Single and pair production of Higgs bosons of the MSSM at e^+e^- colliders

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4. Summary and outlook

References:
(4) A.Akeroyd (KIAS), A.A & M.C.Capdequi (Montpellier) **MPLA14** 2093 (1999), **PRD64 075007 (2001)** and **PRD64 095018 (2001)** and work in progress

1. Introduction

• CP-odd Higgs boson A^0 can be produced at e^+e^- colliders via:
$e^+e^- \to h^0A^0$, H^0A^0 (Drell-Yan process),
$e^+e^- \to b\bar{b}A^0$, $t\bar{t}A^0$ (Yukawa process)
$\gamma\gamma \to A^0$, ($\gamma\gamma$ fusion)

• In the MSSM $e^+e^- \to h^0A^0$ is suppressed by $\cos(\beta-\alpha)^2$ for $M_A \geq 250$ GeV, while $e^+e^- \to H^0A^0$ is phase space suppressed.

• In the MSSM, at tree level $VVA^0 = 0$, $e^+e^- \to ZA^0/\gamma A^0$ and $e^+e^- \to \nu_e\bar{\nu}_eA^0$ are loop mediated.

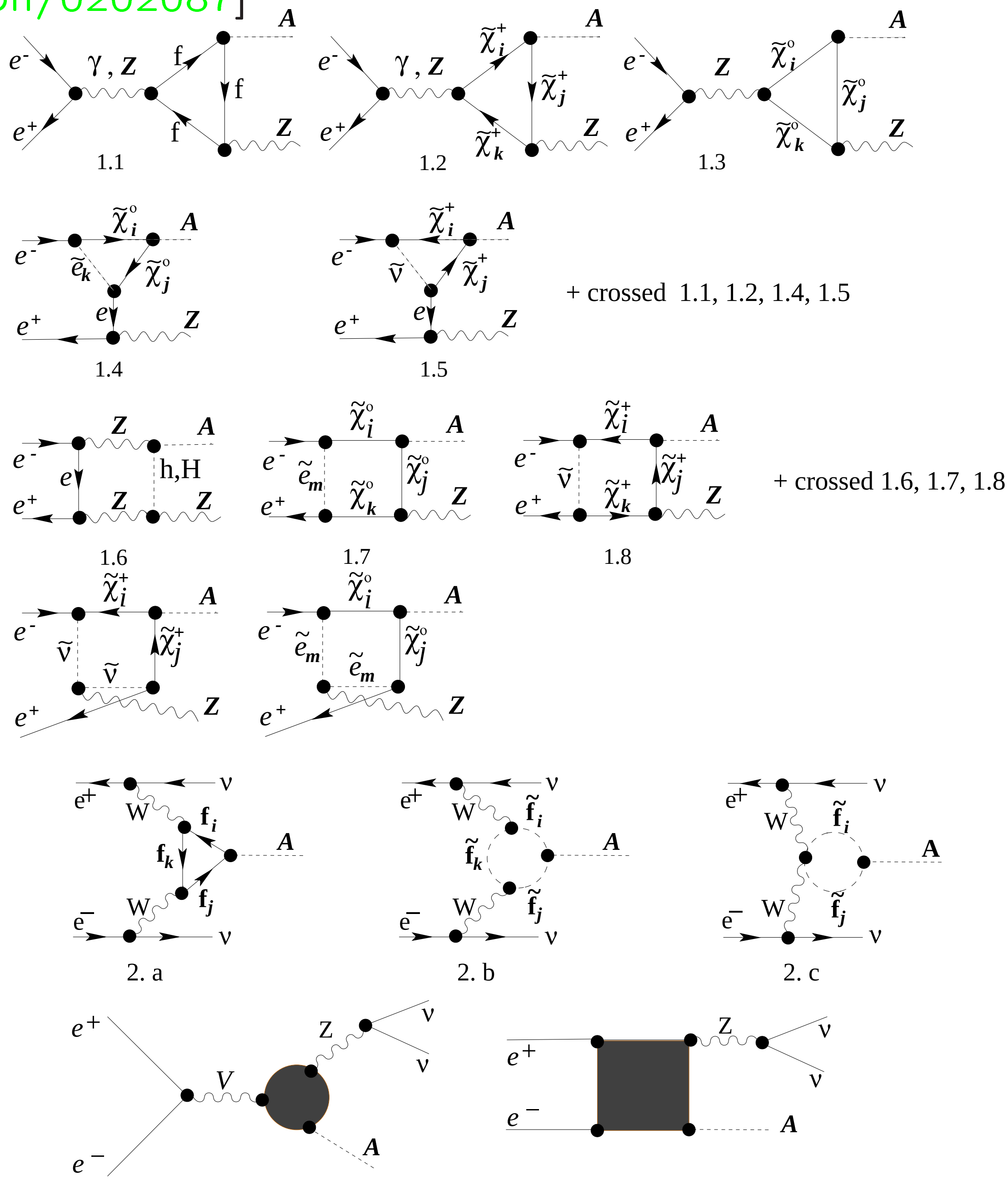
• If $e^+e^- \to ZA^0/\gamma A^0$ and $e^+e^- \to \nu_e\bar{\nu}_eA^0$ are sizeable, it would provide an alternative way of producing A^0 at e^+e^- collider.

• Informations on $\gamma\gamma A^0$, γZA^0, ZZA^0 and WWA^0.

• At LEPII ($\sqrt{s} = 200$-209 GeV), $e^+e^- \to h^0A^0$, $h^0A^0 \to 2b2\bar{b}/b\bar{b}\tau^+\tau^-$; $M_A > 91.9$ GeV, hep-ex/0107030

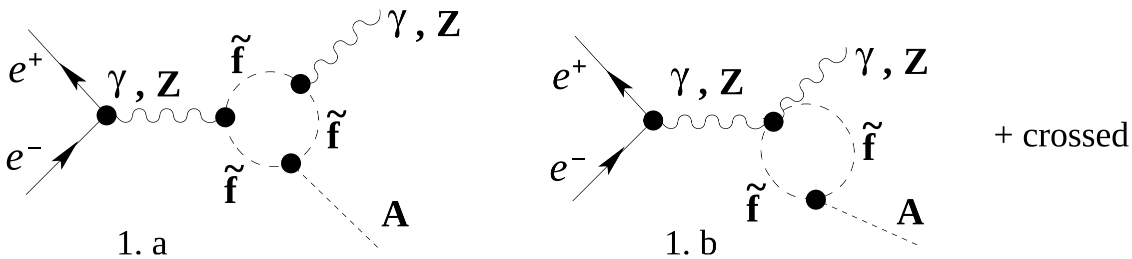
- $e^+e^- \to \gamma A^0$ in MSSM [A.Djouadi et alNPB491,68(1997)]

- $e^+e^- \to ZA^0$ & $e^+e^- \to \nu_e\bar{\nu}_e A^0$ in 2HDM: [T.Farris et al hep-ph/0202087]



- FeynArts3, FormCalc [T.Hahn et al CPC 01, CPC 02]

- In MSSM with real parameters, $A^0 \tilde{f}_i^* \tilde{f}_j = -A^0 \tilde{f}_j^* \tilde{f}_i$



- With complex parameters:

$$
\begin{aligned}
A^0 \tilde{f}_1^* \tilde{f}_2 = & -\frac{g m_f}{2M_W}\{|A_f(\tan\beta)^{-2I_3^f} + \mu^*|e^{-i\delta_f}\sin\theta_f^2 \\
& +|A_f^*(\tan\beta)^{-2I_3^f} + \mu|e^{i\delta_f}\cos\theta_f^2\} \\
A^0 \tilde{f}_1^* \tilde{f}_1 = & \frac{-igm_f}{2M_W}\sin 2\theta_f\{|A_f|(\tan\beta)^{-2I_3^f}\sin(\arg(A_f)-\delta_f) \\
& -|\mu|\sin(\arg(\mu)+\delta_f)\} \\
A^0 \tilde{f}_2^* \tilde{f}_2 = & -(A^0 \tilde{f}_1^* \tilde{f}_1)
\end{aligned}
$$

The sfermions contribution is $\neq 0$.

- Only A_f are complex $\arg(A_t) = \arg(A_b)$

- 1st and 2nd gen @ TeV scale, μ real $\rightarrow$ EDMs

- $\delta\rho(\tilde{t} - \tilde{b}) < 0.003$

- @ 500 GeV, $\mathcal{L} = 500\text{fb}^{-1}$, the threshold of observability is $\sigma = 0.1\text{fb} \rightarrow 50$ events.

