Science & Technology Facilities Council

LEVERHULME TRUST

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 Sakarov 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, Λ, 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:

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

Extensions to the SM induce anomalous interactions

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

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

Subset of CP-odd operators that affect HVV interactions

Interference considerations: how to observe CPV

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

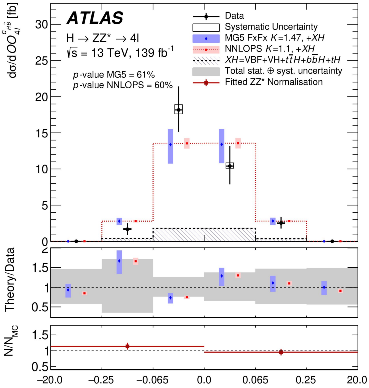
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}}) + |\mathcal{M}_{\mathrm{d6}}|^2$$

- 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

  …but integrates to zero for CP-even observables.

Searching for CPV in HVV interactions at the LHC



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

EFT coupling parameter	Observed 68% CL	Observed 95% CL
$c_{H\tilde{B}}$	[−0.42, 0.31]	[−0.61, 0.54]
$c_{H\widetilde{W}B}$	[−0.56, 0.53]	[−0.97, 0.98]
$c_{H\widetilde{W}}$	[−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 → H → 4l and VBF H → $\tau^+\tau^-$

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 → 4l production, VBF Higgs production (i.e. ZZ→H) as well as ZH production.

- Today: show preliminary results for e^+e^-→ZH, pp→ZH, pp→H → 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

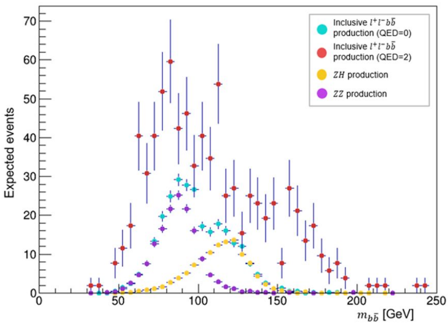
- Neural-net (NN) based observables**.
  - CP-asymmetries arise from the interference between SM and CP-odd amplitudes.
  - generate interference-only contribution to process (e.g Madgraph5 + SMEFTSim)
  - split interference sample into constructive and destructive interference.
  - train NN to distinguish 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

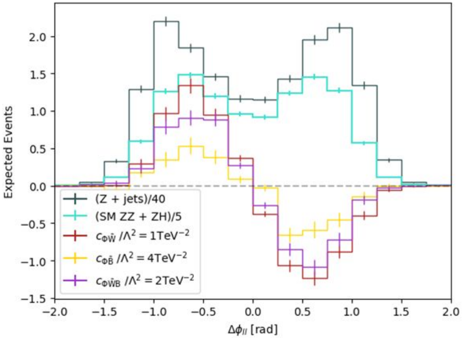
ZH → l^+l^-bb in pp collisions: validation and yields

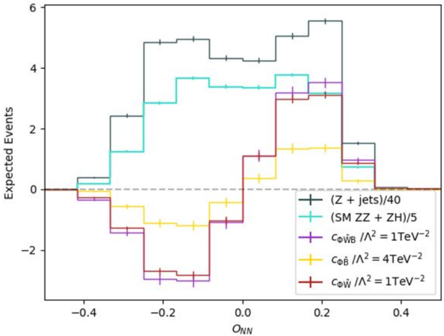
- Two samples: ZH+ZZ production & Z+jets, produced at √s=13TeV and √s=100TeV.
  - k-factor derived for ZH and ZZ production to account for NLO QCD effects.
- Event selection follows the relevant ATLAS analysis: https://arxiv.org/abs/2007.02873
  - Notably, this is a boosted-Higgs analysis ($p_{T,ll}$ > 150 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 → l^+l^-bb in pp collisions: CP-sensitive observables



