Probing the Higgs boson CP properties in the SMEFT

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LPTHE / UPMC

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Outline

Effective field theories for new physics

- The effective field theory (EFT) approach for new physics
  - All new phenomena are assumed to appear at a large energy scale Λ
  - Departures from the Standard Model expressed as a series in $1/\Lambda$
    - In terms of the SM fields (no assumption on the form of new physics)
    - Addition of higher-dimensional operators
    - Leading effects usually assumed to be of dimension six (sometimes dimension-eight operators are relevant as well)
  - Not predictive at scales larger than Λ (loss of unitarity)

- The EFT parameter space is large (1 parameter / new operator)
  - Observables usually depend on specific linear combinations of coefficients
    - A much smaller subset of parameters is relevant with respect to data
    - EFT are testable

- Current data is constraining, but room for deviations still exists
  - Large classes fo scenarios feature CP-violating Higgs couplings

What are the current constraints?
What are the prospects?
Can we distinguish CP-violating from CP-conserving effects?

CP-violation in the gauge sector

✦ CP-violation in the gauge sector can be parameterized with 6 operators

$$\mathcal{L}^{(6)}_{\rm CPV} = \frac{ig}{\Lambda^2}\tilde{c}_{HW}\big[D_\mu\Phi^\dagger T_{2k} D_\nu\Phi\big]\widetilde{W}^{k,\mu\nu} + \frac{ig'}{\Lambda^2}\tilde{c}_{HB}\big[D_\mu\Phi^\dagger D_\nu\Phi\big]\widetilde{B}^{\mu\nu} + g'^2\frac{\tilde{c}_\gamma}{\Lambda^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu}$$
$$+ g_s^2\frac{\tilde{c}_g}{\Lambda^2}\Phi^\dagger\Phi G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a + g^3\frac{\tilde{c}_{3W}}{\Lambda^2}\epsilon_{ijk}W^i_{\mu\nu}W^{\nu j}{}_\rho\widetilde{W}^{\rho\mu k} + g_s^3\frac{\tilde{c}_{3G}}{\Lambda^2}f_{abc}G^a_{\mu\nu}G^{\nu b}{}_\rho\widetilde{G}^{\rho\mu c}$$

- ✤ CP-violating fermionic operators neglected
- ✤ Focus on electroweak Higgs production and decays: $\tilde{c}_{3G}$ irrelevant

5D parameter space: $\tilde{c}_{HW}, \tilde{c}_{HB}, \tilde{c}_\gamma, \tilde{c}_g, \tilde{c}_{3W}$

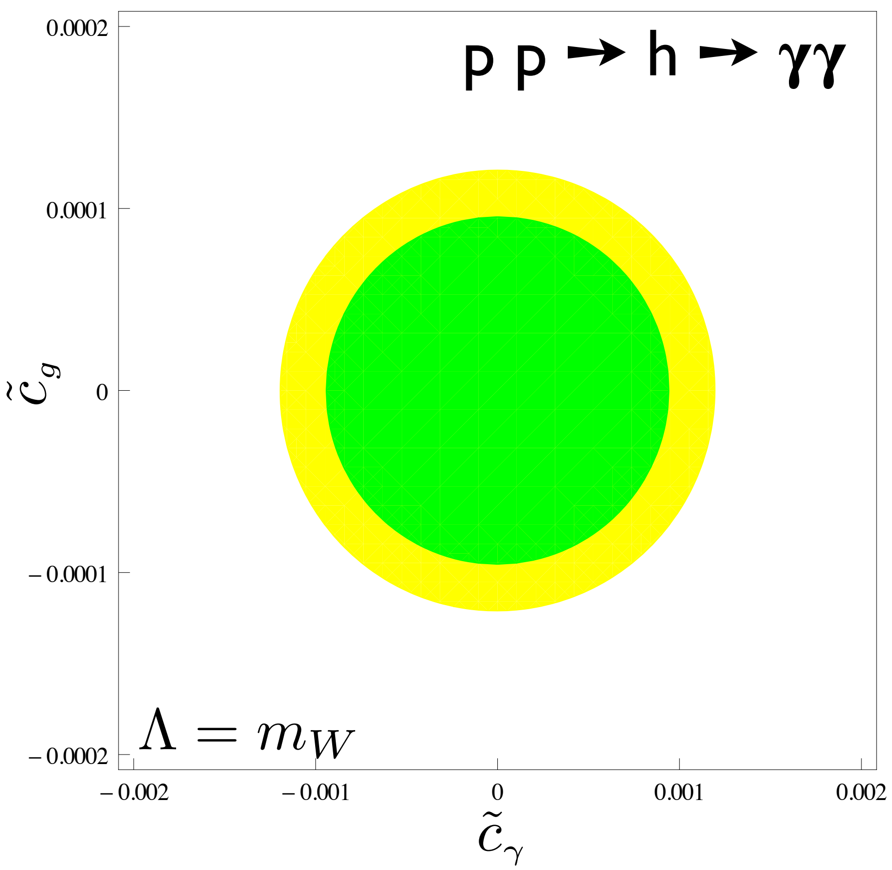
✦ Most stringent constraints: LHC and Tevatron signal strengths

- ✤ LHC Run I, p p → h → γγ: $\tilde{c}_\gamma, \tilde{c}_g$
- ✤ LHC Run I + Tevatron, VH + p p → h → 4l: $\tilde{c}_{HW}, \tilde{c}_{HB}$
- ✤ LHC Run I, WBF: $\tilde{c}_{HW}$
- ✤ LHC Run I, W-boson pair production: $\tilde{c}_{3W}$

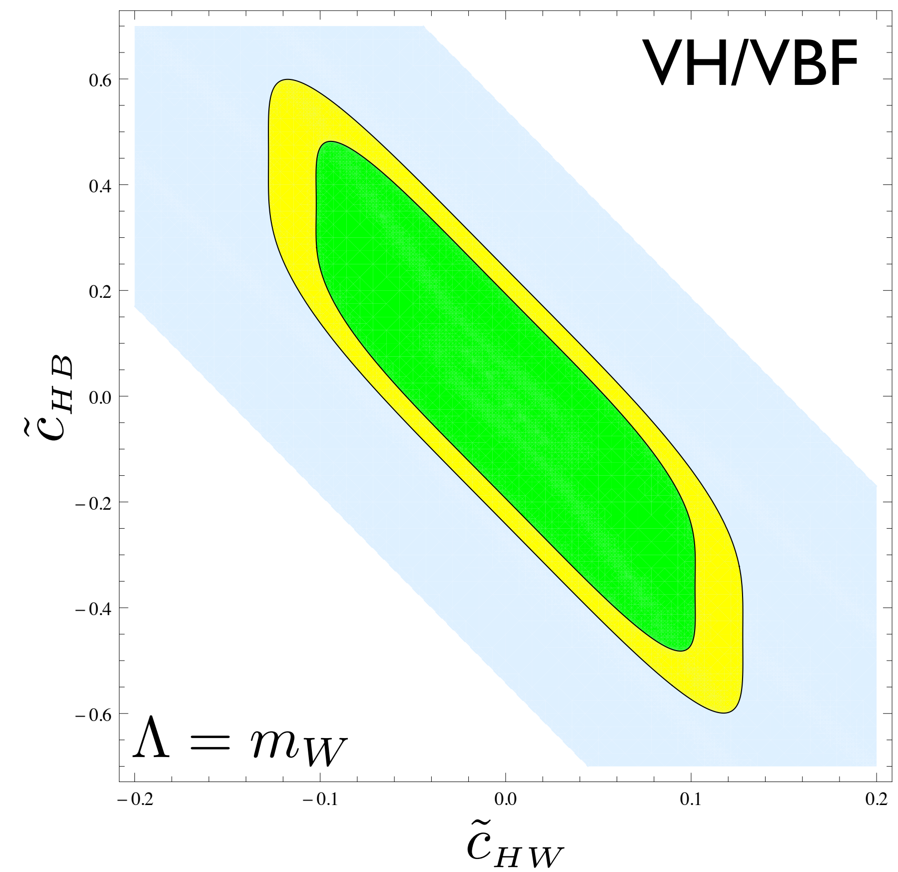
Signal strengths @ Tevatron & LHC Run I

✦ Allowed region of the parameter space @ 1σ (green) and 2σ (yellow)

LHC Run I



Tevatron + LHC Run I



LHC Run I

$|\tilde{c}_{3W}| < 0.18$

★ Very strong constraints on $\tilde{c}_\gamma$ and $\tilde{c}_g$ (the SM is loop-induced)

★ $\tilde{c}_{HB}$, $\tilde{c}_{HW}$ and $\tilde{c}_{3W}$ are still allowed to be large

- Alternatively, Λ may be low (care must be taken when extracting bounds)