- @ 800 GeV, $\mathcal{L} = 1000\text{fb}^{-1}$, the threshold of observability is $\sigma = 0.05\text{fb} \rightarrow 50$ events.

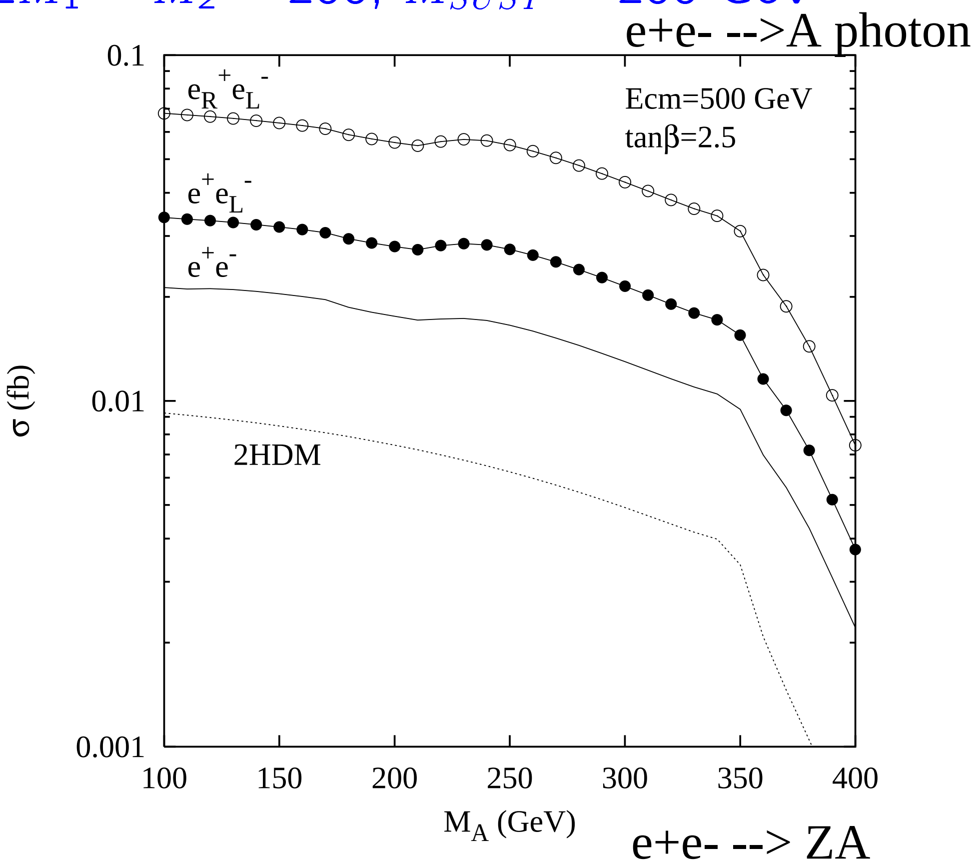
- the cross section can be enhanced:

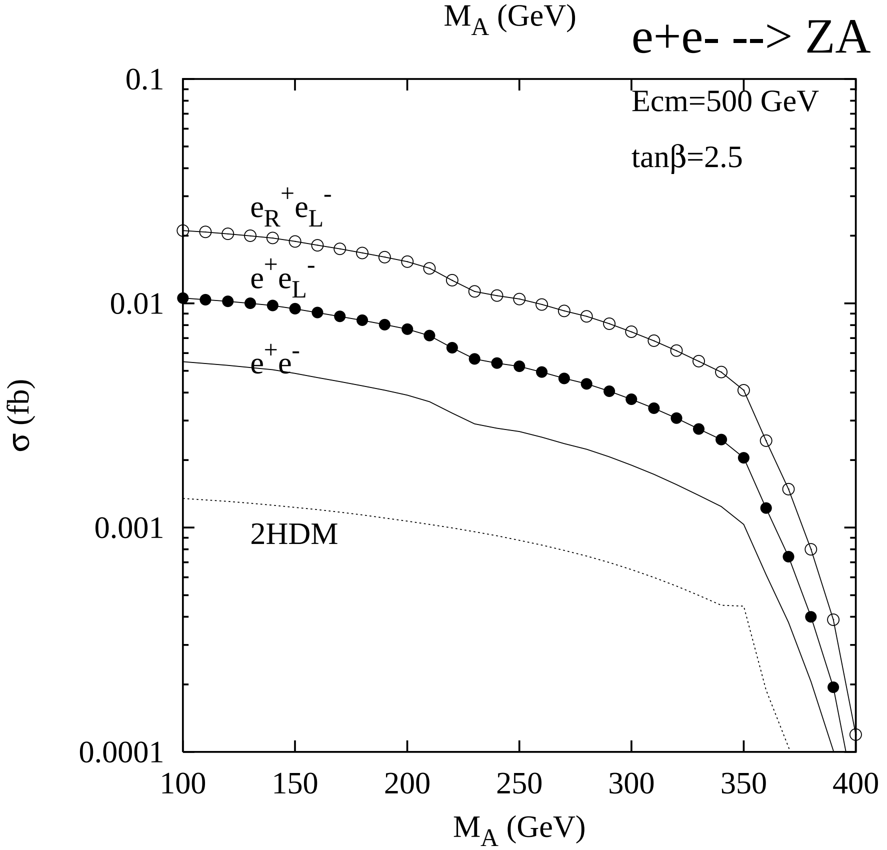
  - in 2HDM for small $\tan\beta < 1$ ($A^0 t\bar{t} = \frac{m_t}{\tan\beta}$)

  - in MSSM with light charginos

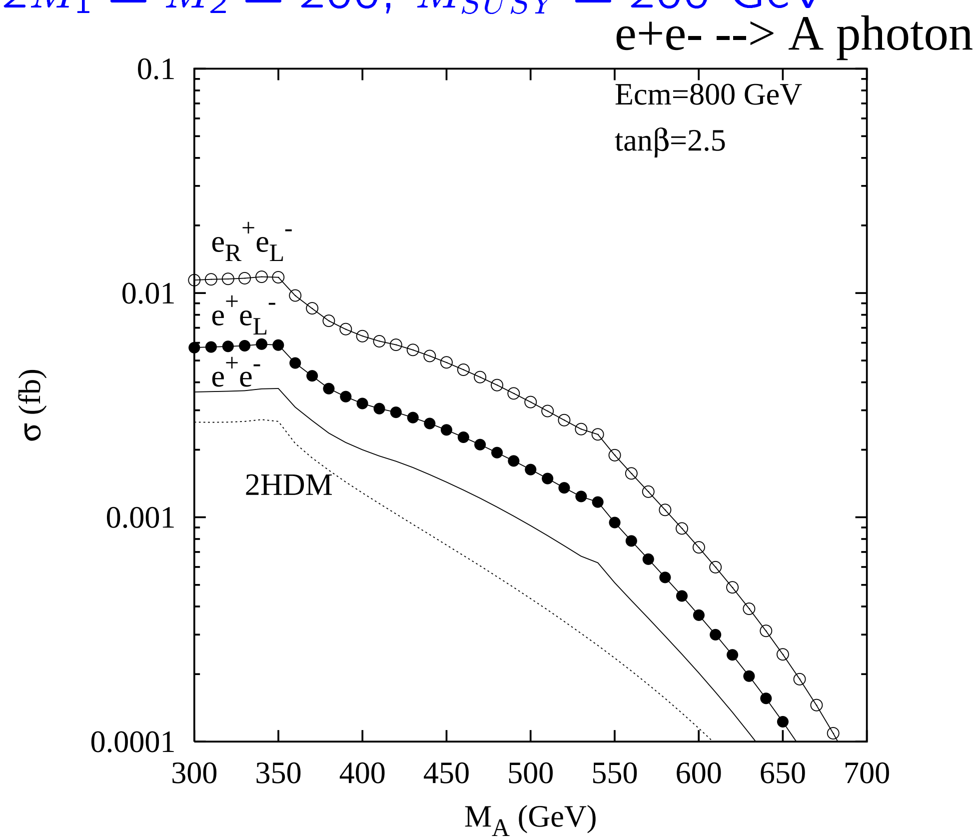
  - in complex MSSM with large CP phases and $M_A \approx 2m_{\tilde{t}_1}$ ($A^0 \rightarrow \tilde{t}_1 \tilde{t}_1^*$)

