Test of CP Invariance in H+2jets: VBF and ggF CP studies in H $\rightarrow \tau\tau$

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Higgs plus dijets at the LHC

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BMBF-Forschungsschwerpunkt ATLAS-EXPERIMENT
Physik auf der TeV-Skala am Large Hadron Collider
FSP 103 ATLAS

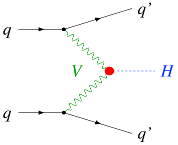
DFG Deutsche Forschungsgemeinschaft

Masse und Symmetrien nach der GRK 2044 Entdeckung des Higgs-Teilchens am LHC

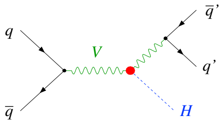
Motivation

- Observed baryon asymmetry in our universe
- One of the Sakharov conditions to explain this asymmetry: **CP violation**
- CP violation in SM (via CKM matrix) not sufficienct
  $\rightarrow$ Additional sources in Higgs boson production and/or decay?
- SM prediction: CP-even Higgs boson
- Look for small CP odd contribution to SM-like interactions:
  $\rightarrow$ CP violation, physics beyond the SM
- Testing CP invariance in H+2jets via:

Vector-Boson Fusion:

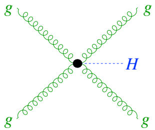


Higgs-strahlung:



Probing HVV coupling

Gluon-Gluon Fusion:



Probing (effective) Hgg coupling

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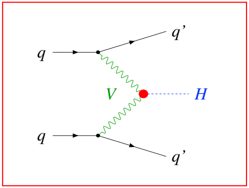

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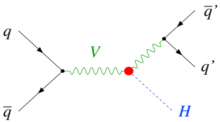
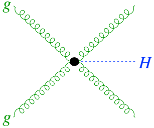


Probing HVV coupling

Gluon-Gluon Fusion:



Probing (effective) Hgg coupling

Effective Lagrangian

- Ansatz: effective $SU(2) \times U(1)_Y$ invariant Lagrangian with additional CP-odd operators V.Hankele et al.; Phys. Rev. D74(2006)

  $$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{f_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{f_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + O\left(\frac{1}{\Lambda^3}\right) + \dots$$

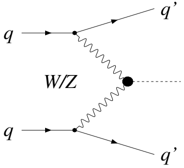
  f_i : Wilson coefficients, $\mathcal{O}_i$: operators, Λ : energy scale
- Model-independent approach
- Only consider CP-odd dimension 6 operators:

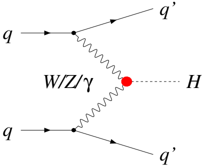
  $$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{f_{\tilde{W}W}}{\Lambda^2}\mathcal{O}_{\tilde{W}W} + \frac{f_{\tilde{B}B}}{\Lambda^2}\mathcal{O}_{\tilde{B}B} + \frac{f_{\tilde{B}}}{\Lambda^2}\mathcal{O}_{\tilde{B}}$$

  constrained by measurements of CP-violating triple gauge-boson couplings at LEP

  Phys. Lett. B614 (2005), Eur. Phys. J. C54 (2008), Eur. Phys. J. C19 (2001)
- After electroweak symmetry breaking:

  $$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \tilde{g}_{HAA} H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ} H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ} H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW} H\tilde{W}^{+}_{\mu\nu}W^{\mu\nu}_{-}$$





Coupling constants

- $SU(2) \times U(1)_Y$ invariance: coupling constants can be expressed with two dimensionless parameters $\tilde{d}$ & $\tilde{d}_B$ P.Achard et al.; Phys. Lett. B589 (2004):

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}$$

- Experiment: no distinction of these couplings in Vector-Boson Fusion possible $\rightarrow$ with $\tilde{d} = \tilde{d}_B$:

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d}$$
$$\tilde{g}_{HAZ} = 0$$

