New techniques for studying CP violation

Andrew Pilkington, SM@LHC conference, Rome, 7th May 2024

Why do we need additional sources of CP violation?

- We live in a matter-dominated Universe

- Sakarov conditions for producing this baryon asymmetry in early Universe:
  - Baryon number violation
  - C- and CP- violating interactions
  - Thermal inequilibrium

- The electroweak/Higgs sector of the Standard Model fails to provide a complete answer:
  - CP-violation in quark sector is way too small
  - The EW phase transition is a second-order phase transition.

Effective field theory approach

- Assume there is new physics at some high energy scale, Λ, that provides the additional sources of CP-violation (and possibly the requisit first-order phase transition)

- At lower energy scales, the effects of this physics can be expressed as operators in an effective Lagrangian:

$$\mathcal{L}_{\rm SMEFT} \approx \mathcal{L}_{\rm SM}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} O_j^{(8)}.$$

Extensions to the SM induce anomalous interactions

- Additional sources of CP-violation included via CP-odd operators.

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

Subset of CP-odd operators that affect HVV, VVV, VVVV interactions

Interference considerations

- Considering only dimension-6 operators, the scattering amplitude is

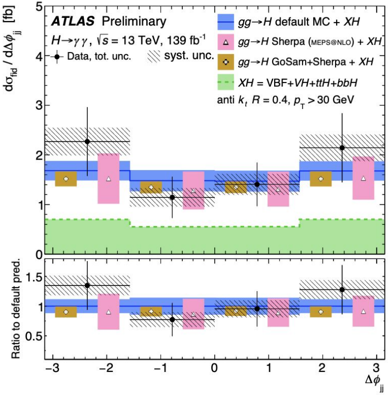
$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\,\mathrm{Re}(\mathcal{M}_{SM}^*\mathcal{M}_{d6}) + |\mathcal{M}_{d6}|^2$$

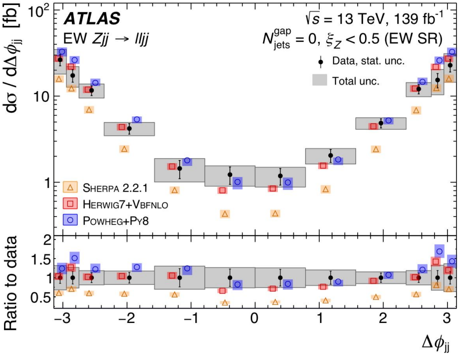
- Ideally, we should construct observables sensitive to the interference term:
  - $\mathcal{M}_{SM}^*\mathcal{M}_{d6}$ *should* be the leading correction to the SM, proportional to $1/\Lambda^2$.
  - $|\mathcal{M}_{d6}|^2$ *should* be subleading as proportional to $1/\Lambda^4$.
  - Leading dimension-8 terms are missing and also proportional to $1/\Lambda^4$.

- The interference term is CP-odd and produces asymmetries in CP-odd observables

  …but integrates to zero for CP-even observable.

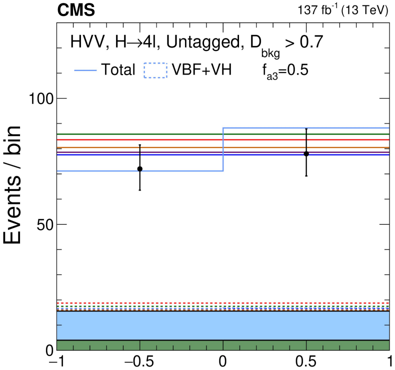
CP-sensitive observables: differential cross sections



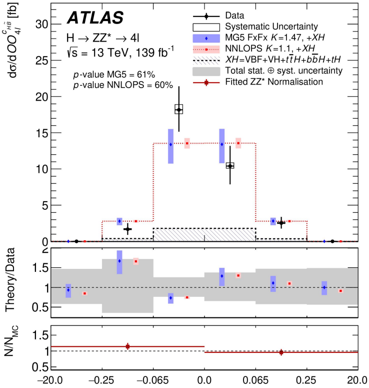


- Increasingly common to measure differential cross sections as a function of CP-odd observables, for both Higgs boson production and diboson/VBF/VBS processes.
- Advantages: model-independent, easily unfolded and therefore easy to reinterpret.
- Disadvantages: sensitivity, i.e. how to optimise the phase-space?

