Optimization of the search for CP violation in the Higgs-WW interaction

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Matter-antimatter asymmetry and the need for BSM sources of CP violation

The SM is a remarkable theory but... there's a problem.

Observed: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$ **Expected:** $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-18}$

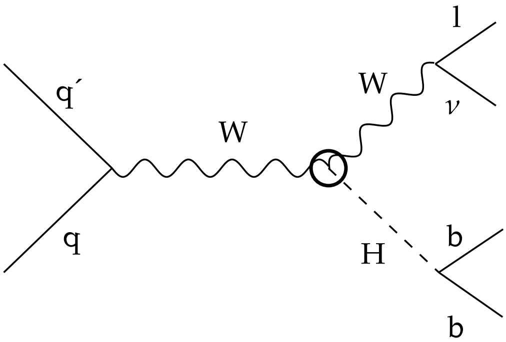
(numbers from Héctor Gisbert's presentation at PANIC 2021)

BSM sources of CP violation are needed !

HWW interaction and WH production

Probing the HWW interaction in WH production for BSM CP-violating components.

- EFT formalism: single D6 operator with coefficient $c_{H\tilde{W}}$



Main challenge: CP-violating BSM components **don't change total cross-sections**

Differential cross-sections

Key idea 1: CP-violating BSM components shift energy distributions to higher values.

	S+B 95% CL ($\times 10^{-3}$)
Total cross-section	6.63
3 bins in p_{T_W}	4.29
4 bins in p_{T_W}	4.28
5 bins in p_{T_W}	4.24
6 bins in p_{T_W}	4.22
6 bins in p_{T_W} and 3 bins in $m_{T_{tot}}$	4.16

Table 1: Signal+background 95% CL ($\times 10^{-3}$) for $\mathcal{L} = 300$ fb^{-1}. Symmetric limits, $[-x, +x]$.

Differential cross-section measurements lead to limits $\approx 30\%$ tighter w.r.t. total cross-section measurements.

The SALLY method

Key idea 2: CP-violating BSM components change correlations between particles

The (ML-based) SALLY method [5] exploits these to reconstruct **statistically optimal observables**.

	S+B 95% CL ($\times 10^{-3}$)
SALLY	0.763

Table 2: Signal+background 95% CL ($\times 10^{-3}$) for $\mathcal{L} = 300\ \text{fb}^{-1}$. Symmetric limits, $[-x, +x]$.

The SALLY method leads to limits $\approx$ 6 times tighter w.r.t. differential cross-section measurements.

Conclusions

Conclusions:

- differential cross-section measurements lead to tighter exclusion limits than a total cross-section measurement
- the (ML-based) SALLY method leads to much tighter limits than differental cross-section measurements

Ongoing work: benchmarking different angular observables in the literature

Next steps:

- introduce CP-even operators
- introduce possible systematics

Backup

EFT formalism: what it is and why it's used

EFT formalism: extending the SM Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i O_i^{(d)}}{\Lambda^{d-4}}$$

$O_i^{(d)}$ are combinations of low mass fields

- come from "integrating out" heavy fields in a UV-complete model [1]

(Almost) **model independent**

- can be consistently matched to UV-complete models

Why these methods aren't optimal

These methods aren't optimal.

Reduced set of observables:

- **loses information** from other observables and from correlations
- **does not scale well** to a large number of observables

Full kinematic information and matrix elements:

- **requires large approximations**
- integration over all possible paths has to be **done for each event**

Is there a better way to reconstruct the likelihood ?

Simulation-based inference as a solution

Simulation-based inference: using information from the simulator to improve inference [5, 6, 7].

Takes advantage of two features of EFT constraints:

- the likelihood can be factorized (see Eq. **??**).
- the parton-level likelihood, $p(z_p|\theta) \propto \frac{|\mathcal{M}(z_p|\theta)|^2}{\sigma(\theta)}$ can be extracted from event generators

Simulation-based inference

These features can be used to build two functions:

- the **joint likelihood ratio**, $r(x,z|\theta,\theta_{ref}) \equiv \frac{p(x,z|\theta)}{p(x,z|\theta_{ref})}$
- the **joint score**, $t(x,z) = \nabla_\theta \log p(x,z)|_\theta$

$$r(x,z|\theta,\theta_{ref}) = \frac{p(z_p|\theta)}{p(z_p|\theta_{ref})} \approx \frac{|\mathcal{M}(z_p|\theta)|^2}{|\mathcal{M}(z_p|\theta_{ref})|^2} \frac{\sigma(\theta_{ref})}{\sigma(\theta)} \tag{1}$$

$$t(x,z|\theta) = \frac{\nabla_\theta p(z_p|\theta)}{p(z_p|\theta)} \approx \frac{\nabla_\theta |\mathcal{M}(z_p|\theta)|^2}{|\mathcal{M}(z_p|\theta)|^2} - \frac{\nabla_\theta \sigma(\theta)}{\sigma(\theta)} \tag{2}$$

