Classifying the CP properties of the ggH coupling in H+2j production

WG2 / WG3 joint meeting

26.09.2023

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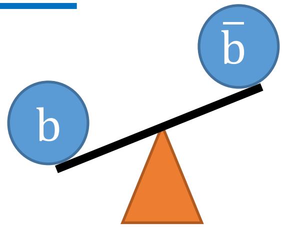
[2309.03146]

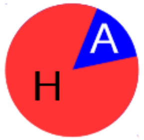
Overview & Motivation



The need for CP violation:

- CP violation is necessary to explain the baryon asymmetry of the universe
- SM does not contain enough CP violation for this
- Current experimental limits leave room for CP violation in the Higgs sector

CMS ´21, ATLAS ´21, ATLAS ´22, CMS ´22

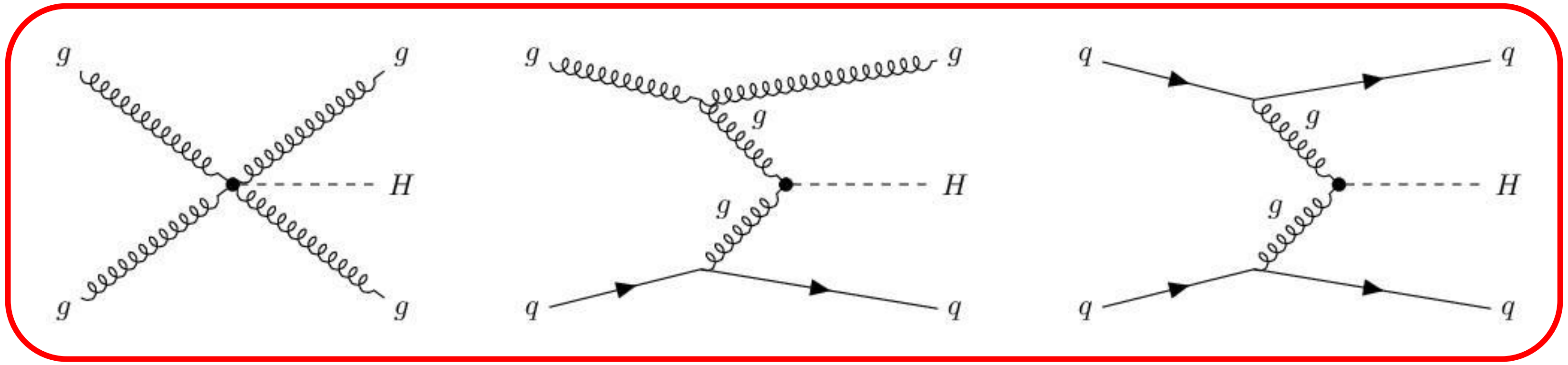


Why use ggF + 2j as a CP test?

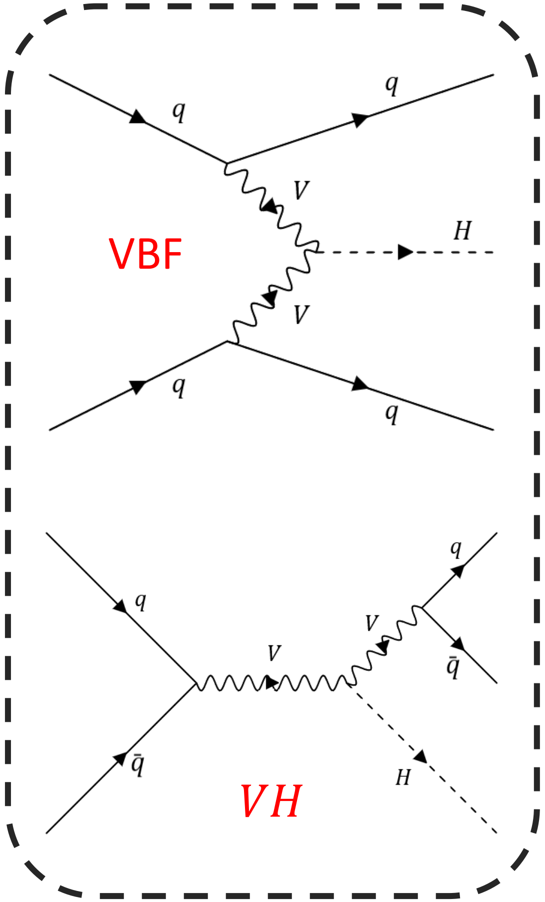
- Gluon fusion is the main Higgs production mode at the LHC ⇒ lots of events
- 2 jets in the final state are needed to construct CP-odd observables
- More direct probe of the top-Yukawa coupling than simple rate information

Klamke & Zeppenfeld ´07, Demartin et al. ´14

Signal & Background processes



	gg	gq	$q\bar{q}$	
$\frac{\sigma_{\text{init}}}{\sigma_{\text{ggF2j}}} =$	72%	26.5%	1.5%	@13TeV



- ggF2j shows different topologies based on the initial state
- High CP sensitivity in $q\bar{q}$ initial states? Hagiwara et al. ´09
- Considered background (BG) processes: VBF and VH
- $H \to \gamma\gamma$ decay: non-Higgs BG smoothly falling, easy to substract

- Many analyses consider only signal region with VBF-like kinematics CMS ´22

BSM framework

Free parameters:

- Higgs characterisation model: Higgs H assumed to be mixed CP state
- Effective Higgs-gluon coupling:

Artoisenet et al. ´13

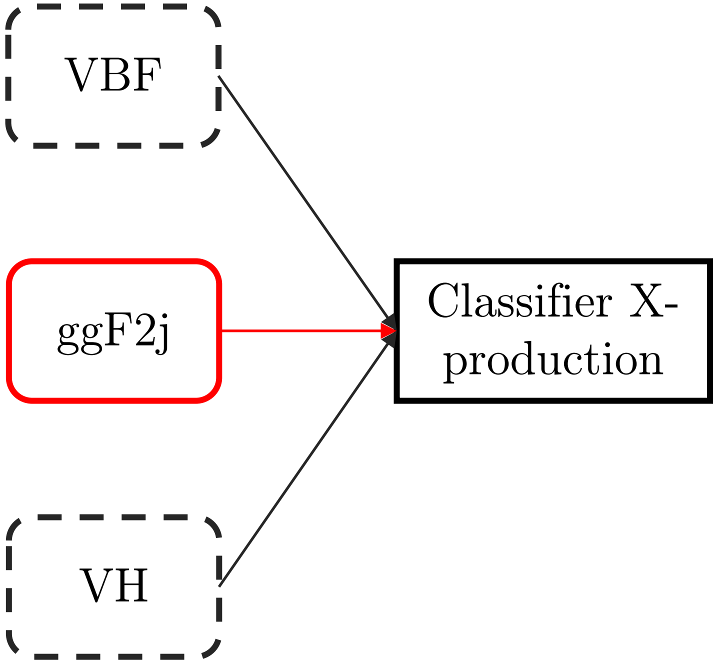
$$\mathcal{L}_{ggH} = -\frac{1}{4v}\left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{\mu\nu,\alpha} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right) H$$

