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Charged Higgs Boson at FCC-hh

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- Decay Width and Branchings
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INTRODUCTION

- After the discovery of a Higgs boson at the LHC in 2012, now an important question arises whether the discovered particle is part of an extended scalar sector.
- A charged Higgs boson $H^{\pm}$ appears in many models with an extended scalar sector such as two Higgs doublet model (THDM) (where a second Higgs doublet introduced [Branco12]) and Higgs triplet model (HTM) (where a triplet is added [Georgi85,Cheung02]).
- In THDM, two complex scalar field ϕ_1 and ϕ_2 have eight degrees of freedom, three of them are identified as Goldstone bosons (they are absorbed as longitudinal components of massive $W^{\pm}$ and Z), the remaining are interpreted as five physical states: neutral scalars (h^0,H^0,A^0) and charged scalars (H^+,H^-).

INTRODUCTION

- We study two types of Yukawa interactions, one in which all SM fermions couple to one doublet (THDM-I), and the other in which down-sector couples to one doublet while up-sector couples to other doublet (THDM-II).

THDM-I	u	d	ν	l
ϕ_1				
ϕ_2	✔	✔	✔	✔

- Phenomenological consideration:
  - two Higgs doublet carry opposite hyper charges
  - these doublets will have different vev (v_1,v_2) with $v=(v_1^2+v_2^2)^{1/2}$.
  - mixing parameters and ratio $\tan\beta=v_2/v_1$
  - masses of the new Higgs bosons

THDM-II	u	d	ν	l
ϕ_1		✔		✔
ϕ_2	✔		✔	

INTRODUCTION

Earlier limits on the mass of charged Higgs boson have been superseded by results of the LHC experiments.

- ATLAS experiment have searched for the process $pp \rightarrow tH^{\pm} + X$ and subsequent decay $H^{\pm} \rightarrow \tau^{\pm}\nu$ in fully hadronic final states for 19.5 fb^{-1} pp data at 8 TeV.
  - set the 95% confidence-level upper limits on the $\sigma(pp \rightarrow tH^{\pm} + X) \times BR(H^{\pm} \rightarrow \tau^{\pm}\nu)$ between 0.76 pb and 4.5 fb for $m_{H\pm}$ ranging from 180 GeV to 1000 GeV, and also exclude parameter space with high tanβ for $m_{H\pm}$ range 200 - 250 GeV [ATLAS2015].
- CMS experiment have searched for the process $pp \rightarrow tH^{+} + X$ and subsequent decay $H^{+} \rightarrow \tau^{+}\nu$ for pp data at 8 TeV.
  - for the high-mass region ($180 GeV < m_{H\pm} < 600 GeV$), limits on tH^{+} production times $BR(H^{+} \rightarrow \tau^{+}\nu_{\tau})$ are set between 0.38 pb and 26 fb. Finally, CMS has a direct search for heavy charged Higgs which decays in both the $H^{+} \rightarrow t\bar{b}$ and the $H^{+} \rightarrow \tau^{+}\nu_{\tau}$ channels [CMS-PAS-HIG-13-026].

CHARGED HIGGS - FERMION COUPLINGS

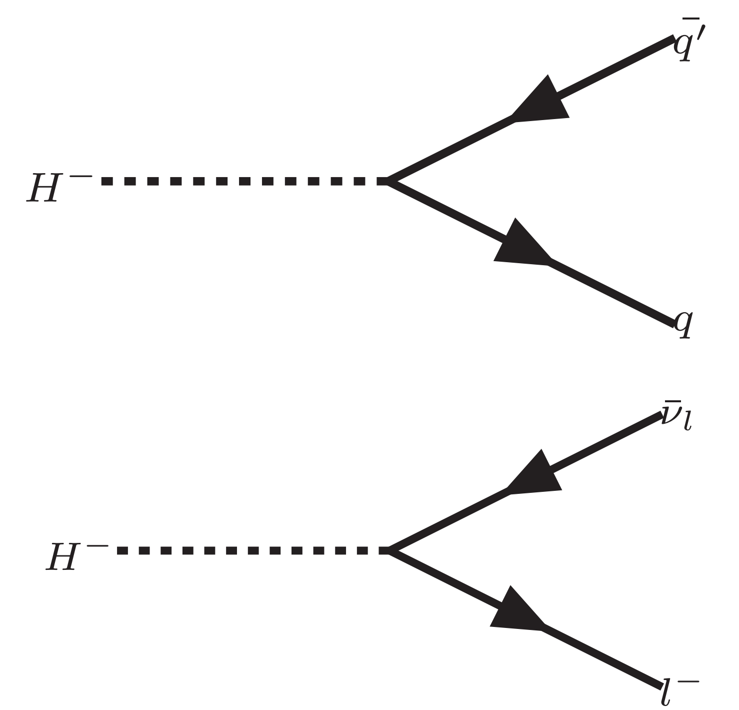
➤ The couplings for $H^- q_i q_j$ and $H^- n_i l_j$ interactions are given

$$g_{H^- q_i \bar{q}_j} \equiv g|V_{q_i q_j}|[m_{q_i} \cot\beta(1+\gamma_5) + T_x m_{q_j} \tan\beta(1-\gamma_5)]/(2\sqrt{2}m_W)$$

$$g_{H^- \nu_i l_j^+} \equiv g|U_{\nu_i l_j}|[T_x m_{l_j} \tan\beta(1-\gamma_5)]/(2\sqrt{2}m_W)$$

where $V_{qi\ qj}$ and $U_{vi\ lj}$ are the elements of the mixing matrices in the quark sector and lepton sector, respectively. We use the parameter T_x to identify the type of THDM such that

- $T_I = -\cot\beta/\tan\beta$ corresponds to THDM-I
- $T_{II} = 1$ corresponds to THDM-II



