Status of heavy charged Higgs boson searches at the Large Hadron Collider

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Talk based on:

- Various ATLAS/CMS searches
- A. Arhrib, AJ, S. Moretti, Phys. Rev. D 98 (2018) 11, 115006
- In progress.

Introduction

- The discovery of the SM Higgs boson at the Large Hadron Collider (LHC) validated the standard model (SM) as a low energy (~EW scale) description of nature.
- Several phenomena (e.g. dark matter) cannot be accounted for/explained in the SM.
- It is not also clear **yet** how many scalar multiplets contribute to the phenomenon of the electroweak symmetry breaking.
- The two-Higgs-doublet model is one of the most minimal options that extend the scalar sector of the SM.
- The two-Higgs-doublet models predict the existence of a pair of charged Higgs bosons.

The SM is working pretty well… so far

- The SM Yukawa couplings have a strong hierarchy, e.g.:

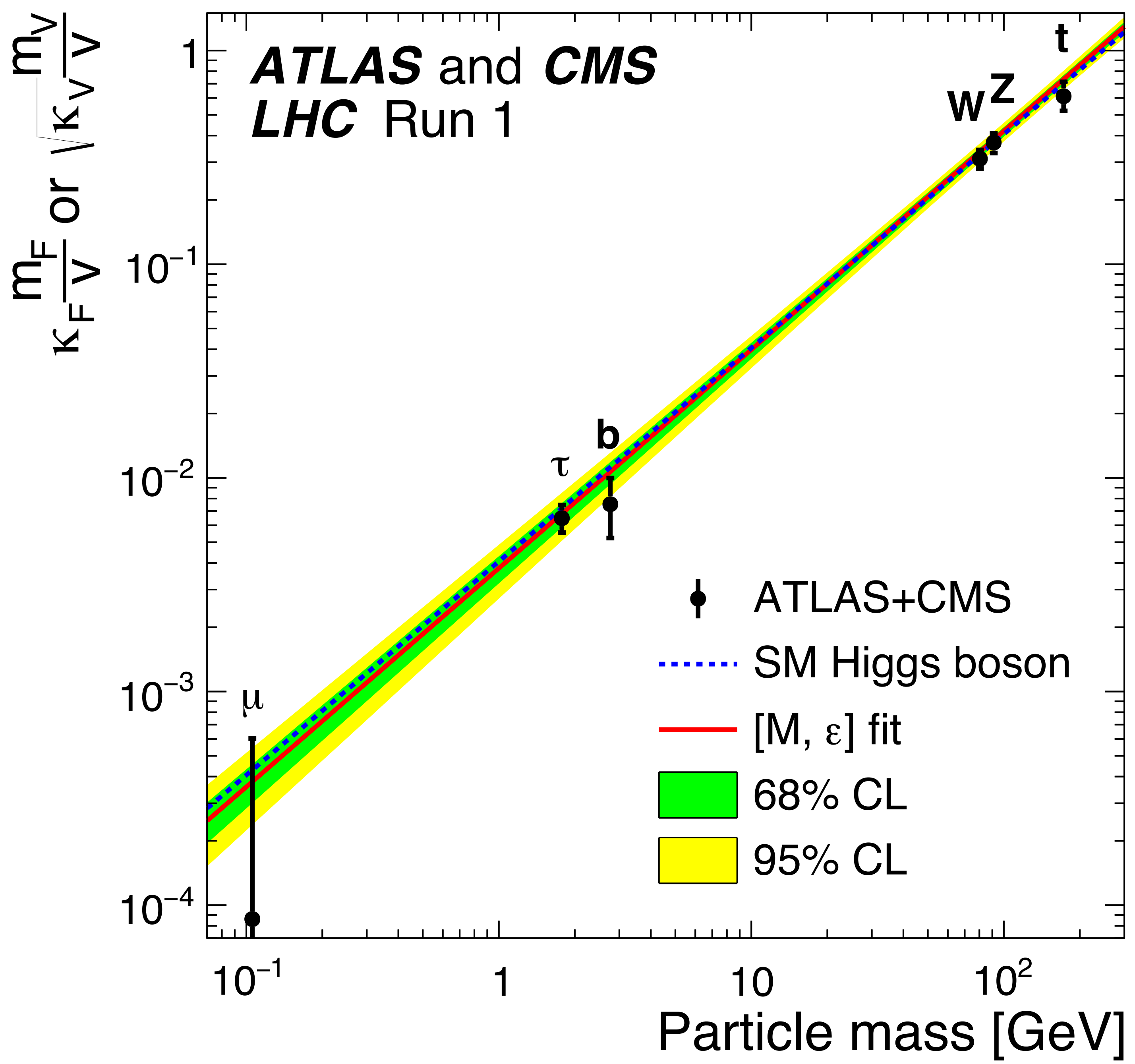
$$\frac{m_t}{m_e} \simeq 3 \times 10^6$$

- Can be measured from the rates of the SM Higgs boson decays

$$\Gamma(H \to f\bar{f}) \propto \frac{m_H m_f^2}{M_W^2} \times \text{PS} \times \text{Radiative corrections}$$

Thanks to the one-to-one correspondence

- Light Higgs-fermion Yukawa couplings are more challenging to measure: see Soreq et al. (2016), Bishara et al. (2017), Gao (2018).



Good agreement between theory and experiment

The two-Higgs doublet model in a nutshell

We extend the SM by two scalar isodoublets

$$\Phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + \eta_i) \end{pmatrix} \sim (\mathbf{1}, \mathbf{2})_1$$

To avoid large tree-level FCNC transition, we impose a Z_2 symmetry that is softly broken $\Longrightarrow$ four types of the two-Higgs-doublet model (also called Yukawa realizations).

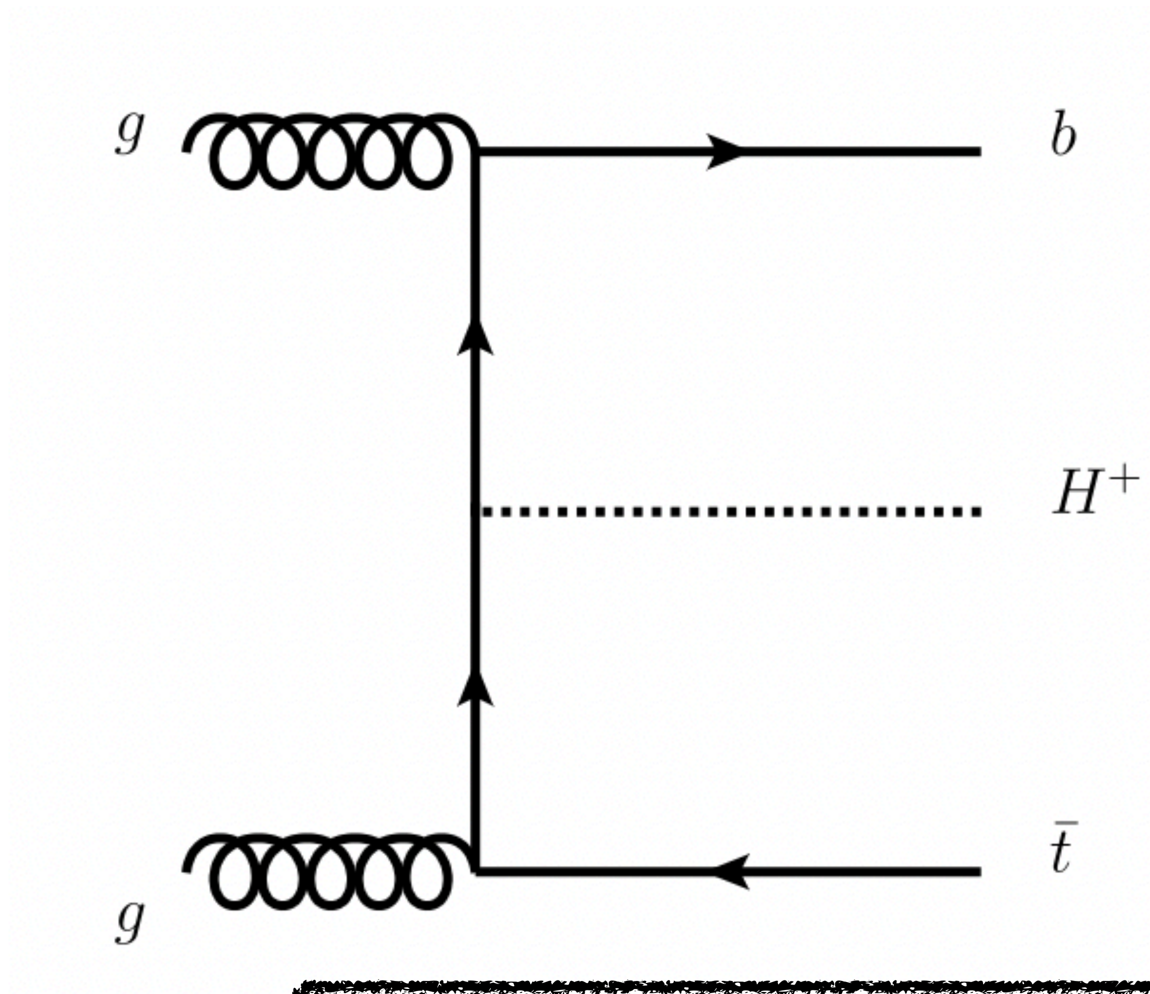
$$-\mathcal{L}_{\text{Yukawa}} = \sum_{\psi=u,d,\ell} \left(\frac{m_\psi}{v} \kappa_\psi^h \bar{\psi}\psi h^0 + \frac{m_\psi}{v} \kappa_\psi^H \bar{\psi}\psi H^0 - i \frac{m_\psi}{v} \kappa_\psi^A \bar{\psi}\gamma_5 \psi A^0 \right)$$
$$+ \left(\frac{V_{ud}}{\sqrt{2}v} \bar{u}(m_u \kappa_u^A P_L + m_d \kappa_d^A P_R) d H^+ + \frac{m_\ell \kappa_\ell^A}{\sqrt{2}v} \bar{\nu}_L \ell_R H^+ + \text{H.c.} \right),$$

