Phenomenology in the μNMSSM

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Motivations

- Embedding inflation-models in collider phenomenology
- Distinction of inflation-inspired SUSY models from SUSY models without inflation

NMSSM and Inflation

- Higgs inflation triggered by non-minimal coupling to Einstein gravity

$$X = \chi \hat{H}_u \cdot \hat{H}_d$$

- Superpotential of Higgs sector

$$\mathcal{W}_{\text{Higgs}} \to \mathcal{W}_{\text{Higgs}} + \tfrac{3}{2} m_{3/2} \chi \hat{H}_u \cdot \hat{H}_d$$

$$\begin{aligned} \mathcal{W}_{\mu\text{NMSSM}} =& (\lambda \hat{S} + \frac{3}{2} m_{3/2} \chi) \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 \\ &+ \mathbf{Y}_u \hat{Q} \cdot \hat{H}_u \hat{U}_R^c + \mathbf{Y}_d \hat{H}_d \cdot \hat{Q} \hat{D}_R^c + \mathbf{Y}_e \hat{H}_d \cdot \hat{\ell} \hat{E}_R^c \end{aligned}$$

NMSSM and Inflation

- Expansion around the vevs:

$$H_u \equiv \begin{pmatrix} h_u^+ \\ h_u \end{pmatrix} = \begin{pmatrix} \eta_u^+ \\ v_u + \frac{1}{\sqrt{2}}(\sigma_u + i\,\phi_u) \end{pmatrix} \quad H_d \equiv \begin{pmatrix} h_d \\ h_d^- \end{pmatrix} = \begin{pmatrix} v_d + \frac{1}{\sqrt{2}}(\sigma_d + i\,\phi_d) \\ \eta_d^- \end{pmatrix}$$

$$S \equiv v_s + \frac{1}{\sqrt{2}}(\sigma_s + i\,\phi_s)$$

- Additional μ-term:

$$\mu_{\text{inf}} = \frac{3}{2} m_{3/2} \chi$$

Effective μ-term:

$$\mu_{\text{eff}} = \lambda v_s$$

Higgs-sector

- Higgs mass matrices

$$M^2_{S,11} = m_Z^2 \cos^2\beta + \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)\tan\beta$$

$$M^2_{S,22} = m_Z^2 \sin^2\beta + \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)/\tan\beta$$

$$M^2_{S,33} = \frac{\lambda^2 v^2}{\mu_{\rm eff}}(\cos\beta\sin\beta A_\lambda - \mu_{\rm inf}) + \frac{\kappa}{\lambda}\mu_{\rm eff}\left(A_\kappa + 4\frac{\kappa}{\lambda}\mu_{\rm eff}\right)$$

$$M^2_{S,12} = M^2_{S,21} = (2v^2\lambda^2 - m_Z^2)\cos\beta\sin\beta - \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)$$

$$M^2_{S,13} = M^2_{S,31} = \lambda v\left(2(\mu_{\rm eff} + \mu_{\rm inf})\cos\beta - \left(A_\lambda + 2\frac{\kappa}{\lambda}\mu_{\rm eff}\right)\sin\beta\right)$$

$$M^2_{S,23} = M^2_{S,32} = \lambda v\left(2(\mu_{\rm eff} + \mu_{\rm inf})\sin\beta - \left(A_\lambda + 2\frac{\kappa}{\lambda}\mu_{\rm eff}\right)\cos\beta\right)$$

$$M^2_{P,11} = \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)\tan\beta$$

$$M^2_{P,22} = \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)/\tan\beta$$

$$M^2_{P,33} = \frac{\lambda^2 v^2}{\mu_{\rm eff}}\left((4\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda)\cos\beta\sin\beta - \mu_{\rm inf}\right) - 3\frac{\kappa}{\lambda}\mu_{\rm eff}A_\kappa$$

$$M^2_{P,12} = M^2_{S,21} = \mu_{\rm eff}\left(\frac{\kappa}{\lambda}\mu_{\rm eff} + A_\lambda\right)$$

$$M^2_{P,13} = M^2_{S,31} = -v\lambda\left(2\frac{\kappa}{\lambda}\mu_{\rm eff} - A_\lambda\right)\sin\beta$$

$$M^2_{P,23} = M^2_{S,32} = -v\lambda\left(2\frac{\kappa}{\lambda}\mu_{\rm eff} - A_\lambda\right)\cos\beta$$

