CPV in Higgs couplings to Z bosons at FCC-ee and FCC-hh

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Introduction

Motivation

Observed baryon asymmetry outstanding question from the SM

- Sakharov criteria require sufficient CPV
- Only known SM source is complex phase of CKM matrix for quark mixing **- not enough CPV!**

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EFT Approach

- Assume CP-violating BSM physics exists at high energy scale (Λ)
  - Effects of new physics expressed as CP-odd higher dimension operators in an effective Lagrangian

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

Extensions to SM induce anomalous interactions

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

Subset of CP-odd operators that affect HVV interactions

How to look for CPV?

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

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

CP-odd

- Ideally, we should construct observables sensitive to the interference term:
  - $\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}}$ *should* be the leading correction to the SM, proportional to $1/\Lambda^2$.
  - $|\mathcal{M}_{\mathrm{d6}}|^2$ *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
  - integrates to 0 for CP-even observables

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CP-odd

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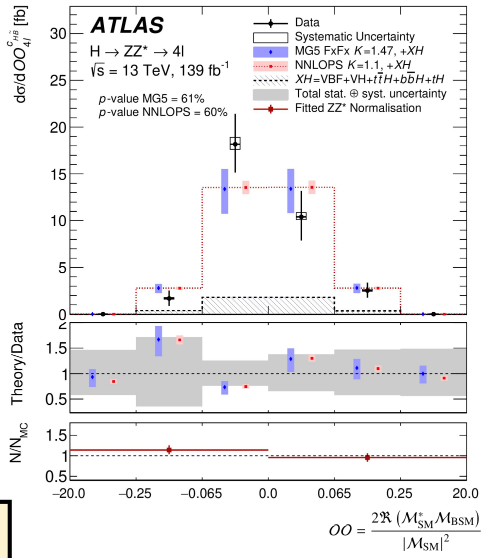
- Operators constrained at the LHC using **angular observables** or **optimal observables**



Latest @ ATLAS

EFT Coupling	Observed 95% CL
$c_{H\tilde{B}}$	[-0.61,0.54]
$c_{H\tilde{W}B}$	[-0.97,0.98]
$c_{H\tilde{W}}$	[-0.31,0.88]

$\left.\begin{array}{l} c_{H\tilde{B}} \\ c_{H\tilde{W}B} \end{array}\right\}$ $H \rightarrow 4l$ [arXiv:2304.09612]

$c_{H\tilde{W}} \longrightarrow$ VBF $H \rightarrow \tau^+\tau^-$ [arXiv:2407.16320]

This work: study of CPV HZZ couplings at FCC

- **CPV HZZ** couplings at **FCC-ee** and **FCC-hh**
- Bonus: study the effect of **beam polarisation in Linear Collider Facility** → compare with FCC

Simulation

- **Madgraph5_aMC@NLO** to generate events at leading order
  - k-factors applied to correct for missing order effects
- **SMEFTSim 3.0** for CPV EFT interactions
- **DELPHES** for detector simulation

pp collisions: SM event yields validated within fiducial regions of recent ATLAS analyses

- LCF beam polarisation configurations:
  - 45% {+80% , -30%}
  - 45% {-80% , +30%}
  - 5% {+80% , +30%}
  - 5% {-80% , -30%}

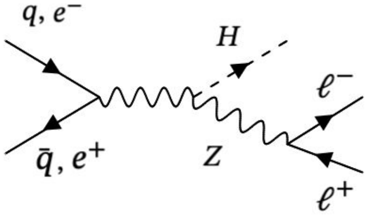
Collider	$\sqrt{s}$	Lumi [ab^{-1}]	Processes	Delphes
FCC-ee	240 GeV	10.8	ZH	IDEA
LCF	250 GeV	3	ZH	ILCgen
HL-LHC	13 TeV	3	ZH, H→4l, WBF	ATLAS
FCC-hh	100 TeV	30	ZH, H→4l, WBF	FCC-hh

CP Sensitive Observables - Angular

ZH

Signed Azimuthal difference between leptons from Z decay

$$\Delta\phi_{\ell\ell} = \phi(\ell_1) - \phi(\ell_2) \text{ for } \eta(\ell_1) > \eta(\ell_2)$$

