Probing $A \to HZ$ vs $H \to AZ$ using top-quark spin correlations at the HL-LHC

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Based on JHEP 06 (2025) 170 [2502.03443]

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HELMHOLTZ

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Motivation for extended Higgs sectors

The search of an EW phase transition

The SM has many shortcomings

- Example: the **baryon asymmetry** of the universe (BAU)
- Physics out of the equilibrium ⇒ **strong first order EW phase transition** (SFOEWPT)
  - The SM predicts a smooth crossover
- The Higgs sector is basically ***unexplored*** at present

BSM extended Higgs sectors ⇒ SFOEWPT possible!

- In the 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

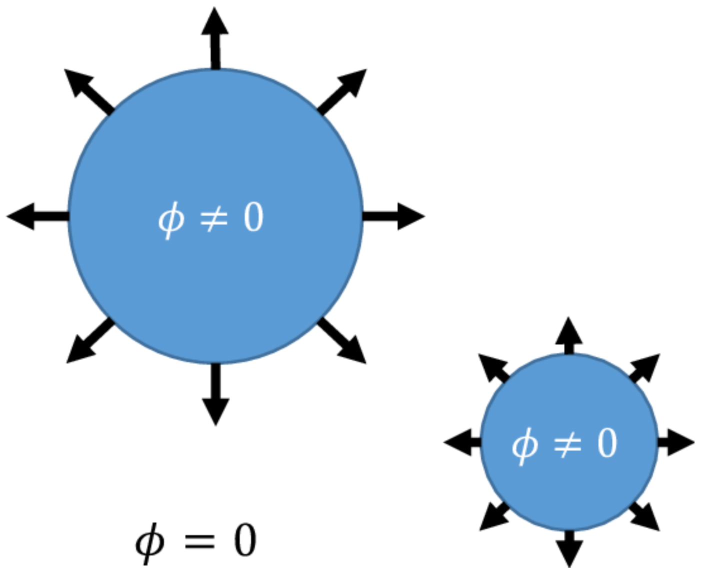


Image by M. Breitbach

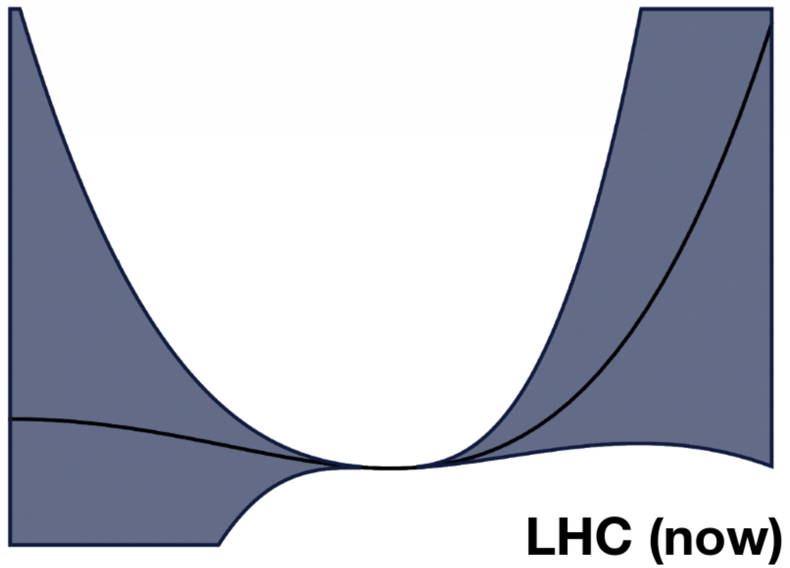


Image by N. Craig

The Two Higgs Doublet Model (2HDM)

SM + a second Higgs doublet

- Potential: $$V = m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) - \left[m_{12}^2\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right] + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right]$$

- EW minimum: $$\langle\Phi_i\rangle = \frac{v_i}{\sqrt{2}}$$

- Five physical Higgs bosons:

Image by K. Radchenko

SM-like

Neutral CP even

Neutral CP odd

Charged

$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

(softly breaks Z_2 symmetry)

- Input parameters:

$$m_h, \quad m_H, \quad m_A, \quad m_{H^\pm}, \quad \tan\beta = v_2/v_1, \quad \cos(\beta-\alpha) = 0, \quad M^2$$

$125\ \text{GeV}$

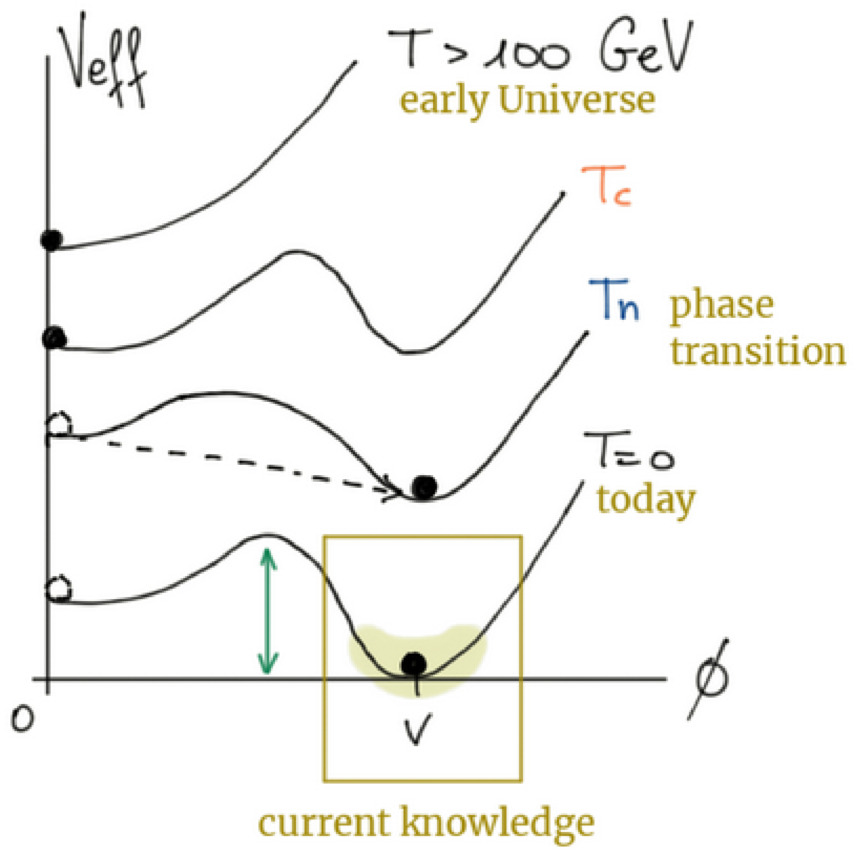
"Alignment limit"
Tree-level SM-like interactions for h
ZHA coupling unsuppressed

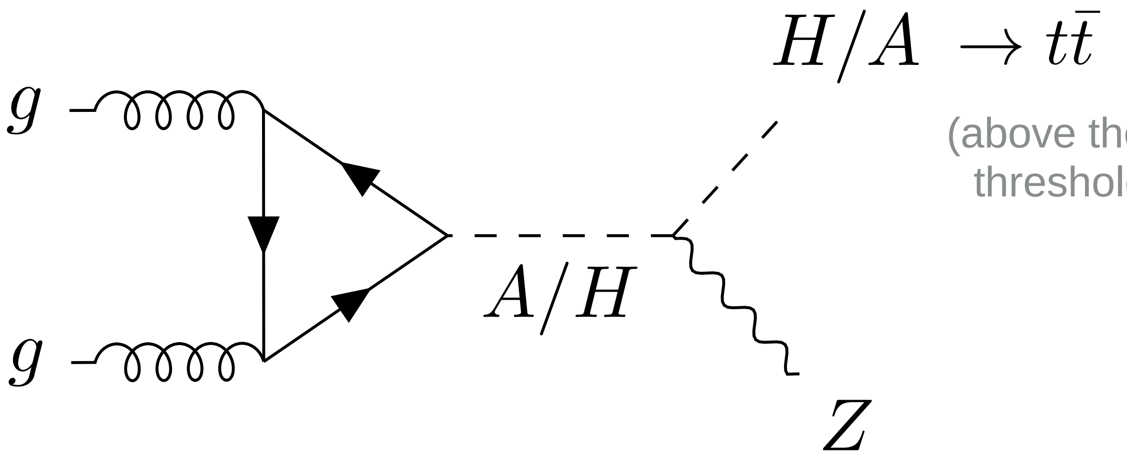
Image by K. Radchenko

An SFOEWPT within the 2HDM

$A \to HZ$ or $H \to AZ$ (*'smoking gun'* signal) can be open

- 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)
- Therefore, the decays $A \to HZ$ **or** $H \to AZ$ can be kinematically allowed ⇒ *'smoking gun'* of a SFOEWPT