κ_i are the coupling modifiers

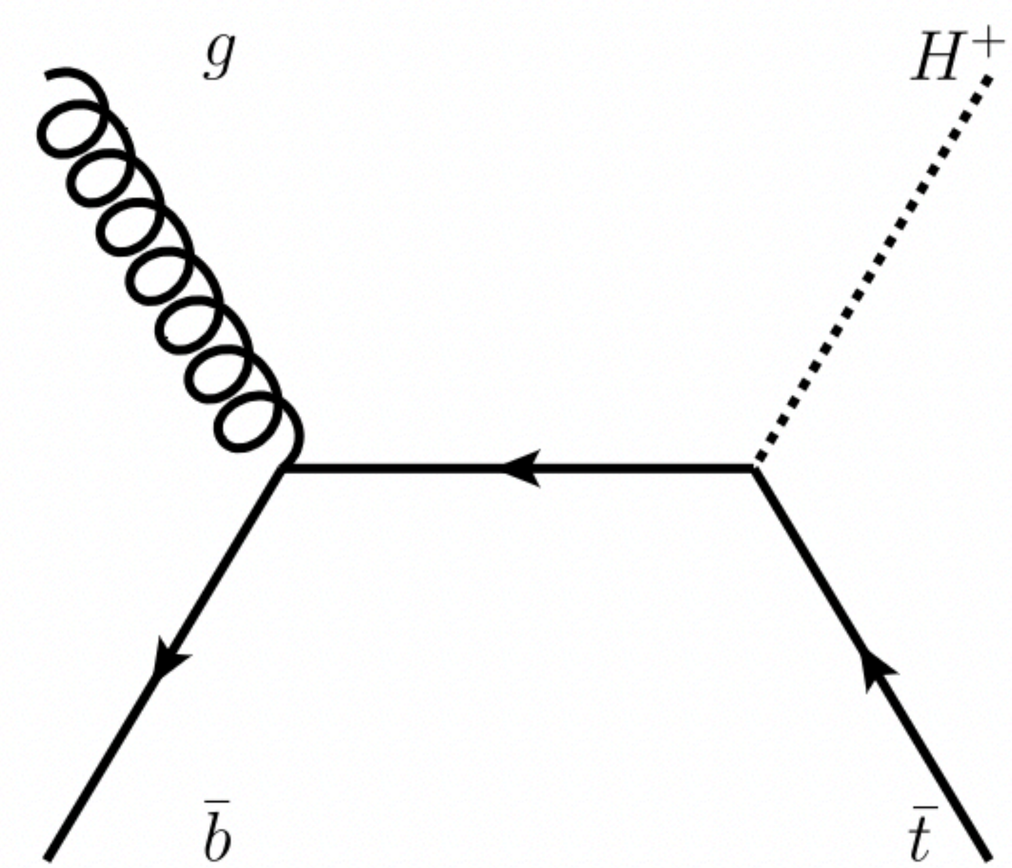
	κ_u^h	κ_d^h	κ_ℓ^h	κ_u^H	κ_d^H	κ_ℓ^H	κ_u^A	κ_d^A	κ_ℓ^A
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

Production of charged Higgs bosons at the LHC

4FS: The charged Higgs boson is produced in association with $b\bar{t}$



5FS: The charged Higgs boson is produced in association with $\bar{t}$



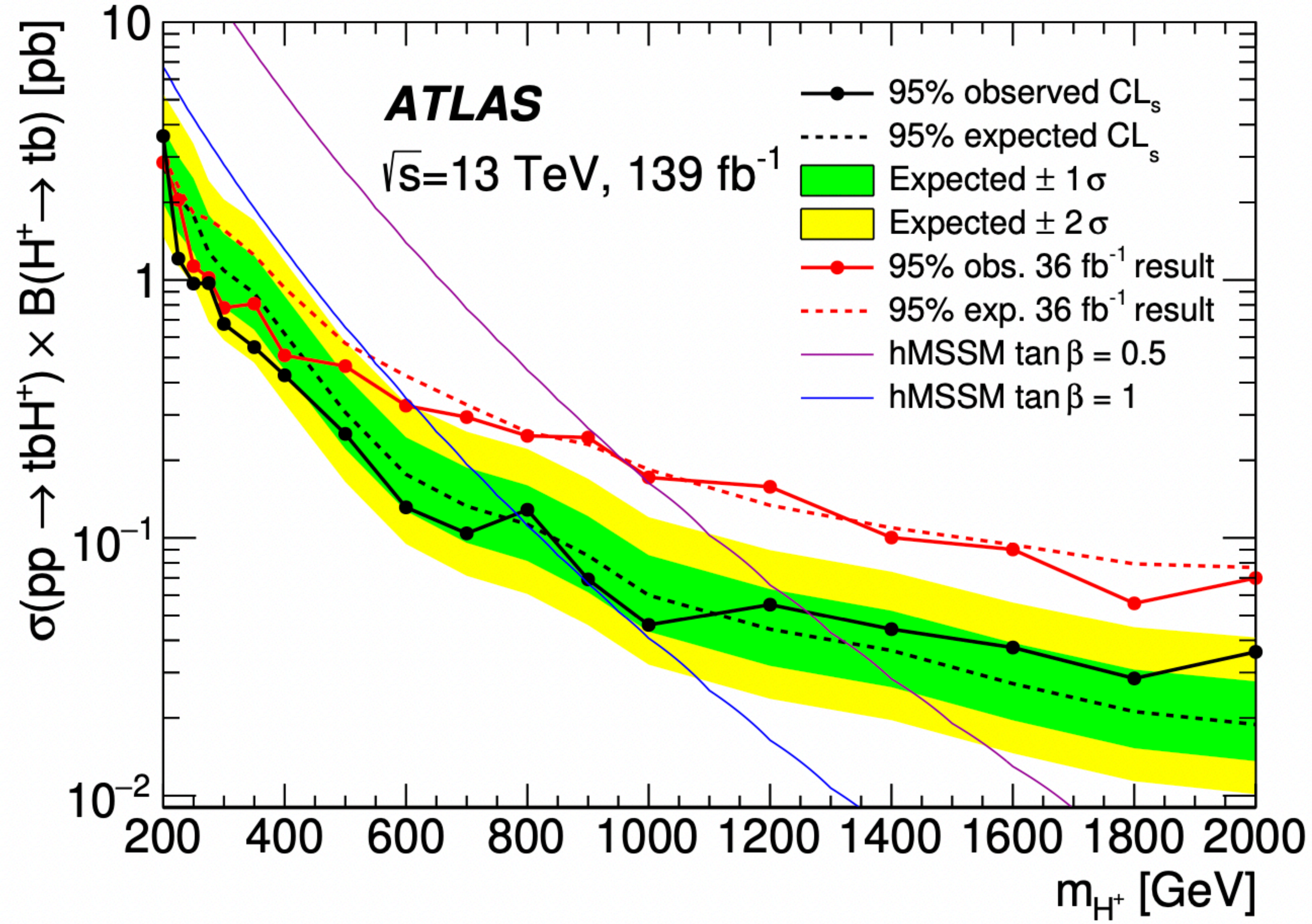
Some disagreement between the two schemes at LO.
Situation improves when we go from LO to NLO.
Also 4FS introduces an extra b-quark in the final state.