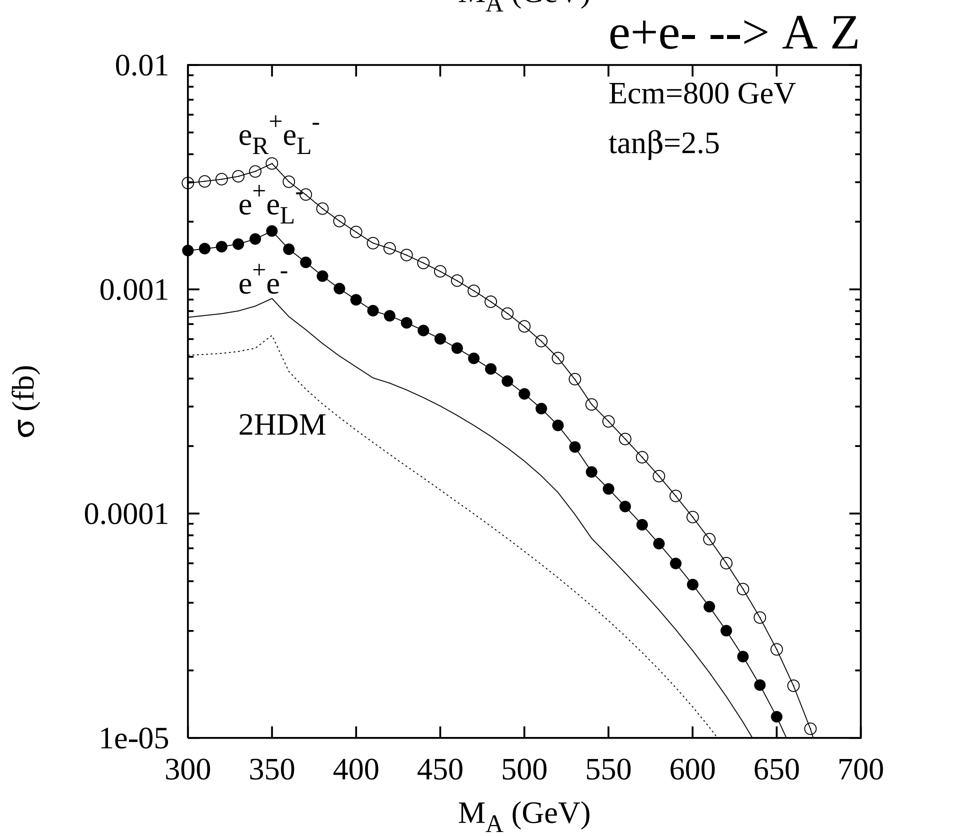
$\mu = 180$, $2M_1 = M_2 = 200$, $M_{SUSY} = 200$ GeV



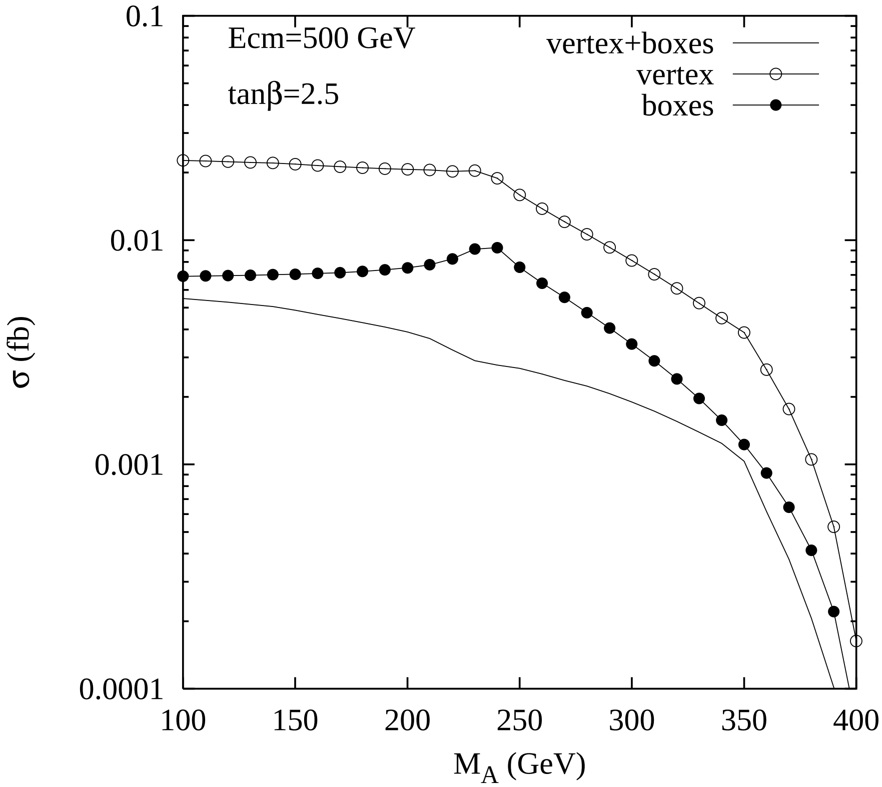


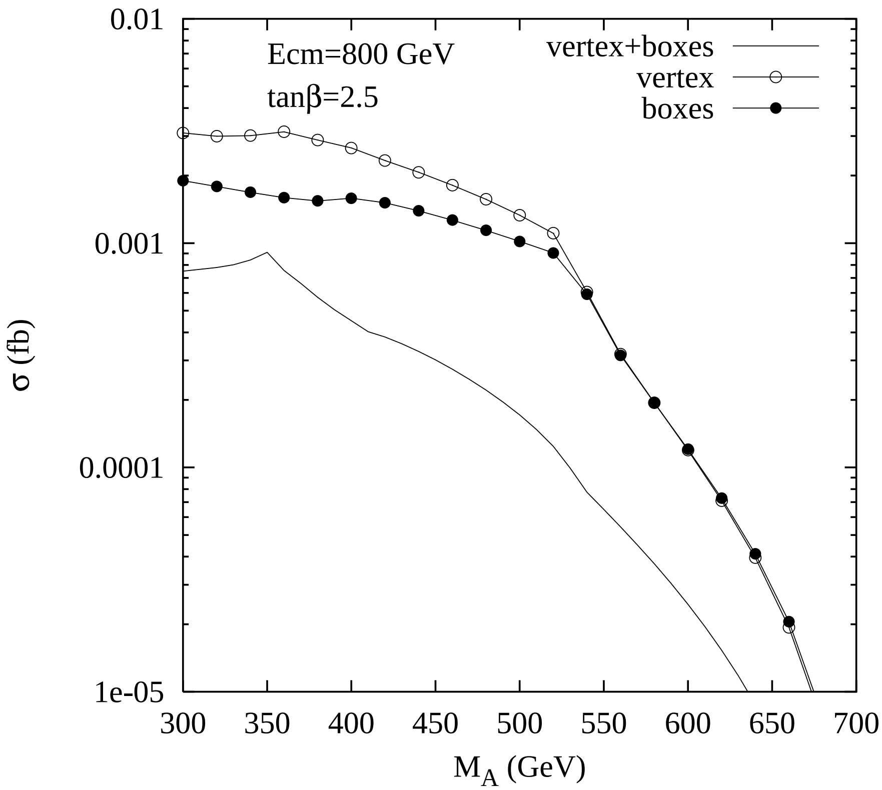
$\mu = 180$, $2M_1 = M_2 = 200$, $M_{SUSY} = 200$ GeV



