Distinguishing $A \to HZ$ and $H \to AZ$ with top-quark spin correlations

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Based on JHEP 06 (2025) 170 [2502.03443]

22nd Workshop of the LHC Higgs Working Group – WG3 (BSM) parallel session
CERN, Geneva, 4 December 2025

HELMHOLTZ

DESY.

Motivation for extended Higgs sectors

The search of an EW phase transition

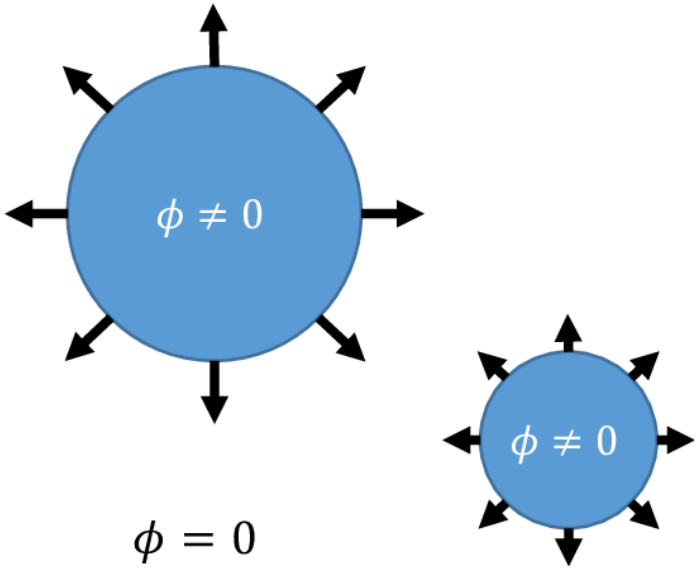


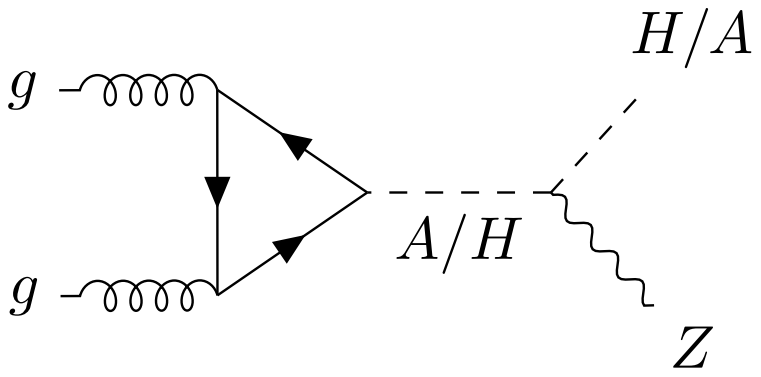
Image by M. Breitbach

The SM has many shortcomings ⇒ BSM extended Higgs sectors!

- Example: the **baryon asymmetry** of the universe
  - Physics out of the equilibrium ⇒ **strong first order EW phase transition** (SFOEWPT)

Many searches of extra Higgs bosons by ATLAS and CMS

- In the Two-Higgs Double model (2HDM) → ***'smoking gun' signal***
- Issue: no current experimental distinction between $A \to HZ$ vs $H \to AZ$



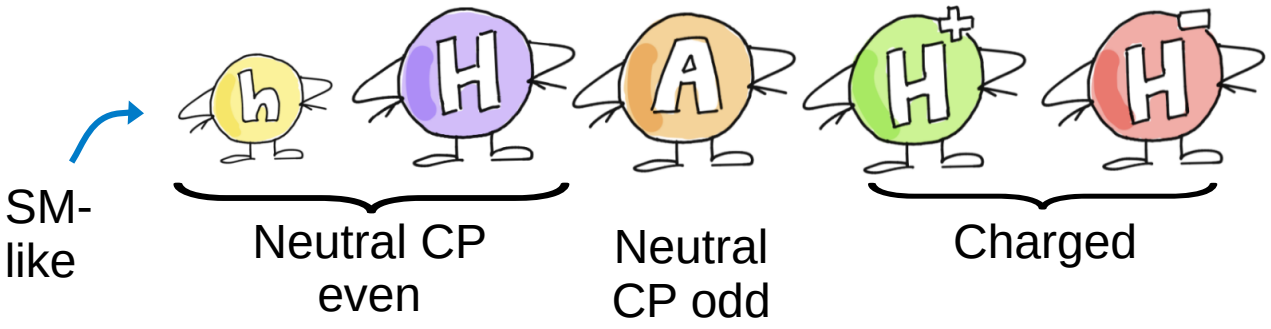
Our proposal: use top-quark spin correlations to distinguish them

An SFOEWPT within the 2HDM

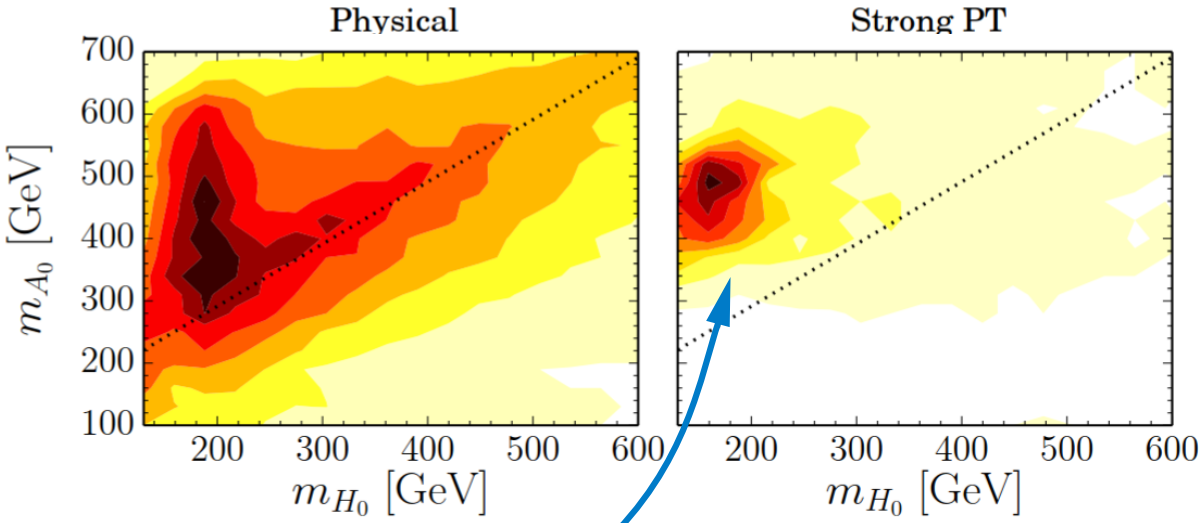
The ‘smoking gun’ signature

- Five physical Higgs bosons:

Image by K. Radchenko



(Density of points)

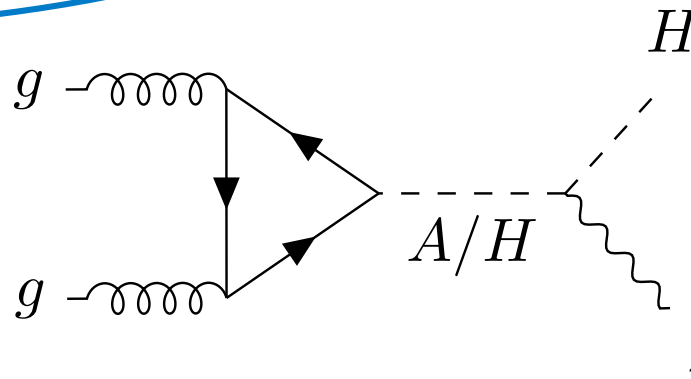


[Dorsch, Huber, Mimasu, No, 13]

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 $m_A > m_H + m_Z$)



(above the tt threshold)

