Top quark polarization as a search strategy for Charged Higgs bosons at the LHC

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Introduction

- The two Higgs doublet model is one of the simplest extensions of the SM. The model contains (after EWSB) two CP-even scalars (h^0 and H^0), one CP-odd scalar (A^0) and a pair of charged scalars $H^\pm$.
- The presence of the new scalars can leave footprints in several channels and measurements (Higgs couplings, differential distributions. . .etc).
- The observation of a direct sign of a Charged Higgs boson is a clear evidence for physics beyond the SM (extended Higgs sector).
- Spin observables are believed to play an important role in pinning down and characterizing a possible signal of Charged Higgs bosons;
  ⇒ Can be used for charged Higgs searches? How?
- They have also the advantage of being resilient to matching of 4FS and 5FS and to NLO QCD corrections.

- The main parameter controlling the production and the decay of Heavy charged Higgs boson is

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

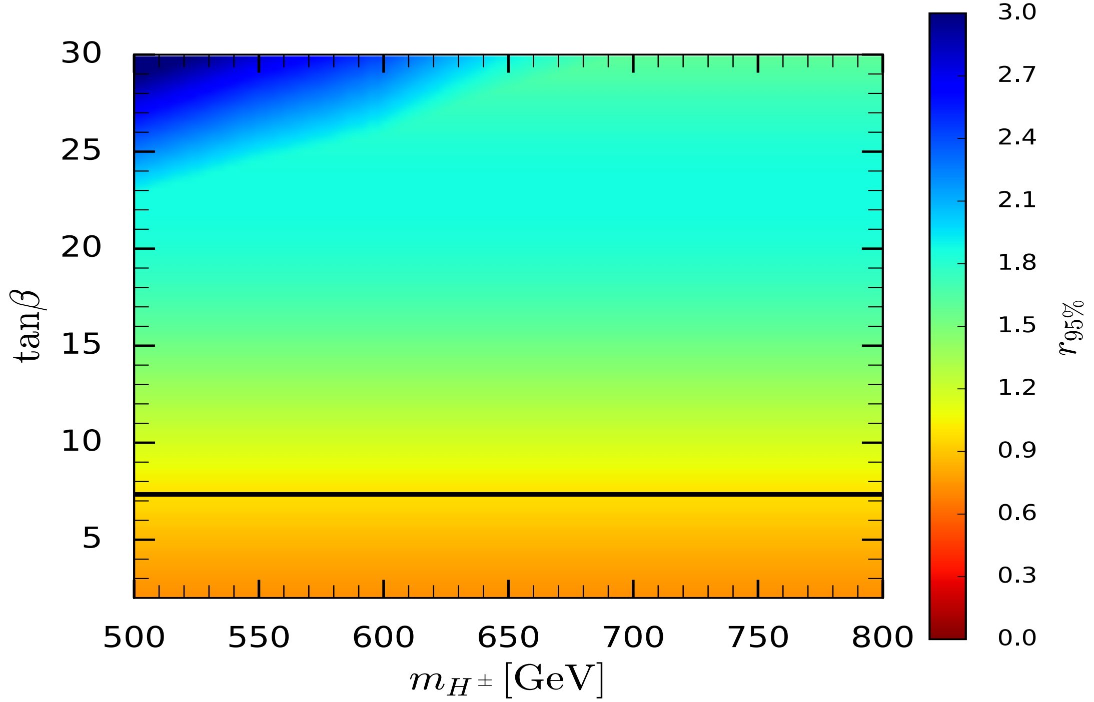
In the 2HDM-I (and the 2HDM-X), both the R- and L-handed components are proportional to $1/\tan\beta$.
In the 2HDM-II (and the 2HDM-Y), the R-component is proportional to $\tan\beta$ while the L-component is proportional to $1/\tan\beta$.

