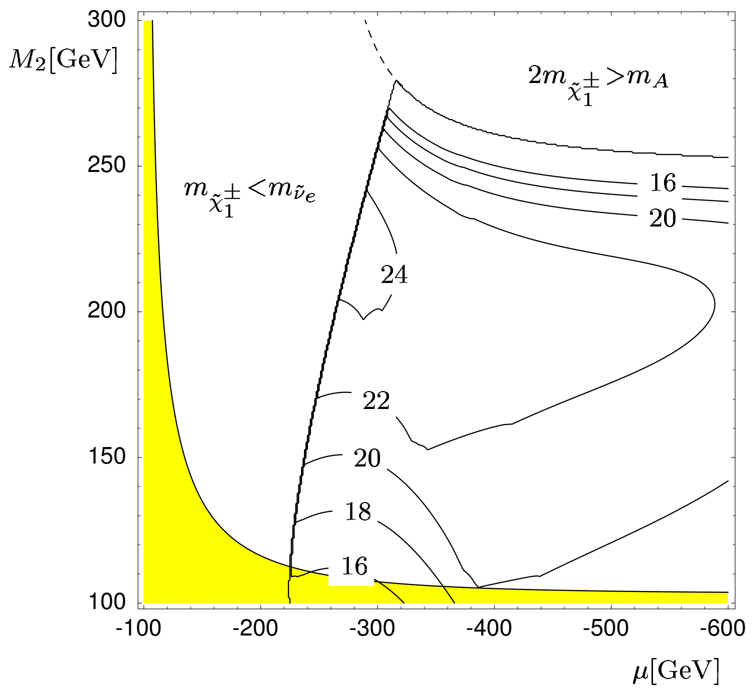
$\tan\beta=10,\ \mu=-500\ \text{GeV},\ \text{M}_2=200\ \text{GeV},\ \text{m}_0=70\ \text{GeV}$

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

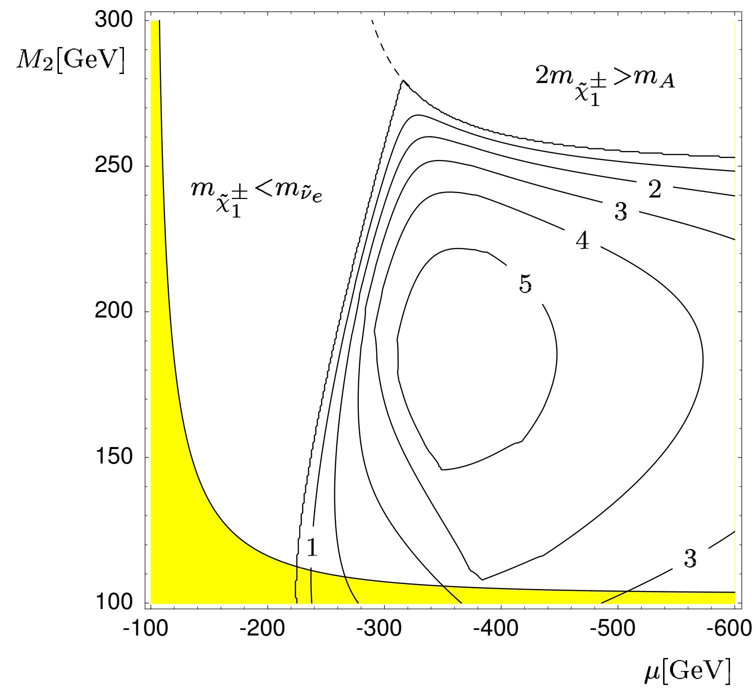
$$\mathcal{S}_e^C=|\mathcal{A}_e^C|\sqrt{2\,\sigma(\mu^+\mu^-\to\tilde{\chi}_i^-\tilde{\chi}_j^+)\text{BR}(\tilde{\chi}_j^+\to e^+\tilde{\nu}_e)\mathcal{L}_{\text{eff}}}$$

