Model*ing*-independent searches for CP violation in differential distributions

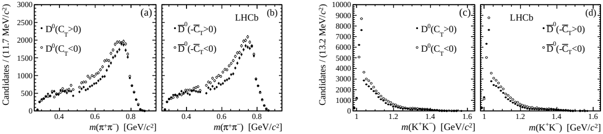
Gauthier Durieux
(DESY)

`[1508.03054]` with Yuval Grossman: spinless multibody decays
`[1608.03288]`: spin-1/2 multibody decays
`[in discussion]` with Christophe and Marc: VBF production of a scalar

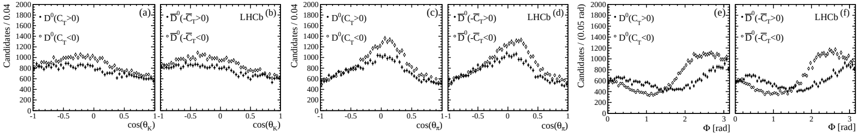
12 September 2016
DESY BSM Mini Workshop

The paradox of richness and complexity

- Multidimensional phase space



[1408.1299]



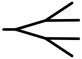
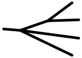
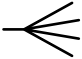
- Large statistics

$B^0 \to K^+K^-K^\pm\pi^\mp$	1700 candidates	[1403.2888]
$B^0_s \to K^+K^-K^+K^-$	4000	[1407.2222]
$\boldsymbol{D^0 \to K^+K^-\pi^+\pi^-}$	**170 000**	[1408.1299]
$B^0_s \to K^+\pi^-K^-\pi^+$	700	[1503.05362]

...

The paradox of richness and complexity

- Rich variety of interfering contributions

	Intermediate states in $D^0 \to K^+K^-\pi^+\pi^-$	Br $/10^{-4}$
	$(\phi\rho^0)_S, \quad \phi \to K^+K^-, \quad \rho^0 \to \pi^+\pi^-$	9.3 ± 1.2
	D	0.83 ± 0.23
	$(K^{*0}\overline{K}^{*0})_S, \quad K^{*0} \to K^\pm\pi^\mp$	1.48 ± 0.30
	$\phi(\pi^+\pi^-)_S, \quad \phi \to K^+K^-$	2.50 ± 0.33
	$(K^-\pi^+)_P(K^+\pi^-)_S$	2.6 ± 0.5
	$K_1^+K^-, \quad K_1^+ \to K^{*0}\pi^+$	1.8 ± 0.5
	$K_1^-K^+, \quad K_1^- \to \overline{K}^{*0}\pi^-$	0.22 ± 0.12
	$K_1^+K^-, \quad K_1^+ \to \rho^0K^+$	1.14 ± 0.26
	$K_1^-K^+, \quad K_1^- \to \rho^0K^-$	1.46 ± 0.25
	$K^*(1410)^+K^-, \ K^*(1410)^+ \to K^{*0}\pi^+$	1.02 ± 0.26
	$K^*(1410)^-K^+, \ K^*(1410)^- \to \overline{K}^{*0}\pi^-$	1.14 ± 0.25

[CLEO '12]

$\Longrightarrow$ Opportunities for CP violation searches
but also modeling challenges!

Model*ing*-independent searches for CP violation in differential distributions

The virtues of $\hat{\mathrm{T}}$-oddity

- When higher-order corrections are mild.
- In untagged samples / With self-conjugate states

Model*ing*-independent analyses

- A spinless example and the impact of spin
- In the scalar sector

Motion reversal $\hat{\mathrm{T}}$

$\hat{\mathrm{T}}$ flips $\vec{p}$ and $\vec{s}$.

(often called *naive time reversal*)

$\hat{\mathrm{T}}$-oddity arises from $\epsilon_{\mu\nu\rho\sigma} p^\mu q^\nu r^\rho s^\sigma$ contractions ...

- ϵ from the Lagrangian: $i\tilde{F}^{\mu\nu} \equiv \frac{i}{2}\epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma}$
- ϵ from chiral fermions: $\gamma^5 \equiv \frac{i}{4!}\epsilon_{\mu\nu\rho\sigma}\gamma^\mu\gamma^\nu\gamma^\rho\gamma^\sigma$

... of four independent momenta or spin vectors.