Feynman diagrams contributing to the charged Higgs fermion interactions

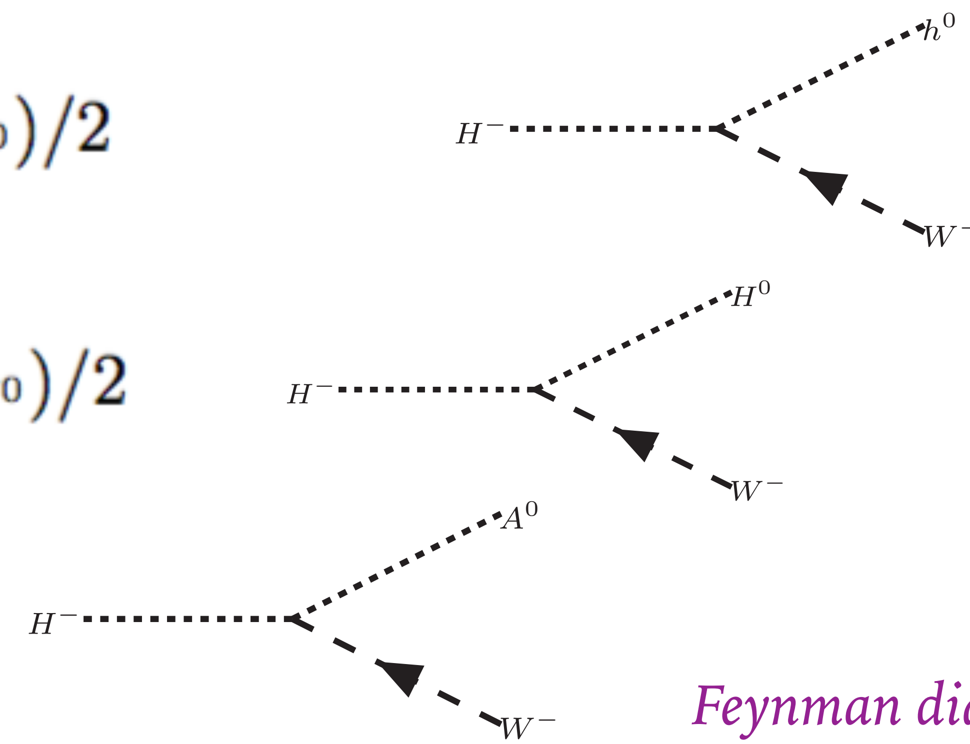
CHARGED HIGGS - NEUTRAL HIGGS COUPLINGS

- The couplings for H^-W^+h, H^-W^+H, H^-W^+A interactions are given as

$$g_{H^-W^+h^0} \equiv g\cos(\beta-\alpha)(p_{H^-}+p_{h^0})/2$$

$$g_{H^-W^+H^0} \equiv g\sin(\beta-\alpha)(p_{H^-}+p_{H^0})/2$$

$$g_{H^-W^+A^0} \equiv ig(p_{H^-}+p_{A^0})/2$$

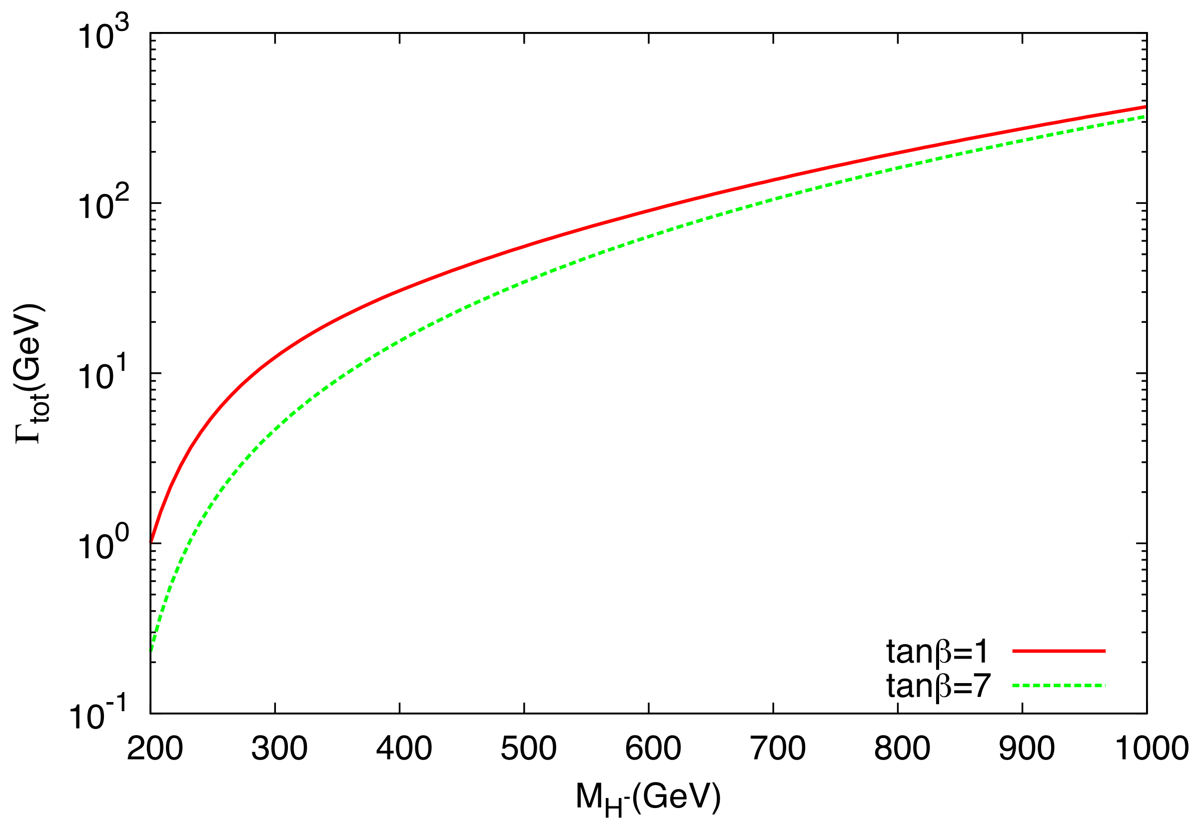


Feynman diagrams contributing to the charged Higgs - neutral Higgs interactions

- For the case $\cos(\beta-\alpha)\cong 0$, couplings of the lightest CP even Higgs boson h^0 are mostly identical to the SM Higgs couplings. We may take $H^{\pm}$, H^0, A^0 sufficiently heavy, while keeping quartic couplings $O(1)$ - decoupling limit - suppression of the FCNC and CPV.

