LHC Higgs Working Group WG3 (BSM) -- Extended Higgs Sector subgroup meeting

New strategies for Heavy Charged Higgs Boson Searches at the Large Hadron Collider

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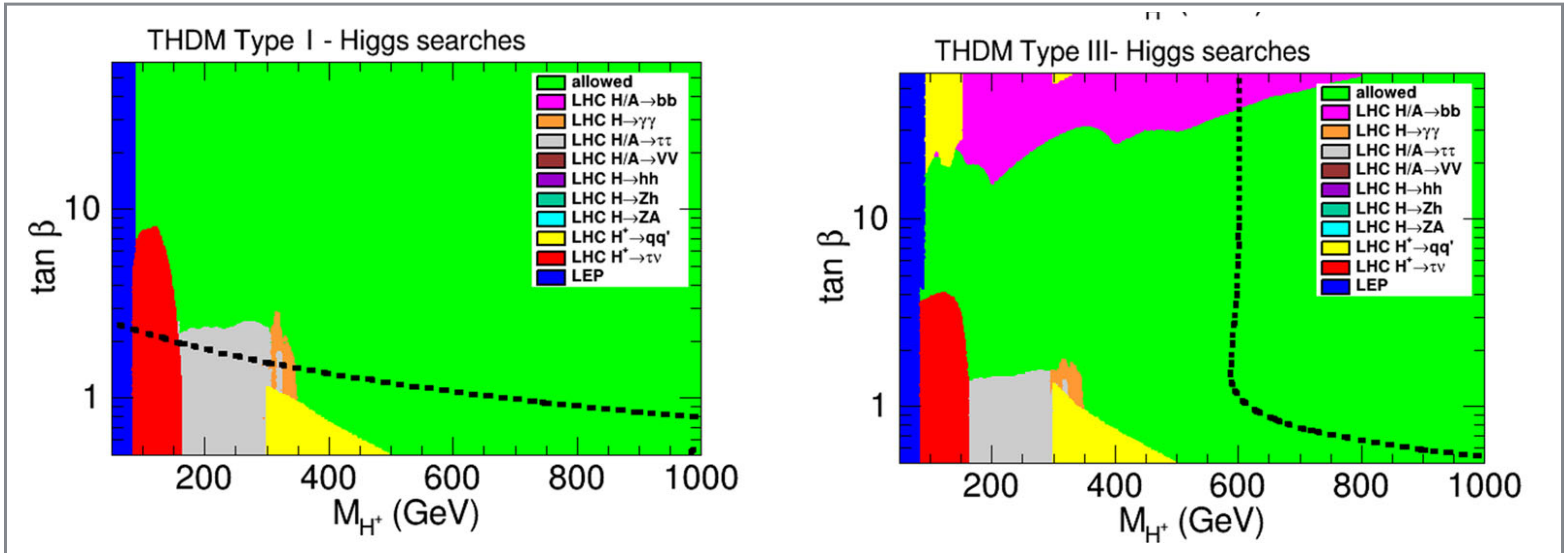
Introduction

- Searches of heavy charged Higgs bosons are getting more complicated due to the large associated backgrounds
- Also bounds from, e.g. $B \to X_s \gamma$ are strongly affecting the lower bounds of the charged Higgs boson masses with constraints of about $\mathcal{O}(800)$ GeV.



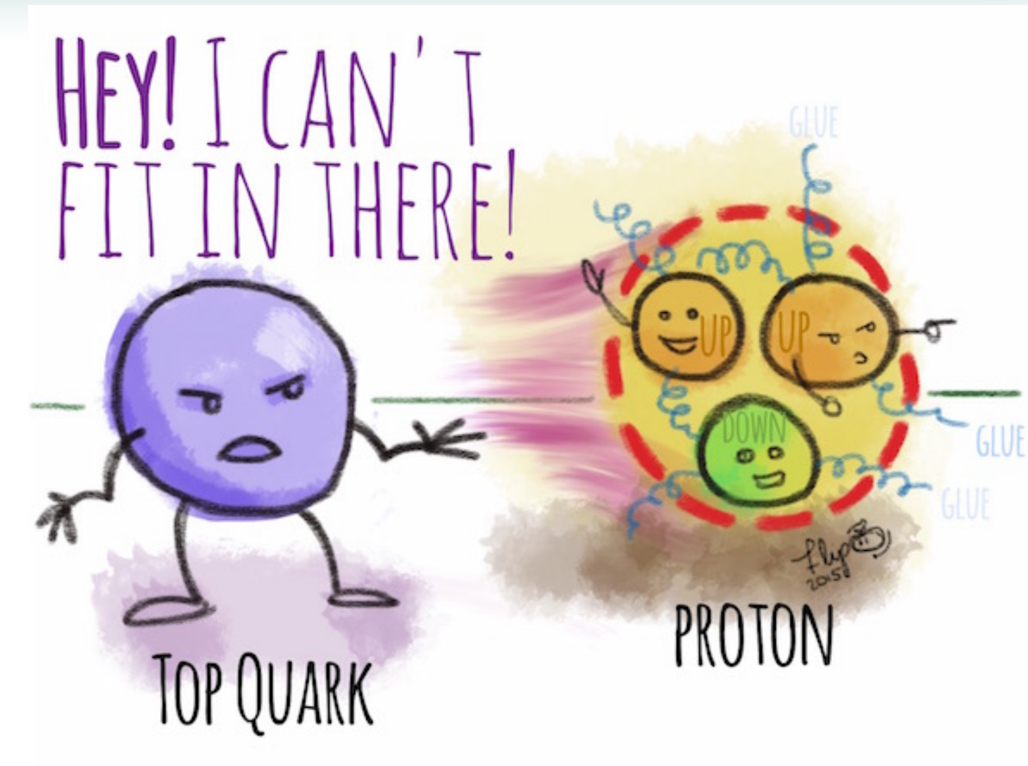
Arbey, Mahmoudi, Stal and Stefaniak;

Different approach: using top quark polarization

Why we study Top quarks?