$\rightarrow$ minimal multiplicity

e.g. spinless four-body decays

Differential CP violation

Compare the CP-conjugate amplitudes (squared)

$$\mathcal{M}(\{\vec{p}_i\}) \quad \text{and} \quad \bar{\mathcal{M}}(\{-\vec{p}_{\bar{\imath}}\})\Big|_{\vec{p}_{\bar{\imath}}=\vec{p}_i}$$

phase-space point by phase-space point (spinless case).

Contributions of definite · *strong* and *weak* phases
· $\hat{\mathrm{T}}$ transformation properties

$$\begin{aligned}\mathcal{M}(\{\vec{p}_i\}) = \\ &+a(\{\vec{p}_i\})\, e^{i(\delta_a+\varphi_a)}\\ &+b(\{\vec{p}_i\})\, e^{i(\delta_b+\varphi_b)}\\ &+c(\{\vec{p}_i\})\, e^{i(\delta_c+[\varphi_c+\pi/2])}\\ &+\ldots\end{aligned}$$

$$\begin{aligned}\bar{\mathcal{M}}(\{-\vec{p}_i\}) = \\ &+a(\{-\vec{p}_i\})\, e^{i(\delta_a-\varphi_a)}\\ &+b(\{-\vec{p}_i\})\, e^{i(\delta_b-\varphi_b)}\\ &+c(\{-\vec{p}_i\})\, e^{i(\delta_c-[\varphi_c+\pi/2])}\\ &+\ldots\end{aligned}$$

Differential CP violation

Compare the CP-conjugate amplitudes (squared)

$$\mathcal{M}(\{\vec{p}_i\}) \quad \text{and} \quad \bar{\mathcal{M}}(\{-\vec{p}_{\bar{\imath}}\})\Big|_{\vec{p}_{\bar{\imath}}=\vec{p}_i}$$

phase-space point by phase-space point (spinless case).

Contributions of definite · *strong* and *weak* phases
· $\hat{\mathrm{T}}$ transformation properties

$$\begin{aligned}\mathcal{M}(\{\vec{p}_i\}) = &\\ &+a(\{\vec{p}_i\})\, e^{i(\delta_a+\varphi_a)}\\ &+b(\{\vec{p}_i\})\, e^{i(\delta_b+\varphi_b)}\\ &+c(\{\vec{p}_i\})\, e^{i(\delta_c+[\varphi_c+\pi/2])}\\ &+\ldots\end{aligned}$$

$$\begin{aligned}\bar{\mathcal{M}}(\{-\vec{p}_i\}) = &\\ &+a(\{+\vec{p}_i\})\, e^{i(\delta_a-\varphi_a)}\\ &+b(\{+\vec{p}_i\})\, e^{i(\delta_b-\varphi_b)}\\ &-c(\{+\vec{p}_i\})\, e^{i(\delta_c-[\varphi_c+\pi/2])}\\ &+\ldots\end{aligned}$$

Differential CP violation

Compare the CP-conjugate amplitudes (squared)

$$\mathcal{M}(\{\vec{p}_i\}) \quad \text{and} \quad \bar{\mathcal{M}}(\{-\vec{p}_{\bar{\imath}}\})\Big|_{\vec{p}_{\bar{\imath}}=\vec{p}_i}$$

phase-space point by phase-space point (spinless case).

Contributions of definite · *strong* and *weak* phases
· $\hat{\mathrm{T}}$ transformation properties

$$\mathcal{M}(\{\vec{p}_i\}) = +a(\{\vec{p}_i\})\, e^{i(\delta_a+\varphi_a)} +b(\{\vec{p}_i\})\, e^{i(\delta_b+\varphi_b)} +c(\{\vec{p}_i\})\, e^{i(\delta_c+[\varphi_c+\pi/2])} +\dots$$

$$\bar{\mathcal{M}}(\{-\vec{p}_i\}) = +a(\{+\vec{p}_i\})\, e^{i(\delta_a-\varphi_a)} +b(\{+\vec{p}_i\})\, e^{i(\delta_b-\varphi_b)} +c(\{+\vec{p}_i\})\, e^{i(\delta_c-\varphi_c+\pi/2)} +\dots$$