★ Tevatron (blue area) is overwhelmed by LHC data

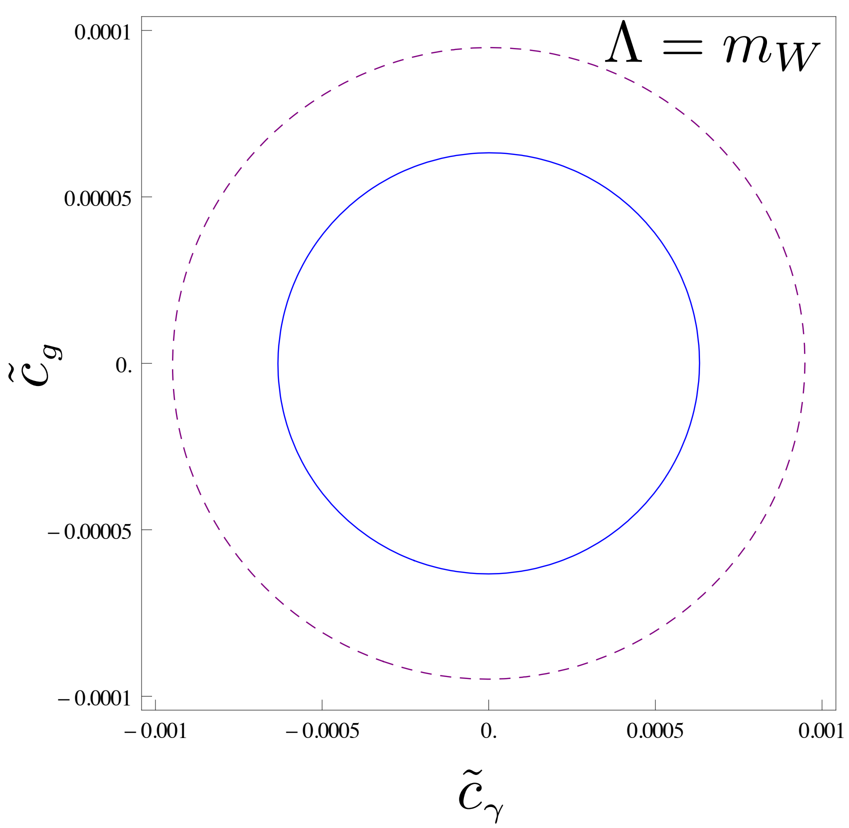
Prospects for Run II?

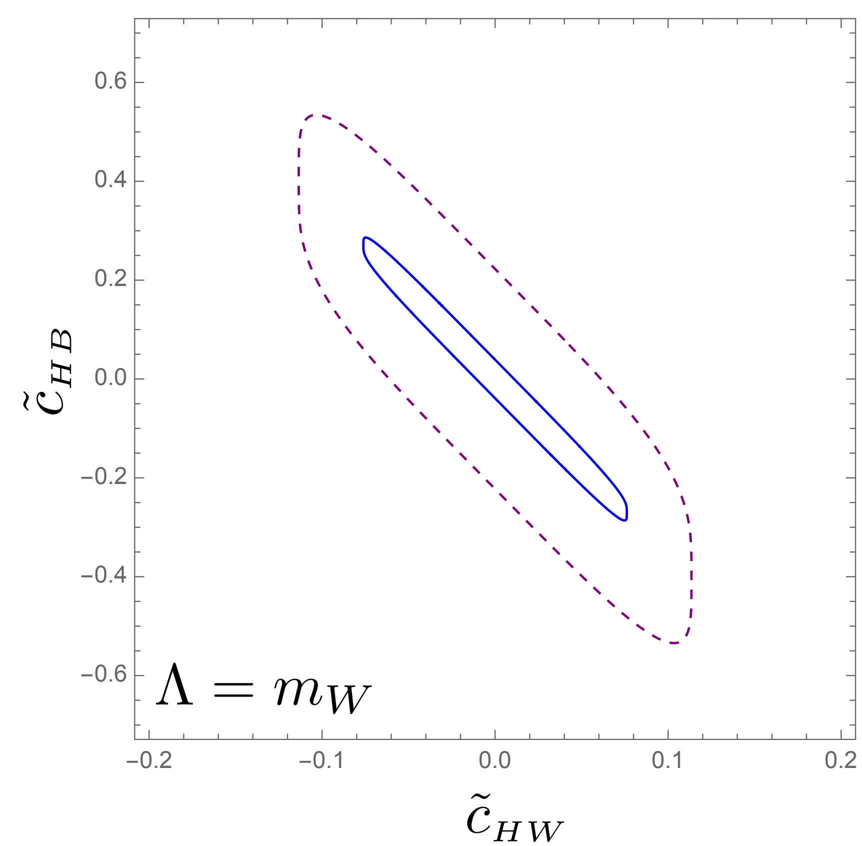
Prospects for the signal strength strategy

✦Reminder: Run I constraints

- $|\tilde{c}_\gamma| < 0.001$ and $|\tilde{c}_g| < 0.0001$
- $|\tilde{c}_{HB}|, |\tilde{c}_{HW}|, |\tilde{c}_{3W}| < 0.05\text{-}0.2$

✦ Expectations (at the 2σ level) for 300 (purple) and 3000 fb^{-1} (blue)





$|\tilde{c}_{3W}| \lesssim 0.1$

★ Mild improvement (a factor of ~2 for the HL-LHC)

Signal strengths are not enough

Getting better in being differential

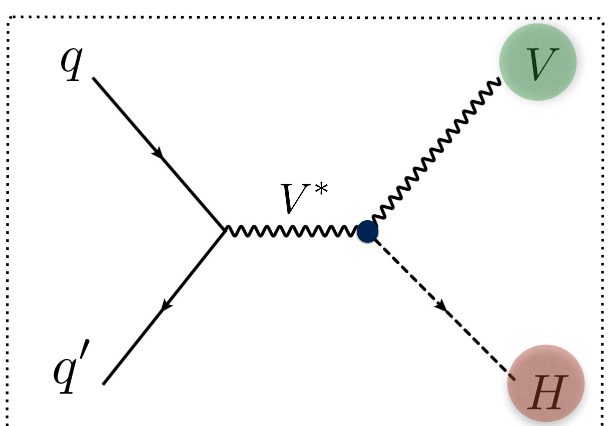
✦ The signal strength approach is powerful but limited

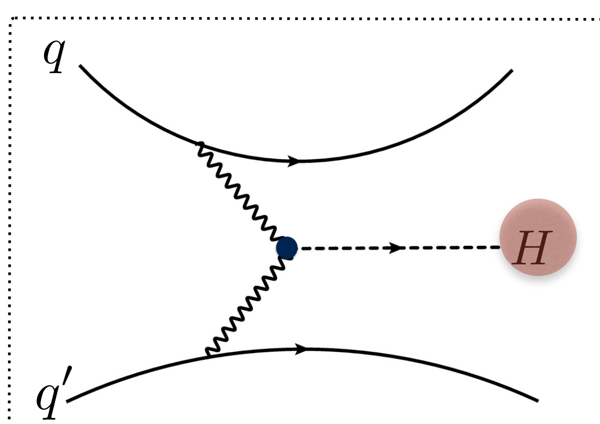
- The next 20 years of LHC running will not improve much the current reach
- A large amount of statistics will be available
- We can pay the price of being differential

✦ Playing with large momentum transfers

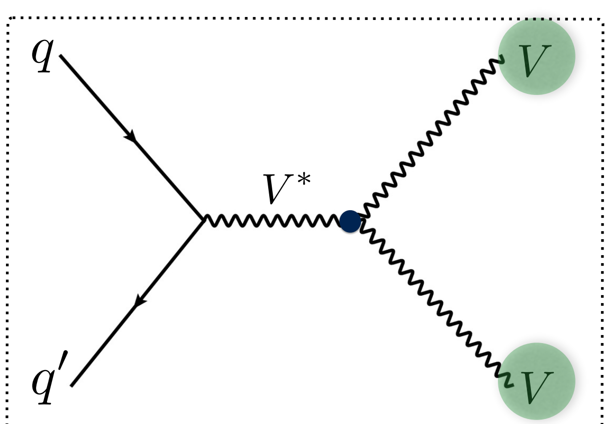
- The impact of derivatives operators is enhanced
- Could help to constrain the (less constrained) $\tilde{c}_{HB}$, $\tilde{c}_{HW}$, $\tilde{c}_{3W}$ parameters

✦ Investigated (electroweak) processes





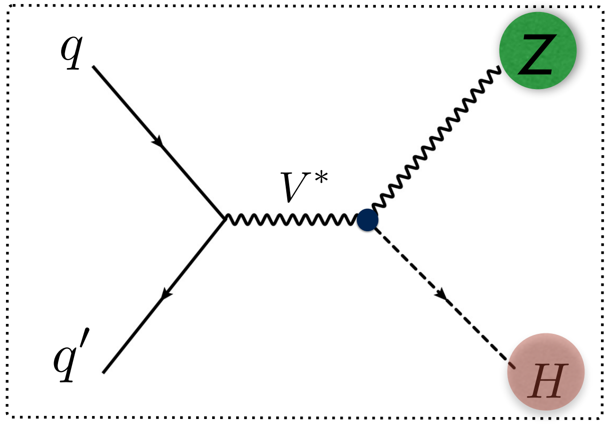
Presented in this talk



Similar conclusions (see the paper)

ZH production: generalities

✦ Final state signature



✤ Decay pattern
- ★ Fully reconstructed Higgs boson
- ★ Leptonic Z decay: 2 leptons as handles for new physics

✤ Analysis strategy
- ★ One dimensionful variable: sensitive to the EFT effects
  - Selection of the high momentum-transfer phase space region
- ★ One angular variable: sensitive to the CPV effects
  - Construction of an asymmetry

