Shedding light on the Higgs: EFT modeling and sensitivity to Higgs couplings to virtual photons

18th workshop LHC Higgs WG

Dec 1st 2021

Savvas Kyriacou (JHU) for

Jeffrey Davis,[1] Andrei V. Gritsan,[1] Lucas S. Mandacarú Guerra,[1] Jeffrey Roskes,[1] and Markus Schulze[2]

[1] *Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA*

[2] *Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*

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Higgs couplings, EFT and virtual photons

- EFT bases and rotations
  - anomalous couplings, mass and weak eigenstate bases with SU(2)xU(1)
  - Motivation for HZγ/Hγγ couplings study
- EFT tools and comparisons
- Phenomenological study of anomalous Hγγ/HZγ couplings in multiple production and decay modes
- Projections @3 ab^{-1}
- SM NLO EW effects

arXiv:2109.13363

Constraining anomalous Higgs boson couplings to virtual photons

Jeffrey Davis,[1] Andrei V. Gritsan,[1] Lucas S. Mandacarú Guerra,[1]
Savvas Kyriacou,[1] Jeffrey Roskes,[1] and Markus Schulze[2]

[1] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[2] Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany

(Dated: September 27, 2021)

We present a study of Higgs boson production in vector boson fusion and in association with a vector boson and its decay to two vector bosons, with a focus on the treatment of virtual loops and virtual photons. Our analysis is performed with the JHU generator framework. Comparisons are made to several other frameworks, and the results are expressed in terms of an effective field theory.

Related talks:

J. Davis @LHC EFT WG
S. Kyriacou @ HIGGS 2021
A. Gritsan @ LHC WG

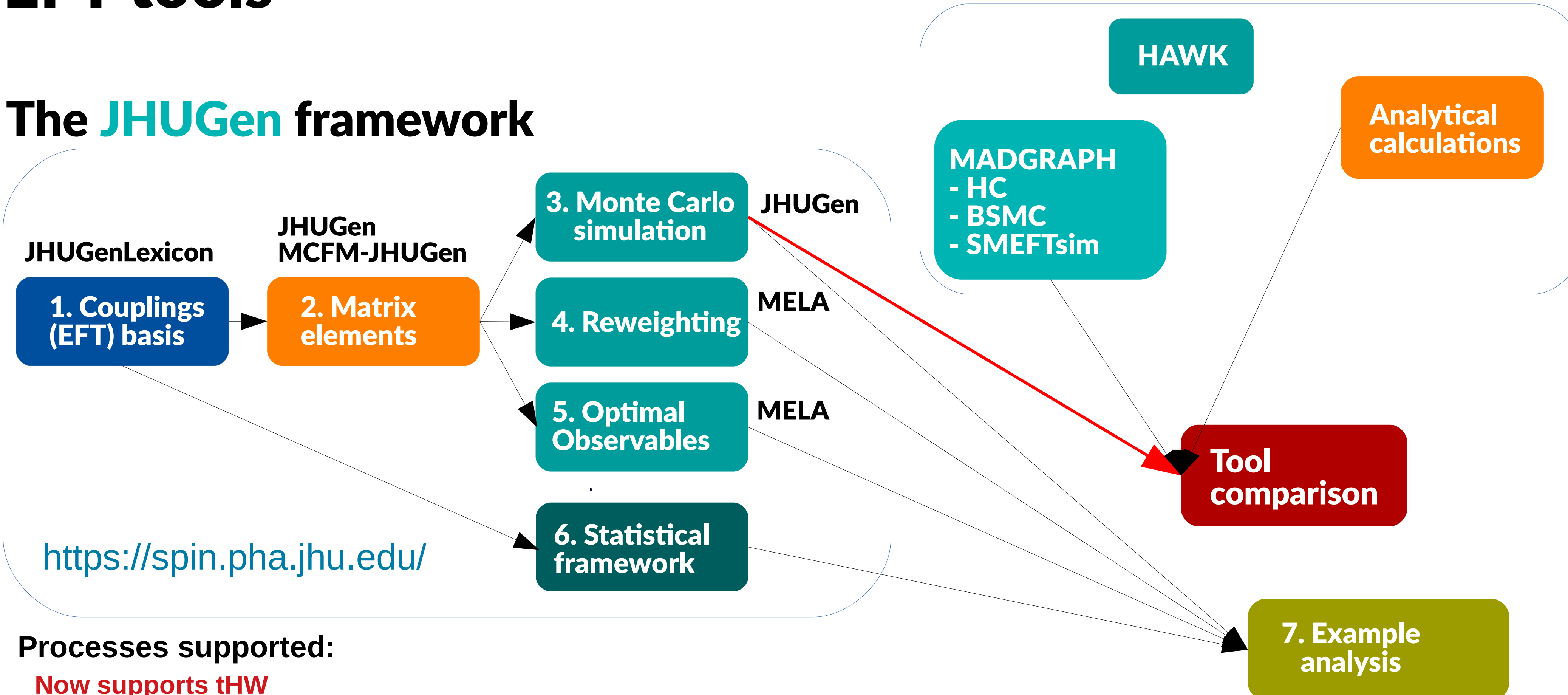
Related JHUGen talks:

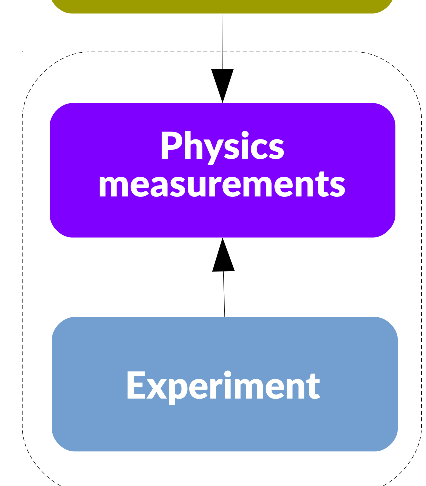
J.Davis at EPS-HEP2021
H.Roskes at LHC EFT WG
H.Roskes at Pheno 2020
M.Xiao at ICHEP 2020
U.Sarica at Higgs 2020
M.Schulze at LHC Higgs WG

EFT tools

Other EFT tools

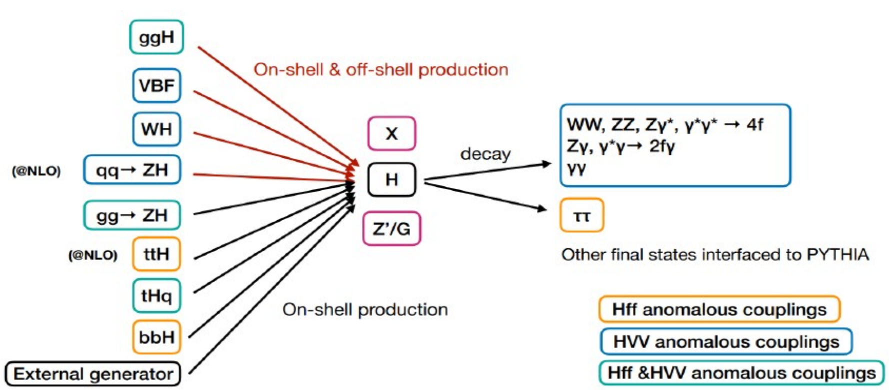
The JHUGen framework





Processes supported:

Now supports tHW



Framework allows:

- Detector level studies
- Optimal observables
- Robust simulation/reweighting

SMEFT operator bases

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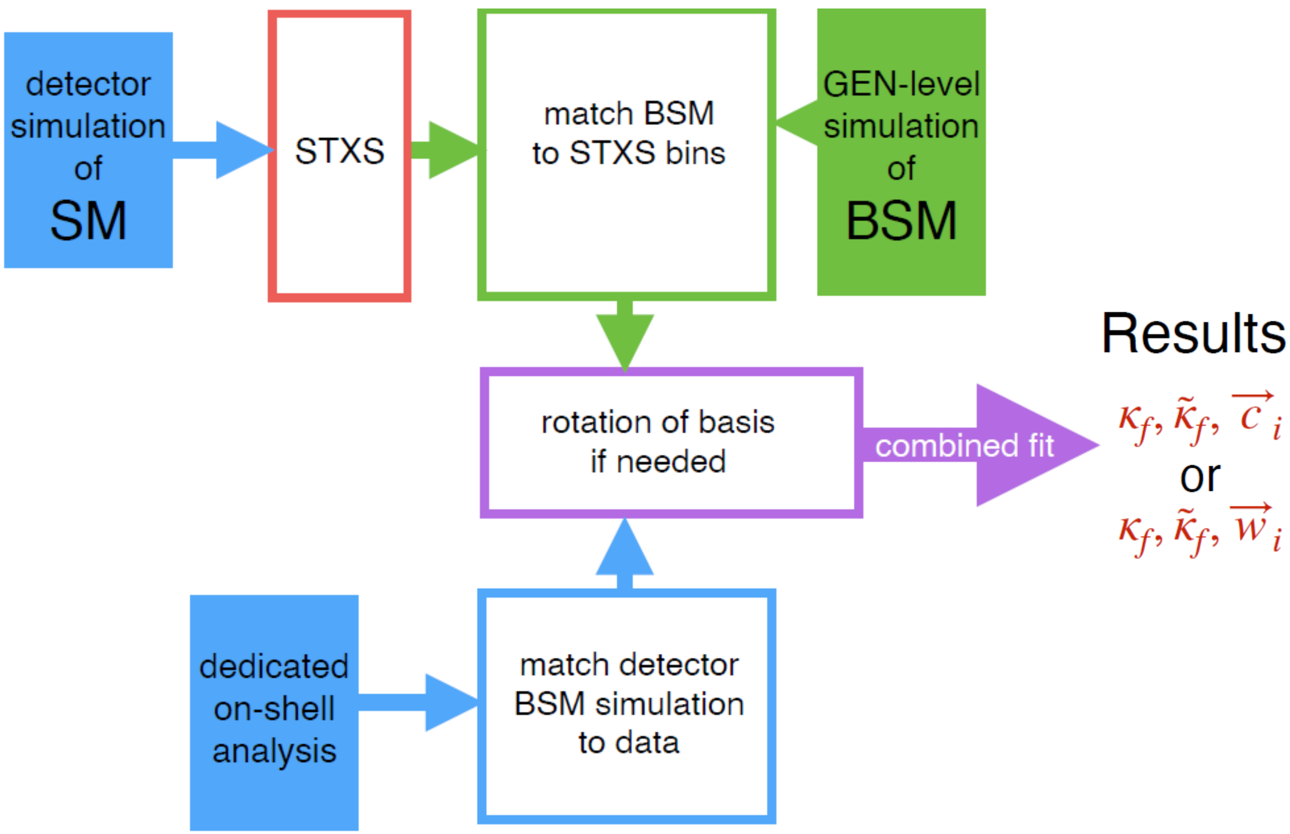

Warsaw basis

(B,W- has SU(2)xU(1) built-in)

- most convenient for theoretical computations
- Target basis for global fits

Higgs basis

(mass-eigenstate b. + SU(2)xU(1))

- **most direct map to experimental observables** (single operator for Hγγ coupling in Higgs , linear comb of many in Warsaw)
- CMS most recent: DOI: 10.1103/PhysRevD.104.052004

SILH basis

- Used in CMS: inspire:1774836

Results of measured couplings can be reported in both choices (@LO)

- Compare results
- Combine results (?)

