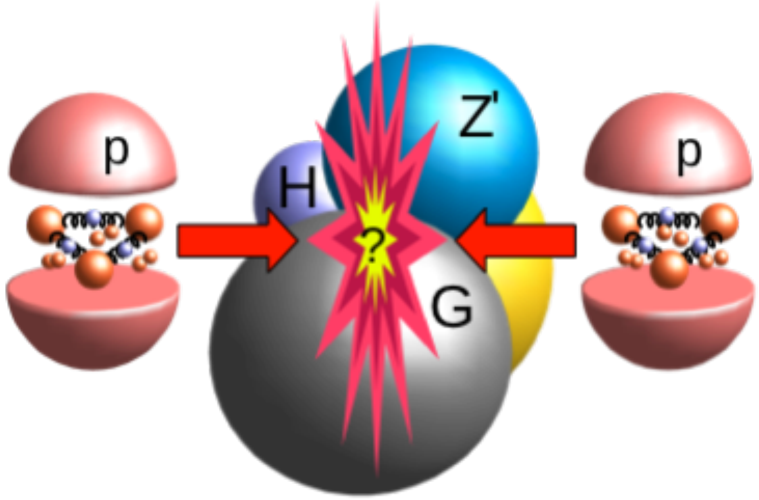
Matrix-Element Methods for EFT and CP measurements with the H boson



Andrei Gritsan

Johns Hopkins University

in collaboration with the **MELA** developers

(Matrix Element Likelihood Approach)

December 15, 2021

LHC Higgs Working Group WG2 (Properties)

Introduction: the idea of M.E.M.

- When we know what we do, M.E.M. is the best tool
  - explore full information
  - guarantee optimal performance
  - some will disagree, but see last bullet below
- Machine Learning (M.L.): could consider a part of M.E.M.
  - same idea
  - based on the same matrix elements in simulation
  - some will disagree, but no distinction for this talk
- The problem is that we do not always know what we do
  - detector effects may be hard to incorporate
  - target of the measurement may not be unique

Credits to **MELA** colleagues

- M.E.M. is a diverse and extensive method

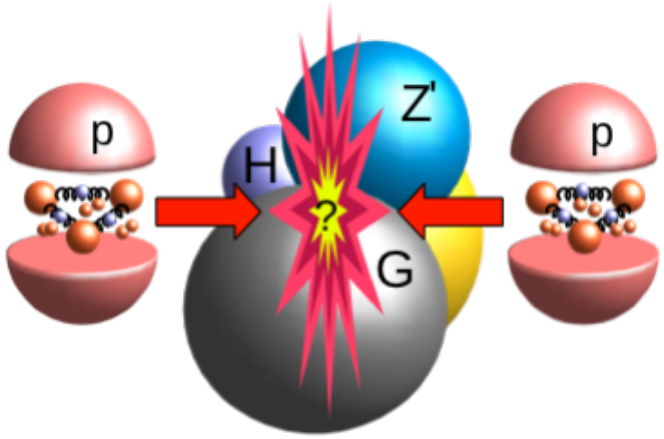
  — this talk is based on our experience with **MELA** version

  — used in the H discovery and characterization since then

MELA — Matrix Element library

JHUGen — generator

JHUGenLexicon — basis translation …



https://spin.pha.jhu.edu

Theory + Experiment collaboration

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

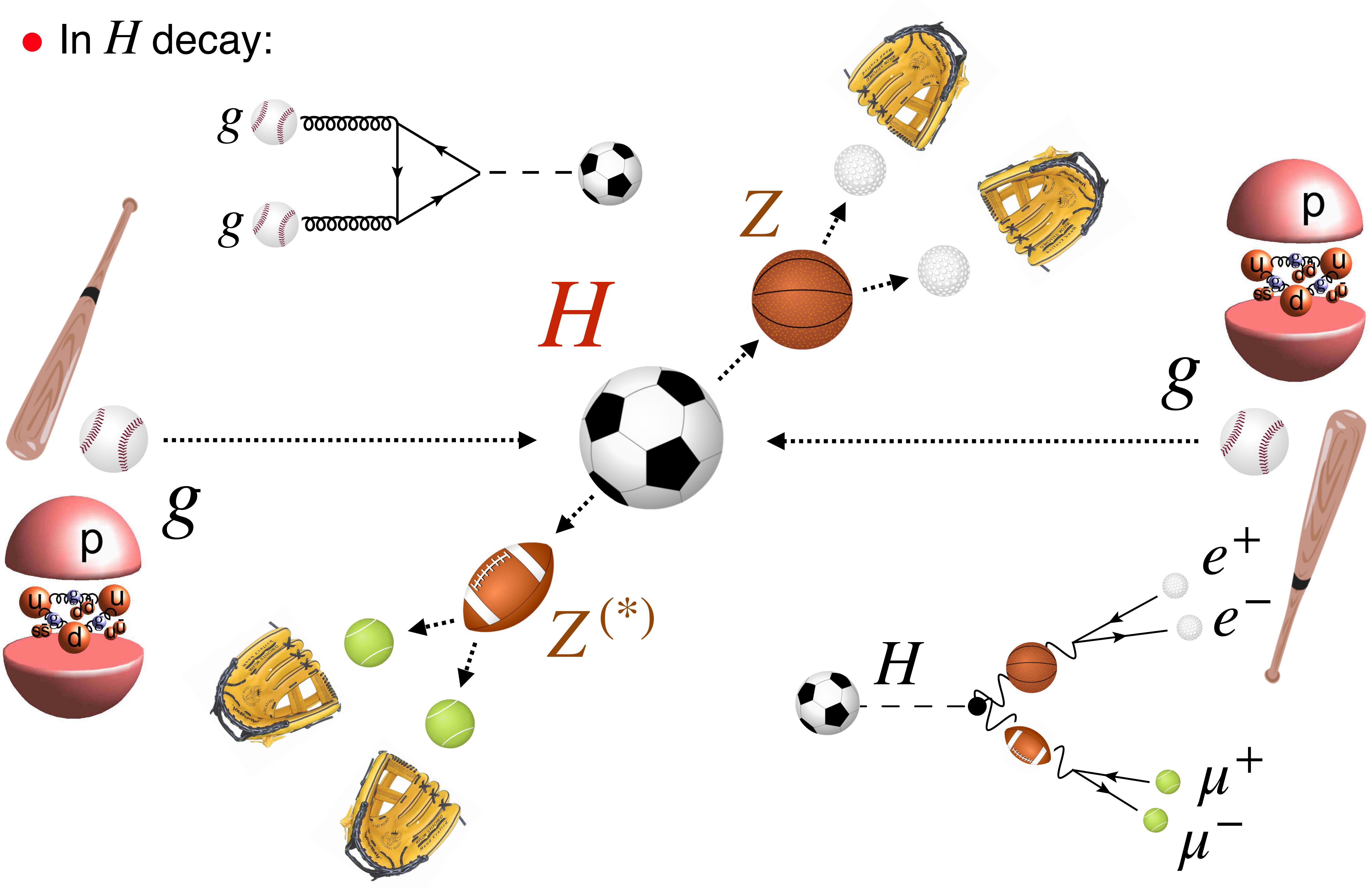
"Probing the CP structure of the top quark Yukawa coupling: Loop sensitivity vs. on-shell sensitivity"
Till Martini, Ren-Qi Pan, Markus Schulze, and Meng Xiao
https://arxiv.org/abs/2104.04277

"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

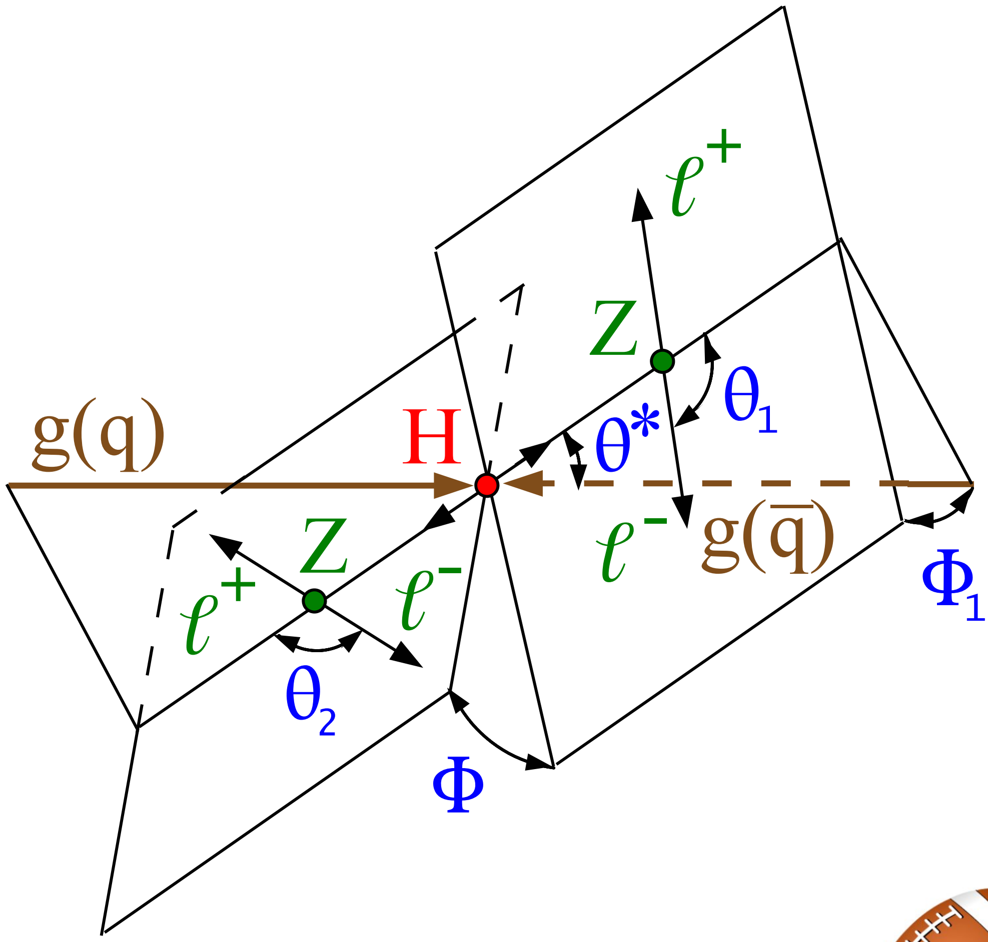
Idea of MEM: explore full information

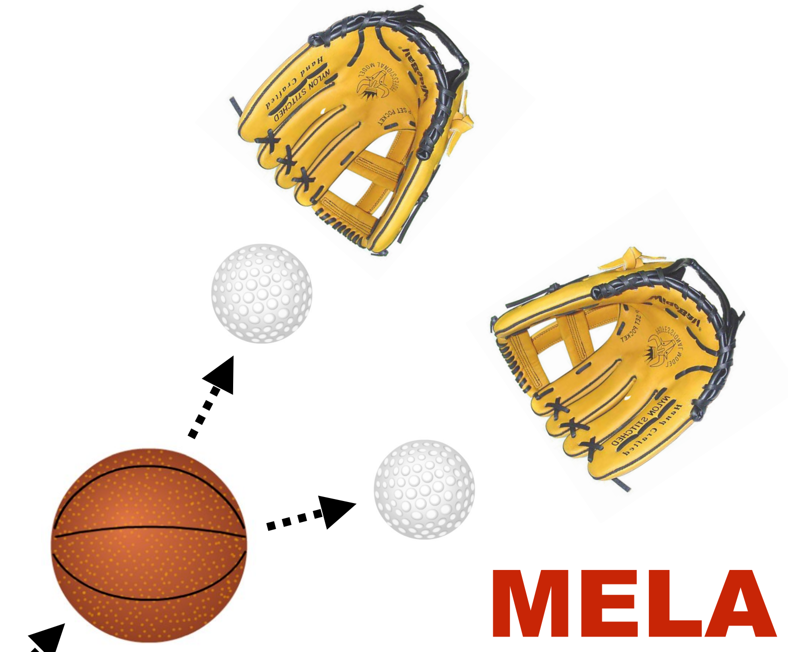
- In H decay:

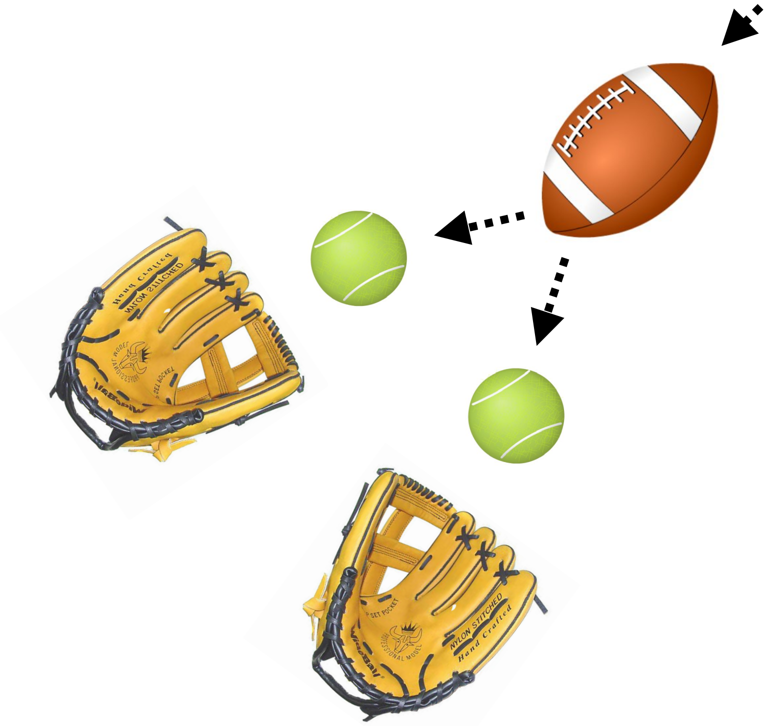


Idea of MEM: explore full information

- In H decay:







MELA

arXiv:1001.3396

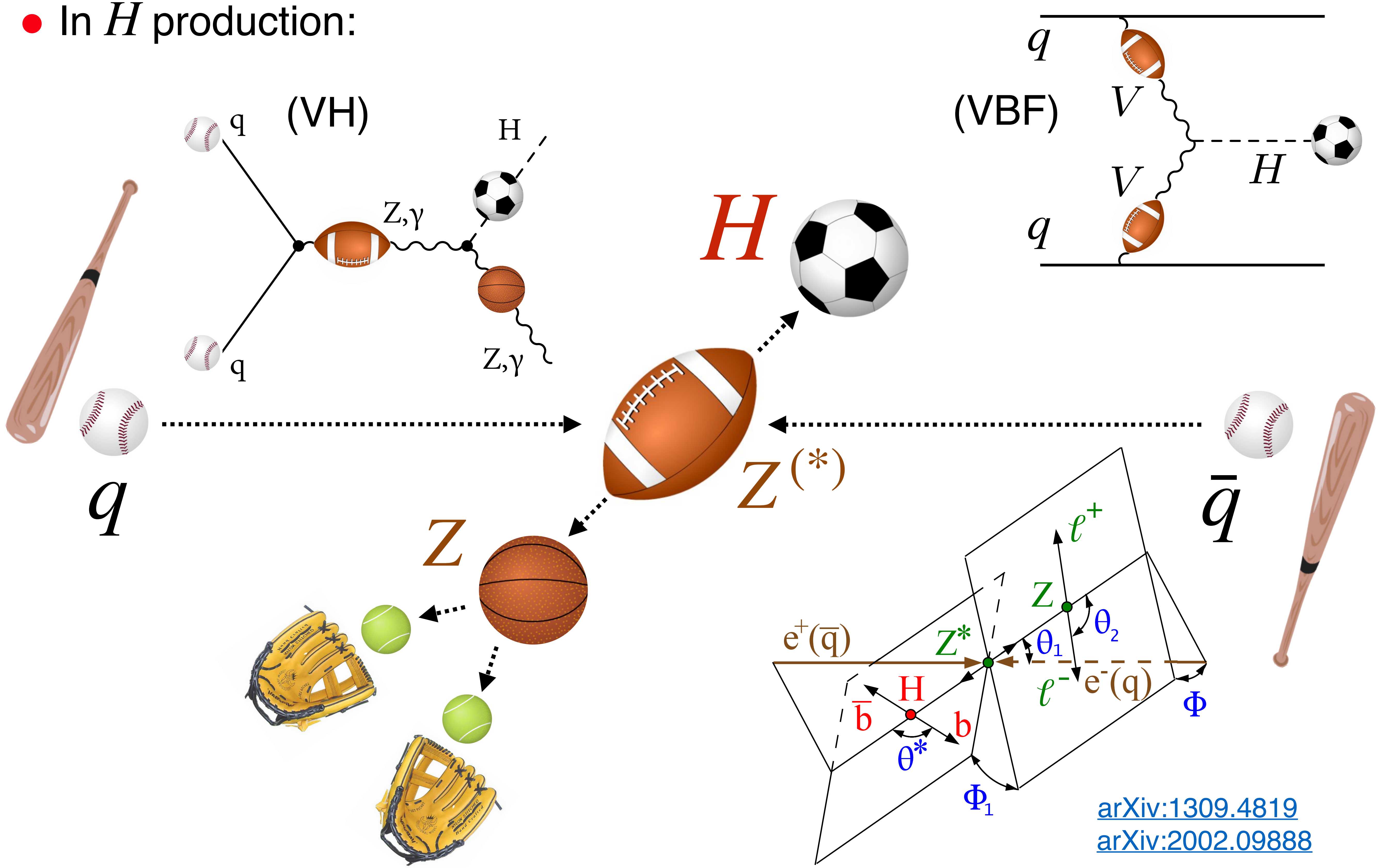
arXiv:1208.4018

$$
\begin{aligned}
F^J_{0,0}(\theta^*) \times & \Big[4\,|A_{00}|^2 \sin^2\theta_1 \sin^2\theta_2 + 2|A_{++}||A_{--}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Phi - \phi_{--} + \phi_{++})\Big] \\
& + |A_{++}|^2 \left(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \\
& + |A_{--}|^2 \left(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1\right)\left(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2\right) \qquad \text{spin} = 0 \;\&\; \geq 1 \\
& + 4|A_{00}||A_{++}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{++}) \\
& + 4|A_{00}||A_{--}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(\Phi - \phi_{--}) \\
+F^J_{1,1}(\theta^*) \times & \Big[2|A_{+0}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0-}|^2 \sin^2\theta_1 (1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2) \\
& + 2|A_{-0}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)\sin^2\theta_2 + 2|A_{0+}|^2 \sin^2\theta_1 (1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2) \\
& + 4|A_{+0}||A_{0-}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{+0} - \phi_{0-}) \\
& + 4|A_{0+}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(\Phi + \phi_{0+} - \phi_{-0})\Big] \qquad \text{spin} \geq 1 \\
+F^J_{1,-1}(\theta^*) \times & \Big[4|A_{+0}||A_{0+}|(A_{f_1} + \cos\theta_1)\sin\theta_1 (A_{f_2} + \cos\theta_2)\sin\theta_2 \cos(2\Psi - \phi_{+0} + \phi_{0+}) \\
& + 4|A_{0-}||A_{-0}|(A_{f_1} - \cos\theta_1)\sin\theta_1 (A_{f_2} - \cos\theta_2)\sin\theta_2 \cos(2\Psi - \phi_{0-} + \phi_{-0}) \\
+4|A_{+0}||A_{-0}|\sin^2\theta_1 \sin^2\theta_2 & \cos(2\Psi - \Phi - \phi_{+0} + \phi_{-0}) + 4|A_{0-}||A_{0+}|\sin^2\theta_1 \sin^2\theta_2 \cos(2\Psi + \Phi - \phi_{0-} + \phi_{0+})\Big] \\
+F^J_{2,2}(\theta^*) \times & \Big[|A_{+-}|^2(1 + 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 - 2A_{f_2}\cos\theta_2 + \cos^2\theta_2) \\
& + |A_{-+}|^2(1 - 2A_{f_1}\cos\theta_1 + \cos^2\theta_1)(1 + 2A_{f_2}\cos\theta_2 + \cos^2\theta_2)\Big] \qquad \text{spin} \geq 2 \\
+F^J_{2,-2}(\theta^*) \times & \Big[2|A_{+-}||A_{-+}|\sin^2\theta_1 \sin^2\theta_2 \cos(4\Psi - \phi_{+-} + \phi_{-+})\Big] + \text{other 26 interference terms for spin}
\end{aligned}
$$

where $\Psi = \Phi_1 + \Phi/2$ and $F^J_{ij}(\theta^*) = \sum\limits_{m=0,\pm1,\pm2} f_m\, d^J_{im}(\theta^*) d^J_{jm}(\theta^*)$

Idea of MEM: explore full information

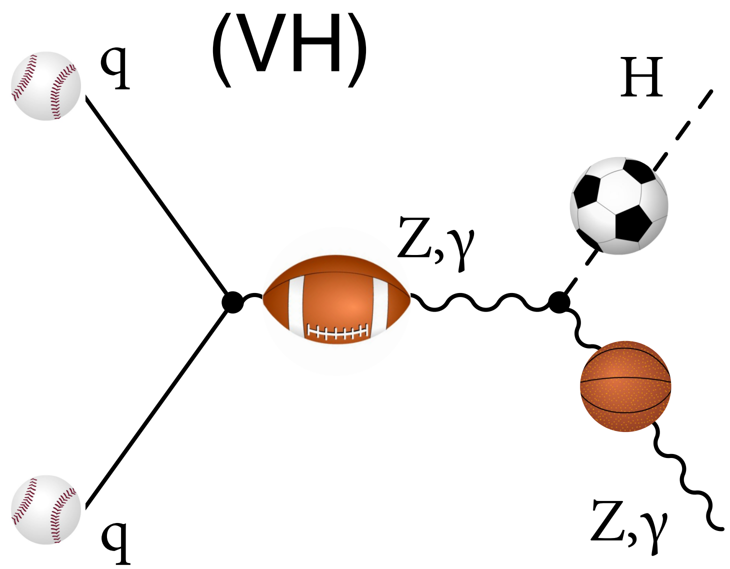
- In H production:

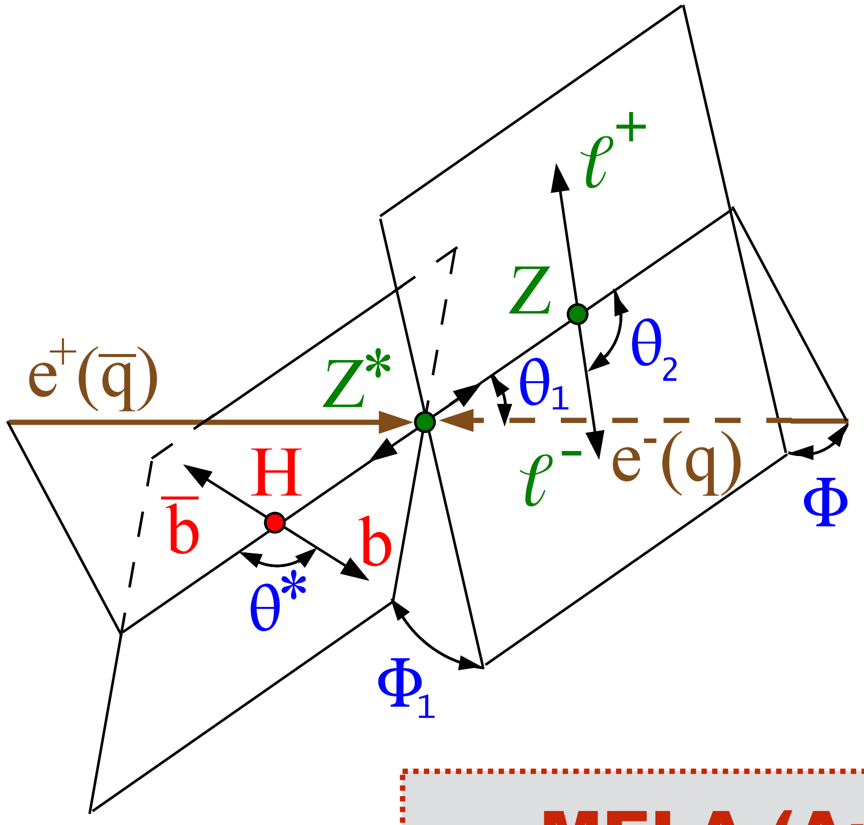


arXiv:1309.4819
arXiv:2002.09888

Idea of MEM: explore full information

- In H production:





arXiv:1309.4819

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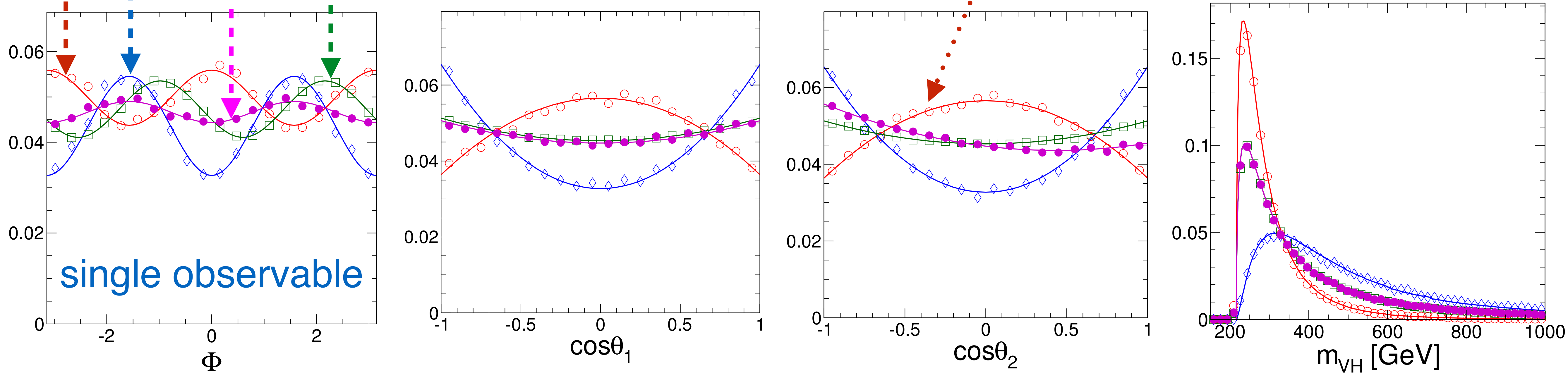
$J^P = 0^+$

$J^P = 0^-$

CP-violating mixture

— **MELA (Analytic+PDF)**

○ **JHUGen**



Two approaches of M.E.M. (or M.L.)

(1) Analyze the full process in one go

— multi-D fit or equivalent

— best approach, but extremely challenging (e.g. in 13D)

(2) Compute dedicated observable(s)

— pack all information in few dedicated observable(s)

— reduce the number of observables (e.g. from ~13D)

(●) Re-use the rest of analysis tools in case of (2)

(a) build dedicated analysis with full simulation

(b) create SM-like differential / STXS distribution

— for pros and cons, see

[WG2 talk on July 1, 2020]

Two types of (2) Dedicated Observables

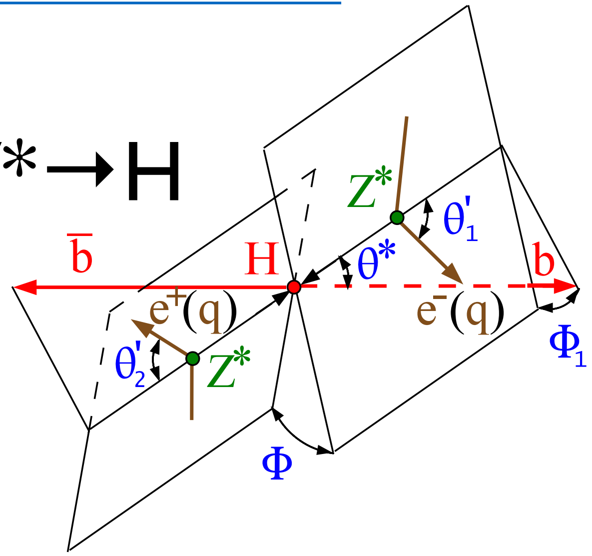
- From 1st principles: 2 $\mathscr{D}$iscriminants to isolate a given $\mathscr{O}$perator:

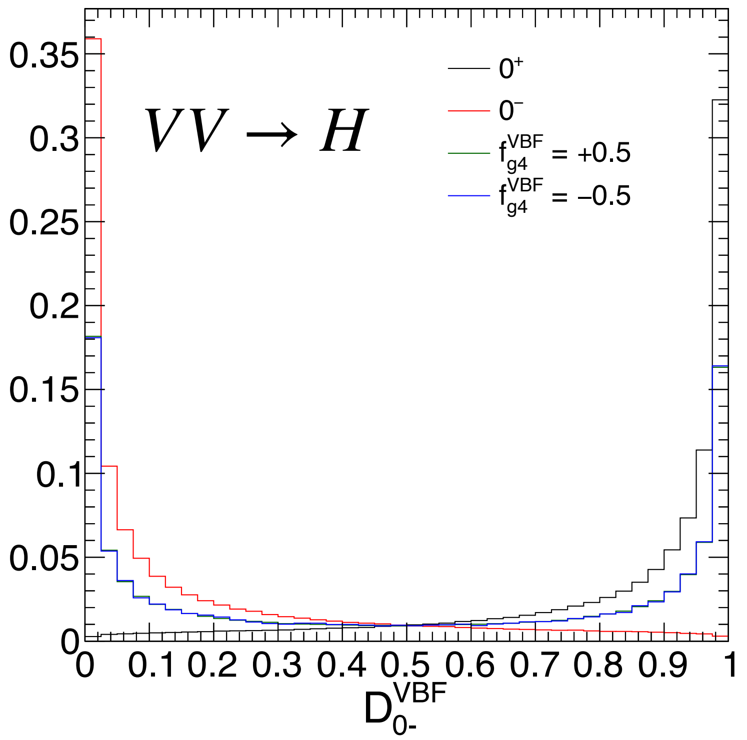
arXiv:1309.4819
arXiv:2002.09888

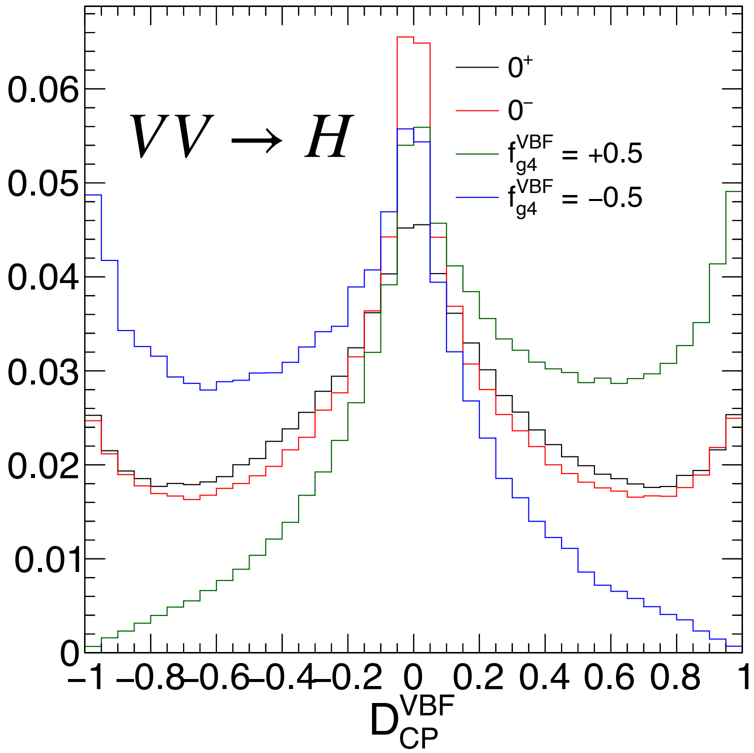
$$\mathcal{D}_{\rm alt}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm sig}(\mathbf{\Omega})}{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) + \mathcal{P}_{\rm alt}(\mathbf{\Omega})}$$