The top quark is

- Rich
- Strong
- Naked
- Popular
- Goes beyond



Top quark is the Cristiano Ronaldo of Particle Physics

Top quark polarization: signals & observables

- Lepton angle distribution in top-quark rest frame

$$\cos\theta_\ell = \frac{\mathbf{p}^0_\ell \cdot \mathbf{p}_t}{|\mathbf{p}^0_\ell| \cdot |\mathbf{p}_t|}$$

True probe of top quark polarization. Independent of the e.g. 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).

- The scaled charged lepton energy distribution

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

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 polarization.
(A. Prasath V, R. M. Godbole, and S. D. Rindani, 2014; A. Jueid, 2018)

Top quark polarization: signals & observables

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

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

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 A. Arhrib, AJ, S. Moretti (2018) as a possible way to look for charged Higgs bosons at the LHC and to distinguish between the different Yukawa realizations of the 2HDM.

- The fraction of the top quark energy taken by the *b*-quark in the laboratory frame

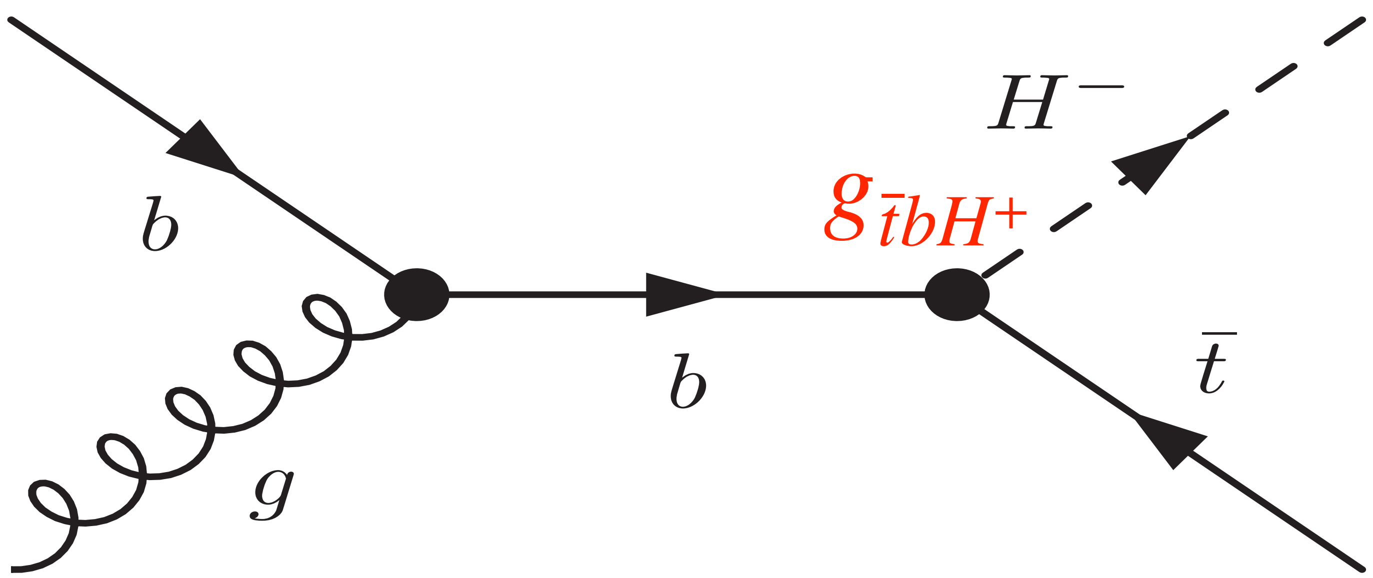
$$z \equiv \frac{E_b}{E_t}$$

Is less sensitive to top quark polarization for many new physics scenarios.

