The Force Aweakens: searching for new sources of CPV

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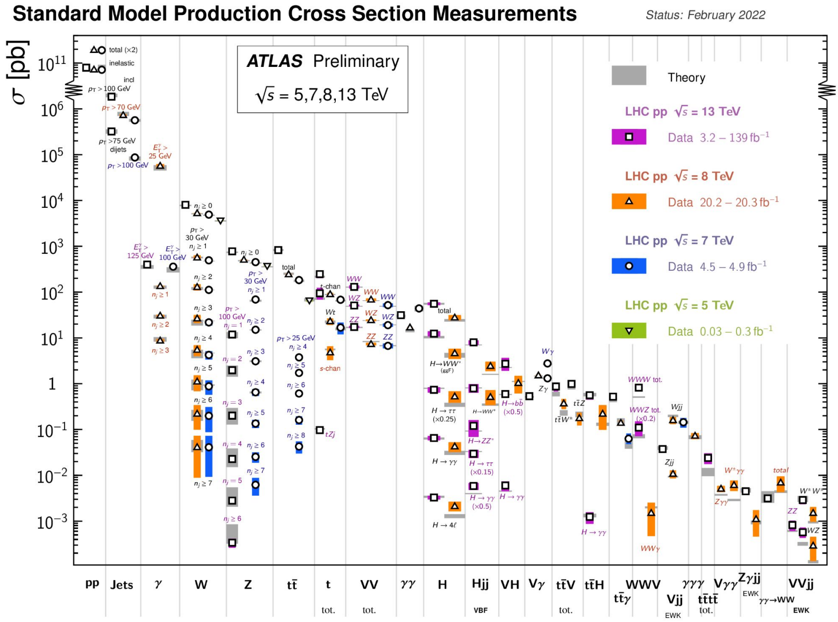
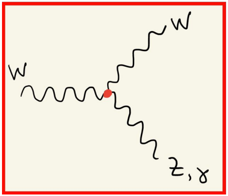
Outline:

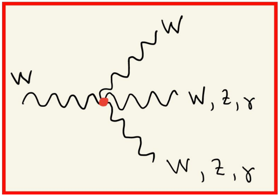
1) Searching new sources of CP-violation in the electroweak sector
2) The state-of-the-art: ATLAS measurements of VBF Z production
3) Beyond-the-state-of-the-art: Machine-enhanced CP-sensitive observables

The state of play at the LHC



Weak-boson self-interactions



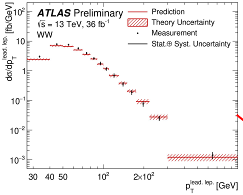


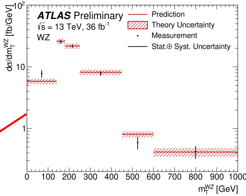
- Weak-boson self-interactions arise because the Standard Model is a non-abelian gauge theory.
- Need to measure as many processes as possible that are sensitive to these interactions………to test the SM predictions.

$$\mathcal{L}_{\text{SMEFT}} \approx \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)}.$$

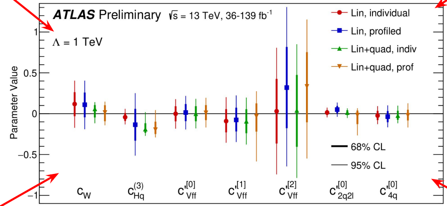
Extensions to the Standard Model induce anomalous weak-boson self-interactions

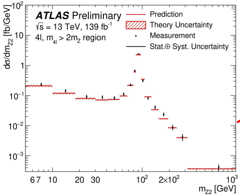
Effective field theory description of the ATLAS data

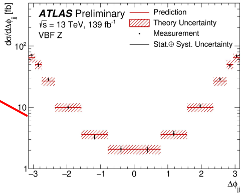




$$\mathcal{L}_{\mathrm{SMEFT}} \approx \mathcal{L}_{\mathrm{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}$$







- EFT operators typically have Lorentz structures that are different to the SM.

  = For any process: SM+EFT can have different kinematic properties to the SM alone.

- Differential cross sections then used to constrain the Wilson coefficients (i.e. the c/Λ^2).

Where does CP violation fit into all of this?

