Study of CP violating EFT bosonic operators with the ATLAS detector

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ATLAS EXPERIMENT

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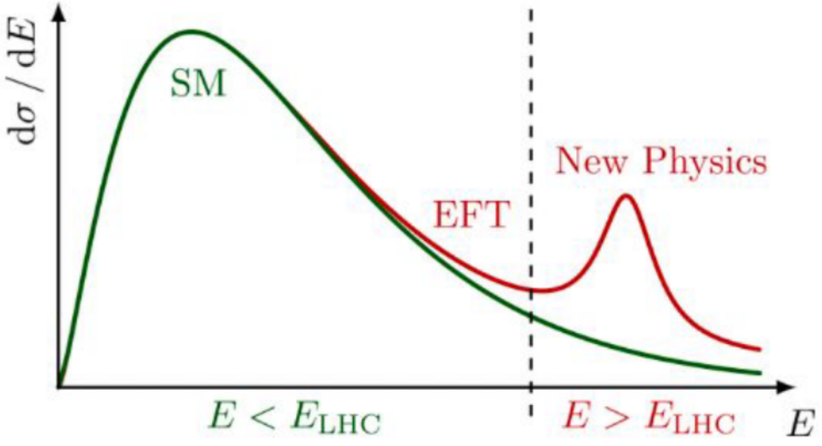
SMEFT for CPV

CP violation (CPV) is one of Sakharov's conditions

→ The CKM phase in SM allows CP breaking, but its effects are not large enough

→ new CPV must occur beyond explored energy range

→ SMEFT offers an indirect way to look for BSM CPV effects



Standard Model EFT Lagrangian

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d>4}\sum_{i} \frac{c_{d,i}}{\Lambda^{d-4}} Q_{d,i}$$

$$= \mathcal{L}_{SM} + \sum_{d>4} \mathcal{L}_d$$

$$= \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \mathcal{L}_8 + \ldots$$

Wilson coefficient

Λ scale of new physics, typically around TeV

Violate B and L conservation

→ Odd dimensions operators generally not considered

Term ~ Λ^{-4}

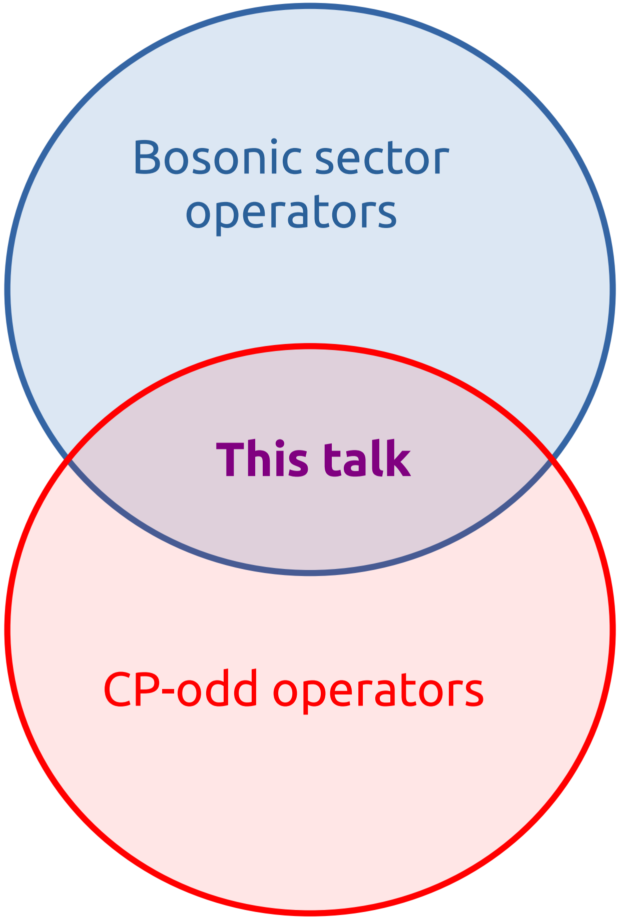
Dominant remaining term ~ Λ^{-2}

CP violation from bosonic operators

Processes involving couplings between bosons abundantly produced at LHC

CP conservation often assumed in most analyses

Specific CP-odd operators challenges,
e.g. almost no modification of the cross section



Standard Model EFT: dim 6 in Warsaw basis

In the Warsaw basis [1] there are
3 types of dim 6 bosonic operators:

* Boson self-coupling (X^3 or H^6)

* Higgs propagator (H^4D^2)

* Higgs-gauge (X^2H^2)

X : field strength tensor (dim 2)
H : Higgs field (dim 1)
D : Covariant derivative (dim 1)

→ 5 + 2 + 8 = **15 operators**

$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc} \widetilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$

$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$

$\mathcal{L}_6^{(3)} - H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$

$\mathcal{L}_6^{(4)} - X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$

$\mathcal{L}_6^{(5)} - \psi^2 H^3$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$\mathcal{L}_6^{(6)} - \psi^2 X H$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W^i_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W^i_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$\mathcal{L}_6^{(7)} - \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{l}_p \sigma^i \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^i_\mu H)(\bar{q}_p \sigma^i \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$\mathcal{L}_6^{(8a)} - (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \sigma^i q_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \sigma^i l_r)(\bar{q}_s \gamma^\mu \sigma^i q_t)$

$\mathcal{L}_6^{(8b)} - (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^a u_r)(\bar{d}_s \gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8c)} - (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{u}_s \gamma^\mu T^a u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^a q_r)(\bar{d}_s \gamma^\mu T^a d_t)$

$\mathcal{L}_6^{(8d)} - (\bar{L}R)(\bar{R}L), (\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^a u_r)\varepsilon_{jk}(\bar{q}_s^k T^a d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

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Standard Model EFT: dim 6 in Warsaw basis

Among those, 6 CP odd operators that include dual tensors

$$\tilde{X}_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} X^{\rho\sigma}$$

In the electroweak sector, 4 remain:

$$\mathcal{Q}_{\tilde{W}}, \mathcal{Q}_{H\tilde{W}}, \mathcal{Q}_{H\tilde{B}}, \mathcal{Q}_{H\tilde{W}B}$$

Sources of anomalous triple gauge coupling (aTGC)

