Status of CP violation in Higgs couplings

Snowmass Energy Frontier EF01 Working Group Meeting

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CP violation in Higgs couplings

- Study expected CP constraints for Hγγ/HZγ in a pp collider

Table 1-26 from arxiv1310.8361

Collider E (GeV) $\mathcal{L}$ (fb^{-1})	pp 14,000 300	pp 14,000 3,000	e^+e^- 250 250	e^+e^- 350 350	e^+e^- 500 500	e^+e^- 1,000 1,000	$\gamma\gamma$ 126 250	$\mu^+\mu^-$ 126	target (theory)
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	$7{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$	$4{\cdot}10^{-5}$	$8{\cdot}10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

- See also presentation by A.Gritsan[1]

[1] https://indico.fnal.gov/event/49756/contributions/222371/attachments/146754/187594/talk_Snowmass-September2021.pdf

Higgs γγ/Zγ couplings

HVV scattering amp. in **mass-eigenstate basis**:

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

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

SM @ tree level
CP even
CP odd

ACs of interest :

$$a_3^{\gamma\gamma}, a_2^{\gamma\gamma}, a_3^{Z\gamma}, a_2^{Z\gamma}$$

$$f_{an}^{(i,f)} = \frac{\alpha_{nn}^{(i,f)} a_n^2}{\sum_m \alpha_{mm}^{(i,f)} a_m^2} \times \mathrm{sign}\left(\frac{a_n}{a_1}\right)$$

$$f_{a3}^{\gamma\gamma}, f_{a2}^{\gamma\gamma}, f_{a3}^{Z\gamma}, f_{a2}^{Z\gamma}$$

> estimate sensitivity projections for the total anomalous contribution in γγ and in Zγ
> estimate sensitivity for CP-odd fraction of these contributions

Higgs γγ/Zγ couplings

> estimate sensitivity projections for the total anomalous contribution in γγ and in Zγ
> estimate sensitivity for CP-odd fraction of these contributions

$$f^{\gamma\gamma} = |f_{a3}^{\gamma\gamma}| + |f_{a2}^{\gamma\gamma}| \qquad f^{Z\gamma} = |f_{a3}^{Z\gamma}| + |f_{a2}^{Z\gamma}|$$

$$f_{CP}^{\gamma\gamma} = \frac{f_{a3}^{\gamma\gamma}}{|f_{a3}^{\gamma\gamma}| + |f_{a2}^{\gamma\gamma}|} \qquad f_{CP}^{Z\gamma} = \frac{f_{a3}^{Z\gamma}}{|f_{a3}^{Z\gamma}| + |f_{a2}^{Z\gamma}|}$$

Consider SM beyond tree level:

$$a_2^{\gamma\gamma,SM} = 0.00423 \qquad f_{a2}^{\gamma\gamma,SM} = 0.00631365$$

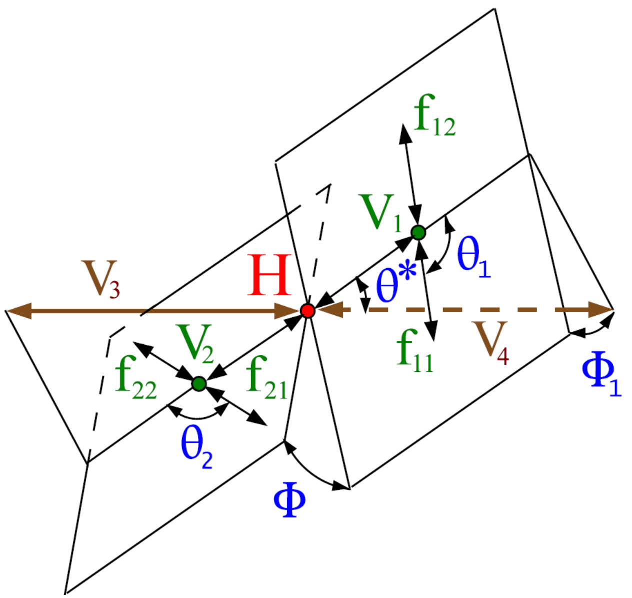
$$\Rightarrow \quad f^{\gamma\gamma,SM} = f_{a2}^{\gamma\gamma,SM} \qquad f_{CP}^{\gamma\gamma,SM} = 0$$

Higgs γγ/Zγ couplings

Use pp → H → 4l based on the pheno study presented in arxiV:2109.13363

H → 4l angular information allows CP measurement
Can study γγ/Zγ couplings through virtual bosons in 4l final state

JHUGen simulation
Utilize MELA discriminants



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

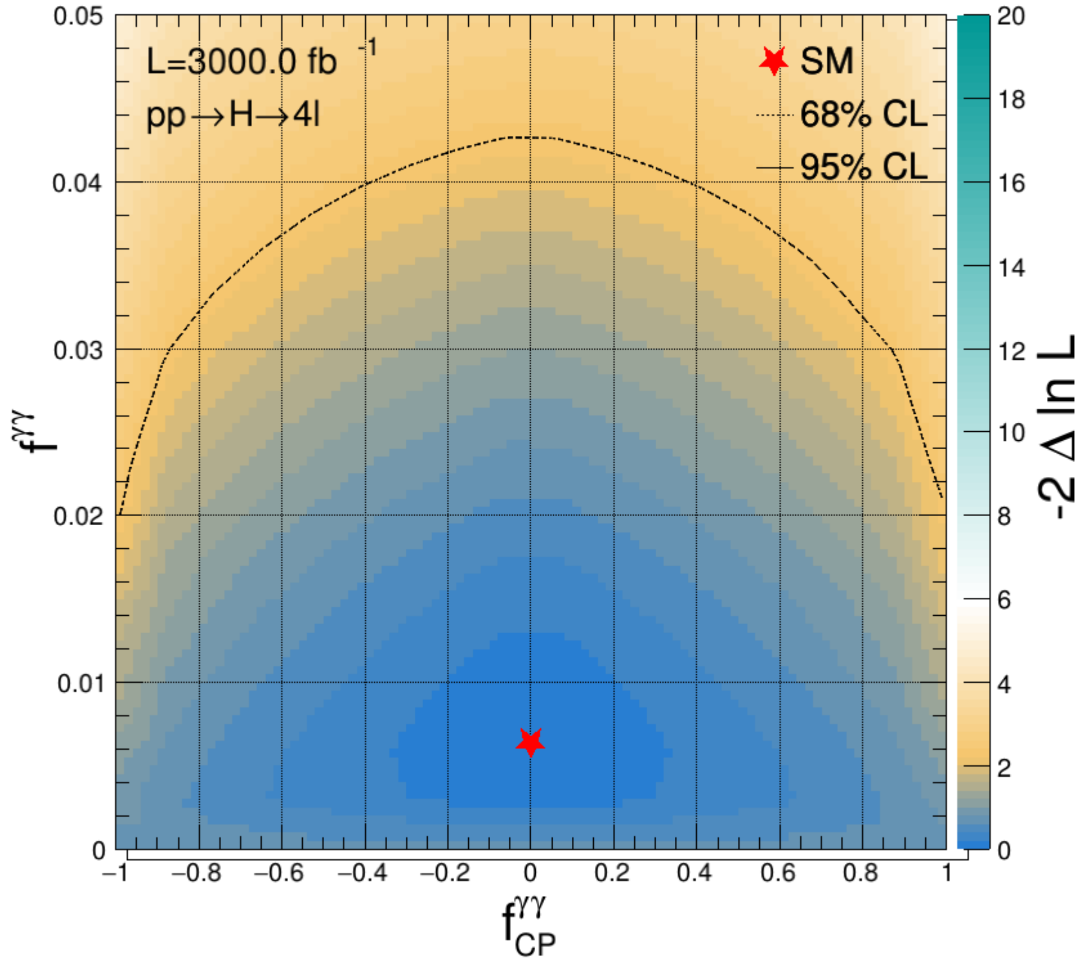
$$\mathcal{D}_{\mathrm{int}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\mathrm{int}}(\boldsymbol{\Omega})}{2\sqrt{\mathcal{P}_{\mathrm{sig}}(\boldsymbol{\Omega})\ \mathcal{P}_{\mathrm{alt}}(\boldsymbol{\Omega})}},$$

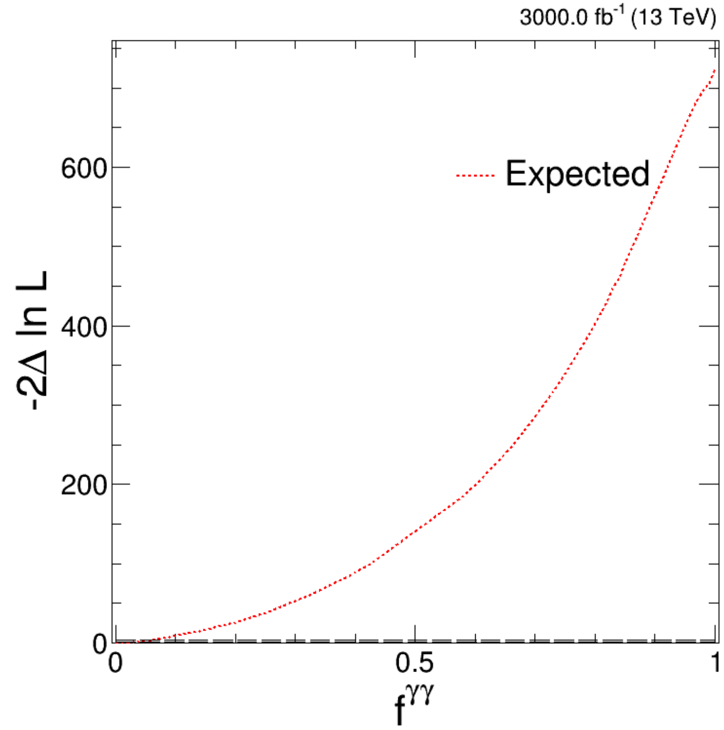
$\mathcal{D}_{g2}^{Z\gamma}$, $\mathcal{D}_{g2}^{\gamma\gamma}$, $\mathcal{D}_{g4}^{Z\gamma}$, and $\mathcal{D}_{g4}^{\gamma\gamma}$

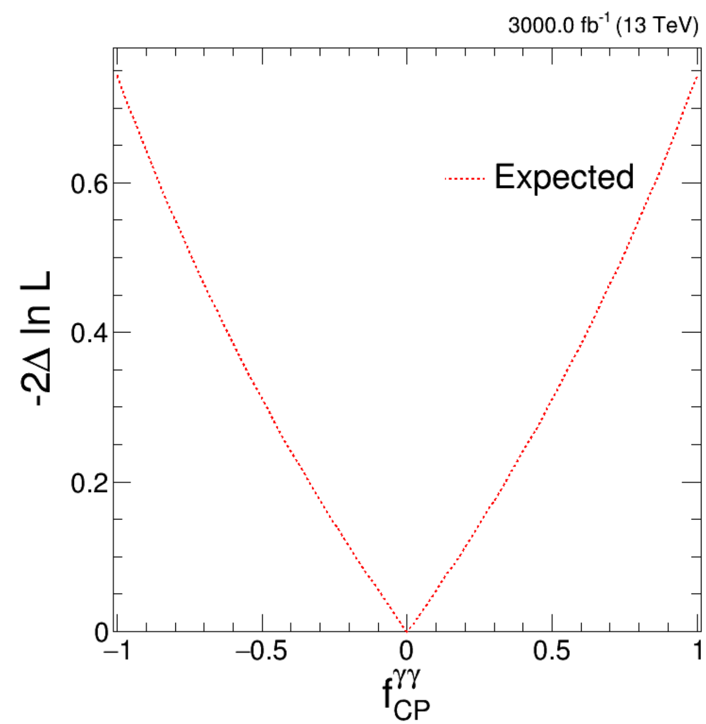
$\mathcal{D}_{\mathrm{int}}^{Z\gamma}$, $\mathcal{D}_{\mathrm{int}}^{\gamma\gamma}$, $\mathcal{D}_{CP}^{Z\gamma}$, $\mathcal{D}_{CP}^{\gamma\gamma}$

> Perform likelihood scans for POIs using template fitting

Hγγ couplings

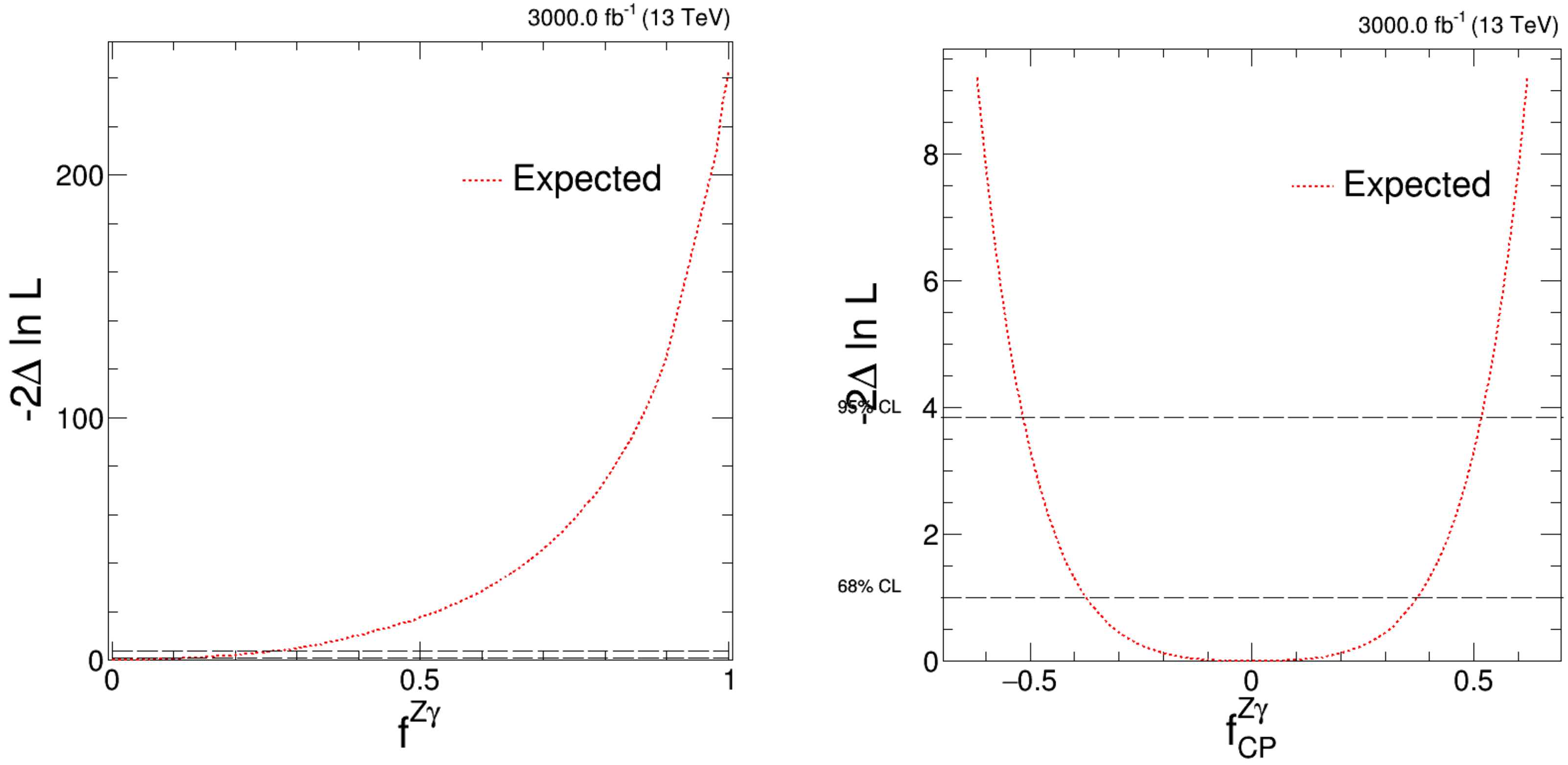






- Projected sensitivity @3.0 ab^{-1}
- $f^{\gamma\gamma}$ 1σ constraint 0.022
- Conservative expectations $f_{CP}^{\gamma\gamma}$

HZγ couplings



- $f^{Z\gamma}$ 1σ constraint 0.1317
- $f_{CP}^{Z\gamma}$ tighter constraints than γγ

Summary

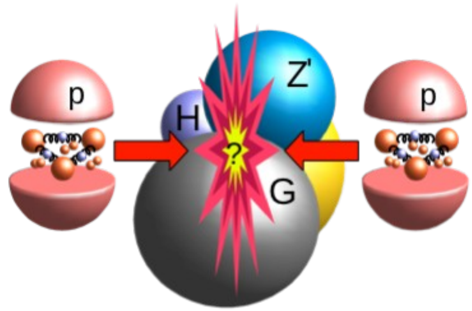
- Projections on pp machine @3ab^{-1}
- focus on H γγ/Zγ couplings

Collider	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	$\gamma\gamma$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	250	350	500	1,000	126	126	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	250	350	500	1,000	250		
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot 10^{-4}$	$1.2\cdot 10^{-4}$	$7\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$4\cdot 10^{-5}$	$8\cdot 10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot 10^{-4}$	$1.3\cdot 10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

Additional material

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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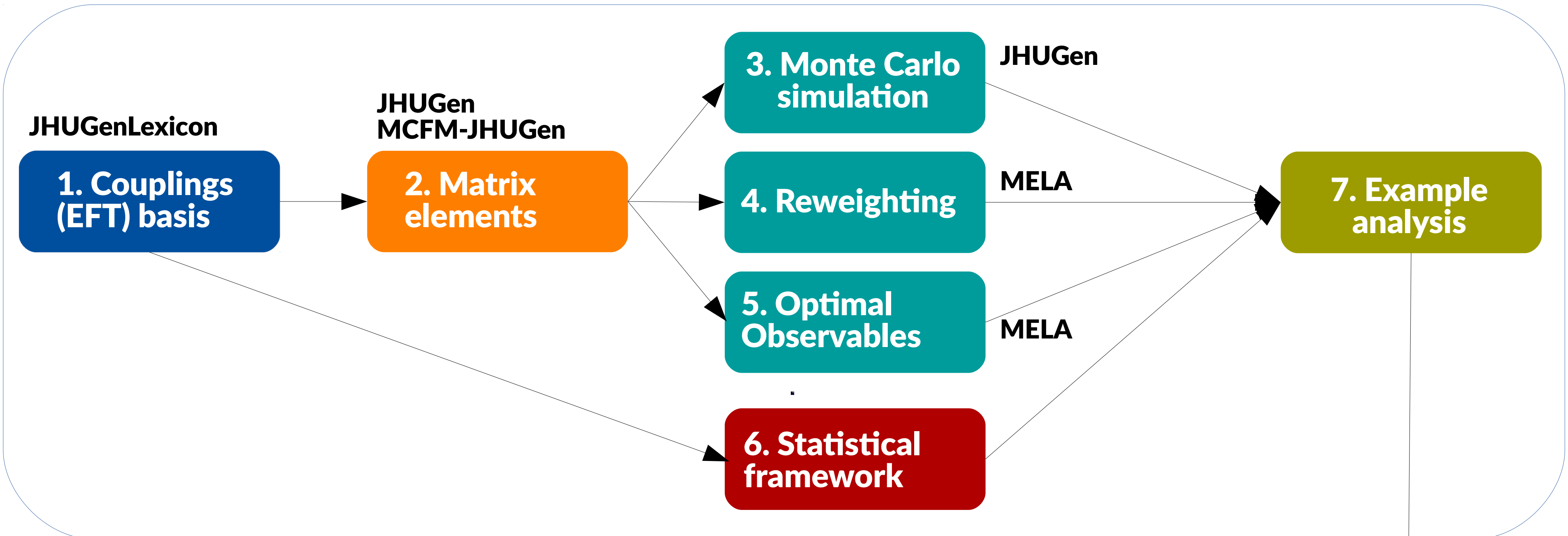
See also talks by:

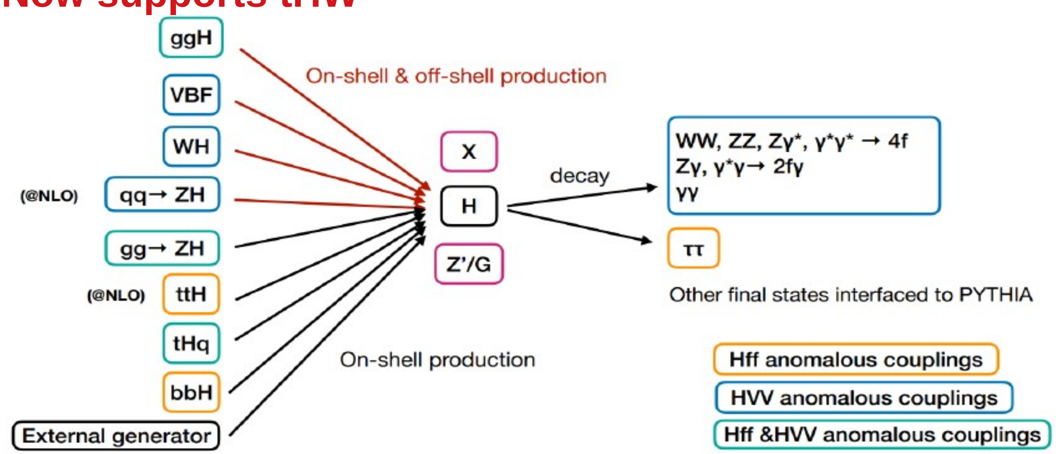
- J.Davis at EPS-HEP2021
- H.Roskes at LHC EFT WG
- H.Roskes at Pheno 2020
- M.Xiao at ICHEP 2020
- U.Sarica at Higgs 2020
- A.Gritsan at LHC Higgs WG
- M.Schulze at LHC Higgs WG

The JHUGen framework



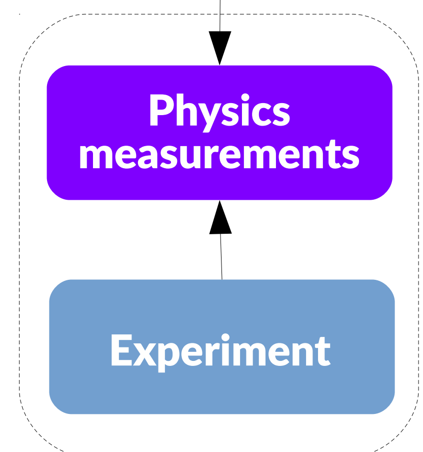
Processes supported:

Now supports tHW



Framework allows:

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



Setting constraints

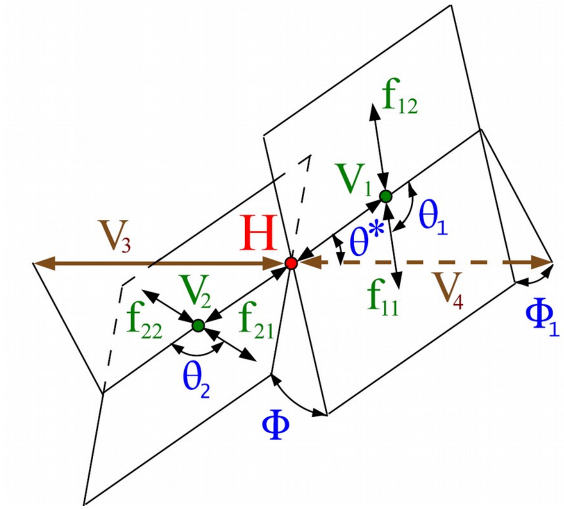
Construct and calibrate dedicated MELA discriminants:

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

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

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

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



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} > 5GeV

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

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	Fraction	$H \to 2e2\mu$	VBF	$ZH/\gamma^* H$
g_n	f_{gn}	$\alpha_{nn}^{(f)}/\alpha_{11}$	$\alpha_{nn}^{(i)}/\alpha_{11}$	$\alpha_{nn}^{(i)}/\alpha_{11}$
$g_2^{\gamma\gamma}$	$f_{g2}^{\gamma\gamma}$	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