Examining the CP properties of the top-Yukawa and the ggH coupling

Marco Menen

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Based on [2309.03146] and [2406.03950]

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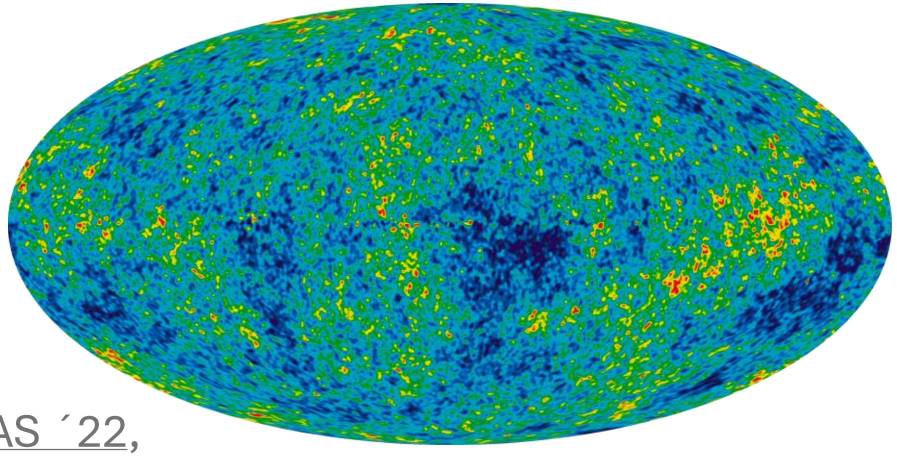
PTB

Overview & Motivation

The need for CP violation:



- The SM fails to explain the observed baryon asymmetry of the universe
- Higgs CP violation could help with this issue
- Current experimental limits leave room for CP violation in the Higgs sector CMS ´21, ATLAS ´21, ATLAS ´22, CMS ´22, CMS ´23, ATLAS ´24 ...

The Higgs-top quark coupling:

- Well accessible at the LHC, only $\mathcal{O}(1)$ Yukawa coupling
- Complementary constraints from indirect probes (ggF2j) and direct probes (ttH)

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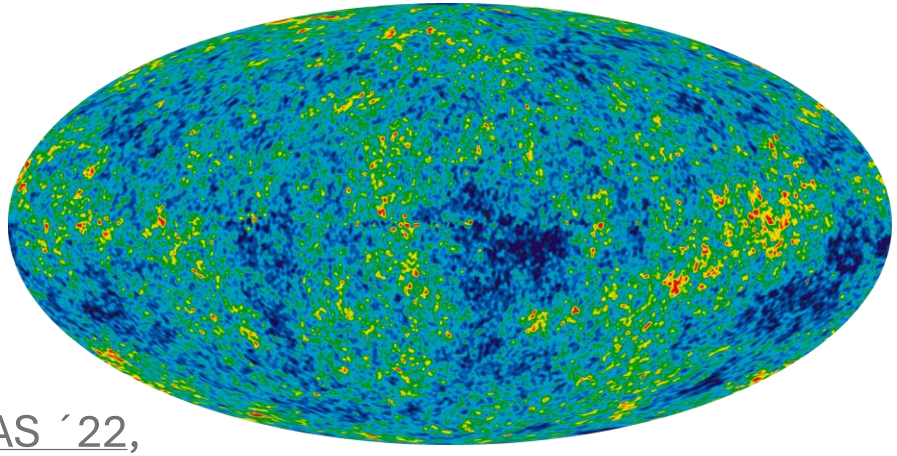

The Higgs-top quark coupling:

- Well accessible at the LHC, only $\mathcal{O}(1)$ Yukawa coupling
- Complementary constraints from indirect probes (ggF2j) and direct probes (ttH)

- Two good choices

(Unlike US presidential election)

((Personal bias included))

Parameterization and framework

- Higgs characterization model: Higgs H assumed to be mixed CP state

  Artoisenet et al. ´13

- Allows for (effective) couplings with modified CP-character via CP-even (CP-odd) coupling modifiers c_i ($\tilde{c}_i$)

Mapping to SMEFT: backup

$$\mathcal{L}_{\text{Yuk}} \supset -\frac{y_t^{\text{SM}}}{\sqrt{2}} \bar{t}(c_t + i\gamma_5 \tilde{c}_t) t H$$

Direct test of y_t
few events (ttH)

Also: $\alpha_i = \tan^{-1} \frac{\tilde{c}_i}{c_i}$

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

with $c_g, \tilde{c}_g \to c_t, \tilde{c}_t$ in the heavy top limit and without low-mass colored BSM particles in the ggF loop

Indirect test of y_t
many events (ggF)

Structure

Part I: ggF2j

- Main production mode at LHC
- 2 jets in the final state needed to construct CP-odd observables
- Combine all CP information in a classifier in the $H \rightarrow \gamma\gamma$ channel
- Many measurements conducted in VBF-like signal region due to more $q\bar{q}$ initial state events, what about ggF-like signal region

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Part II: ttH

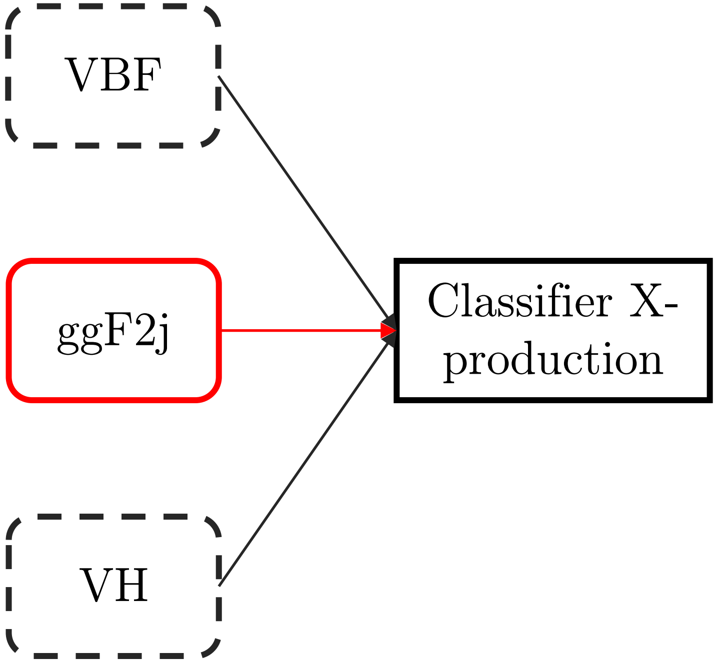
- Fewer events but coupling measured directly
- Measuring CP-odd variables not feasible currently, concentrate on CP-sensitive observables
- Combine $H \rightarrow \gamma\gamma$, $H \rightarrow b\bar{b}$ and multilep. final states
- Extension of the current STXS $p_{T,H}$ binning by a second observable

Part I: ggF2j

Analysis strategy

ggF2j

- First distinguish ggF2j from relevant Higgs backgrounds (backup)
- Current most sensitive study in VBF-like signal region CMS ´22

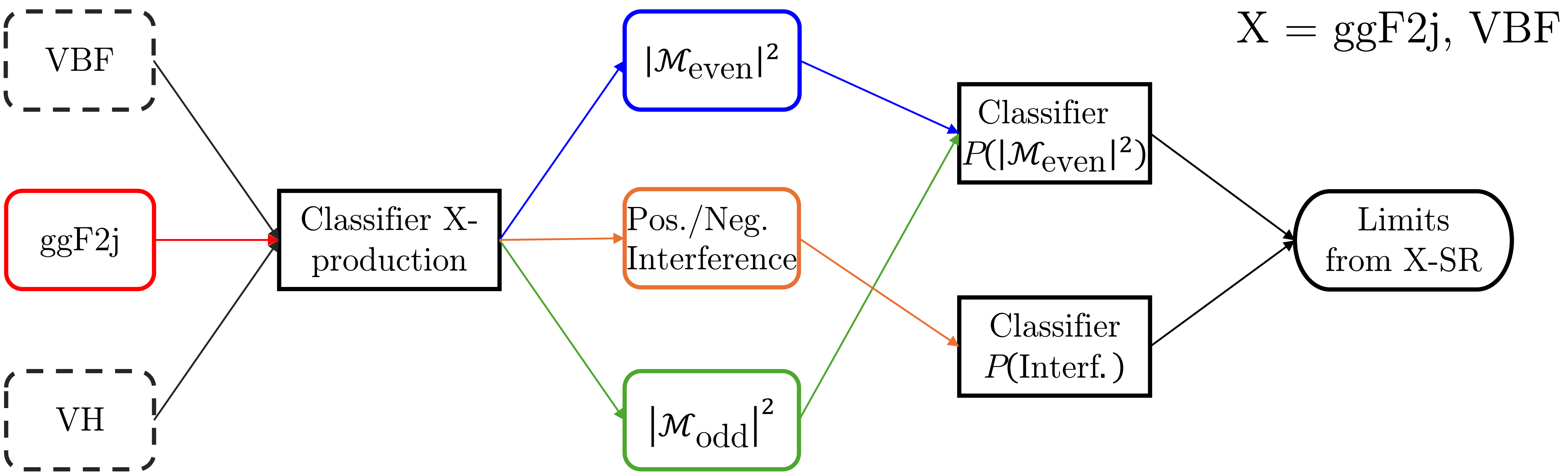


$$X = \text{ggF2j},\ \text{VBF}$$

Analysis strategy

ggF2j

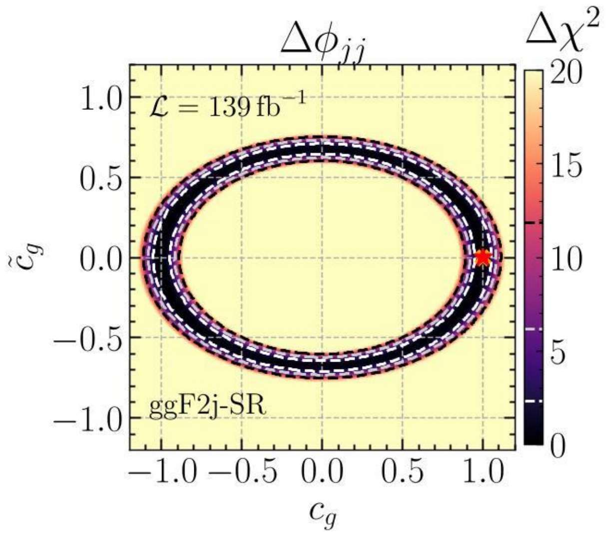
$$|\mathcal{M}_{\text{ggF2j}}|^2 = c_g^2|\mathcal{M}_{\text{even}}|^2 + \underbrace{2c_g\tilde{c}_g\text{Re}[\mathcal{M}_{\text{even}}\mathcal{M}^*_{\text{odd}}]}_{\text{Interference}} + \tilde{c}_g^2|\mathcal{M}_{\text{odd}}|^2$$