- Effective CP-even (c_g) and CP-odd ($\tilde{c}_g$) coupling modifiers
- SM obtained for $c_g = 1$, $\tilde{c}_g = 0$

- Higgs-gluon coupling corresponds to top-Yukawa in the heavy top limit and if there are no low-mass BSM particles in the ggF loop ⇒ $c_g = c_t$, $\tilde{c}_g = \tilde{c}_t$
- We impose a cut $p_T^H < 200\text{GeV}$ to remain in the heavy top limit

Analysis strategy

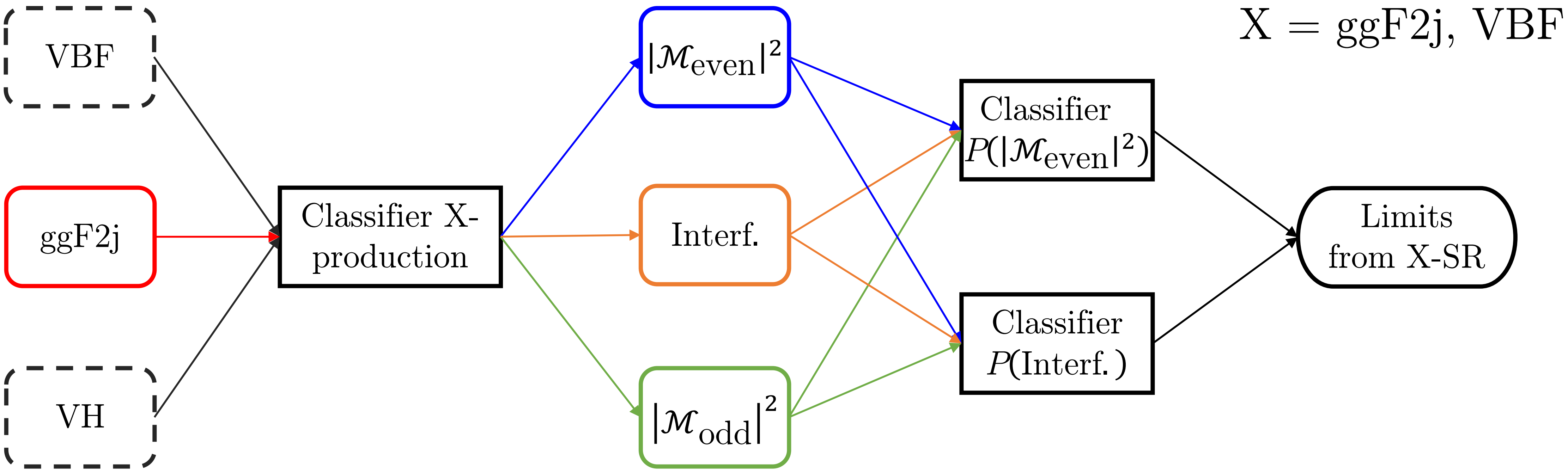
$$\left|\mathcal{M}_{\mathrm{ggF2j}}\right|^2 = c_g^2 |\mathcal{M}_{\mathrm{even}}|^2 + \underbrace{2 c_g \tilde{c}_g \mathrm{Re}[\mathcal{M}_{\mathrm{even}} \mathcal{M}_{\mathrm{odd}}^*]}_{\text{Interference}} + \tilde{c}_g^2 |\mathcal{M}_{\mathrm{odd}}|^2$$