Neutralino and Chargino-sector

- Electroweakino mass matrices

$$M_{\chi^0} = \begin{pmatrix} M_1 & 0 & -m_Z \sin\theta_w \cos\beta & m_Z \sin\theta_w \sin\beta & 0 \\ \cdot & M_2 & m_Z \cos\theta_w \cos\beta & -m_Z \cos\theta_w \sin\beta & 0 \\ \cdot & \cdot & 0 & -(\mu_{\rm inf} + \mu_{\rm eff}) & -\lambda v \sin\beta \\ \cdot & \cdot & \cdot & 0 & -\lambda v \cos\beta \\ \cdot & \cdot & \cdot & \cdot & 2\frac{\kappa}{\lambda}\mu_{\rm eff} \end{pmatrix}$$

$$M_{\chi^\pm} = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu_{\rm inf} + \mu_{\rm eff} \end{pmatrix}$$

$$(\psi^0)^T = (\tilde{B}^0, \tilde{W_3}^0, \tilde{h_d}^0, \tilde{h_u}^0, \tilde{s}^0)$$

NMSSM benchmark points

- Input parameters of benchmark point

$M_1 = 239$ GeV	$M_2 = 500$ GeV	$M_3 = 2500$ GeV	$A_{f_3} = 1200$ GeV	$m_{\tilde{f}_L,\tilde{f}_R} = 2000$ GeV	$m_{H^\pm} = 800$ GeV
$\tan\beta = 12$	$\kappa = 0.01846$	$\lambda = 0.04215$	$\mu_{\rm eff} = -212.3$ GeV	$A_\kappa = 268.6$ GeV	

- Benchmark mass spectrum:

$m_{h_1} = 91.6$ GeV	$m_{h_2} = 123.7$ GeV	$m_{H_3} = 809.1$ GeV
$m_a = 273.7$ GeV	$m_A = 809$ GeV	$M_{H^\pm} = 812.6$ GeV
$m_{\chi_1} = 190$ GeV	$m_{\chi_2} = 193.9$ GeV	$m_{\chi_3} = 225.7$ GeV
$m_{\chi_4} = 254.9$ GeV	$m_{\chi_5} = 537.3$ GeV	
$m_{\chi_1^\pm} = 214.2$ GeV	$m_{\chi_2^\pm} = 537.3$ GeV	

μNMSSM Scan

- Fixing combinations:

$$a = \mu_{\text{inf}} + \mu_{\text{eff}}, \qquad b = \frac{\kappa}{\lambda}\mu_{\text{eff}}, \qquad c = \mu_{\text{eff}}(\frac{\kappa}{\lambda}\mu_{\text{eff}} + A_\lambda)$$

$$M^2_{S,13} = M^2_{S,31} = v\lambda\left(2a\cos\beta - (\frac{c}{a-\mu_{\text{inf}}} + b)\sin\beta\right)$$

$$M^2_{S,23} = M^2_{S,32} = v\lambda\left(2a\sin\beta - (\frac{c}{a-\mu_{\text{inf}}} + b)\cos\beta\right)$$

$$M^2_{S,33} = \lambda^2 v^2\left(\frac{\cos\beta\sin\beta}{a-\mu_{\text{inf}}}(\frac{c}{a-\mu_{\text{inf}}} - b) - \frac{\mu_{\text{inf}}}{a-\mu_{\text{inf}}}\right) + b(A_\kappa + 4b)$$

$$M^2_{P,13} = M^2_{P,31} = -v\lambda\left(3b - \frac{c}{a-\mu_{\text{inf}}}\right)\sin\beta$$

$$M^2_{P,23} = M^2_{P,32} = -v\lambda\left(3b - \frac{c}{a-\mu_{\text{inf}}}\right)\cos\beta$$