CP violation and strong phases

Distributions of definite CP and $\hat{\mathrm{T}}$ transformation properties

$$\left.\frac{d\Gamma}{d\{\vec{p}_i\}}\right|^{\hat{\mathrm{T}}\text{-}^{\text{even}}_{\text{odd}}}_{\mathrm{CP}\text{-}^{\text{even}}_{\text{odd}}} \equiv \frac{\mathbb{I}\pm\hat{\mathrm{T}}}{2}\,\frac{\mathbb{I}\pm\mathrm{CP}}{2}\,\frac{d\Gamma}{d\{\vec{p}_i\}}$$

$$\left.\frac{d\Gamma}{d\{\vec{p}_i\}}\right|^{\hat{\mathrm{T}}\text{-even}}_{\mathrm{CP}\text{-even}} \propto \; a\,a + b\,b + c\,c \\ +2\,a\,b\;\cos(\delta_a-\delta_b)\cos(\varphi_a-\varphi_b)$$

$$\left.\frac{d\Gamma}{d\{\vec{p}_i\}}\right|^{\hat{\mathrm{T}}\text{-odd}}_{\mathrm{CP}\text{-even}} \propto \;\; 2\,a\,c\;\sin(\delta_a-\delta_c)\;\cos(\varphi_a-\varphi_c) \\ +2\,b\,c\;\sin(\delta_b-\delta_c)\;\cos(\varphi_b-\varphi_c)$$

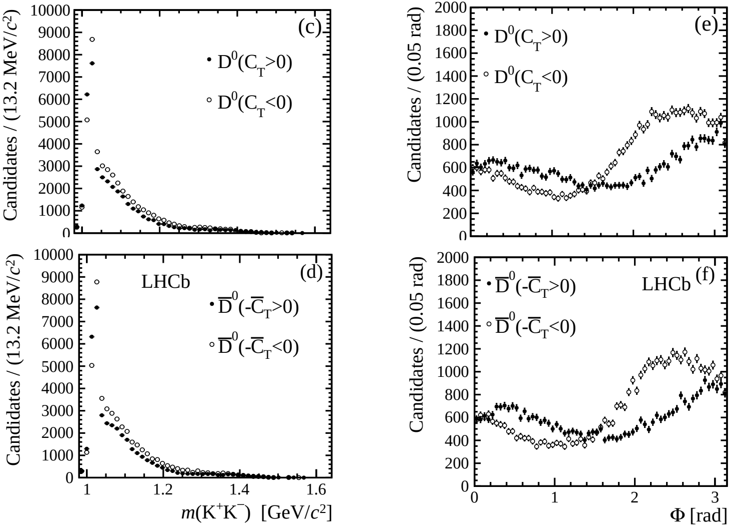
$$\left.\frac{d\Gamma}{d\{\vec{p}_i\}}\right|^{\hat{\mathrm{T}}\text{-even}}_{\mathrm{CP}\text{-odd}} \propto -2\,a\,b\;\sin(\delta_a-\delta_b)\;\sin(\varphi_a-\varphi_b)$$

$$\left.\frac{d\Gamma}{d\{\vec{p}_i\}}\right|^{\hat{\mathrm{T}}\text{-odd}}_{\mathrm{CP}\text{-odd}} \propto \;\; 2\,a\,c\;\cos(\delta_a-\delta_c)\sin(\varphi_a-\varphi_c) \\ +2\,b\,c\;\cos(\delta_b-\delta_c)\sin(\varphi_b-\varphi_c)$$

