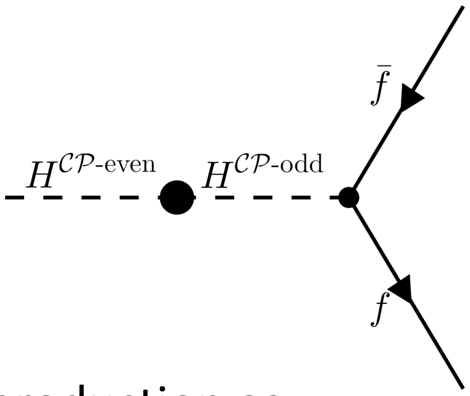
CP structure of the top-Yukawa interaction: Phenomenology status and prospects

Henning Bahl

THE UNIVERSITY OF CHICAGO

LHC Higgs WG2 meeting, 12/10/2022

A CP-violating top-Yukawa coupling?

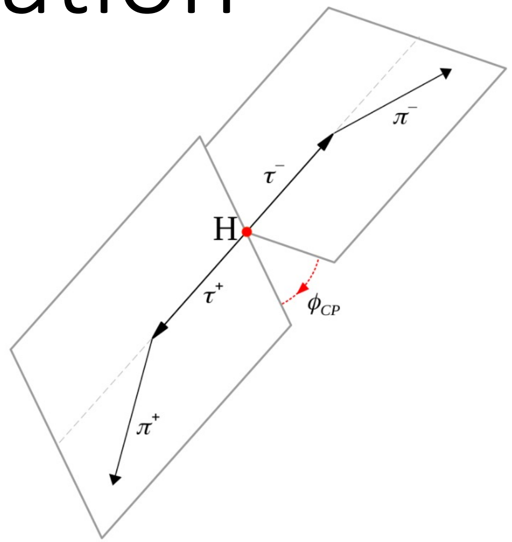


- CP violation can manifest in many Higgs couplings.
- CP violation in HVV couplings already tightly constrained via VBF and $pp \to VH$ production as well as $H \to 4l$ decay. [ATLAS,CMS: ...,2002.05315, 2104.12152,2109.13808,2202.06923,2205.05120]
- CP-violating HVV coupling can only be induced at the loop level → expected to be small in most BSM theories.
- CP violation in Higgs–fermion couplings can be induced at the tree level.
- The largest Higgs–fermion coupling is the top-Yukawa coupling making it the prime target for current and future studies.

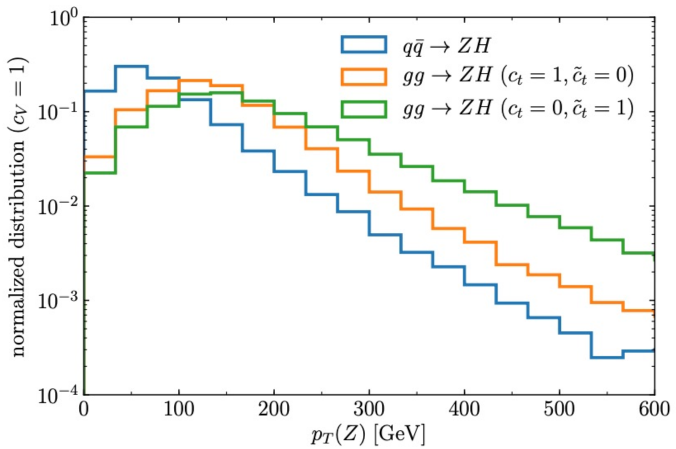
Focus of this talk: Overview of current status and prospects for constraining the CP structure of the **top-Yukawa coupling at the LHC**.

Note: Most studies concentrate on $t\bar{t}H$, but also tH, tWH, $t\bar{t}$, … have been studied and can potentially be important.

Different methods to constrain CP violation



1. **Direct approach — pure CP-odd observables**:
   - Unambiguous markers for CP violation: e.g.
     - EDM measurements,
     - decay angle in $H \to \tau^+\tau^-$.
   - Experimentally difficult since often polarization information is needed.
2. **Indirect approach — pure CP-even observables**:
   - Many rate measurements are indirectly sensitive: e.g. ggH or $H \to \gamma\gamma$.
   - Deviations from SM need not be due to CP violation.
3. **Kinematic approach:**
   - CP-odd coupling affects kinematics.
   - High sensitivity expected if all available kinematic information is used.
   - Deviations from SM do not have to be due to CP violation.



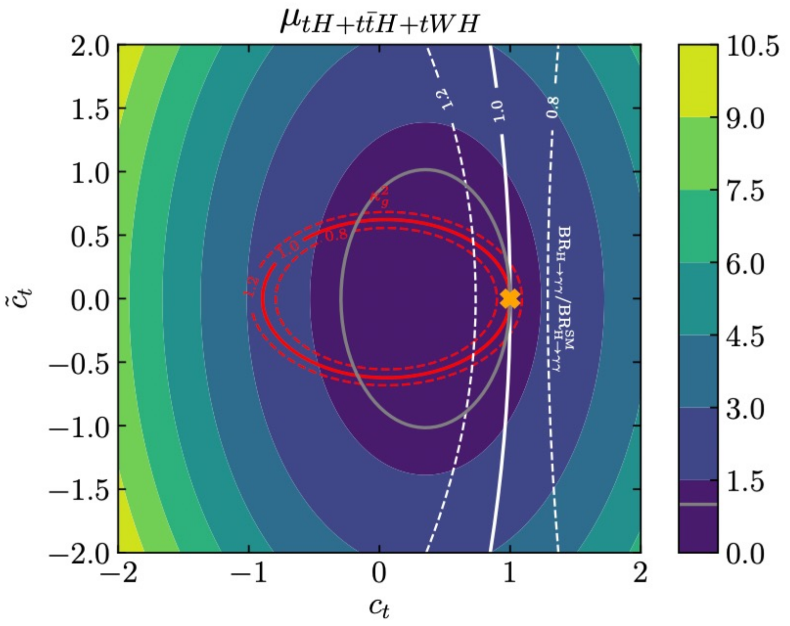
➡ Exploit all three complementary approaches to learn as much as possible!

