Probing Extended Higgs Sectors with Top-Quark Spin Correlations

Francisco Arco

Based on JHEP 06 (2025) 170 [2502.03443], FA, T. Biekötter, P. Stylianou, G. Weiglein

+ ongoing work of FA, R. Kumar, P. Stylianou, G. Weiglein

Workshop on Multi-Higgs Models 2026

Instituto Superior Técnico, Lisboa, Portugal, 26 August 2026

HELMHOLTZ

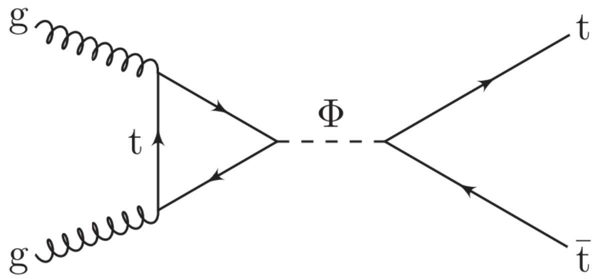
DESY.

Particle Physics after the discovery of the Higgs boson

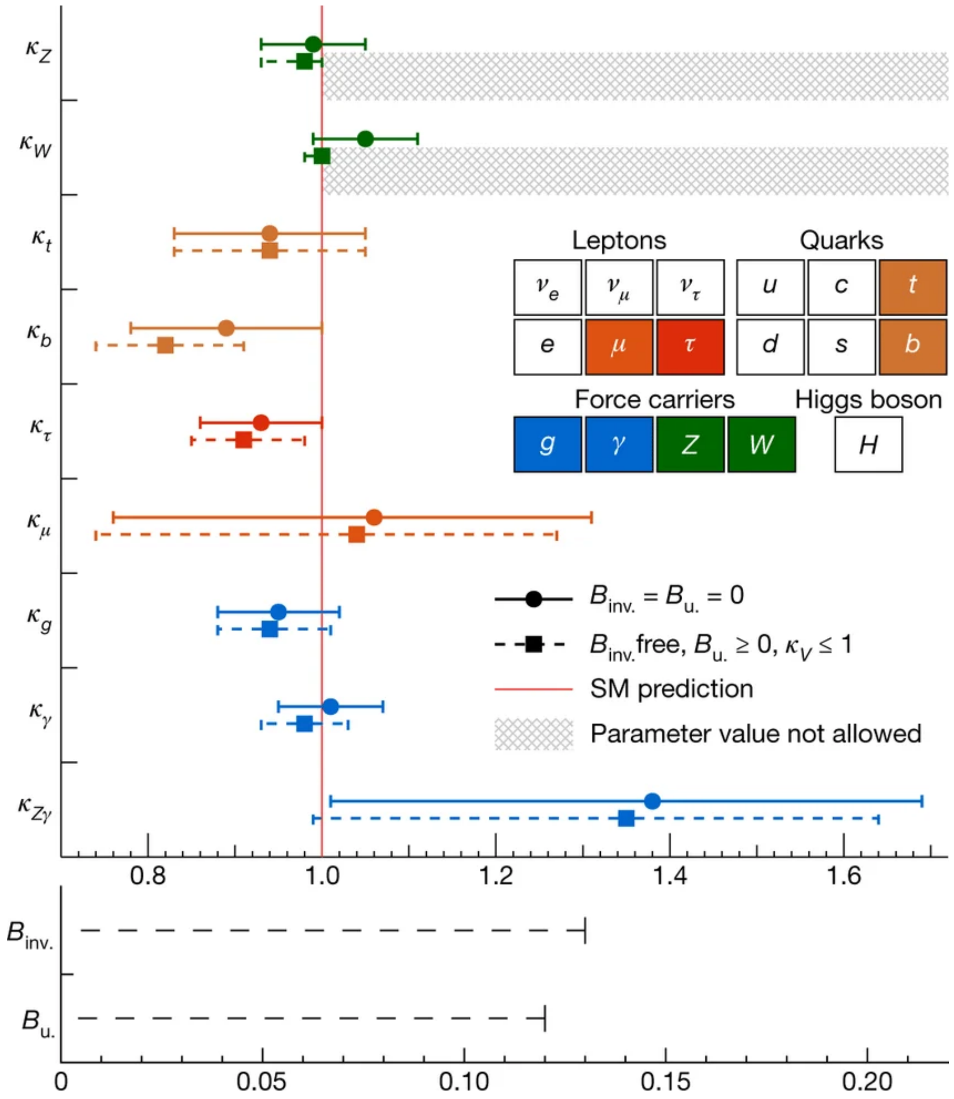
Importance and interplay between Higgs and top physics

- The discovered Higgs boson is **compatible with the SM** (within uncertainties)
- *However*… the SM has **many shortcomings**!
  - DM, baryon asymmetry, flavor puzzle, hierarchy problem, etc…

    ⇒ **BSM Physics**, e.g. the 2HDM
- Many BSM searches at the LHC
  - Channels with **top-quark final states** play a key role:



Spin-correlations of the top-quark pairs can give valuable information!

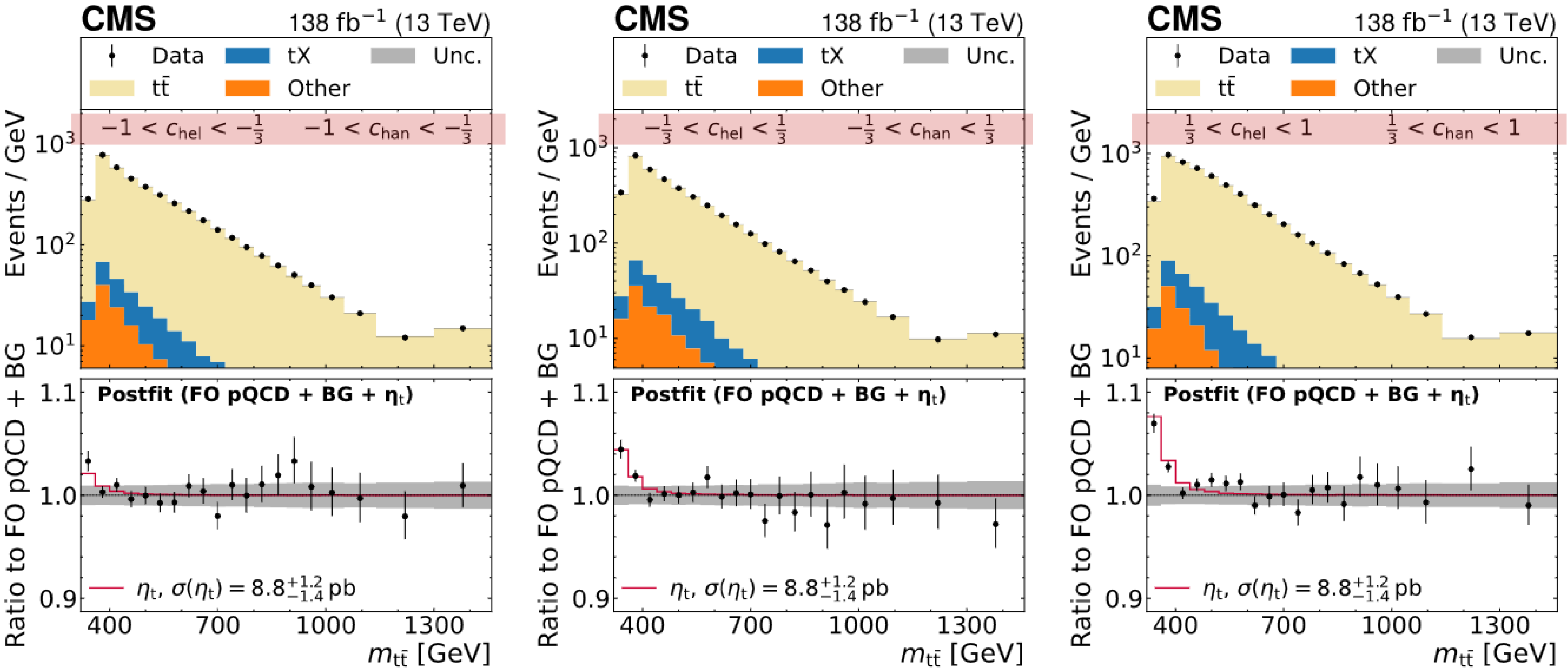


Importance of top-quark spin correlations

Example: observation of a ‘toponium’ bound state at ATLAS and CMS

[2507.05119, 2503.22382, ATLAS-CONF-2025-008]

- **Observation of a pseudoscalar excess** (> 5σ) at the $t\bar{t}$ threshold
  - Compatible with a NR-QCD effect, *aka* ***toponium***
- **The angular variables c_{han} and c_{hel} were essential!**



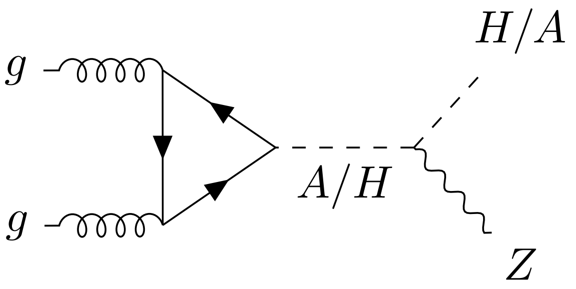
**Here the ‘toponium’ is modeled with a simplified model, see e.g. [2102.11281, 2401.08751]*

Top-quark spin correlations shine at probing BSM physics

Two projects I would discuss today

JHEP 06 (2025) 170 [2502.03443]
FA, T. Biekötter, P. Stylianou, G. Weiglein

- **Distinguish $A \to HZ$ and $H \to AZ$**
  - Relevant for EWPT scenarios in the 2HDM, 'smoking gun' signature



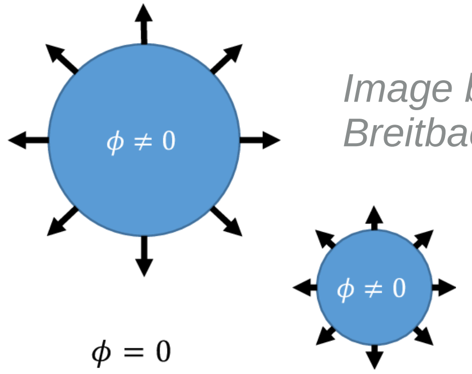
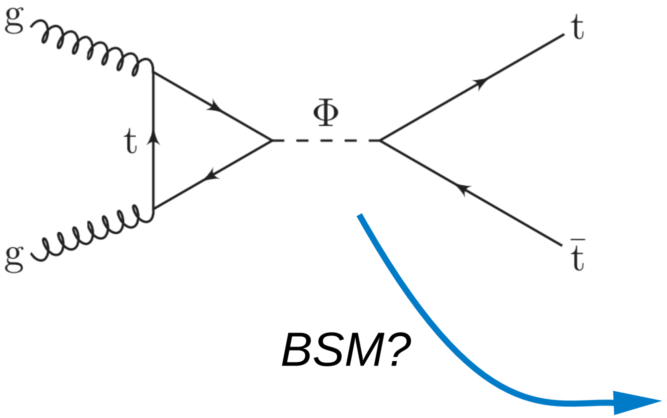
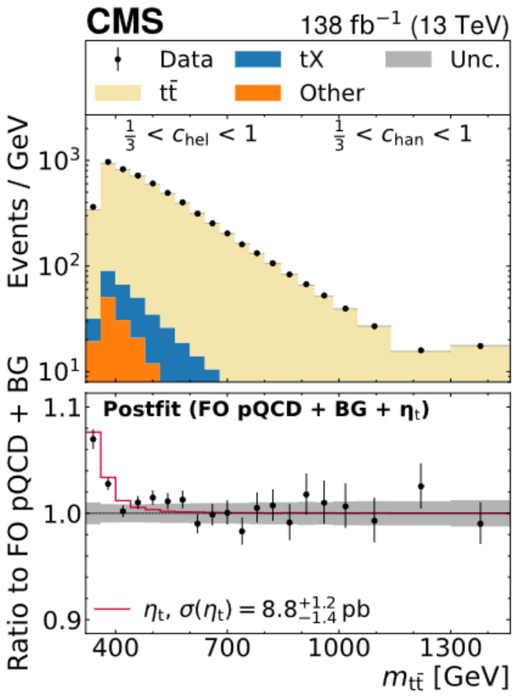


Image by M. Breitbach

Ongoing [26xx.xxxxx]
FA, R. Kumar, P. Stylianou, G. Weiglein

- **BSM interpretations of the toponium excess**
  - What is the largest excess still allowed?