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

V*V*→H







$$A_{\rm CP\,even} + A_{\rm CP\,odd}$$

$$a_1^{\rm ZZ\&WW} \quad a_3^{\rm ZZ\&WW}$$

$$\left|A_{\rm CP\,even}\right|^2 \quad + \left|A_{\rm CP\,odd}\right|^2 \quad + 2{\rm Re}\left(A_{\rm CP\,even} A^*_{\rm CP\,odd}\right)$$

do not constrain to SM rate

discriminant against background

suppressed in EFT

for amplitude analysis

$\int$ often $= 0$ $\Rightarrow$ kinematic distributions

true CP-sensitive observation

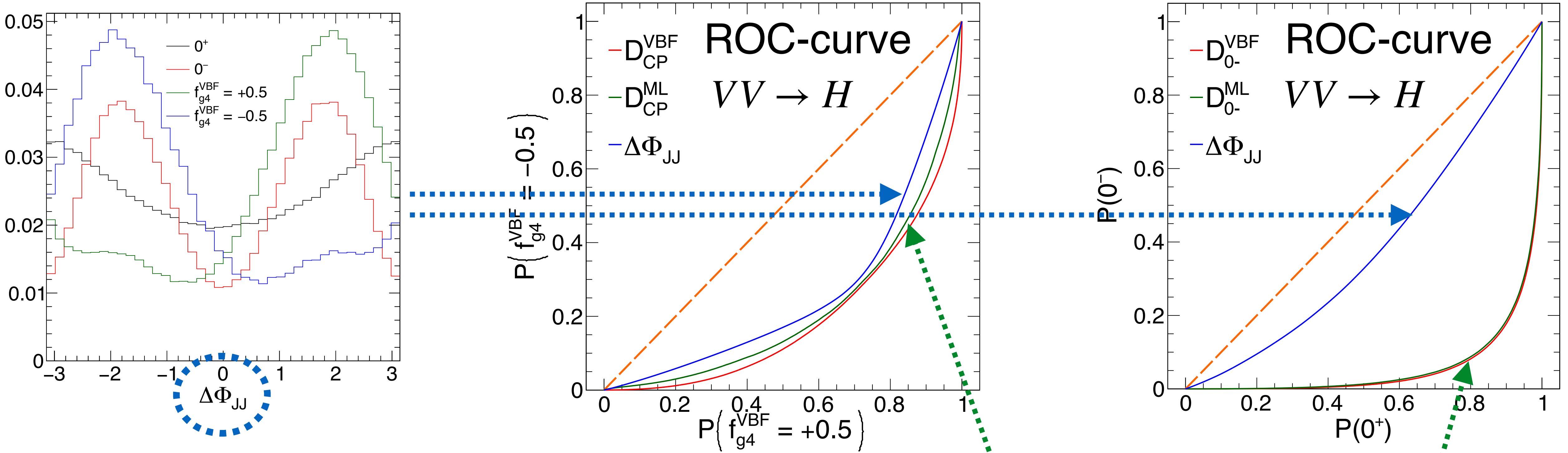
arXiv:1309.4819

Dedicated Observables: MEM vs ML vs single

V*V*→H (VBF)

$$\mathcal{D}_{\rm int}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm int}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) \times \mathcal{P}_{\rm alt}(\mathbf{\Omega})}} \qquad \mathcal{D}_{\rm alt}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm sig}(\mathbf{\Omega})}{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) + \mathcal{P}_{\rm alt}(\mathbf{\Omega})}$$

single observable



challenging kinematics

- Machine Learning — easier to account for parton shower, reconstruction effects…

arXiv:2002.09888

(!) $\mathscr{D}^{\rm ML}_{\rm int}$ → train $-50\,\%$ mixture $\mathscr{O}$/SM against $+50\,\%$

$\mathscr{D}^{\rm ML}_{\rm alt}$ → train $100\,\%$ state $\mathscr{O}$ against SM

key aspect: provide complete input as to Matrix Element (e.g. 13D)

Side comment about CP-odd interference

Rate of

$H \to ZZ/Z\gamma^*/\gamma^*\gamma^* \to 4f$

$$
\begin{aligned}
R_{ZZ/Z\gamma^*/\gamma^*\gamma^*} = {} & \left(\frac{g_1^{ZZ}}{2}\right)^2 + 0.17\left(\kappa_1^{ZZ}\right)^2 + 0.09\left(g_2^{ZZ}\right)^2 + 0.04\left(g_4^{ZZ}\right)^2 + 0.10\left(\kappa_2^{Z\gamma}\right)^2 \\
& +79.95\left(g_2^{Z\gamma}\right)^2 + 75.23\left(g_4^{Z\gamma}\right)^2 + 29.00\left(g_2^{\gamma\gamma}\right)^2 + 29.47\left(g_4^{\gamma\gamma}\right)^2 \\
& +0.81\frac{g_1^{ZZ}}{2}\kappa_1^{ZZ} + 0.50\frac{g_1^{ZZ}}{2}g_2^{ZZ} + 0\times\frac{g_1^{ZZ}}{2}g_4^{ZZ} - 0.19\frac{g_1^{ZZ}}{2}\kappa_2^{Z\gamma} \\
& -1.56\frac{g_1^{ZZ}}{2}g_2^{Z\gamma} + 0\times\frac{g_1^{ZZ}}{2}g_4^{Z\gamma} + 0.06\frac{g_1^{ZZ}}{2}g_2^{\gamma\gamma} + 0\times\frac{g_1^{ZZ}}{2}g_4^{\gamma\gamma} \\
& +0.21\kappa_1^{ZZ}g_2^{ZZ} + 0\times\kappa_1^{ZZ}g_4^{ZZ} - 0.07\kappa_1^{ZZ}\kappa_2^{Z\gamma} - 0.64\kappa_1^{ZZ}g_2^{Z\gamma} \\
& +0\times\kappa_1^{ZZ}g_4^{Z\gamma} + 0.00\kappa_1^{ZZ}g_2^{\gamma\gamma} + 0\times\kappa_1^{ZZ}g_4^{\gamma\gamma} + 0\times g_2^{ZZ}g_4^{ZZ} \\
& -0.05g_2^{ZZ}\kappa_2^{Z\gamma} - 0.51g_2^{ZZ}g_2^{Z\gamma} + 0\times g_2^{ZZ}g_4^{Z\gamma} - 0.02g_2^{ZZ}g_2^{\gamma\gamma} \\
& +0\times g_2^{ZZ}g_4^{\gamma\gamma} + 0\times g_4^{ZZ}\kappa_2^{Z\gamma} + 0\times g_4^{ZZ}g_2^{Z\gamma} + 0.36g_4^{ZZ}g_4^{Z\gamma} \\
& +0\times g_4^{ZZ}g_2^{\gamma\gamma} - 0.57g_4^{ZZ}g_4^{\gamma\gamma} + 1.80\kappa_2^{Z\gamma}g_2^{Z\gamma} + 0\times\kappa_2^{Z\gamma}g_4^{Z\gamma} \\
& -0.05\kappa_2^{Z\gamma}g_2^{\gamma\gamma} + 0\times\kappa_2^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_2^{Z\gamma}g_4^{Z\gamma} - 1.84g_2^{Z\gamma}g_2^{\gamma\gamma} \\
& +0\times g_2^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_4^{Z\gamma}g_2^{\gamma\gamma} - 2.09g_4^{Z\gamma}g_4^{\gamma\gamma} + 0\times g_2^{\gamma\gamma}g_4^{\gamma\gamma}
\end{aligned}
$$

arXiv:2109.13363

Slide adjusted after the talk: thanks to Céline Degrande for checking the cross-terms!

$$\int 2\mathrm{Re}\left(A_{\mathrm{CP\,even}}A^*_{\mathrm{CP\,odd}}\right) = 0$$

Target of a dedicated observable

- Both strength and weakness of a dedicated observable:

target certain operator $\mathcal{O}$perator

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

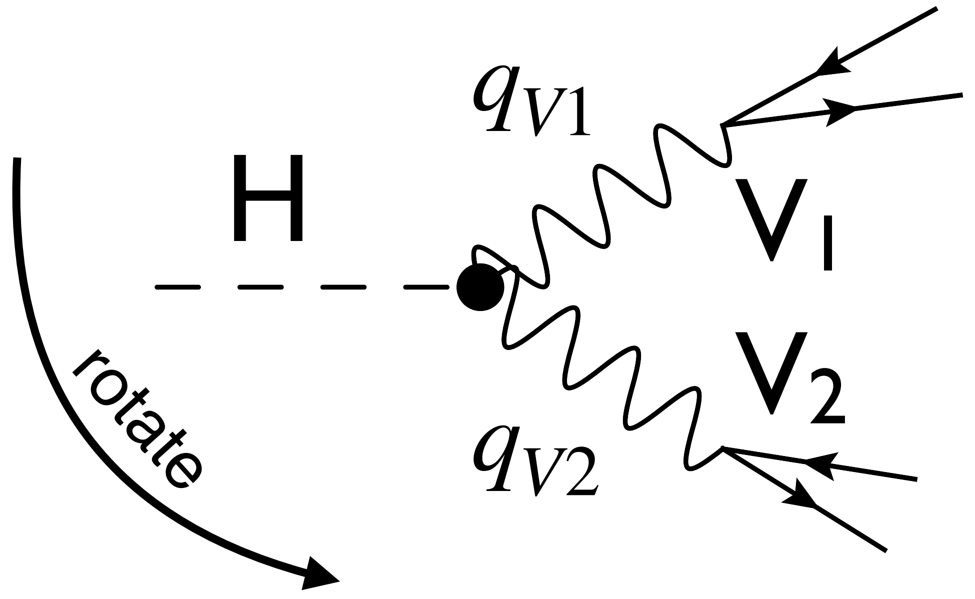
$$\mathcal{D}_{\rm alt}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\rm sig}(\mathbf{\Omega})}{\mathcal{P}_{\rm sig}(\mathbf{\Omega}) + \mathcal{P}_{\rm alt}(\mathbf{\Omega})}$$

- M.E.M. does not work when:
  - — we do not know which $\mathcal{O}$perator(s) to target in advance
  - — target $\mathcal{O}$perator(s) change(s) with time (reinterpretation)
  - — too many target $\mathcal{O}$perators in a given process

- For M.E.M. essential:
  - — pick optimal basis of $\mathcal{O}$perators
  - — isolate small set of $\mathcal{O}$perators to target in each process

Target of a MEM observable: HVV Operators

- Describe $V_i = W, Z, \gamma, g$
  - — e.g. in VBF



dimension-6 $\mathcal{O}$perators in EFT

3 Lorentz tensor structures:

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

tree-level HZZ, HWW (dim-4)

