Interference effects for the top quark decays $t \to b + W^+/H^+(\to \tau + \nu_\tau)$

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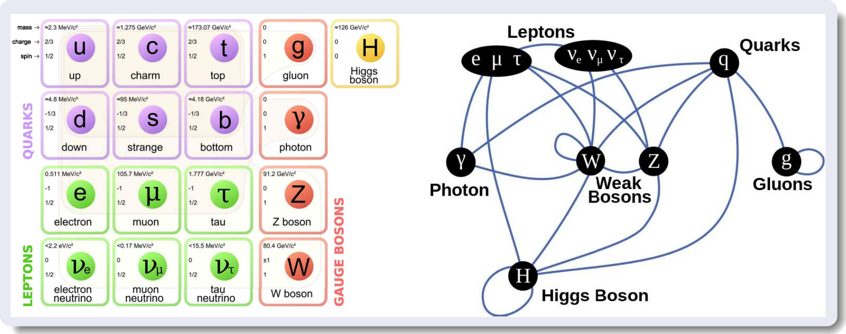
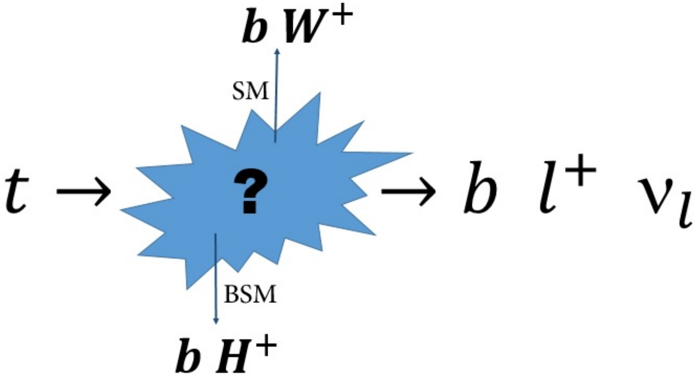
Overview: Standard Model of Elementary Particle Physics

The SM of particles, developed in 1970's, includes 61 particles as follows:

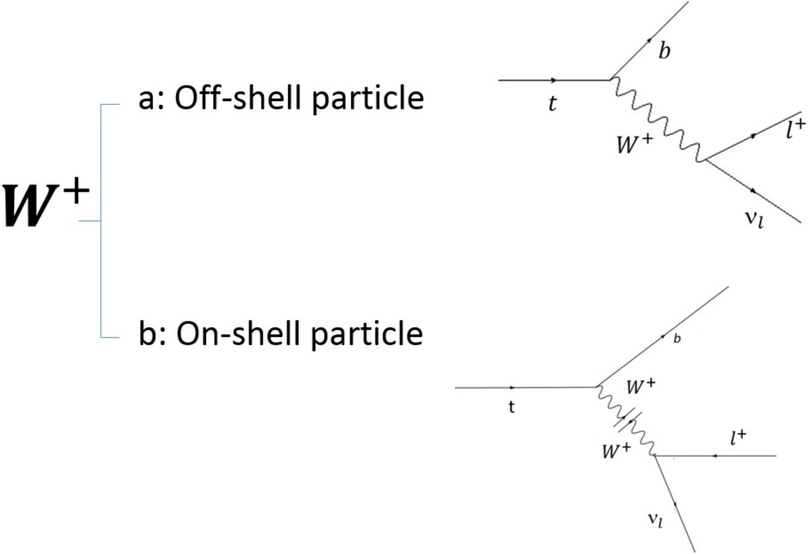
- 12 Leptons, 36 Quarks , 8 Gluons, $W^{\pm}$, Z^{0}, Photon and Higgs boson