Heavy charged Higgs boson production

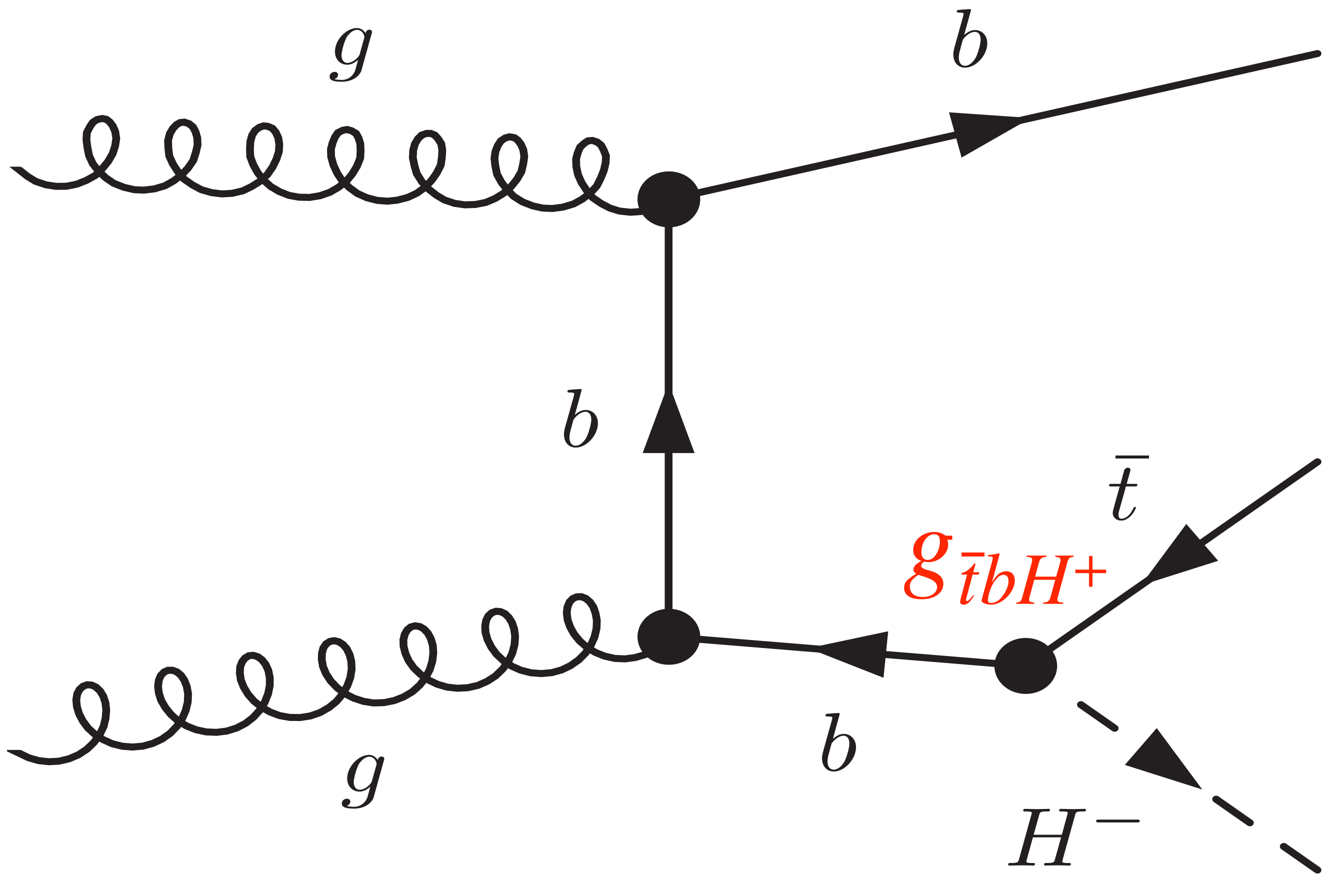
We consider Charged Higgs boson production at the LHC for $m_{H^\pm} > m_t + m_b$

The 5 flavor scheme (5FS)



b-quark is part of the proton; its PDF can be obtained by solving the DGLAP equations.

The 4 flavor scheme (4FS)



An additional b-quark is produced in the final state

(i) Differences between the two schemes are observed at LO.

(ii) NLO QCD corrections improve the agreement between the two schemes.

The structure of the charged Higgs boson coupling

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

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

- In the 2-Higgs-Doublet Model type-I (type-X), both the L- and R-components of g_{tbH^+} 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 $1/\tan\beta$.