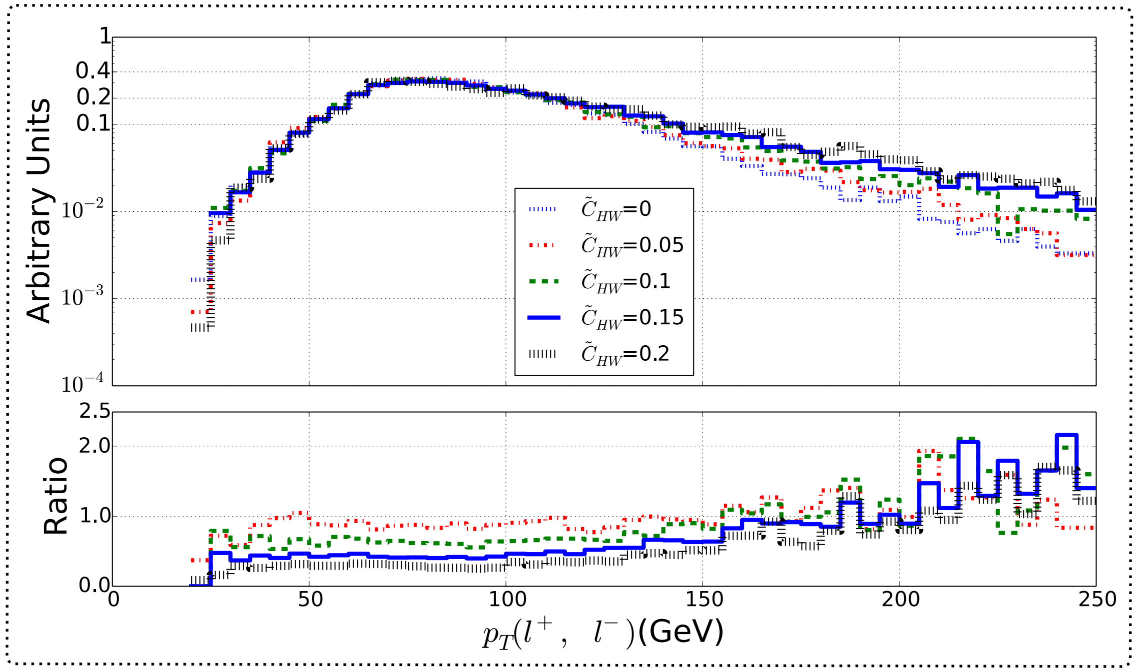
✦ Variables

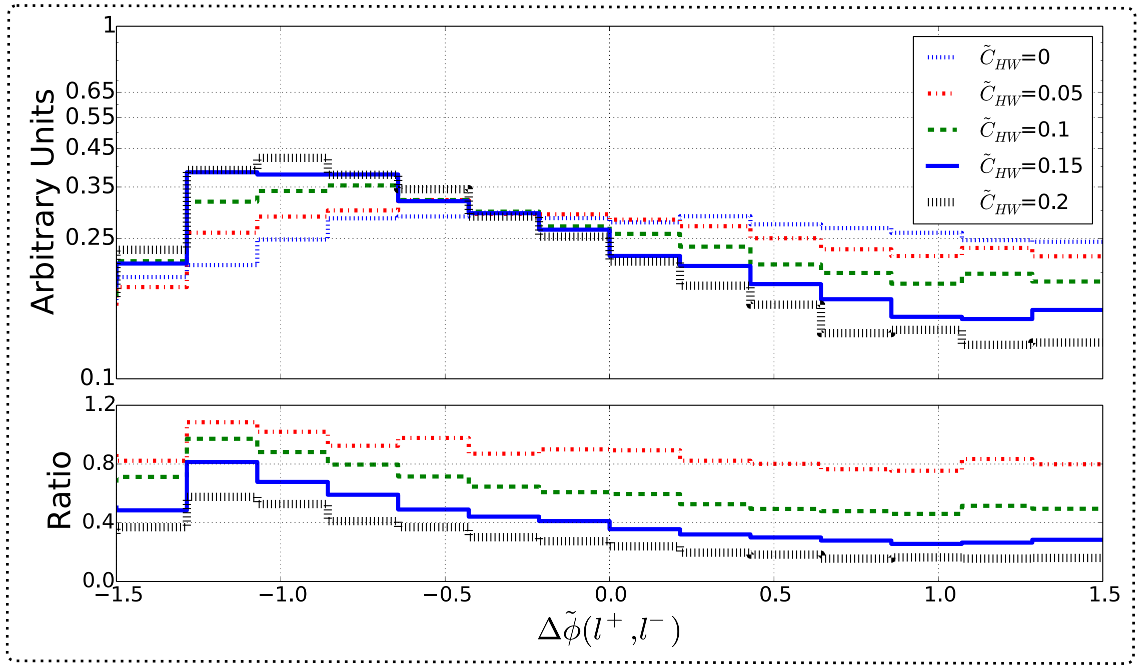
✤ The sum of the p_T of the two leptons $p_T(\ell^+, \ell^-) = p_T(\ell^+) + p_T(\ell^-)$

✤ The angular separation of the two leptons $\Delta\tilde{\phi}(\ell^+, \ell^-) = |\Delta\phi(\ell^+, \ell^-)| - \frac{\pi}{2}$

ZH production: distributions

- Results for the O_{HW} operator (parton-level after showering, perfect reco)
  - The sum of the p_T of the two leptons $p_T(\ell^+,\ell^-) = p_T(\ell^+) + p_T(\ell^-)$
  - The angular separation of the two leptons $\Delta\tilde{\phi}(\ell^+,\ell^-) = |\Delta\phi(\ell^+,\ell^-)| - \frac{\pi}{2}$





★ EFT operators impact the full p_T spectrum
- Distortion of the p_T spectrum (the fall at high p_T is reduced)
- EFT validity range: OK but one must be careful

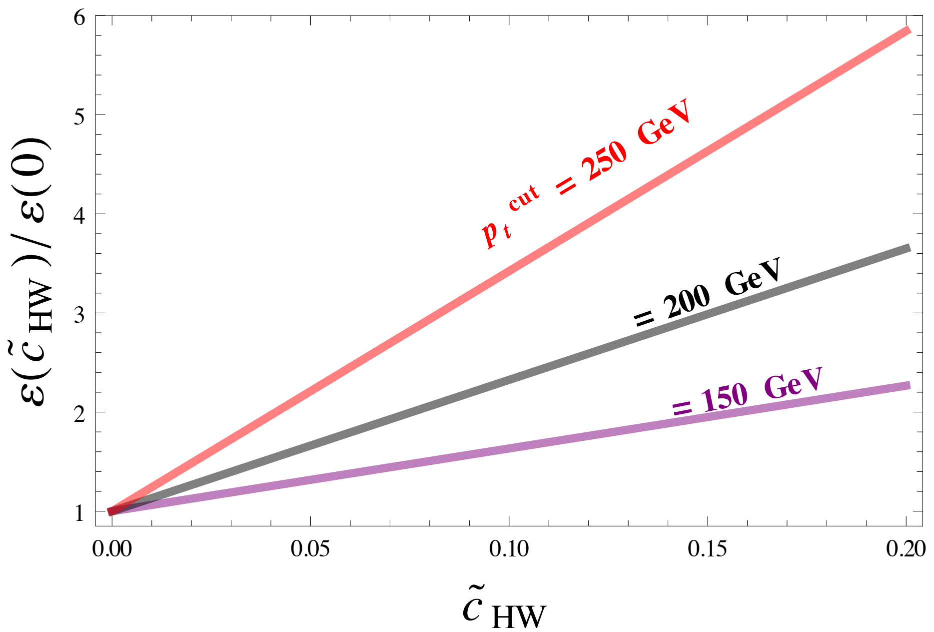
★ Very important distortion of the angular spectrum
- Bumps and dips more pronounced

New handles on new physics

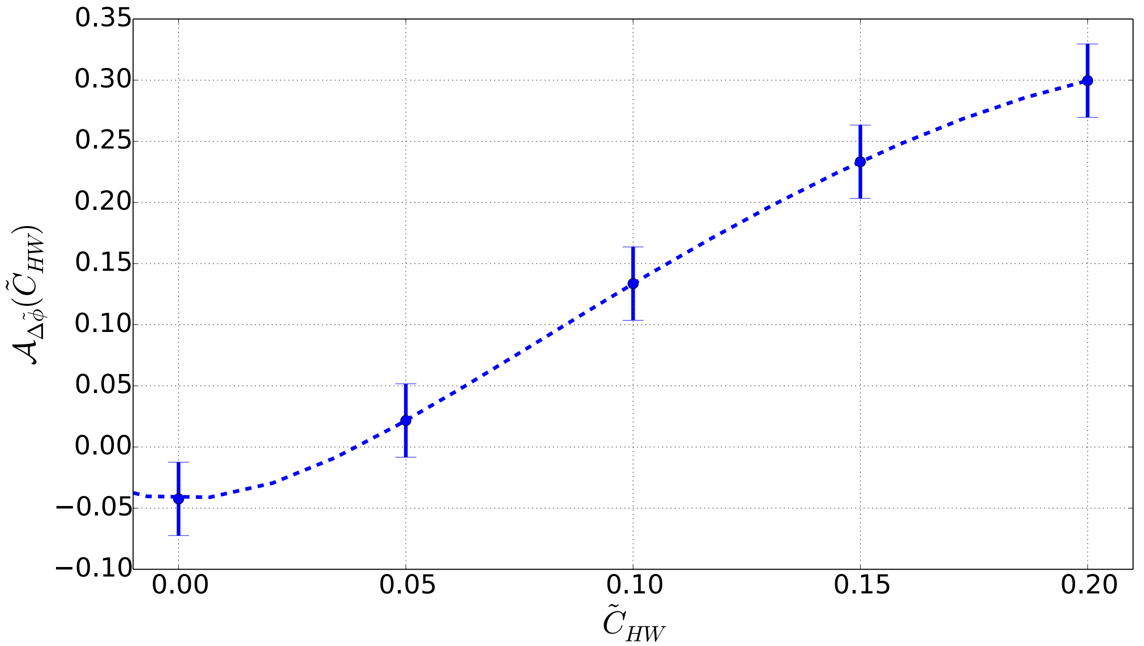
ZH production: new handles on new physics

