Higgs CP Through Information Geometry

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Higgs WG2, December 2017

CP symmetry tests

C and *P* and *T* and $\hat{T}$

– transformations on state with spin/momentum

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

– transformation of complex scalar

$$C\phi(t,\vec{x})C^{-1} = \eta_C\phi^*(t,\vec{x}) \qquad P\phi(t,\vec{x})P^{-1} = \eta_P\phi(t,-\vec{x}) \qquad T\phi(t,\vec{x})T^{-1} = \phi(-t,\vec{x})$$

– naive time reversal avoiding inital $\leftrightarrow$ final state

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

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– naive time reversal avoiding inital $\leftrightarrow$ final state

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

– *U*-odd vs genuine *U*-odd observable [$U = C, P, \hat{T}$, theorists wanting 'genuine']

$$O(U\,|i\rangle \to U\,|f\rangle) = -O\,(|i\rangle \to |f\rangle) \quad \overset{p(|i\rangle)=p(U|i\rangle)}{\Longrightarrow} \quad \langle O\rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0\ .$$

– genuine $\hat{T}$-odd means *CP*-violating theory, provided

1- phase space $\hat{T}$-symmetric
2- initial state distribution invariant under $\hat{T}$
3- not re-scattering

$\Rightarrow$ use $\hat{T}$ as proxy to *CP*

CP in Higgs-gauge sector

Dimension-6 Lagrangian

– *CP*-conserving couplings [defining Higgs properties]

$$\mathcal{O}_B = i\frac{g}{2}\,(D^\mu\phi^\dagger)(D^\nu\phi)\,B_{\mu\nu} \qquad \mathcal{O}_W = i\frac{g}{2}\,(D^\mu\phi)^\dagger\sigma^k(D^\nu\phi)\,W^k_{\mu\nu}$$

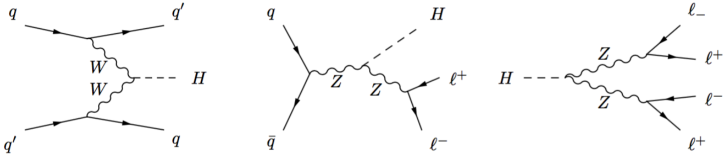
$$\mathcal{O}_{BB} = -\frac{g'^2}{4}\,(\phi^\dagger\phi)\,B_{\mu\nu}\,B^{\mu\nu} \qquad \mathcal{O}_{WW} = -\frac{g^2}{4}\,(\phi^\dagger\phi)\,W^k_{\mu\nu}\,W^{\mu\nu\,k}$$

$$\mathcal{O}_{\phi,2} = \frac{1}{2}\,\partial^\mu(\phi^\dagger\phi)\,\partial_\mu(\phi^\dagger\phi)$$

– *CP*-violating couplings [defining *CP*-violation]

$$\mathcal{O}_{B\tilde{B}} = -\frac{g'^2}{4}\,(\phi^\dagger\phi)\,\widetilde{B}_{\mu\nu}\,B^{\mu\nu} \qquad \mathcal{O}_{W\tilde{W}} = -\frac{g^2}{4}\,(\phi^\dagger\phi)\,\widetilde{W}^k_{\mu\nu}\,W^{\mu\nu\,k}$$

– processes with same vertex/information



⇒ fit Lagrangian, but choose symmetries first

Information geometry

Quantify what is there to learn

– covariance matrix [measurement error in model space **g**]

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

– Fisher information [sensitivity in model space]

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

– Cramèr-Rao bound

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

– model-space distance [probability to measure $\mathbf{g}_b$ with true $\mathbf{g}_a$]

$$d(\mathbf{g}_b;\mathbf{g}_a) = \sqrt{(\mathbf{g}_a - \mathbf{g}_b)_i\, I_{ij}(\mathbf{g}_a)\,(\mathbf{g}_a - \mathbf{g}_b)_j}$$

– phase space distribution [phase space **x**]

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

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1– use elipses of constant distance for correlations

2– diagonalize I_{ij}, define model-space eigenvectors

3– compute information in distributions or phase space regions

$\Rightarrow$ a modern tool to get things right

Application to WBF production

Testing *CP* in WBF

– four external 4-momenta $\to$ 10 scalar products

four external masses
four *C*-even, *P*-even, $\hat{T}$-even
one *C*-even, *P*-odd, $\hat{T}$-odd

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

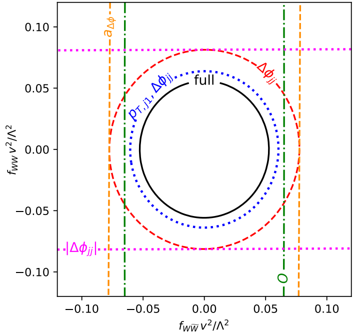
– azimuthal angle difference [lab frame]