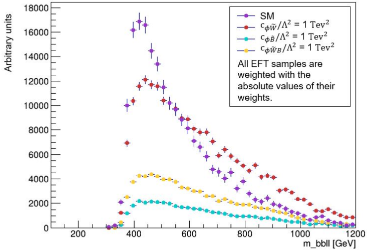


- Studied both simple angular observable and NN-based observable
- NN improves sensitivity as expected (interference effect is bigger compared to SM)

ZH → l^+l^-bb in pp collisions: derived constraints

Observable	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\varphi_{ll}$ (LHC)	[-6.1, 6.1]	[-53, 53]	[-15,15]
O_{NN} (LHC)	[-4.3, 4.3]	[-41, 41]	[-11, 11]
$\Delta\varphi_{ll}$ (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→4l analysis channel.
- However:
  - EFT effects grow with energy: go to very high p_T?
  - Scope for improvement using multiclass / 2D fit?

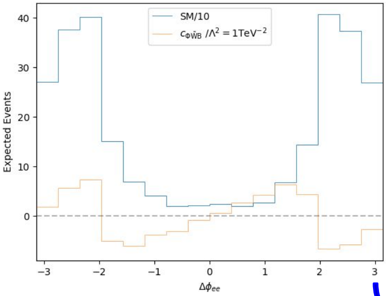


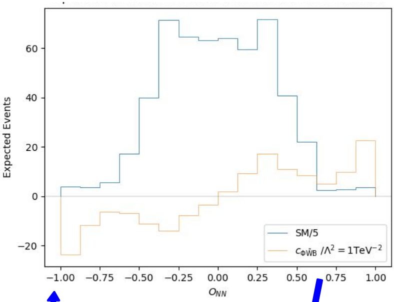
ZH → l^+l^-bb in e^+e^- collisions: selection and validation

- Single sample generated covering ZH and ZZ production at $\sqrt{s}$=240GeV.
- Studied H→bb decay channel,
  - followed selection for LEP3 H→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.

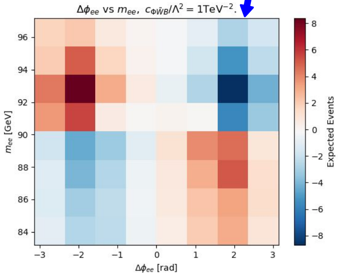
Process	LEP3 yield	MG yield (IDEA)
$e^+e^-\rightarrow l^+l^-bb$	9500	5910

ZH → l^+l^-bb in e^+e^- collisions: CP-sensitive observables





NN



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

ZH → l^+l^-bb in e^+e^- collisions: constraints on EFT

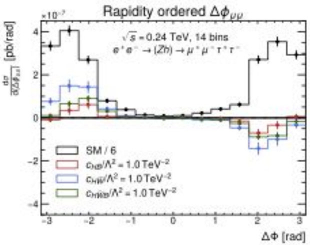
Observable	$c_{\Phi\widetilde{W}}/\Lambda^2$	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
$\Delta\varphi_{ll}$	[-0.41, 0.41]	[-0.60, 0.60]	[-1.2, 1.2]
$\Delta\varphi_{ll}$ vs m_{12}	[-0.35, 0.35]	[-0.30, 0.30]	[-0.5, 0.5]
O_{NN}	[-0.35, 0.35]	[-0.22, 0.22]	[-0.4,0.4]

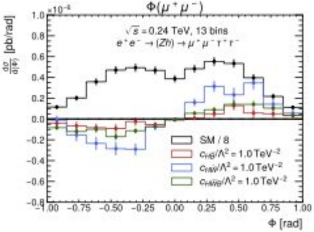
- H→bb: 95% confidence intervals improved by factor 2 compared to current LHC constraints from H→4l. Would therefore be beaten by H→4l at HL-LHC.
- However, that conclusion would be pessimistic:
  - all sensitivity in this analysis comes from analysis of the Z→ll topology. Can carry out the analysis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

ZH → $l^+l^-\tau\tau$ 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→ll decay.