Efficiency and asymmetry

$$\varepsilon(\tilde{c}) = \frac{1}{\sigma(\tilde{c})} \int_{p_T^{\rm cut}}^{\infty} \frac{{\rm d}\sigma(\tilde{c})}{{\rm d}p_T(\ell^+,\ell^-)} {\rm d}p_T(\ell^+,\ell^-)$$



$$\mathcal{A}_{\Delta\tilde{\phi}}(\tilde{c}) = \frac{{\rm d}\sigma\big(\Delta\tilde{\phi}(\ell^+,\ell^-) < 0\big) - {\rm d}\sigma\big(\Delta\tilde{\phi}(\ell^+,\ell^-) > 0\big)}{{\rm d}\sigma\big(\Delta\tilde{\phi}(\ell^+,\ell^-) < 0\big) + {\rm d}\sigma\big(\Delta\tilde{\phi}(\ell^+,\ell^-) > 0\big)}$$



★ Efficiencies

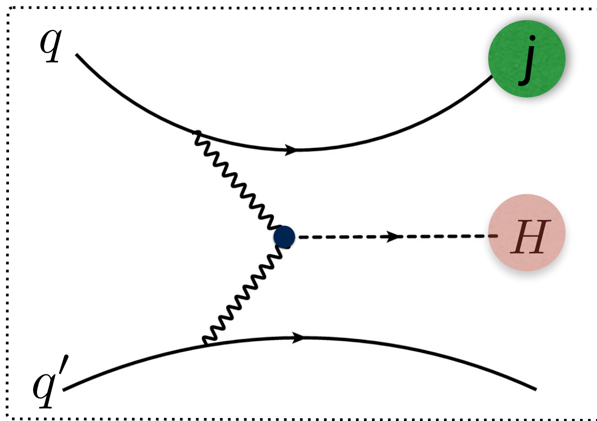
- The stronger is the cut, the larger is the expected sensitivity to the EFT operator
- The effects is enhanced with the magnitude of the EFT parameter

★ Asymmetries

- Very large dependence on the EFT parameter (including the sign)

VBF production: generalities

✦ Final state signature



✤ Decay pattern
- ★ Fully reconstructed Higgs boson
- ★ Leading jet

✤ Similar analysis strategy
- ★ One dimensionful and one angular variable

✦ Variables

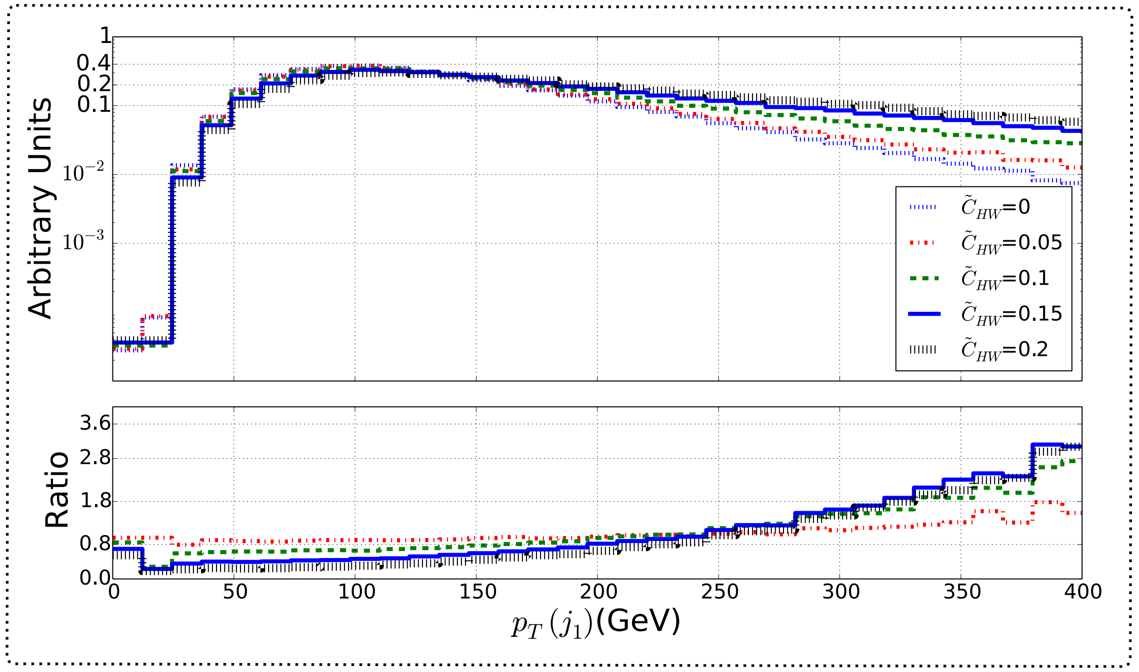
✤ The p_T of the leading jet

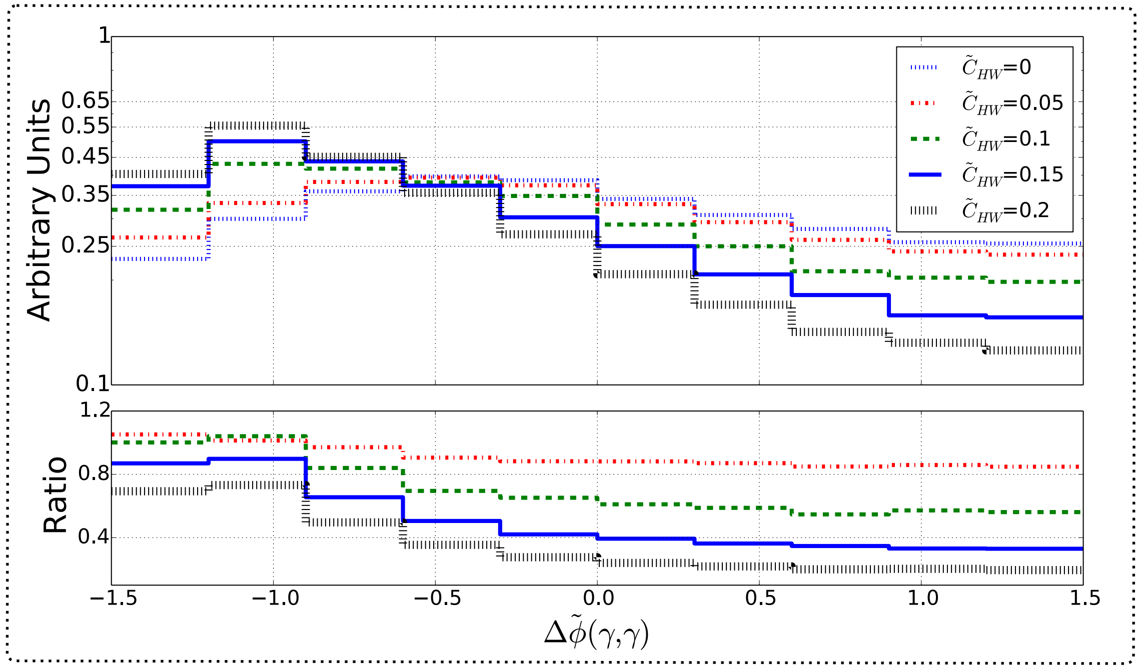
✤ The angular separation between the Higgs decay products (2 particles)

VBF production: distributions

✦ Results for the O_{HW} operator (parton-level after showering, perfect reco)

- ✤ The p_T of the leading jet
- ✤ The angular separation between the Higgs decay products (2 photons here)





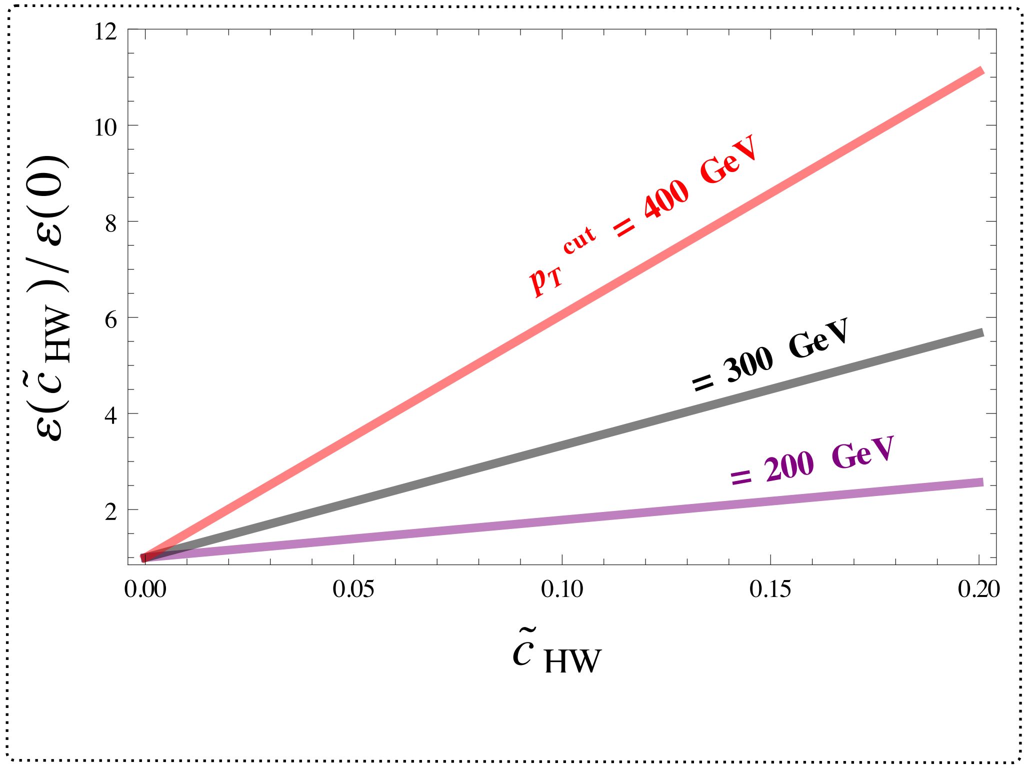
★ EFT operators impact the full p_T spectrum

