

Higgs at Run II

Tilman Plehn

Higgs EFT

Higgs-TGV EFT

Higgs-EW EFT

Higgs-LHC EFT

CP symmetry

Information

The Higgs Bottom Line of Run II

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Cambridge, February 2019

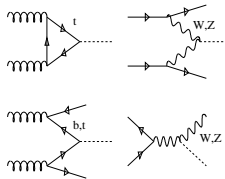
1– Higgs couplings

How the LHC became a precision Higgs machine

- assume: narrow CP -even scalar
Standard Model operators
- Lagrangian like non-linear symmetry breaking

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W g m_W H W^\mu W_\mu + \Delta_Z \frac{g}{2c_W} m_Z H Z^\mu Z_\mu - \sum_{\tau, b, t} \Delta_f \frac{m_f}{v} H (\bar{f}_R f_L + \text{h.c.})$$

$$+ \Delta_g F_G \frac{H}{v} G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \frac{H}{v} A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$



$gg \rightarrow H$
 $gg \rightarrow H + j$ (boosted)
 $gg \rightarrow H^*$ (off-shell)
 $qq \rightarrow qqH$
 $gg \rightarrow ttH$
 $qq' \rightarrow VH$

\longleftrightarrow

$$g_{HXX} = g_{HXX}^{\text{SM}} (1 + \Delta_X)$$

\longleftrightarrow

$H \rightarrow ZZ$
 $H \rightarrow WW$
 $H \rightarrow b\bar{b}$
 $H \rightarrow \tau^+ \tau^-$
 $H \rightarrow \gamma\gamma$
 $H \rightarrow \text{invisible}$

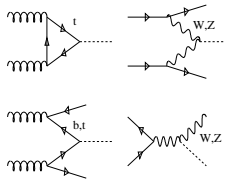
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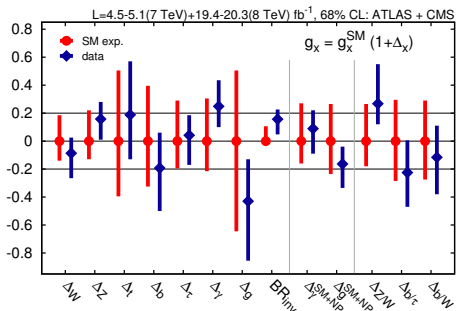
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Brilliant Run I analyses, but issues... [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

- 1 **renormalizability** broken
- 2 **total rates** only
- 3 hard to extend to **full SM**



D6 Lagrangian [SMEFT; review Brivio & Trott, ask Tevong and BenG]

– set of Higgs operators [renormalizable, #1 solved]

$$\mathcal{O}_{GG} = \phi^\dagger \phi G_{\mu\nu}^a G^{a\mu\nu} \quad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \quad \mathcal{O}_{BB} = \dots$$

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2– Effective Higgs operators

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- actual basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{D6} = - \frac{\alpha_s V}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

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- Higgs couplings to SM particles [derivatives = momentum, #2 solved]

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- plus Yukawa structure $f_{\tau,b,t}$
- 7 Δ -like coupling modifications plus 4 new Lorentz structures

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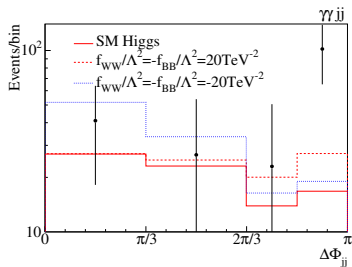
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Improved Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

- kinematics: $p_{T,V}, \Delta\phi_{jj}$ [#2 solved]



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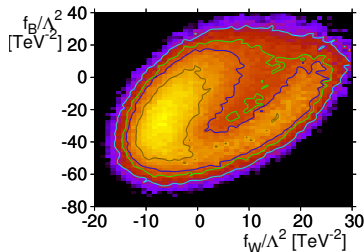
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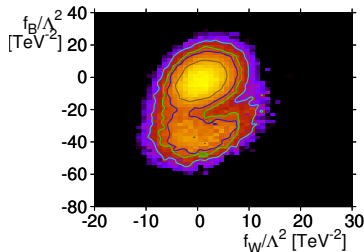
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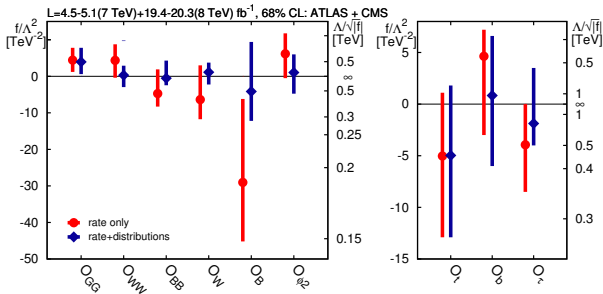
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- **key observable**