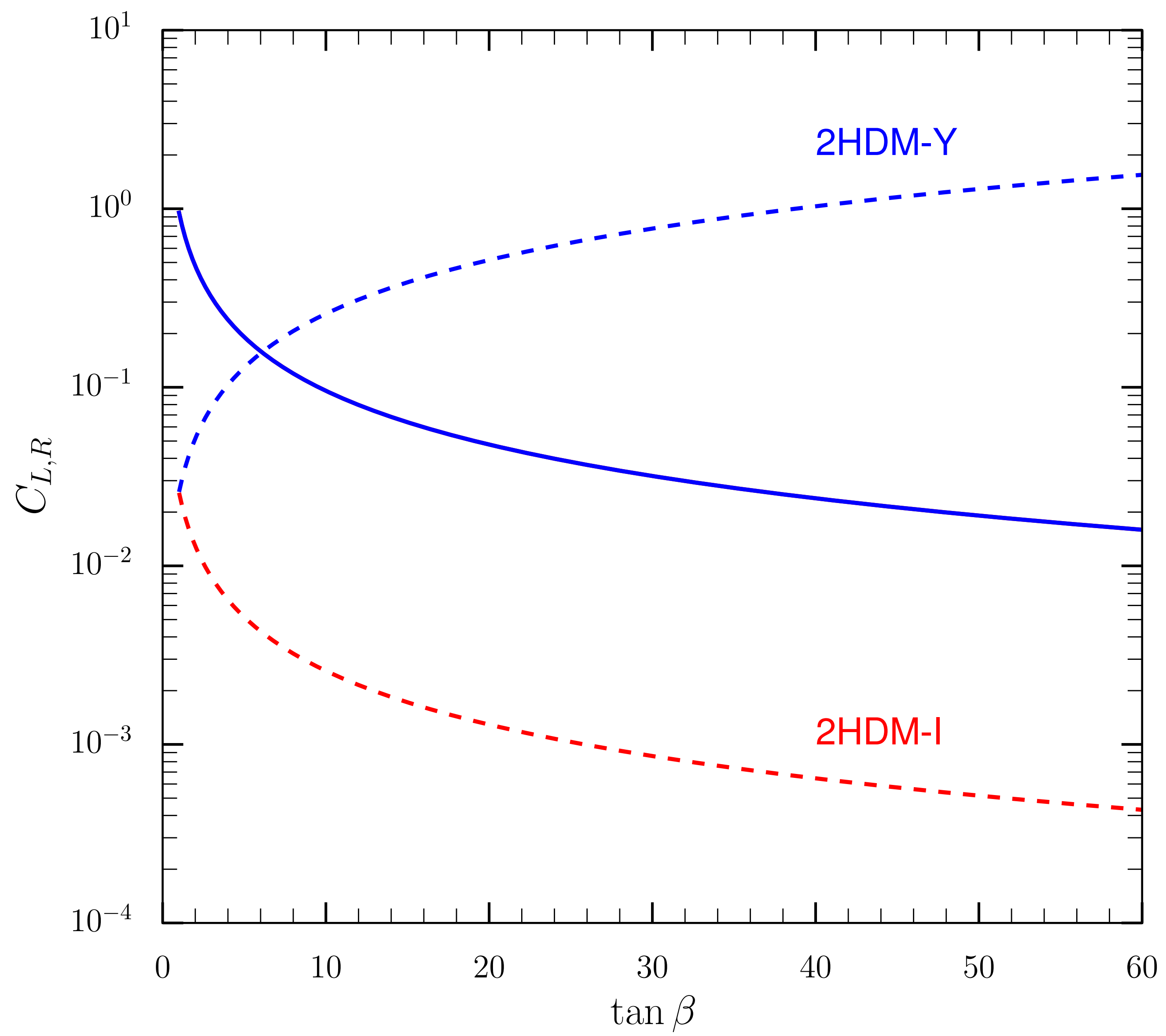
Consequences

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

  $\Longrightarrow$ The top quark is produced with negative polarization in the helicity basis.
- In type-II (type-Y), $g_{\bar{t}bH^+}$ can be L- dominated, R- dominated or purely scalar.

  $\Longrightarrow$ Top quark polarization is arbitrary (positive, negative or zero).

The structure of the charged Higgs boson coupling



- 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.

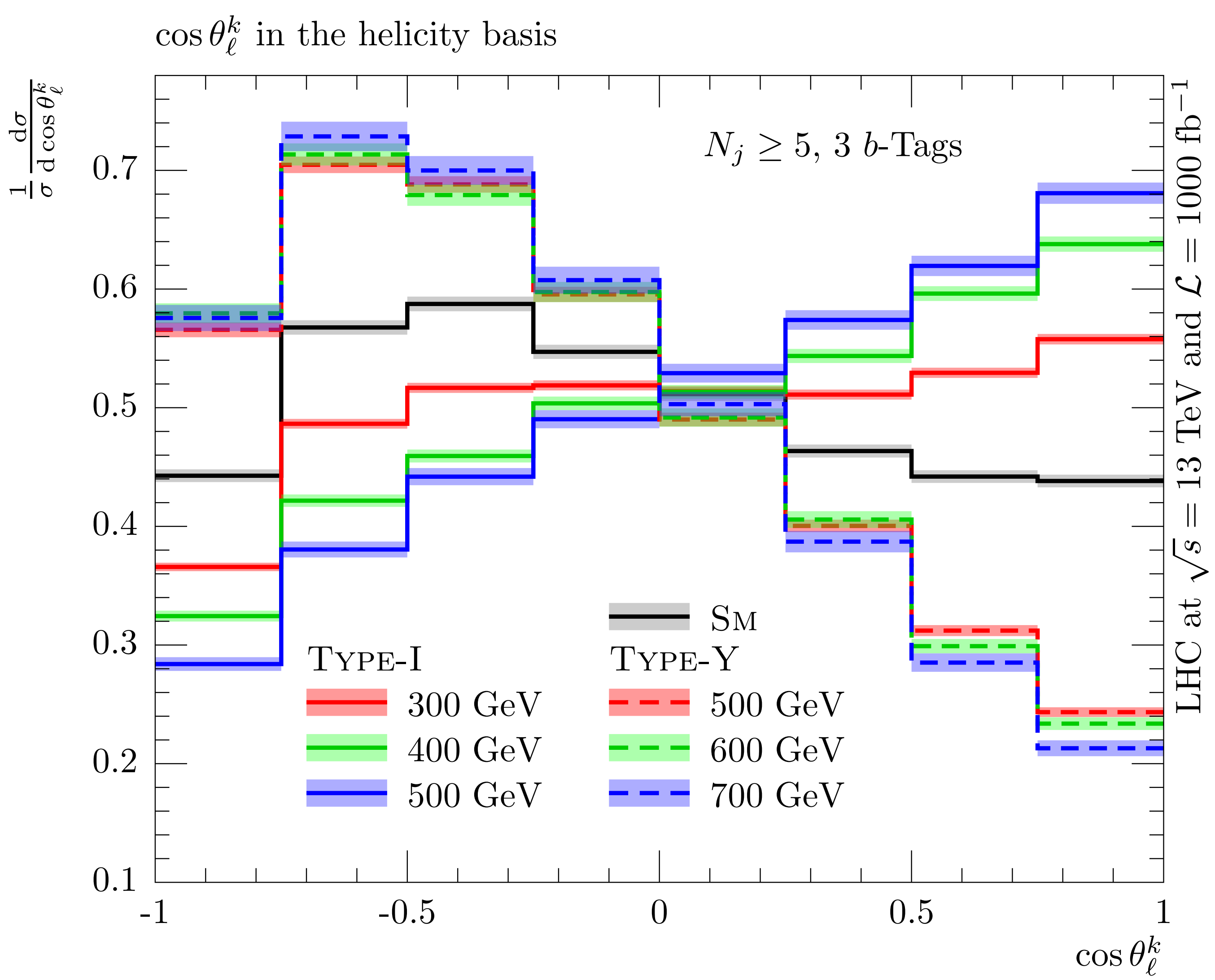
We choose $\tan\beta = 1$ in 2HDM-I and $\tan\beta = 50$ in 2HDM-Y