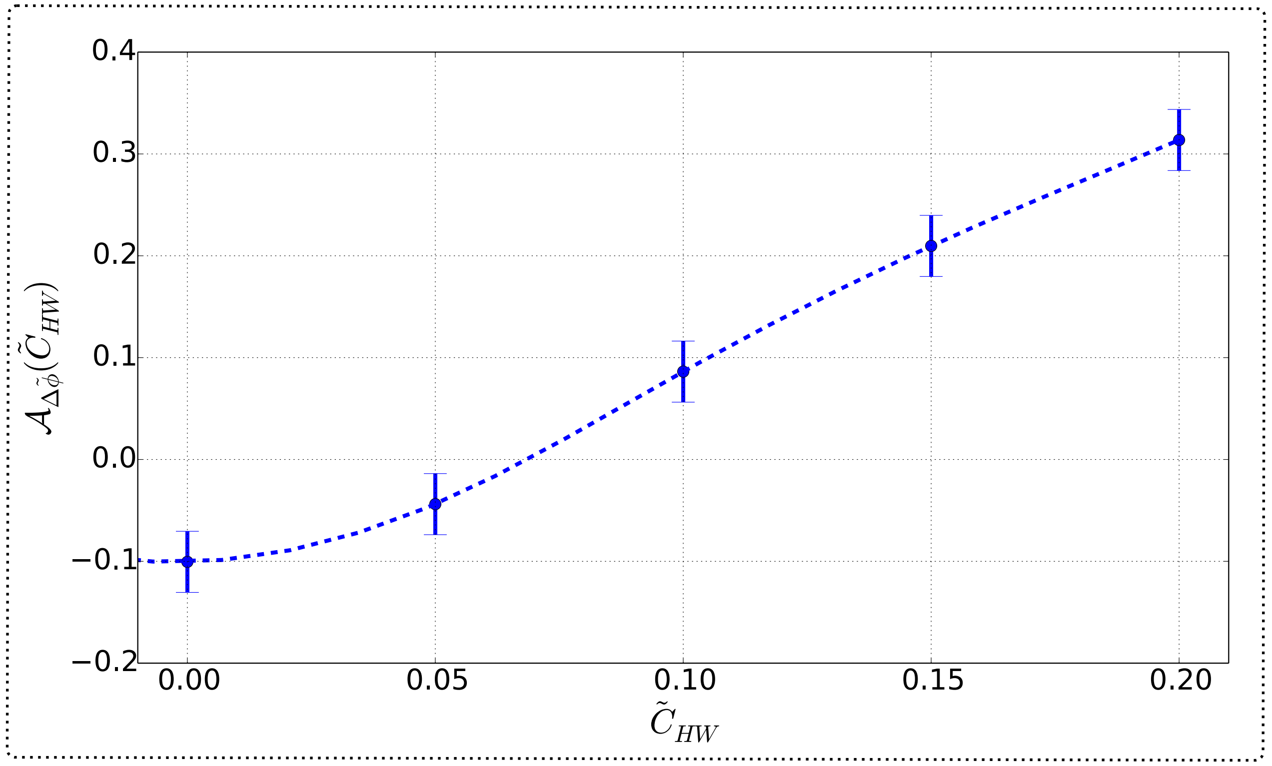
- Distortion of the p_T spectrum (the fall at high p_T is reduced)
- EFT validity range: OK but one must be careful

★ Important distortions of the angular spectrum

VBF production: new handles on new physics

✦ Efficiency and asymmetry





★ Efficiencies

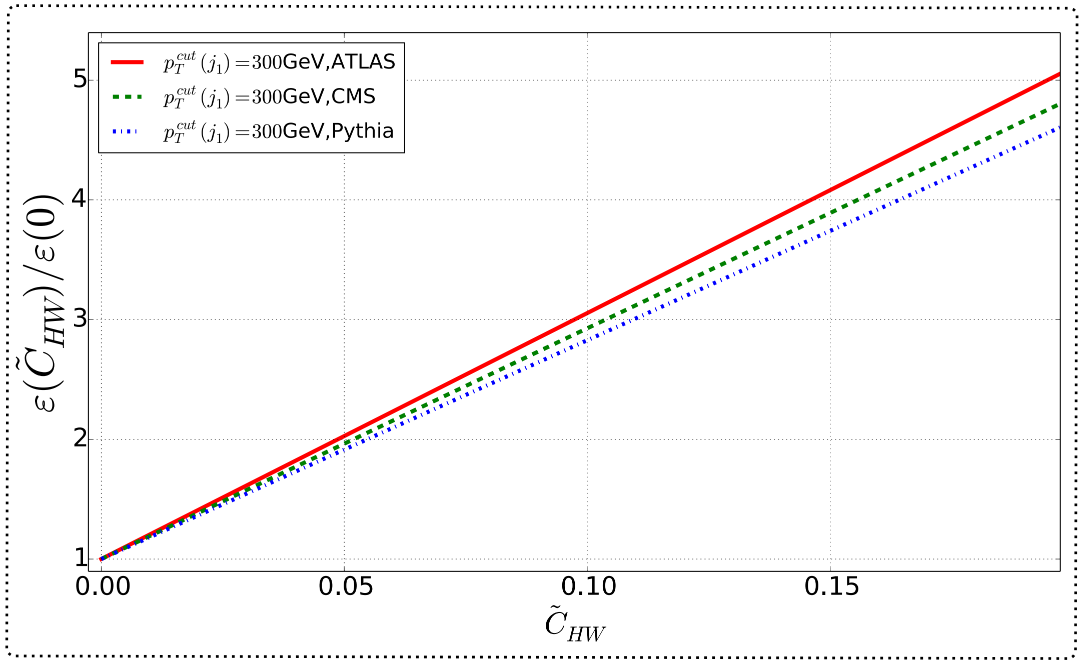
- The stronger is the cut, the larger is the expected sensitivity to the EFT operator
- The effects is enhanced with the magnitude of the EFT parameter

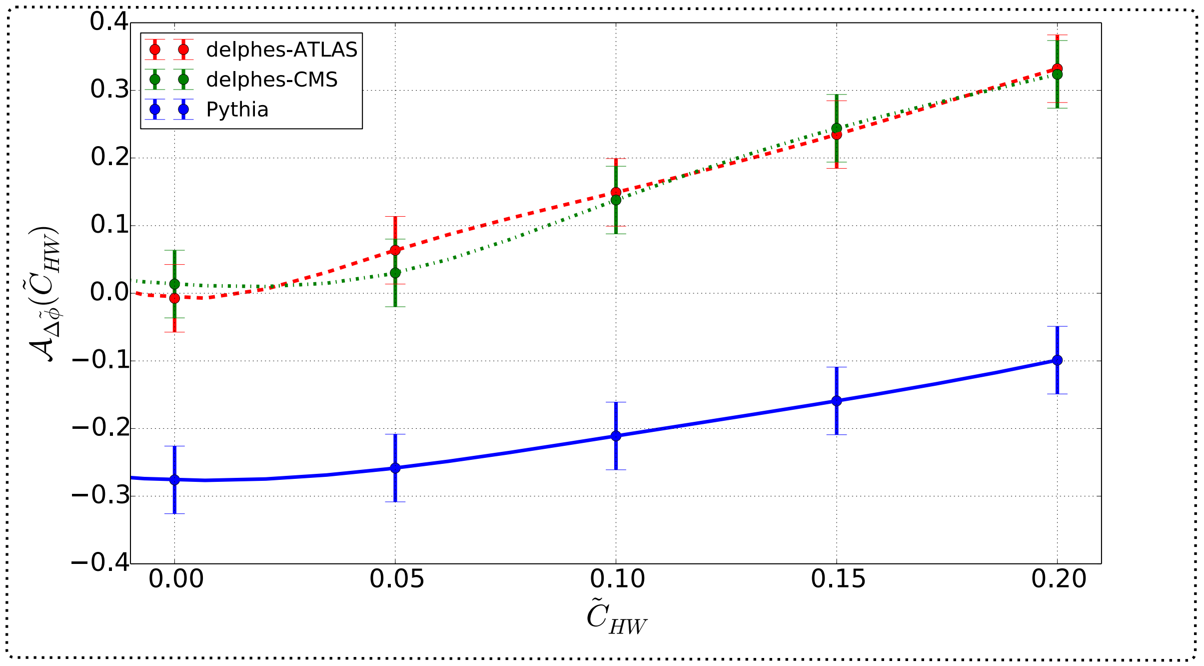
★ Asymmetries

- Very large dependence on the EFT parameter (including the sign)

VBF production - Detector effects

✦ Adding hadronization and DELPHES (with both the ATLAS and CMS cards)