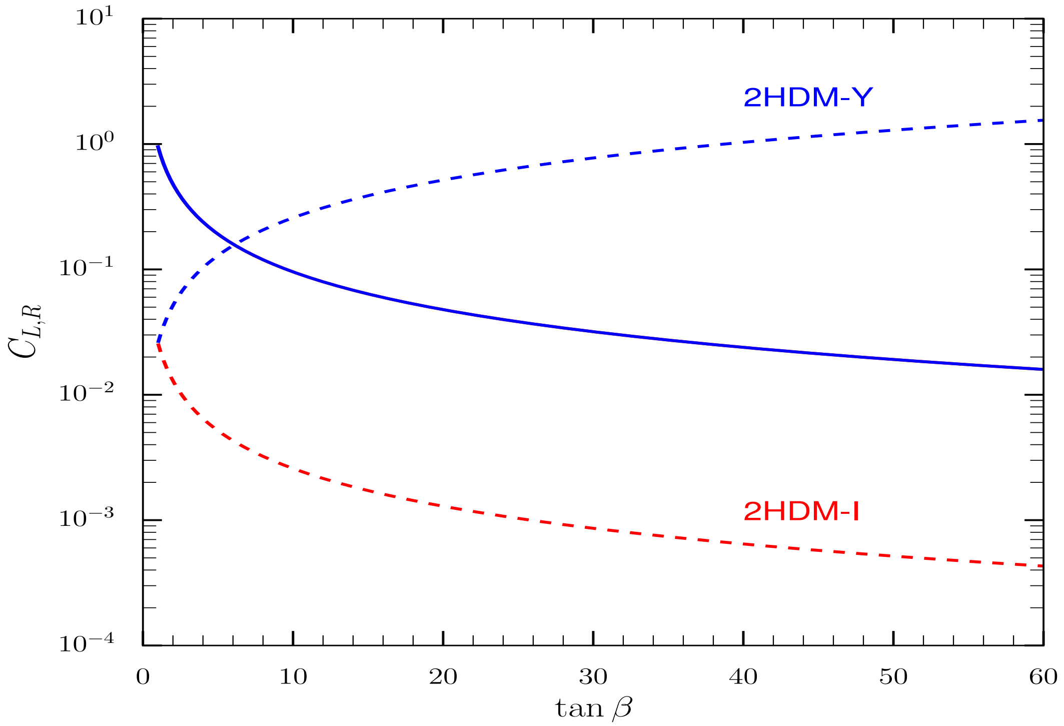
- In type-I (type-X), this coupling is always left-handed (with very small contribution from right-handed component)

⇒ The top quark is produced with negative polarisation in the helicity basis.

- In type-II (type-Y), g_{tbH^+} can be L- dominated, R- dominated or purely scalar.

⇒ Top quark polarization is arbitrary and it's only controlled by $\tan\beta$ (in addition to the Charged Higgs boson mass).





The strong constraints from $gg \to A^0 \to \tau\tau$ on the parameter space of type-II 2HDM (they exclude large values of $\tan\beta$).

In 2HDM-II, the right handed component of the coupling cannot dominate.

We choose the 2HDM-Y, due to $1/\tan\beta$ suppression of the $gg \to A^0 \to \tau\tau$ cross section (constraints are avoided) and large values of $\tan\beta$ can be attained

Blue color shows the 2HDM-Y (2HDM-II) and 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