Status of charged Higgs boson searches at the LHC

$H^+ \to t\bar{b}$

Limits have been put on the product of the cross section times the branching in the context of the hMSSM for some choices of $\tan\beta$.

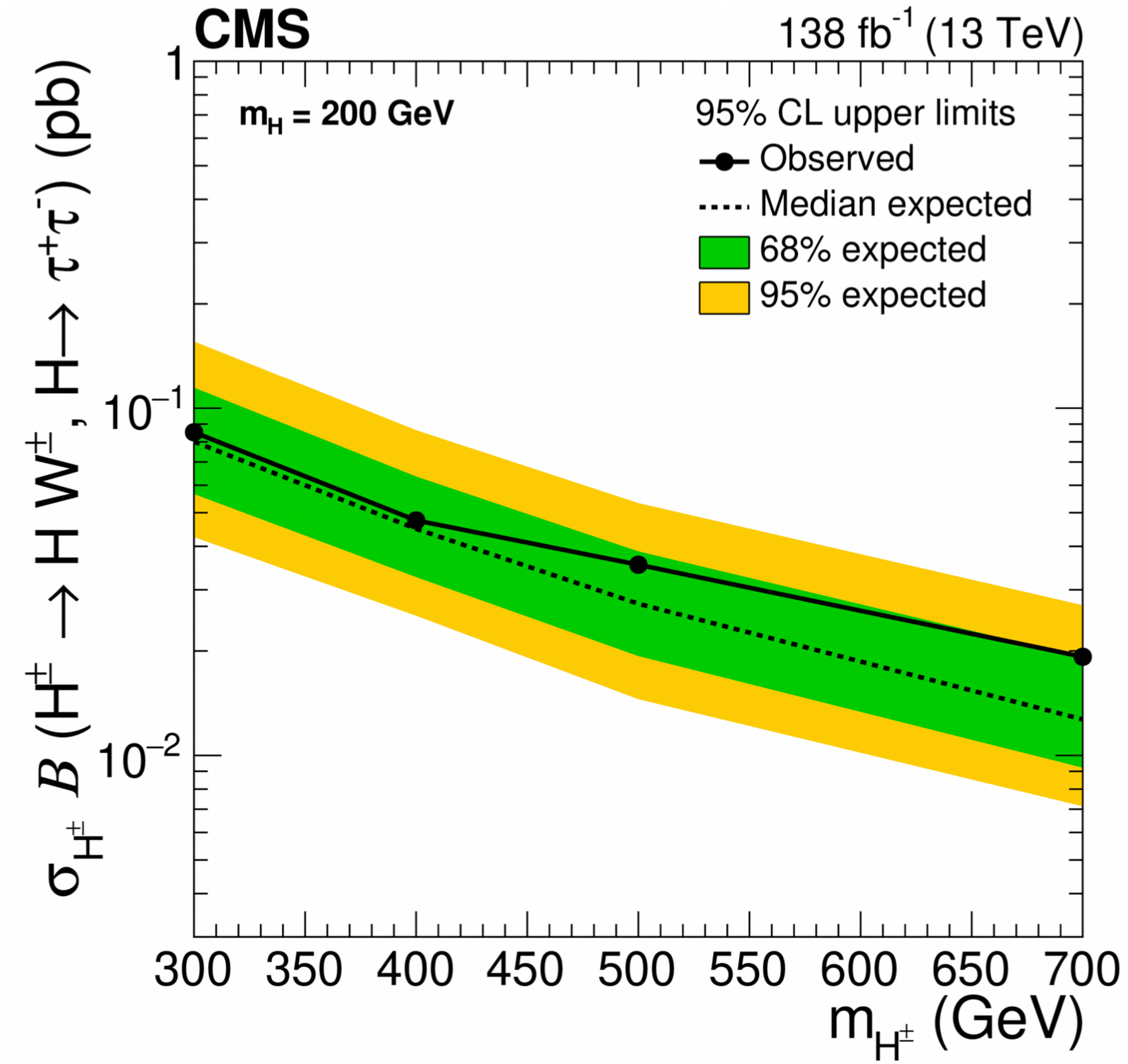
Can be re-interpetred in the framework of the two-Higgs-doublet by using MA5 or HB/HS.



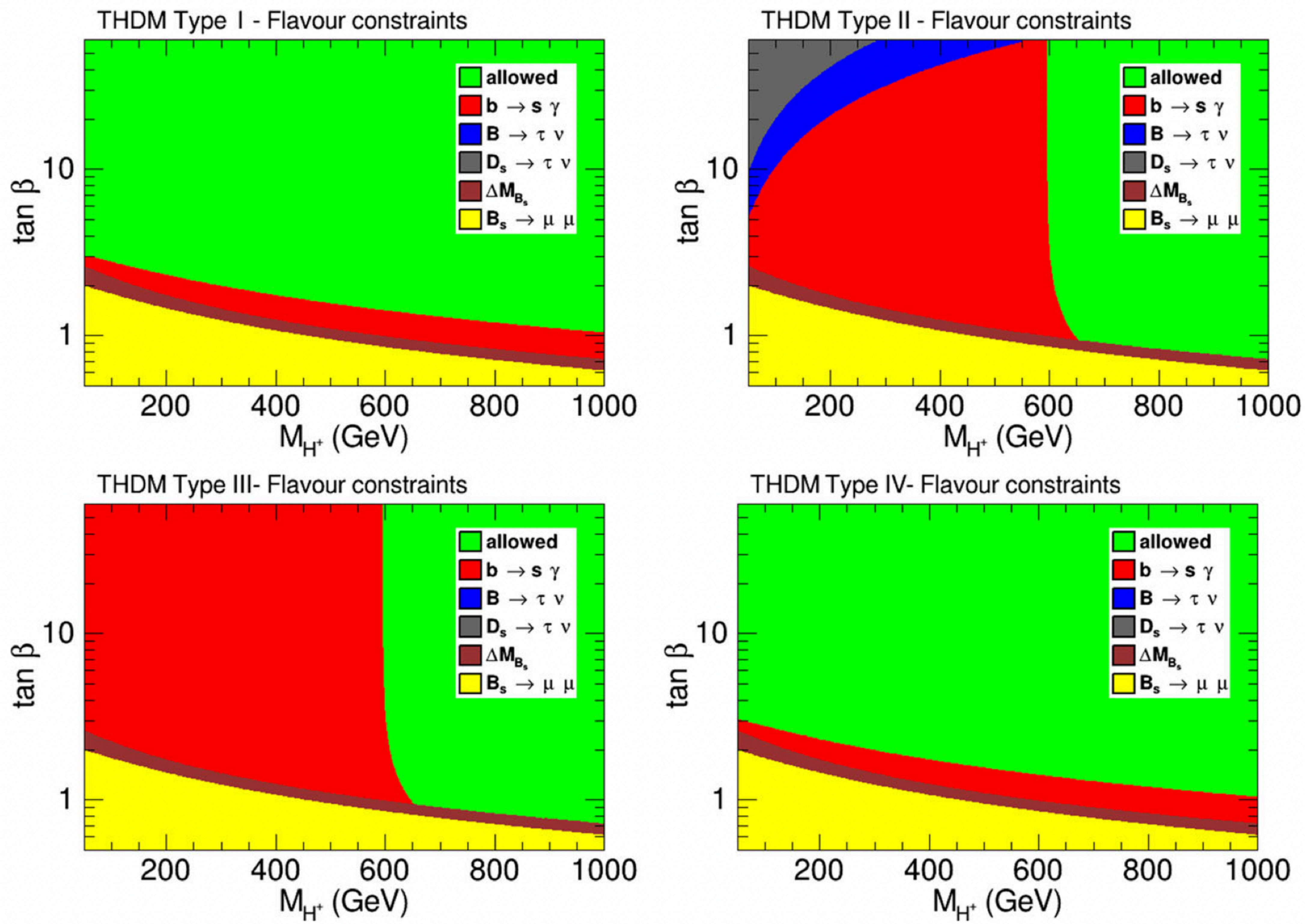
Status of charged Higgs boson searches at the LHC

$$H^+ \to H(\to \tau\tau)\ W^+$$

Bounds are weaker in this case.