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

ggF2j signal region

- Ellipse from total rate
- $\Delta\phi_{jj}$ alone is not able to resolve the ellipse



ggF2j signal region

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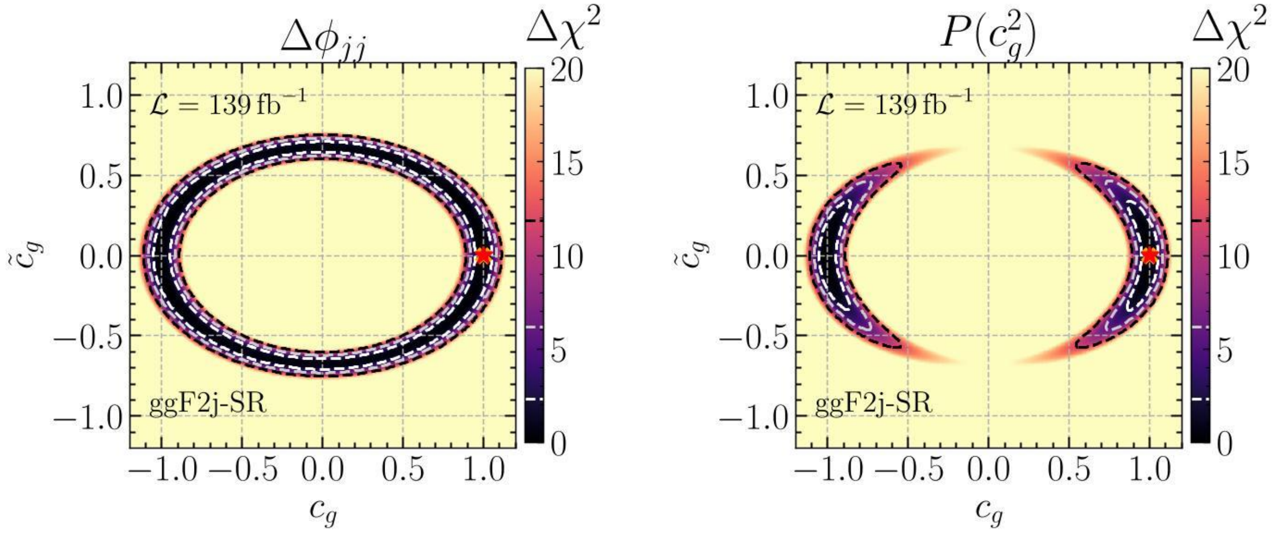

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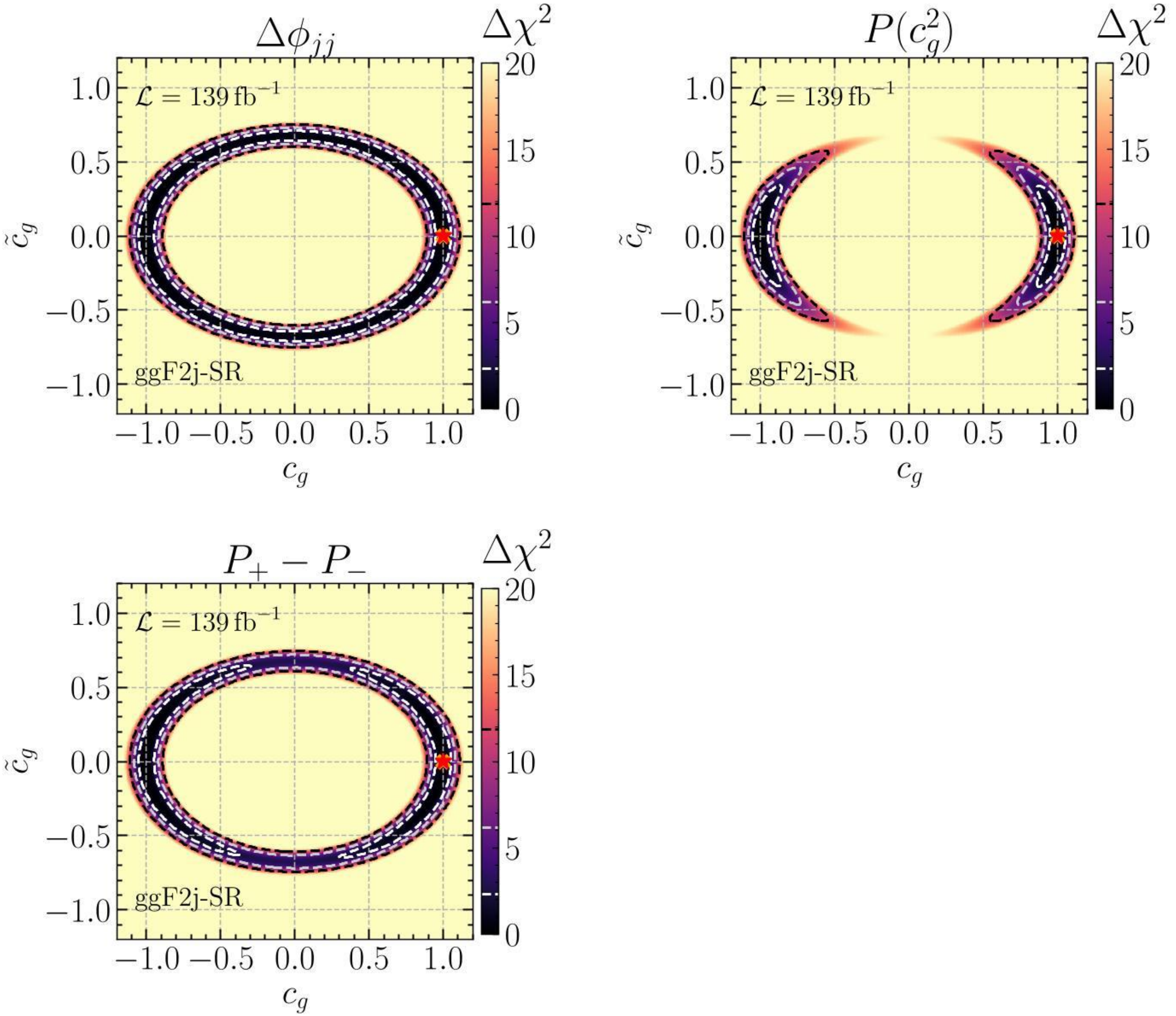

ggF2j signal region

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- Ellipse from total rate
- $\Delta\phi_{jj}$ alone is not able to resolve the ellipse
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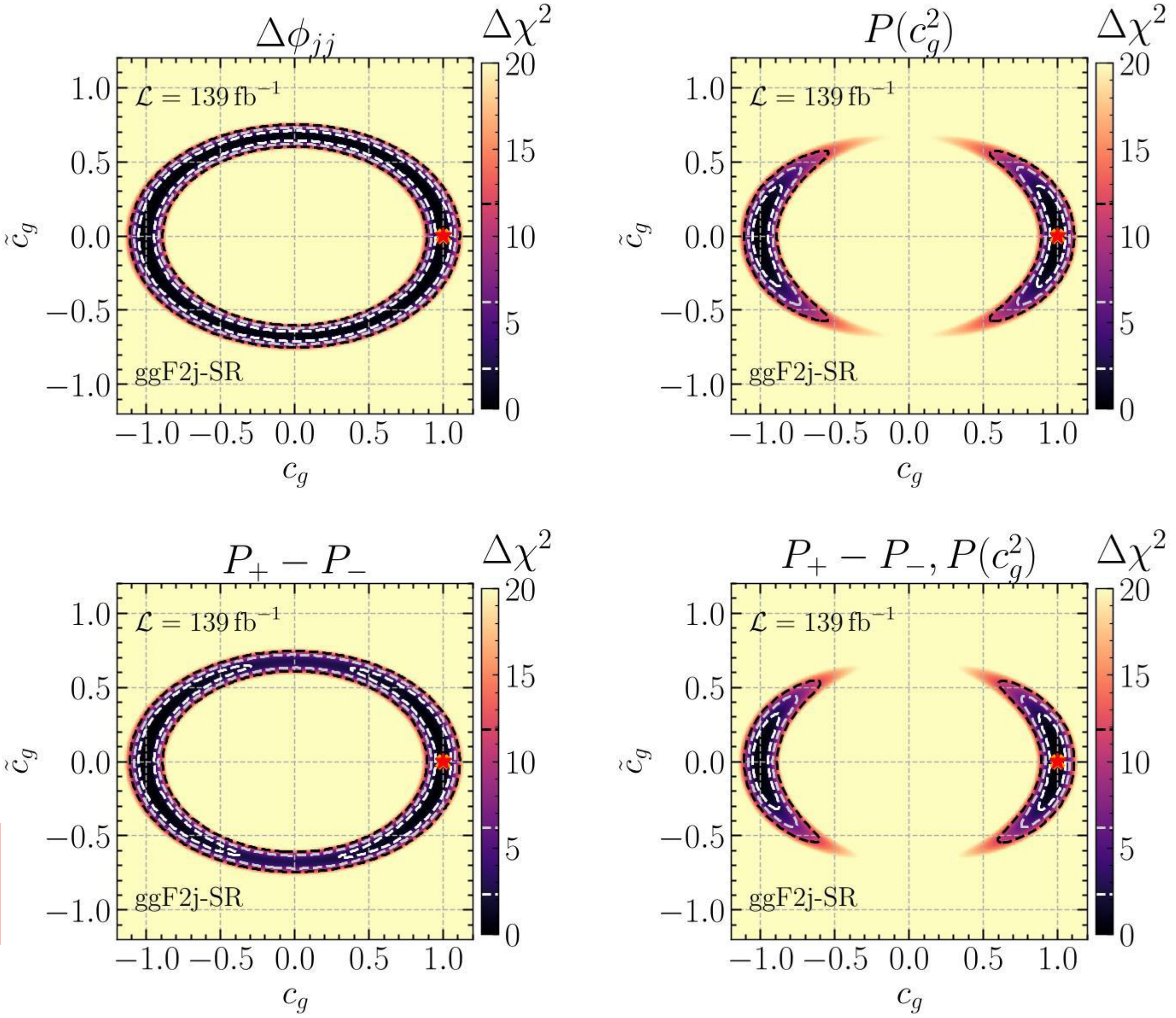
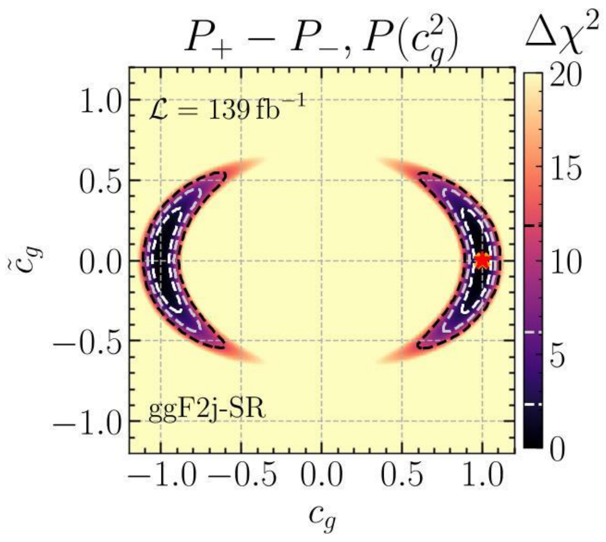
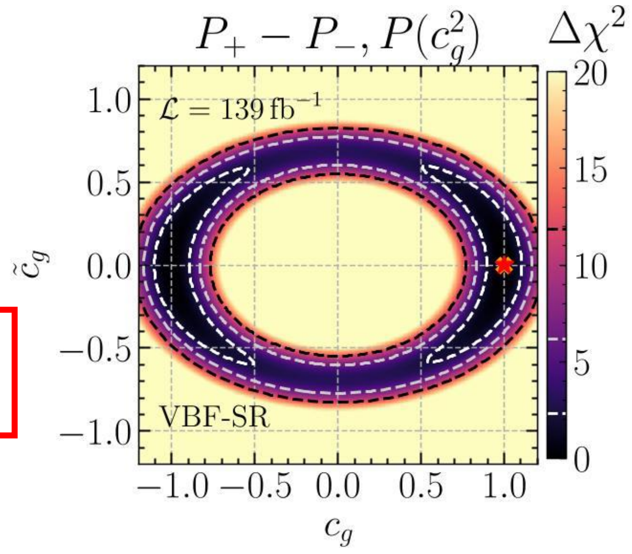
- CP-odd classifier performs much worse
- Combined: $|\alpha_g| \leq 15° \ @ \ 1\sigma$