CP-violating distributions

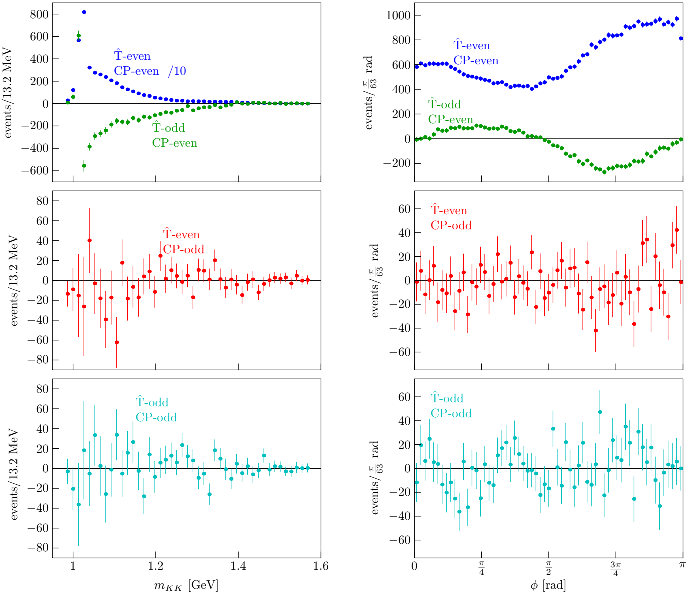
$D^0 \to K^+K^-\pi^+\pi^-$

[1408.1299]



CP-violating distributions

$D^0 \to K^+K^-\pi^+\pi^-$



Model*ing*-independent searches for CP violation in differential distributions

The virtues of $\hat{\mathrm{T}}$-oddity

When higher-order corrections are mild.

In untagged samples / With self-conjugate states

Model*ing*-independent analyses

A spinless example and the impact of spin

In the scalar sector

Untagged samples / self-conjugate states

- Tagging CP-conjugate processes may cost efficiency, and is N/A with self-conjugate initial and final states.

- An untagged sample [as in 1503.05362]

e.g. $$\begin{cases} B_s^0 \to K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \quad K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \\ \bar{B}_s^0 \to K^-(-\vec{p}_1) \quad \pi^+(-\vec{p}_2) \quad K^+(-\vec{p}_3) \quad \pi^-(-\vec{p}_4) \end{cases}$$

$$\frac{\mathbb{I} + \mathrm{CP}}{2} \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}$$

Untagged samples / self-conjugate states

– Tagging CP-conjugate processes may cost efficiency, and is N/A with self-conjugate initial and final states.

– An untagged sample [as in 1503.05362]

e.g. $$\begin{cases} B_s^0 \to K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \quad K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \\ \bar{B}_s^0 \to K^-(+\vec{p}_1) \quad \pi^+(+\vec{p}_2) \quad K^+(+\vec{p}_3) \quad \pi^-(+\vec{p}_4) \end{cases}$$

$$\frac{\mathbb{I} + \mathrm{CP\hat{T}}}{2} \, \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}$$

Untagged samples / self-conjugate states

– Tagging CP-conjugate processes may cost efficiency, and is N/A with self-conjugate initial and final states.

– An untagged sample [as in 1503.05362]

e.g. $$\begin{cases} B_s^0 \to K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \quad K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \\ \bar{B}_s^0 \to K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \quad K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \end{cases}$$

$$\frac{\mathbb{I} + \mathrm{CP\hat{T}E}^*}{2} \, \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}$$

Untagged samples / self-conjugate states

- Tagging CP-conjugate processes may cost efficiency, and is N/A with self-conjugate initial and final states.

- An untagged sample [as in 1503.05362]

e.g. $\begin{cases} B_s^0 \to K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \quad K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \\ \bar{B}_s^0 \to K^-(+\vec{p}_3) \quad \pi^+(+\vec{p}_4) \quad K^+(+\vec{p}_1) \quad \pi^-(+\vec{p}_2) \end{cases}$

$$\frac{\mathbb{I} + \mathrm{CP\hat{T}E^*}}{2} \, \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}$$

has two CP-odd distributions, of opposite $\hat{\mathrm{T}}$ and E^* parities

$$\frac{\mathbb{I} \pm \hat{\mathrm{T}}}{2} \, \frac{\mathbb{I} \mp \mathrm{E}^*}{2} \left(\frac{\mathbb{I} + \mathrm{CP\hat{T}E^*}}{2} \, \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}} \right) = \frac{\mathbb{I} \pm \hat{\mathrm{T}}}{2} \, \frac{\mathbb{I} \mp \mathrm{E}^*}{2} \, \frac{\mathbb{I} - \mathrm{CP}}{2} \, \frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}$$