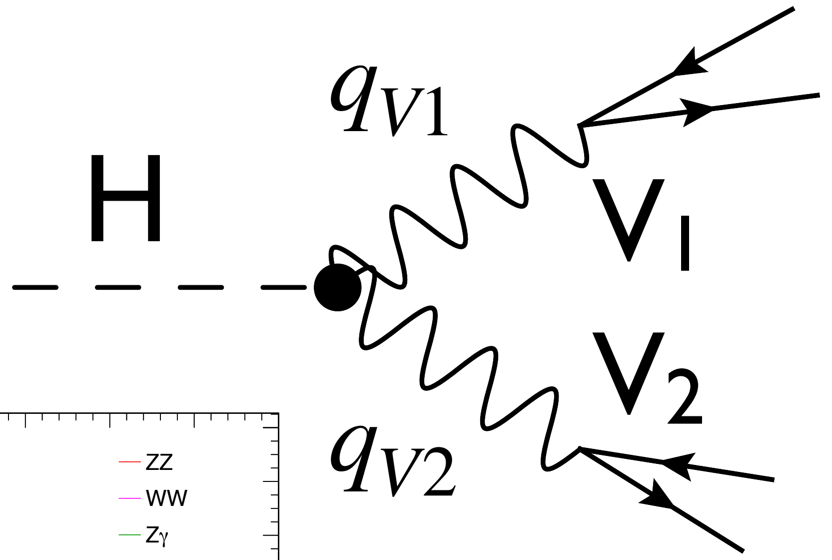
CP-odd

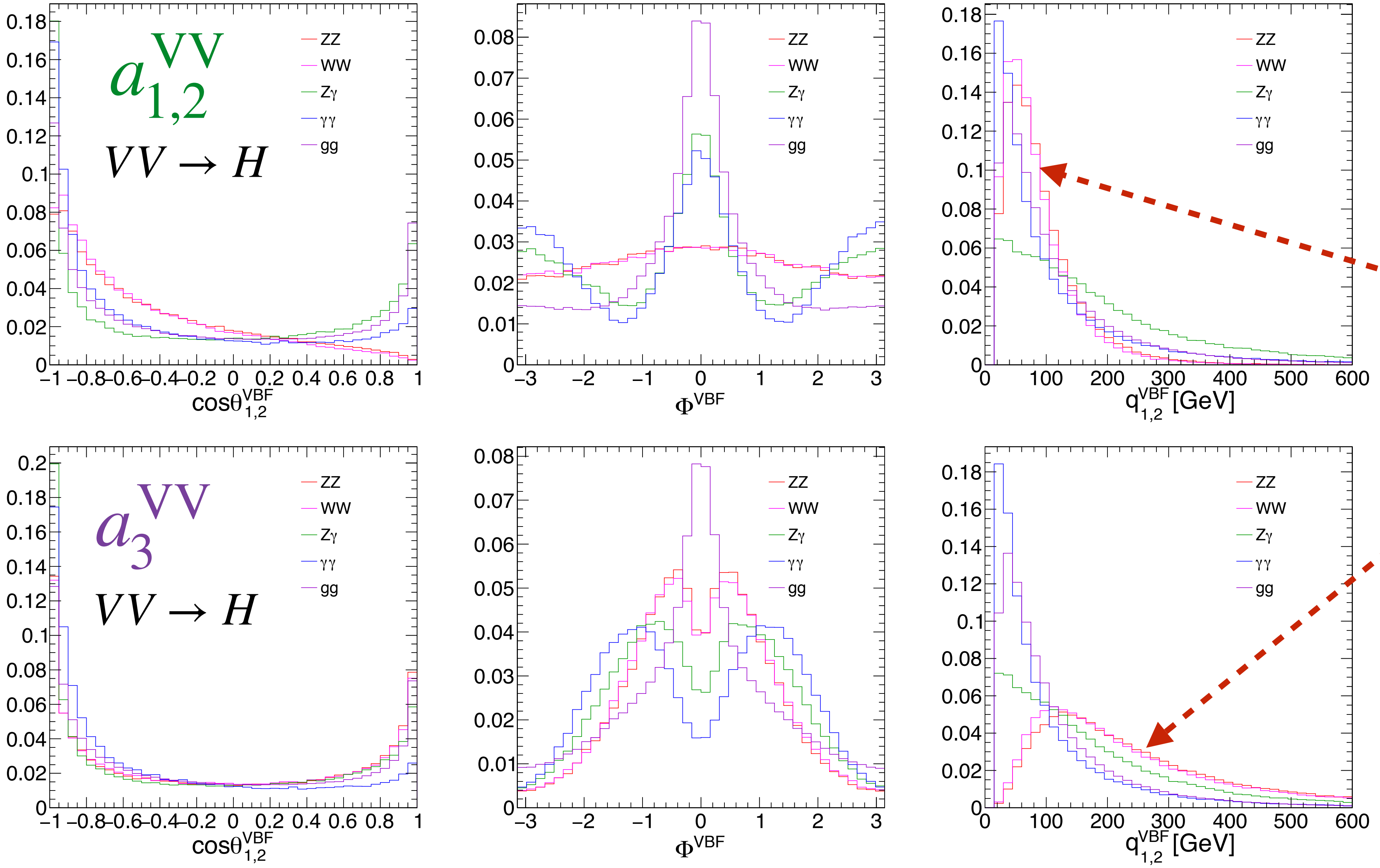
- Many parameters: $13 + 2 + 2 \times N_f$ params of HVV + Hgg + Hff

+ other operators (if considered, may be constrained elsewhere)

Target of a MEM observable: HVV Operators

- Describe $V_i = W, Z, \gamma, g$
  - — e.g. in VBF
    $13 + 2$ params of HVV + Hgg





HZZ & HWW very similar kinematics

arXiv:2002.09888
arXiv:2109.13363

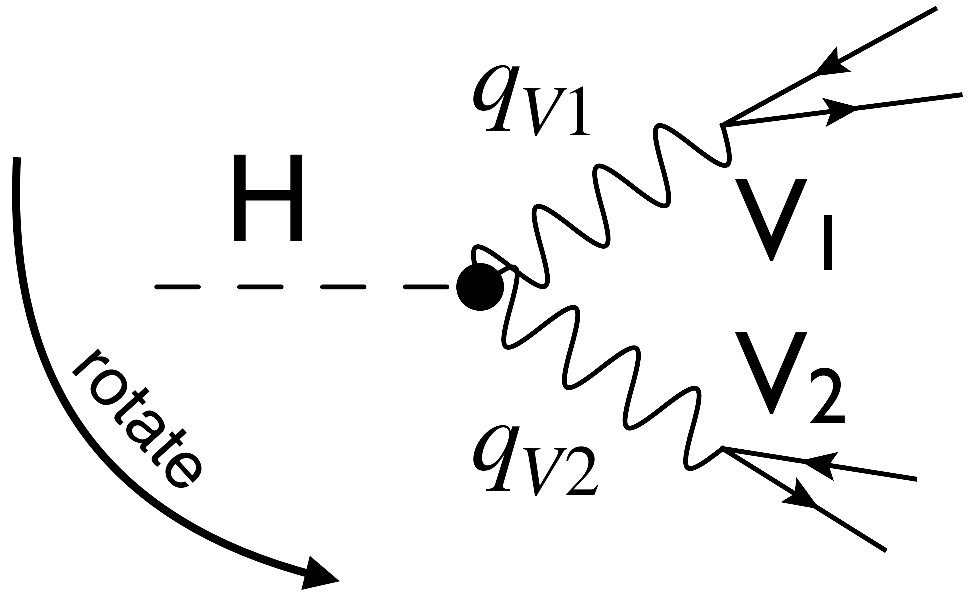
$10/15$ of $HVV(gg)$ $\mathcal{O}$perators shown

Target of a MEM observable: HVV Operators

- $13+2$ params of HVV+Hgg

  — too many to target, e.g. in VBF

  > 20 dedicated observables?



- Reduce with considerations:

(1) SU(2)xU(1) symmetry (SMEFT)

(2) "custodial" symmetry ($\delta c_w = \delta c_z$)

reduce to $8+2$

mostly relate HZZ vs HWW

(3) not all $\mathcal{O}$perators are equal

only 1 CP-odd operator to target in mass eigenstate basis

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

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

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

much better constrained from $H \to \gamma\gamma, Z\gamma$

arXiv:2109.13363

reduce to $4+2$ params of HVV+Hgg

More on HVV Operators

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

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

much better constrained from $H \to \gamma\gamma, Z\gamma$

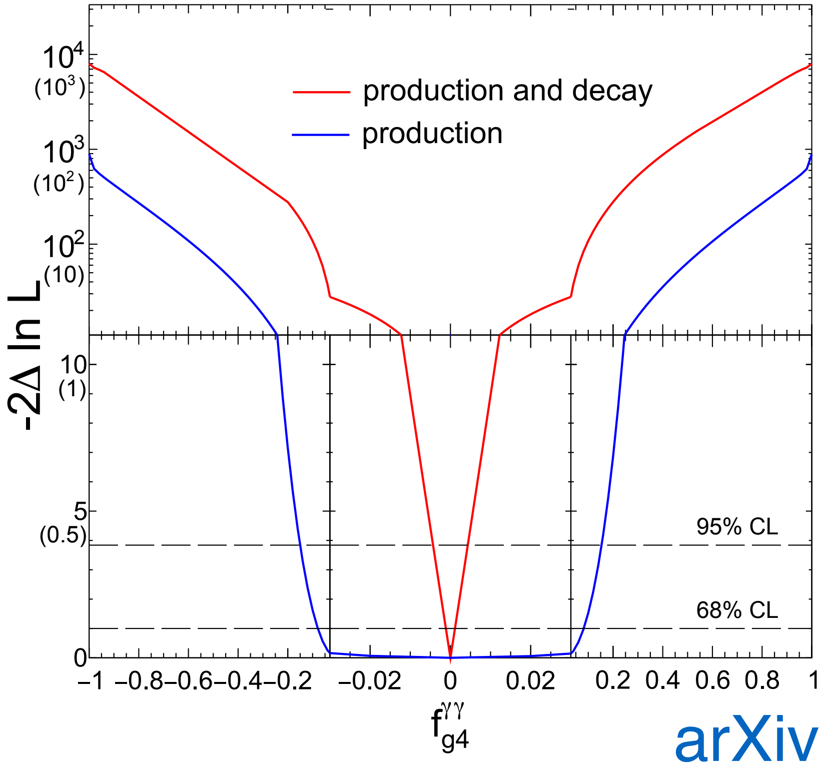
- See talk by S.Kyriacou at the 18th Workshop of WG on Dec.1,2021
  — at HL-LHC will start resolving constraints from $H \to \gamma\gamma, Z\gamma$