(above the tt threshold)

- However, currently there is **no experimental distinction between these two signals** :(

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

Experimental situation at present

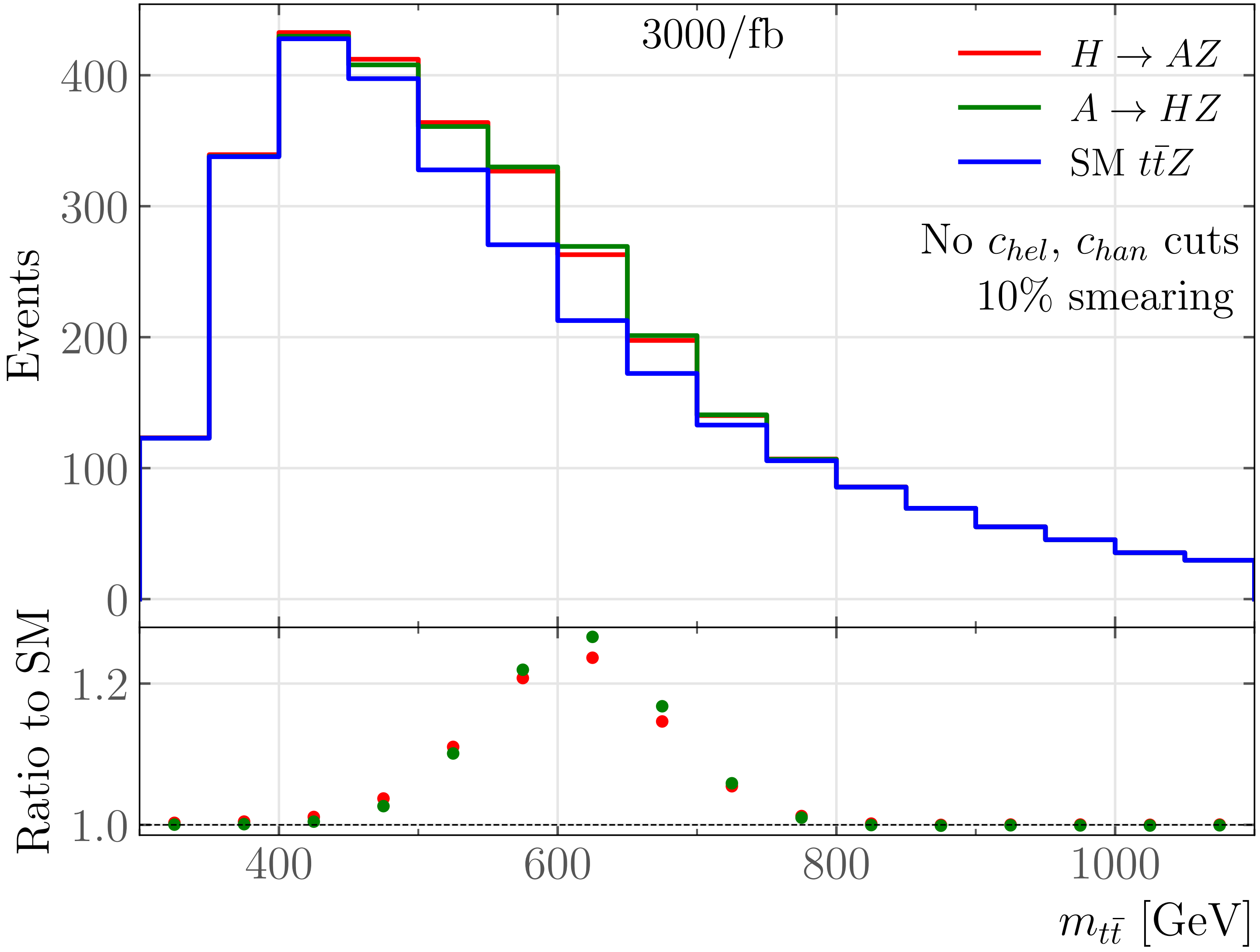
No possible distinction between $A\to HZ$ and $H\to AZ$

- Two benchmark points such that $A\to HZ$ and $H\to AZ$ have the **same total cross section** in the $t\bar{t}Z$ final state
  - Tune the top Yukawa coupling via $\tan\beta$

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

- Neutral heavy Higgs bosons at 600 and 800 GeV
  - Allowed by present searches

- Nearly identical shape for both processes $\Rightarrow$ **Insensitive to the CP properties of the Higgs bosons** :(



Our proposal: top-quark spin correlations

Image from 2105.11478

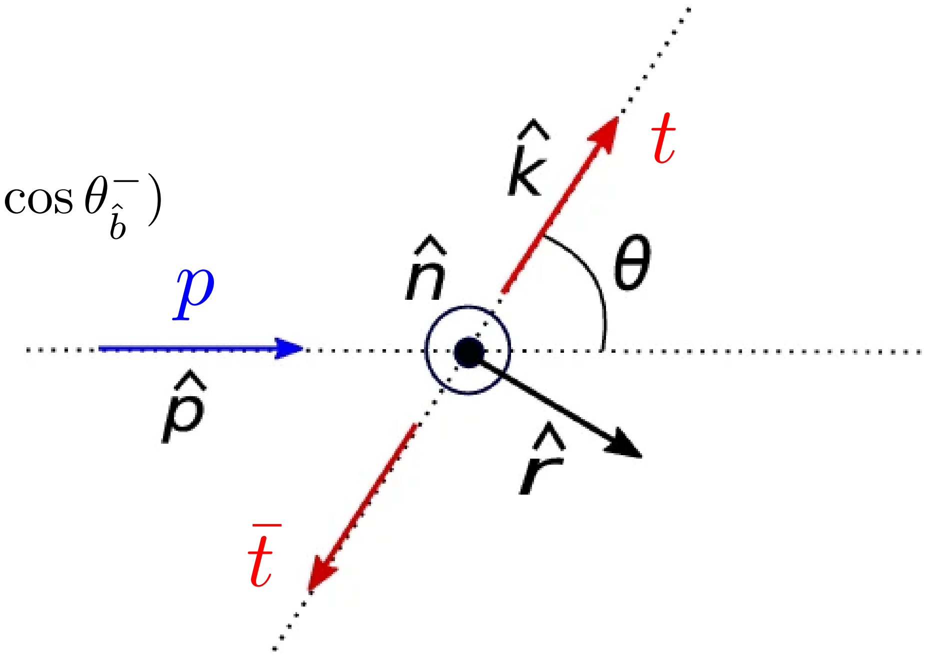
Sensitive observables: angular variables c_{han} and c_{hel}