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

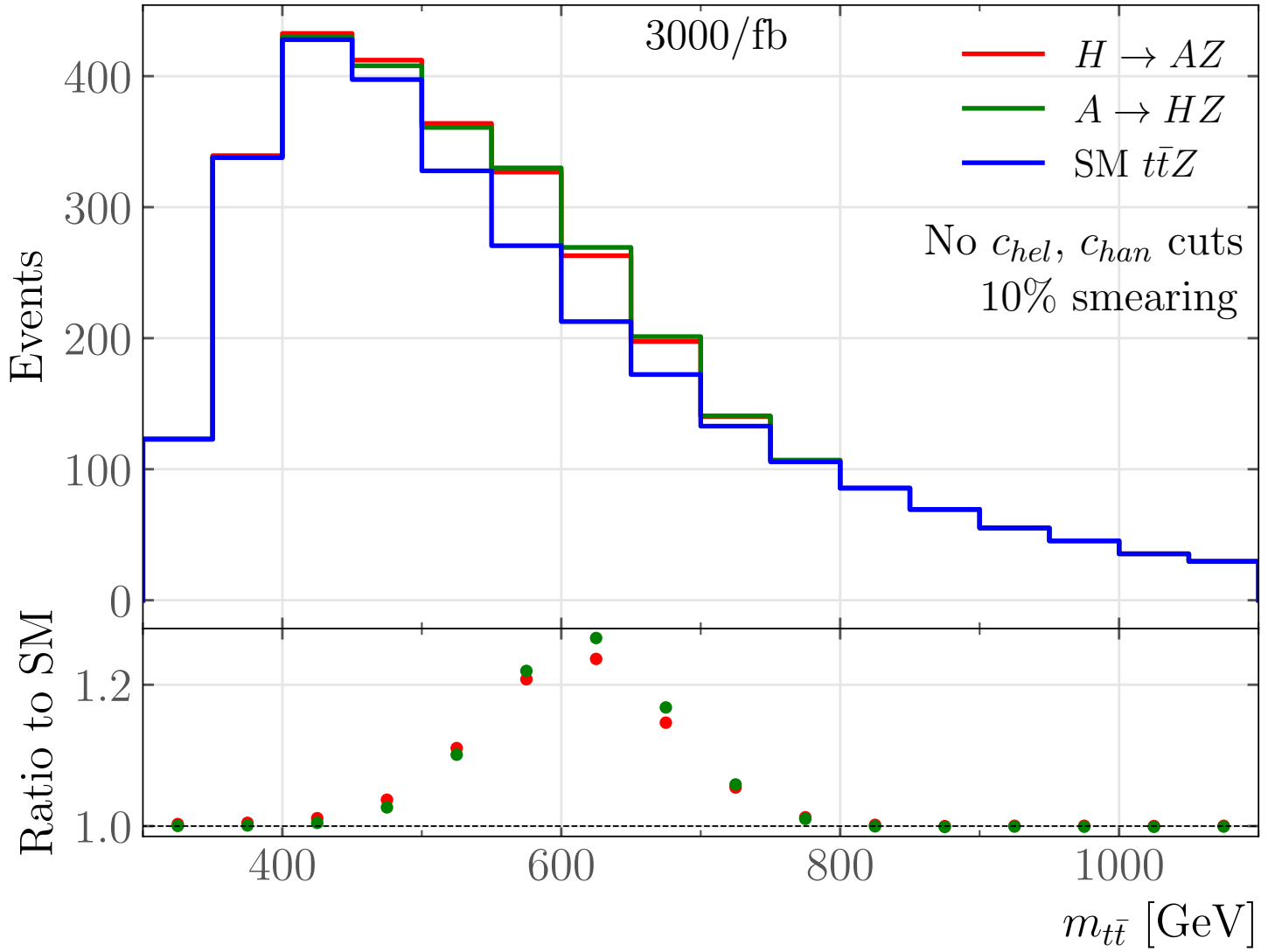
No possible distinction between $A \to HZ$ and $H \to AZ$:(

$m_{\text{heavy}} = 800$ 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 $H \to AZ$**



Our proposal: top-quark spin correlations

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

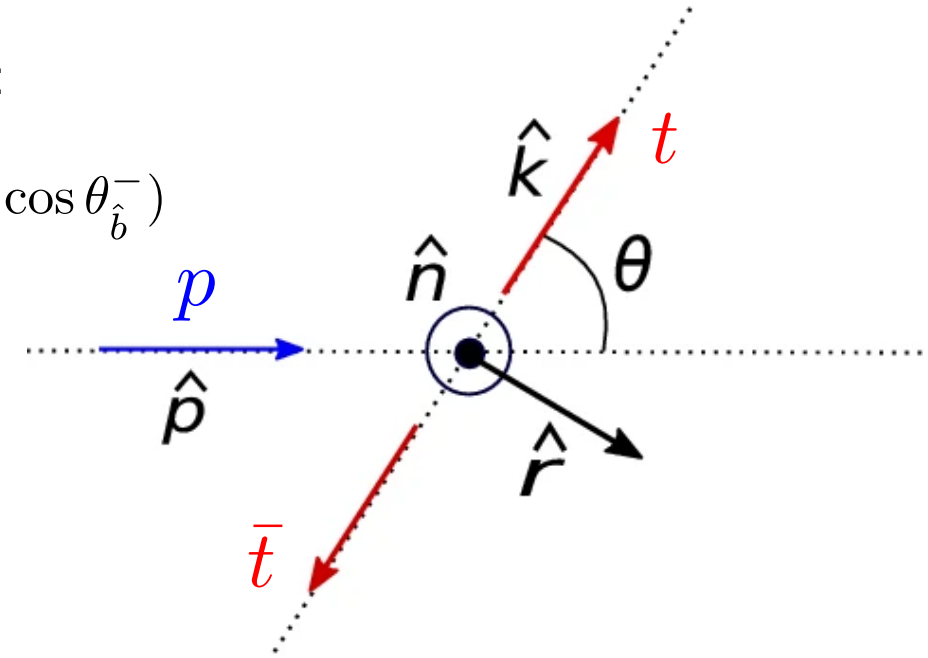
Image from 2105.11478

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

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

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!**

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

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

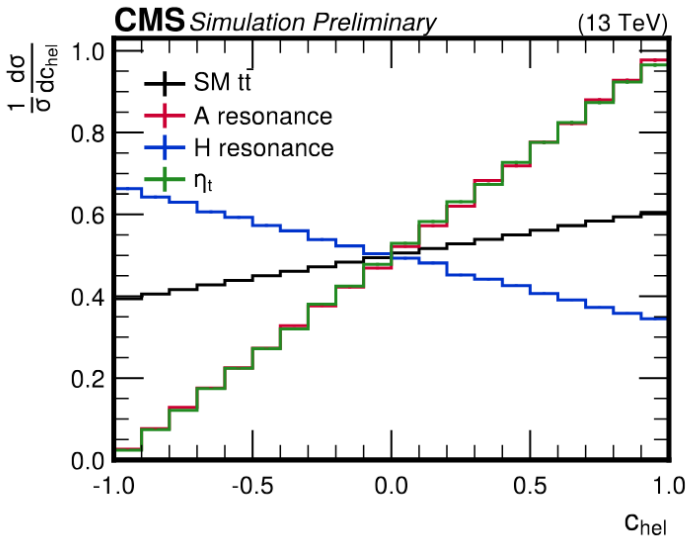
More on $t\bar{t}$ spin correlations: *[Bernreuther, Heisler, Si, 15, Ravina, Simpson, Howarth, 21, Rübenach PhD Thesis, …]*

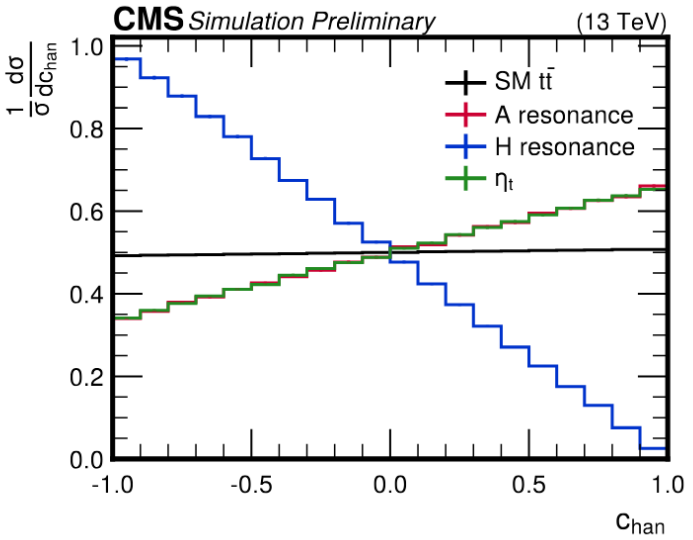
- **Important!** This method requires the top-pair to decay into the fully leptonic channel