$\mathrm{X} = \mathrm{ggF2j},\ \mathrm{VBF}$

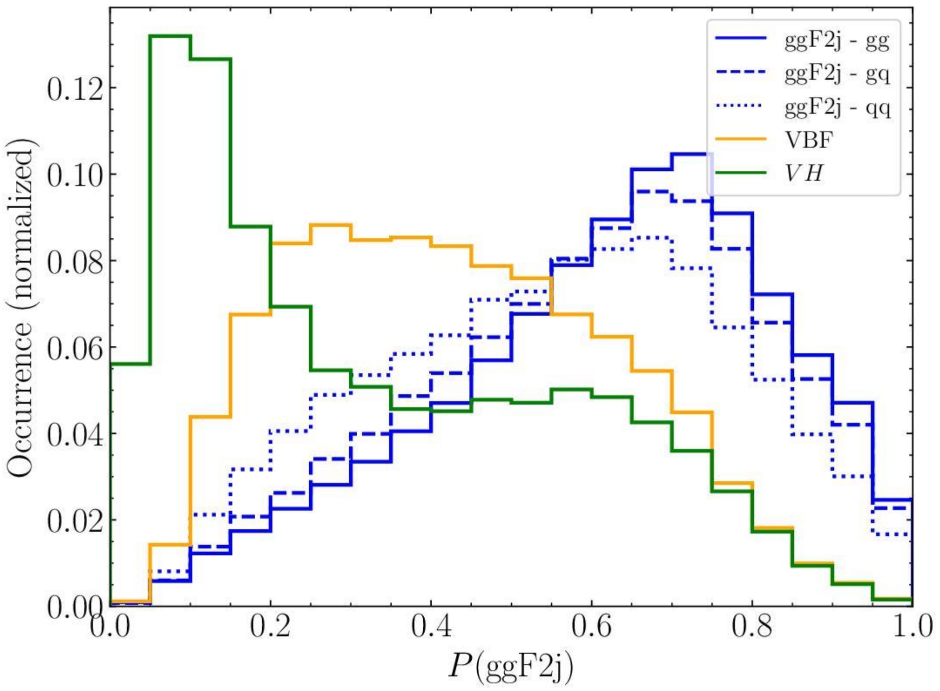
Analysis strategy

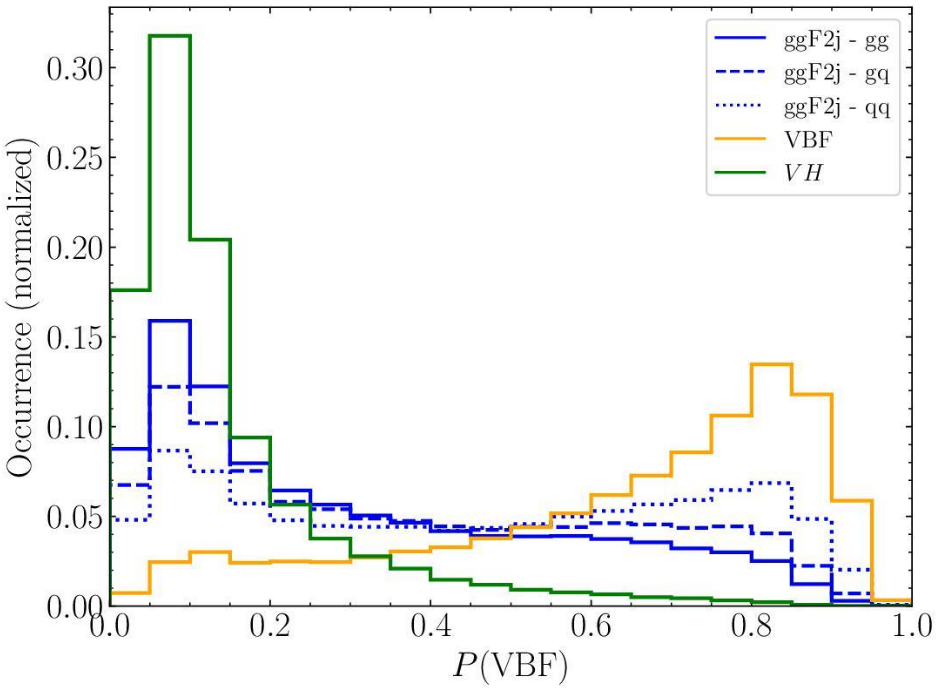
$$\left|\mathcal{M}_{\mathrm{ggF2j}}\right|^2 = c_g^2|\mathcal{M}_{\mathrm{even}}|^2 + \underbrace{2c_g\tilde{c}_g\mathrm{Re}[\mathcal{M}_{\mathrm{even}}\mathcal{M}_{\mathrm{odd}}^*]}_{\text{Interference}} + \tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$$



➢ Train a CP-even and a CP-odd classifier in a ggF2j-SR and a VBF-SR

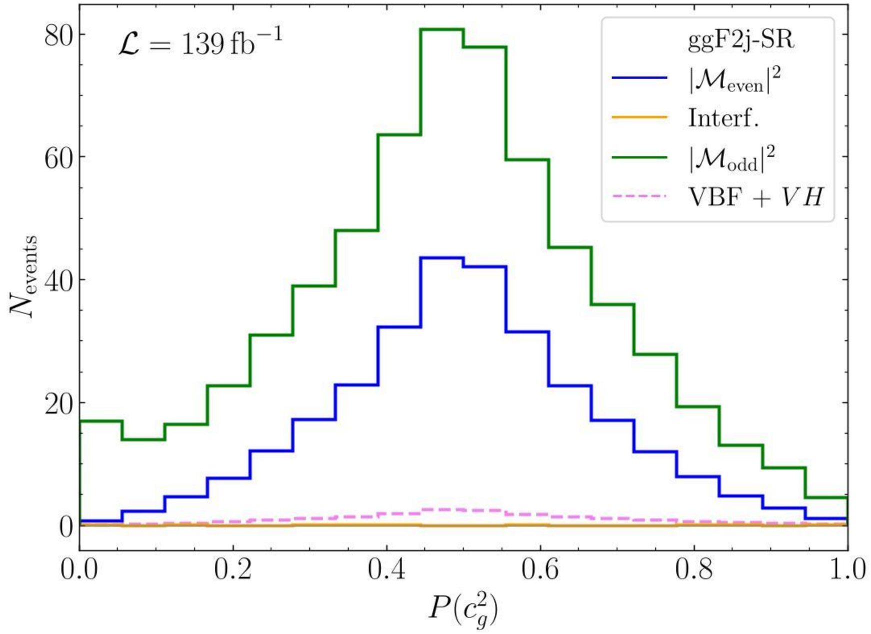
Signal regions





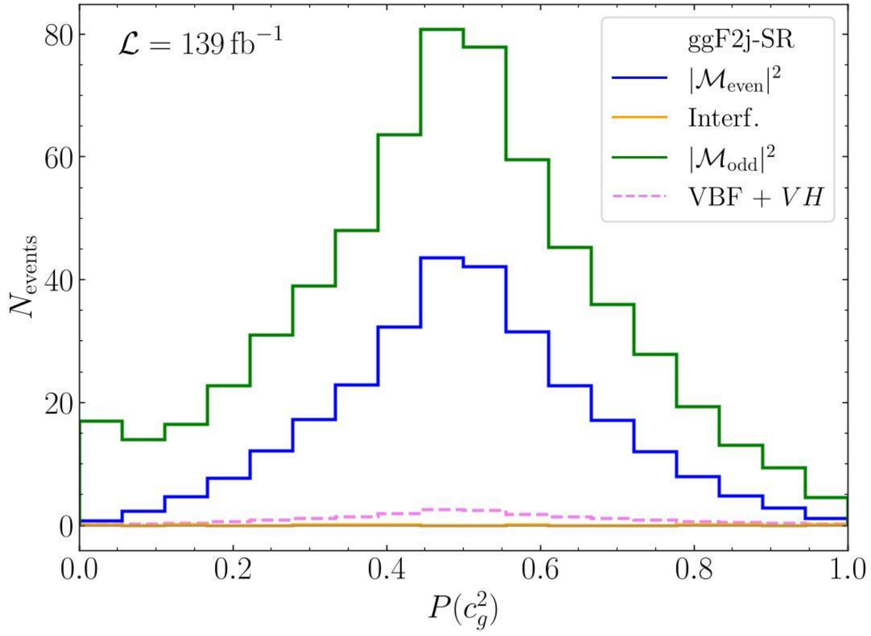
- Use $P(\text{signal}) > 0.5$ as a cut to define signal regions
- ggF2j with $q\bar{q}$ initial state are identified as VBF-like more often
- ggF2j interference events are also identified as VBF-like more often

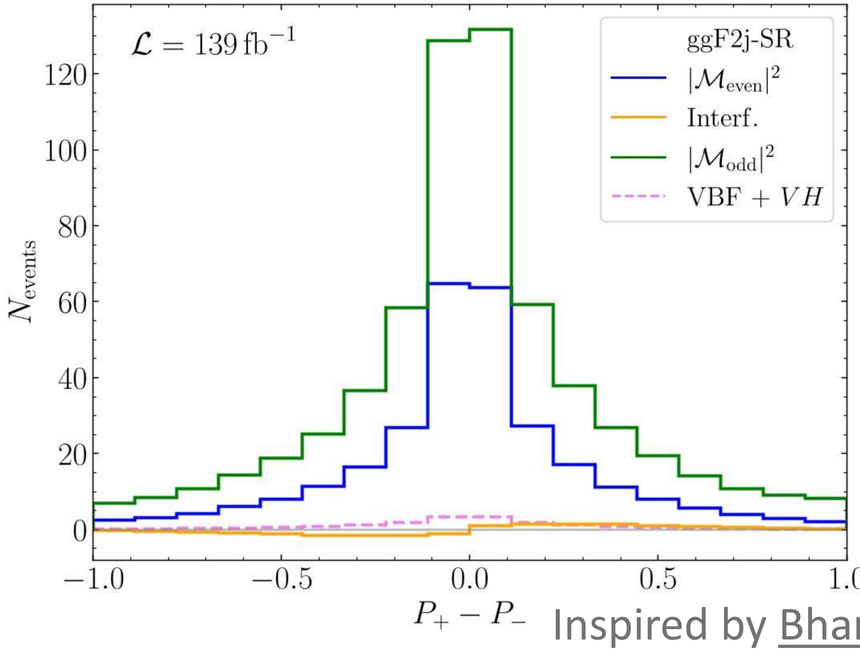
ggF2j signal region



- $P\left(c_g^2\right)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Kinematically very similar, but some separation in outer bins
- Interference term cancels out