★ Barely effect on the efficiencies
- Robust observables with respect to detector effects

★ Asymmetries
- Large detector effects on angular variables
- Conclusive statements can still be achieved (still dependent on the EFT parameters)

The next steps

- ✦ Identification of 2 variables to be jointly used to constrain CPV operators
  - ✤ For each studied processes
  - ✤ One dimensionful variable (enhanced sensitivity to EFT operators)
  - ✤ One angular variable (enhanced sensitivity to CPV effects)
- ✦ Detector effects seem to be under good control

- ✦ In the agenda
  - ✤ Background and signal analysis on-going
  - ✤ NLO effects to be incorporated (this is for free in the aMC@NLO framework)
  - ✤ Deeper checks about the EFT validity range
  - ✤ Disentangling CP-violating from CP-conserving operator effects

Results in the CP-conserving case

(Higgs) Effective Field Theory at NLO in QCD

✦ Illustrative Lagrangian (more operators can be included)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} + \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu} + \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu}$$

✦ Blue benchmark (allowed by LEP/LHC)

- $\bar{c}_B = \bar{c}_W = 0$; $\bar{c}_{HW} = 0.03$
- Two HVV structures arise

$$-g^{(1)}_{hvv}\left[V_{\mu\nu}V^{\mu\nu}h\right] - g^{(2)}_{hvv}\left[V_\nu\partial_\mu V^{\mu\nu}h\right]$$

✦ Orange benchmark (allowed by LEP/LHC ➢ cancellations)

- $\bar{c}_B = 0.015$; $\bar{c}_{HW} = -\bar{c}_W = 0.03$
- One HVV structure arises

$$-g^{(1)}_{hvv}\left[V_{\mu\nu}V^{\mu\nu}h\right]$$

✦ Effective field theories at NLO

- Renormalizability: order by order in $1/\Lambda^2$ (double perturbative series)
- Precision of the QCD corrections can be included

$$\sigma \approx \underbrace{1}_{\text{SM@LO}} + \underbrace{O(\alpha_s)}_{\text{SM@NLO}} + \underbrace{O(1/\Lambda^2)}_{\text{EFT@LO}} + \underbrace{O(\alpha_s/\Lambda^2)}_{\text{EFT@NLO}}$$

Example 1 - WH production at the LHC

✦ Considered process

- ✤ We focus on a Higgs decay into b-jets and a leptonic W decay

$$pp \to HW \to b\bar{b} + \ell + \not{E}_T$$

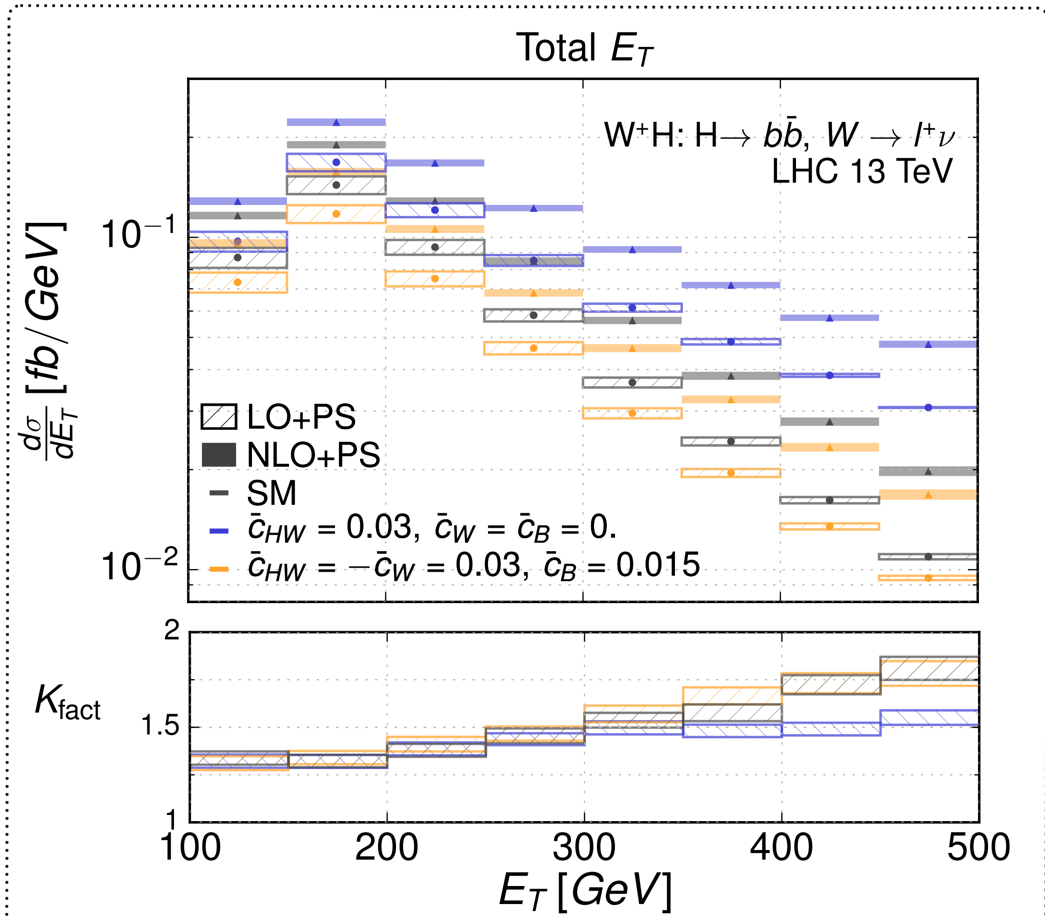
- ✤ Hard (p_T > 25 GeV) and central ($|\eta|$ < 2.5) decay products
- ✤ Extra hard jets are allowed with $|\eta|$ < 4

✦ Study of various observables

- ✤ NLO effects (via differential K-factors)
- ✤ Benchmark effects (via their deviations δ from the Standard Model)

