Top-quark spin correlations to distinguish $A \to HZ$ and $H \to AZ$

Prospects for the HL-LHC

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Working Group on Two Higgs Doublet Models

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

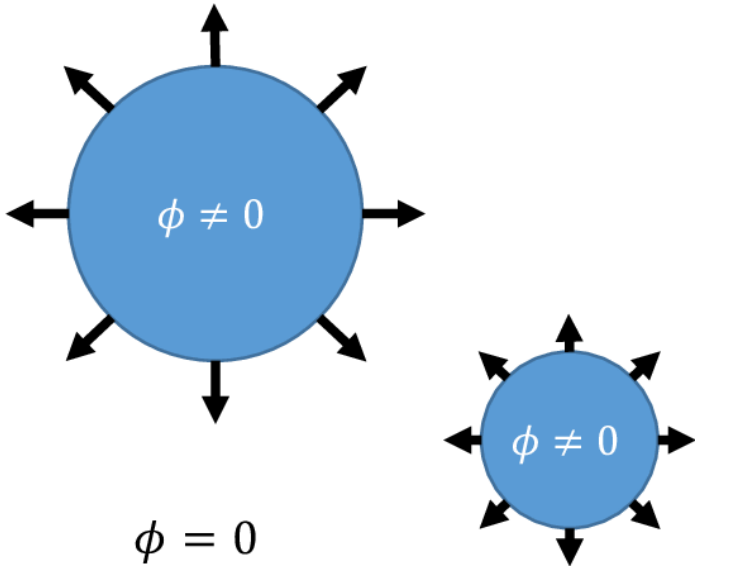


Image by M. Breitbach

BSM extended Higgs sectors ⇒ SFOEWPT possible!

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

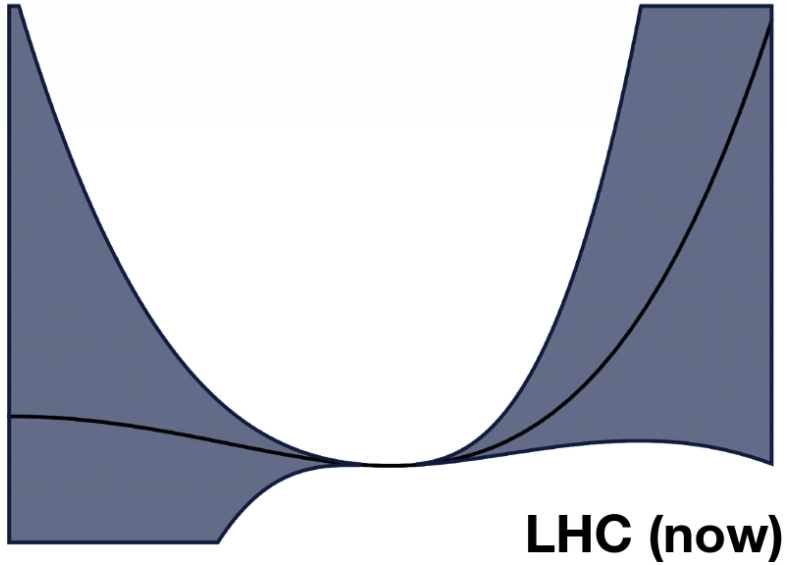


Image by N. Craig

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

The Two Higgs Doublet Model (2HDM)

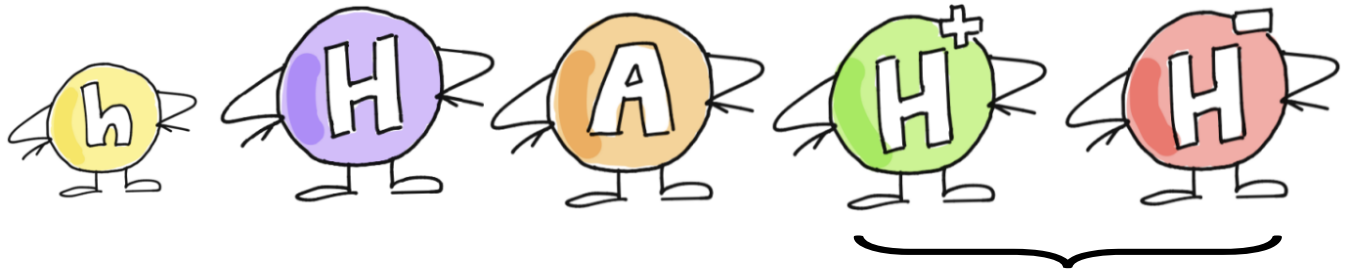
SM + a second Higgs doublet

- 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

- Input parameters:

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

m_h: 125 GeV

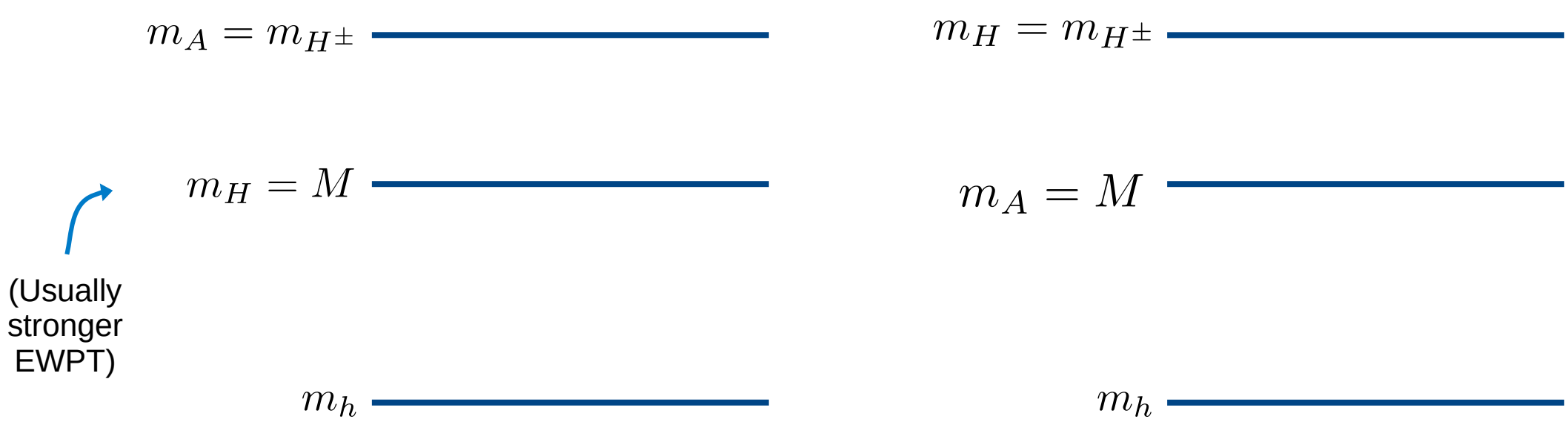
$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$ (softly breaks Z_2 symmetry)

"Alignment limit": Tree-level SM-like interactions for h

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)