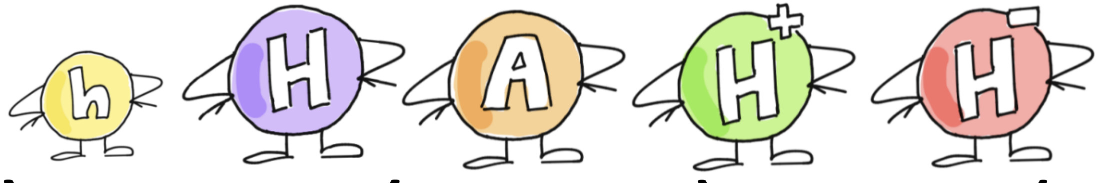




Why $A \to HZ$ and $H \to AZ$?

Relevance for a strong first-order EW phase transition

- Five physical Higgs bosons within the 2HDM:



SM-like

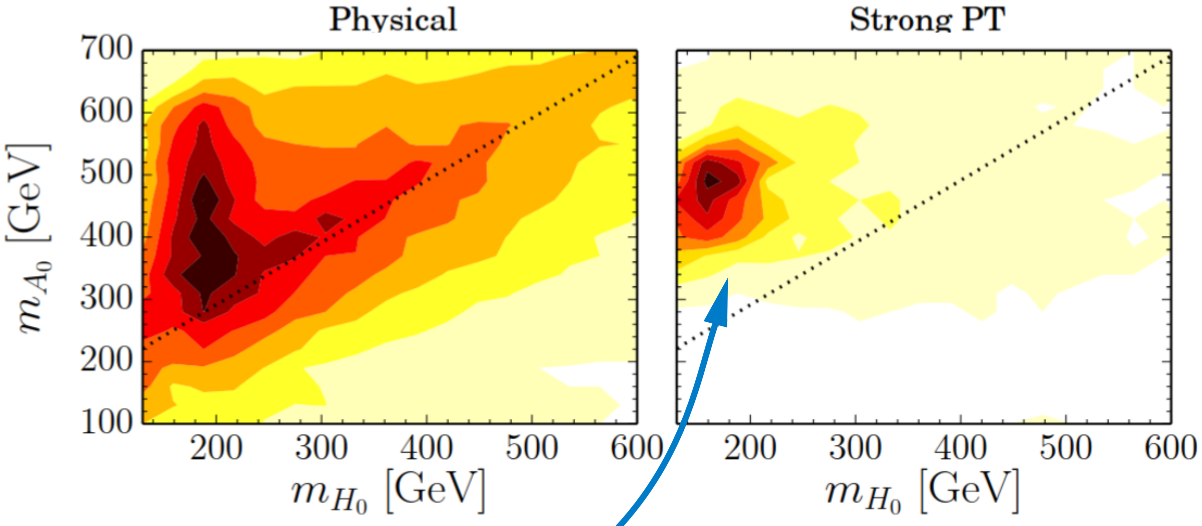
Neutral CP even

Neutral CP odd

Charged

Image by K. Radchenko

(Density of points)

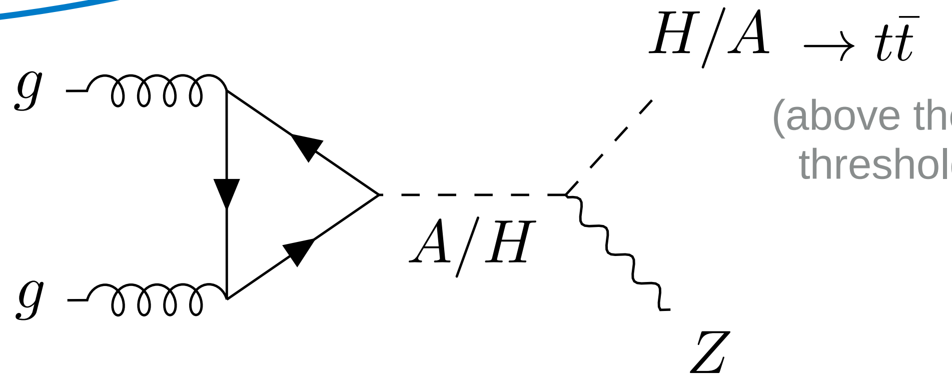


[Dorsch, Huber, Mimasu, No, 13]

Generally, **large scalar couplings** are needed to generate a potential barrier

⇒ **Large mass splitting** between **heavy Higgs bosons**

⇒ The decays $A \to HZ$ **or** $H \to AZ$ can be kinematically allowed (Stronger transitions for $m_A > m_H + m_Z$)



Some literature on 2HDM and SFOEWPT (post Higgs discovery)
[Dorsch, Huber, Mimasu, No, 13, 14, 17] [Basler, Krause, Mühlleitner, Wittbrodt, Wlotzka, 16] [Basler, Mühlleitner, Wittbrodt, 17] [Gonçalves, Kaladharan, Wu, 21] [Biekötter, Heinemeyer, No, Olea-Romacho, Weiglein, 22] …….

Experimental situation at present

No possible distinction between $A \to HZ$ and $H \to AZ$:(

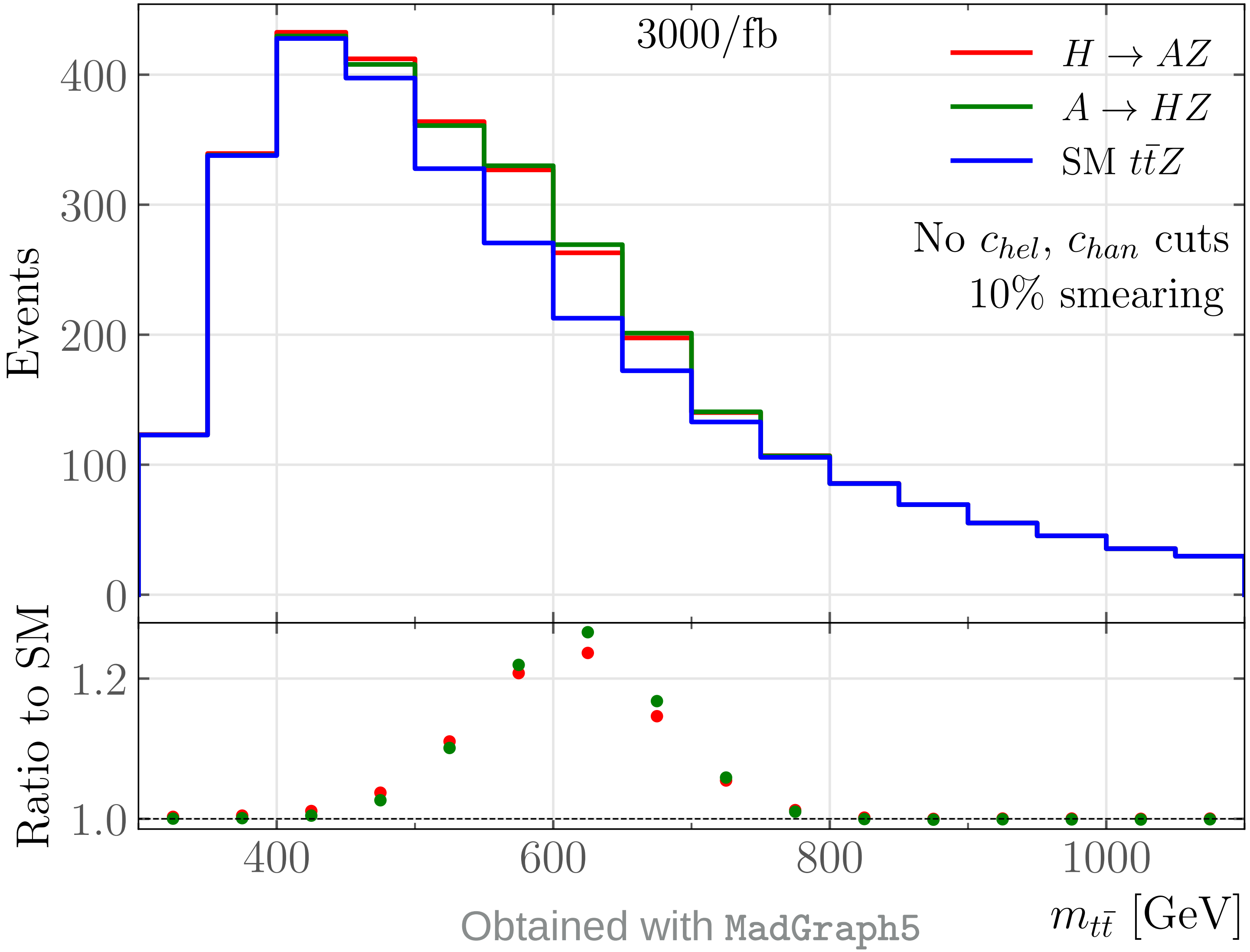
$m_{\text{heavy}} = 800$ GeV, $m_{\text{light}} = 600$ GeV
(allowed by present searches)

- The current analyses yield **no information about the CP properties** of the Higgs bosons

- Example:
  Two points within the 2HDM such that **$A \to HZ$ and $H \to AZ$ have the same total cross section** in the $t\bar{t}Z$ final state (changing the Yukawa coupling)

$$\sigma(gg \to A \to ZH \to Zt\bar{t}) =$$
$$\sigma(gg \to H \to ZA \to Zt\bar{t}) = 0.1 \text{ pb}$$

- Nearly identical shape
  ⇒ **No way to distinguish $A \to HZ$ from $H \to AZ$**



Obtained with `MadGraph5`

Our proposal: top-quark spin correlations

Sensitive observables: angular variables c_{han} and c_{hel}

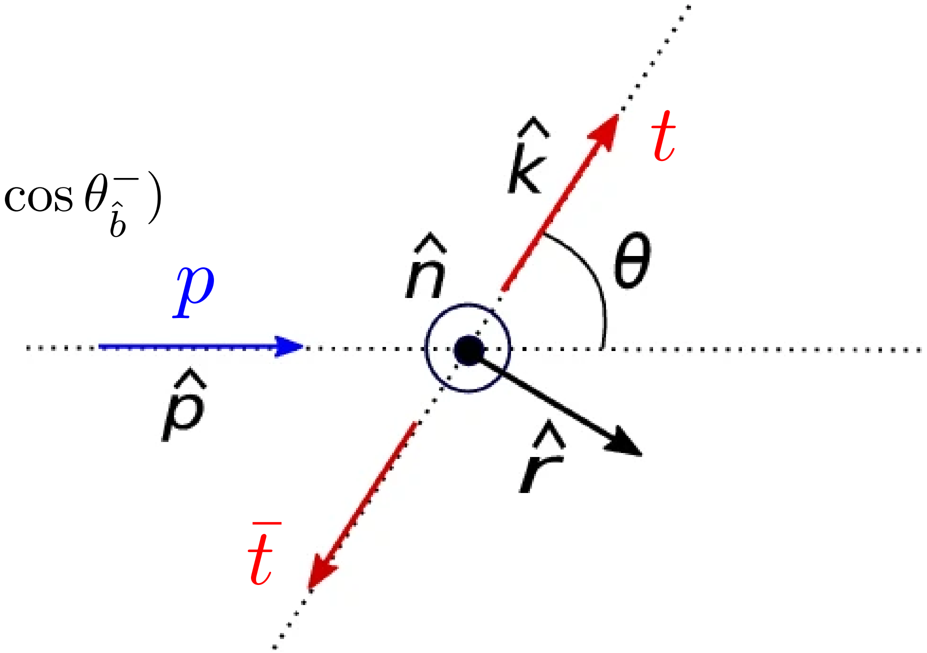
Image from 2105.11478

- Cross section dependence on the spin density matrix of the $t\bar{t}$ system:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^{+}_{\hat{a}}\, d\cos\theta^{+}_{\hat{b}}} = \frac{1}{4}\left(1 + B^{+}_{\hat{a}}\cos\theta^{+}_{\hat{a}} + B^{-}_{\hat{a}}\cos\theta^{-}_{\hat{a}} - C_{\hat{a}\hat{b}}\cos\theta^{+}_{\hat{a}}\cos\theta^{-}_{\hat{b}}\right)$$

with $a, b \in \{\hat{k}, \hat{r}, \hat{n}\}$

Spin-correlation matrix



- $\hat{\ell}^{\pm}$ is the direction of flight of the **leptons** in the top (or anti-top) rest frame and $\cos\theta^{\pm}_{\hat{a}} = \pm\hat{\ell}^{\pm}\cdot\hat{a}$
- Use the angular variables c_{hel} and c_{han} ⇒ **Sensitive to the CP-nature of the state producing the $t\bar{t}$ pair!**

$$c_{hel} = -\cos\theta^{+}_{\hat{k}}\cos\theta^{-}_{\hat{k}} - \cos\theta^{+}_{\hat{r}}\cos\theta^{-}_{\hat{r}} - \cos\theta^{+}_{\hat{n}}\cos\theta^{-}_{\hat{n}} = \hat{\ell}^{+}\cdot\hat{\ell}^{-}$$

$$c_{han} = \cos\theta^{+}_{\hat{k}}\cos\theta^{-}_{\hat{k}} - \cos\theta^{+}_{\hat{r}}\cos\theta^{-}_{\hat{r}} - \cos\theta^{+}_{\hat{n}}\cos\theta^{-}_{\hat{n}}$$

