BMBF-ErUM-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Ausbau von ATLAS am LHC: Physik mit dem ATLAS-Experiment
ErUM-FSP T02
ATLAS

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Search for CP violation in Higgs boson interactions at the ATLAS experiment

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für Bildung
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ATLAS
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Introduction

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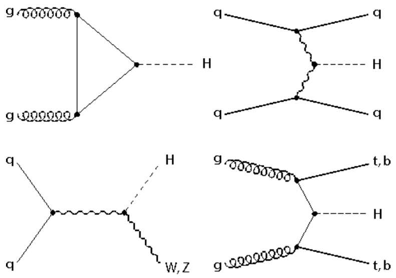
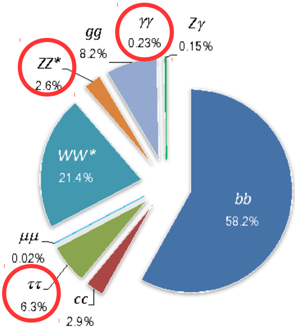
- Baryon asymmetry observed in the universe
- Sakharov: Need CP violating processes
- But CP violation in Standard Model (SM) presumably not sufficient

$\longrightarrow$ Probe Higgs sector for additional sources of CP violation





- Presenting four Run-2 ATLAS analyses
- Search for CP-odd contribution to Higgs interaction vertices

$H \to ZZ^* \to 4\ell$ analysis

arXiv:2004.03447

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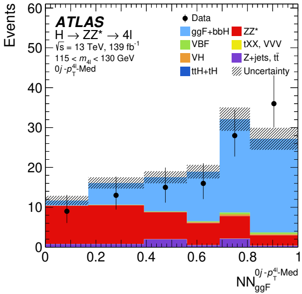
- Classify events with neural networks (NN)
- Discriminants combine 3 NNs for: 4ℓ system, jets and additional event info
- Distinguish between dominating processes in different (STXS) event categories



- Probe for BSM physics in SMEFT framework in Warsaw basis
- $\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_k c_k O_k$, CP-odd contributions marked with a $\sim$

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\widetilde{G}}$	$HH^\dagger \widetilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\widetilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

$H \to ZZ^* \to 4\ell$ results

arXiv:2004.03447

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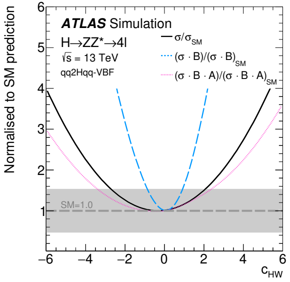
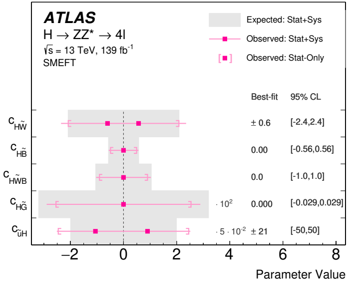
Warsaw basis parameters $\vec{c}$ change (NLO predicted) signal strength $\mu = \frac{N^{\text{signal}}_{\text{Obs}}}{N^{\text{signal}}_{\text{SM}}}$ through cross-section σ, branching ratio $B^{4\ell}$ and detector acceptance A:

$$\mu(\vec{c}) = \frac{\sigma(\vec{c})}{\sigma_{\text{SM}}} \frac{B^{4\ell}(\vec{c})}{B^{4\ell}_{\text{SM}}} \frac{A(\vec{c})}{A_{\text{SM}}}$$





- Limits on single c_i assuming $c_{j\neq i} = 0$
- No deviation from SM observed
- Only used impact on total event rates $\Rightarrow$ Cannot fully distinguish CP-even and CP-odd contributions
- No pure CP test