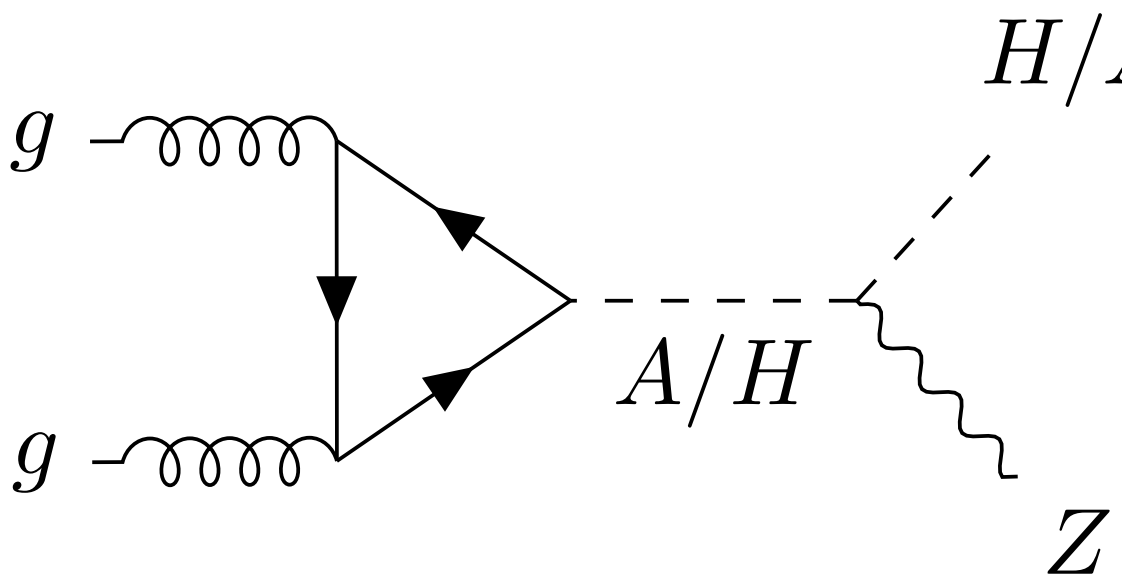


Much literature on 2HDM and SFOEWPT: 1405.5537, 1612.04086, 1705.09186, 1711.04097, 2108.05356, 2208.14466 2309.17431, …

The “smoking gun” signal

$A \to HZ$ or $H \to AZ$ can be open

- This process is a ‘smoking gun’ of a SFOEWPT



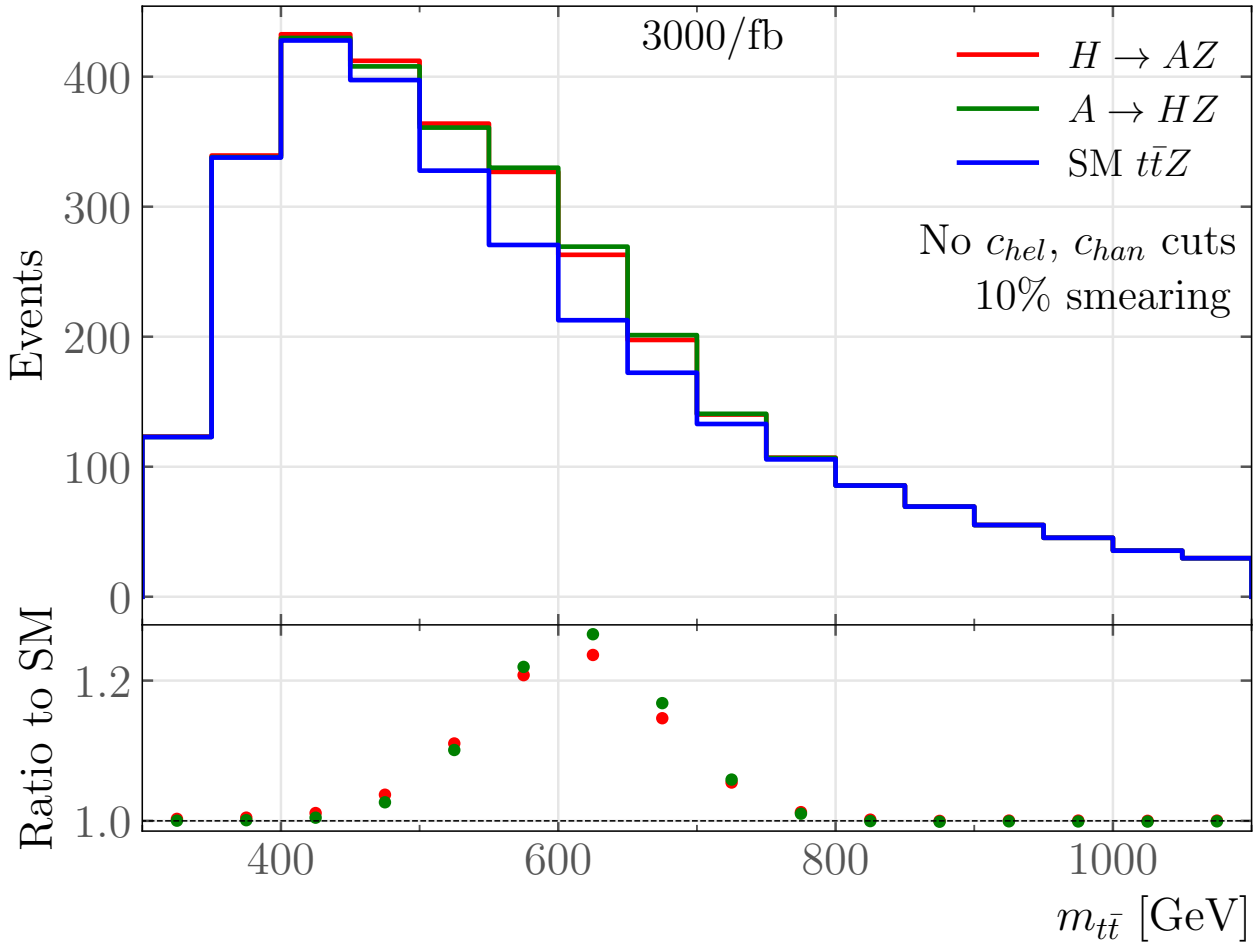
above the tt threshold

$$gg \to \begin{pmatrix} A \\ H \end{pmatrix} \to \begin{pmatrix} ZH \\ ZA \end{pmatrix} \to Z\,t\bar{t}$$

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

Experimental situation at present

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



Nearly identical shape for both processes ⇒ Insensitive to the CP properties of the Higgs bosons

Our proposal: top-quark spin correlations

Image from 2105.11478

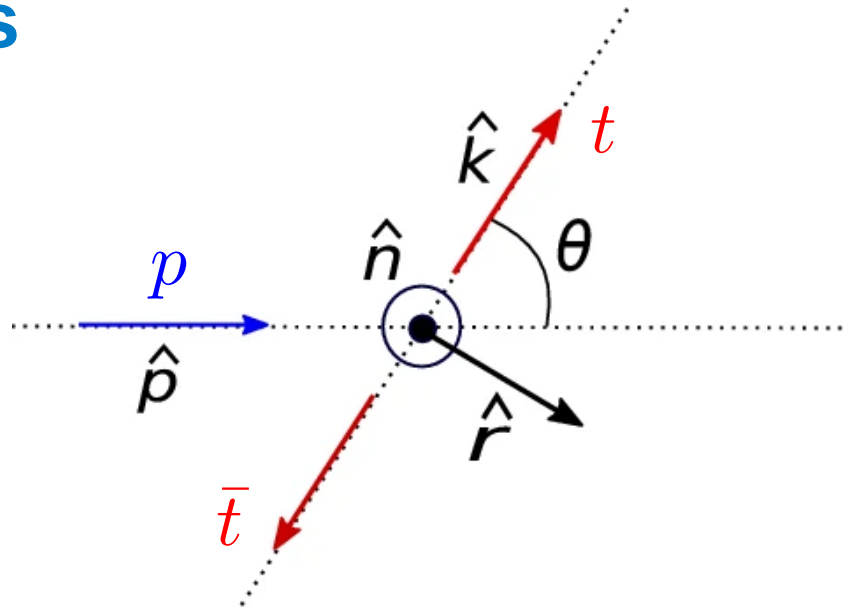
Relation with the angular variables c_{han} and c_{hel}

- 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:

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

- $\hat{\ell}^\pm$ 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!**

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

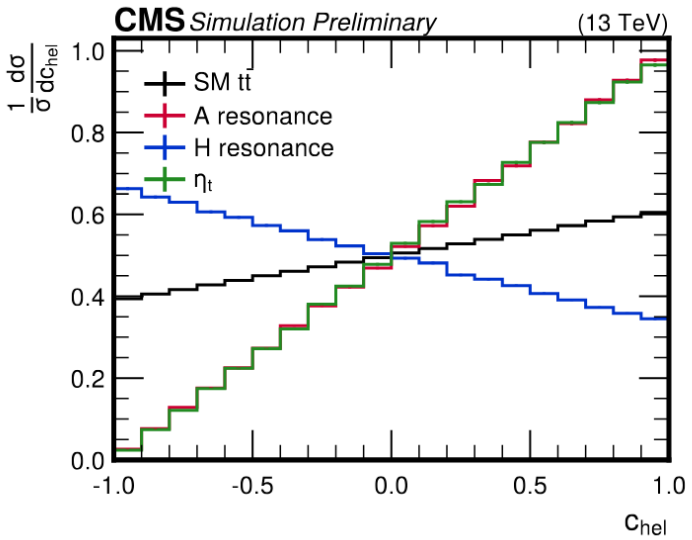
$$c_{han} = \cos\theta_{\hat{k}}^+ \cos\theta_{\hat{k}}^- - \cos\theta_{\hat{r}}^+ \cos\theta_{\hat{r}}^- - \cos\theta_{\hat{n}}^+ \cos\theta_{\hat{n}}^-$$

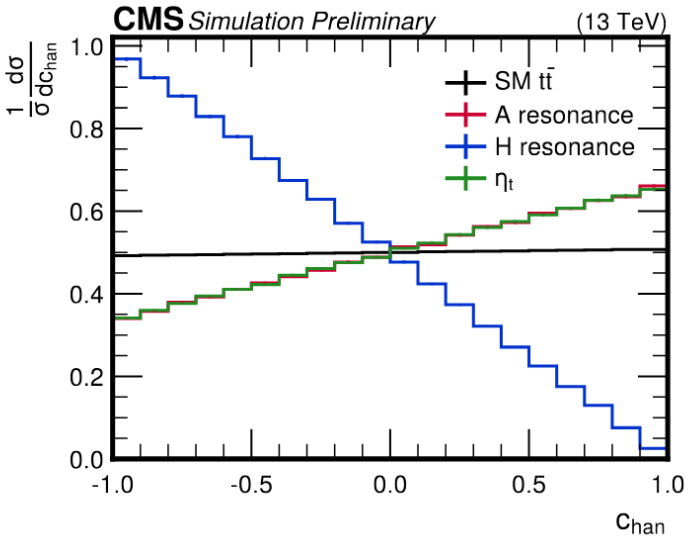
More on $t\bar{t}$ spin correlations:
1508.05271
2106.09690
CMS-PAS-HIG-22-013
Rübenach PhD Thesis
…

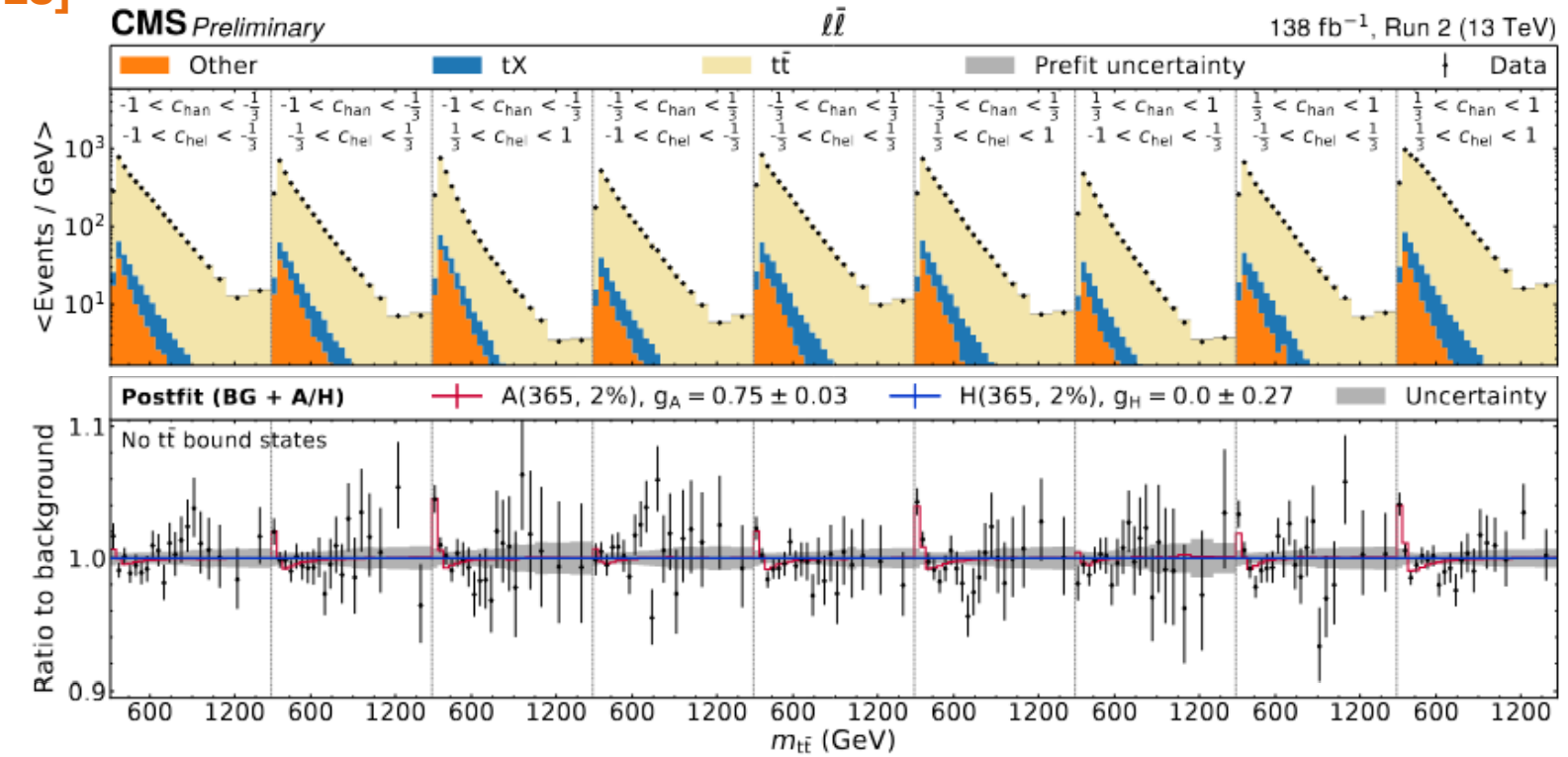
Already used in $t\bar{t}$ searches!

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

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







- > 5σ 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!