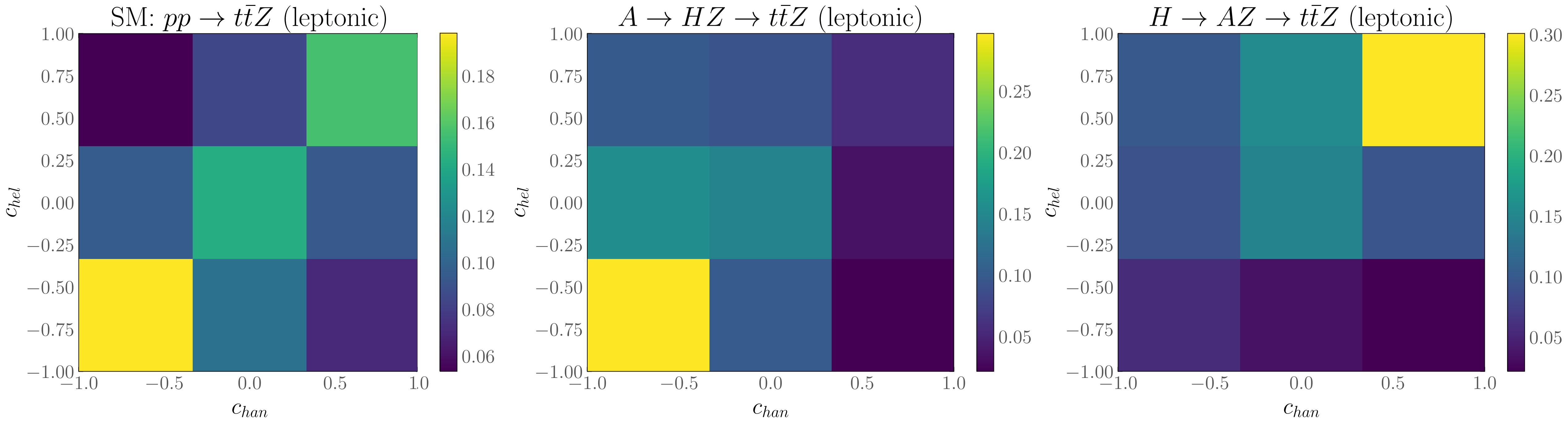
More on $t\bar{t}$ spin correlations: *[Bernreuther, Heisler, Si, 15, Ravina, Simpson, Howarth, 21, Rübenach PhD Thesis, …]*

- We only consider the **fully-leptonic decay channel**!

Our proposal: top-quark spin correlations for the $Zt\bar{t}$ channel

The two signals become potentially distinguishable with c_{han} and c_{hel} binning!

- Cross section distributions normalized to the total cross section



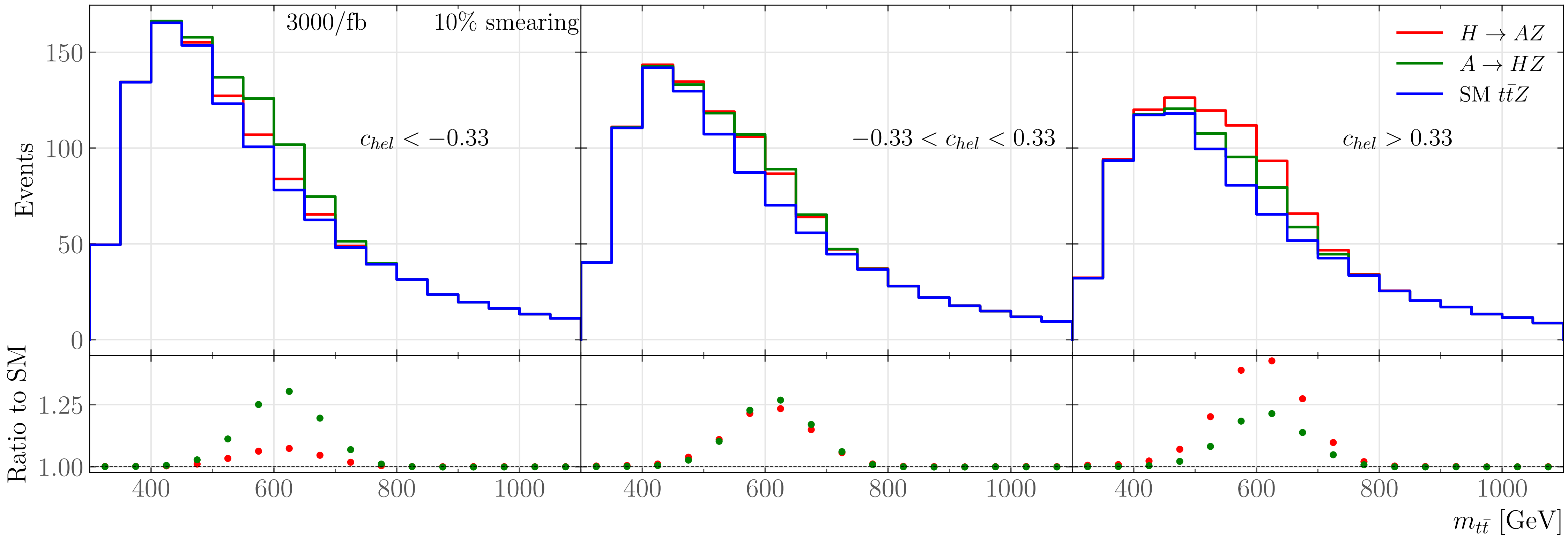
$A \to HZ$ and $H \to AZ$ peak in different regions in the $c_{han}-c_{hel}$ plane!

Results: di-top invariant mass distributions

Bins in c_{hel}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



Both signals become distinguishable!!

- After some selection cuts taken from ATLAS *[2312.04450]*, efficiency cuts and smearing

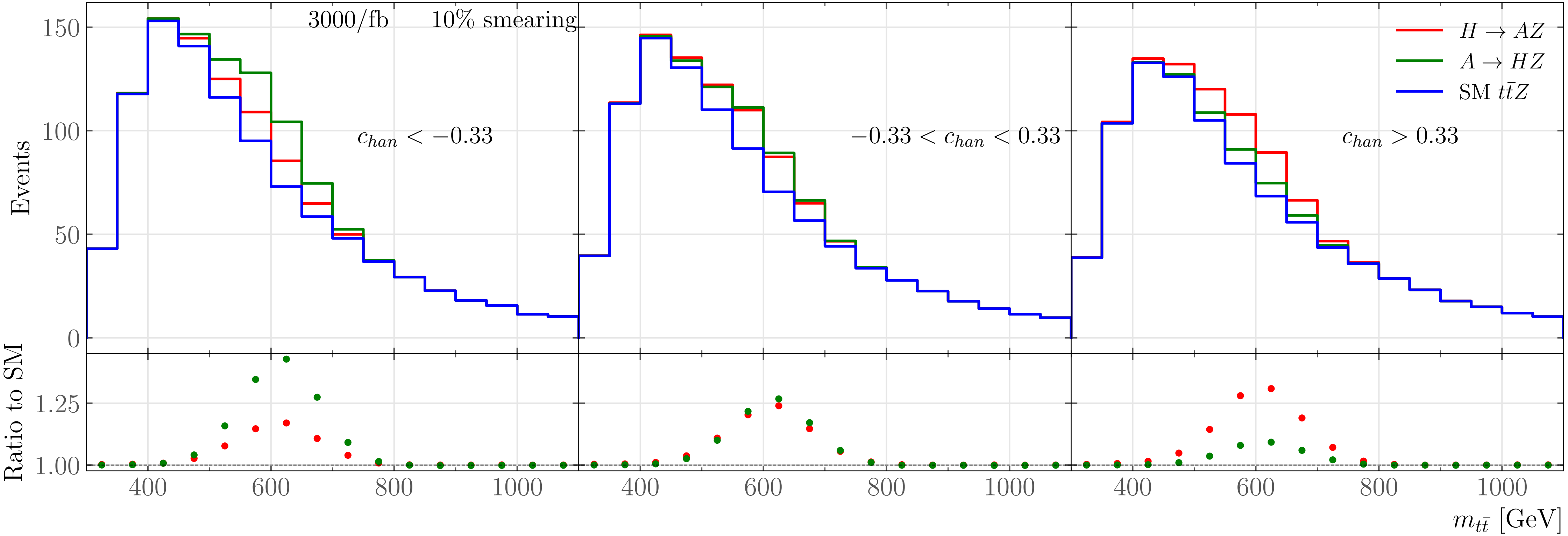
Obtained with `MadGraph5`

Results: di-top invariant mass distributions

Bins in c_{han}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



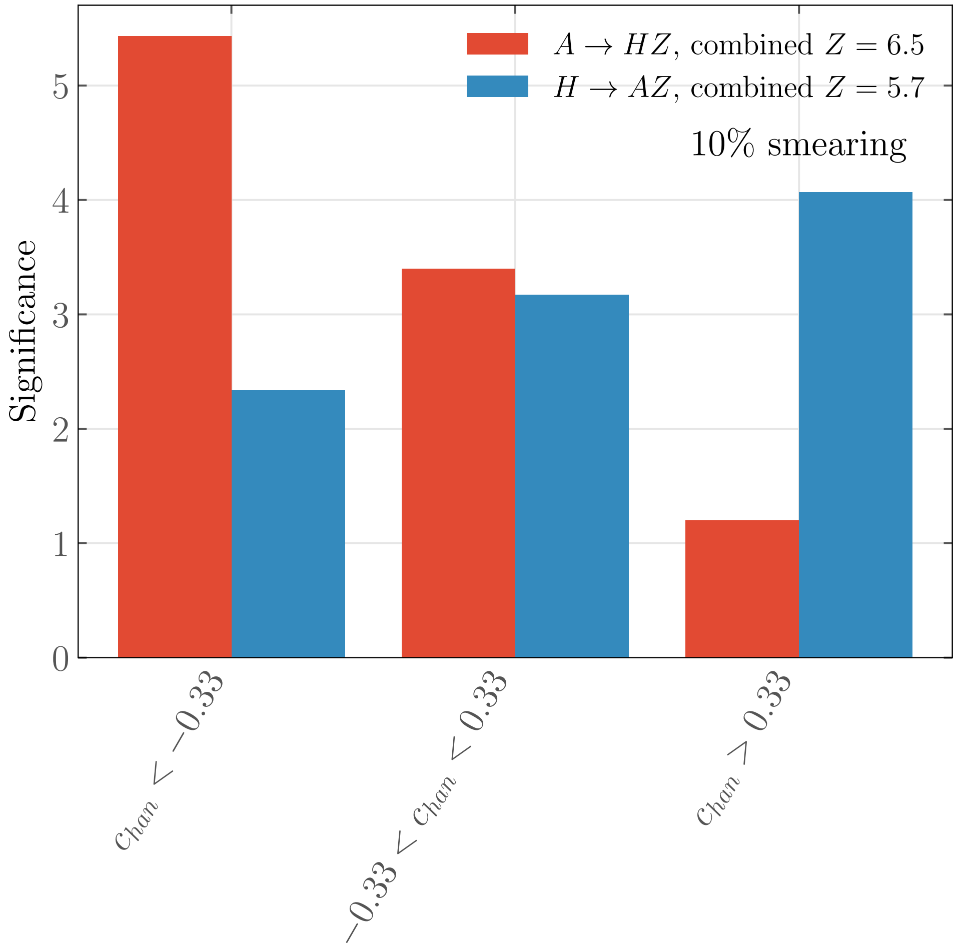
Both signals become distinguishable!!