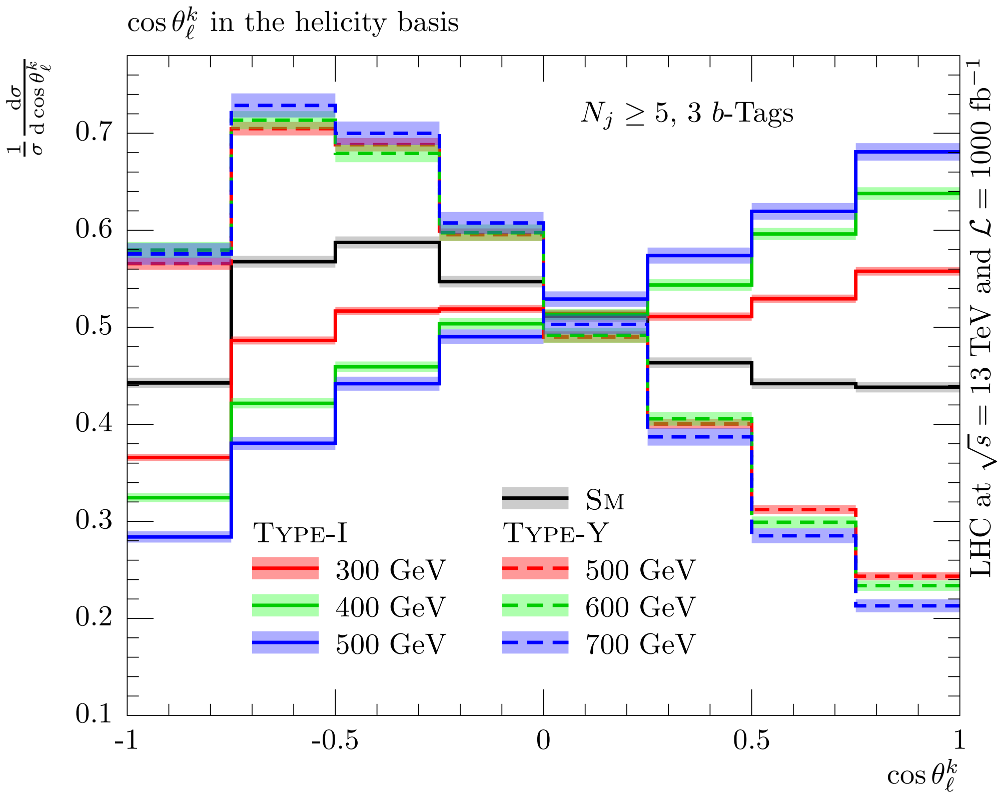
- $(C_L, C_R) = (0.94, -0.025)$ for 2HDM-I.
- $(C_L, C_R) = (0.019, 1.3)$ for 2HDM-Y.

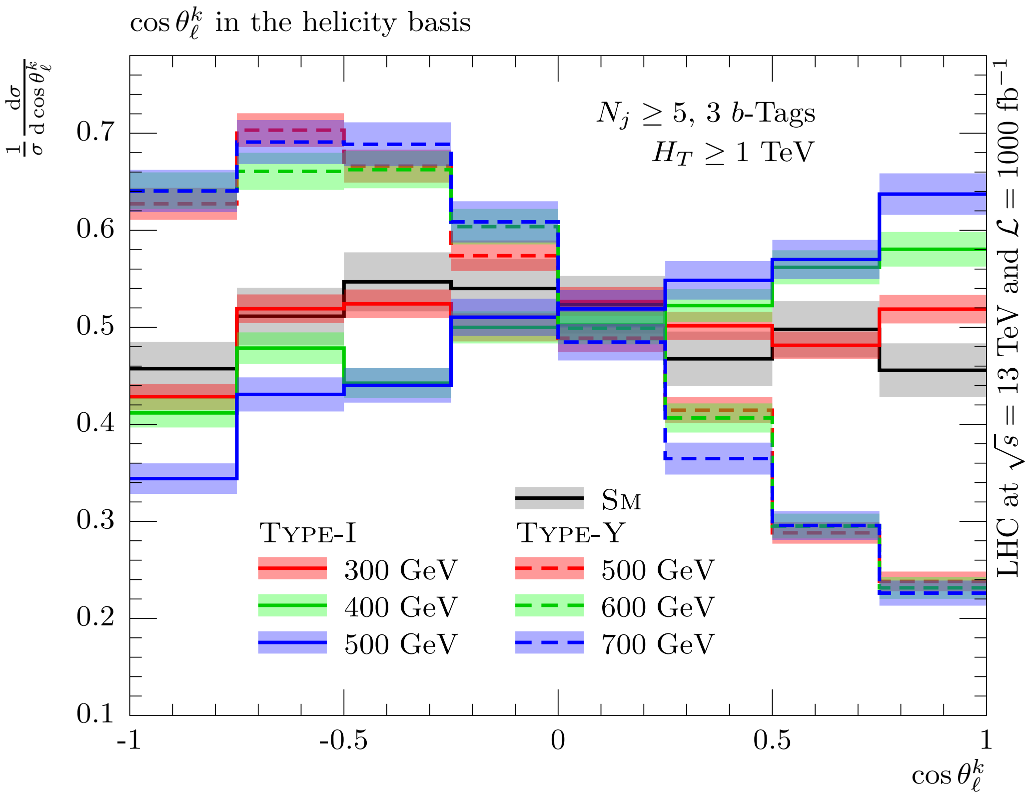
- Top quark polarization can be measured by using the several observables (most sensitive one is the angular distribution of the charged lepton); Most sensitive one is the angular distribution in the helicity basis.
- Due to boost factors (take the top quark decay product from the top quark rest to the laboratory frame), the energy observables pick up some dependence on the angle and therefore are sensitive to the top quark polarization.
- We use one angular observable and two observables (built upon the ratios of energies)

