Search for violation in the charmless decay $B^0 \to p\bar{p}K^+\pi^-$ using triple product asymmetries and Test of lepton universality in beauty-quark decays at LHCb

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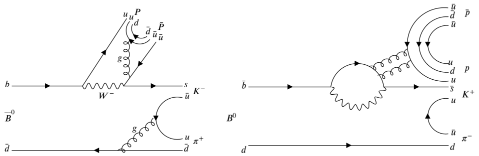
Riunione gruppo 1

26/05/2021

Overview

- Search for CP violation in charmless baryonic $B^0 \to p\bar{p}K^+\pi^-$ decays using data collected by the LHCb experiment (Preliminary)
- Test of lepton universality in beauty-quark decays

$B^0 \to p\bar{p}K^+\pi^-$



The charmless region is mediated by weak interaction and mainly governed by two amplitudes:

- tree $b \to u\bar{u}s$
- penguin $b \to s\bar{u}u$

Weak phase difference is given here by $\arg(\frac{V_{ub}V^*_{us}}{V_{tb}V^*_{ts}})$ → In SM this is dominated by the CKM angle γ [1]
$K^+\pi^-$ system forms many intermediate K^* resonances that could in principle interfere and cause CP violation effects
Primary areas of interest in baryonic B decays include:

- hierarchy of branching fractions to the various decay modes
- presence of resonances (also possibly exotic ones)
- existence of a threshold enhancement in the baryon-antibaryon mass spectrum
- search for manifestation of CP violation → huge phase-space with many intermediate resonances in the $K^+\pi^-$ system

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[1] M. Gronau and J. L. Rosner,Triple product asymmetries in Λ_b and Ξ_b decays, Physics Letters B749(2015) 104

CPV in charmless baryonic B decays

Four-body decays are particularly suited for $\hat{T}$-odd CP asymmetries

- One can build $\hat{T}$-odd CP asymmetries using only momenta of the final-state particles
- $\hat{T}$-odd CP asymmetries are expected to be sensitive to new physics [3]
- $\hat{T}$-odd CP asymmetries have been used to search for CP violation in 4-body b-baryon decays [1], [2]

Triple product correlations (TPC)

We can build $f(\Phi)$ using the momentum $\vec{p}_i$ of the final state particles in the mother C.M frame: $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{K^+} \times \vec{p}_{\pi^-})$, $\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{K^-} \times \vec{p}_{\pi^+})$:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

$$\overline{A}_{\hat{T}} = \frac{\overline{N}(-\overline{C}_{\hat{T}} > 0) - \overline{N}(-\overline{C}_{\hat{T}} < 0)}{\overline{N}(-\overline{C}_{\hat{T}} > 0) + \overline{N}(-\overline{C}_{\hat{T}} < 0)}$$

where N and $\overline{N}$ are the numbers of B^0 and $\overline{B}^0$ decay
Consequently a true CP violating and a true P violating observable is defined as:

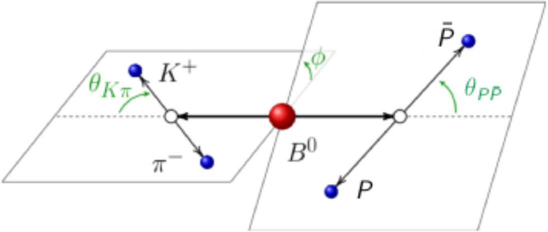
$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}}) \qquad a_{P}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \overline{A}_{\hat{T}})$$

Search for CPV in the charmless $B^0 \to p\bar{p}K^+\pi^-$ using TPC

Triple product are calculated in the B^0 rest frame:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{K^+} \times \vec{p}_{\pi^-}) \propto \sin(\phi)$$
$$\overline{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot (\vec{p}_{K^-} \times \vec{p}_{\pi^+}) \propto \sin(\phi)$$