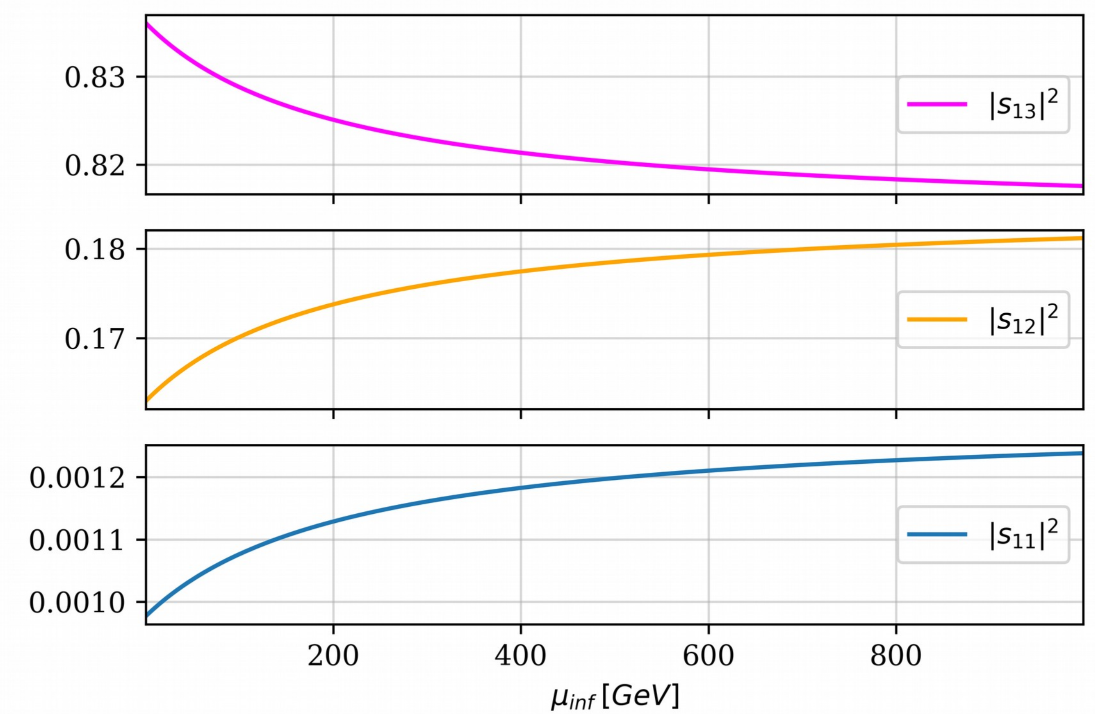
$$M^2_{P,33} = \lambda^2 v^2\left(\frac{\cos\beta\sin\beta}{a-\mu_{\text{inf}}}(3b + \frac{c}{a-\mu_{\text{inf}}}) - \frac{\mu_{\text{inf}}}{a-\mu_{\text{inf}}}\right)$$

μ_{inf} effects: Mixing

- $|S_{11}|^2$, $|S_{12}|^2$ determine the coupling of h_1 to b quark and gauge bosons

