CP violation in baryons: theoretical perspective

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(DESY)

Modelling-independent searches for CP violation in multibody decays

PRD 92 (2015) 076013, [1508.03054]
with Yuval Grossman (Cornell), spin-0 multibody decays

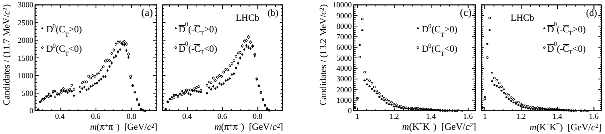
JHEP 10 (2016) 005, [1608.03288]
spin-1/2 multibody decays

12-14 October 2016
LHCb Implications Workshop

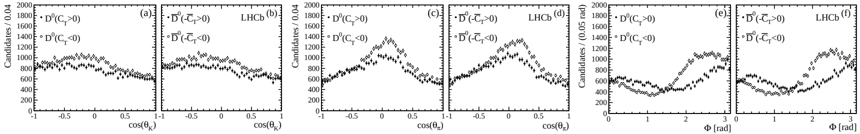
Multibody hadronic decays

- Multidimensional phase space

  e.g. 5d in $D^0 \to K^+K^-\pi^+\pi^-$:



[1408.1299]



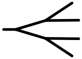
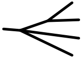
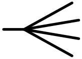
- Large statistics

$\boldsymbol{D^0 \to K^+K^-\pi^+\pi^-}$	171 300 ± 600 candidates	[1408.1299]
$\Lambda_b \to p\pi^-\pi^+\pi^-$	6 646 ± 105	[1609.05216]
$\Lambda_b \to p\pi^-K^+K^-$	1 030 ± 56	[1609.05216]
$\Lambda_b \to \Lambda\phi \to p\pi^-K^+K^-$	89 ± 13	[1603.02870]
$\Lambda_b \to \Lambda K^+K^- \to p\pi^-K^+K^-$	185 ± 15	[1603.00413]
$\Lambda_b \to pK^-J/\psi \to pK^-\mu^+\mu^-$	28 834 ± 204	[1603.06961]
$\Lambda_b \to pK^-\psi(2S) \to pK^-\mu^+\mu^-$	665 ± 28	[1603.06961]

...

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 modelling challenges!

CP violation in baryons: theoretical perspective

CP-violation in distributions and motion reversal $\hat{\mathrm{T}}$

Targeting '$\cos\delta\sin\varphi$' terms in decay amplitudes

- Spinless case: modelling-independent analysis
- Spinful case: resolving ambiguities

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)

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

phase-space point by phase-space point.

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

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

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

with

$$a(\{-\vec{p}_i,-\sigma_i\}) = +a(\{\vec{p}_i,\sigma_i\}) \quad \hat{\mathrm{T}}\text{-even}$$
$$b(\{-\vec{p}_i,-\sigma_i\}) = +b(\{\vec{p}_i,\sigma_i\}) \quad \hat{\mathrm{T}}\text{-even}$$
$$c(\{-\vec{p}_i,-\sigma_i\}) = -c(\{\vec{p}_i,\sigma_i\}) \quad \hat{\mathrm{T}}\text{-odd}$$
$$\cdots$$

Differential CP violation

Compare the CP-conjugate amplitudes (squared)

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

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with $a(\{-\vec{p}_i, -\sigma_i\}) = +a(\{\vec{p}_i, \sigma_i\})$ $\hat{\text{T}}$-even
$b(\{-\vec{p}_i, -\sigma_i\}) = +b(\{\vec{p}_i, \sigma_i\})$ $\hat{\text{T}}$-even
$c(\{-\vec{p}_i, -\sigma_i\}) = -c(\{\vec{p}_i, \sigma_i\})$ $\hat{\text{T}}$-odd
$\cdots$

$\Longrightarrow$ The φ phases is defined to contain all ‘CP-oddity’.

CP violation and strong phases

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

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

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

$\Longrightarrow$ Four different sensitivities to strong and weak phases.

CP violation and strong phases

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

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

$\left.\frac{d\Gamma}{d\Phi}\right|^{\hat{\mathrm{T}}\text{-odd}}_{\mathrm{CP}\text{-odd}} \propto$ ‘$\cos\delta\sin\varphi$’	Sensitivity to small differences of CP-odd phases between decay amplitudes of identical —or vanishing— CP-even phases.

$\Longrightarrow$ Four different sensitivities to strong and weak phases.