$t \to$  $\to b \; l^+ \; \nu_l$


b W+
SM
t →
?
→ b l+ νl
BSM
b H+

Top quark decay in the SM: $t(p_t) \rightarrow b(p_b)W^+(p_W) \rightarrow bl^+(p_l)\nu_l(p_\nu)$



$$d\Gamma_0 = \frac{1}{2m_t}\overline{|M_0|^2} dPS_3 \quad (1)$$

$$\overline{|M_0|^2} = \sum_{spin} |M_0|^2/(1+2s_t)$$

$$dPS_3 = (2\pi)^{-5}\frac{d^3\vec{p}_b}{2E_b}\frac{d^3\vec{p}_\nu}{2E_\nu}\frac{d^3\vec{p}_l}{2E_l}\delta^4(p_t - p_b - p_\nu - p_l) = \frac{1}{2^5\pi^3}dE_b dE_l$$

The Breit-Wigner prescription of the W^+ boson propagator:

$$(\frac{1}{p_W^2 - M_W^2})^2 \stackrel{B-W}{\longrightarrow} (\frac{1}{p_W^2 - M_W^2 + iM_W\Gamma_W})^2 = \frac{1}{(p_W^2 - M_W^2)^2 + (M_W\Gamma_W)^2}$$

The decay rate at the loest order(a: Full calculation)

$$\Gamma_0^{SM}(t \to b l^+ \nu_l) = \frac{m_t \alpha^2 |V_{tb}|^2}{192\pi \sin^4\theta_W} \Bigg\{ 2(R-1)(1+R-2\omega) + \left[3(\omega-1)(R-\omega) + \omega\frac{\Gamma_W^2}{m_t^2}\right] \ln\frac{\omega\Gamma_W^2 + m_t^2(R-\omega)^2}{\omega\Gamma_W^2 + m_t^2(1-\omega)^2} + \frac{1}{m_t\sqrt{\omega}\Gamma_W}\Big[3\omega\Gamma_W^2(1+R-2\omega) + m_t^2(1-R)^3 + m_t^2(R-\omega)^2 \times (R+2\omega-3)\Big]\left(\tan^{-1}\frac{m_t(\omega-R)}{\sqrt{\omega}\Gamma_W} + \tan^{-1}\frac{m_t(1-\omega)}{\sqrt{\omega}\Gamma_W}\right)\Bigg\} \quad (2)$$

$$R = (m_b/m_t)^2, \qquad \omega = (m_W/m_t)^2, \qquad l^+\nu_l = \tau^+\nu_\tau$$

Narrow width approximation (b)

we introduce the following identity

$$1 = \int dp_W^2 \int \frac{d^3 p_W}{2E_W} \delta^4(p_{W^+} - p_{l^+} - p_{\nu_l}) \qquad (3)$$

$$d\Gamma_0 = 2m_W \int \frac{dp_W^2}{2\pi} \overline{|M_0^{SM}|^2}$$

$$\times \frac{1}{2m_t} \overbrace{\left\{ \frac{d^3 p_b}{(2\pi)^3 2E_b} \frac{d^3 p_W}{(2\pi)^3 2E_W} (2\pi)^4 \delta^4(p_t - p_b - p_{W^+}) \right\}}^{dPS_2(t \to bW^+)}$$

$$\times \frac{1}{2m_W} \underbrace{\left\{ \frac{d^3 p_l}{(2\pi)^3 2E_l} \frac{d^3 p_{\nu_l}}{(2\pi)^3 2E_{\nu_l}} (2\pi)^4 \delta^4(p_{W^+} - p_{l^+} - p_{\nu_l}) \right\}}_{dPS_2(W^+ \to l^+ \nu_l)}$$

$$|M_0^{SM}|^2 = \frac{1}{(p_W^2 - m_W^2)^2 + (m_W \Gamma_W)^2} |M^{Born}(t \to bW^+)|^2 \times |M^{Born}(W^+ \to l^+ \nu_l)|^2$$

Narrow width approximation (b)

$$\Gamma(t \to bl^+\nu_l) = \Gamma(t \to bW^+)\frac{\Gamma(W^+ \to l^+\nu_l)}{\Gamma_W} = \Gamma(t \to bW^+)Br(W^+ \to l^+\nu_l), \quad (4)$$

$$\Gamma_0^{SM}(t \to bW^+) = \frac{m_t\alpha\sqrt{S^2 - R}}{8\sin^2\theta_W}(1 + R - 2\omega + \frac{(1-R)^2}{\omega}) \quad (5)$$

$S = (1 + R - \omega)/2$
$Br(W^+ \to \tau^+\nu_\tau) = 11.25 \pm 0.20($ in units $10^{-2})$[1]

[1] J. Beringer *et al.* [Particle Data Group], Phys. Rev. D **86** (2012) 010001.

