IBS-Busan Joint Workshop on New Physics Beyond the SM

Probing charged Higgs bosons using top quark polarisation

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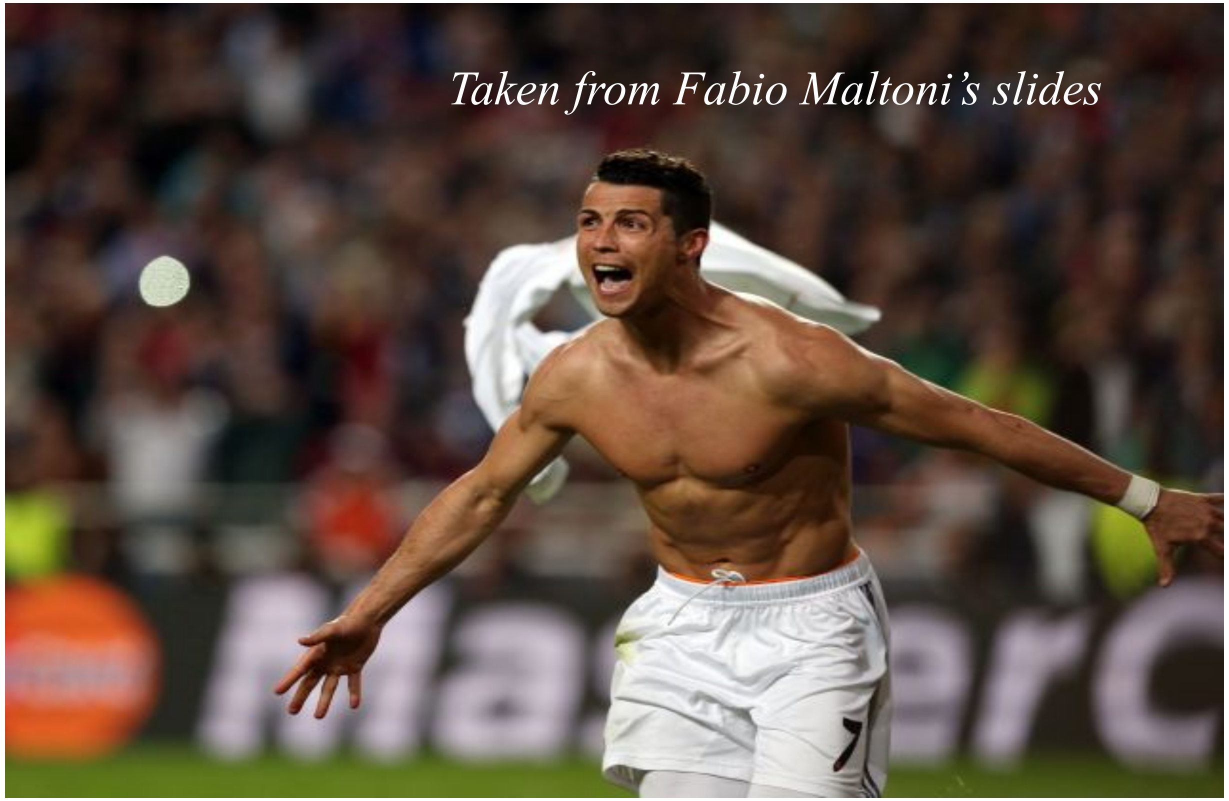
based on 1807.11306 (published in PRD)

Why we study Top quarks?



Top quark is
1) Rich
2) Strong
3) Naked
4) Popular
5) Goes beyond

Top quark is the Cristiano Ronaldo of Particle Physics

Top quark | Brief format | Search | Easy Search | Advanced Search

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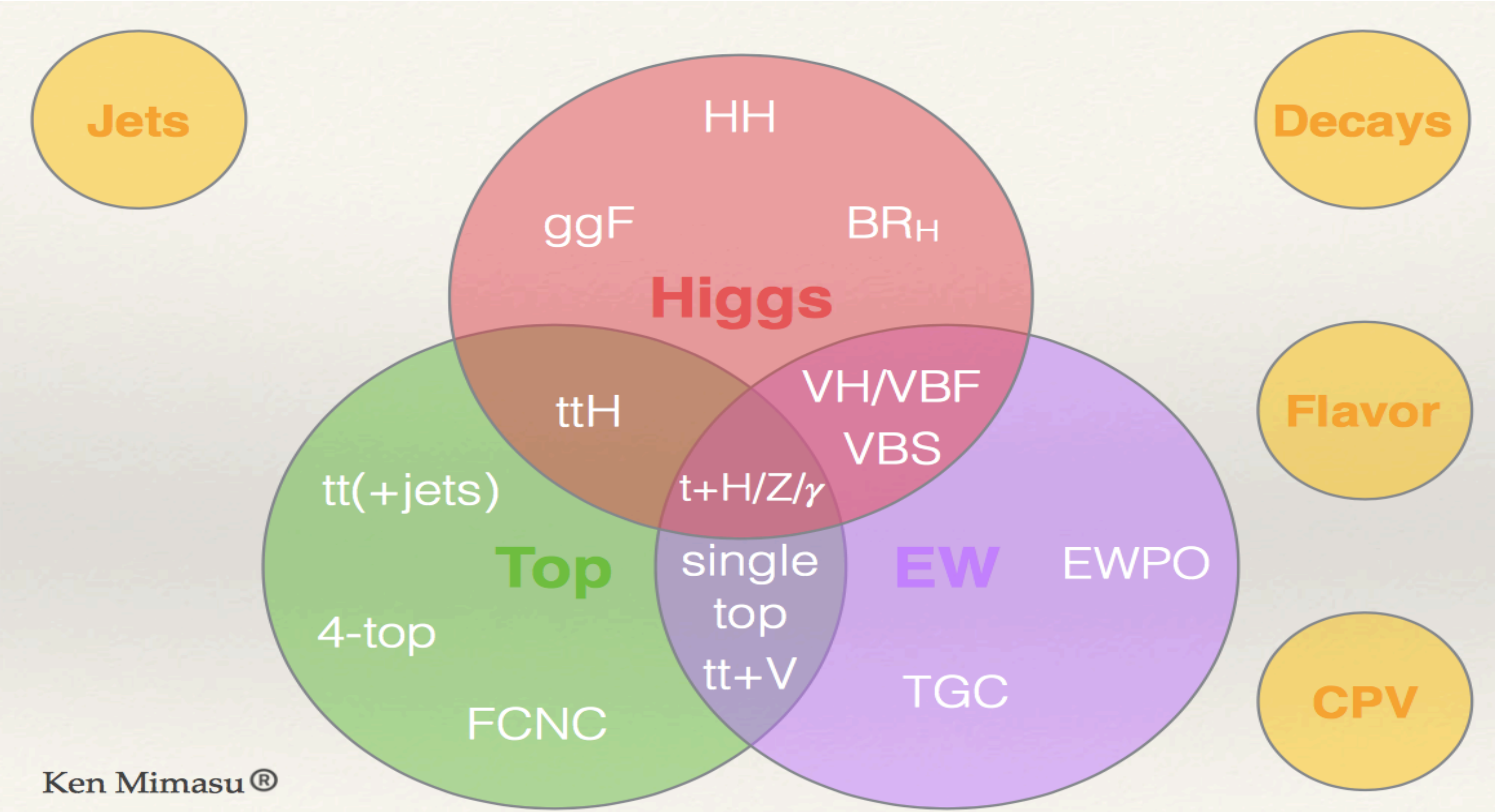
...and there is an intimate connection with the other sectors!



The two Higgs Doublet Model

- The Two Higgs Doublet Model (2HDM) is one of the simplest extensions of the SM extending the Higgs sector by an additional doublet.
- The two scalar doublets contribute to fermion, and gauge boson masses.
- Possibility of having large tree-level flavor changing neutral currents (FCNC); Further discrete symmetry is imposed to avoid these FCNC processes.
- This result in four types of the CP-conserving 2HDM depending on the Z2 assignments of fermions, and scalar fields.
- After electroweak symmetry-breaking, one has five additional particles; two CP-even states, one CP-odd state, and a pair of charged scalars.

The two Higgs Doublet Model

- The Z2 symmetric (with soft breaking), and gauge invariant potential

$$V(\Phi_1,\Phi_2) = \mu_{11}^2|\Phi_1|^2 + \mu_{22}^2|\Phi_2|^2 - \mu_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}].$$

- The scalar doublets are given by

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ v_i + \frac{1}{\sqrt{2}}(h_i + i\omega_i) \end{pmatrix}$$

- After electroweak symmetry breaking

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha)\begin{pmatrix} H^0 \\ h^0 \end{pmatrix}, \quad \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix} = R(\beta)\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix}, \quad \begin{pmatrix} \omega_1 \\ \omega_2 \end{pmatrix} = R(\beta)\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

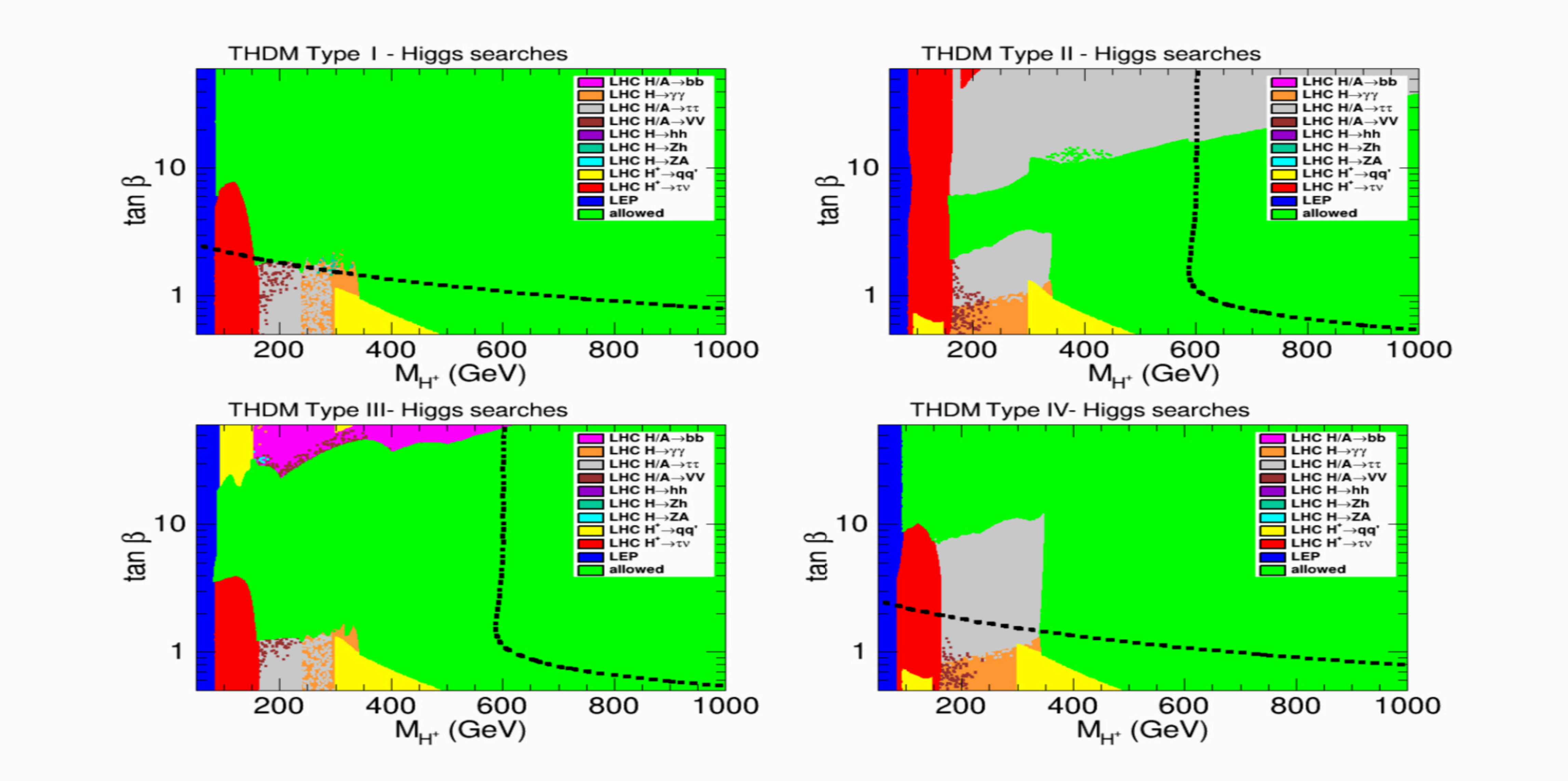
Yukawa sector

- The Yukawa sector after EWSB

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

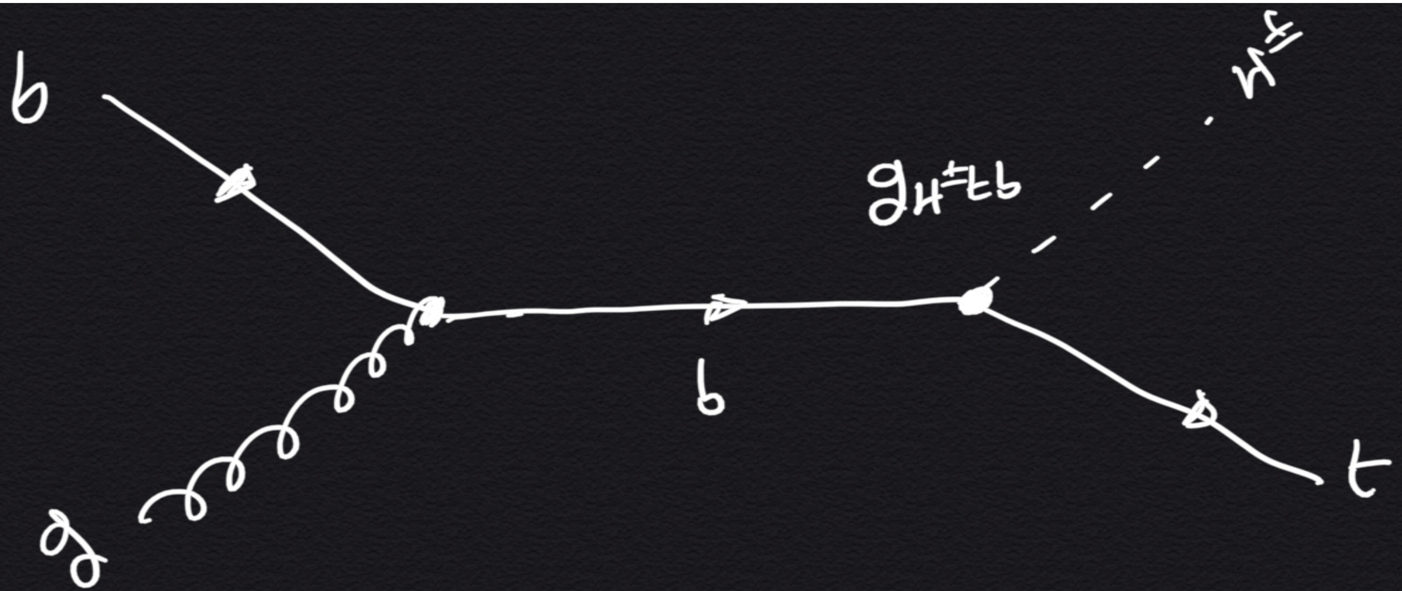
	κ_u^h	κ_d^h	κ_l^h	κ_u^H	κ_d^H	κ_l^H	κ_u^A	κ_d^A	κ_l^A
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$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

The model is severely constrained!

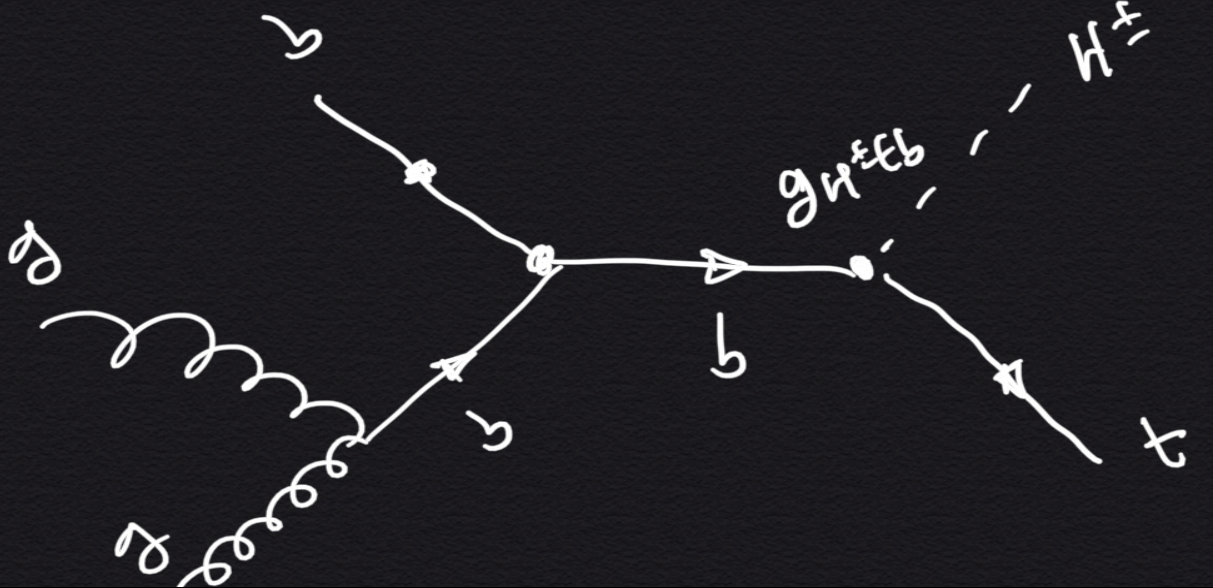


Taken from A. Arbey, F. Mahmoudi, O. Stal, and T. Stefaniak (2017)

Charged Higgs boson production at the LHC



5FS: b-quark PDF obtained by solving the DGLAP evolution equations



4FS: b-quark is massive and not contained in the proton

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

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

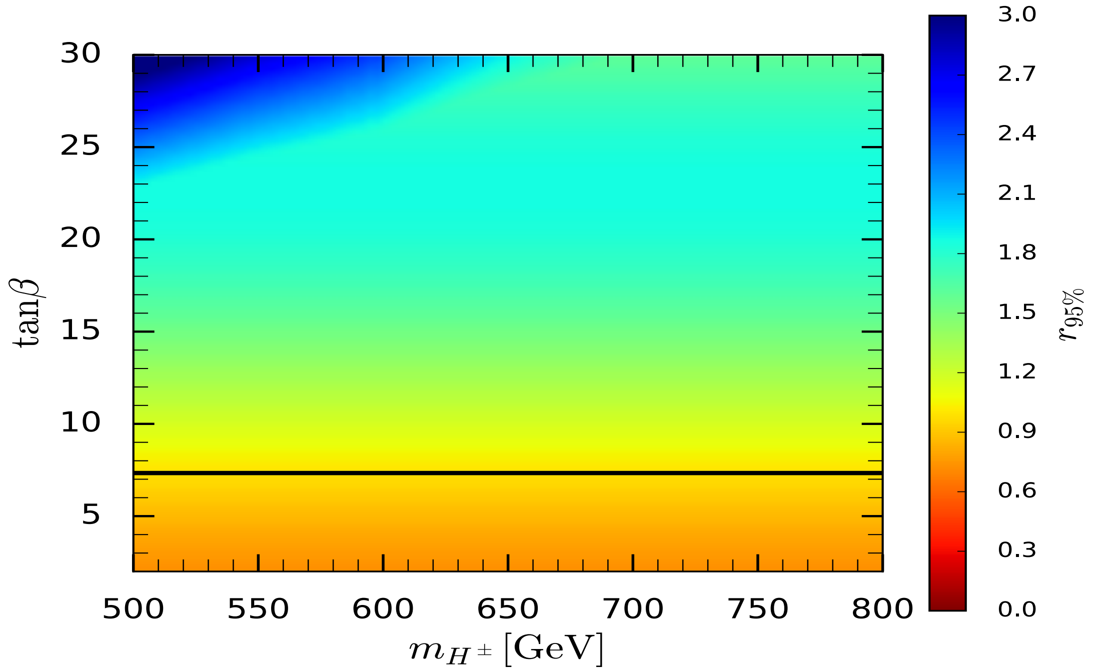
In the 2HDM-I (and the 2HDM-X), both the R- and L-handed components are proportional to $1/\tan\beta$.
In the 2HDM-II (and the 2HDM-Y), the R-component is proportional to $\tan\beta$ while the L-component is proportional to $1/\tan\beta$.

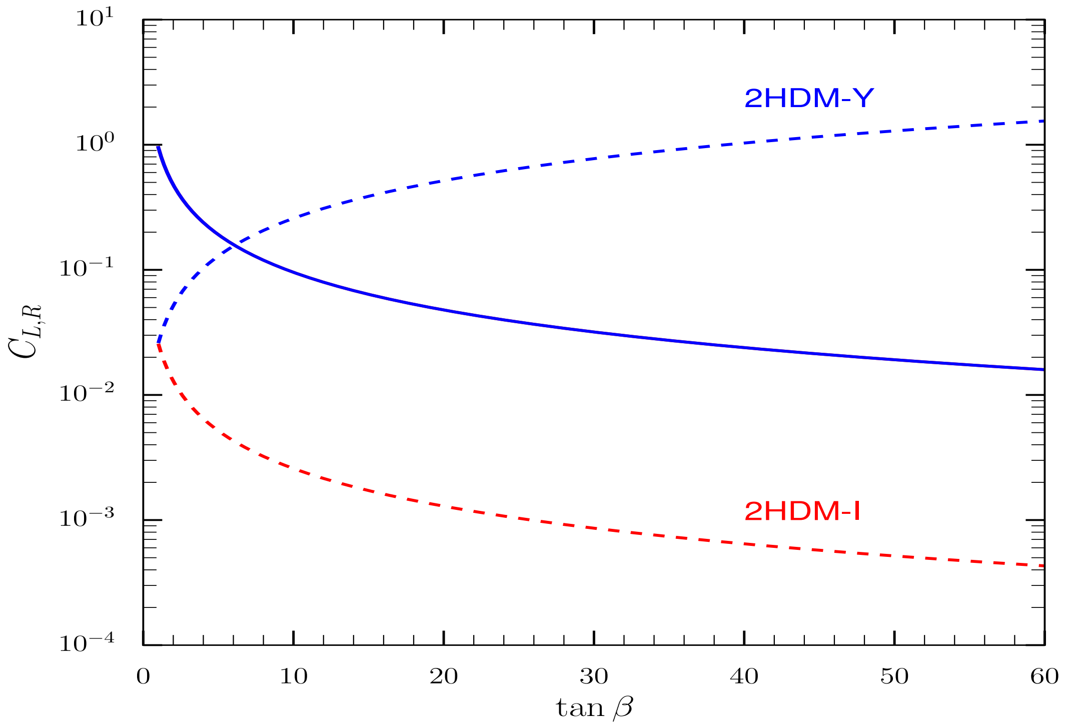
- In type-I (type-X), this coupling is always left-handed (with very small contribution from right-handed component)

⇒ 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 (positive, negative or zero).





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.

- 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 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.

We study the sensitivity of new observables to the anomalous couplings

- Lepton angle distribution in top quark rest frame

$$\cos\theta_\ell = \frac{p_\ell . p_t}{|p_\ell . p_t|}$$

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

Note that in the case for single top quark production, presence of anomalous couplings in the production changes the chiral structure of the top quark and therefore it's polarization.

- The scaled charged lepton energy distribution

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

In the top quark rest frame, no dependence on the polarization at all.

In the laboratory frame, depends on both the anomalous Wtb couplings and top quark polarizatio (A. Prasath V, R. M. Godbole, and S. D. Rindani, 2014).

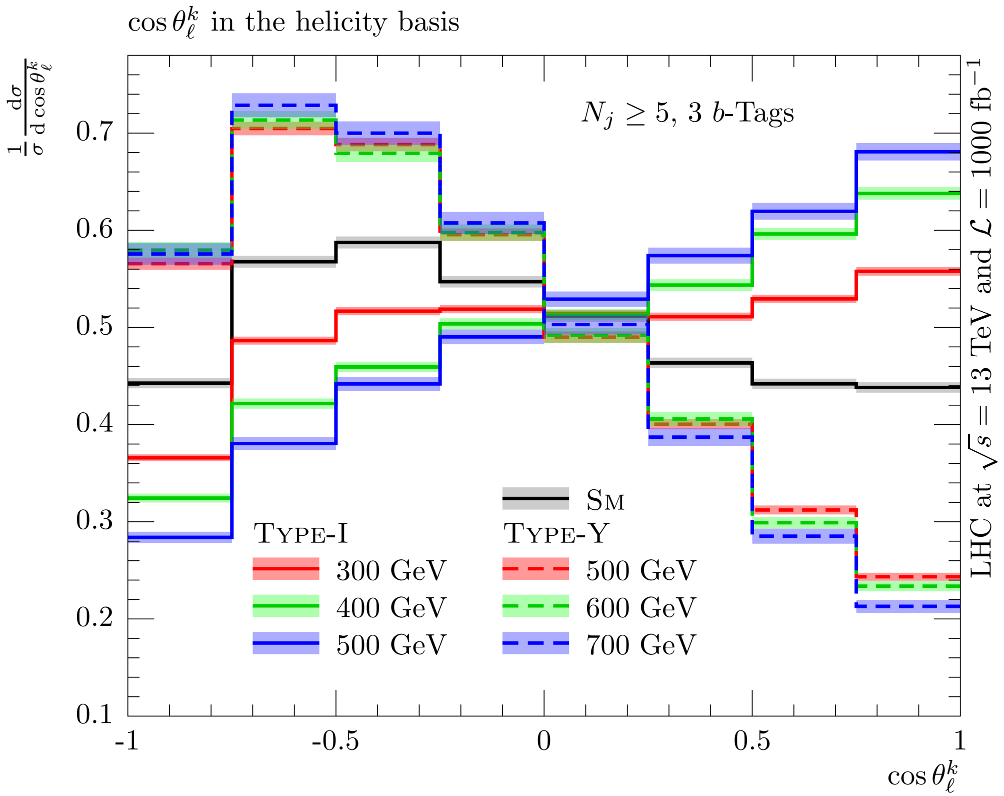
- The energy ratio of the charged lepton to the total visible energy (of the top quark decay products)

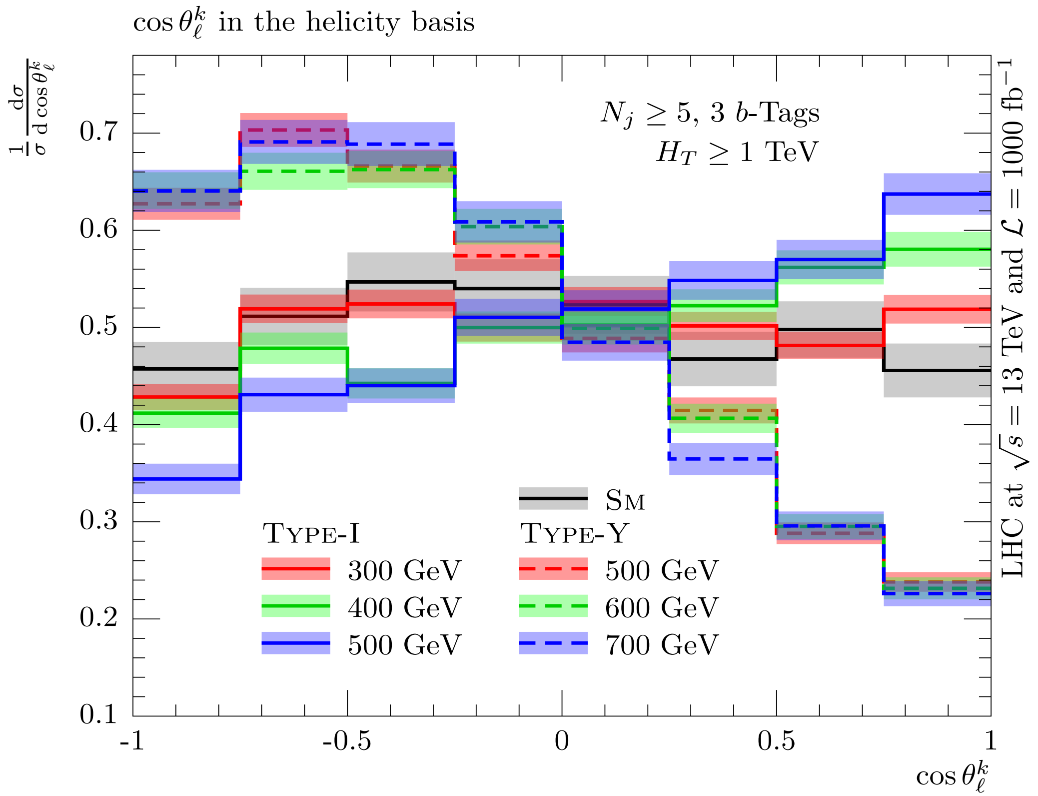
$$u = \frac{E_\ell}{E_\ell + E_b}$$

Can be used to extract both the top polarization and the anomalous Wtb couplings. More sensitive on the anomalous Wtb couplings in cases where the top quark is produced with non-trivial polarization, e.g. as in single mode. Proposed long time by J. Shelton (2009) as probe of new physics for boosted tops. Studied in the context of charged higgs boson production by R. M. Godbole, L. Hartgring, I. Niessen, and C. D. White (2011) as way to distinguish Wt production from $H^{\pm}t$ production and by AJ (2018) to study the nature of the anomalous Wtb vertex in single top production.

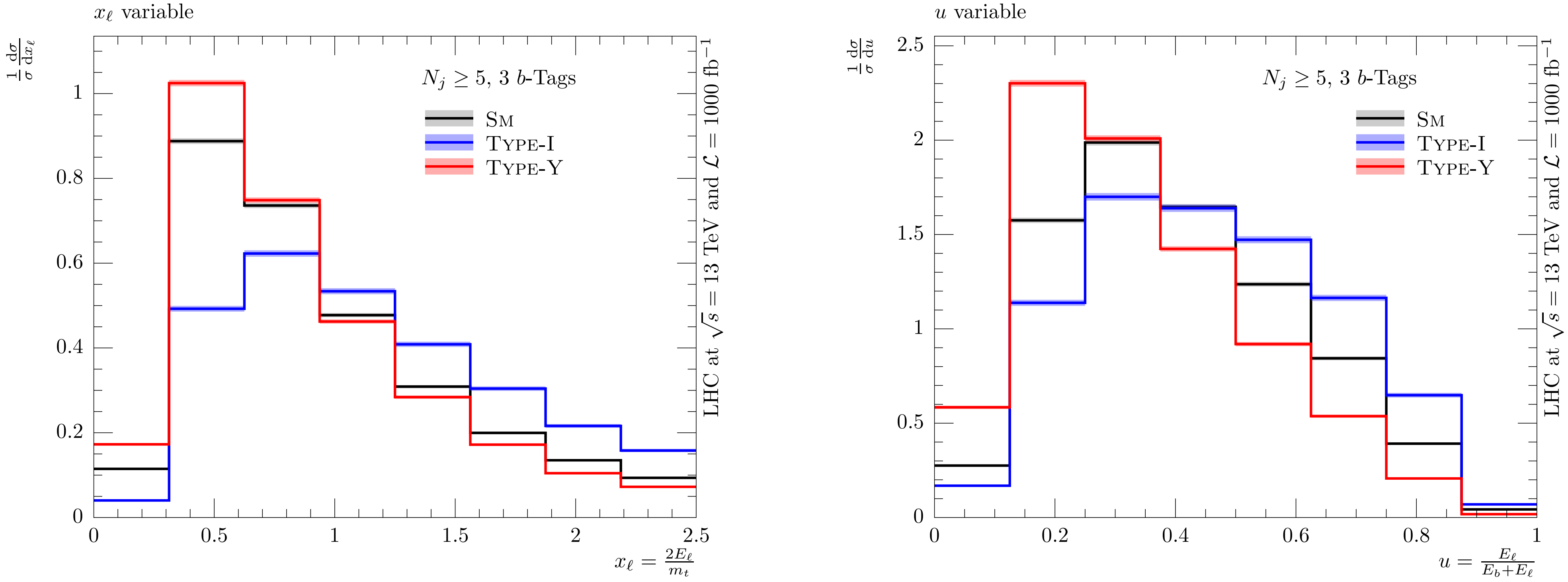
- The fraction of the top quark energy taken by the *b*-quark in the laboratory frame is less sensitive on the anomalous Wtb couplings.

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





- 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.

Forward-Backward Asymmetries

- Energy and angle observables proposed to study anomalous couplings in single top quark production through t-channel are very sensitive.
- Need to quantify the differences using e.g. "forward-backward" asymmetries. We define an asymmetry by

$$A_X = \frac{\sigma(X < X_c) - \sigma(X > X_c)}{\sigma(X < X_c) + \sigma(X > X_c)}$$

X_c is a reference point chosen to optimize the sensitivity and $X = u, x_\ell, x_\ell^0, z, \cos\theta_\ell$

- The reference points are chosen in such a way to maximise the sensitivity on the model's parameters, and to distinguish between the different values of a given parameter.

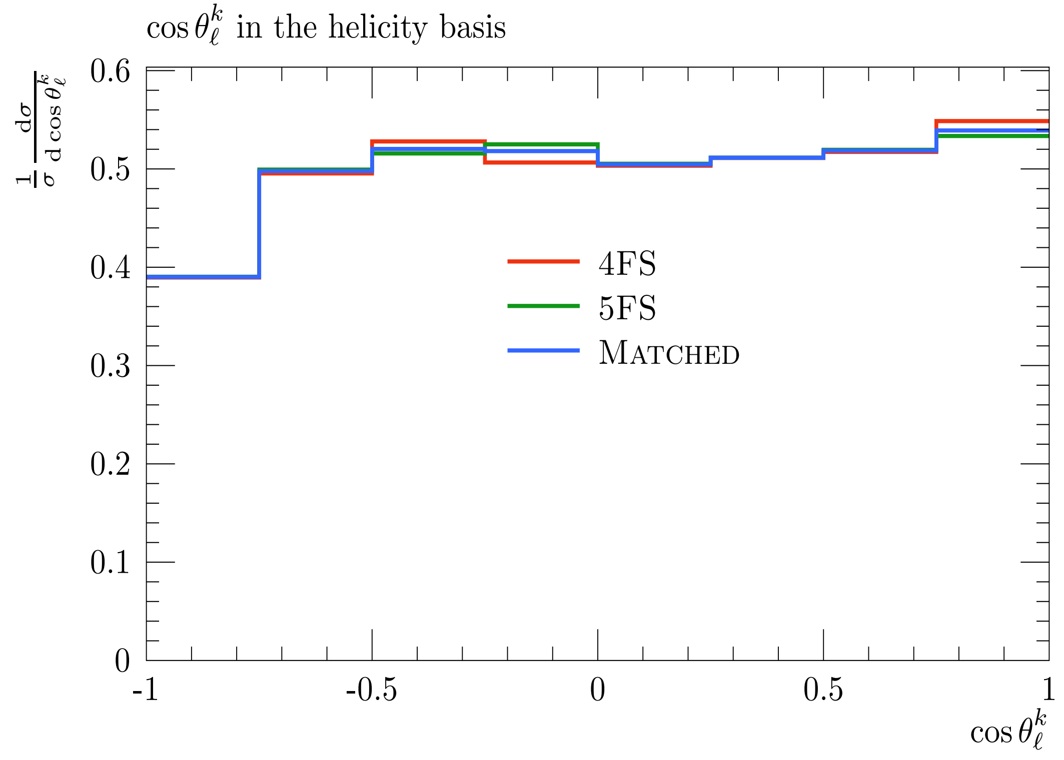
Asymmetry	Background	2HDM-I			2HDM-Y		
		300 GeV	400 GeV	500 GeV	500 GeV	600 GeV	700 GeV
A_{θ_ℓ}	-0.04 ± 0.001	0.05 ± 0.003	0.14 ± 0.004	0.20 ± 0.005	-0.27 ± 0.004	-0.28 ± 0.005	-0.31 ± 0.007
	-0.01 ± 0.003	0.01 ± 0.014	0.08 ± 0.012	0.13 ± 0.013	-0.28 ± 0.009	-0.28 ± 0.011	-0.31 ± 0.013
A_{x_ℓ}.	0.37 ± 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

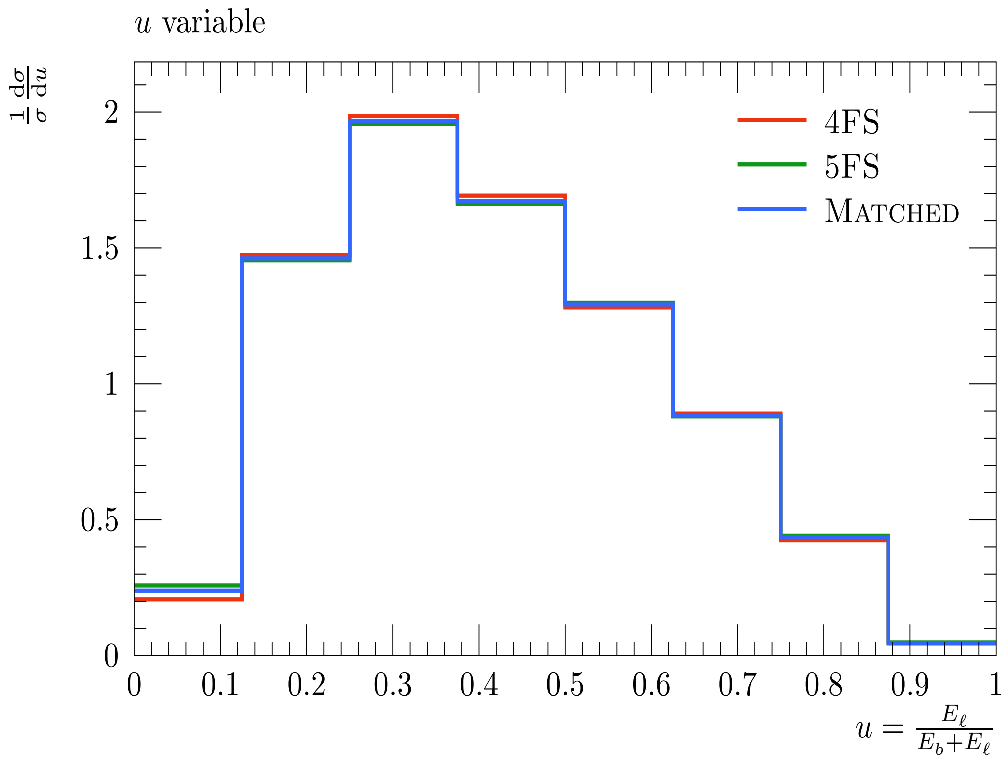
- Employing asymmetries can be *very useful* to distinguish between e.g. different masses in the same Yukawa model of 2HDM.
- For instance, the x_l can be used to distinguish between the different masses in 2HDM-Y (whereas the other observables can't do).
- The three observables can be combined to give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

Effect of matching?

- It's very important to study the effect of matching, i.e. combining matrix elements in the 4FS ($pp \to tH^{\pm}b$) and in the 5FS ($pp \to t\,H^{\pm}$).
- Of course, we expect that spin observables to be resilient to the PDF scheme used in the calculations.
- Using the Santander Matching:

$$\sigma_{\mathrm{matched}} = \frac{\sigma_{4\mathrm{FS}} + \omega\sigma_{5\mathrm{FS}}}{1+\omega}$$





Conclusions

- We studied the sensitivity of spin observables on Charged Higgs bosons in top-associated production.
- These observables can be used both for discovery as well as for characterization studies.
- The spin observables are remarkably resilient to higher order corrections, and the matching scheme (although their measurement can be challenging).
- Asymmetries constructed from spin observables are also resilient to theoretical uncertainties.
- Our findings can be applied to any model which contains a charged Higgs that couples to a top quark; *Universality of the spin structure of the top quark?*
- Important question arise; what is the efficiency after a realistic ATLAS-like selection adding smearing of jets and leptons? Can we still observe those differences? If so, what is the minimum required luminosity?
- Can Machine Learning techniques trained to learn the different spin structures in both the signal and the background be efficient in this case (after full realistic selection)?

Thank you for your kind attention