Probing CP-violating MSSM Higgs mixing at the Muon Collider

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in collaboration with Herbi Dreiner and Olaf Kittel

based on JHEP 0808:030 & JHEP 0801:017

Muon Collider Workshop, Fermilab, 10-12 November 2009

- Introduction
  - Supersymmetry and the CP-violating MSSM
  - CP-violating Higgs sector: mixing and couplings
- Observables
  - Resonant process: $\mu^+\mu^- \to H_i \to$ charginos, neutralinos
  - Analysis of beam and chargino/neutralino polarization
  - CP asymmetries
- Summary and Outlook

Introduction: SUSY

Supersymmetry (SUSY)

Symmetry between Bosons $\leftrightarrow$ Fermions

$$\begin{aligned} Q|\mathrm{Fermion}\rangle &\rightarrow |\mathrm{Boson}\rangle \\ Q|\mathrm{Boson}\rangle &\rightarrow |\mathrm{Fermion}\rangle \end{aligned}$$

Same masses and gauge structure

Introduction: SUSY

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\end{aligned}
$$

Same masses and gauge structure

No light SUSY particles observed
$\Rightarrow$ SUSY must be broken!

Low-energy SUSY:
Breaking scale $M_{\mathrm{SUSY}} = \mathcal{O}(\mathrm{TeV})$
$\Rightarrow$ Next generation of colliders!

Introduction: CP-violating SUSY

- Solves hierarchy/naturalness problem
- Dark matter candidate
- Unification of gauge couplings
- Local SUSY leads to quantum gravity

- Complex parameters $\Rightarrow$ CP-violating phases

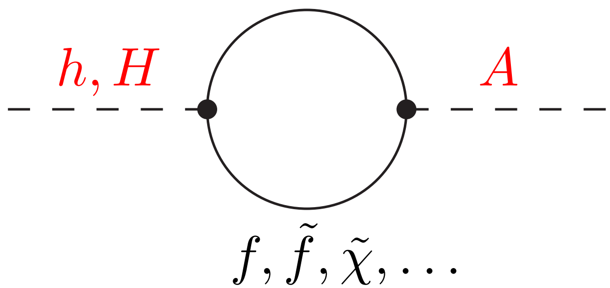
  Explain matter/anti-matter asymmetry of the Universe!
  Complex MSSM: A_f, μ, M_1, m_g, $\ldots$

  - Baryon asymmetry of the Universe (baryo/leptogenesis)
  - Change the relic density of neutralinos (dark matter)
  - Relax Higgs boson mass limits (allow for $m_H \approx 45\ \mathrm{GeV}$)
  - Parameters strongly constrained by EDM's

Introduction: CP-violating MSSM Higgs sector

– CP-conserving at tree level: $h, H, A, H^{\pm}$

– CP-violation from radiative corrections:



$h, H, A \rightarrow H_1, H_2, H_3$

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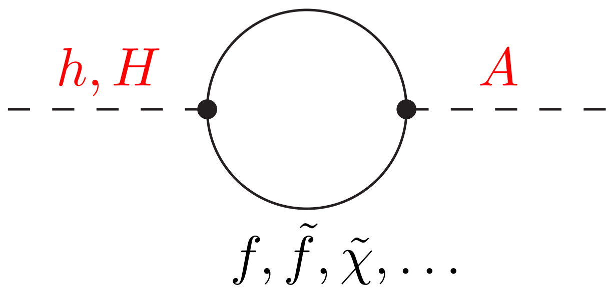


$h, H, A \rightarrow H_1, H_2, H_3$

Choose $A_t = A_b = A_\tau \equiv A_f$ complex

$\Rightarrow$ CP-conserving chargino/neutralino sector

$\Rightarrow$ Can fulfill EDM constraints

CP phases in Higgs sector $\Rightarrow$ need new CP-odd observables

Introduction: CP-violating MSSM Higgs sector

- $\mathbf{Q}_1$: How do we include these radiative corrections?
- $\mathbf{Q}_2$: When are they dominant?

– Higgs mass matrix and propagator

– Higgs mixing

– Resonant Higgs exchange process

Introduction: CP-violating MSSM Higgs sector

Higgs mass matrix:

$$\mathbf{M}(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

Complex self energies $\hat{\Sigma}_{ij}(p^2)$: imaginary part $\leftrightarrow$ absorptive phases

Higgs propagator matrix:

$$\Delta(p^2) = -i[p^2 - \mathbf{M}(p^2)]^{-1}$$

real part of complex poles $\longrightarrow$ Higgs boson on-shell masses

Introduction: CP-violating MSSM Higgs sector

H–A mixing may be large, even for small $\hat{\Sigma}_{HA}(p^2)$:

For $a \approx b$ the symmetric matrix $\begin{pmatrix} a & c \\ c & b \end{pmatrix}$ $\Rightarrow$ maximal mixing

Introduction: CP-violating MSSM Higgs sector

H–A mixing may be large, even for small $\hat{\Sigma}_{HA}(p^2)$:

For $a \approx b$ the symmetric matrix $\begin{pmatrix} a & c \\ c & b \end{pmatrix}$ $\Rightarrow$ maximal mixing