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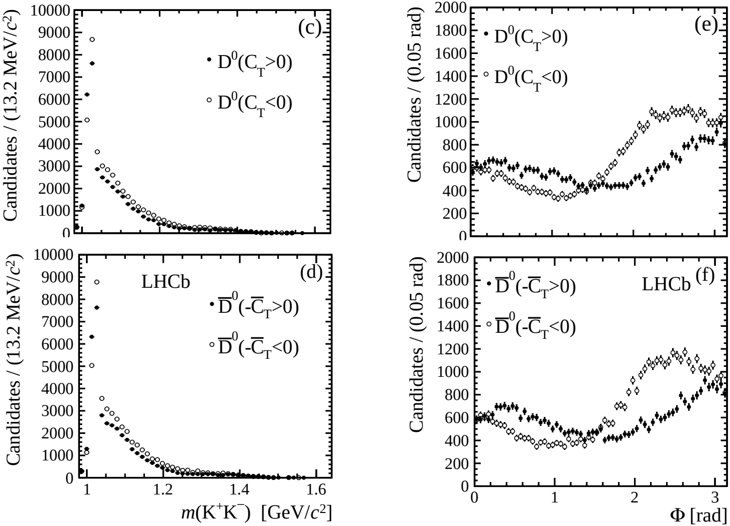
Targeting '$\cos\delta \sin\varphi$' terms in decay amplitudes

- Spinless case: modelling-independent analysis
- Spinful case: resolving ambiguities

Spinless case: $\hat{T}$-folding of the phase space

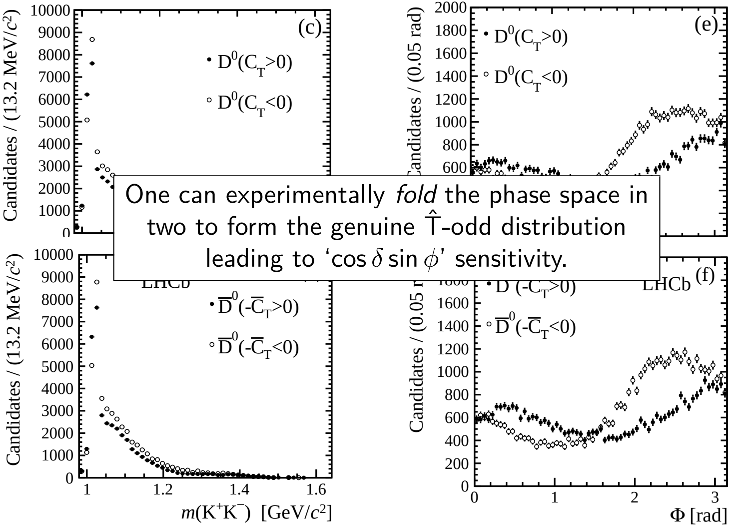
$D^0 \to K^+ K^- \pi^+ \pi^-$

[1408.1299]



Spinless case: $\hat{T}$-folding of the phase space

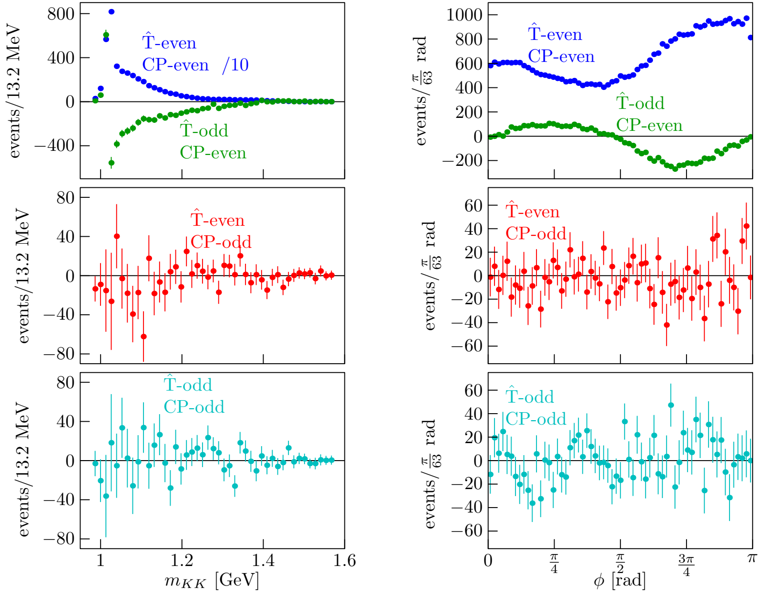
$D^0 \to K^+K^-\pi^+\pi^-$ [1408.1299]



One can experimentally *fold* the phase space in two to form the genuine $\hat{T}$-odd distribution leading to '$\cos\delta\sin\phi$' sensitivity.