Numerical results

$m_\tau = 1.776$ GeV, $m_t = 172.98$ GeV,
$m_W = 80.339$ GeV, $m_b = 4.78$ GeV,
$\Gamma_W = 2.085 \pm 0.042$ GeV, $\sin^2\theta_W = 0.2312$,
$\alpha = 0.0077$ and $|V_{tb}| \approx 1$[2]:

$$\begin{aligned} \Gamma_0^{SM}(t \to b\tau^+\nu_\tau) &\stackrel{a}{=} 0.1543 \\ \Gamma_0^{SM}(t \to b\tau^+\nu_\tau) &\stackrel{b}{=} 0.1645 \end{aligned} \quad (6)$$

[2] C. Patrignani *et al.* [Particle Data Group], Chin. Phys. C **40** (2016) no.10, 100001.

Top quark decay in Beyond the Standard Model

Simplest scenario of BSM: Two-Higgs-Doublet Model

- In particle physics, a two-Higgs-doublet model (2HDM) is an extension of the Standard Model in which a second Higgs doublet is added to the Higgs sector of the SM
- The addition of the second Higgs doublet, after spontaneous symmetry breaking, leads to five physical states:
  1. The light and heavy CP-even neutral Higgs bosons h and H ($m_H > m_h$)
  2. The CP-odd pseudoscalar Higgs A
  3. Two charged Higgs bosons $H^{\pm}$
- Such a model has six free parameters:
  1. Four Higgs masses ($m_h, m_H, m_A, m_{H^{\pm}}$)
  2. Ratio of the vacuum expectation values of the two electrically neutral components of the two Higgs doublets ($\tan\beta = < H_2 > / < H_1 >$)
  3. A mixing angle (α)

Top decay in the 2HDM: $t \to bH^+ \to bl^+\nu_l$

The Yukawa couplings between $H^\pm$, b and t quarks are expressed as :

$$L_I = \frac{g_W}{2\sqrt{2}m_W} H^+ \{ V_{tb}[\bar{u}_t(p_t)\{A(1+\gamma_5) + B(1-\gamma_5)\}u_b(p_b)] + C\bar{\psi}_{\nu_l}(1-\gamma_5)\psi_l \} \quad (7)$$

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	A	B	C
Type I	$m_t \cot\beta$	$-m_b \cot\beta$	$-m_\tau \cot\beta$
Type II	$m_t \cot\beta$	$m_b \tan\beta$	$m_\tau \tan\beta$
Type III	$m_t \cot\beta$	$m_b \tan\beta$	$-m_\tau \cot\beta$
Type IV	$m_t \cot\beta$	$-m_b \cot\beta$	$m_\tau \tan\beta$

The decay rate at the loest order (a: full calculation)

$$\begin{aligned}
\Gamma_0^{BSM}(t \to b l^+ \nu_l) \quad = \quad & \Big(\frac{C\alpha|V_{tb}|}{16\sqrt{\pi}m_W^2 \sin^2\theta_W}\Big)^2 \times \Bigg\{ m_t(R-1)\Big[8AB\sqrt{R} \\
& +(A^2+B^2)(3+R-4y)\Big] + 2\frac{\sqrt{y}}{\Gamma_H}\Bigg(\tan^{-1}\frac{m_t(y-R)}{\sqrt{y}\Gamma_H} \\
& + \tan^{-1}\frac{m_t(1-y)}{\sqrt{y}\Gamma_H}\Bigg)\Big[4AB\sqrt{R}(\Gamma_H^2+(1-y)m_t^2) \\
& +(A^2+B^2)\big[(2+R-3y)\Gamma_H^2 + m_t^2(1-y)(1+R-y)\big]\Big] \\
& +m_t\Big[4AB(2y-1)\sqrt{R} + (A^2+B^2)\Big(\frac{y\Gamma_H^2}{m_t^2} \\
& -(1+R-4y-2Ry+3y^2)\Big)\Big] \ln\frac{y\Gamma_H^2 + m_t^2(R-y)^2}{y\Gamma_H^2 + m_t^2(1-y)^2}\Bigg\} \quad (8)
\end{aligned}$$

