CMS Studies: Comparison of EFT Monte Carlo modeling of the Higgs boson couplings

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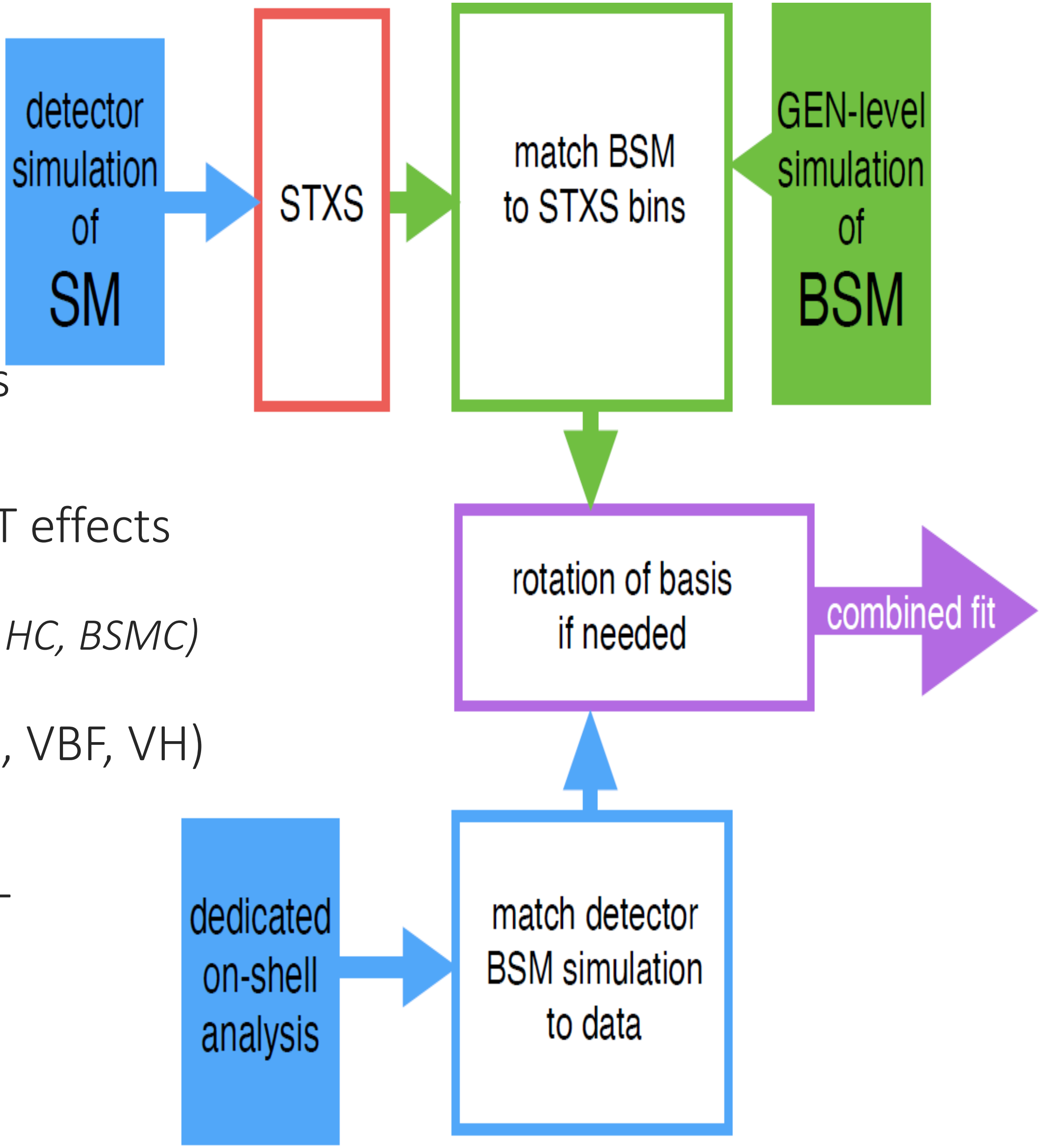
Motivation

The general ideas and techniques presented here apply to more than HVV coupling measurements

Many tools for modelling EFT effects
- Madgraph (Full EFT)
  - *-(SMEFTSim, SMEFT@NLO, HC, BSMC)*
- JHUGen (Higgs EFT)
- HAWK (Higgs EFT EWNLO, VBF, VH)
- Analytic functions

In order to interpret any EFT measurement correctly, all conventions must be understood fully



SMEFT operator bases:

(1) "Anomalous Couplings" + $SU(2) \times U(1)$ symmetry

most direct map to observables (e.g. Z/γ instead of B^0/W^0)

historically used in CMS Higgs since 2012 — most recent CMS: arxiv:2104.12152

(2) Warsaw basis with built-in $SU(2) \times U(1)$ symmetry (B^0, W^0, W^1, W^2)

most convenient for computation (e.g. min. derivatives) — target of global fits

(3) SILH basis (strongly-interacting light Higgs) — CMS: inspire:1774836

more direct map to some BSM models

"Anomalous Couplings"

$$\Delta\mathcal{L}_h = \frac{h}{v}\Big[2\delta c_w m_W^2\, W_\mu^+ W^{-\mu} + \delta c_z m_Z^2\, Z_\mu Z^\mu + c_{gg}\frac{g_s^2}{4}\, G_{\mu\nu}^a G_a^{\mu\nu} + c_{ww}\frac{g^2}{2}\, W_{\mu\nu}^+ W^{-\mu\nu} + c_{zz}\frac{g^2}{4c_\theta^2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{z\gamma}\frac{gg'}{2}\, Z_{\mu\nu}A^{\mu\nu} + c_{\gamma\gamma}\frac{g'^2 c_\theta^2}{4}\, A_{\mu\nu}A^{\mu\nu} + c_{w\Box} g^2\left(W_\mu^-\partial_\nu W^{+\mu\nu} + \text{h.c.}\right) + c_{z\Box} g^2\, Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} gg'\, Z_\mu\partial_\nu A^{\mu\nu}\Big]. \quad (7)$$

Warsaw basis

$$\Delta\mathcal{L}_h^{\mathrm{W}} = \frac{1}{v^2}\Big[c_{GG}\frac{g_s^2}{4}\,\Phi^\dagger\Phi\, G_{\mu\nu}^a G_a^{\mu\nu} + c_{WW}\frac{g^2}{4}\,\Phi^\dagger\Phi\, W_{\mu\nu}^i W_i^{\mu\nu} + c_{WB}\, gg'\,\Phi^\dagger\sigma_i\Phi\, W_{\mu\nu}^i B^{\mu\nu} + c_{BB}\frac{g'^2}{4}\,\Phi^\dagger\Phi\, B_{\mu\nu}B^{\mu\nu} + c_H\,\partial_\mu\left[\Phi^\dagger\Phi\right]\partial^\mu\left[\Phi^\dagger\Phi\right] + c_T\left[\Phi^\dagger \overleftrightarrow{D}_\mu\Phi\right]\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\Big]. \quad (11)$$

Basis Translation and Tools

arxiv:1508.05895

Rosetta allows for translation between different EFT operator basis

- Covers full EFT basis

For our study, we use JHUGenLexicon, which is integrated with JHUGen

- Supports translation of HVV couplings

arxiv:2109.13363

$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2w_{\phi bx} + \frac{6e^2}{s_w^2}w_{\phi BW} + \left(\frac{3c_w^2}{2s_w^2} - \frac{1}{2}\right)w_{\phi D}\right),$$

$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}w_{\phi BW} + \left(1 - \frac{1}{2s_w^2}\right)w_{\phi D}\right),$$

$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 w_{\phi B} + c_w^2 w_{\phi W} + s_w c_w w_{\phi BW}\right),$$

$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w (w_{\phi W} - w_{\phi B}) + \frac{1}{2}(s_w^2 - c_w^2) w_{\phi BW}\right)$$

$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 w_{\phi B} + s_w^2 w_{\phi W} - s_w c_w w_{\phi BW}\right),$$

$$g_2^{gg} = -2\frac{v^2}{\Lambda^2} w_{\phi G},$$

$$g_4^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 w_{\phi\tilde{B}} + c_w^2 w_{\phi\tilde{W}} + s_w c_w w_{\phi B\tilde{W}}\right),$$

$$g_4^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w (w_{\phi\tilde{W}} - w_{\phi\tilde{B}}) + \frac{1}{2}(s_w^2 - c_w^2) w_{\phi B\tilde{W}}\right),$$

$$g_4^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 w_{\phi\tilde{B}} + s_w^2 w_{\phi\tilde{W}} - s_w c_w w_{\phi B\tilde{W}}\right),$$

$$g_4^{gg} = -2\frac{v^2}{\Lambda^2} w_{\phi\tilde{G}},$$

HVV translations used in this study

Conventions on HVV couplings

Thanks to all authors

MadGraph - **H**iggs **C**haracterization tools (**HC**), **BSMC**, **SMEFTsim**

JHUGen

HAWK

Analytical

Many months (>1y) of discussion, many thanks to

Markus Schulze - JHUGen and physics

Marco Zaro, Fabio Maltoni, Kentarou Mawatari - MadGraph (HC) and physics

Ansgar Denner, Stefan Dittmaier, Alexander Muck - HAWK and physics

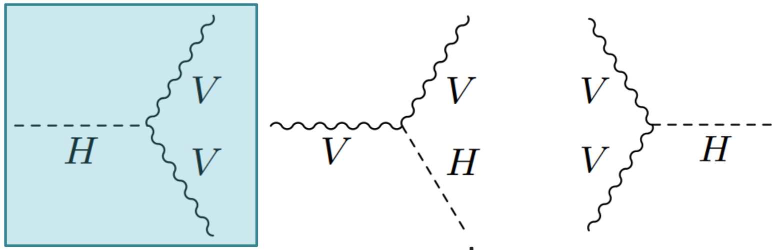
Ilaria Brivio, Michael Trott - SMEFTsim (MG) and physics

Adam Falkowski, Ken Mimasu - Rosetta, BSMC (MG) and physics

Werner Bernreuther, Long Chen - loop calculations and physics

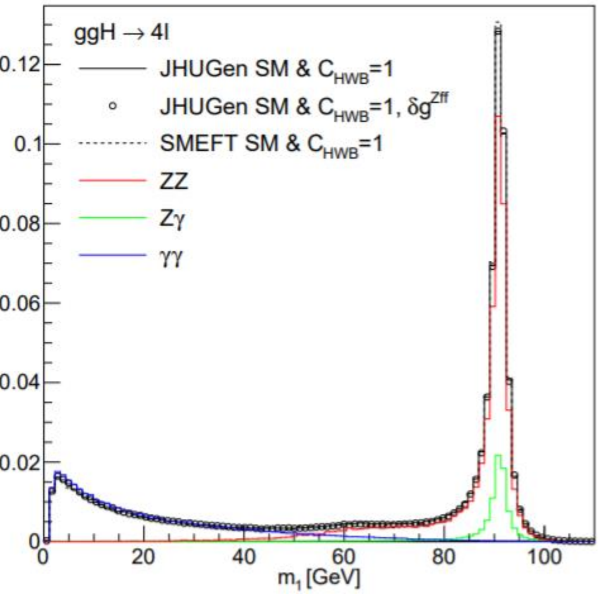
Ian Low, Roberto Vega-Morales - analytical calculations and physics

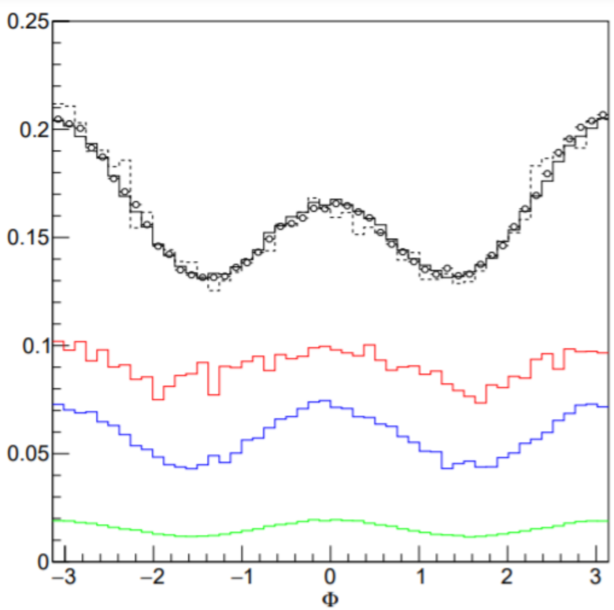
Comparisons of Tools

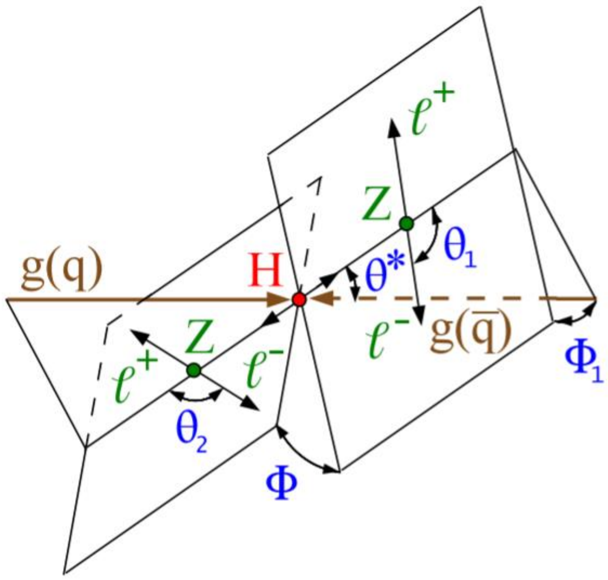


Rotation tools produce excellent agreement between samples generated with different EFT operator bases

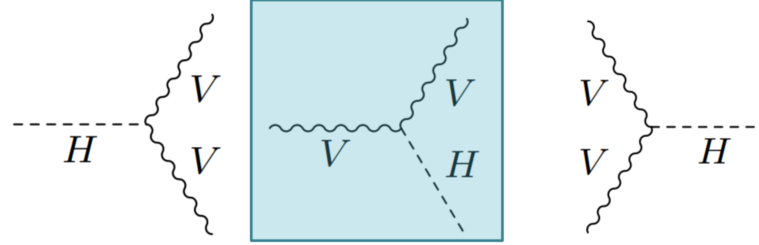
Ex) Generate ggH->4l in SMEFTSim for some non-zero Wilson coefficient → Use Rotation tools to map Wilson coefficient to mass eigenstate basis (JHUGenLexicon) → Generate ggH->4l in JHUGen with translated couplings







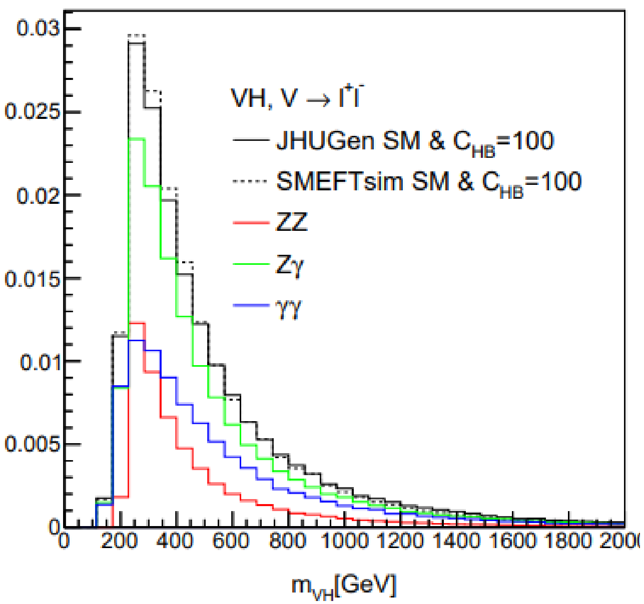
Comparisons of Tools

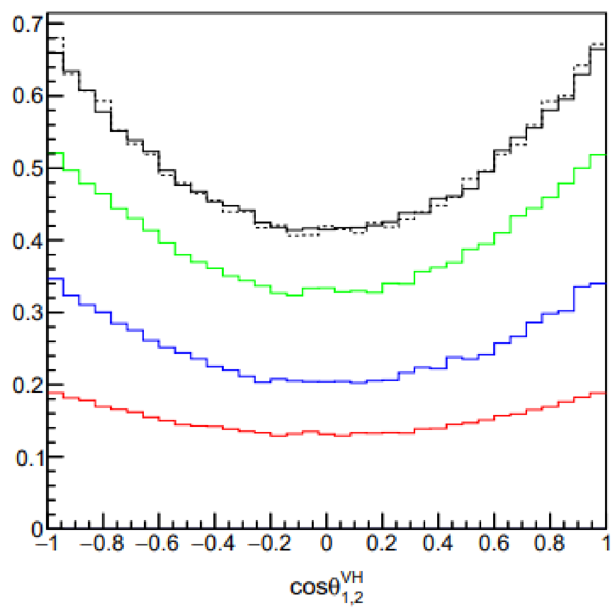


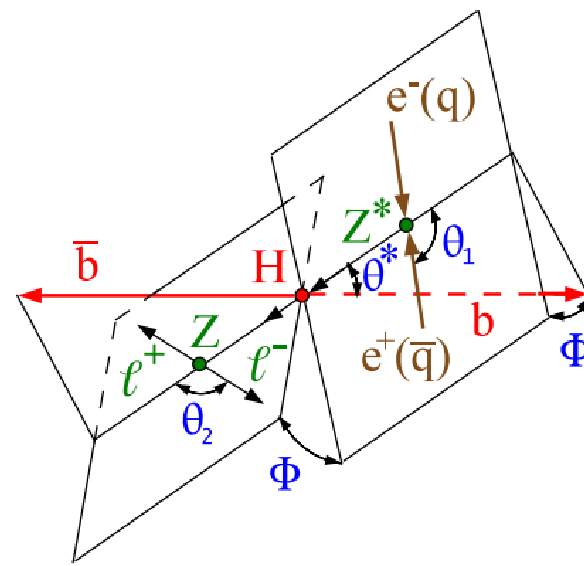
Excellent Agreement in all VH observables

Verified in MadGraph(SMEFTSim,BSMC), JHUGen and HAWK

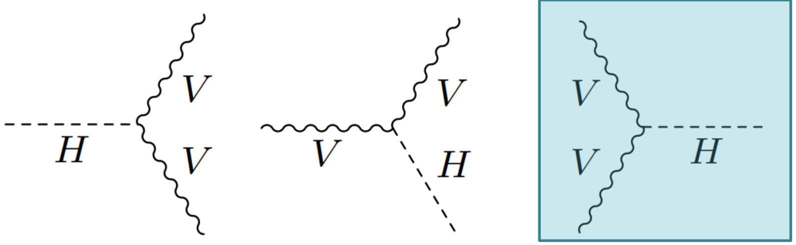
Comparison to HAWK and BSMC will be shown later







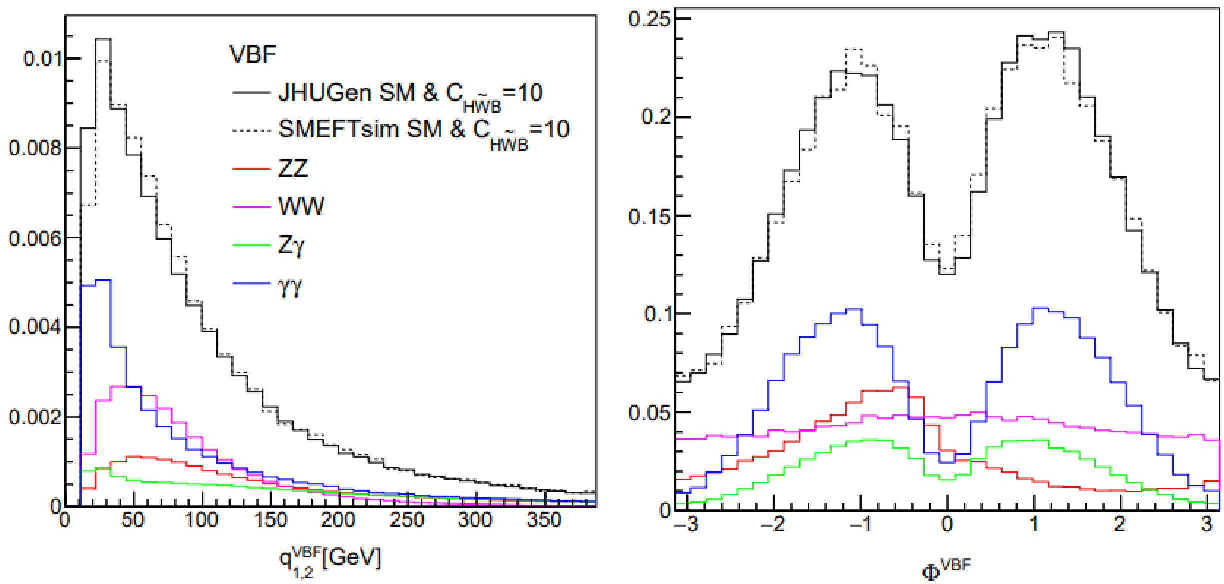
Comparisons of Tools

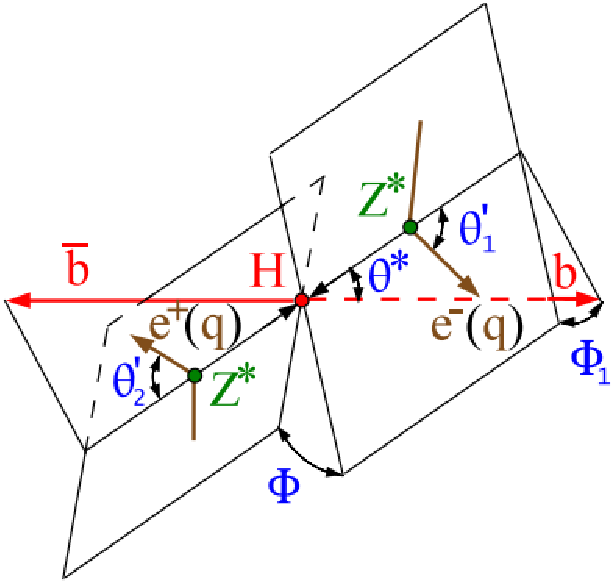


Excellent Agreement in all VBF observables

Verified in MadGraph(SMEFTSim,BSMC) JHUGen and HAWK

Comparison to HAWK and BSMC will be shown later





Summary of Conventions

We observe great agreement across all tools for many Higgs Processes

HOWEVER

Agreement requires precise understanding of underlying structure of tools

(1) $ggH, \gamma\gamma H, \gamma ZH$ opposite sign (CP-odd) vs $t\bar{t}H$ in **MadGraph**

(2) $\epsilon_{0123} = +1$ in **MadGraph**, **JHUGen**, and **Analytical**

$\epsilon^{0123} = +1 \Rightarrow \epsilon_{0123} = -1$ in **HAWK** (sign switch in v3.0.1)

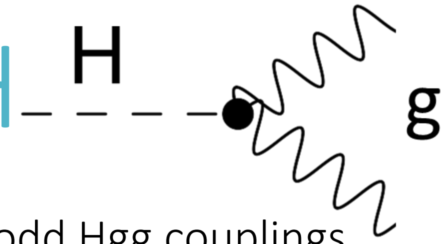
(3) $D_\mu = \partial_\mu - \mathrm{i}\frac{e}{2s_w}\sigma^i W_\mu^i - \mathrm{i}\frac{e}{2c_w}B_\mu$ in **MadGraph** and **Analytical**

$D_\mu = \partial_\mu - \mathrm{i}\frac{e}{2s_w}\sigma^i W_\mu^i + \mathrm{i}\frac{e}{2c_w}B_\mu$ in **HAWK** and **JHUGen**

(4) Using point-like couplings to approximate EWNLO effects

(5) Analytical calculation of point like couplings

(1) Sign of CP odd terms in ggH



Testing $pp \rightarrow H + \text{jets}$ discovered sign difference in connecting cp-even cp-odd Hgg couplings

The κ_Q and $\tilde{\kappa}_Q$ couplings are connected to the g_2^{gg} and g_4^{gg} point-like interactions introduced in Eq. (1) through

arXiv:2002.09888

$$g_2^{gg} = -\alpha_s \kappa_Q/(6\pi)\,, \qquad g_4^{gg} = -\alpha_s \tilde{\kappa}_Q/(4\pi)$$

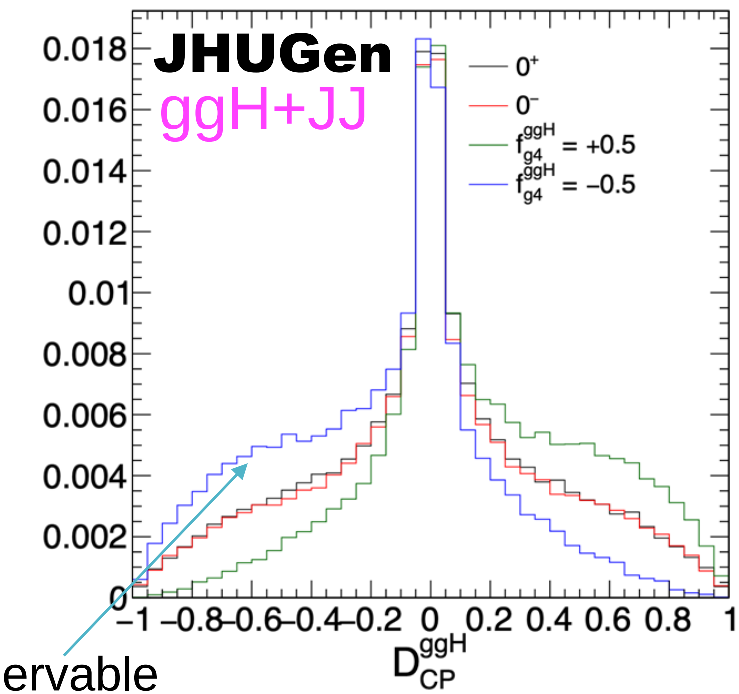
same sign in **JHUGen** - CMS results rely on this

$g_{Xyy'} \times v$	ff	ZZ/WW	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m^2_{Z/W}$	$47\alpha_{\rm EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
A	m_f	0	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

Table 2. Values in units of v taken by the couplings $g_{Xyy'}$. $C = \sqrt{\frac{\alpha_{\rm EM} G_F m_Z^2}{8\sqrt{2}\pi}}$.

opposite sign in **MadGraph** arXiv:1306.6464

Solution: Change the model and all the documentation or to have the sign mismatch clearly documented somewhere



makes a difference in $ttH + ggH$ (!) effect in observable distributions

(2)VBF: Sign of Anti-symmetric tensor

Compare sign of $c_{\gamma\gamma}$ and $\tilde{c}_{\gamma\gamma}$ → Simulate $c_{\gamma\gamma}$ and $\tilde{c}_{\gamma\gamma}$ no SM

Higgs Characterization (MadGraph)

JHUGen $\epsilon_{0123} = +1$ →Relative sign $\frac{c_{\gamma\gamma}}{\widetilde{c_{\gamma\gamma}}} = 1$

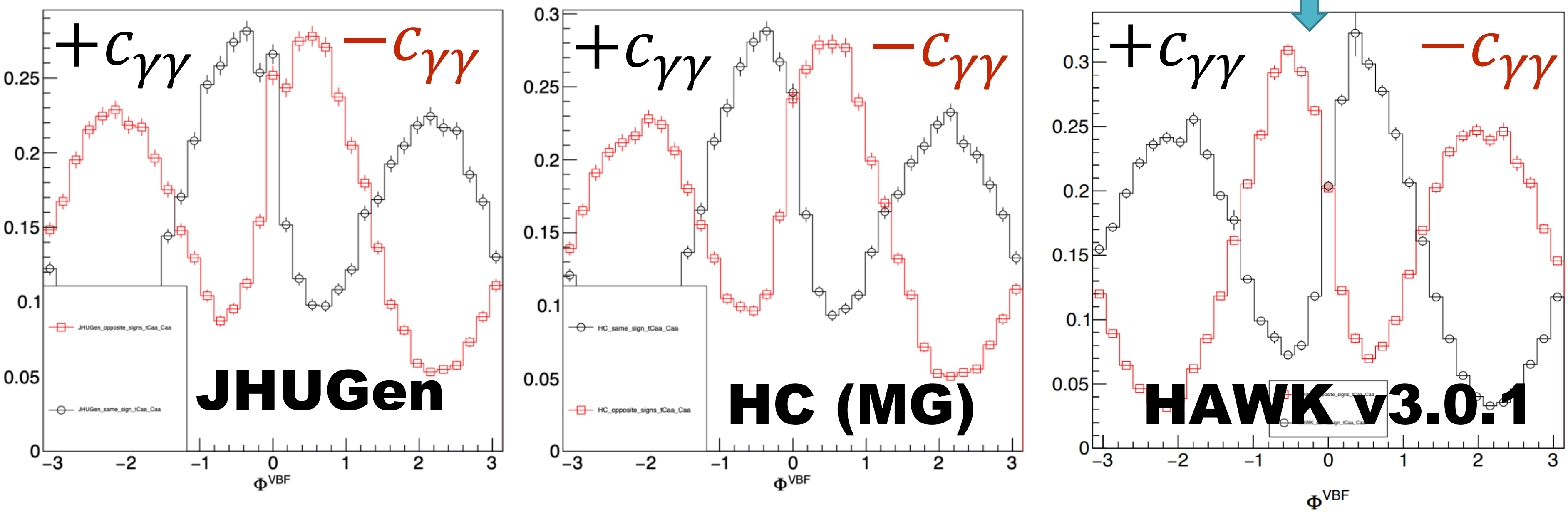
HAWK $\epsilon_{0123} = -1$ →Relative sign $\frac{c_{\gamma\gamma}}{\widetilde{c_{\gamma\gamma}}} = -1$

- Fix $\widetilde{c_{\gamma\gamma}}$ = 1
- Simulate $c_{\gamma\gamma}$ =1 and $c_{\gamma\gamma}$ = -1
- Compare distributions

CP-sensitive observables dependent on relative sign

Differences expected due to sign convention

Consistent with expectations since 03/09/2021



(3) Sign convention: covariant derivative

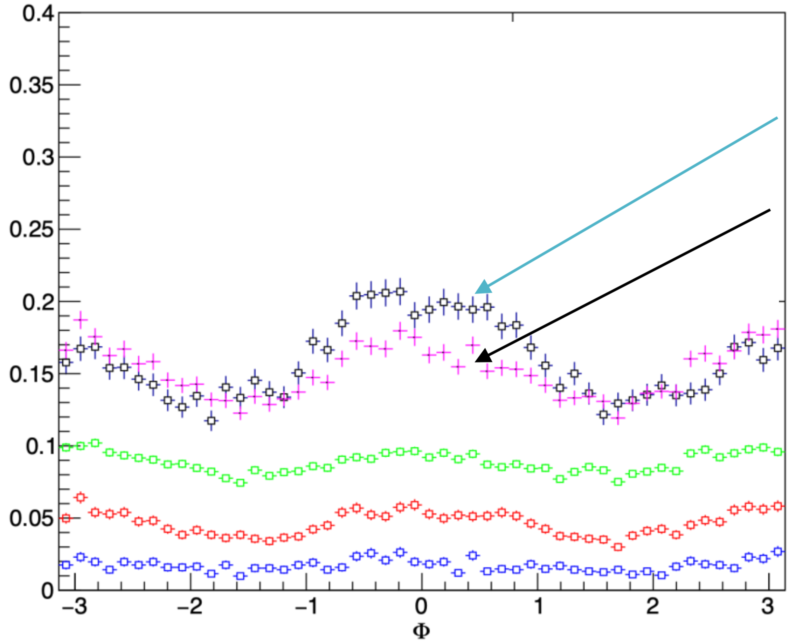
$$D_\mu = \partial_\mu - \mathrm{i}\frac{e}{2s_w}\sigma^i W_\mu^i - \mathrm{i}\frac{e}{2c_w}B_\mu$$ **MadGraph**

$$c_{HW} = -0.0929 g_2^{ZZ} - 0.0513 g_2^{Z\gamma} - 0.0281 g_2^{\gamma\gamma}$$

$$D_\mu = \partial_\mu - \mathrm{i}\frac{e}{2s_w}\sigma^i W_\mu^i + \mathrm{i}\frac{e}{2c_w}B_\mu$$ **HAWK** and **JHUGen**

$$c_{HW} = -0.0929 g_2^{ZZ} + 0.0513 g_2^{Z\gamma} - 0.0281 g_2^{\gamma\gamma}$$

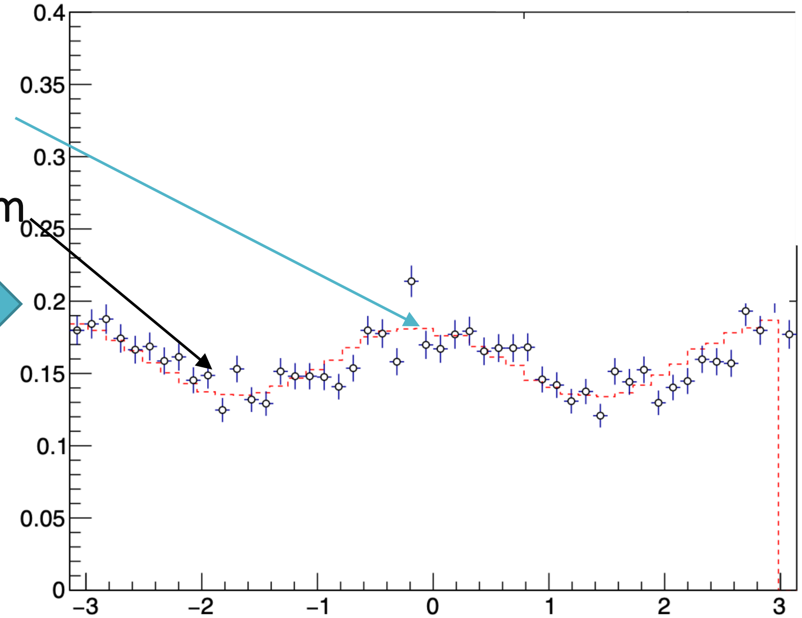
Sign difference in Covariant derivative definition, if not accounted for can affect observables



Incorrect assumptions

JHUGen

SMEFTSim



Correct assumptions

(4) NLO EW vs. Ad-Hoc

Effective point-like couplings $g_2^{Z\gamma}$ and $g_2^{\gamma\gamma}$ correctly model on-shell $H \to Z\gamma,\gamma\gamma$

Used sometimes to model NLO EW effects in Higgs processes with off-shell photons

SMEFTSim (SMHLOOP=1)

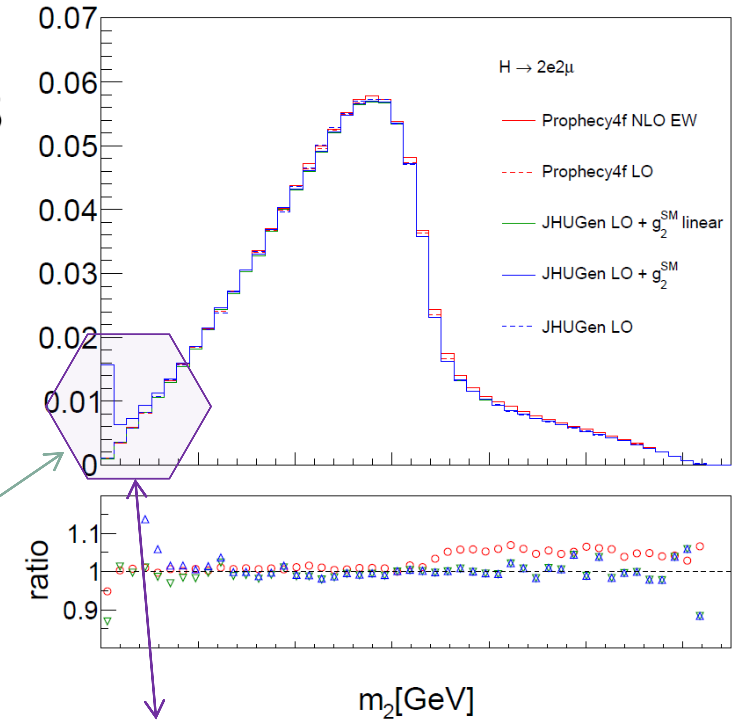
JHUGen $g_2^{Z\gamma,\mathrm{SM}} = 0.00675 \quad g_2^{\gamma\gamma,\mathrm{SM}} = 0.00423$

Type of Correction	Correction to SM
EW NLO (Prophecy4f)	+1.50 %
LO+Effective g2 (JHUGen)	+1.96 %
LO+Effective g2 (Linear Only)	-0.60 %

$$\sigma_{gg\to H\to 4l} \propto (g_1^{ZZ})^2 + \cdots (g_1^{ZZ})(g_2^{Z\gamma,SM}) + \cdots + \cdots (g_2^{\gamma\gamma,SM})^2 + \ldots$$

Linear Terms
Full EW NLO

Squared Terms
Effective g2



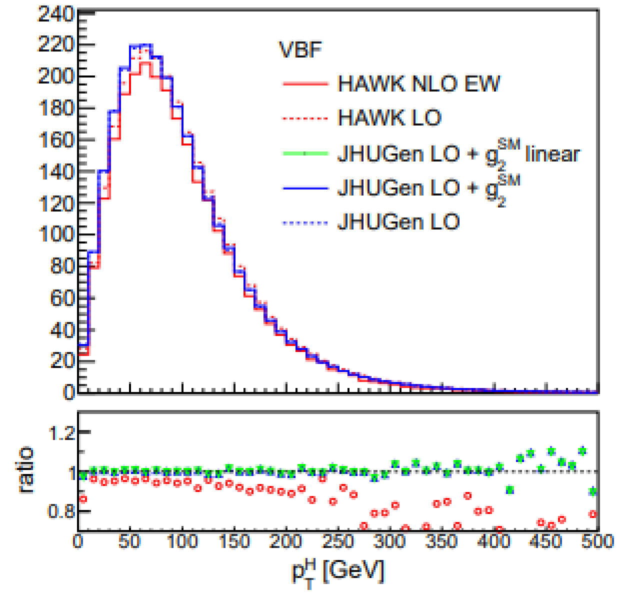
Squared terms for effective point-like couplings have different decay kinematics than NLO EW corrections

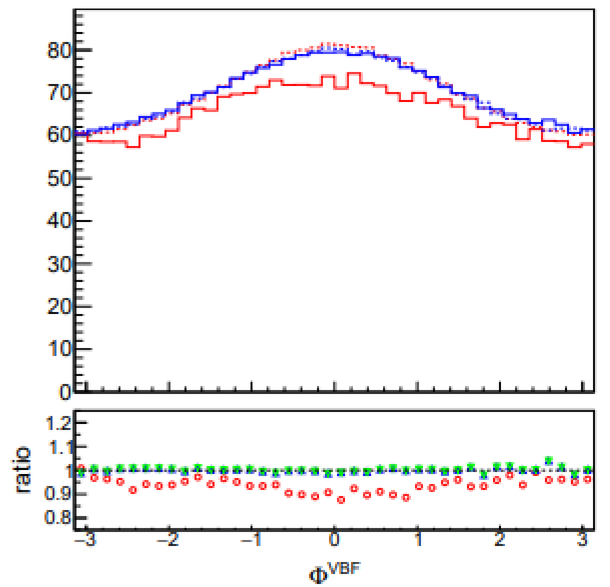
(4) NLO EW vs. Ad-Hoc

Type of Correction	Correction to SM
EW NLO (HAWK)	-6.7. % ≠
LO+Effective g2 (JHUGen)	+0.2 %
LO+Effective g2 (Linear Only)	+0.1 %

Effective SM EW corrections, do not account for NLO corrections to SM cross sections

$$g_2^{Z\gamma,\mathrm{SM}} = 0.00675 \quad g_2^{\gamma\gamma,\mathrm{SM}} = 0.00423$$





(5) Analytical Calculations

$g_{Xyy'} \times v$	ff	ZZ/WW	$\gamma\gamma$	$Z\gamma$	gg
H	m_f	$2m^2_{Z/W}$	$47\alpha_{\rm EM}/18\pi$	$C(94\cos^2\theta_W - 13)/9\pi$	$-\alpha_s/3\pi$
A	m_f	0	$4\alpha_{\rm EM}/3\pi$	$2C(8\cos^2\theta_W - 5)/3\pi$	$\alpha_s/2\pi$

MG (HC) arXiv:1306.6464.v3

SMEFTsim EW (SMHLOOP):

same sign

$c_\gamma^{SM} \propto \text{gHaa} < 0$

$c_{Z\gamma}^{SM} \propto \text{gHza} < 0$

Relative sign of $\gamma\gamma$ vs $Z\gamma$ was an issue which seems to get a general agreement now. The CP-odd part also checked by Werner Bernreuther and Long Chen

arXiv:1207.1093v3

$$c_g^{(SM)}(125\text{ GeV}) = 1\,, \quad c_\gamma^{(SM)}(125\text{ GeV}) = -6.48\,, \quad c_{Z\gamma}^{(SM)}(125\text{ GeV}) = -10.96 \quad (7)$$

$$+c_g \frac{\alpha_s}{12\pi v} h\, G^a_{\mu\nu} G^{a\,\mu\nu} + c_\gamma \frac{\alpha}{8\pi v} h\, F_{\mu\nu} F^{\mu\nu} + c_{Z\gamma} \frac{\alpha}{8\pi v s_w} h\, F_{\mu\nu} Z^{\mu\nu}$$

arXiv:1207.1093v2

$$c_{Z\gamma}^{(SM)}(125\text{ GeV}) = 5.48$$

Thanks to Ian Low for an update

opposite sign

Analytical calculations are now in agreement with Monte Carlo tools

Conclusion

Many useful tools for modelling EFT in the Higgs sector

We have good tools for EFT bases translation

-Allow for comparison of different EFT measurements

-Translations show that all tools are now consistent

Translations are only valid once all conventions are considered

- In this study, EFT effects only in HVV couplings are sorted out
- May be other examples in other EFT measurements
- Conventions need to be agreed upon or well documented