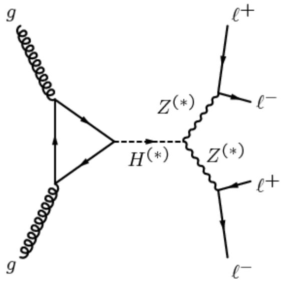


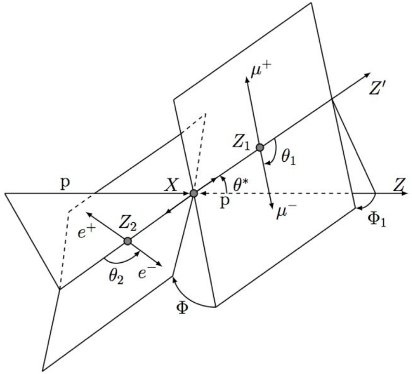
H→4l

Azimuthal angle between decay planes

$$\Phi_{4\ell} = \frac{\mathbf{q}_1 \cdot (\hat{\mathbf{n}}_1 \times \hat{\mathbf{n}}_2)}{|\mathbf{q}_1 \cdot (\hat{\mathbf{n}}_1 \times \hat{\mathbf{n}}_2)|} \arccos(\hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2),$$

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

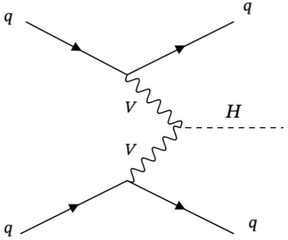




VBF

Signed Azimuthal difference between jets

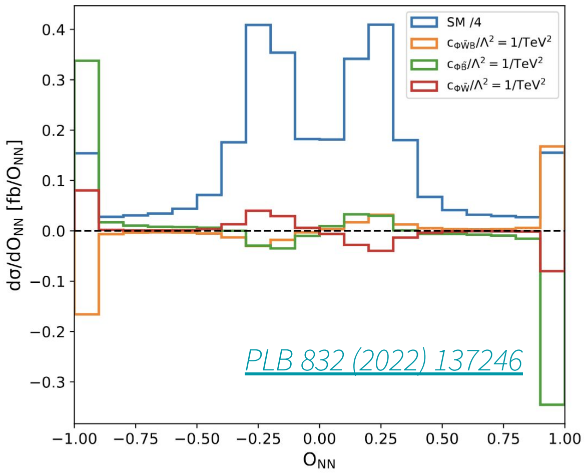
$$\Delta\phi_{jj} = \phi(j_1) - \phi(j_2) \text{ for } \eta(j_1) > \eta(j_2)$$



CP Sensitive Observables - NN

- **NN-based Observables:**
  - CP-asymmetries arise from the interference between SM and CP-odd amplitudes
  - generate interference-only contribution to process
  - split interference sample into positive and negative interference
  - **train NN** to distinguish between the 2 (binary classification)
  - can include SM as well (multiclass classification)
  - construct observable from classification result - one per operator

$$\mathbf{O_{NN} = P_{+} - P_{-}}$$



methodology demonstrated in:
PLB 832 (2022) 137246; PRD 107 (2023) 016008

Limit Setting

- **95% confidence intervals set on Wilson coefficients (c/Λ^2)**:
  - derived using a binned likelihood ratio test
  - using Wilks theorem

predicted n under SMEFT hypothesis

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

expected n under SM-only hypothesis

- Does not account for systematics:
  - impact of systematics is typically suppressed when searching for these types of asymmetries

ZH production at FCC-ee

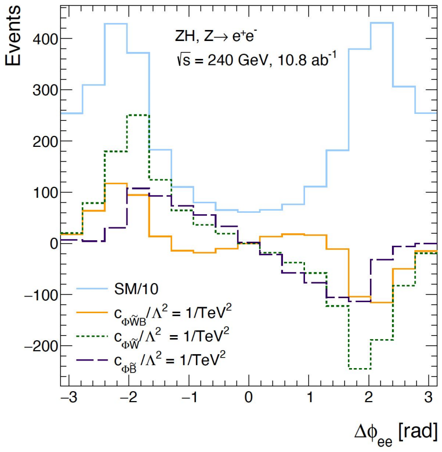
- **Inclusive Higgs boson decays**
  - Signal sample: $\mathbf{e^+e^- \rightarrow l^+l^-H}$
- Dominant ZZ and WW backgrounds generated separately
- k-factor to account for ISR effects

