CP violation in charged Higgs decays in MSSM

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$H^{\pm} \Rightarrow$ **Physics beyond SM**

- 2HDM
- Higgs triplet model
- MSSM
- ...

If $H^{\pm}$ will be found at the Tevatron or LHC:

$\Rightarrow$ **more work is needed to find which New Physics it is**

$\Rightarrow$ **couplings must be measured**

We consider: CP violation in $H^{\pm}$ in MSSM

MSSM: 5 Higgs bosons $h^0, H^0, A^0, H^{\pm}$

- 2 parms. only: tan β, $m_A \Leftrightarrow$ 50 (if FV 124) in MSSM
- TH *and* Exp. bounds:

1) TH: $m^2_{H+} = m^2_W + m^2_{A^0} \geq m^2_{W+}$

2) Exp: LEP: $m_{H+} \geq$ 78.6 GeV, Tevatron: $m_{H+} \geq$ 200 GeV

- CP inv. at tree level
- CPV in Higgs sector $\rightarrow$ loop effects

We consider

$H^{\pm}$-decays into ordinary particles:

$$H^{\pm} \to tb$$

$$H^{\pm} \to \tau^{\pm}\nu$$

$$H^{\pm} \to W^{\pm}h^{0}$$

- decay rate asymmetries:

$$\delta^{CP} = \frac{\Gamma(H^{+}\to\ldots)-\Gamma(H^{-}\to\ldots)}{\Gamma(H^{+}\to\ldots)+\Gamma(H^{-}\to\ldots)}$$

$$\delta_{tb}, \qquad \delta_{\nu\tau}, \qquad \delta_{Wh^{0}}$$

We consider

t decays keeping its momentum and polarization!

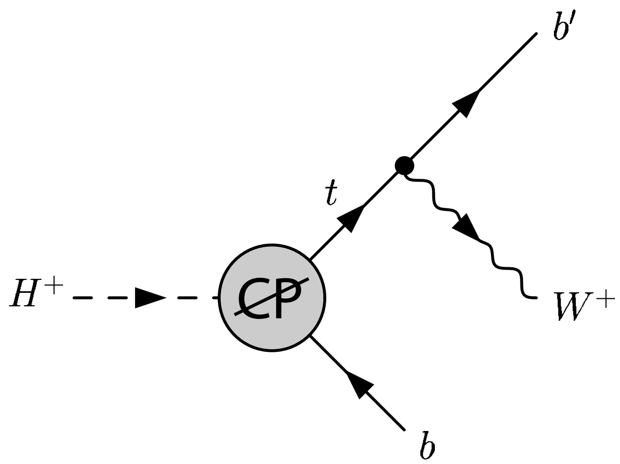
We study the decay products of t:

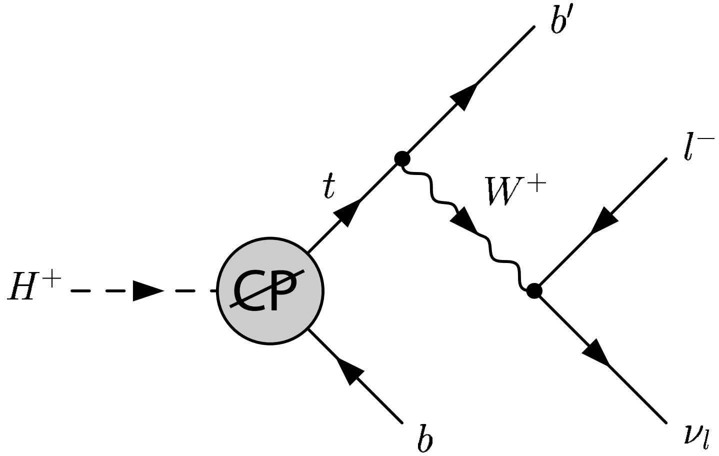
$$H^{\pm} \rightarrow tb \rightarrow bb'W^{\pm}$$

$$H^{\pm} \rightarrow tb \rightarrow bb'W^{\pm} \rightarrow bb'l^{\pm}\nu$$

- angular asymmetries: b', $l^{\pm} \Rightarrow \Delta A^{CP} = A_{+}^{FB} - A_{-}^{FB}$