Model*ing*-independent searches for CP violation in differential distributions

The virtues of $\hat{T}$-oddity

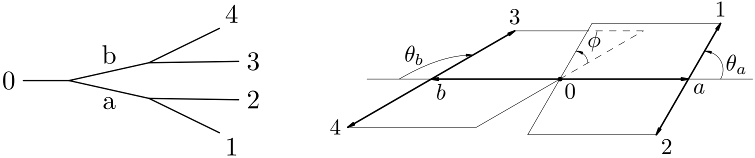
- When higher-order corrections are mild.
- In untagged samples / With self-conjugate states

Model*ing*-independent analyses

- A spinless example and the impact of spin
- In the scalar sector

A spinless example: four-body decay

1. Fix a phase-space parametrisation



2. Identify the discrete symmetry properties of each kinematic variable.

3. Measure asymmetries systematically

$$\int \mathrm{d}\{\vec{p}_i\} \;\; \mathrm{sign}\left\{ P_l(\cos\theta_a)\, P_m(\cos\theta_b)\, \sin n\phi \prod_i (m_a^2 - M_i^2) \prod_j (m_b^2 - M_j^2) \right\} \left.\frac{\mathrm{d}\Gamma}{\mathrm{d}\{\vec{p}_i\}}\right|_{\text{CP-odd}}^{\hat{\text{T}}\text{-odd}} \qquad \text{for } \{l, m, n\} \in \mathbb{N}^3$$

The impact of spin

[1608.03288]

$\hat{\mathrm{T}}$-oddity with lower multiplicity

e.g., in the three-body decay of a polarized particle

Correlation between (strong) production and (weak) decay

+ Caveat: Spins are not quite measurable.
  Observables are defined from momenta.

→ Qualitatively new observables

(T̂-even angular distributions) $\times$ (T̂-odd polarization)
have the properties of T̂-odd observables

→ Qualitatively new ambiguities

(T̂-odd angular distributions) $\times$ (T̂-odd polarization)
have the properties of T̂-even observables

The impact of spin

Ambiguities are lifted with *some* modeling

The Jacob–Wick helicity formalism only relies on angular momentum conservation. [Jacob, Wick '59]

e.g. for spin $\frac{1}{2} \to \frac{1}{2}\ 1 \to \frac{1}{2}\ 0\ \frac{1}{2}\ \frac{1}{2}$:

$+3/2$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$					$\sin^2\theta_b$	
$+3/4$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$					$1+\cos^2\theta_b$	
$+3/2$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$	α_a			$\cos\theta_a$	$\sin^2\theta_b$	
$+3/4$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$	α_a			$\cos\theta_a$	$1+\cos^2\theta_b$	
$-3/2\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} - \mathrm{Re}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3/2$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$		P_z	$\cos\theta$		$\sin^2\theta_b$	
$-3/4$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$		P_z	$\cos\theta$		$1+\cos^2\theta_b$	
$-3/2\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} - \mathrm{Re}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\cos\phi_b$
$+3/2$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$\sin^2\theta_b$	
$-3/4$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$1+\cos^2\theta_b$	
$-3/2\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} + \mathrm{Re}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$-3/2\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} + \mathrm{Re}\{A_-^* B_-\}$	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\cos\phi_b$
-3	$\mathrm{Re}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\cos\phi_a$
$-3/2$	$\mathrm{Re}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\cos(\phi_a+2\phi_b)$
$+3/2\sqrt{2}$	$\mathrm{Im}\{A_+^* B_+\} + \mathrm{Im}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\sin\phi_b$
$-3/2\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} - \mathrm{Im}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$
$+3/2\sqrt{2}$	$\mathrm{Im}\{A_+^* B_+\} - \mathrm{Im}\{A_-^* B_-\}$	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\sin\phi_b$
-3	$\mathrm{Im}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\sin\phi_a$
$-3/2$	$\mathrm{Im}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\sin(\phi_a+2\phi_b)$
$-3/2\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} + \mathrm{Im}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$

Model*ing*-independent searches for CP violation in differential distributions

The virtues of $\hat{\mathrm{T}}$-oddity

- When higher-order corrections are mild.
- In untagged samples / With self-conjugate states

Model*ing*-independent analyses

- A spinless example and the impact of spin
- In the scalar sector

$H \to 4\ell$ and $e^+e^- \to HZ$

Modeling is non longer an issue.