Differential XS of CP-odd observables sensitive to the interference

$$|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6) + |\mathcal{M}_6|^2$$

$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
$Q_{\tilde{G}}$	$f^{abc} \tilde{G}_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk} W_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
$Q_{\tilde{W}}$	$\varepsilon^{ijk} \widetilde{W}_\mu^{i\nu} W_\nu^{j\rho} W_\rho^{k\mu}$
$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$
$\mathcal{L}_6^{(3)} - H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$
$\mathcal{L}_6^{(4)} - X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^a_{\mu\nu} G^{a\mu\nu}$
$Q_{H\tilde{G}}$	$H^\dagger H\, \tilde{G}^a_{\mu\nu} G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W^i_{\mu\nu} W^{I\mu\nu}$
$Q_{H\tilde{W}}$	$H^\dagger H\, \widetilde{W}^i_{\mu\nu} W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\tilde{B}}$	$H^\dagger H\, \tilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^i H\, W^i_{\mu\nu} B^{\mu\nu}$
$Q_{H\tilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$

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Constraints on Wilson coefficients

Perform maximal likelihood fit on relevant observable

Example: Gaussian likelihood (typically for diboson)

$$\mathcal{L}(c_i|\theta) = \frac{1}{\sqrt{(2\pi)^k|C|}} \exp\left(-\frac{1}{2}(\vec{x}_{data} - \vec{x}_{pred}(c_i|\theta))^T C^{-1} (\vec{x}_{data} - \vec{x}_{pred}(c_i|\theta))\right) \times \prod_{i}^{n_{syst}} f_i(\theta_i)$$

Floating Wilson coefficient

Nuisance parameters (systematics, theory uncertainties, etc.)

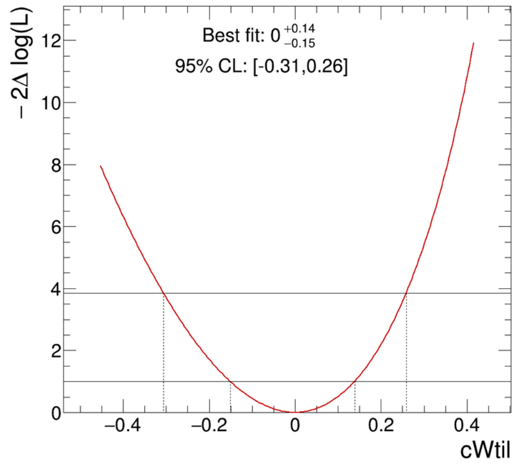
Covariance matrix

Measurement

MC prediction

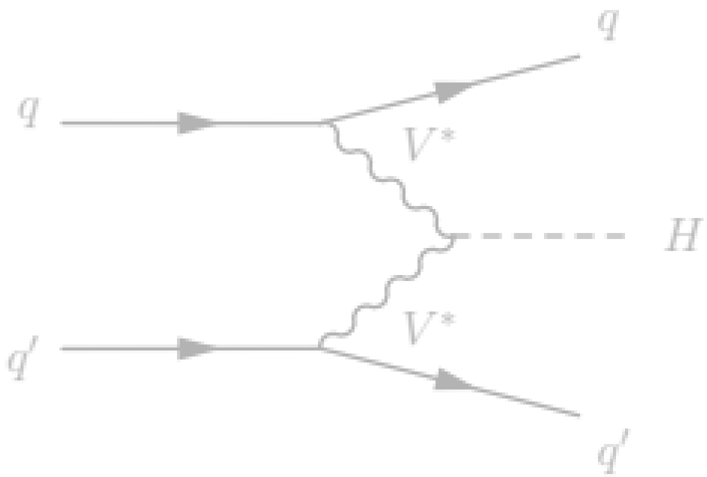
$x_{pred} = x_{SM} + x_{int}(c_i) + x_{quad}(c_i^2)$

$$-2\Delta\log\mathcal{L}(c_i) = -2\log\left(\frac{\mathcal{L}(c_i)}{\mathcal{L}(\hat{c}_i)}\right)$$

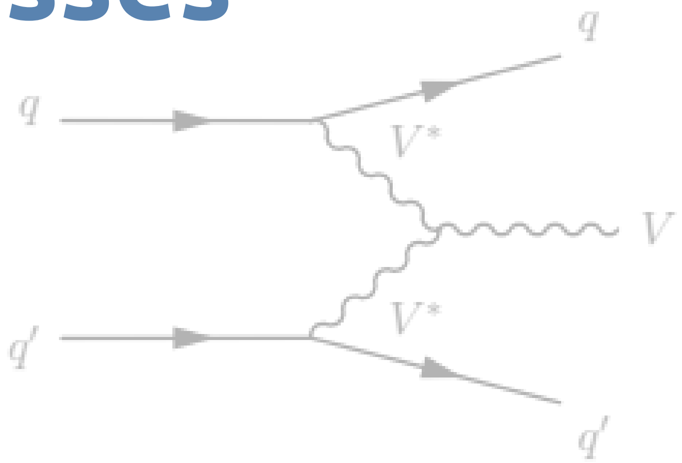


95 % CI

68 % CI



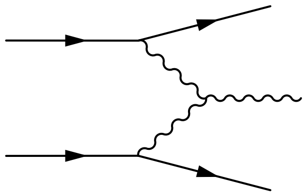
VBF processes

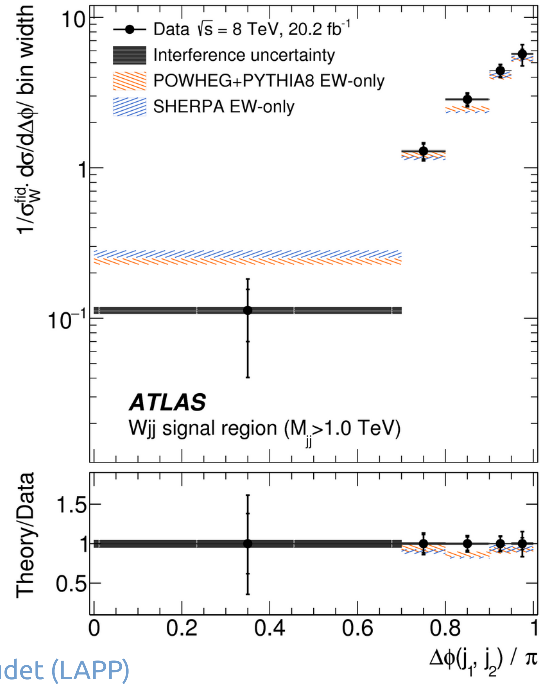


* V jj (V= W,Z) : TGC

* H jj : HVV coupling
  - H → γγ
  - H → ττ
  - H → WW
  (- H → ZZ)

VBF Wjj @ √s = 8 TeV (first in ATLAS)





Eur. Phys. J. C77 (2017)

Challenging analysis in a pp collider:

- Neutrino of W→lν decay only reconstructed as missing E_T
- Complicated reconstruction of p_W
- Handling QCD produced Wjj (expected fraction of 78% QCD production in EW enhanced signal region)