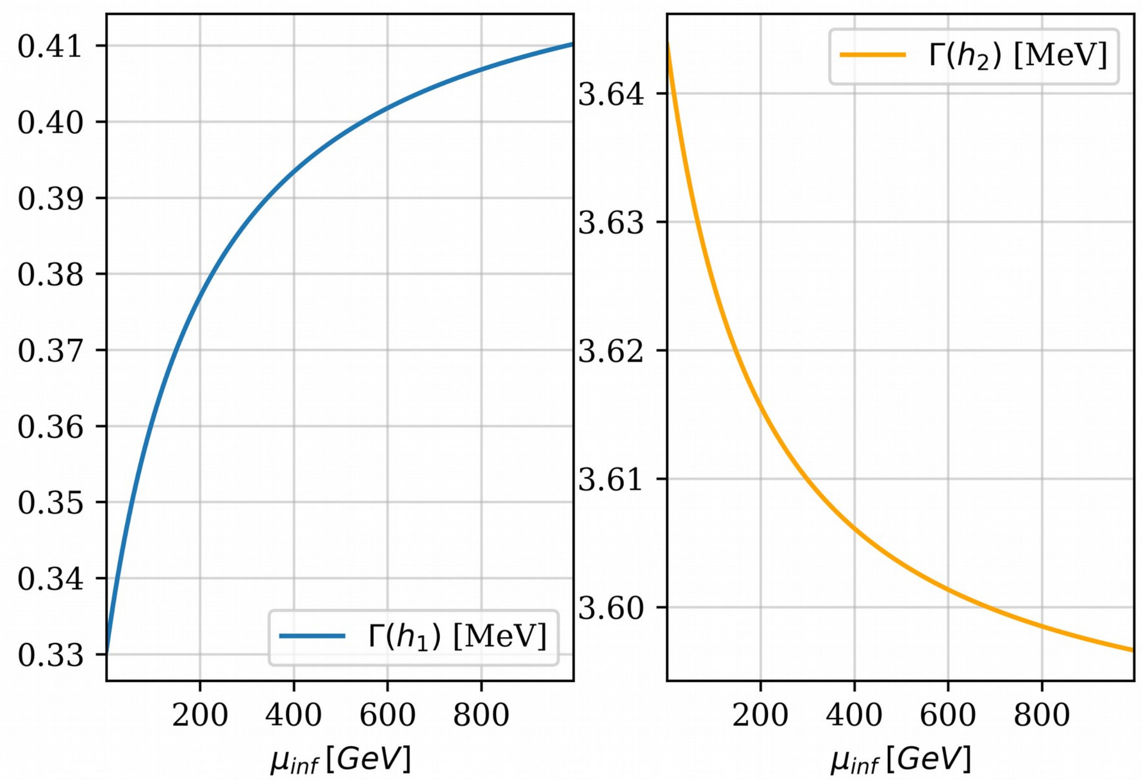
$$\frac{g_{h_i ZZ}}{g_{H_{SM} ZZ}} = \frac{g_{h_i W^+ W^-}}{g_{H_{SM} W^+ W^-}} = \cos\beta S_{i1} + \sin\beta S_{i2}$$