3– Effective Higgs-gauge operators

Higgs-Goldstone doublets [Falkowski et al; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

- one more operator for TGV [#3 solved]

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \quad \dots \quad \mathcal{O}_{WWW} = \text{Tr} \left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right)$$

- kinematics: $p_{T,\ell}$ in VV production

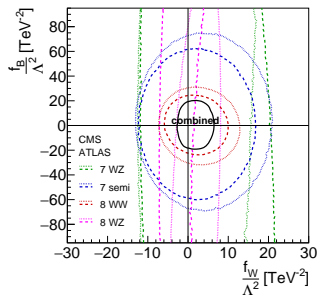
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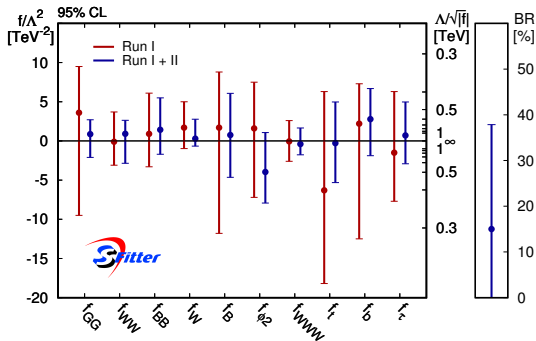
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⇒ **Higgs-gauge analysis at Run II** [Biekötter, Corbett, TP (2018)]



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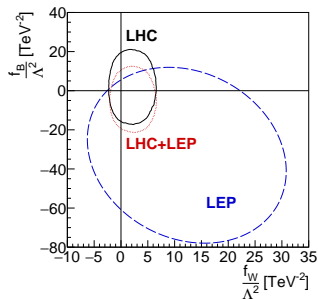
LHC vs LEP [Grojean, Montull, Riemann; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

- triple vertices g_1, κ, λ vs gauge-invariant operators
- generic EFT feature:

LEP driven by precision

LHC driven by energy

⇒ **LHC the leading precision machine**



4– Electroweak fermion couplings

After beating LEP once... [Biekötter, Corbett, TP (2018); also Alves etal; Tevong etal]

- gauge-fermion operators visible [Zhang; Baglio, Dawson, Lewis]

$$\mathcal{O}_{\phi L}^{(1)} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{L}_i \gamma^\mu L_i) \quad \mathcal{O}_{\phi e}^{(1)} = \phi^\dagger \overleftrightarrow{D}_\mu \phi (\bar{e}_{R,i} \gamma^\mu e_{R,i}) \quad \mathcal{O}_{\phi L}^{(3)} = \phi^\dagger \overleftrightarrow{D}_\mu^a \phi (\bar{L}_i \gamma^\mu \sigma_a L_i)$$

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- bosonic operators bounded by EWPD

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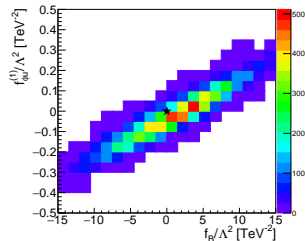
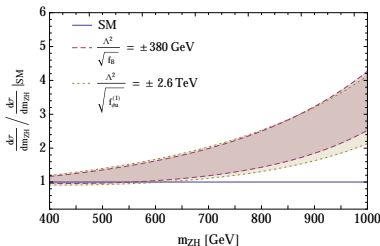
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Side remark: being tricked by LHC kinematics

- m_{ZH} perfect, exotics search to 1.2 TeV
- scale hierarchy $\mathcal{O}_{\phi u}^{(1)} \rightarrow g_{qqZH}$ vs $\mathcal{O}_W \rightarrow g_{ZZH}$ broken by 4-point vertex



5– More effective couplings

Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai; for our QCD friends]