- CP violation parametrised by single parameter $\tilde{d}$

- Connection to Higgs characterisation model:
P. Artoisenet, P. de Aquino, F. Demartin, R. Frederix, S. Fixion et al.; JHEP 11 (2013) 043

$$\mathcal{L}^V_{eff} = \mathcal{L}_{SM} - \tilde{\kappa}_{AZZ} \cdot \tan(\alpha) Z_{\mu\nu}\widetilde{Z}^{\mu\nu} - \frac{1}{2} \cdot \tilde{\kappa}_{AWW} \cdot \tan(\alpha) W^+_{\mu\nu}\widetilde{W}^{-,\mu\nu}$$

  - Parametrization used by $H \rightarrow WW/ZZ$: $\frac{\tilde{\kappa}_{AZZ}}{\kappa_{SM}} \cdot \tan(\alpha)$, $\frac{\tilde{\kappa}_{AWW}}{\kappa_{SM}} \cdot \tan(\alpha)$
  - Assumption: $\tilde{\kappa}_{AZZ} = \tilde{\kappa}_{AWW} = \tilde{\kappa}_{AVV} \;\widehat{=}\; \tilde{d} = \tilde{d}_B$
  - $\tilde{d} = -\frac{\tilde{\kappa}_{AVV}}{\kappa_{SM}} \cdot \tan\alpha$

Optimal Observable

Matrix element for process with CP-odd contribution:

$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \tilde{d} \cdot \mathcal{M}_{\text{CP-odd}}$$

$$|\mathcal{M}|^2 = \underbrace{|\mathcal{M}_{\text{SM}}|^2}_{\text{CP-even}} + \underbrace{\tilde{d} \cdot 2\text{Re}\left(\mathcal{M}^*_{SM}\,\mathcal{M}_{CPodd}\right)}_{\text{CP-odd (source of CP violation)}} + \underbrace{\tilde{d}^2 \cdot |\mathcal{M}_{CPodd}|^2}_{\text{CP-even (increase of cross section)}}$$

- Optimal Observable: $\boxed{OO = \frac{2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CPodd})}{|\mathcal{M}_{SM}|^2}}$

  - CP-odd observable

  - Contains full phase-space information in 1-dim. observable for small $\tilde{d}$

    D. Atwood & A.Soni; Phys Lett. D45 (1992)
    M. Davier et al.; Phys. Lett B306 (1993)
    M. Diehl & O. Nachtmann; Z. Phys. C62 (1994)

  - $\langle OO \rangle \neq 0 \rightarrow$ CP violation

- Matrix elements (LO) from HAWK

  A.Denner, S.Dittmaier, S.Kallweit & A.Möck; Comput. Phys. Commun. 195(2015)

Optimal Observable

- Input for ME calculation (reconstruction level):
  - Lorentzvector of reconstruced Higgs boson (MMC A. Elagin et al.; Nul.Instrum.Meth. A654 (2011))
  - Lorentzvector of two leading jets
- Higgs-boson decay products not directly used

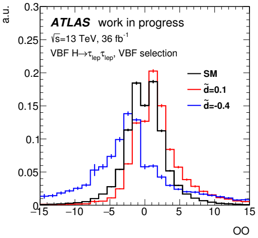
  $\rightarrow$ method independent of decay channel
- Flavour of incoming and outgoing partons not known in experiment:

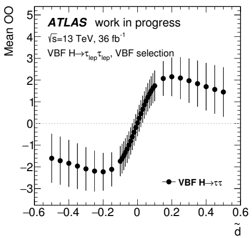
  $\rightarrow$ summation over all possible flavour configurations $ij \rightarrow klH$

  weighted by parton distribution functions $f_i(x_{1,2})$:

  $| \mathcal{M}_{SM} |^2 = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) \mid \mathcal{M}_{SM} \mid^2 (ij \rightarrow klH)$

  $2\mathrm{Re}\left(\mathcal{M}^*_{SM}\mathcal{M}_{CPodd}\right) = \sum_{i,j,k,l} f_i(x_1) f_j(x_2) 2\mathrm{Re}\left(\mathcal{M}^*_{SM}\mathcal{M}_{CPodd}\right)(ij \rightarrow klH)$