- ϕ is $\hat{T}$-odd and so is $\sin(\phi)$



Data sample & signal selection

$\sim 9fb^{-1}$ **of data analyzed (full LHCb data-sample available):**

- **Run1:** 0.98 fb^{-1} of 2011 data collected at $\sqrt{s}$=7 TeV and 1.99 fb^{-1} of 2012 data at $\sqrt{s}$=8 TeV
- **Run2:** 1.67 fb^{-1}, 1.71 fb^{-1}, 2.19 fb^{-1} collected during 2016 ($\sqrt{s} = 13$ TeV) and 2017 ($\sqrt{s} = 13$ TeV) and 2018 ($\sqrt{s} = 13$ TeV)

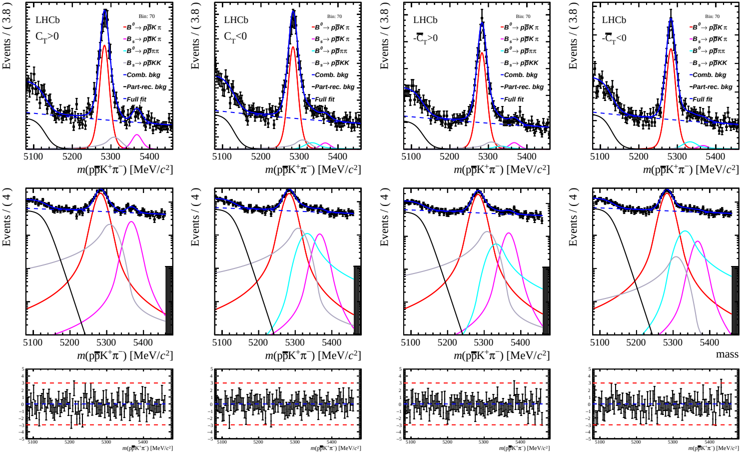
Selection procedure (common to Run1 and Run2 data sets):

1. **The hardware trigger stage:** Hadron with high transverse energy in the calorimeters
2. **The software trigger stage:** two-, three- or four-track secondary vertex with a significant displacement from any primary proton-proton interaction vertices
3. **Offline selection stage & Signal/Background optimization:**
    - Combination of a multivariate classifier (Boosted Decision Tree)+Particle IDentification (PID) cuts in order to maximise $FOM = \frac{S}{\sqrt{S+B}}$

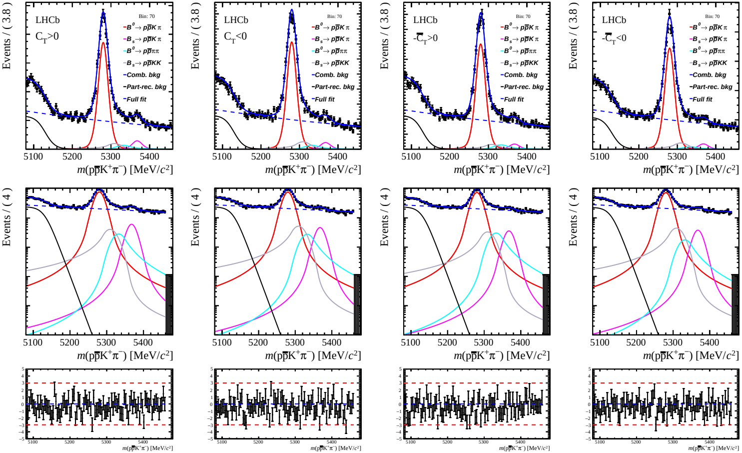
Phase space integrated a_{CP}^{T-odd} and a_{P}^{T-odd}

1. Split $m(p\bar{p}K^{+}\pi^{-})$ in 4 sub-samples depending on the B^{0} flavour and the $C_{\hat{T}}$ sign
2. Charmless region selected by requiring $m_{p\bar{p}} < 2850 MeV/C^{2}$
3. Simultaneous extended Unbinned Maximum Likelihood (UML) fit to combined Run 1 & Run 2 datasets
4. $\mathcal{L}(\theta, \theta_{Run1}, \theta_{Run2}) = \mathcal{L}_{Run1}(\theta, \theta_{Run1})\mathcal{L}_{Run2}(\theta, \theta_{Run2})$

Search for CP violation in the charmless region (Run 1)