- Additional variables considered that will be added into the analysis targeting inclusive decays.





H → 4l at pp colliders

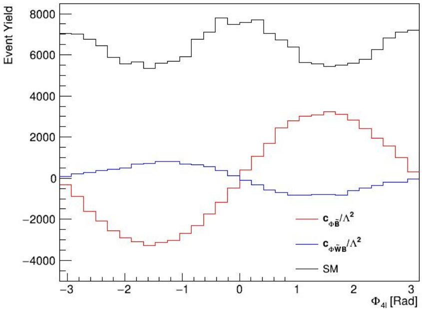
- Two samples: gg→H→4l and pp→4l (latter includes qq→4l events)
  - k-factor derived for gg→H production to account for NLO QCD effects.
  - Additional correction derived for branching ratio for H→4l

- 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

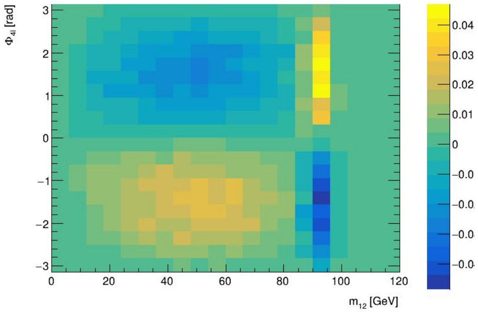
Process	ATLAS yields	MG yields (LHC)	MG yields (FCC)
gg→H→2e2μ	93	79	367000
qq→2e2μ (bkd)	50	17	32,000

H → 4l at pp colliders

FCC



LHC



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

H → 4l at pp colliders

Observable	$c_{\Phi\widetilde{B}}/\Lambda^2$	$c_{\Phi\widetilde{W}B}/\Lambda^2$
Φ_{4l} vs m_{12} (LHC)	[-0.70, 0.70]	[-1.4, 1.4]
Φ_{4l} vs m_{12} (FCC)	[-0.007, 0.007]	[-0.014, 0.014]

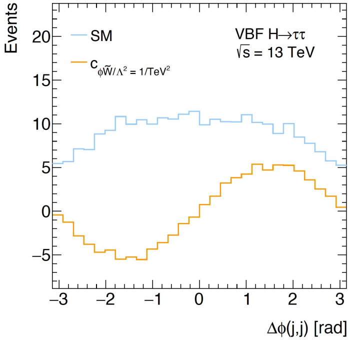
- Best constraints on two operators in this channel with order of magnitude improvement over HL-LHC and FCC-ee expectations.

VBF H→τ+τ- at pp colliders

- VBF H and VH processes generated together at √s=13TeV (to-do: √s=100TeV)
  - k-factor derived for to account for NLO QCD effects.
- Event selection follows ATLAS H→ττ analysis: https://arxiv.org/abs/2201.08269
  - three ττ 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 ± 3.5	27.40 ± 0.96
lep-had	136.4 ± 12.7	93.23 ± 1.76
had-had	112.0 ± 11.2	125.30 ± 2.04

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



Rapidity ordered azimuthal angle between jets (for all ττ 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:
    - 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
  - aim to include as ECFA write-ups and FCC-hh notes for feasibility study

BACK-UP

Limit setting procedure

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

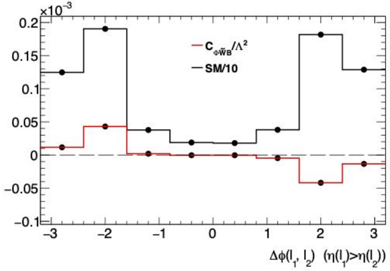
$$\mathcal{L}(\{c_j\}/\Lambda^2) = \prod_k \exp\{-\lambda_k\} \frac{\lambda_k^{n_k}}{n_k!}$$

- 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)

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- => l+l-h (inclusive) without PDFs and using “isronlyll” PDF set gives reduction in SM cross-section ~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.

Without lepton PDFs



With lepton PDFs