Fit on **azimuthal angle difference between jets $\Delta\Phi(j_1,j_2)$**

$$\Delta\Phi(j_1, j_2) = |\Phi_{j1} - \Phi_{j2}|$$

Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
$\frac{c_W}{\Lambda^2}$	[−39, 37]	[−33, 30]
$\frac{c_B}{\Lambda^2}$	[−200, 190]	[−170, 160]
$\frac{c_{WWW}}{\Lambda^2}$	[−16, 13]	[−13, 9]
$\frac{c_{\tilde{W}}}{\Lambda^2}$	[−720, 720]	[−580, 580]
$\frac{c_{\tilde{W}WW}}{\Lambda^2}$	[−14, 14]	[−11, 11]

(NB: coefficients expressed in HISZ basis here, not Warsaw)

VBF Zjj ($\sqrt{s}$ = 13 TeV)

- Increased $\sqrt{s}$ (8→13 TeV)
- Full Run 2 statistics (20 → 139 fb^{-1})

Two leptons final state, well reconstructed

Main challenge: **extract EW component**

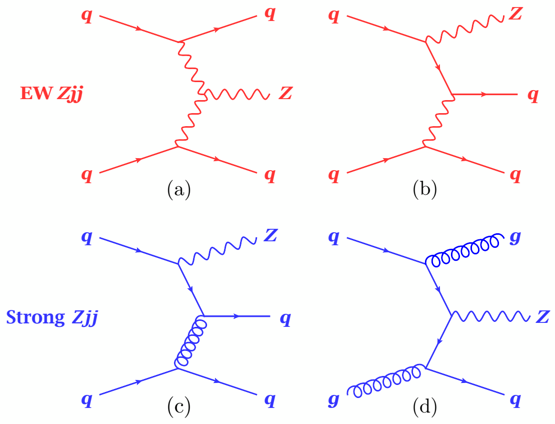
→ **VBF topology** related variables

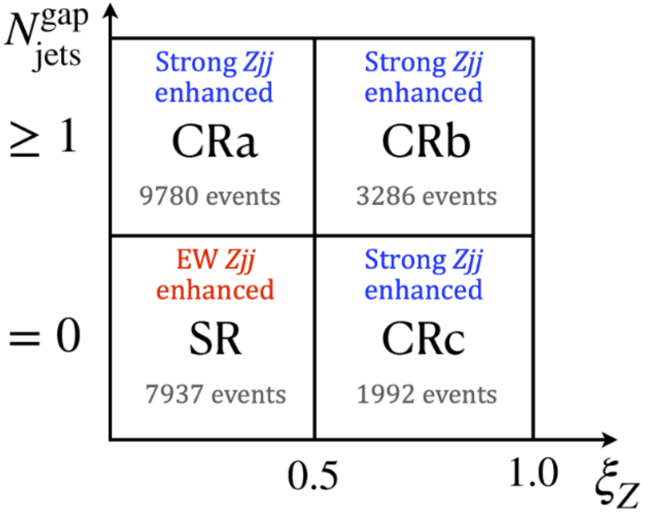
→ binned maximum-likelihood fit in SR

$$\xi_Z = \left| y_{ll} - \frac{y_{j1} + y_{j2}}{2} \right| / \left| y_{j1} - y_{j2} \right|$$

- $j_1(j_2)$ = (sub)leading jet

- gap jets = jets with rapidity y such as $\min(y_{j1},y_{j2}) < y < \max(y_{j1},y_{j2})$





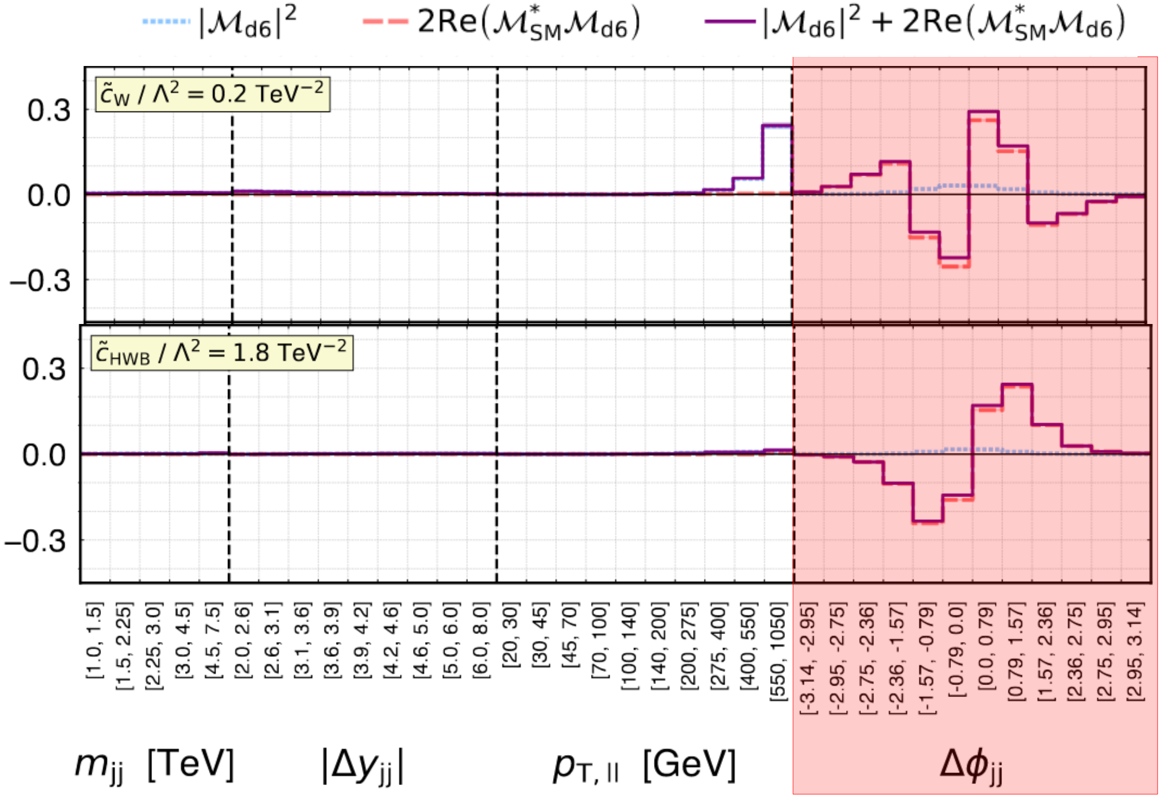
Eur. Phys. J. C 81 (2020)

VBF Zjj ($\sqrt{s}$ = 13 TeV)

Full **ΔΦ(j₁,j₂)** range : [-π,π]