$\mu - M_2$ plane

Asymmetry $\mathcal{A}_e^C$ in %



Significance $\mathcal{S}_e^C$



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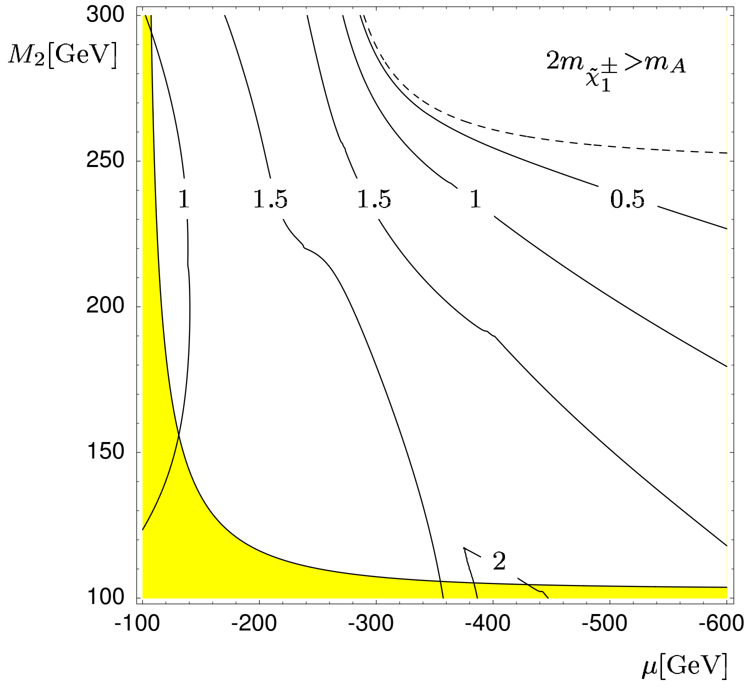
$\mathcal{P}_-^L = \mathcal{P}_+^L = -0.3,\ \mathcal{L}_{\text{eff}} = 1\ \text{fb}^{-1}$

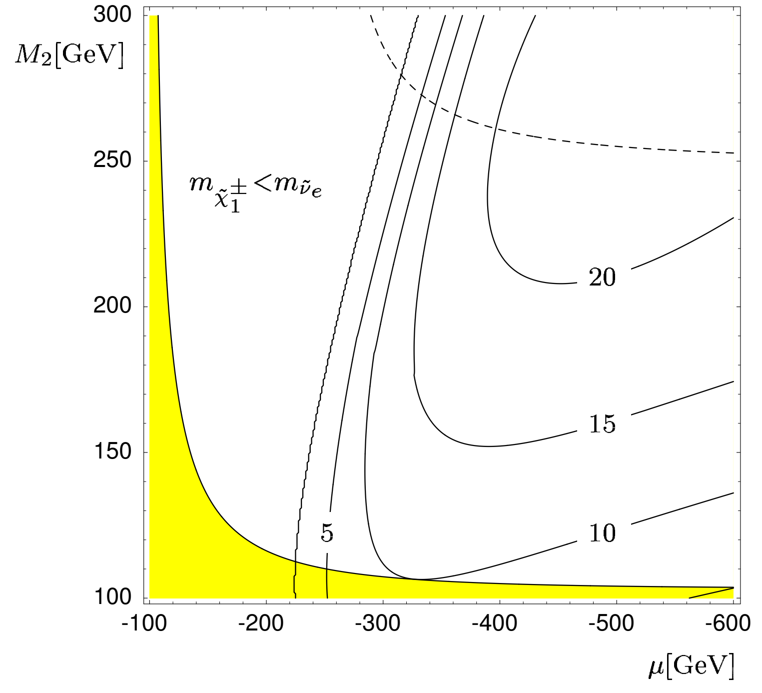
$$\mathcal{S}_e^C = |\mathcal{A}_e^C| \sqrt{2\,\sigma(\mu^+\mu^- \to \tilde{\chi}_i^- \tilde{\chi}_j^+)\text{BR}(\tilde{\chi}_j^+ \to e^+ \tilde{\nu}_e)\mathcal{L}_{\text{eff}}}$$