Perform translation of results from Higgs to Warsaw basis as proof of principle + test tools

arXiv:2109.13363

A.C. in mass eigenstate basis

Most general HVV scat. amplitude parametrisation:

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$

$$+ \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM – tree level
CP even
CP odd

- **Consider SU(2)xU(1)*** → enforces relations between couplings → **Higgs basis**

$$\begin{aligned}
g_1^{WW} &= g_1^{ZZ} \\
g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\
g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\
\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2}, + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\
\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2}\right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}
\end{aligned}$$

4 + 4 independent HVV couplings

We focus on **Hγγ/HZγ** couplings

A.C. in weak + mass eigenstate basis

arXiv:2109.13363

$c_{HD} = -4c_T$
$c_{H\square} = c_H - c_T$

c_{BB}
c_{WW}
c_{WB}

$c_{\tilde{B}B}$
$c_{\tilde{W}W}$
$c_{\tilde{W}B}$

8 independent Warsaw b. couplings

4 + 4 independent Higgs b. couplings

Allows for transparent basis rotation

We use JHUGenLexicon to perform this translation

Focusing on **Hγγ/HZγ** couplings

$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w\left(C_{HW} - C_{HB}\right) + \frac{1}{2}\left(s_w^2 - c_w^2\right)C_{HWB}\right),$$

$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 C_{HB} + s_w^2 C_{HW} - s_w c_w C_{HWB}\right),$$

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

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

Decomposition of Warsaw coupl. in terms of cross-section contribution from Higgs basis couplings in paper Tables I-VI and back up

+ full Higgs → Warsaw relations for all HVV couplings in backup

Comparing EFT tools

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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

11/22/2021

JEFFREY DAVIS

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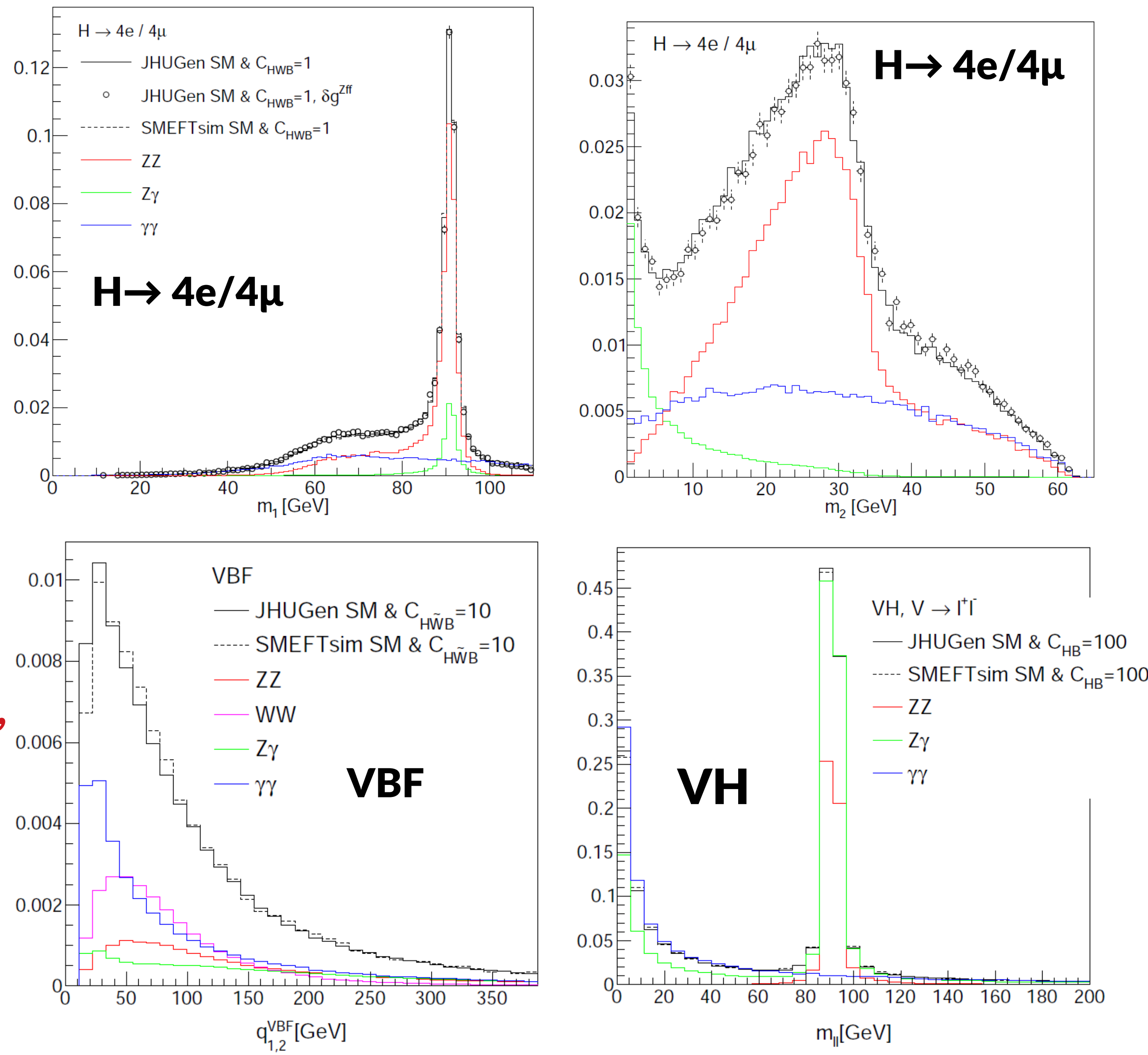
See detailed talk by
J. Davis @LHC EFT WG

Anomalous γγ/Zγ couplings

arXiv:2109.13363

- Decompose SM + Warsaw a.c. production and decay processes to individual anomalous contributions (ZZ,WW,γγ,Zγ,)
- Comparison to SMEFTsim (agreement taking into account sign conventions)
- **A.C. Zγ/γγ couplings enhanced in low m2 for decay, low q^2 in VBF and low $m_{l^+l^-}$ in VH**



Γ_H modification from A.C.

arXiv:2109.13363

$$\sigma(i \to H \to f) \propto \frac{\left(\sum \alpha_{jk}^{(i)} a_j a_k\right)\left(\sum \alpha_{lm}^{(f)} a_l a_m\right)}{\Gamma_{\text{tot}}}$$

Total cross-section for Higgs on-shell depended on **Higgs total width**

Γ_H modified by anomalous couplings!!

$$\Gamma_{\text{known}} = \Gamma_{\text{tot}}^{\text{SM}} \times \sum_f \left(\frac{\Gamma_f^{\text{SM}}}{\Gamma_{\text{tot}}^{\text{SM}}} \times \frac{\Gamma_f}{\Gamma_f^{\text{SM}}}\right) = \sum_f \Gamma_f^{\text{SM}} R_f$$

Study and parameterize the width modification from γγ/Zγ a.c. + others

$$\begin{aligned} R_{\gamma\gamma} = \; & 1.60932 \left(\frac{g_1^{WW}}{2}\right)^2 - 0.69064 \left(\frac{g_1^{WW}}{2}\right)\kappa_t + 0.00912 \left(\frac{g_1^{WW}}{2}\right)\kappa_b - 0.49725 \left(\frac{g_1^{WW}}{2}\right)(N_c Q^2 \kappa_Q) \\ & + 0.07404\,\kappa_t^2 + 0.00002\,\kappa_b^2 - 0.00186\,\kappa_t\kappa_b \\ & + 0.03841\,(N_c Q^2 \kappa_Q)^2 + 0.10666\,\kappa_t\,(N_c Q^2 \kappa_Q) - 0.00136\,\kappa_b\,(N_c Q^2 \kappa_Q) \\ & + 0.20533\,\tilde\kappa_t^2 + 0.00006\,\tilde\kappa_b^2 - 0.00300\,\tilde\kappa_t\tilde\kappa_b \\ & + 0.10252\,(N_c Q^2 \tilde\kappa_Q)^2 + 0.29018\,\tilde\kappa_t\,(N_c Q^2 \tilde\kappa_Q) - 0.00202\,\tilde\kappa_b\,(N_c Q^2 \tilde\kappa_Q)\,. \end{aligned}$$

↓

$$R_{\gamma\gamma} \simeq \frac{1}{\left(g_2^{\gamma\gamma,\text{SM}}\right)^2}\left[\left(g_2^{\gamma\gamma,\text{SM}} + g_2^{\gamma\gamma}\right)^2 + \left(g_4^{\gamma\gamma}\right)^2\right]$$

All the new Rf functions in paper

channel (f)	$\Gamma_f^{\text{SM}}/\Gamma_{\text{tot}}^{\text{SM}} = \mathcal{B}_f^{\text{SM}}$	$\Gamma_f/\Gamma_f^{\text{SM}} = R_f(\vec{g}_j)$
$H \to b\bar{b}$	0.5824	$(\kappa_b^2 + \tilde\kappa_b^2)$
$H \to W^+W^-$	0.2137	$R_{WW}(\vec{g}_j)$
$H \to gg$	0.08187	$R_{gg}(\vec{g}_j)$
$H \to \tau^+\tau^-$	0.06272	$(\kappa_\tau^2 + \tilde\kappa_\tau^2)$
$H \to c\bar{c}$	0.02891	$(\kappa_c^2 + \tilde\kappa_c^2)$
$H \to ZZ/Z\gamma^*/\gamma^*\gamma^*$	0.02619	$R_{ZZ/Z\gamma^*/\gamma^*\gamma^*}(\vec{g}_j)$
$H \to \gamma\gamma$	0.002270	$R_{\gamma\gamma}(\vec{g}_j)$
$H \to Z\gamma$	0.001533	$R_{Z\gamma}(\vec{g}_j)$
$H \to \mu^+\mu^-$	0.0002176	$(\kappa_\mu^2 + \tilde\kappa_\mu^2)$

Pheno study of Hγγ/HZγ in H→ 4l

How?

→ **virtual photons in production and decay**

- Previous studies of sensitivity in H→4l[1] and H→Zγ/γγ[2] decay and experimental measurements exist
- Study production sensitivity
- Investigate sensitivity in γH,H→ 4l associated production
- Combine from onshell photon measurements

References:
[1] arXiv:1411.3441
[2] arXiv:1902.00134

Setting constraints

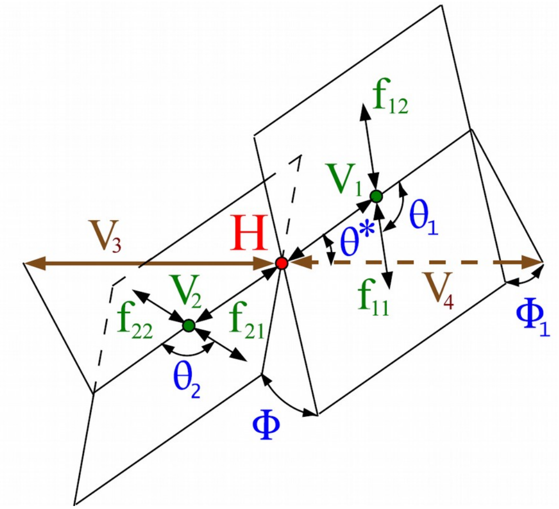
Construct and calibrate dedicated MELA discriminants:

$$\mathcal{D}_{\rm alt}(\Omega) = \frac{\mathcal{P}_{\rm sig}(\Omega)}{\mathcal{P}_{\rm sig}(\Omega) + \mathcal{P}_{\rm alt}(\Omega)},$$

$$\mathcal{D}_{\rm int}(\Omega) = \frac{\mathcal{P}_{\rm int}(\Omega)}{2\sqrt{\mathcal{P}_{\rm sig}(\Omega)\,\mathcal{P}_{\rm alt}(\Omega)}},$$

$$\mathcal{D}_{g2}^{Z\gamma},\ \mathcal{D}_{g2}^{\gamma\gamma},\ \mathcal{D}_{g4}^{Z\gamma},\ \text{and}\ \mathcal{D}_{g4}^{\gamma\gamma}$$

$$\mathcal{D}_{\rm int}^{Z\gamma},\ \mathcal{D}_{\rm int}^{\gamma\gamma},\ \mathcal{D}_{CP}^{Z\gamma},\ \mathcal{D}_{CP}^{\gamma\gamma}$$