Angular variable → negligeable impact of quadratic term

Wilson coefficient	Includes $\|\mathcal{M}_{d6}\|^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%



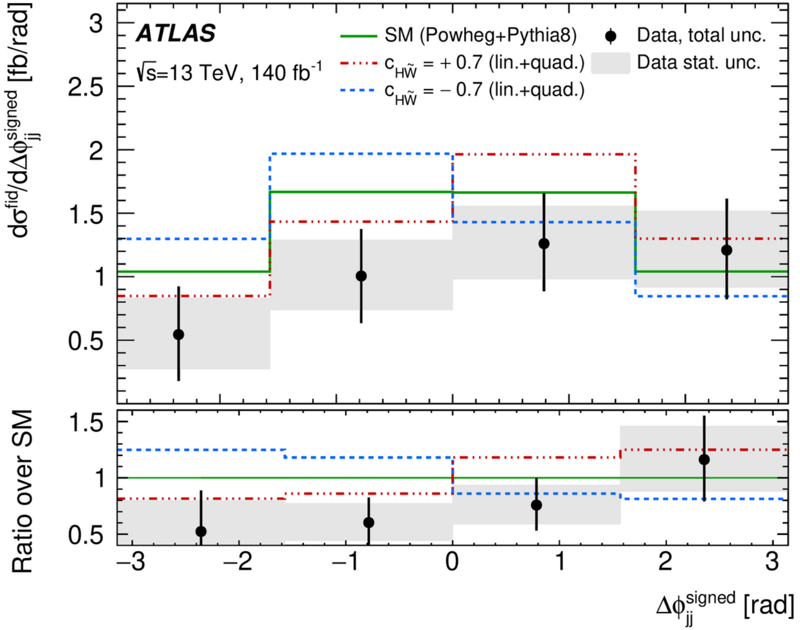
Most competitive limits to this day

Eur. Phys. J. C 81 (2020)

VBF H → ττ and γγ

Sensitive to $Q_{H\tilde{B}}$ and $Q_{H\tilde{W}}$ complementarily to Vjj

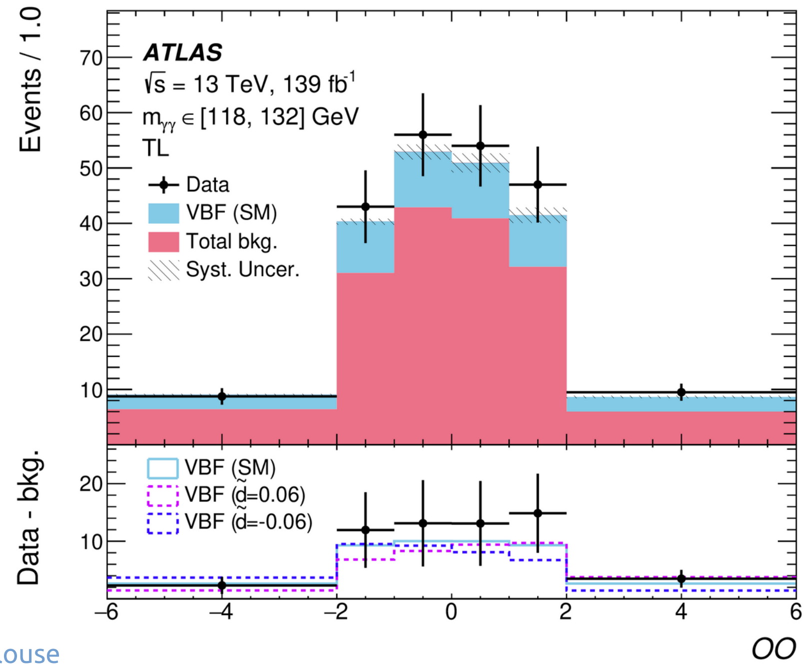
H → ττ: ΔΦ(j₁,j₂)



http://arxiv.org/abs/2407.16320

H → γγ: Optimal observable

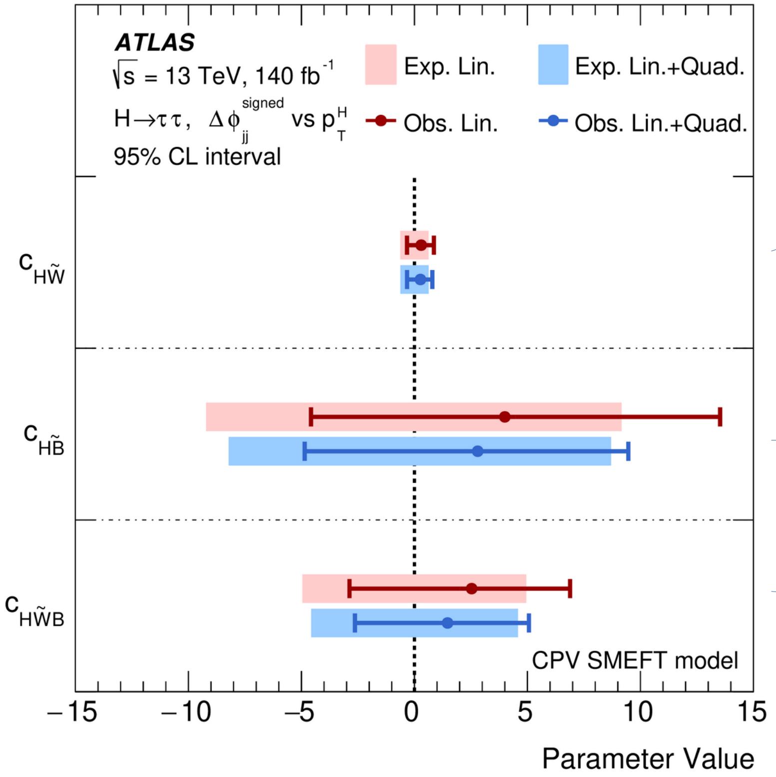
$$OO = \frac{2\Re(\mathcal{M}_{SM}^{*}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$



Phys. Rev. Lett. 131 (2023)

VBF H → ττ and γγ

H → ττ



Observed 95 % CI best to date on $c_{HW\sim}$ with $\Delta\Phi(j_1,j_2)$: [-0.31, 0.88]