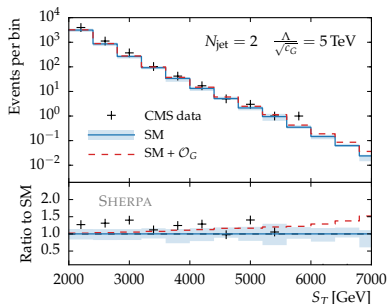
- anomalous gluon coupling

$$\mathcal{O}_G = g_s f_{abc} G_{a\nu}^\rho G_{b\lambda}^\nu G_{c\rho}^\lambda$$

- multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$

gluon operator for $N_{\text{jets}} \geq 5$



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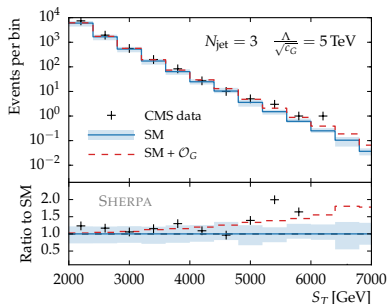
- anomalous gluon coupling

$$\mathcal{O}_G = g_s f_{abc} G_{a\nu}^\rho G_{b\lambda}^\nu G_{c\rho}^\lambda$$

- multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$

gluon operator for $N_{\text{jets}} \geq 5$



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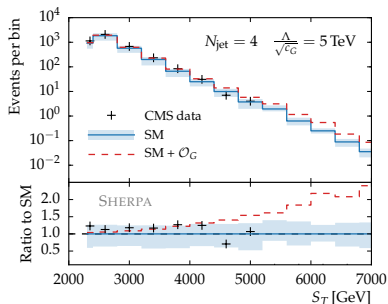
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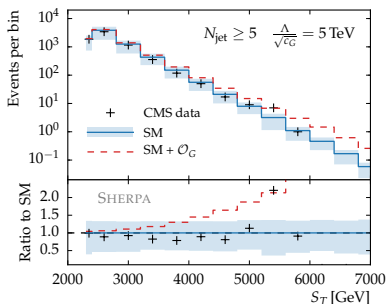
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gluon operator for $N_{\text{jets}} \geq 5$

- input to Higgs analysis $\Lambda/f_G > 5.2 \text{ TeV}$



EFT musings

Ideal LEP and flavor worlds

- unique EFT Lagrangian: linear realization matching unbroken phase
- chain of well separated energy scales $E \ll \Lambda_1 \ll \dots \ll \Lambda_N$
- ⇒ systematic expansion in E/Λ and α [example: ew precision data]

Rotten LHC world [Brehmer, Freitas, Lopez-Val, TP]

- range of (partonic) energy scales [H +jets production]
- electroweak symmetry breaking at $v \sim E_{\text{LHC}}$
- low precision, reach from energy

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \approx 10\% \quad \xleftrightarrow{g=1} \quad \Lambda \approx 400 \text{ GeV}$$

⇒ D8 operators not obviously suppressed

Task for LHC theory

- **develop a working D6 framework**
- keep theorist's self respect
- remember we really care about UV models [BenA does...]
- truncation uncertainties as **matching uncertainties**

Symmetries of the effective Lagrangian

Recap: C and P and T and \hat{T}

- transformations on state with spin/momentum [review: Valencia]

$$C |\phi(\mathbf{p}, \mathbf{s})\rangle = |\phi^*(\mathbf{p}, \mathbf{s})\rangle \quad P |\phi(\mathbf{p}, \mathbf{s})\rangle = \eta_\phi |\phi(-\mathbf{p}, \mathbf{s})\rangle \quad T |\phi(\mathbf{p}, \mathbf{s})\rangle = \langle\phi(-\mathbf{p}, -\mathbf{s})|$$

CPT symmetry generally assumed, T proxy for CP

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- genuine U -odd** is what we want [$U = C, P, T$, Atwood, Bar-Shalom, Eilam]

$$\langle O \rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0 .$$

U -odd is what we usually get, but genuine U -odd under conditions

$$O(U|i\rangle \rightarrow U|f\rangle) \stackrel{\text{odd}}{=} -O(|i\rangle \rightarrow |f\rangle) \quad \overset{P(|i\rangle)=P(U|i\rangle)}{\implies} \langle O \rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0 .$$