- Additional sources of CP-violation are required to explain the matter-antimatter asymmetry in the Universe = signpost for physics analyses at the LHC.

- These new sources can manifest as anomalous Higgs/weak boson interactions:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \widetilde{\mathcal{O}}_i$$

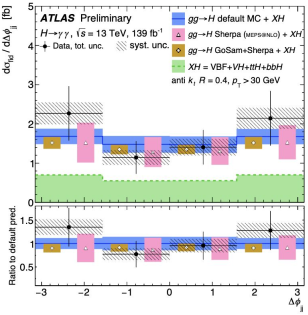
$$\begin{aligned}
\widetilde{\mathcal{O}}_{\widetilde{W}} &= \varepsilon_{ijk} \widetilde{W}^i_{\mu\nu} W^{j\,\nu\rho} W^{k\,\mu}_{\rho} \,, \\
\widetilde{\mathcal{O}}_{\Phi\widetilde{B}} &= \Phi^\dagger \Phi B^{\mu\nu} \widetilde{B}_{\mu\nu} \,, \\
\widetilde{\mathcal{O}}_{\Phi\widetilde{W}} &= \Phi^\dagger \Phi W^{i\,\mu\nu} \widetilde{W}^i_{\mu\nu} \,, \\
\widetilde{\mathcal{O}}_{\Phi\widetilde{W}B} &= \Phi^\dagger \sigma^i \widetilde{W}^{i\,\mu\nu} B_{\mu\nu} \,.
\end{aligned}$$

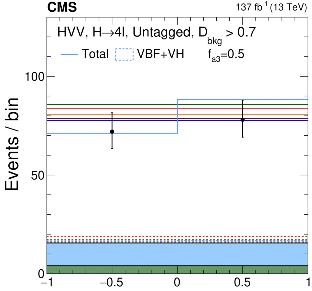
- The dimension-6 operators modify the scattering amplitude as follows:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,{\rm Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm d6}) + |\mathcal{M}_{\rm d6}|^2,$$

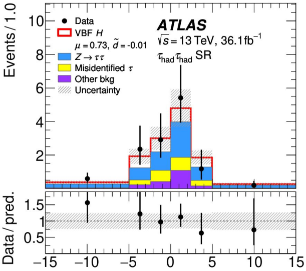
- Interference term is CP-odd and induces asymmetries in suitable CP-odd observables.

CP-sensitive observables in the Higgs sector





$$\mathcal{D}_{\rm int}(\Omega) = \frac{\mathcal{P}_{\rm int}(\Omega)}{2\sqrt{\mathcal{P}_{\rm sig}(\Omega)\ \mathcal{P}_{\rm alt}(\Omega)}},$$



$$O_{\rm opt} = \frac{2\,{\rm Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm CP\text{-}odd})}{|\mathcal{M}_{\rm SM}|^2}\,.$$

Plethora of CP-sensitive observables measured in many Higgs boson final states:

- angular observables (special construction to enforce CP-odd)
- so-called *optimal observables* based on matrix-element information.

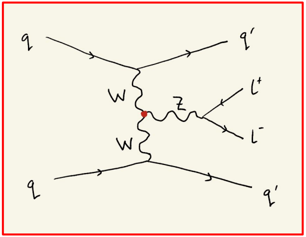
CP-sensitive observables in the electroweak sector?

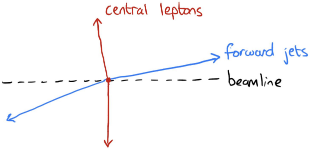
- Recent review of observables and processes in arXiv:2110.02993
- Many simple observables could have been measured for diboson processes (sensitive to weak-boson self-interactions)........but were not.
- One CP-sensitive observable measured for EW Zjj production, covered in this talk.

