



# Studies of CPV HZZ couplings at FCC

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# Why do we need additional sources of CP violation?

- We live in a matter-dominated Universe. The Sakharov conditions for producing this baryon asymmetry in early Universe are well known:
  - Baryon number violation
  - C- and CP- violating interactions
  - Thermal in-equilibrium
- 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 cross-over transition.

# Effective field theory approach

- Assume there is new physics at some high energy scale,  $\Lambda$ , that provides the additional sources of CP-violation (and possibly the requisite first-order phase transition)
- At lower energy scales, the effects of this physics can be expressed as operators in an effective Lagrangian:

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

Extensions to the SM induce anomalous interactions

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

$$\left. \begin{aligned} \tilde{\mathcal{O}}_{\Phi\tilde{B}} &= \Phi^\dagger \Phi B^{\mu\nu} \tilde{B}_{\mu\nu}, \\ \tilde{\mathcal{O}}_{\Phi\tilde{W}} &= \Phi^\dagger \Phi W^{i\mu\nu} \tilde{W}_{\mu\nu}^i, \\ \tilde{\mathcal{O}}_{\Phi\tilde{W}B} &= \Phi^\dagger \sigma^i \tilde{W}^{i\mu\nu} B_{\mu\nu}. \end{aligned} \right\}$$

Subset of CP-odd operators that affect HVV interactions

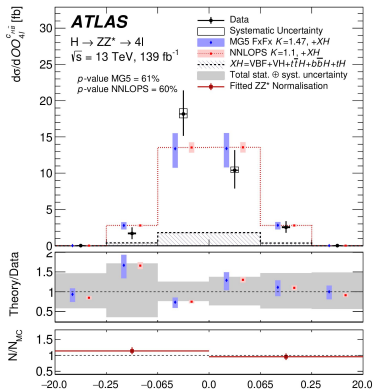
# Interference considerations: how to observe CPV

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

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

- Ideally, we should **construct observables sensitive to the interference term**:
  - $\mathcal{M}_{\text{SM}}^* \mathcal{M}_{\text{d6}}$  *should* be the leading correction to the SM, proportional to  $1/\Lambda^2$ .
  - $|\mathcal{M}_{\text{d6}}|^2$  *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.

# Searching for CPV in HVV interactions at the LHC



$$OO = \frac{2\Re(M_{SM}^* M_{BSM})}{|M_{SM}|^2}$$

EFT coupling parameter	Observed 68% CL	Observed 95% CL
$c_{H\tilde{B}}$	[-0.42, 0.31]	[-0.61, 0.54]
$c_{H\tilde{W}B}$	[-0.56, 0.53]	[-0.97, 0.98]
$c_{H\tilde{W}}$	[-0.07, 1.09]	[-0.81, 1.54]

- Operators constrained using CP-odd observables, either angular observables or optimal observables based on matrix-element information.
- Most constraining processes:  $gg \rightarrow H \rightarrow 4l$  and  $VBF H \rightarrow \tau^+\tau^-$

# This work: study of CPV HZZ couplings at the FCC

- Goal is to study CPV HZZ couplings across all relevant processes at FCC-ee and FCC-hh
- At FCC-ee: natural to study the ZH associated production
- At FCC-hh, have to study inclusive  $H \rightarrow 4l$  production, VBF Higgs production (i.e.  $ZZ \rightarrow H$ ) as well as ZH production.
  
- Today: show preliminary results for  $e^+e^- \rightarrow ZH$ ,  $pp \rightarrow ZH$ ,  $pp \rightarrow H \rightarrow 4l$ .

# 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.
- DELPHES cards used for detector simulation at LHC (ATLAS, HL-LHC cards), FCC-ee (IDEA), or FCC-hh (FCC-hh card)
- For each process at each collider:
  - SM events simulated and normalisation (k) factors applied to cover missing higher-order effects.
  - Interference-only events generated for each EFT operator.
  - In pp collisions: SM event yields validated within fiducial regions of recent ATLAS or CMS analyses
  - In  $e^+e^-$  collisions: comparison to previous literature where possible to ensure expected yields coincide with expected uncertainties.