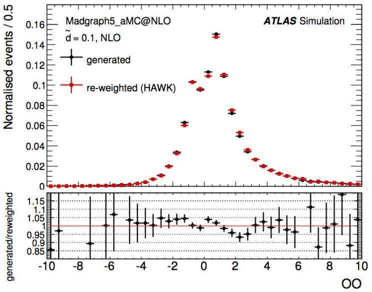
- symmetric for SM coupling
- shifted to $OO > (<) 0$ for $\tilde{d} > (<) 0$
- $\langle OO \rangle$ as function of $\tilde{d}$:
  - linear for small $\tilde{d}$,
  - $\langle OO \rangle \rightarrow 0$ for large $\tilde{d}$

Signal reweighting

- Signal predictions for $\tilde{d} \neq 0$ obtained by reweighting SM prediction:

$$w(\tilde{d}) = \frac{|\mathcal{M}_{\tilde{d}}|^2}{|\mathcal{M}_{SM}|^2}$$

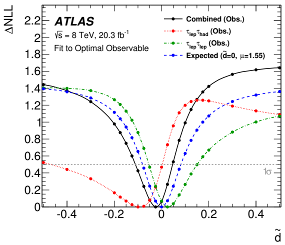
- Reweighting depends on :
  - Process: $qq \to qqH$
    $qq \to qqgH$ & $qq \to qq\bar{q}H$
  - Flavour of incoming and outgoing partons
  - Bjorken $x_{1,2} = M_{\text{final state}} e^{\pm y_{\text{final state}}}$
- Color information neglected for reweighting

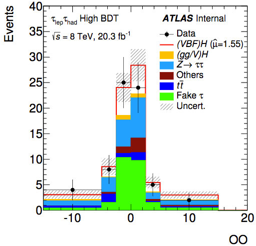


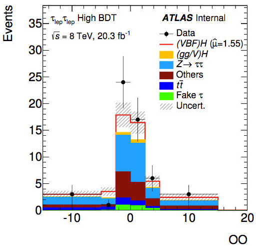
→ Good agreement between LO reweighted and directly generated NLO events

Run-1 results

- Publication with OO method in Run-1 ATLAS Collaboration; Eur. Phys. J. C76 (2016)
- $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ included
- Maximum-Likelihood-Fit in OO





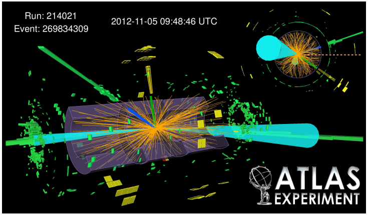


- Confidence intervals at 68% CL: [-0.11,0.05] ([-0.08,0.08]) observed(expected) with $\mu_{bestfit}(\tilde{d} = 0) = 1.55^{+0.86}_{-0.76}$
- Comparison to limits from $H \rightarrow VV$ ATLAS Collaboration; Eur. Phys. J. C75(2015): 68% CL factor 10 better, but no 95% CL reached

VBF CP analysis in $H \to \tau\tau$ in Run 2

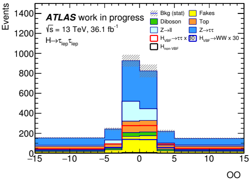
- **Aim of analysis:** use OO to improve limits on $\tilde{d}$-parameter
- At the moment: mainly follow Run 1 approach
- CP analysis is based on $H \to \tau\tau$ coupling analysis in terms of
  - Background estimation
  - Systematic uncertainties
  - Event selection
  - MVA analysis
- Use complete 2015+2016 dataset: 36.1 fb^{-1}
- No official ATLAS results so far
- in this talk: preliminary results of studies by Dirk Sammel and A.L., focus on analysis in $\tau_{lep}\tau_{lep}$ and $\tau_{lep}\tau_{had}$ channels