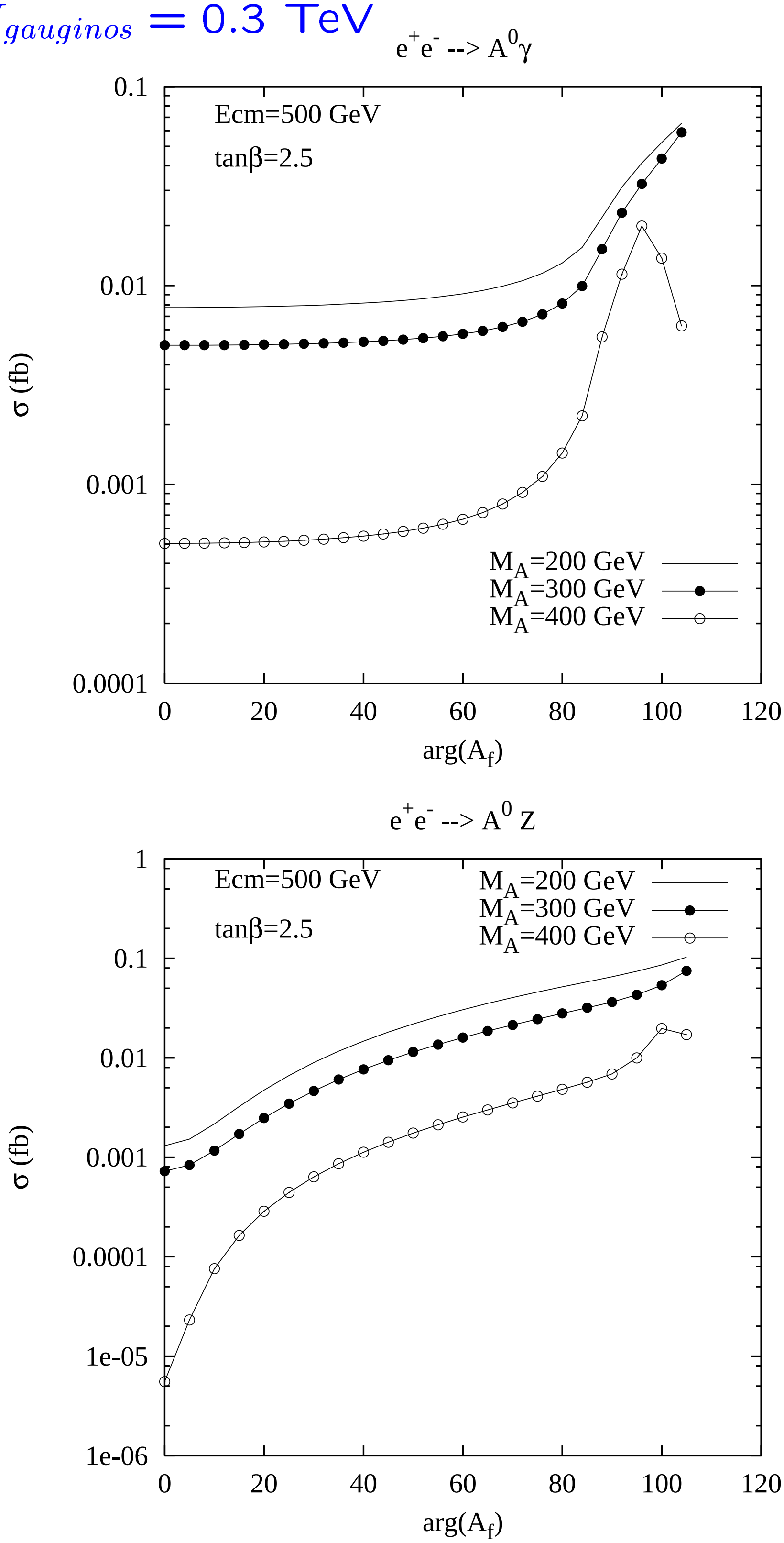


Cancellation between boxes and triangles: light SUSY

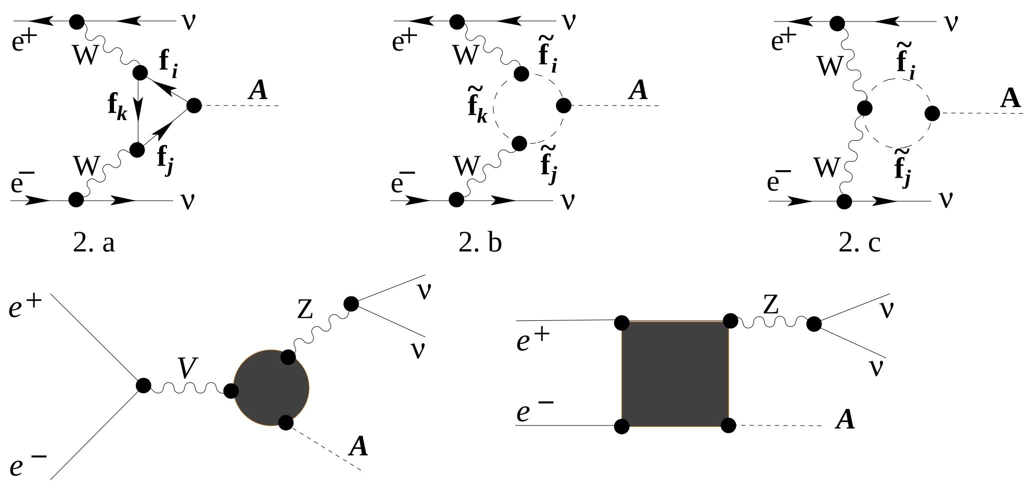




In MSSM with CP phases: $M_{SUSY} = 0.5$, $\mu = 2$, $A_{t,b} = 1$ TeV and $M_{gauginos} = 0.3$ TeV



• $e^+e^- \to \nu_e\bar{\nu}_e A^0$ computed in 2HDM by T.Farris et al. (correction to W-W-A vertex only)
[S.Su talk]



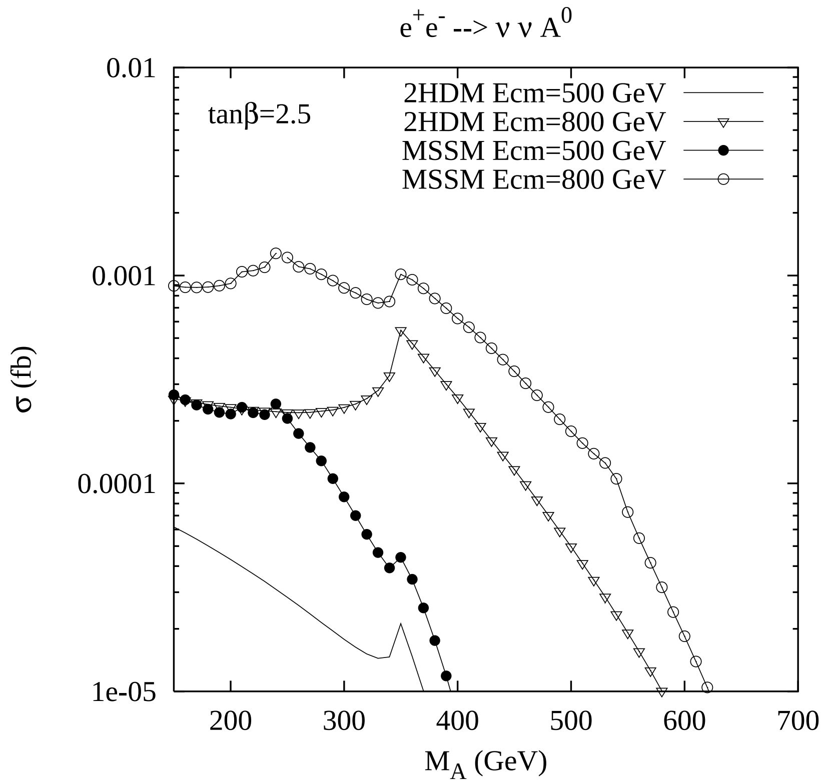
Preliminary results:

• in 2HDM for $\tan\beta = 0.5$ and $M_A = 250$ GeV $\sigma = 7\ 10^{-4}$ fb @ 500 GeV and 5.5 10^{-2} fb @ 800 GeV

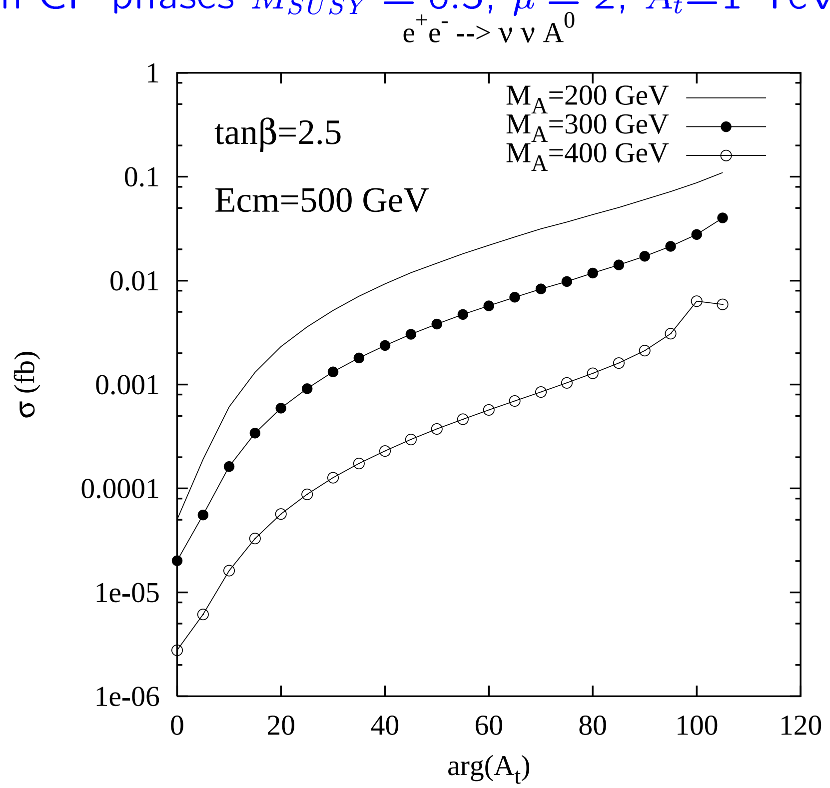
• in MSSM $\tan\beta = 2.5$ and $M_A = 250$ GeV with light SUSY, $\sigma = 2.1\ 10^{-4}$ fb

• in complex MSSM $\tan\beta = 2.5$ the CP phase can enhance the cross section up to $\sigma = 0.1$ fb.