Status of Higgs boson searches within the 2HDM

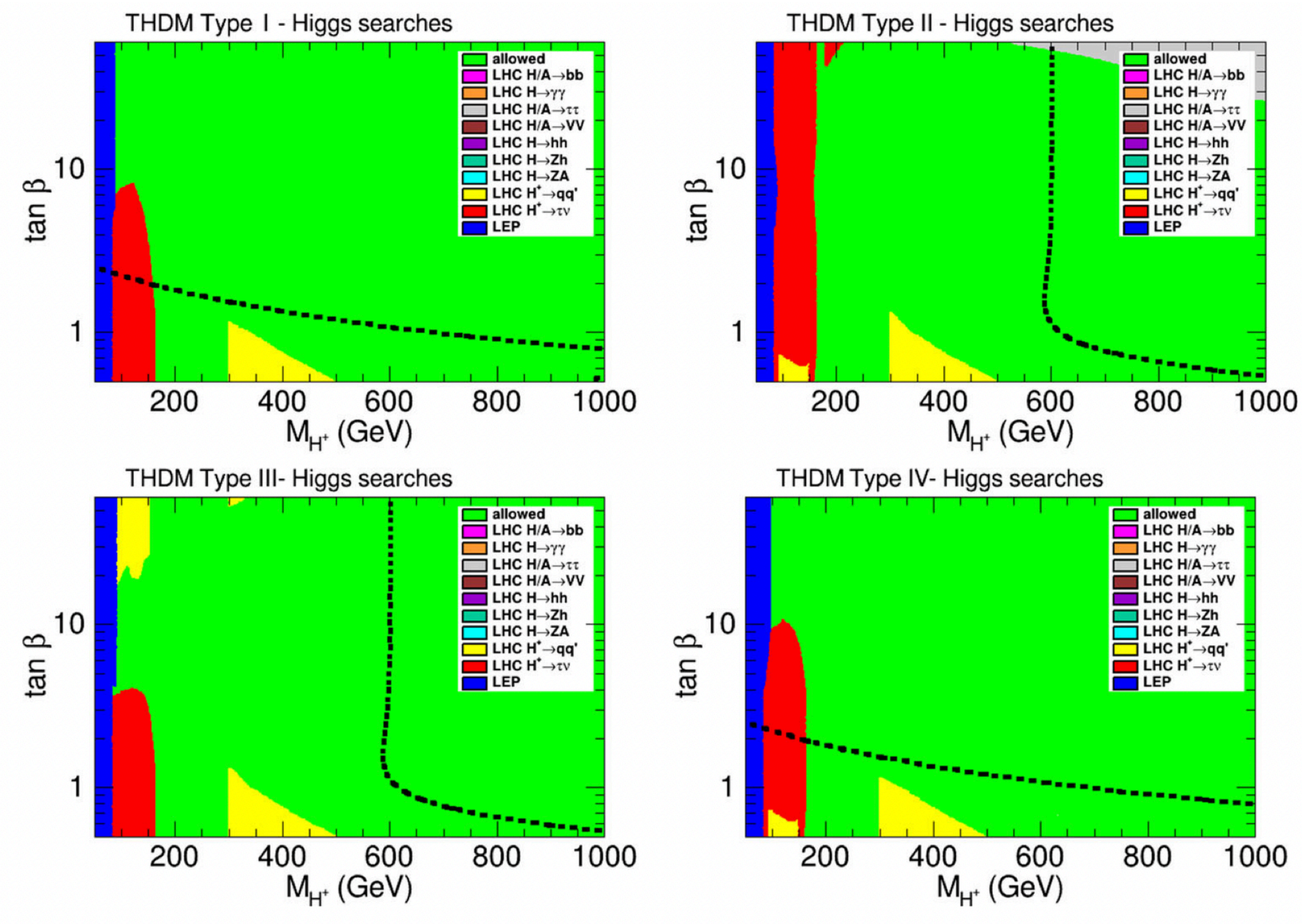


Type III = Type Y

Type IV = Type X

A. Arbey, F. Mahmoudi, O. Stal, T. Stefania (1706.07414)

Status of Higgs boson searches within the 2HDM



Type III = Type Y

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Chirality of the $H^+\bar{t}b$ coupling

- The main vertex characterizing charged Higgs boson production at the LHC is the $g_{H^+\bar{t}b}$ coupling given at LO by

$$g_{\bar{t}bH^+} = i(C_L P_L + C_R P_R); \quad C_L = \frac{1}{\sqrt{2}v} m_t \kappa_u^A, C_R = \frac{1}{\sqrt{2}v} m_b \kappa_d^A$$

In the 2HDM-I and the 2HDM-X, both the R- and L-handed components are proportional to $1/\tan\beta$

In the 2HDM-II and the 2HDM-Y, the R-component is proportional to $\tan\beta$ while the L-component is proportional to $1/\tan\beta$.

Implications?

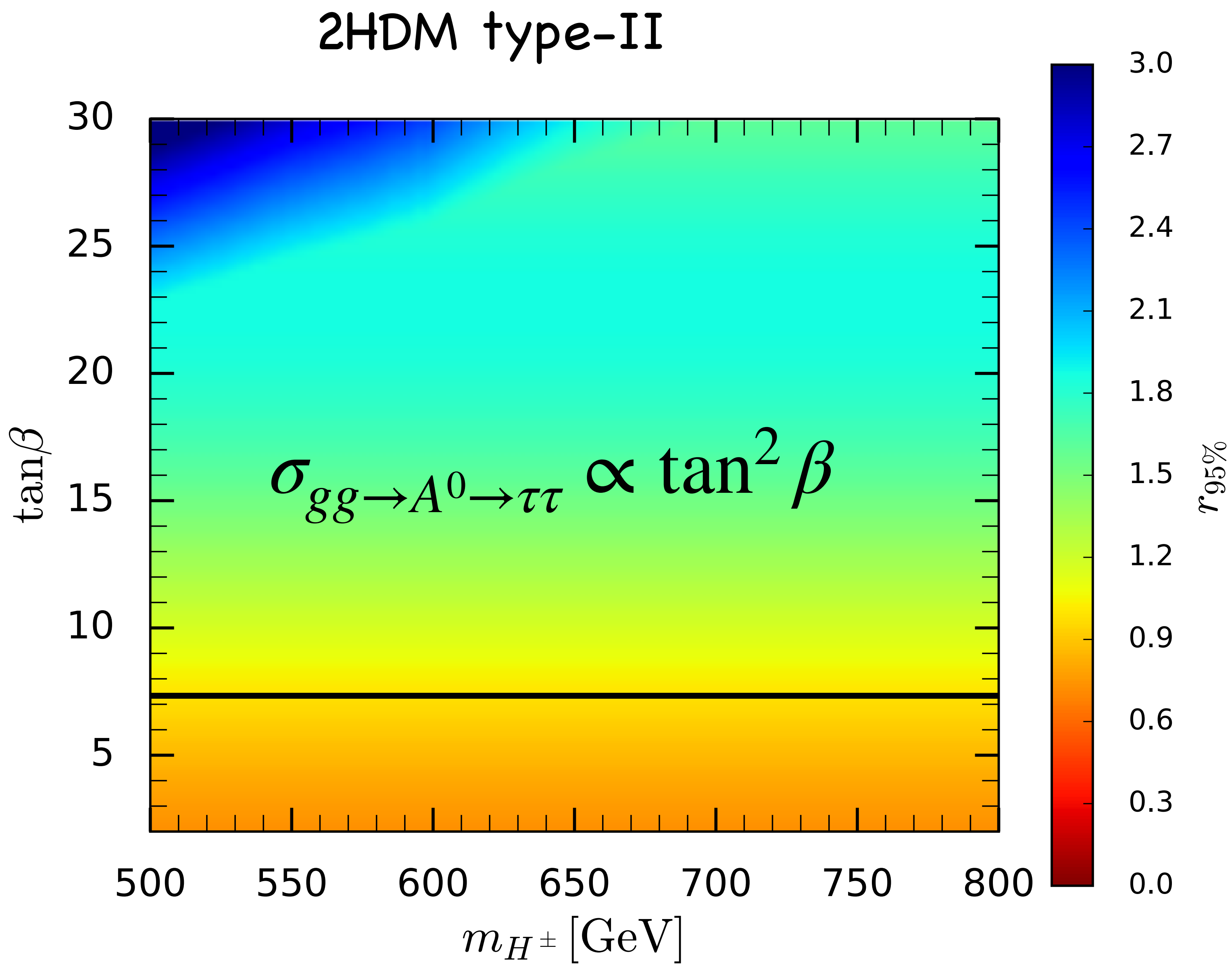
In type-I (type-X), this coupling is always left-handed — small contribution from the right-handed component —.