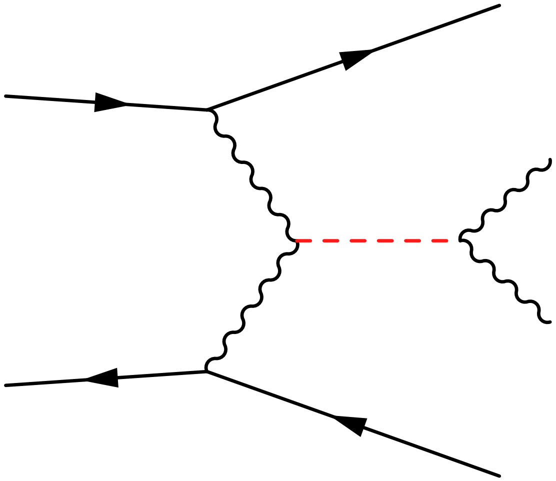
VBF H →γγ : [-0.55, 1.07] TeV^{-2}

Expected to have small effect

Not as constraining as VBF with EW bosons

VBF H → ZZ : [-0.97, 0.98] TeV^{-2} with OO

VBF H→WW*

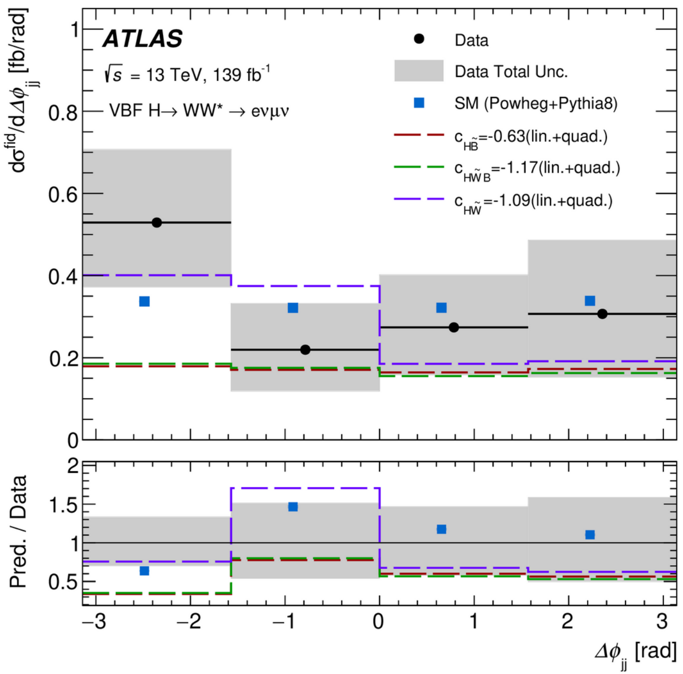


- VBF process with two bosons in final states
  → Two HVV vertices (both production and decay)
- H to WW* has second largest BR

Experimental challenges:

- Two final state neutrinos
- Important top and VV backgrounds

VBF H→WW*

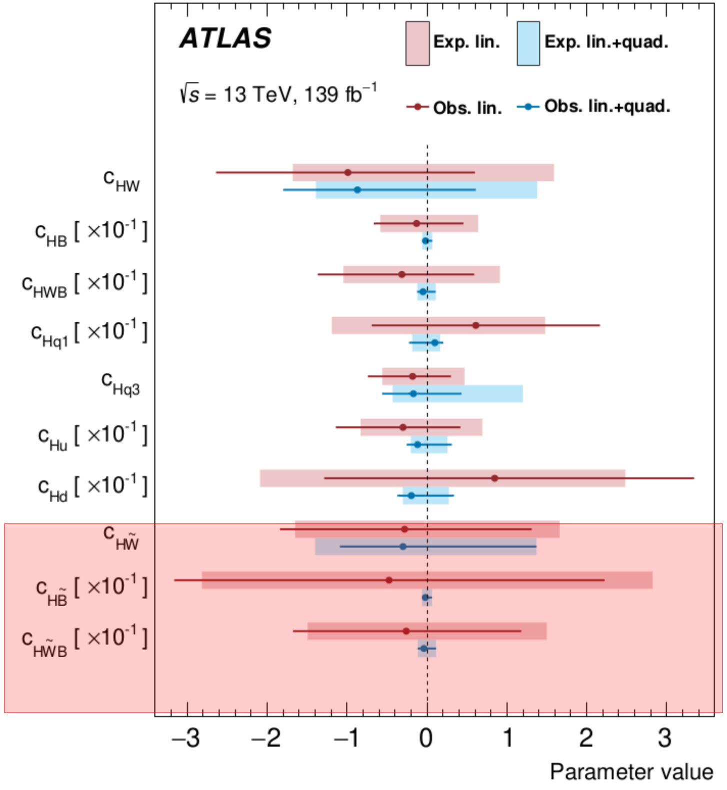


Increased sensitivity to the quadratic term

Expected limits (lin→lin+quad) :

$C_{H\tilde{B}}$ [-28,28] → [-0.62,0.62]
$C_{H\tilde{W}B}$ [-15,15] → [-1.2,1.1]

(competitive with VBF Zjj and H→ZZ results)



Phys Rev D 108, 072003 (2023)

VBF summary

- Single angular observable $\Delta\Phi(j_1,j_2)$ gives stringent constraints for CP-odd c_i

- Optimal observable not as widely used as angular ones

- $Q_{W\sim WW}$ and $Q_{HW\sim B}$ well constrained by EW bosons VBF

- $Q_{HW\sim}$ and $Q_{HB\sim}$ better constrained by Higgs VBF

- Impact of quadratic term negligeable when using angular variables except in VBF H → WW channel

  → exploit additional variables sensitive to quadratic term

CP violating aNTGC

Searches for CPV e.g. ZZ→4l, ZZ→vvll, Zɣ→vvɣ

Investigate CP-odd **anomalous Neutral Triple Gauge Coupling** (aNTGC)

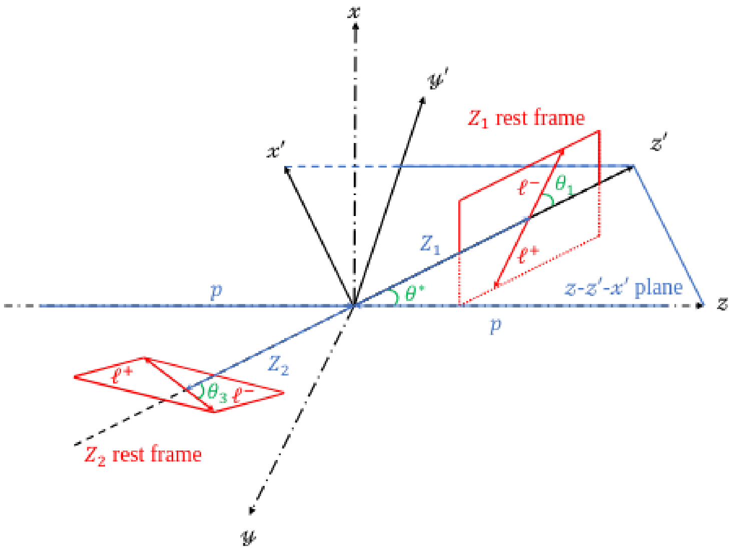
$$\mathcal{L}_{VZZ} \supset -\frac{e}{m_Z^2} f_V^4 (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta)$$