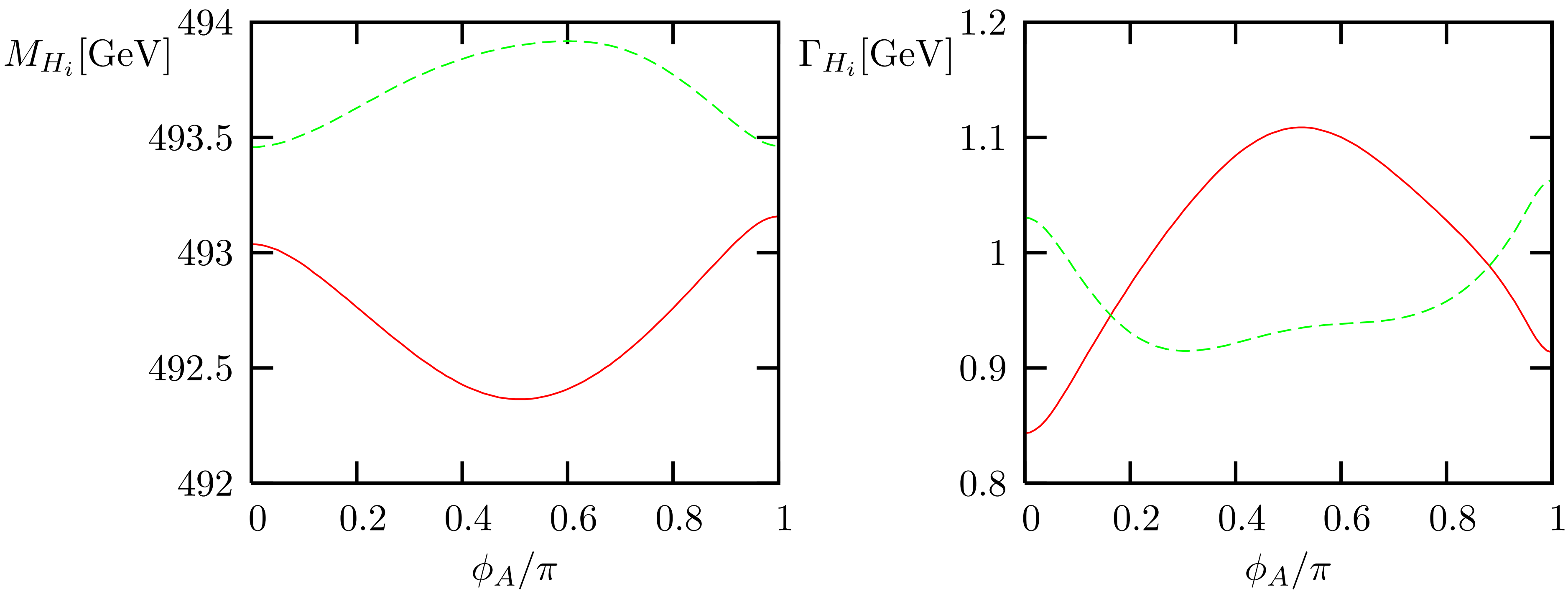
In the Higgs decoupling limit ($M_{H^\pm} \gg m_W$) $m_H \approx m_A$,

$$\mathbf{M}(p^2) = \begin{pmatrix} m_h^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_H^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_A^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

May have maximal CP-violation in the Higgs sector!

Introduction: CP-violating MSSM Higgs sector

Enhanced resonant H–A mixing in the decoupling limit:

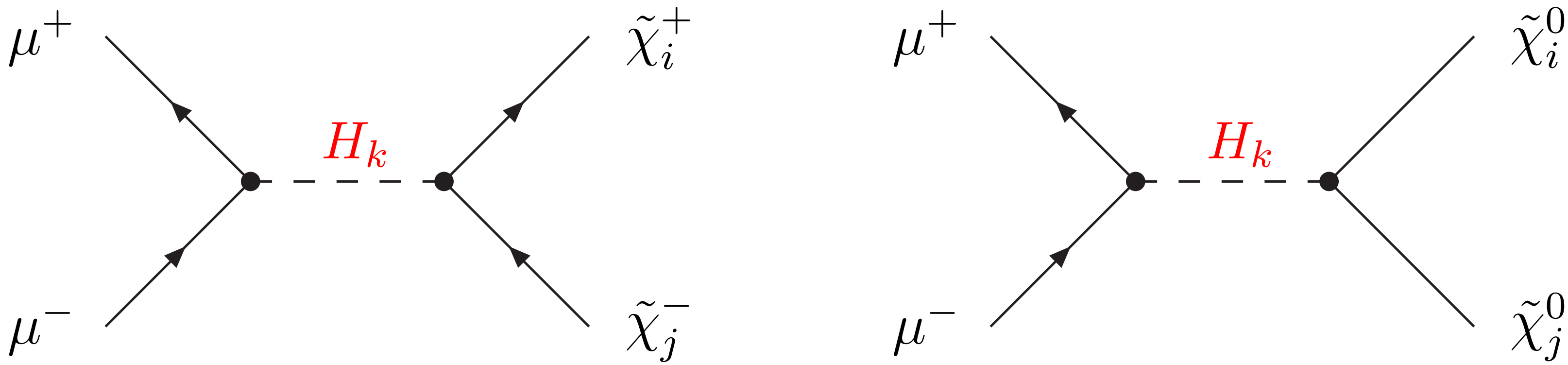


$M_{H^\pm} = 500$ GeV, $|A_t| = 2M_{\text{SUSY}} = 1$ TeV

mixing tends to split the degenerate resonances

Here: widths $\sim$ mass splitting $\Rightarrow$ large absorbtive phases

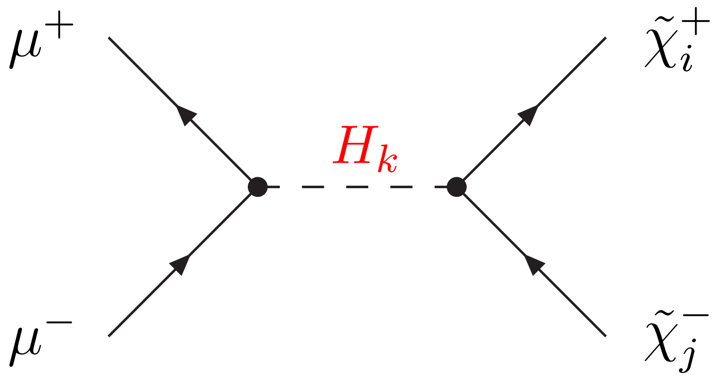
Higgs s-channel exchange

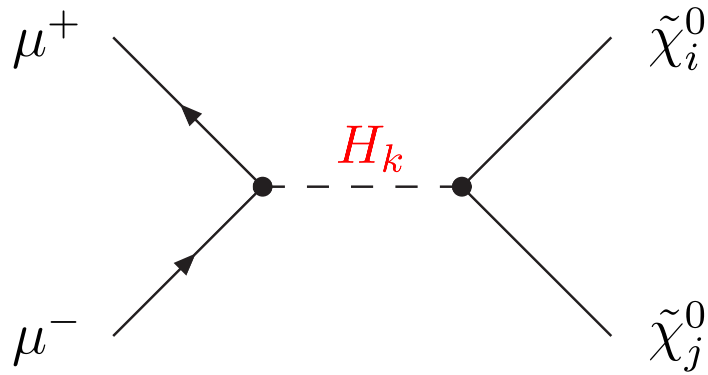


Resonant enhancement $\Rightarrow$ relevant paramenter $c^{\phi\mu}\frac{m_\phi}{\Gamma_\phi} \sim \mathcal{O}(1)$

Amplitude: $T = \Gamma^{(\chi)}\Delta(p^2)\Gamma^{(\mu)}$

Higgs s-channel exchange





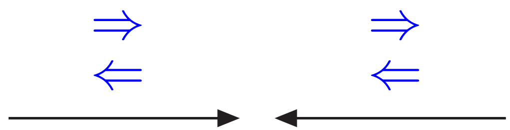
Resonant enhancement $\Rightarrow$ relevant paramenter $c^{\phi\mu}\frac{m_\phi}{\Gamma_\phi} \sim \mathcal{O}(1)$

Amplitude: $T = \Gamma^{(\chi)}\Delta(p^2)\Gamma^{(\mu)}$

Our approximation:
compute $\Delta(p^2)$ with the program `Feynhiggs`
at $p^2 = (p_{\mu^+} + p_{\mu_-})^2$,
the one-point-irreducible functions $\Gamma^{(\chi)},\ \Gamma^{(\mu)}$ at tree level

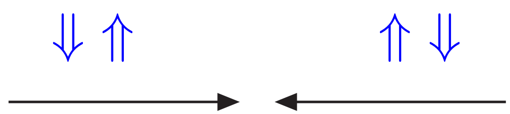
Polarization: overview

fermions: longitudinal $L_z = 0 \Rightarrow S_z = J_z$

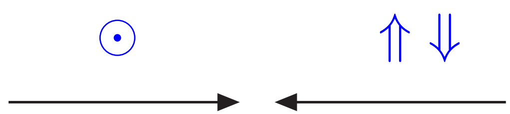


$J = 0$: Higgs channels; $J_z = \pm 1$: continuum

fermions: transverse



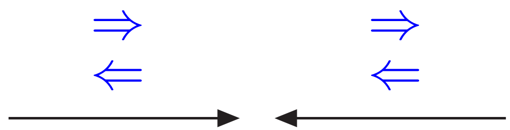
(anti)parallel spins: $\leftrightarrow$ CP-even/CP-odd Higgs ch.



orthogonal spins: $\leftrightarrow$ triple products (CP-odd obs.)

Polarization: overview

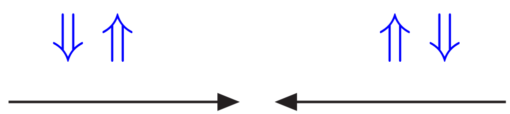
fermions: longitudinal $L_z = 0 \Rightarrow S_z = J_z$



$J = 0$: Higgs channels; $J_z = \pm 1$: continuum

Higgs observables $\propto$ polarization sum $+ \ldots$

fermions: transverse



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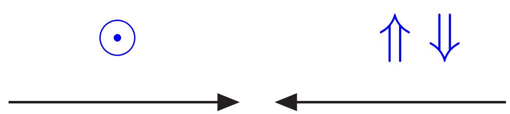
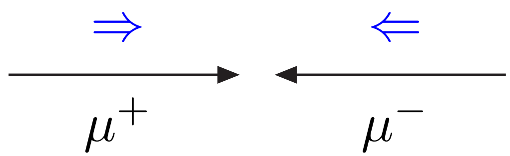


orthogonal spins: $\leftrightarrow$ triple products (CP-odd obs.)