Search for CP violation in the charmless region (Run 2)



Results of the phase-space integrated charmless region

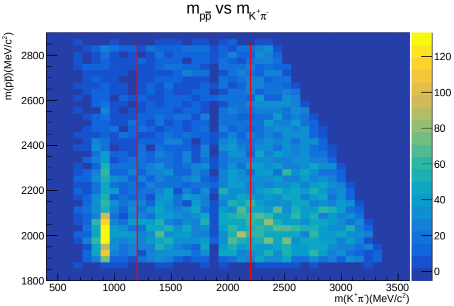
PHS-integrated asymmetries (results are blind):

Run	$A_{\hat{T}}(\%)$	$\bar{A}_{\hat{T}}(\%)$	$a_{CP}^{\hat{T}-odd}(\%)$	$a_{P}^{\hat{T}-odd}(\%)$	corr(A_T,$\bar{A}_T$)
1	-1.2 ± 3.1	2.0 ± 2.9	-1.6 ± 2.1	0.4 ± 2.1	-0.00055
2	-1.2 ± 1.4	-0.4 ± 1.4	-0.4 ± 0.99	-0.8 ± 0.99	0.00015
1+2	0.058 ± 1.2	0.65 ± 1.2	-0.3 ± 0.85	0.35 ± 0.85	-0.000095

Search for CP violation in regions of the phase space

We decided to parametrize the phase space according to the 5 kinematical variables:

- $m_{K^+\pi^-}$
- $m_{p\bar{p}}$
- $\cos\theta_{K^+\pi^-} \rightarrow$ helicity angle of the K^+ in the rest frame of the $K^+\pi^-$
- $\cos\theta_{p\bar{p}} \rightarrow$ helicity angle of the p in the rest frame of the $p\bar{p}$
- $\phi \rightarrow$ angle between the planes defined by $K^+\pi^-$ and $p\bar{p}$ tracks



Choice of the binning scheme

- Charmless region $m_{p\bar{p}} < 2.85\ GeV/c^2 \rightarrow$ invariant mass range of the $K\pi$ system is up to 3.5 GeV/c^2:
  - All the neutral K^* resonances known to decay to $K^+\pi^-$ could in principle interfere and cause violation effects

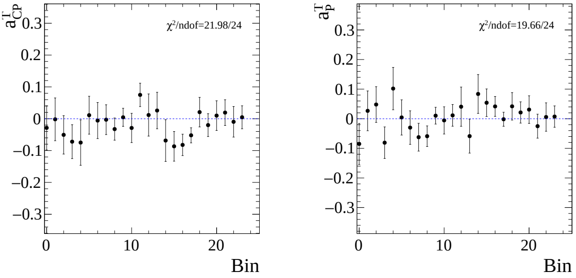
State	Mass (MeV/c^2)	Width (MeV/c^2)	J^P	$\mathcal{B}(K^* \rightarrow K\pi)$
$K^*(800)$	682 ± 29	547 ± 24	0^+	$\sim 100\%$
$K^*(892)$	895.81 ± 0.19	47.4 ± 0.6	1^-	$\sim 100\%$
$K^*(1410)$	1414 ± 15	232 ± 21	1^-	$(6.6 \pm 1.3)\%$
$K_0^*(1430)$	1425 ± 50	270 ± 80	0^+	$(93 \pm 10)\%$
$K_2^*(1430)$	1432.4 ± 1.3	109 ± 5	2^+	$(49.9 \pm 1.2)\%$
$K^*(1680)$	1717 ± 27	322 ± 110	1^-	$(38.7 \pm 2.5)\%$
$K_3^*(1780)$	1776 ± 7	159 ± 21	3^-	$(18.8 \pm 1.0)\%$
$K_0^*(1950)$	1945 ± 22	201 ± 90	0^+	$(52 \pm 14)\%$
$K_2^*(1980)$	1974 ± 26	376 ± 70	2^+	not seen yet
$K_4^*(2045)$	2045 ± 9	198 ± 30	4^+	$(9.9 \pm 1.2)\%$
$K_5^*(2380)$	2382 ± 24	178 ± 50	5^-	$(6.1 \pm 1.2)\%$