In MSSM with $M_{SUSY} = 200$ GeV



In MSSM with CP phases $M_{SUSY} = 0.5$, $\mu = 2$, A_t=1 TeV



3. Probing scalar-pseudoscalar mixing in $\not{C}$PMSSM

• CP violation in MSSM:
[S. Heinemeyer and A. Pilaftsis talks]

• With Extended Higgs sector, CP can be violated either explicitly or spontaneously in Higgs sector.

• In the MSSM, there is no Explicit/Spontaneous $\not{C}$P at tree level

• Beyond tree level, one can have both: Explicit $\not{C}$P and Spontaneous $\not{C}$P (light $M_A < 40$ GeV)

• After using the two global $U(1)$ symmetries of the MSSM Lagrangian, only 2 physical phases remains:

Arg(μ) and Arg(A_f)

• From the one loop effective potential, the neutral Higgs boson mass matrix in the reduced basis $(\Re\Phi_1^0, \Re\Phi_2^0, \sin\beta\Im\Phi_1^0+\cos\beta\Im\Phi_2^0)$: [S.P.Li et al'84, J.Ellis et al'90, Y.Okada et al '90, E.Haber et al'90,.. M.Carena et al'95...A.Demir'99, A.Pilaftsis et al'99...S.Y.Choi et al'99]

$$M_N^2 = \begin{pmatrix} m_Z^2 c_\beta^2 + M_A^2 s_\beta^2 + \Delta_{11} & -(m_Z^2 + M_A^2)s_\beta c_\beta + \Delta_{12} & \Delta_{13} \\ * & m_Z^2 s_\beta^2 + M_A^2 c_\beta^2 + \Delta_{22} & \Delta_{23} \\ * & * & M_A^2 + \Delta_{33} \end{pmatrix}$$

• The size of CP violating off diagonal terms Δ_{13} and Δ_{23} may be estimated as:

$$\Delta_{13} \simeq \mathcal{O}\left(\frac{m_t^4}{v^2} \frac{|\mu||A_t|}{32\pi^2 M_S^2} \right) \sin\phi_{CP} \{1, \frac{|A_t|^2}{M_S^2}, \frac{|\mu|^2}{\tan\beta M_S^2}, \frac{|\mu||A_t|}{M_S^2}\}$$

M_S is stop mass average , $\Phi_{CP} = arg(\mu) + arg(A_{t,b})$

• To get sizeable CP violation, large $|\mu|$, large $|A_{t,b}|$ and large $\sin\phi_{CP}$ are needed.

• $\text{Diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2) = O^T M_N^2 O$, with $M_{H_1} < M_{H_2} < M_{H_3}$

After diagonalization the Physical mass eigenstates are mixed states of CP, $H_{1,2,3}$ have undefined CP properties.

- The interaction between Higgs and gauge bosons:

$$\mathcal{L}_{H_iVV} = g m_W \sum_{i=1}^{3} C_i \, [H_i W_\mu^+ W^{-,\mu} + \frac{1}{2c_W^2} H_i Z_\mu Z^\mu]$$

$$\mathcal{L}_{H_iH_jZ} = \frac{g}{2c_W} \sum_{j>i=1}^{3} C_{ij} \, (H_i \overleftrightarrow{\partial}_\mu \, H_j)$$

$$C_i = O_{1i} \cos\beta + O_{2i} \sin\beta \quad , \quad C_k = \epsilon_{ijk} \, C_{ij}$$

- We have the following Sum rules:

$$C_1^2 + C_2^2 + C_3^2 = 1 \quad , \quad C_{ij}^2 = C_k^2 \quad , \; i \neq j \neq k$$

- In MSSM, $C_1 = \sin(\beta - \alpha)$, C_2 or $C_3 = \cos(\beta - \alpha)$ and $VVA = C_2$ or $C_3 = 0$, we have access only to two Higgs h, H in the Higgs-Strahlung / WW fusion process

- In $\not{C}$PMSSM, all H_i (i=1,2,3) can be produced in the Higgs-Strahlung process: ($e^+e^- \rightarrow ZH_i$) and/or in the WW fusion ($e^+e^- \rightarrow H_i \nu_e \bar{\nu_e}$)

- In $\not{C}$PMSSM, the splitting between M_{H_2} and M_{H_3} may be larger than in the CP conserving MSSM: $0 < |M_{H_2} - M_{H_3}| < 60$ GeV [A.Pilaftsis et al'99, M. Carena et al'00, S. Heinemeyer '01].

• $\phi_{CP} = Arg(\mu) + Arg(A_{t,b})$, to evade EDM constraints, we take μ real and $0 < \mathrm{Arg}(A_{t,b}) < \pi$

• We are interested in $M_{H^\pm} \lesssim 350$ GeV; $M_{H^\pm} >$ 350 is the decoupling scenario and H_1 is SM like: $ZZH_1 = C_1 = 1$, $C_2 = C_3 = 0$

• Our parameters are fixed as:
$\widetilde{M}_Q = \widetilde{M}_t = \widetilde{M}_b = M_S = 0.5 \to 1\mathrm{TeV}$, $|\mu| = 4M_S$,
$|A_t| = |A_b| = 2M_S$, $\mathrm{Arg}(A_t) = \mathrm{Arg}(A_b)$,
$\tan\beta = 3 \to 15$

• For the one-loop renormalisation-group-improved effective potential of MSSM:

A.Pilaftsis et al NPB553'99, NPB586'00,

S.Y.Choi et al PLB481'00

http://home.cern.ch/p/pilaftsi/www

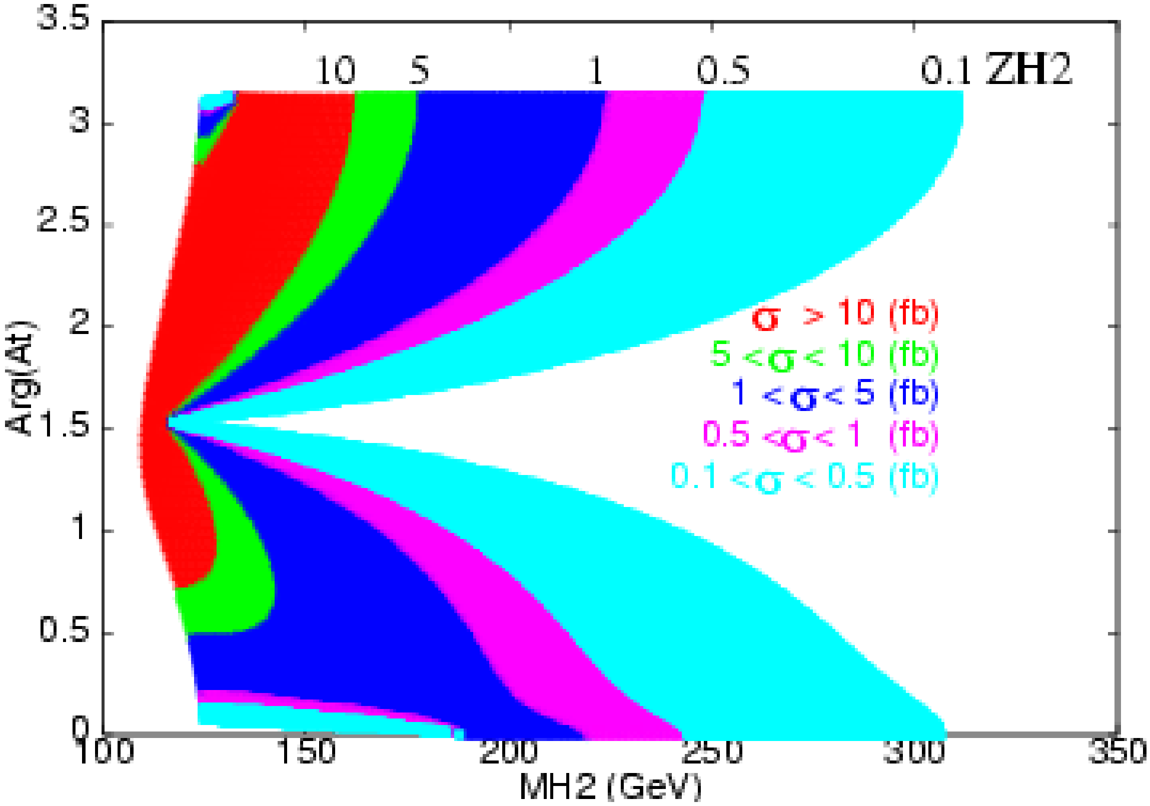
CP conserving MSSM	$\not{C}$PMSSM
$e^+e^- \to Zh$, ZH tree level [FeynHiggsXS: S.Heinemeyer et al] $e^+e^- \to ZA$ (1-loop) $\sigma \lesssim$ 0.1 fb	$e^+e^- \to ZH_1, ZH_2, ZH_3$ tree level
$e^+e^- \to \nu_e\bar{\nu}_e h$, $\nu_e\bar{\nu}_e H$ tree level $e^+e^- \to \nu_e\bar{\nu}_e A$ (1-loop) $\sigma \lesssim$ 0.1 fb	$e^+e^- \to \nu_e\bar{\nu}_e H_1, \nu_e\bar{\nu}_e H_2, \nu_e\bar{\nu}_e H$ tree level
$e^+e^- \to hA$, HA tree level $e^+e^- \to hH$ (1-loop) $\sigma \lesssim$ 0.01 fb A.Djouadi et al PRD54(1996)	$e^+e^- \to H_1H_2, H_1H_3, H_2H_3$ tree level

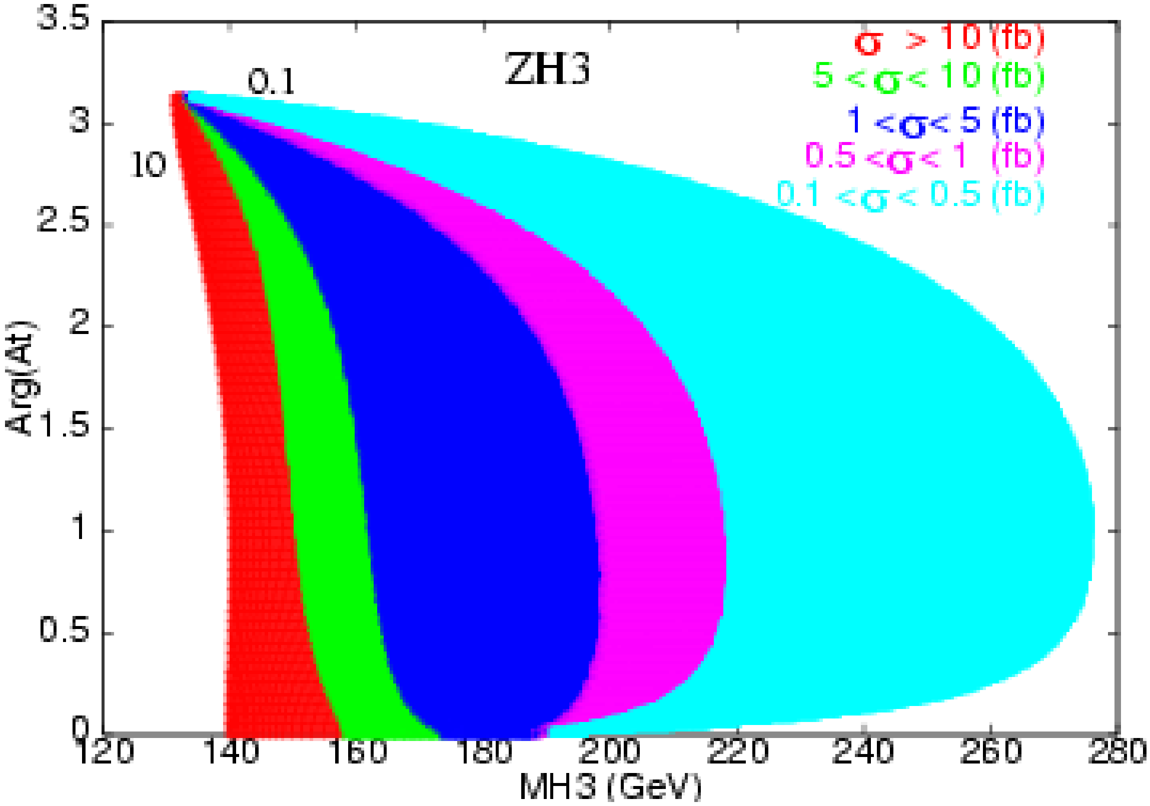
• A sizeable signal in both $e^+e^- \to ZH_2, ZH_3$ and/or $e^+e^- \to H_1H_2, H_1H_3$ would be a way of probing CP violation in the Higgs sector.

• The SM Higgs mass is going to be measured with very high precision at NLC $\approx$ 110 MeV.

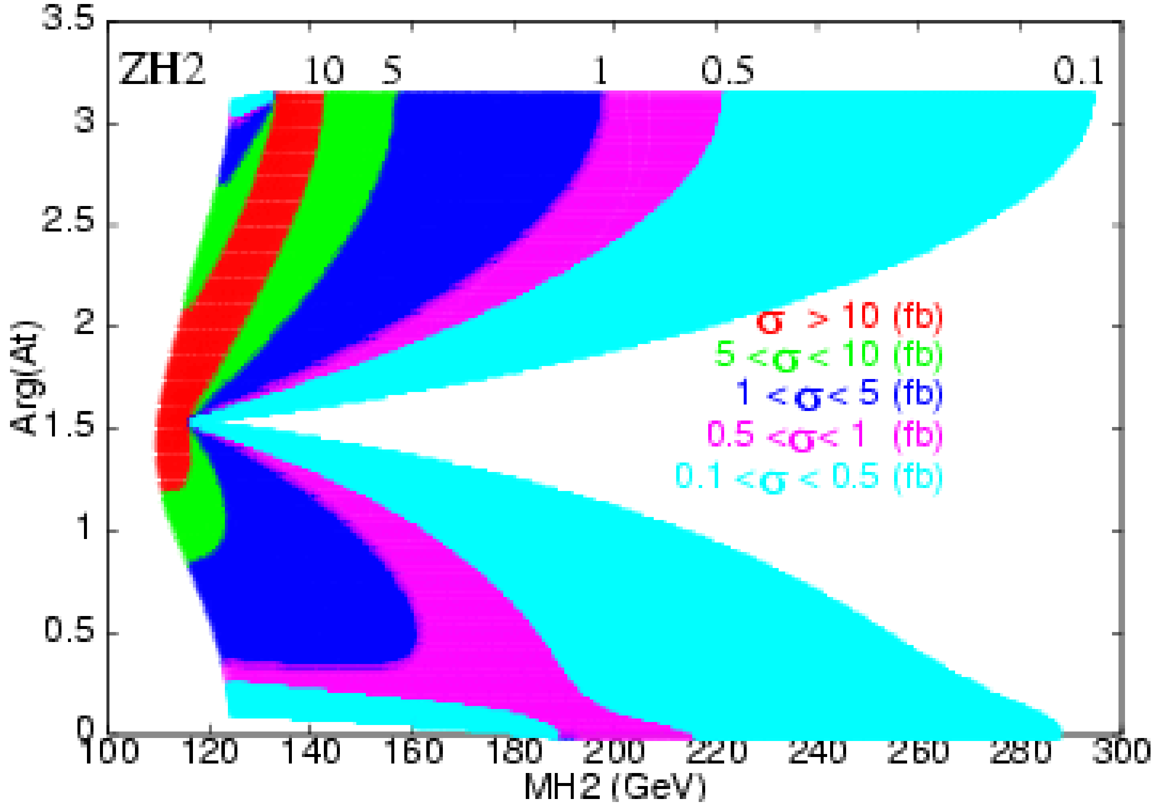
• If such precision is reached for the MSSM Higgs bosons, observation of 3 peaks in the Higgs-Strahlung process would be a signature of scalar-pseudoscalar mixing