(V = A, Z)

ZZ→4l analysis : CP-odd observable built from polar and azimuthal angles

$$\mathcal{O}_{T_{yz,1}T_{yz,3}} = (\sin\varphi_1 \times \cos\theta_1) \times (\sin\varphi_3 \times \cos\theta_3)$$

aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	[−0.16, 0.16]	[−0.12, 0.20]	[−0.013, 0.012]	[−0.012, 0.012]
f_γ^4	[−0.30, 0.30]	[−0.34, 0.28]	[−0.015, 0.015]	[−0.015, 0.015]



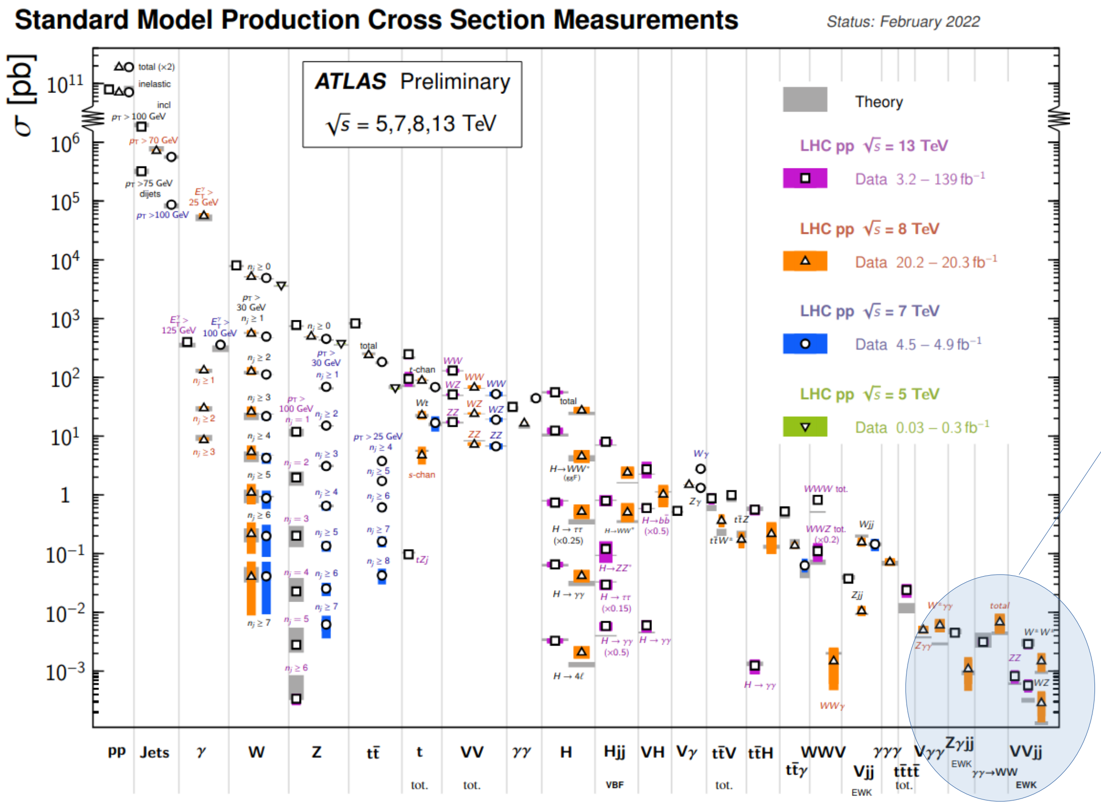
Including quadratic term improves limits by a factor 10

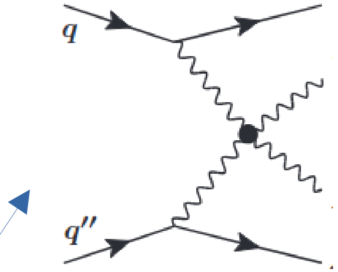
JHEP 12 (2023) 107

What about VBS ?

aQGC probed in VBS processes → cross section ~ fb → low statistics

ATLAS Std Model summary





Interference
~ Λ^{-4}

Existing VBS analyses considered so far only dim 8 CP-even operators within Eboli's model

e.g. Wγjj or WZjj or Zγjj

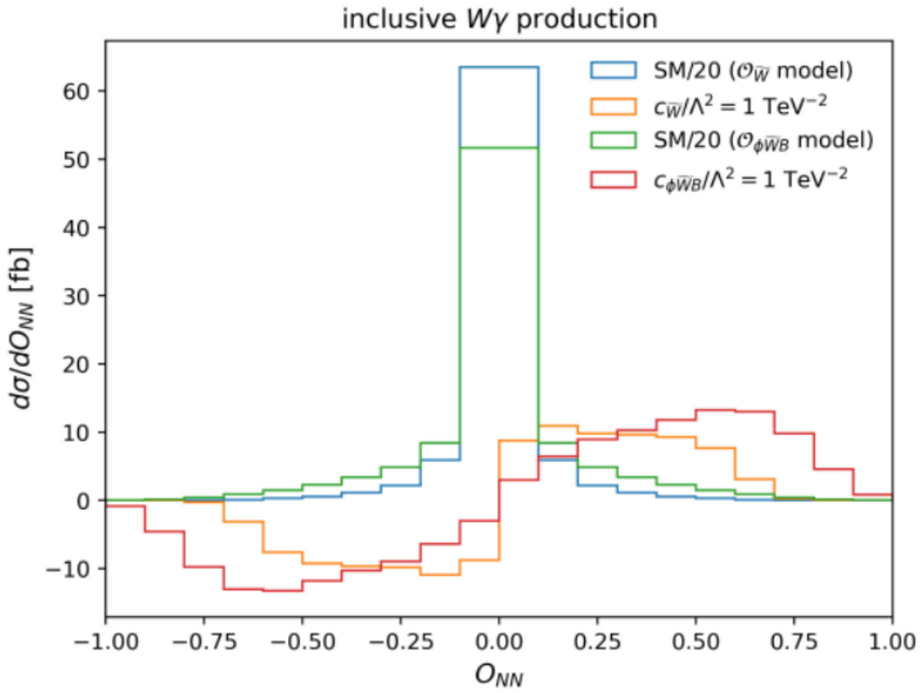
Conclusion & outlook

- Vjj and Hjj analyses **complentary** to constrain dim 6 CP-odd SMEFT bosonic operators
- Constraints on CPV are also put on aNTGC

- Combine additional observables, including **angular** and **energy** related observables (ML)

- Exploit additional final states:
    - inclusive diboson final states (WZ, Wy)
    - VBS for dimension 8 operators

In progress ...