Operator(s)	Observable	Process
$\mathcal{O}_{WW\widetilde{W}}$	$\sin 2\phi_Z + \sin 2\phi_W$ $\sin 2\phi_W$	$pp \to ZW$ $pp \to W\gamma$
$\mathcal{O}_{\widetilde{W}WW}$ $\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\widetilde{W}B}$	$sign[(p_Z)^z]sign[(p_l \times p_Z)^z]$	$pp \to ZW$
$\mathcal{O}_{tG}$	$B_{1,2}$ and $O^{CP}_{1,2}$	$pp \to t\bar{t}$
$\mathcal{O}_{\phi\widetilde{W}}$	$\sin \phi_W$	$pp \to Wh$
$\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\tilde{B}}$	$\Delta\phi_{ll}$ $\Delta\phi_{ll}$ $\sin\Phi$	$pp \to hqq'$ (WBF) $pp \to hZ$ $pp \to h \to 4l$
$\widetilde{O}_g \subset \mathcal{O}_{\phi G}$ $i\bar{t}\gamma_5 th$	$\Delta\phi_{ll}$ $\Delta\phi_{jj}$	$pp \to hqq'$ (WBF) $pp \to tth$
$\mathcal{O}_{\phi\widetilde{W}}$	$\Delta\phi_{jj}$	$pp \to hqq'$ (WBF)
$\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\tilde{B}}$ $\mathcal{O}_{\phi\widetilde{W}B}$	$\sin\Phi$ $\sin 2\phi$	$pp \to h \to 4l$
$\mathcal{O}_{\phi\tilde{G}}$ $\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\tilde{B}}$ $\mathcal{O}_{\phi\widetilde{W}B}$	$\Delta\phi_{ll}$	$pp \to h \to ZZ^*/\gamma\gamma$
$\mathcal{O}_{\phi\tilde{B}}$ $\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\widetilde{W}B}$	$\sin\varphi$	$pp \to Zh$
$\mathcal{O}_{\phi\widetilde{W}}$ $\mathcal{O}_{\phi\widetilde{W}B}$	$\frac{\vec{p}_\gamma.(\vec{p}_{j2}\times\vec{p}_{bb})}{\lvert\vec{p}_\gamma\rvert\lvert\vec{p}_{j2}\rvert\lvert\vec{p}_{bb}\rvert}$	$pp \to h(\to b\bar{b})\gamma jj$ (WBF)
$\mathcal{O}_{\phi\widetilde{W}B}$ $\mathcal{O}_{\widetilde{W}WW}$	$\Delta\phi_{Zl}$ $\Delta\phi_{ll'}$ $\Delta\phi_{\gamma l}$	$pp \to WZ$ $pp \to WW$ $pp \to W\gamma$

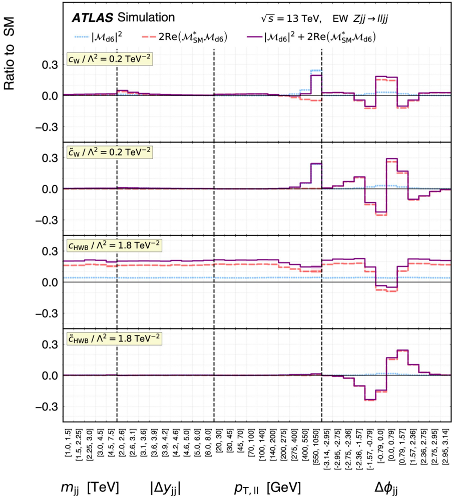
EW Zjj production as a probe of anomalous couplings

EW Zjj production





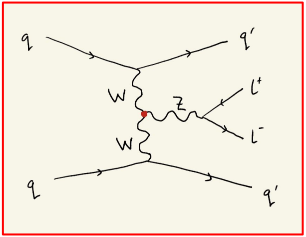
- Rapidity-ordered azimuthal angle between the jets is sensitive to the interference term, for CP-odd operators.



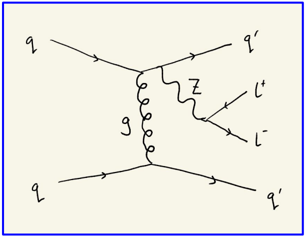
$$\Delta\phi_{jj} = \phi_f - \phi_b \quad \textit{with} \quad y_f > y_b$$

Backgrounds from QCD-initiated jet production

EW Zjj production



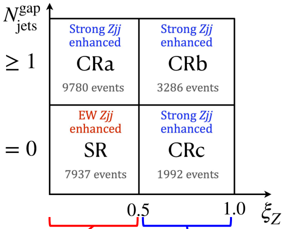
'strong' Zjj production



- Large background from QCD-induced jet production in association with the Z boson (factor of 100 larger than EW Zjj)