CP-sensitive observables: matrix-element inspired



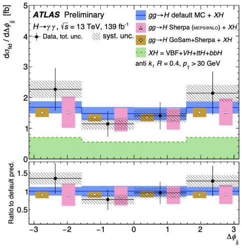
$$\mathcal{D}_{\text{int}}\left(\mathbf{\Omega}\right) = \frac{\mathcal{P}_{\text{int}}\left(\mathbf{\Omega}\right)}{2\sqrt{\mathcal{P}_{\text{sig}}\left(\mathbf{\Omega}\right)\ \mathcal{P}_{\text{alt}}\left(\mathbf{\Omega}\right)}},$$

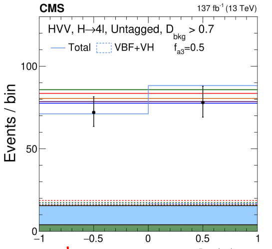


$$OO = \frac{2\Re\left(\mathcal{M}_{\text{SM}}^{*}\mathcal{M}_{\text{BSM}}\right)}{\left|\mathcal{M}_{\text{SM}}\right|^{2}}$$

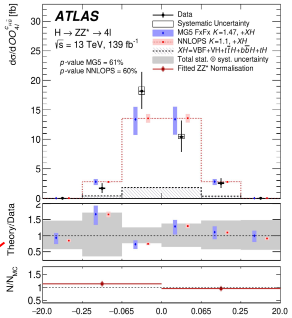
- Alternative approach is to use discriminants based on matrix-element information.
- Advantages: optimal in terms of sensitivity for a given analysis.
- Disadvantages: more complicated (i.e. time-consuming); often not unfolded; when unfolded difficult to reinterpret using tools like Rivet.

The long view: need global fit for CP-violating operators





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



$$OO = \frac{2\Re\left(\mathcal{M}^*_{\rm SM}\mathcal{M}_{\rm BSM}\right)}{|\mathcal{M}_{\rm SM}|^2}$$

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

- Best sensitivity will be via a global fit to CP-sensitive observables:
  - not currently done
  - requires model-independent measurements that are easy to reinterpret.

Alternative approach: CP-odd observables from ML

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

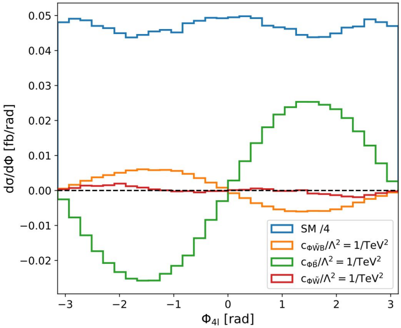
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}}) + |\mathcal{M}_{\mathrm{d6}}|^2$$

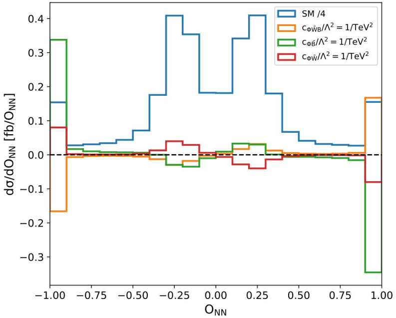
- Neural networks (NN) offer an easy way to understand these asymmetries.
  - generate interference-only contribution to process (e.g Madgraph5 + SMEFTSim)
  - split sample into positive-weights and negative-weights.
  - train NN to distinguish between the two samples (binary classification)
  - easy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

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

based on: PLB 832 (2022) 137246 and PRD 107 (2023) 016008
see also: PRD 102 (2020) 056022 and JHEP 05 (2021) 147