Event selection

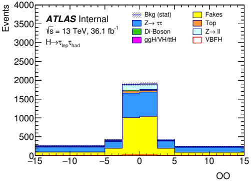


$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$
Preselection:	
2 isolated leptons	1 isolated lepton, 1 τ_{had} candidate
$30 < m_{mvis} < 75(100)$ GeV for $ee/\mu\mu(e\mu)$	$m_T(l, E_T^{miss}) < 70$ GeV
$E_T^{miss} > 55(20)$ GeV for $ee/\mu\mu(e\mu)$	
b-jet veto	b-jet veto
Common VBF selection:	
$n_{jets} \geq 2$	
$m_{jj} > 300$ GeV	
$\mid \Delta\eta_{jj} \mid > 3$	

$\tau_{lep}\tau_{lep}$



$\tau_{lep}\tau_{had}$



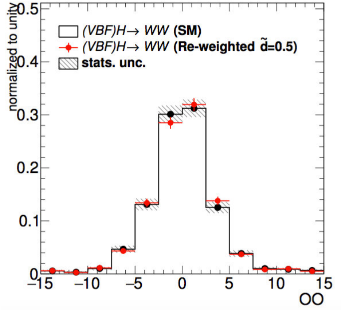
	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$
VBF $H \to \tau\tau$	27.8 ± 0.1	56.7 ± 0.35
VBF $H \to WW$	15.0 ± 0.3	-
Non-VBF $H \to \tau\tau, WW$	26.3 ± 0.6	35.9 ± 0.8
Sum of bkgs	2598.7 ± 90.6	5160.8 ± 67.9
S/B	0.02	0.01

- $\tau_{lep}\tau_{lep}$: VBF $H \to WW \to 2l2\nu$ considered as signal
- Non-VBF production treated as background (assuming SM coupling)

Checks on VBF $H \to WW$

Contribution from anomlous HVV couplings in $H \to WW$ decay:

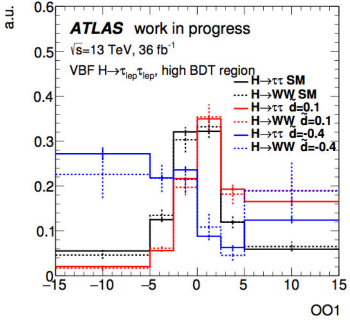
- OO shape with anomalous coupling in decay vertex only for SM and $\tilde{d} = 0.5$:



- Only small differences → Effect is considered to be negligible

Comparison of OO shape for VBF $H \to \tau\tau$ and $H \to WW$:

- Check if VBF $H \to WW$ events introduce artificial distortion in OO:



- Good agreement between $H \to \tau\tau$ and $H \to WW$ for various $\tilde{d}$-models

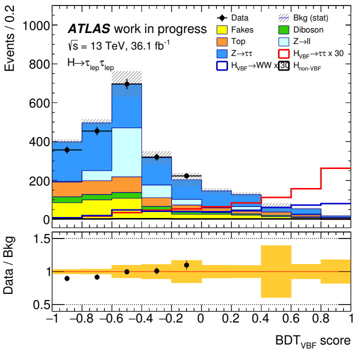
Signal and background samples

Process	Generator		PDF set		Tune	Order
	ME	PS	ME	PS		
$H \rightarrow \tau\tau, WW$						
ggF	Powheg	Pythia8	PDF4LHC15	CTEQ6L1	AZNLO	NNLO+NNLL
VBF	Powheg	Pythia8	PDF4LHC15	CTEQ6L1	AZNLO	(N)NLO
VH	Powheg	Pythia8	PDF4LHC15	CTEQ6L1	AZNLO	NNLO
ttH	Powheg	Pythia8	PDF4LHC15	CTEQ6L1	AZNLO	NLO
Background						
V+jets	Sherpa 2.2.1		NNPDF30		Sherpa	NNLO
$t\bar{t}$	Powheg	Pythia6	CT10	CTEQ6L1	Perugia2012	NNLO+NNLL
Single top	Powheg	Pythia6	CT10	CTEQ6L1	Perugia2012	NNLO
Di-Boson	Sherpa 2.2.1		NNPDF30		Sherpa	NNLO