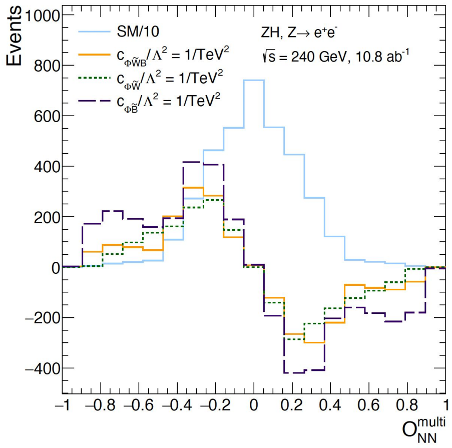
- followed selection for [LEP3 analysis]
  - 77300 signal events + 2470 + 26100 for ZZ & WW

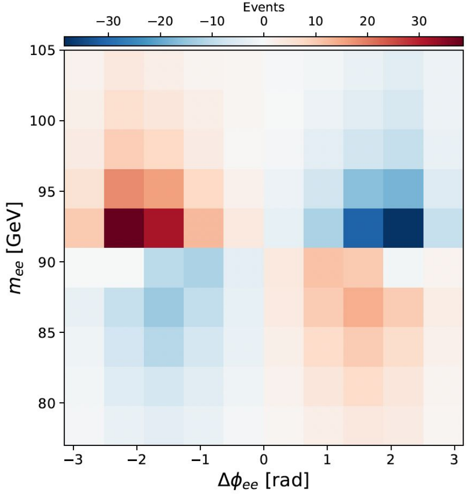
Observable	95% confidence intervals		[TeV^{-2}]
	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\phi_{ee}$	[-0.25,0.25]	[-0.36,0.36]	[-0.57,0.57]
$\Delta\phi_{\mu\mu}$	[-0.24,0.24]	[-0.89,0.89]	[-0.47,0.47]
$\Delta\phi_{\ell\ell}$	[-0.17,0.17]	[-0.33,0.33]	[-0.36,0.36]
$O_{\rm NN}^{\rm binary}$	[-0.13,0.13]	[-0.08,0.08]	[-0.12,0.12]
$O_{\rm NN}^{\rm multi}$	[-0.13,0.13]	[-0.07,0.07]	[-0.12,0.12]

sensitivity driven by electron channel

O_{NN} leads to factor 3-4 improvement







sign-flip only observed for electron channel - interference with VBF

ZH production at FCC-ee

- **Dedicated study for dominant H→bb channel**
- Dedicated **e^+e^- → l^+l^-bb** sample produced
  - includes both signal (ZH) and bkgd (ZZ)

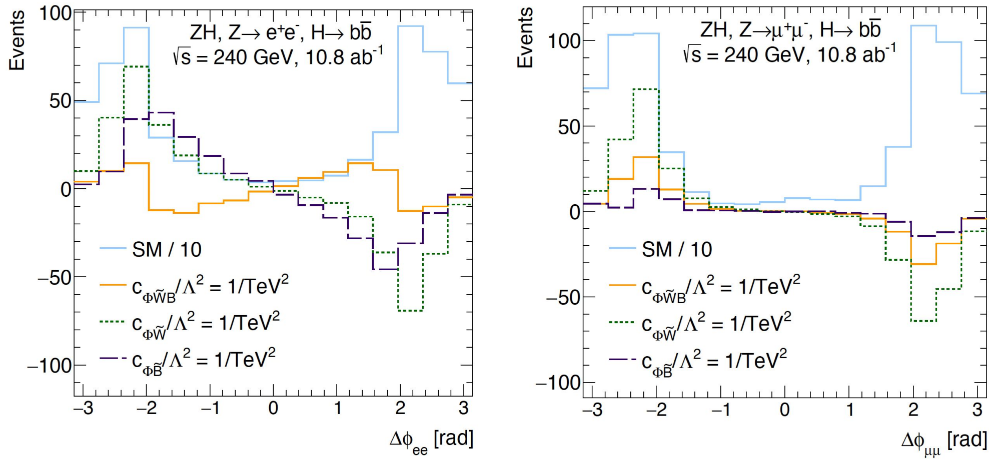
- followed selection for LEP3 analysis but explicitly requiring **two b-tagged jets**
  - 12900 SM events predicted