Choice of the binning scheme

In order to optimize the binning scheme to enhance the sensitivity to violation effects we decided to divide the phase space defined by $m_{K^+\pi^-}$ and $m_{p\bar{p}}$ in 3 regions:

- **scheme 1**: Charmless region ($m_{p\bar{p}} < 2850$ MeV$/c^2$) and dominated by the $K^*(892)$ resonance in the $K^+\pi^-$ spectrum ($m_{K^+\pi^-} < 1200$ MeV$/c^2$)
- **scheme 2**: Charmless region ($m_{p\bar{p}} < 2850$ MeV$/c^2$) and region in the $m_{K^+\pi^-}$ spectrum where many resonances are overlapping ($m_{K^+\pi^-} \in [1200, 2200]$)
- **scheme 3**: Charmless region ($m_{p\bar{p}} < 2850$ MeV$/c^2$) and dominated by the $K_5^*(2380)$ resonance in the $K^+\pi^-$ spectrum ($m_{K^+\pi^-} > 2200$ MeV$/c^2$)

Results (blind)



The compatibility with the no *CP* and no *P* violation hypothesis is established by the following quantity

$$\chi^2 = \vec{X}^T V^{-1} \vec{X}$$

- $\vec{X}$ is a vector whose i-th element contains the a_{CP}^{T-odd}
- V^{-1} is the inverse of the covariance matrix
  - statistical error matrix
  - systematic error matrix

Systematic uncertainties

Main sources of systematic uncertainties:

1. **Reconstruction efficiency and selection procedure:**
    - High statistics MC sample $\sim 0.3\%$:
    - From data using a control channel with similar kinematics ($B^0 \to p\bar{p}\bar{D}^0(\to K^+\pi^-)$): $\sim 1.5\%$
2. **Detector resolution:** negligible ($< 0.1\%$) from MC sample
3. **Fit model:** negligible ($< 0.1\%$) using toy MC

Conclusion

- **This work**
  1. Precision of $\sim$ % already reached in binned analysis
  2. The analysis is in the internal LHCb collaboration wide review process before publication
  3. I will unblind the results once I get the green light from the reviewers
- **Future perspectives: will not be included in the current analysis, but..**
  1. Expected significant improvement in sensitivity in Run 3 data taking starting in 2022
  2. Higher instantaneous luminosity
  3. Channels with final state hadrons will be selected with higher efficiencies after the removal of the L0 hardware trigger

Test of lepton universality in beauty-quark decays at LHCb

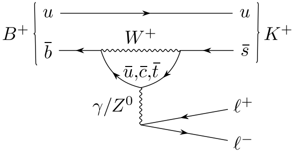
- Accroding to the SM theory, the three different charged leptons have identical electroweak interaction strengths
- Measurements performed so far by different experiments have shown that a wide range of particle decays are consistent with the principle of lepton universality
- LHCb has recently (March 2021) released a new measurement of the test of lepton universality in beauty-quark decays by measuring the branching fractions ratio R_K:

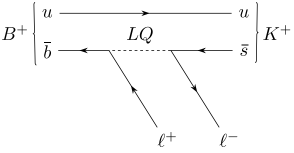
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

LHCb Collaboration, Test of lepton universality in beauty-quark decays, arXiv:2103.11769, submitted to Nature Physics

Test of lepton universality in beauty-quark decays at LHCb (II)

- SM predictions for the branching fractions of these two decays is complicated by the strong nuclear force that binds together the quarks into hadrons
- Strong force does not couple directly to leptons and its effect on the two decays is identical
  - R_K predicted with $\sim 1\%$ precision
- Possible new physics contribution to the decay may include hypothetical leptoquarks





Test of lepton universality in beauty-quark decays at LHCb (II)

- Test of lepton universality is obtained by measuring experimentally R_K in the range $1.1 < q^2 < 6.0$:

$$R_K = \frac{\int_{1.1}^{6.0} \frac{d\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{1.1}^{6.0} \frac{d\mathcal{B}(B^+ \to K^+ e^+ e^-)}{dq^2} dq^2}$$