- 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!**

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

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

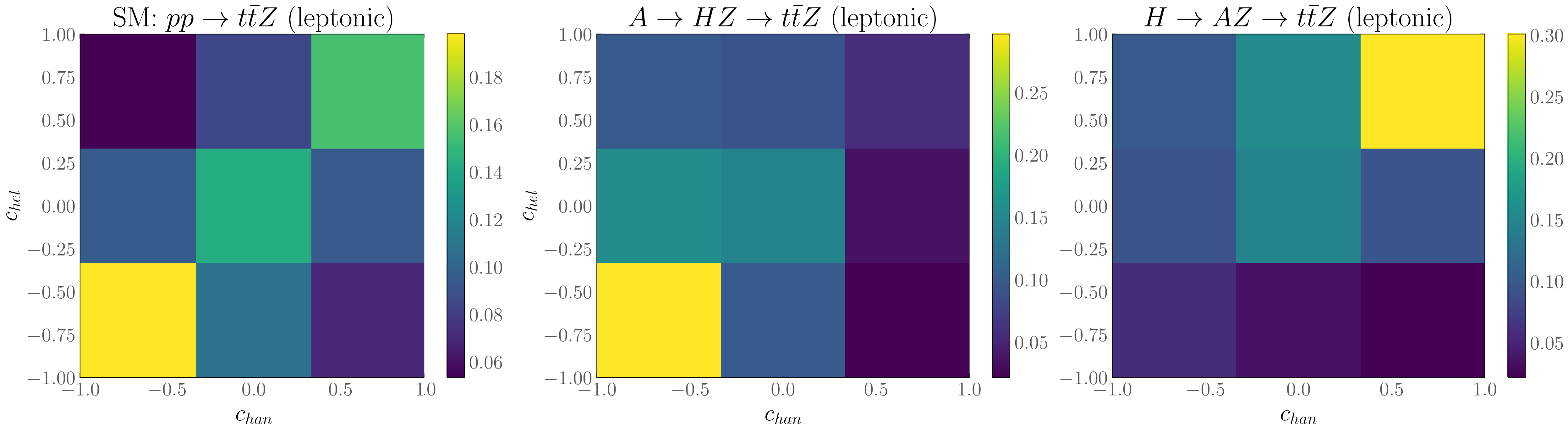
- These angular variables are used in the $t\bar{t}$ searches by both ATLAS and CMS!
[2507.05119, 2503.22382, ATLAS-CONF-2025-008]

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

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

The two signals become potentially distinguishable!

- Cross section distributions normalized to the total cross section

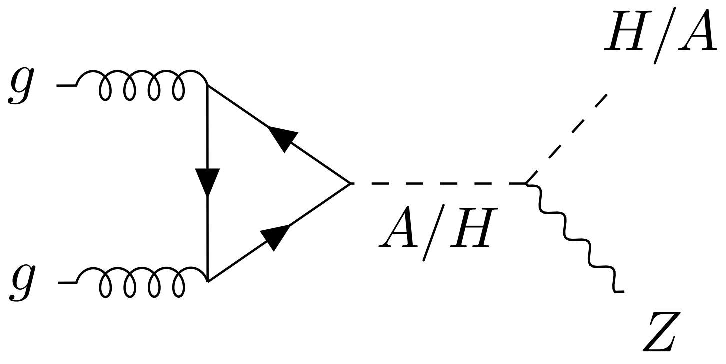


$A \to HZ$ and $H \to AZ$ peak in different regions in the c_{han}—c_{hel} plane!

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` with an effective gg-Higgs vertex with p^2-dependence + 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 (with 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

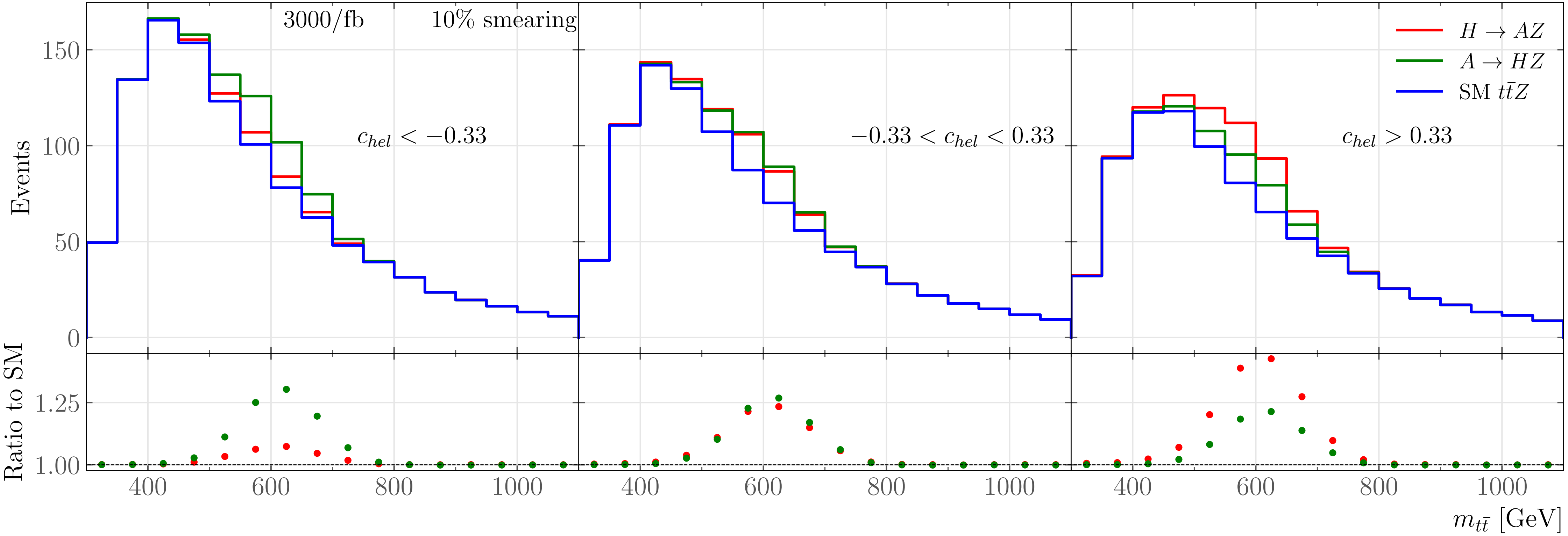
- $(0.7)^2$ for b-tagging
- 0.9 for top quark reconstruction
- 10% smearing in the $t\bar{t}$ distributions to mimic the detector resolution

Results: di-top invariant mass distributions

Bins in c_{hel}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



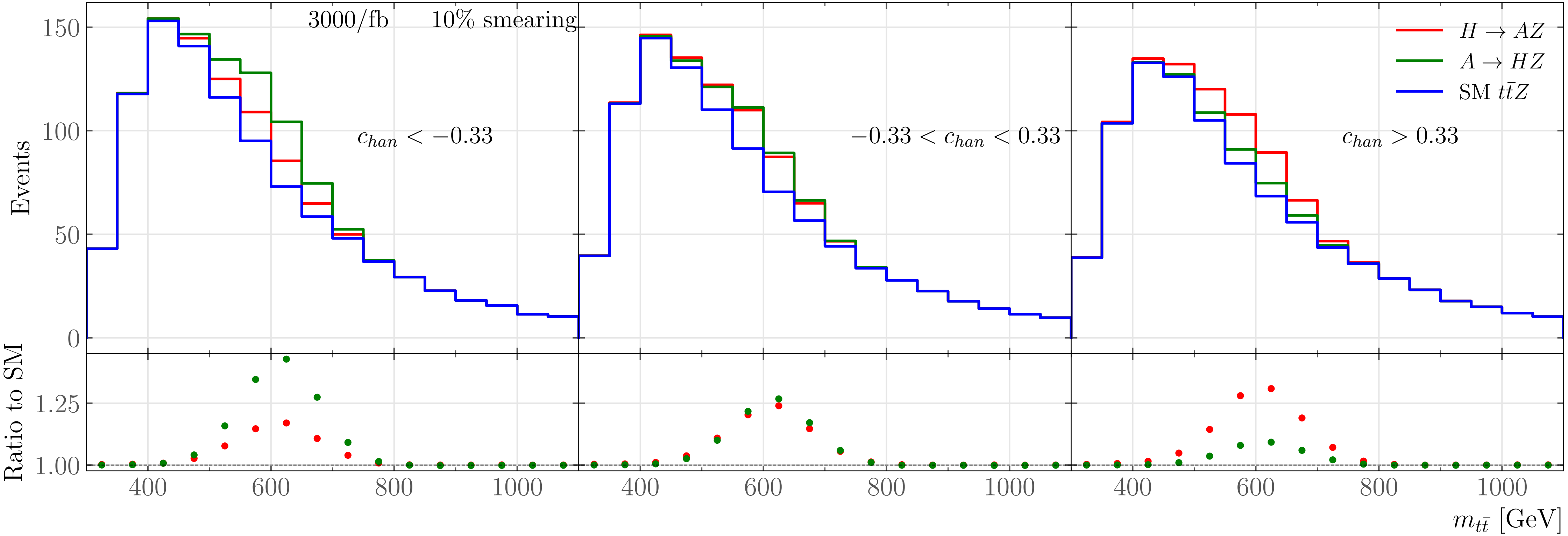
Both signals become distinguishable!!