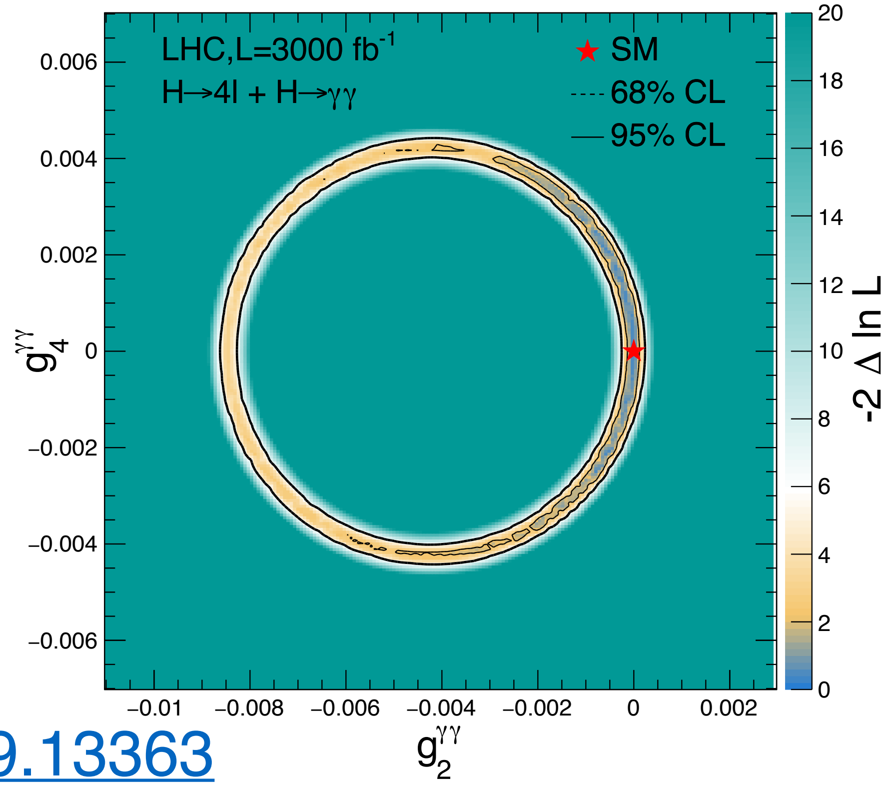
(1) VBF+VH production

(2) $H \to 4\ell$ decay

(3) γH production

(4) $H \to \gamma\gamma, Z\gamma$ decay





arXiv:2109.13363

Example implementation on LHC: HVV

- Example of CMS arXiv:2104.12152 with dedicated observables:

Category	Selection	Observables $\vec{x}$ for fitting
Boosted	$p_{\mathrm{T}}^{4\ell} > 120\,\mathrm{GeV}$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-1jet	$\mathcal{D}_{\mathrm{1jet}}^{\mathrm{VBF}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
VBF-2jet	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{EW}}, \mathcal{D}_{0h+}^{\mathrm{VBF+dec}}, \mathcal{D}_{0-}^{\mathrm{VBF+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{VBF+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{Z}\gamma,\mathrm{VBF+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VBF}}, \mathcal{D}_{CP}^{\mathrm{VBF}}$
VH-hadronic	$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VH}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{EW}}, \mathcal{D}_{0h+}^{\mathrm{VH+dec}}, \mathcal{D}_{0-}^{\mathrm{VH+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{VH+dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{Z}\gamma,\mathrm{VH+dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{VH}}, \mathcal{D}_{CP}^{\mathrm{VH}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, p_{\mathrm{T}}^{4\ell}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}_{0h+}^{\mathrm{dec}}, \mathcal{D}_{0-}^{\mathrm{dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{dec}}, \mathcal{D}_{\Lambda1}^{\mathrm{Z}\gamma,\mathrm{dec}}, \mathcal{D}_{\mathrm{int}}^{\mathrm{dec}}, \mathcal{D}_{CP}^{\mathrm{dec}}$

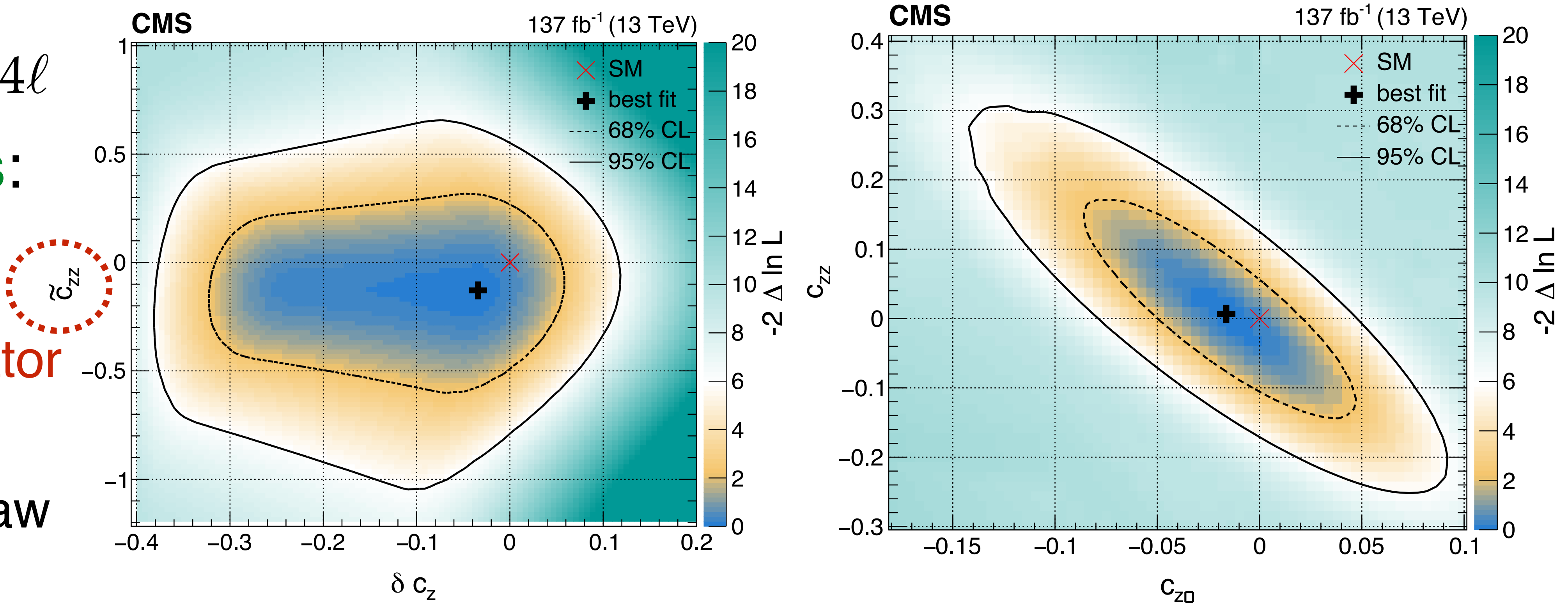
M.E.M.

VBF & VH & $\mathrm{H} \to 4\ell$

Target $\mathcal{O}$perators:

1 CP-odd operator

4 Higgs → 8 Warsaw



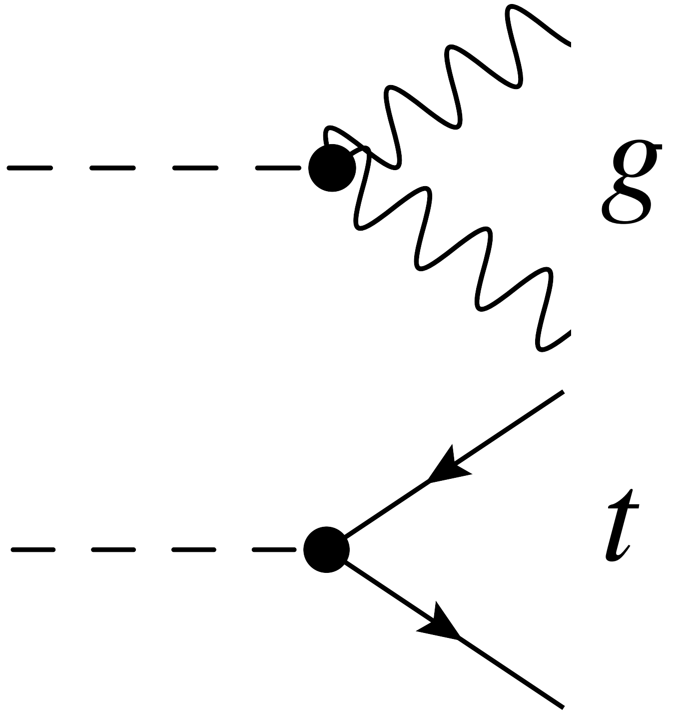
Example implementation on LHC: *Htt* & *Hgg*

- Example of CMS arXiv:2104.12152 with dedicated observables:

Category	Selection	Observables $\vec{x}$ for fitting
VBF-1jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{1jet}} > 0.7$	$\mathcal{D}_{\mathrm{bkg}}$
VBF-2jet	$\mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{VBF}}_{\mathrm{2jet}}, \mathcal{D}^{\mathrm{ggH}}_{0-}, \mathcal{D}^{\mathrm{ggH}}_{CP}$
VH-hadronic	$\mathcal{D}^{\mathrm{VH}}_{\mathrm{2jet}} > 0.5$	$\mathcal{D}_{\mathrm{bkg}}$
VH-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}$
$\mathrm{t\bar{t}H}$-hadronic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
$\mathrm{t\bar{t}H}$-leptonic	see Section 3	$\mathcal{D}_{\mathrm{bkg}}, \mathcal{D}^{\mathrm{t\bar{t}H}}_{0-}$
Untagged	none of the above	$\mathcal{D}_{\mathrm{bkg}}$

M.E.M.

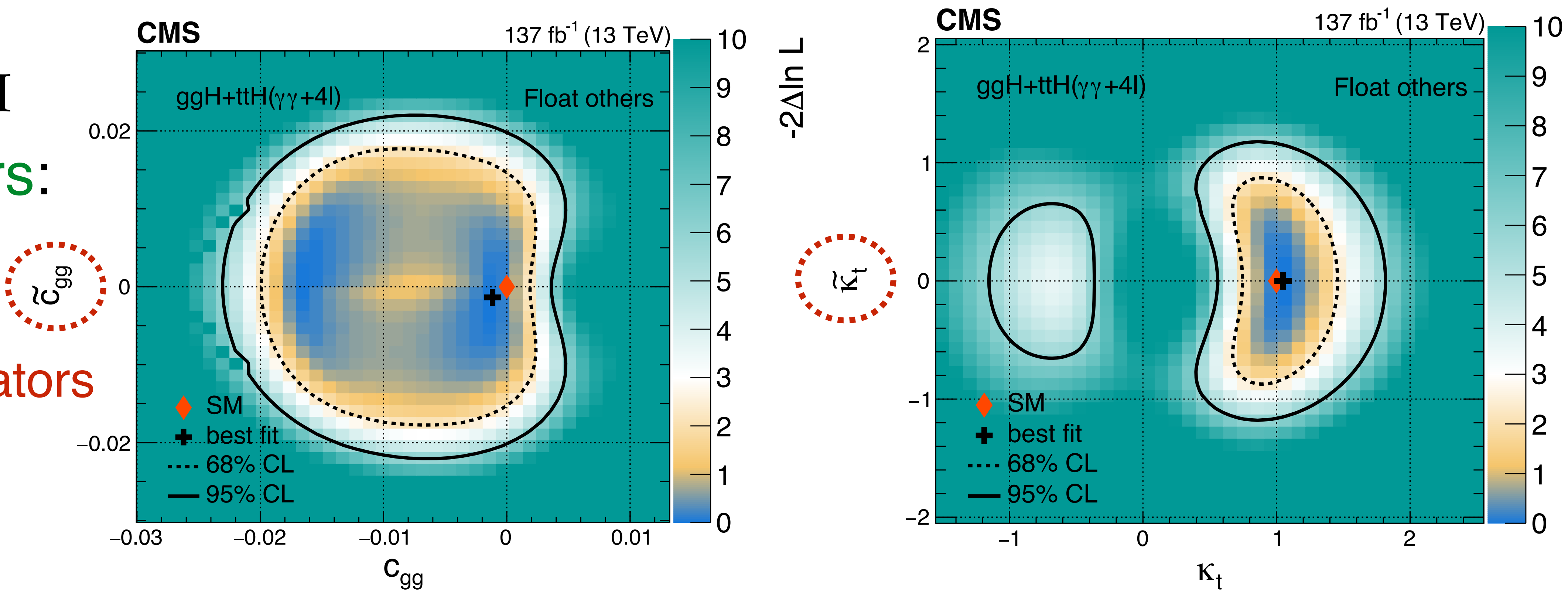
M.L.



tH & $\mathrm{t\bar{t}H}$ & ggH

Target $\mathcal{O}$perators:

2 CP-odd operators



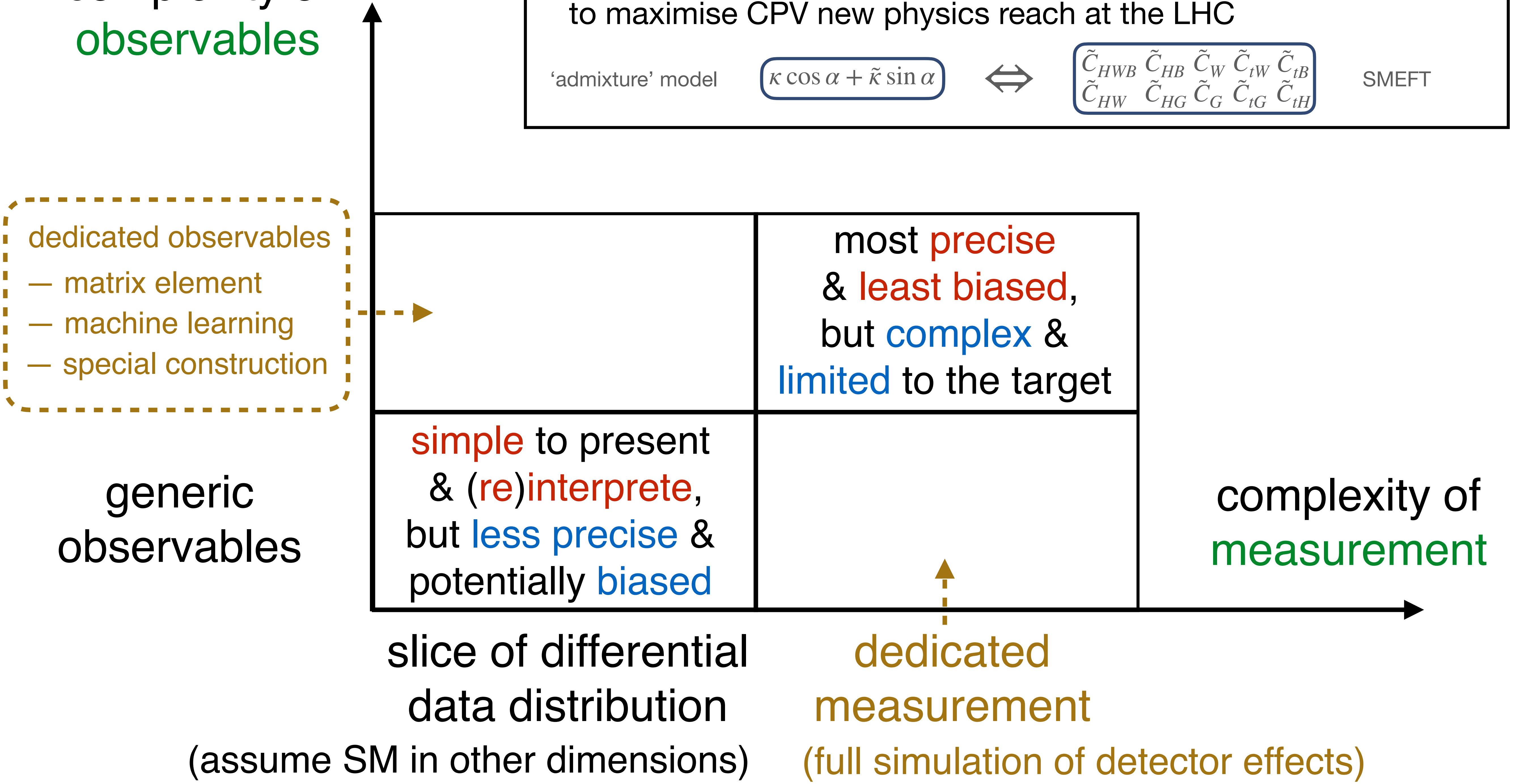
Dedicated observable vs. measurement

- How to present results of a dedicated measurement?

from WG2 convener's report Dec.3,2021

- Recommendations for common parametrisation & measurements to maximise CPV new physics reach at the LHC

‘admixture’ model $\kappa\cos\alpha + \tilde{\kappa}\sin\alpha$ $\Leftrightarrow$ $\tilde{C}_{HWB}\ \tilde{C}_{HB}\ \tilde{C}_{W}\ \tilde{C}_{tW}\ \tilde{C}_{tB}$ $\tilde{C}_{HW}\ \tilde{C}_{HG}\ \tilde{C}_{G}\ \tilde{C}_{tG}\ \tilde{C}_{tH}$ SMEFT



complexity of observables

dedicated observables
— matrix element
— machine learning
— special construction

most precise & least biased, but complex & limited to the target

simple to present & (re)interprete, but less precise & potentially biased

generic observables

complexity of measurement

slice of differential data distribution
(assume SM in other dimensions)

dedicated measurement
(full simulation of detector effects)

Dedicated measurement

- Recommendations for common parametrisation & measurements to maximise CPV new physics reach at the LHC

'admixture' model $\boxed{\kappa \cos\alpha + \tilde{\kappa} \sin\alpha}$ $\Leftrightarrow$ $\boxed{\begin{matrix} \tilde{C}_{HWB} & \tilde{C}_{HB} & \tilde{C}_{W} & \tilde{C}_{tW} & \tilde{C}_{tB} \\ \tilde{C}_{HW} & \tilde{C}_{HG} & \tilde{C}_{G} & \tilde{C}_{tG} & \tilde{C}_{tH} \end{matrix}}$ SMEFT

- In experiment we measure cross sections, e.g. with 2 operators:
  - $\sigma_{\text{CP odd}}$ & $\sigma_{\text{CP even}}$ (carry the sign as well)
  - $\sigma_{\text{tot}}/\sigma_{\text{SM}}$ & $\sigma_{\text{CP odd}}/\sigma_{\text{CP even}}$ (better to report)

$$\sigma_{\text{CP odd}}/\sigma_{\text{CP even}} \Leftrightarrow \alpha_{\text{CP}} \Leftrightarrow f_{\text{CP}} = \sin^2 \alpha_{\text{CP}}$$

- Measurement dedicated to $N+1$ operators in a given process:
  - $\sigma_{\text{tot}}/\sigma_{\text{SM}}$ & $f_{\mathcal{O}1}$ & $f_{\mathcal{O}2}$ &… $f_{\mathcal{O}N}$
- Interpretation of cross sections as couplings requires a "global fit"

$$\sigma_j^{\text{prod}} \times \mathcal{B}^{\text{dec}} \propto \frac{\left(\sum_{il} \alpha_{il}^{(\text{prod j})} a_i a_l\right)\left(\sum_{mn} \alpha_{mn}^{(\text{dec})} a_m a_n\right)}{\Gamma_{\text{H}}}$$

Summary

- Dedicated observables in a given process:
  - use full kinematic information
  - best approach if we know what we do
  - need clear target $\mathcal{O}$perators
  - optimize $\mathcal{O}$perator basis
  - prioritize $\mathcal{O}$perators
  - two types of dedicated observables for each $\mathcal{O}$perator
  - conceptually M.E.M. and M.L. equivalent

see backup:

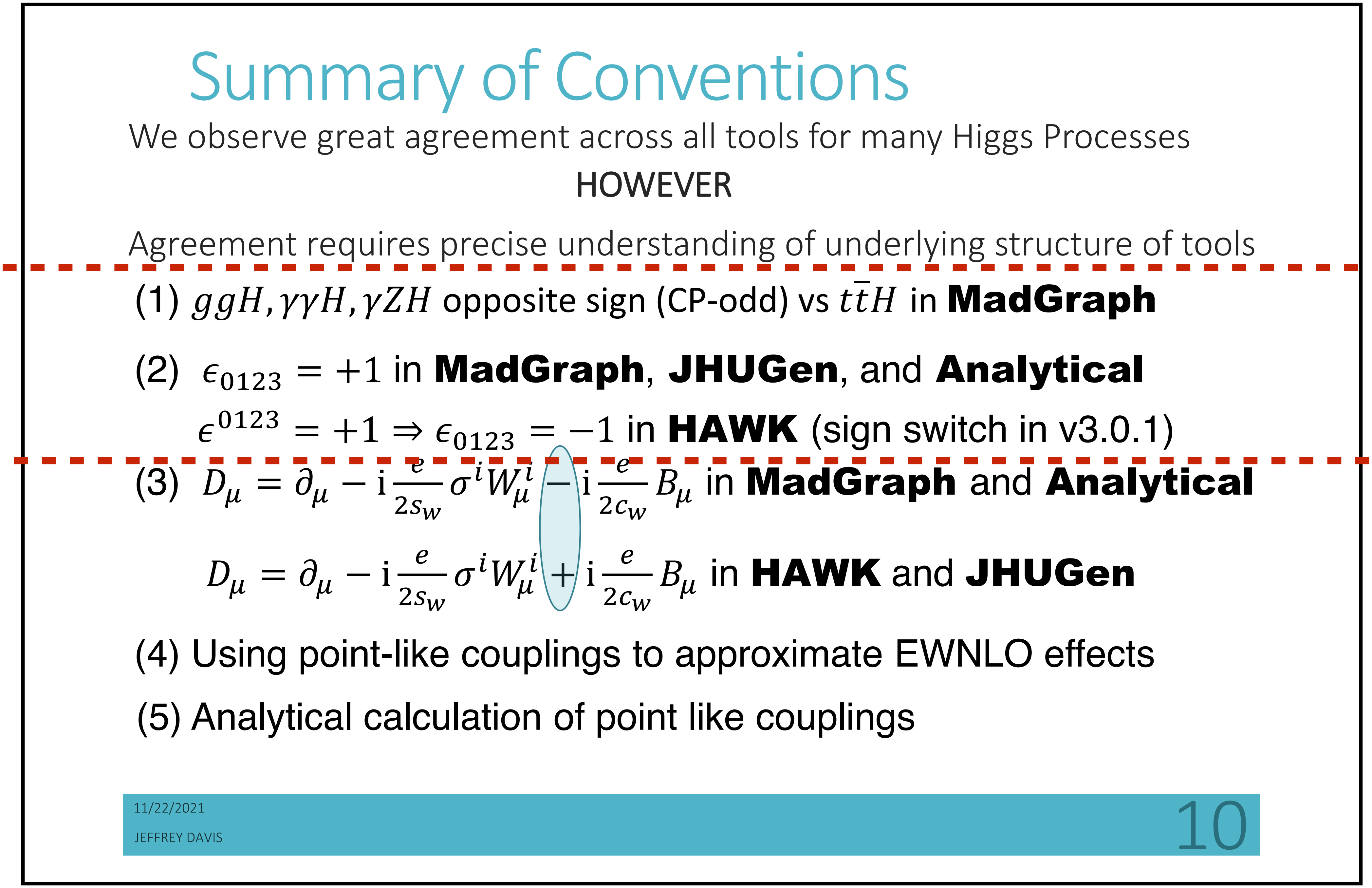
- sync on CP tools
- CP at Snowmass

- Dedicated measurements in a given process:
  - measure cross sections, later interpret as couplings
  - best result (unbiased & optimal) for the target $\mathcal{O}$perators
  - (a) complex (=difficult), (b) limited to the target $\mathcal{O}$perators only

BACKUP

Sync on tools

- See talk by J.Davis at the 3rd General Meeting of LHC EFT WG
  - — ATLAS and CMS need to sync on conventions in tools!