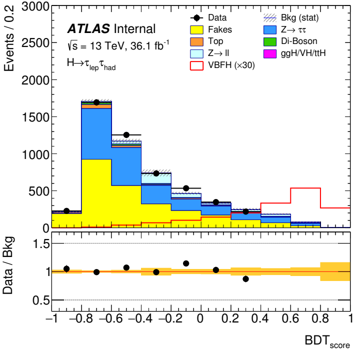
- in Run 1: used τ-embedded $Z \rightarrow \mu\mu$ data to model $Z \rightarrow \tau\tau$ processes
  ATLAS Collaboration, JINST 10(2015) no.09
- Not available in Run 2 (yet)

- Enhance signal-to-background ratio: select events with high $\mathrm{BDT}_{\mathrm{score}}$

$\tau_{lep}\tau_{lep}$



$\tau_{lep}\tau_{had}$

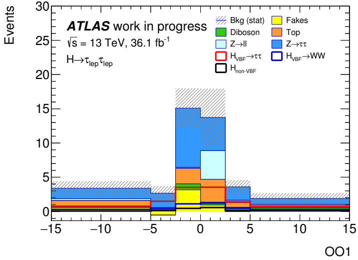


high BDT signal region:

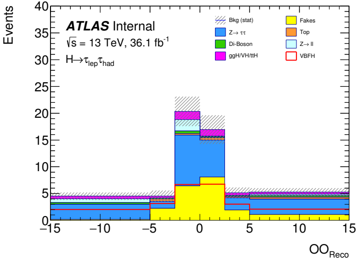
$\mathrm{BDT}_{\mathrm{score}} > 0.70$ $\mathrm{BDT}_{\mathrm{score}} > 0.64$

High BDT signal region

$\tau_{lep}\tau_{lep}$



$\tau_{lep}\tau_{had}$



	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$
VBF $H \to \tau\tau$	11.6 ± 0.1	23.8 ± 0.2
VBF $H \to WW$	4.0 ± 0.2	-
Non-VBF $H \to \tau\tau, WW$	2.5 ± 0.2	4.6 ± 0.3
Sum of bkgs	41.8 ± 5.1	56.7 ± 4.2
S/B	0.37	0.42

- signal-to-background ratio improved

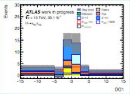
Fitmodel

$\tau_{lep}\tau_{lep}$

High BDT Signal Region

BDT score > 0.70

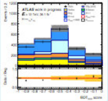
Optimal Observable



Low BDT Control Region

BDT score < 0.0

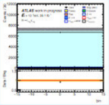
BDT classifier



Zll Control Region

80 < mll < 100 GeV

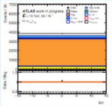
Single Bin



Top Control Region

at least one b-jet

Single Bin

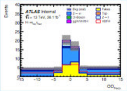


$\tau_{lep}\tau_{had}$

High BDT Signal Region

BDT score > 0.64

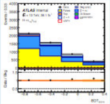
Optimal Observable



Low BDT Control Region

BDT score < 0.34

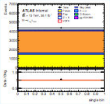
BDT classifier



Top Control Region

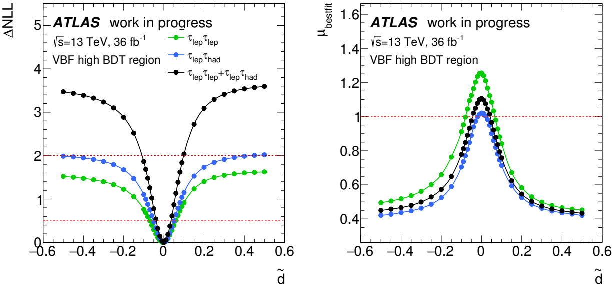
at least one b-jet, mT > 40 GeV

Single Bin



- For each $\tilde{d}$-model: Maximum Likelihood Fit → ΔNLL-curve
- No rate information used