Higgs observables $\propto$ polarization product $+ \ldots$

Polarization dependence: CP$\tilde{\mathrm{T}}$

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



$|RR\rangle$

Polarization dependence: CP$\tilde{\mathrm{T}}$

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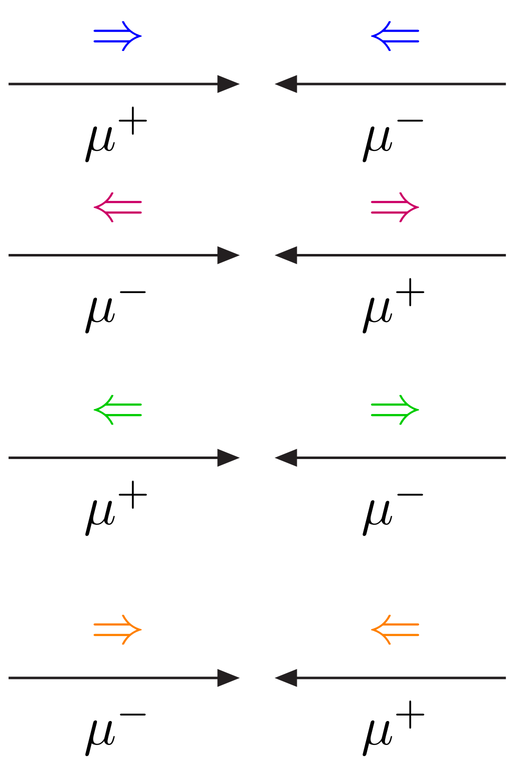


$|RR\rangle$

P Parity

$|LL\rangle$

C Parity

$|LL\rangle$

$\tilde{\mathrm{T}}$ Parity: (naive time reverseal)

$|LL\rangle$

Similarly for fermions from Higgs boson decay

$\Rightarrow$ Classify observables und C, P, $\tilde{\mathrm{T}}$.

Polarization dependence: CP$\tilde{\mathrm{T}}$: Observables

Table 1:

C	P	CP	prod. obs.	prod.& decay
$+$	$+$	$+$	$\sigma_{ij}^{\mathrm{C}_+\mathrm{P}_+}$	$\mathcal{A}_{ij,\ell}^{\mathrm{C}_+\mathrm{P}_-}$
$+$	$-$	$-$	$\mathcal{A}_{ij}^{\mathrm{C}_+\mathrm{P}_-}$	$\mathcal{A}_{ij,\ell}^{\mathrm{C}_+\mathrm{P}_+}$
$-$	$+$	$-$	$\mathcal{A}_{ij}^{\mathrm{C}_-\mathrm{P}_+}$	$\mathcal{A}_{ij,\ell}^{\mathrm{C}_-\mathrm{P}_-}$
$-$	$-$	$+$	$\mathcal{A}_{ij}^{\mathrm{C}_-\mathrm{P}_-}$	$\mathcal{A}_{ij,\ell}^{\mathrm{C}_-\mathrm{P}_+}$

Asymmetries in chargino/neutralino production

$\mu^+\mu^- \to \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp},\ \tilde{\chi}_i^0\tilde{\chi}_j^0\ ,$

$$\mathcal{A}^{\mathrm{C_+P_-}} = \frac{[\sigma_{ij}(\mathcal{P}) - \sigma_{ij}(-\mathcal{P})]}{[\sigma_{ij}(\mathcal{P}) + \sigma_{ij}(-\mathcal{P})]} \longrightarrow \frac{\sigma_{ij}(RR) - \sigma_{ij}(LL)}{\sigma_{ij}(RR) + \sigma_{ij}(LL)} \ \text{for}\ \mathcal{P} = 1$$

$$\begin{array}{ccc}
\overset{\Rightarrow}{\underset{\mu^+}{\longrightarrow}} & \overset{\Leftarrow}{\underset{\mu^-}{\longleftarrow}} & |RR\rangle \\
 & & \pm \\
\overset{\Leftarrow}{\underset{\mu^+}{\longrightarrow}} & \overset{\Rightarrow}{\underset{\mu^-}{\longleftarrow}} & |LL\rangle
\end{array}$$

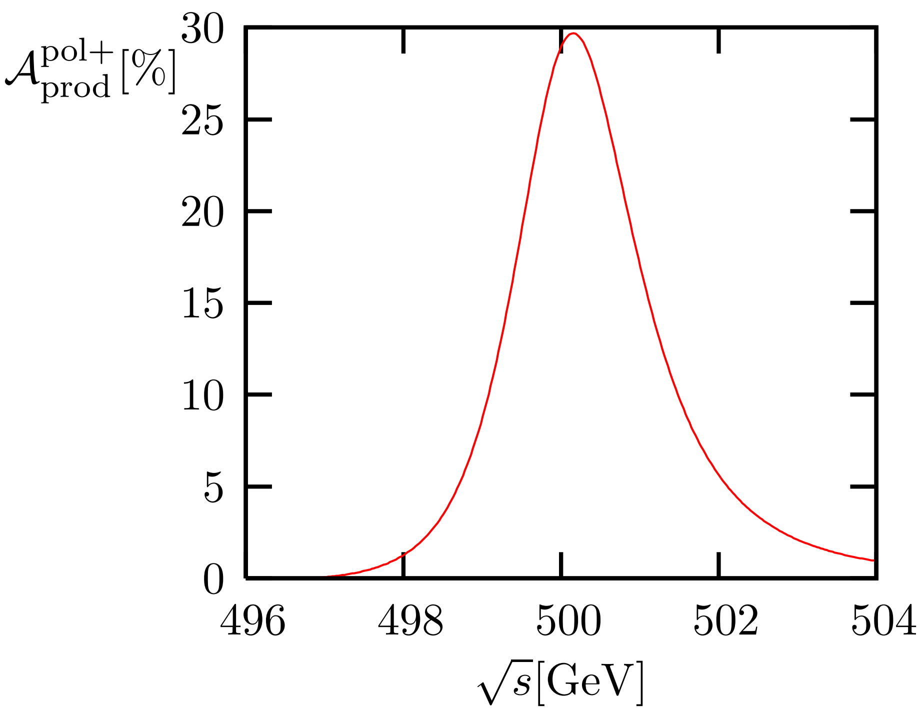
CP-odd and CP$\tilde{\mathrm{T}}$-odd asymmetry