- energy asymmetries: $b' \Rightarrow \Delta R^{CP} = R_{+} - R_{-}$





we measure CPV induced by loop corrections in $H^{\pm} \to bt$

in general: vertex & self energy loop corrections

$$\Downarrow$$

$$CPV:\ \delta\Gamma^{CP} \approx \underbrace{\left(ig^{CP}\right)}_{CPV\,coupling} \times i\,\underbrace{\Im m\,(MSSM\,loops)}_{a\,SUSY\ channel\ open}$$

for CPV we need both:

- ig^{CP}

- at least 1 SUSY channel open for $H^{\pm}$-decay

$$m_{H^+} > \tilde{m}_1 + \tilde{m}_2 > 200\,GeV$$

MSSM

- **The particles in the loops:**

$\tilde{g}$, $\tilde{\chi}^{\pm}$, $\tilde{t}$, $\tilde{b}$ and $\tilde{\chi}^{0}$ in the loops

Recall: gluino $\tilde{g} \leftrightarrow g$,

charginos $\tilde{\chi}^{\pm} \leftrightarrow (\tilde{W}^{\pm}, \tilde{H}^{\pm})$,

neutralinos $\tilde{\chi}^{0} \leftrightarrow (\tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0)$

scalar quarks $\tilde{q} \leftrightarrow q$

scalar leptons $\tilde{l} \leftrightarrow l$

- The CP phases:

1) the Higgs mass parameter $\mu = |\mu| e^{i\phi_\mu}$,

- exp: $d_e, d_n \Rightarrow \phi_\mu < 10^{-2}$, $\tilde{m}_{SUSY} \sim$ few 100 GeV

2) the gaugino masses: M_1, M_2

GUT: $M_1 = (5/3)\tan^2\theta_W M_2 \Rightarrow \phi_1 = 0$

$|M_1| = (5/3)\tan^2\theta_W |M_2| \Rightarrow \phi_1 \neq 0$

3) the trilinear coupls. of sfermions and Higgs:

$A_t = |A_t| e^{i\phi_t}$, $A_b = |A_b| e^{i\phi_b}$, $A_\tau = |A_\tau| e^{i\phi_\tau}$,

$\underline{\underline{\mathrm{H}^{\pm} \to tb}}$

H. Eberl, S. Kraml,
W. Majerotto, E. Ch.

N.P. **B**

$$\mathcal{M}_{H^\pm} = \frac{i\,g}{\sqrt{2}\,m_W}\,\bar{u}(p_t)\left[Y_t^{\pm}\,P_L + Y_b^{\pm}\,P_R\right]u(-p_{\bar{b}})$$

$$Y_i^{\pm} \;=\; y_i + \delta Y_i^{inv} \pm \delta Y_i^{CP}$$

$$y_t \;=\; m_t \cot\beta, \qquad y_b = m_b \tan\beta$$

$$\delta Y_i^{CP} = \Re e\,\delta Y_i^{CP} + i\Im m\,\delta Y_i^{CP}$$

2 CPV formfactors: $\Re e\,\delta Y_t^{CP}$ & $\Re e\,\delta Y_b^{CP}$

- we have: 2 CPV form factors $\Re e\,\delta Y_t^{CP}$ and $\Re e\,\delta Y_b^{CP}$

- we need: 2 measurable quantities:

  1) the decay rate: $\Gamma^{\pm} = \Gamma^{inv} \pm \Gamma^{CP}$

  2) the t polarization: $\mathcal{P}^{\pm} = \pm\mathcal{P}^{inv} + \mathcal{P}^{CP}$

$$\begin{aligned}\Gamma^{CP} &= [y_t\,\Re e\,\delta Y_t^{CP} + y_b\,\Re e\delta Y_t^{CP}](p_t p_b) - \\ &\quad -m_t m_b[y_b\,\Re e\delta Y_t^{CP} + y_t\,\Re e\delta Y_t^{CP}]\end{aligned}$$

$$\mathcal{P}^{CP} = \frac{y_t\,\Re e\delta Y_t^{CP} - y_b\,\Re e\delta Y_t^{CP}}{(y_t^2+y_b^2)(p_t p_b) - 2m_t m_b y_t y_b}$$

Our CPV asymmetries:

H. Eberl, E. Ginina,

W. Majerotto, E. Ch.

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- **decay rate asymmetries:** $\delta^{CP} \simeq \Gamma^{CP}$
- **CPV forward-backward asymmetries:** $\Delta A_f^{CP} \simeq \mathcal{P}^{CP}$
- **CPV energy asymmetry** $\Delta R^{CP} \simeq \mathcal{P}^{CP}$

$$\Delta A_f^{CP} \;=\; A_+^{FB} - A_-^{FB} = \alpha_f \, m_t^2 m_H^2 \frac{m_H^2 - m_t^2}{(m_H^2 + m_t^2)^2} \, \mathcal{P}^{CP}$$

$$A_+^{FB} = \frac{N_+^F - N_+^B}{N_+^F + N_+^B}, \qquad A_-^{FB} = \frac{N_-^F - N_-^B}{N_-^F + N_-^B}$$

$$\text{sensitivity to } t \text{ polar :} \qquad \alpha_b = \frac{m_t^2 - 2m_W^2}{m_t^2 + 2m_W^2} \simeq 0.4, \qquad \alpha_l = 1$$

$$\Delta R^{CP} = R_+ - R_- = \alpha_b \, (m_H^2 - m_t^2) \, \mathcal{P}^{CP}, \qquad R_+ = \frac{N_+(E>E_0) - N_+(E<E_0)}{N_+(E>E_0) + N_+(E<E_0)}$$

$H^+ \to \nu\tau$

H. Eberl, S. Kraml,
W. Majerotto, E. Ch.
JHEP

$m_\nu = 0 \Rightarrow$ **one formfactor** δY_τ^{CP}:

$$Y_\tau^\pm = y_\tau + \delta Y_\tau^{inv} \pm \delta Y_\tau^{CP}, \qquad \delta_{\nu\tau} = \frac{Re\,\delta Y_\tau^{CP}}{y_\tau}$$

$H^{\pm} \to W^{\pm} h^0$

E.Ginina, M. Stoilov,
E. Ch. JHEP

The difference: h^0 = not observed (yet!)

TH: $m_{h^0} = m_{h^0}(m_{H^+}, \tan\beta)$, $g_{WH^+h^0} = g_{WH^+h^0}(m_{H^+}, \tan\beta)$

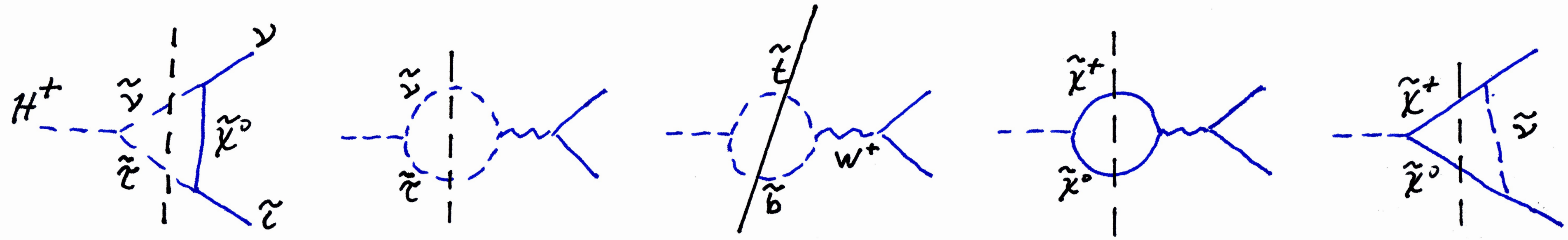
$$\mathcal{M}_{H^{\pm}} = ig\, \varepsilon^{\lambda}_{\alpha}(p_W)\, p_h^{\alpha}\, Y^{\pm},$$

$$Y^{\pm} = y + \delta Y^{inv} \pm \delta Y^{CP}, \qquad y = \cos(\alpha - \beta)$$

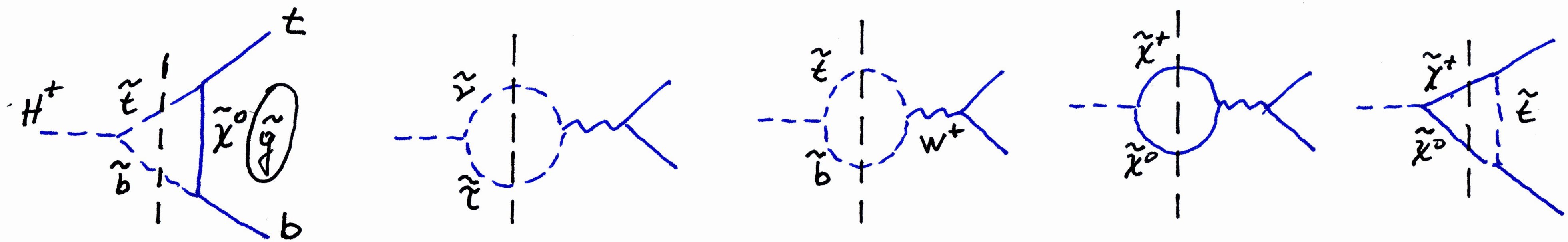
$$\delta_{Wh} \simeq \frac{\Re e\, \delta Y^{CP}}{y}$$