- q^2 is the di-lepton invariant mass-squared

Data sample

$\sim 9fb^{-1}$ **of data analyzed (full LHCb data-sample available):**

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The results supersede those of the previous LHCb analysis with the addition of 4 fb^{-1} data collected in 2017 and 2018

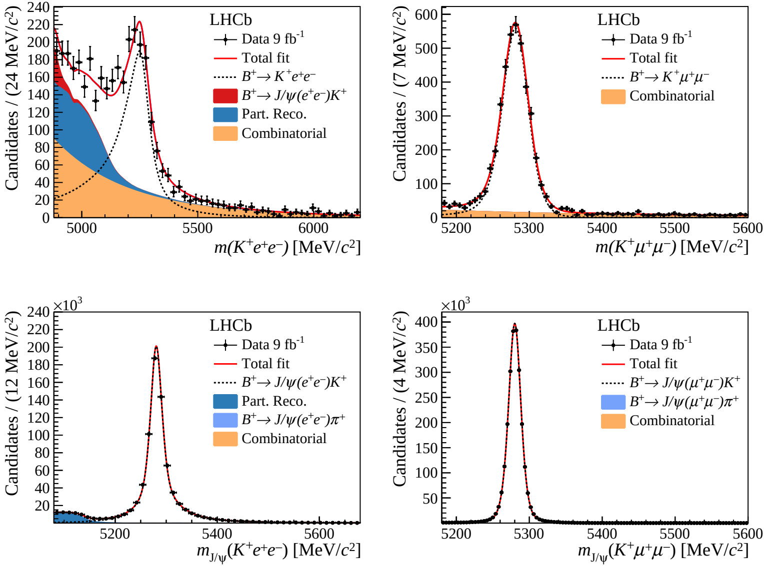
Analysis strategy

- Different reconstruction of decays with muons in the final state, compared to decays with electrons
  - significant bremsstrahlung radiation emitted by the electrons
  - L0 trigger thresholds higher for electrons than muons
- The major challenge of the measurement is correcting for the efficiency of the selection requirements
- To help overcome the challenge of modelling precisely the different electron and muon reconstruction efficiencies the following ratio is measured instead:

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+ \mu^-) K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+ e^-) K^+)}$$

- $J/\psi \to \ell^+ \ell^-$ branching fractions are known to respect lepton universality to within 0.4%

Analysis strategy (II)



Results

R_K is measured to be:

$$R_K(1.1 < q^2 < 6.0 GeV^2/c^4) = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

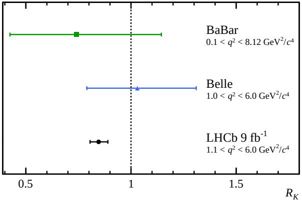
Combining the statistical with the systematic uncertainties gives:

$$R_K = 0.846^{+0.044}_{-0.041}$$

SM expectation is :

$$R_K^{SM} = 1.00 \pm 0.01$$

Consistent with SM at the level of 0.10% (**3.1 standard deviations**)



Previous results of tests of lepton universality at LHCb

- $B^+ \to K^+\ell^+\ell^-$ (**Phys. Rev. Lett. 122 (2019) 191801**) $\to$ 5.0 fb^{-1}

$$R_K(1.1 < q^2 < 6.0 GeV^2/c^4) = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

compatible with the Standard Model at the level of 2.5 standard deviations

- $B^0 \to K^{*0}\ell^+\ell^-$ (**JHEP 08 (2017) 055**) $\to$ 3.0 fb^{-1}

$$R_{K^{*0}}(0.045 < q^2 < 1.1\ GeV^2/c^4) = 0.66^{+0.11}_{-0.07}(stat) \pm 0.03(syst)$$

$$R_{K^{*0}}(1.1 < q^2 < 6.0\ GeV^2/c^4) = 0.69^{+0.11}_{-0.07}(stat) \pm 0.03(syst)$$