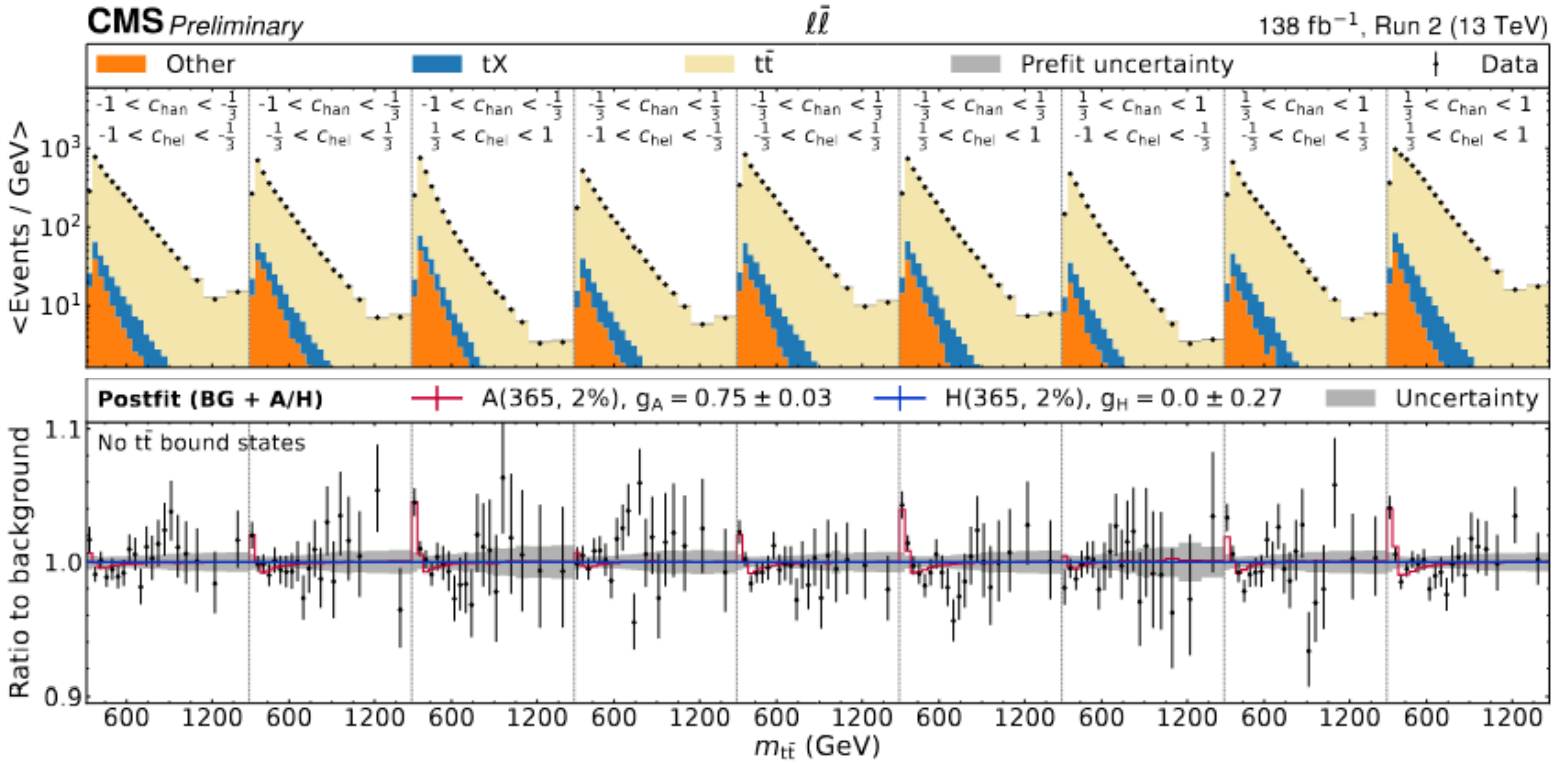
Already used in $t\bar{t}$ searches!

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

Example at CMS, similar results for ATLAS







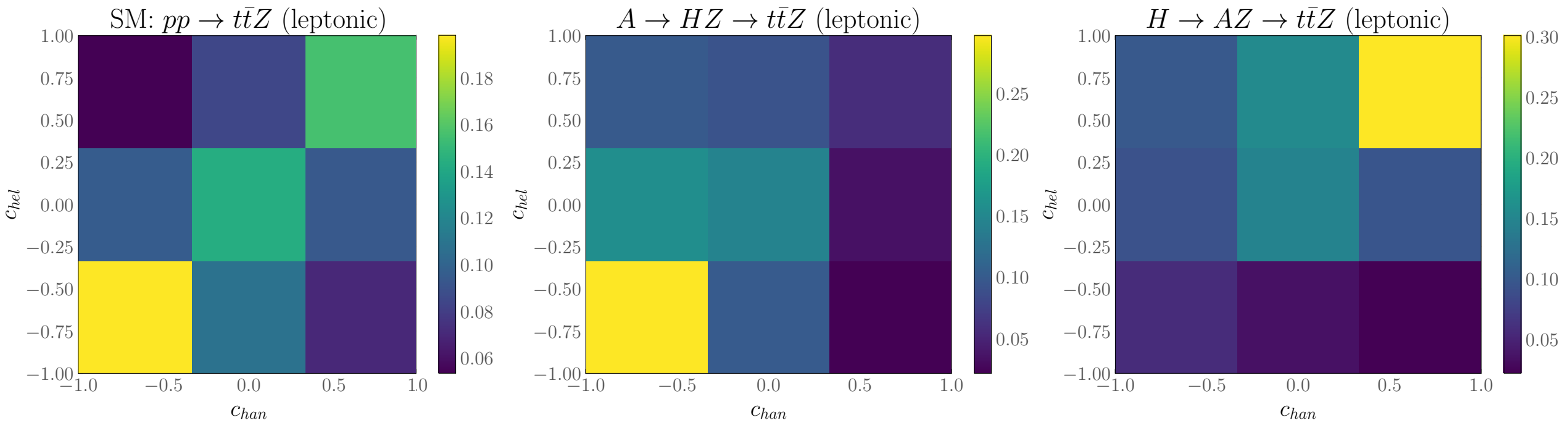
- Observation of a pseudoscalar excess (> 5σ) at the $t\bar{t}$ threshold
  (compatible with a di-top quasi-bound state or a BSM pseudoscalar boson)
- The angular variables c_{han} and c_{hel} in the di-lepton channel were essential!

Our proposal: use them also in the $t\bar{t}Z$ 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

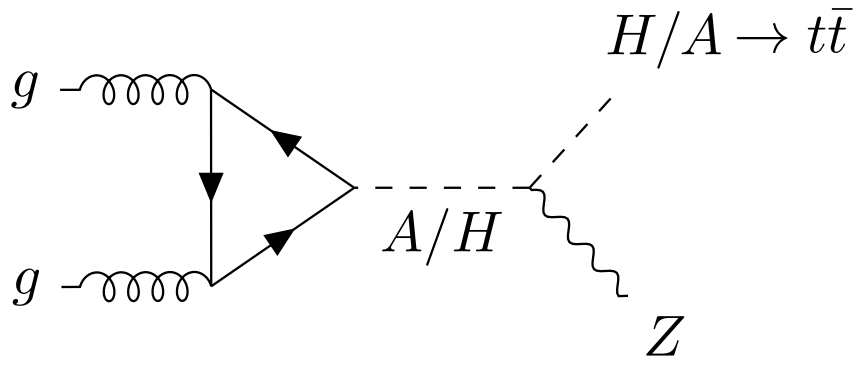


$A \to HZ$ and $H \to AZ$ peak in different regions in the c_{han}–c_{hel} plane!

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]*

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

Efficiency factors

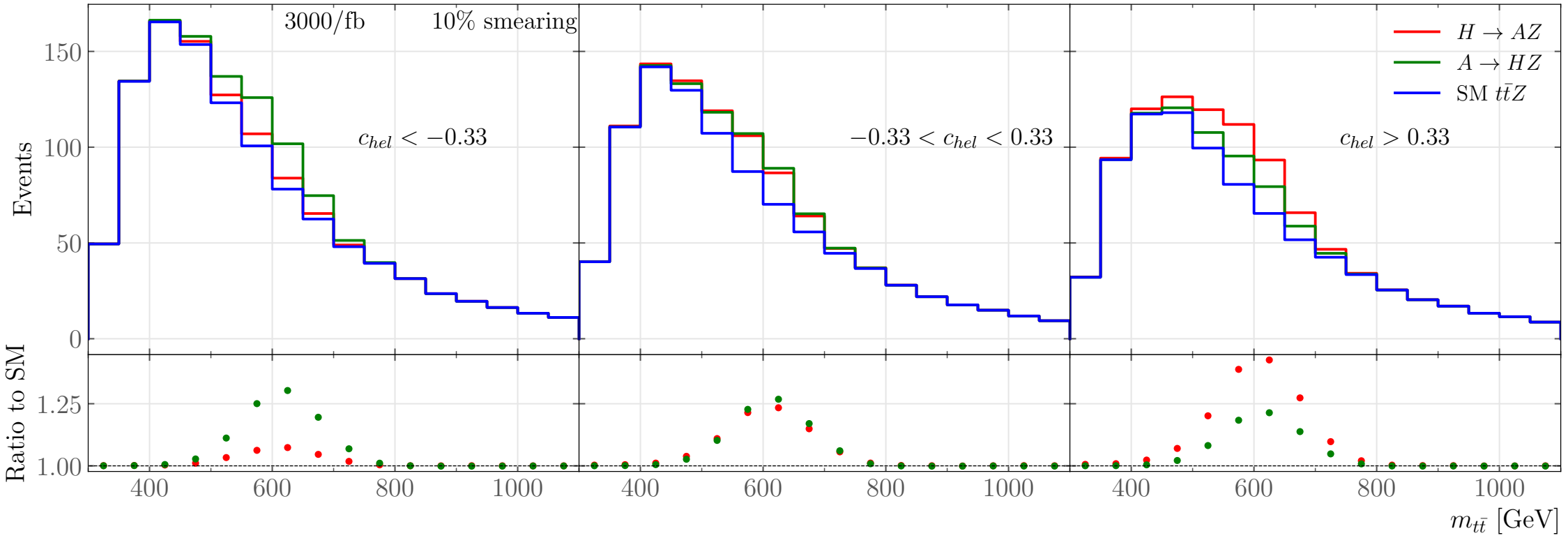
- $(0.7)^2$ for b-tagging
- 0.9 for top quark reconstruction
- 10% smearing in the $t\bar{t}$ distributions to mimic the detector resolution