$BR(H^{\pm} \to W^{\pm} h^0) \sim$ 10% for low m_{H^+} & low $\tan\beta$, quickly drops with $\tan\beta$

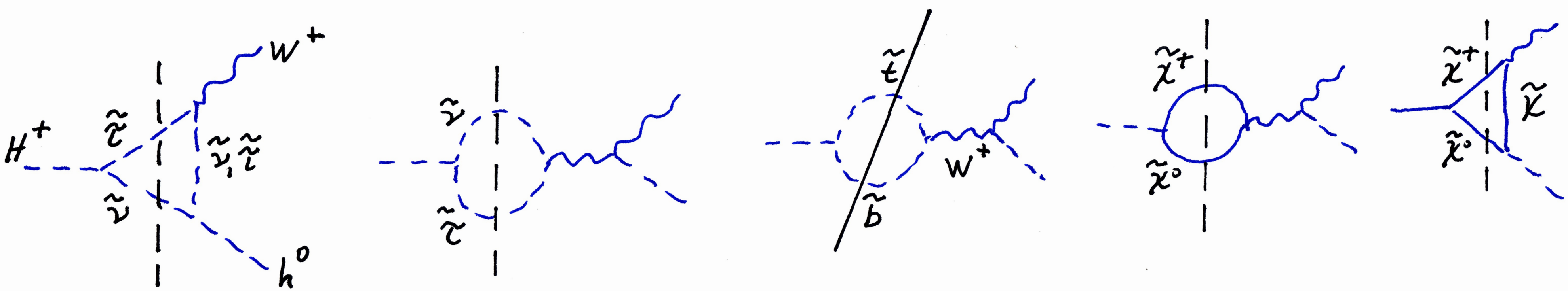
$H^{\pm} \rightarrow \nu\tau$: $m_H \simeq 200 - 300\, GeV$, $\tan\beta > 10$



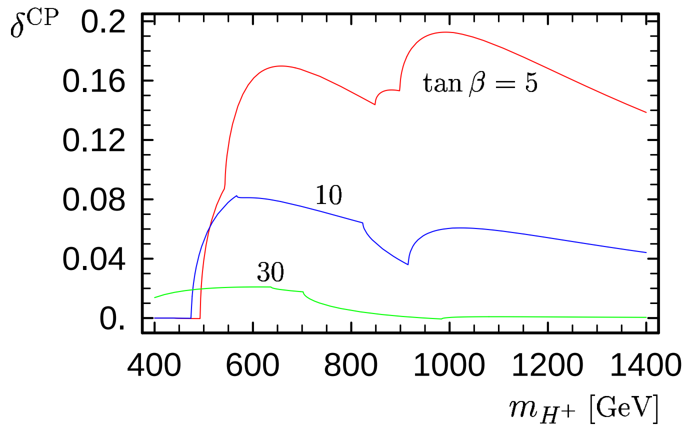
$H^{\pm} \rightarrow tb$: $m_H > m_t + m_b > 200\, GeV$

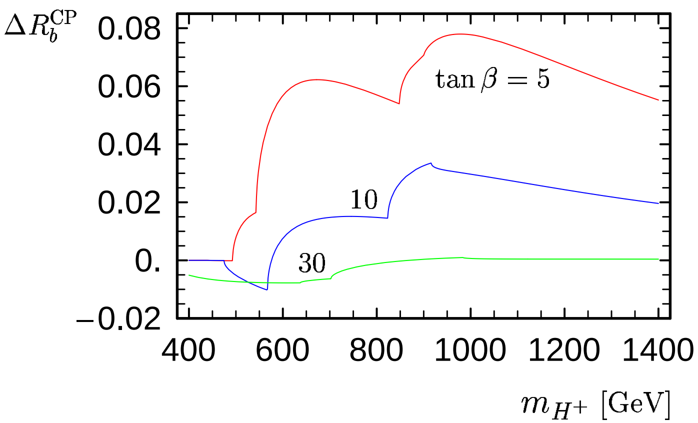


$H^{\pm} \rightarrow W^{\pm}h^0$: $m_H \simeq 200 - 250\, GeV$, $\tan\beta \simeq 3 - 5$