Phys Rev D 107, 016008 (2023)

Thank you for your attention

Poisson likelihood

Alternative to the Gaussian likelihood, used for instance in Higgs EFT analyses

$$\mathcal{L}(x;\mu,\theta) = \prod_{c}^{N_{cat}} \Big(\prod_{k}^{N_{bin}} \mathrm{Pois}(\sum_s N_c^s + \sum_b N_c^b, n_{obs,k}) \Big) \times \prod_i^{n_{syst}} f_i(\theta_i)$$

MC events (sig + bkg)

Data

Nuisance parameters

Operators definitions

$\mathcal{L}_6^{(1)} - X^3$	
Q_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
$Q_{\widetilde{G}}$	$f^{abc}\widetilde{G}_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
Q_W	$\varepsilon^{ijk}W_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$Q_{\widetilde{W}}$	$\varepsilon^{ijk}\widetilde{W}_\mu^{i\nu}W_\nu^{j\rho}W_\rho^{k\mu}$
$\mathcal{L}_6^{(2)} - H^6$	
Q_H	$(H^\dagger H)^3$
$\mathcal{L}_6^{(3)} - H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(D^\mu H^\dagger H)\,(H^\dagger D_\mu H)$
$\mathcal{L}_6^{(4)} - X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^a G^{a\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^a G^{a\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^i W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^i W^{i\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \sigma^i H\, W_{\mu\nu}^i B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \sigma^i H\, \widetilde{W}_{\mu\nu}^i B^{\mu\nu}$

$$W_\mu^{i,\nu} = \partial_\mu W^{i,\nu} - \partial^\nu W_\mu^i - g\varepsilon^{ijk} W_\mu^j W^{k,\nu}$$

$$B^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$$

$$\mathrm{H} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

HISZ and Warsaw basis

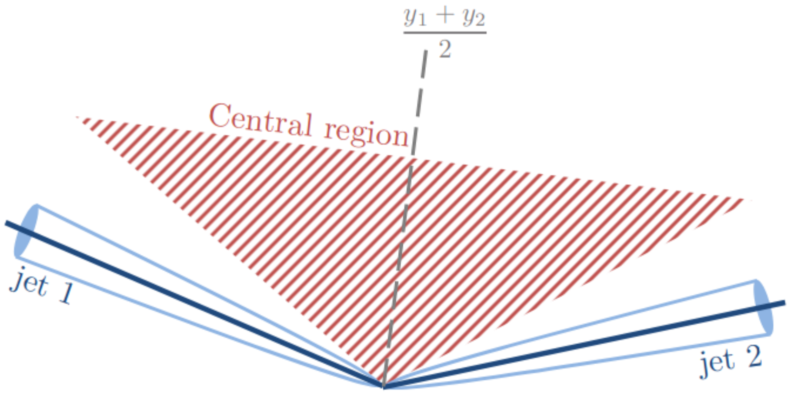
HISZ

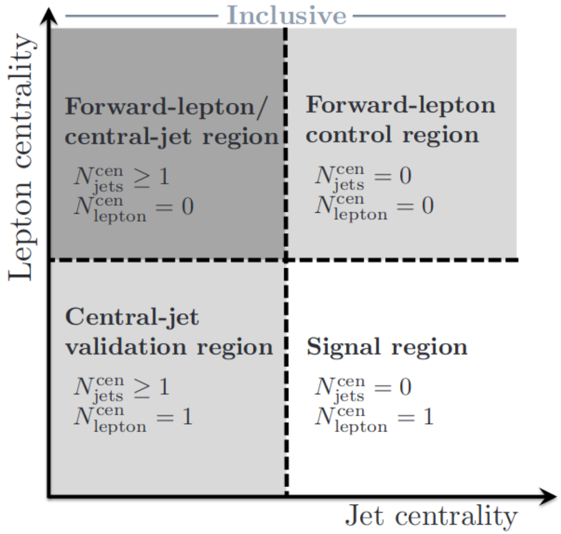
$$\mathcal{O}_{\tilde{B}} = (D_\mu H)^\dagger \tilde{B}^{\mu\nu}(D_\nu H)$$
$$\mathcal{O}_{\tilde{W}} = (D_\mu H)^\dagger \tilde{W}^{\mu\nu}(D_\nu H)$$
$$\mathcal{O}_{\tilde{W}WW} = \mathrm{Tr}(W_{\mu\nu}W^{\nu}_{\rho}\tilde{W}^{\rho\mu})$$

Warsaw

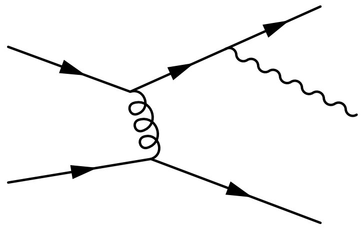
$$\mathcal{Q}_{H\tilde{W}} = \phi^\dagger\phi\tilde{W}^i_{\mu\nu}W^{i,\mu\nu}$$
$$\mathcal{Q}_{H\tilde{B}} = \phi^\dagger\phi\tilde{B}_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{Q}_{\tilde{W}WW} = \varepsilon_{ijk}\tilde{W}^{i,\nu}_{\mu}W^{j,\rho}_{\nu}W^{k,\mu}_{\rho}$$
$$\mathcal{Q}_{H\tilde{W}B} = \phi^\dagger\sigma^i\phi\tilde{W}^i_{\mu\nu}B^{\mu\nu}$$

Wjj control, validation, signal regions





QCD Wjj



EFT fit region :

Dedicated high energy SR to increase EFT/SM ratio
→ m_{jj} > 1 TeV, leading jet p_T > 600 GeV

Only accounting for SM-dim6 interference term

Quadratic term impact in VBF H → γγ

$$OO = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$

By definition only accounting for interference, not sensitive to quadratic term

$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

CP even counterparts and constraints

WW/WZ → lvqq’ (Eur. Phys. J. C77 (2017) 563)