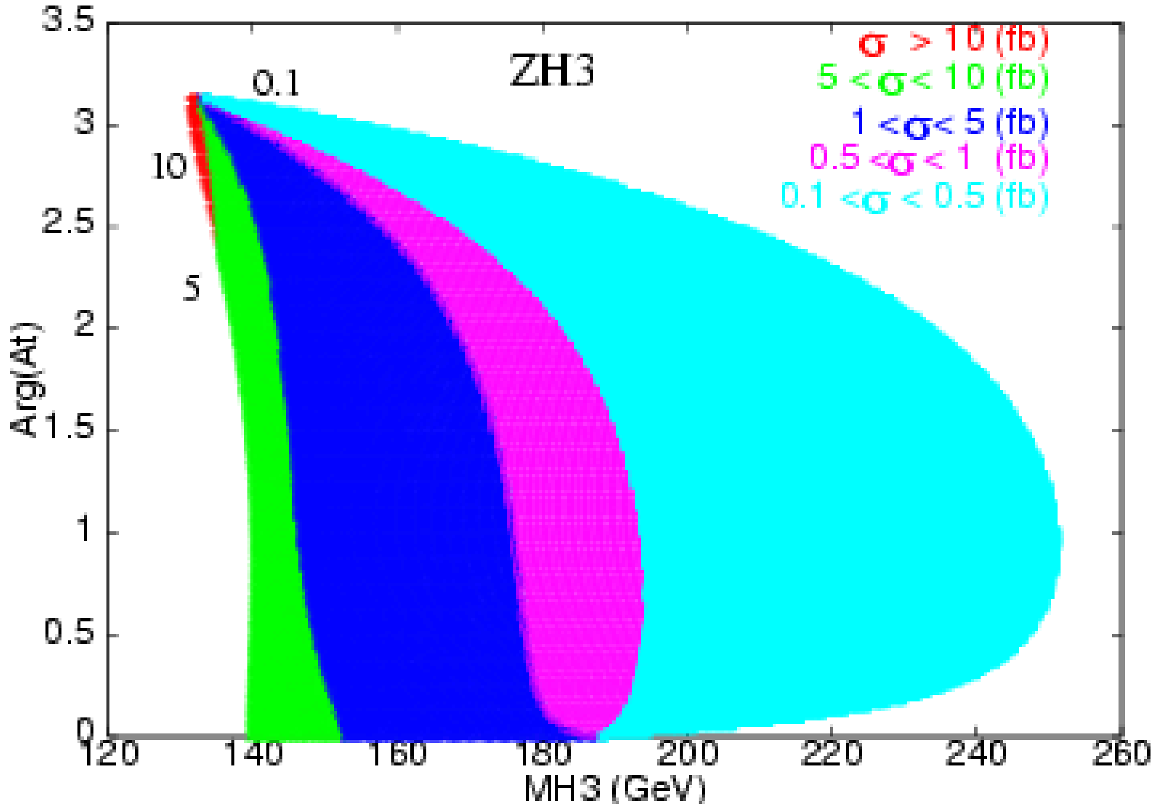
$M_{SUSY} = 1$ TeV, $\tan\beta = 6$, $\sqrt{s} = 500$ GeV



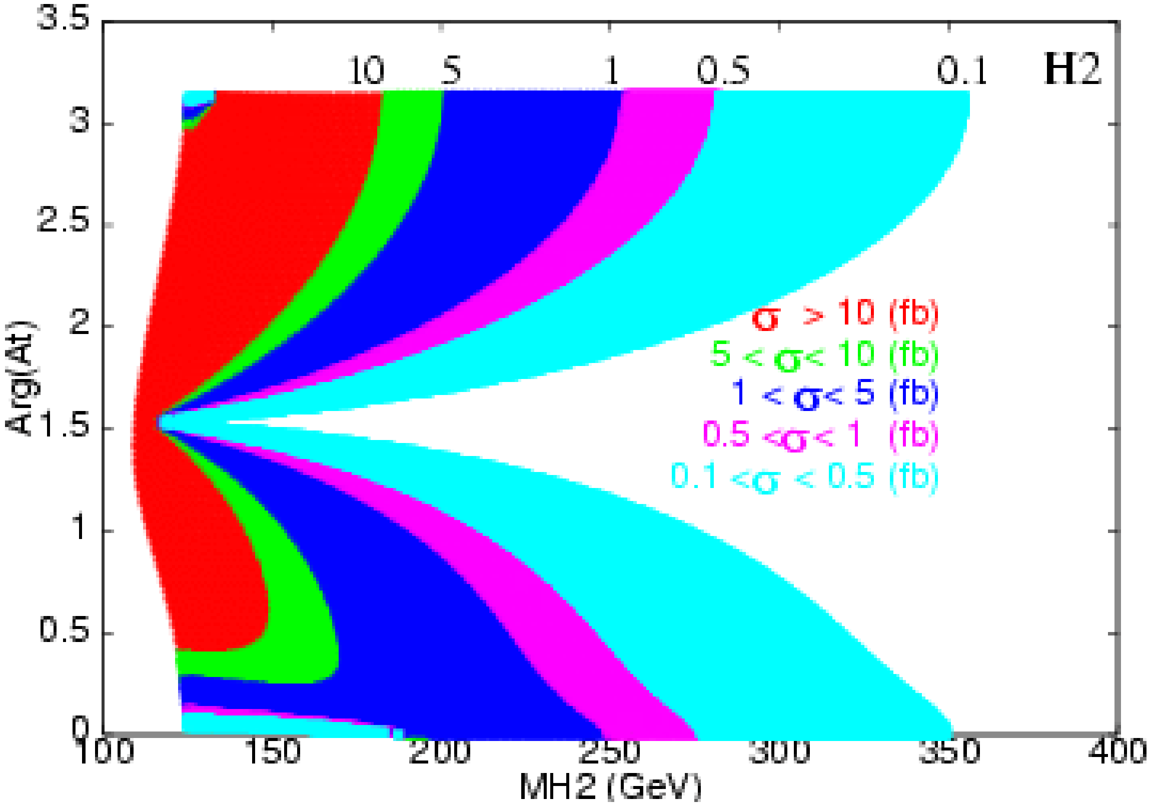


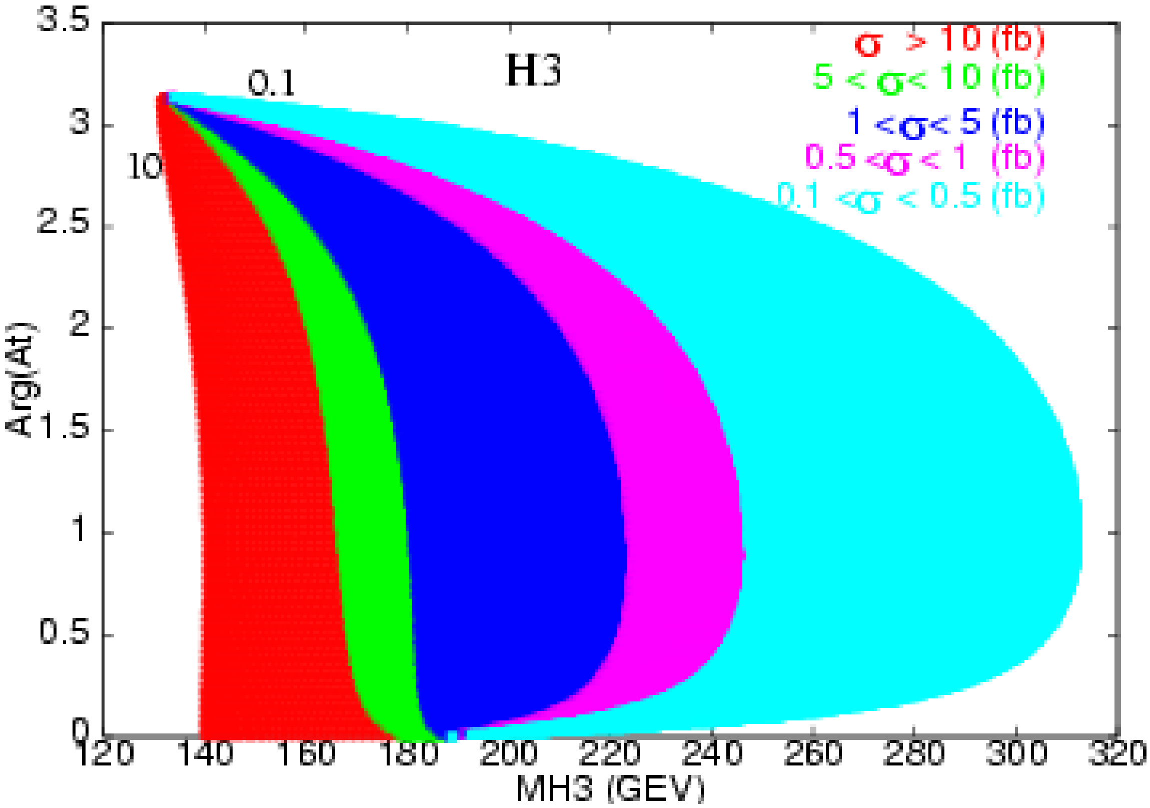
$M_{SUSY} = 1$ TeV, $\tan\beta = 6$, $\sqrt{s} = 800$ GeV