- ΔNLL $= 0.5$: expected confidence intervals at 68% CL
- Asimov data (SM signal+bkgs) in signal region, data in control regions
- Only statistical uncertainties included here



Parameter	Postfit@SM
$\mu_{bestfit}$	$1.11^{+0.35}_{-0.33}$
NF(Zll)	0.92 ± 0.03
NF(Top, $\tau_{lep}\tau_{lep}$)	1.09 ± 0.03
NF(Top, $\tau_{lep}\tau_{had}$)	1.09 ± 0.03
NF($Z\tau\tau$, $\tau_{lep}\tau_{lep}$)	0.82 ± 0.06
NF($Z\tau\tau$, $\tau_{lep}\tau_{had}$)	1.09 ± 0.03

$\tau_{lep}\tau_{lep}+\tau_{lep}\tau_{had}$ combination:

- (1σ) exclusion for $\tilde{d}$ outside [-0.038,0.035]
- (2σ) exclusion for $\tilde{d}$ outside [-0.108,0.098]

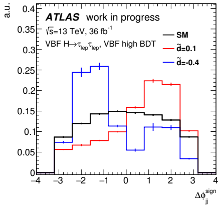
Comparison to $\Delta\Phi_{jj}^{sign}$ ($\tau_{lep}\tau_{lep}$ only)

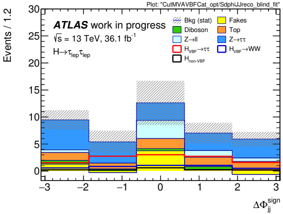
- Other CP odd observable:

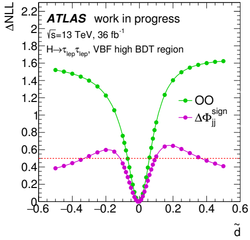
$$\boxed{\Delta\Phi_{jj}^{sign} = \Phi_{j+} - \Phi_{j-}}$$

$j+(-)$: jet in positive(negative) detector hemispheres

- Same fitmodel as for OO in high BDT signal region





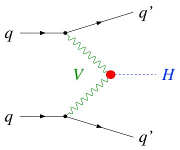


	(1σ) exclusion $(\tau_{lep}\tau_{lep})$
OO	$[-0.071, 0, 058]$
$\Delta\Phi_{jj}^{sign}$	$[-0.116, 0.095]$, $[-0.331, 0.366]$

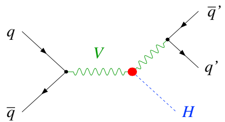
- In comparison to OO: $\Delta\phi_{jj}^{sign}$ less sensitive

Testing CP Invariance in H+2jets

Vector-Boson Fusion:

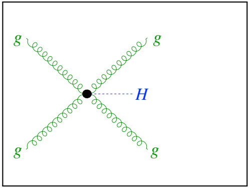


Higgs-strahlung:



Probing HVV coupling

Gluon-Gluon Fusion:



Probing (effective) Hgg coupling

- First studies in context of master thesis (A.L. 2015):

  Test of CP Invariance in gluon-gluon fusion production in $H \rightarrow \tau_{lep}\tau_{lep}$ at $\sqrt{s} = 8\,\text{TeV}$
- Dataset corresponding to $20.3\,\text{fb}^{-1}$
- Signal sample for ggF $H \rightarrow \tau_{lep}\tau_{lep}$: H+1jet NLO MiNLO

  J. M. Campbell, R. K. Ellis, R. Frederix, P. Nason, C. Oleari & C. Williams; JHEP 07 (2012)
- Matrix element calculation for OO and reweighting extracted from MadGraph5

  J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer & T. Stelzer; JHEP 06 (2011)

Higgs-gluon coupling

Higgs-gluon coupling in EFT approach for $m_{top} \rightarrow \infty$:
(*HiggsCharacterisation* framework)

$$\mathcal{L}_{eff} = \underbrace{a_2 G^a_{\mu\nu} G^{a,\mu\nu} \mathrm{H}}_{\text{SM contribution}} + \underbrace{a_3 G^a_{\mu\nu} G^a_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma} \mathrm{A}}_{\text{CP odd contribution}}$$