Use both decay or production and decay+production information

Fix ZZ/WW/Λ1/Λ1Zγ a.c. couplings, profile γγ/Zγ

Apply $|m_{ll}|>12$ GeV , $pt_{lept} > 5$GeV

Categorize events in **6 categories** x **3 decay channels (4e, 4μ, 2e2μ)**

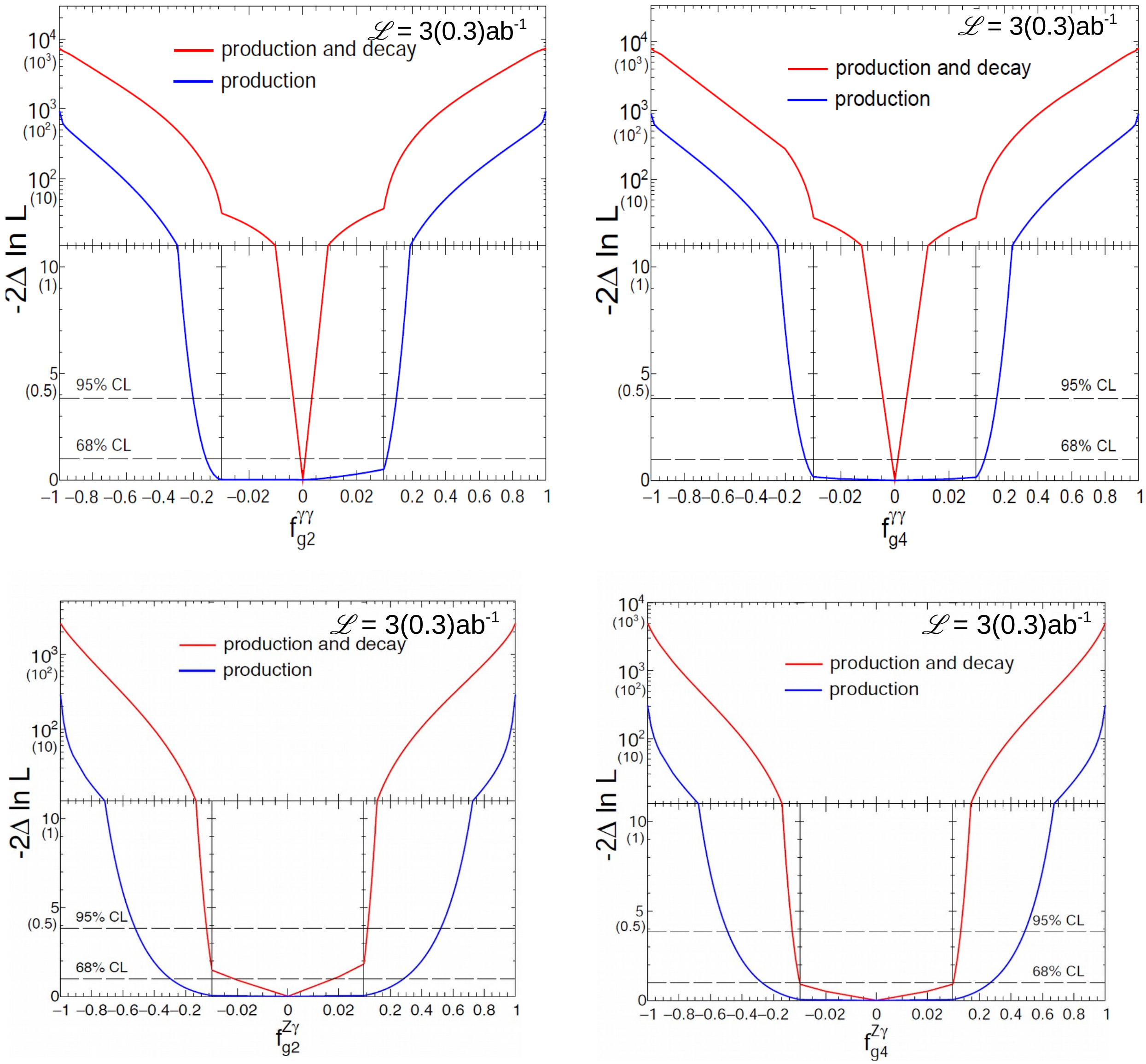
As in previous JHUGen pheno papers:

$$f_{gn} = \frac{g_n^2 \alpha_{nn}^{(f)}}{\sum_j g_j^2 \alpha_{jj}^{(f)}}\ \mathrm{sign}\left(\frac{g_n}{g_1}\right)$$

Coupling g_n	Fraction f_{gn}	$H \to 2e2\mu$ $\alpha_{nn}^{(f)}/\alpha_{11}$	VBF $\alpha_{nn}^{(i)}/\alpha_{11}$	$ZH/\gamma^* H$ $\alpha_{nn}^{(i)}/\alpha_{11}$
$g_2^{\gamma\gamma}$	$f_{g2}^{\gamma\gamma}$	355.1	65.04	2.330
$g_2^{Z\gamma}$	$f_{g2}^{Z\gamma}$	438.5	24.89	50.51
$g_4^{\gamma\gamma}$	$f_{g4}^{\gamma\gamma}$	348.0	64.28	1.790
$g_4^{Z\gamma}$	$f_{g4}^{Z\gamma}$	356.7	23.44	32.50
g_4^{ZZ}	f_{g4}^{ZZ}	0.153	11.27	47.94

We expect decay information to dominate sensitivity based on cross-section ratios for γγ/Zγ

fai scans for Zγ/γγ



> **Decay dominates scans**

> **No "prod valley" feature as in HZZ couplings**

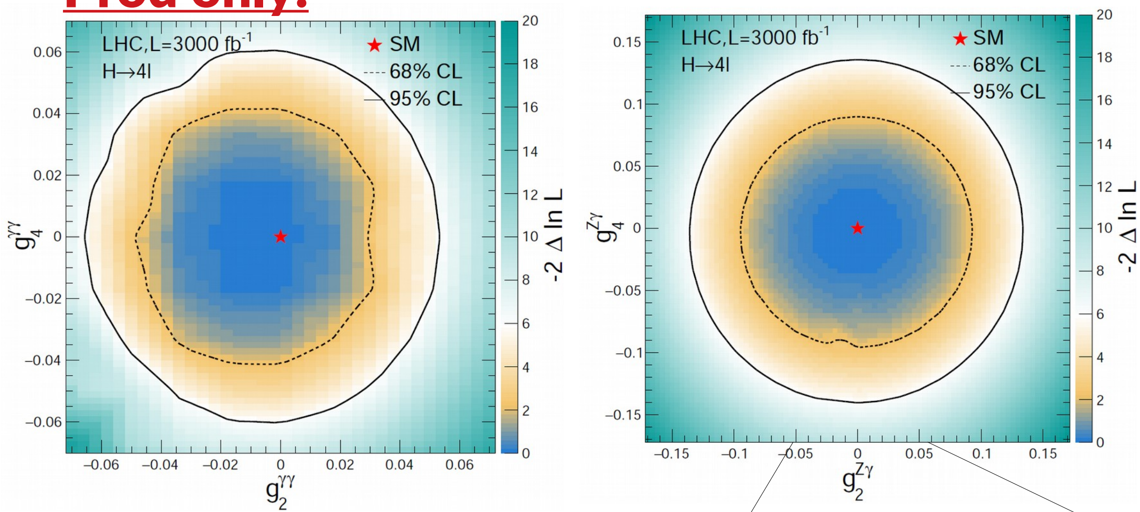
> **Asymmetries observed between neg. and pos. gi values.**

> **HZγ not as tight as Hγγ**

Amplitude couplings scans : Prod vs Dec

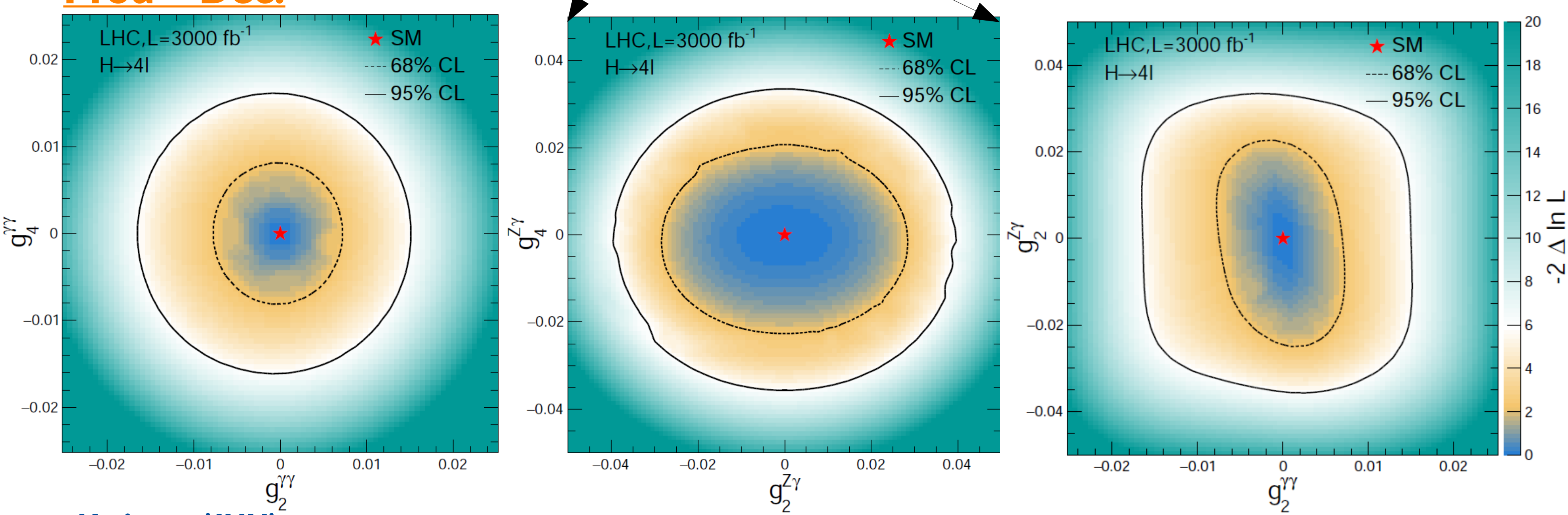
arXiv:2109.13363

Prod only:



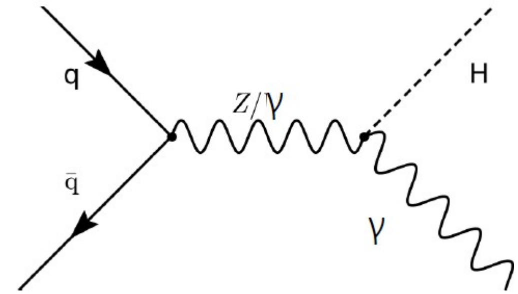
- Tighter constraints in decay
- **Production** constraints can be improved
  - Consider combining all available decay channels
- Tighter constraints for Hγγ than HZγ

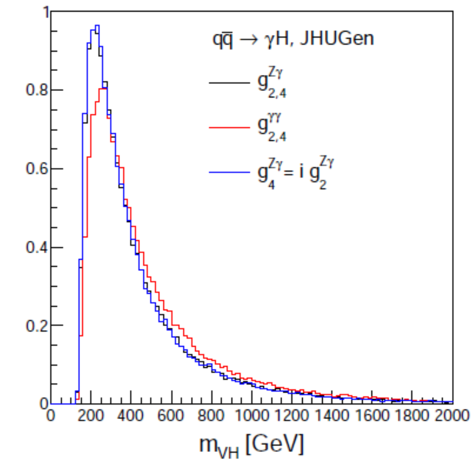
Prod + Dec:



γH production at the LHC

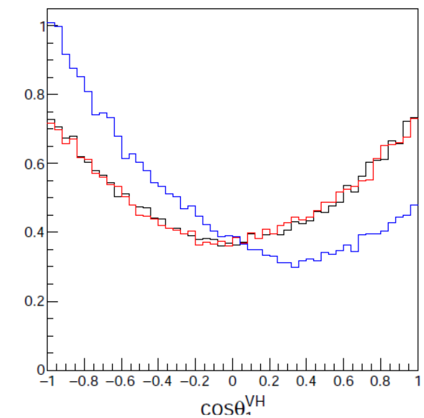
arXiv:2109.13363



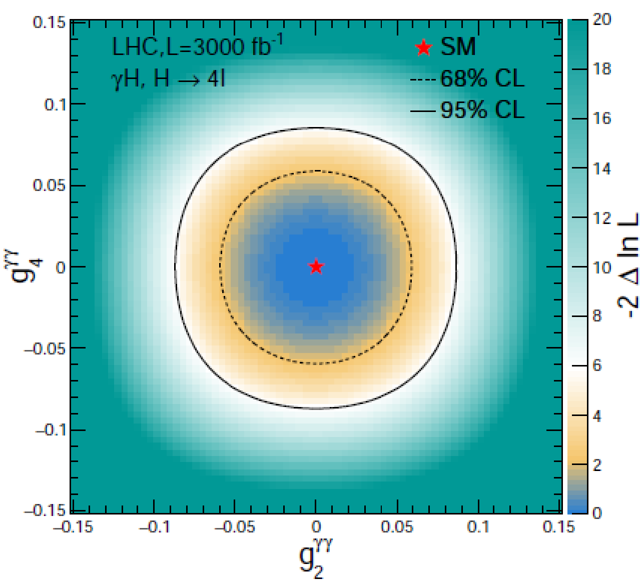


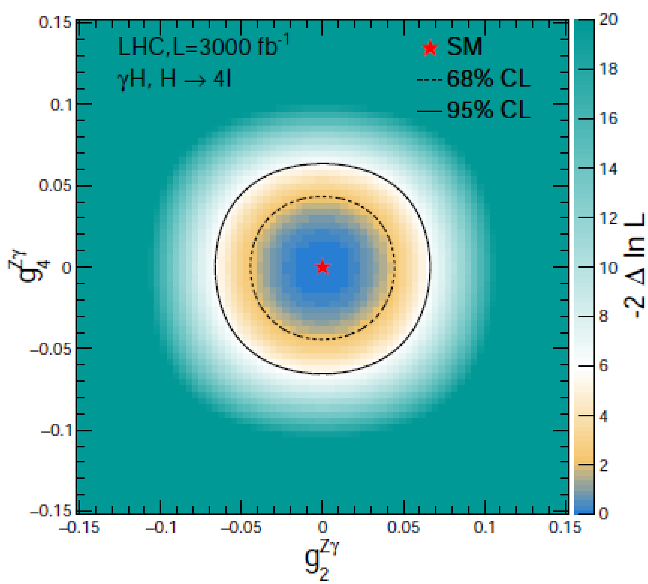
Associated γH,(H→4l) sensitive to Hγγ,HZγ couplings.
Background greatly supressed by H→ 4l + photon req.
SM ~0.1 events signal events expected at $3ab^{-1}$

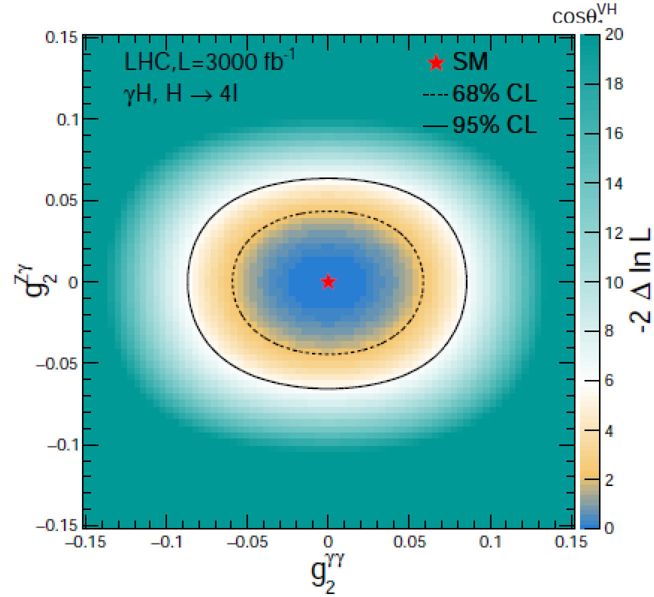
A.C. can enhance the yield well above the background and SM expectation
No such measurement performed at the LHC up to now!