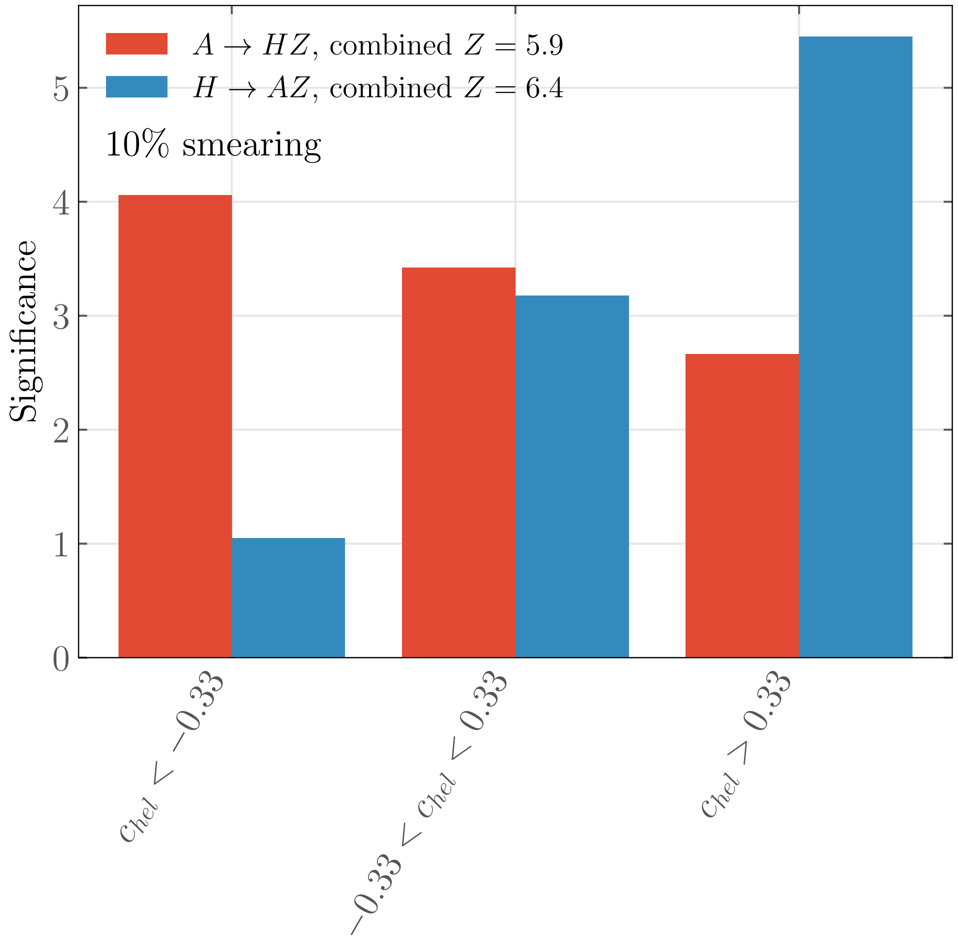
Results: significance Z at the HL-LHC

Binning only in c_{han} OR c_{hel}

$$Z_i = \sqrt{2\left[(S_i + B_i)\log\left(1 - \frac{S_i}{B_i}\right) - S_i\right]}$$

- Significance values of ~6.5 in the optimal case
- The significance without c_{han}/c_{hel} is below 6



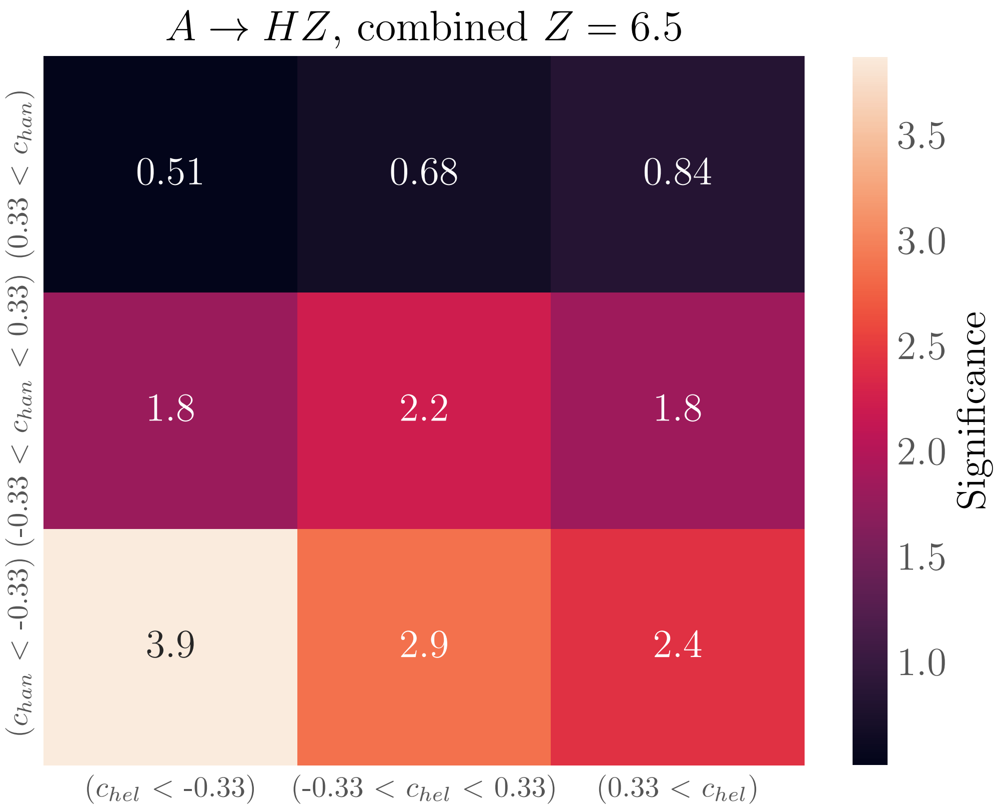


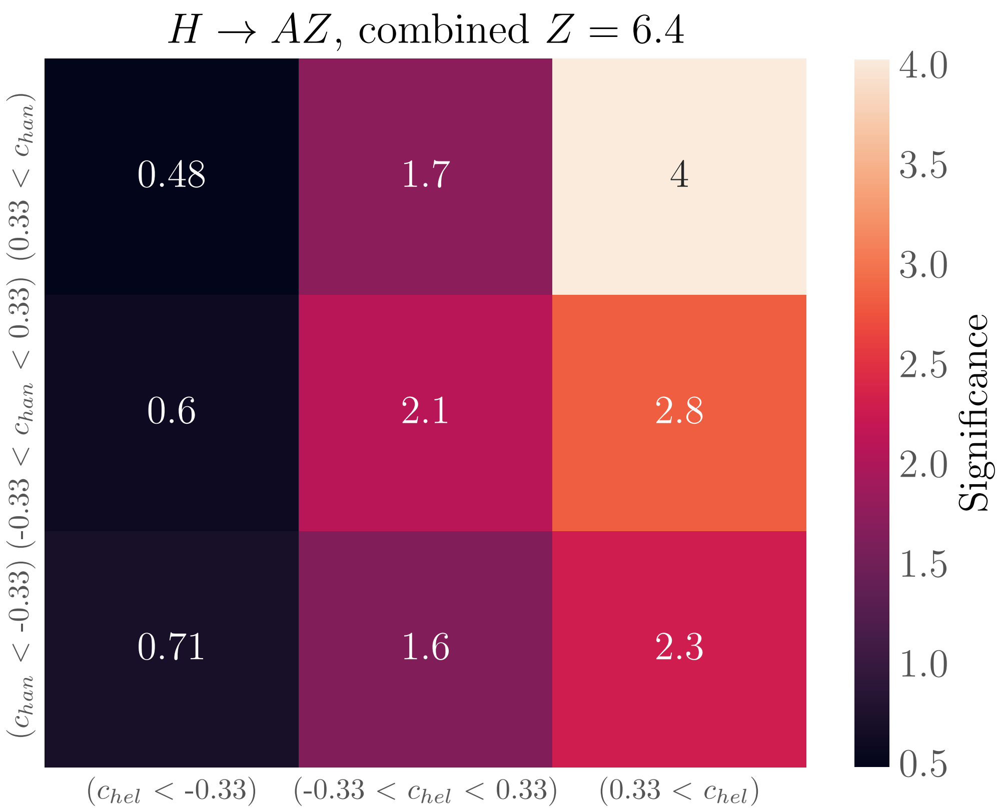
Results: significance Z at the HL-LHC

Binning in both c_{han} AND c_{hel}

$$Z_i = \sqrt{2\left[(S_i + B_i)\log\left(1 - \frac{S_i}{B_i}\right) - S_i\right]}$$

- Significance values of ~6.5 after combining all bins
- The significance without c_{han}/c_{hel} is below 6



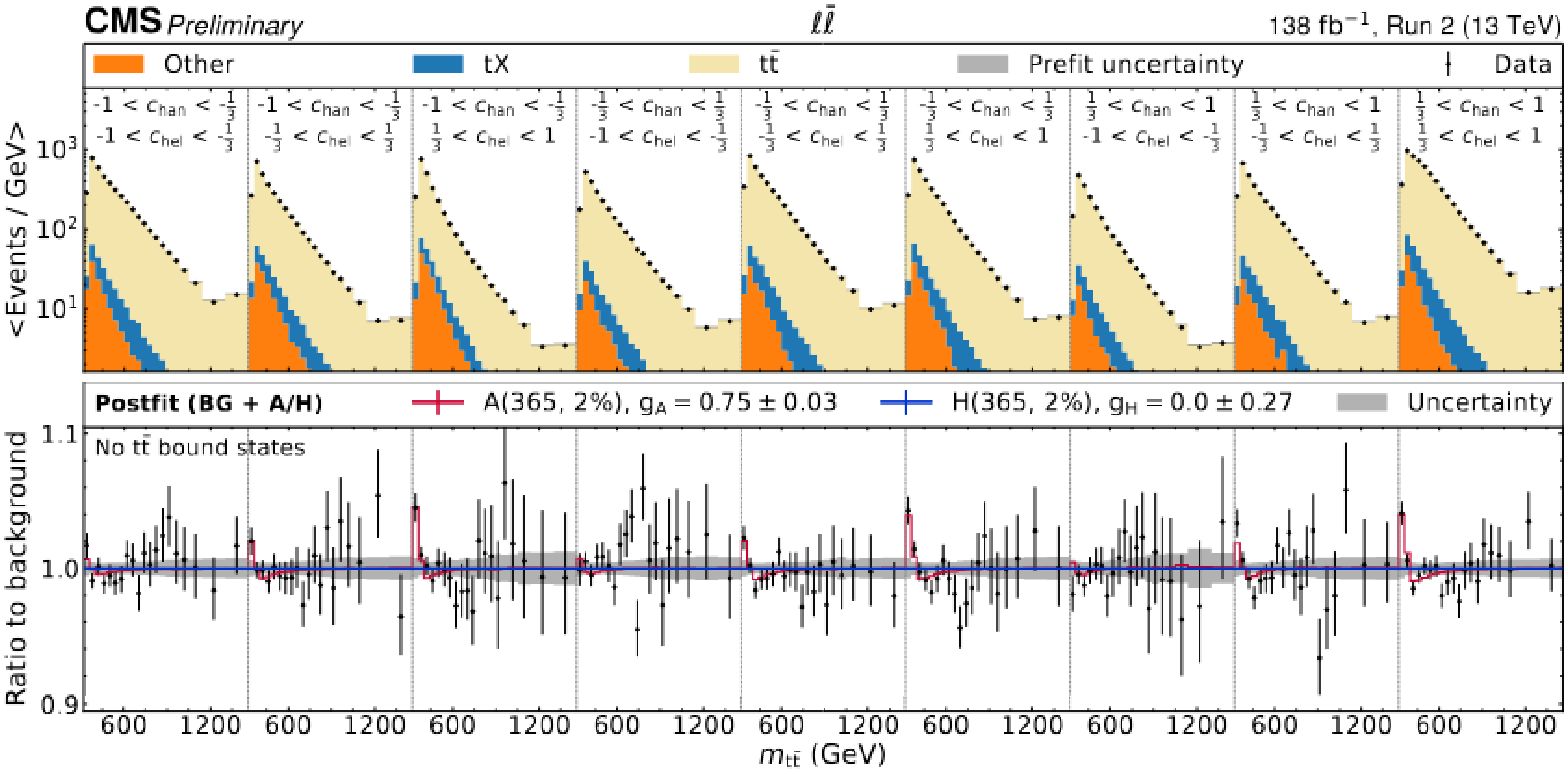


Conclusion: **binning in c_{han} and c_{hel} can help differentiate between both signals**