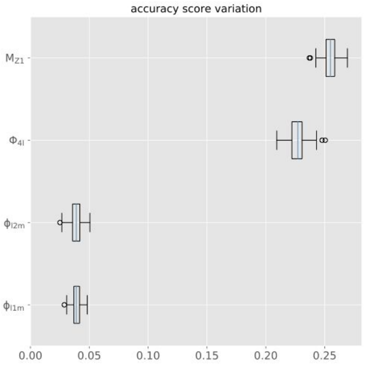
Inclusive H→4l

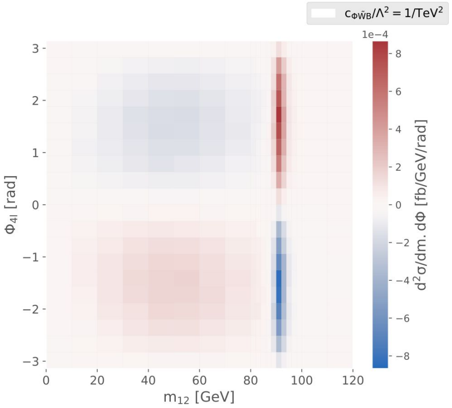




- Analysis carried out in the *Higgs Mass* region of the ATLAS inclusive *4l* measurement (JHEP 07, 005 (2021) for H→2e2μ events.
- Simple CP-odd variable (PRD 86, 095031 [2012]): $$\Phi_{4\ell} = \frac{\mathbf{q}_1\cdot(\hat{\mathbf{n}}_1\times\hat{\mathbf{n}}_2)}{|\mathbf{q}_1\cdot(\hat{\mathbf{n}}_1\times\hat{\mathbf{n}}_2)}| \times \cos^{-1}(\hat{\mathbf{n}}_\mathbf{1}\cdot\hat{\mathbf{n}}_\mathbf{2}),$$
- NN trained using the interference induced by the $\mathcal{O}_{\Phi\widetilde{W}B}$ operator in the Warsaw basis.

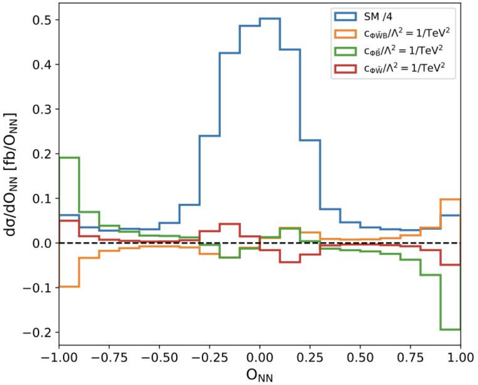
What has the network learned?





- Origin of extra sensitivity investigated using feature importance techniques, i.e. change in accuracy / loss evaluated after decorrelating input variables in the trained network.
- Clear interplay between Φ_{4l} and m_{Z1} (e^+e^- or $\mu^+\mu^-$ pair with mass closest to Z pole).

Multiclass models



- Multiclass = including the SM prediction as a third class in the training ($P_+ + P_- + P_{sm} = 1$).
- Optimises the separation of the interference contributions for a process, by accounting for any kinematic differences between the SM and the interference.

Limits on CP-odd operators for H→2e2μ

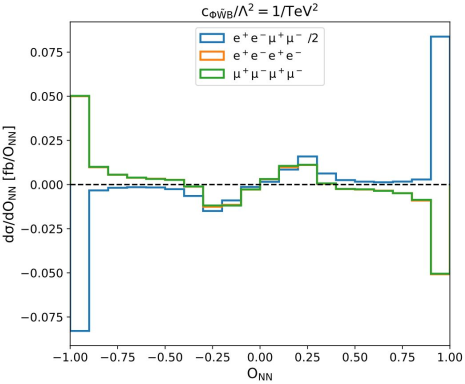
CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{B}}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
$\Phi_{4\ell}$	[-6.2,6.2]	[-1.4,1.4]	[-30,30]
$\Phi_{4\ell}$, m_{12}	[-1.9,1.9]	[-0.85,0.85]	[-3.7,3.7]
O_{NN} (binary)	[-1.5,1.5]	[-0.75,0.75]	[-3.0,3.0]
O_{NN} (multi-class)	[-1.4,1.4]	[-0.71,0.71]	[-2.7,2.7]

Sensitivity to specific operators established using the Profile Likelihood method, after normalising the MC samples to the number of events observed in the ATLAS analyses.