$H \to \gamma\gamma$ analysis

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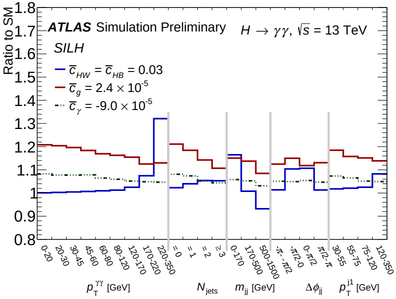
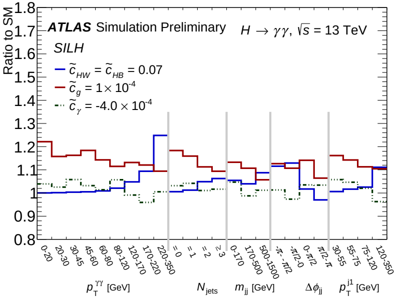
- Analyzing events with $m_{\gamma\gamma} \in [105\ \text{GeV},\ 160\ \text{GeV}]$
- Simultaneous fit to 5 distributions (correlations taken into account)





- Use EFT in SILH basis, same setup as before, slightly different operators
- Variable for CP test: $\Delta\varphi_{jj}$

Pure CP test

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CP-even and odd operators both change yield

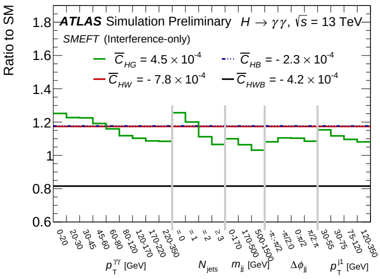
$\Rightarrow$ Should not rely on yield change wrt SM for CP test

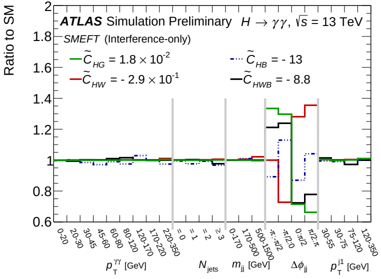
For CP-odd operators:

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{\text{CP-even}} + 2 \underbrace{Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}_{\text{CP-odd, source of CP violation}} + \underbrace{|\mathcal{M}_{\text{CP-odd}}|^2}_{\text{CP-even}}$$

Integrated over CP-even selection, CP-odd interference term vanishes

$\Rightarrow$ Using only interference term, can conduct shape-only analysis, less model-dependent CP test





$H \to \gamma\gamma$ results

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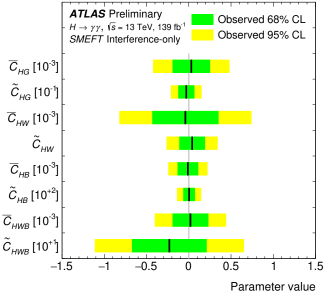
- Limits on single c_i assuming $c_{j \neq i} = 0$
- No deviation from SM observed
- Not taking event rate into account reduces sensitivity to CP-odd Wilson coefficients
- But makes test of CP violation less model-dependent



Coefficient	95% CL, interference-only terms	95% CL, interference and quadratic terms
$\overline{C}_{HG}$	$[-4.2, 4.8] \times 10^{-4}$	$[-6.1, 4.7] \times 10^{-4}$
$\widetilde{C}_{HG}$	$[-2.1, 1.6] \times 10^{-2}$	$[-1.5, 1.4] \times 10^{-3}$
$\overline{C}_{HW}$	$[-8, 2, 7.4] \times 10^{-4}$	$[-8.3, 8.3] \times 10^{-4}$
$\widetilde{C}_{HW}$	$[-0.26, 0.33]$	$[-3.7, 3.7] \times 10^{-3}$
$\overline{C}_{HB}$	$[-2.4, 2.3] \times 10^{-4}$	$[-2.4, 2.4] \times 10^{-4}$
$\widetilde{C}_{HB}$	$[-13.0, 14.0]$	$[-1.2, 1.1] \times 10^{-3}$
$\overline{C}_{HWB}$	$[-4.0, 4.4] \times 10^{-4}$	$[-4.2, 4.2] \times 10^{-4}$
$\widetilde{C}_{HWB}$	$[-11.1, 6.5]$	$[-2.0, 2.0] \times 10^{-3}$

