

Neutralino pair annihilations with supersymmetric CP violation

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SUSY 2005

July 18-23, 2005

IPPP, Durham

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1. Introduction

Relic density

Recent cosmological observations have convinced us that
Our Universe \approx Dark Energy + CDM.

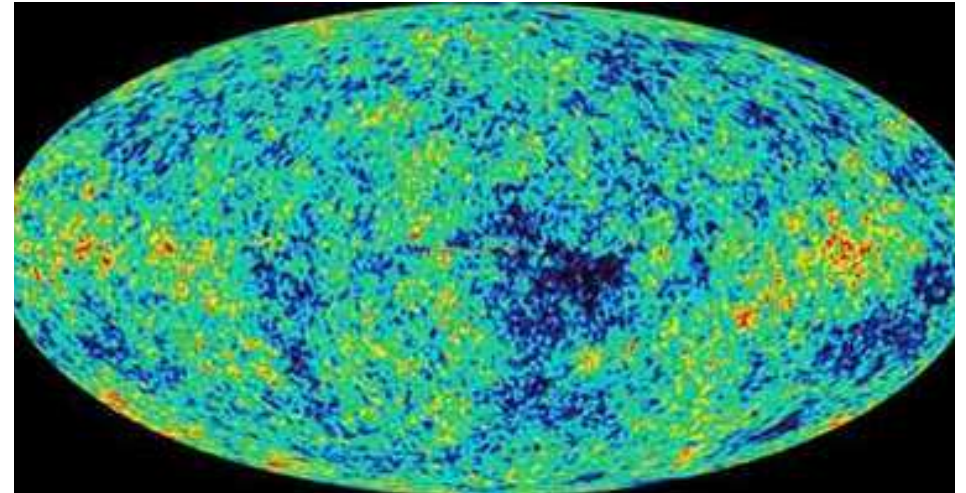
WMAP (2001–, NASA)

$$\Omega_\chi h^2 = 0.1126^{+0.008}_{-0.009}$$

(χ : CDM)

$$\Omega_\chi \equiv \rho_\chi / \rho_c$$

$$h \approx 0.7 \quad (H_0 = 100 h \text{ km/s/Mpc})$$



SUSY naturally accommodates a candidate for CDM.

Effect of supersymmetric CP violation on DM observables

2. Minimal SUSY SM with CP violation

- Relevant parameters

M_1, M_2 – gaugino mass

μ – higgsino mass

m_0 – sfermion mass for the 3rd generation
(10 TeV for the first two gen. to suppress EDM)

A – scalar trilinear coupling for the 3rd gen.

$\tan \beta$ – ratio of higgs vevs

m_A – pseudoscalar higgs mass

- CP violating phases

$$\mu = |\mu| \exp(i \theta_\mu), \quad A = A_0 \exp(i \theta_A)$$

- GUT relation for gaugino masses

$$M_1 = \frac{5}{3} \tan^2 \theta_W M_2 \quad (M_i : \text{real})$$

- Scalar–pseudoscalar mixing

Pilaftsis (1998)

$\text{Im}(A \mu)$ induces S–PS mixing at one-loop level.

$$\begin{pmatrix} H_1^0 \\ H_2^0 \\ H_3^0 \end{pmatrix} = O_H \begin{pmatrix} \phi_1 \\ \phi_2 \\ A \end{pmatrix}$$

For $\theta_\mu = \theta_A = 0$, $H_1^0 = H$, $H_2^0 = h$, $H_3^0 = A$

- Neutralino DM

$$\chi = N_{11} \tilde{B} + N_{12} \tilde{W}^3 + N_{13} \tilde{H}_1^0 + N_{14} \tilde{H}_2^0$$

$$M_1 \ll |\mu| \rightarrow \tilde{B}\text{-like LSP}$$

$$M_1 \approx |\mu| \rightarrow \text{Mixed LSP}$$

$$M_1 \gg |\mu| \rightarrow \tilde{H}\text{-like LSP}$$

3. Neutralino pair annihilations

- Relic density

Boltzmann equation

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_\chi^{\text{eq}2})$$

- Indirect detection

Positron flux from χ pair annihilation in the halo

Most important process

$\chi\chi \rightarrow W^+W^-$ followed by $W^+ \rightarrow e^+\nu_e$

$$\frac{dF(e^+)}{dE} = \frac{\rho_0^2}{m_\chi^2} \int d\epsilon G(E, \epsilon) \sum_i \langle\sigma_i v\rangle f_i(\epsilon)$$

Local halo DM density $\rho_0 = 0.43$ GeV/cc

Containment time $\tau = 10^7$ yr

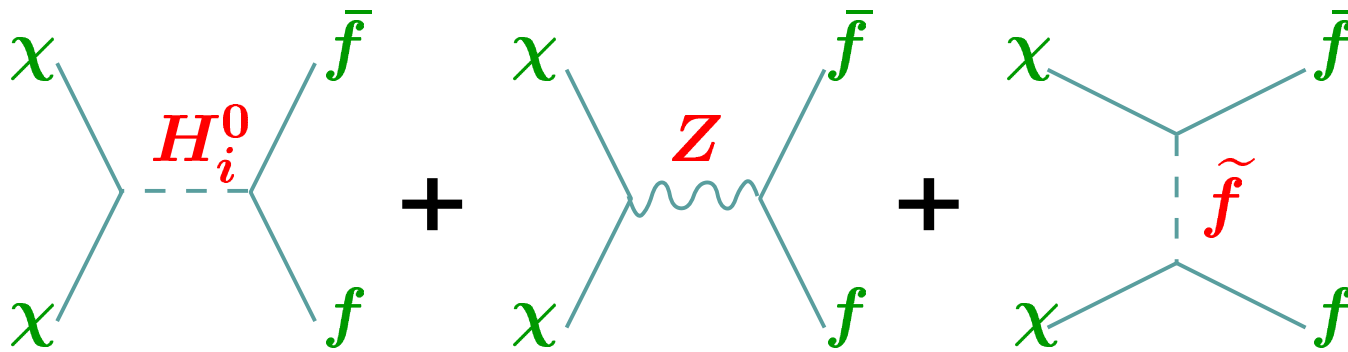
Galactic Halo: $v \approx 10^{-3}$

Kamionkowski–Turner
(1991)