# CP-sensitive observables: our approach

- Angular observables, such as:
  - Angles between decay planes
  - Rapidity-ordered azimuthal angle between two objects
- Neural-net (NN) based observables\*\*.
  - CP-asymmetries arise from the interference between SM and CP-odd amplitudes.
  - generate interference-only contribution to process (e.g Madgraph5 + SMEFTSim)
  - split interference sample into constructive and destructive interference.
  - train NN to distinguish between the two samples (binary classification)
  - easy to include Standard-Model contribution in NN (multiclass)
  - construct observable from NN classifications, i.e  $O_{NN} = P_+ - P_-$ .  
→ one dedicated observable optimised for each EFT operator

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



# Limit setting procedure

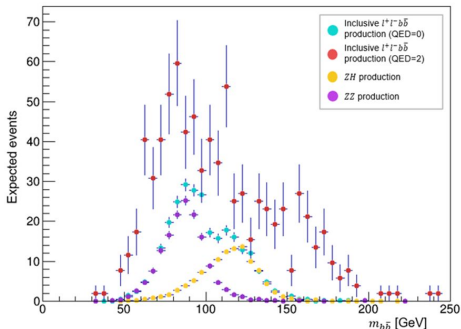
- Constraints on Wilson coefficients ( $c/\Lambda^2$ ) derived using a profile likelihood test:

$$\mathcal{L}(\{c_j\}/\Lambda^2) = \prod_k \exp\{-\lambda_k\} \frac{\lambda_k^{n_k}}{n_k!}$$

- Accounts for statistical fluctuations in the observable.
- Does not account for systematics. However, the impact of systematics is typically suppressed when searching for these types of asymmetries (see e.g. the discussion in <https://arxiv.org/pdf/2209.05143>)

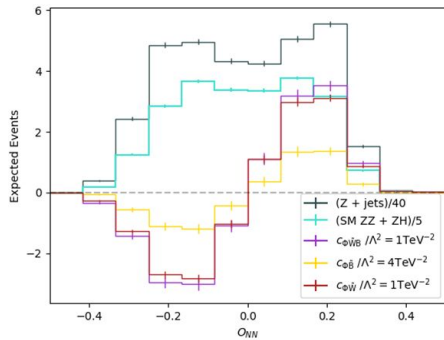
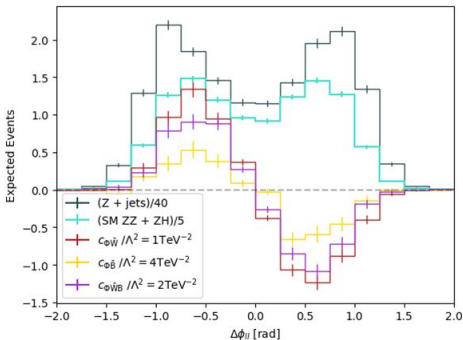
# ZH $\rightarrow$ $l^+l^-bb$ in pp collisions: validation and yields

- Two samples: ZH+ZZ production & Z+jets, produced at  $\sqrt{s}=13\text{TeV}$  and  $\sqrt{s}=100\text{TeV}$ .
  - k-factor derived for ZH and ZZ production to account for NLO QCD effects.
- Event selection follows the relevant ATLAS analysis: <https://arxiv.org/abs/2007.02873>
  - Notably, this is a boosted-Higgs analysis ( $p_{T,H} > 150\text{ GeV}$ )



Process	ATLAS yields	MG yields (LHC)	MG yields (LHC, $m_{bb}$ cut)	MG yields (FCC, $m_{bb}$ cut)
ZH + ZZ	445	462	133	207,527
Z + jets	3836	2509	644	10,668,478

# ZH $\rightarrow$ l<sup>+</sup>l<sup>-</sup>bb in pp collisions: CP-sensitive observables

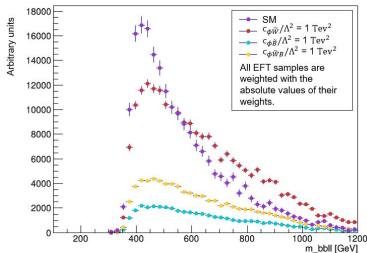


- Studied both simple angular observable and NN-based observable
- NN improves sensitivity as expected (interference effect is bigger compared to SM)