VBF $H \to \tau\tau$ analysis

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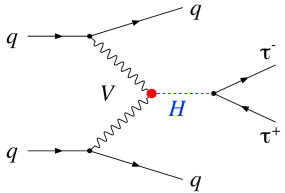
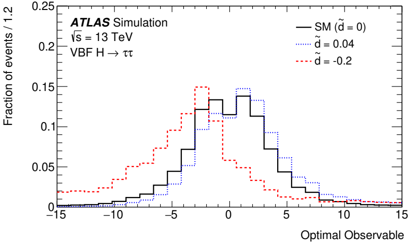
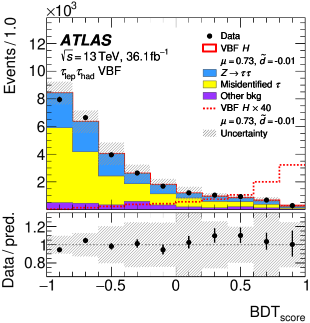
- Investigating only HVV couplings
- EFT Lagrangian: $\mathcal{L} =$
  $\mathcal{L}_{\text{SM}} + \frac{f_{\tilde{B}B}}{\Lambda^2} H^\dagger \hat{\tilde{B}}_{\mu\nu} \hat{B}^{\mu\nu} H + \frac{f_{\tilde{W}W}}{\Lambda^2} H^\dagger \hat{\tilde{W}}_{\mu\nu} \hat{W}^{\mu\nu} H$
- Simplified with one CP-violating parameter:
  $\tilde{d} = -\frac{m_W^2}{\Lambda^2} f_{\tilde{W}W} = -\frac{m_W^2}{\Lambda^2} \tan^2(\theta_W) f_{\tilde{B}B}$



Measure CP-sensitive Optimal Observable $OO = \frac{Re(\mathcal{M}^*_{\text{SM}} \mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$





Signal-isolating BDTs to find Higgs, di-tau decay and VBF properties

VBF $H \to \tau\tau$ results

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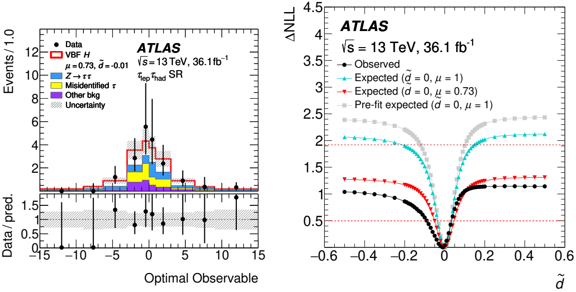
- Least model-dependent: mean values of observed OO distributions in high-BDT SRs
- For $\tilde{d}$ limits: Fit OO in high-BDT SRs
- μ unconstrained in fit $\Rightarrow$ no rate info used

Channel	$\langle$Optimal Observable$\rangle$
$\tau_{lep}\tau_{lep}$ SF	-0.54 ± 0.72
$\tau_{lep}\tau_{lep}$ DF	0.71 ± 0.81
$\tau_{lep}\tau_{had}$	0.74 ± 0.78
$\tau_{had}\tau_{had}$	-1.13 ± 0.65
Combined	-0.19 ± 0.37

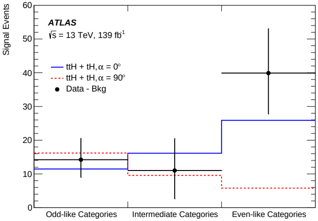


Expected: $\tilde{d} \in [-0.035, 0.033]([-0.21, 0.15])$ at 68% (95%) CL

Observed: $\tilde{d} \in [-0.090, 0.035]$ at 68% CL $\Rightarrow$ No sign of CP violation

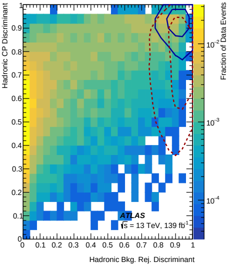
$ttH \to \gamma\gamma$ analysis

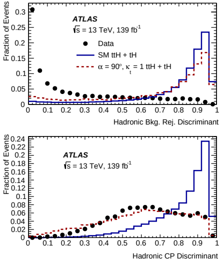
arXiv:2004.04545

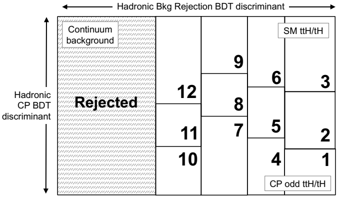


- Search for CP-odd contribution to top Yukawa coupling
- In Higgs Characterization model:
  $\mathcal{L} = -\frac{m_t}{\nu}\left(\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma^5\right]\psi_t\right) H$
- CP-odd term $\propto \sin(\alpha)$ has dimension 4
  $\Rightarrow$ not suppressed by $1/\Lambda^2$ as before