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- naive time reversal \hat{T} avoiding initial \leftrightarrow final state

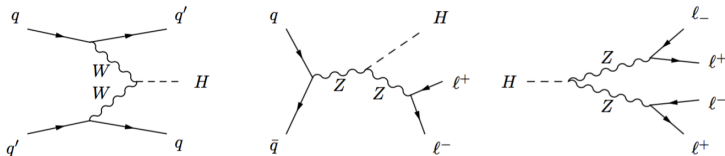
$$\hat{T} |\phi(p, s)\rangle = |\phi(-p, -s)\rangle$$

genuine \hat{T} -odd observable means CP -violating theory, provided

- 1- phase space \hat{T} -symmetric
- 2- initial state distribution invariant under \hat{T}
- 3- no re-scattering, means no imaginary parts

Two ways to test CP at the LHC

Identical amplitudes with $\mathcal{O}_{W\tilde{W}}$ [BenG on EDMs]



- four 4-momenta defining 10+1 observables [Han, Li,...]

four external masses

four C -even, P -even, and \hat{T} -even scalar products

two C -odd, P -even, and \hat{T} -even scalar products

one C -even, P -odd, and \hat{T} -odd observable with Levi-Civita-tensor

- 1– CP -odd and \hat{T} -odd

for symmetric initial state also genuine CP -odd and genuine \hat{T} -odd
non-zero expectation value means CP violation

- 2– CP -odd and \hat{T} -even [for our LHCb friends]

for symmetric initial state also genuine CP -odd

for CP -violating theory, CP -expectation value non-zero

but without re-scattering, \hat{T} -expectation value zero

need complex phase for $\langle O \rangle$ to match symmetry

⇒ single CP -odd and \hat{T} -odd observable vs kinematic analysis?

Quantifying the available information

Information geometry for LHC [Brehmer, Cranmer, Kling, TP (2017)]

- covariance matrix [measurement error in model space \mathbf{g}]

$$C_{ij}(\mathbf{g}) \equiv E [(\hat{g}_i - \bar{g}_i)(\hat{g}_j - \bar{g}_j) | \mathbf{g}]$$

- Fisher information [sensitivity in model space]

$$I_{ij}(\mathbf{g}) \equiv -E \left[\frac{\partial^2 \log f(\mathbf{x} | \mathbf{g})}{\partial g_i \partial g_j} \Big| \mathbf{g} \right]$$

- Cramèr-Rao bound defining best measurement [lowest possible covariance]

$$C_{ij}(\mathbf{g}) \geq (I^{-1})_{ij}(\mathbf{g})$$

- computable over phase space [phase space \mathbf{x} , additive]

$$I_{ij} = \frac{L}{\sigma} \frac{\partial \sigma}{\partial g_i} \frac{\partial \sigma}{\partial g_j} - L \sigma E \left[\frac{\partial^2 \log f^{(1)}(\mathbf{x} | \mathbf{g})}{\partial g_i \partial g_j} \right]$$

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- 1– parametrization-invariant ellipses of constant distance/reach in model space
 - 2– diagonalize I_{ij} , define model-space eigenvectors
 - 3– compute information in distributions or phase space regions
- ⇒ **tool to compare analysis ideas** [MadMiner: Brehmer, Cranmer, Kling]

WBF production

Testing CP in WBF

- four external 4-momenta \rightarrow 10 scalar products
- one C -even, P -odd, \hat{T} -odd [yeah]

$$\epsilon_{\mu\nu\rho\sigma} k_1^\mu k_2^\nu q_1^\rho q_2^\sigma \rightarrow O \equiv \epsilon_{\mu\nu\rho\sigma} k_1^\mu k_2^\nu q_1^\rho q_2^\sigma \text{ sign} [(k_1 - k_2) \cdot (q_1 - q_2)]$$

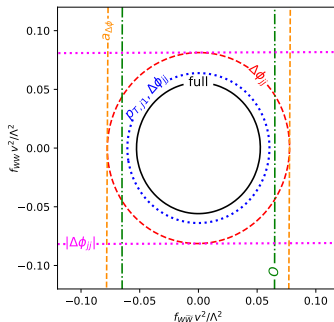
- azimuthal angle difference [lab frame]

$$O = 2E_- (\vec{q}_- \times \vec{q}_+) \cdot \vec{k}_+ \rightarrow \sin \Delta\phi_{jj}$$