Results: di-top invariant mass distributions

Bins in c_{hel}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



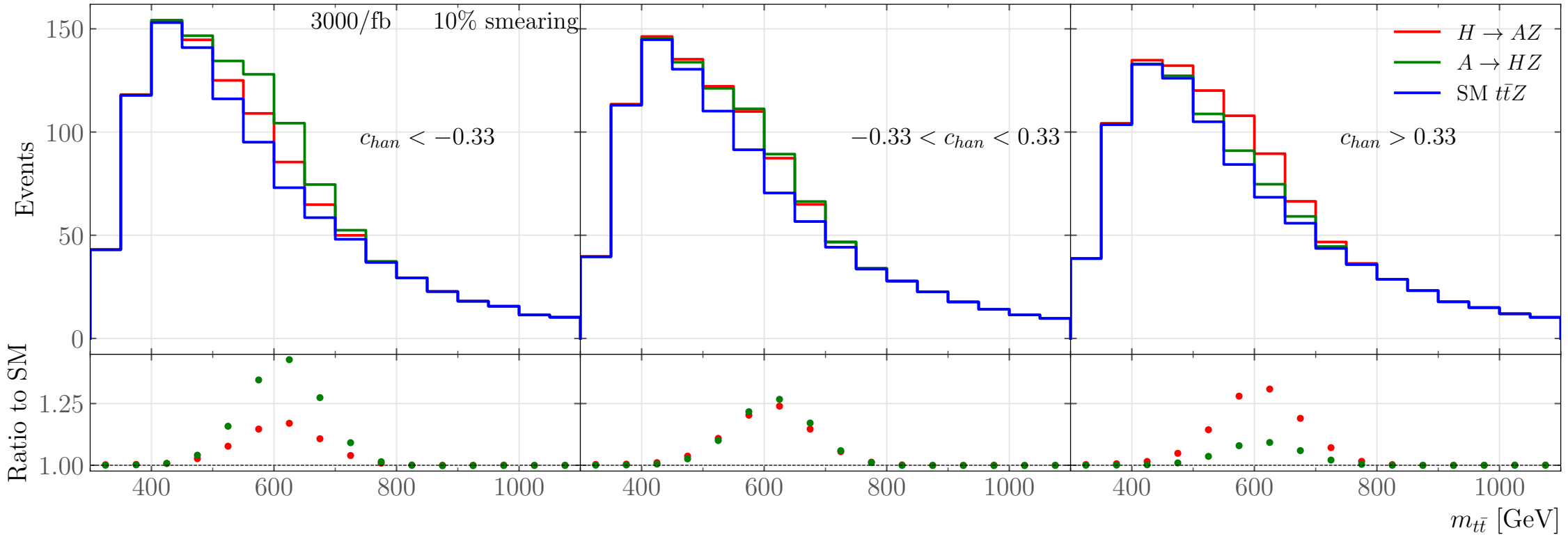
Both signals become distinguishable!!

Results: di-top invariant mass distributions

Bins in c_{han}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



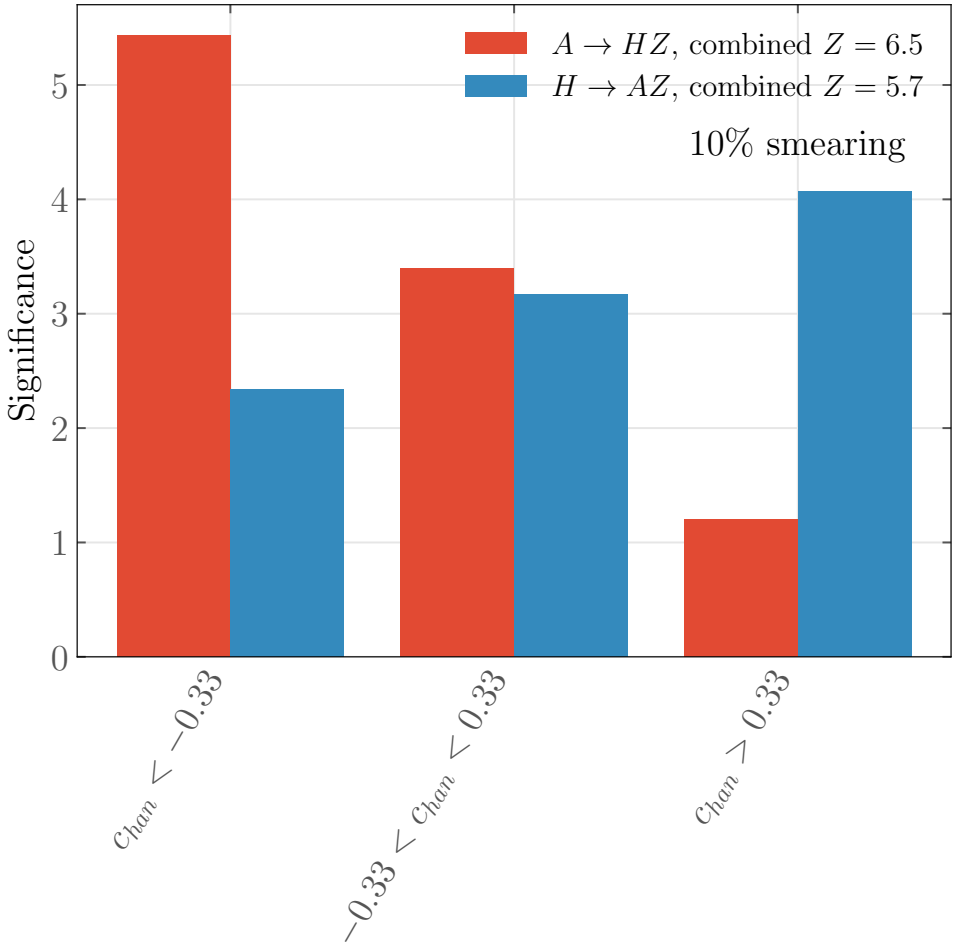
Both signals become distinguishable!!

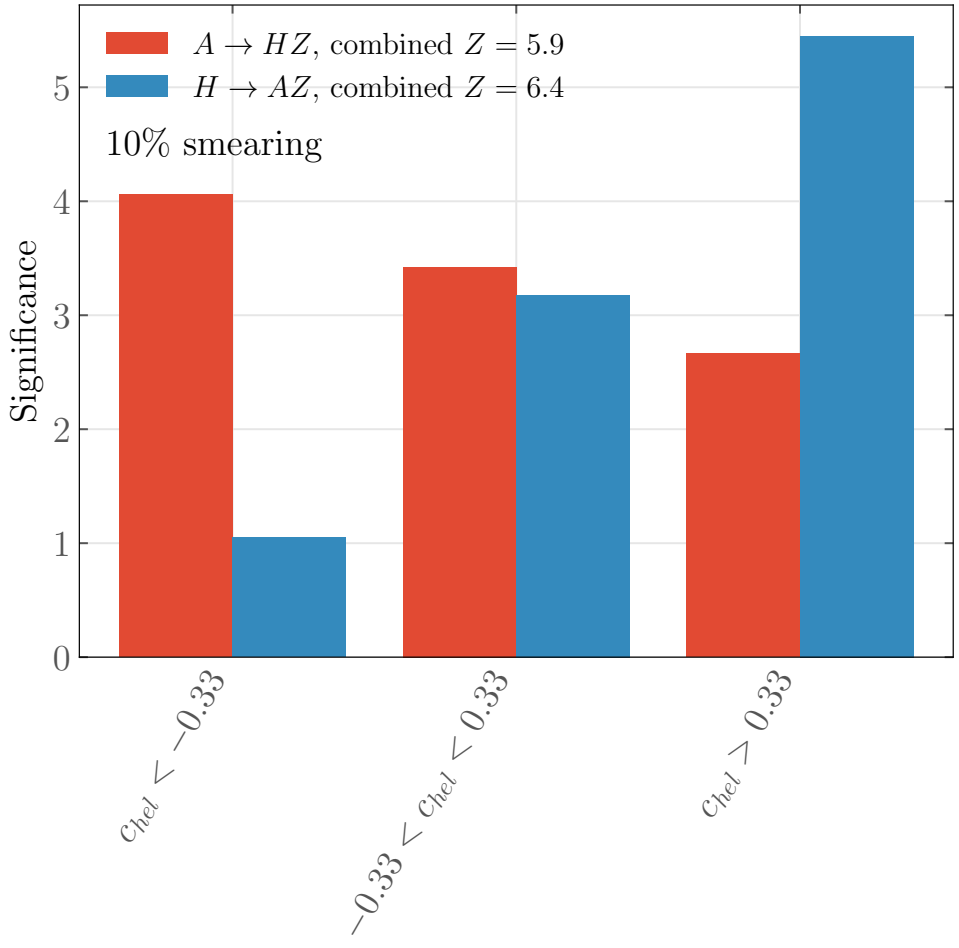
Results: significance Z at the HL-LHC

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

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

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



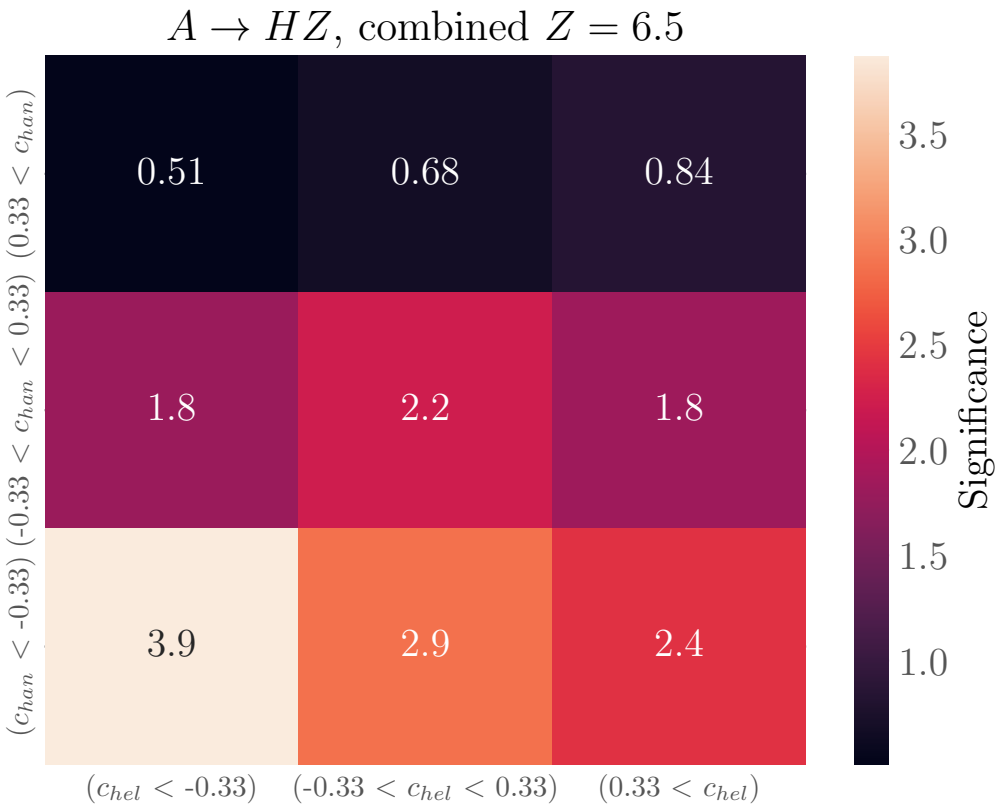


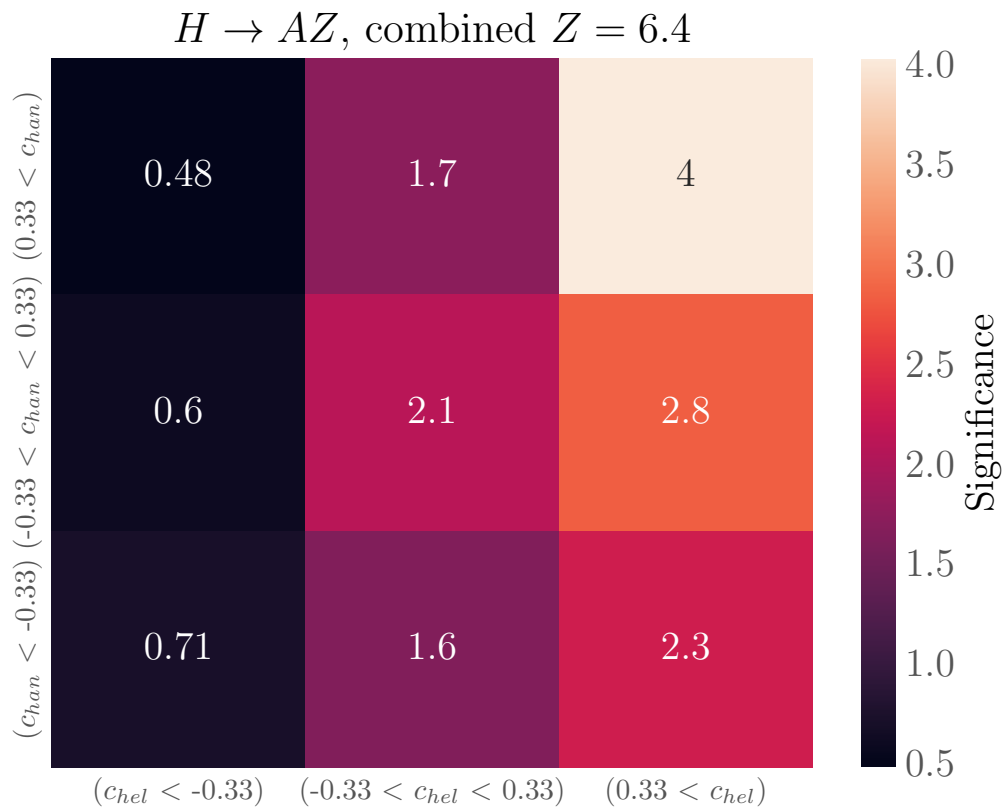
Results: significance Z at the HL-LHC

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

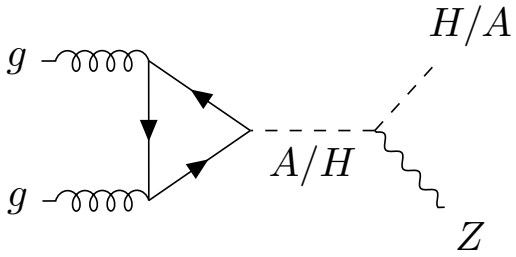
Binning in both c_{han} AND c_{hel}

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





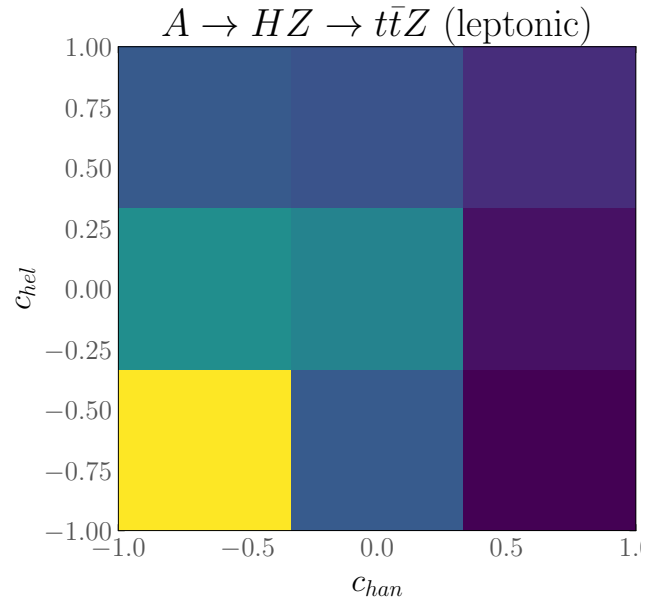
Summary & Conclusions

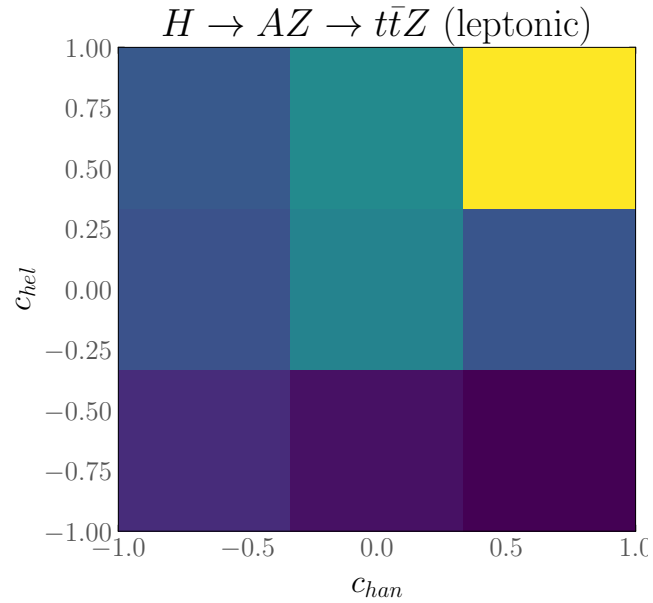


- Experimentally *at present*, there is no sensitivity between

$$gg \to A \to ZH \to Zt\bar{t} \quad \text{vs.} \quad gg \to H \to ZA \to Zt\bar{t}$$

- **Our proposal**: use **top-quark spin correlations** to distinguish the CP nature of the Higgs bosons!
- We analyzed the m_{tt} distributions for two benchmark points with the same total cross section
  - We show that binning in c_{han} **and** c_{hel} **can help differentiate between both signals** in the fully leptonic channel
  - In addition, we find a moderate gain in the signal significance
- **Message to experimentalists:** we encourage you to use them in the $Zt\bar{t}$ searches!

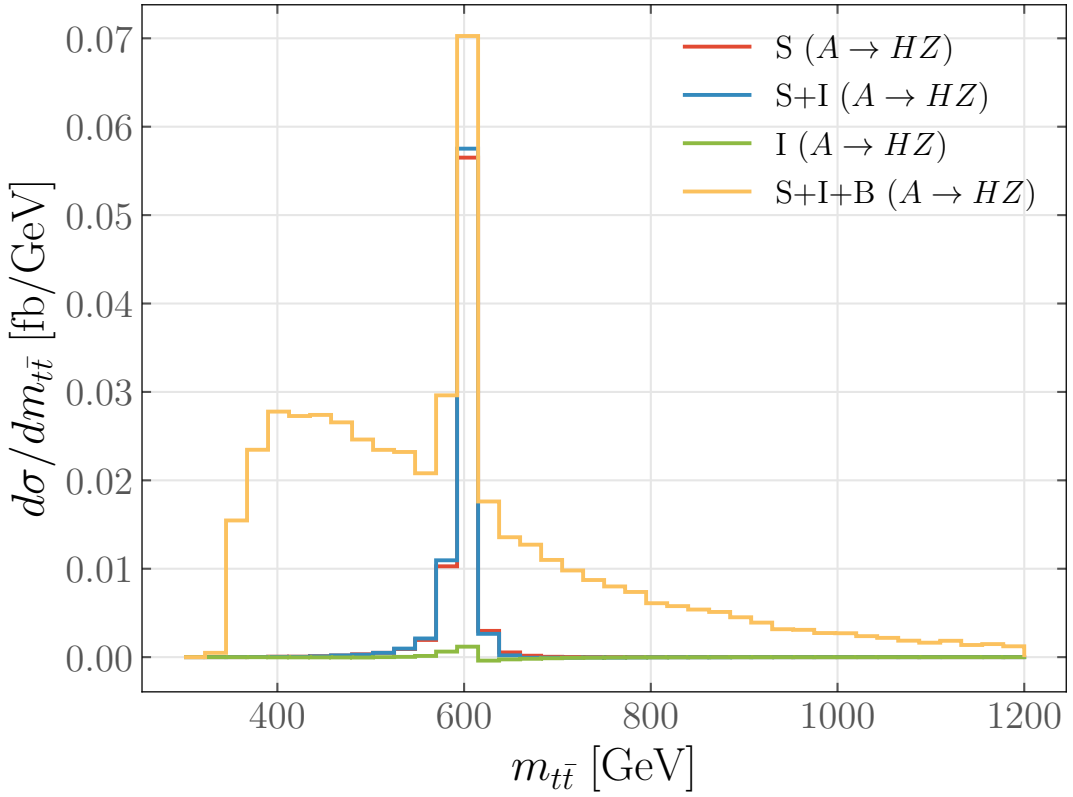


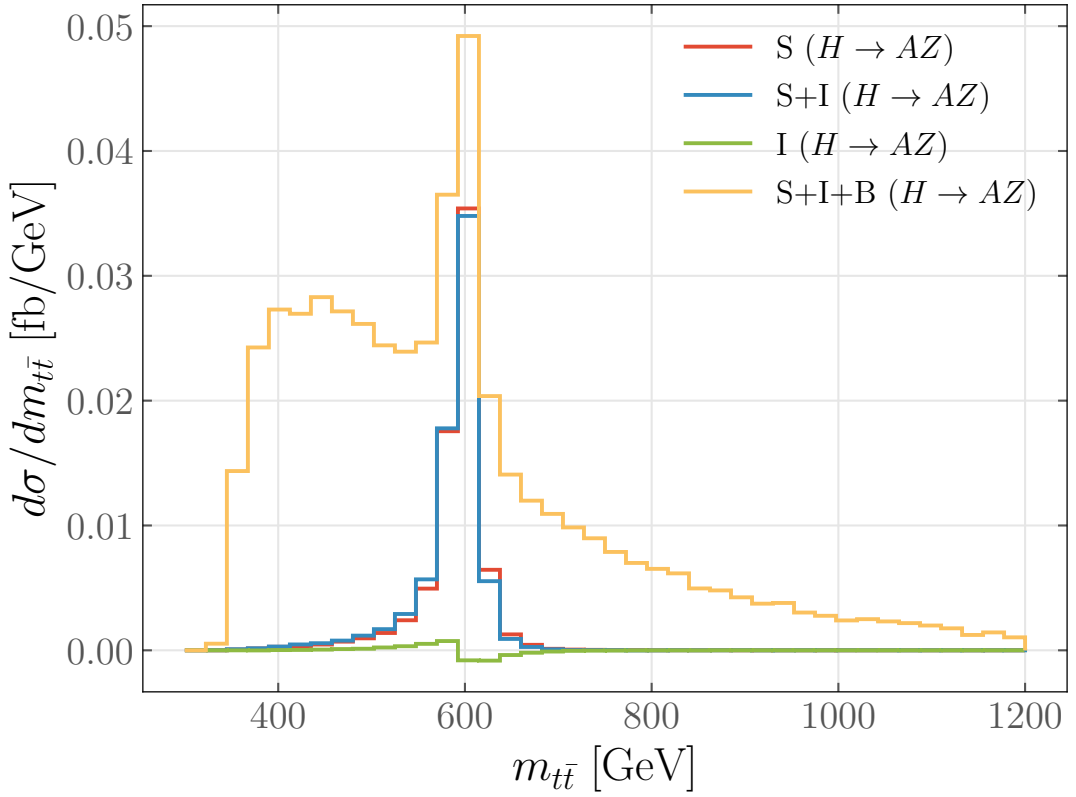


Back-up

Signal and background interference

Not very large, but it is included





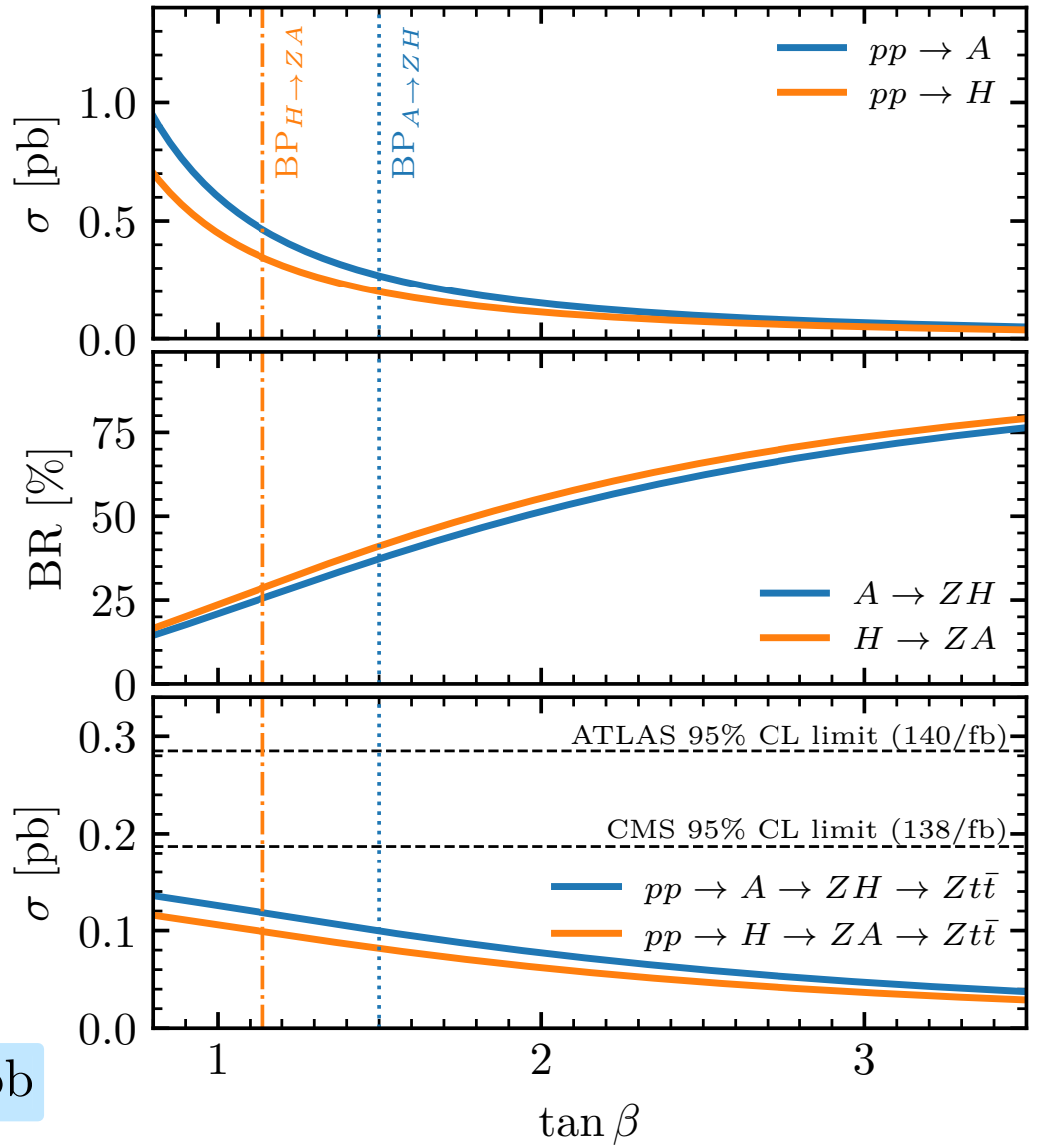
Benchmark point scenarios with the same cross section

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

	$\mathrm{BP}_{H\to ZA}$	$\mathrm{BP}_{A\to ZH}$
$\tan\beta$	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

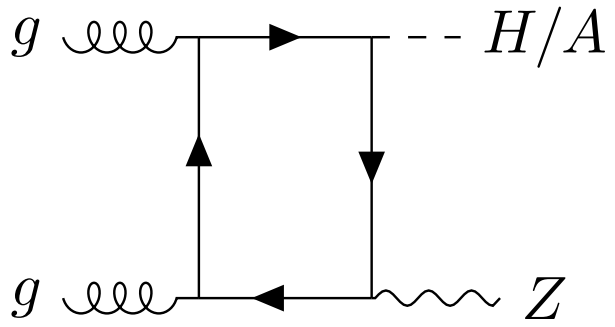
OK with theoretical constraints

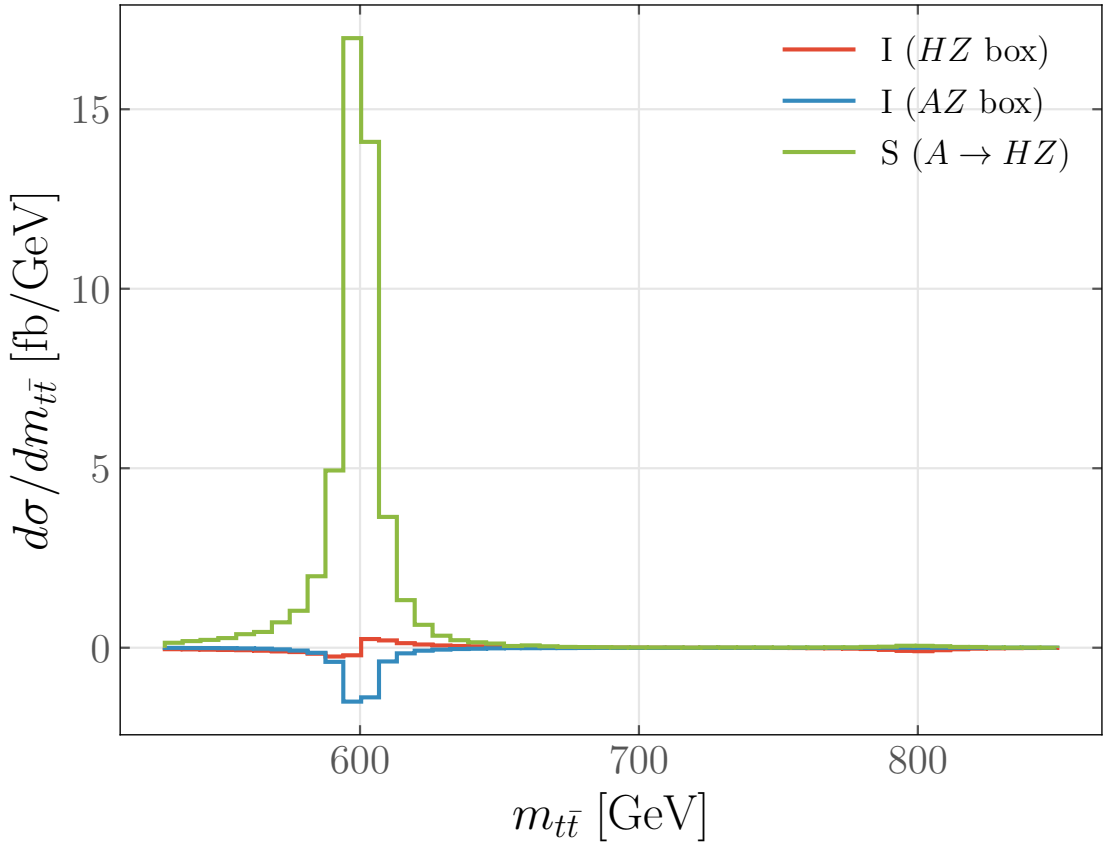


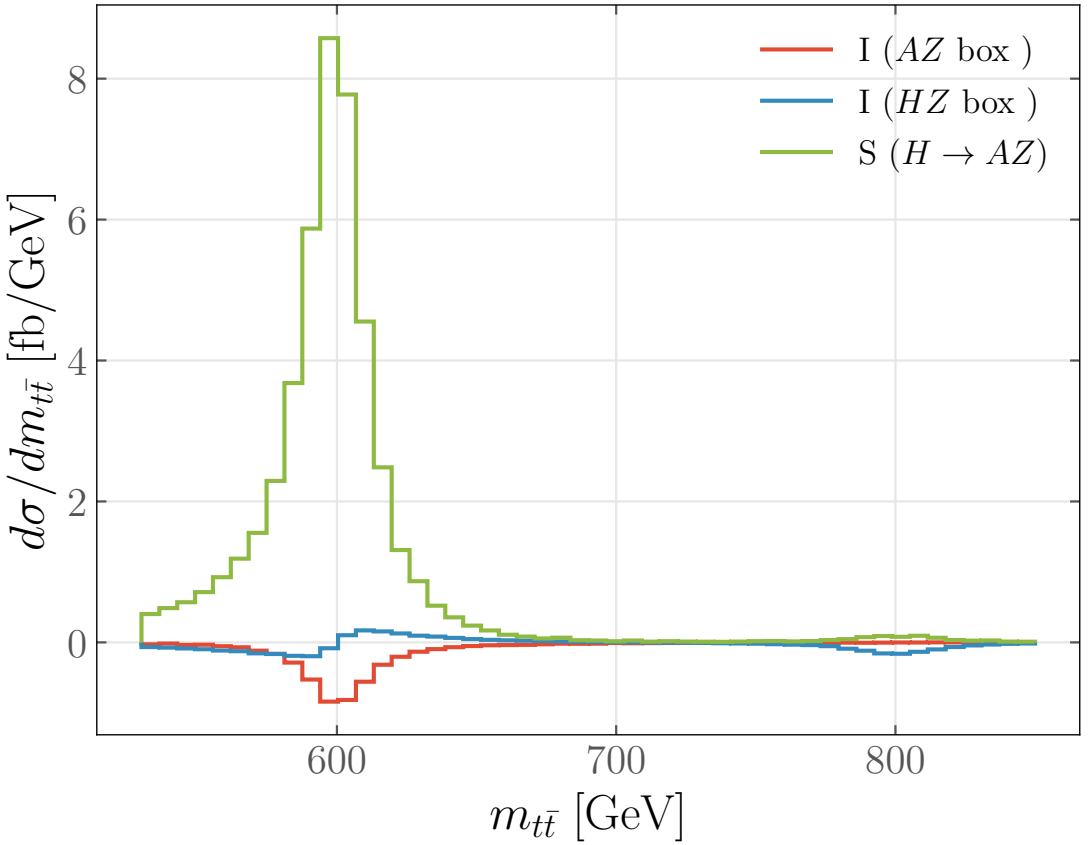
$$\sigma(gg\to A\to ZH\to Zt\bar{t}) = \sigma(gg\to H\to ZA\to Zt\bar{t}) = 0.1\ \mathrm{pb}$$