CP-sensitive rate measurements

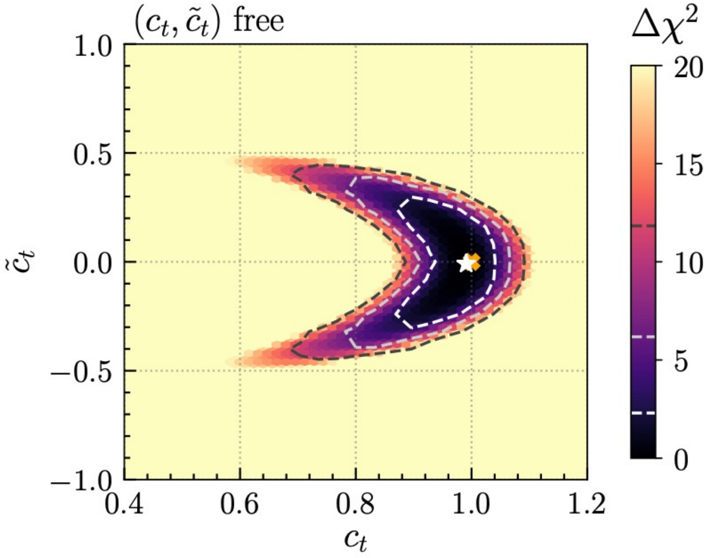
[Freitas `12; Djouadi `13; Agrawal `12; Ellis `13; Chang `14; He `15; Boudjema `15; Demartin `15,`16; Kobakhidze `16; Hou `18; Cao `19; Fuchs `20; HB `20, `22;  Brod `22]

- The total rate of many processes is indirectly sensitive to the CP structure of the top-Yukawa coupling:

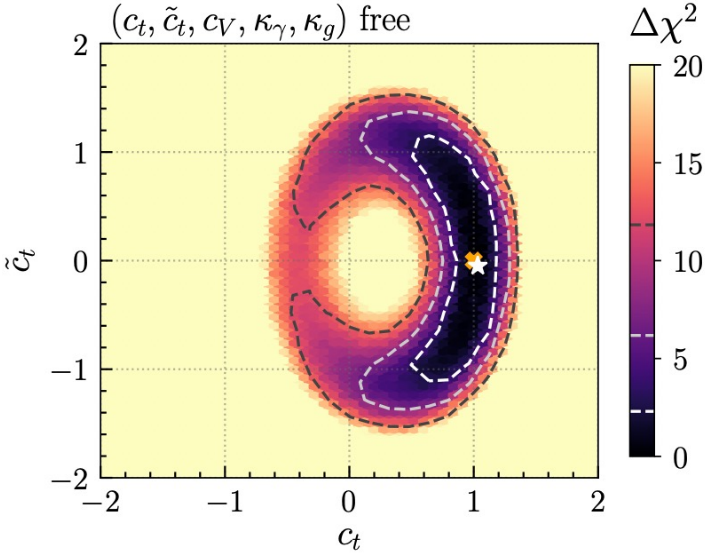
  $gg \to H, H \to \gamma\gamma, t\bar{t}H, tH, tWH, gg \to ZH, t\bar{t}, t\bar{t}t\bar{t}$, etc.



calculate $gg \to H, H \to \gamma\gamma$ in terms of $c_t, \tilde{c}_t$



float $gg \to H, H \to \gamma\gamma$ freely



→ To improve indirect constraints in the future, need to disentangle channels ($t\bar{t}H$ vs tH, $q\bar{q} \to ZH$ vs $gg \to ZH$).

CP-odd observables for $t\bar{t}H$

[Ellis `13; Boudjema `15; Buckley `15; Mileo `16; Azevedo `17; Goncalves `18; Faroughy `19; Bortolato `20; Goncalves `21; Barman `21; Azevedo `21]

- Writing $\mathcal{L}_{\text{top-Yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}(c_t + i\gamma_5\tilde{c}_t)tH$, we can split up the $t\bar{t}H$ amplitude into a CP-even and a CP odd part: $\mathcal{M}_{t\bar{t}H} = c_t\mathcal{M}_{t\bar{t}H}^{\text{CP-even}} + \tilde{c}_t\mathcal{M}_{t\bar{t}H}^{\text{CP-odd}}$.
- The squared amplitude is then decomposed as:

$$|\mathcal{M}_{t\bar{t}H}|^2 = c_t^2\left|\mathcal{M}_{t\bar{t}H}^{\text{CP-even}}\right|^2 + 2c_t\tilde{c}_t Re[\mathcal{M}_{t\bar{t}H}^{\text{CP-even}}\mathcal{M}_{t\bar{t}H}^{\text{CP-odd}^*}] + \tilde{c}_t^2\left|\mathcal{M}_{t\bar{t}H}^{\text{CP-odd}}\right|^2$$

- CP violation is only caused by the second term, which involves a factor

$$\text{Tr}[\gamma^\mu\gamma^\nu\gamma^\sigma\gamma^\rho\gamma^5] \propto \epsilon^{\mu\nu\rho\sigma}$$

⇒ At least four independent four-vectors are needed to construct CP-odd observables.

⇒We need to reconstruct the top-quark polarization vectors.

CP-odd observables for $t\bar{t}H$ – top decays

- The polarization of the top-quarks can be reconstructed from the top decay products: works best for leptons, worse for light jets, even worse for b-jets and W bosons.