# ZH $\rightarrow$ l<sup>+</sup>l<sup>-</sup>bb in pp collisions: derived constraints

Observable	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\phi_{\parallel}$ (LHC)	[-6.1, 6.1]	[-53, 53]	[-15, 15]
$O_{NN}$ (LHC)	[-4.3, 4.3]	[-41, 41]	[-11, 11]
$\Delta\phi_{\parallel}$ (FCC)	[-0.3, 0.3]	[-2.7, 2.7]	[-0.9, 0.9]
$O_{NN}$ (FCC)	[-0.2, 0.2]	[-2.0, 2.0]	[-0.6, 0.6]

- LHC limits not as sensitive as H $\rightarrow$ 4l analysis channel.
- However:
  - EFT effects grow with energy: go to very high  $p_T$ ?
  - Scope for improvement using multiclass / 2D fit?

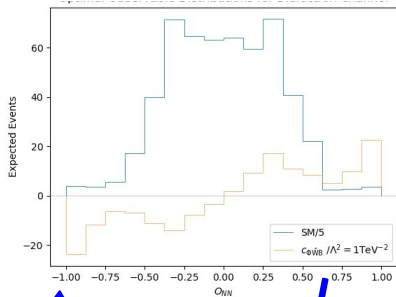
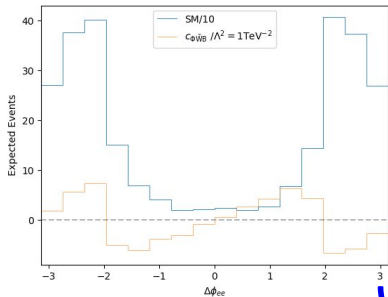


# ZH $\rightarrow$ $l^+l^-bb$ in $e^+e^-$ collisions: selection and validation

- Single sample generated covering ZH and ZZ production at  $\sqrt{s}=240\text{GeV}$ .
- Studied  $H\rightarrow bb$  decay channel,
  - followed selection for LEP3  $H\rightarrow bb$  analysis in: <http://www.arxiv.org/abs/1208.1662> but explicitly requiring two b-tagged jets.
  - b-jet selection (efficiency\*acceptance) hard to compare like-for-like between LEP3 and this analysis. But our yields seem a bit low.

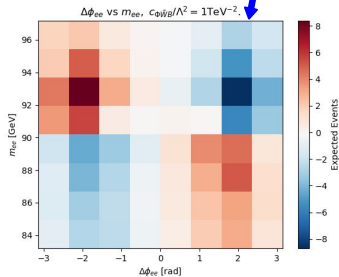
Process	LEP3 yield	MG yield (IDEA)
$e^+e^- \rightarrow l^+l^-bb$	9500	5910

# ZH $\rightarrow$ $l^+l^-bb$ in $e^+e^-$ collisions: CP-sensitive observables



NN

Interference between ZH and VBF diagrams for  $e^+e^-bb$  channel ?



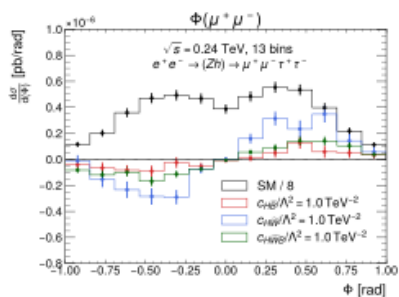
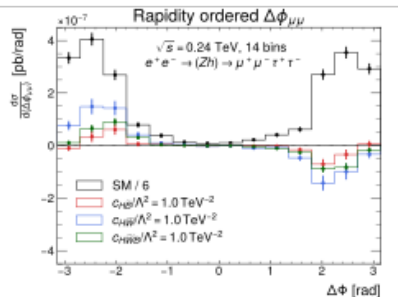
# ZH $\rightarrow$ $l^+l^-bb$ in $e^+e^-$ collisions: constraints on EFT