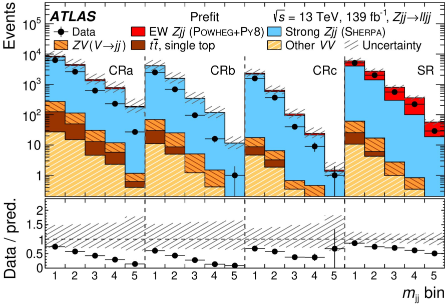
muons	$p_T > 25$ GeV and $\|\eta\| < 2.4$
electrons	$p_T > 25$ GeV and $\|\eta\| < 2.37$ (excluding $1.37 < \|\eta\| < 1.52$)
Jets	$p_T > 25$ GeV and $\|y\| < 4.4$
VBF topology	$N_\ell = 2$ (same flavour, opposite charge), $m_{\ell\ell} \in (81, 101)$ GeV
	$\Delta R_{\min}(\ell_1, j) > 0.4$, $\Delta R_{\min}(\ell_2, j) > 0.4$
	$N_{\text{jets}} \geq 2$, $p_T^{j1} > 85$ GeV, $p_T^{j2} > 80$ GeV
	$p_{T,\ell\ell} > 20$ GeV, $p_T^{\text{bal}} < 0.15$
	$m_{jj} > 1000$ GeV, $\|\Delta y_{jj}\| > 2$, $\xi_Z < 1$

Signal extraction



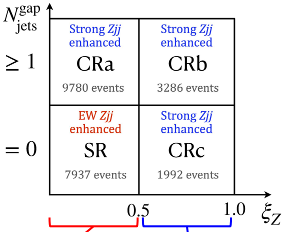
$$\nu^{\text{strong}}_{\text{CRa},i} = b_{\text{L},i}\, \nu^{\text{strong,MC}}_{\text{CRa},i} ,$$
$$\nu^{\text{strong}}_{\text{SR}i} = b_{\text{L},i}\, f(x_i)\, \nu^{\text{strong,MC}}_{\text{SR},i}$$

$$\nu^{\text{strong}}_{\text{CRb},i} = b_{\text{H},i}\, \nu^{\text{strong,MC}}_{\text{CRb},i} ,$$
$$\nu^{\text{strong}}_{\text{CRc},i} = b_{\text{H},i}\, f(x_i)\, \nu^{\text{strong,MC}}_{\text{CRc},i}$$



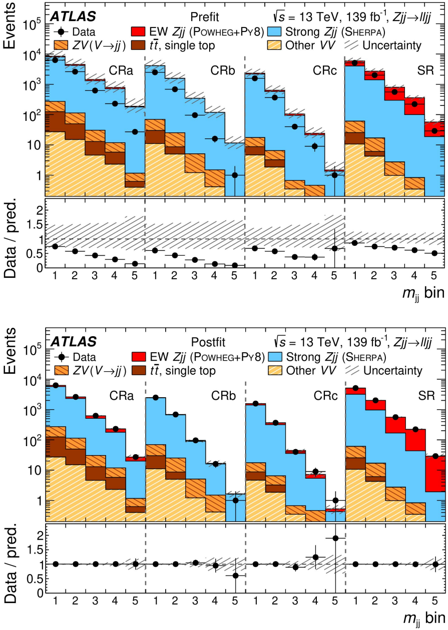
- strong Zjj background found to be poorly modelled (not a surprise)
- EW-suppressed control regions used to constrain the shape of the background