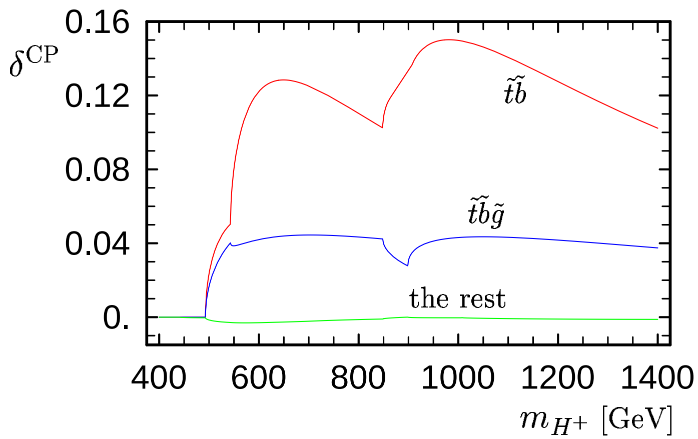
The CPV asymmetries in $H^{\pm} \to tb$

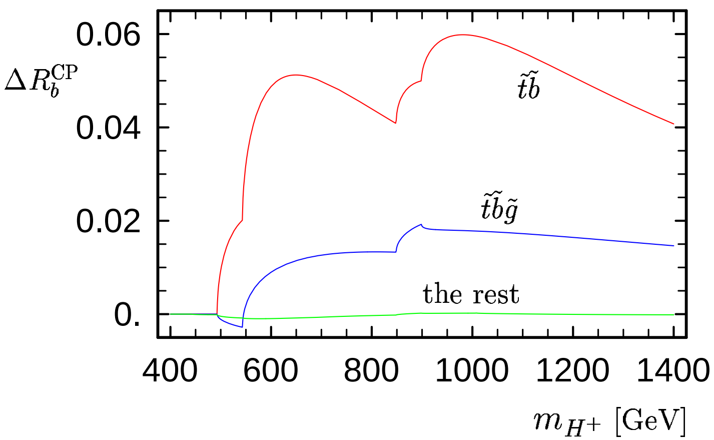




$\phi_{A_t} = \pi/2$, **no sensitivity to** ϕ_{A_b}

The different contributions to $H^\pm \to tb$

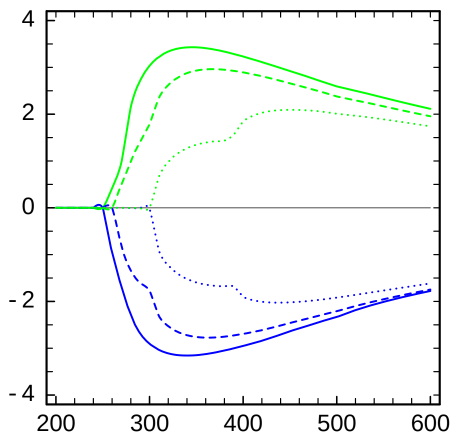




δ_{tb} significant when $H^+ \to \tilde{t}\tilde{b}$ open (sensitive to $\phi_{\tilde{t}}$), otherwise – negligible,