Interpretations of the $t\bar{t}$ threshold excess

[CMS-PAS-HIG-22-013]
* This result is superseded [2507.05119], but in the new result they do not report the best fit with only one pseudoscalar

CMS interpretation with one pseudoscalar

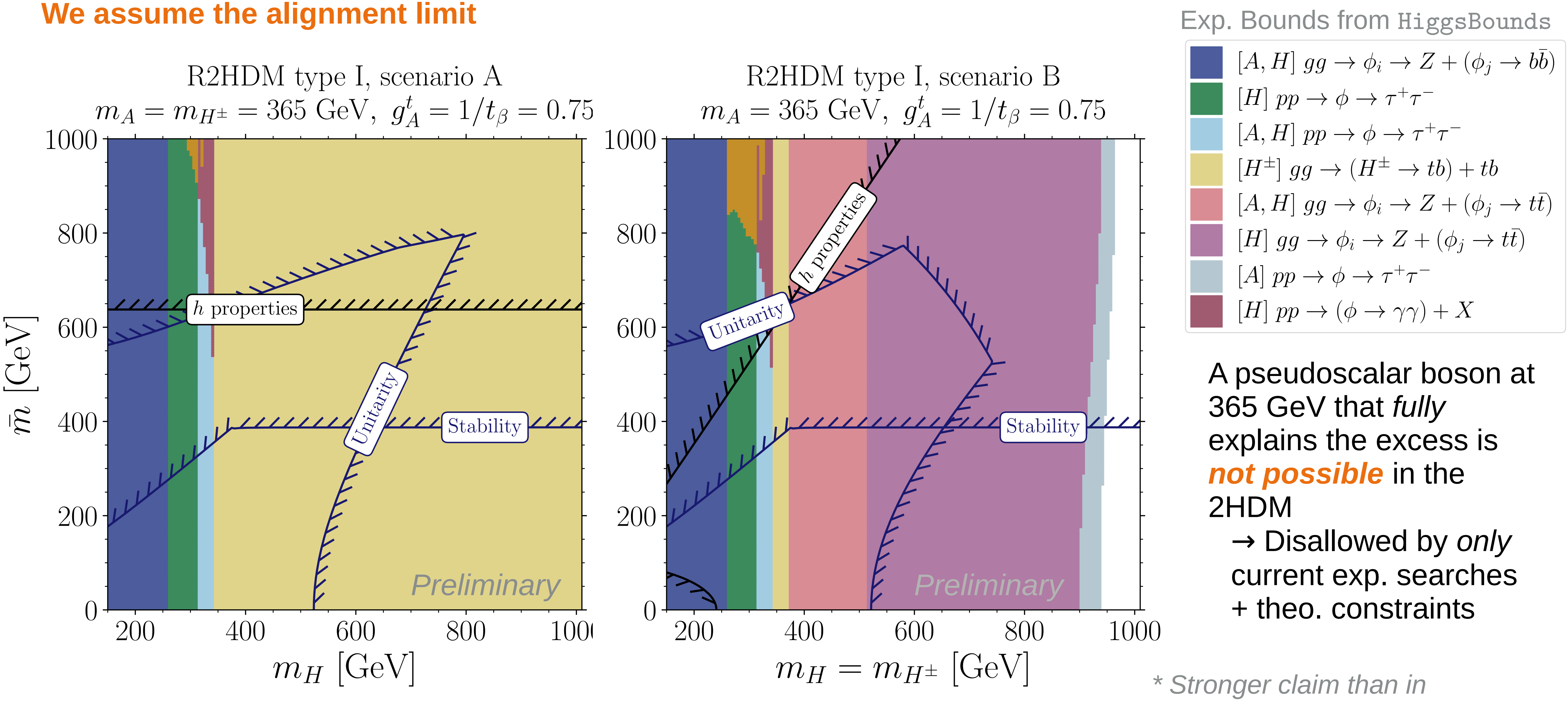


Is this allowed in concrete BSM models?

- Best fit from CMS with a pseudoscalar: $m_A = 365\ \mathrm{GeV},\ \ g_A = 1/\tan\beta = 0.75 \pm 0.03$

2HDM parameter space with a 365 GeV pseudoscalar

We assume the alignment limit



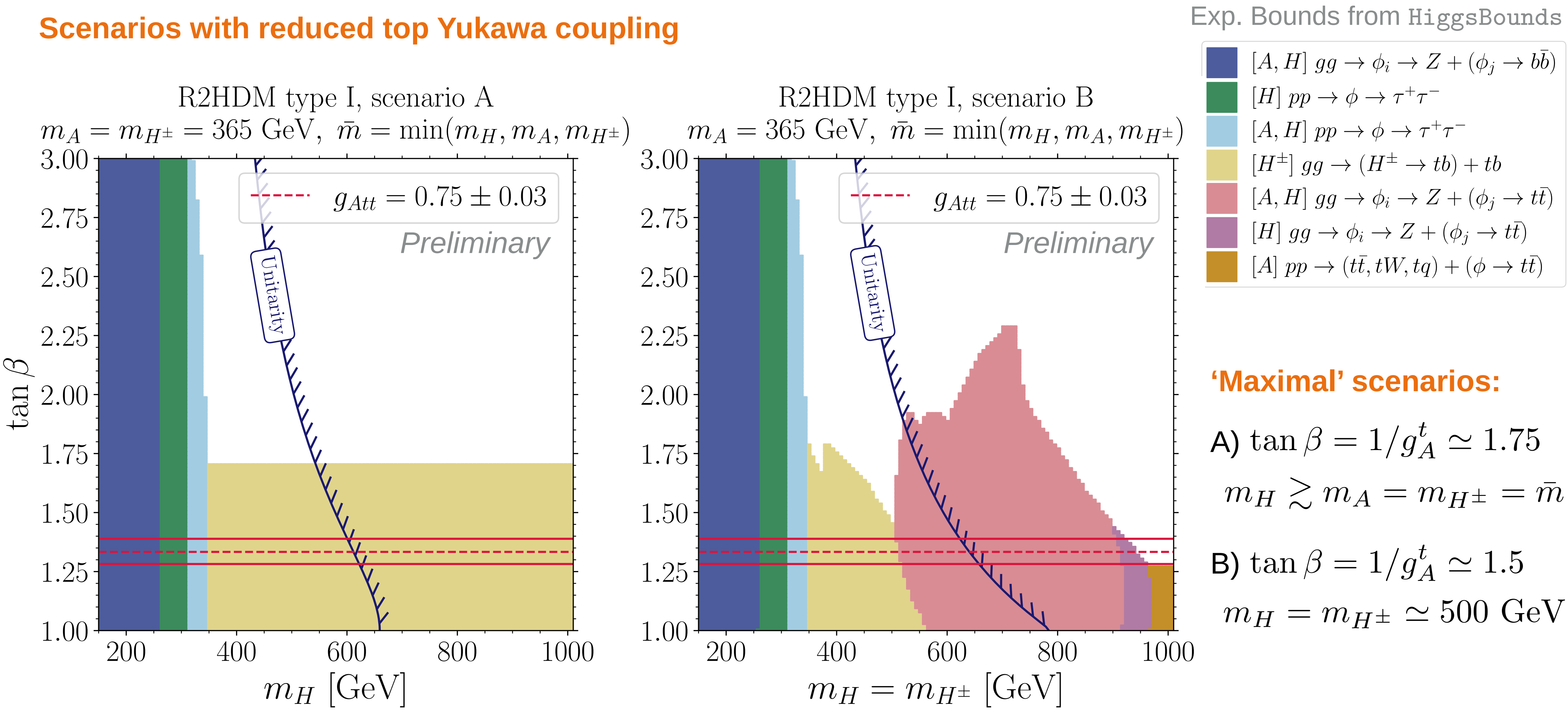
A pseudoscalar boson at 365 GeV that *fully* explains the excess is ***not possible*** in the 2HDM

→ Disallowed by *only* current exp. searches + theo. constraints

** Stronger claim than in [2601.12806], where perturbativity and flavor are invoked*

What is the ‘maximal’ signal still allowed?

Scenarios with reduced top Yukawa coupling



‘Maximal’ scenarios:

A) $\tan\beta = 1/g_A^t \simeq 1.75$

$m_H \gtrsim m_A = m_{H^\pm} = \bar{m}$

B) $\tan\beta = 1/g_A^t \simeq 1.5$

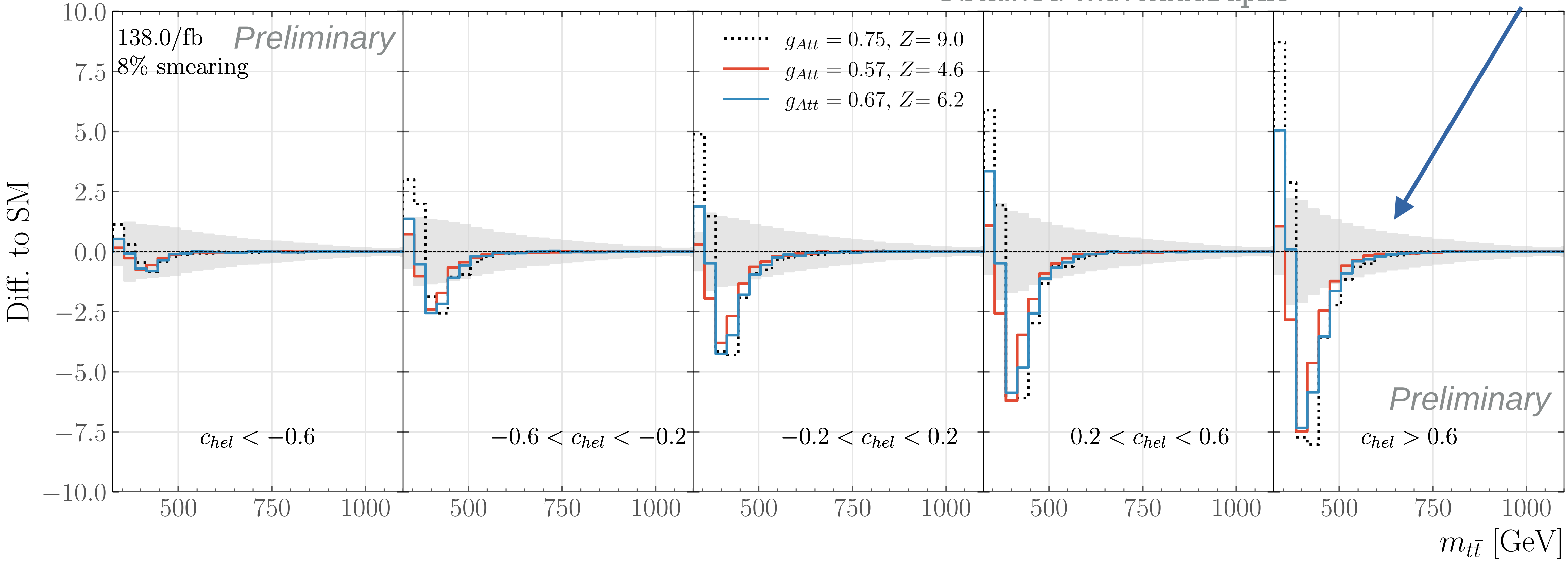
$m_H = m_{H^\pm} \simeq 500$ GeV

Top-quark spin correlations would help finding them

How can we exclude (or discover) them?