Simulation-based inference II

Refs. [5, 6, 7] show that:

- joint likelihood ratio can be used to build estimators which converge to the true likelihood ratio
- joint score can be used to build estimators which converge to the true score
  - **sufficient statistic** of the likelihood in a neighborhood of a reference point

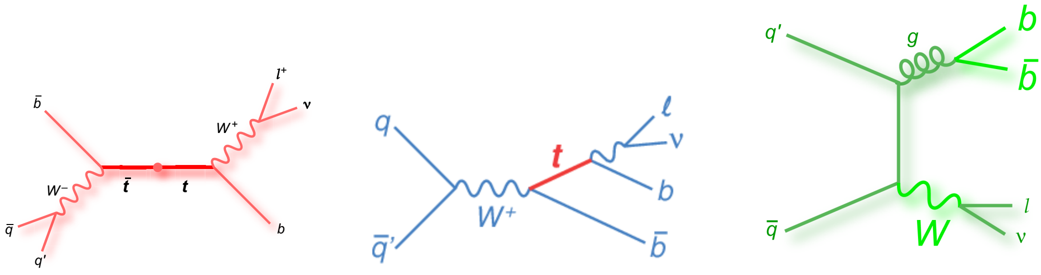
"Learn" the parton shower, hadronization and detector response.

Advantages:

- can use as input the full set of reconstruction-level observables
- don't require approximations

Backgrounds

The main (reducible) backgrounds are: semileptonic $t\bar{t}$, s-channel single top production and W + (b) jets



(a) (b) (c)

Figure 1: Feynman diagrams for the main backgrounds in WH associated production: semileptonic $t\bar{t}$ (left), single top production in the s-channel (middle) and associated production of a W boson and b-jets (right).

Setup and sample generation

Using version 0.7.6 of `MadMiner` [11].

Samples generated at LO in QCD with `Madgraph5_aMC@NLO` [12].

- signal: `SMEFTsim 3` [13], $c_{H\tilde{W}} = 0$ (SM) and $c_{H\tilde{W}} = -0.963$, $\Lambda = 1$ TeV.
- background: default SM model

Generator-level cuts are applied (following Ref. [8]):

- $p_{T,\ell} > 10$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
- $p_{T,b} > 35$ GeV
- $|\eta_{l,b}| < 2.5$
- $\Delta R_{bb,\ell b} > 0.4$
- $80 \text{ GeV} < m_{bb} < 160$ GeV
- $p_{T,l} < 30$ GeV
- $\Delta R_{bj,\ell j} > 0.4$

Analysis

Parton-level b-quark energies and $E_{\mathrm{T}}^{\mathrm{miss}}$ are smeared to approximate detector response.

- b-quark energies smeared by a Gaussian with $\sigma_E/E = 0.1$
- $E_{\mathrm{T}}^{\mathrm{miss}}$ (or neutrino) components smeared by a Gaussian with $\sigma_E = 12.5\,\mathrm{GeV}$

Two sets of observables are used (defined in backup):

- full final state particle kinematics (w/ 4-vector of the neutrino)
- only observable degrees of freedom (w/ $E_{\mathrm{T}}^{\mathrm{miss}}$)

B-tagging probability of 70% is assumed (no light or charm mistagging).

No systematics taken into account.

Data augmentation and ML method training

Using the SALLY method [5, 6, 7] to estimate the true score around the SM.

Training samples with joint score created for each of the observable sets.

- 10^6 (4×10^6) signal-only (signal+background) events

The estimator is a neural network:

- 3-layers with 50 hidden units each
- loss minimized with AMSGrad for 50 epochs w/ batch size of 128
- learning rate exponentially decaying between 10^{-3} and 10^{-4}

Training data into training and validation set (75%/25%) and early stopping is used.

Training ensemble of 5 networks, for robustness against different random seeds.

Information in observables

Observable degrees of freedom scanned to determine the optimal observables

- largest value of Fisher information

Most sensitive observables are $m_{T_{\text{tot}}}$ and p_{T_W}.

- same result for CP-even operators [8]
- sensitive to shift of energy distributions to higher values [14]

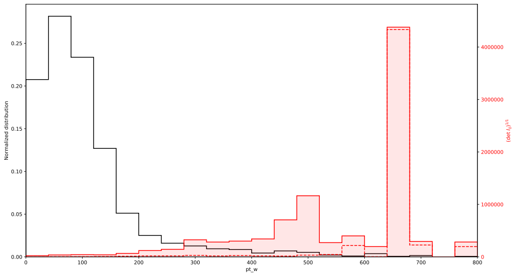


Figure 2: Distributions of p_{T_W} (black) and the distribution of the Fisher information in p_{T_W} (red).

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Warsaw basis definition

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