ggF2j signal region





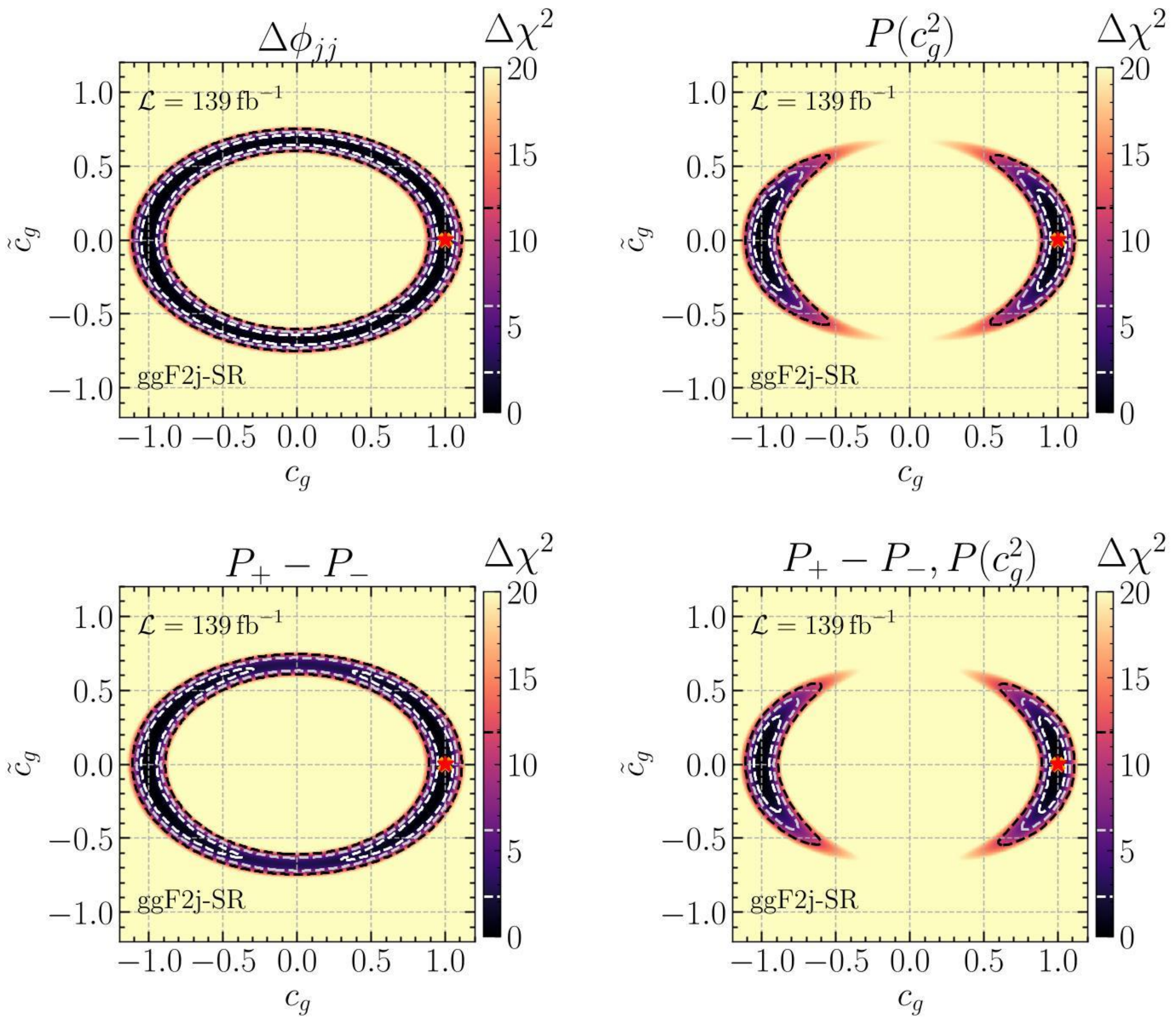
Inspired by Bhardwaj et al. `21

- $P(c_g^2)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Kinematically very similar, but some separation in outer bins
- Interference term cancels out

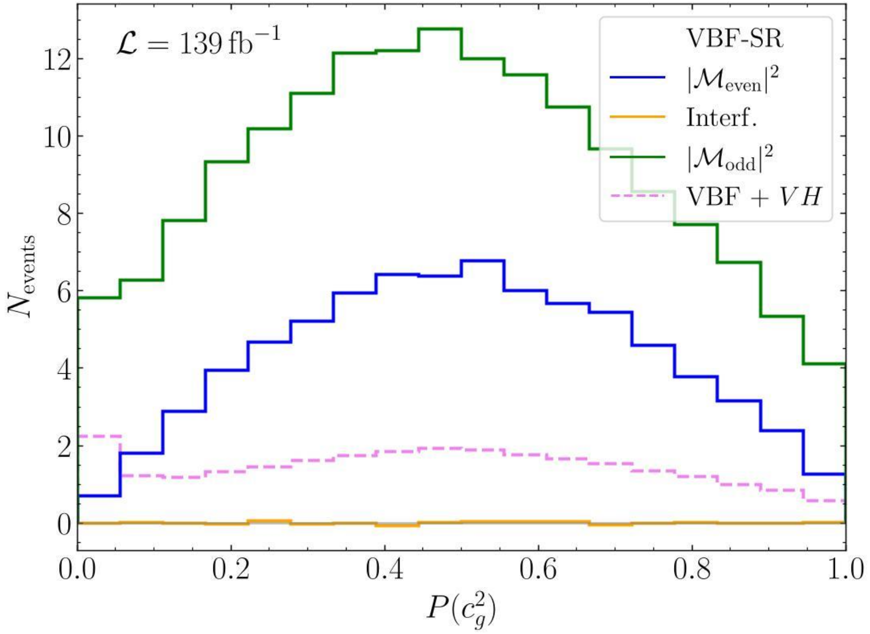
- $P_+ - P_-$ differentiates between positive and negative interference
- Interference barely visible due to low cross section & looks more VBF-like
- CP-even terms are symmetric

ggF2j signal region

- Ellipse from total rate
- $\Delta\phi_{jj}$ alone is not able to resolve the ellipse
- 2D-limits dominated by the $P\left(c_g^2\right)$ classifier (low interference contribution)
- $\left|\tilde{c}_g\right| \leq 0.32$ @ 1σ