- Mixings are changed less than 10%



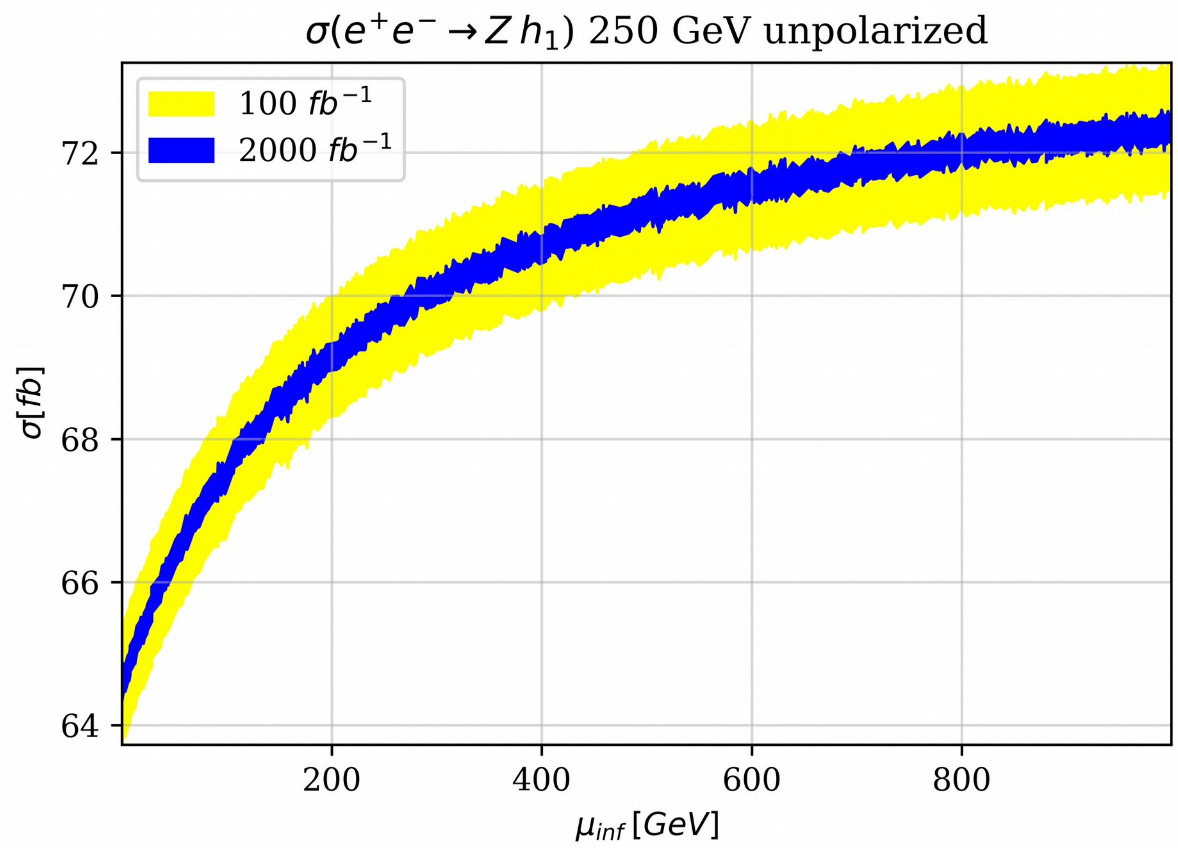
μ_{inf} effects: Total Width

- $\Gamma(h_1)$ is too small to measure
- There would be more than 10% difference between the NMSSM case and the μ_{inf}>100 GeV cases