Narrow width aproximation (b)

- $$\Gamma_0^{BSM}(t \to b l^+ \nu_l) = \Gamma_0^{BSM}(t \to b H^+) \times Br(H^+ \to l^+ \nu_l) \quad (9)$$

- $$\Gamma_0^{BSM}(t \to b H^+) = m_t\left(\frac{g_W |V_{tb}|}{8\sqrt{\pi} m_W}\right)^2 \Big\{(A^2 + B^2)(1 + R - y) + 2AB)\sqrt{R}\Big\}\lambda^{\frac{1}{2}}(1, R, y) \quad (10)$$

$\lambda(x, y, z) = (x - y - z)^2 - 4yz$ is the Källén function (triangle function)

Narrow width aproximation (b)

- $$\Gamma_0^{BSM}(t \to b l^+ \nu_l) = \Gamma_0^{BSM}(t \to b H^+) \times Br(H^+ \to l^+ \nu_l) \qquad (9)$$

- $$\Gamma_0^{BSM}(t \to b H^+) = m_t \left(\frac{g_W |V_{tb}|}{8\sqrt{\pi} m_W}\right)^2 \Big\{(A^2 + B^2)(1 + R - y) + 2AB)\sqrt{R}\Big\} \lambda^{\frac{1}{2}}(1, R, y) \qquad (10)$$

$\lambda(x, y, z) = (x - y - z)^2 - 4yz$ is the Källén function (triangle function)

$$Br(H^+ \to \tau^+ \nu_\tau)_{model-I} = \frac{1}{1 + 3|V_{cs}|^2[(\frac{m_s}{m_\tau})^2 + (\frac{m_c}{m_\tau})^2]}$$

$$Br(H^+ \to \tau^+ \nu_\tau)_{model-II} = \frac{1}{1 + 3|V_{cs}|^2[(\frac{m_s}{m_\tau})^2 + (\frac{m_c}{m_\tau})^2 \cot^4 \beta]}$$

Numerical results in the 2HDM

$m_s = 95$ MeV, $m_c = 1.67$ GeV, $m_\tau = 1.776$ GeV, $|V_{cs}| = 0.9734$,
$m_{H^+} = 95$ GeV and $\tan\beta = 8$
from full calculation:

$$\begin{aligned} \Gamma_0^{\textbf{Model I}} &= 36 \times 10^{-4} \\ \Gamma_0^{\textbf{Model II}} &= 559 \times 10^{-4} \end{aligned} \qquad (11)$$

In the NWA scheme:

$$\begin{aligned} \Gamma_0^{\textbf{Model I}} &= 35 \times 10^{-4} \\ \Gamma_0^{\textbf{Model II}} &= 568 \times 10^{-4} \end{aligned} \qquad (12)$$

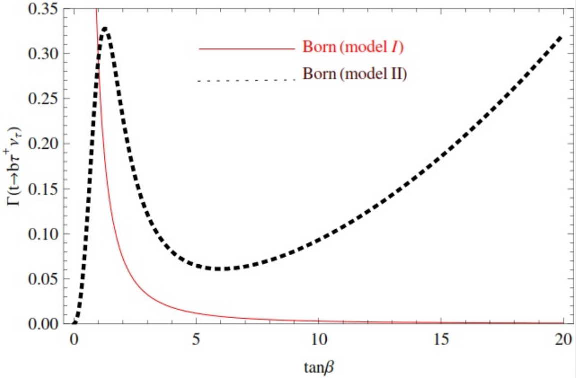

Figure: The Born decay rate of $t \to b\tau^+\nu_\tau$ as a function of $\tan\beta$ for $m_{H^+} = m_{W^+}$.