$\mu - M_2$ plane

$\sigma(\mu^+\mu^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ in pb



$\mathrm{BR}(\tilde{\chi}_1^+ \to e^+\tilde{\nu}_e)$ in %



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$\mathcal{P}_-^L = \mathcal{P}_+^L = -0.3$

Neutralino production and decay

$\mu^+\mu^- \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \qquad \tilde{\chi}_i^0 \to \ell^\pm\tilde{\ell}_{L,R}, \quad \ell = e, \mu, \qquad (\tilde{\chi}_i^0 \to \tau^\pm\tilde{\tau}_{1,2})$

Energy distribution of primary decay lepton $\ell = e, \mu$

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

$\eta^n_{\ell^\pm}$: measure of $\not{P}$ in decay. $\eta^R_{\ell^\pm} = -\eta^L_{\ell^\pm} = \pm 1$,

$\mathcal{P}_\chi$: average neutralino polarization

$E_\lambda^{\max/\min} = \bar{E}_\lambda \pm \Delta_\lambda$: kinematical end points

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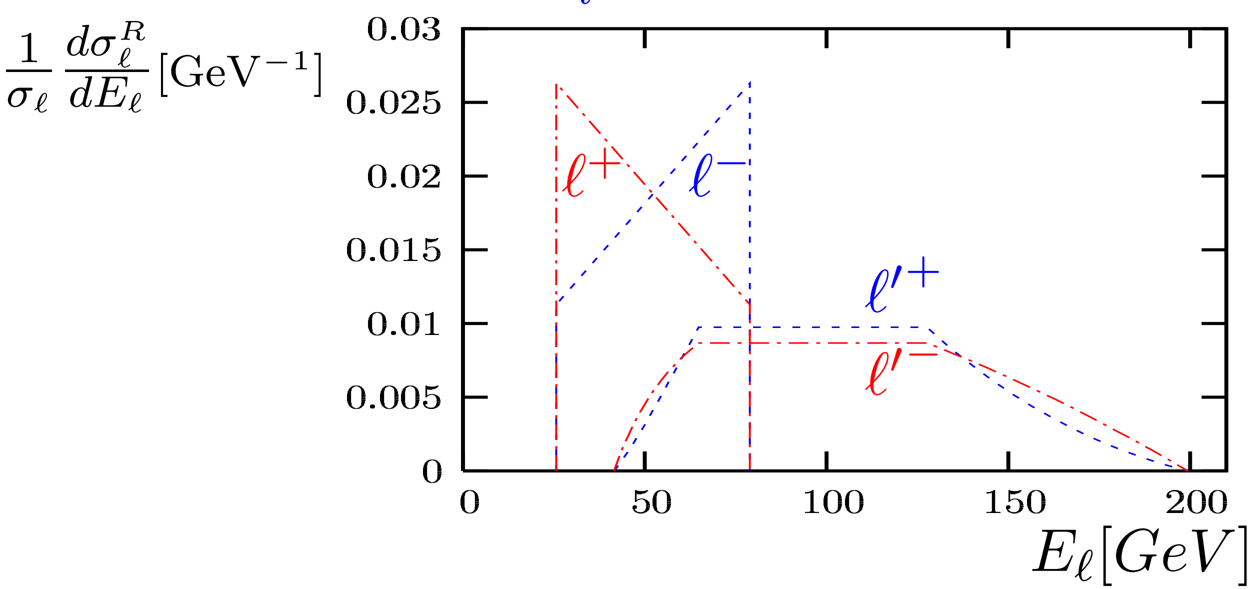
$\tilde{\chi}_i^0 \to \ell \tilde{\ell}_R, \quad \tilde{\ell}_R \to \ell' \tilde{\chi}^0$