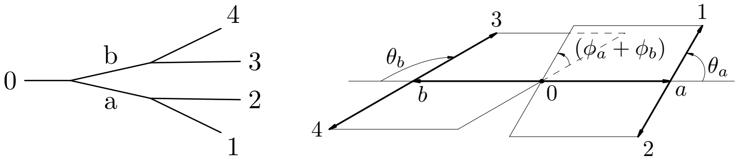
Spinless case: $\hat{T}$-folding of the phase space

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



Spinless case: modelling-independent analysis

1. Fix a phase-space parametrisation
   which biases the analysis sensitivity



2. Define $\hat{\mathrm{T}}$-odd–CP-odd asymmetries systematically
   over the full phase space

$$\mathcal{A}^{kl}_{m\,\{M_i\}\{M_j\}} \equiv \int \mathrm{d}\Phi \;\; \mathrm{sign}\left\{ P_k(\cos\theta_a)\; P_l(\cos\theta_b)\;\; \sin n(\phi_a+\phi_b) \prod_i (m_a^2 - M_i^2) \prod_j (m_b^2 - M_j^2) \right\} \left(\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi} - \frac{1}{\bar{\Gamma}}\frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}\Phi} \right)$$

3. back to 1., with another parametrisation

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Spinful case: preliminary remarks

One does not measure the spins of stable particles.

Final-state spins will be summed over.

Only is the initial polarization kept,

only the P-even–$\hat{\text{T}}$-odd component P_z ($\perp$ to the production plane).

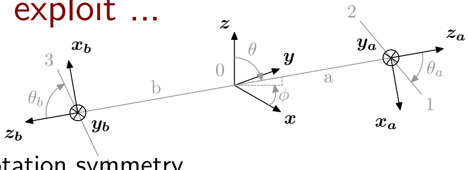
One targets the phases of the weak decay amplitudes,

rather than that of the strong production amplitudes.

One targets '$\cos\delta \sin\varphi$' terms

with sensitivity to small differences of CP-odd phases between amplitudes of identical —or vanishing— CP-even phases.

Spinful case: more richness to exploit ...



More angles

The polarization axis breaks a rotation symmetry.
The azimuthal angles appear in other combinations than $(\phi_a + \phi_b)$.

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

namely, in the three-body decay of a polarized particle
(3 independent momenta and 1 spin to form a $\epsilon_{\mu\nu\rho\sigma} p^\mu q^\nu r^\rho s^\sigma$)

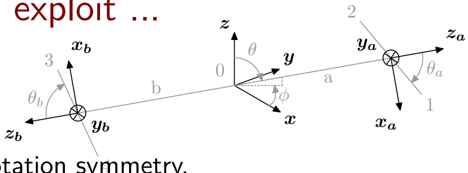
e.g. $\Lambda_b \to \Lambda^* \gamma \to pK\gamma$
$\Lambda_b \to N^* K \to p\pi K$

New $\hat{\mathrm{T}}$-odd observables ...

- proportional to the $\hat{\mathrm{T}}$-odd polarization P_z
- many more $\hat{\mathrm{T}}$-odd angular variables than $\sin n(\phi_a + \phi_b)$:

$\cos\theta$,
$\cos\phi_a$, $\cos\phi_b$,
$\cos(\phi_a + 2\phi_b)$,
$\ldots$

Spinful case: more richness to exploit ...



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New $\hat{\text{T}}$-odd observables ...

- proportional to the $\hat{\text{T}}$-odd polarization P_z
- many more $\hat{\text{T}}$-odd angular variables than $\sin n(\phi_a + \phi_b)$:

$\cos\theta$,
$\cos\phi_a$, $\cos\phi_b$,
$\cos(\phi_a + 2\phi_b)$,
$\ldots$

... which cause $\hat{\text{T}}$-folding issues.

Spinful case: ... and new ambiguities

The folding along the P_z direction is not feasible.
$\Longrightarrow$ the genuine $\hat{\mathrm{T}}$-odd decay distribution is not accessible!

One can only form *angular* $\angle\hat{\mathrm{T}}$-odd distributions
but, some only provide '$\sin\delta\sin\varphi$' sensitivities!
and, some $\angle\hat{\mathrm{T}}$-even ones provide '$\cos\delta\sin\varphi$' sensitivities!