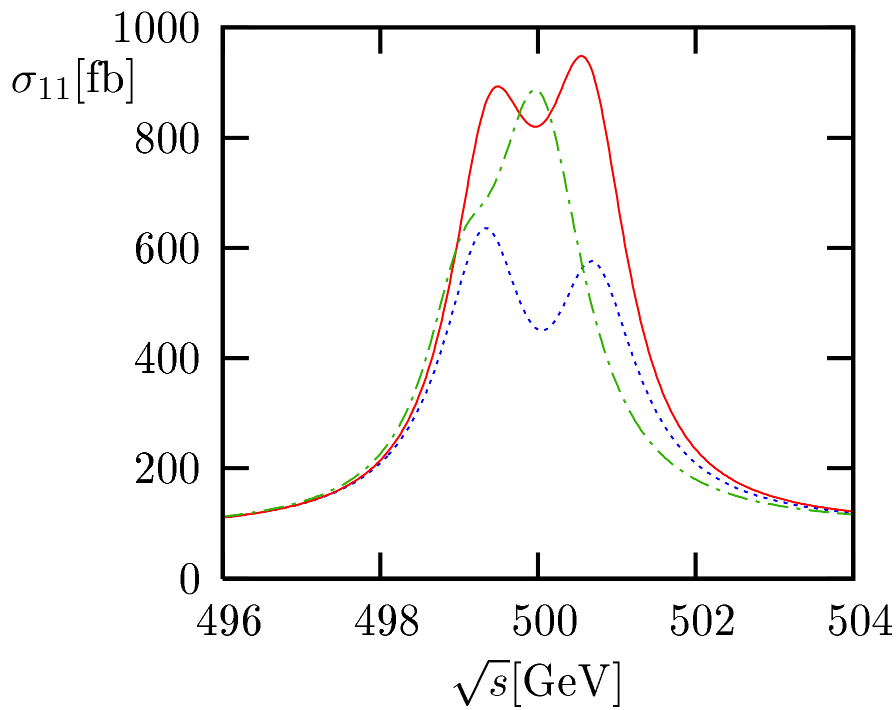
$\Rightarrow$ need absorbtive phases

strongly enhanced for nearly degenerate resonaces!

Asymmetries in chargino production: $\sqrt{s}$ dependence

$$\mathcal{A}^{C_+P_-} = \frac{[\sigma_{11}(\mathcal{P}) - \sigma_{11}(-\mathcal{P})]}{[\sigma_{11}(\mathcal{P}) + \sigma_{11}(-\mathcal{P})]}$$





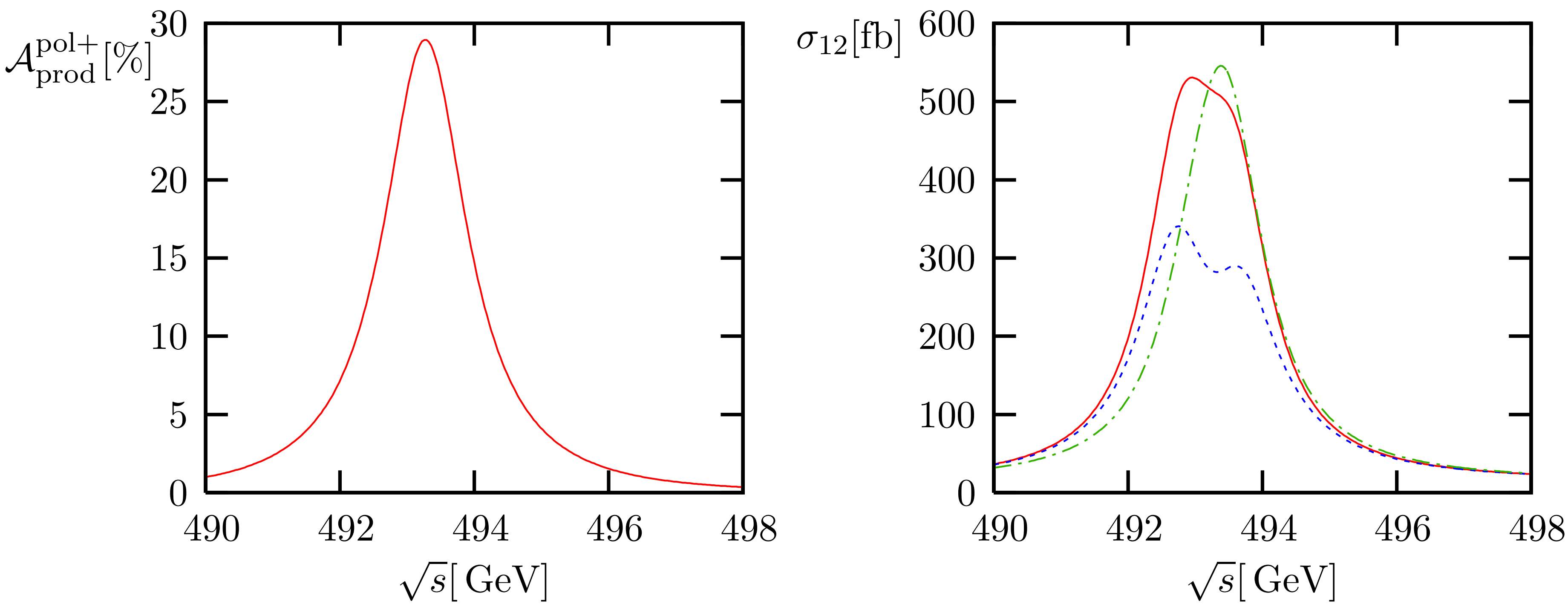
[Kittel,Dreiner,FP 07]