My thesis

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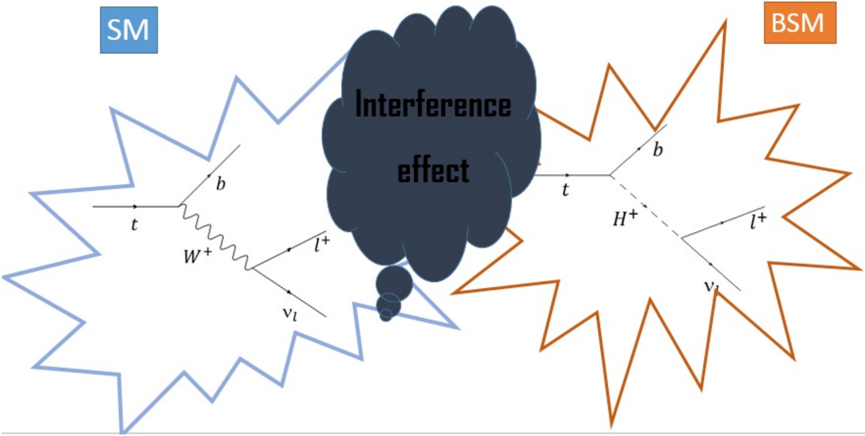

SM
BSM
Interference effect
t
b
W+
l+
νl
t
b
H+
l+
νl

Interference effects: $t \to b + W^+/H^+(\to l^+\nu_l)$

$$M^{Total}(t \to bl^+\nu^+) = M^{SM}_{t\to bl^+\nu^+} + M^{BSM}_{t\to bl^+\nu^+} \quad (13)$$

$$|M_0|^2 = |M_0^{SM}|^2 + |M_0^{BSM}|^2 + 2Re(M_0^{BSM} \cdot M_0^{SM\dagger}) \quad (14)$$

$$\Gamma_t^{Tot} = \Gamma_0^{SM}(t \to bl^+\nu_l) + \Gamma_0^{BSM}(t \to bl^+\nu_l) + \Gamma_0^{Int} \quad (15)$$

Interference effects: $t \to b + W^+/H^+(\to l^+\nu_l)$

$$\Gamma_0^{Int}(t \to b l^+ \nu_l) = \frac{C\alpha^2\sqrt{I}}{2^7\pi m_t^2 \omega \sin^4\theta_W}\Big\{2m_t(R-1)(A-B\sqrt{R}) + \frac{1}{m_t^2(y-\omega)^2+(\sqrt{y}\Gamma_H+\sqrt{\omega}\Gamma_W)^2}\big[f(y,\omega,\Gamma_H,\Gamma_W) + g(y,\omega,\Gamma_H,\Gamma_W) + h(y,\omega,\Gamma_H,\Gamma_W) + Q(y,\omega,\Gamma_H,\Gamma_W)\big]\Big\}$$

$$g(y,\omega,\Gamma_H,\Gamma_W) = f(y\leftrightarrow\omega, \Gamma_H\leftrightarrow\Gamma_W)$$
$$Q(y,\omega,\Gamma_H,\Gamma_W) = h(y\leftrightarrow\omega, \Gamma_H\leftrightarrow\Gamma_W)$$

$$f(y,\omega,\Gamma_H,\Gamma_W) = m_t \ln \frac{(R-y)^2 m_t^2 + y\Gamma_H^2}{(1-y)^2 m_t^2 + y\Gamma_H^2}\Bigg(m_t^2(y-\omega)\big[A(1-y)^2 + B\sqrt{R}(1-y^2)\big] + 2\sqrt{y\omega}\Gamma_H\Gamma_W\big[A(y-1) - By\sqrt{R}\big] + y\Gamma_H^2\big[A(y+\omega-2) - B(y+\omega)\sqrt{R}\big]\Bigg)$$