Comparison between signal regions



$|\tilde{c}_g| \leq 15° @ 1\sigma$



$|\tilde{c}_g| \leq 25° @ 1\sigma$

- Ellipse in VBF-SR much wider due to lower number of events
- Most sensitivity in the VBF-SR comes from interference events (Backup)
- Caveat: No non-Higgs backgrounds taken into account

Part II: ttH

Analysis strategy

- Look for extension of STXS-framework to combine decay channels with focus on CP
- Test most promising CP-even observables, no need to distinguish t & $\bar{t}$
- Variables are generally not Lorentz-invariant

Observable	Definition	Frame
$p_{T,H}$	--	lab, $t\bar{t}$, $t\bar{t}H$
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant

Observables

ttH

Observable	Definition	Frame
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$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
ϕ_C	$\cos^{-1}\left(\frac{\lvert(p_{p,1} \times p_{p,2})(p_t \times p_{\bar{t}})\rvert}{\lvert p_{p,1} \times p_{p,2}\rvert \lvert p_t \times p_{\bar{t}}\rvert}\right)$	H
$\cos\theta^*$	$\vec{p}_t\vec{n} / \lvert\vec{p}_t\rvert\lvert\vec{n}\rvert$	$t\bar{t}$
b_1	$(\vec{p}_t \times \vec{n})(\vec{p}_{\bar{t}} \times \vec{n}) / p_{T,t}p_{T,\bar{t}}$	all
b_2	$(\vec{p}_t \times \vec{n})(\vec{p}_{\bar{t}} \times \vec{n}) / \lvert\vec{p}_t\rvert\lvert\vec{p}_{\bar{t}}\rvert$	all
b_3	$p_t^x p_{\bar{t}}^x / p_{T,t}p_{T,\bar{t}}$	all
b_4	$p_t^z p_{\bar{t}}^z / \lvert\vec{p}_t\rvert\lvert\vec{p}_{\bar{t}}\rvert$	all

Angular observables (ϕ_C, $\cos\theta^*$)

Variables based on top-quark momenta (b_1–b_4)

Collins, Soper ´77, Gunion, He ´96, Q. Cao et al. ´20

Significances

$\alpha_t = 35°$ $t\bar{t}H$ @ $\mathcal{L} = 300\ \text{fb}^{-1}$ 14 (6 × 6) bins for 1d (2d) dist. **comb. w/ $p_{T,H}^{\text{lab}}$**

	$p_{T,H}$
$H \to \gamma\gamma$	1.51
Multilep.	0.53
$H \to b\bar{b}$	0.35
Combined	1.64

Significance per channel to exclude $\alpha_t = 35°$ with a SM measurement

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Significance per channel to exclude $\alpha_t = 35°$ with a SM measurement

- Each bin must have > 2 events, otherwise bins are merged
- Significances were examined for all 30 variables and all possible 2-dimensional combinations
- Multilep. and $b\bar{b}$ final states suffer from large background normalization uncertainty

Significances

$\alpha_t = 35^\circ$ $\quad t\bar{t}H$ @ $\mathcal{L} = 300\ \text{fb}^{-1}$ $\quad$ 14 (6×6) bins for 1d (2d) dist. $\quad$ **comb. w/ $p_{T,H}^{\text{lab}}$**

	lab frame							indep.		$t\bar{t}$ frame					
	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	$m_{t\bar{t}}$	$m_{t\bar{t}H}$	$p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
$H\to\gamma\gamma$	1.51	1.56	1.54	1.56	1.55	1.52	1.55	1.48	1.5	1.51	1.58	1.59	1.5	1.58	1.51
Multilep.	0.53	0.69	0.9	0.89	0.87	0.73	0.69	0.54	0.52	0.45	0.77	0.8	0.48	0.82	0.56
$H\to b\bar{b}$	0.35	0.43	0.52	0.52	0.51	0.45	0.44	0.38	0.36	0.29	0.47	0.49	0.3	0.5	0.38
Combined	1.64	1.76	1.86	1.87	1.85	1.75	1.75	1.62	1.63	1.61	1.82	1.84	1.6	1.85	1.65

- Lab and $t\bar{t}$ frame shown due to overall higher significances
- Combinations of variables with $p_{T,H}$ can yield close-to-optimal significances

Comparison with BDT: backup

- Best combined 2d significance: 1.91σ ($\Delta\phi_{t\bar{t}}^{\text{lab}} + b_4^{\text{lab}}$, not shown here)

Significances

$\alpha_t = 35°$ $t\bar{t}H$ @ $\mathcal{L} = 300$ fb^{-1} 14 (6 × 6) bins for 1d (2d) dist. **comb. w/ $p_{T,H}^{lab}$**

	lab frame: $p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	b_3	b_4	indep.: $m_{t\bar{t}}$	$m_{t\bar{t}H}$	$t\bar{t}$ frame: $p_{T,H}$	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$	b_1	b_2	b_3
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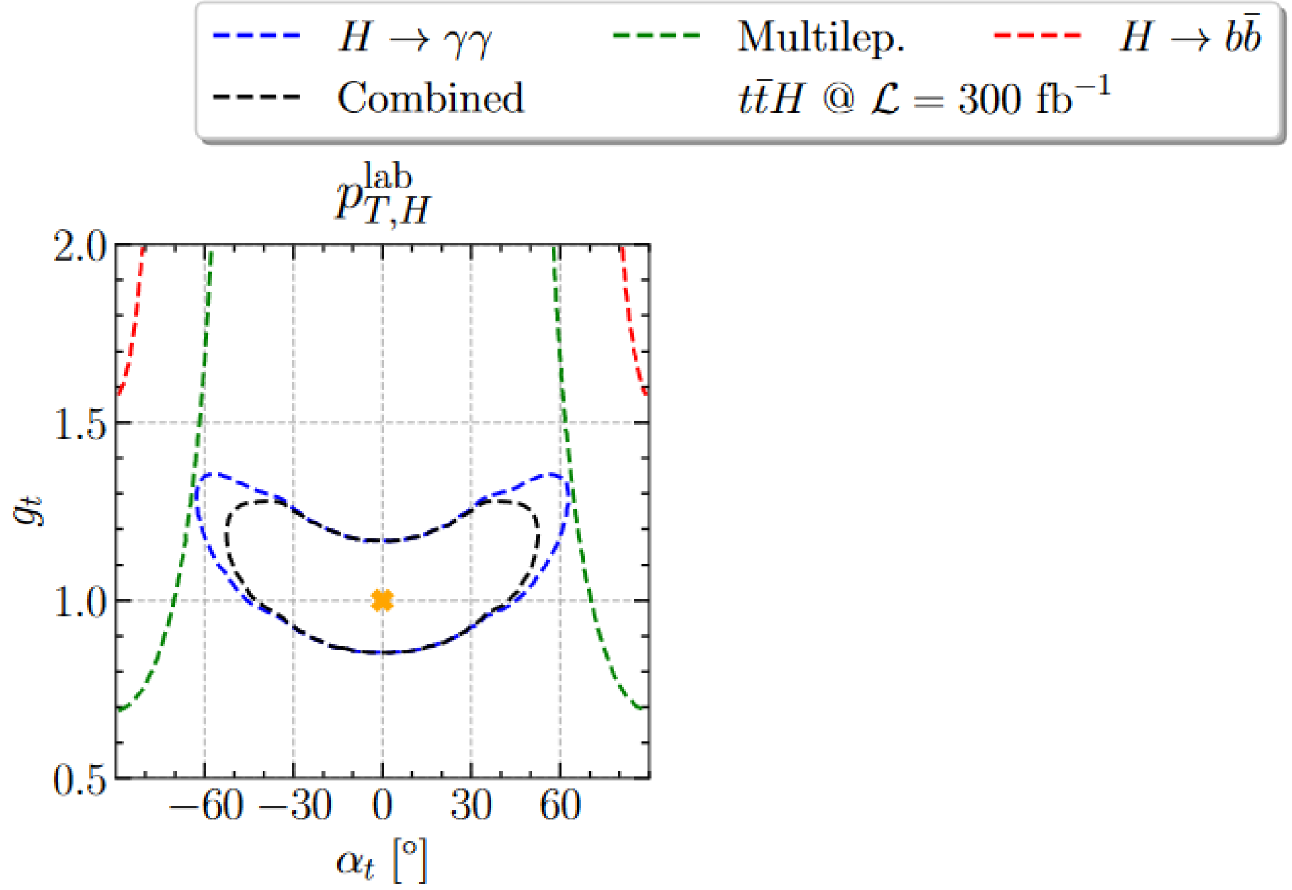
Exclusion limits

ttH

- Expected exclusion limits taking $p_{T,H}^{\mathrm{lab}}$ only:
- $H \to \gamma\gamma$ dominates the constraints