$\mu = 500$ GeV, $\tan\beta = 10$, $M_2 = 220$ GeV

$|A_t| = 2M_{\mathrm{SUSY}} = 1\mathrm{TeV}$, $\mathrm{Arg}(A_t) = 0.2\pi$, $\mathcal{P} = 0.3$, $\mathcal{P} = -0.3$, $\mathcal{P} = 0$

Asymmetries in neutralino production: $\sqrt{s}$ dependence

$$\mathcal{A}^{\mathrm{C_+P_-}} = \frac{[\sigma_{12}(\mathcal{P}) - \sigma_{12}(-\mathcal{P})]}{[\sigma_{12}(\mathcal{P}) + \sigma_{12}(-\mathcal{P})]}$$



[Kittel,FP 08]

$\mu = 400$ GeV, $\tan\beta = 10$, $M_2 = 300$ GeV

$|A_t| = 2M_{\mathrm{SUSY}} = 1\mathrm{TeV}$, $\mathrm{Arg}(A_t) = 0.2\pi$, $\mathcal{P} = 0.3$, $\mathcal{P} = -0.3$, $\mathcal{P} = 0$

Asymmetry in chargino/neutralino production

Why are these asymmetries so large?

Asymmetry in chargino/neutralino production

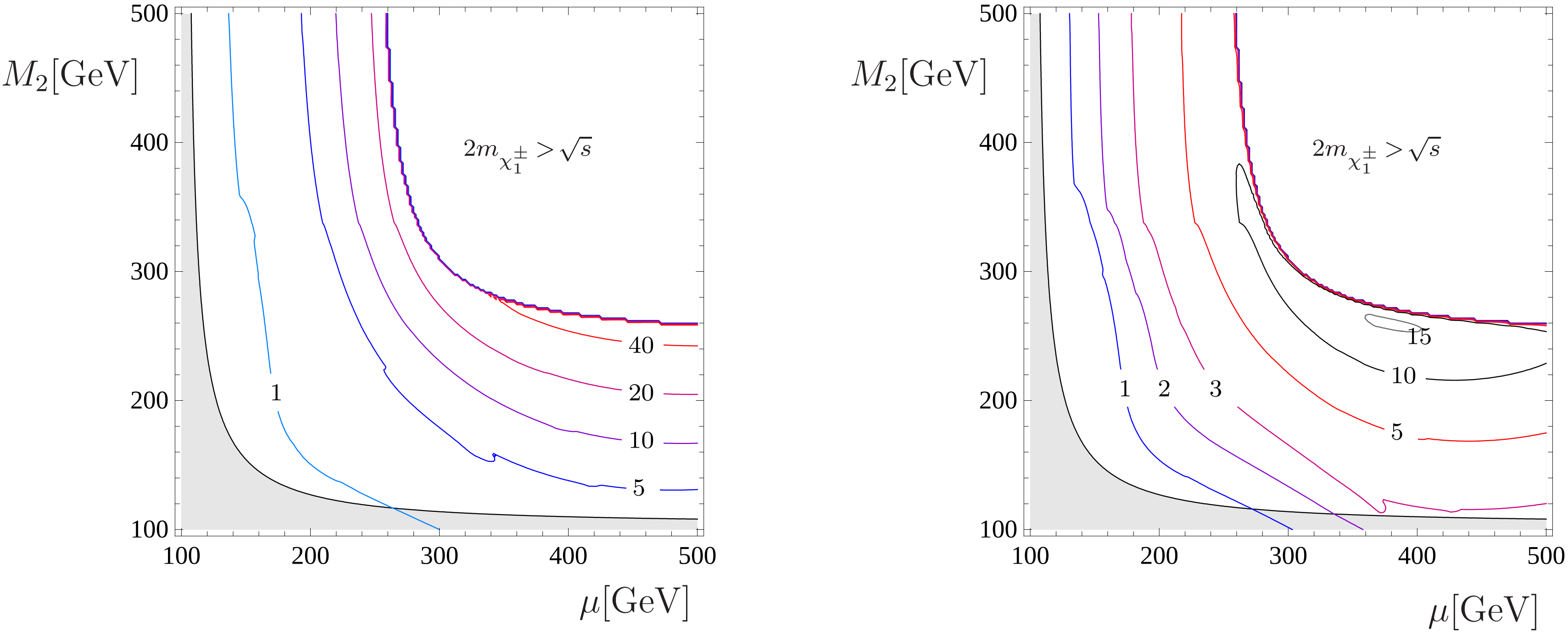
Why are these asymmetries so large?