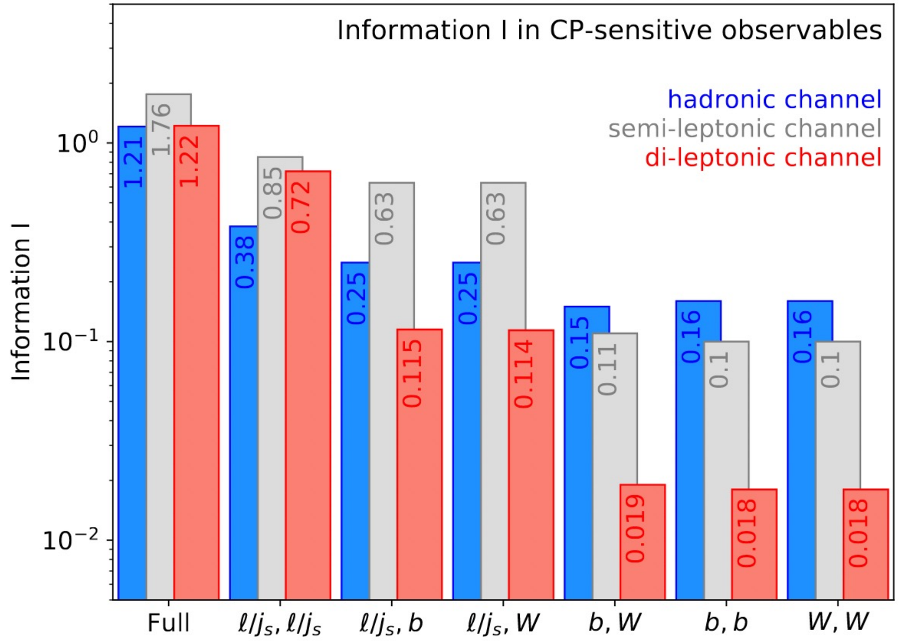
  ⇒ Trade-off between rate and spin analyzing power.

- In the $t\bar{t}$ rest frame. the CP-odd observables can be written in the form

$$\Delta\phi_{ik}^{t\bar{t}} = \mathrm{sgn}\left[\vec{p}_t \cdot (\vec{p}_i \times \vec{p}_k)\right] \arccos\left[\frac{\vec{p}_t \times \vec{p}_i}{|\vec{p}_t \times \vec{p}_i|} \cdot \frac{\vec{p}_t \times \vec{p}_k}{|\vec{p}_t \times \vec{p}_k|}\right].$$

⇒ $\Delta\phi_{\ell\ell}^{t\bar{t}}$ and $\Delta\phi_{\ell j_{\mathrm{soft}}}^{t\bar{t}}$ most promising.

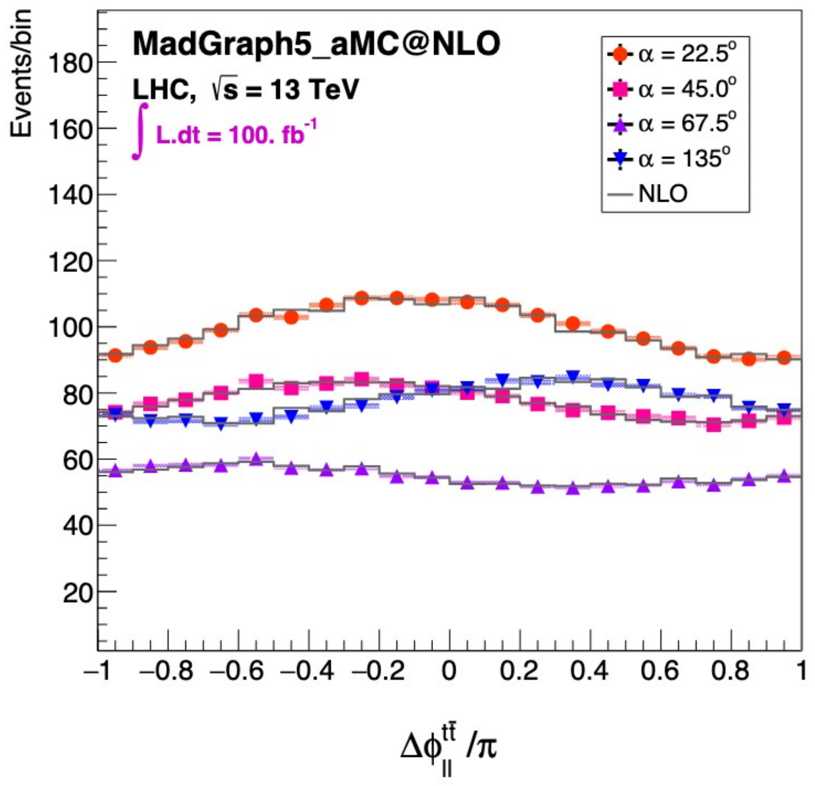
[Barman `21]