Observable	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\phi_{\parallel}$	[-0.41, 0.41]	[-0.60, 0.60]	[-1.2, 1.2]
$\Delta\phi_{\parallel}$ vs $m_{12}$	[-0.35, 0.35]	[-0.30, 0.30]	[-0.5, 0.5]
$O_{NN}$	[-0.35, 0.35]	[-0.22, 0.22]	[-0.4, 0.4]

- $H\rightarrow bb$ : 95% confidence intervals improved by factor 2 compared to current LHC constraints from  $H\rightarrow 4l$ . Would therefore be beaten by  $H\rightarrow 4l$  at HL-LHC.
- However, that conclusion would be pessimistic:
  - all sensitivity in this analysis comes from analysis of the  $Z\rightarrow ll$  topology. Can carry out the analysis inclusively (ignoring Higgs decays), i.e. with factor 5 higher yields.
  - Can also exploit  $\sqrt{s}=365\text{GeV}$  data, with interesting interplay between VBF and VH.....

# ZH $\rightarrow$ $l^+l^-\tau\tau$ in $e^+e^-$ collisions

- Initial studies support conclusion on previous slide that the sensitivity for the considered operators is driven by variables related to the  $Z \rightarrow ll$  decay.
- Additional variables considered that will be added into the analysis targeting inclusive decays.

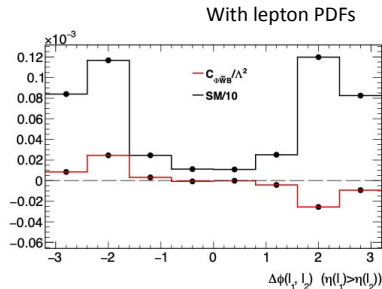
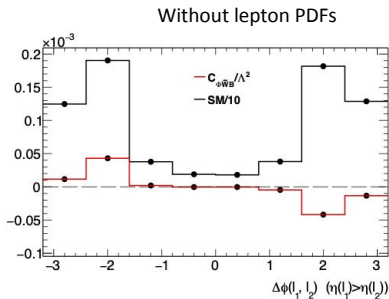


$$\Phi = \text{sgn}((\hat{\ell}^+ - \hat{\ell}^-) \cdot \hat{z}) \arcsin((\hat{\ell}^+ \times \hat{\ell}^-) \cdot \hat{z})$$



# Including beam ISR effects

- Have started studying inclusion of QED ISR effects which can be incorporated in Madgraph through lepton PDFs as described in <https://arxiv.org/pdf/2108.10261>
- Generating  $e^+e^- \Rightarrow l+l-h$  (inclusive) without PDFs and using “isronlyl” PDF set gives reduction in SM cross-section  $\sim 15\%$  (0.0129pb vs 0.0153pb)
  - this effect looks bigger when applying cuts on Zh topology (to be studied further).
  - does not appear to affect the shapes of the CP-sensitive observables
- Aim to include effects in final analysis.

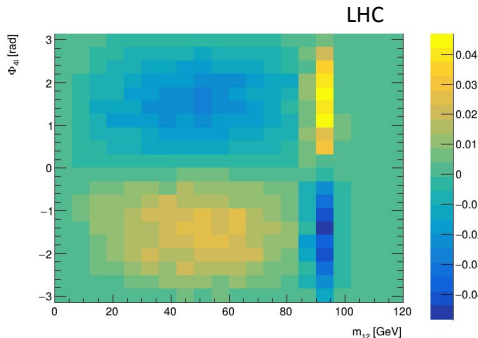
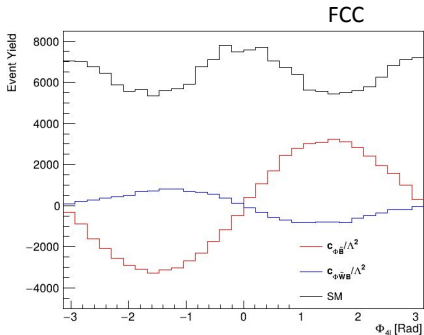


# H $\rightarrow$ 4l at pp colliders

- Two samples:  $gg \rightarrow H \rightarrow 4l$  and  $pp \rightarrow 4l$  (latter includes  $qq \rightarrow 4l$  events)
  - k-factor derived for  $gg \rightarrow H$  production to account for NLO QCD effects.
- Event selection follows ATLAS 4-lepton analysis: <https://arxiv.org/abs/2004.03969>
  - Notably, allows very low lepton  $p_T$  (5 GeV) and this may not be possible at FCC-hh
  - Currently have factor of  $\sim 2$  difference in yields with respect to ATLAS results. This is not a fast detector sim issue. Persists at cross section level when cross checked against pheno paper with different cuts (PLB 832 (2022) 137246).