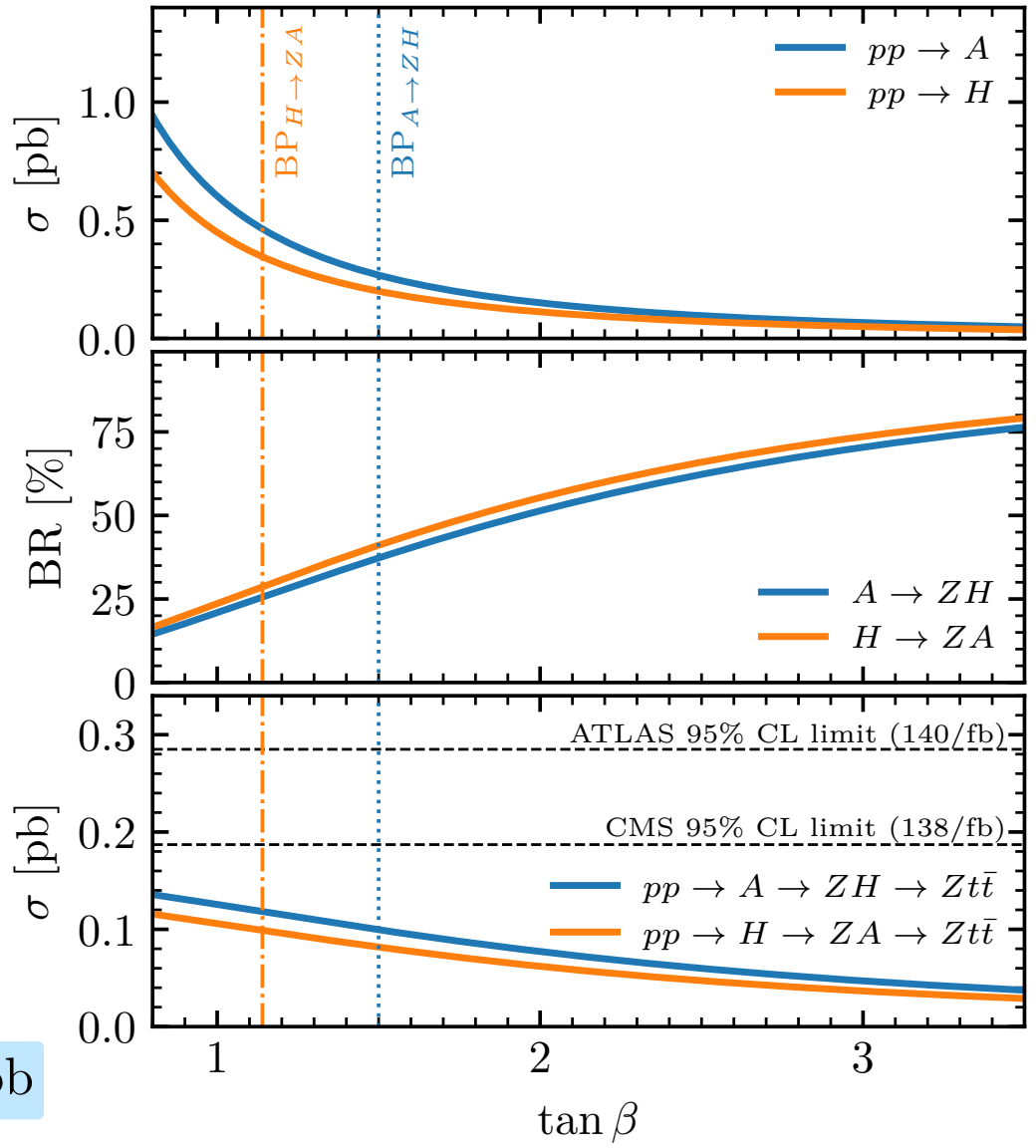
Benchmark point scenarios with the same cross section

Potentially observable at the HL-LHC

- Two benchmark points such that they have the **same total cross section**
  - Tune the value of $\tan\beta$

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

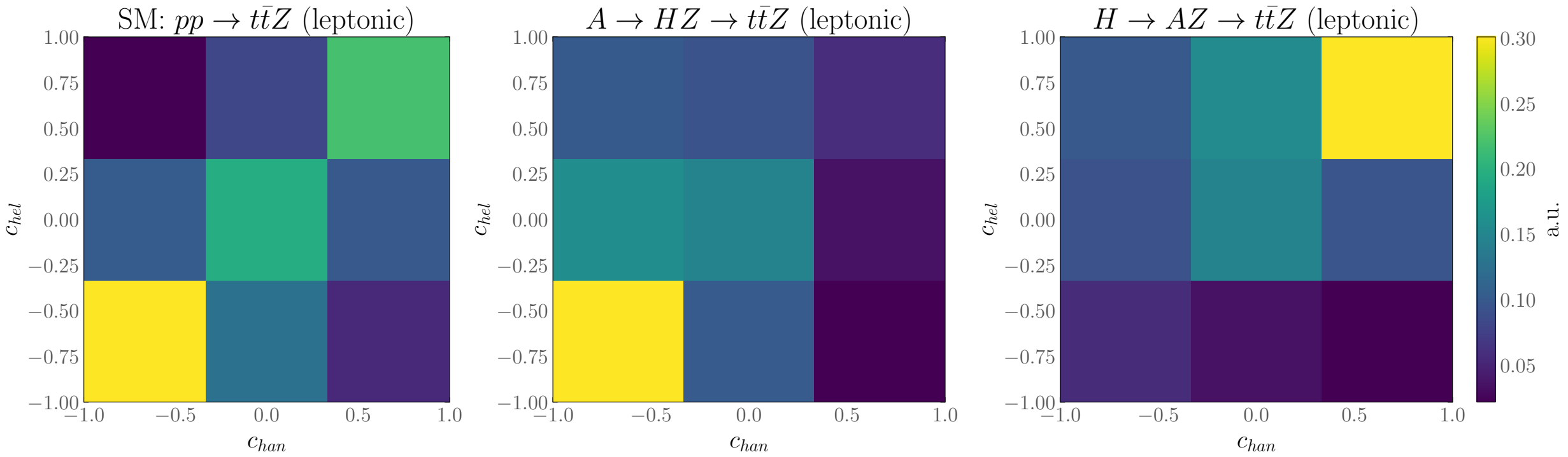


$$\sigma(gg\to A\to ZH\to Zt\bar{t}) = \sigma(gg\to H\to ZA\to Zt\bar{t}) = 0.1\ \mathrm{pb}$$

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

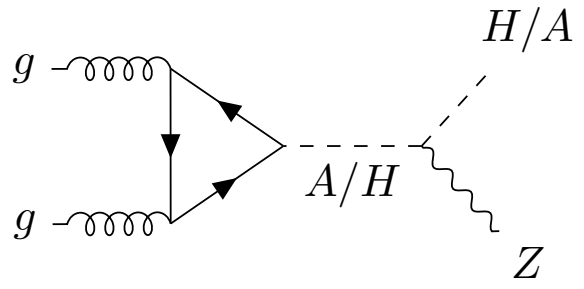
The two signals become potentially distinguishable!

- Cross section 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 [2312.04450]