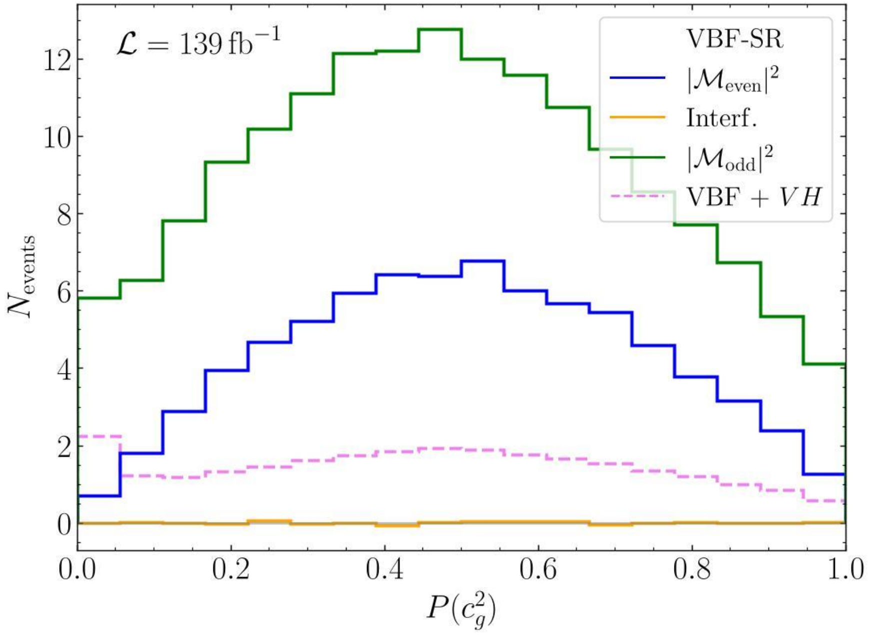


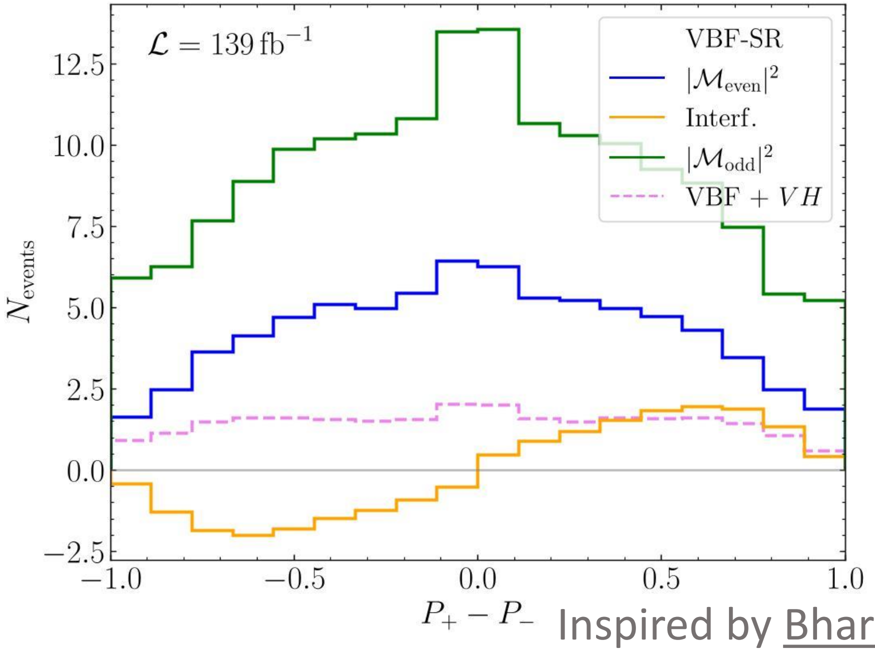
VBF signal region



- $P(c_g^2)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Less events than in ggF2j-SR, statistical fluctuations visible
- Wider peak around $P(c_g^2) = 0.5$

VBF signal region





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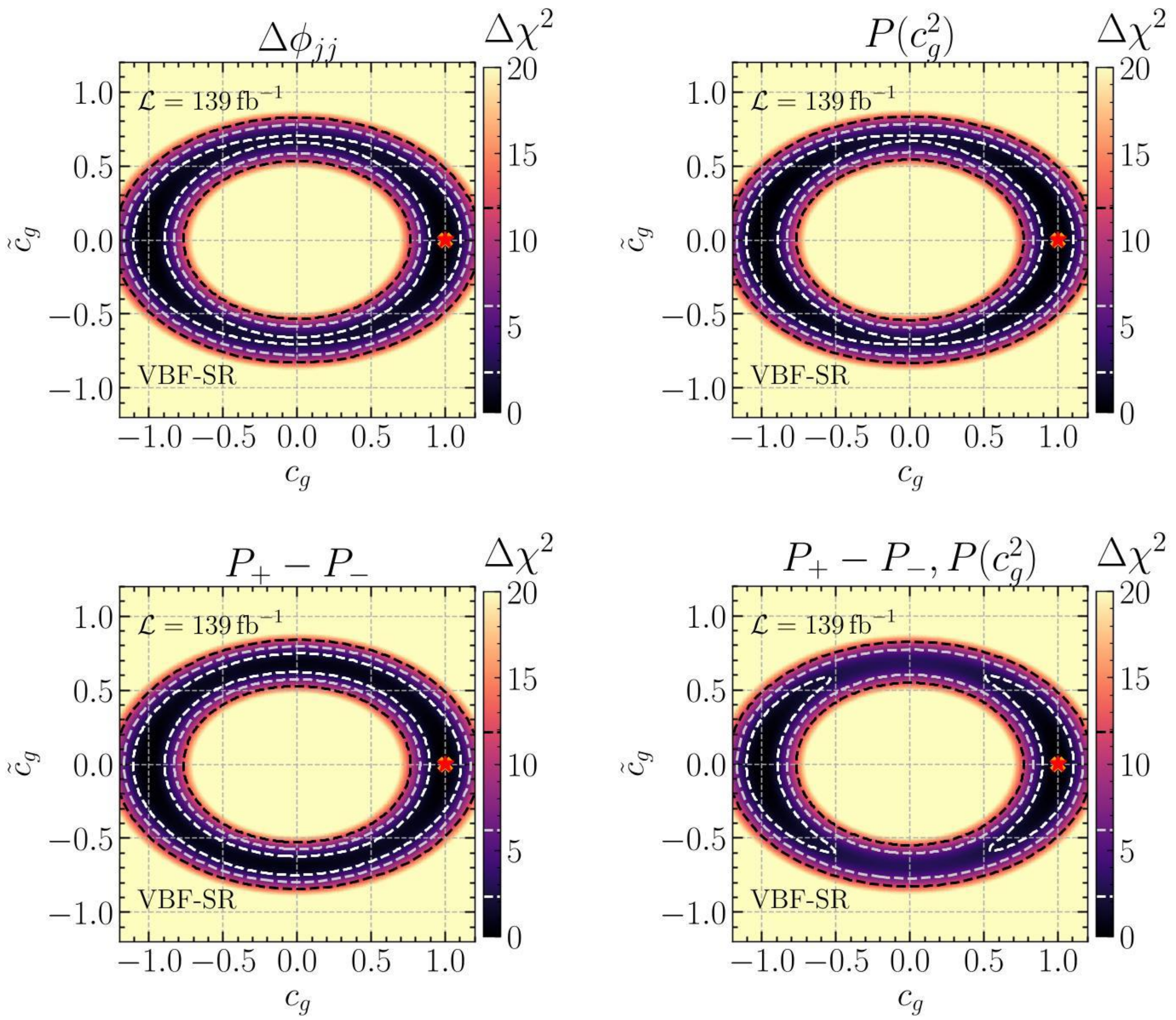
- $P(c_g^2)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Less events than in ggF2j-SR, statistical fluctuations visible
- Wider peak around $P(c_g^2) = 0.5$