Similar features to what is seen in inclusive study

Higgs boson decay products carry no information on CPV

Observable	95% confidence intervals		[TeV^{-2}]
	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\phi_{ee}$	[-0.35,0.35]	[-0.31,0.31]	[-0.67,0.67]
$\Delta\phi_{\mu\mu}$	[-0.46,0.46]	[-2.2,2.2]	[-1.0,1.0]
$\Delta\phi_{\ell\ell}$	[-0.28,0.28]	[-0.31,0.31]	[-0.56,0.56]
$O_{\rm NN}^{\rm binary}$	[-0.23,0.23]	[-0.08,0.08]	[-0.14,0.14]

electron channel has similar sensitivity to the one obtained in inclusive study due to different H→bb efficiency for SM and interference samples



Impact of beam polarisation at LCF

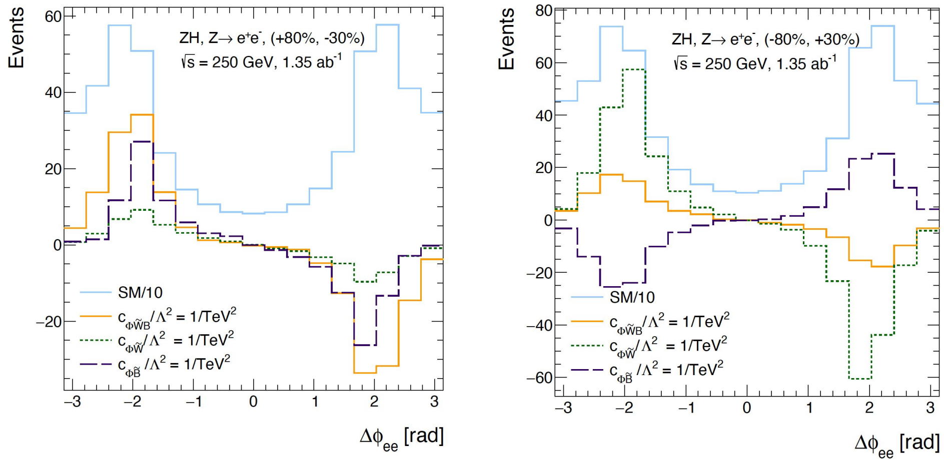
- **Inclusive Higgs boson decays**
  - Signal sample: **$e^+e^- \rightarrow l^+l^-H$**
- ZZ and WW backgrounds generated separately

- Samples generated for each of the **4 initial-state polarisation configurations**

- same selection as for inclusive H at FCC-ee
  - 25300 signal events + 1110 + 7960 for ZZ & WW

Observable	95% confidence intervals		[TeV^{-2}]
	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\phi_{\ell\ell}$ (pol)	[-0.28,0.28]	[-0.35,0.35]	[-0.38,0.38]
$\Delta\phi_{\ell\ell}$ (unpol)	[-0.33,0.33]	[-0.63,0.63]	[-0.69,0.69]
$O_{\rm NN}^{\rm binary}$ (pol)	[-0.21,0.21]	[-0.11,0.11]	[-0.19,0.19]
$O_{\rm NN}^{\rm binary}$ (unpol)	[-0.25,0.25]	[-0.14,0.14]	[-0.23,0.23]