Process	ATLAS yields	MG yields (LHC)	MG yields (FCC)
$gg \rightarrow H \rightarrow 2e2\mu$	93	42	219,898
$qq \rightarrow 2e2\mu$ (bkd)	50	17	34,200

# H $\rightarrow$ 4l at pp colliders



- 2D analysis of  $\Phi_{4l}$  vs  $m_{12}$  shows interesting (but already known) interference sign flip (at both colliders) for on-shell and off-shell Z bosons.

# H $\rightarrow$ 4l at pp colliders

Observable	$c_{\Phi\tilde{B}}/\Lambda^2$	$c_{\Phi\tilde{W}B}/\Lambda^2$
$\Phi_{4l}$ vs $m_{12}$ (LHC)	[-0.71, 0.71]	[-1.5, 1.5]
$\Phi_{4l}$ vs $m_{12}$ (FCC)	[-0.006, 0.006]	[-0.012, 0.012]
$\Phi_{4l}$ vs $m_{12}$ (FCC, high lepton $p_T$ )	[-0.007, 0.007]	[-0.013, 0.013]

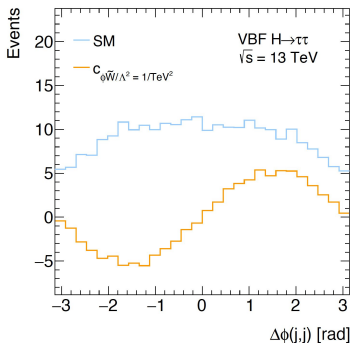
- Best constraints on two operators in this channel with order of magnitude improvement over HL-LHC and FCC-ee expectations.
- Increasing minimum lepton  $p_T$  to 20 GeV has little impact.

# VBF $H \rightarrow \tau^+ \tau^-$ at pp colliders

- VBF H and VH processes generated together at  $\sqrt{s}=13\text{TeV}$  (to-do:  $\sqrt{s}=100\text{TeV}$ )
  - k-factor derived for to account for NLO QCD effects.
- Event selection follows ATLAS  $H \rightarrow \tau\tau$  analysis: <https://arxiv.org/abs/2201.08269>
  - three  $\tau\tau$  final states considered: lep-lep, lep-had and had-had
  - selection requirements targeting VBF topology

	ATLAS yields (VBF category)	MG yields
lep-lep	$36.3 \pm 3.5$	$27.40 \pm 0.96$
lep-had	$136.4 \pm 12.7$	$93.23 \pm 1.76$
had-had	$112.0 \pm 11.2$	$125.30 \pm 2.04$

**Next steps: consider sensitivity at HL-LHC and FCC-hh**



**Rapidity ordered azimuthal angle between jets (for all  $\tau\tau$  final states)**

# Conclusion and outlook

- Currently bringing together CPV HZZ studies performed by Masters students
- A few updates are needed based on the work already completed:
  - understand the event yield discrepancies for  $H \rightarrow 4l$  when comparing to ATLAS result
  - update the  $e^+e^- \rightarrow ZH$  analysis to be inclusive of Higgs decays
  - investigate the high  $p_T$  region for  $pp \rightarrow ZH$
  - include the VBF  $H \rightarrow \tau^+\tau^-$  limits (FCC-hh)
- Aiming for publication ~ end of 2024
  - will not have an FCC note ready by 25th September (i.e. tomorrow) but would like to be included in feasibility study report.
  - As plan to include both FCCee and FCChh, perhaps this could be included in the FCC-hh writeup (on slightly longer timescales?).