Signal extraction

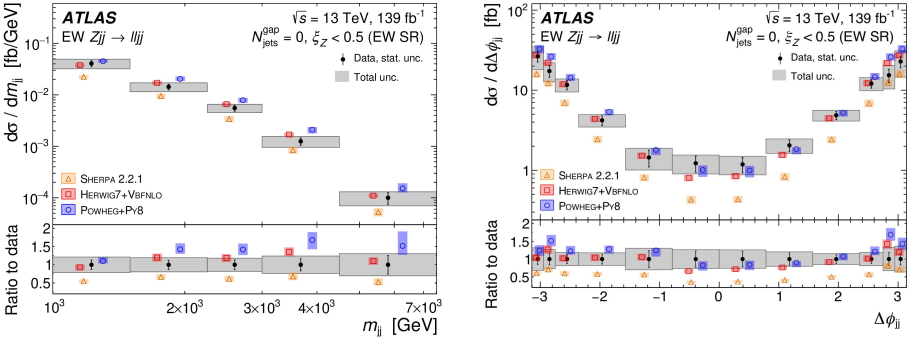


$$\nu^{\text{strong}}_{\text{CRa},i} = b_{\text{L},i}\, \nu^{\text{strong,MC}}_{\text{CRa},i},$$
$$\nu^{\text{strong}}_{\text{SR}i} = b_{\text{L},i}\, f(x_i)\, \nu^{\text{strong,MC}}_{\text{SR},i}$$

$$\nu^{\text{strong}}_{\text{CRb},i} = b_{\text{H},i}\, \nu^{\text{strong,MC}}_{\text{CRb},i},$$
$$\nu^{\text{strong}}_{\text{CRc},i} = b_{\text{H},i}\, f(x_i)\, \nu^{\text{strong,MC}}_{\text{CRc},i}$$

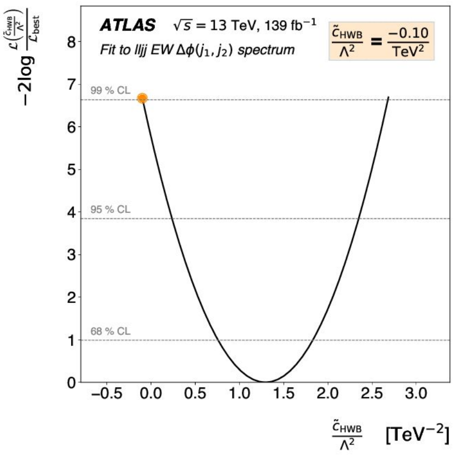


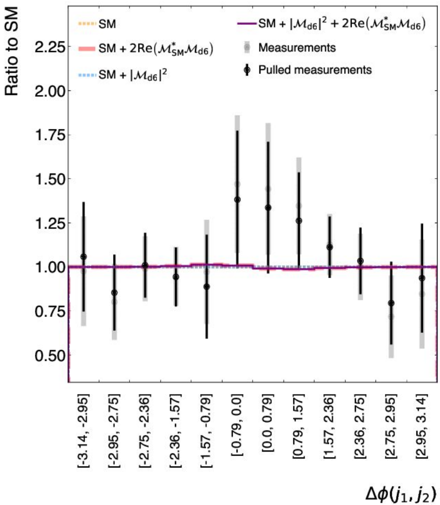
Differential cross section measurements



- Data is unfolded: i.e. corrected for detector effects.
- Measurements sensitive enough to distinguish between different SM predictions, which differ mainly in the parton shower and colour flow treatment.
- Rapidity-ordered azimuthal separation then can be used to test for CP-violating effects

Sensitivity to EFT parameters



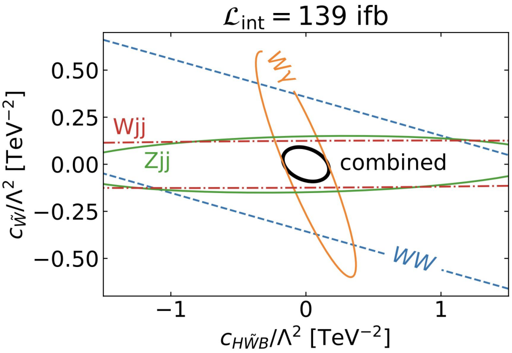


EFT results

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	$[-0.30,\ 0.30]$	$[-0.19,\ 0.41]$	45.9%
	yes	$[-0.31,\ 0.29]$	$[-0.19,\ 0.41]$	43.2%
$\tilde{c}_W/\Lambda^2$	no	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	82.0%
	yes	$[-0.12,\ 0.12]$	$[-0.11,\ 0.14]$	81.8%
c_{HWB}/Λ^2	no	$[-2.45,\ 2.45]$	$[-3.78,\ 1.13]$	29.0%
	yes	$[-3.11,\ 2.10]$	$[-6.31,\ 1.01]$	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	$[-1.06,\ 1.06]$	$[0.23,\ 2.34]$	1.7%
	yes	$[-1.06,\ 1.06]$	$[0.23,\ 2.35]$	1.6%

- Only one CP-sensitive angular observable measured for the purely electroweak sector
- But…. this set the best constraints on three of the operators in the linearised EFT.