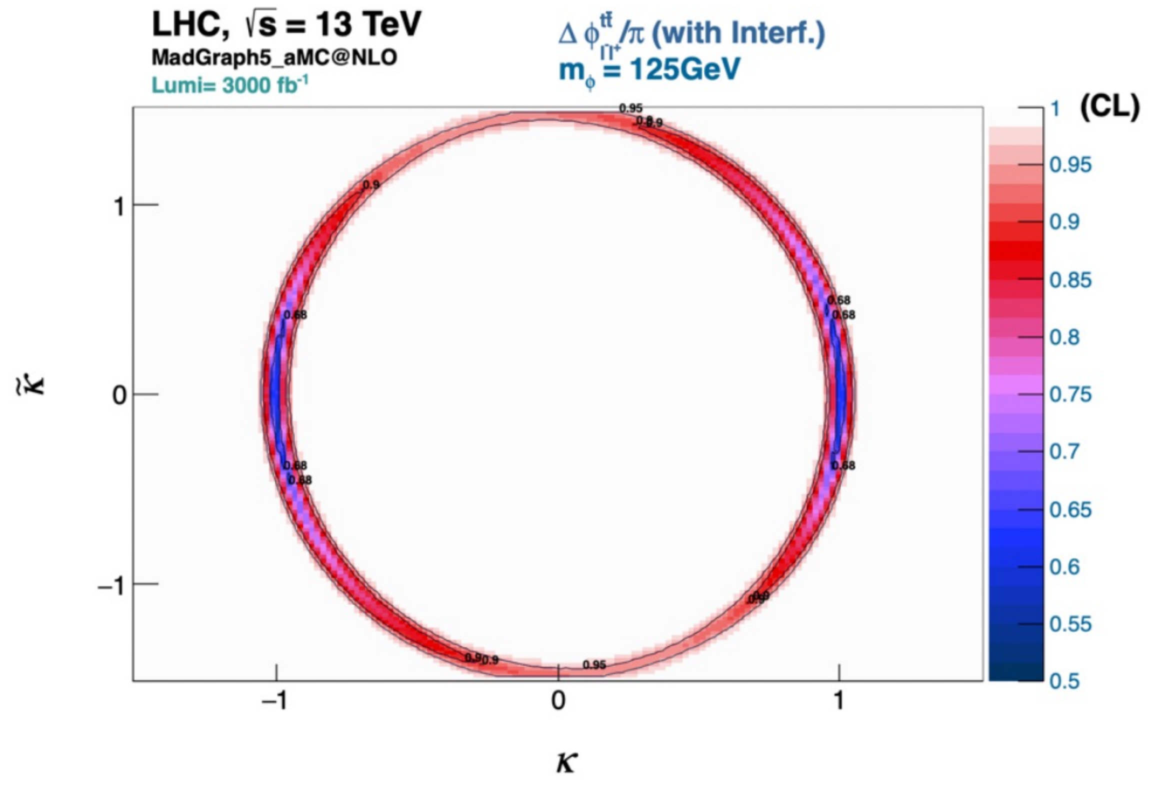


CP-odd observables for $t\bar{t}H$ – HL-LHC sensitivity.

[Azevedo, Capucha, Onofre, Santos `22]

$$\mathcal{L} = \kappa_t y_t \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)t\phi \; = y_t\bar{t}(\kappa + i\gamma_5\tilde{\kappa})t\phi,$$





After taking into account shower and detector effects, CP asymmetries are quite small
⇒ Interference term will be hard to measure even at HL-LHC.

Kinematic approach – CP-sensitive observables I

[Gunion `96; Ellis `13; Yue `14; Demartin `14,`15,`16; He `15; Buckley `15; Gritsan `16; Azevedo `17; Goncalves `18; Cao `20; Barman `21; HB `21; Azevedo `22; ATLAS `22]

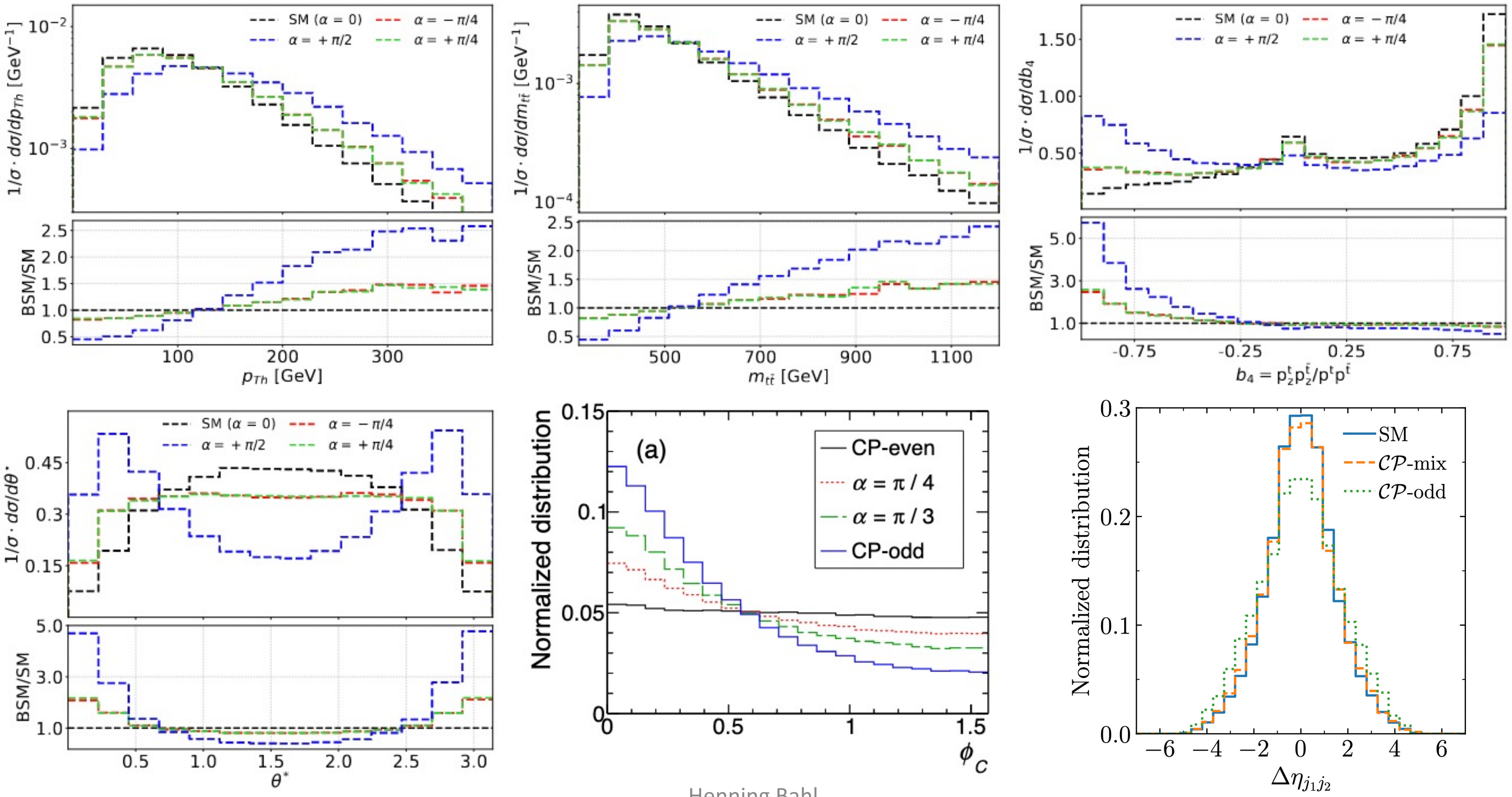
Various CP-sensitive (but not CP-odd) observables have been investigated and used in the literature:

- Higgs transverse momentum: $p_{T,\mathrm{H}}$,
- invariant mass of the top-quark system: $m_{t\bar{t}}$,
- angle between top-beam and anti-top-beam planes: $b_2 = (\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n}) / (|\vec{p}_t||\vec{p}_{\bar{t}}|)$
- projection of top-quark momenta: $b_4 = p_t^z p_{\bar{t}}^z / p_t p_{\bar{t}}$,
- angle between the top quark and the beam direction in the $t\bar{t}$ CM frame: θ^*,
- angular separations between the two leading jets: $\Delta\phi_{j_1 j_2}$, $\Delta\eta_{j_1 j_2}$,
- angle between plane of incoming protons and $t\bar{t}$ plane in Higgs CMS: ϕ_C
- etc.

→ Sensitivity of various observables depends on Higgs decay process, kinematic region, …

Kinematic approach – CP-sensitive observables II

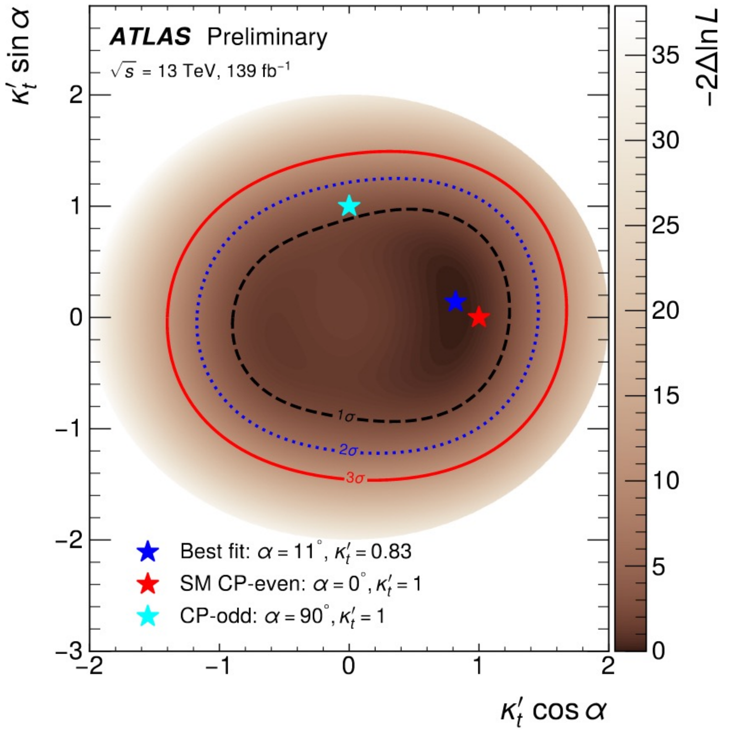
[Cao, Xie, Zhang, Zhang `20; Barman, Goncalves, Kling `21; HB, Brass `21]

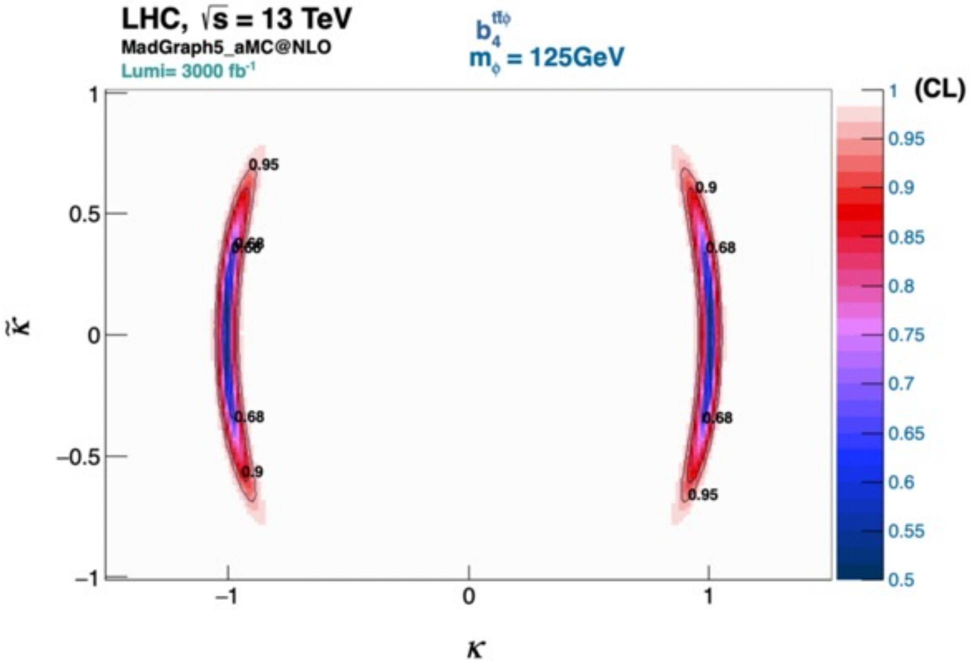


Kinematic approach – CP-sensitive observables III

[Azevedo `22, ATLAS `22]