- CP asymmetry

$$a_{\Delta\phi_{jj}} \equiv \frac{d\sigma(\Delta\phi_{jj}) - d\sigma(-\Delta\phi_{jj})}{d\sigma(\Delta\phi_{jj}) + d\sigma(-\Delta\phi_{jj})}$$

- difference from dimension-6 kinematics



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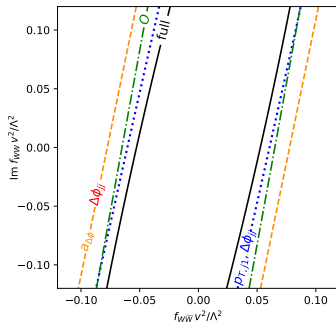
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- difference from dimension-6 kinematics
- check with imaginary Wilson coefficients
- \Rightarrow testing CP , but assuming no re-scattering



ZH production

Testing CP in ZH production

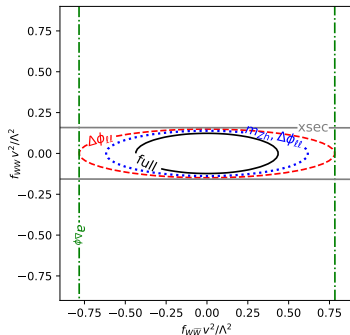
- same 10 scalar products
one CP -odd and \hat{T} -odd angle as for WBF

$$O_1 = \epsilon_{\mu\nu\rho\sigma} k_1^\mu k_2^\nu q_{\ell+}^\rho q_{\ell-}^\sigma \text{sign}((k_1 - k_2) \cdot (q_1 - q_2)) \rightarrow \sin \Delta\phi_{\ell\ell}$$

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- difference from dimension-6 kinematics
- ⇒ testing CP without assumptions [to leading order]



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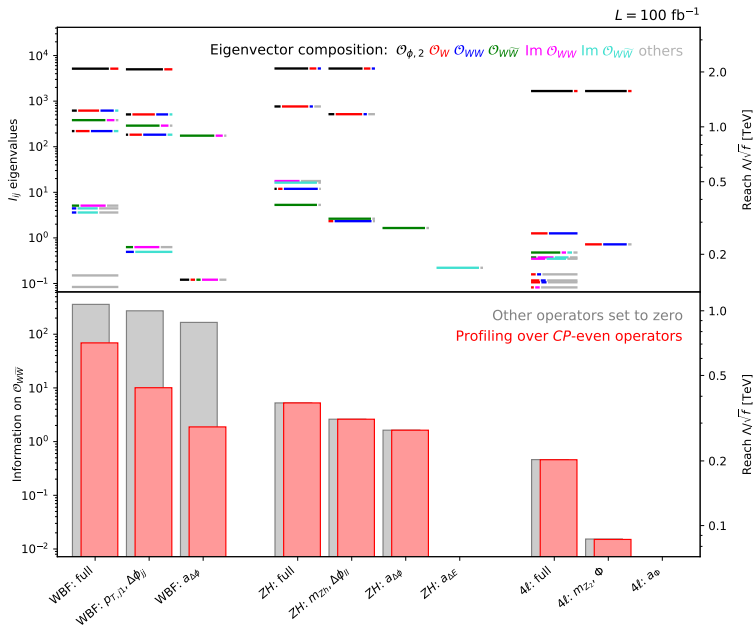
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Testing CP in $H \rightarrow 4\ell$ decays

- same 10 scalar products
- momentum flow limited by m_H
- reach for CP -even operators shit [Brehmer, Cranmer, Kling, TP (2016)]
- even showing plots is waste of time
- ⇒ what's the point...

Comparison of CP tests

Questions

Theory contribution to bottom-up precision physics at the LHC

Is it really the Standard Model Higgs? [no]

Is there WIMP dark matter? [yes]

Is there TeV-scale physics beyond the Standard Model? [yes]

Are EFT analyses un-inspired? [totally]

Are there nice theory aspects to work on? [plenty]

Are there nice statistics aspects to work on? [always]

Will I stop doing EFT once we find new physics? [definitely]

⇒ **Welcome to a data-driven era!**