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

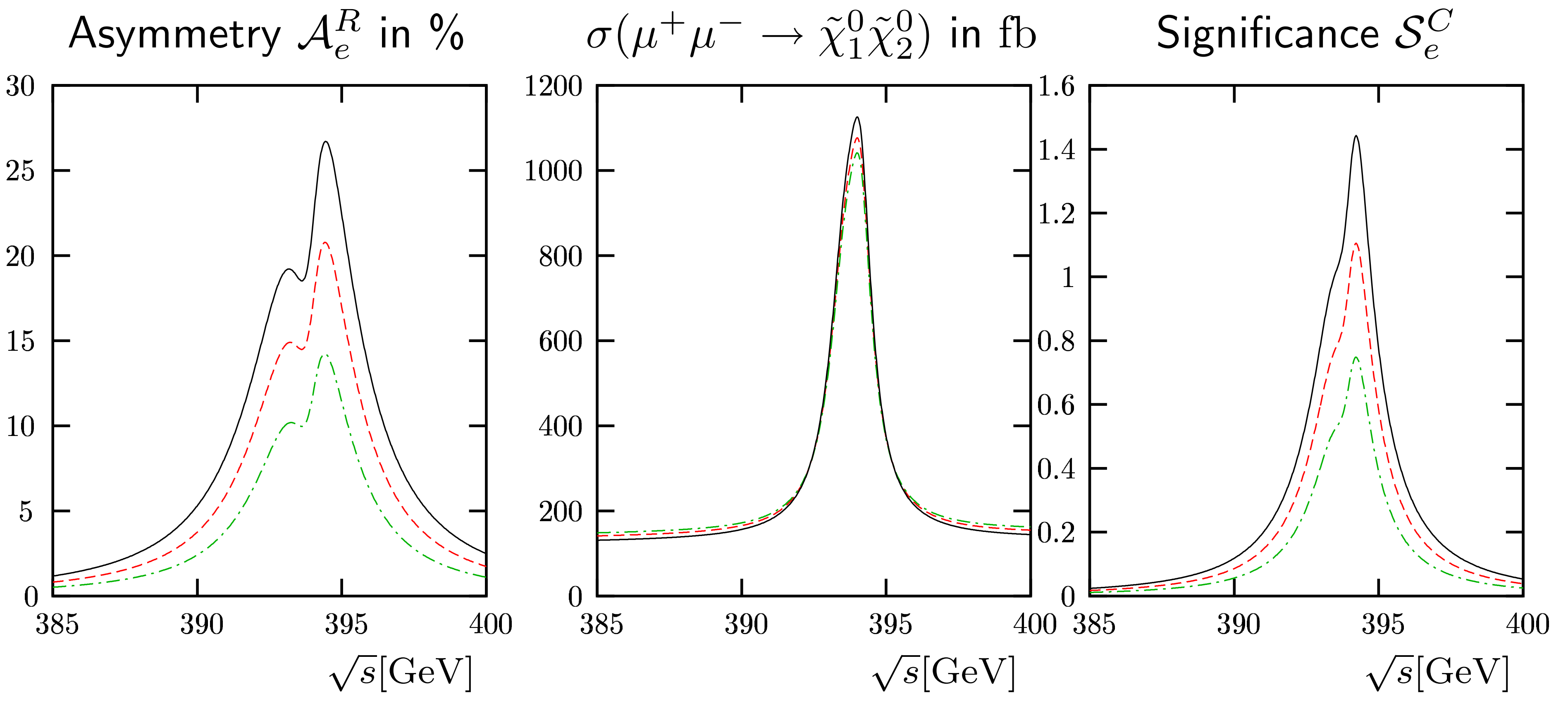
Charge distribution asymmetry

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

Formally $\mathcal{A}^{nC}_\lambda = \mathcal{A}^n_{\lambda^+}$