WH production at the LHC - QCD corrections

✦ QCD effects on VH production with BSM effects

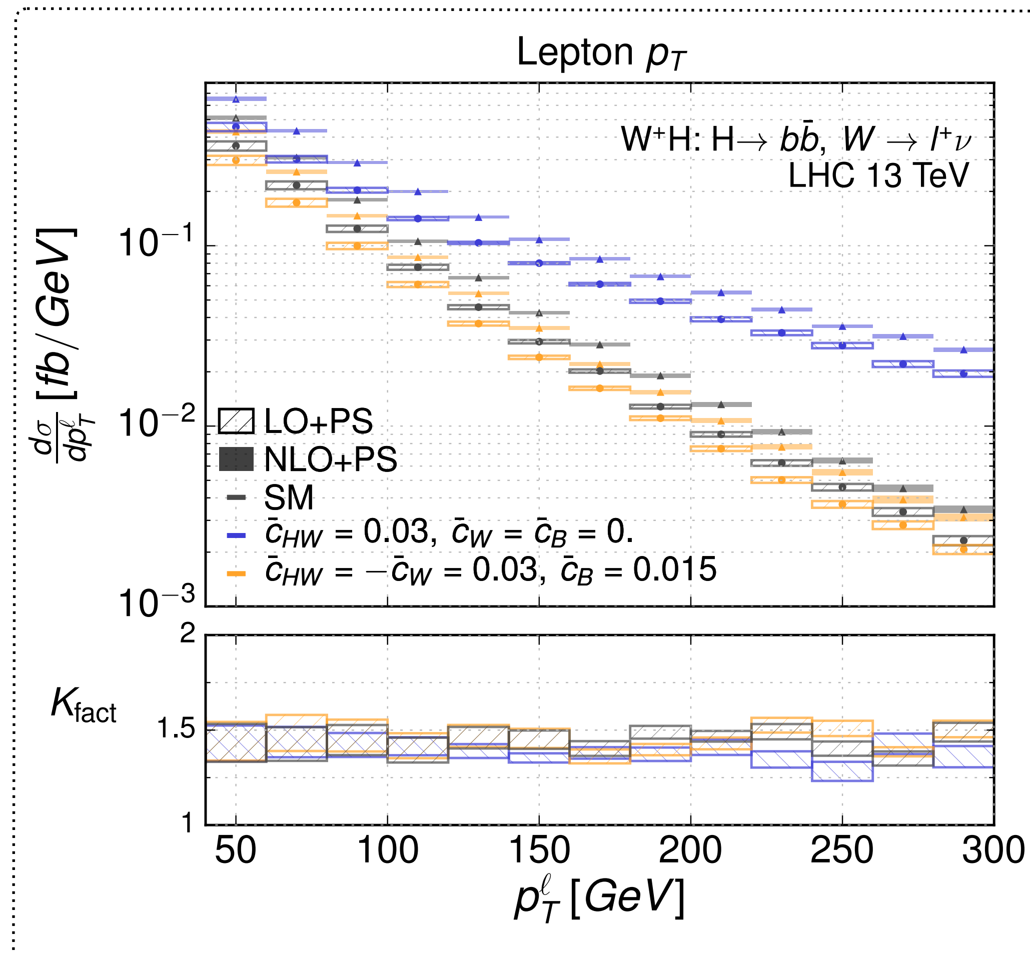


✤ Differential K-factors are scenario-dependent

★ Orange is very close to the SM case

★ Blue is in contrast flat

★ LO predictions are in both cases inaccurate



✤ Some observables show very flat K-factors

★ Typical for a Drell-Yan like topology

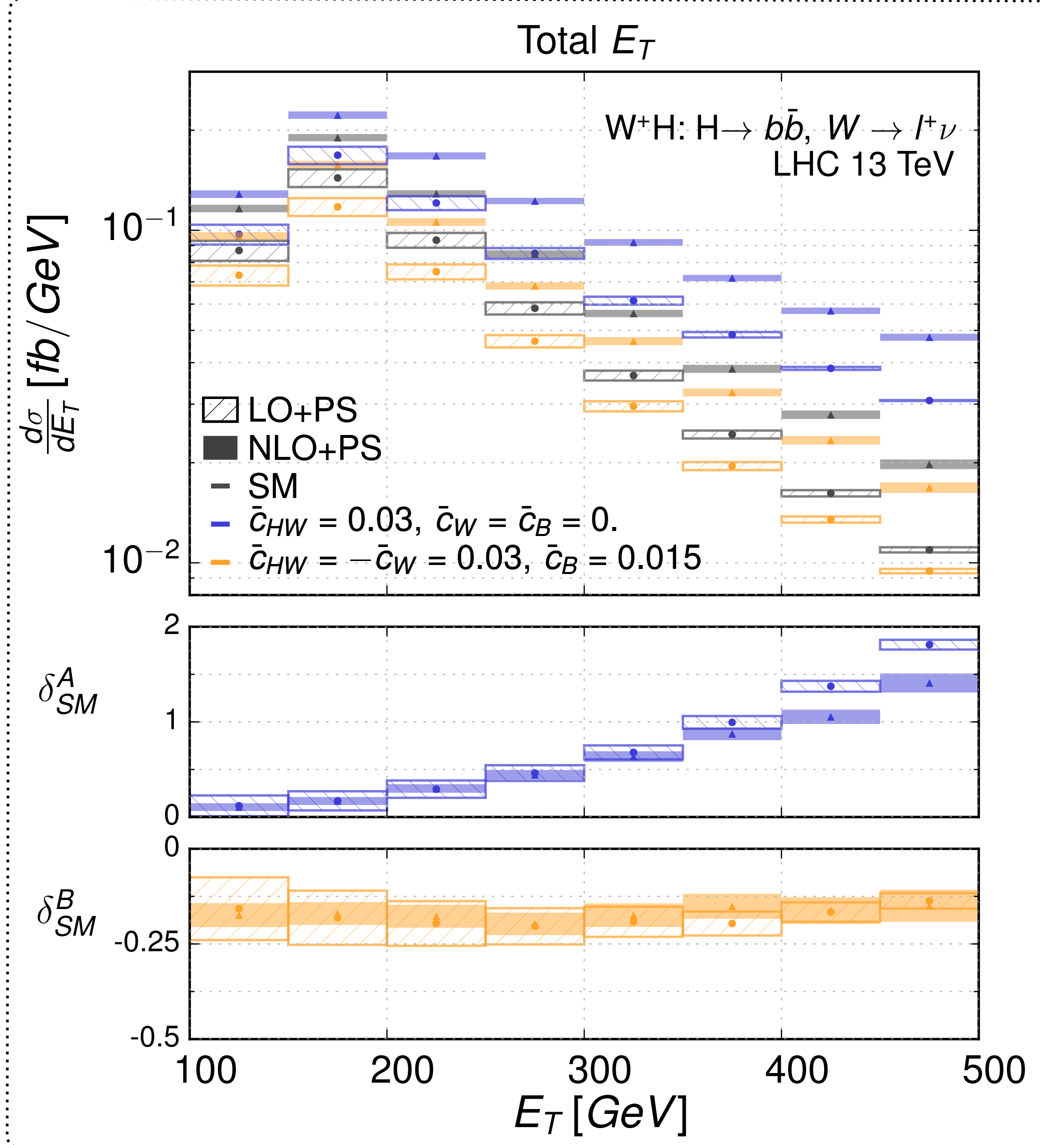
★ Not true when the leading jet is involved (we cannot multiply the LO result with K)

✤ LO and NLO predictions do not overlap

★ LO uncertainties could be underestimated

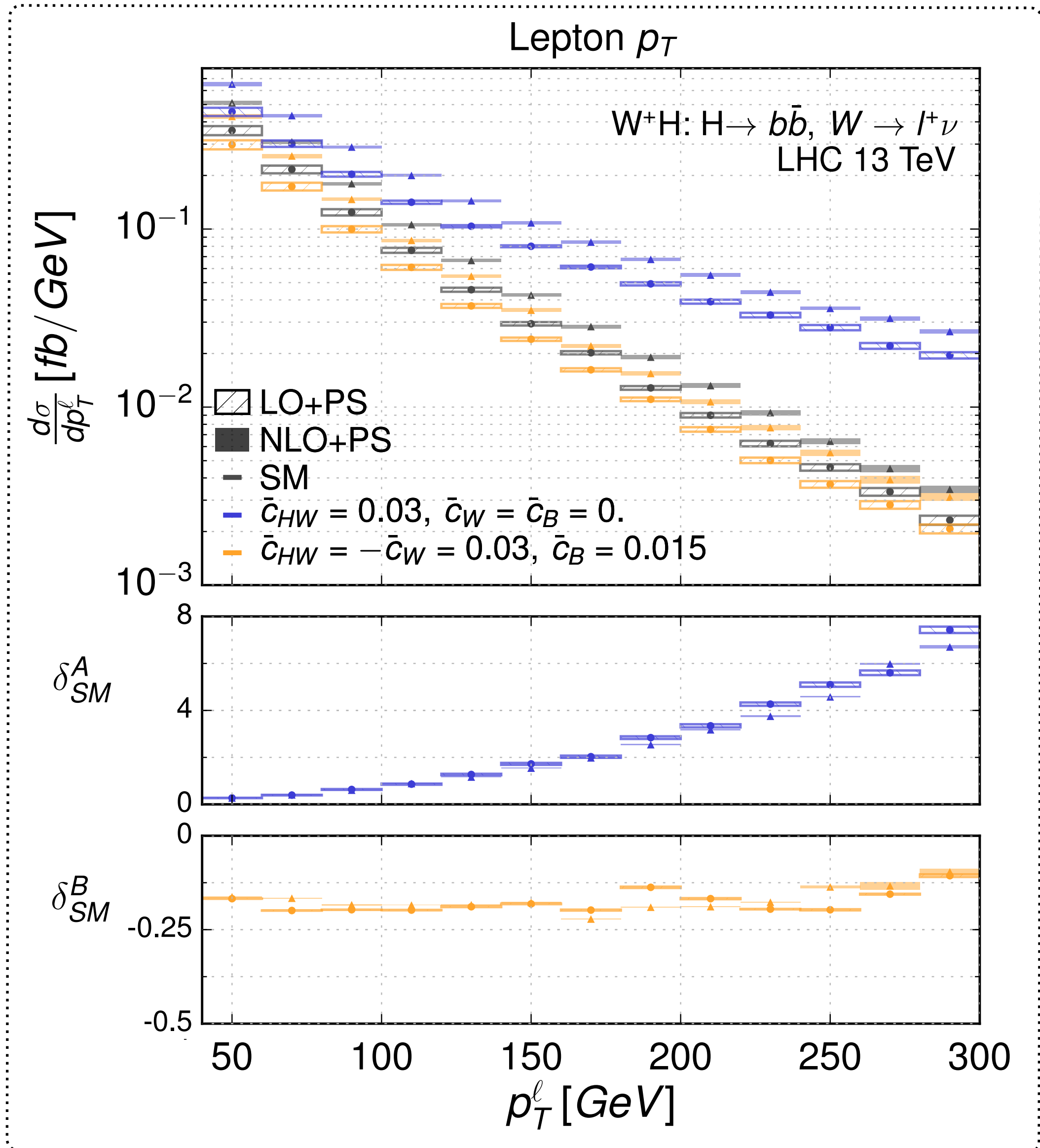
WH production at the LHC - EFT effects

✦ EFT effects on VH production



✤ Significant deviations from the Standard Model

- ★ The *blue* scenario features 2 hVV structures
- ★ Deviations in the tails: scenario-dependent



✤ Could be exploited to constrain the SM EFT

- ★ Care to be taken with EFT validity range

Example 2 - WBF production at the LHC

✦ Considered process

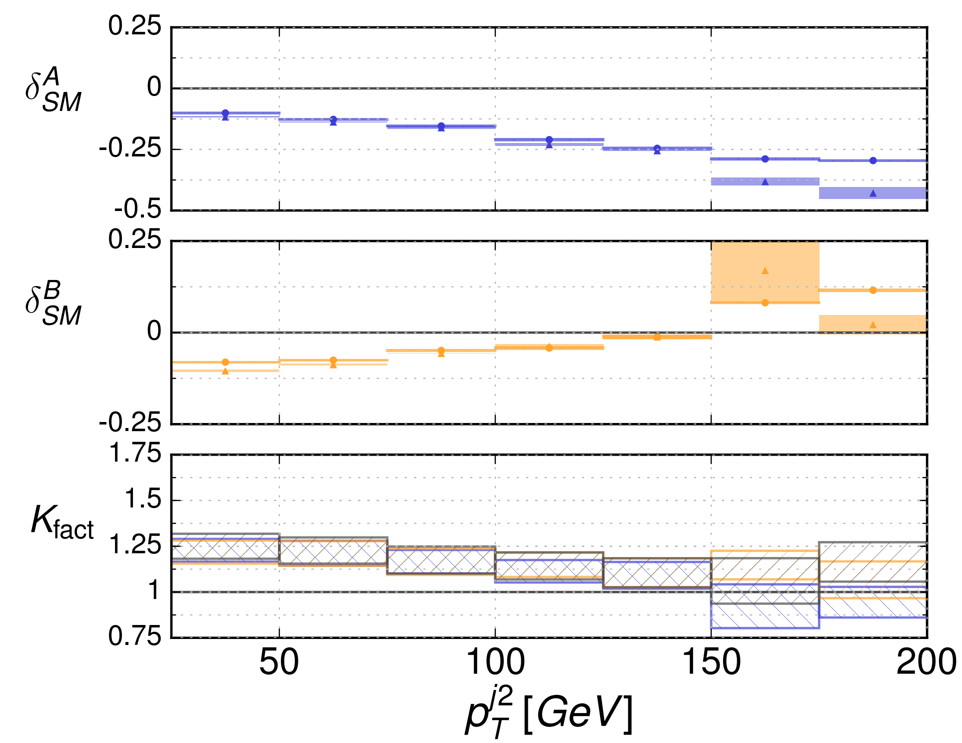
- ✤ Higgs decays into a photon pair

$$pp \to H + jj \to \gamma\gamma \; + jj$$

- ✤ Hard (p_T > 25 GeV) and forward (|η| < 4.5) jets
- ✤ Hard (p_T > 20 GeV) and central (|η| < 2.5) photons
- ✤ VBF cuts: M_{jj} > 500 GeV and $\Delta\eta_{jj}$ > 3