- $P_+ - P_-$ differentiates between positive and negative interference
- Interference much more pronounced due to overall lower events and their VBF-like kinematic

VBF signal region

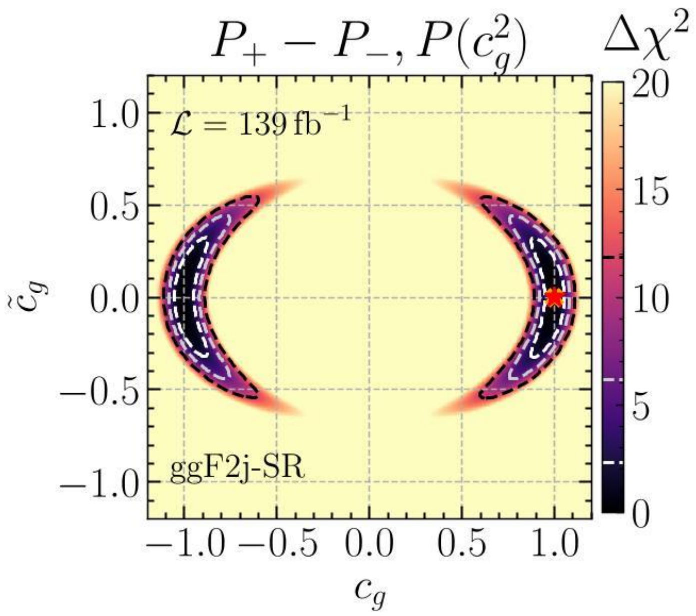
- Ellipse wider due to lower number of events
- Individual classifiers perform worse than $\Delta\phi_{jj}$ (less information) – large importance of $\Delta\phi_{jj}$
- 2D-limits are significantly stronger than 1D-limits
- $|\tilde{c}_g| \leq 0.58$ @ 1σ



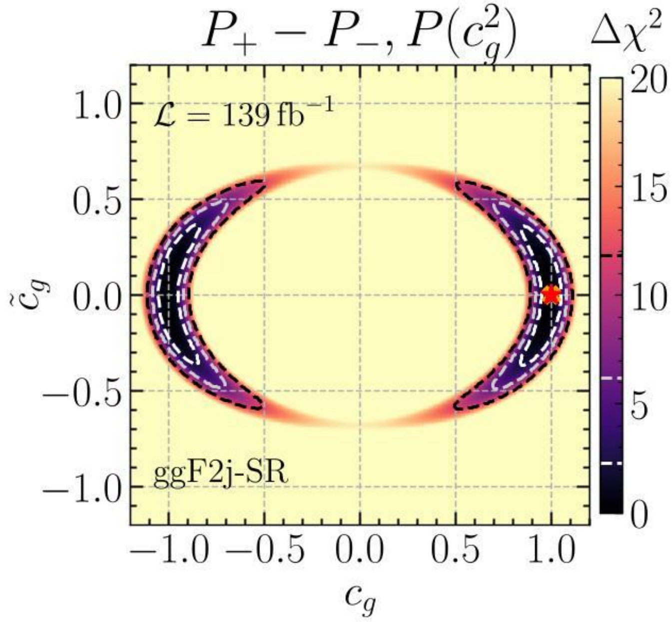
CP violation in HVV – ggF2j-SR

BSM physics might introduce CP violation in multiple Higgs couplings
⇒ inject CP violation in VBF production, evaluate effect on $c_g, \tilde{c}_g$ limits

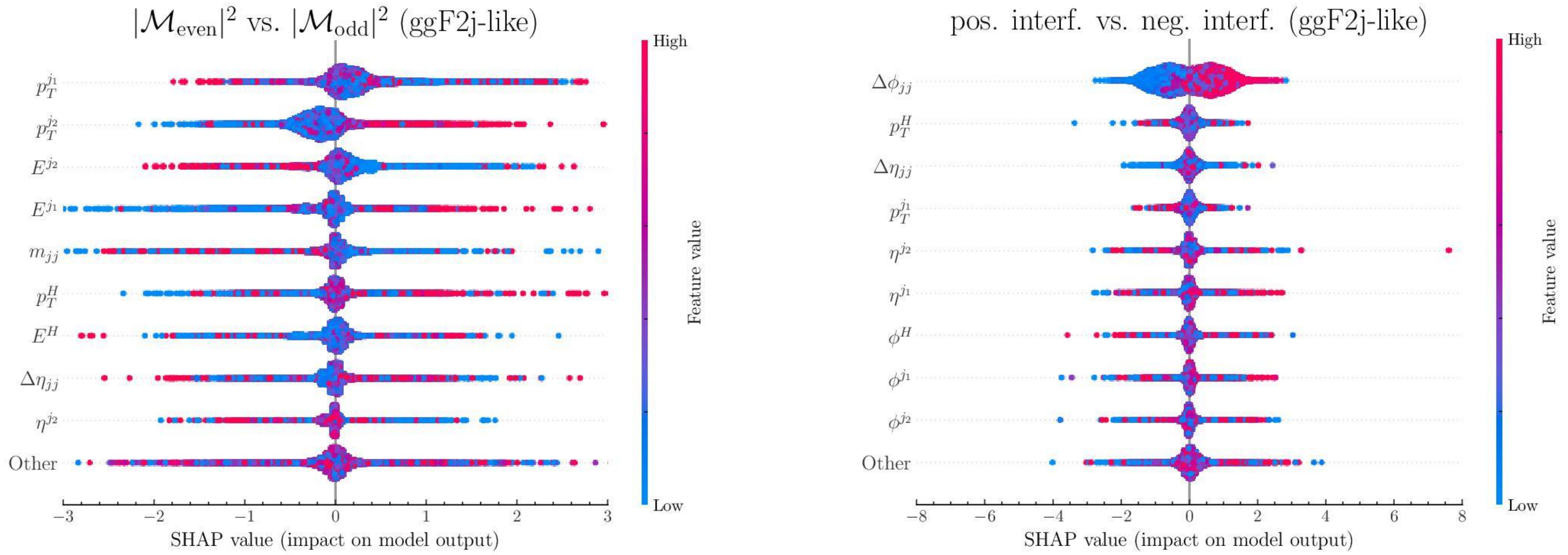
- Limits slightly weaken from $|\tilde{c}_g| \leq 0.32$ @ 1σ to $|\tilde{c}_g| \leq 0.37$ @ 1σ
- ggF2j-SR provides conservative results for limited knowledge of the HVV coupling
- Opposite effect in VBF-SR ⇒ fakes much stronger limits on $\tilde{c}_g$ (see backup)