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

– *CP* asymmetry

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

– separating dimension-6 effects



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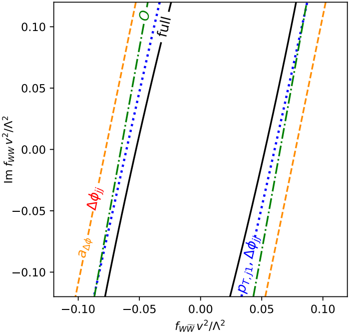
$\Rightarrow$ testing *CP*, but assuming no re-scattering



Application to ZH production

Testing CP in ZH production

– same 10 scalar products as for WBF

– CP-odd and $\hat{T}$-odd angle

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

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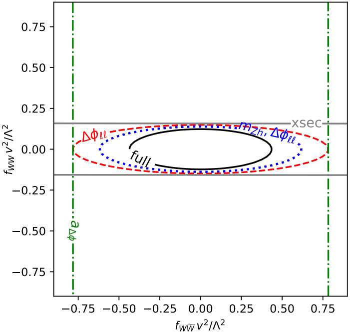
– CP-odd and $\hat{T}$-even, requiring second phase

$$O_2 \to \Delta E_{\ell\ell} \qquad\qquad O_3 \to \Delta p_{T,\ell\ell}$$

– separating dimension-6 effects



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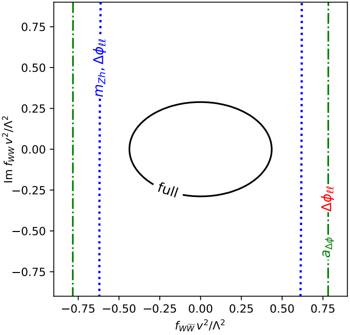
⇒ testing *CP* no assumtions



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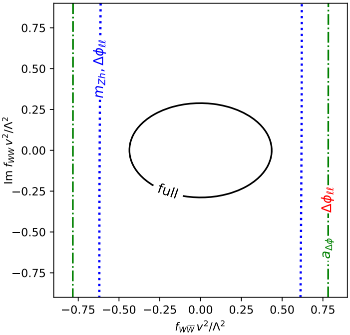


Testing *CP* in $H \to 4\ell$ decays

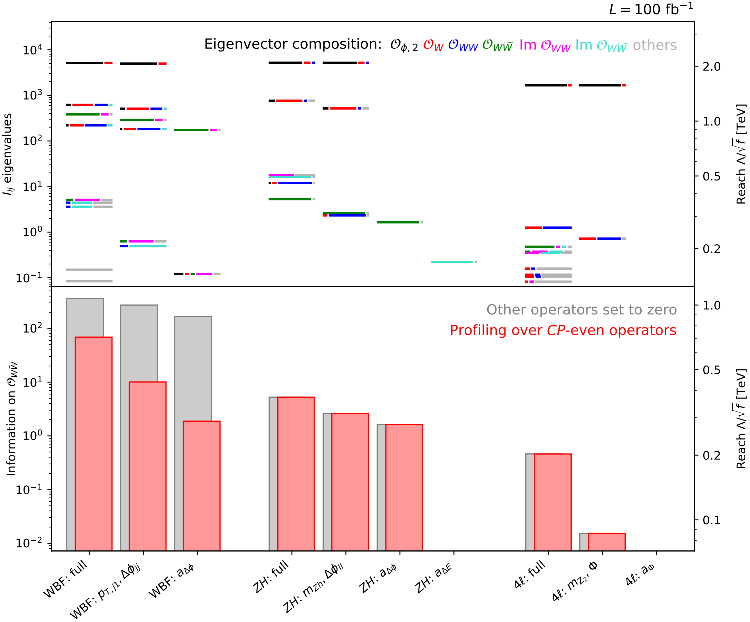
– again same 10 scalar products

– momentum flow limited by m_H

– reach for *CP*-even operators shit [1612.05261]

⇒ what's the point...

Summary


$L = 100$ fb^{-1}
Eigenvector composition: $\mathcal{O}_{\phi,2}$ $\mathcal{O}_W$ $\mathcal{O}_{WW}$ $\mathcal{O}_{W\widetilde{W}}$ Im $\mathcal{O}_{WW}$ Im $\mathcal{O}_{W\widetilde{W}}$ others
I_{ij} eigenvalues
Reach $\Lambda/\sqrt{f}$ [TeV]
Other operators set to zero
Profiling over CP-even operators
Information on $\mathcal{O}_{W\widetilde{W}}$
WBF: full
WBF: $p_{T,j1}$, $\Delta\phi_{jj}$
WBF: $a_{\Delta\phi}$
ZH: full
ZH: m_{Zh}, $\Delta\phi_{ll}$
ZH: $a_{\Delta\phi}$
ZH: $a_{\Delta E}$
4ℓ: full
4ℓ: m_{Z_2}, Φ
4ℓ: a_Φ