$\Longrightarrow$ The top quark is produced with negative polarization in the helicity basis.

In type-II (type-Y), this coupling can be left-handed, right-handed or purely scalar ($\tan\beta = \sqrt{m_t/m_b}$).

$\Longrightarrow$ The top quark can be produced with negative/positive/zero polarization.

Bounds from Higgs and collider data?



$$m_{H^\pm} \simeq m_{A^0} \simeq m_{H^0}$$

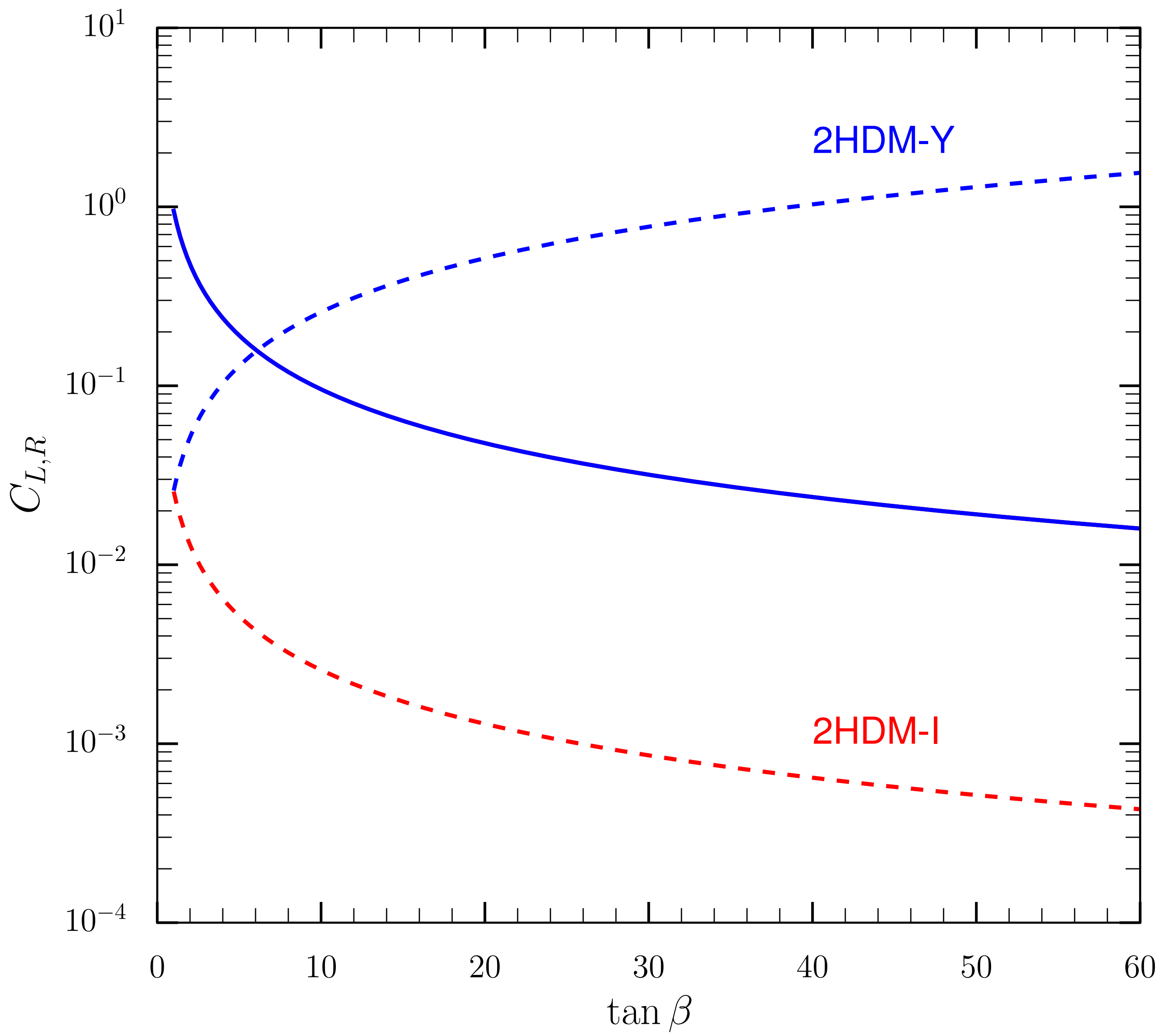
The strong constraints from $gg \to A^0 \to \tau\tau$ on the parameter space of type-II 2HDM exclude regions of $\tan\beta \geq 8$.

$\Longrightarrow$ In 2HDM type-II, the right-handed component of the coupling cannot dominate.

We choose 2HDM type-Y as our benchmark model since the cross section of $gg \to A^0 \to \tau\tau$ is suppressed by $1/\tan^2\beta$

$\Longrightarrow$ Large values of $\tan\beta$ can be attained and the right-handed component of the coupling may dominate.

Chirality of the $H^+\bar{t}b$ coupling



Blue color shows the 2HDM-Y (2HDM-Y) while red color shows the 2HDM-I (2HDM-X).

Solid lines show the left-handed component while the dashed lines correspond to the right-handed component.

We choose $\tan\beta = 1$ in 2HDM-I and $\tan\beta = 50$ in 2HDM-Y

- $(C_L, C_R) = (0.94, -0.025)$ in 2HDM-I
- $(C_L, C_R) = (0.019, 1.3)$ in 2HDM-Y

Observables

- Lepton angle distribution in the top-quark rest frame

$$\cos\theta_\ell^k = \frac{\mathbf{p}_\ell \cdot \mathbf{p}_t}{|\mathbf{p}_\ell \cdot \mathbf{p}_t|}$$

  True probe of top quark polarization. Independent of any anomalous couplings if they are involved in the decay stage only, e.g. top quark pair production (R. M. Godbole, M. E. Peskin, S.D. Rindani and R. K. Singh, 2018).

- The scaled charged lepton energy distribution

$$x_\ell = \frac{2E_\ell}{m_t}$$

  In the rest frame, there is no dependence on the polarization of the top quark.
  In the laboratory frame, it is sensitive to both top quark polarization and any anomalous couplings (A. Prasath, R. M. Godbole, and S.D. Rindani, 2014).