$$u = \frac{E_\ell}{E_\ell + E_b}, x_l = \frac{2E_\ell}{m_t}$$

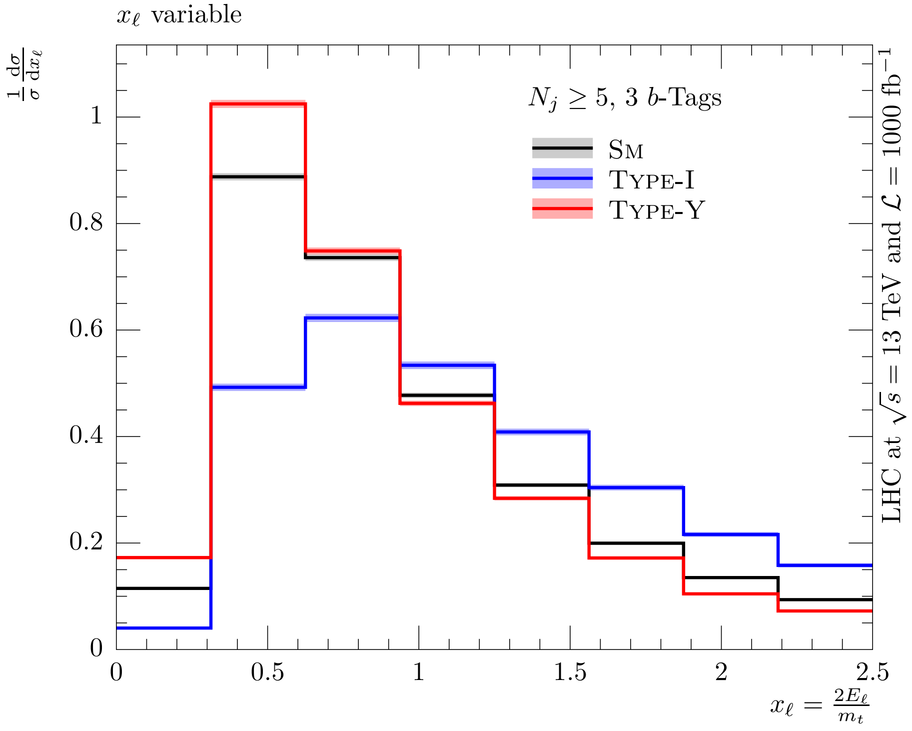
- These observables were proposed to study new physics in highly boosted top quarks (Shelton 2005'), then studied for several purposes; Distinguishing Higgs-top from W-top production (Laenen et al. 2012), and anomalous Wtb couplings (Godbole et al. 2014, Jueid 2018).
- We study these observables for the purpose of searching for Charged Higgs bosons at the LHC and to characterize the model assumption (post-discovery tool).