- Two BDTs for event classification: signal vs bkg & CP-odd vs CP-even
- Extract signal yields in each category from a fit to $m_{\gamma\gamma}$

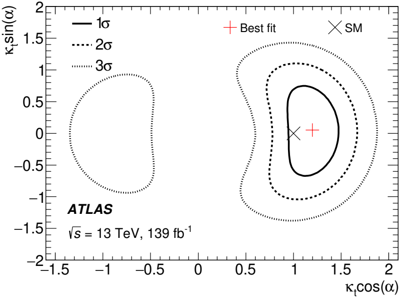






- Fit model allows for variation of coupling strength parameter κ_t and CP-mixing angle α (SM: $\kappa_t = 1$, α=0)

Simultaneous fit for $\kappa_t \sin(\alpha)$ and $\kappa_t \cos(\alpha)$:



Fit to α with free κ_t excluded $|\alpha| > 43^\circ$ at 95% CL $\Rightarrow$ no sign of CP violation

Conclusion

ATL-PHYS-PUB-2019-008

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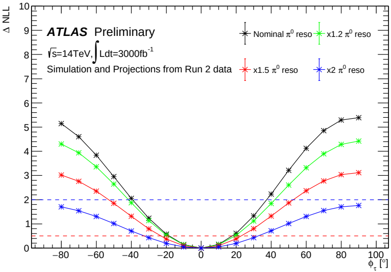
- Searched for CP-odd contribution to effective *HVV*, *ggH* and *ttH* vertices
- No hint of CP violation yet, but analyses still statistics-limited
- new (multivariate) analysis techniques being explored

HL-LHC could even bring sensitivity to $H\tau\tau$ vertex:



⇒ Now is not the time to lose hope!

Thank you for your attention!

Additional Material

Samples $H \to \gamma\gamma$

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Process	Generator	Cross-section normalisation	$\sigma \times$ BR[fb]
ggF	Powheg NNLOPS	N^3LO(QCD)+NLO(EW)	110
VBF	Powheg-Box	approx. NNLO(QCD)+NLO(EW)	8.58
W^+H	Powheg-Box	NNLO(QCD)+NLO(EW)	1.90
W^-H	Powheg-Box	NNLO(QCD)+NLO(EW)	1.21
$q\bar{q} \to ZH$	Powheg-Box	NNLO(QCD)+NLO(EW)	1.73
$gg \to ZH$	Powheg-Box	NLO(QCD)+NLO(EW)	0.28
$t\bar{t}H$	Powheg-Box	NLO(QCD)+NLO(EW)	1.15
$b\bar{b}H$	Powheg-Box	5FS (NNLO), 4FS (NLO)	1.10

Signal $H \to ZZ^* \to 4\ell$

arXiv:2004.03447

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Production process		σ [pb]
ggF	$(gg \to H)$	48.6 ± 2.4
VBF	$(qq' \to Hqq')$	3.78 ± 0.08
WH	$(qq' \to WH)$	1.373 ± 0.028
ZH	$(qq/gg \to ZH)$	0.88 ± 0.04
ttH	$(qq/gg \to ttH)$	0.51 ± 0.05
bbH	$(qq/gg \to bbH)$	0.49 ± 0.12
tH	$(qq/gg \to tH)$	0.09 ± 0.01
Decay process		$\mathcal{B}$ [$\cdot 10^{-4}$]
$H \to ZZ^*$		262 ± 6
$H \to ZZ^* \to 4\ell$		1.240 ± 0.027

The simulation of ggF Higgs boson production used the Powheg method for merging the NLO Higgs boson + jet cross-section with the parton shower and the multi-scale improved NLO (MINLO) method [40–43] to simultaneously achieve NLO accuracy for the inclusive Higgs boson production. In a second step, a reweighting procedure (NNLOPS) [44, 45], exploiting the Higgs boson rapidity distribution, was applied using the HNNLO program [46, 47] to achieve NNLO accuracy in the strong coupling constant α_S. The transverse momentum spectrum of the Higgs boson obtained with this sample is compatible with the fixed-order calculation from HNNLO and the resummed calculation at next-to-next-to-leading-logarithm accuracy matched to NNLO fixed-order with Hres2.3 [48, 49].