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

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

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

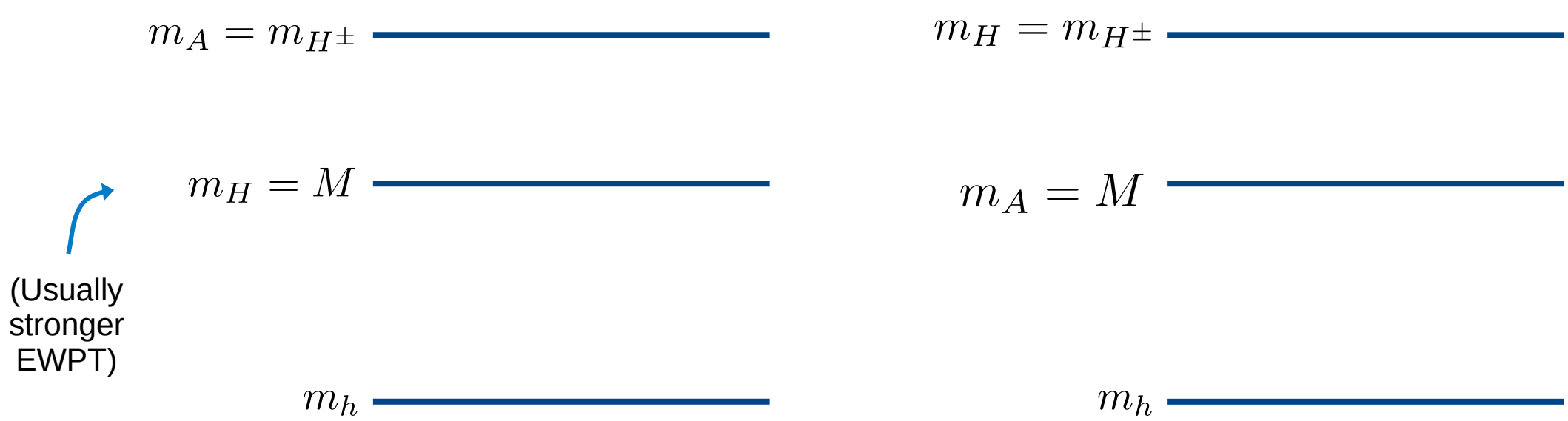
when $B_i >> S_i$

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

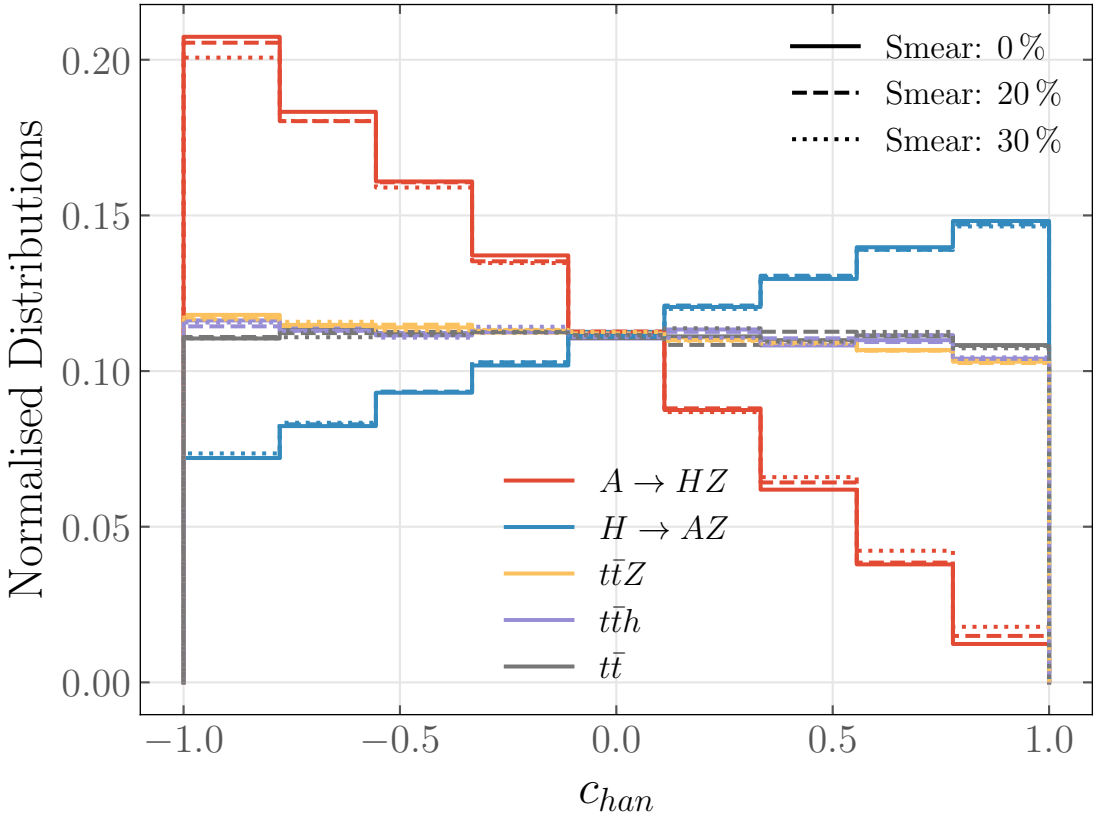
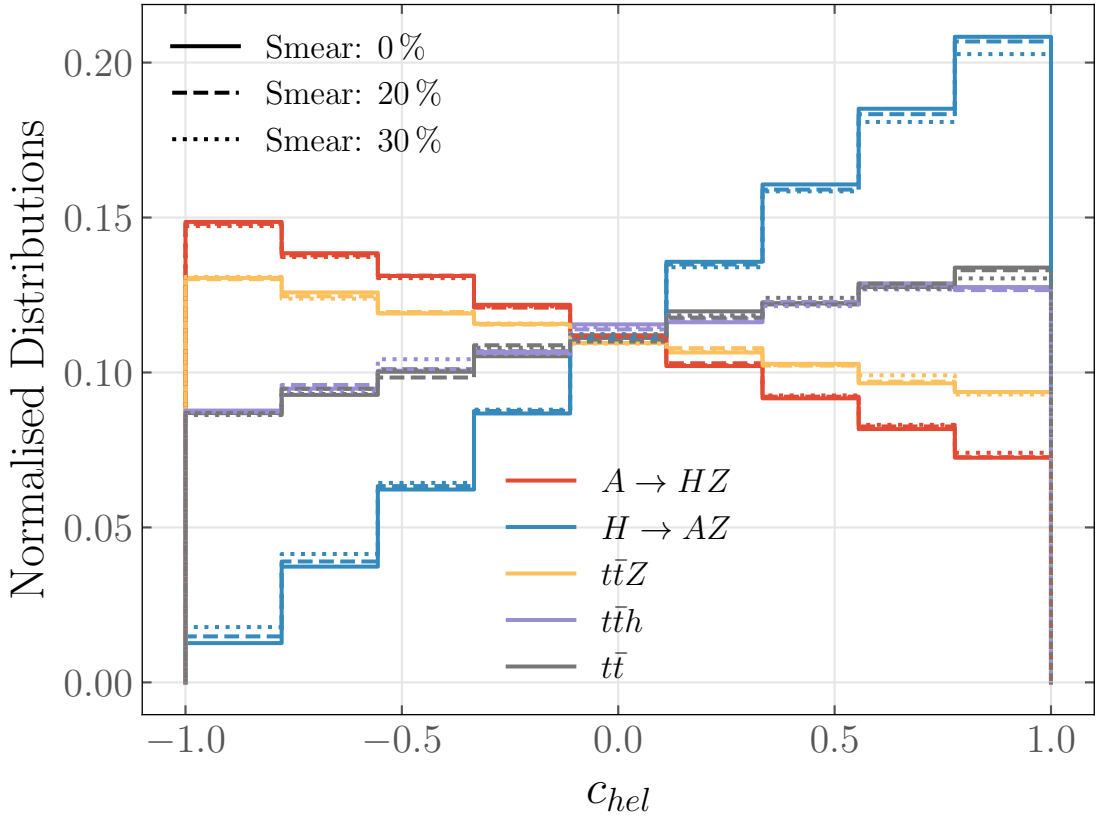
Ingredients for a Strong First Order EW Phase Transition

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