Cross sections

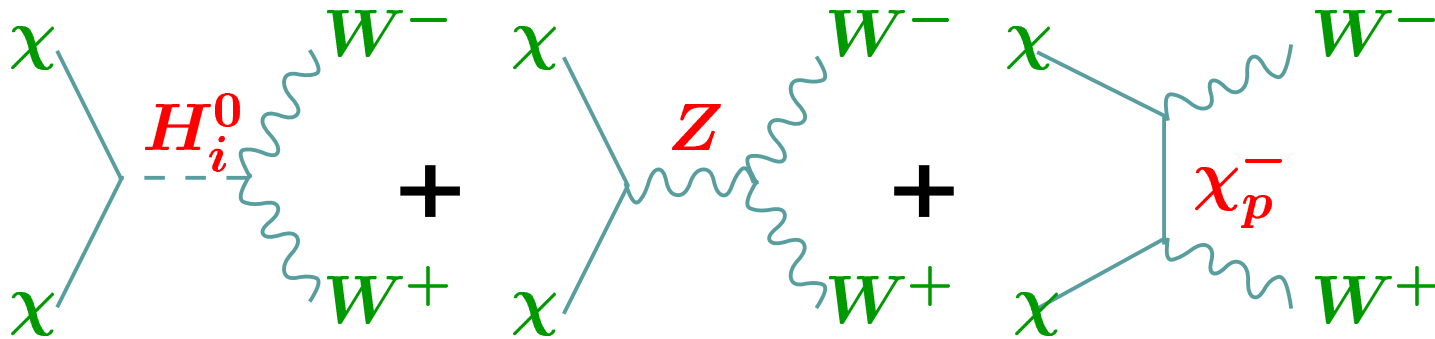
	Process	s-channel	t & u-channel
\tilde{B} -like	$\chi\chi \rightarrow f\bar{f}$	H_i^0, Z	\tilde{f}_{1-6}
	$\chi\chi \rightarrow H_i^0 H_j^0$ $H^+ H^-$	H_k^0, Z H_i^0, Z	χ_{1-4}^0 $\chi_{1,2}^\pm$
\tilde{H} -like	$\chi\chi \rightarrow W^+ W^-$ $Z Z$	H_i^0, Z H_i^0	$\chi_{1,2}^\pm$ χ_{1-4}^0
	$\chi\chi \rightarrow Z H_i^0$ $W^\pm H^\mp$	H_j^0, Z H_i^0	χ_{1-4}^0 $\chi_{1,2}^\pm$

$$\chi\chi \rightarrow f\bar{f}$$



- Typically dominant for \tilde{B} -like LSP
- S-wave suppression for $v \ll 1$ ($\sigma v \sim m_f^2/m_\chi^2$)

$$\chi\chi \rightarrow W^+W^-$$



- Open for $m_\chi > m_W$
- Typically dominant for \tilde{H} -like LSP
- No s-wave suppression

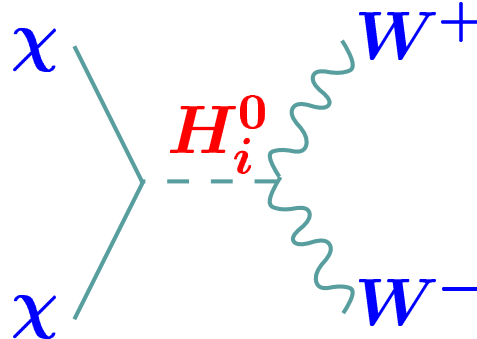
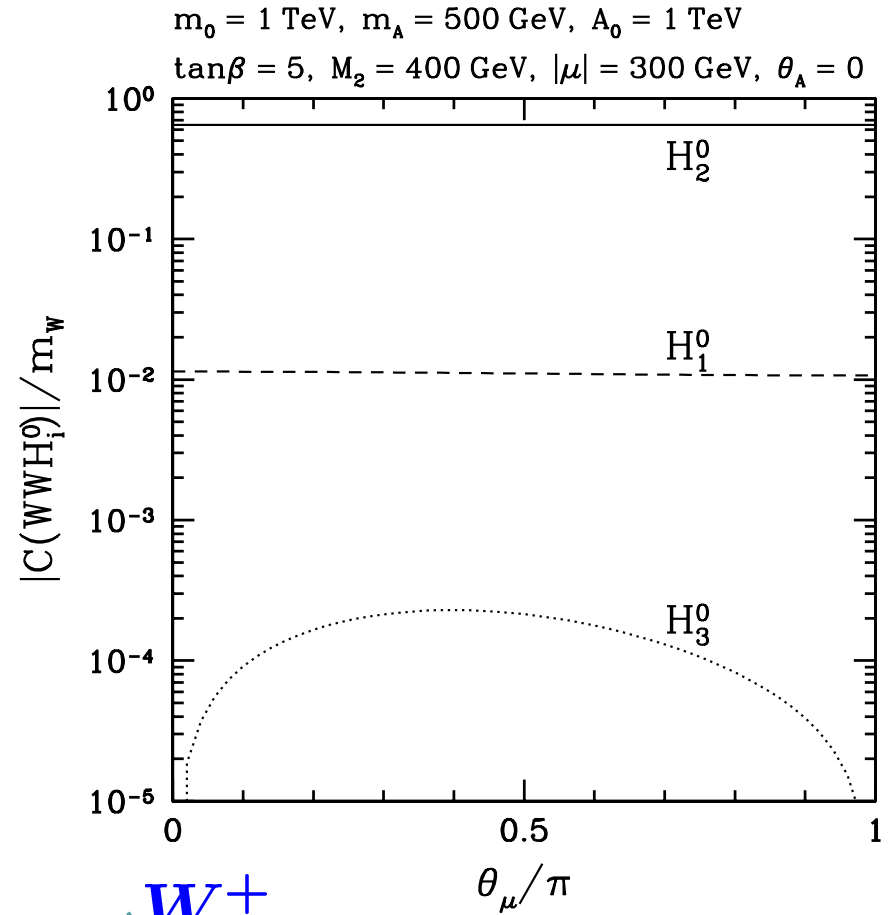
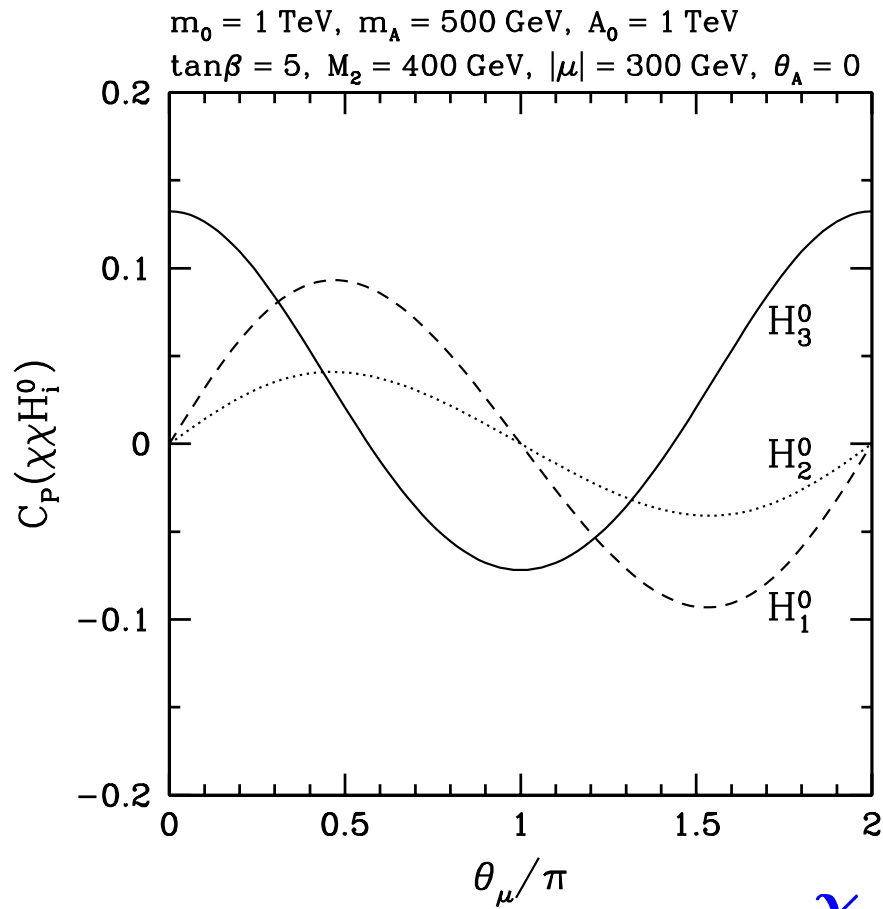
$\chi\chi H^0$ interaction

$$\mathcal{L} = \sum_{i=1}^3 \bar{\chi} \left(C_S^{\chi\chi H_i^0} + C_P^{\chi\chi H_i^0} \gamma_5 \right) \chi H_i^0$$

H_i^0 exchange contribution to $\chi\chi \rightarrow WW$

$$\sigma v = \frac{1}{32\pi m_\chi^2} \left[(s - 4m_\chi^2) \left| \sum_{r=H_i^0} \frac{C^{WWr} C_S^{\chi\chi r}}{s - m_r^2 + i\Gamma_r m_r} \right|^2 \right. \\ \left. + s \left| \sum_{r=H_i^0} \frac{C^{WWr} C_P^{\chi\chi r}}{s - m_r^2 + i\Gamma_r m_r} \right|^2 \right] \frac{s^2 - 4m_W^2 s + 12m_W^4}{8m_W^4}$$

Relevant couplings for H_i^0 exchange



4. Numerical results

Parameters

$$m_0 = A_0 = 1 \text{ TeV}$$

$$m_A = 500 \text{ GeV}, \tan \beta = 5$$

$$\theta_\mu = 0 - \pi$$

$$\theta_A = 0 - \pi$$

$$M_2 = 100 - 700 \text{ GeV}$$

$$|\mu| = 100 - 700 \text{ GeV}$$

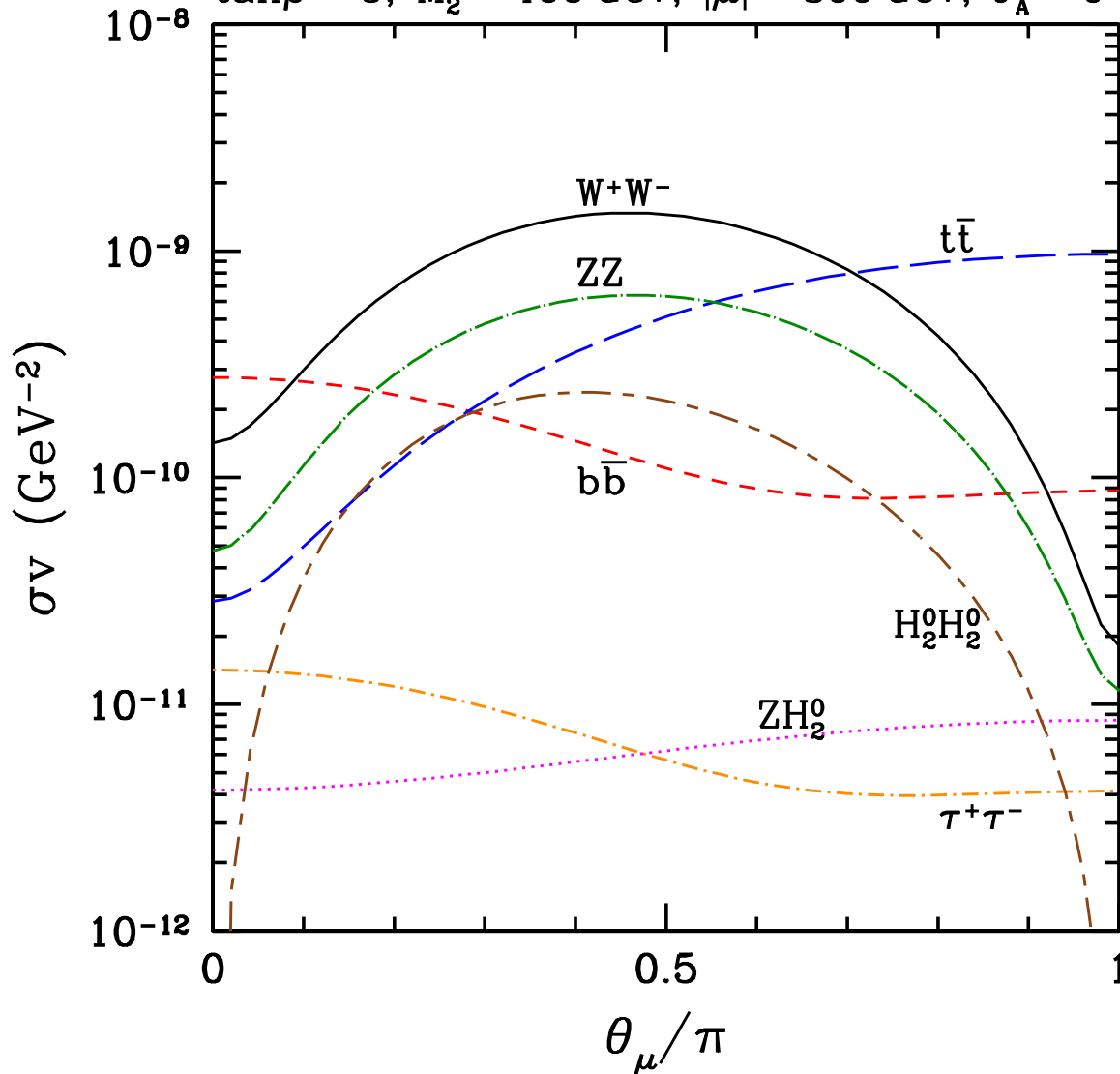
$$\longrightarrow \sigma v \text{ at } v = 10^{-3}$$

relic density ($\Omega_\chi h^2$)

positron fraction ($e^+ / (e^+ + e^-)$)

σv at $v = 10^{-3}$

$m_0 = 1 \text{ TeV}, m_A = 500 \text{ GeV}, A_0 = 1 \text{ TeV}$
 $\tan\beta = 5, M_2 = 400 \text{ GeV}, |\mu| = 300 \text{ GeV}, \theta_A = 0$