Observables

- The energy ratio of the charged lepton to the total visible energy (of the top quark decay products

$$u = \frac{E_\ell}{E_\ell + E_b}$$

Can be used to extract the information on the top quark quark polarization and any anomalous couplings. Proposed some time ago (J. Shelton, 2009) as a probe of new physics in channels involving boosted top quarks. Studied in the context of charged Higgs boson production in association with a top quark (R. M. Godbole, L. Hartgring, I. Niessen, and C. D. White, 2011) to distinguish $H^{\pm}t$ production from $W^{\pm}t$ production and as possible method to search a characterize charged Higgs bosons at the LHC for different Yukawa realizations (A. Arhrib, AJ, S. Moretti, 2018)

- The ratio of the b-quark energy with respect to top quark energy

$$z = \frac{E_b}{E_t}$$

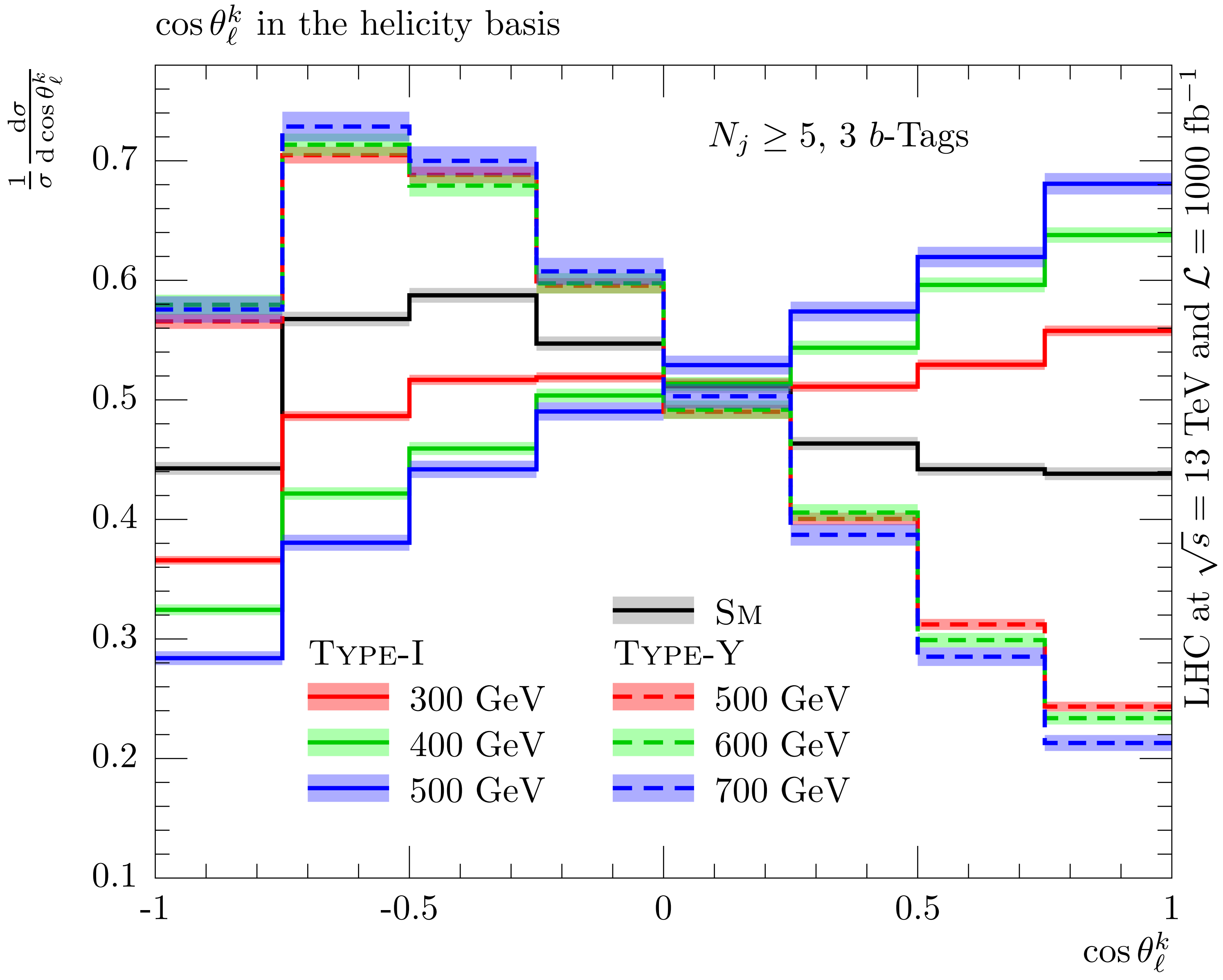
Sensitive to transverse top quark polarization (useful for CP-violation).

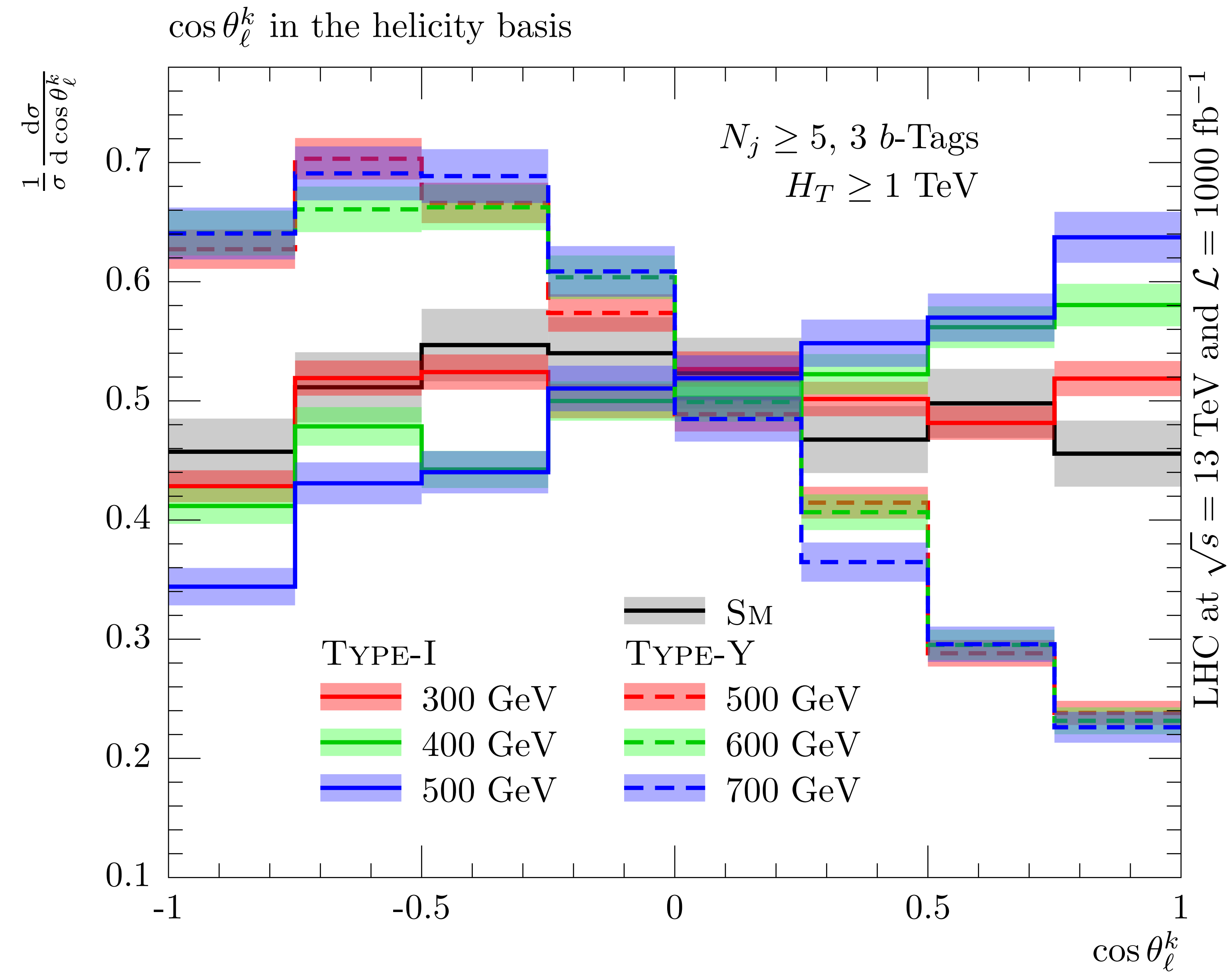
Technical setup

- We consider charged Higgs boson production in association with a top quark in the 5FN scheme at the LHC with $\sqrt{s} = 13$ TeV and $\mathscr{L} = 1\ \mathrm{ab}^{-1}$.
- We focus on the lepton (electron or muon) and jets final state in which case the dominant background are $t\bar{t} + X$.
- Using basic selection cuts and pseudo-top quark definition method (implemented in RIVET), we perform a basic signal-to-background optimization without spoiling the spin properties of the top quark produced in the signal processes.
- We used forward-backward asymmetries constructed from various kinematical distributions as an example to show the possible discriminative power.
- All the calculations are done at leading order (LO) in QCD.