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

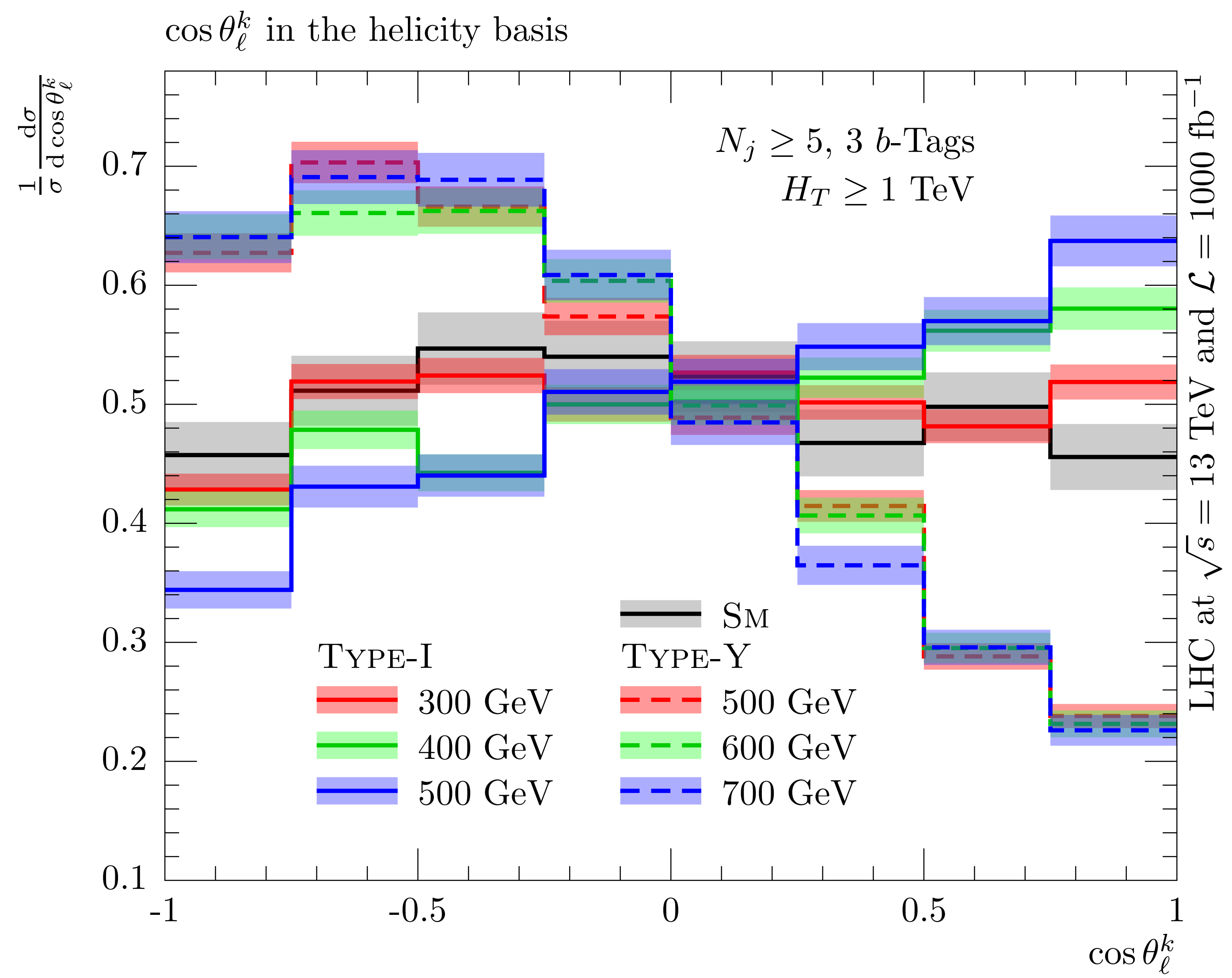
Phenomenological setup

- 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 $t\bar{t} + X, W(\to \ell\nu) + \text{jets}, Z(\to \ell\ell) + \text{jets}$.
- 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 (see slide 14).