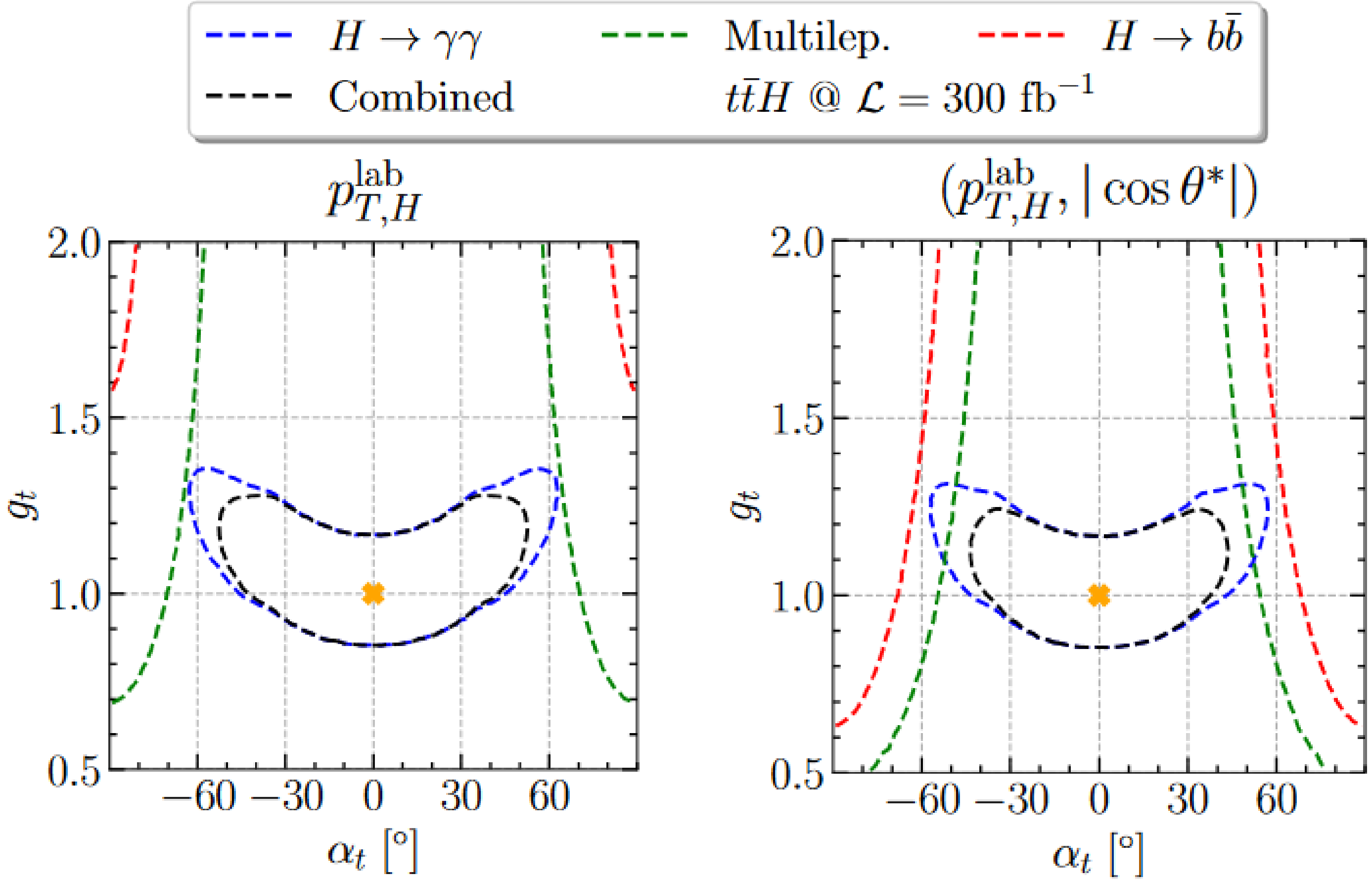
Exclusion limits

- Expected exclusion limits taking $p_{T,H}^{\text{lab}}$ only and taking $p_{T,H}^{\text{lab}} + |\cos\theta^*|$:

- $H \to \gamma\gamma$ dominates the constraints

- Strong potential improvement from a second variable, here: $\alpha_t \lesssim 52° \to \alpha_t \lesssim 43°$

- Very similar results for $p_{T,H}^{\text{lab}} + b_2^{\text{lab}}/\Delta\eta_{t\bar{t}}^{t\bar{t}}$



Conclusion & Takeaways

[2309.03146]

Part I: ggF2j

- Performed a multivariate CP analysis in a ggF2j-like SR

- Expect much stronger constraints than in VBF-like SR (driven by CP-even observables)

- Improvement at $139\mathrm{fb}^{-1}$ (1σ):

  $$\alpha_{g/t} \lesssim 25° \rightarrow \alpha_{g/t} \lesssim 15°$$

- Outlook: Investigate behaviour of the irreducible background

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- Expect much stronger constraints than in VBF-like SR (driven by CP-even observables)
- Improvement at 139fb^{-1} (1σ): 300fb^{-1} (2σ) similar

  $$\alpha_{g/t} \lesssim 25° \rightarrow \alpha_{g/t} \lesssim 15°$$
- Outlook: Investigate behaviour of the irreducible background

Part II: ttH

[2406.03950]

- Studied CP violation combining three Higgs decay channels
- b_2^{lab}, $\Delta\eta_{t\bar{t}}^{t\bar{t}}$ and $|\cos\theta^*|$ as a second STXS dimension have close to optimal sensitivity towards CP
- Improvement at 300fb^{-1} (2σ) :

  $$\alpha_t \lesssim 52° \rightarrow \alpha_t \lesssim 43°$$
- Outlook: Agree on common top quark definition

Backup

Backup: Other notations

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

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

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: $c_{g/t} \sim 1 + \sum_i {}^{c_i}/_{\Lambda^2} + \cdots, \quad \tilde{c}_{g/t} \sim \sum_i {}^{\tilde{c}_i}/_{\Lambda^2} + \cdots$

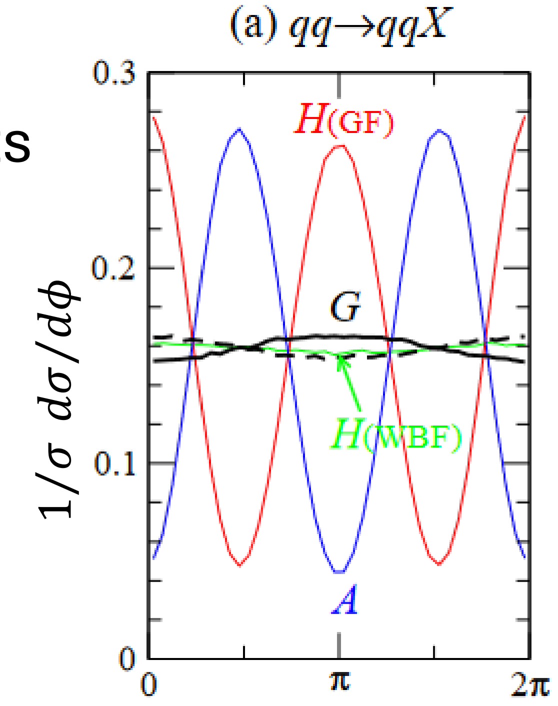
$c_i, \tilde{c}_i$: Wilson coefficients

Backup: CP information in ggF2j

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

- Current most sensitive study from CMS in VBF-like signal region CMS ´22
- VBF-SR is enriched in ggF2j $q\bar{q}$ initial state and interference events
- Does the $q\bar{q}$ initial state have most CP-sensitivity?
- Problems: Initial study conducted with heavy Higgs, in VBF-like signal region, only variable used is $\Delta\phi_{jj}$

⇒ ggF2j-SR has tons of events, can we gain sensitivity from them?