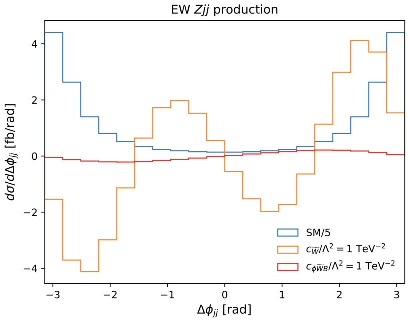
What to do next?

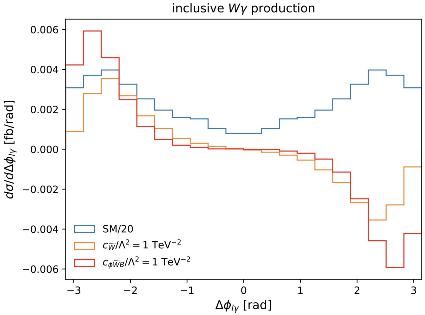


- More measurements of more final states!
- More advanced analysis techniques, i.e. use machine learning learning to construct the CP-sensitive observable.

Rest of this talk is a phenomenology study to establish whether/how machine learning can help.

Standard CP-sensitive observables





For diboson and VBF V processes, rapidity-ordered difference in azimuthal angle between two objects is CP-sensitive:

$$\Delta\phi_{ij} = \phi_i - \phi_j \quad \textit{with} \quad y_i > y_j$$

Key features:

- The SM prediction is symmetric.
- The interference contribution is asymmetric and integrates to zero.

Alexa: build me a CP-sensitive observable!

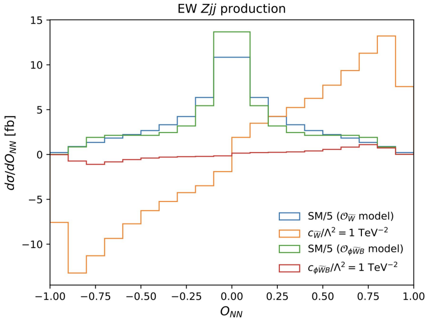
- Reminder: CP-asymmetries arise from the interference between SM amplitude and the CP-odd amplitude:

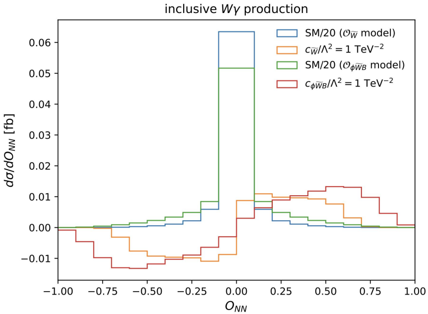
$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + \boxed{2\,\mathrm{Re}(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm d6})} + |\mathcal{M}_{\rm d6}|^2,$$

- Neural networks (NN) offer an easy way to exploit these asymmetries.
  - generate interference-only contribution to process (Madgraph5, SMEFTSim)
  - split sample into positive-weights and negative-weights.
  - train NN to distinguish between the two samples (binary classification)
  - include Standard-Model contribution in the training (multiclass model)

- Options with trained network:
  - construct observable from NN classifications, i.e $O_{NN} = P_+ - P_-$.
  - improve differential cross-section measurements.

NN-constructed CP-sensitive observables

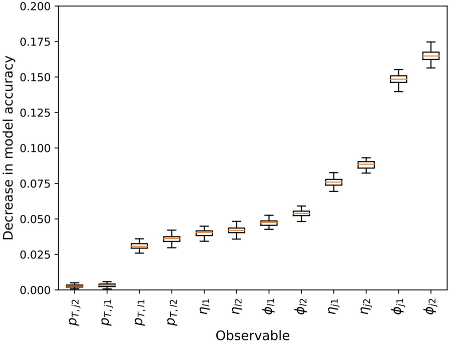


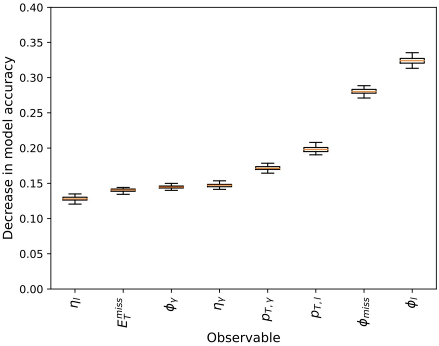


Result as expected (or hoped for):