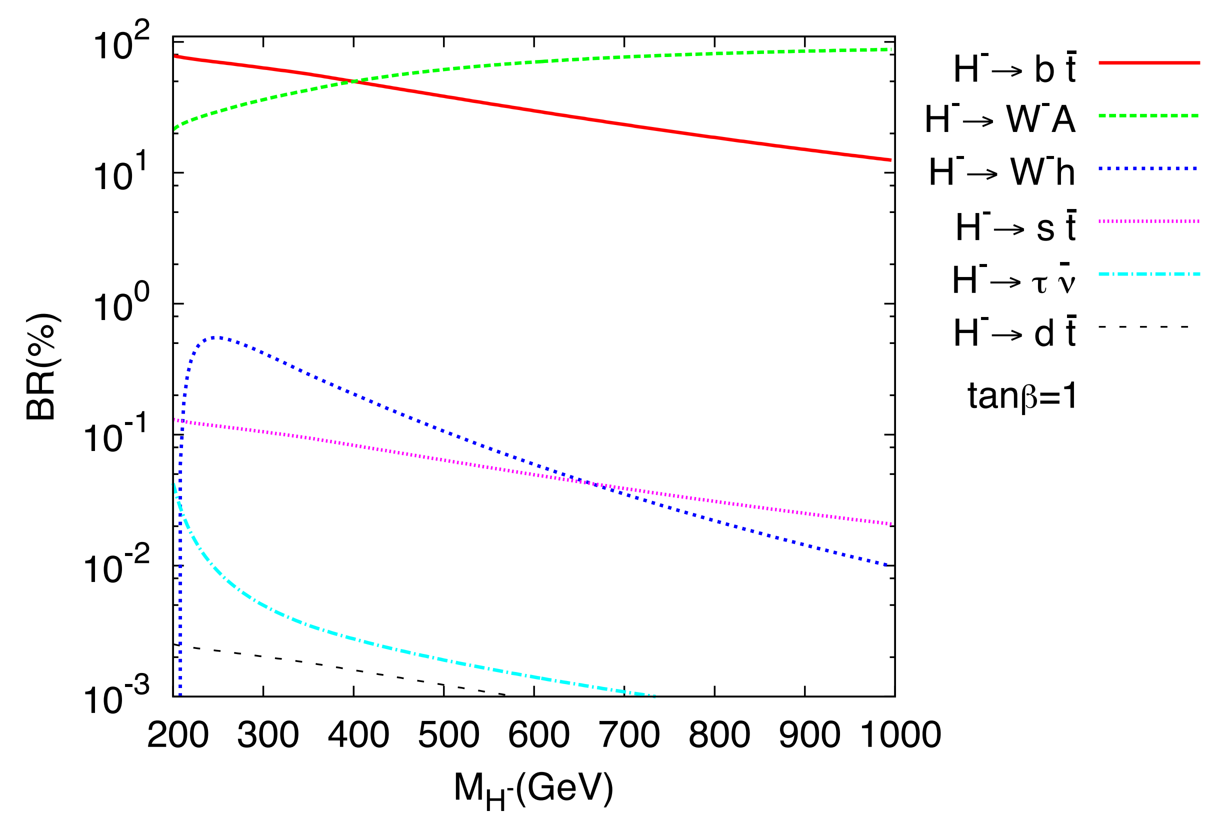
DECAY WIDTH AND BRANCHINGS

- Total decay width and branchings depending on different parameters within THDM-I



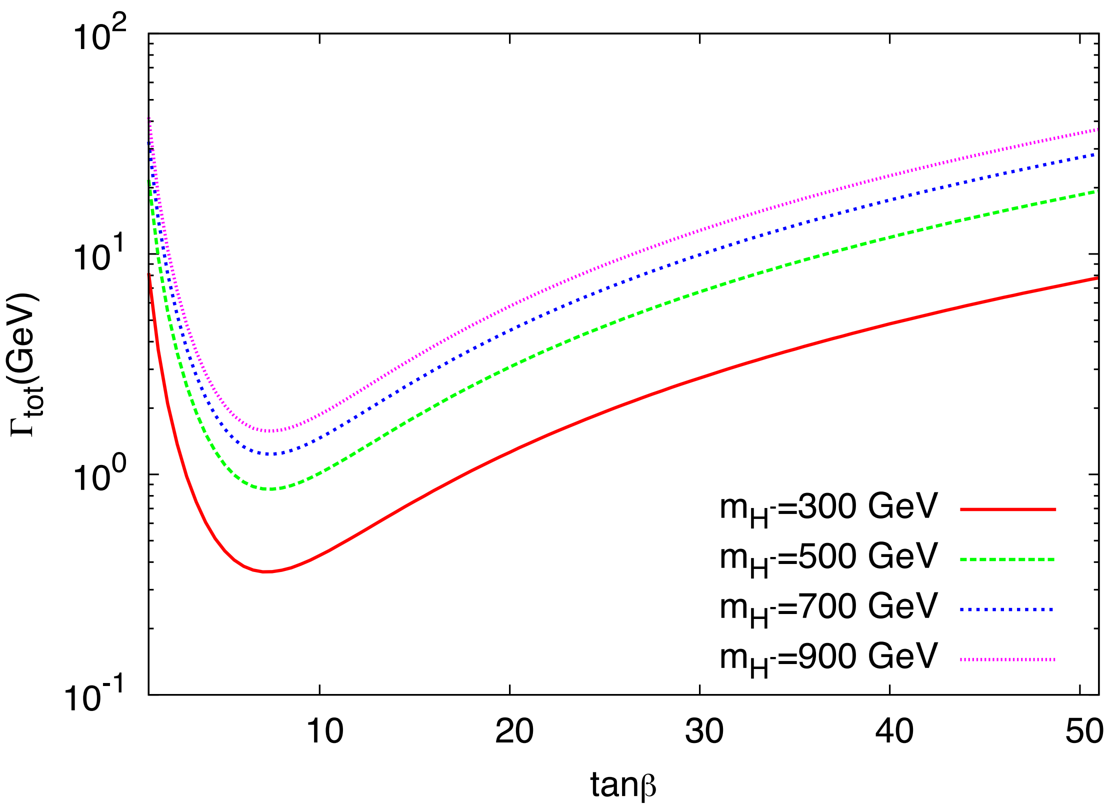
Decay width of $H^{\pm}$ boson depending on its mass for different values of tanβ, with parameters (PI) $m_{A^0}=100$ GeV and $m_{H^0}=m_{H^-}$.

Branching ratios to different decay modes of charged Higgs boson depending on its mass, with the same set of parameters.



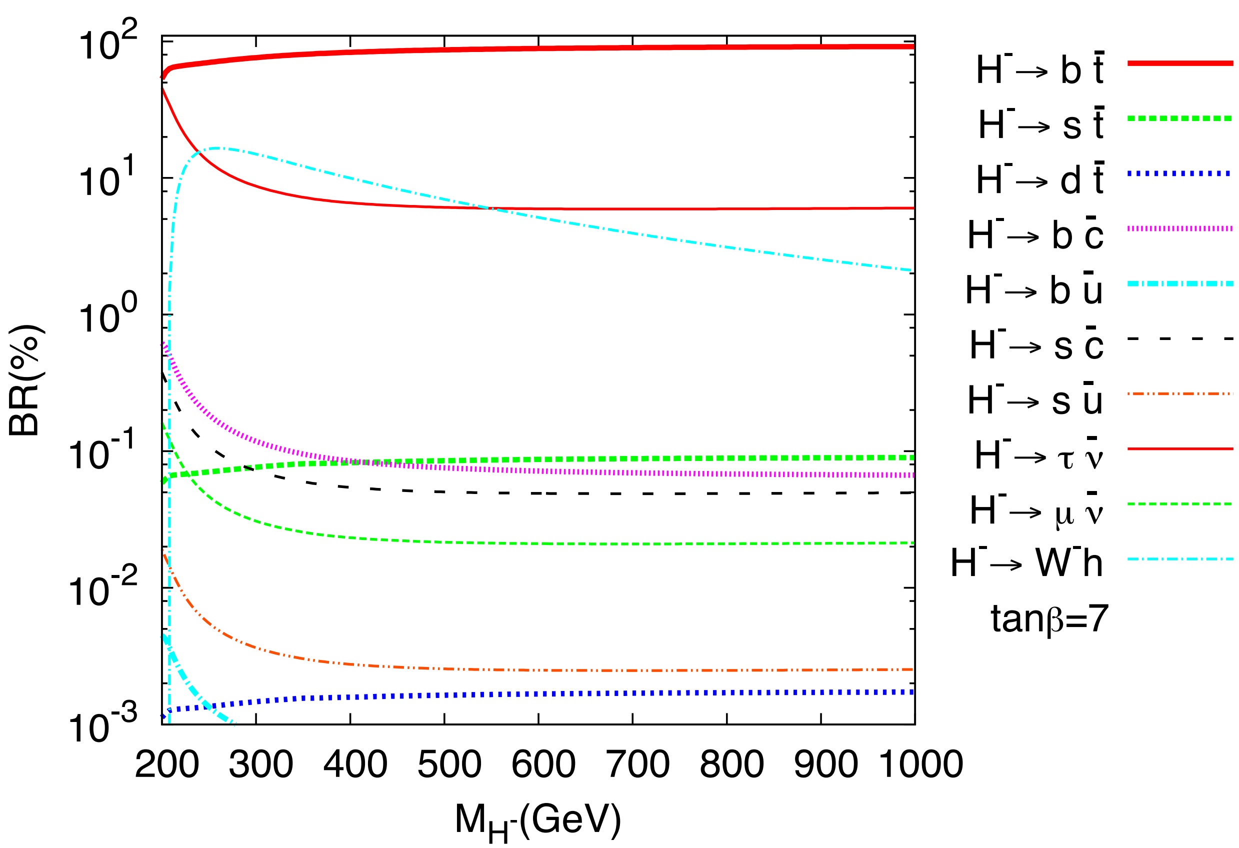
DECAY WIDTH AND BRANCHINGS

➤ Total decay width and branchings depending on different parameters within THDM-II



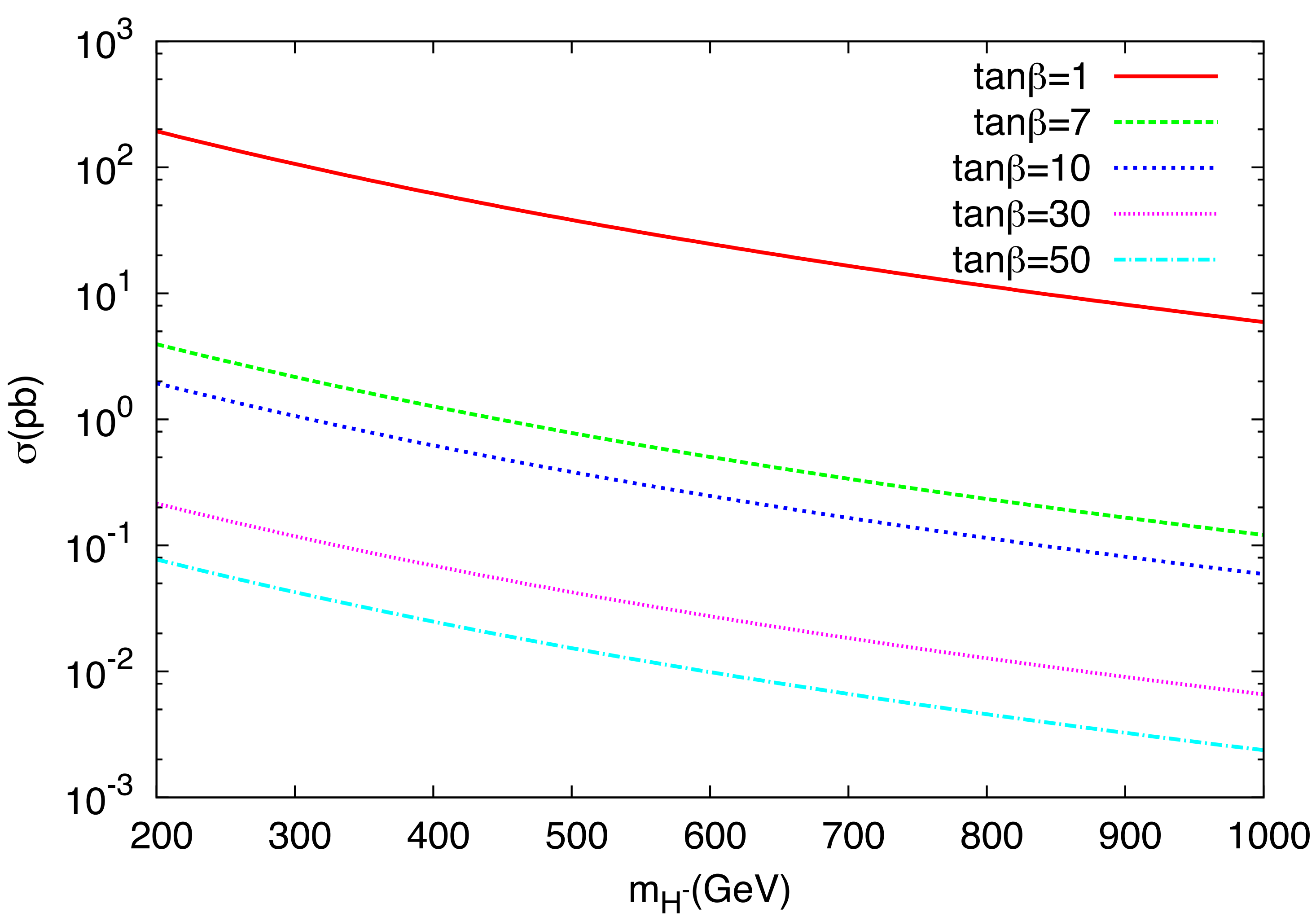
Decay width of $H^{\pm}$ boson depending on tanβ for different mass values, with parameters (PII) $m_{A^0}=m_{H^0}=m_{H^-}$ and THDM-II.

Branching ratios to different decay modes of charged Higgs boson depending on its mass, with the same set of parameters.

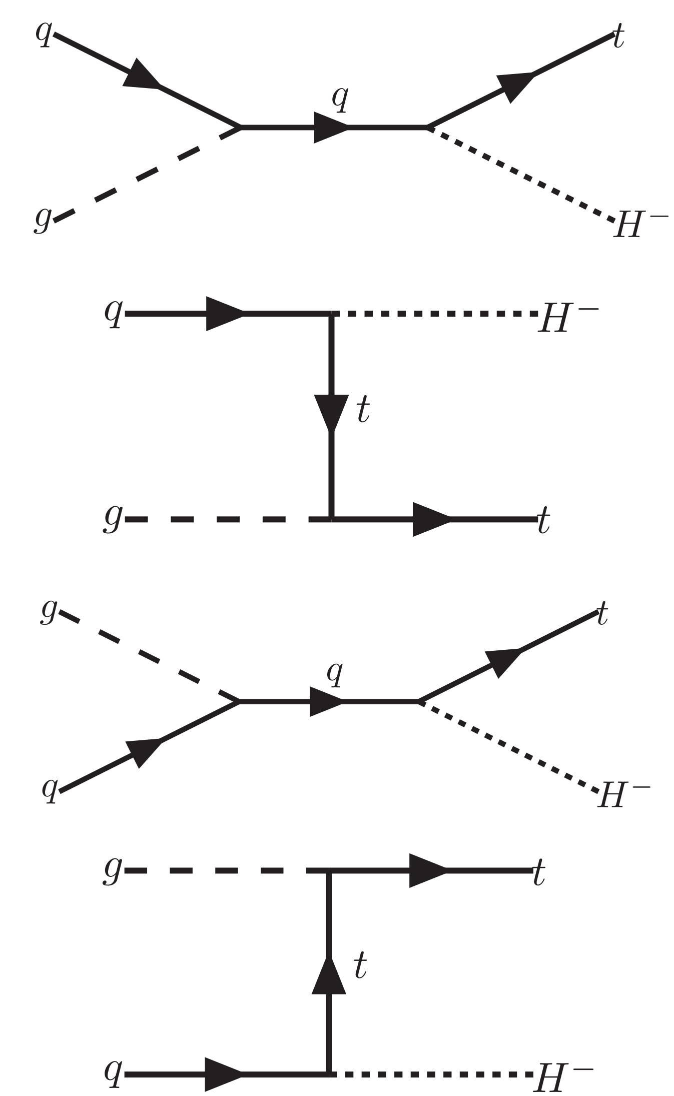


CROSS SECTIONS

- The FCC-hh has the potential to search for a wide parameter range than the ongoing searches at the LHC which rely on specific production and decay mechanism.



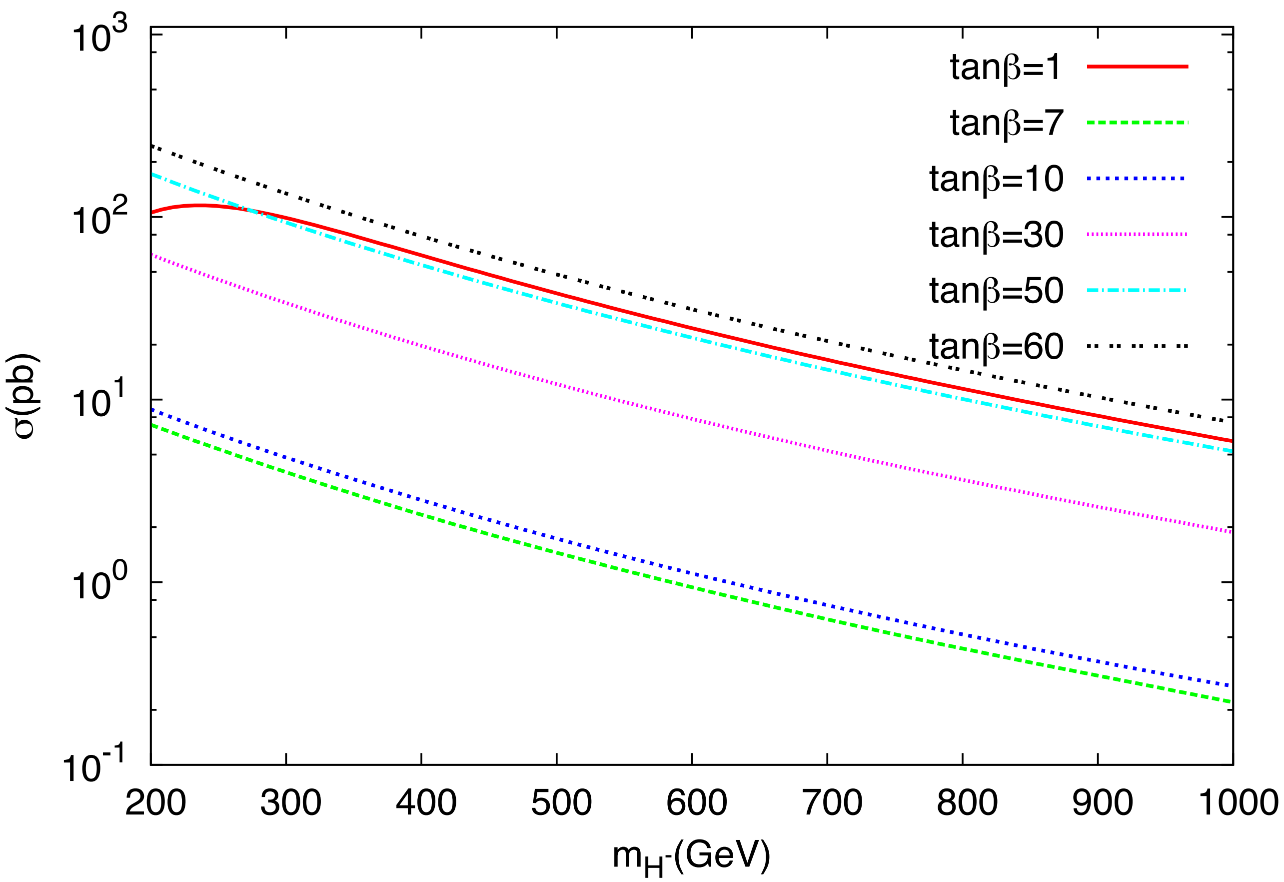
For THDM-I, the cross section decreases with the increasing mass and tanβ values.



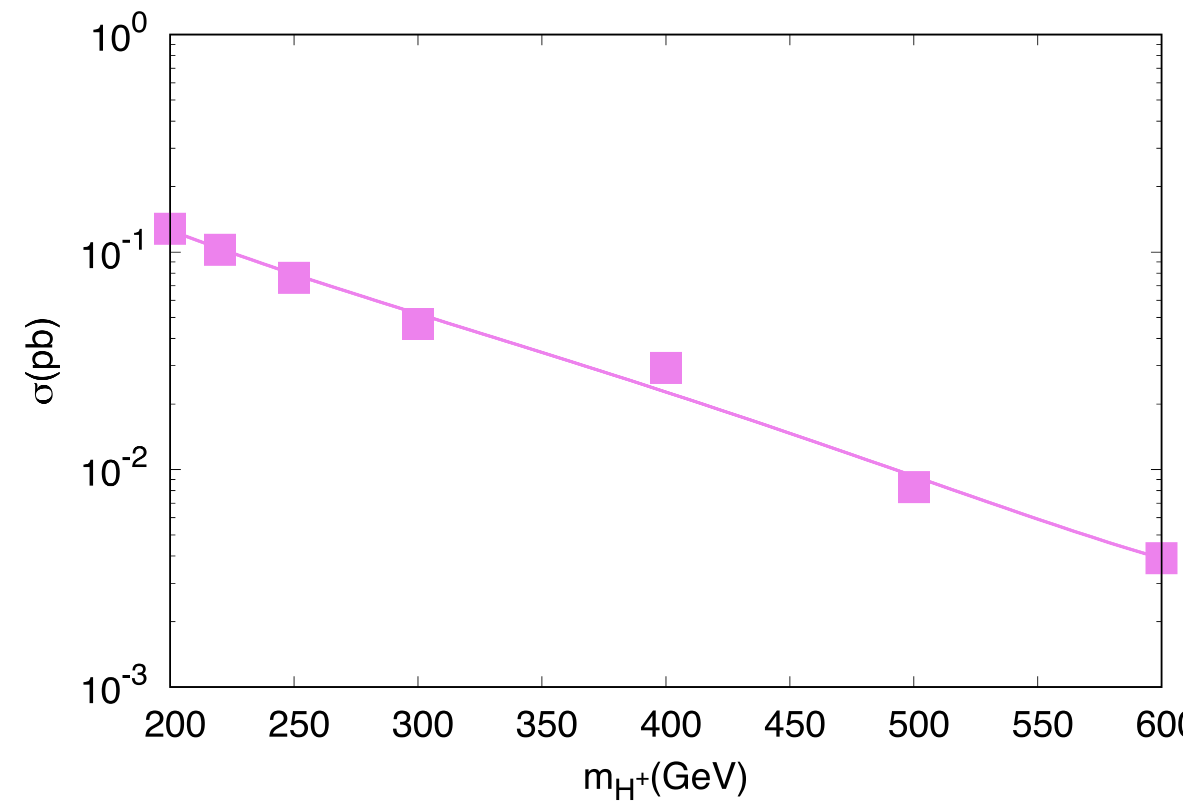
Feynman diagrams contributing to the H⁻ and top production.

CROSS SECTIONS

- Process $pp \rightarrow tH^{\pm}+X$ has the cross section 15 pb for $m_{H^{\pm}}=500$ GeV and $\tan\beta=30$ at FCC-hh with $\sqrt{s}=100$ TeV.



For THDM-II, the cross section depending on the m_{H^-} and $\tan\beta$ at the FCC-hh with $\sqrt{s}=100$ TeV.



For a comparison at the LHC, the cross section depending on the m_{H^+} with $\tan\beta=30$ for pp collisions at $\sqrt{s}=8$ TeV. The data points used from [CMS-PAS-HIG-13-026].

ANALYSIS

- Signal: $tH^{-} \longrightarrow t\bar{t}+b(\bar{b})$
- Background: $t\bar{t}+b(\bar{b})$, $t\bar{t}+c(\bar{c})$, $t\bar{t}+j$
    - Basic cuts:

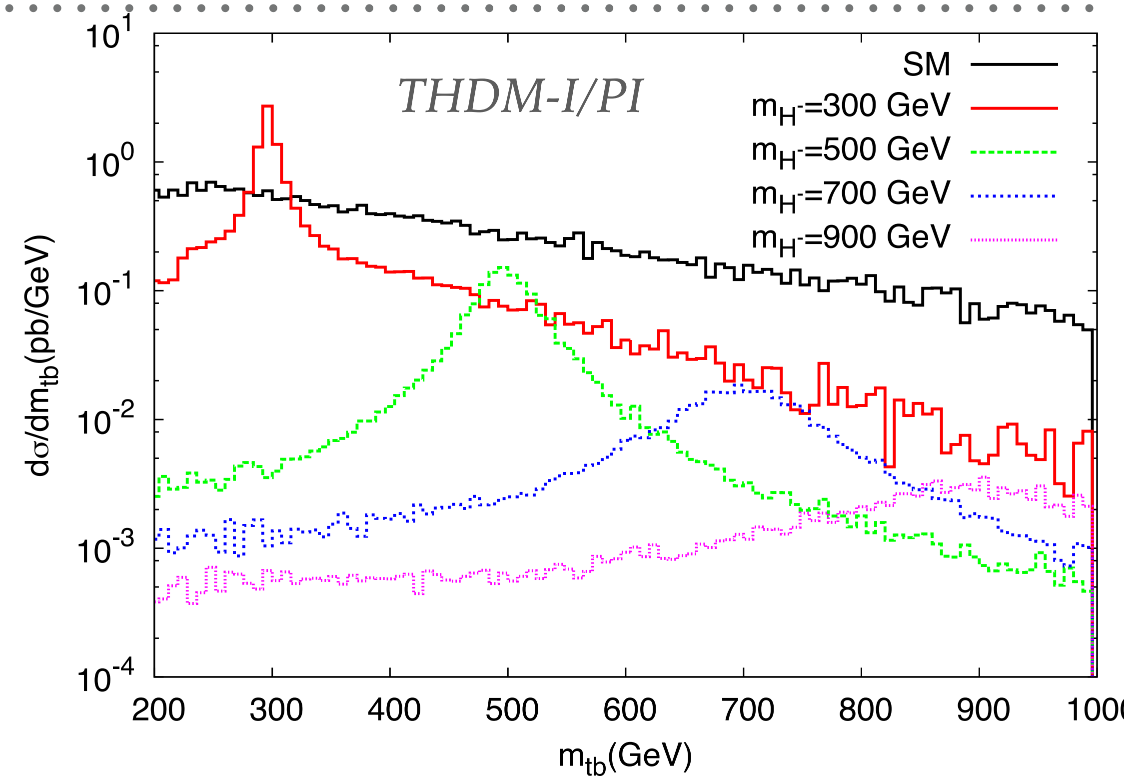
      $p_T^{b,c,j} > 20$ GeV, $|\eta^{b,c,j}| < 2.5$
    - Analysis cuts:

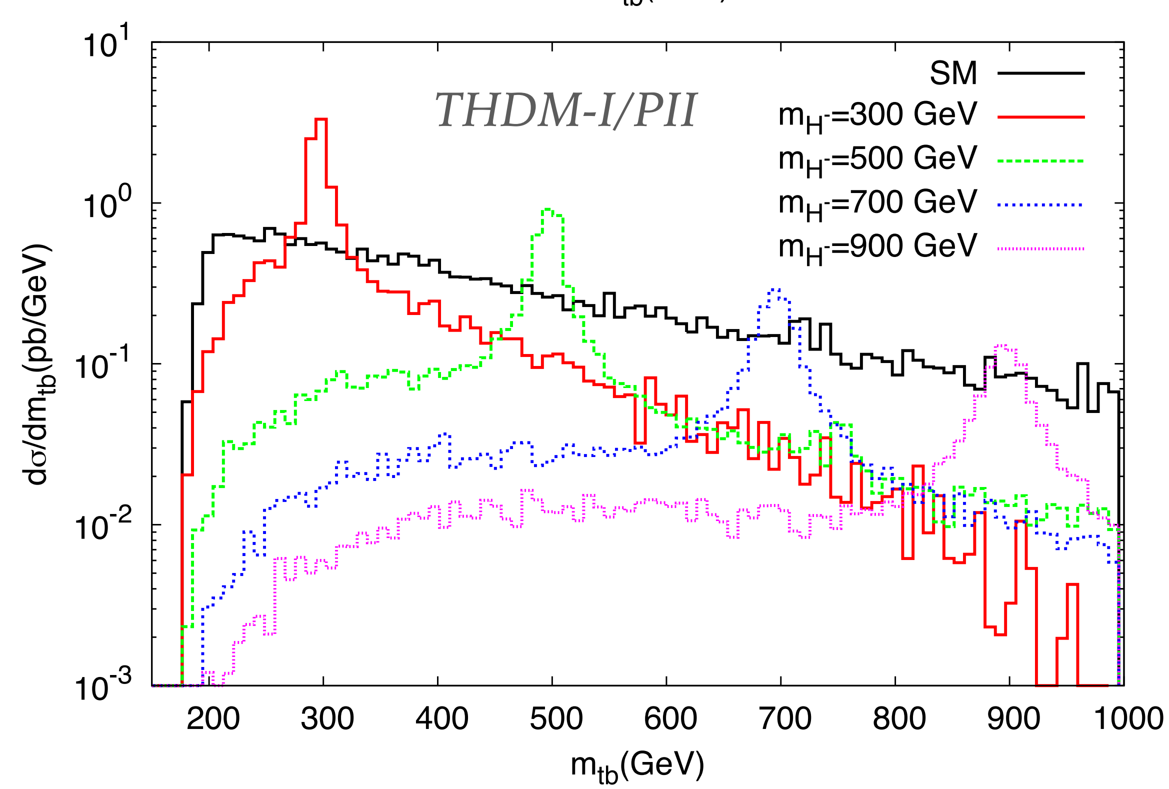
      $|m_{tb} - m_{H^-}| \leq 0.1 m_{H^-}$
    - Efficiencies:

      . $\epsilon_b = 50\%$ b-tagging

      . $r_c = 10\%$ rejection for c quark

      . $r_j = 1\%$ rejection for light jets

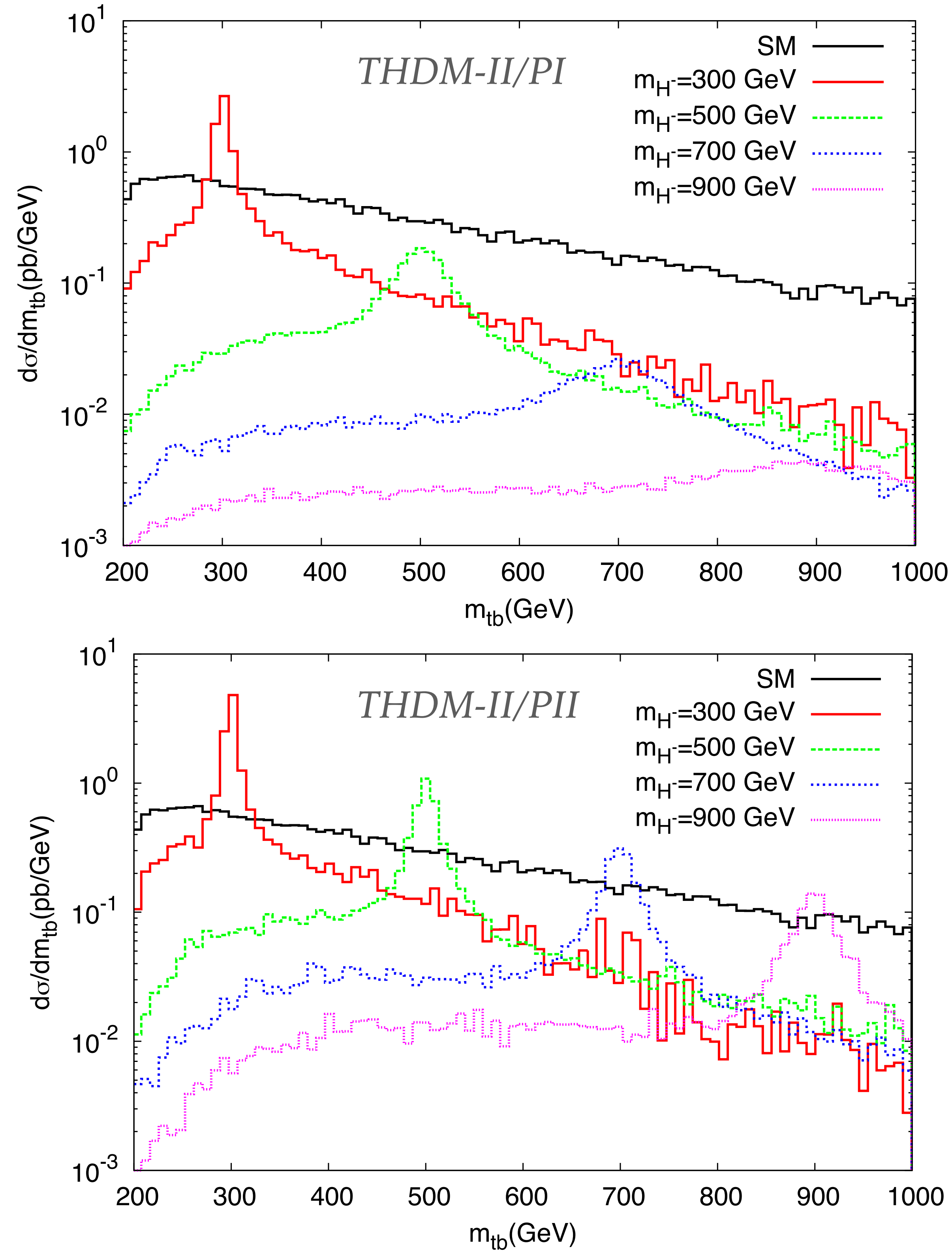




Invariant mass distributions of tb system for PI and PII of THDM-I at FCC-hh.

ANALYSIS

- For the analysis, we use invariant mass distributions of tb system for parameter set PI and PII of the THDM-I and THDM-II at the FCC-hh with $\sqrt{s}$=100 TeV.
- Here, we consider the background due to one leading b-jet. Other b-jets originating from top quark decays will have different kinematical distributions.
- The final state is accounted for $W^+W^-+3b_{jet}$ (where at least one W-boson decay leptonically).



The m_{tb} distributions for PI and PII of THDM-II

RESULTS

- In order to calculate the statistical significance ($S/\sqrt{B}$), the cross sections for the signal and background are calculated in the invariant mass bin width of $0.2m_{H^-}$.

m_{tb} (GeV)	$pp \to t\bar{t}b(\bar{b}) + X$	$pp \to t\bar{t}c(\bar{c}) + X$	$pp \to t\bar{t}j + X$	$\Delta\sigma_B(pb)$
300 ± 30	2.99×10^0	3.65×10^0	2.51×10^2	4.37×10^0
500 ± 50	2.88×10^0	3.62×10^0	1.23×10^2	3.03×10^0
700 ± 70	1.89×10^0	2.40×10^0	8.04×10^1	1.99×10^0
900 ± 90	1.34×10^0	1.86×10^0	5.47×10^1	1.40×10^0

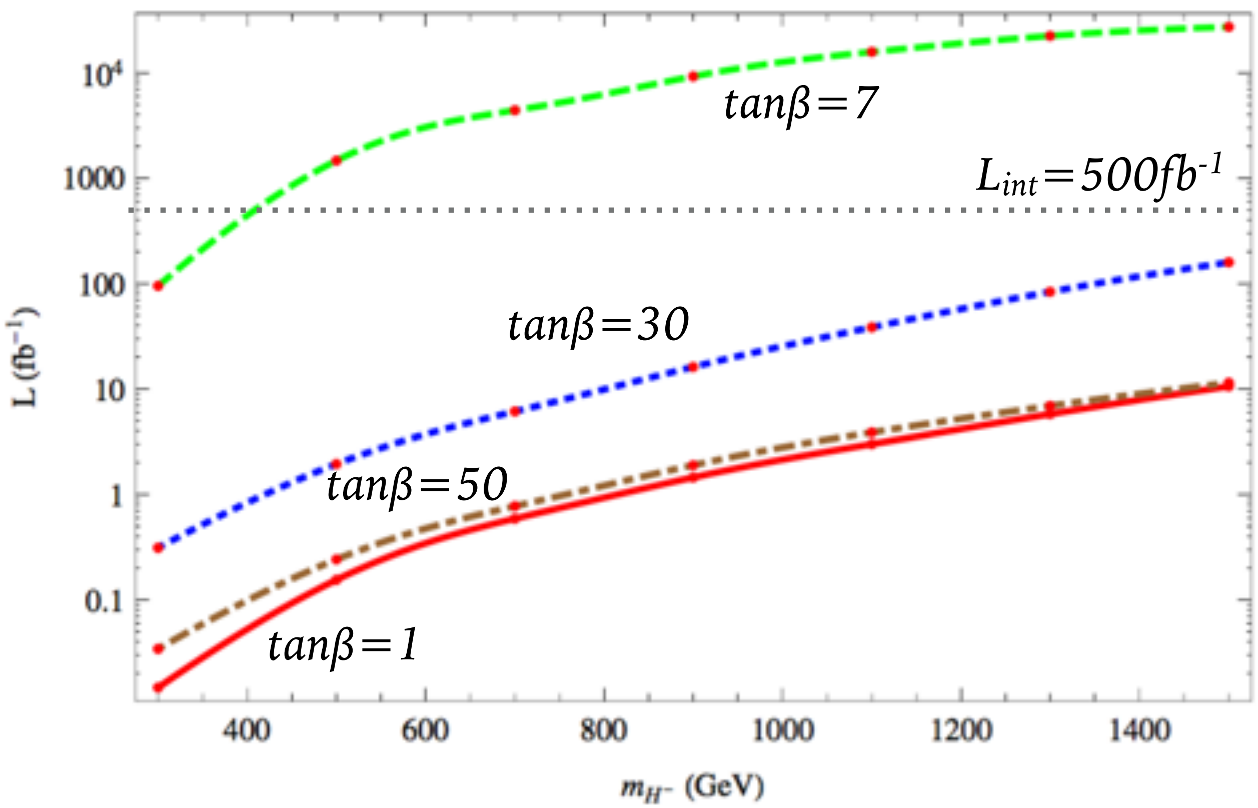
Cross section for the background ($t\bar{t}b_{jet}$)

Model ($\tan\beta = 1$)	THDM-I		THDM-II	
m_{tb} (GeV)	PI	PII	PI	PII
300 ± 30	402.65 (230.73)	612.95 (351.24)	395.02 (226.35)	553.09 (316.93)
500 ± 50	89.53 (51.30)	324.52 (185.96)	95.45 (54.69)	338.11 (193.75)
700 ± 70	26.56 (15.22)	164.31 (94.16)	18.76 (10.75)	124.56 (71.38)
900 ± 90	6.50 (3.73)	91.53 (52.45)	5.73 (3.61)	69.53 (39.84)

Statistical significance $S/\sqrt{B}$ at L_{int}=500 fb^{-1} at FCC-hh.

RESULTS

➤ We obtain the luminosity need to reach a 3σ significance depending on the mass of charged Higgs boson and different tanβ values. FCC-hh extends the parameter space of Higgs sector with a high luminosity of 500 fb^{-1}.



Results for final state
$t\bar{t}+b(\bar{b})$ -> $3b_{jet}+2j+l+MET$

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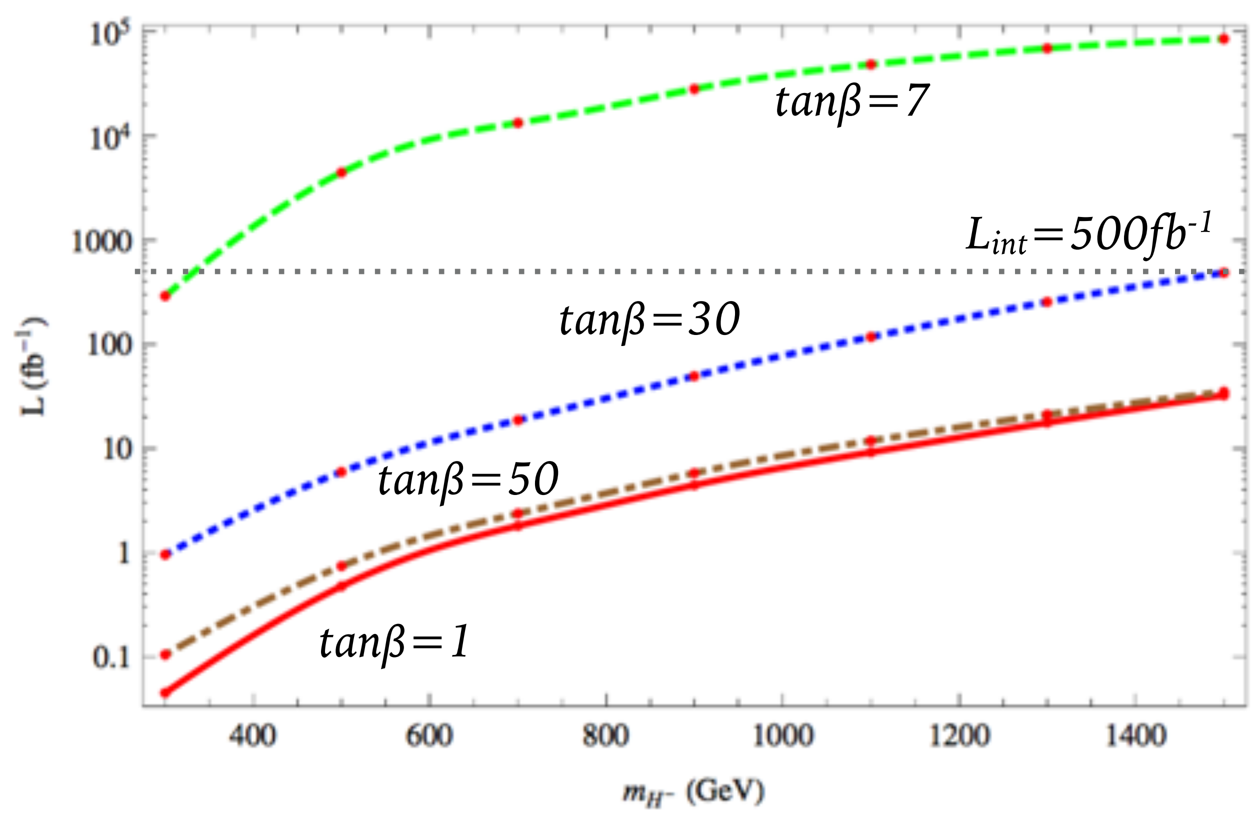
$t\bar{t}+b(\bar{b})$ -> $3b_{jet}+2l+MET$



CONCLUSIONS

Possible extensions of the Higgs sector can be searched for a wide range of parameter space in the high energy proton-proton collisions.

The decay modes of the Higgs bosons can be well similar to the background reactions from top and bottom quarks and other sources.

It is shown that with an integrated luminosity of 500 fb^{-1} at the center of mass energy $\sqrt{s}=100$ TeV of FCC-hh collider, the charged Higgs boson signal can be distinguished from the background for m_{H^-} up to 1 TeV for a large parameter space of two Higgs doublet model.

There are theoretical uncertainties in the calculation of cross sections at very high energies, such as the scales of renormalization and factorization as well as different schemes for the parton distribution functions, however the complete next to leading order results will reduce the scale dependence and theoretical uncertainties. Even it seems challenging to measure precisely due to the large hadronic background and systematic uncertainties we look forward to its exploitation in precision LHC physics and FCC physics programmes.