beam polarisation improves results by factor of 1.2-1.8



Shape of interference sample highly dependent on beam polarisation

Separate NN training for each configuration

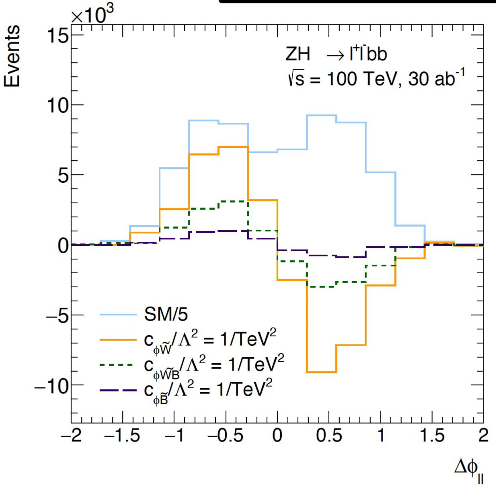
ZH production at pp colliders

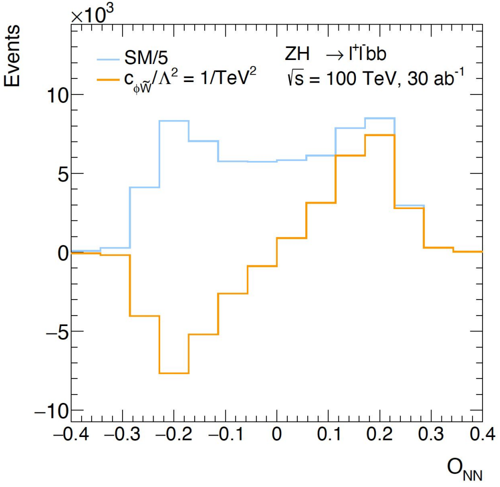
- Two samples: **ZH+ZZ** & **Z+jets**
  - k-factor derived for ZH+ZZ production to account for NLO QCD effects
- Followed selection from relevant ATLAS analysis (boosted Higgs region, **H→bb channel**)
- 133 ZH+ZZ events predicted for LHC, 207000 for FCC-hh
  - Good agreement with ATLAS signal yields
- Z+jets underestimated wrt ATLAS due to missing higher order contributions
  - scaling factor derived at LHC level

Overall lower sensitivity wrt FCC-ee

O_{NN} leads to factor ~30% improvement (negligible improvement from multiclass)

Collider	Observable	95% confidence intervals $[\mathrm{TeV}^{-2}]$ $c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
LHC	$\Delta\phi_{\ell\ell}$	[-5.5, 6.0]	[-50, 50]	[-15, 14]
	$O_{\mathrm{NN}}^{\mathrm{binary}}$	[-3.8, 3.8]	[-36, 36]	[-9.7, 9.7]
HL-LHC	$\Delta\phi_{\ell\ell}$	[-1.2, 1.2]	[-15, 15]	[-4.3, 2.2]
	$O_{\mathrm{NN}}^{\mathrm{binary}}$	[-0.83, 0.83]	[-7.7, 7.7]	[-2.1, 2.1]
FCC-hh	$\Delta\phi_{\ell\ell}$	[-0.31, 0.31]	[-2.6, 2.6]	[-0.82, 0.82]
	$O_{\mathrm{NN}}^{\mathrm{binary}}$	[-0.22, 0.22]	[-2.2, 2.2]	[-0.56, 0.56]





H → 4l at pp colliders

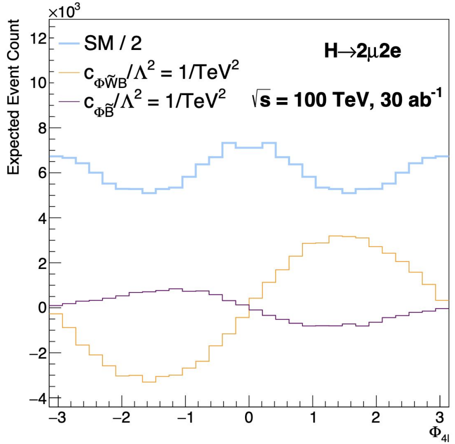
- Two samples: **gg→H→2e2μ** and **pp→2e2μ**
  - k-factor derived for gg→H production to account for N^{3}LO QCD effects.
  - Additional correction derived for branching ratio for H→4l
- Followed selection from ATLAS H→4l differential x-section measurement
- 79 H→2e2μ events predicted for LHC, and 367000 for FCC-hh
  - Good agreement with ATLAS signal yields
- Bkgd predictions scaled by factor N_{ATLAS}/N_{study}

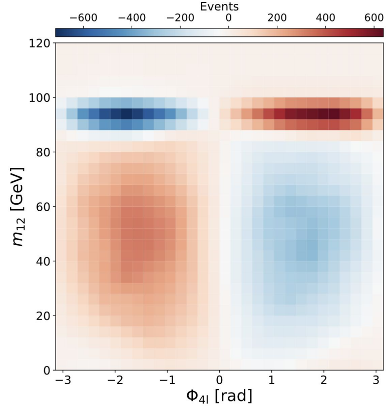
constraints at FCC-hh are 20x better than HL-LHC

O(10) better constraints wrt to ZH @FCC-ee

Collider	Observable	95% confidence intervals [TeV^{-2}]	
		$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
LHC	$\Phi_{4\ell}$	[-1.4, 1.4]	[-5.5, 5.5]
	$\Phi_{4\ell}$ vs m_{12}	[-0.83, 0.84]	[-1.7, 1.7]
HL-LHC	$\Phi_{4\ell}$	[-0.29, 0.29]	[-1.2, 1.2]
	$\Phi_{4\ell}$ vs m_{12}	[-0.14, 0.14]	[-0.27, 0.27]
FCC-hh	$\Phi_{4\ell}$	[-0.017, 0.017]	[-0.077, 0.077]
	$\Phi_{4\ell}$ vs m_{12}	[-0.007, 0.007]	[-0.015, 0.015]

sign-flip when moving from Z boson off-shell to on-shell regime





Hjj production at pp colliders

- Two samples: **Hjj signal** & **Zjj** (dominant background)
  - k-factor derived for WBF production to account for NNLO QCD effects