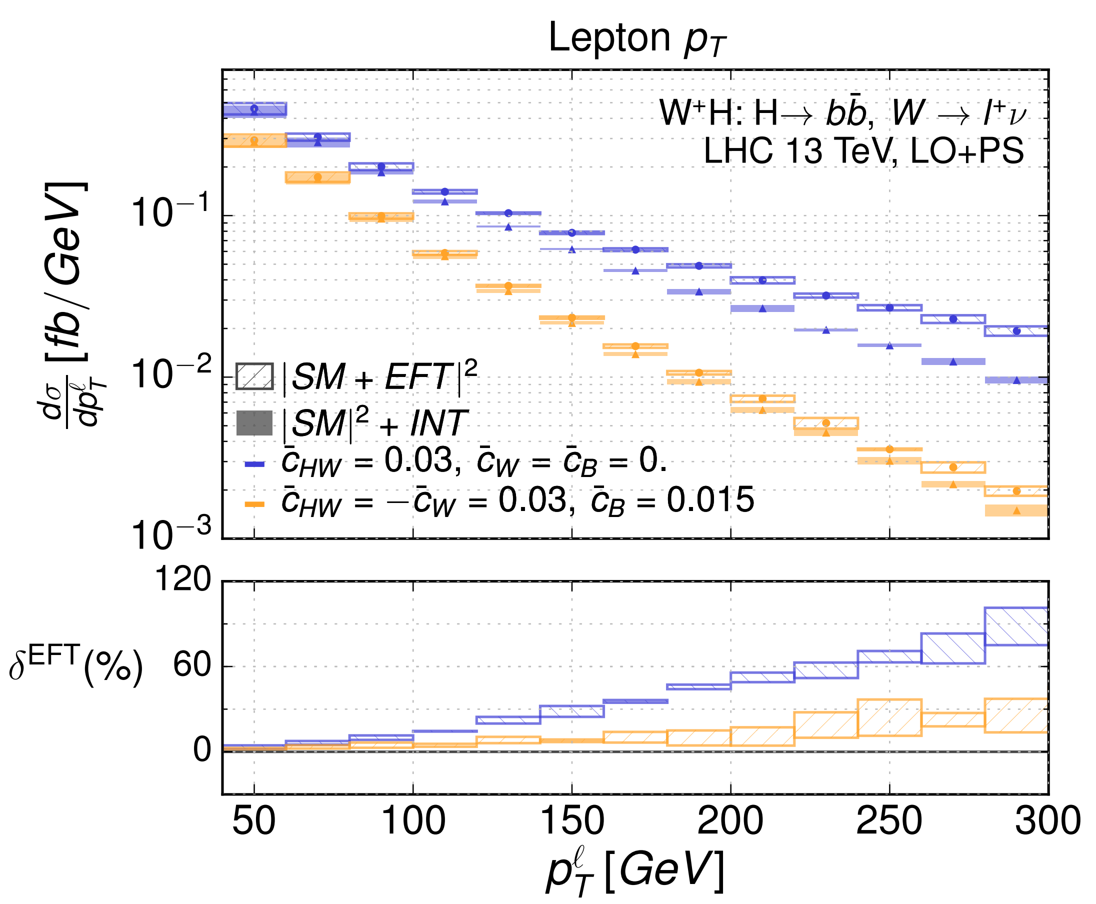
✦ Study of various observables

- ✤ Sensitive to the momentum flow
- ✤ NLO effects (via differential K-factors)
  - ★ K-factors EFT-independent
  - ★ In agreement with the SM
  - ★ Not flat
- ✤ EFT effects are destructive
  (this contrasts with VH)



EFT validity

✦Unitarity and perturbativity checks



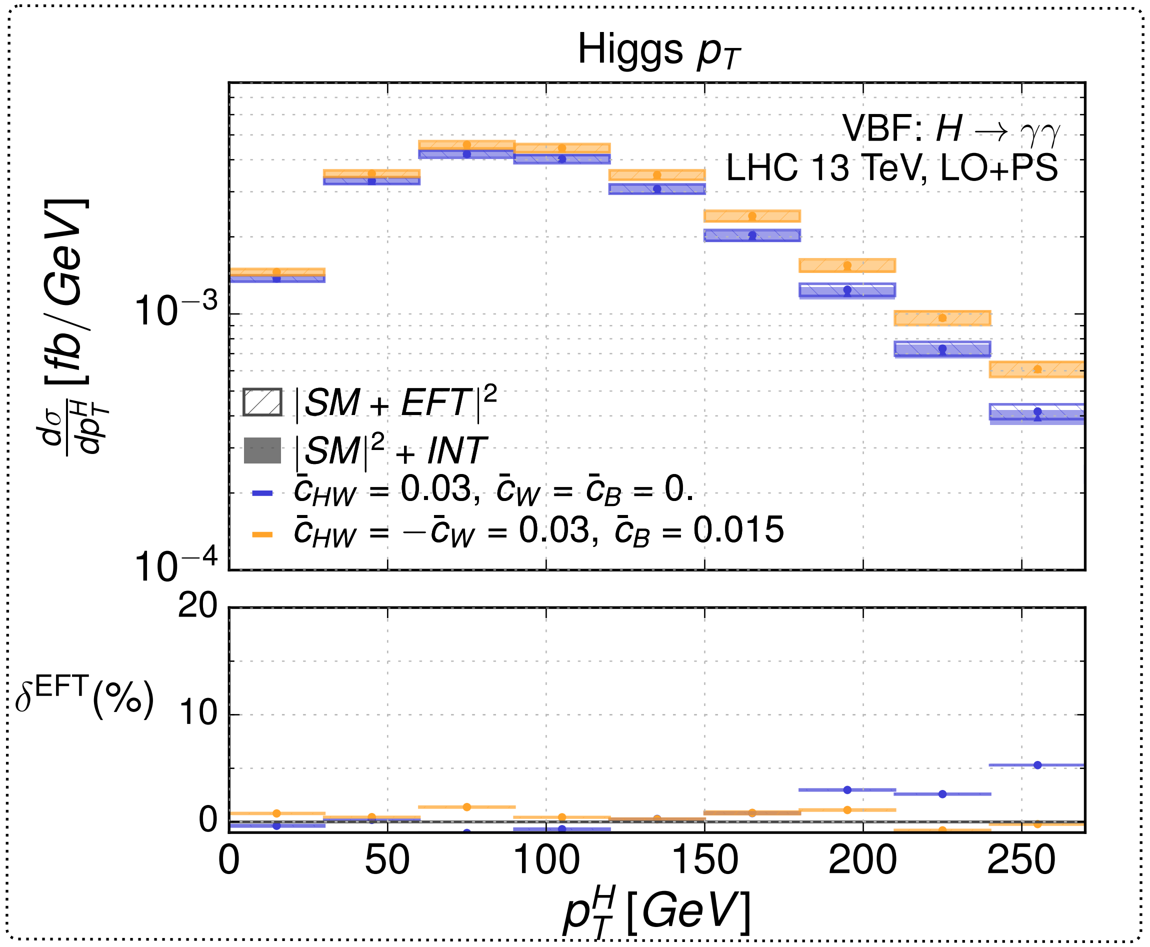
★ $1/\Lambda^4$ effects possibly large in the tails

★ Benchmark- and process-dependent

★ Care must be taken with the EFT interpretation

➢ WH: *orange* is OK, *blue* is not

➢ WBF: *orange* and *blue* OK



✤ VBF/VH complementarity for extracting constraints

Summary

✦ We have initiated a program to investigate the CP properties of the Higgs

- ✤ Investigation signal strengths
  - ★ Mild constraints on most CPV operators
  - ★ Not exciting expectation from the future HL-LHC run
- ✤ Getting differential could potentially help
  - ★ The joint use of a dimensionful and dimensionless observable is promising
  - ★ Maximizing the sensitivity to both the EFT and CPV effects

✦ Outlook: disentangling of CP-violating and conserving effects

- ✤ A full signal and background analysis is on its way
- ✤ Inclusion of NLO effects
- ✤ Check of the EFT range of validity

✦ Those questions have already been addressed in the CP-conserving sector

- ✤ NLO effects are important (normalization and shapes)
- ✤ Care must be taken in the tails (for some processes)