Main observations:

- NN-based observables offer the best sensitivity.
- Multiclass models improve sensitivity w.r.t binary classification, i.e. networks learn the difference between the SM and the interference contributions.
- Double-differential analysis of Φ_{4l} and m_{Z1} captures most of the sensitivity gained by NN

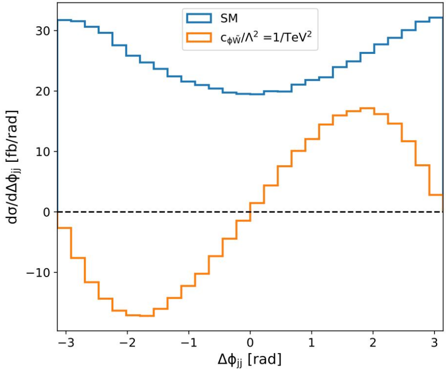
Subtleties: decay channel considerations

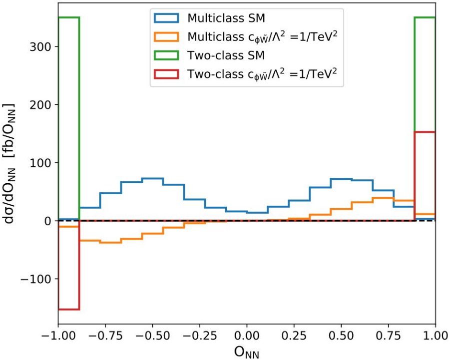


- Difference in sign and magnitude of interference depending on channel (2e2μ, 4e, 4μ)
  - Mispairing of leptons in 4e and 4μ channels when both pairs are off-shell.
  - Additional diagrams in the 4e/4μ channels.

→ Channels need to be measured independently.

VBF Higgs production





- Analysis carried out in the *VBF_1* region of the ATLAS H→ττ analysis (ATLAS-CONF-2021-044)
- Classic CP-odd variable: $\Delta\phi_{jj} = \phi(j_1) - \phi(j_2)$
- NN trained using the interference induced by the $\mathcal{O}_{\Phi\widetilde{W}}$ operator in the Warsaw basis.

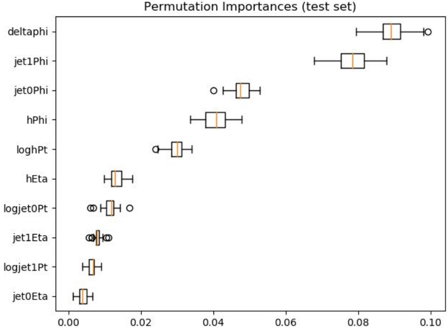
VBF Higgs production

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]

Main conclusions:

- multiclass training more important
- matching NN sensitivity using differential cross sections will be trickier

Both of these features arise because VBF is a multiscale process.

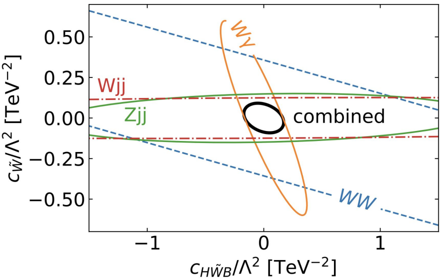


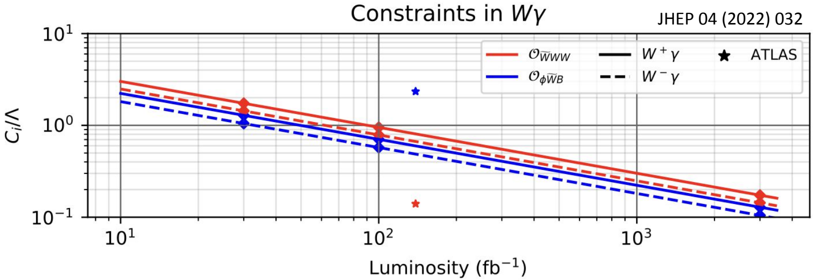
Higgs-without-Higgs: VVV interactions at LHC

Two operators affect weak-boson self-interactions:

- $\mathcal{O}_{\widetilde{W}}$ can only be measured in VVV interactions
- $\mathcal{O}_{\phi\widetilde{W}B}$ can be measured in HVV and VVV interactions, but notoriously hard to constrain