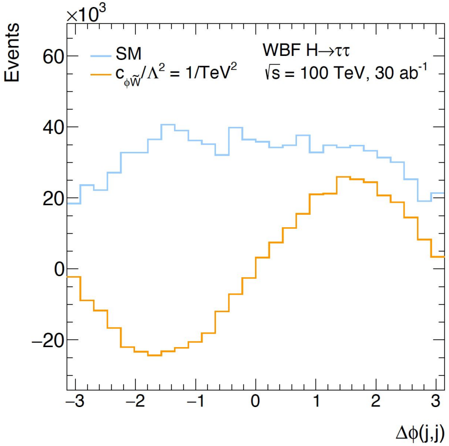
- Analysis performed in $H \to \tau\tau$ channel
  - following VBF region selection from ATLAS $H \to \tau\tau$ x-sec measurement
  - **three $\tau\tau$ final states**: lep-lep, lep-had and had-had
  - extra requirement on $m_{\tau\tau}^{coll} > 110$ GeV
- 212 $H(\to\tau\tau)jj$ events predicted for LHC and 862000 for FCC-hh
  - Good agreement with ATLAS signal yields
- Bkgd prediction scaled by factor N_{ATLAS}/N_{study}

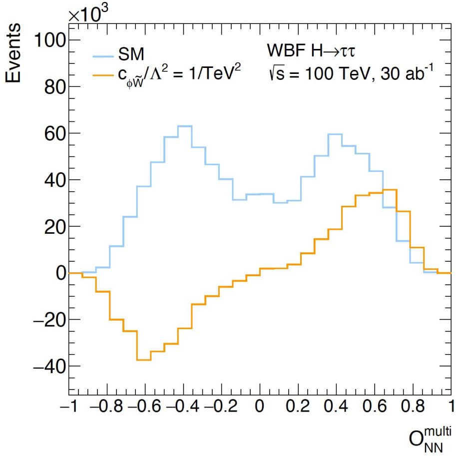
Collider	Observable	$c_{\Phi\widetilde{W}}/\Lambda^2[\mathrm{TeV}^{-2}]$
LHC	$\Delta\phi_{jj}$	[-0.89, 0.89]
	$O_{\mathrm{NN}}^{\mathrm{multi}}$	[-0.74, 0.73]
HL-LHC	$\Delta\phi_{jj}$	[-0.19, 0.19]
	$O_{\mathrm{NN}}^{\mathrm{multi}}$	[-0.16, 0.16]
FCC-hh	$\Delta\phi_{jj}$	[-0.016, 0.016]
	$O_{\mathrm{NN}}^{\mathrm{multi}}$	[-0.007, 0.007]

LHC sensitivity similar to recent ATLAS results

constraints at FCC-hh are 20x better than HL-LHC

O(10) better wrt to ZH @ FCC-ee





Summary

- **CPV Higgs couplings make a strong case for FCC-hh**
  - take advantage of wide range of production mechanisms and final states and extra kinematic info!
  - constraints on CP-odd Wilson coeffs are O(1), O(0.1) and O(0.01) for LHC, HL-LHC/FCC-ee/LCF and FCC-hh respectively
  - FCC-hh constraints are one order of magnitude better than HL-LHC constraints and ZH FCC-ee constraints

- **Paper submitted to Arxiv yesterday** [link]

- **Included as inputs for European strategy**
  - ECFA Higgs, electroweak, and top factory study
  - Prospects for physics at FCC-hh

Wilson c.	FCC-ee	LCF	HL-LHC	FCC-hh
$c_{H\tilde{B}}$	[-0.07,0.07]	[-0.11,0.11]	[-0.14,0.14]	[-0.007,0.007]
$c_{H\tilde{W}B}$	[-0.12,0.12]	[-0.19,0.19]	[-0.27,0.27]	[-0.015,0.015]
$c_{H\tilde{W}}$	[-0.13,0.13]	[-0.21,0.21]	[-0.16,0.16]	[-0.007,0.007]

best limits, regardless of process