Obtained with MadGraph5

Bkg. unc. from CMS [1908.01115]



- Next step: *how to include toponium?*
- Method to include toponium by re-weighting the Green's function *[2411.18962, 2512.03220, Fuks et al]* ⇒ Work on progress!

A trustworthy NR-QCD prediction (including SM *and* BSM parts) will be crucial to probe this parameter space

** Spin-correlations are also useful in the complex 2HDM with extra signal-signal interference (see backup)*

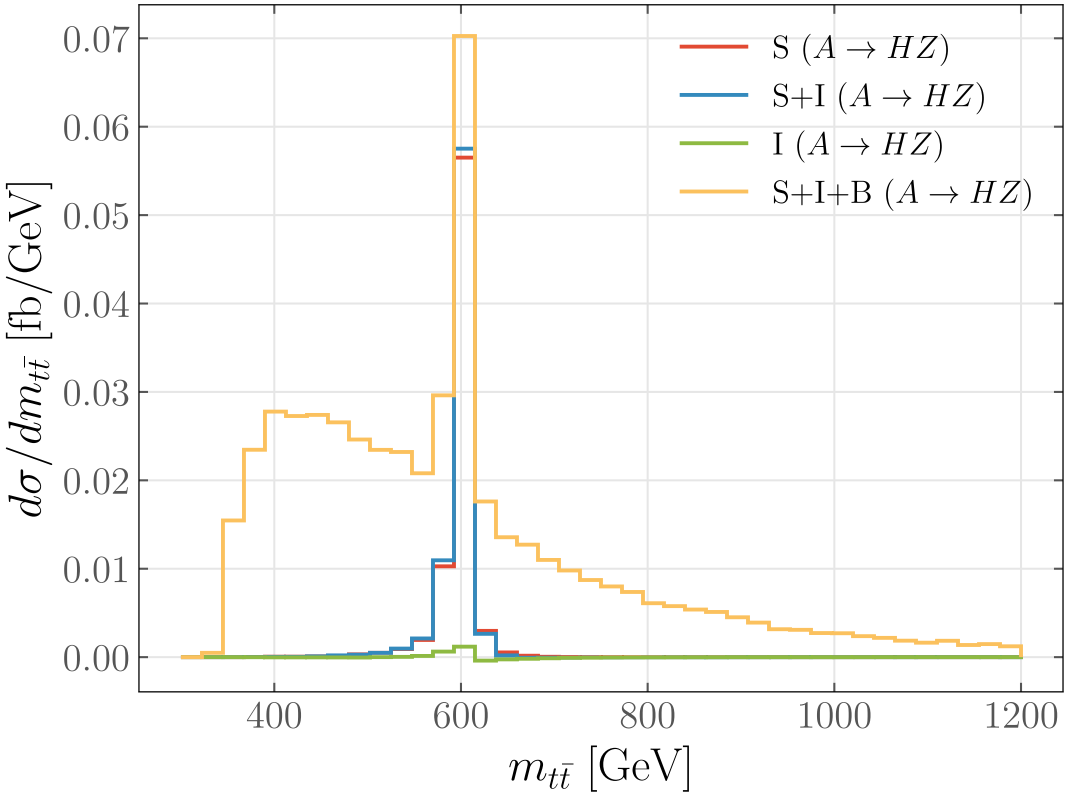
Summary & Conclusions

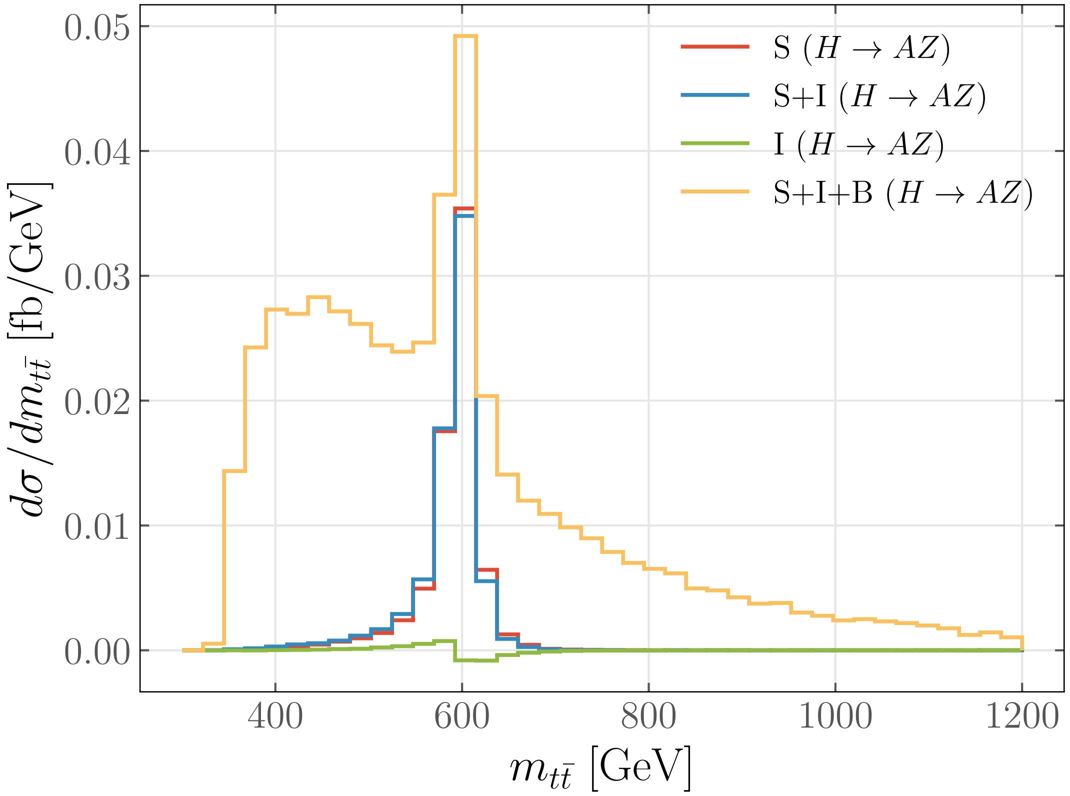
- **Top-quark spin correlations** constitute a great way to explore **BSM physics in the Higgs sector**
  - Crucial to observe an excess at $t\bar{t}$ threshold, compatible with a ***toponium NRQCD effect***
- They can help to **distinguish $A \to HZ$ and $H \to AZ$** (relevant for first order EW phase transitions)
  - **Binning in c_{han} and/or c_{hel}** gives information about the CP-nature of the bosons BSM searches in the $Zt\bar{t}$ final state channel
- They will also play a key role at exploring the **BSM parameter space around the $t\bar{t}$ threshold**
  - It is **impossible to accommodate the excess within the 2HDM** (also unrealistic to ignore toponium!)
  - A proper interpretation of NRQCD + BSM signals is required

Back-up

Signal and background interference

Not very large, but it is included





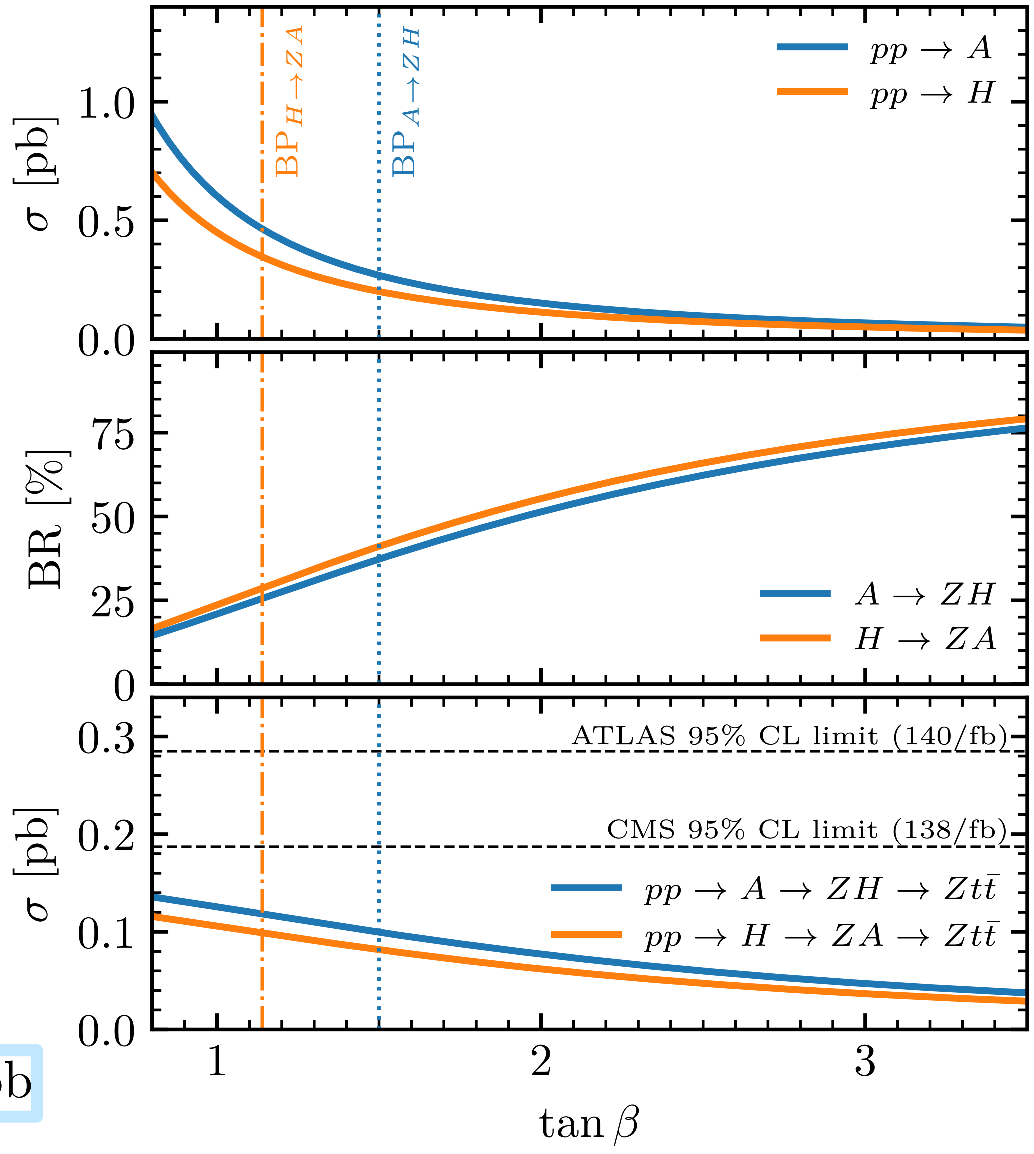
Benchmark point scenarios with the same cross section

Potentially observable at the HL-LHC

- Two benchmark points such that they have the **same total cross section**
- Very hard to distinguish at current searches

OK with theoretical constraints

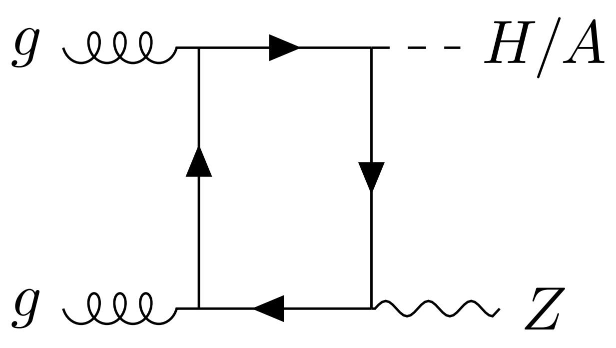
	$\mathrm{BP}_{H\to ZA}$	$\mathrm{BP}_{A\to ZH}$
$\tan\beta$	1.14	1.50
$\cos(\beta-\alpha)$	0	0
m_h/GeV	125	125
m_H/GeV	800	600
m_A/GeV	600	800
$m_{H^\pm}/\mathrm{GeV}$	800	800
M/GeV	600	600
$\mathrm{BR}(H\to t\bar{t})$	71%	99%
$\mathrm{BR}(A\to t\bar{t})$	99%	63%
$\mathrm{BR}(H\to ZA)$	29%	–
$\mathrm{BR}(A\to ZH)$	–	37%
Γ_H/m_H	4.3%	1.5%
Γ_A/m_A	3.5%	3.3%
$\sigma(gg\to H)/\mathrm{pb}$	0.35	0.89
$\sigma(gg\to A)/\mathrm{pb}$	2.43	0.27