Perform simple counting experiment and constrain Hγγ/HZγ couplings
> Apply simple photon pt cut 400GeV to suppress background
> Constraints looser than H→4l







Constraints from onshell photons

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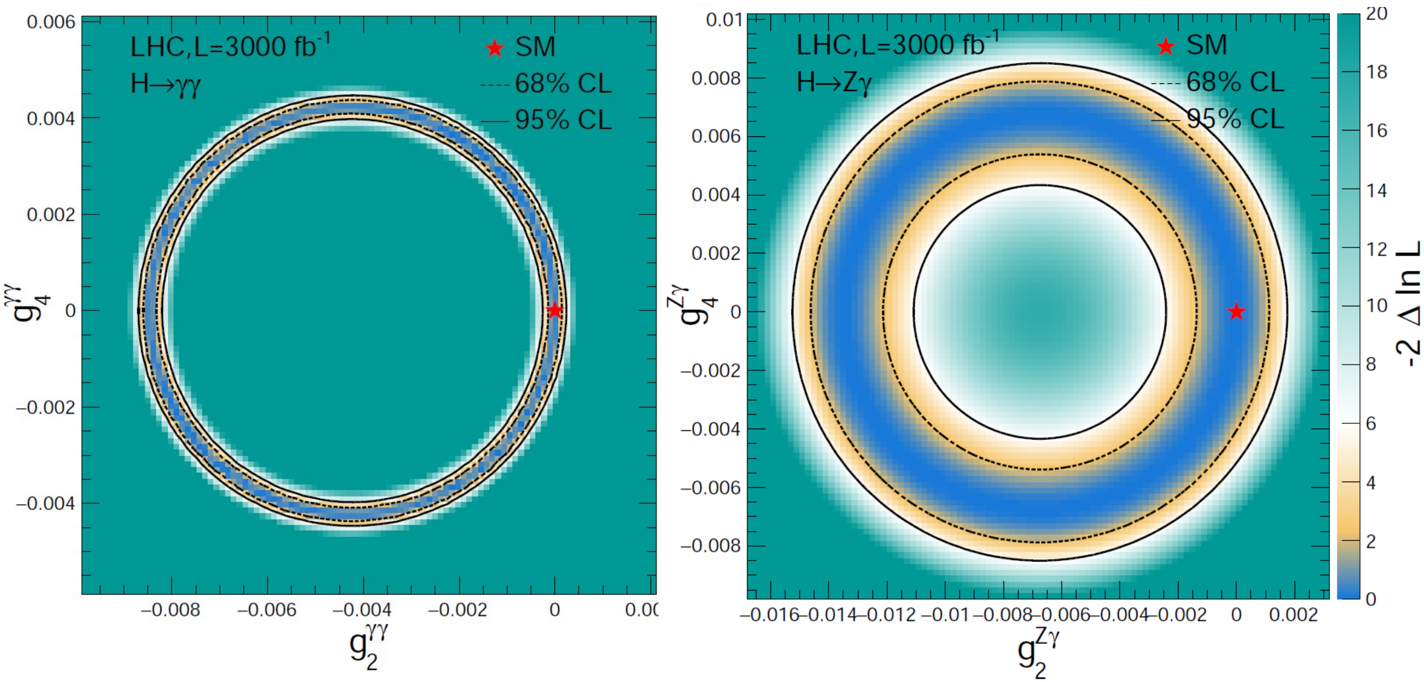


$$R_{Z\gamma} \simeq 1.00 \pm 0.24$$
$$R_{\gamma\gamma} \simeq 1.00 \pm 0.05$$

Constrain values from arxiv:1902.00134

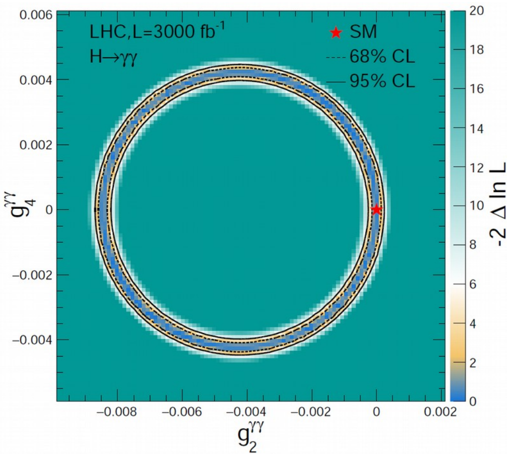
$$g_2^{Z\gamma,\mathrm{SM}} = 0.00675 \quad g_2^{\gamma\gamma,\mathrm{SM}} = 0.00423$$

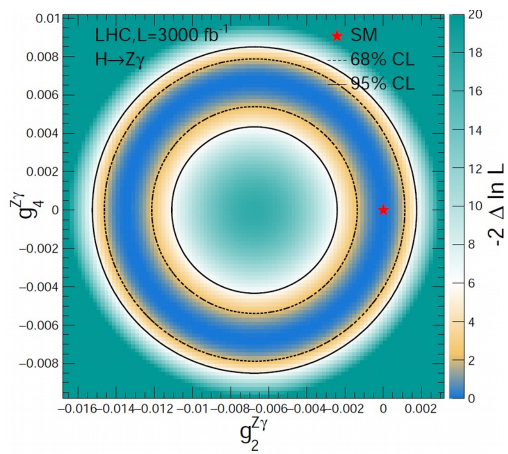
- Parameterize Rγγ - RZγ with a.c.
- Construct 2D likelihood scans

- Tight constraints
- Degenerate minima

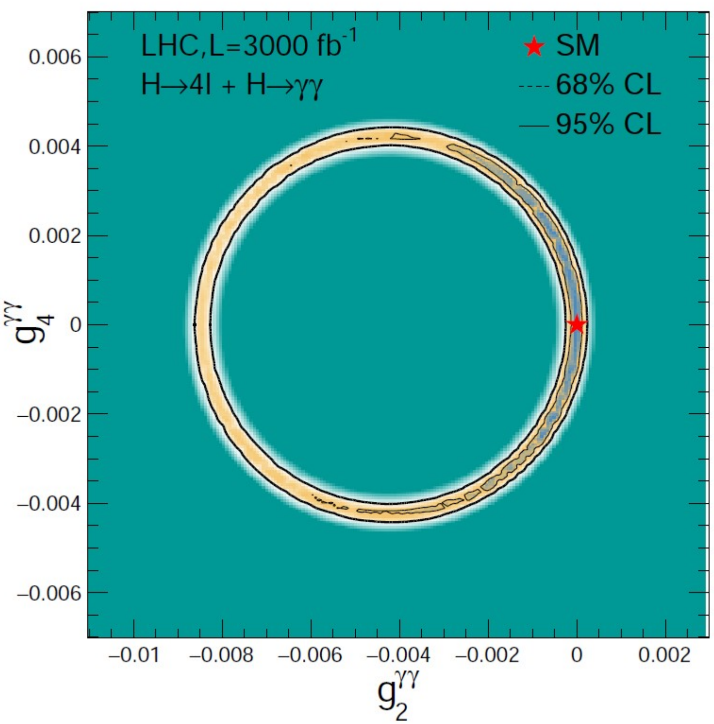
$$R_{Z\gamma} \simeq \frac{1}{\left(g_2^{Z\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{Z\gamma,\mathrm{SM}} + g_2^{Z\gamma}\right)^2 + \left(g_4^{Z\gamma}\right)^2\right]$$
$$R_{\gamma\gamma} \simeq \frac{1}{\left(g_2^{\gamma\gamma,\mathrm{SM}}\right)^2}\left[\left(g_2^{\gamma\gamma,\mathrm{SM}} + g_2^{\gamma\gamma}\right)^2 + (g_4^{\gamma\gamma})^2\right]$$

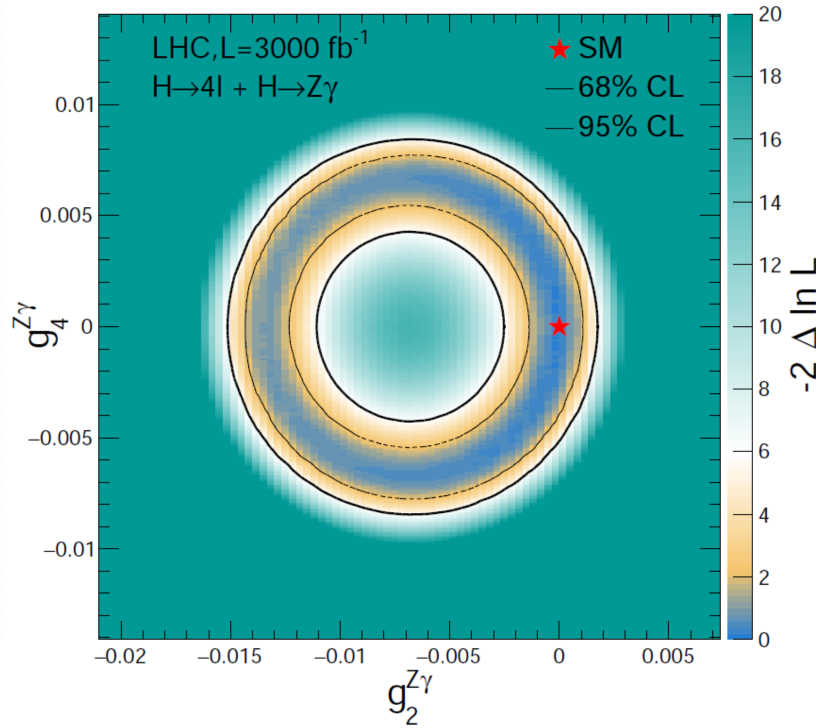
Combination: γH/VBF/VH/H→4l + H→γγ/Zγ





Inclusion of 4l :