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

$D_\mu = \partial_\mu - \mathrm{i}\frac{e}{2s_w}\sigma^i W^i_\mu + \mathrm{i}\frac{e}{2c_w}B_\mu$ 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

10

likely out of sync

Sync on 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**

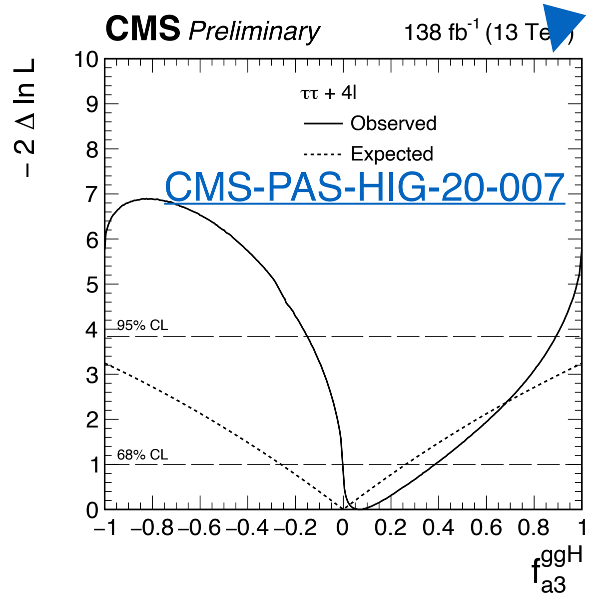
$\epsilon^{0123} = +1 \Rightarrow \epsilon_{0123} = -1$ in **HAWK** (sign switch in v3.0.1)

CMS:

ATLAS:

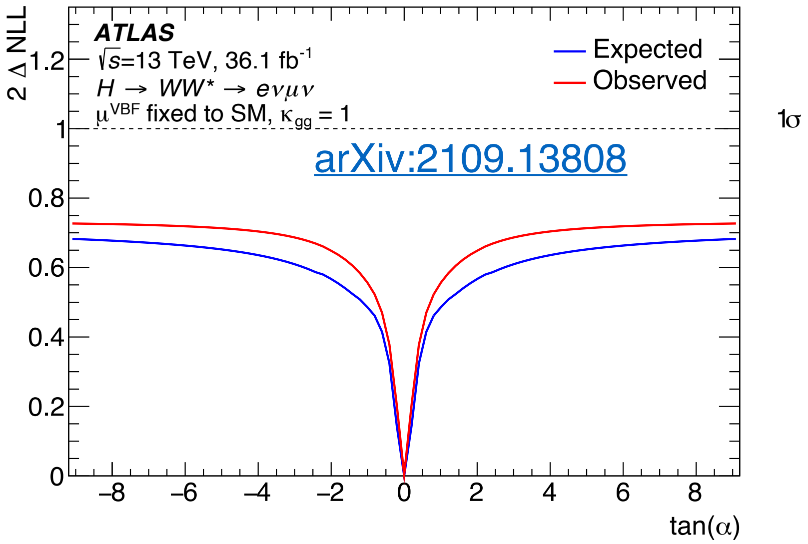
Examples:

(1) CP in $ggH + jj$



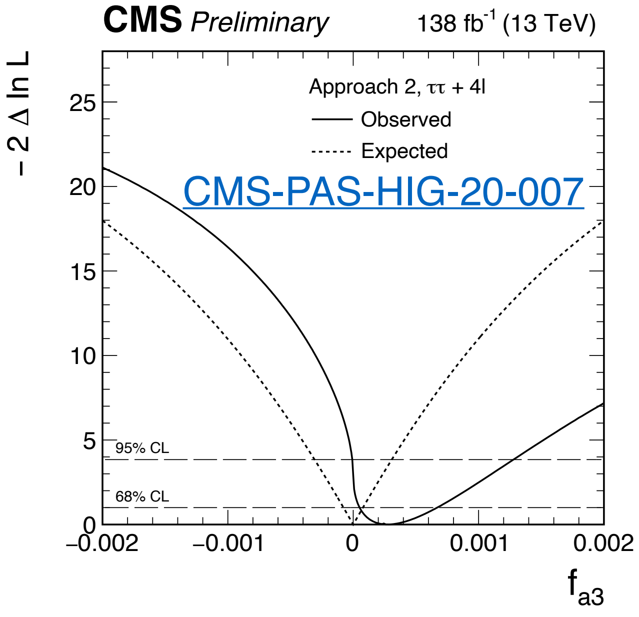
CMS-PAS-HIG-20-007

sign ←?→



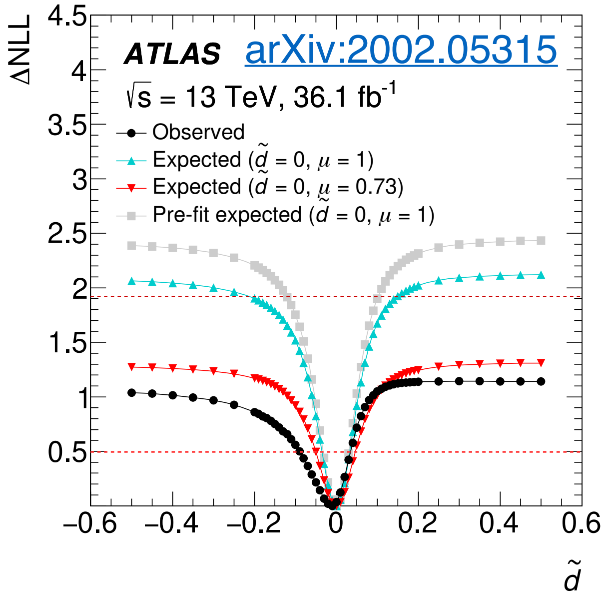
arXiv:2109.13808

(2) CP in VBF ($H \to \tau\tau$)



CMS-PAS-HIG-20-007

sign ←?→



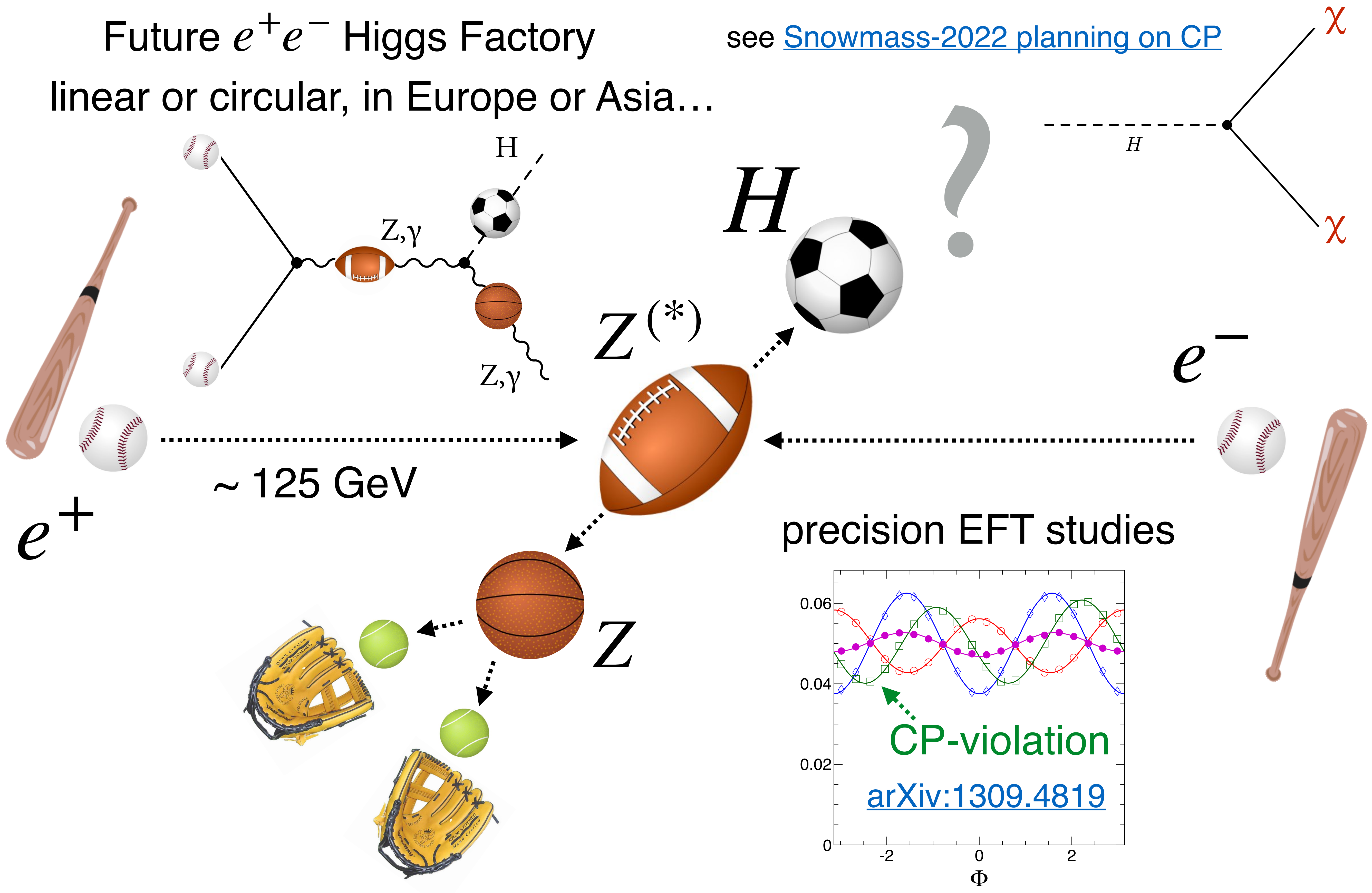
arXiv:2002.05315

Snowmass-2022 activities on CP with H

Future e^+e^- Higgs Factory

linear or circular, in Europe or Asia…

see Snowmass-2022 planning on CP



precision EFT studies

CP-violation

arXiv:1309.4819