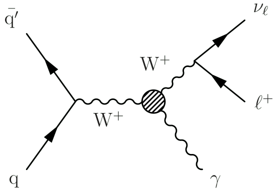
PLB 817 (2021) 136311

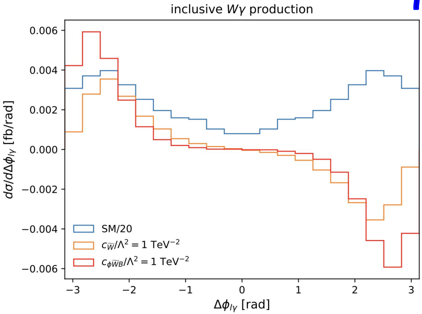




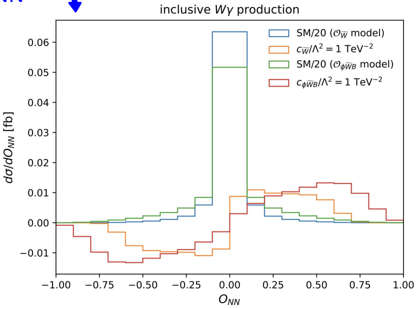
Higgs-without-Higgs: inclusive Wγ production

- Analysis carried out in the fiducial region of the CMS inclusive Wγ measurement [PRD 105 (2022) 052003]
- Signed $\Delta\varphi_{l\gamma}$ is sensitive to the CP-odd interference
- O_{NN} (multiclass) exploits other kinematics to improve sensitivity.





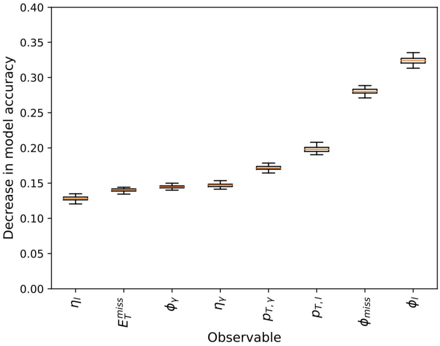
NN



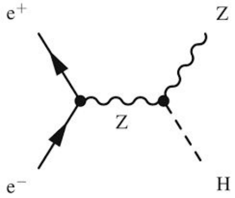
Higgs-without-Higgs: inclusive Wγ production

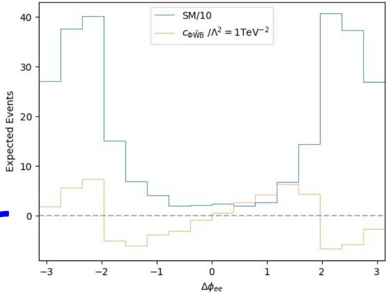
Process	CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
inclusive $W\gamma$	$\Delta\phi_{l\gamma}$	[-0.165,0.165]	[-0.255,0.255]
	O_{NN} (multi-class)	[-0.049,0.049]	[-0.056,0.056]
	$\Delta\phi_{l\gamma}$ vs $\lvert\phi_l - \phi_{\text{miss}}\rvert$	[-0.154,0.154]	[-0.219,0.219]
	$\Delta\phi_{l\gamma}$ vs $E_{\text{T}}^{\text{miss}}$	[-0.163,0.163]	[-0.206,0.206]

For this process difficult to recover the NN sensitivity using a 2D differential measurement.



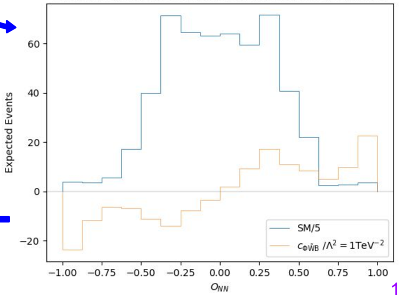
Tool for scoping future colliders: example FCC-ee

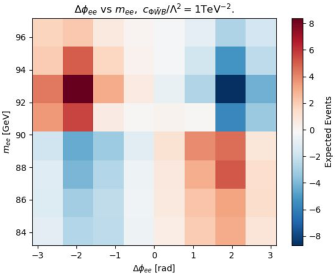




Interference between ZH and VBF diagrams?

NN





Summary and outlook

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) 137246] and diboson/VBS [PRD 107 (2023) 016008] final states.

Simulation details

- Madgraph5_aMC@NLO used to generate events at leading order in pQCD.
- SMEFTSim 3.0 used to include the anomalous interactions from the EFT operators.

- For each process:
  - SM events simulated and validated within the fiducial regions of recent ATLAS or CMS analyses.
  - Normalisation factors applied to cover missing higher-order effects.
  - Interference-only events generated for each EFT operator.

Higgs-without-Higgs: electroweak boson scattering

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.