background from secondary leptons is reduced

Beam polarization dependence

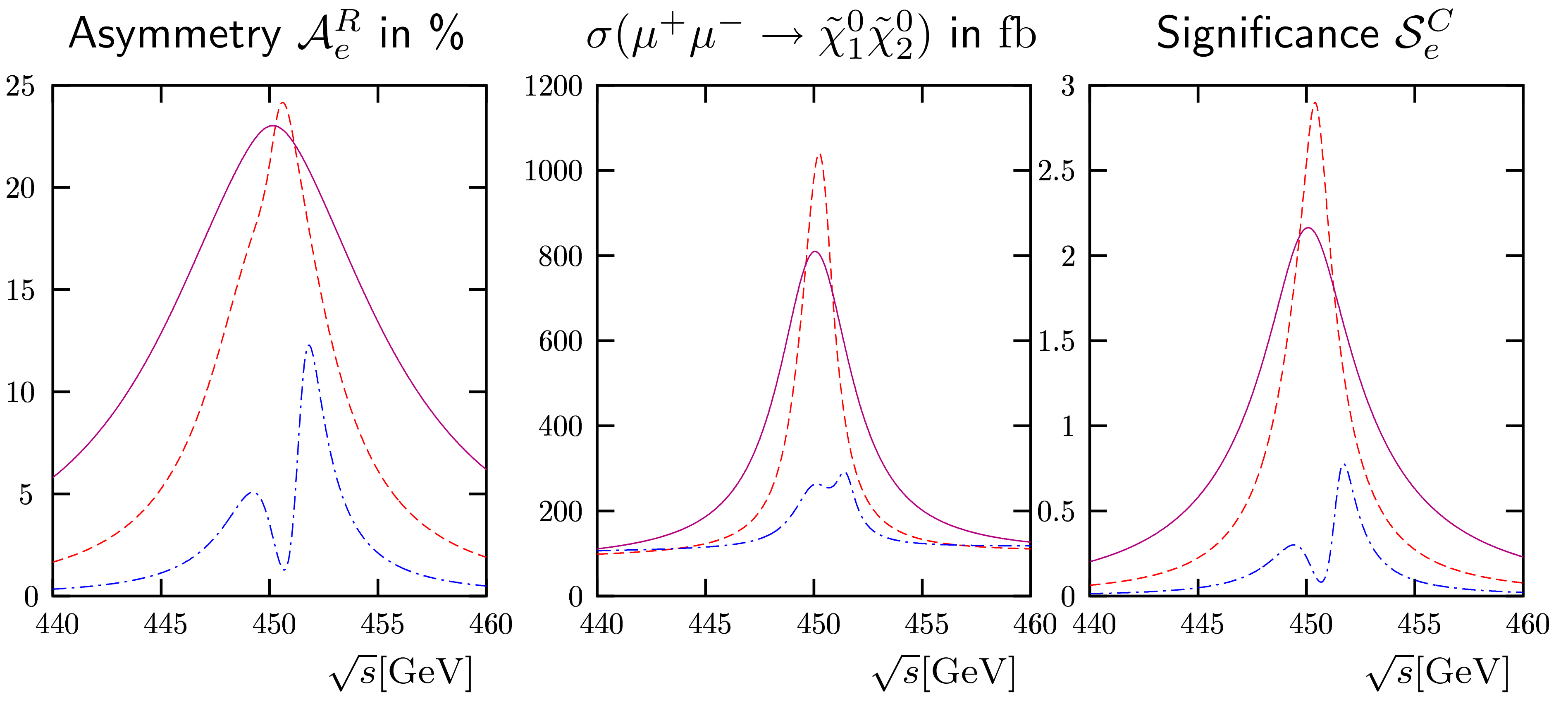


Longitudinal beam polarization $\mathcal{P}_+ = \mathcal{P}_- = -0.4, -0.3, -0.2$