(projected) limits for $t\bar{t}H$ with $H \to \bar{b}b$ based on CP-sensitive observables:





Kinematic approach – multivariate analyses I

[Gritsan`16; Ren `19; Kraus `19; CMS `20, `21, `22; ATLAS `20, `22; Martini `21; Butter `22]

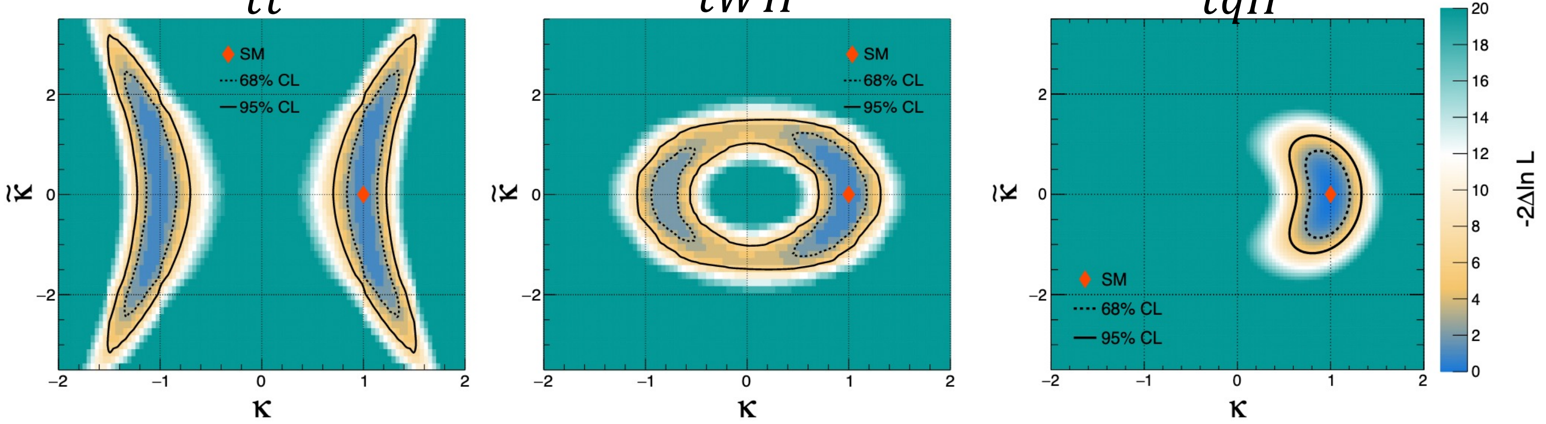
1. **Matrix-element approach**:

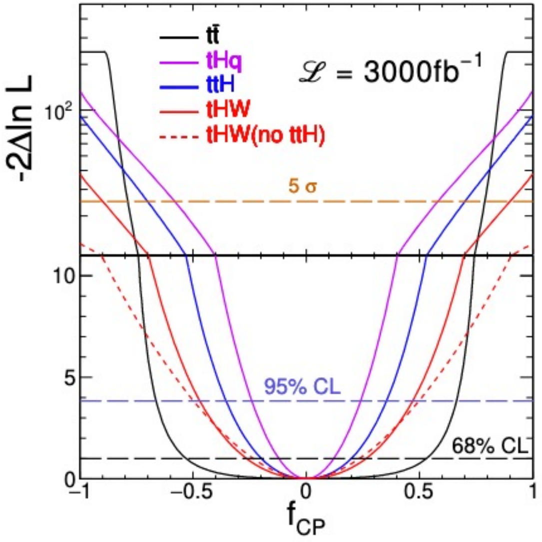
Transfer function

$$P(\mathbf{x}|\alpha) = \frac{1}{\sigma(\alpha)} \int d^n y \, \frac{d^n\sigma(\mathbf{y}|\alpha)}{dy_1 ... dy_n} \, W(\mathbf{y}, \mathbf{x}) \qquad - \log(\mathcal{L}) = - \sum_{i=1}^{N} \log(P(\mathbf{x}_i|\alpha))$$

Transfer function encodes parton shower and detector effects.

$t\bar{t}$ $\qquad$ tWH $\qquad$ tqH





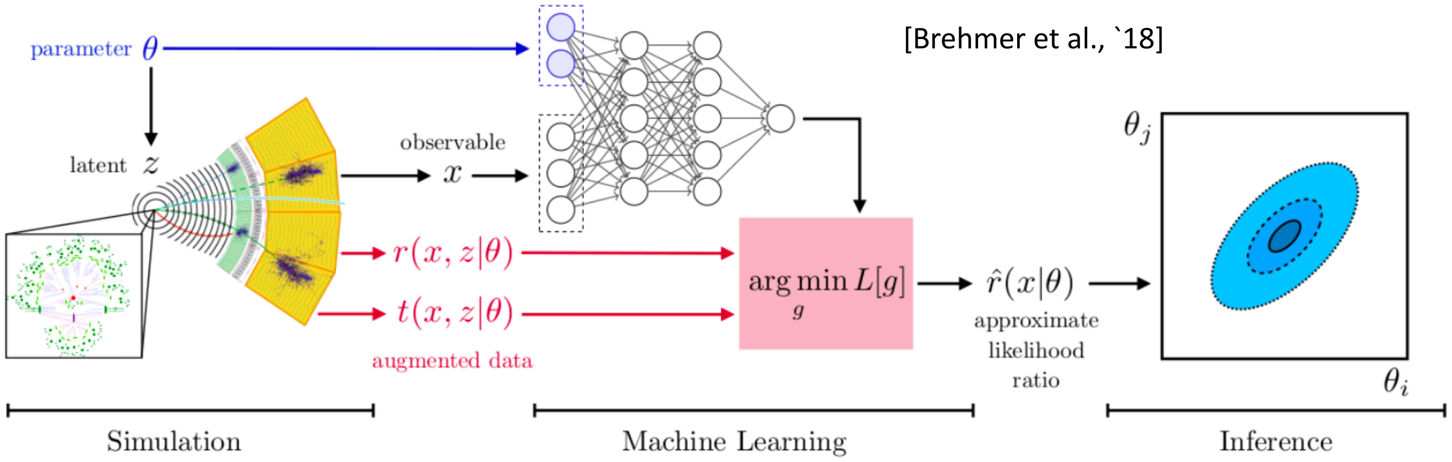
$$f_{CP} = \frac{|\tilde{\kappa}|^2}{|\kappa|^2 + |\tilde{\kappa}|^2} \text{sign}\left(\frac{\tilde{\kappa}}{\kappa}\right)$$