$G^{a,\mu\nu}$: gluon field strength tensor
$\epsilon^{\mu\nu\rho\sigma}$: total asymmetric tensor

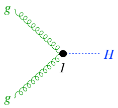
$$\boxed{a_2 = g_{Hgg} \kappa_{Hgg} \cos(\alpha),\ \ a_3 = g_{Agg} \kappa_{Agg} \sin(\alpha)}$$

g_{Hgg}, g_{Agg}: coupling strength, $\kappa_{Hgg}, \kappa_{Agg}$: dimensionless constants

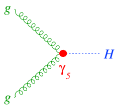
$\rightarrow$ Mixing between CP even and CP odd coupling driven by $\mathbf{cos(\alpha)}$

$\rightarrow$ CP violation for $\kappa_{Hgg}, \kappa_{Agg} \neq 0$ and $\cos(\alpha) \neq 0, \pm 1$

CP even state:



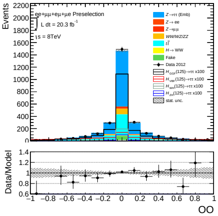
CP odd state:



ggF H+2jets: Event selection

(1) Basic preselection:

- two isolated leptons
- at least two jets with $p_T > 40(30)$ GeV
- $E_T^{miss} > 20(70)$ GeV for $e\mu(ee/\mu\mu)$
- $30 < m_{vis} < 100(75)$ GeV for $e\mu(ee/\mu\mu)$
- b-jet veto

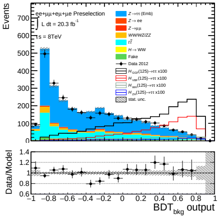


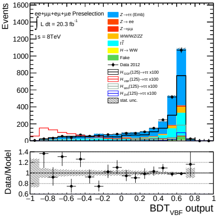
$$\frac{\text{ggF H+2jets}}{B} = 7.4 \times 10^{-3}$$

$$\frac{\text{ggF H+2jets}}{\text{VBF H}} = 2.1$$

(2) Enhance signal-to-background ration by using BDTs:

- BDT_{bkg}: separate **ggF signal** from all considered backgrounds
- BDT_{VBF}: separate **ggF signal** from VBF $H \to \tau\tau$ background





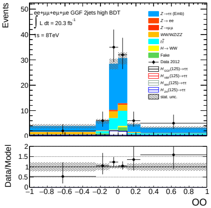
Signal region:

$\text{BDT}_{\text{bkg}} > 0.6$ and

$\text{BDT}_{\text{VBF}} > -0.3$

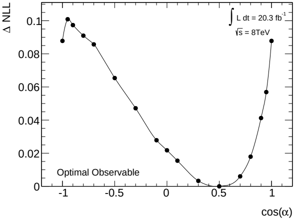
ggF H+2jets: Sensitivity at $\sqrt{s} = 8$ TeV

- OO in signal region:



- $\frac{\text{ggF H+2jets}}{B} = \frac{5.1}{73.5} = 0.07$
- $\frac{\text{ggF H+2jets}}{\text{VBF H}} = 5$

- Likelihood fit in OO (same fitmodel as for VBF CP analysis)
- Full set of systematic uncertainties included here



Parameter	Postfit@SM	Postfit@$c_\alpha = 0.50$
$\mu_{betsfit}$	$2.60^{+2.57}_{-2.08}$	$2.67^{+2.66}_{-2.03}$
NF(Top)	1.00 ± 0.12	1.00 ± 0.12
NF(Zll)	0.93 ± 0.42	0.92 ± 0.41
NF($Z\tau\tau$)	0.99 ± 0.11	0.99 ± 0.11