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

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

$\tan\beta$ **dependence**



$\tan\beta = 5, 10, 20$

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

$\mathcal{L}_{\mathrm{eff}} = 1\ \mathrm{fb}^{-1},\ \mu = 250\ \mathrm{GeV},\ \mathrm{M}_2 = 280\ \mathrm{GeV},\ \mathrm{m}_0 = 100\ \mathrm{GeV}$

Summary and conclusions

- Interference of Higgs bosons with different CP phases in $\mu^+\mu^- \longrightarrow$ charginos, neutralinos

  $\Rightarrow$ determine relative sign of Higgs couplings to charginos/neutralinos and muons:
  correlation of initial and final longitudinal polarizations

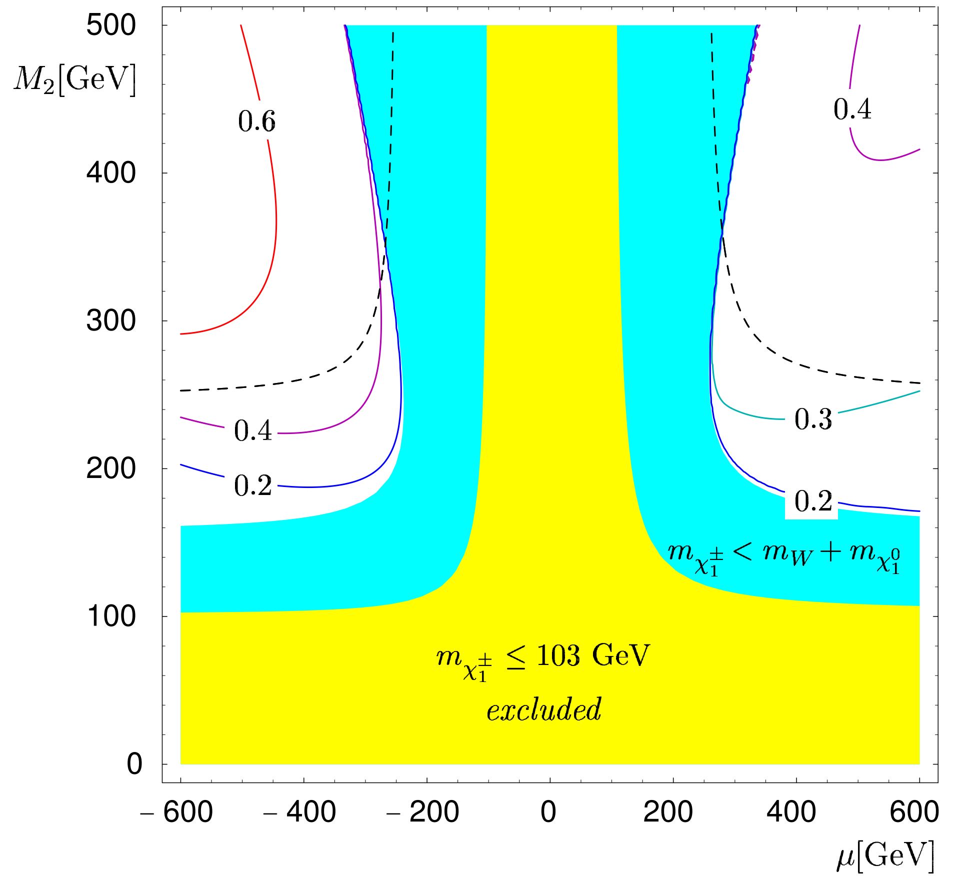
- Numerical results:

  need equal longitudinal beam polarizations

  expect large asymmetries and enough statistics

backup transparencies

Parity violation factor η_W for $\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}_1^0$



$\tan\beta$=10

m_A=500 GeV