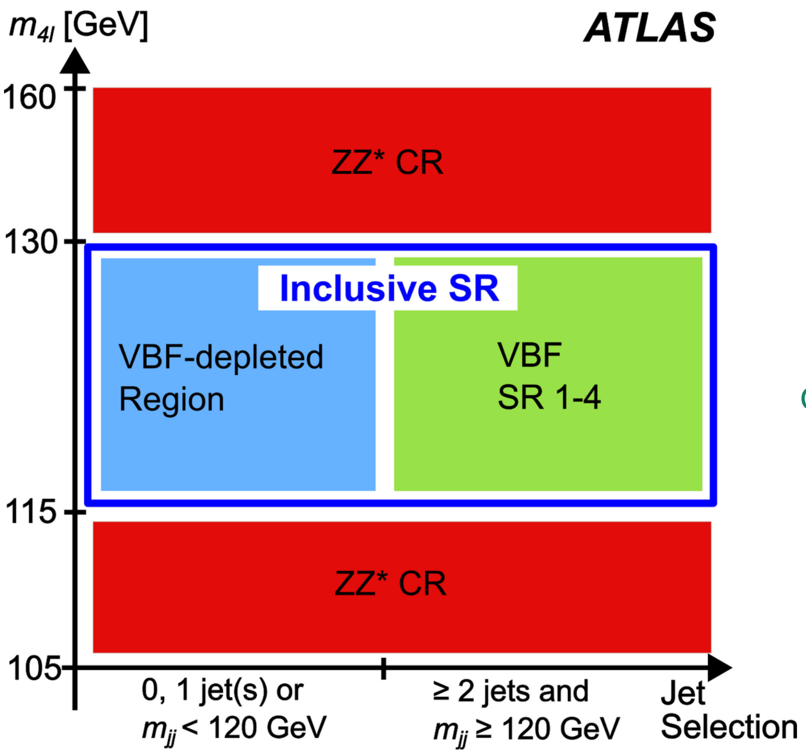
Parameter	Observed [TeV^{-2}]	Expected [TeV^{-2}]	Observed [TeV^{-2}]	Expected [TeV^{-2}]
	$WV \to \ell\nu jj$		$WV \to \ell\nu J$	
c_{WWW}/Λ^2	[−5.3, 5.3]	[−6.4, 6.3]	[−3.1, 3.1]	[−3.6, 3.6]
c_B/Λ^2	[−36, 43]	[−45, 51]	[−19, 20]	[−22, 23]
c_W/Λ^2	[−6.4, 11]	[−8.7, 13]	[−5.1, 5.8]	[−6.0, 6.7]

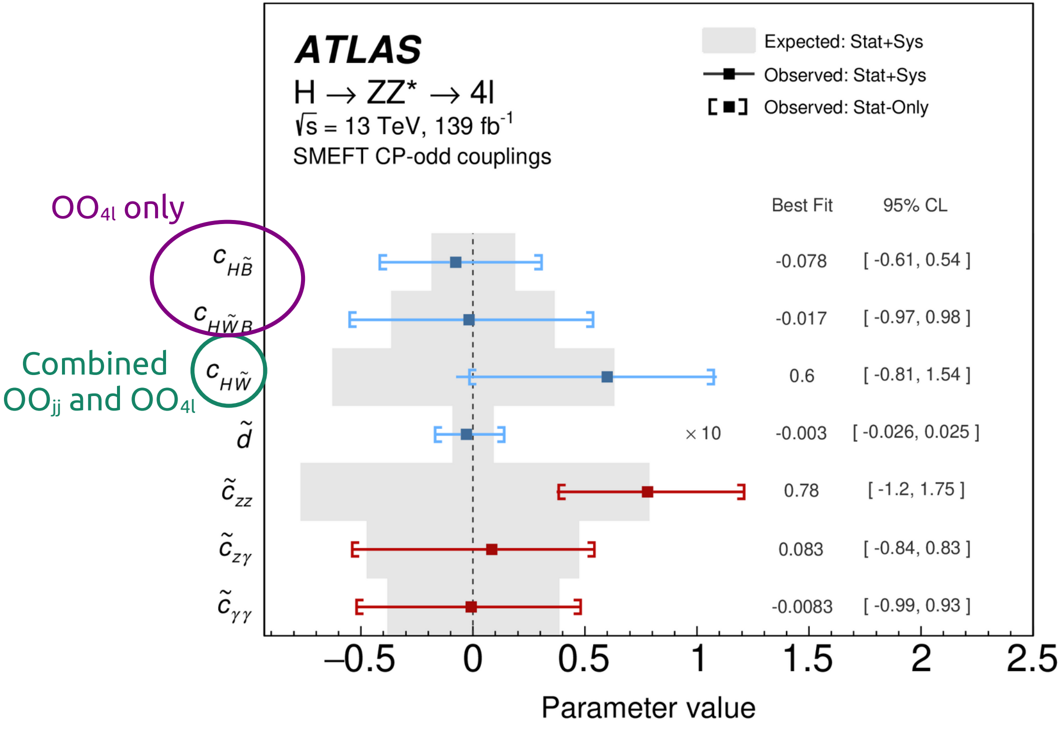
In HISZ basis

Higgs → ZZ* → 4l

Considering **VBF enriched signal region**, using optimal observable for both

1. H **production** vertex **OO_{jj}**
2. H **decay** vertex **OO_{4l}**





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Wilson coefficients from aNTGC

Linear combination of aNTGC parameters gives EFT Wilson coefficients

$$f_4^Z = \frac{M_Z^2 v^2 \left({c_w}^2 \frac{C_{WW}}{\Lambda^4} + 2 c_w s_w \frac{C_{BW}}{\Lambda^4} + 4 {s_w}^2 \frac{C_{BB}}{\Lambda^4} \right)}{2 c_w s_w}$$

$$f_4^\gamma = - \frac{M_Z^2 v^2 \left(- c_w s_w \frac{C_{WW}}{\Lambda^4} + \frac{C_{BW}}{\Lambda^4} \left({c_w}^2 - {s_w}^2 \right) + 4 c_w s_w \frac{C_{BB}}{\Lambda^4} \right)}{4 c_w s_w}$$

arXiv:1308.6323v2

Parameter	Limit 95% CL	
	Measured [TeV^{-4}]	Expected [TeV^{-4}]
$C_{\widetilde{B}W}/\Lambda^4$	(−1.1, 1.1)	(−1.3, 1.3)
C_{BW}/Λ^4	(−0.65, 0.64)	(−0.74, 0.74)
C_{WW}/Λ^4	(−2.3, 2.3)	(−2.7, 2.7)
C_{BB}/Λ^4	(−0.24, 0.24)	(−0.28, 0.27)

From $Z\gamma \to \nu\nu\gamma$

Optimal Observable in Hjj

$$OO = \frac{2\Re(\mathcal{M}^*_{SM}\mathcal{M}_6)}{|\mathcal{M}_{SM}|^2}$$

Inputs:

- Higgs 4-momentum
- Jets 4-momenta
- $x_{1,2}$ momentum fraction of both initial partons

$$x^{reco}_{1,2} = \frac{m_{Hjj}}{s} e^{\pm y_{Hjj}}$$

→

HAWK Monte Carlo:

Computes LO matrix elements

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