- H-A mixing is nearly maximal for a class of scenarios:
  - large A_f (source of CP-violation)
  - slow charginos/neutralinos
  - heavy squarks: similar Higgs boson widths
    $\Rightarrow$ diagonal mass matrix elements nearly degenerate

$\Rightarrow$ large CP-violation without requiring a large parameter μ

Asymmetries in chargino production: μ–M_2 dependence

CP-odd production asymmetry and significance [for 1 fb^{-1}]



[Kittel,FP 08]

$\tan\beta = 10$

$|A_t| = 2M_{\rm SUSY} = 1{\rm TeV},\ {\rm Arg}(A_t) = 0.2\pi,\ \ \mathcal{P} = 0.3,$

Summary and Outlook

- The Muon Collider at the Higgs boson resonances:
  Unique Higgs factory to analyze the SUSY Higgs sector!
- Use longitudinal polarization of beams and produced particles:
  - More than disentangle degenerate resonances!
    build CP-even and CP-odd observables
  - We analyzed $\mu^+\mu^- \to$ charginos, neutralinos:
    analogous for SM fermions
  - Don't need very large beam polarization:
    CP-odd asymmetries up to 40%.
- Outlook:
  - Assess feasibility of polarization: cost vs. benefits!
  - longitudinal vs. transverse polarization
  - Complementarity with ILC/CLIC: photon collider

Thanks!

For further discussion

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Backup transparencies

Production of equal charginos: beam energy spread

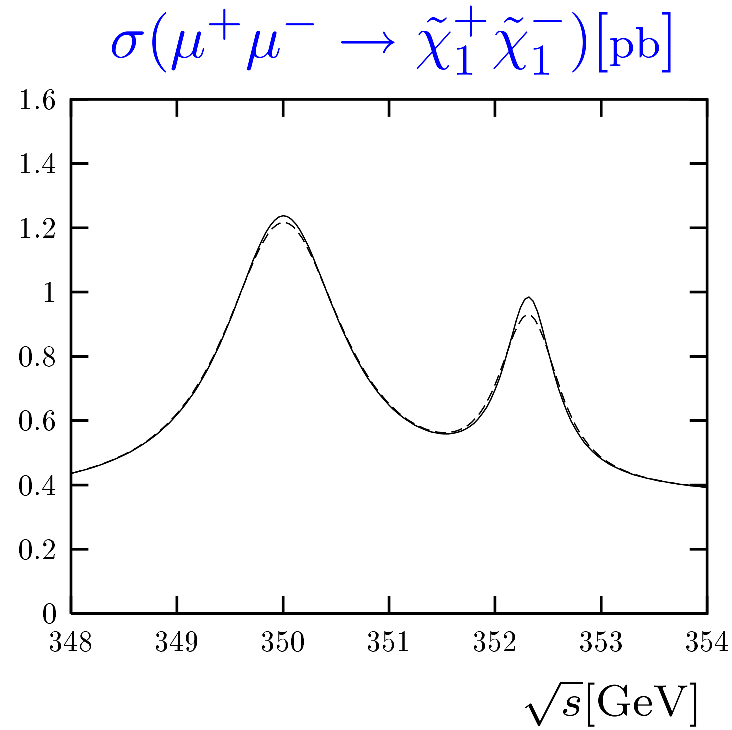
M_A=350 GeV

μ=M_2, $m_{\chi_1^\pm}$=155 GeV

$\tan\beta$=5

Beam energy resolution

R=0.06 % (dashed)



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M_A=350 GeV

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Beam energy resolution

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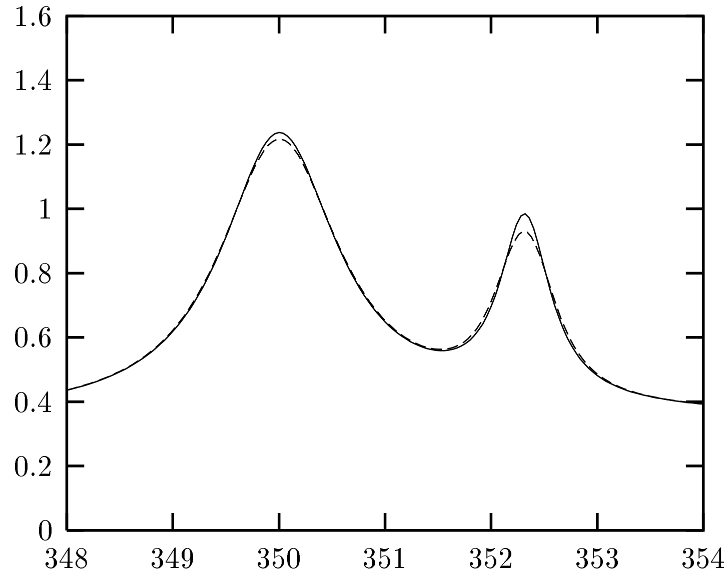
$\sigma(\mu^+\mu^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$[pb]



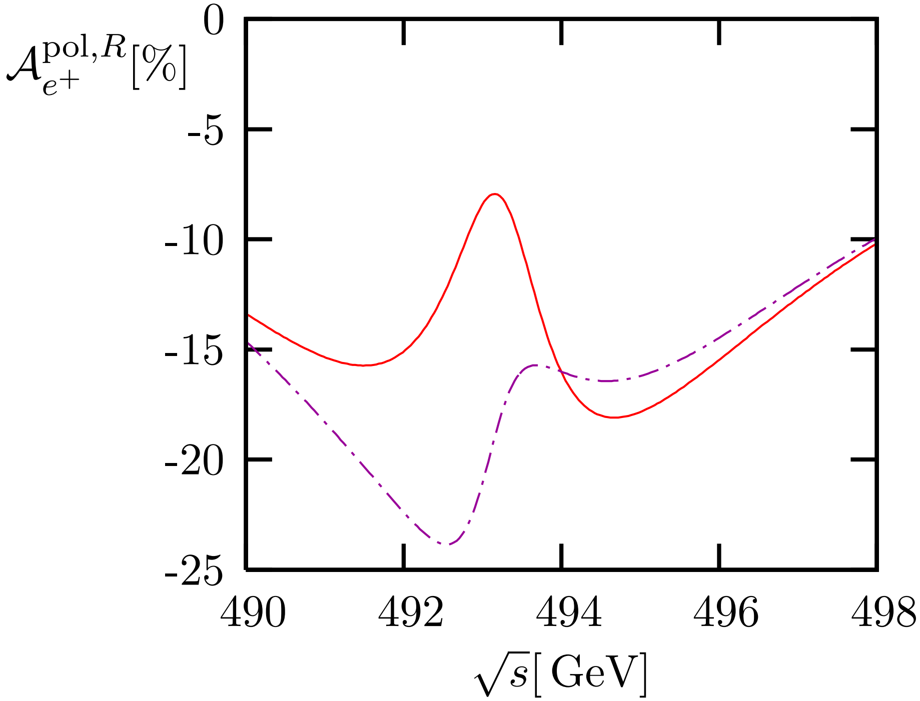
$\sqrt{s}$[GeV]

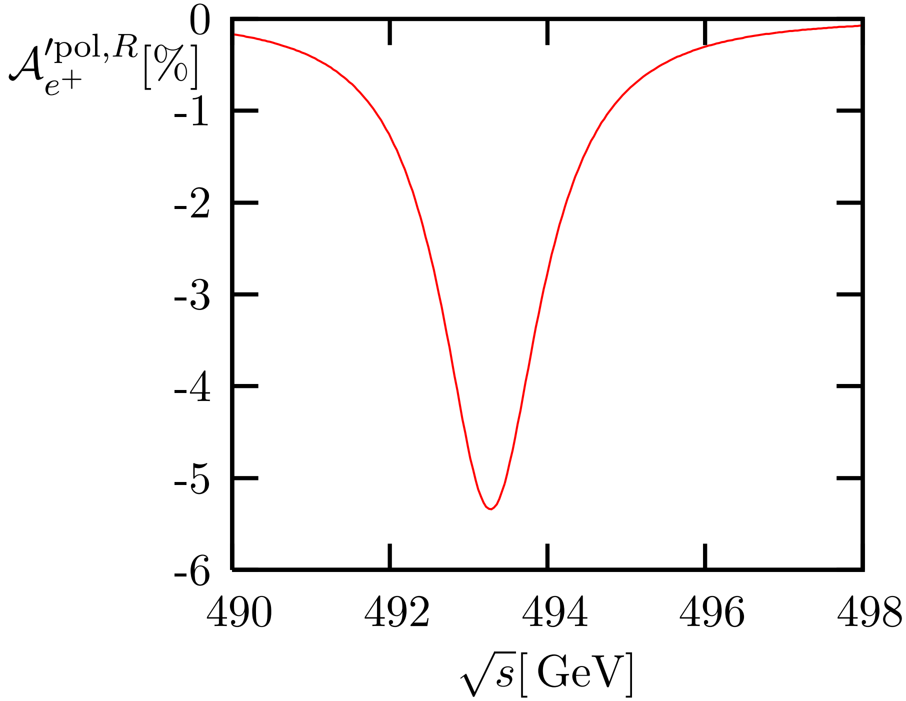
$\Rightarrow$ Estimate continuum from σ^{ii} above and below the resonances

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

Asymmetries in neutralino production and decay

$$\mathcal{A}^{\text{pol},n}_{\ell^\pm} = \frac{\Delta\sigma_{\ell^\pm}(\mathcal{P}) - \Delta\sigma_{\ell^\pm}(-\mathcal{P})}{\sigma_{\ell^\pm}(\mathcal{P}) + \sigma_{\ell^\pm}(-\mathcal{P})} \qquad \mathcal{A}'^{\text{pol},n}_{\ell^\pm} = \frac{\Delta\sigma_{\ell^\pm}(\mathcal{P}) + \Delta\sigma_{\ell^\pm}(-\mathcal{P})}{\sigma_{\ell^\pm}(\mathcal{P}) + \sigma_{\ell^\pm}(-\mathcal{P})}$$





$$\Delta\sigma_{\ell^\pm} = \sigma_{\ell^\pm}(E_\ell > \hat{E}_\ell) - \sigma_{\ell^\pm}(E_\ell < \hat{E}_\ell)$$

[Dreiner,Kittel,FP 07] $\mu = 400$ GeV, $\tan\beta = 10$, $M_2 = 300$ GeV

$\mathcal{P} = 0.3$, $\text{Arg}(A_t) = 0.2\pi$