Distributions of interested can be identified,
e.g., in the SM EFT [Beneke, Boito, Wang '14]

$$\begin{aligned}\mathcal{J}(q^2,\theta_1,\theta_2,\phi) = \; & J_1(1+\cos^2\theta_1\cos^2\theta_2+\cos^2\theta_1+\cos^2\theta_2)\\ &+ J_2\sin^2\theta_1\sin^2\theta_2 + J_3\cos\theta_1\cos\theta_2\\ &+ (J_4\sin\theta_1\sin\theta_2 + J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi\\ &+ (J_6\sin\theta_1\sin\theta_2 + J_7\sin 2\theta_1\sin 2\theta_2)\cos\phi\\ &+ J_8\sin^2\theta_1\,\sin^2\theta_2\,\sin 2\phi + J_9\sin^2\theta_1\,\sin^2\theta_2\,\cos 2\phi.\end{aligned}$$

$$\begin{aligned}J_1 &= 2\,r\,s\,\left(g_A^2+g_V^2\right)\left(|H_{1,V}|^2+|H_{1,A}|^2\right),\\ J_2 &= \kappa\,\left(g_A^2+g_V^2\right)\left[\kappa\,\left(|H_{1,V}|^2+|H_{1,A}|^2\right)+\lambda\,\mathrm{Re}\left(H_{1,V}H_{2,V}^*+H_{1,A}\right.\right.\\ J_3 &= 32\,r\,s\,g_A\,g_V\,\mathrm{Re}\left(H_{1,V}\,H_{1,A}^*\right),\\ J_4 &= 4\kappa\,\sqrt{r\,s\,\lambda}\,g_A\,g_V\,\mathrm{Re}\left(H_{1,V}H_{3,A}^*+H_{1,A}H_{3,V}^*\right),\\ J_5 &= \frac{1}{2}\kappa\,\sqrt{r\,s\,\lambda}\,\left(g_A^2+g_V^2\right)\mathrm{Re}\left(H_{1,V}H_{3,V}^*+H_{1,A}\,H_{3,A}^*\right),\\ J_6 &= 4\sqrt{r\,s}\,g_A\,g_V\,\left[4\kappa\,\mathrm{Re}\left(H_{1,V}H_{1,A}^*\right)+\lambda\,\mathrm{Re}\left(H_{1,V}H_{2,A}^*+H_{1,A}H_{2,V}^*\right.\right.\\ J_7 &= \frac{1}{2}\sqrt{r\,s}\left(g_A^2+g_V^2\right)\left[2\kappa\,\left(|H_{1,V}|^2+|H_{1,A}|^2\right)+\lambda\,\mathrm{Re}\left(H_{1,V}H_{2,V}^*+\right.\right.\\ J_8 &= 2\,r\,s\,\sqrt{\lambda}\left(g_A^2+g_V^2\right)\mathrm{Re}\left(H_{1,V}H_{3,V}^*+H_{1,A}H_{3,A}^*\right),\\ J_9 &= 2\,r\,s\,\left(g_A^2+g_V^2\right)\left(|H_{1,V}|^2+|H_{1,A}|^2\right).\end{aligned}$$

$$\begin{aligned}\mathcal{A}_\phi^{(1)} &= \frac{1}{d\Gamma/dq^2}\int_0^{2\pi}d\phi\;\mathrm{sgn}(\sin\phi)\,\frac{d^2\Gamma}{dq^2d\phi} = \frac{9\,\pi}{32}\,\frac{J_4}{4J_1+J_2},\\ \mathcal{A}_\phi^{(2)} &= \frac{1}{d\Gamma/dq^2}\int_0^{2\pi}d\phi\;\mathrm{sgn}(\sin(2\phi))\,\frac{d^2\Gamma}{dq^2d\phi} = \frac{2}{\pi}\,\frac{J_8}{4J_1+J_2},\end{aligned}$$

Model-independence potentially remains an issue.