> 4l information **resolves the degenerate minima** in the ring for γγ

> 4l information change **1σ** band thickness in the ring

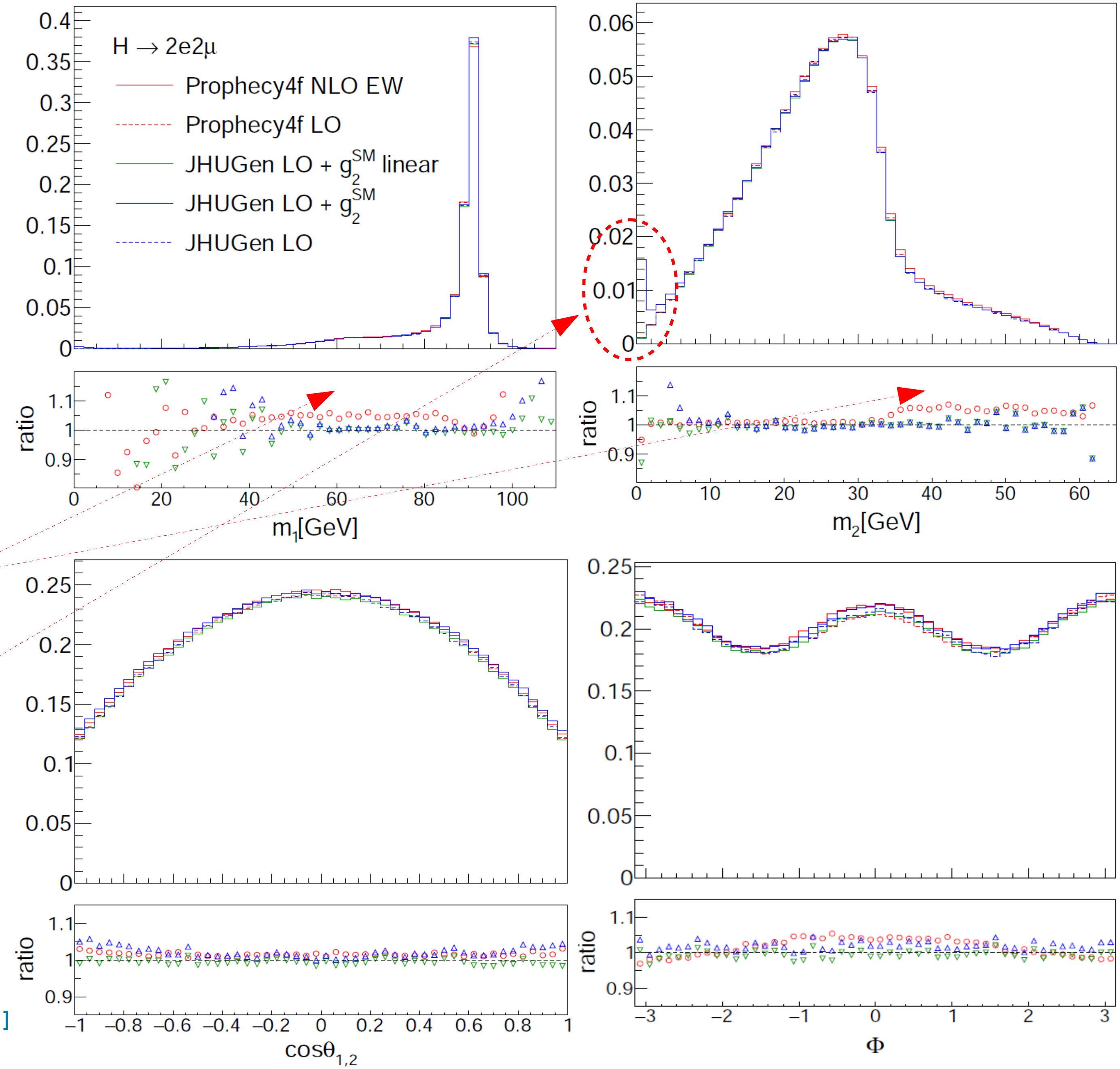
EW NLO Effects in H→ 2e2μ

arXiv:2109.13363

Use **PROPHECY**[1] and **HAWK**[2] to model **SM NLO EW** corrections

Compare to Ad. Hoc. ac couplings as used in somecases to model NLO EW effects (SMEFTSim (SMHLOOP=1))

- Effect present for events where leading Z is offshell
- Majority of the events unaffected
- Quadratic A.C. terms enhanced at low q^2



References:

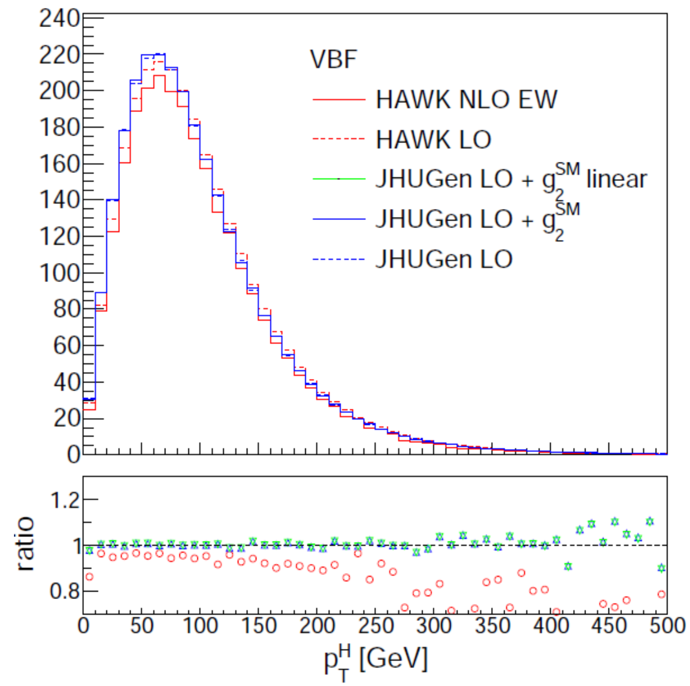
[1]Phys.Rev.D 74 (2006) 013004 [hep-ph/0604011]

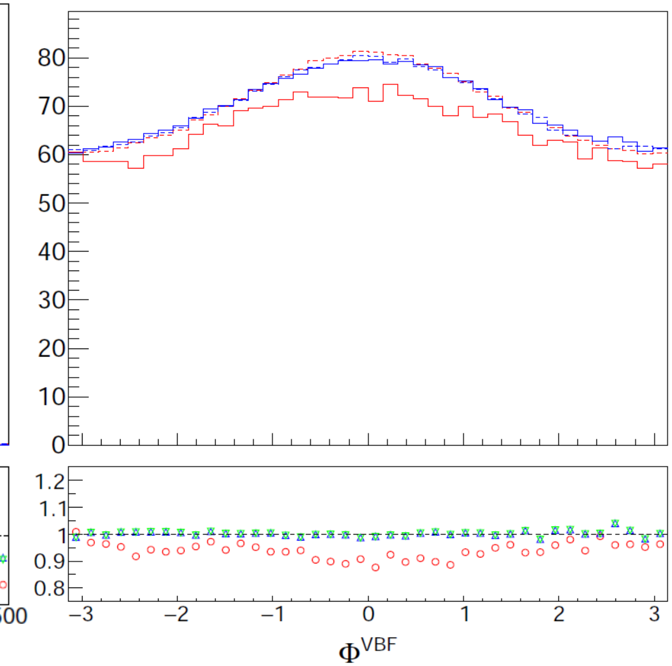
[2]arXiv:1412.5390

arXiv:2109.13363

SM EW NLO Effects in Production

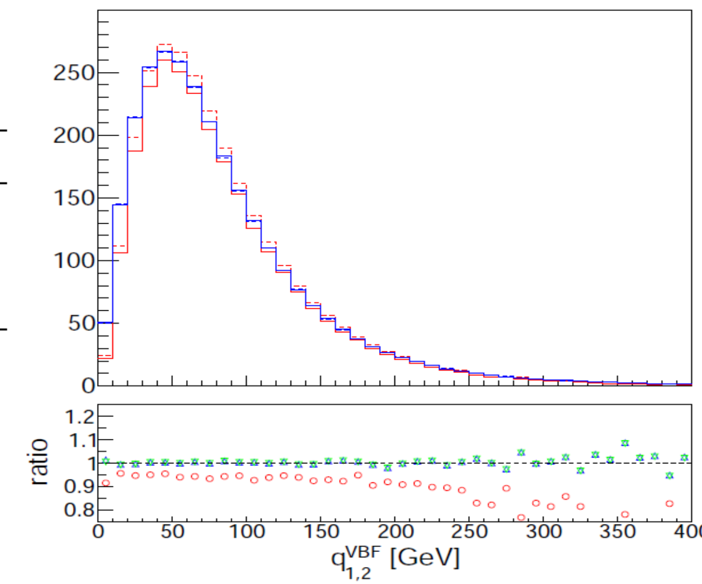
- Overall **negative effect** in VBF production
- Corrections show pt/energy dependence
- corrections Flat in terms of angular dependencies
- Pseudo-EW corrections are minuscule
- Similar effects in ZH (see back-up)





Incl. Cross-section NLO effects:

	EW NLO/LO	(LO + g_2^{SM})/LO	(LO + g_2^{SM} linear)/LO
$H \to 4\ell$	$+1.5\%$	$+2.0\%$	-0.6%
VBF	-6.7%	$+0.2\%$	$+0.1\%$
$Z(\to \ell^+\ell^-)H$	-6.4%	-1.2%	-1.2%



Pseudo EW corrections fail to decribe correctly NLO effects both in production and decay

Summary

We study anomalous Hγγ and HZγ couplings using the JHUGen framework

- JHUGenLexicon allows for rotations between basis as demonstrated (Higgs →Warsaw)
- Comparison of EFT simulation in JHUGen Framework vs SMEFTsim, HAWK + other tools – Agreement once all conventions and asumptions are taken into account.
- Effects in production and decay for a number of processes studied

An EFT analysis is setup with dedicated JHUGen MELA discriminants in H→4l

Sensitivity studies with projections for L =3 ab^{-1}

Decay only, Production only and Combined analyses

- **Production information sensitivity first time checked**
- Decay dominates scans vs Production
- Combination of multiple H decay channels can enhance sensitivity from production
- 4l measurements not as sensitive as in H→γγ H→ Zγ

First sensitivity of photon+H(H→4l) search is presented

Comparing to STXS:

> gammaH production is not included

> VBF/VH kinematic production information only, less sensitive to Hγγ/HZγ couplings than H→ VV→ 4f

> lacking CP information in VBF/VH/H→ VV

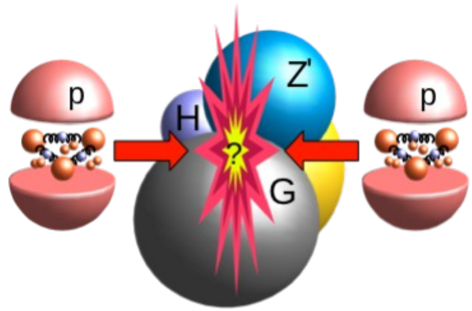
Study of SM NLO EW effects in decay and production

> may become important soon, approximate corrections do not work

End

The JHUGen framework

https://spin.pha.jhu.edu/



- JHUGenerator
- JHUGen MELA
- JHUGen Lexicon

MC Generator based on the papers:

"Spin Determination of Single-Produced Resonances at Hadron Colliders"
Yanyan Gao, Andrei V. Gritsan, Zijin Guo, Kirill Melnikov, Markus Schulze, and Nhan V. Tran
http://arxiv.org/abs/1001.3396

"On the Spin and Parity of a Single-Produced Resonance at the LHC"
Sara Bolognesi, Yanyan Gao, Andrei V. Gritsan, Kirill Melnikov, Markus Schulze, Nhan V. Tran, and Andrew Whitbeck
http://arxiv.org/abs/1208.4018

"Constraining anomalous HVV interactions at proton and lepton colliders"
Ian Anderson, Sara Bolognesi, Fabrizio Caola, Yanyan Gao, Andrei V. Gritsan, Christopher B. Martin, Kirill Melnikov, Markus Schulze, Nhan V. Tran, Andrew Whitbeck, and Yaofu Zhou
http://arxiv.org/abs/1309.4819

"Constraining anomalous Higgs boson couplings to the heavy flavor fermions using matrix element techniques"
Andrei V. Gritsan, Raoul Rontsch, Markus Schulze, and Meng Xiao
http://arxiv.org/abs/1606.03107

"New features in the JHU generator framework: constraining Higgs boson properties from on-shell and off-shell production"
Andrei V. Gritsan, Jeffrey Roskes, Ulascan Sarica, Markus Schulze, Meng Xiao, and Yaofu Zhou
http://arxiv.org/abs/2002.09888

"Probing the CP structure of the top quark Yukawa coupling: Loop sensitivity vs. on-shell sensitivity"
Till Martini, Ren-Qi Pan, Markus Schulze, and Meng Xiao
https://arxiv.org/abs/2104.04277

"Constraining anomalous Higgs boson couplings to virtual photons"
Jeffrey Davis, Andrei V. Gritsan, Lucas S. Mandacaru Guerra, Savvas Kyriacou, Jeffrey Roskes, and Markus Schulze
https://arxiv.org/abs/2109.13363

contacts: Jeffrey Davis ,Jeffrey (Heshy) Roskes,Ulascan Sarica,Markus Schulze

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*************************************************************************************
*                            JHU Generator v7.5.0                                   *
*************************************************************************************
*                                                                                   *
*   Spin and parity determination of single-produced resonances at hadron colliders *
*                                                                                   *
*         I. Anderson, S. Bolognesi, F. Caola, J. Davis, Y. Gao, A. Gritsan,        *
*          Z. Guo, C. Martin, K. Melnikov, R. Rontsch, H. Roskes, U. Sarica,        *
*                 M. Schulze, N. Tran, A. Whitbeck, M. Xiao, Y. Zhou                *
*              Phys.Rev. D81 (2010) 075022;  arXiv:1001.3396  [hep-ph],             *
*              Phys.Rev. D86 (2012) 095031;  arXiv:1208.4018  [hep-ph],             *
*              Phys.Rev. D89 (2014) 035007;  arXiv:1309.4819  [hep-ph],             *
*              Phys.Rev. D94 (2016) 055023;  arXiv:1606.03107 [hep-ph],             *
*              Phys.Rev. D102 (2020) 056022; arXiv:2002.09888 [hep-ph],             *
*                                            arXiv:2104.04277 [hep-ph].             *
*                                                                                   *
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See also talks by:

- J.Davis at EPS-HEP2021
- H.Roskes at LHC EFT WG
- H.Roskes at Pheno 2020
- M.Xiao at ICHEP 2020
- U.Sarica at Higgs 2020
- A.Gritsan at LHC Higgs WG
- M.Schulze at LHC Higgs WG

JHUGenerator

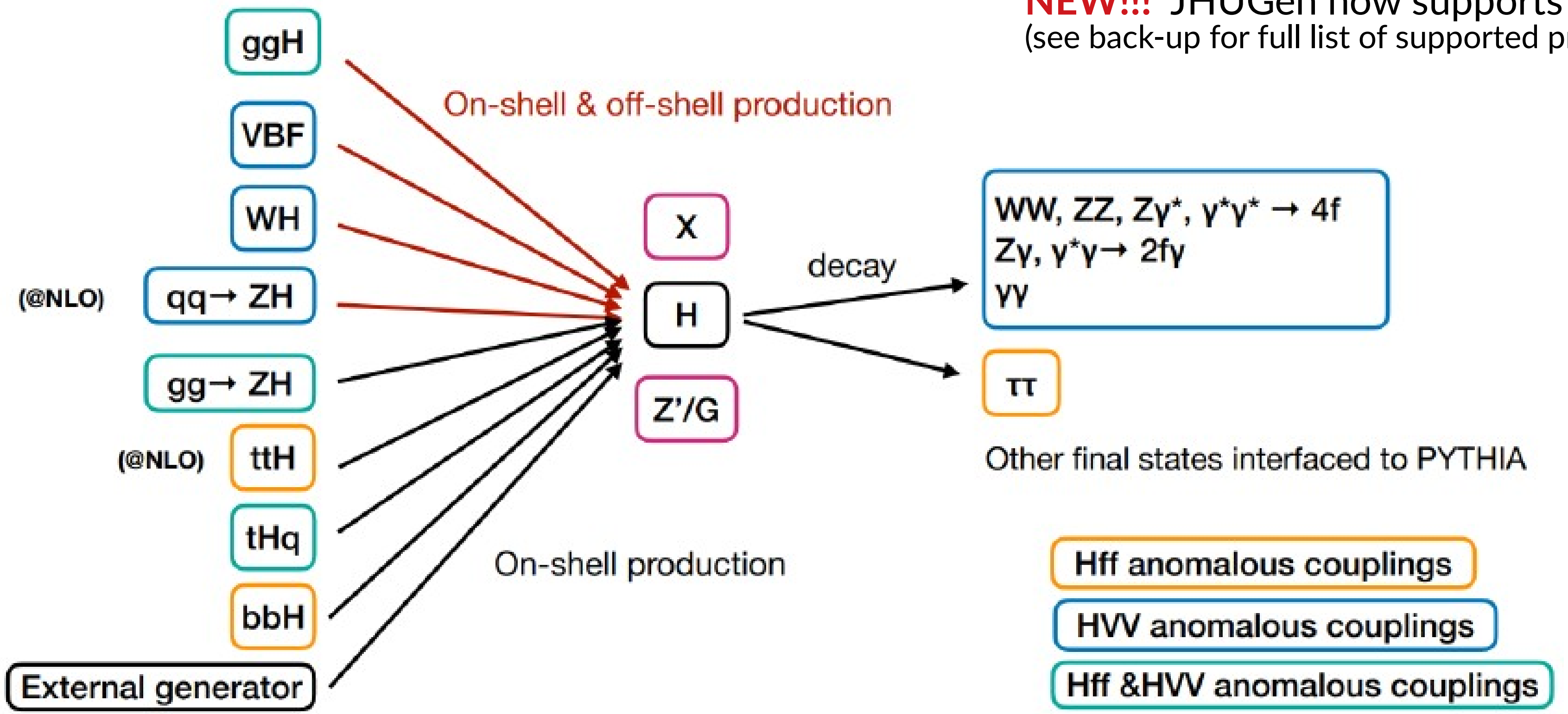
Framework allows:

- Detector level studies
- Optimal observables
- Robust simulation/reweighting

NEW!!! JHUGen now supports the tWH process

(see back-up for full list of supported processes)

Processes supported:



Symmetries and more...

- One can consider Zγ and γγ couplings well constrained
- **Custodial symmetry**
- **Consider $g^{WW} = g^{ZZ}$**

$$
\begin{aligned}
g_1^{WW} &= g_1^{ZZ} \\
g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\
g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\
\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\
\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} \right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}
\end{aligned}
$$

Or...

5 independent HVV couplings

- **Consider SU(2)xU(1)** → enforces relations between couplings:

$$
\begin{aligned}
g_1^{WW} &= g_1^{ZZ} \\
g_2^{WW} &= c_w^2 g_2^{ZZ} + s_w^2 g_2^{\gamma\gamma} + 2 s_w c_w g_2^{Z\gamma}, \\
g_4^{WW} &= c_w^2 g_4^{ZZ} + s_w^2 g_4^{\gamma\gamma} + 2 s_w c_w g_4^{Z\gamma}, \\
\frac{\kappa_1^{WW}}{(\Lambda_1^{WW})^2}(c_w^2 - s_w^2) &= \frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + 2 s_w^2 \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} + 2\frac{s_w}{c_w}(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}, \\
\frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2}(c_w^2 - s_w^2) &= 2 s_w c_w \left(\frac{\kappa_1^{ZZ}}{(\Lambda_1^{ZZ})^2} + \frac{g_2^{\gamma\gamma} - g_2^{ZZ}}{M_Z^2} \right) + 2(c_w^2 - s_w^2)\frac{g_2^{Z\gamma}}{M_Z^2}
\end{aligned}
$$

4 independent HVV couplings

Warsaw ↔ Higgs basis relations

arXiv:2109.13363

CP even (VV ,gg couplings)

$$\delta c_w = -c_H - \frac{4g^2g'^2}{g^2-g'^2}c_{WB} + \frac{4g^2}{g^2-g'^2}c_T - \frac{3g^2+g'^2}{g^2-g'^2}\delta v\,,$$

$$\delta c_z = -c_H - 3\delta v\,,$$

$c_{gg} = c_{GG}$, (free parameter in present VV scans)

$$c_{ww} = c_{WW}\,,$$

$$c_{zz} = \frac{g^4c_{WW} + 4g^2g'^2c_{WB} + g'^4c_{BB}}{(g^2+g'^2)^2}\,,$$

$$c_{z\gamma} = \frac{g^2c_{WW} - 2(g^2-g'^2)c_{WB} - g'^2c_{BB}}{g^2+g'^2}\,,$$

$$c_{\gamma\gamma} = c_{WW} + c_{BB} - 4c_{WB}\,,$$

$$c_{w\Box} = \frac{2}{g^2-g'^2}\left[g'^2c_{WB} - c_T + \delta v\right],$$

$$c_{z\Box} = -\frac{2}{g^2}\left[c_T - \delta v\right],$$

$$c_{\gamma\Box} = \frac{2}{g^2-g'^2}\left[(g^2+g'^2)c_{WB} - 2c_T + 2\delta v\right].$$

: Independent ZZ coupling

: independent γγ/Zγ couplings

: Dependent coupling

Rosetta
arXiv:1508.05895

Custodial symmetry fixes δcz and δcw:

$$\delta c_w = \delta c_z + 4\delta m\,,$$

$$> \delta v = -g^2 c_{WB} + \frac{g^2}{g'^2}c_T$$

see presentation by Jeff :
https://indico.cern.ch/event/922767/contributions/3955274/attachments/2077970/3494832/Relating_and_validating_EFT_bases_and_symmetries_in_Higgs_studies.pdf

(Important choice that affects the rotation relations)

SU(2)xU(1) enforces relations between AC ww to AC zz

$$c_{ww} = c_{zz} + 2s_\theta^2 c_{z\gamma} + s_\theta^4 c_{\gamma\gamma}\,,$$

$$c_{w\Box} = \frac{g^2c_{z\Box} + g'^2c_{zz} - (g^2-g'^2)s_\theta^2c_{z\gamma} - g^2s_\theta^4c_{\gamma\gamma}}{g^2-g'^2}\,,$$

$$c_{\gamma\Box} = \frac{2g^2c_{z\Box} + (g^2+g'^2)c_{zz} - (g^2-g'^2)c_{z\gamma} - g^2s_\theta^2c_{\gamma\gamma}}{g^2-g'^2}$$

Mass eigenstate basis to Warsaw

- SU(2)xU(1) + $\Delta m_W = 0$

$$\kappa_1^{ZZ} = \kappa_2^{ZZ}$$

$$a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = \kappa_1^{\gamma\gamma} = \kappa_2^{\gamma\gamma} = \kappa_1^{gg} = \kappa_2^{gg} = \kappa_1^{Z\gamma} = \kappa_3^{VV} = 0$$

$$\delta g_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(2C_{H\Box} + \frac{6e^2}{s_w^2}C_{HWB} + \left(\frac{3c_w^2}{2s_w^2} - \frac{1}{2}\right)C_{HD}\right),$$

$$\kappa_1^{ZZ} = \frac{v^2}{\Lambda^2}\left(-\frac{2e^2}{s_w^2}C_{HWB} + \left(1 - \frac{1}{2s_w^2}\right)C_{HD}\right),$$

$$g_2^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 C_{HB} + c_w^2 C_{HW} + s_w c_w C_{HWB}\right),$$

$$g_2^{Z\gamma} = -2\frac{v^2}{\Lambda^2}\left(s_w c_w\left(C_{HW} - C_{HB}\right) + \frac{1}{2}\left(s_w^2 - c_w^2\right)C_{HWB}\right),$$

$$g_2^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 C_{HB} + s_w^2 C_{HW} - s_w c_w C_{HWB}\right),$$

$$g_2^{gg} = -2\frac{v^2}{\Lambda^2}C_{HG},$$

$$g_4^{ZZ} = -2\frac{v^2}{\Lambda^2}\left(s_w^2 C_{H\widetilde{B}} + c_w^2 C_{H\widetilde{W}} + s_w c_w C_{H\widetilde{W}B}\right),$$

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

$$g_4^{\gamma\gamma} = -2\frac{v^2}{\Lambda^2}\left(c_w^2 C_{H\widetilde{B}} + s_w^2 C_{H\widetilde{W}} - s_w c_w C_{H\widetilde{W}B}\right),$$

$$g_4^{gg} = -2\frac{v^2}{\Lambda^2}C_{H\widetilde{G}},$$

Warsaw couplings decomposition

arXiv:2109.13363

- H→4l

	$\sigma/\sigma_{\rm SM}$	$\delta g_1^{ZZ} = \delta g_1^{WW}$	κ_1^{ZZ}	g_2^{ZZ}	$g_2^{Z\gamma}$	$g_2^{\gamma\gamma}$	g_4^{ZZ}	$g_4^{Z\gamma}$	$g_4^{\gamma\gamma}$	$\kappa_2^{Z\gamma}$	κ_1^{WW}	g_2^{WW}	g_4^{WW}
$C_{H\Box}$	0.004	1	0	0	0	0	0	0	0	0	0	0	0
C_{HD}	0.017	1.078	0.068	0	0	0	0	0	0	0.486	0	0	0
C_{HW}	0.635	0	0	0.00117	0.685	0.238	0	0	0	0	0	0	0
C_{HWB}	0.781	0.007	0.001	0.00029	0.268	0.632	0	0	0	0.018	0	0	0
C_{HB}	2.215	0	0	0.00003	0.243	0.759	0	0	0	0	0	0	0
$C_{H\widetilde{W}}$	0.579	0	0	0	0	0	0.00052	0.713	0.286	0	0	0	0
$C_{H\widetilde{W}B}$	0.749	0	0	0	0	0	0.00012	0.239	0.683	0	0	0	0
$C_{H\widetilde{B}}$	2.196	0	0	0	0	0	0.00001	0.194	0.720	0	0	0	0

For production modes see paper

NLO EW effects

arXiv:2109.13363

Quantify effect of NLO EW corrections:

- cross-section
- kinematic distributions

Test if effects can be modeled with anomalous couplings

JHUGen LO a.c. to model "pseudo-EW" corrections – 2 approaches taken, excluding and including the quadratic ac terms (linear / inclusive)

-Unified lhe processing framework used for all generators.
-Developed lhe writer subroutines for HAWK (that does not output lhe format)
-Implemented **recombination of FSR photons** to the leptons

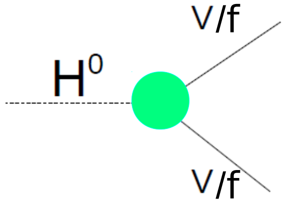
References:

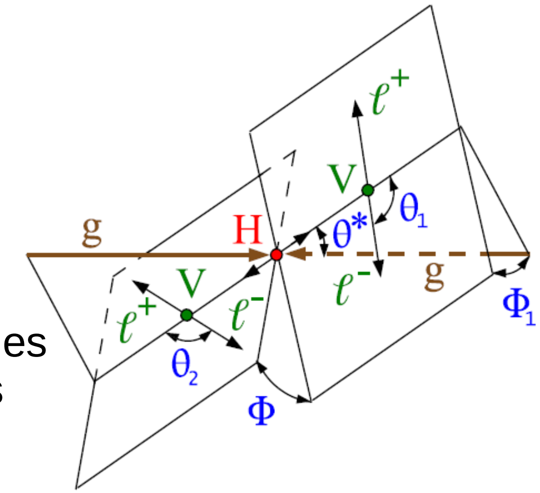
[1] A.Bredenstein, A.Denner, S.Dittmaier and M.M.Weber,Precise predictions for the Higgs-boson decay H → WW/ZZ → 4 leptons, Phys.Rev.D 74 (2006) 013004 [hep-ph/0604011]

[2] A.Denner, S.Dittmaier, S.Kallweit and A.Mück,HAWK 2.0: A Monte Carlo program for Higgs production in vector-boson fusion and Higgs strahlung at hadron colliders,Comput.Phys.Commun. 195 (2015) 161-171 [arXiv:1412.5390]

How to measure anomalous HVV/Hff couplings: the H→ 4l channel

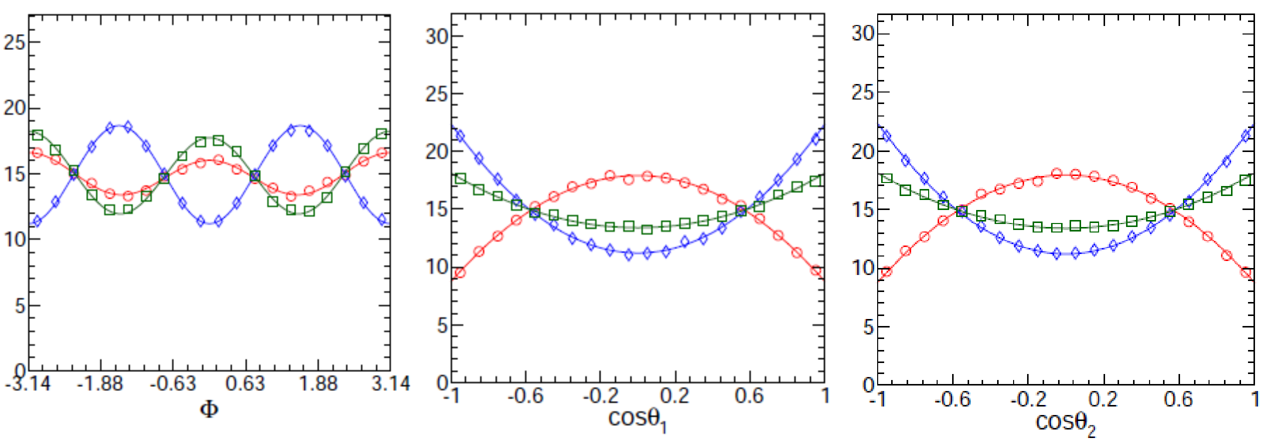
single vertex

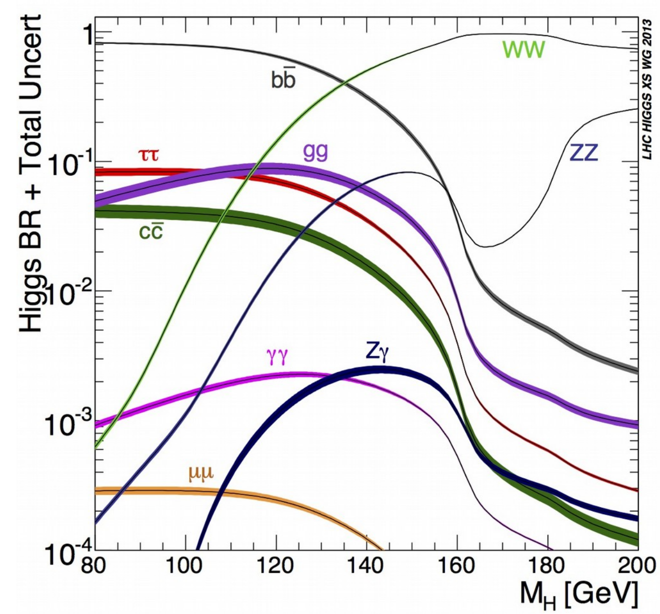




- 4-momenta of final states particles affected by H quantum numbers and couplings

SM 0h+ 0-





H→ γγ : can not measure CP + large background
H→ WW : Not fully reconstructed final state
H→ ZZ→ 4l : **Sensitive** Angular information + low background

EW NLO corrections

Basic kinematic cuts on leptons and jets applied:

ZHl^+l^- :

min lept pt >5GeV

min ml^+l^- > 0.1 GeV

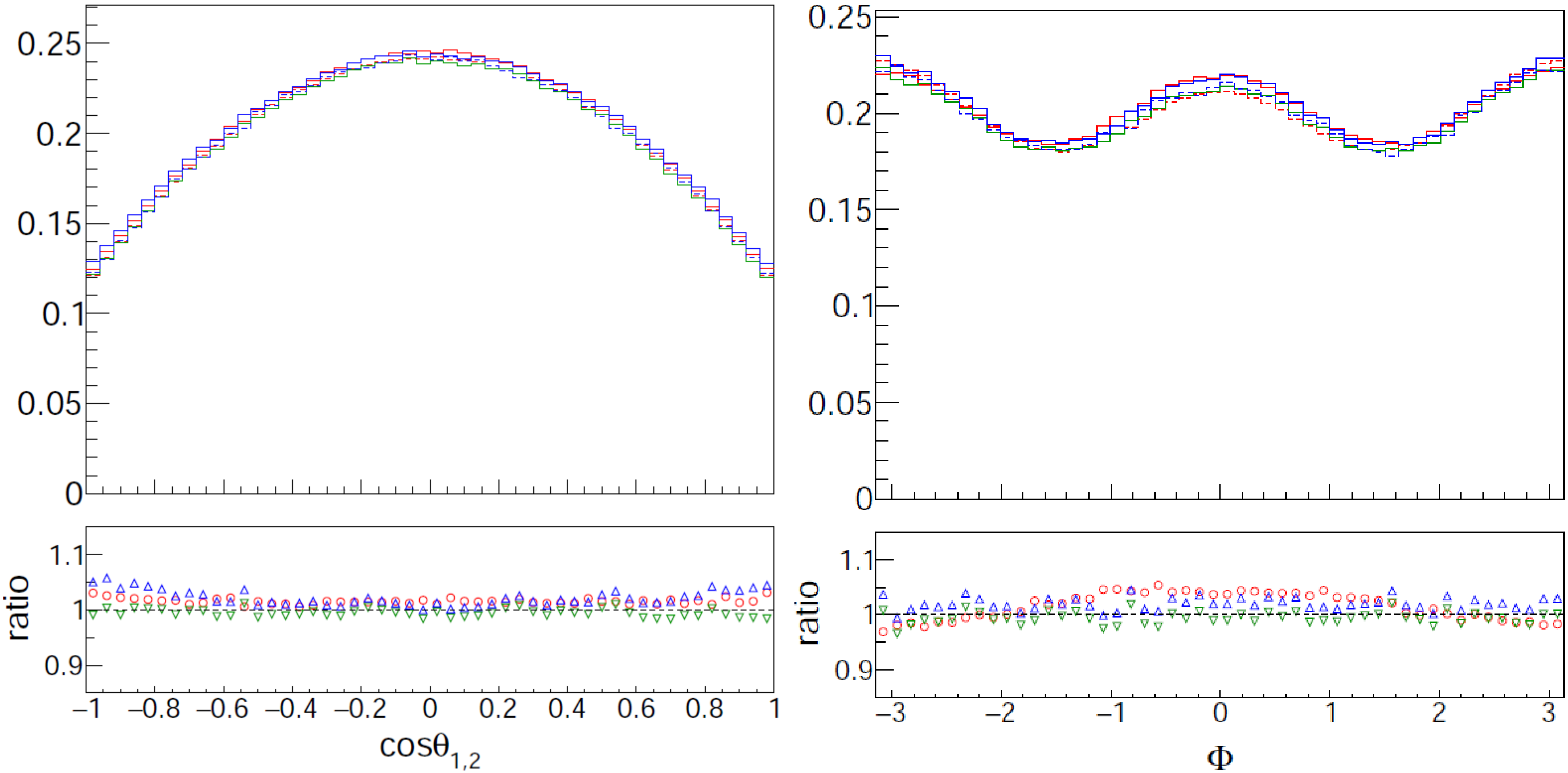
VBF :

mJJ > 300 GeV

	EW NLO/LO	(LO + g_2^{SM})/LO	(LO + g_2^{SM} linear)/LO
$H \to 4\ell$	+1.5%	+2.0%	−0.6%
VBF	−6.7%	+0.2%	+0.1%
$Z(\to \ell^+\ell^-)H$	−6.4%	−1.2%	−1.2%

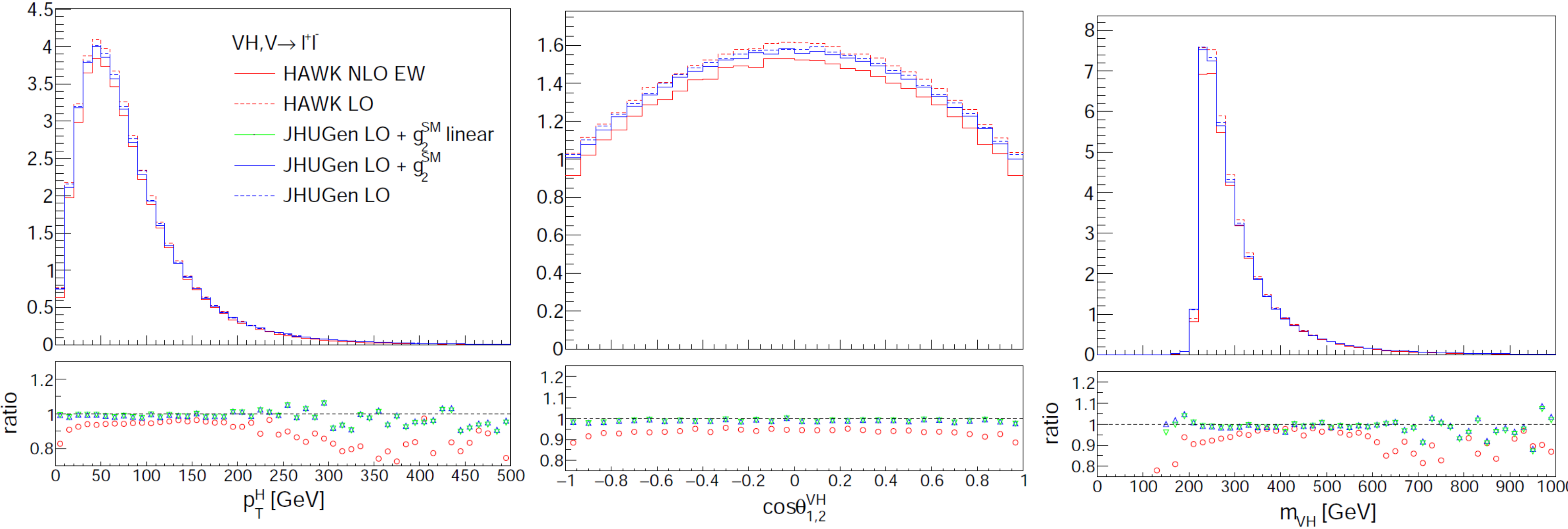
$H\to 2e2\mu$ corrections

arXiv:2109.13363



> Pseudo-EW modeling in ballpark of EW NLO effect but not sufficient to properly describe the effect