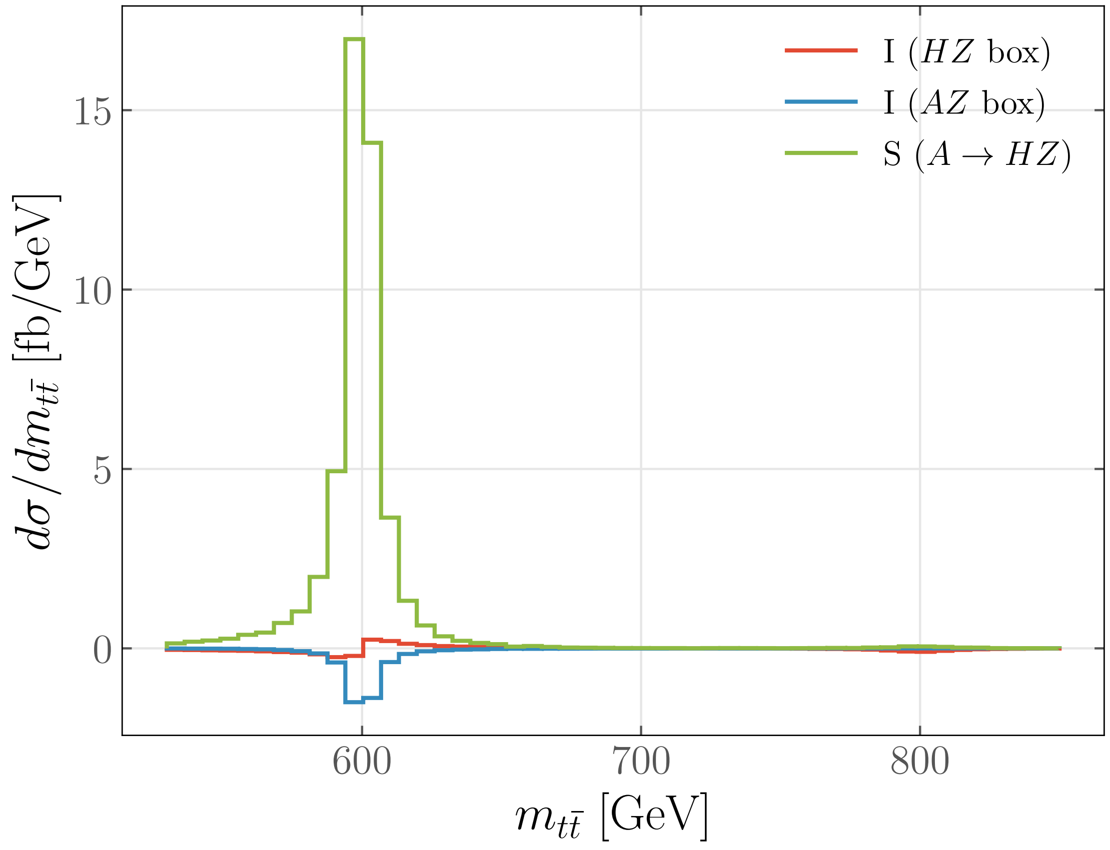


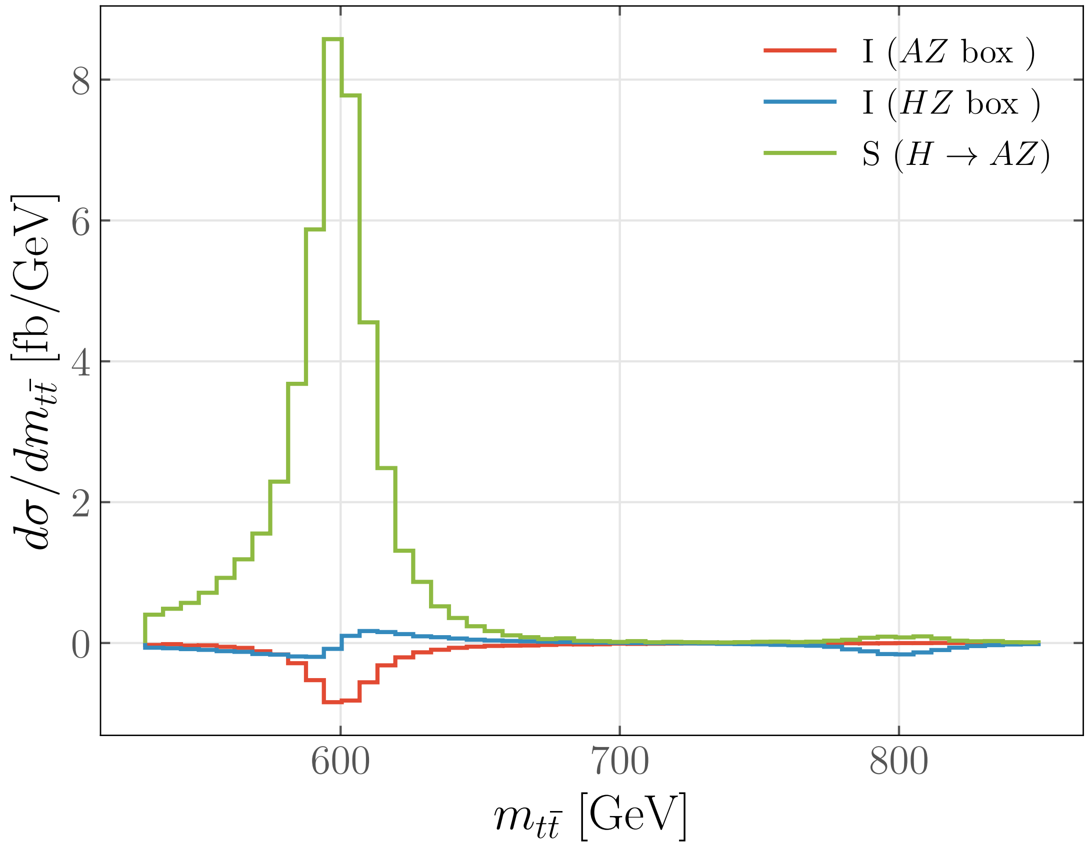
$$\sigma(gg\to A\to ZH\to Zt\bar{t}) = \sigma(gg\to H\to ZA\to Zt\bar{t}) = 0.1\ \mathrm{pb}$$

Box Interference

Negligible ⇒ Not included







Significance estimation

Systematics between bins are not included

B_i : SM background in the ith bin
S_i : Signal + interference with background in the ith bin

$$Z_i = \sqrt{2\left[(S_i + B_i)\log\left(1 - \frac{S_i}{B_i}\right) - S_i\right]}$$

$$Z_i \simeq S_i/\sqrt{B_i}$$

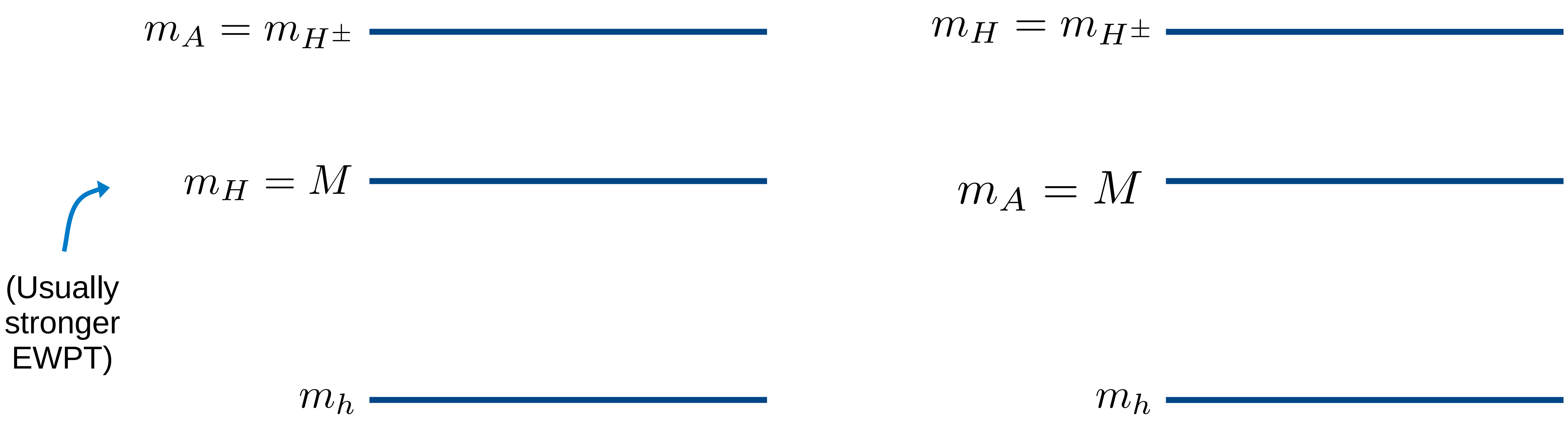
when $B_i >> S_i$

Total significance: $$Z = \sqrt{\sum_i Z_i^2}$$

Ingredients for a Strong First Order EW Phase Transition

Large scalar couplings!

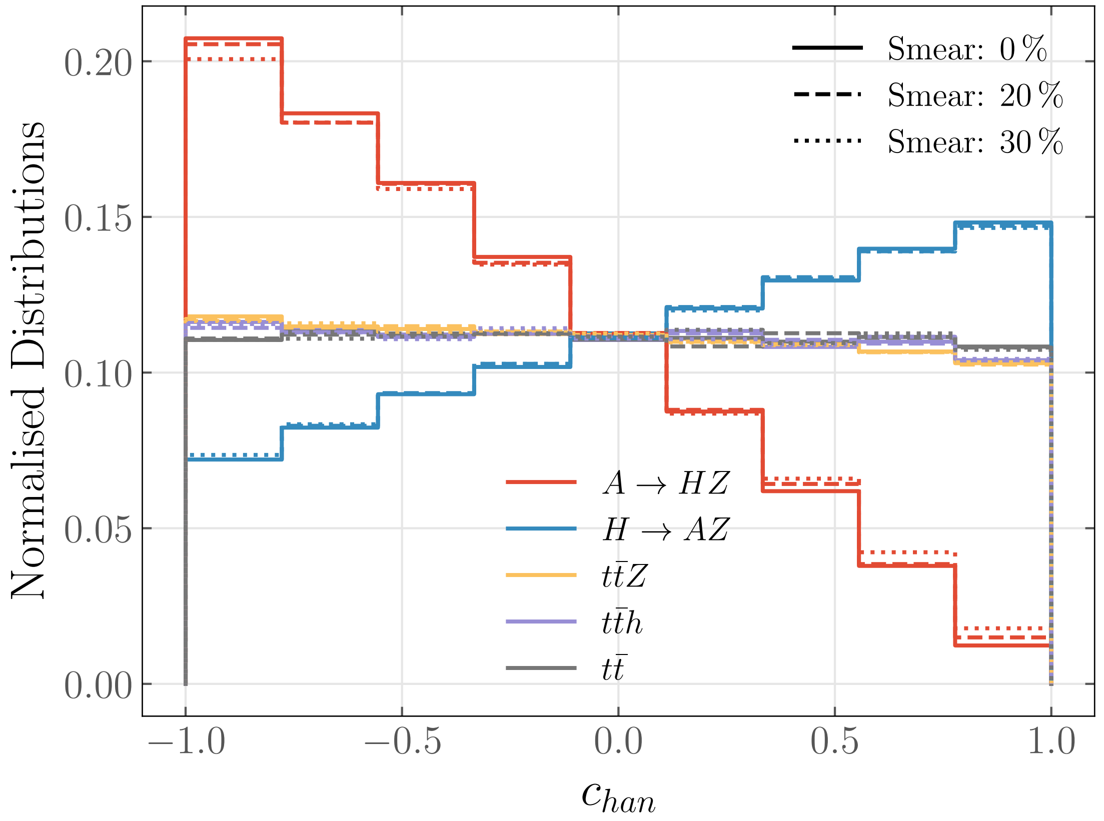
- In the 2HDM a SFOEWPT happens due to a large radiative and thermally induced barrier
- Generally, **large scalar couplings** are needed ⇒ **Large mass splitting** between **heavy Higgs bosons** (non-decoupling regime)