One electron or muon with $p_T^e > 30$ GeV; $|\eta_e| < 2.5$ / $p_T^\mu > 27$ GeV; $|\eta_\mu| < 2.4$ **+** At least 5 jets, 3 of them are b-tagged $p_T > 30$ GeV; $|\eta_e| < 2.4$

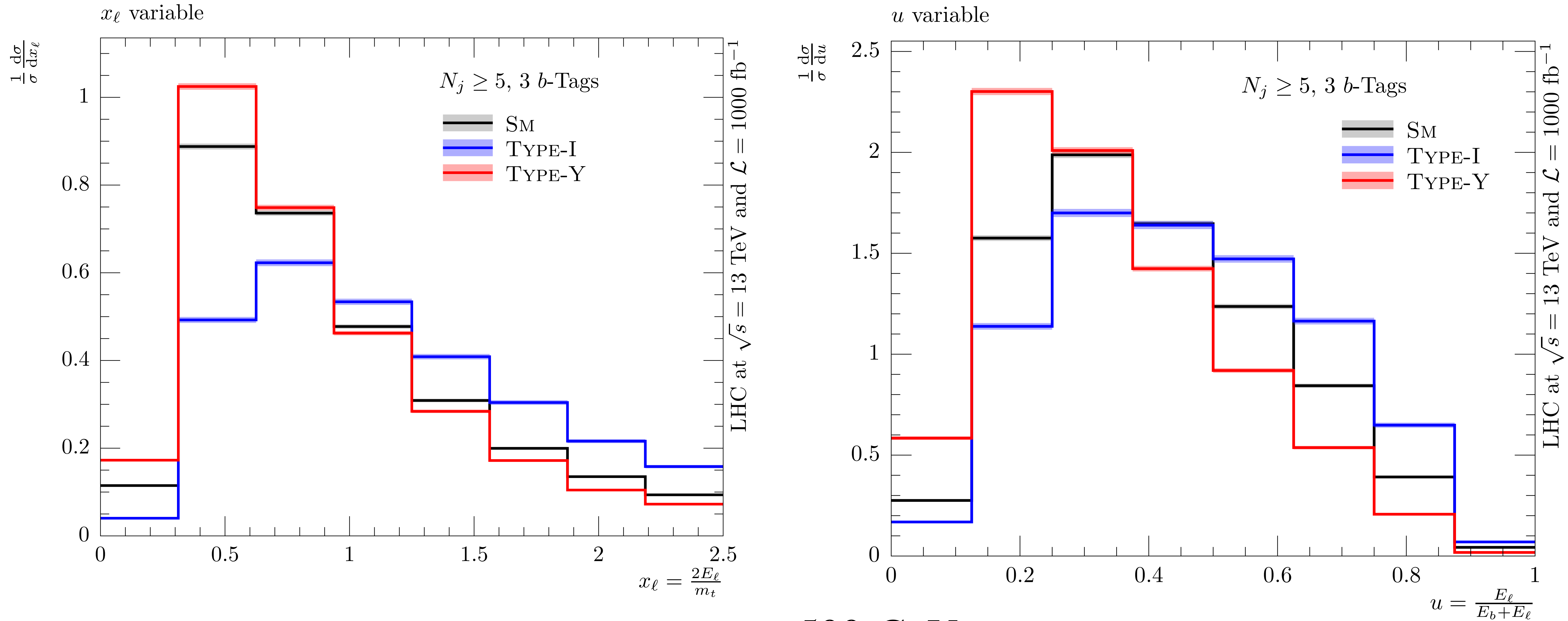
Results





- We observe a flip in the sign of the $\cos\theta_\ell^k$ distribution (positive in type-I and negative in type-Y).
- The $\cos\theta_\ell^k$ can distinguish between the different values of the charged Higgs mass in type-I 2HDM (not the case for type-Y 2HDM).
- Sensitivity decreases when strong cuts on H_T are imposed.

Results



$m_{H^\pm} = 500$ GeV

- Good discriminative power for energy-based observables.
- Almost the same behavior in the x_ℓ distribution between the SM and type-Y.
- The u shows more sensitivity for $u > 0.5$.

Asymmetries

We define an asymmetry on an observable $\mathcal{O}$ by

$$A_{\mathcal{O}} = \frac{\sigma(\mathcal{O} > R) - \sigma(\mathcal{O} < R)}{\sigma(\mathcal{O} > R) + \sigma(\mathcal{O} < R)}$$

(R is a reference point)

- Asymmetries are resilient to next-to-leading order QCD corrections! (Actually the spin itself is).
- Asymmetries are robust against the choice of the PDF scheme inside the proton (will show later)
- Systematic uncertainties may cancel between the numerator and the denominator (more studies are in order).