Some modelling is needed to resolve these new ambiguities.
General modelling is provided by the helicity formalism. [Jacob, Wick 59']
Specifying the resonance+spin structure however becomes needed.

Spinful case: resolving ambiguities

e.g. for $\frac{1}{2} \to \frac{1}{2}\, 1 \to \frac{1}{2}\, 0\, 0\, 0$ like $\Lambda_b \to N^* \rho \to p\pi\pi\pi$
$\Lambda_b \to \Lambda\, \phi \to p\pi KK$

$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$					$\cos^2\theta_b$	
$+3/2$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$					$\sin^2\theta_b$	
$+3$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$	α_a			$\cos\theta_a$	$\cos^2\theta_b$	
$+3/2$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$	α_a			$\cos\theta_a$	$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} - \mathrm{Re}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$		P_z	$\cos\theta$		$\cos^2\theta_b$	
$-3/2$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$		P_z	$\cos\theta$		$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} - \mathrm{Re}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\cos\phi_b$
$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$\cos^2\theta_b$	
$-3/2$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} + \mathrm{Re}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} + \mathrm{Re}\{A_-^* B_-\}$	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\cos\phi_b$
-6	$\mathrm{Re}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\cos^2\theta_b$	$\cos\phi_a$
$+3$	$\mathrm{Re}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\cos(\phi_a+2\phi_b)$
$-3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_+\} + \mathrm{Im}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\sin\phi_b$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} - \mathrm{Im}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$
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$+3$	$\mathrm{Im}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\sin(\phi_a+2\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} + \mathrm{Im}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$

Spinful case: resolving ambiguities

e.g. for $\frac{1}{2} \to \frac{1}{2}\, 1 \to \frac{1}{2}\, 0\, 0\, 0$ like $\Lambda_b \to N^* \rho \to p\pi\pi\pi$

$\Lambda_b \to \Lambda\, \phi \to p\pi KK$

$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$					$\cos^2\theta_b$	
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$+3$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$	α_a			$\cos\theta_a$	$\cos^2\theta_b$	
$+3/2$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$	α_a			$\cos\theta_a$	$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} - \mathrm{Re}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3$	→ 'sin δ sin φ'		P_z	$\cos\theta$		$\cos^2\theta_b$	
$-3/2$	[illegible]		P_z	$\cos\theta$		$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} - \mathrm{Re}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\cos\phi_b$
$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$\cos^2\theta_b$	
$-3/2$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$	α_a	P_z	$\cos\theta$	$\cos\theta_a$	$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} + \mathrm{Re}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} + \mathrm{Re}\{A_-^* B_-\}$	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\cos\phi_b$
-6	$\mathrm{Re}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\cos^2\theta_b$	$\cos\phi_a$
$+3$	$\mathrm{Re}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\cos(\phi_a+2\phi_b)$
$-3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_+\} + \mathrm{Im}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\sin\phi_b$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} - \mathrm{Im}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$
$-3/\sqrt{2}$	Im [illegible] → 'cos δ sin φ'	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\sin\phi_b$
-6	$\mathrm{Im}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\cos^2\theta_b$	$\sin\phi_a$
$+3$	$\mathrm{Im}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\sin(\phi_a+2\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} + \mathrm{Im}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$

Spinful case: resolving ambiguities

e.g. for $\frac{1}{2} \to \frac{1}{2}\ 1 \to \frac{1}{2}\ 0\ 0\ 0$ like $\Lambda_b \to N^* \rho \to p\pi\pi\pi$, $\Lambda_b \to \Lambda\,\phi \to p\pi KK$