μ_{inf} effects: Cross-sections

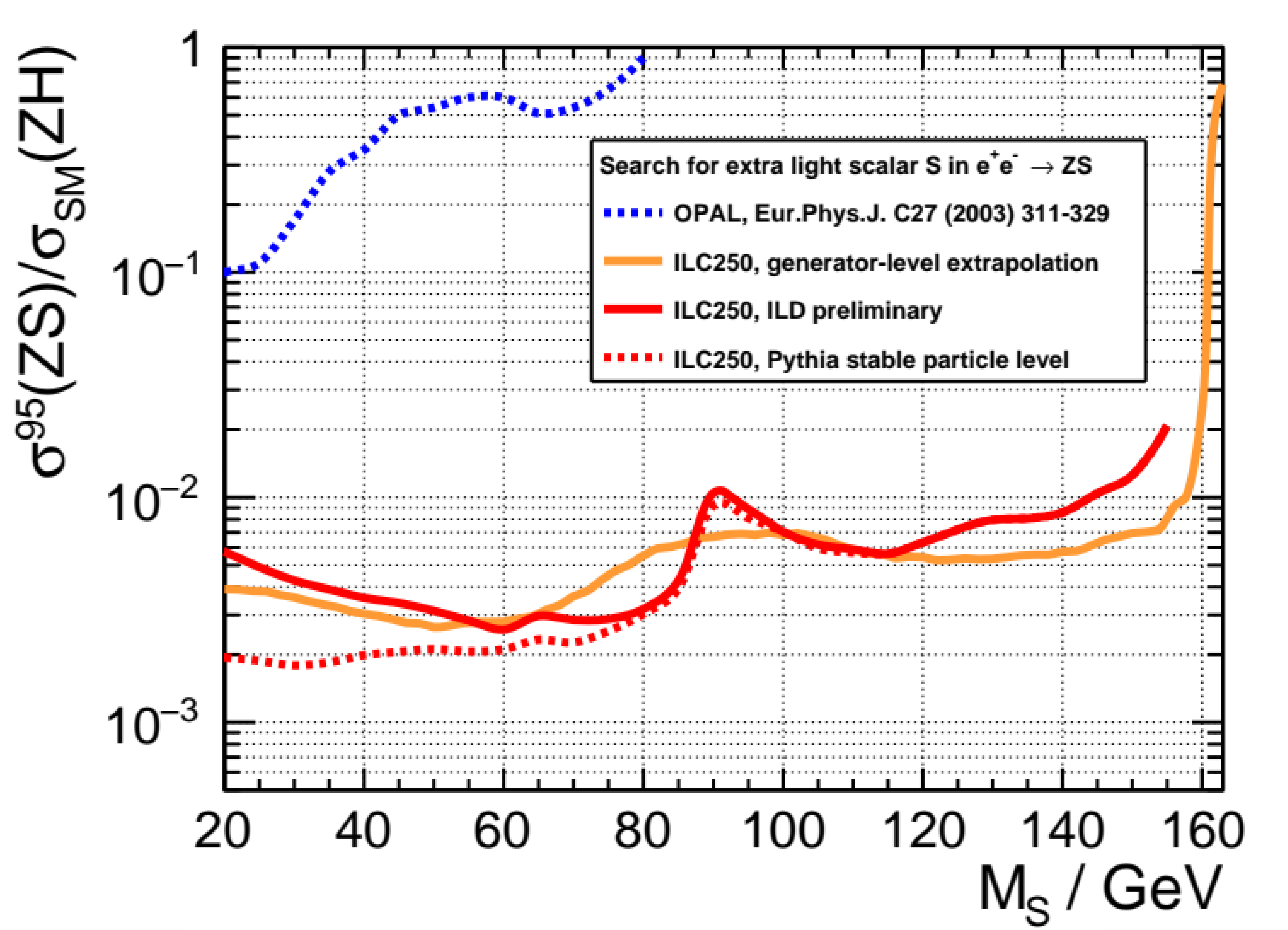
- For 100 fb^{-1} luminosity, the μ_{inf}>50 GeV cases can be distinguished from NMSSM case
- For higher luminosity, the distinguishable μ_{inf} values would be smaller



Conclusions

- We discussed that how do the observables depend on pure $\mu_{\rm inf}$ effect
- We found that μNMSSM can be experimentally distinguished from NMSSM with sufficient integral luminosity

Backup



Search for extra light scalar S in $e^+e^- \rightarrow ZS$
OPAL, Eur.Phys.J. C27 (2003) 311-329
ILC250, generator-level extrapolation
ILC250, ILD preliminary
ILC250, Pythia stable particle level
$\sigma^{95}(ZS)/\sigma_{SM}(ZH)$
1
10^{-1}
10^{-2}
10^{-3}
20
40
60
80
100
120
140
160
M_S / GeV

Backup

- Other NMSSM points

  ($\tan\beta=12$, $m_{H\pm}=800$)

$\kappa=0.0298$	$\lambda=0.0726$	$\mu_{eff}= -126.32$	$A_\kappa=15.06$	$M_1=341.998$	$M_2=253.065$	$A_{f3}=2000$
$M_{h1}=95.7$	$M_{h2}=124.6$	$M_a=48.87$	$M_{\chi1+}=121.9$	$M_{\chi10}=105.6$	$M_{\chi20}=112.0$	$M_{\chi30}=143.3$

$\kappa=0.0045$	$\lambda=0.0148$	$\mu_{eff}= 247.51$	$A_\kappa=-130.65$	$M_1=286.04$	$M_2=193.51$	$A_{f3}=2500$
$M_{h1}=112.0$	$M_{h2}=125.3$	$M_a=172.3$	$M_{\chi1+}=170.68$	$M_{\chi10}=154.5$	$M_{\chi20}=166.8$	$M_{\chi30}=260.1$