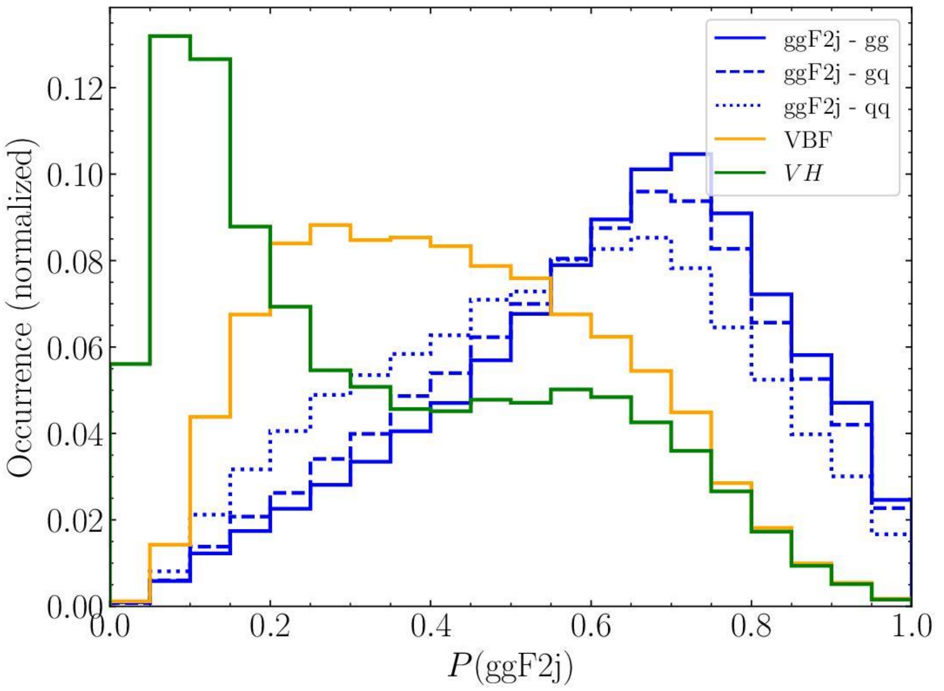
Hagiwara et al. ´09 $\Delta\phi_{jj}$

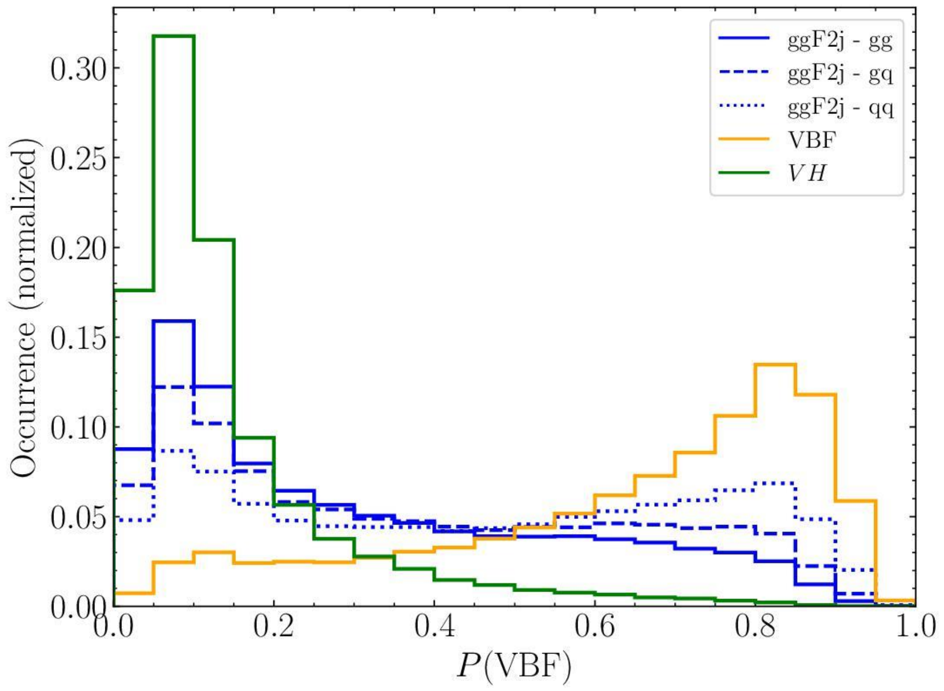
Backup: Cutflow

	Fraction of accepted events				
Applied cut	**ggF2j $\|\mathcal{M}_{\text{even}}\|^2$**	**ggF2j Interf.**	**ggF2j $\|\mathcal{M}_{\text{odd}}\|^2$**	**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%
$\|\eta_j\| \leq 2.5$ $\|\eta_\gamma\| \leq 2.5$	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

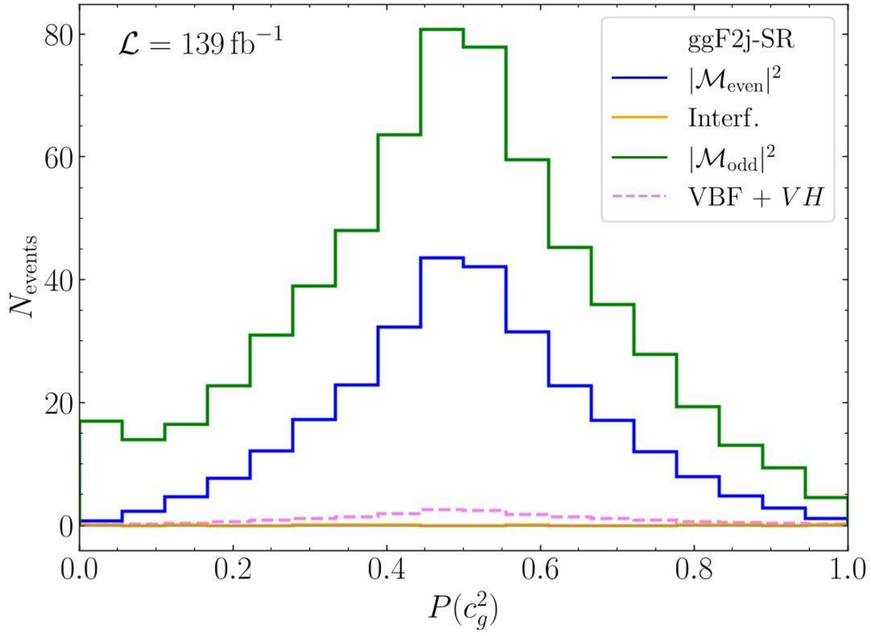
Backup: Signal regions

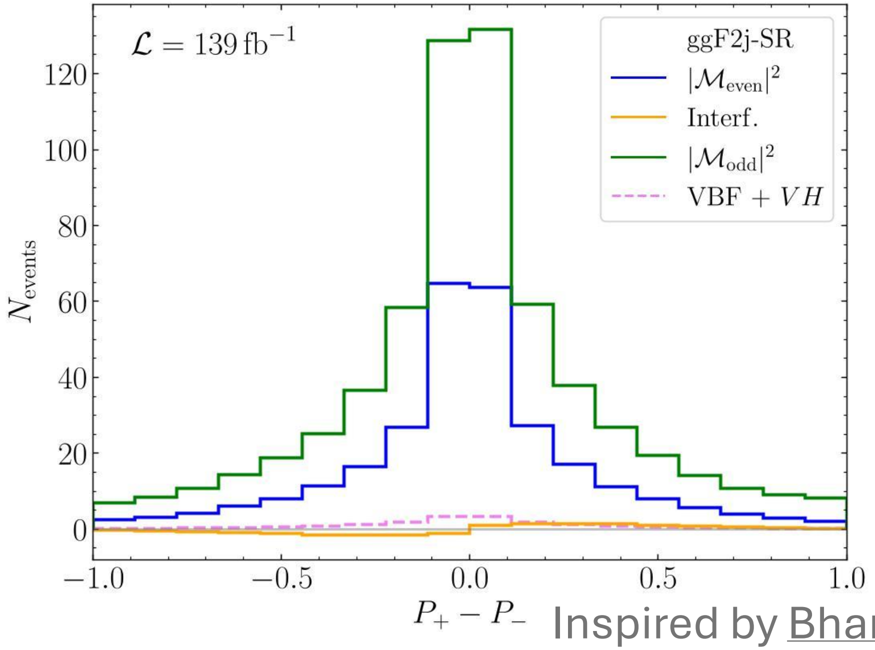




- Use $P(\text{signal}) > 0.5$ as a cut to define signal regions
- ggF2j with $q\bar{q}$ initial state are identified as VBF-like more often
- ggF2j interference events are also identified as VBF-like more often