Results: di-top invariant mass distributions

Bins in c_{han}

$A \rightarrow HZ$ more prominent!

$H \rightarrow AZ$ more prominent!

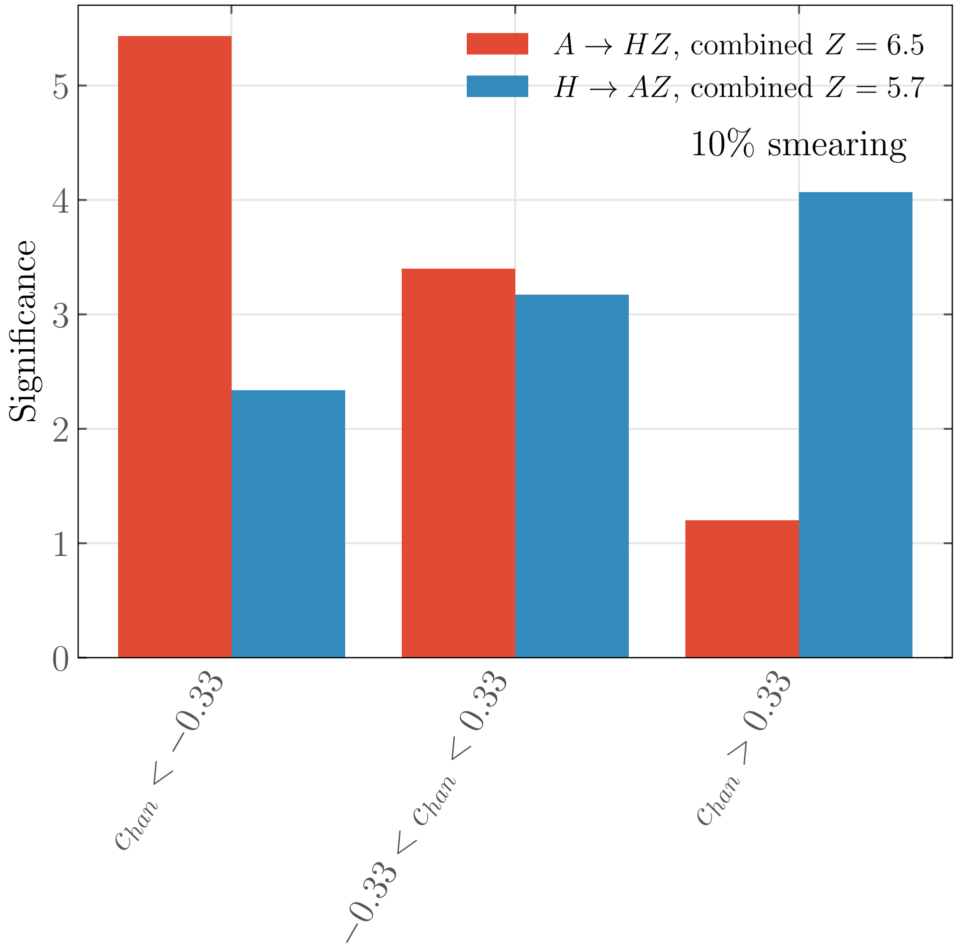


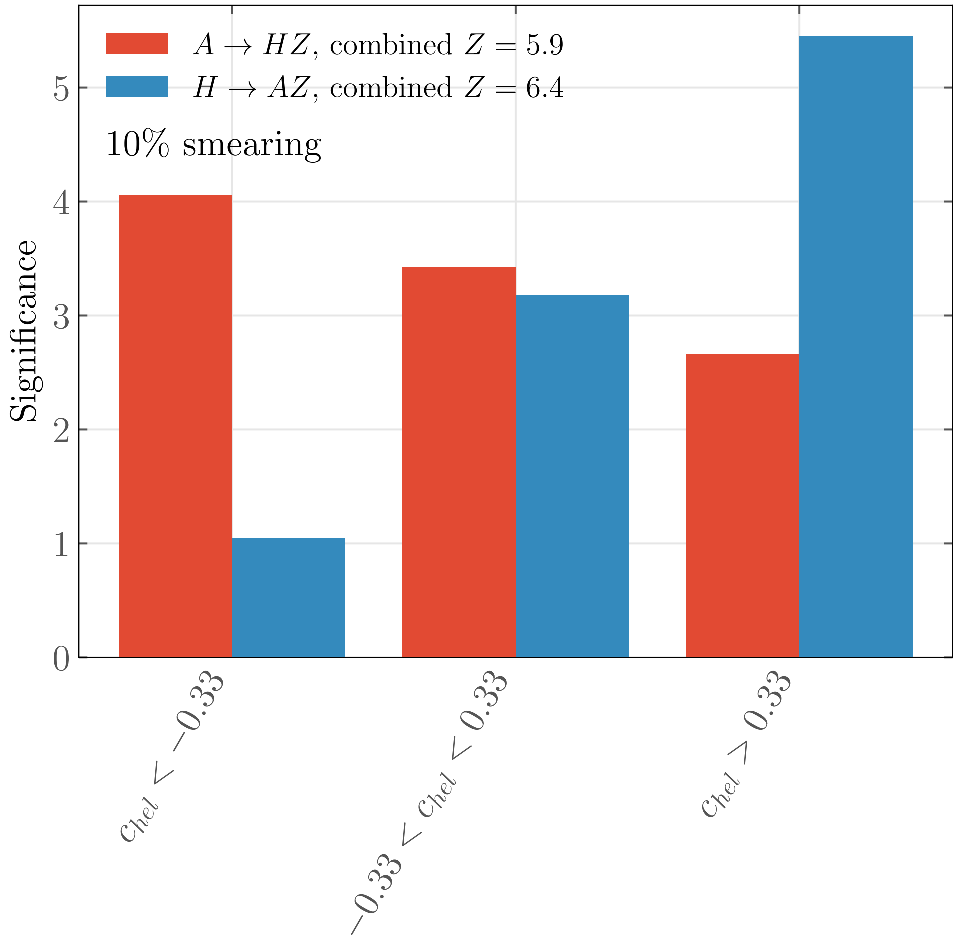
Both signals become distinguishable!!