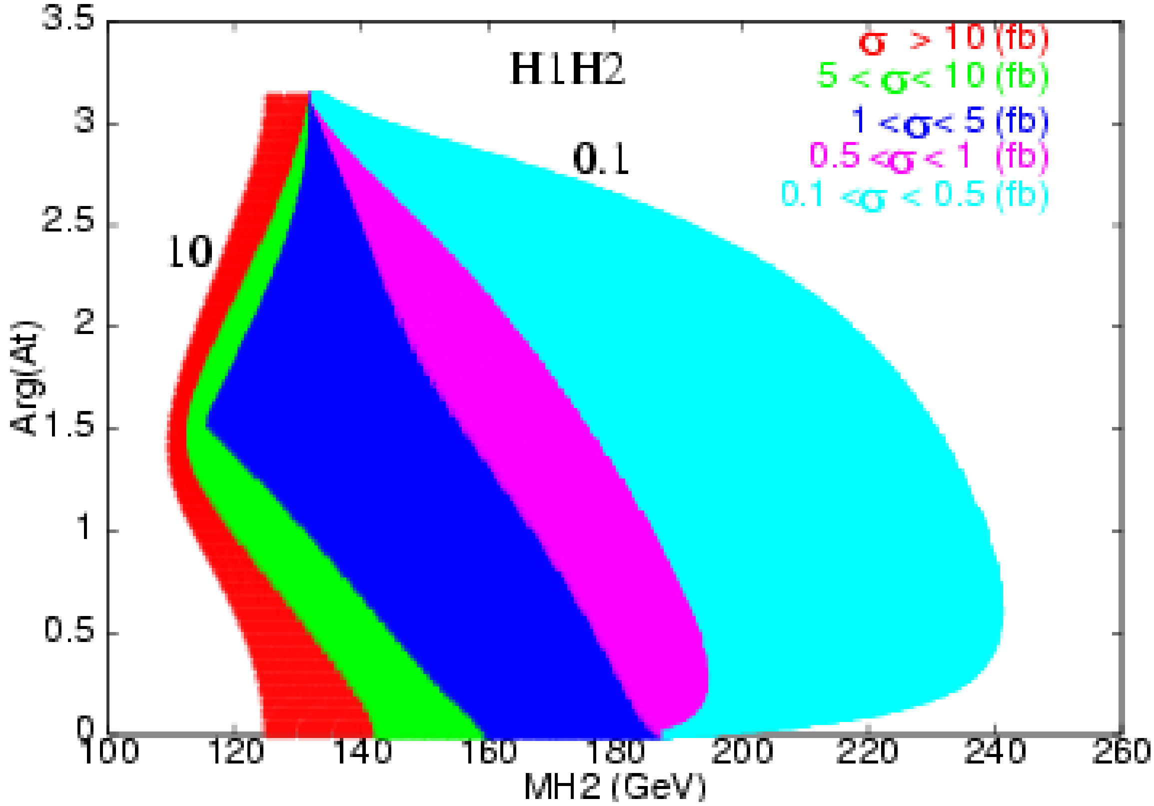


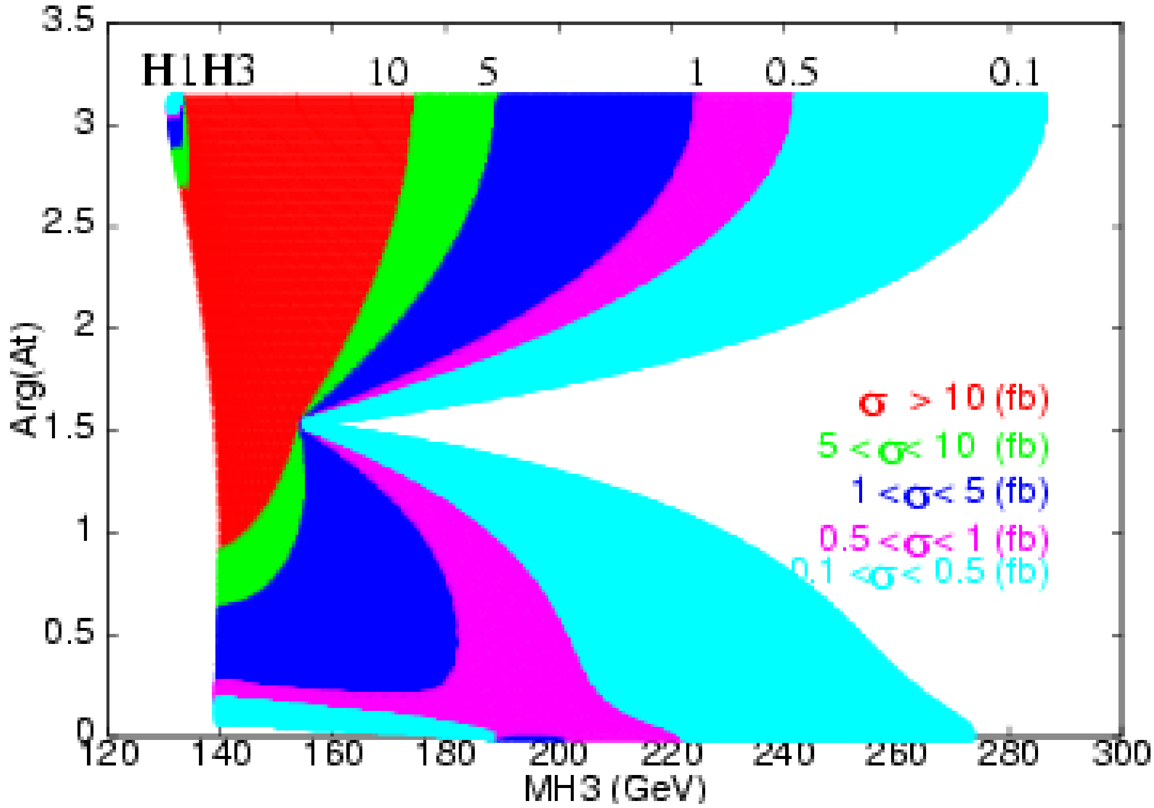
$M_{SUSY} = 1$ TeV, $\tan\beta = 6$, $\sqrt{s} = 800$ GeV





$M_{SUSY} = 1$ TeV, $\tan\beta = 6$, $\sqrt{s} = 500$ GeV





4. Summary and outlook

• In the MSSM with real parameters, $\sigma(e^+e^- \to ZA)$ & $\sigma(e^+e^- \to \nu_e\bar{\nu}_e A^0)$ are too small

• In the complex MSSM, large CP phases can enhance $\sigma(e^+e^- \to ZA)$ & $\sigma(e^+e^- \to \nu_e\bar{\nu}_e A^0)$ up to 0.1 fb

• If all three H_i are produced in $e^+e^- \to ZH_i$ with cross section $\gtrsim$ 0.1 fb, this would be evidence for scalar-pseudoscalar mixing

• A sizeable signal in both $e^+e^- \to ZH_2, ZH_3$, $e^+e^- \to \nu_e\bar{\nu}_e H_2$, $\nu_e\bar{\nu}_e H_3$ and/or $e^+e^- \to H_1H_2, H_1H_3$ would be evidence for scalar-pseudoscalar mixing.

• In $\not{C}$PMSSM, $ZZH_1 \approx 0$, difficult to observe, in this case $e^+e^- \to H_1H_2$, H_1H_3 and/or $e^+e^- \to b\bar{b}H_1$, $t\bar{t}H_1$ may be useful.