Backup: ggF2j signal region



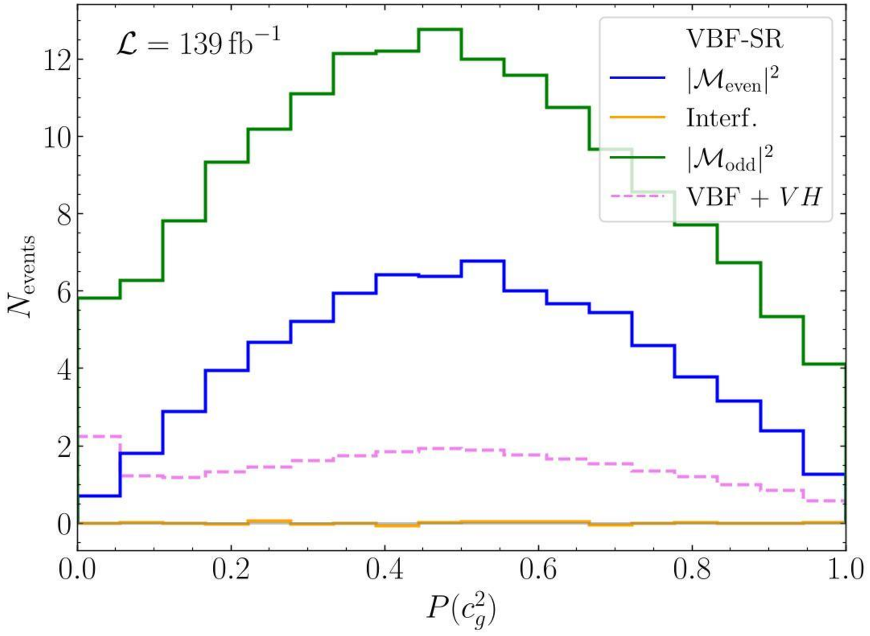


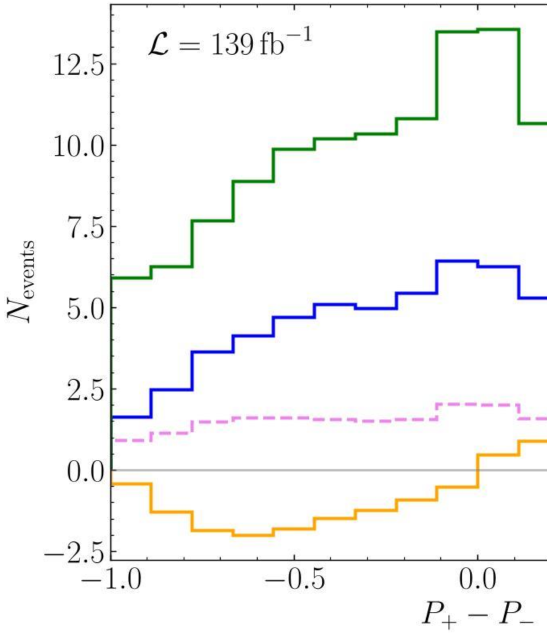
Inspired by Bhardwaj et al. `21

- $P(c_g^2)$ 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

Backup: VBF signal region





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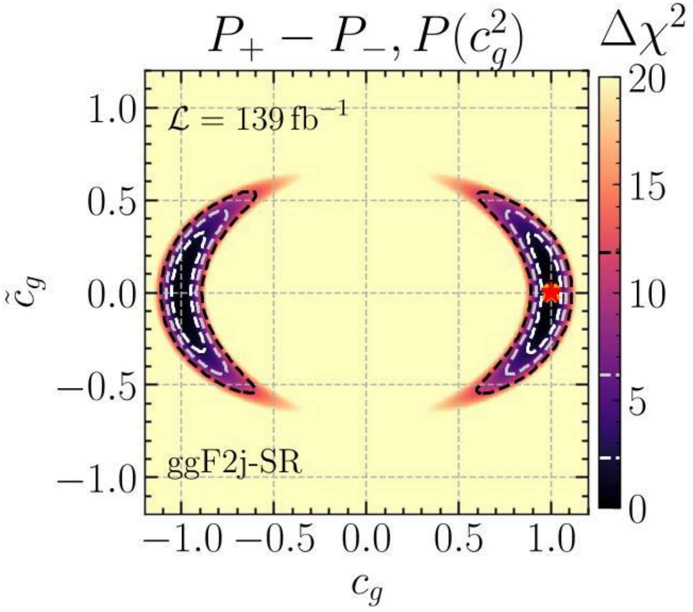
- $P(c_g^2)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Less events than in ggF2j-SR, statistical fluctuations visible
- Wider peak around $P(c_g^2) = 0.5$

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

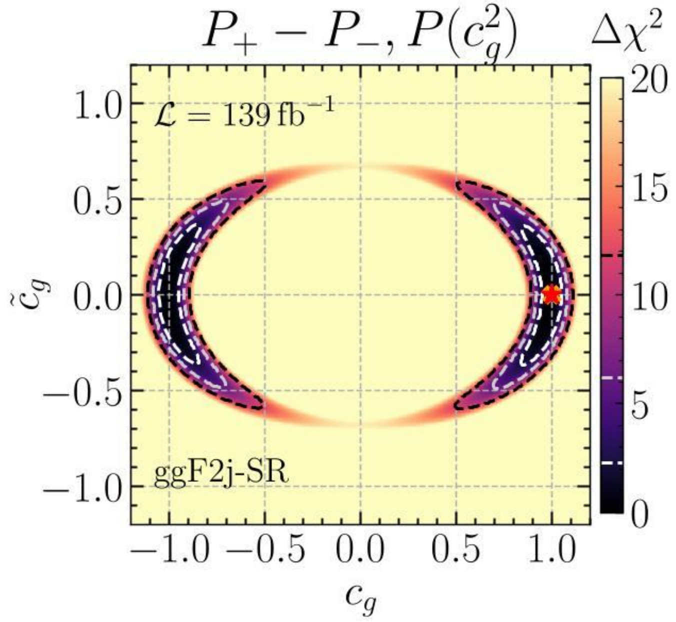
Backup: CP violation in HVV – ggF2j-SR

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
- Mainly a washout effect between SRs due to wrong BG assumption