Effects on *(Z→l+l-)H* kinematics



> SM EW NLO effect has a **negative effect** in VH production

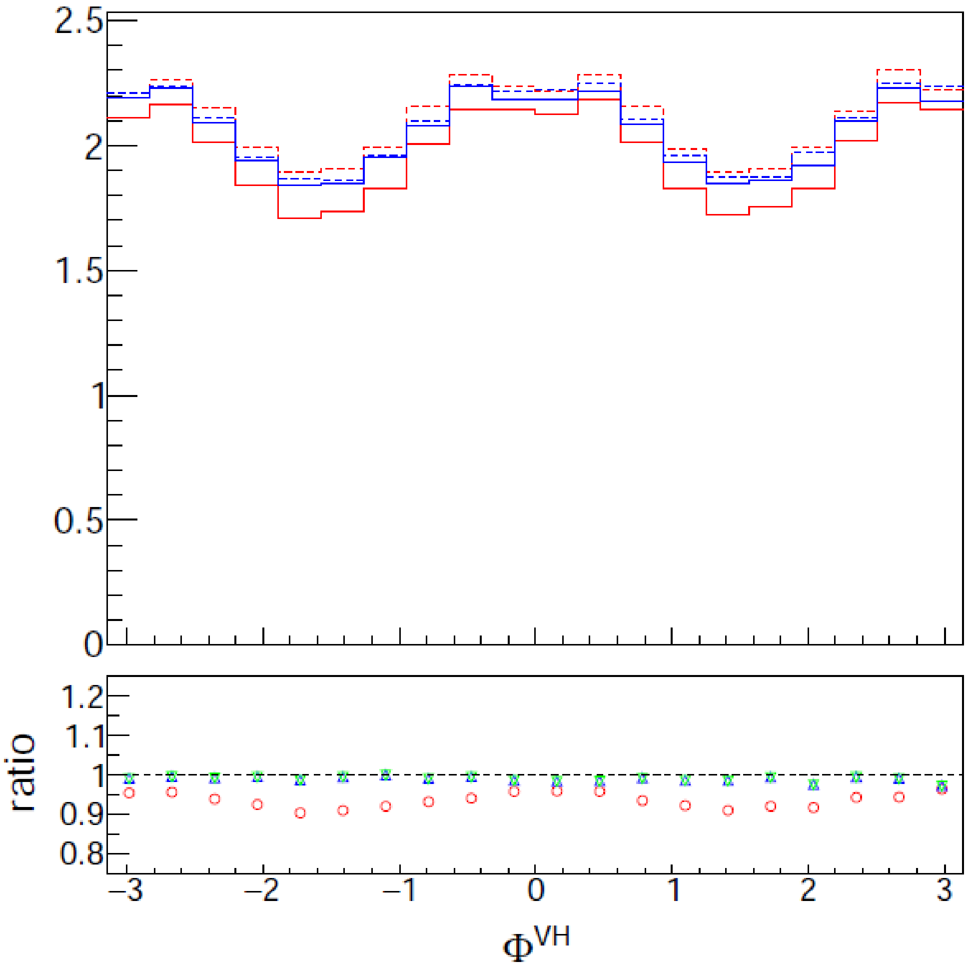
> Pt dependence observed

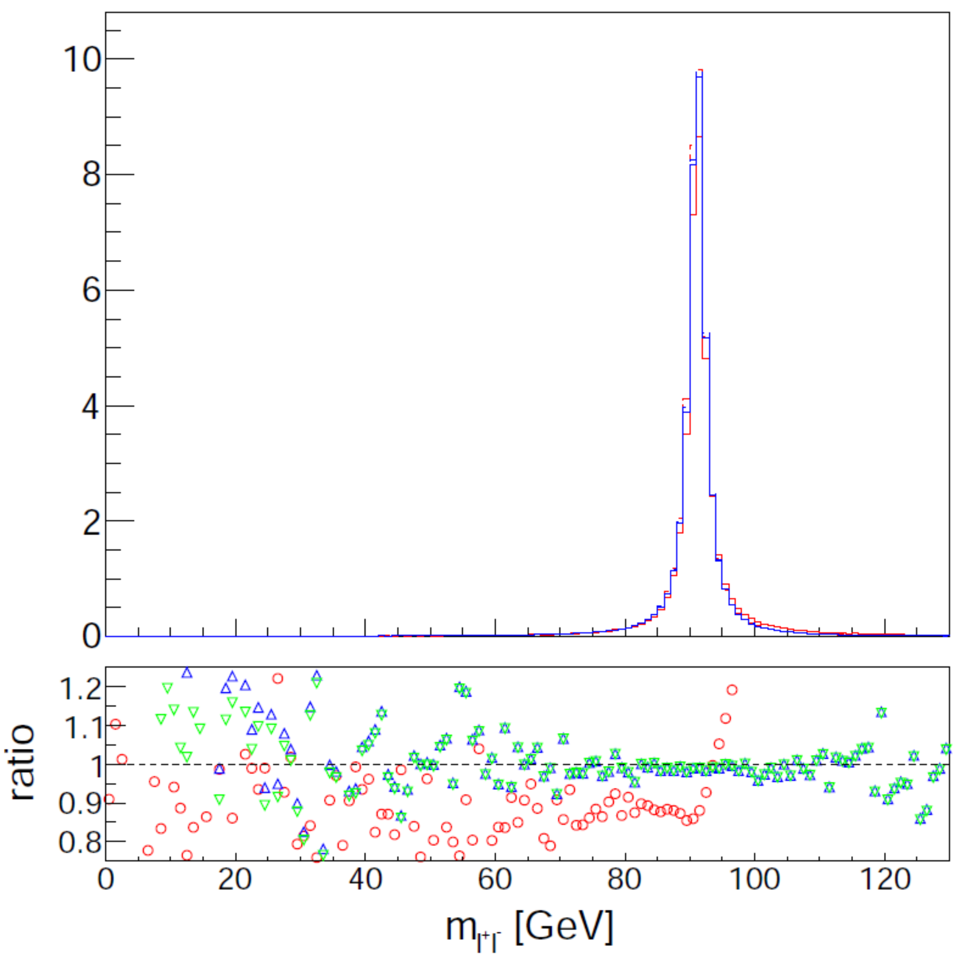
> Pseudo-EW corrections tiny in production

> No strong angular dependencies

Effects on (Z→l+l-)H kinematics

arXiv:2109.13363





> No strong angular dependencies

SM NLO effects

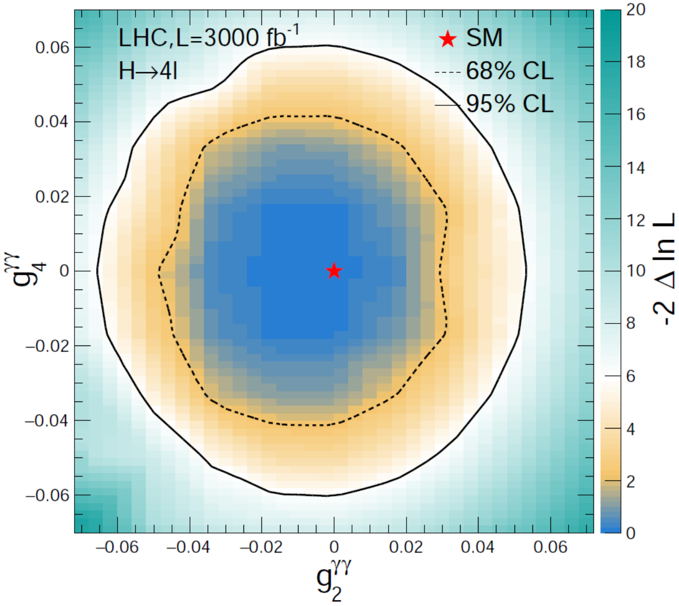
arXiv:2109.13363

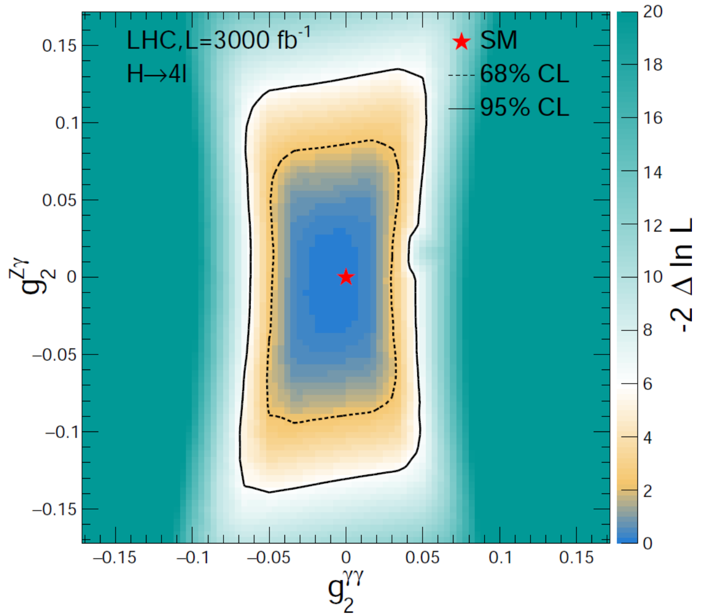
Inclusive corrections:

	EW NLO/LO	(LO + g_2^{SM})/LO	(LO + g_2^{SM} linear)/LO
$H \to 4\ell$	+1.5%	+2.0%	−0.6%
VBF	−6.7%	+0.2%	+0.1%
$Z(\to \ell^+\ell^-)H$	−6.4%	−1.2%	−1.2%

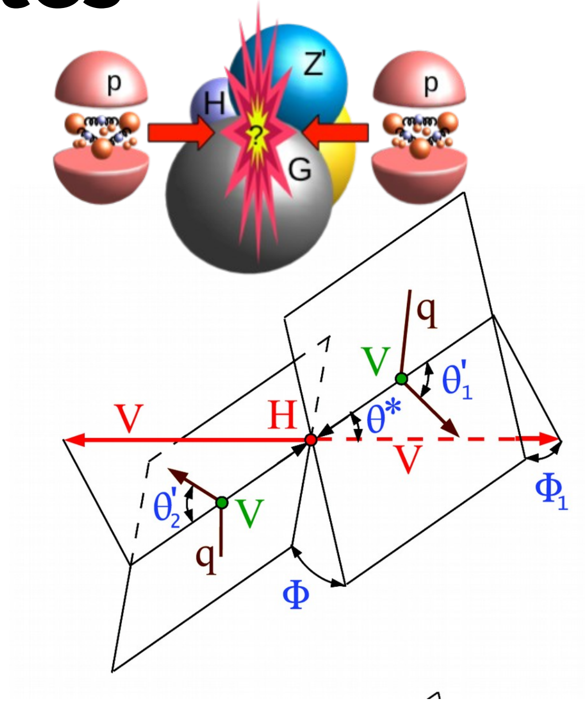
- EW NLO effect affect decay and production differently with production being more sensitive
- Corrections indicate some pt,q^2 dependence
- A pseudo-EW modeling of the effect, with anomalous couplings is not sufficient

Amplitude couplings scans : Production





$\mathcal{D}$-iscriminants and templates



- Construct discriminants using MELA probabilities

- Input to probabilities both decay and production kinematics

$$\boldsymbol{\Omega}^{\rm dec} = \{\theta_1, \theta_2, \Phi, \theta^*, \Phi_1, m_1, m_2, m_{4\ell}\}$$

$$\boldsymbol{\Omega}^{\rm prod}$$

$$\mathcal{D}_{\rm alt}\left(\boldsymbol{\Omega}\right) = \frac{\mathcal{P}_{\rm sig}\left(\boldsymbol{\Omega}\right)}{\mathcal{P}_{\rm sig}\left(\boldsymbol{\Omega}\right) + \mathcal{P}_{\rm alt}\left(\boldsymbol{\Omega}\right)},$$

$$\mathcal{D}_{\rm int}\left(\boldsymbol{\Omega}\right) = \frac{\mathcal{P}_{\rm int}\left(\boldsymbol{\Omega}\right)}{2\sqrt{\mathcal{P}_{\rm sig}\left(\boldsymbol{\Omega}\right)\ \mathcal{P}_{\rm alt}\left(\boldsymbol{\Omega}\right)}},$$

<u>HVV VBF2-jet category discriminants:</u>

VBF-2jet $\mathcal{D}_{\rm 2jet}^{\rm VBF} > 0.5$ $\mathcal{D}_{\rm bkg}^{\rm EW}, \mathcal{D}_{0h+}^{\rm VBF+dec}, \mathcal{D}_{0-}^{\rm VBF+dec}, \mathcal{D}_{\Lambda1}^{\rm VBF+dec}, \mathcal{D}_{\Lambda1}^{Z\gamma,\rm VBF+dec}, \mathcal{D}_{\rm int}^{\rm VBF}, \mathcal{D}_{CP}^{\rm VBF}$