- Positive (negative) interference contribution located at $O_{NN} \to 1$ ($O_{NN} \to -1$)
- SM contribution well separated from the interference contributions.
- Ratio of interference/SM is improved with respect to simple angular observables.

What is the network learning?





Origin of extra sensitivity determined using feature importance techniques, whereby the change in accuracy and/or loss is evaluated after decorrelating input variables in the trained network.

The network has learned:

- angular correlations to optimally distinguish between positive- and negative- interference
- the optimal fiducial region to distinguish between the SM and the CP-asymmetry

Constraints on SMEFT operators

Process	CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
EW Zjj	$\Delta\phi_{jj}$	[-1.05,1.05]	[-0.081,0.081]
	O_{NN} (multi-class)	[-0.83,0.83]	[-0.047,0.047]
	$\Delta\phi_{jj}$ vs $\Delta\phi_{\ell\ell}$	[-0.99,0.99]	[-0.074,0.074]
	$\Delta\phi_{jj}$ vs $p_{\mathrm{T},\ell\ell}$	[-1.04,1.04]	[-0.066,0.066]
inclusive $W\gamma$	$\Delta\phi_{l\gamma}$	[-0.165,0.165]	[-0.255,0.255]
	O_{NN} (multi-class)	[-0.049,0.049]	[-0.056,0.056]
	$\Delta\phi_{l\gamma}$ vs $\|\phi_l - \phi_{\mathrm{miss}}\|$	[-0.154,0.154]	[-0.219,0.219]
	$\Delta\phi_{l\gamma}$ vs $E_{\mathrm{T}}^{\mathrm{miss}}$	[-0.163,0.163]	[-0.206,0.206]

Sensitivity to specific operators established using Profile Likelihood method.

Main observations:

- NN-based observable offers the best sensitivity to each operator.
- Double-differential analysis can capture some of the sensitivity gained by NN.

What about other processes?

Process	CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{B}}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{W}}/\Lambda^2$ [TeV^{-2}]	$c_{\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
EW $ZZjj$	$\Delta\phi_{jj}$	[-3.7,3.7]	[-43,43]	-	-
	$\Phi_{4\ell}$	[-51,51]	[-64,64]	-	-
	O_{NN} (multi-class)	[-3.0,3.0]	[-12,12]	-	-
EW $W^\pm W^\pm jj$	$\Delta\phi_{jj}$	-	-	[-35,34]	[-1.83,1.83]
	$\Delta\phi_{\ell\ell}$	-	-	[-105,105]	[-14,14]
	O_{NN} (multi-class)	-	-	[-17,17]	[-0.76,0.76]
$\gamma\gamma \to WW$	$\Delta\phi_{\ell\ell}$	[-32,32]	[-14,14]	[-48,48]	[-19,19]
	O_{NN} (multi-class)	[-11,11]	[-13,13]	[-43,43]	[-11,11]

- NN-constructed observables improve sensitivity for all processes that were studied.
- Open question: what sensitivity will be obtained from WW and WZ production.

Summary and outlook

Measurements of diboson production and EW Vjj production can provide the best sensitivity to CP-violating effects predicted by dimension-six effective field theory.

- Very few measurements done at the LHC to date.
- ATLAS EW Zjj measurement provide first such constraints [EPJ C 81, 163 (2021)]
- Ideal opportunity for early Run-III measurements!

Neural networks offer a simple approach to constructing optimised CP-sensitive observables:

- distinguishes between the positive and negative interference contributions
- exploits differences in kinematics between the interference and Standard-Model
- Origin of CP-asymmetries can be easily explored and used to improve differential cross section measurements
- Full explanation of this method is available for Higgs [PLB 832 (2022), 137245] and diboson/VBS [arXiv:2209.05143] final states.