- No sensitivity with Run 1 data yet

Summary and outlook

- Sensitivity studies for tests of CP invariance in VBF $H \to \tau\tau$ with 36 fb^{-1}
- Using Optimal Observable
- Expected sensitivity ($\tau_{lep}\tau_{lep} + \tau_{lep}\tau_{had}$) with stat. uncert, only:
  - (1σ) exclusion for $\tilde{d}$ outside [-0.038,0.035]
  - (2σ) exclusion for $\tilde{d}$ outside [-0.108,0.098]
- Test of CP invariance in ggF $H + 2\text{jets} \to \tau_{lep}\tau_{lep}$ with 20.3 fb^{-1}:
  - Limited sensitivity with Run 1 dataset
  - Still interesting to look into this for Run 2

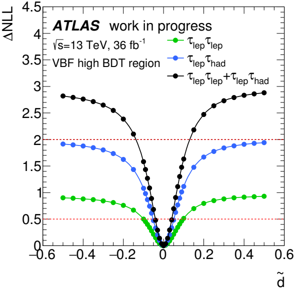
Outlook:

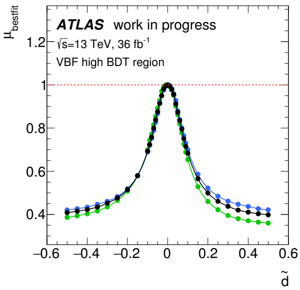
- Expected sensitivity with systematic uncertainties
- Combination of all final states (so far only $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}$)
- Pure CP test by measuring
  - Mean of Optimal Observable $\langle OO \rangle$
  - Asymmetry of Optimal Observable $\mathcal{A}(OO) = \frac{N(OO>0)-N(OO<0)}{N(OO>0)+N(OO<0)}$
- Include rate information
- Consider more general EFT Lagrangian

Thank you for your attention

BACKUP

- ΔNLL $= 0.5$: expected confidence intervals at 68% CL
- Asimov data (SM signal+bkgs) in signal region and control regions
- only statistical uncertainties included here





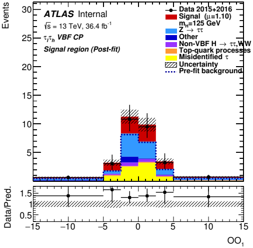
Parameter	Postfit@SM
$\mu_{bestfit}$	$1.00^{+0.34}_{-0.33}$
NF(Zll)	1.00 ± 0.01
NF(Top, $\tau_{lep}\tau_{lep}$)	1.00 ± 0.03
NF(Top, $\tau_{lep}\tau_{had}$)	1.00 ± 0.03
NF($Z\tau\tau$, $\tau_{lep}\tau_{lep}$)	1.00 ± 0.06
NF($Z\tau\tau$, $\tau_{lep}\tau_{had}$)	1.00 ± 0.04

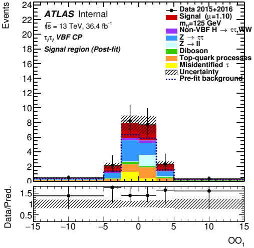
$\tau_{lep}\tau_{lep}+\tau_{lep}\tau_{had}$ combination:

- (1σ) exclusion for $\tilde{d}$ outside [-0.041, 0.040]
- (2σ) exclusion for $\tilde{d}$ outside [-0.135, 0.132]

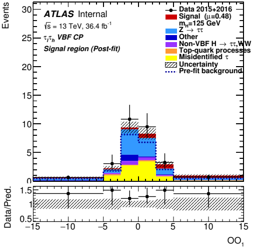
Postfit plots ($\tau_{lep}\tau_{lep} + \tau_{lep}\tau_{lep}$ combination)

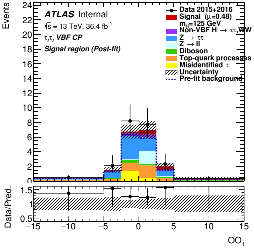
SM signal hypothesis:





$\tilde{d} = 0.30$ signal hypothesis:





Comparison to $\Delta\Phi_{jj}^{sign}$ ($\tau_{lep}\tau_{lep}$ only)

- bestfit signal strength $\mu_{bestfit}$ from hybrid fit: