Machine Learning for Higgs CP properties

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Motivation

- CP violating operators affecting the Higgs/multiboson interactions can be probed via Effective Field Theory:

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

c_i/Λ^2 the Wilson coefficients,
Λ the scale of new physics

$$\widetilde{\mathcal{O}}_{\Phi\widetilde{B}} = \Phi^\dagger \Phi B^{\mu\nu} \widetilde{B}_{\mu\nu}\,,$$
$$\widetilde{\mathcal{O}}_{\Phi\widetilde{W}} = \Phi^\dagger \Phi W^{i\,\mu\nu} \widetilde{W}^i_{\mu\nu}\,,$$
$$\widetilde{\mathcal{O}}_{\Phi\widetilde{W}B} = \Phi^\dagger \sigma^i \widetilde{W}^{i\,\mu\nu} B_{\mu\nu}\,.$$

- Beyond-the-SM amplitude is then given by: $|\mathcal{M}_{\mathrm{BSM}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \boxed{2\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{d6}}\}} + |\mathcal{M}_{\mathrm{d6}}|^2$
- Interference term leads to asymmetries in CP-odd observables

- Possible CP-odd observables
  - Statistically optimal observables
  - Angular observables – less sensitivity but easier implementation
  - Machine-learning observables – attempt to recover best sensitivity while keeping feasibility

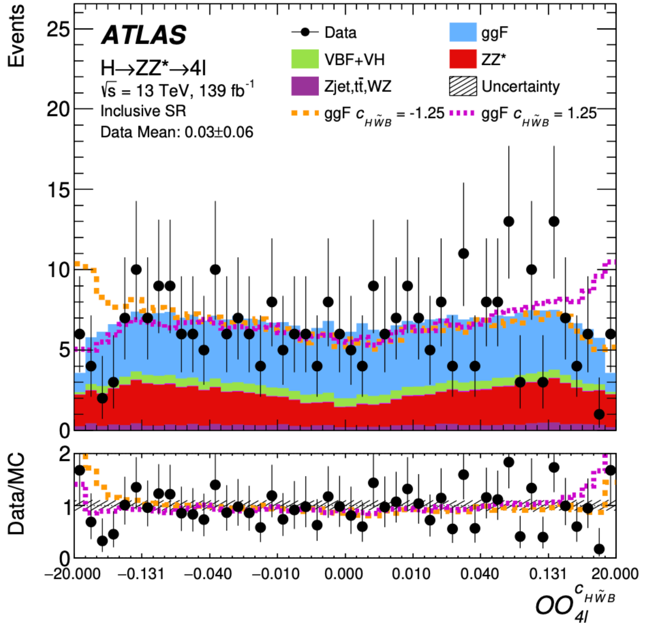
Statistically optimal observables

- Statistically optimal observable (PhysRevD.45.2405, Phys. Lett. B 306 (1993) 411, arXiv:hep-ph/9603207) is defined as:

$$\mathcal{O}_{\mathrm{opt}} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2} \quad , \qquad 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2\,\mathrm{Re}((\mathcal{M}^{ij\to klH}_{\mathrm{SM}})^* \mathcal{M}^{ij\to klH}_{\text{CP-odd}})$$

$$|\mathcal{M}_{\mathrm{SM}}|^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) |\mathcal{M}^{ij\to klH}_{\mathrm{SM}}|^2 .$$

- Needs sum over all possible flavour configurations $ij \to klH$ weighted by PDF
- Calculated from the four-momentum of the Higgs boson candidate and the two leading jets in VBF configuration or from the four-momenta of the decay objects
- Highest sensitivity to small values of the parameter of interest



- $h \to 4\ell$ differential cross-section (corrected for detector inefficiency and resolution effects) as function of OO (arXiv:2304.09612)
- Confidence intervals using OO with an integrated luminosity of 139 fb−1

EFT coupling parameter	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL
$c_{H\tilde{B}}$	[−0.18, 0.19]	[−0.37, 0.37]	[−0.42, 0.31]	[−0.61, 0.54]
$c_{H\widetilde{W}B}$	[−0.36, 0.36]	[−0.72, 0.72]	[−0.56, 0.53]	[−0.97, 0.98]
$c_{H\widetilde{W}}$	[−0.63, 0.63]	[−1.26, 1.28]	[−0.07, 1.09]	[−0.81, 1.54]

Angular observables

- $\phi_{4\ell}$ (PhysRevD.94.055023, PhysRevD.86.095031) in $h \rightarrow 4\ell$

$$\Phi = \frac{\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_2)}{|\boldsymbol{q}_1 \cdot (\hat{\boldsymbol{n}}_1 \times \hat{\boldsymbol{n}}_2)|} \times \cos^{-1}(-\hat{\boldsymbol{n}}_1 \cdot \hat{\boldsymbol{n}}_2)$$

  - with the normal vectors to the planes defined as

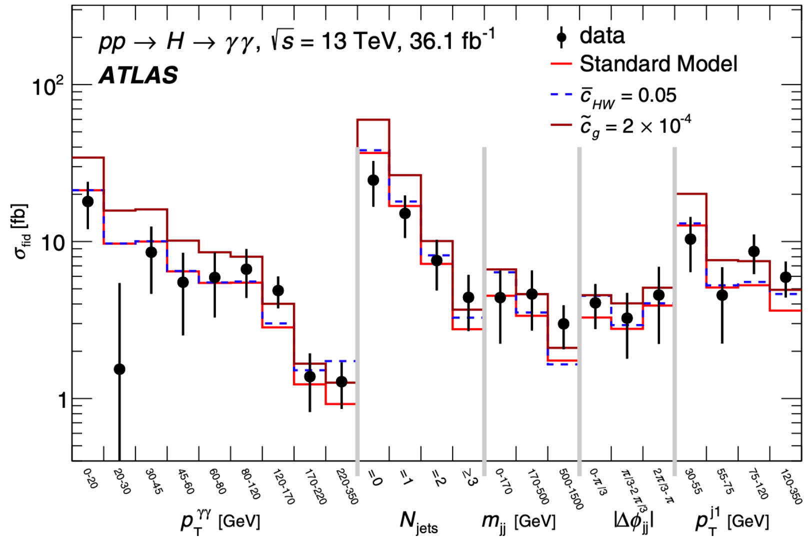
$$\hat{\boldsymbol{n}}_1 = \frac{\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}}{|\boldsymbol{q}_{11} \times \boldsymbol{q}_{12}|} \qquad \hat{\boldsymbol{n}}_2 = \frac{\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}}{|\boldsymbol{q}_{21} \times \boldsymbol{q}_{22}|}$$

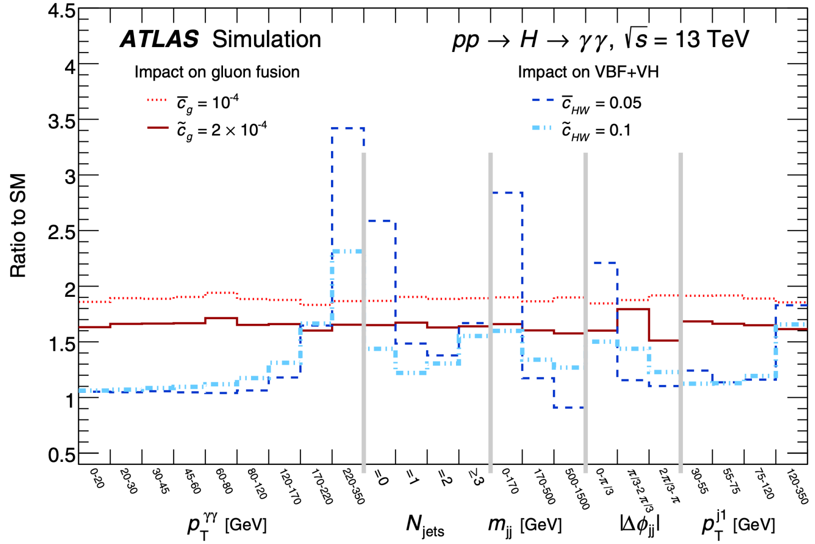
  - and $q_{\alpha i}$ being the three-momentum of the lepton/antilepton i from the Z_α boson decay, and $q_\alpha = q_{\alpha 1} + q_{\alpha 2}$ being the three-momentum of the Z_α boson

- $\Delta\phi_{\text{jj}} = \phi_{j1} - \phi_{j2}$ (PhysRevLett.88.051801)
  - with two highest transverse-momentum jets ordered by $y_{j1} > y_{j2}$
  - Sensitive to anomalous weak-boson self-interactions

- Expected 95% confidence intervals using $\Delta\phi_{\text{jj}}$ for an integrated luminosity of 36 fb^{-1} (PhysRevD.98.052005)

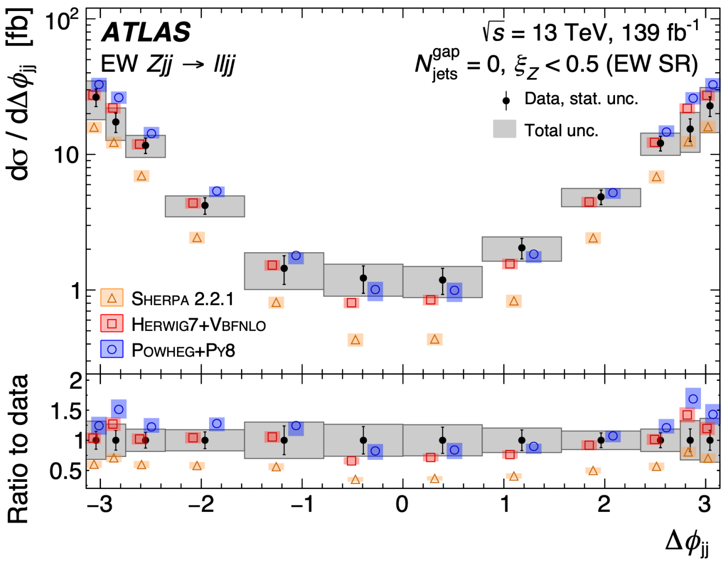
Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\tilde{c}_{HW}$	$[-0.16, 0.16]$	$[-0.14, 0.14]$





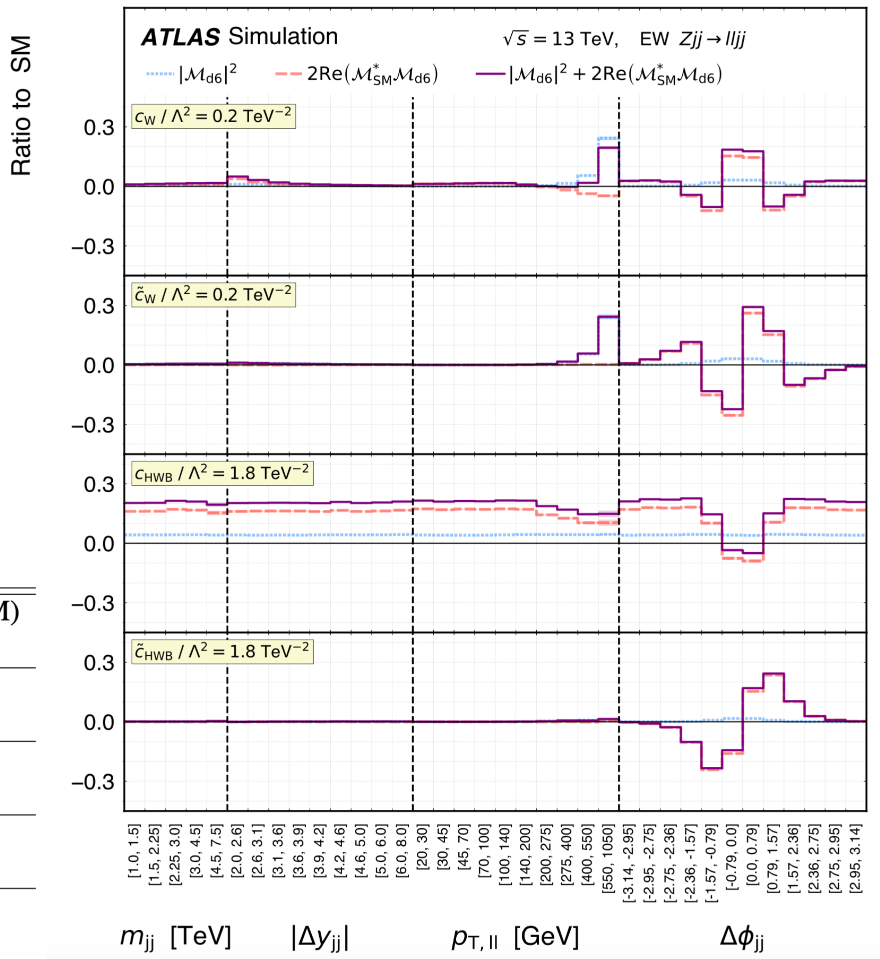
Angular observables: Electroweak Zjj production

- Differential cross-section (corrected for detector inefficiency and resolution effects) as function of $\Delta\phi_{jj}$ (Eur. Phys. J. C 81 (2021) 163)



- Expected and observed 95% confidence interval for the four Wilson coefficients for an integrated luminosity of 36 fb^{-1}

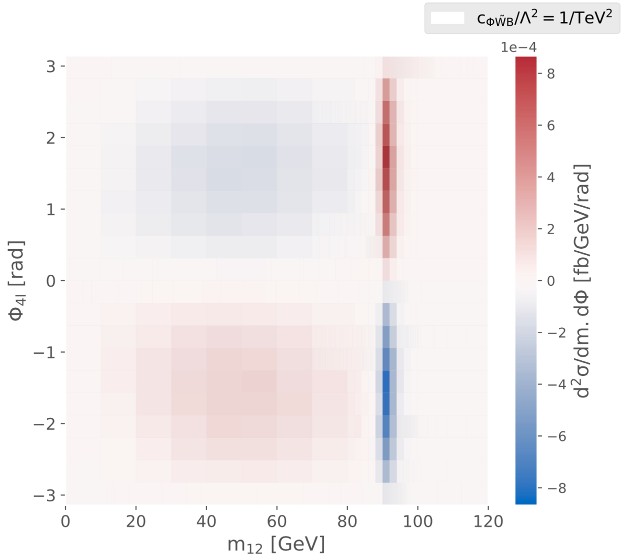
Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	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%



Neural network-based observable: Method

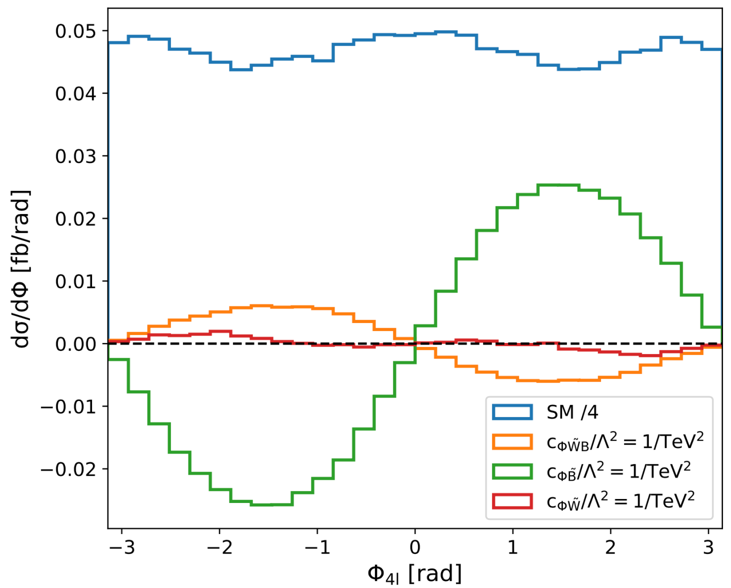
- Differential cross-section as function of NN-constructed CP-odd observable (Phys. Lett. B 832 (2022) 137246)
- Events generated for $h \to 4\ell$ and VBF $h + 2$ jets for SM and interference induced by dim-6 CP-odd operators in SMEFTsim
- Multi-class model trained in interference and pure Standard Model events, defining the probabilities
  - $P_+(P_-), P_{SM}$ as the probability of an event being a positive (negative)-weighted interference or SM event
  - $P_+ + P_- + P_{SM} = 1$
- NN-constructed observable defined then as:
  - $O_{NN} = P_+ - P_-$

- Inputs to NN including lepton/jet four vectors and derived variables
- Importance of each variable evaluated via feature importance techniques
  - Evaluates decrease in accuracy when each input variable is randomly shuffled
- $\phi_{4\ell}$ and m_{12} (mass of lepton-antilepton pair) are the most important variables in $h \to 4\ell$ production
  - Sign flip due to different contributions from the $h \to ZZ$, $h \to \gamma\gamma$ and $h \to Z\gamma$ dim-6 amplitudes in on- and off-shell regions
- Sensitivity in VBF $h + 2$ jets driven by $\Delta\phi_{jj}$

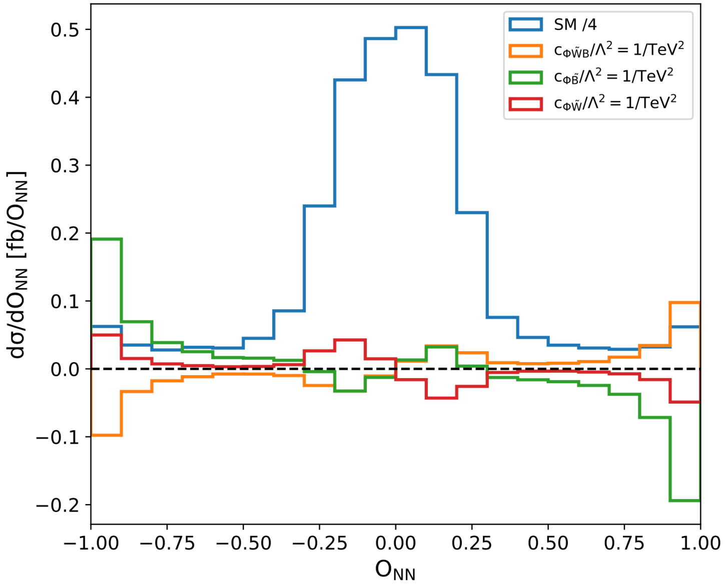


Neural network-based observable: $h \to 4\ell$ results

$\phi_{4\ell}$



O_{NN}



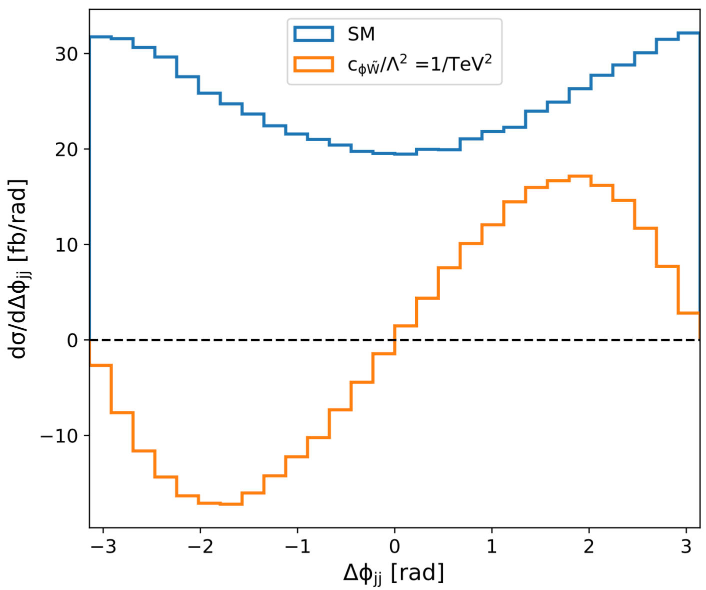
- Expected 95% confidence intervals for the three Wilson coefficients given an integrated luminosity of 139 fb^{-1}

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}]
$\Phi_{4\ell}$	$[-6.2, 6.2]$	$[-1.4, 1.4]$	$[-30, 30]$
$\Phi_{4\ell}, m_{12}$	$[-1.9, 1.9]$	$[-0.85, 0.85]$	$[-3.7, 3.7]$
O_{NN} (binary)	$[-1.5, 1.5]$	$[-0.75, 0.75]$	$[-3.0, 3.0]$
O_{NN} (multi-class)	$[-1.4, 1.4]$	$[-0.71, 0.71]$	$[-2.7, 2.7]$

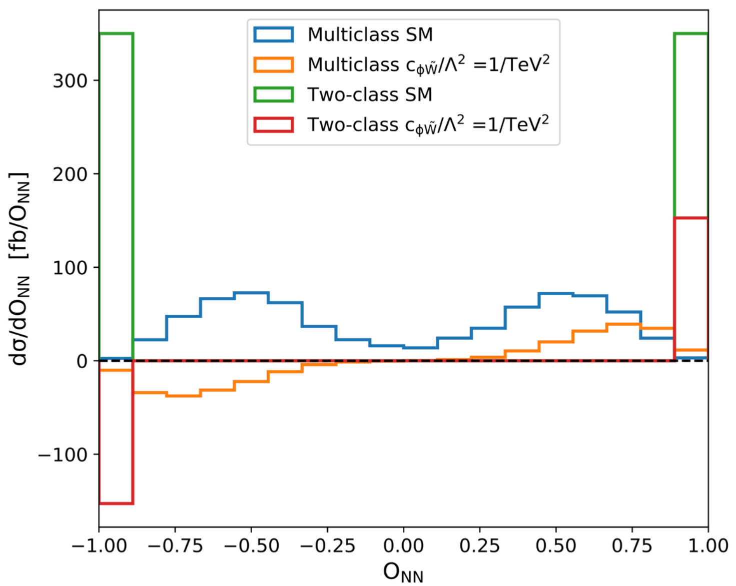
- Factor 2 to 10 **improvement using O_{NN}** in sensitivity to Wilson coefficients
- Considerable gain can be recovered by two-dimensional fit to $\phi_{4\ell}$ and m_{12}

Neural network-based observable: VBF $h + 2$ jets results

$\Delta\phi_{jj}$



O_{NN}



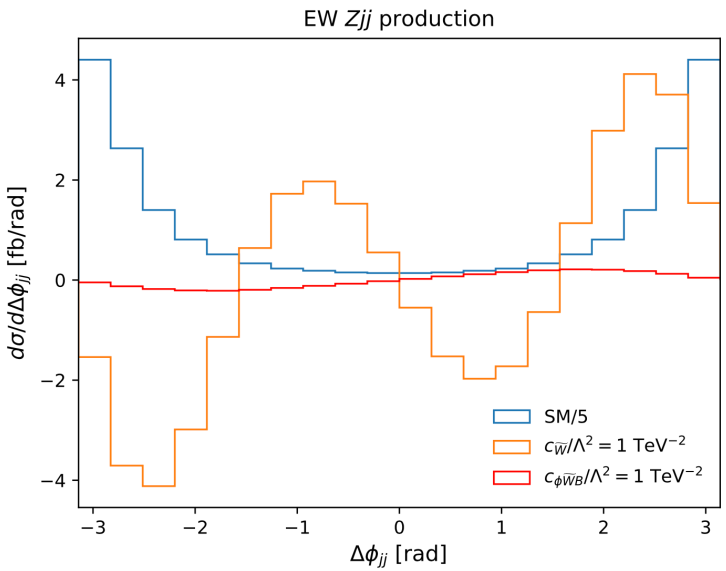
- Expected 95% confidence intervals for the three Wilson coefficients given an integrated luminosity of 139 fb^{-1}

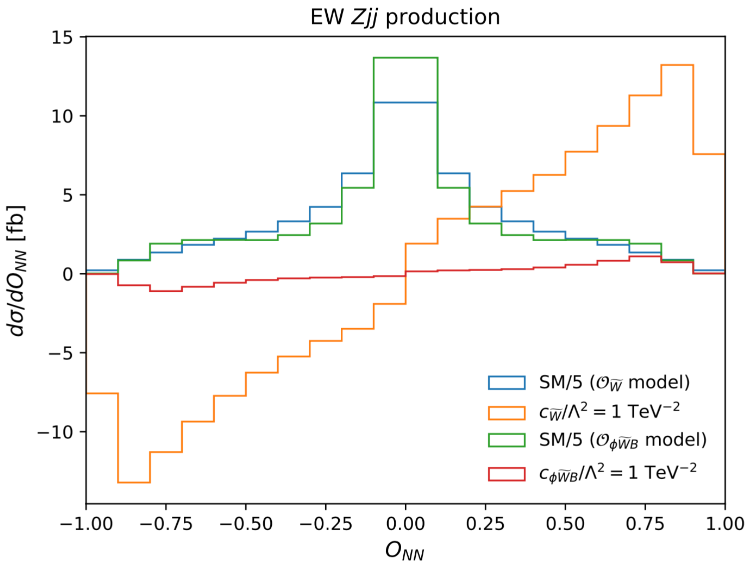
CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{B}}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
$\Delta\phi_{jj}$	$[-21, +21]$	$[-149, +149]$	$[-0.60, +0.60]$
O_{NN} (binary)	$[-11, +11]$	$[-43, +43]$	$[-0.66, +0.66]$
O_{NN} (multi-class)	$[-10, +10]$	$[-36, +36]$	$[-0.42, +0.42]$

- Factor 1.5 to 4 **improvement using O_{NN}** in sensitivity to Wilson coefficients
- Full kinematic information accessible in multi-class providing best performance

Neural network-based observable: Electroweak final states

- O_{NN} can provide direct sensitivity to CP-odd operators in the electroweak sector (2209.05143)
- It can also be used as a guide to most sensitive variables





- O_{NN} more effective at separating the positively and negatively-weighted interference contributions beyond $\Delta\phi_{jj}$ by accessing lepton kinematics
- Expected 95% confidence interval for the targeted Wilson coefficients given an integrated luminosity of 139 fb^{-1}
- Factor of up to two improvements in expected limits

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]

Summary

- CP-odd effects can be proved in EFT context via construction of appropriate variables

- Three main approaches:
  - Optimal observables
  - Angular observables
  - Machine-learning based observables

- Differential cross-section as function of NN-constructed CP-odd, $O_{NN} = P_+ - P_-$, can provide sensitivity to CP-odd effects
  - Outperforms angular observables

- Preservability of optimal observables in Rivet difficult due to PDF usage in matrix element calculation; preservability of NN-based observables to be investigated

Backup