WW is significantly enhanced
 due to lightest higgs exchange
 for $\text{Im}(\mu) \neq 0$.
 (\tilde{B} -like or mixed LSP)

$$|N_{11}| \approx 0.9$$

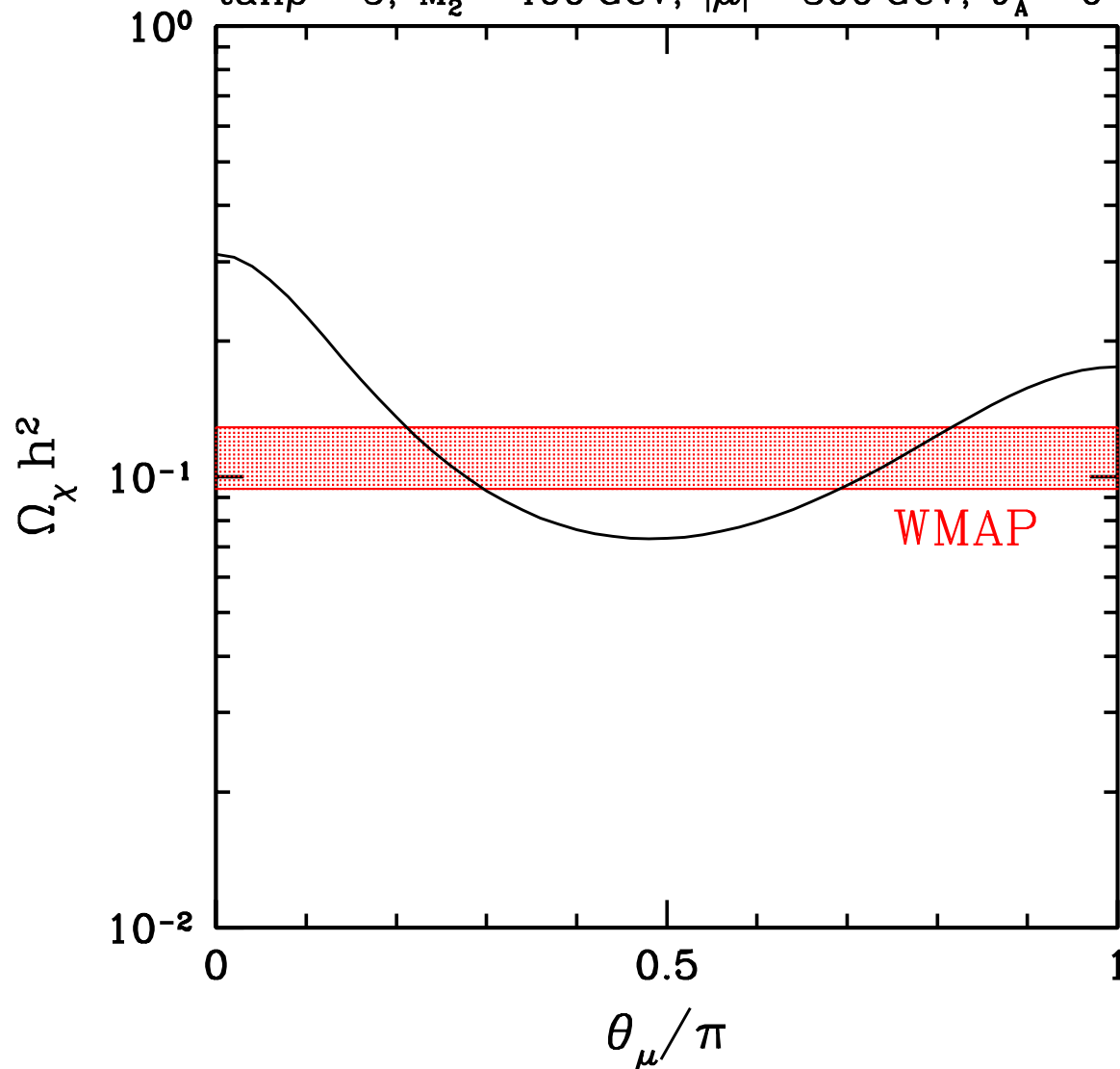
$$|N_{12}| \approx 0.01$$

$$|N_{13}| \approx |N_{14}| \approx 0.05$$

Relic density

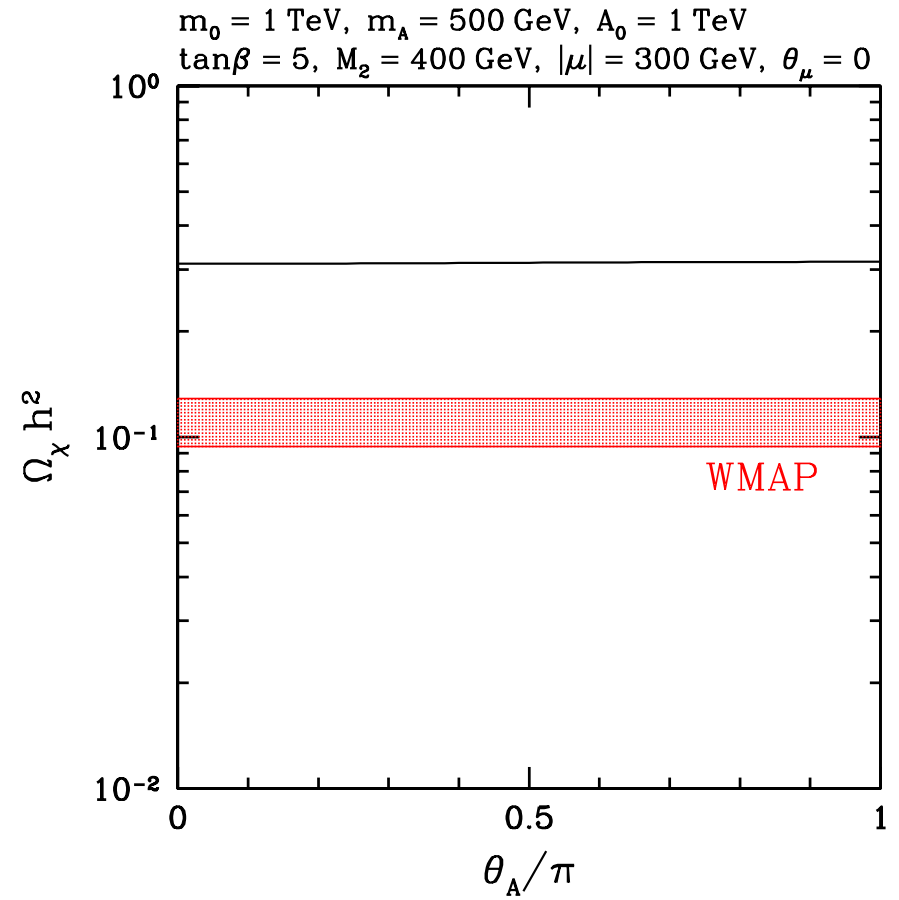
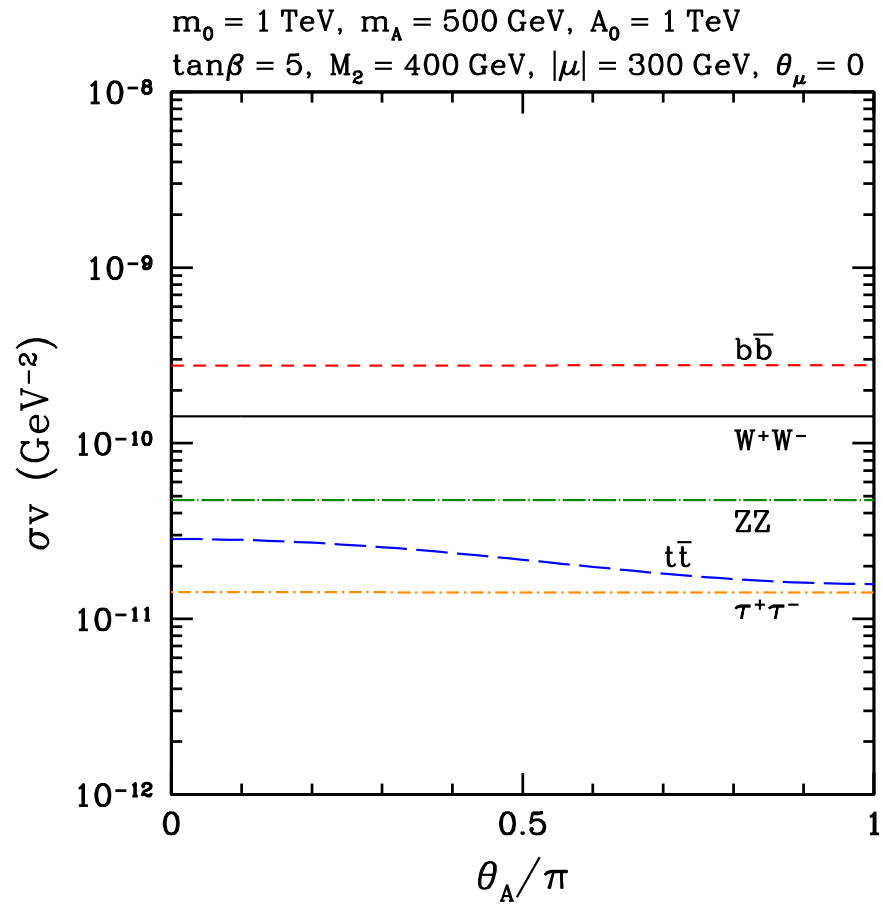
$m_0 = 1 \text{ TeV}$, $m_A = 500 \text{ GeV}$, $A_0 = 1 \text{ TeV}$
 $\tan\beta = 5$, $M_2 = 400 \text{ GeV}$, $|\mu| = 300 \text{ GeV}$, $\theta_A = 0$

(cf) T.N.–Sasagawa (PRD70, 2004)

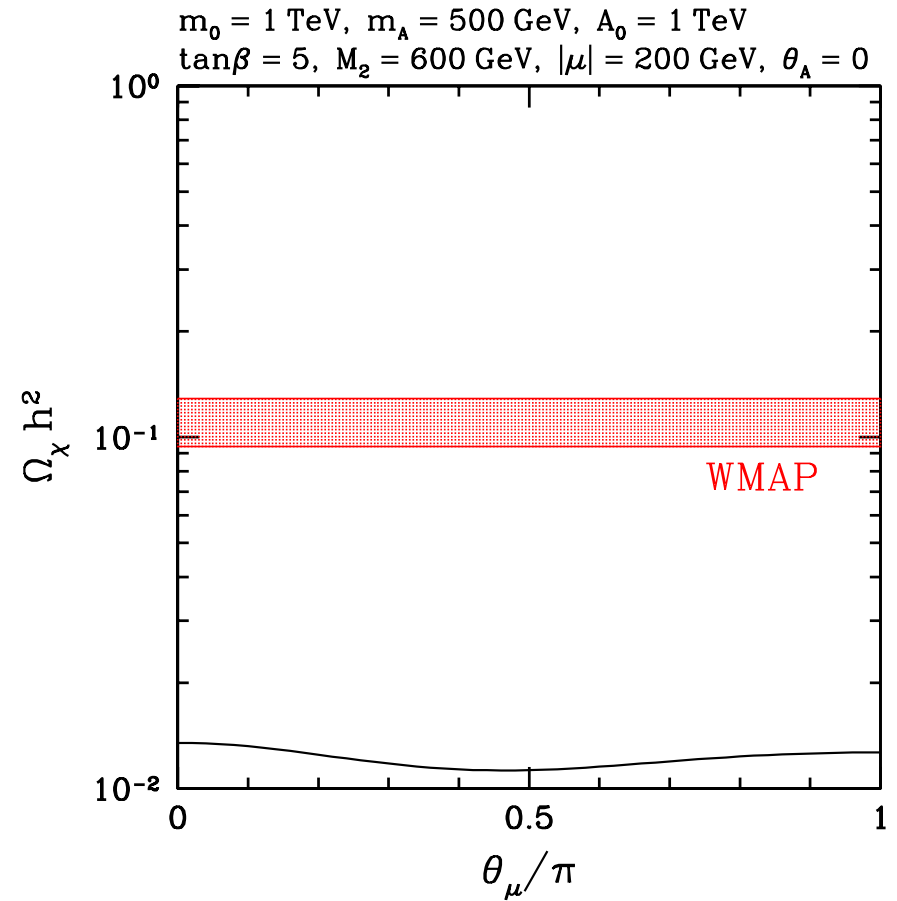
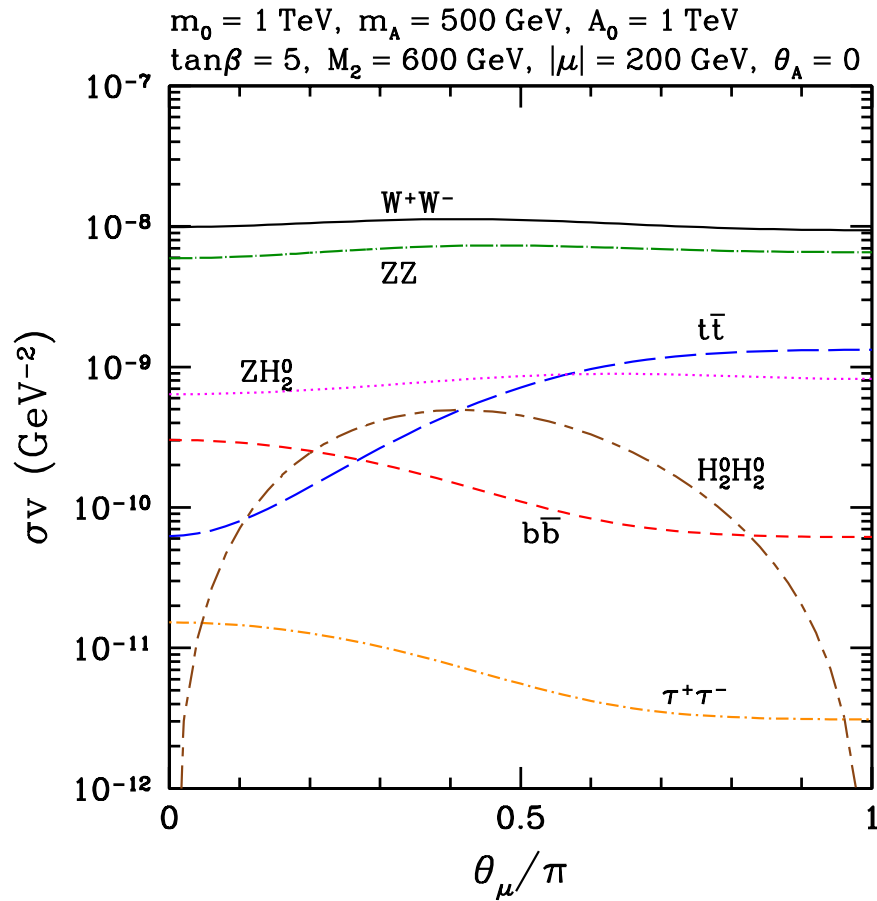


$\Omega_\chi h^2$ depends on θ_μ significantly.

Allowed regions consistent with WMAP appear for non-trivial θ_μ .

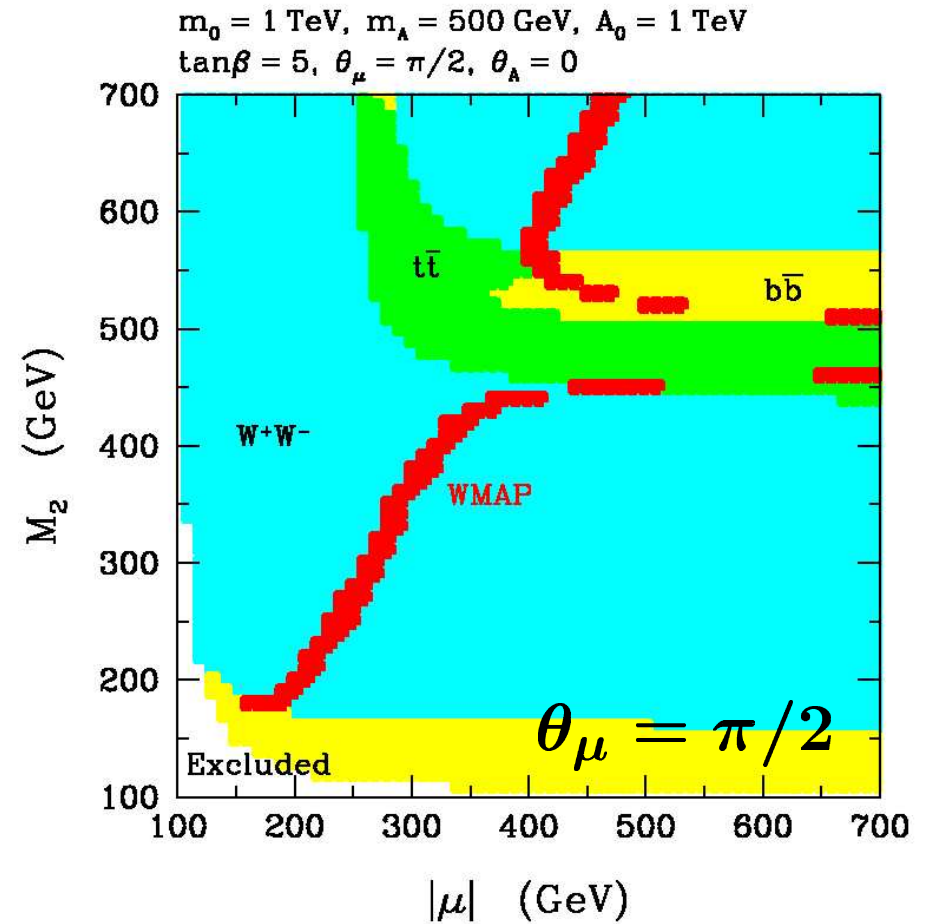
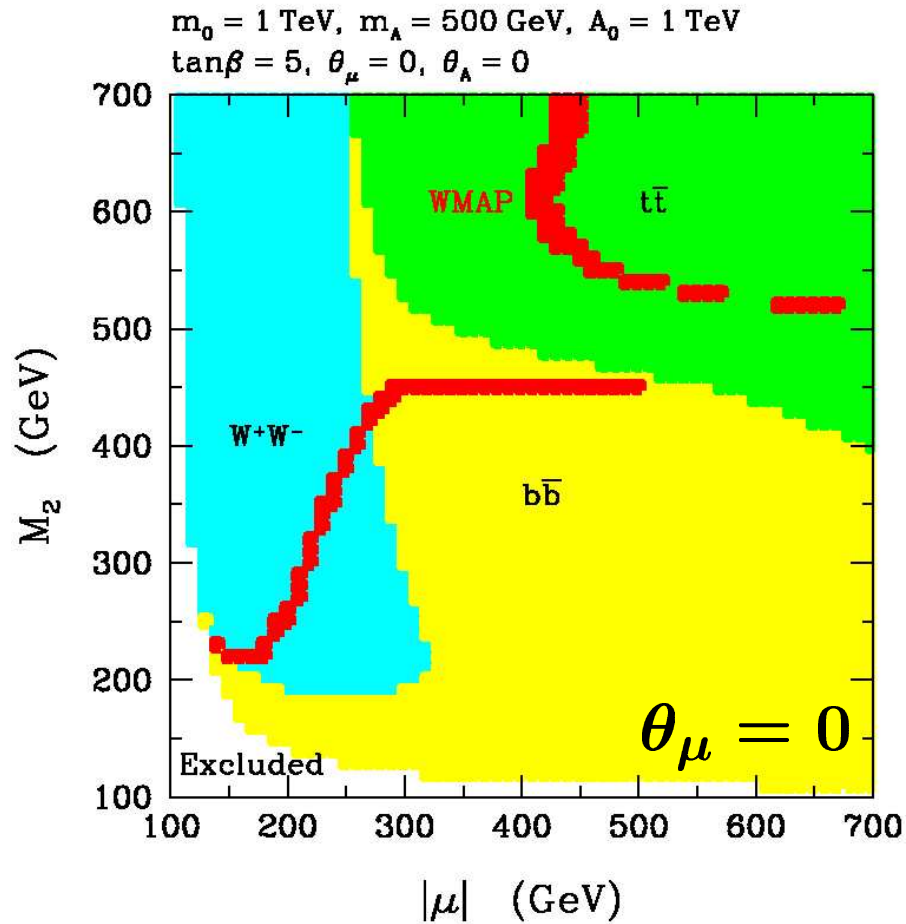


Effect of θ_A is typically small.



For \tilde{H} -like LSP, θ_μ dependence is weak.
 (Chargino exchange is dominant.)

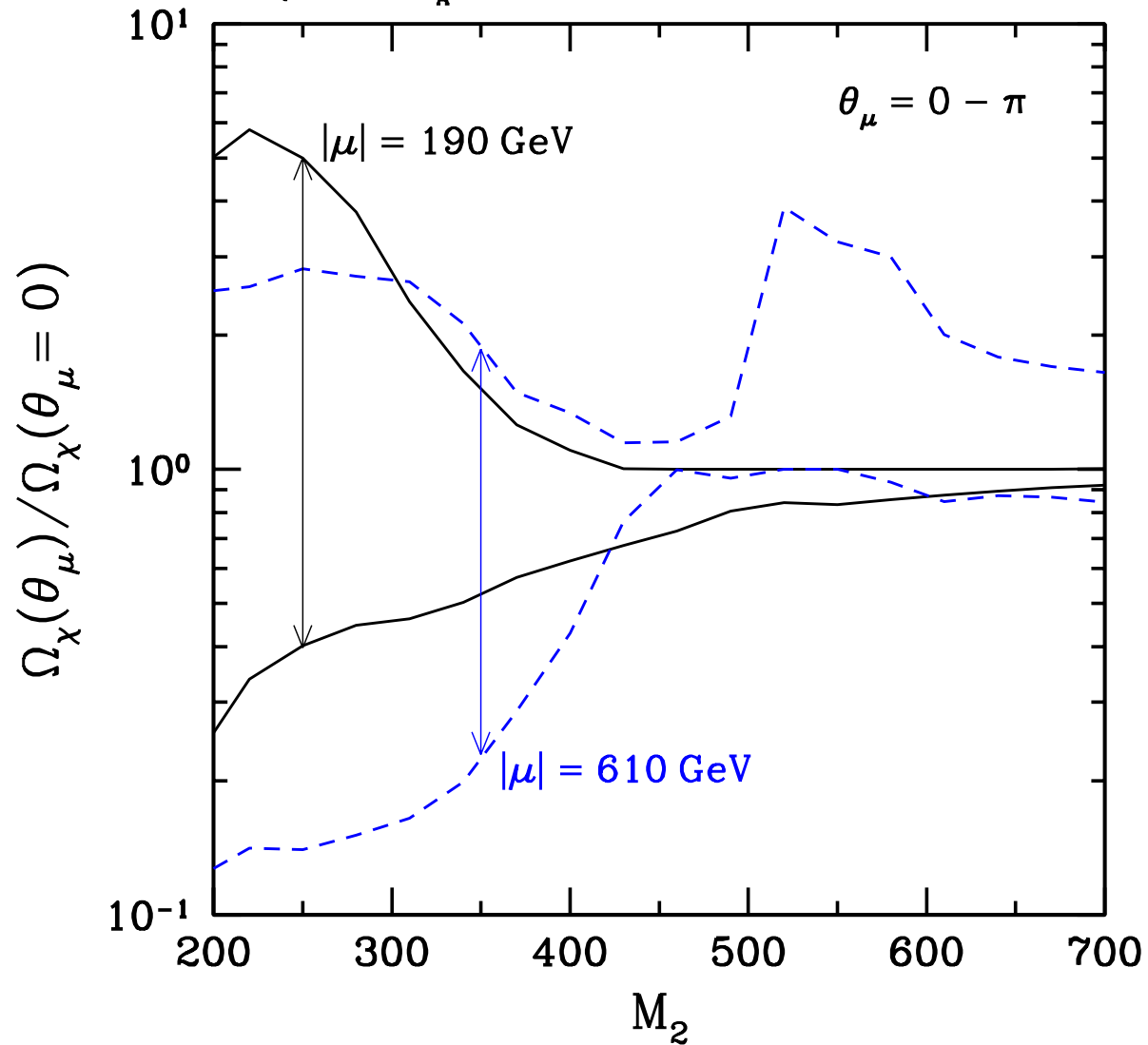
Dominant final state at $v = 10^{-3}$



In the presence of CP violation,
 W^+W^- final state can be dominant even for \tilde{B} -like LSP.

Variation with θ_μ

$m_0 = 1 \text{ TeV}$, $m_A = 500 \text{ GeV}$, $A_0 = 1 \text{ TeV}$
 $\tan\beta = 5$, $\theta_A = 0$

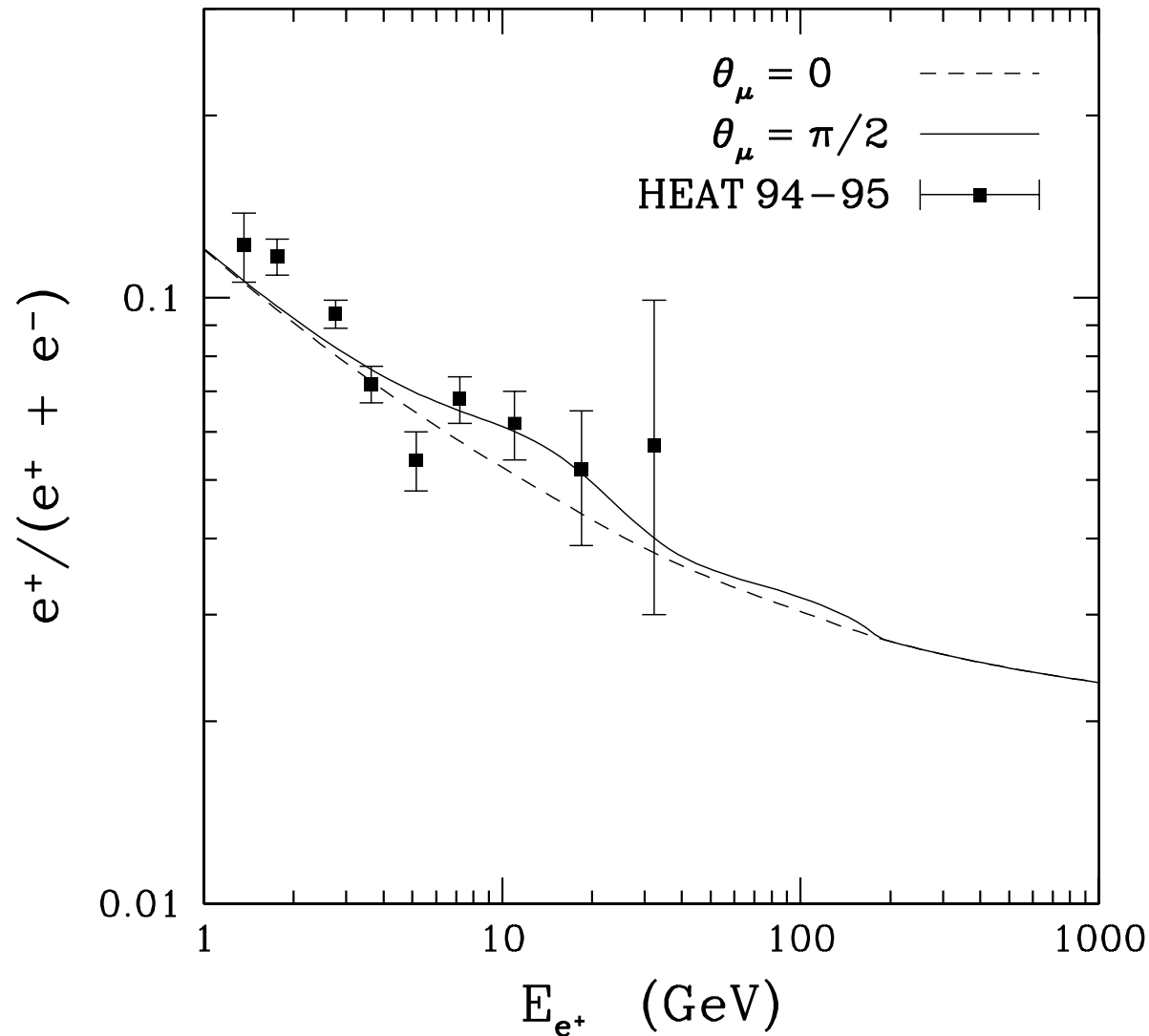


Strong θ_μ dependence
 for \tilde{B} -like or mixed LSP.

Positron fraction

$m_0 = 1 \text{ TeV}$, $m_A = 500 \text{ GeV}$, $A_0 = 1 \text{ TeV}$

$\tan\beta = 5$, $M_2 = 400 \text{ GeV}$, $|\mu| = 300 \text{ GeV}$, $\theta_A = 0$



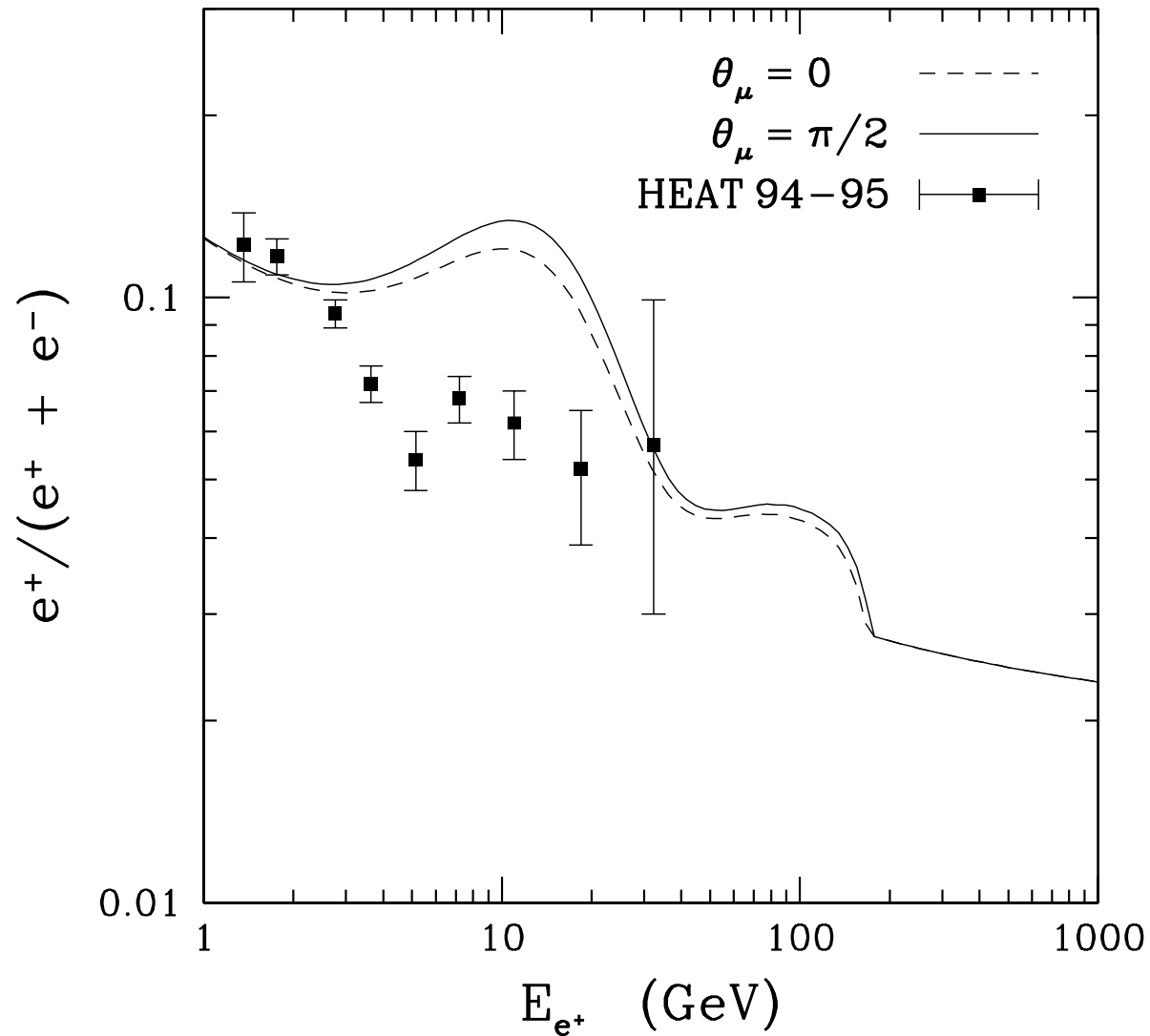
Sizable effect
in the e^+ flux

$$\Omega_\chi h^2 = 0.312 \quad (\theta_\mu = 0)$$

$$0.073 \quad (\theta_\mu = \pi/2)$$

$m_0 = 1 \text{ TeV}, m_A = 500 \text{ GeV}, A_0 = 1 \text{ TeV}$

$\tan\beta = 5, M_2 = 600 \text{ GeV}, |\mu| = 200 \text{ GeV}, \theta_A = 0$



Large excess
for \tilde{H} -like LSP

$$\Omega_\chi h^2 = 0.013 \quad (\theta_\mu = 0)$$
$$0.011 \quad (\theta_\mu = \pi/2)$$

5. Conclusions

Neutralino (χ) dark matter with SUSY CP violation

- Effect of supersymmetric CP-violating phases (θ_μ , θ_A) on χ pair annihilation cross section
 - $\chi\chi \rightarrow W^+W^-$ is significantly enhanced due to lightest higgs exchange for $\text{Im}(\mu) \neq 0$. (\tilde{B} -like or mixed LSP)
 - Strong phase dependence of $\Omega_\chi h^2$
 - WMAP allowed region for nonvanishing CP phases
 - Sizable effect in the positron flux