Results



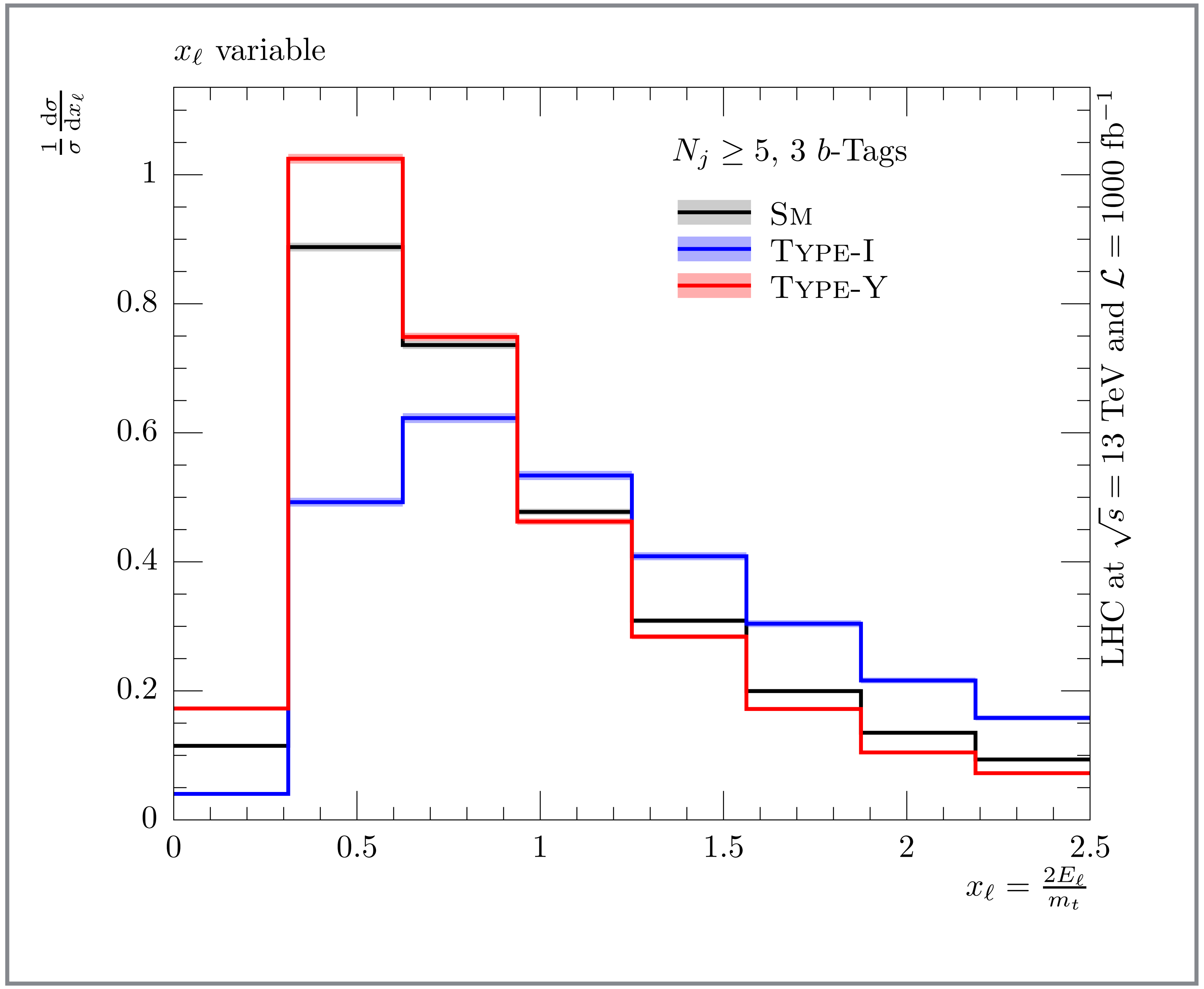
without the H_T cut

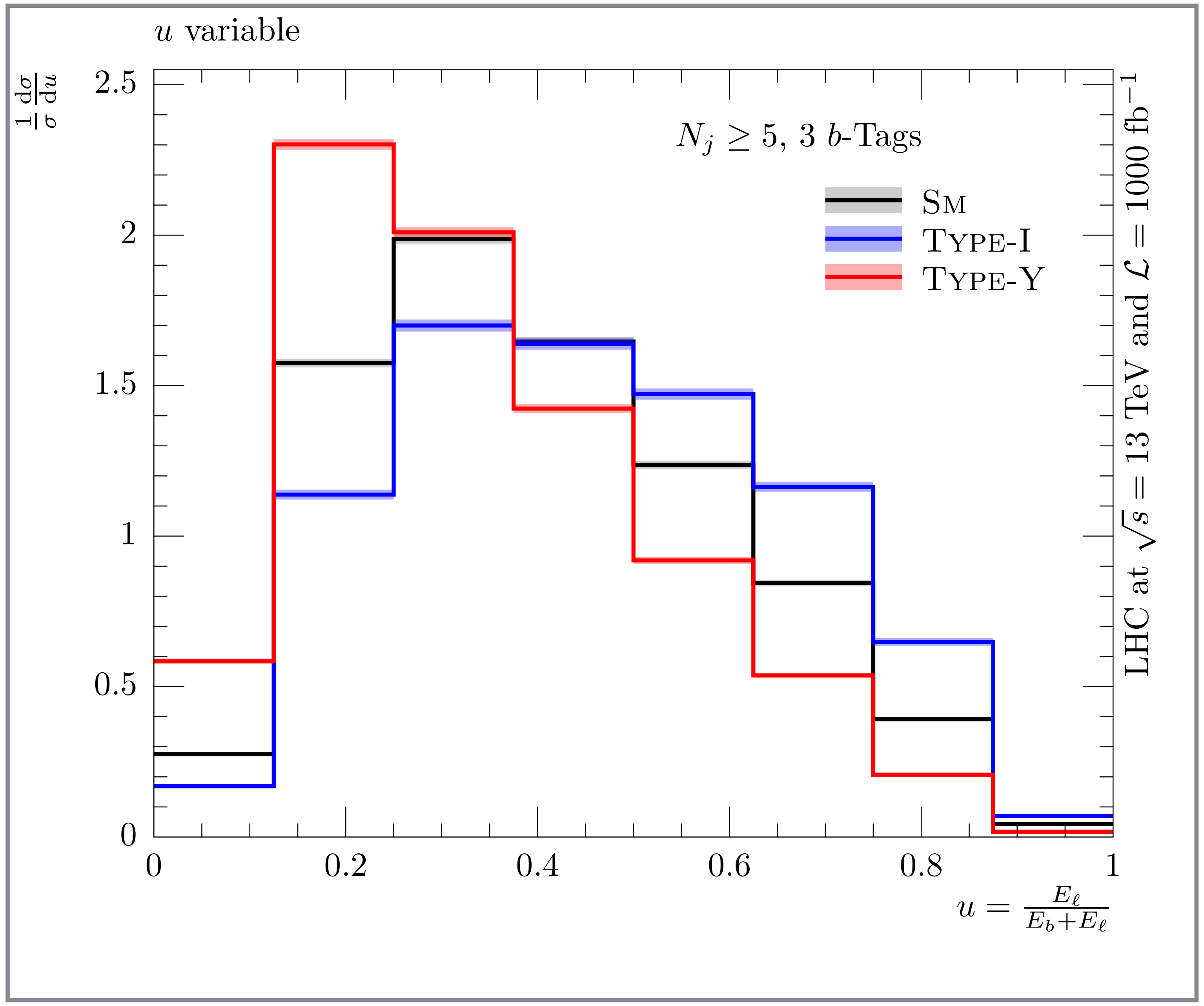


With the H_T cut

- Flip in the sign of the slope of the $\cos\theta_\ell$ distribution — positive for 2HDM-I and negative for 2HDM-Y.
- The $\cos\theta_\ell$ distribution is sensitive to the changes in $m_{H^\pm}$ in 2HDM-I — not the case in 2HDM-Y.
- The sensitivity decreases slightly when strict cuts on the scalar sum of jet p_T are imposed (right pane).