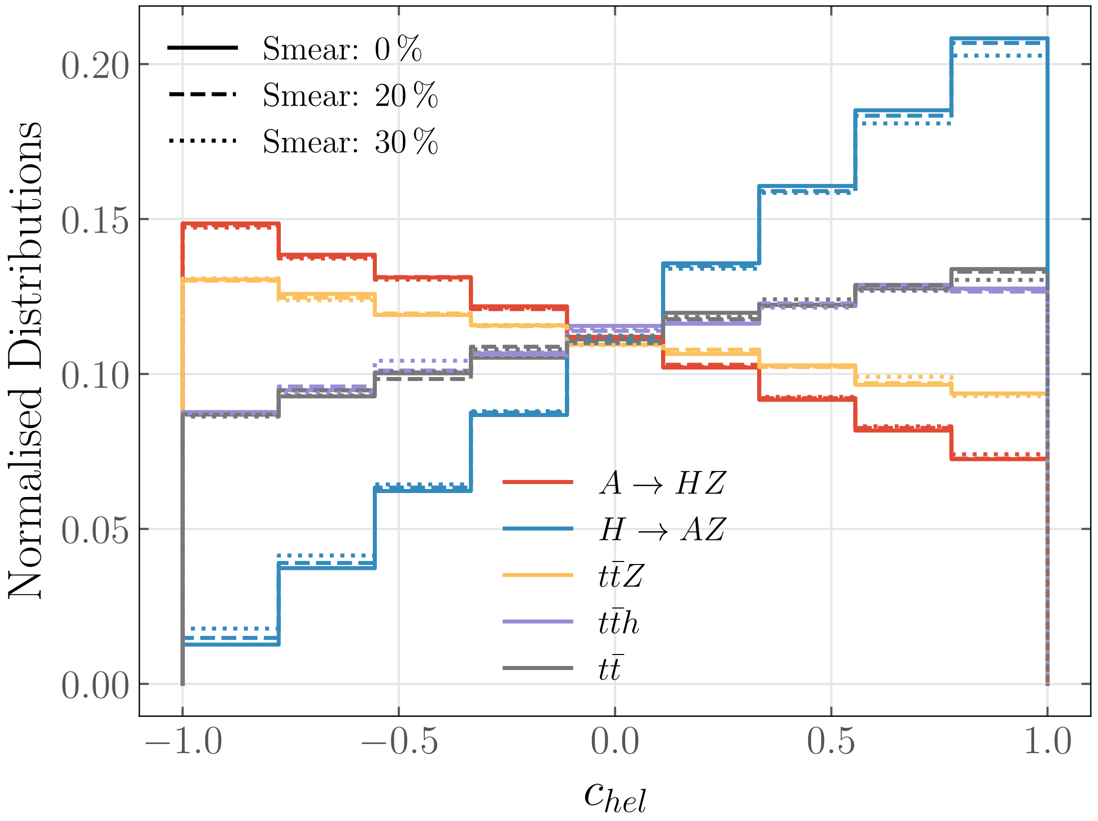


Much literature on 2HDM and SFOEWPT: 1405.5537, 1612.04086, 1705.09186, 1711.04097, 2108.05356, 2208.14466 2309.17431, …

Smearing in c_{han} and c_{hel}

Small impact of from the uncertainty from top-quark momenta

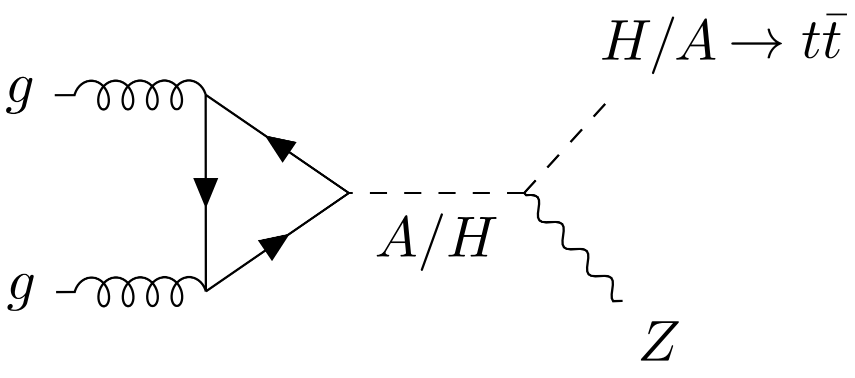




Signal and background simulation

Numerical setup

Signal $gg \to \begin{pmatrix} A \\ H \end{pmatrix} \to \begin{pmatrix} ZH \\ ZA \end{pmatrix} \to Z\, t\bar{t} \to \ell^+\ell^-\, b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$



- $gg \to A/H$ at LO with `MadGraph5` + NNLO QCD K-factor from `HiggsTools/SusHi`
- Decay of the heavy Higgs at NLO QCD from `HDECAY`

Background $gg \to Z\, t\bar{t} \to \ell^+\ell^-\, b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$

- At LO with `MadGraph5` + rescaled with the ATLAS result (including other subleading backgrounds) *[2312.04450]*

Cuts based on the ATLAS measurement *[2312.04450]*

- $p_T(\ell) > 10$ GeV, $\quad |\eta(\ell)| < 2.5, \quad |m_Z - m_{\ell\ell}| < 20$ GeV, $\quad p_T(j) > 20$ GeV, $\quad |\eta(j)| < 2.5$
- Two pairs of opposite-sign same-flavor leptons with $p_T(\ell_{\text{leading}}) > 27$ GeV

Efficiency factors

- $(0.7)^2$ for b-tagging
- 0.9 for top quark reconstruction
- 10% smearing in the $t\bar{t}$ distributions to mimic the detector resolution

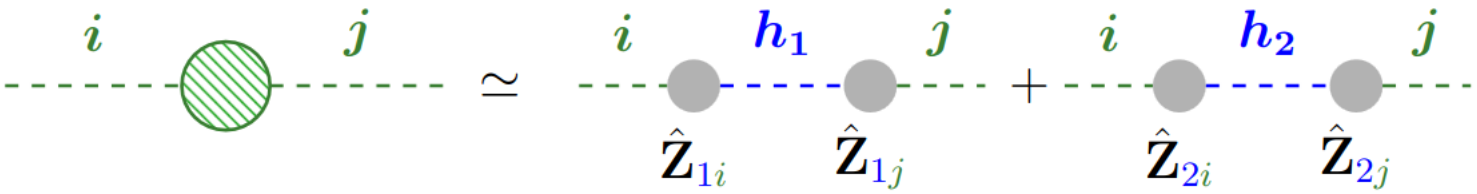
Interpretations within the complex 2HDM

[1610.06193] Fuchs, Weiglein
[2503.02705] Bahl, Kumar, Weiglein

Loop-level mixing between neutral scalars

- In the complex 2HDM (C2HDM) the neutral states mix: $\mathcal{L}_{\text{Yuk}} = -\frac{y_t}{2} \sum_j t \left(c_{j,t} + i\gamma^5 \tilde{c}_{j,t} \right) \bar{t}\, \Phi_j$

- Z-factors can approximately capture the loop-induced mixing



$$\mathcal{A}_{\text{BSM}} \simeq \sum_{a=h_1,h_2} \left(\sum_{\substack{i=h_{1,\text{tree}},\\ h_{2,\text{tree}}}} \boldsymbol{Z}_i^a \hat{\Gamma}^{ggi} \right) \Delta_a^{\text{BW}}(p^2) \left(\sum_{\substack{j=h_{1,\text{tree}},\\ h_{2,\text{tree}}}} \boldsymbol{Z}_j^a \hat{\Gamma}^{j\to t\bar{t}} \right) .$$

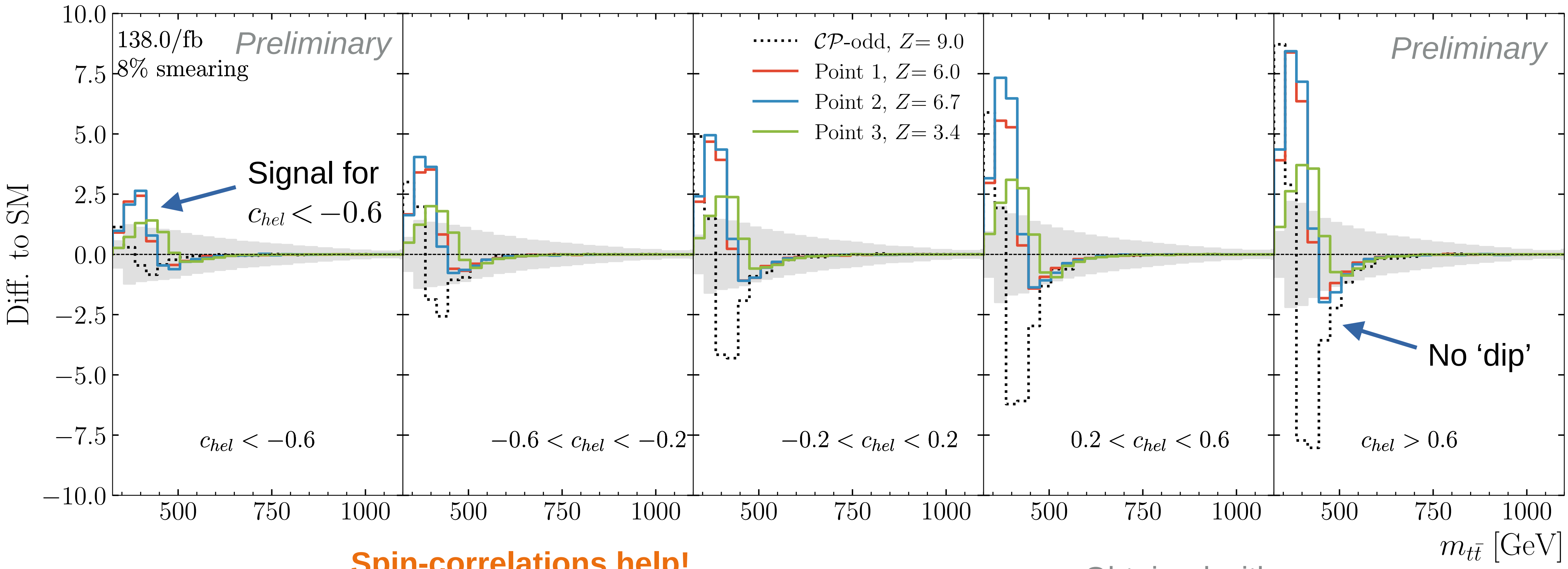
$$\begin{aligned}
c_{t,1} &\to \boldsymbol{Z}^{h_1}_{h_{1,\text{tree}}} c_{t,1} + \boldsymbol{Z}^{h_1}_{h_{2,\text{tree}}} c_{t,2} \,, \\
\tilde{c}_{t,1} &\to \boldsymbol{Z}^{h_1}_{h_{1,\text{tree}}} \tilde{c}_{t,1} + \boldsymbol{Z}^{h_1}_{h_{2,\text{tree}}} \tilde{c}_{t,2} \,, \\
c_{t,2} &\to \boldsymbol{Z}^{h_2}_{h_{2,\text{tree}}} c_{t,2} + \boldsymbol{Z}^{h_2}_{h_{1,\text{tree}}} c_{t,1} \,, \\
\tilde{c}_{t,2} &\to \boldsymbol{Z}^{h_2}_{h_{2,\text{tree}}} \tilde{c}_{t,2} + \boldsymbol{Z}^{h_2}_{h_{1,\text{tree}}} \tilde{c}_{t,1} \,.
\end{aligned}$$

Interpretations within the complex 2HDM

[1610.06193] Fuchs, Weiglein
[2503.02705] Bahl, Kumar, Weiglein

Additional signal-signal interference!

- Loop-level mixing between the scalars included in the $\mathcal{Z}$-factor formalism
- Important for nearly degenerate bosons (here 400/450 GeV) ⇒ signal close to the threshold!



Spin-correlations help!

Obtained with `MadGraph5`