$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$					$\cos^2\theta_b$	
$+3/2$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$					[illegible]	
$+3$	$\lvert A_+\rvert^2 - \lvert A_-\rvert^2$	α_a			[illegible]	[illegible]	
$+3/2$	$\lvert B_+\rvert^2 - \lvert B_-\rvert^2$	α_a			$\cos\theta_a$	[illegible]	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} - \mathrm{Re}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3$	[illegible]		P_z	$\cos\theta$		$\cos^2\theta_b$	
$-3/2$	[illegible]		P_z	$\cos\theta$		$\sin^2\theta_b$	
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} - \mathrm{Re}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\cos\phi_b$
$+3$	$\lvert A_+\rvert^2 + \lvert A_-\rvert^2$	α_a	P_z	[illegible]	[illegible]	[illegible]	[illegible]
$-3/2$	$\lvert B_+\rvert^2 + \lvert B_-\rvert^2$	α_a	P_z	[illegible]	[illegible]	[illegible]	[illegible]
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_-\} + \mathrm{Re}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\cos(\phi_a+\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Re}\{A_+^* B_+\} + \mathrm{Re}\{A_-^* B_-\}$	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\cos\phi_b$
-6	$\mathrm{Re}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\cos^2\theta_b$	$\cos\phi_a$
$+3$	$\mathrm{Re}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\cos(\phi_a+2\phi_b)$
$-3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_+\} + \mathrm{Im}\{A_-^* B_-\}$		P_z	$\sin\theta$		$\sin 2\theta_b$	$\sin\phi_b$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} - \mathrm{Im}\{A_-^* B_+\}$	α_a	P_z	$\cos\theta$	$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$
$-3/\sqrt{2}$	Im [illegible]	α_a	P_z	$\sin\theta$	$\cos\theta_a$	$\sin 2\theta_b$	$\sin\phi_b$
-6	$\mathrm{Im}\{A_+^* A_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\cos^2\theta_b$	$\sin\phi_a$
$+3$	$\mathrm{Im}\{B_+^* B_-\}$	α_a	P_z	$\sin\theta$	$\sin\theta_a$	$\sin^2\theta_b$	$\sin(\phi_a+2\phi_b)$
$+3/\sqrt{2}$	$\mathrm{Im}\{A_+^* B_-\} + \mathrm{Im}\{A_-^* B_+\}$	α_a			$\sin\theta_a$	$\sin 2\theta_b$	$\sin(\phi_a+\phi_b)$

$\angle\hat{T}$-even angular distrib.

$\rightarrow$ '$\sin\delta\sin\varphi$'

$\angle\hat{T}$-odd angular distrib.

$\rightarrow$ '$\cos\delta\sin\varphi$'

Spinful case: resolving ambiguities

With a resonance structure isolated, the helicity formalism determines which $\angle\hat{\mathrm{T}}$-odd and $\angle\hat{\mathrm{T}}$-even *angular* distributions lead to '$\cos\delta \sin\varphi$' sensitivities in decay amplitudes.

$$\mathcal{A}^{jkl}_{mno} \equiv \int d\Omega \left(\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega} - \frac{1}{\bar{\Gamma}}\frac{d\bar{\Gamma}}{d\Omega}\right) \text{sign}\left\{ f_j(\cos\theta)\, f_k(\cos\theta_a)\, f_l(\cos\theta_b)\, \sin\left(m\phi_a + n\phi_b + o\frac{\pi}{2}\right)\right\}$$

with $o \in \{0,1\}$, $\quad j+m+n+o \in 2\mathbb{Z} \to \angle\hat{\mathrm{T}}$-odd

$j+m+n+o \in (2\mathbb{Z}+1) \to \angle\hat{\mathrm{T}}$-even

\+ further understanding gained:

e.g., in strongly-produced $\frac{1}{2} \to \frac{1}{2}\,1 \to \frac{1}{2}\,0\,0\,0$,

- vanishing 'classic' $\sin(\phi_a + \phi_b)$ asymmetry (integrated $a_{CP}^{\hat{T}\text{-odd}}$)
- vanishing asymmetries based on 'special' angles [hep-ph/0602043]

$$\cos\Phi_a = \frac{\cos\theta\cos\phi\sin\phi_a + \sin\phi\cos\phi_a}{\sqrt{1-\sin^2\phi_a\sin^2\theta}}, \quad \sin\Phi_a = \frac{\cos\theta\sin\phi\sin\phi_a - \cos\phi\cos\phi_a}{\sqrt{1-\sin^2\phi_a\sin^2\theta}},$$

$$\cos\Phi_b = \frac{\cos\theta\cos\phi\sin\phi_b - \sin\phi\cos\phi_b}{\sqrt{1-\sin^2\phi_b\sin^2\theta}}, \quad \sin\Phi_b = \frac{\cos\theta\sin\phi\sin\phi_a + \cos\phi\cos\phi_b}{\sqrt{1-\sin^2\phi_b\sin^2\theta}}.$$

measured in $\Lambda_b \to \Lambda\phi \to p\pi KK$ [1603.02870]

CP violation in baryons: theoretical perspective

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

Genuine $\hat{\text{T}}$-odd distributions allow to probe CP violation with
'$\cos\delta \sin\varphi$' sensitivity.

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

In spinful decays, the genuine $\hat{\text{T}}$-odd distributions
do not seem accessible.

But the helicity formalism indicates which *angular* distributions
lead to '$\cos\delta \sin\varphi$' sensitivities to decay amplitude phases.