Adding CP Violation in VBF



Feature importance (SHAPLEY) – ggF2j-SR



- No clear „best“ variables for differentiating $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ vs $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- $\Delta\phi_{jj}$ is most important for interference classification (CP-odd)
- $\Delta\phi_{jj}$ much less significance than in the VBF-SR (see backup)

Results & Conclusion

Expected limits on $|\alpha^{Htt}| = \left|\tan^{-1}\frac{\tilde{c}_t}{c_t}\right|$:

Process / SR	Our work		Literature		References
	68% CL	95% CL	68% CL	95% CL	
ggF2j (ggF2j-SR)	15°	25°	--	--	
ggF2j (VBF-SR)	25°	--	26°	--	CMS `22
ttH	--	--	35°	43°	ATLAS `20
Global fit	21°	28°	--	--	Update from Bahl et al. ´22

- A multivariate analysis in the ggF2j-SR is expected to give strongest limits on α^{Htt}
- The ggF2j-SR is robust against CP violation in HVV mimicking CP violation in ggH
- Our findings consolidate the need for a dedicated ggF2j signal region

Backup

Backup: Other notations

Our work: $\mathcal{L}_{ggH} = -\frac{1}{4v}\left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{\mu\nu,a} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right) H$

Separate top loop: $\mathcal{L}_{ggH} = -\frac{\alpha_s \pi}{v}\left(c_{gg} G^a_{\mu\nu} G^{\mu\nu,a} + \tilde{c}_{gg} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right) H$

Used in CMS `22

$$\Rightarrow \quad c_g = 1 + 12\pi^2 c_{gg}, \quad \tilde{c}_g = -8\pi^2 \tilde{c}_{gg}$$

SMEFT: $c_g \sim 1 + \sum_i {c_i}/{\Lambda^2} + \cdots, \quad \tilde{c}_g \sim \sum_i {\tilde{c}_i}/{\Lambda^2} + \cdots$

$c_i, \tilde{c}_i$: Wilson coefficients

Backup: Cutflow

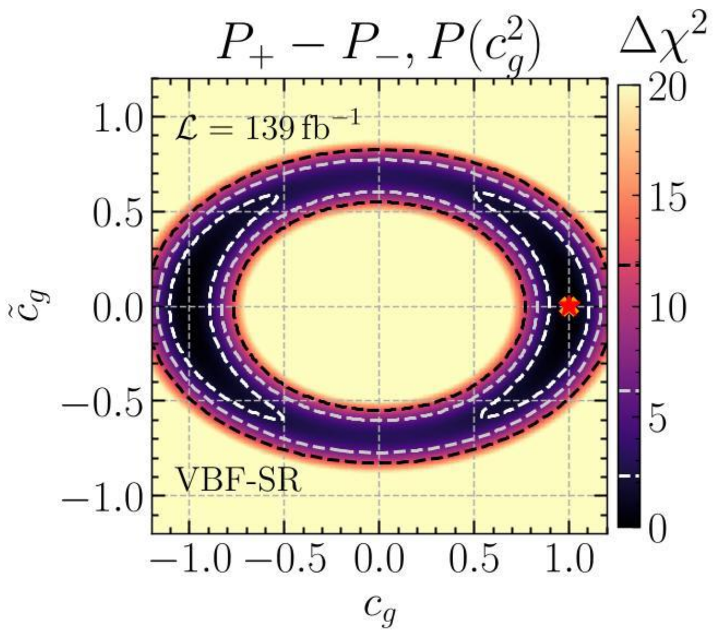
	Fraction of accepted events				
Applied cut	**ggF2j $\lvert\mathcal{M}_{\text{even}}\rvert^2$**	**ggF2j Interf.**	**ggF2j $\lvert\mathcal{M}_{\text{odd}}\rvert^2$**	**VBF**	**VH**
Initial events	100%	100%	100%	100%	100%
$N_j \geq 2, N_\gamma \geq 2$	48.1%	50.8%	48.1%	62.6%	49.8%
$100\text{GeV} \leq m_{\gamma\gamma}$ $m_{\gamma\gamma} \leq 140\text{GeV}$	47.8%	50.5%	47.9%	62.0%	49.4%
$p_T^{\gamma_1}/m_{\gamma\gamma} \geq 0.35$ $p_T^{\gamma_2}/m_{\gamma\gamma} \geq 0.25$	39.4%	40.9%	39.8%	50.0%	40.5%
$p_T^{j_1} \geq 30\text{GeV}$ $p_T^{j_2} \geq 20\text{GeV}$	38.6%	40.2%	38.6%	49.7%	39.9%
$\lvert\eta_j\rvert \leq 2.5$ $\lvert\eta_\gamma\rvert \leq 2.5$	22.9%	21.5%	22.7%	39.8%	31.2%
$p_T^H \leq 200\text{GeV}$ *	18.6%	18.4%	18.3%	34.4%	26.8%

* It is possible to relax this cut using $\text{FT}_{\text{approx}}$ → see Maltoni et al. ´14

CP violation in HVV – VBF-SR

BSM physics might introduce CP violation in multiple Higgs couplings
⇒ inject CP violation in VBF production, evaluate effect on $c_g, \tilde{c}_g$ limits

- Limits tighten from $|\tilde{c}_g| \leq 0.58$ @ 1σ to $|\tilde{c}_g| \leq 0.48$ @ 1σ
- VBF-SR might "fake" stronger limits not originating from CP violation in ggH