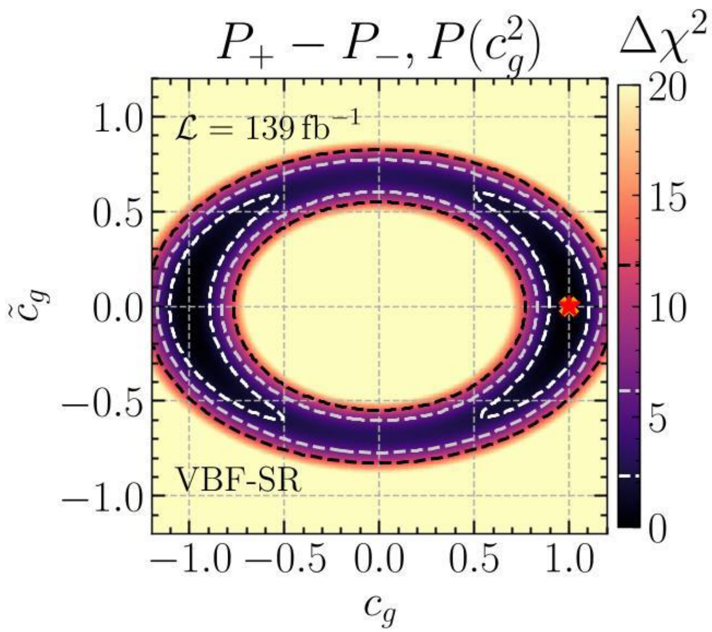
Adding CP Violation in VBF



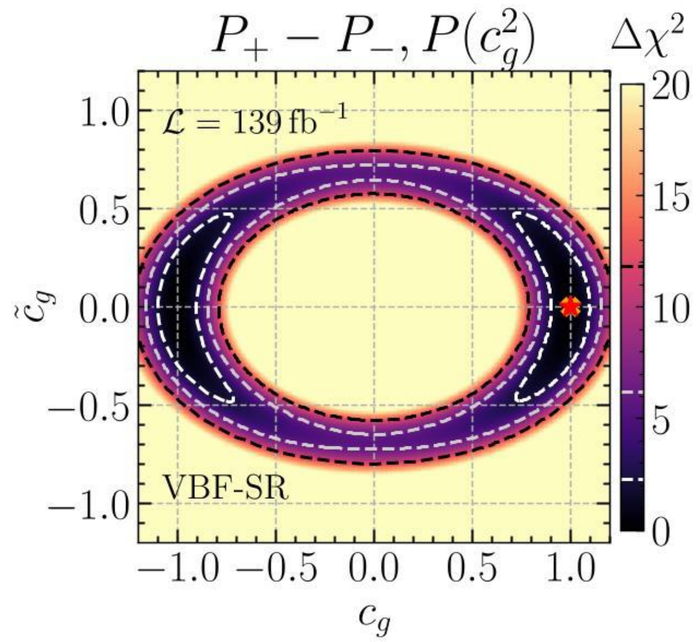
Backup: CP violation in HVV – VBF-SR

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



Adding CP Violation in VBF

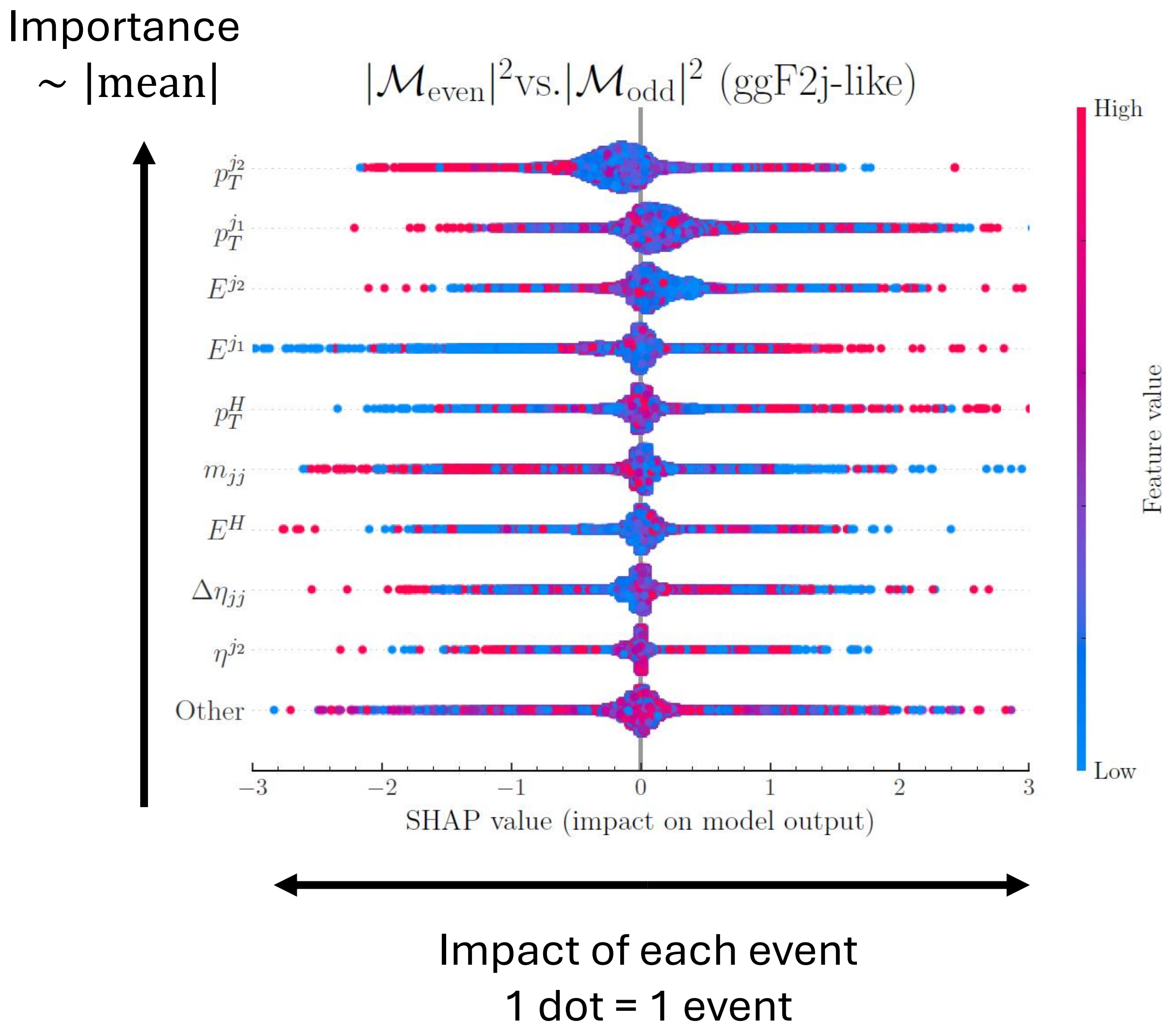


Backup: Feature importance – ggF2j-SR

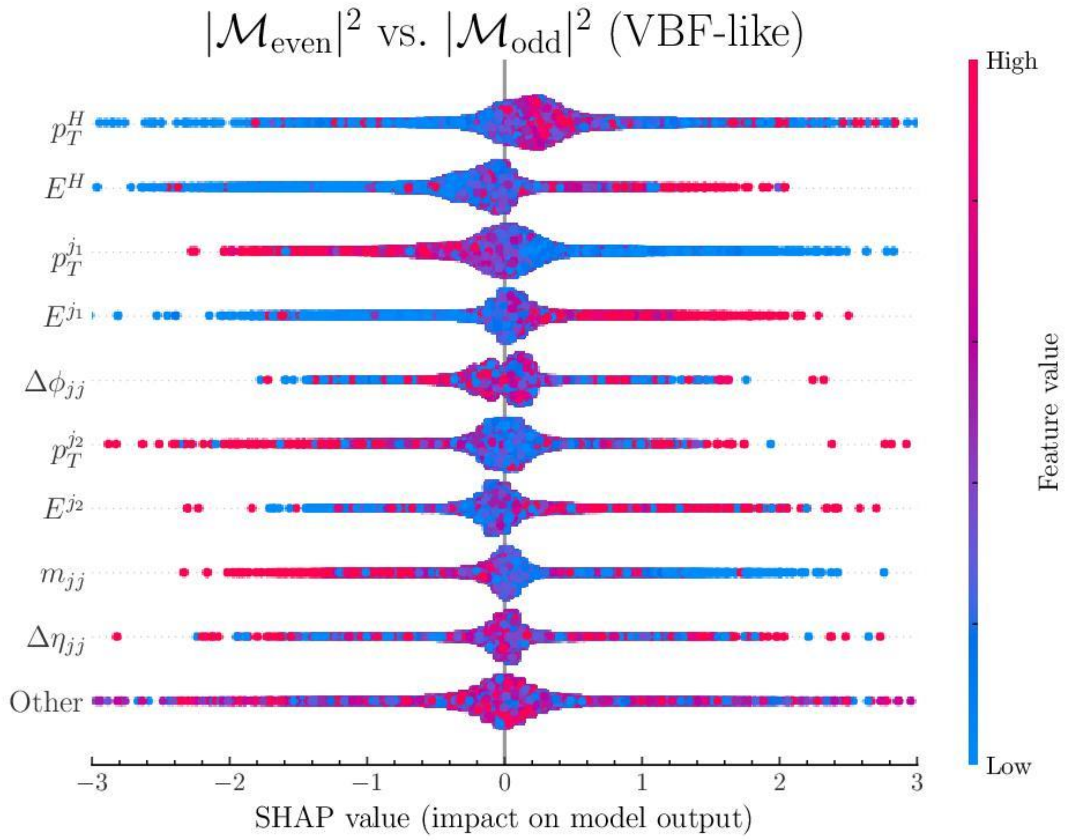
CP-even classifier:

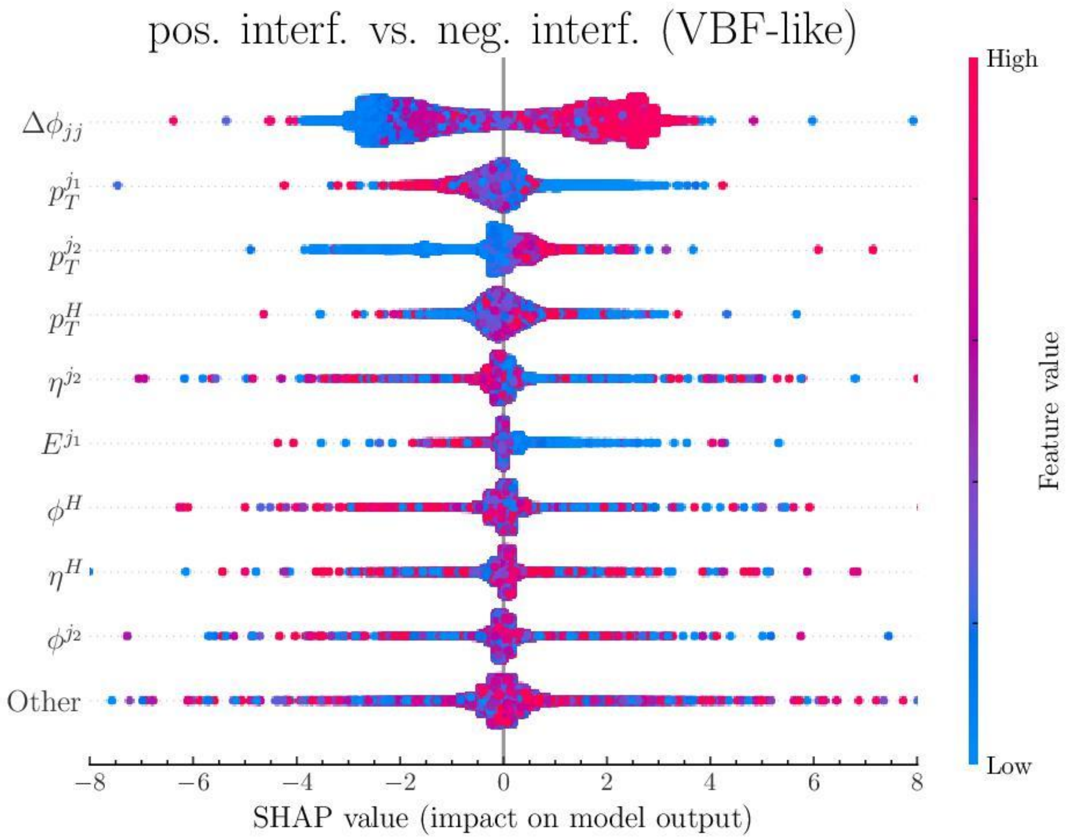
- ➢ $p_T^{j_1}$ and $p_T^{j_2}$ seem to be the most important variables
- ➢ Variable importance much less pronounced than in CP-odd case
- ➢ Hard to judge interplay

⇒ symbolic regression (WIP)