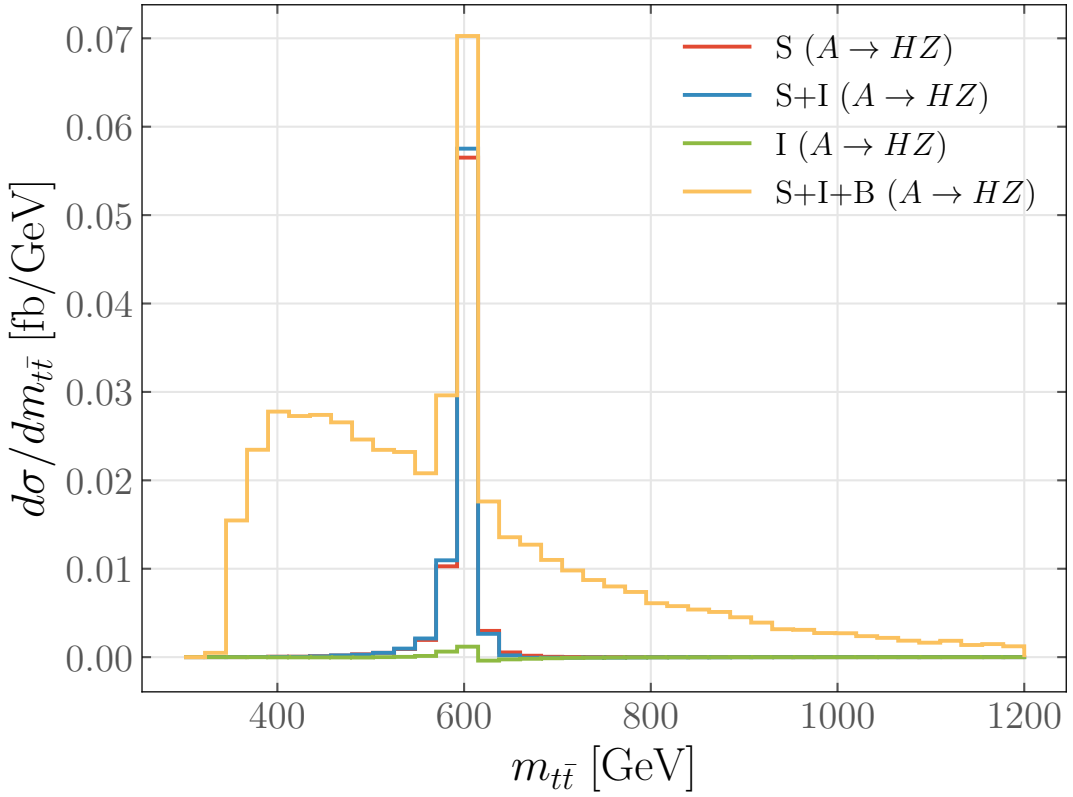
- $p_T(\ell) > 20\ \text{GeV}, \quad |\eta(\ell)| < 2.5, \quad |m_Z - m_{\ell\ell}| < 20\ \text{GeV}, \quad p_T(j) > 20\ \text{GeV}, \quad |\eta(j)| < 2.5$
- Two pairs of opposite-sign same-flavor leptons with $p_T(\ell_{\text{leading}}) > 27\ \text{GeV}$

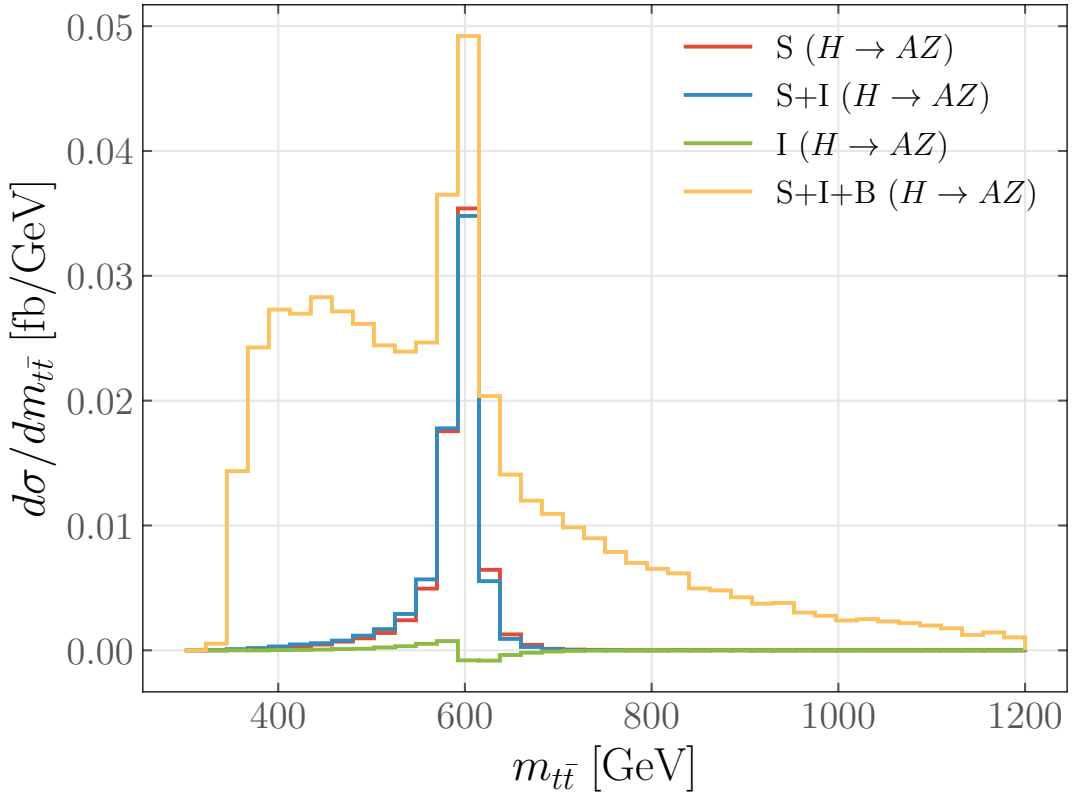
Efficiency factors

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

Signal and background interference

Not very large, but it is included



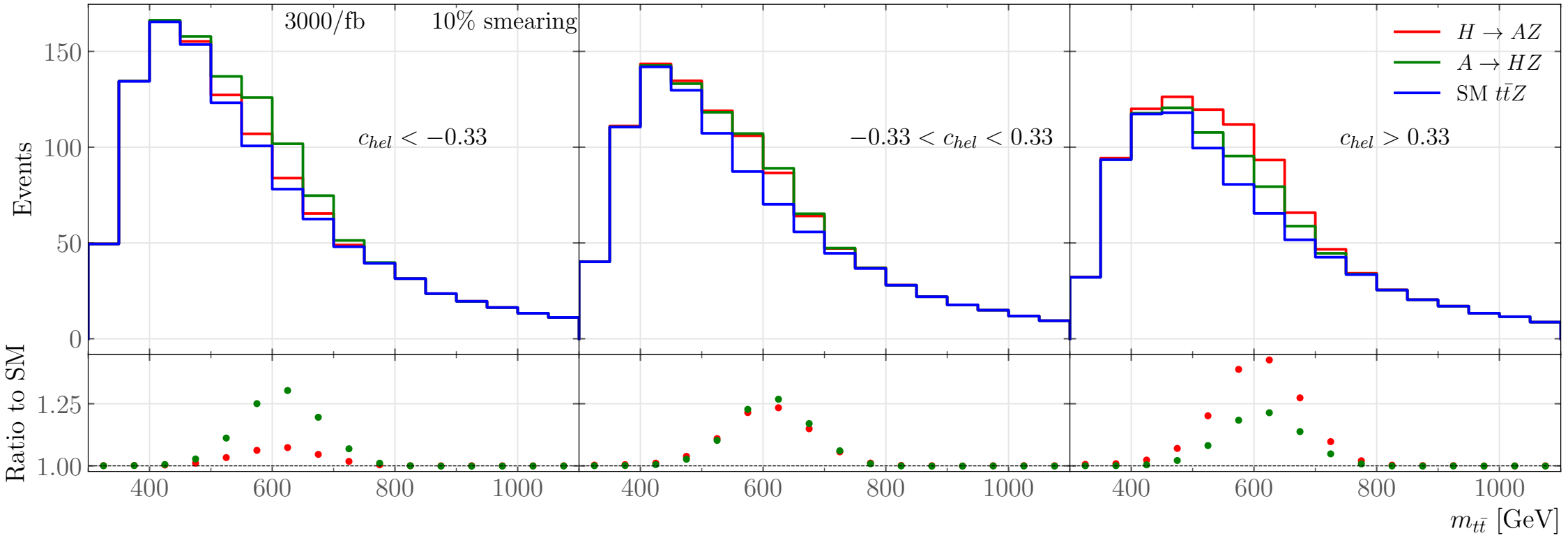


Results: di-top invariant mass distributions

Bins in c_{hel}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!



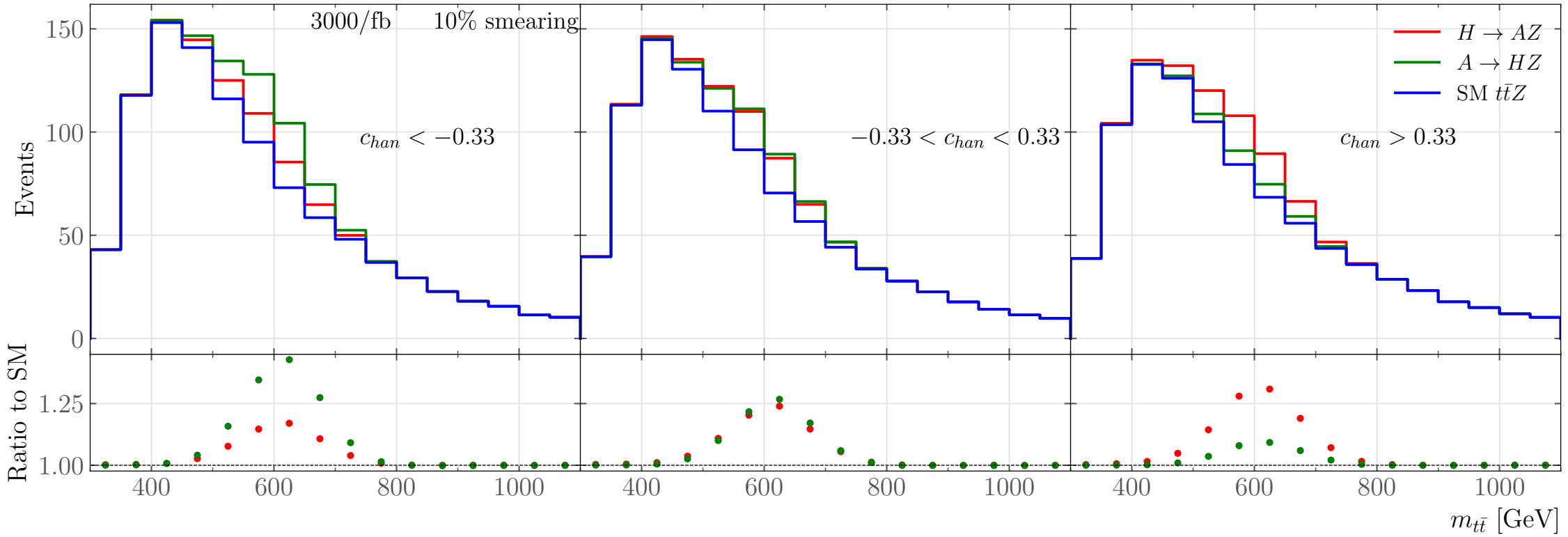
Both signals become distinguishable!!

Results: di-top invariant mass distributions

Bins in c_{han}

$A \to HZ$ more prominent!

$H \to AZ$ more prominent!

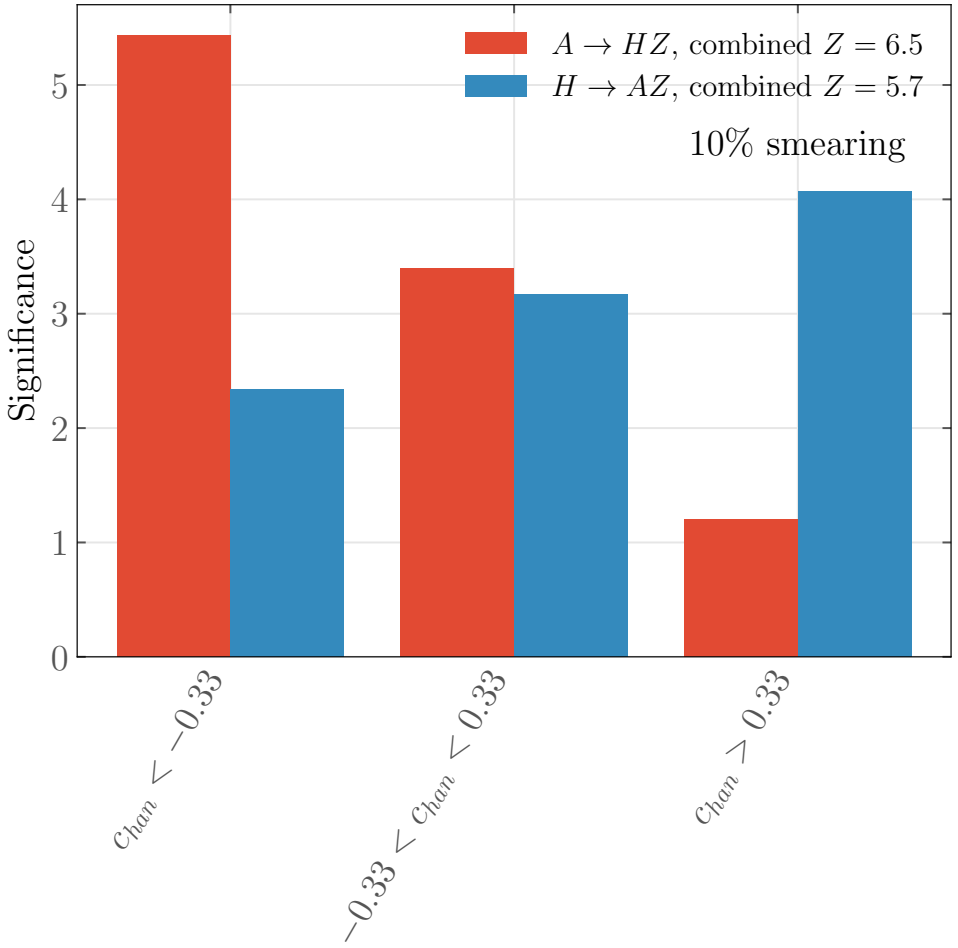


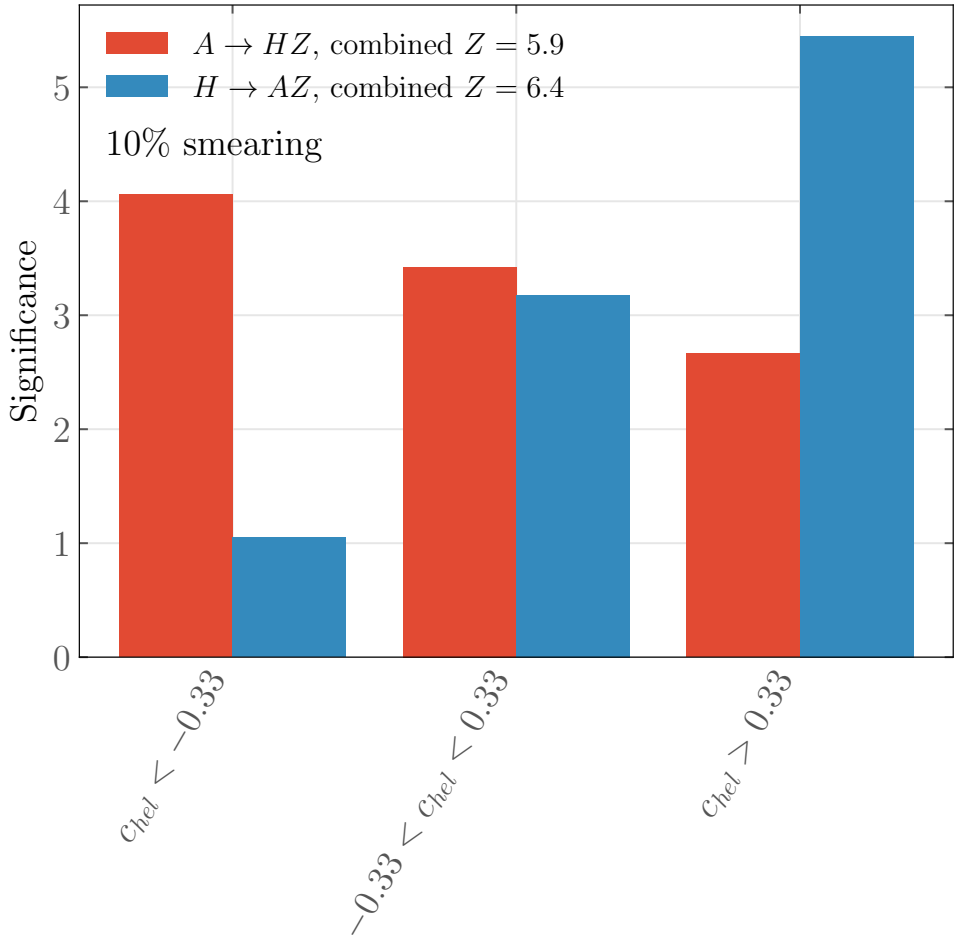
Both signals become distinguishable!!

Results: significance Z at the HL-LHC

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

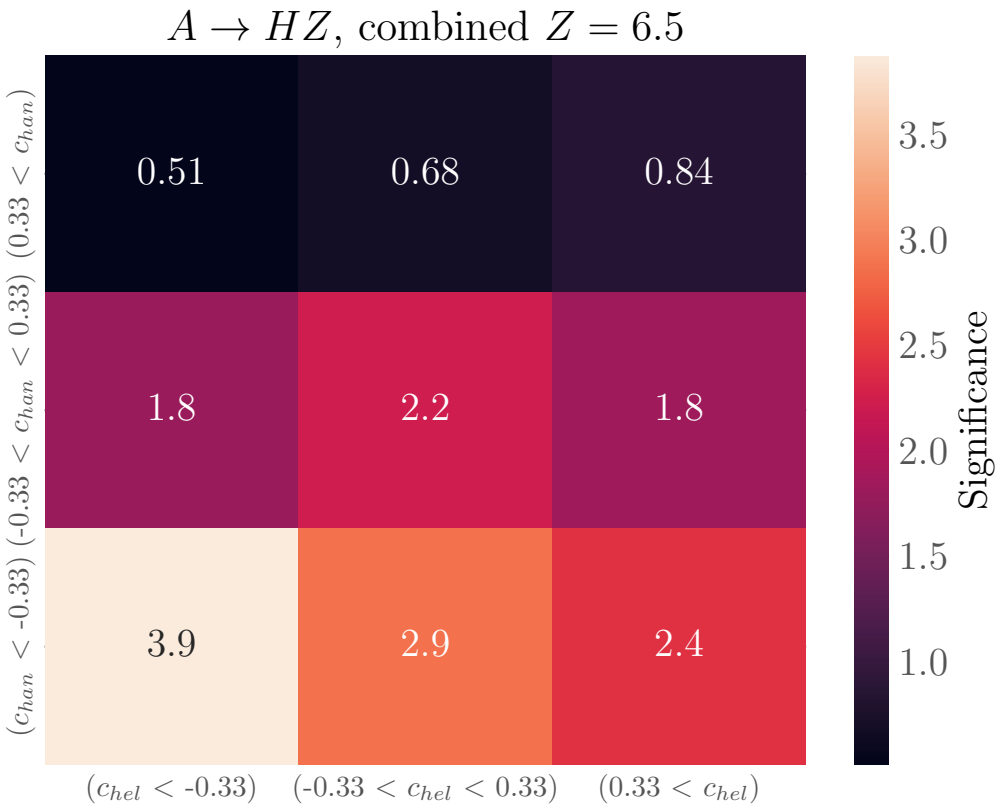


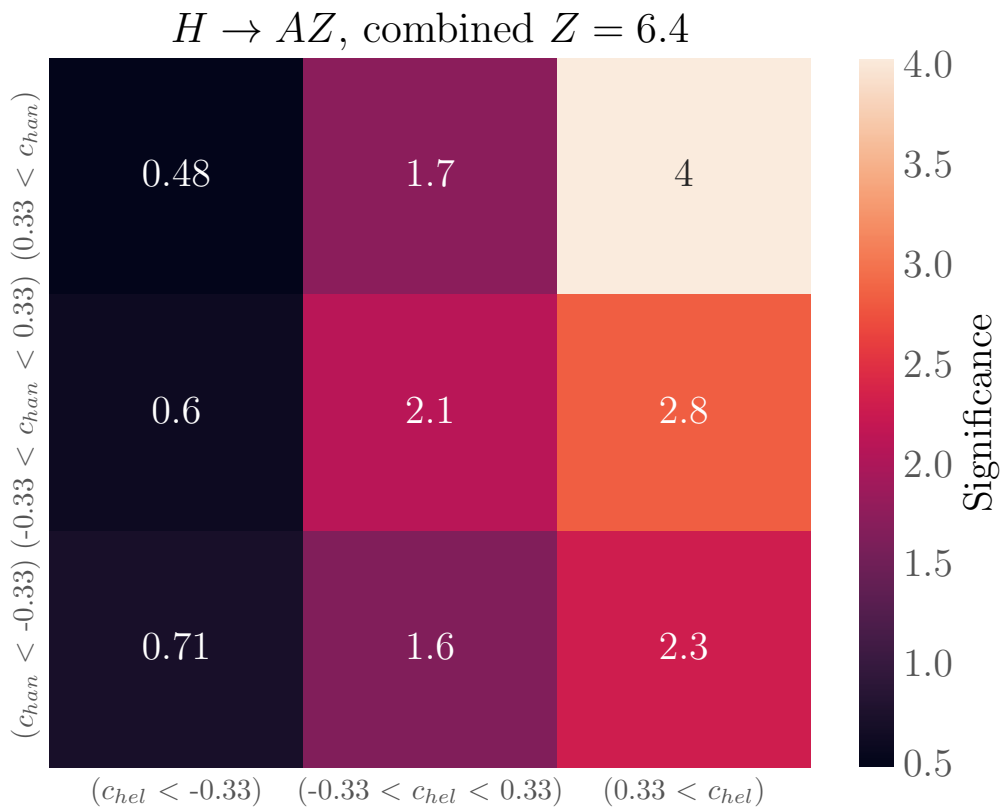


Results: significance Z at the HL-LHC

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



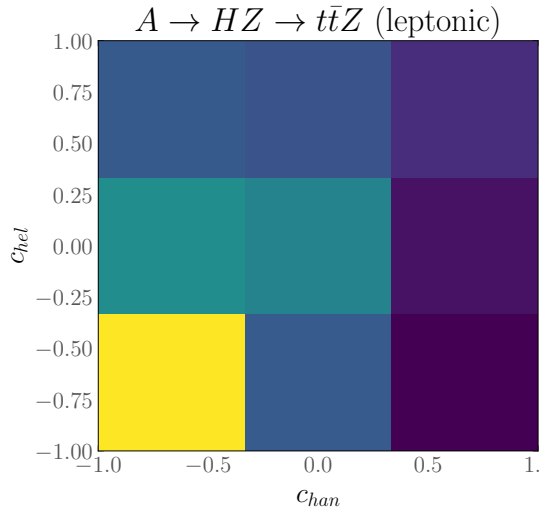


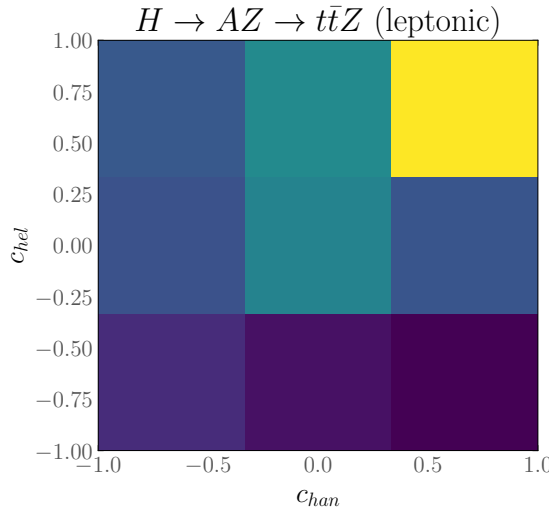
Summary & Conclusions

- One of the key collider probes of an SFOEWPT in the 2HDM is the **"smoking gun" signature**
- Experimentally, there is no sensitivity between

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

- **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!



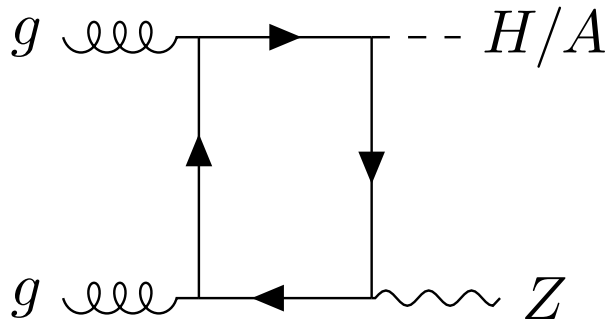


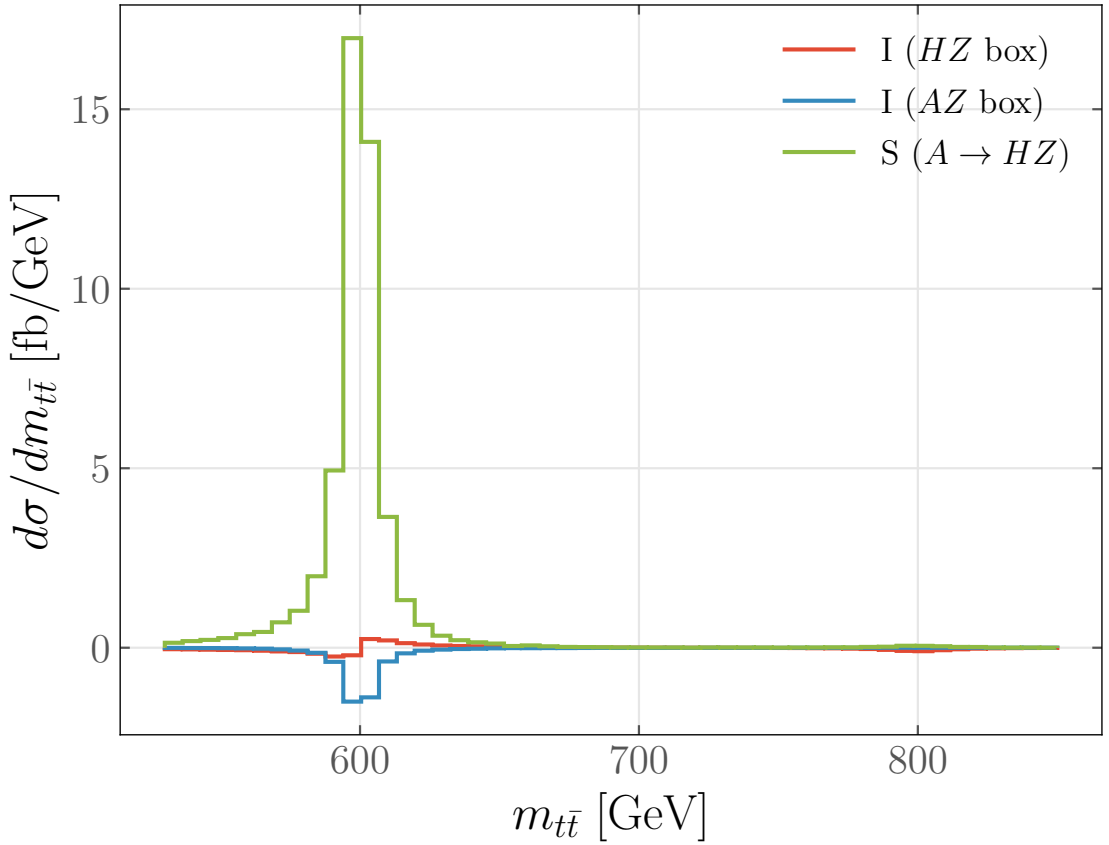
Thank you!

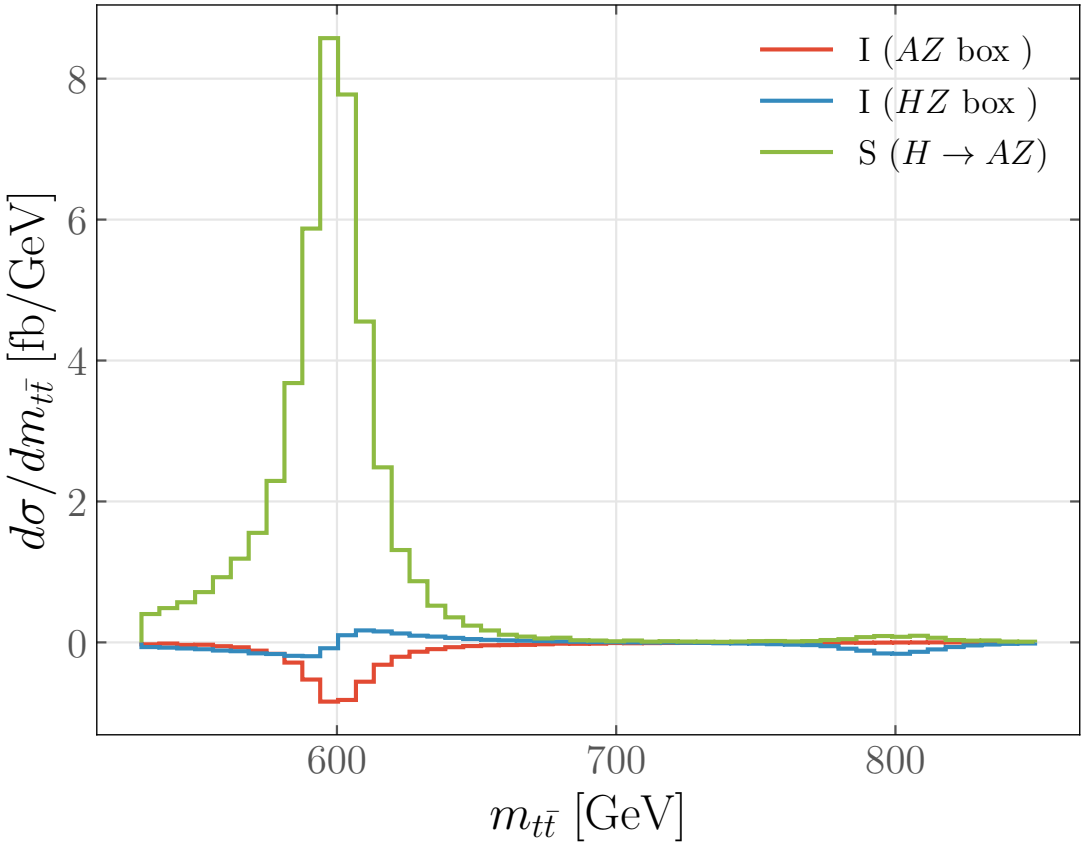
Back-up

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