The matrix elements of the VBF, $qq \to VH$, and ttH production mechanisms were calculated up to NLO in QCD. For VH production, the MINLO method was used to merge 0-jet and 1-jet events [40, 42, 50–53]. The $gg \to ZH$ contribution was modelled at leading order (LO) in QCD.

The production of a Higgs boson in association with a bottom quark pair (bbH) was simulated at NLO with MadGraph5_aMC@NLO v2.3.3 [54, 55], using the CT10 NLO PDF [56]. The production in association with a single top quark (tH+X where X is either jb or W, defined in the following as tH) [57, 58] was simulated at NLO with MadGraph5_aMC@NLO v2.6.0 using the NNPDF3.0nlo PDF set [59].

Samples VBF $H \to \tau\tau$
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Process	Matrix element (alternative)	PDF set	UEPS model (alternative model)	Prediction order for total cross section
VBF H	Powheg-Box v2 [59–63]	PDF4LHC15 NLO [64]	Pythia 8 [65] (Herwig 7 [67, 68])	approx. NNLO QCD + NLO EW [45, 46, 66]
ggF H	Powheg-Box v2 NNLOPS [73–75]	PDF4LHC15 NNLO	Pythia 8 (Herwig 7)	N^3LO QCD + NLO EW [69–72]
VH	Powheg-Box v2 [76]	PDF4LHC15 NLO	Pythia 8	$qq/qg \to VH$: NNLO QCD + NLO EW [77, 78] $gg \to ZH$: NLO + NLL QCD [79, 80]
$t\bar{t}H$	MG5_aMC@NLO 2.2.2 [81, 82]	NNPDF3.0LO [83]	Pythia 8	NLO QCD + NLO EW [84–89]
W/Z+jets	Sherpa 2.2.1 [90] (MG5_aMC@NLO 2.2.2)	NNPDF3.0NNLO	Sherpa 2.2.1 [91] (Pythia 8)	NNLO [92, 93]
Electroweak W/Zjj	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	LO
$VV/V\gamma^*$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	NLO
$t\bar{t}$	Powheg-Box v2 [94]	CT10 [48]	Pythia 6.428 [95]	NNLO+NNLL [96]
Wt	Powheg-Box v1 [97]	CT10	Pythia 6.428	NLO [97]

Samples $ttH \to \gamma\gamma$

arXiv:2004.04545

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Simulated $t\bar{t}H$ and tH samples were generated using MadGraph5_aMC@NLO at next-to-leading order in QCD for different α and κ_t (for tH) values, with the NNPDF30NLO [21] parton distribution function (PDF) set used for the matrix element (ME) evaluation, and interfaced to Pythia 8 [22] using the NNPDF23LO [23] PDF set for parton showering (PS). The A14 parameter set [24], tuned to data, was used here. From these samples, a yield parameterization as a function of α and κ_t is derived and used in the statistical interpretations. Samples for other Higgs boson production processes, ggF [25], vector-boson fusion (VBF) [26], and vector-boson associated production (VH) [27, 28] were produced with Powheg-Box generator [29] using the PDF4LHC15 PDF set [30] for ME, with the AZNLO set of tuned parameters [31] and Pythia 8 for PS using the CTEQ6L1 [32] PDF set. Samples generated with Herwig 7 [33] are used for systematic uncertainty studies that involve modeling of the PS, hadronization and underlying event (UE). The simulated Higgs boson samples are normalized to the SM cross sections (Refs. [34–52]) times the SM branching ratio (BR) to diphotons (Refs. [34, 53–56]) with a Higgs boson mass of 125.09 GeV [57].

STXS binning ggF

Stage 1.2