Better Higgs Measurements through Information Geometry

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arXiv:1612.05261, 1712.02350

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March 18th 2018, Moriond QCD 2018
Introduction and Outline

Higgs Coupling Measurements
- Higgs discovery: Standard Model complete
- further Higgs measurements: validity of SM
  ➔ multivariate analysis/information geometry
- possible BSM physics: CP-violation in the Higgs sector

Are there additional sources of CP-violation in the Higgs sector?
1. Which observables are sensitive to Higgs CP?
2. What assumptions link those observables to CP?
3. How well can we quantitatively test Higgs CP?
   a) What is the maximum precision to measure theory parameters?
   b) Where in phase space is the information?
   c) What are the most powerful observables?

Can easily be answered by Information Geometry
Higgs-Gauge Coupling
- WBF and ZH production, H>4l decay
- same hard process
- different final state (charge measurement)

Theory Language:
- dim-6-operators of SMEFT: $\mathcal{L} \supset \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i$
- operators such as
  - CP-even: $\mathcal{O}_{WW} \sim (\phi^\dagger \phi) \ W_{\mu\nu} \ W^{\mu\nu}$
  - CP-odd: $\mathcal{O}_{W\bar{W}} \sim (\phi^\dagger \phi) \ W_{\mu\nu} \ \bar{W}^{\mu\nu}$
- goal: measure Wilson coefficients: $f_i$

Observables: 4 independent 4-momenta $p_i$

4 C-even and P-even scalar products $p_1 \cdot p_2 \cdot p_3 \cdot p_4$

2 C-odd and P-even scalar products:

1 C-even and P-odd $\epsilon_{\alpha\beta\gamma\delta} \ p_1^\alpha p_2^\beta p_3^\gamma p_4^\delta$:

up to 3 CP sensitive observables

<table>
<thead>
<tr>
<th></th>
<th>WBF</th>
<th>ZH</th>
<th>H&gt;4l</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta p_{T,ll}$, $\Delta E_{ll}$</td>
<td>$\Delta \phi_{jj}^s$</td>
<td>$\Delta \phi_{ll}^s$</td>
<td>$\theta_{1,2}$, $\Phi$</td>
</tr>
</tbody>
</table>

[WBF: Hankele, Klamke, Zeppenfeld hep-ph/0609075, ZH: Christensen, Han, Li 1005.5393, H>4l: Bolognesi et al. 1208.4018]
What assumptions link those observables to CP?

Is WBF Higgs production sensitive to CP?
- naive time reversal $\hat{T}$ : $|p, s\rangle \rightarrow | -p, -s\rangle$
- $\hat{T}$-symmetric initial state at pp-collider
- $\hat{T}$-invariant squared matrix element
  in absence of CP-violation and re-scattering
  $$\langle f | \mathcal{T} | i \rangle \xrightarrow{\text{CP-invariant}} \langle i_T | \mathcal{T} | f_T \rangle \text{ no re-scattering} \xrightarrow{\text{optical theorem}} \langle f_T | \mathcal{T} | i_T \rangle^*$$
- genuine $\hat{T}$-odd observable $\epsilon_{\alpha\beta\gamma\delta} p_1^\alpha p_2^\beta p_3^\gamma p_4^\delta$
  $\rightarrow$ signed angle $\Delta \phi_{jj}^s$

$\Delta \phi_{jj}^s$ is sensitive to CP-violation if re-scattering effects are known to be small

\[ \frac{d\sigma}{d\Delta \phi_{jj}} \text{[fb/bin]} \]

![Graph showing interference term vs. $\Delta \phi_{jj}$]
What is the maximum sensitivity of a measurement?

Measurement process

\[ \theta_0 \rightarrow f(x|\theta_0) \rightarrow x \rightarrow \hat{\theta}(x) \rightarrow \hat{\theta} \]

true parameters 
observables 
estimator

Cramer-Rao Bound for unbiased estimators

\[ \text{cov}[\hat{\theta}|\theta_0] \leq I^{-1}_{ij}(\theta_0) \]

[F. Cramér 1945; H. Cramér 1946]

Fisher Information
- encodes the maximum sensitivity of observables to model parameters
\[ I_{ij}(\theta) = -E \left[ \frac{\partial^2 \log f(x|\theta)}{\partial \theta_i \partial \theta_j} \right] \]

- use Monte Carlo

\[ I_{ij}(\theta) = \sum_{\text{events}} \frac{1}{\Delta \sigma(\theta)} \frac{\partial \Delta \sigma(\theta)}{\partial \theta_i} \frac{\partial \Delta \sigma(\theta)}{\partial \theta_j} \]

- additive between phase-space regions

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[Figure by J. Brehmer]
How well can we quantitatively test Higgs CP?

a) What is the maximum precision to measure theory parameters?
- encoded in Fisher Information

Example: WBF Higgs Production with $H \rightarrow \tau \tau$

$$I_{ij}(0) = \begin{pmatrix}
 715 & -191 & 1 & 0 \\
-191 & 321 & -1 & 0 \\
1 & -1 & 359 & -81 \\
0 & 1 & -81 & 23
\end{pmatrix}$$

- **sensitivity** to CP-violating operator
- large mixing between CP-conserving operators
- no mixing between CP-conserving and CP-violating operators
- re-scattering can mimic CP-violation

→ calculate the maximum sensitivity of any LHC process

we assume 13 TeV LHC, L=100 fb$^{-1}$, take into account ggF and Z+jets BG, for more analysis details see 1612.05261, 1712.02350
b) Where in phase space is the information?
- binned kinematic distribution of information

Example: Jet Rapidity Difference in WBF
- smaller background at large $\Delta \eta_{jj}$
- momentum dependent operator
  $\rightarrow$ largest effect at medium $\Delta \eta_{jj}$
- strong WBF cuts ($\Delta \eta_{jj} > 4.2$):
  $\rightarrow$ lose information of dim-6 operators

identify relevant phase-space regions
How well can we quantitatively test Higgs CP?

c) What are the most powerful observables?
- information of binned kinematic distribution
- minimum measurement error $\Delta f \geq 1/\sqrt{I}$

**Example:** Higgs coupling measurement in WBF
- $|\Delta \phi_{jj}|$ sensitive to CP-conserving physics only
- asymmetry sensitive to CP-violating physics only
- signed $\Delta \phi_{jj}$ probes both
- 2D histogram better, but still not close to full information
- re-scattering effects can mimic CP-violation
- asymmetry in $\Delta \phi_{jj}$ implies CP violation (in the absence of re-scattering)
- re-scattering small in SM

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**Identify most powerful observables**
**Example:** Information on CP-violating Higgs couplings

- More sensitivity in WBF and ZH than H>4l due to larger momentum transfer
- WBF requires additional theory assumption on re-scattering
- CP-information mostly captured in asymmetry of $\epsilon_{\alpha\beta\gamma\delta} p_1^\alpha p_2^\beta p_3^\gamma p_4^\delta \sim \Delta \phi$
- Adding momentum transfer measures/multivariate analysis increase sensitivity

- Quantitatively compare histogram-based vs. multivariate analyses
Information Geometry let us calculate maximum sensitivity of any LHC process. Identify and select the important phase space regions. Quantitatively compare histogram-based vs. multivariate analyses.