$\tan\beta = 5,\ \phi_{A_t} = \pi/2,\ \phi_{A_b} = \phi_\mu = 0.$

The CPV asymmetry in $H^+ \to \nu\tau$

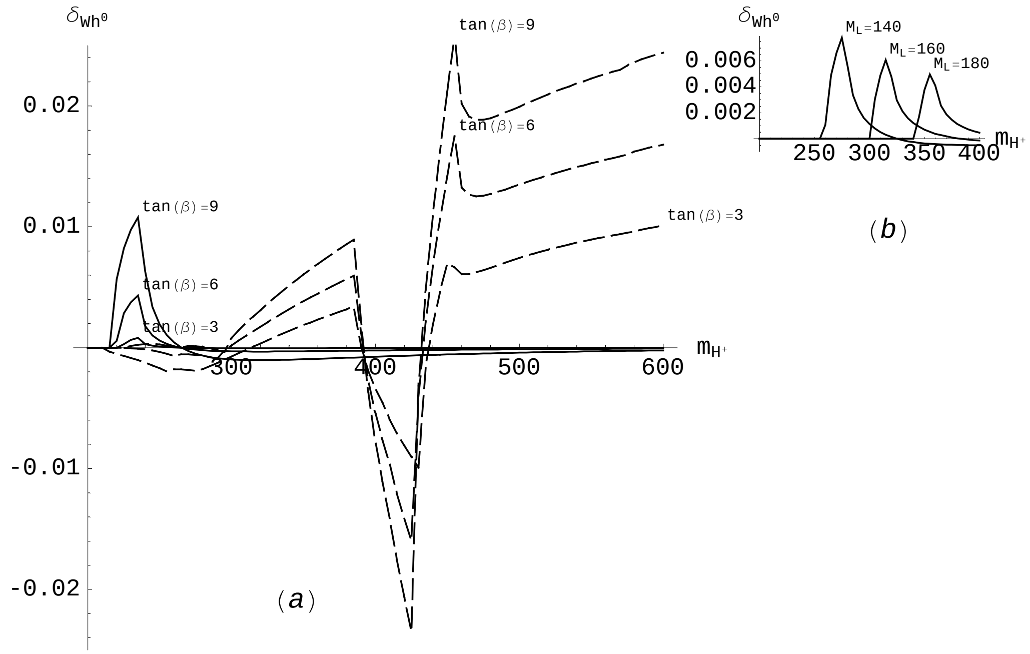


- $\delta_{\nu\tau}[10^{-3}]$ as function of m_{H^+}, sensitive to ϕ_τ and ϕ_1; $m_{H+} > m_{\tilde{\nu}} + m_{\tilde{\tau}}$

$$\delta(\phi_\tau = \pi/2) \simeq -\delta(\phi_1 = \pi/2), \quad \delta(\phi_\tau = \phi_1 = \pi/2) \simeq 0,$$

- BR important for low m_{H^+} and $\tan\beta > 10$

The CPV asymmetry in $H^+ \to W^\pm h^0$



δ_{Wh^0} as a function of m_{H^+} a) , $M_L = 120$ GeV; solid lines are for $\phi_\tau = -\pi/2$, $\phi_1 = 0$; dashed lines are for $\phi_\tau = 0$, $\phi_1 = -\pi/2$. b) for different values of M_L, at $\tan\beta = 9$, $\phi_\tau = -\pi/2$, $\phi_1 = 0$.

BR important for low m_{H^+} and low $\tan\beta \simeq 3 - 5$

The BR of $H^{\pm}$

For example, for $m_{H^+} = 250$ GeV, we have

$$\begin{aligned} \tan\beta &= 5 \\ BR(H^+ \to t\bar{b}) &= 0.90 \\ BR(H^+ \to \nu\tau) &= 0.062 \\ BR(H^+ \to W^+h^0) &= 0.04 \end{aligned}$$

$$\begin{aligned} \tan\beta &= 30 \\ BR(H^+ \to t\bar{b}) &= 0.64 \\ BR(H^+ \to \nu\tau) &= 0.36 \\ BR(H^+ \to W^+h^0) &= 0.0006 \end{aligned}$$

Conclusions

CPV in MSSM: $H^{\pm} \to tb,\ H^{\pm} \to \nu\tau,\ H^{\pm} \to W^{\pm}h^{0}$:

$\Rightarrow$ $\tan\beta$ & m_{H^+} are unknown

$\Rightarrow$ depending on $\tan\beta$ & m_{H^+} different decay modes will play role

$\Rightarrow$ different phases will be measured

$$\delta^{CP} = \frac{\Gamma(H^+ \to ...) - \Gamma(H^- \to ...)}{\Gamma(H^+ \to ...) + \Gamma(H^- \to ...)}$$

- simple measurement – only the decay rates

- always decay modes $H^+ \to$ SUSY partls. needed for $\delta^{CP} \neq 0$

  $\Rightarrow$ this decreases $BR(H^+ \to$ ordinary partls.)