Results: significance Z at the HL-LHC

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

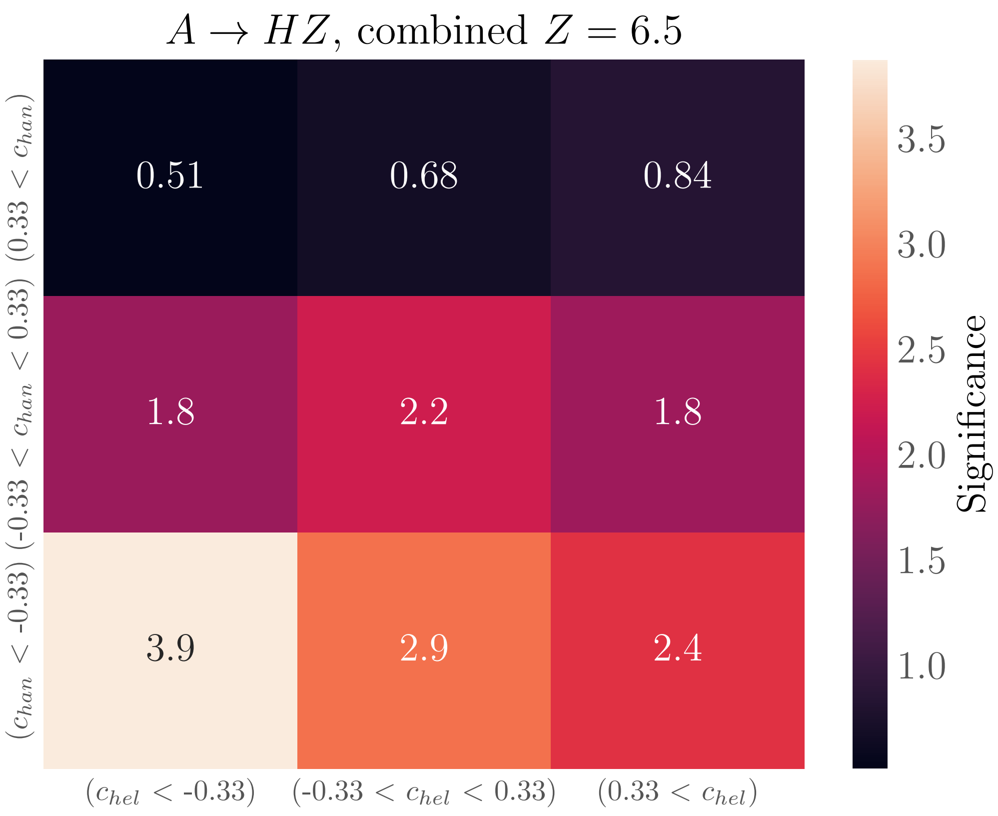


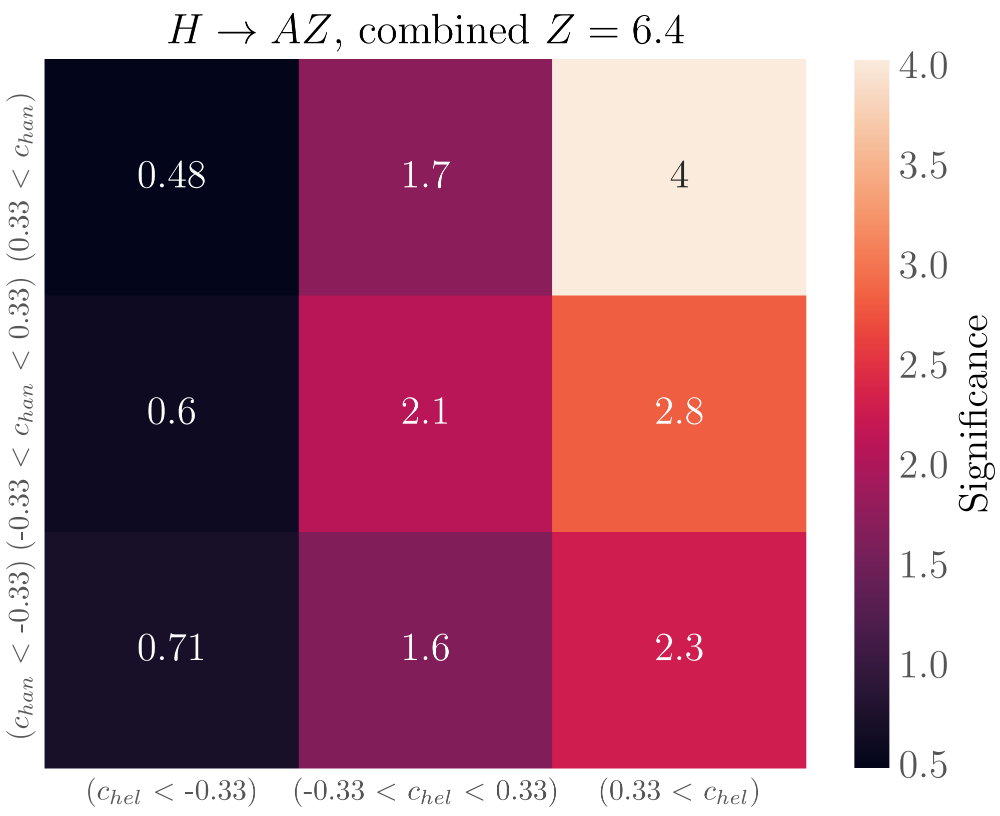


Results: significance Z at the HL-LHC

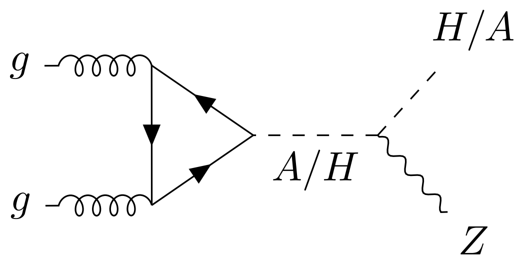
Binning in both c_{han} AND c_{hel}

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





Summary & Conclusions



- An SFOEWPT in the 2HDM often requires mass splitting between heavy Higgs bosons ⇒ Probed at colliders through the so-called ***"smoking gun"* signature**

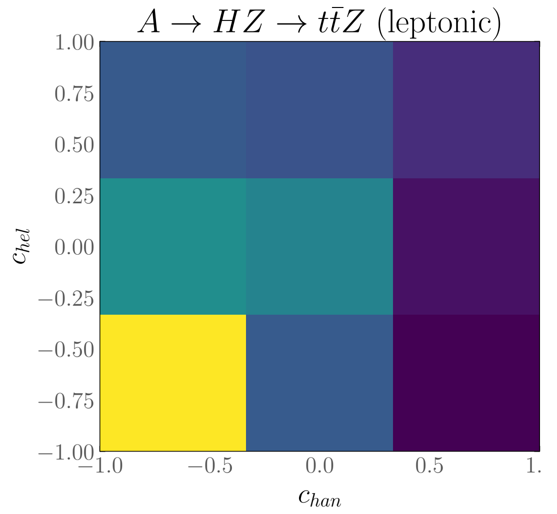
- Experimentally, there is no sensitivity between

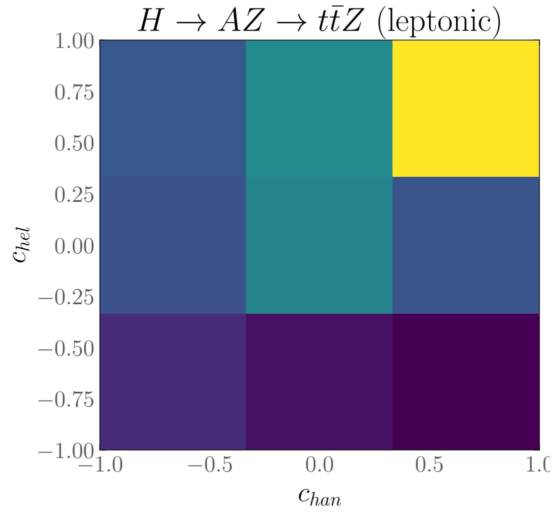
$$gg \to A \to ZH \to Zt\bar{t} \quad \text{vs.} \quad gg \to H \to ZA \to Zt\bar{t}$$

- **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!

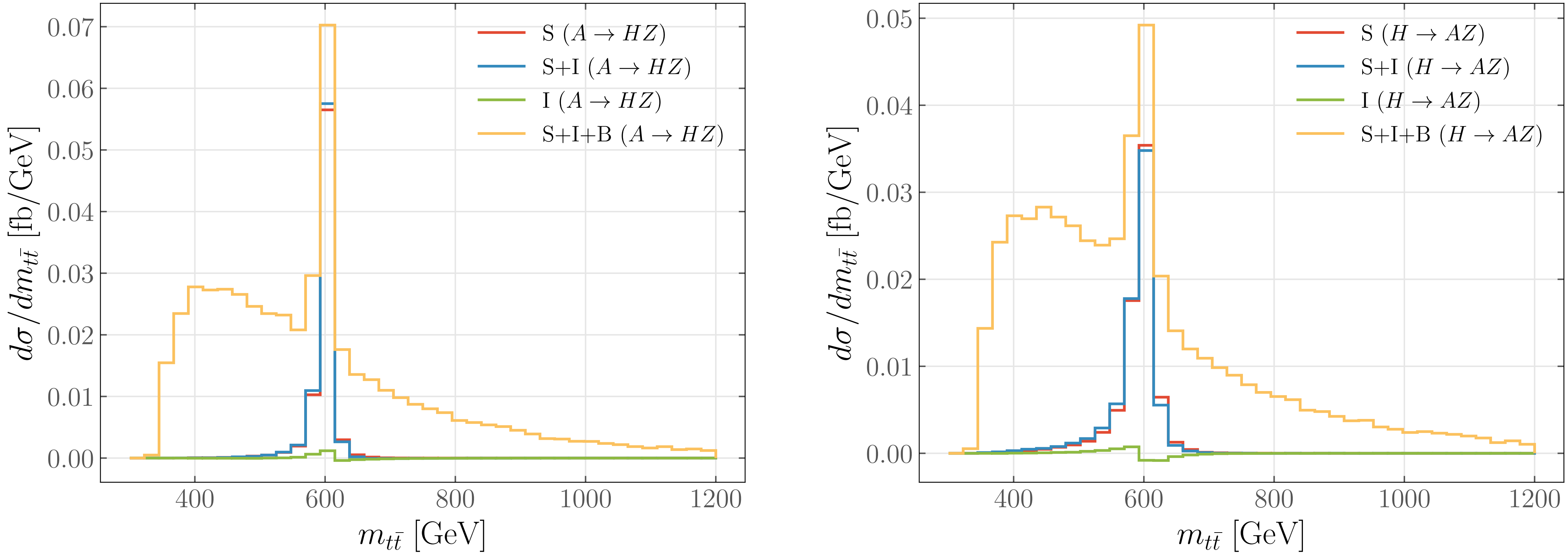




Back-up

Signal and background interference

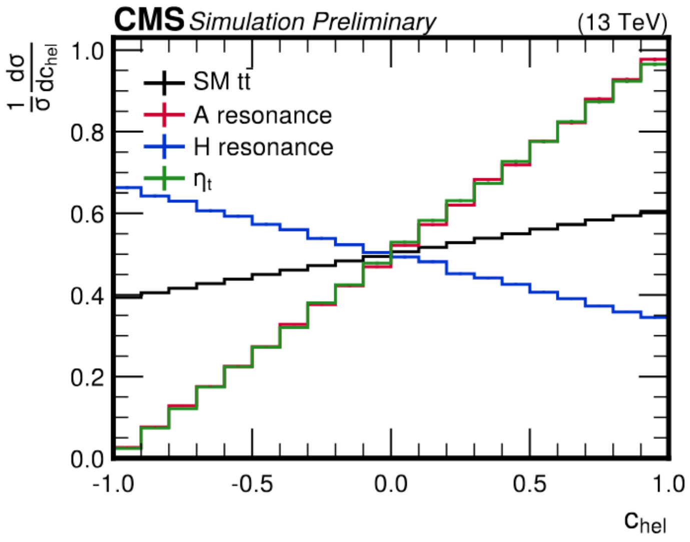
Not very large, but it is included

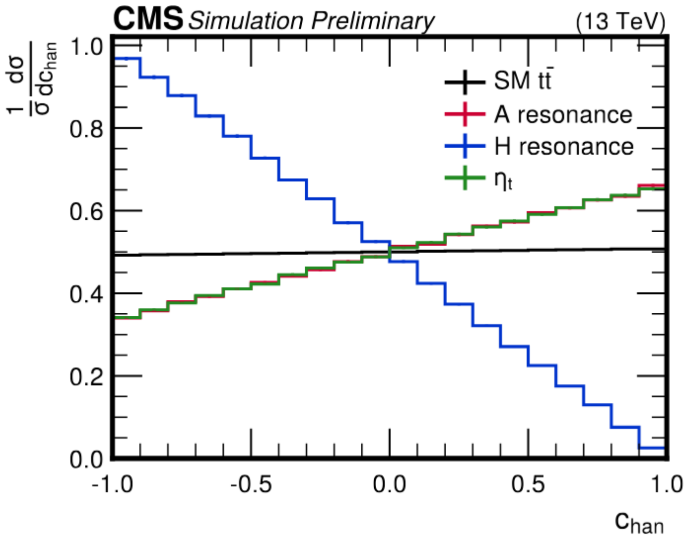


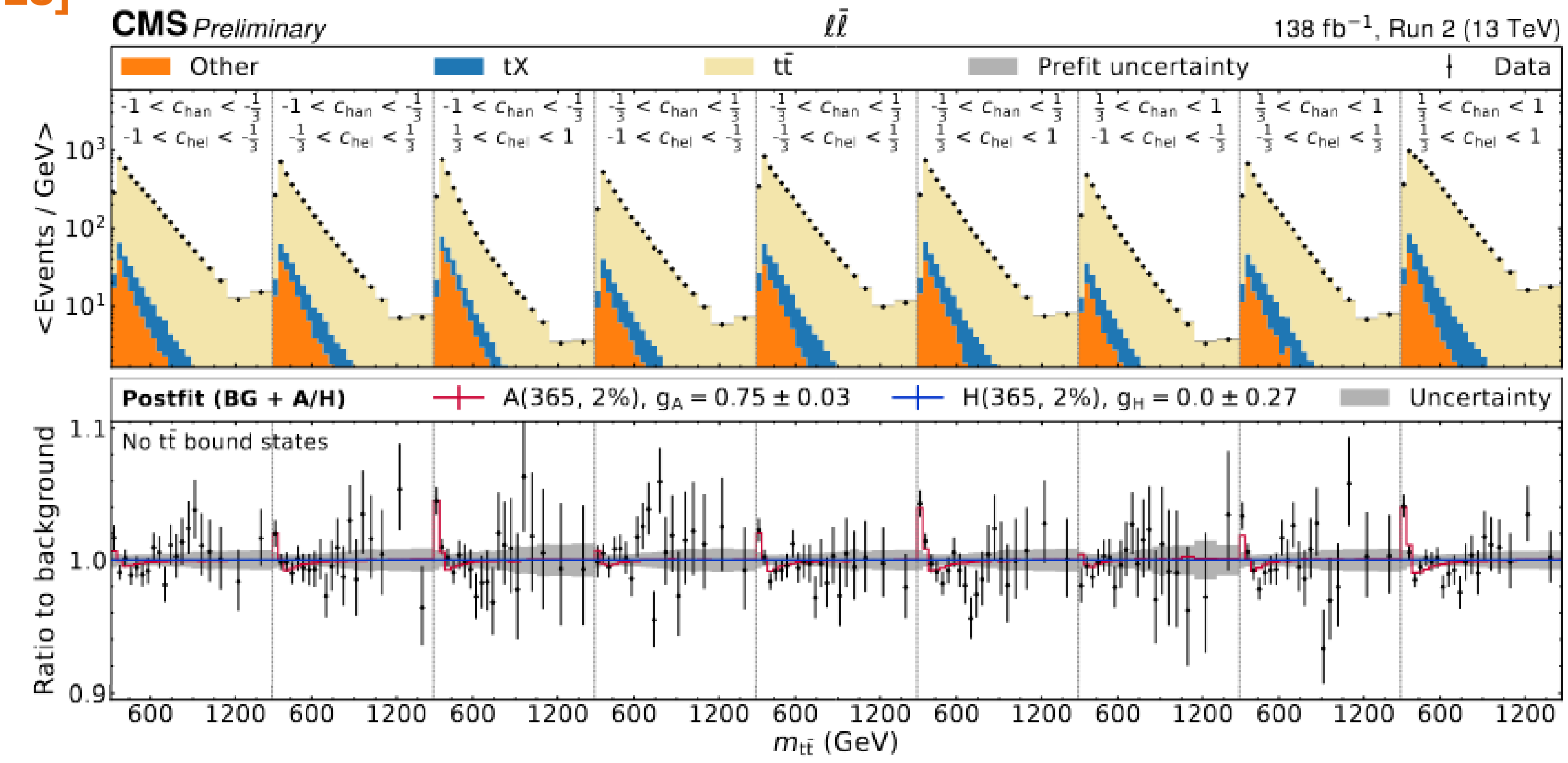
Already used in $t\bar{t}$ searches!

Example at CMS [CMS-PAS-HIG-22-013]

$$pp \to H/A \to t\bar{t} \to b\bar{b}\ell^+\ell^-\nu_\ell\bar{\nu}_\ell$$







- $> 5\sigma$ excess close to the $t\bar{t}$ threshold for a pseudoscalar boson
- Observed in the di-lepton channel by using the variables c_{han} and c_{hel}

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

Image from 2105.11478

Definition of c_{han} and c_{hel}

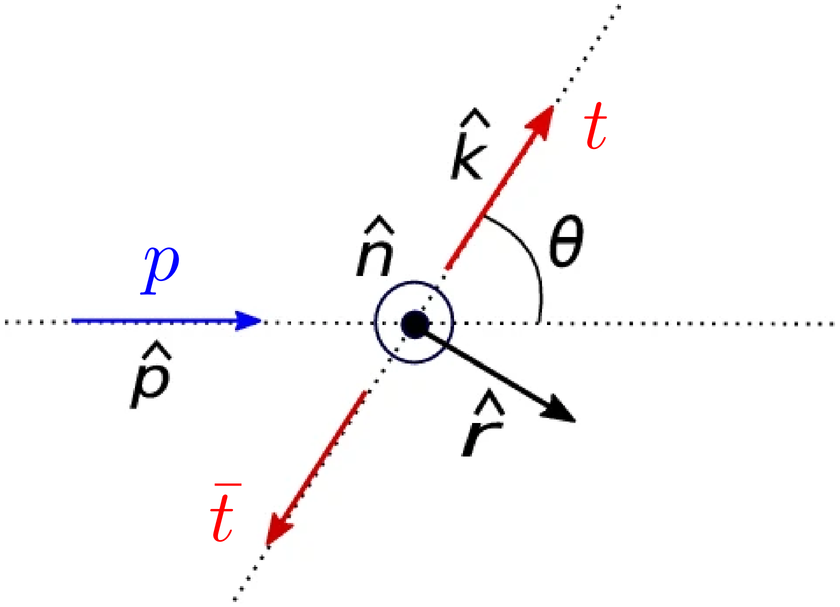
Relation with the top-quark spin correlation matrix

- Spin density matrix of the $t\bar{t}$ system:

$$R \propto A\, 1 \otimes 1 + B_i^+ \sigma^i \otimes 1 + B_i^- 1 \otimes \sigma^i + C_{ij} \sigma^i \otimes \sigma^j$$

Spin-correlation matrix

- Choice of basis: $\hat{k}, \quad \hat{n} \propto \hat{p} \times \hat{k}, \quad \hat{r} \propto \hat{k} \times \hat{n}$



- Relation to the cross section:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_{\hat{a}}^+ \, d\cos\theta_{\hat{b}}^+} = \frac{1}{4}\left(1 + B_{\hat{a}}^+ \cos\theta_{\hat{a}}^+ + B_{\hat{a}}^- \cos\theta_{\hat{a}}^- - C_{\hat{a}\hat{b}} \cos\theta_{\hat{a}}^+ \cos\theta_{\hat{b}}^-\right) \quad \text{with} \quad a, b \in \{\hat{k}, \hat{r}, \hat{n}\}$$

- $\hat{\ell}^{\pm}$ is the direction of flight of the **leptons** in the top (or anti-top) rest frame and $\cos\theta_{\hat{a}}^{\pm} = \pm \hat{\ell}^{\pm} \cdot \hat{a}$
- 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:
1508.05271
2106.09690
CMS-PAS-HIG-22-013
Rübenach PhD Thesis
...

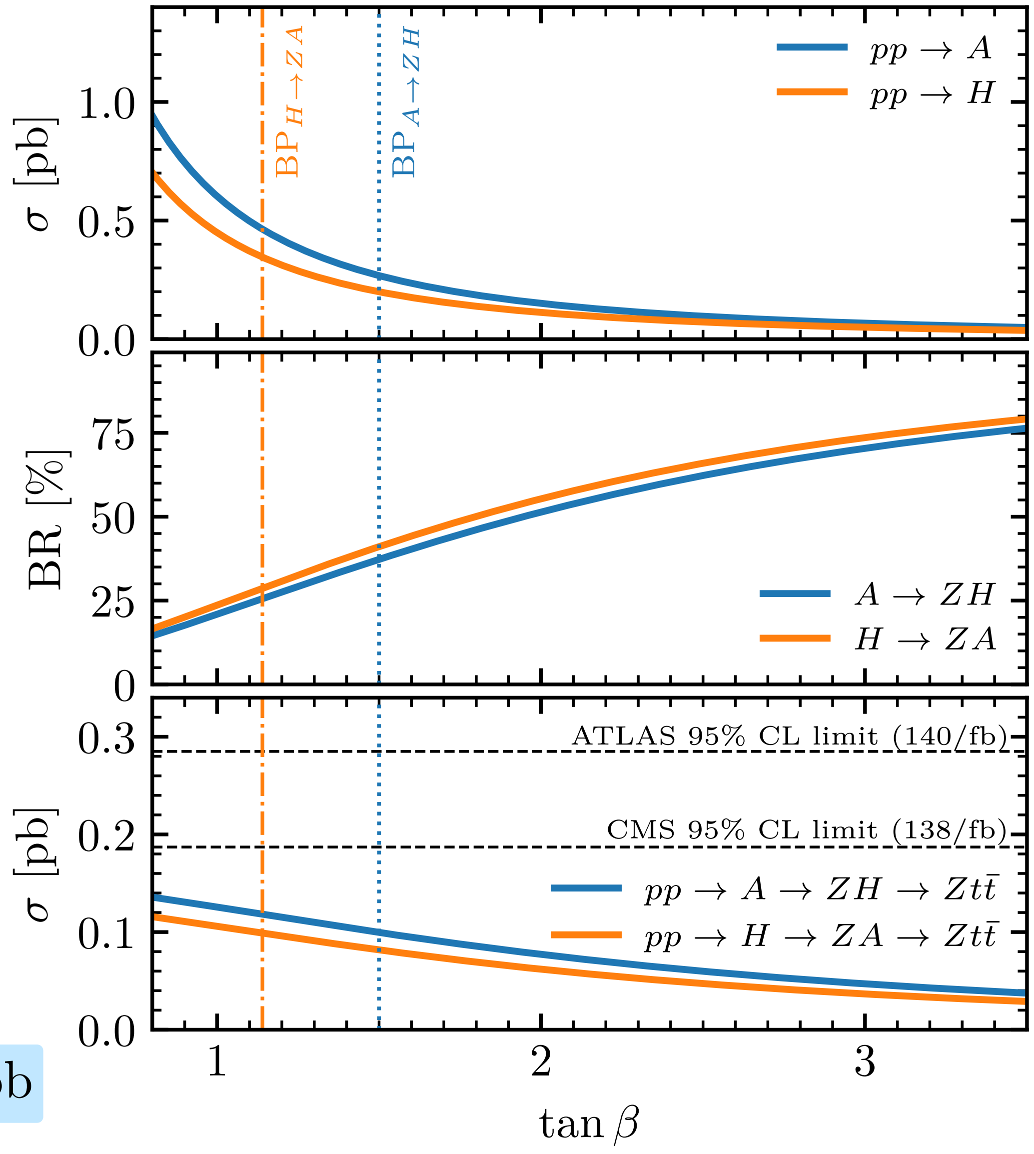
Benchmark point scenarios with the same cross section

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

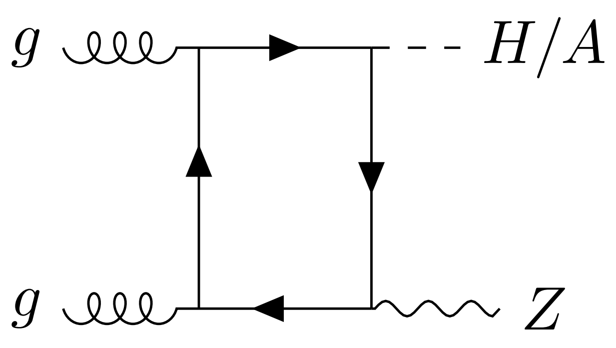
	$\mathrm{BP}_{H\to ZA}$	$\mathrm{BP}_{A\to ZH}$
$\tan\beta$	1.14	1.50
$\cos(\beta-\alpha)$	0	0
m_h/GeV	125	125
m_H/GeV	800	600
m_A/GeV	600	800
$m_{H^\pm}/\mathrm{GeV}$	800	800
M/GeV	600	600
$\mathrm{BR}(H\to t\bar{t})$	71%	99%
$\mathrm{BR}(A\to t\bar{t})$	99%	63%
$\mathrm{BR}(H\to ZA)$	29%	–
$\mathrm{BR}(A\to ZH)$	–	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

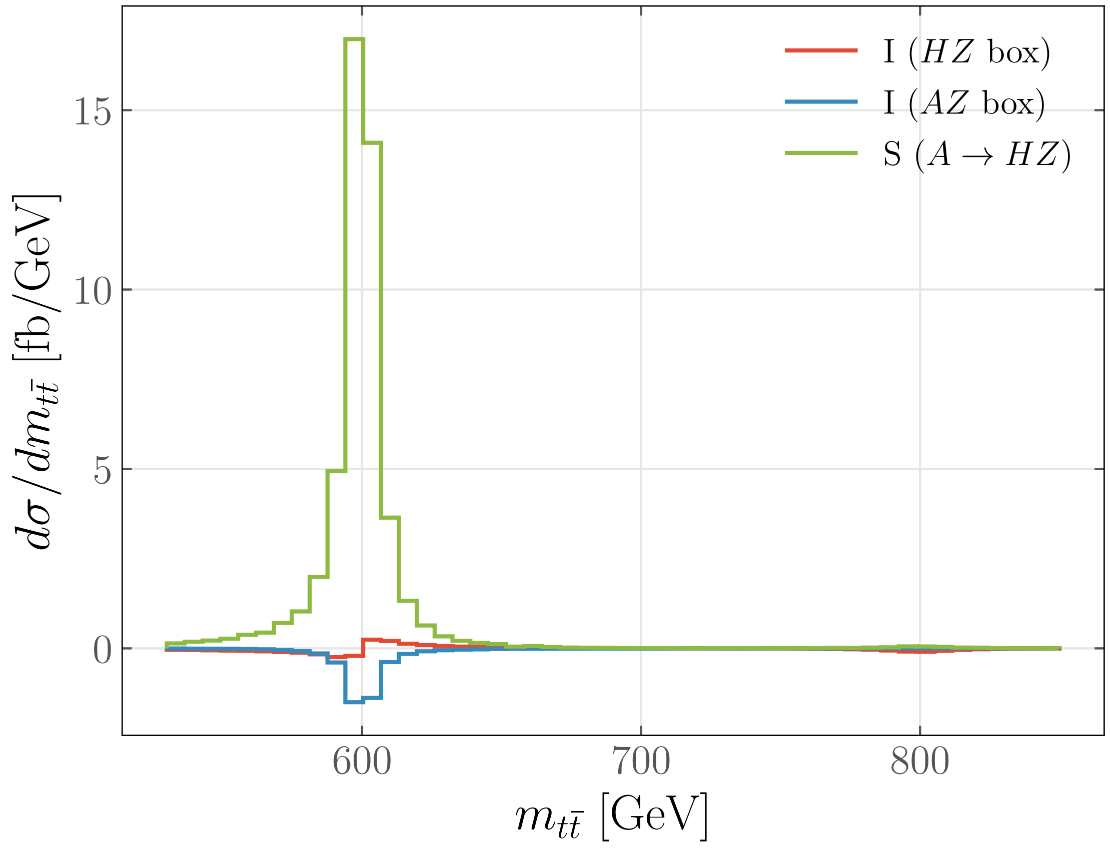


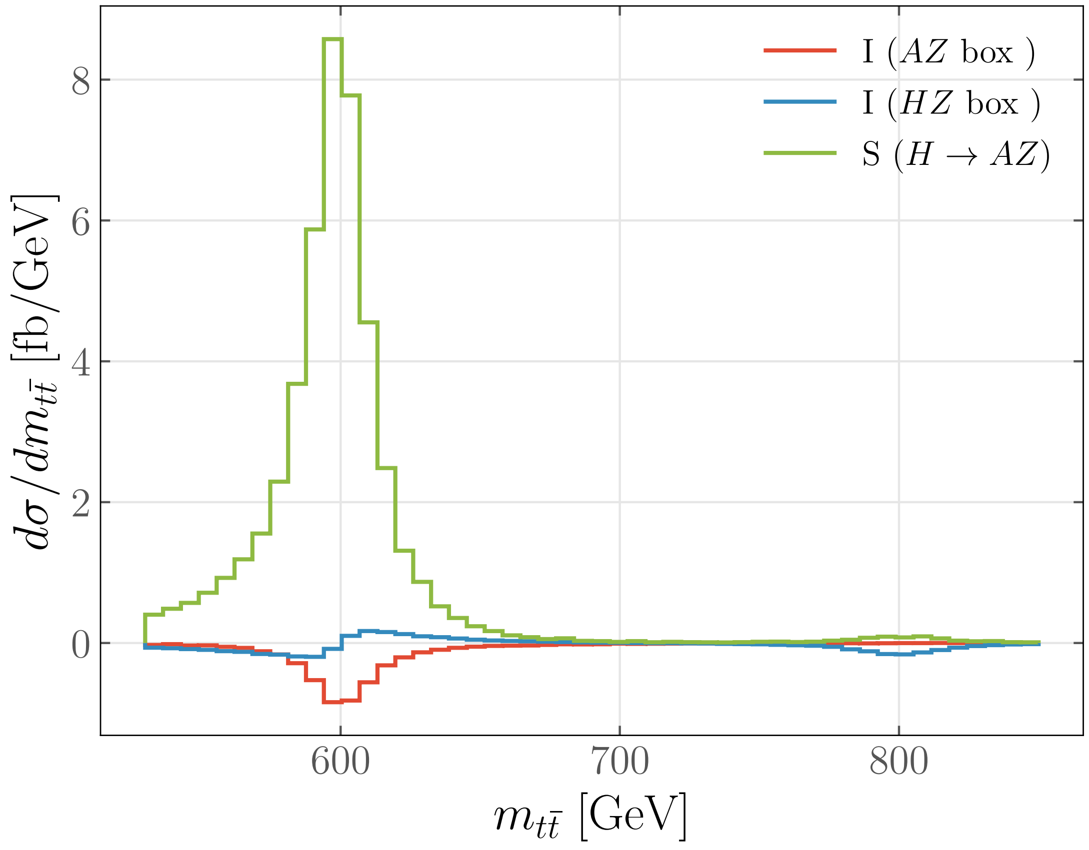
$$\sigma(gg\to A\to ZH\to Zt\bar{t}) = \sigma(gg\to H\to ZA\to Zt\bar{t}) = 0.1\ \mathrm{pb}$$

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

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

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

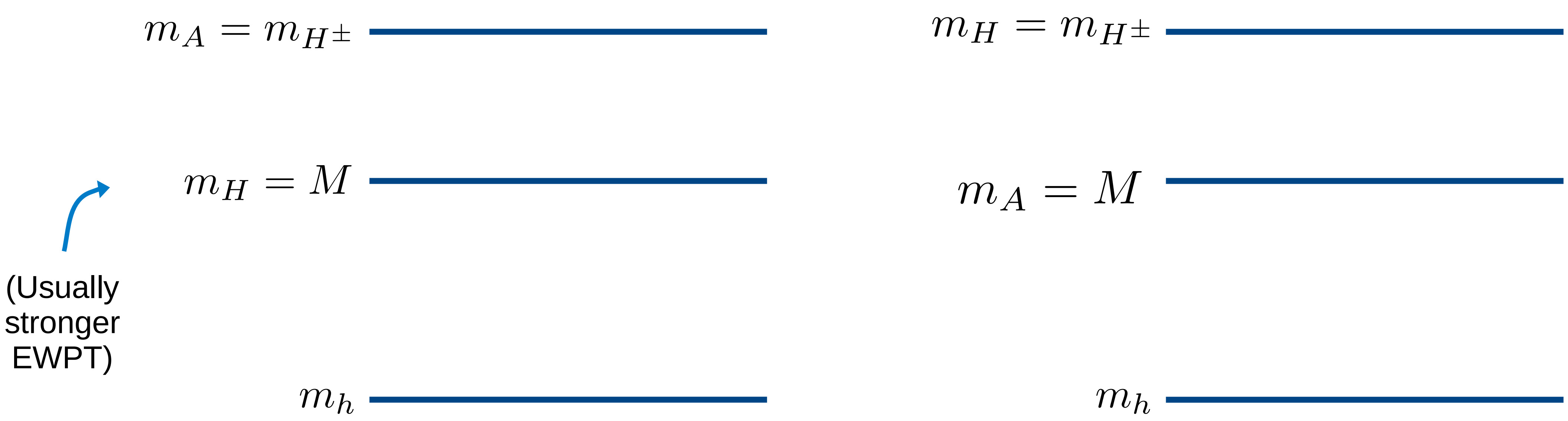
when $B_i >> S_i$

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, …