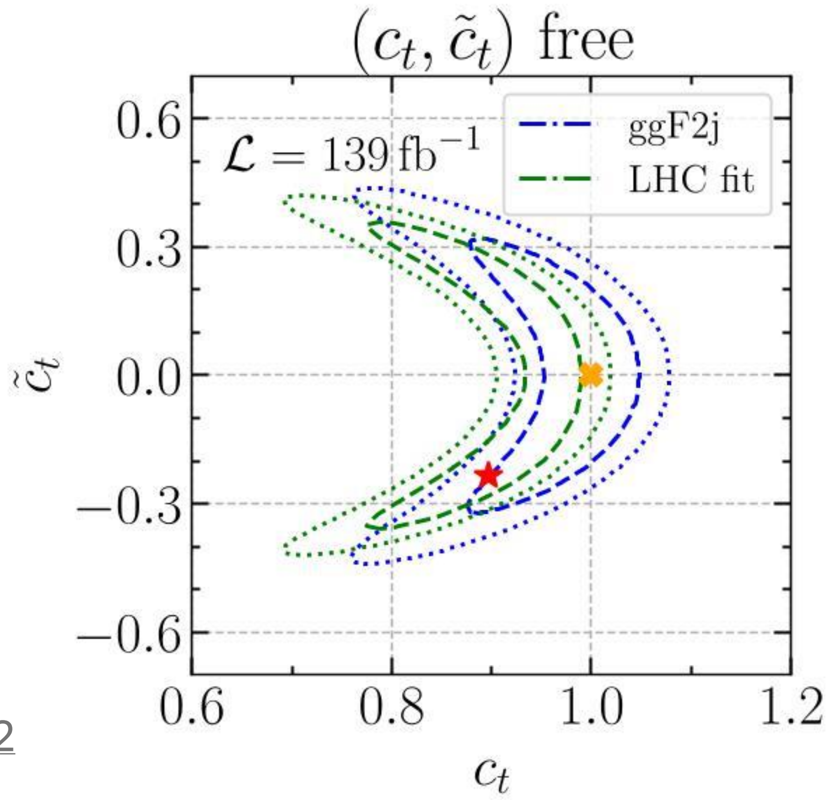
Backup: Feature importance – VBF-SR





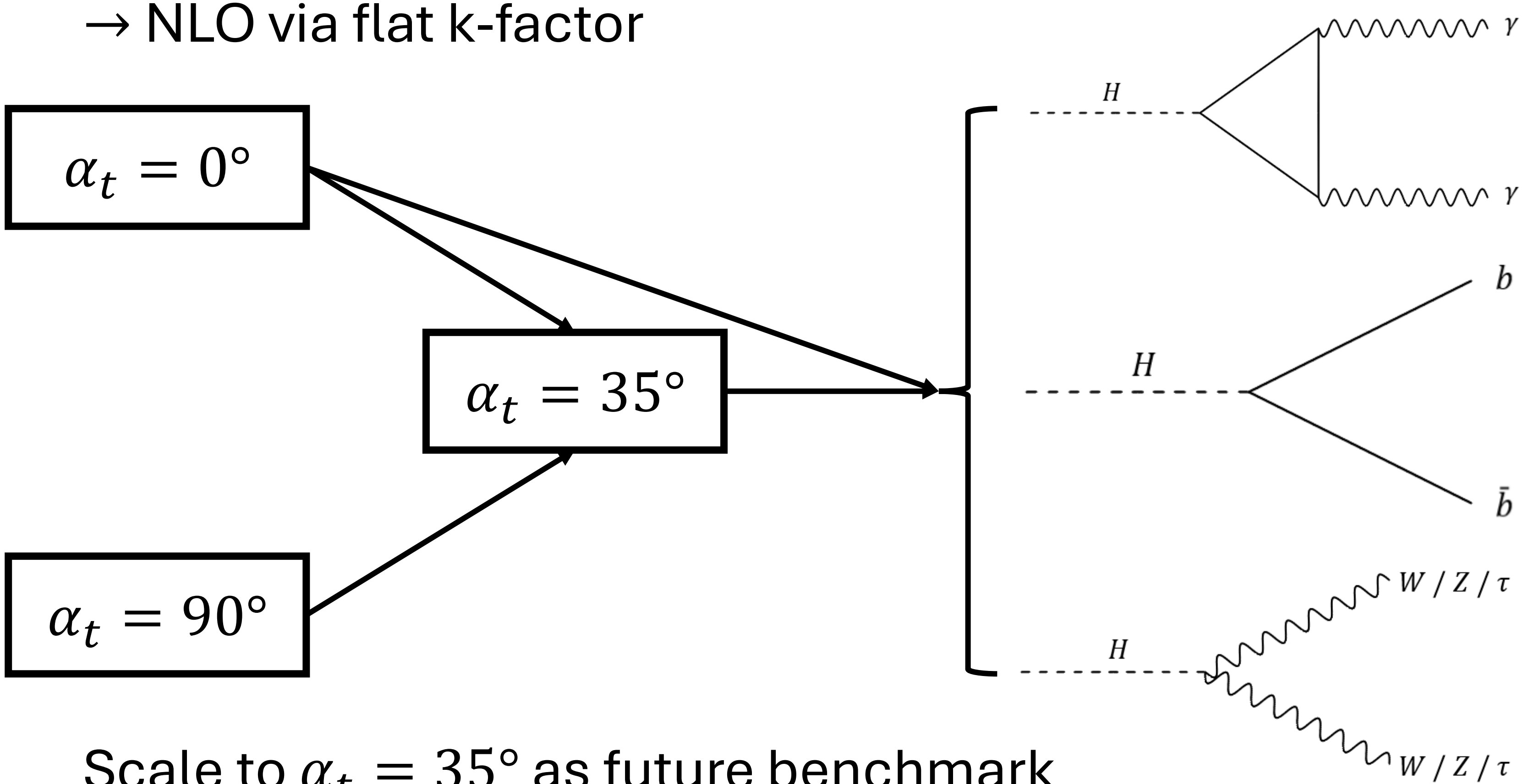
Backup: Comparison to global fit

- 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



Backup: ttH event generation

Generate samples at LO
→ NLO via flat k-factor



Add (channel-specific):

- Acceptance factors for event selection
- Smearing of kinematics from limited resolution
- Uncertainties

Scale to $\alpha_t = 35°$ as future benchmark

$$N(\alpha_t) = N_{0°} \cos \alpha_t{}^2 + N_{90°} \sin \alpha_t{}^2$$

ATLAS ´12, ATLAS ´14, ATLAS ´19, ATLAS ´21
ATLAS ´20, CMS ´23, ATLAS ´24

Backup: ttH significance evaluation

- Significance of excluding a BSM-hypothesis evaluated for all single variables and all 2-dimensional combinations at 300fb^{-1}
- Each bin is required to have > 2 events, otherwise bins are merged
- $H \to b\bar{b}, H \to$ multilep. use no rate information to account for large uncertainty in the non-Higgs background normalization
- Additional uncertainties from statistics and shape:

ATLAS ´20, CMS ´23, ATLAS ´24

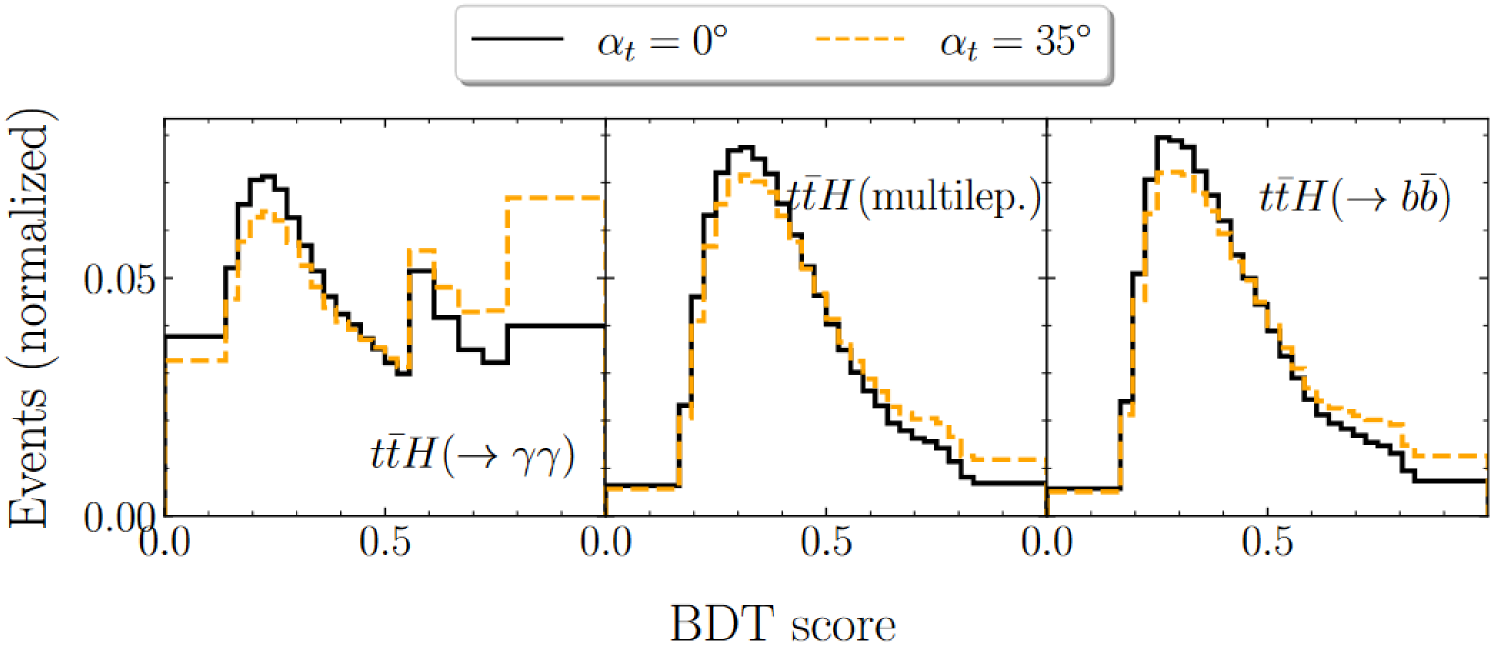
$$\sigma_i = \sqrt{\sigma_{\text{sys}}^2 + \sigma_{\text{stat}}^2}$$

- Total significance evaluation from SM yield n_i and BSM yield m_i

$$S = \sqrt{2 \sum_i^{N_{\text{bins}}} \left(n_i \ln\left[\frac{m_i(n_i + \sigma_i^2)}{n_i^2 + m_i \sigma_i^2}\right] - \frac{n_i^2}{\sigma_i^2} \ln\left[1 + \frac{\sigma_i^2 (m_i - n_i)}{n_i(n_i + \sigma_i^2)}\right]\right)}$$

ATLAS ´20

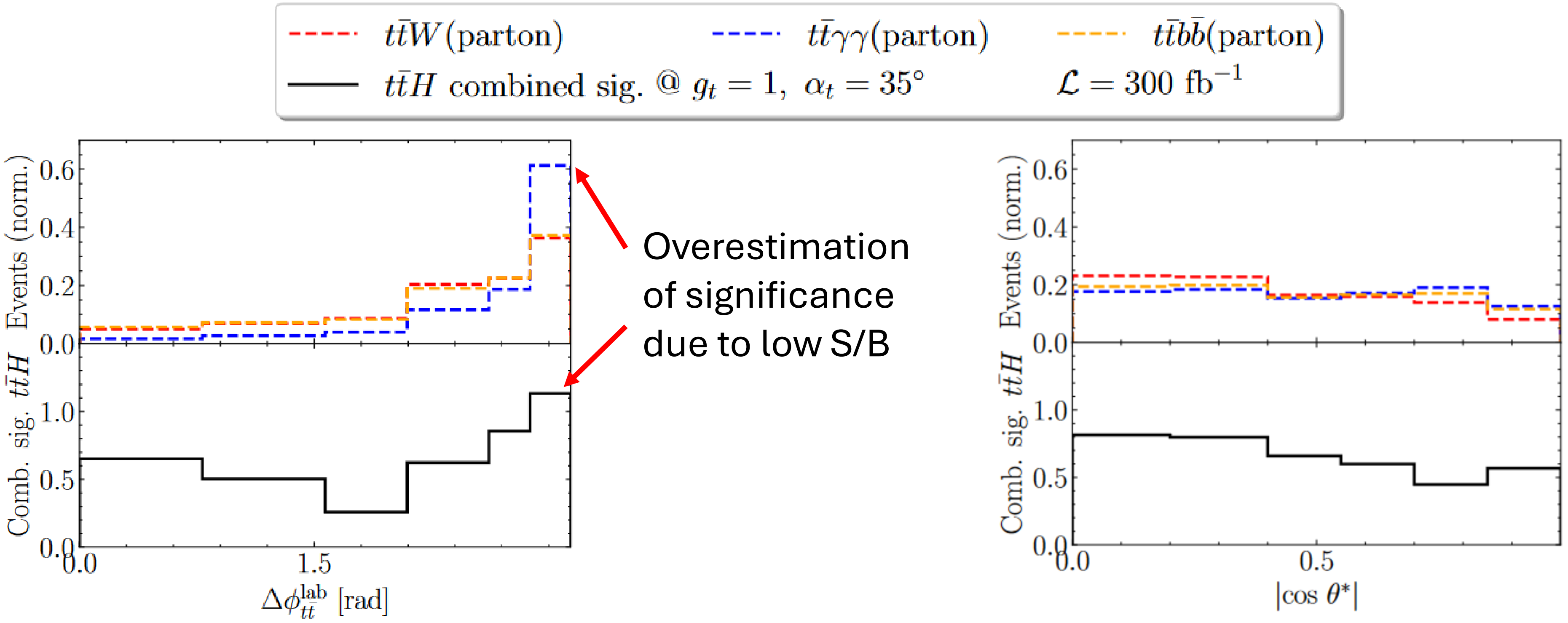
Backup: Comparison with BDT approach



Channel	$t\bar{t}H(\to\gamma\gamma)$	$t\bar{t}H$(multilep.)	$t\bar{t}H(\to bb)$	Combined
Significance (2D)	1.57	0.94	0.55	1.91
Significance (BDT)	1.75	1.17	0.69	2.21

Backup: ttH background shape

- The shape of the background has been neglected so far by considering S/B to be equal in each bin but it could spoil the significances



We consider $\Delta\phi^{\mathrm{lab}}_{t\bar{t}}$ and b_1^{lab} to be disfavoured by the background

Our final shortlist of variables includes b_2^{lab}, $\Delta\eta^{t\bar{t}}_{t\bar{t}}$ and $|\cos\theta^*|$