  - a simult. considr. of δ^{CP} & BR needed

- $H^\pm \to tb$, $\delta^{CP}(\tilde{t}\tilde{b}) \sim$ **16% - 20 %**, $\Rightarrow \phi_t$ **&** ϕ_b, $m_{H^+} > 500$ **GeV**

- $H^\pm \to \nu\tau^\pm$, $\delta^{CP}(\tilde{\nu}\tilde{\tau}) \leq 0, 5.10^{-3} \Rightarrow \phi_\tau$ **&** ϕ_1,
  $\tan\beta > 10$, $m_{H^+} \simeq 200 - 300$ **GeV**

- $H^\pm \to W^\pm h^0$, $\delta^{CP}(\tilde{\nu}\tilde{\tau}) \leq 10^{-2} \Rightarrow \phi_\tau$ **&** ϕ_1,
  $\tan\beta \simeq 3 - 5$, $m_{H^+} \simeq 200 - 300$ **GeV**

- $H^\pm \to tb_1 \to b_1 b_2 W \to b_1 b_2 l\nu$

  $\Rightarrow \Delta A_{FB}^{CP}$ **&** $\Delta R_b^{CP} \sim 10\%$

- **Measurability**

  δ^{CP} **depends on** $H^\pm$**-production:**

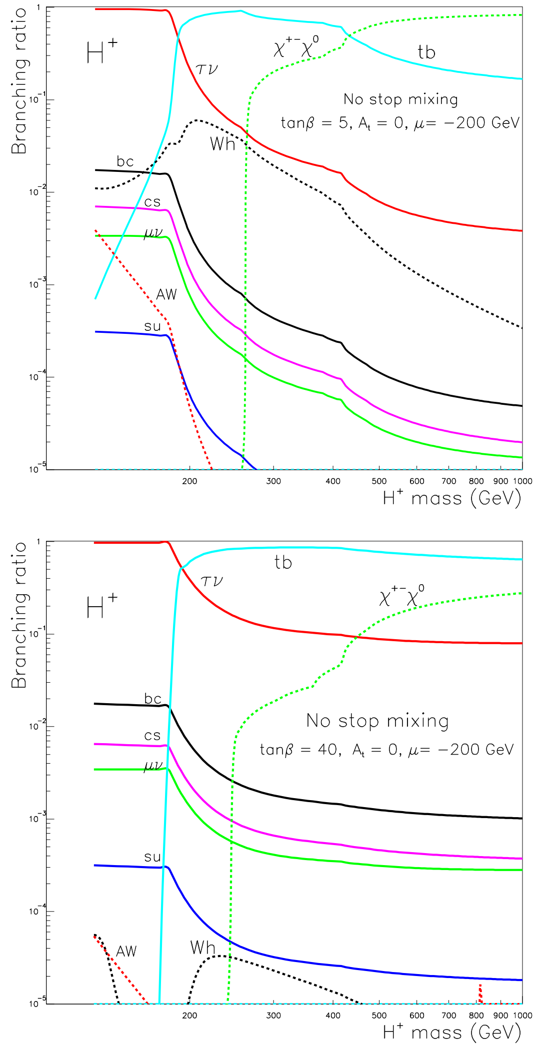
$$\delta^{CP} = \delta_P^{CP} + \delta_D^{CP}$$

  $\Rightarrow$ **at the Tevatron:** $m_{H^+} < 200$ **GeV**

  $\Rightarrow$ **at LHC:** $m_{H^+} < 1000$ **GeV**

  $\Rightarrow$ **at LC:** $m_{H^+} < \sqrt{s}/2$ **GeV**

  LHC: $pp \to H^\pm t$ **see the next talk!**



The BR of H^+ for $\tan\beta = 5, 40$ (A.Djouadi, J.Kalinowski, M.Spira)

Measurability – depends on the $H^{\pm}$-production

• $H^{\pm} \to tb$

LHC: $gb \to H^{\pm}t$ with large background

SLHC needed! L=1000-3000 fb

• $H^{\pm} \to \nu\tau$, $H^{\pm} \to W^{\pm}h^0$

LHC: BR too low

interesting for e^+e^--colliders: $e^+e^- \to H^+H^-$: $m_H^{\pm}$ - the only param.

• the number of $H^{\pm}$ needed to measure $\delta^{CP}_{...}$ in $H \to ...$ with N_σ standard deviations is

$$N \geq \frac{N_\sigma^2}{\delta^2 \, BR(H \to ...)}$$

• the number of $H^{\pm} \to ...$ seen at LHC at the given mode is

$$N = \sigma_P \, BR \times \; acceptance \; \times \; luminosity$$

The loops in $H^{\pm} \to tb$