Asymmetries

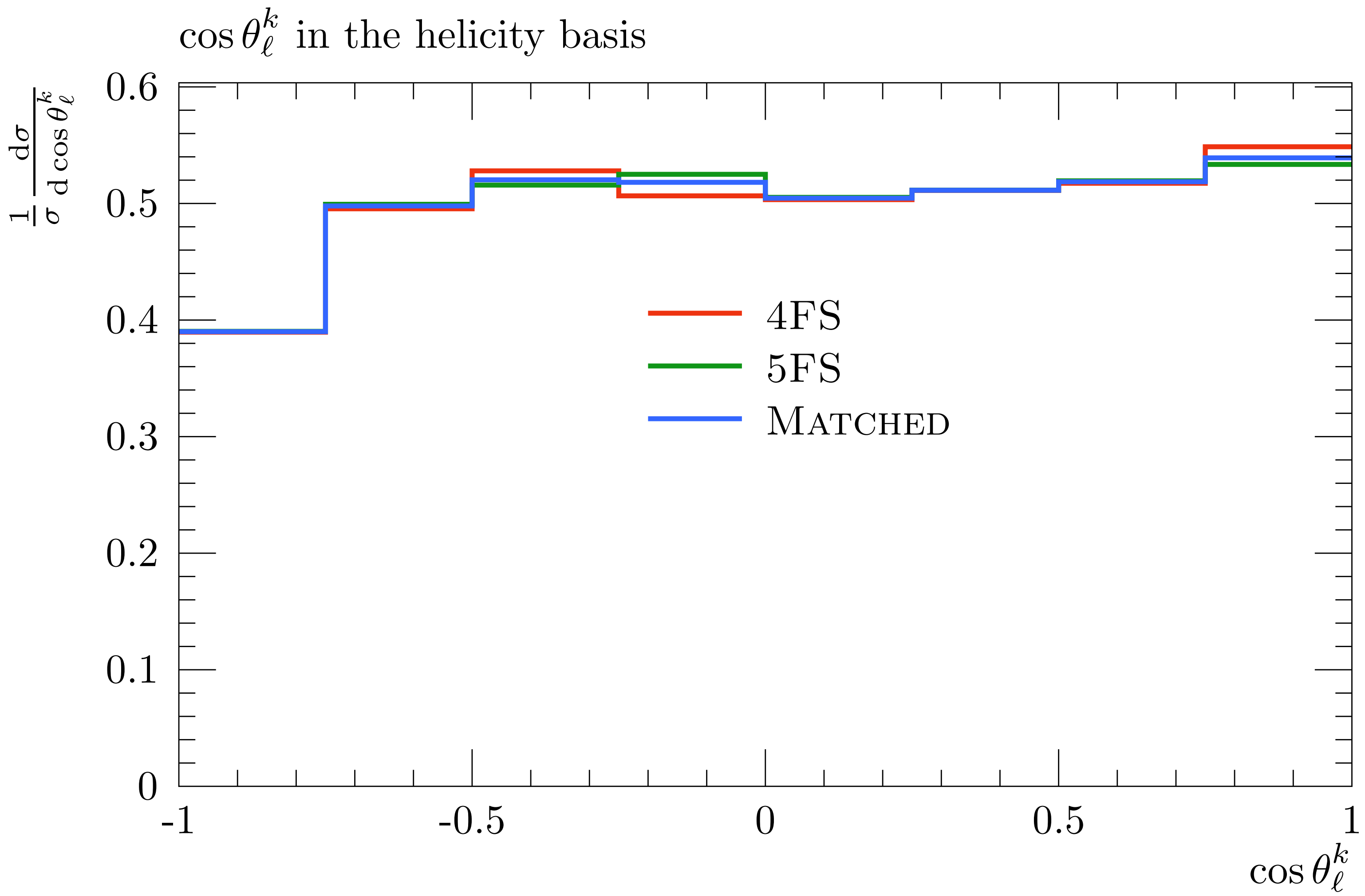
Asymmetry	Background	2HDM-I			2HDM-Y		
		300 GeV	400 GeV	500 GeV	500 GeV	600 GeV	700 GeV
A_{θ_ℓ}	-0.04 ± 0.001	0.05 ± 0.003	0.14 ± 0.004	0.20 ± 0.005	-0.27 ± 0.004	-0.28 ± 0.005	-0.31 ± 0.007
$H_T > 1$ TeV	-0.01 ± 0.003	0.01 ± 0.014	0.08 ± 0.012	0.13 ± 0.013	-0.28 ± 0.009	-0.28 ± 0.011	-0.31 ± 0.013
A_{x_ℓ}.	0.37 ± 0.001	0.40 ± 0.003	0.52 ± 0.003	0.65 ± 0.004	0.21 ± 0.004	0.27 ± 0.005	0.33 ± 0.007
$H_T > 1$ TeV	0.54 ± 0.003	0.53 ± 0.008	0.57 ± 0.009	0.65 ± 0.010	0.30 ± 0.009	0.33 ± 0.010	0.38 ± 0.012
A_u	-0.35 ± 0.001	-0.30 ± 0.003	-0.22 ± 0.004	-0.16 ± 0.005	-0.58 ± 0.003	-0.58 ± 0.004	-0.58 ± 0.006
$H_T > 1$ TeV	-0.35 ± 0.003	-0.27 ± 0.009	-0.31 ± 0.011	-0.26 ± 0.012	-0.63 ± 0.008	-0.64 ± 0.009	-0.62 ± 0.010

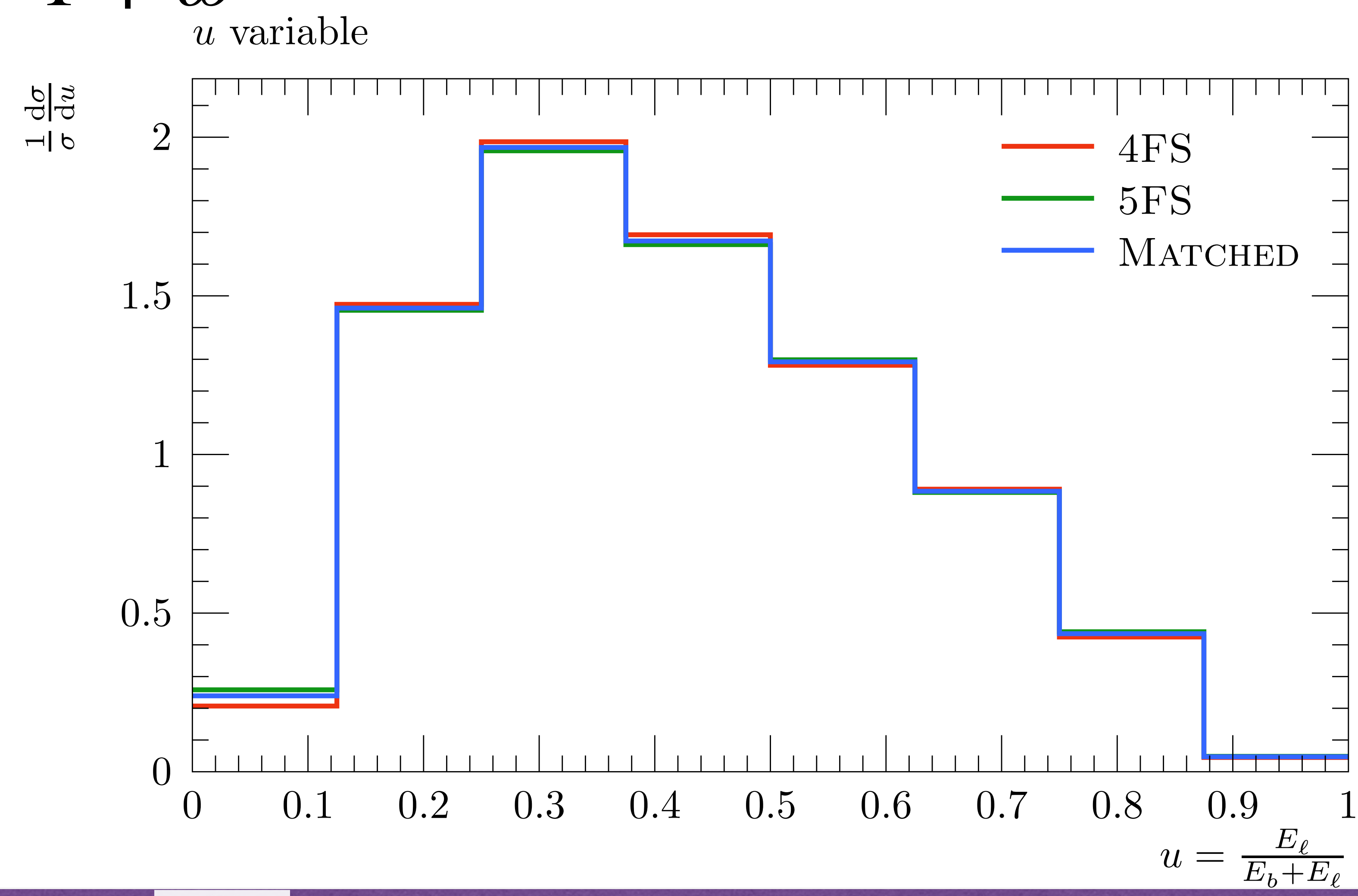
- The A_{θ_ℓ} is very sensitive to the choice of the charged mass in type-I (not in type-Y). Both models yield very different results from the SM.
- A_{x_ℓ} is sensitive to the mass choice for the two Yukawa realizations of the 2HDM.
- More work is needed to use these asymmetries in a fully-fledged signal-to-background analysis (ongoing).

Effect of Matching?

- It is very important to study the robustness of these observables against the choice of PDF schemes.
- In general, we can use the 4FS ($pp \to H^+\bar{t}b$) and 5FS ($pp \to H^+\bar{t}$). Total rates of these schemes are extremely different (we expect also the final state to be different).
- We use the Santander matching to combine these two schemes

$$\sigma_{\text{matched}} = \frac{\sigma_{4\text{FS}} + \omega\sigma_{5\text{FS}}}{1+\omega} \qquad \omega = \log(m_{H^\pm}/m_b) - 2$$





Conclusions

- We studied the sensitivity of top quark polarization observables on the charged Higgs boson production at the LHC (focusing on masses greater or equal to 300 GeV)

- We found that these observables are very robust against higher order QCD corrections, PDF schemes and can be used for characterization.

- More work is needed for a full exploitation of these observables using ML, DL and combined with traditional kinematical variables (ongoing).

- Also will be very important to exploit the scenario where the top quark is boosted. In this case, top tagging methods will allow to access to the polarization information directly (ongoing).


Thank you for your attention