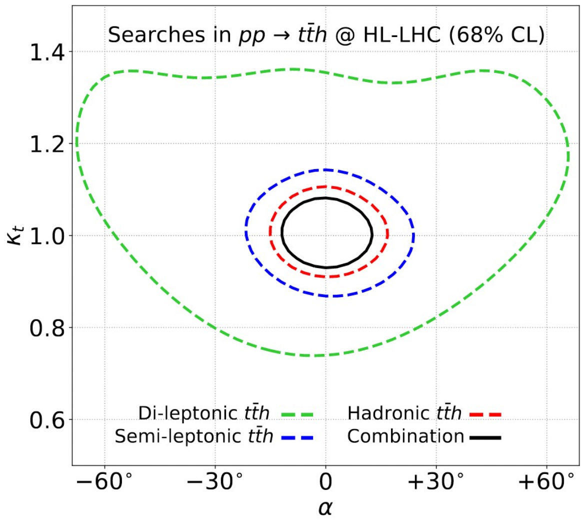
2. **BDTs**: Train BDT to differentiate CP-even and CP-odd events.

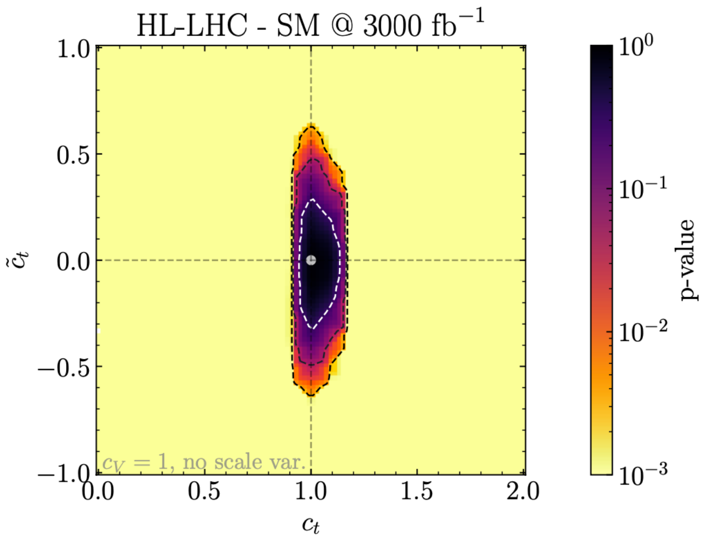
Kinematic approach – multivariate analyses II

[Barman `21; HB `21]

3. **Machine-learning-based inference**: Train neural network to learn likelihood directly.