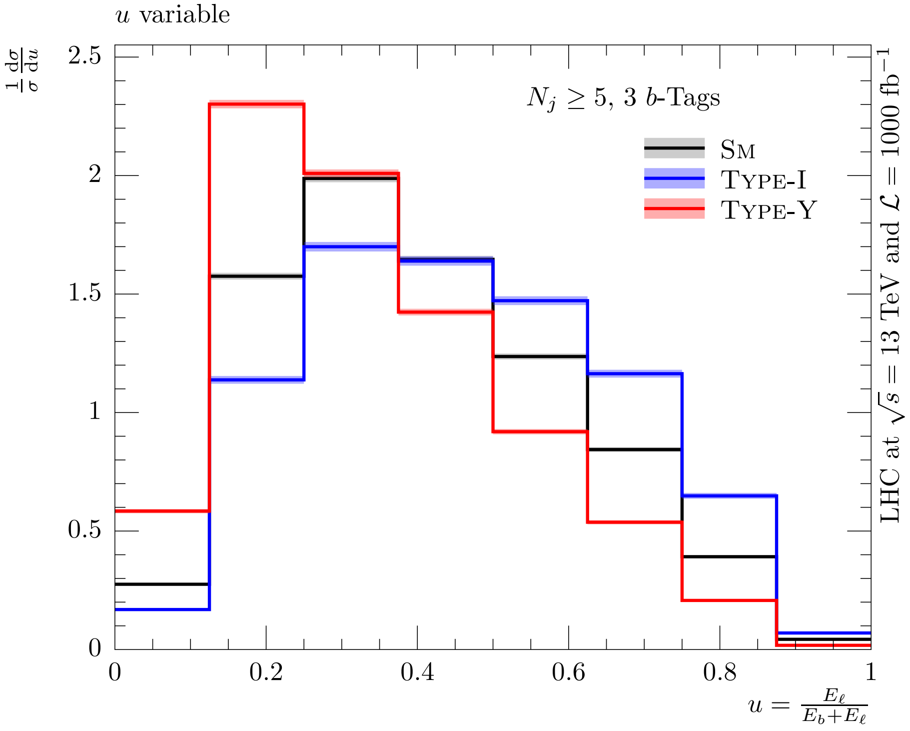
- We consider Charged Higgs boson production in association with a top quark in the 5F scheme at the HL-LHC.
- We focus on the lepton (electron or muon) and jets final state in which case the dominant backgrounds are $t\bar{t} + X$.
- Using basic selection cuts and Pseudo-Top quark definition method, we optimize (not as a full study) the signal-to-background ratio without spoiling the spin-properties of the top quark produced in signal processes.
- We used the asymmetries constructed from spin-distributions a as an example to show the possible discriminative power.
- The advantage of these asymmetries is their resilience against next-to-leading (NLO) QCD corrections.
- All the observables are independent of the flavor scheme of the incoming particles.





- Flip in the sign of the slope of the $\cos\theta_l$ distribution (positive for 2HDM-I and negative for 2HDM-Y).
- $\cos\theta_l$ distribution is able to distinguish between the values of the Charged Higgs boson masses in the 2HDM-I (not the case in 2HDM-Y)
- Such sensitivity is decreasing when severe cuts on the scalar sum of jet p_T are imposed ($H_T > 1$ TeV).



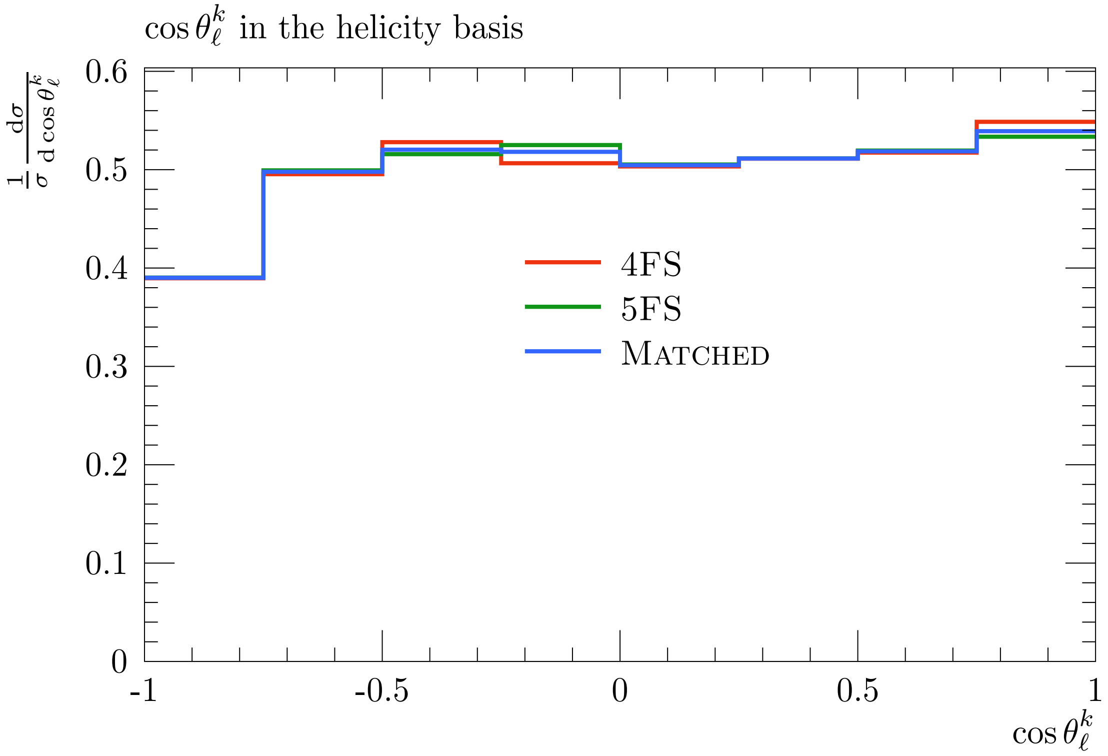


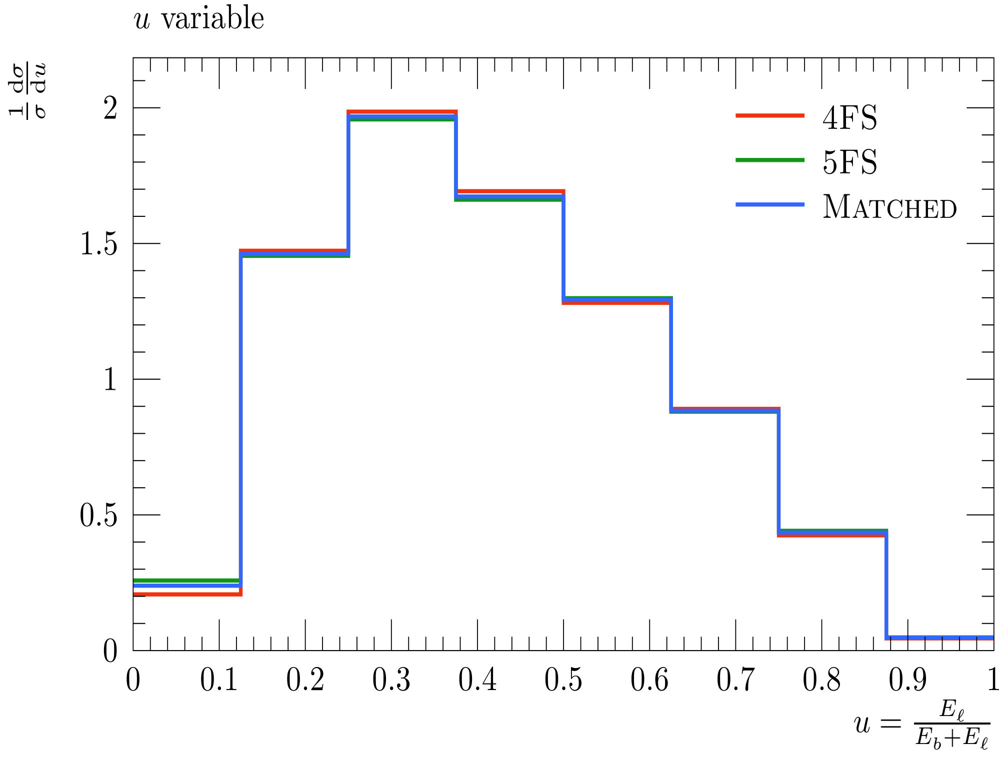
- Good discriminative power of the energetic observables (shown here for $m_{H^\pm} = 500$ GeV).
- Almost the same behavior in x_l distribution for the SM and type-Y (not the case for the u-variable).
- These observables can be used in conjunction with the angular distribution to distinguish between different masses of the charged Higgs boson.

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
	-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
	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
	-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 use of asymmetries can be very useful to distinguish between e.g. different masses in the same Yukawa model of 2HDM.
- For instance, the x_l can be used to distinguish between the different masses in 2HDM-Y (whereas the other observables can't do).
- The three observables can be combined to give complementary information about the Charged Higgs boson mass in 2HDM-I.
- More studies might be in order!

Effect of matching?





Conclusions and Outlook

- We studied the sensitivity of spin observables on the presence of Charged Higgs bosons in top-associated production.
- We found very important sensitivities on the model assumption (can be used as a discovery as well as a characterization tool).
- More sophisticated methods might be in order to find such a signal at the LHC (e.g. machine learning methods).
- Asymmetries can be used as well in the conjunction with ML and cut-based methods.
- Our findings can be applied to any model which contains a charged Higgs that couples to a top quark.
- Gives further motivations to study the presence of new states (charged or neutral) with different spin quantum numbers and in different production modes.

Thank you for your kind attention