2.1–2.5 standard deviations below their respective SM expectations

- $\Lambda_b^0 \to pK^-\ell^+\ell^-$ (**JHEP 05 (2020) 040**) $\to$ 4.7 fb^{-1}

$$R_{pK}(0.1 < q^2 < 6.0\ GeV^2/c^4) = 1.17^{+0.18}_{-0.16}(stat) \pm 0.07(syst)$$

compatible with unity at the level of one standard deviation

BACKUP

Search for CPV in the charmless $B^0 \to p\bar{p}K^+\pi^-$ using TPC

TPA and direct CPV are complementary [2]:

$$a_{CP} \propto \sin\left(\delta_e^1 - \delta_e^2\right) \sin\left(\phi_e^1 - \phi_e^2\right)$$

$$a_{CP}^{\hat{T}-odd} \propto \cos\left(\delta_e^1 - \delta_o^2\right) \sin\left(\phi_e^1 - \phi_o^2\right)$$

- a_{CP} more sensitive to CPV effects when difference in strong phase between interfering amplitudes is large
- $a_{CP}^{\hat{T}-odd}$ more sensitive to CPV effects when difference in strong phase between interfering is small
- $a_{CP}^{\hat{T}-odd}$ not affected by reconstruction efficiency and $b-$hadron production asymmetries

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[2] A. Datta and D.London, Int.J.Mod.Phys. A19 (2004) 2505

$\hat{T}$-odd CP asymmetries

The $\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}$ of any pair of CP-conjugate processes can be decomposed in four pieces of definite $\hat{T}$ and CP transformation properties

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

$\hat{T}$ is the motion reversal operator:

- it reverts both momentum and spin three-vectors
- its action on helicities and momenta identical to that of CP operator
- it is the unitary component of the antiunitary time-reversal operator T

$\hat{T}$-odd CP asymmetries

The usual total rate CP asymmetry is defined as:

$$\int d\Phi \frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}\Big|_{CP-odd}^{\hat{T}-even} = \frac{\bar{A}_{\bar{f}}^2 - A_f^2}{\bar{A}_{\bar{f}}^2 + A_f^2}$$

Other asymmetries can be obtained from $\hat{T}$-odd components:

$$A_{\hat{T}} = \frac{\int d\Phi f(\Phi)[\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-even}^{\hat{T}-odd} + \frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-odd}^{\hat{T}-odd}]}{\int d\Phi[\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-even}^{\hat{T}-even} + \frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-odd}^{\hat{T}-even}]}$$

$$\bar{A}_{\hat{T}} = \frac{\int d\Phi f(\Phi)[\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-even}^{\hat{T}-odd} - \frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-odd}^{\hat{T}-odd}]}{\int d\Phi[\frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-even}^{\hat{T}-even} - \frac{\mathrm{d}\Gamma}{\mathrm{d}\Phi}|_{CP-odd}^{\hat{T}-even}]}$$

- Without a $\hat{T}$-odd function $f(\Phi)$ the 2 integrals would vanish
- $A_{\hat{T}}$ and $\overline{A}_{\hat{T}}$ are not true CP violating asymmetries

References I

[1] R Aaij et al. Search for cp violation using triple product asymmetries in $\Lambda_b^0 \to pk^-\pi^+\pi^-$, $\Lambda_b^0 \to pk^-k^+k^-$ and $\Xi_b^0 \to pk^-k^-\pi^+$ decays. *Journal of High Energy Physics*, 2018(8), Aug 2018. ISSN 1029-8479. doi: 10.1007/jhep08(2018)039. URL http://dx.doi.org/10.1007/JHEP08(2018)039.

[2] R Aaij et al. Search for *cp* violation and observation of *p* violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays. *Phys. Rev. D*, 102:051101, Sep 2020. doi: 10.1103/PhysRevD.102.051101. URL https://link.aps.org/doi/10.1103/PhysRevD.102.051101.

[3] Eugene Golowich and German Valencia. Triple-product correlations in semileptonic decays. *Phys. Rev. D*, 40:112–118, Jul 1989. doi: 10.1103/PhysRevD.40.112. URL https://link.aps.org/doi/10.1103/PhysRevD.40.112.