$(pp)^{|m|} \to X^J \to (\gamma\gamma)^S$

[Panico, Vecchi, Wulzer '16]

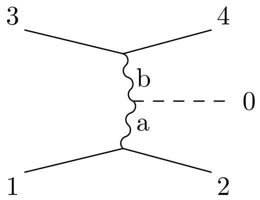
- List angular distributions for $J = 0$, 2, 3, etc. without Lagrangian.
- Allow the determination of spin provide *some* CP information.

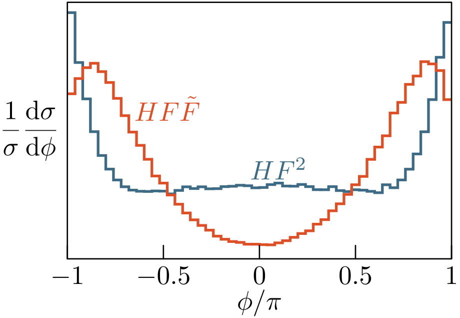
$\mathbf{J=0}$	$\mathcal{D}^{(0)}_{0,0} = 1$
$\mathbf{J=2}$	$\mathcal{D}^{(2)}_{\|m\|,S} = \begin{bmatrix} \frac{5}{4}(3c^2-1)^2 & \frac{15}{8}s^4 \\ \frac{15}{2}s^2c^2 & \frac{5}{4}s^2(1+c^2) \\ \frac{15}{8}s^4 & \frac{5}{16}(1+6c^2+c^4) \end{bmatrix}$
$\mathbf{J=3}$	$\mathcal{D}^{(3)}_{\|m\|,S} = \begin{bmatrix} \frac{7}{4}c^2(3-5c^2)^2 & \frac{105}{8}s^4c^2 \\ \frac{21}{16}s^2(5c^2-1)^2 & \frac{35}{32}s^2(1-2c^2+9c^4) \\ \frac{105}{8}s^4c^2 & \frac{7}{16}(4-15c^2+10c^4+9c^6) \end{bmatrix}$

VBF scalar production

The phase space and pdf have a non-trivial angular dependence

$$d\sigma(\Phi) = \mathrm{pdf}(\Phi)\ \ \mathrm{ps}(\Phi)\ \ |\mathcal{M}|^2(\Phi)$$

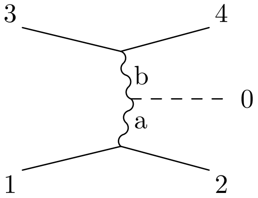


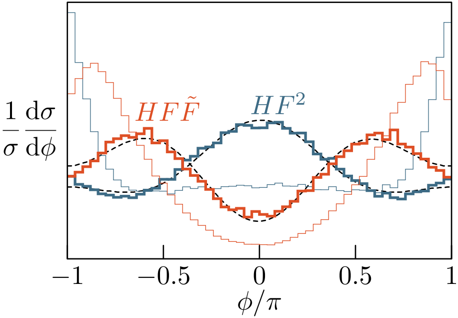


VBF scalar production

The phase space and pdf have a non-trivial angular dependence

$$\left[d\sigma(\Phi) = \text{pdf}(\Phi)\ \text{ps}(\Phi)\ |\mathcal{M}|^2(\Phi) \right] \Big/ \text{ps}(\Phi)$$





A 5D reweighing *almost* yields the intrinsic amplitude dependence

... on which one can perform a model-independent angular analysis.

Model*ing*-independent searches for CP violation in differential distributions

Differential distributions are rich of opportunities
to search for CP violation.

$\hat{\mathrm{T}}$-odd distributions allow to probe CP violation:

- when higher-order corrections are mild
- in untagged samples / with self-conjugate states

In spinless decays, systematic search procedures
are free of modeling limitations.

Beyond this simplest case, the Jacob–Wick helicity formalism
yields valuable model-independence.