$$h(y,\omega,\Gamma_H,\Gamma_W) = 2\left[\tan^{-1}\frac{m_t(R-y)}{\sqrt{y}\Gamma_H} - \tan^{-1}\frac{m_t(1-y)}{\sqrt{y}\Gamma_H}\right] \times \Bigg[(B\sqrt{R}-A)\Big(y\Gamma_W\Gamma_H^2\sqrt{\omega} + (\Gamma_H\sqrt{y})^3 + m_t^2\Gamma_H(y^2-2y\omega+1)\sqrt{y} - m_t^2(y^2-1)\Gamma_W\sqrt{\omega}\Big) + 2Am_t^2\Big((1-\omega)\Gamma_H\sqrt{y} + (1-y)\Gamma_W\sqrt{\omega}\Big)\Bigg]$$

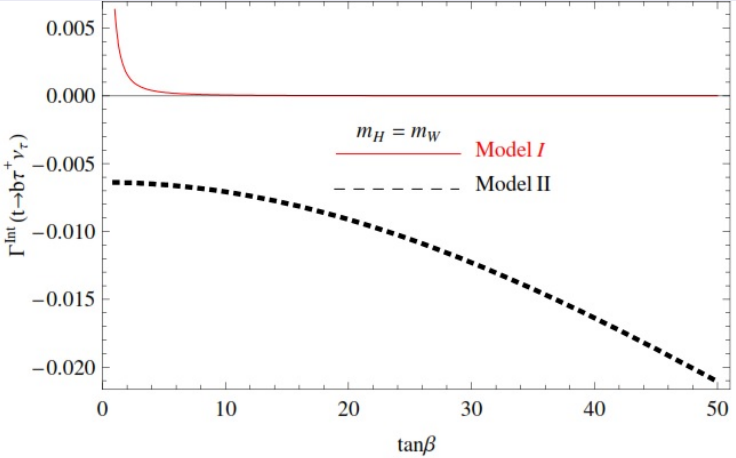
Numerical results

$m_{H^+} \approx m_{W^+}$ and $\tan\beta = 8$:

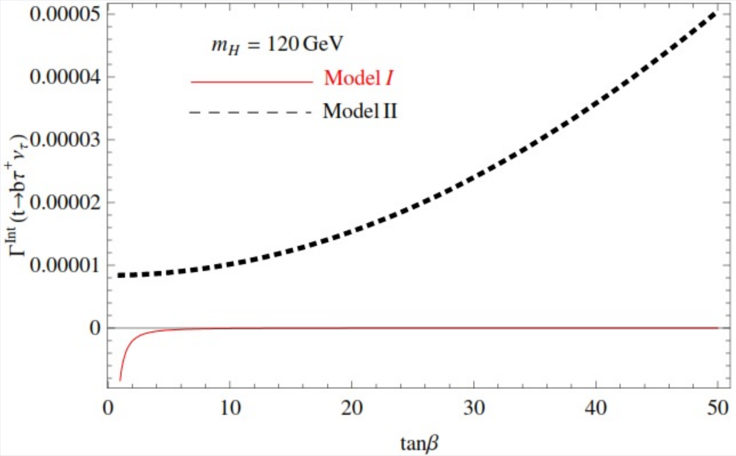
	Γ_0^{SM}	Γ_0^{BSM}	Γ_0^{Int}
Type I	0.1543	4.53×10^{-3}	9.95×10^{-5}
Type II	0.1543	69.4×10^{-3}	-682×10^{-5}

$m_{H^+} = 85$ GeV and $\tan\beta = 8$:

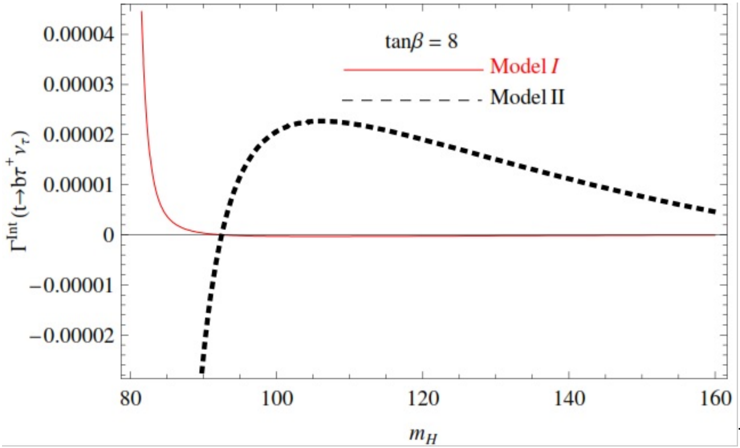
	Γ_0^{SM}	Γ_0^{BSM}	Γ_0^{Int}
Type I	0.1543	4.2×10^{-3}	9.2×10^{-6}
Type II	0.1543	65.1×10^{-3}	-129×10^{-6}



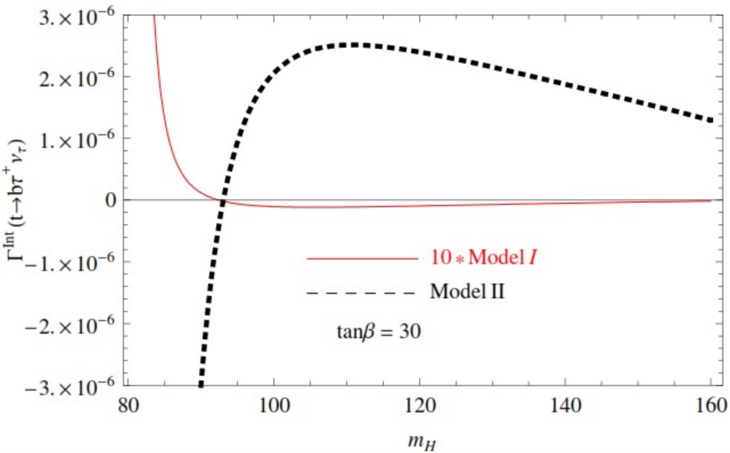
The interference contribution as a function of $\tan\beta$ for $m_{H^+} = m_{W^+}$.



The interference contribution as a function of $\tan\beta$ for $m_{H^+} = 120$ GeV.



The contribution of interference term in the Born decay rate of $t \to b\tau^+\nu_\tau$ as a function of m_{H^+} in two scenarios for $\tan\beta = 8$.



The interference term as a function of m_{H^+} for $\tan\beta = 30$.

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S. Mohammad Moosavi Nejad (Yazd U. & IPM, Tehran), S. Abbaspour, R. Farashahian (Yazd U.). Apr 21, 2019. 11 pp.

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References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

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Detailed record


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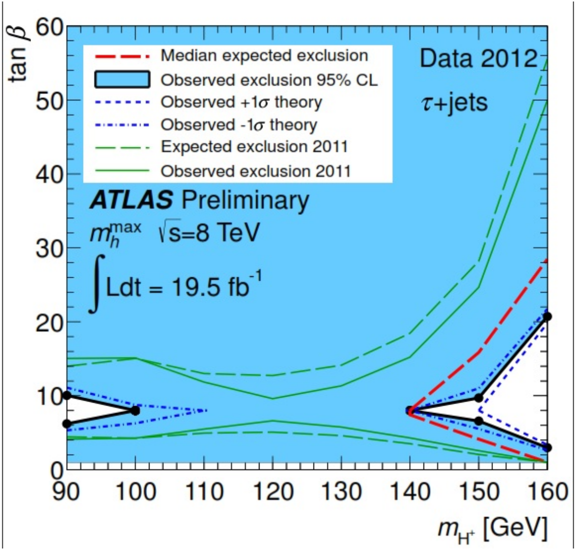

tan β
m_{H+} [GeV]
Median expected exclusion
Observed exclusion 95% CL
Observed +1σ theory
Observed -1σ theory
Expected exclusion 2011
Observed exclusion 2011
Data 2012
τ+jets
ATLAS Preliminary
m_h^max √s=8 TeV
∫Ldt = 19.5 fb^-1

References

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