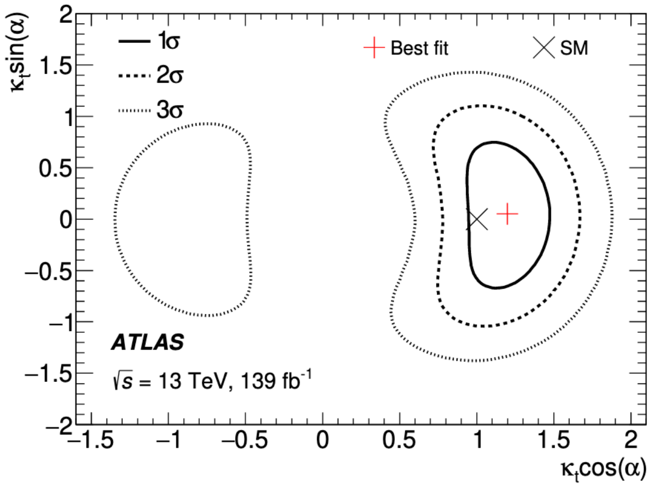


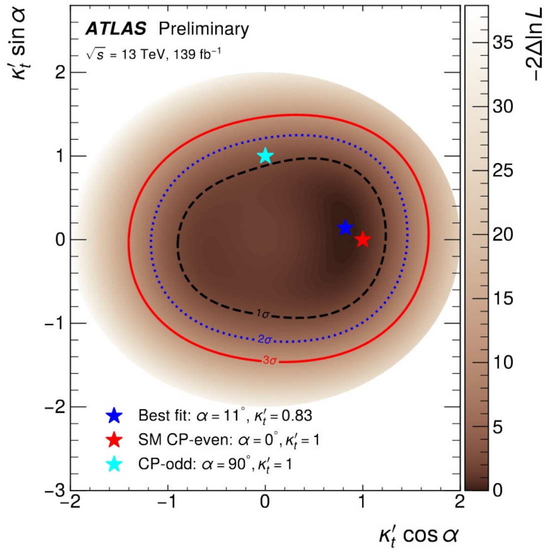


Experimental results

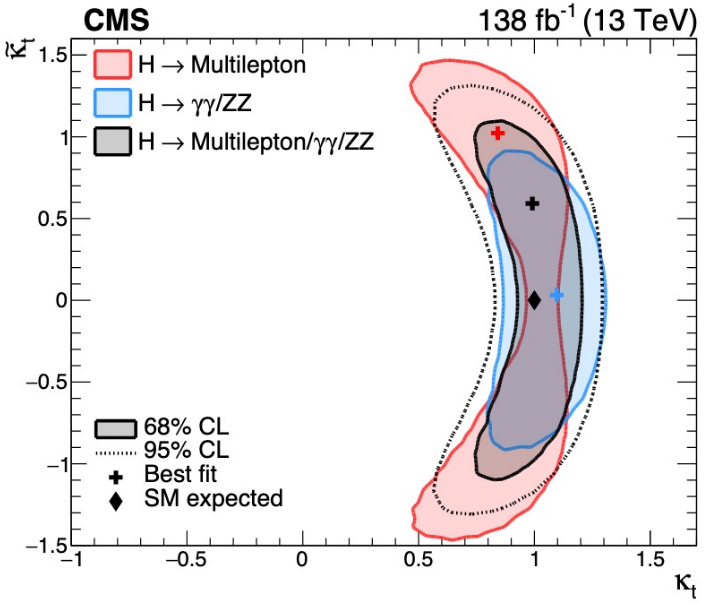
Several Run-2 results are already available:

- ATLAS: [2004.04545, ATLAS-CONF-2022-016]
  - $t\bar{t}H + tH$ with $H \to \gamma\gamma$ (BDTs)
  - $t\bar{t}H + tH$ with $H \to \bar{b}b$ (CP-sensitive observables + BDTs)





- CMS: [2003.10866,2104.12152,2208.02686]
  - $t\bar{t}H$ with $H \to \gamma\gamma$ (BDTs)
  - $t\bar{t}H$ with $H \to 4l$ (BDTs)
  - $t\bar{t}H + tH$ with $H \to WW, \tau\tau$ (BDTs)



Literature overview

Indirect approach via rate measurements

- Freitas & Schwaller, https://arxiv.org/pdf/1211.1980.pdf
- Agrawal et al., https://arxiv.org/pdf/1211.4362.pdf
- Djouadi & Moreau, https://arxiv.org/pdf/1303.6591.pdf
- Ellis et al., https://arxiv.org/pdf/1312.5736.pdf
- Chang et al., https://arxiv.org/pdf/1403.2053.pdf
- He et al., https://arxiv.org/pdf/1501.00012.pdf
- Boudjema et al., https://arxiv.org/pdf/1501.03157.pdf
- Demartin et al., https://arxiv.org/pdf/1504.00611.pdf
- Demartin et al., https://arxiv.org/pdf/1607.05862.pdf
- Kobakhidze et al., https://arxiv.org/pdf/1610.06676.pdf
- Hou et al., https://arxiv.org/pdf/1806.06018.pdf
- Cao et al., https://arxiv.org/pdf/1901.04567.pdf
- Fuchs et al., https://arxiv.org/pdf/2003.00099.pdf
- Brod et al., https://arxiv.org/pdf/2203.03736.pdf
- Bahl et al. https://arxiv.org/pdf/2007.08542.pdf
- Bahl et al. https://arxiv.org/pdf/2202.11753.pdf

CP-sensitive observables

- Gunion & He, https://arxiv.org/pdf/hep-ph/9602226.pdf
- Ellis et al., https://arxiv.org/pdf/1312.5736.pdf
- Yue, https://arxiv.org/pdf/1410.2701.pdf
- Demartin et al., https://arxiv.org/pdf/1407.5089.pdf
- He et al., https://arxiv.org/pdf/1501.00012.pdf
- Demartin et al., https://arxiv.org/pdf/1504.00611.pdf
- Buckley & Goncalves, https://arxiv.org/pdf/1507.07926.pdf
- Demartin et al., https://arxiv.org/pdf/1607.05862.pdf
- Gritsan et al., https://arxiv.org/pdf/1606.03107.pdf
- Azevedo et al., https://arxiv.org/pdf/1711.05292.pdf
- Goncalves et al., https://arxiv.org/pdf/1804.05874.pdf
- Cao et al., https://arxiv.org/abs/2008.13442
- Martini et al., https://arxiv.org/pdf/2104.04277.pdf
- Barman et al., https://arxiv.org/pdf/2110.07635.pdf
- Bahl & Brass, https://arxiv.org/pdf/2110.10177.pdf
- Azevedo et al., https://arxiv.org/pdf/2208.04271.pdf

Multivariate analyses

- Gritsan et al., https://arxiv.org/pdf/1606.03107.pdf
- Ren et al., https://arxiv.org/pdf/1901.05627.pdf
- Kraus et al., https://arxiv.org/pdf/1908.09100.pdf
- Martini et al., https://arxiv.org/pdf/2104.04277.pdf
- Barman et al., https://arxiv.org/pdf/2110.07635.pdf
- Bahl & Brass, https://arxiv.org/pdf/2110.10177.pdf
- Butter et al., https://arxiv.org/pdf/2210.00019.pdf

Experimental results

- CMS, https://arxiv.org/pdf/2003.10866.pdf
- ATLAS, https://arxiv.org/pdf/2004.04545.pdf
- CMS, https://arxiv.org/pdf/2104.12152.pdf
- CMS, https://arxiv.org/pdf/2208.02686.pdf
- ATLAS, http://cds.cern.ch/record/2805772/files/ATLAS-CONF-2022-016.pdf

Conclusions

- Many BSM theories predict largest amount of CP violation in Higgs–fermion couplings.

  → much work has been invested in constraining the CP character of the top-Yukawa interaction.
- Three different approaches can be pursued:
  - Indirect approach based on rate measurements

    → very strong but model-dependent constraints.
  - Direct approach based on CP-odd observables

    → easily interpretable results but low sensitivity.
  - Kinematic approach (specific observables or multivariate analysis)

    → strong constraints possible but deviations need not be due to CP violation.

➡ Exploit all three complementary approaches to learn as much as possible!

Thanks for your attention!