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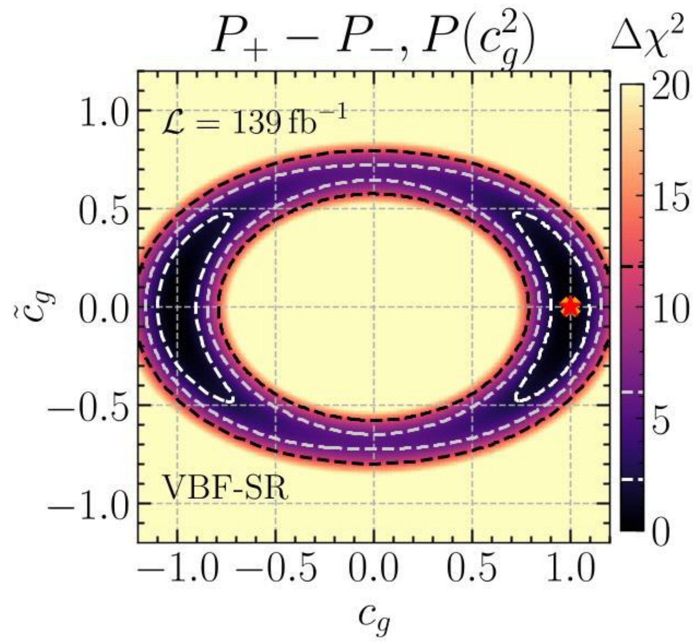
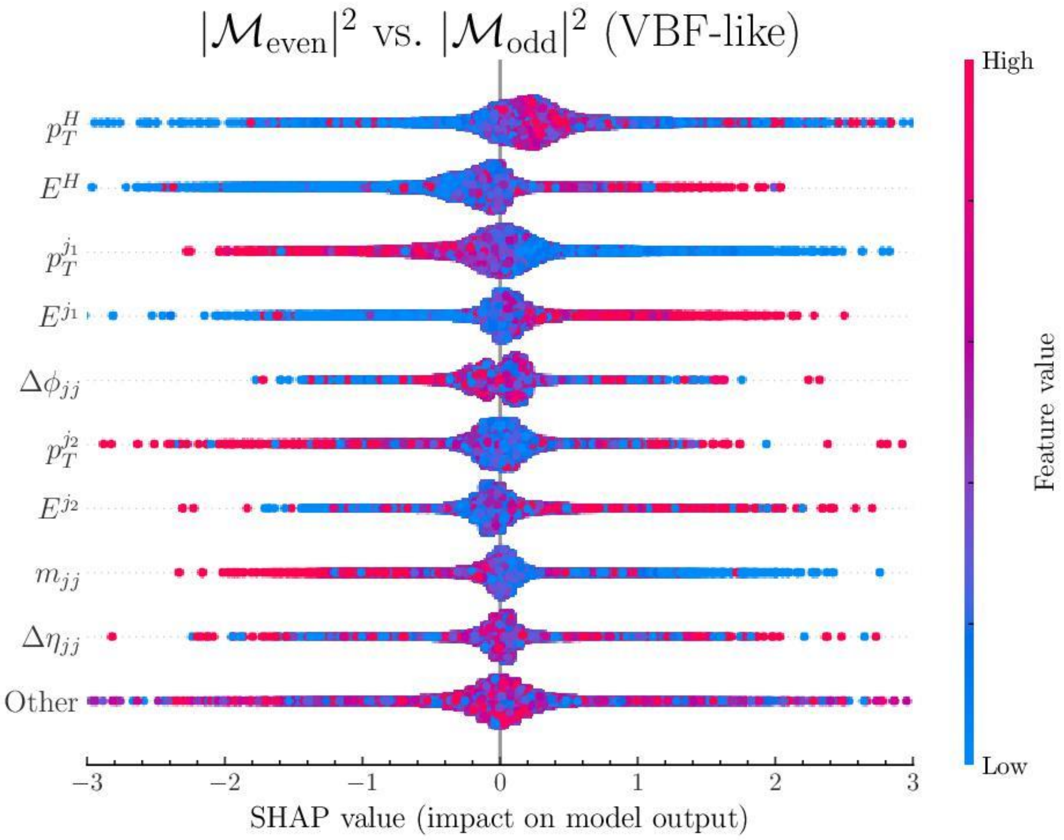
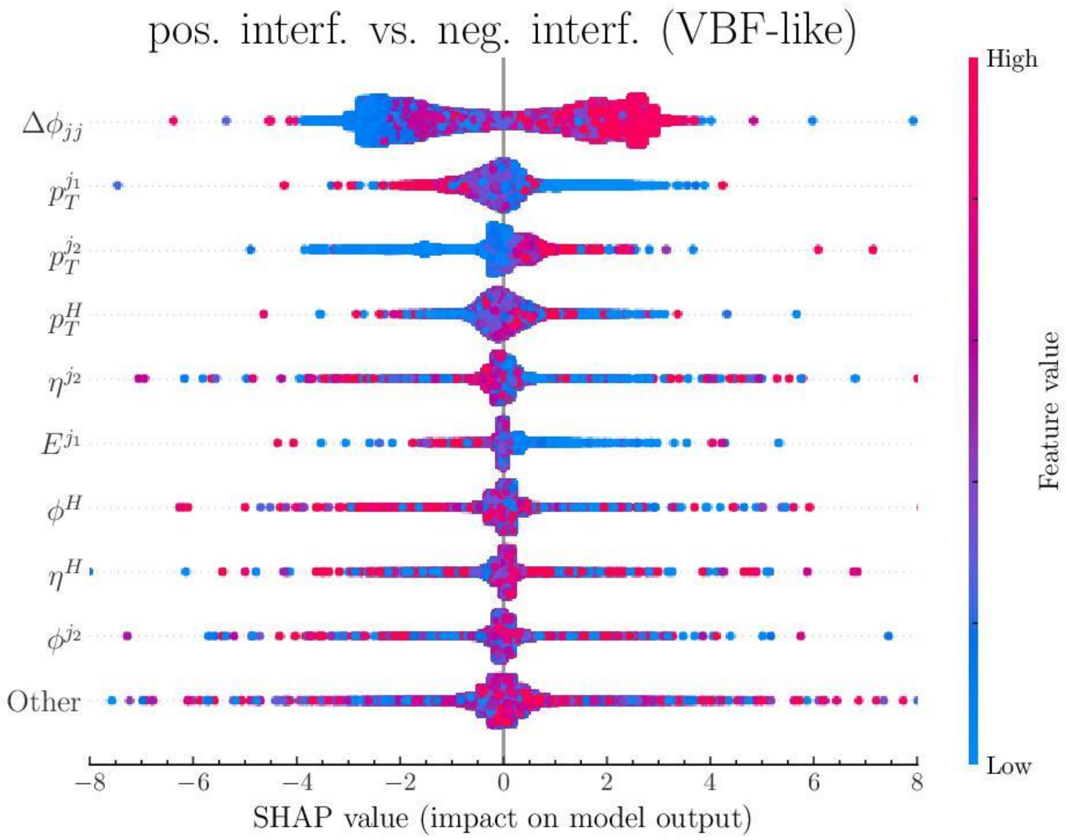


Backup: Feature importance – VBF-SR





Backup: Comparison to global fit

- Interpret $c_g, \tilde{c}_g$ as top-Yukawa coupling modifiers $c_t, \tilde{c}_t$ (heavy top limit / strong limits on colored BSM particles)
- Global fit based on experimental results for Higgs signal rates
- Performed with HiggsTools Bahl et al. \`22
- Different form of ellipsis due to recent $ttH(bb)$ measurements ATLAS \`19, ATLAS \`22
- Similar constraints from our analysis