Results





- Energy-based observables are showing very good discriminative power — here, I show $m_{H^\pm} = 500$ GeV.
- The x_ℓ distribution is showing a similar shape in both type-Y and type-I 2HDMs.

Results

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

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

- Employing asymmetries can be very useful to distinguish between different charged Higgs masses in the same Yukawa type of 2HDM.
- The A_{x_ℓ}-asymmetry can be used to distinguish the different masses for type-Y 2HDM.
- More work is needed to implement these observables in real analysis.

Phenomenology

Benchmark Scenarios

To close the decays $H^{\pm} \to W^{\pm}A^0/H^0$

	$\tan\beta$	$\sin(\beta-\alpha)$	m_{h^0} [GeV]	$m_{H^{\pm}}$ [GeV]	m_{H^0} [GeV]	m_{A^0} [GeV]	m_{12}^2 [GeV^2]
Type-I (BP1)	1	0.999	125	300	400	400	1850
Type-Y (BP2)	50	0.999	125	500	700	700	9794

$\to$ $\mathrm{BR}(H^{\pm} \to tb) \approx 100\,\%$

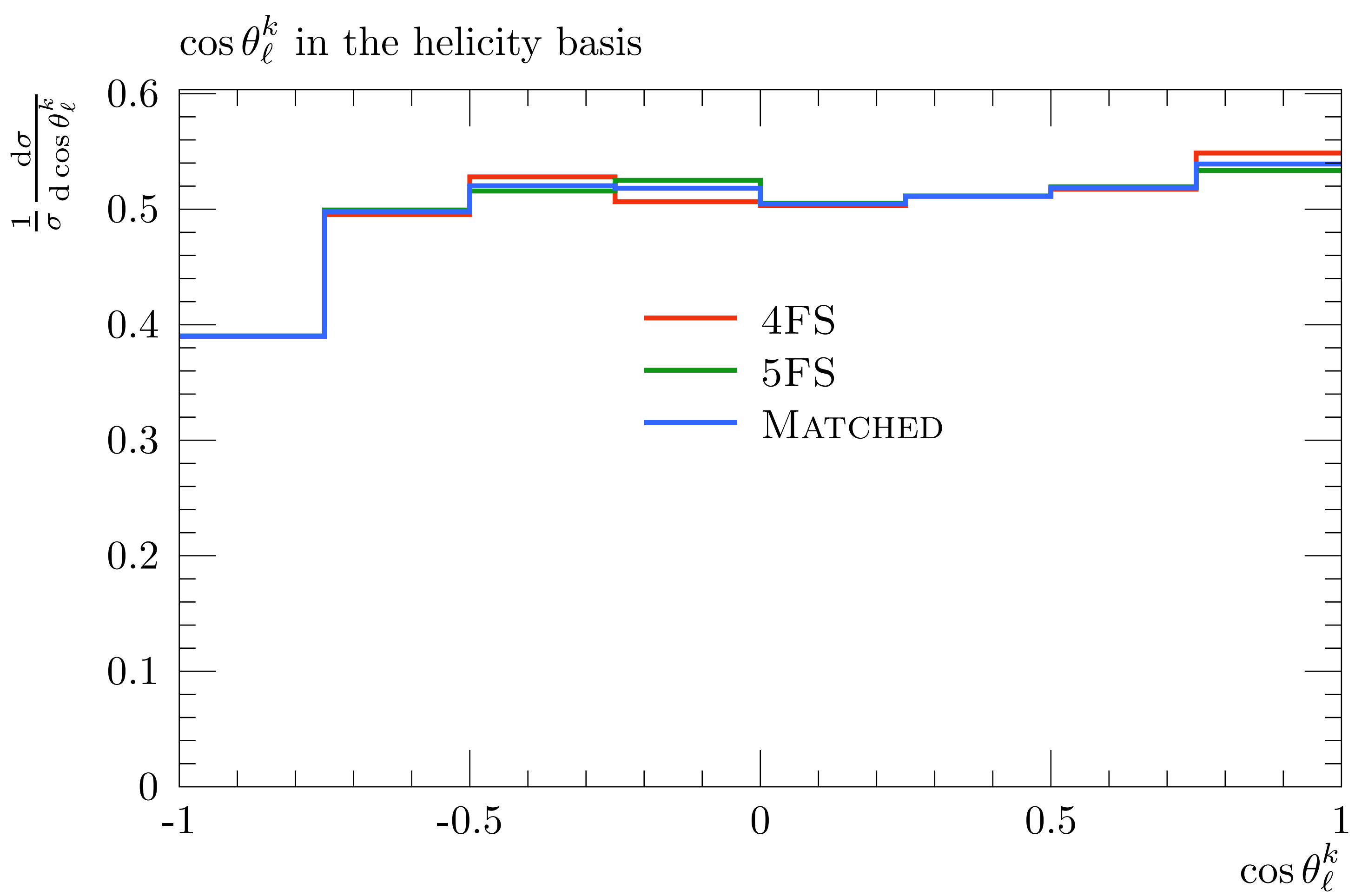
These benchmarks need to be revised due to the updated constraints (in progress):

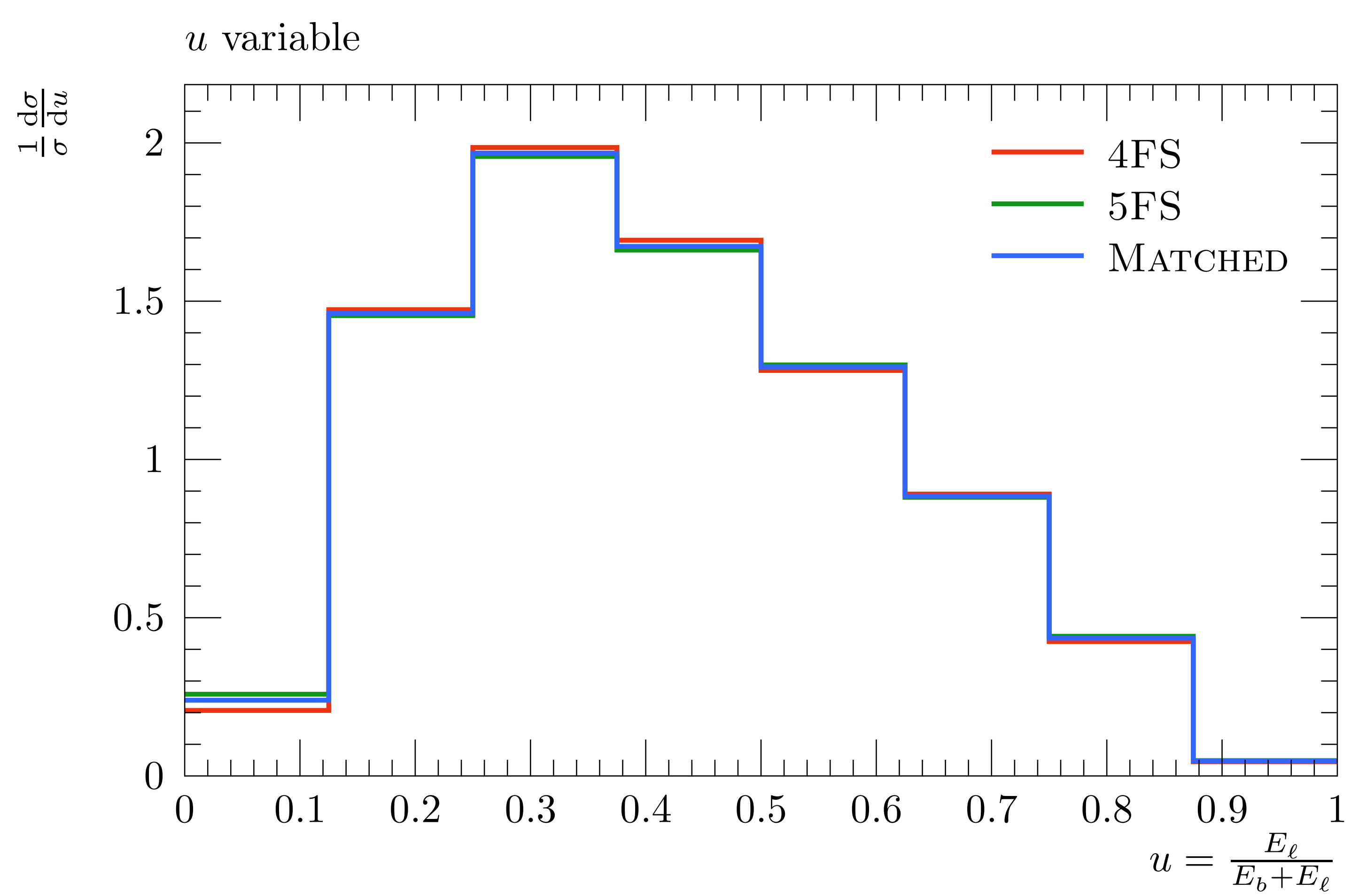
- For type-I, constraints from $Z \to b\bar{b}$ require $m_{H^{\pm}} \geq 350$ GeV.
- For type-Y, constraints from $\mathrm{BR}(B \to X_s\gamma)$ require $m_{H^{\pm}} \geq 600\ (800)$ GeV.

Benchmark	$\sigma(tH^{\pm}) \times \mathrm{BR}(H^{\pm} \to tb) \times \mathrm{BR}(t \to b\ell\nu) \times \mathrm{BR}(t \to bjj)$
BP1 (type-I)	$0.367 \pm 10.2\,\%$ (scale) $\pm 16.6\,\%$ (PDF) pb
BP1 (type-Y)	$0.162 \pm 9.5\,\%$ (scale) $\pm 19.3\,\%$ (PDF) pb

Effects of Matching?

- It is very important to study the effects of Matching; i.e. combining matrix-elements in the 4FS ($pp \to H^- tb$) and 5FS ($pp \to H^- t$).
- Including the b-quark in the proton induces a logarithmic correction which strongly depends on the charged Higgs mass.
- We find that the polarization observables are resilient to the proton scheme.





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

How to implement these?

- The cut-and-count method — with uncertainties — is not suitable in this kind of analyses; lots of variables are multi-modal $\Longrightarrow$ both signal & background efficiencies will drop dramatically.

- We plan to implement these variables in new search strategies where basic kinematical variables, high-level variables and spin observables (both for resolved and boosted topologies) are fed into ML algorithms;
  - Boosted-Decision Trees (BDT) with just kinematical variables — no spin information — improves the selection by about $40\,\%$ plus another(?) $50\,\%$ from spin.
  - We plan to implement also Neural Networks (NNs) based algorithms.

- Now we are in the process of Monte Carlo event generation of about $\approx 10^{10}$ events — mostly from $W/Z + \text{jets}$ with up two jets with NLO precision (could take about few months).
- The implementation is done in the meantime.
- We expect some preliminary results probably in the next meeting (provided it will held after 2–3 months).

Stay tuned

Conclusions

- We studied the sensitivity of spin observables on both the anomalous couplings in single top quark production through t-channel and as a search strategy for Charged Higgs bosons in top-associated production.
- We found very important sensitivities and they can be used both as a discovery as well as a characterization tools.
- 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?*
- Gives further motivations to study the presence of new states (charged or neutral) with different spin quantum numbers and in different production modes.

It ain't over till it's over


Thank you for your attention