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THE CKM ANGLE α AT LHC*

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The potential of LHCb in the extraction of the angle α from the analysis of the $B \to (\rho\pi)^0$ and $B \to (\rho\rho)^{\pm,0}$ decays has been extensively studied. The expected performance are summarized in this document.

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1. Introduction

In the CKM model, α is one of the angles of the Unitarity Triangle (UT) relying on the first and third quarks families. The decays of the oscillating B_d-mesons that proceed via the $b \to u\bar{u}d$ transition are sensitive to the sum, $\beta+\gamma$, of the two other angles of the UT. The $B_d \to (\rho\pi)^0$, $B^0 \to \rho^+\rho^-$ and $B^0 \to \pi^+\pi^-$ modes are thus good candidates for the extraction of the angle $\alpha = \pi - \beta - \gamma$. Despite the non negligible contribution from Penguin transitions, the current B factories have demonstrated that a well-constrained determination of α can be achieved with these modes, when adding Isospin constraints from the SU(2)-related modes.

In the hadronic environment of the LHC collisions, the reconstruction of multi-pions final states, including neutrals, is a challenge. The potential of the LHCb experiment in the decays $B \to \rho\pi$ and $B \to \rho\rho$ has been extensively studied. This document provides a summary of the expected performance.

2. α from $B_d \to (\rho\pi)^0 \to \pi^+\pi^-\pi^0$ modes

2.1. The method

Assuming that the $B_d(\overline{B}_d) \to \pi^+\pi^-\pi^0$ transition mainly proceeds through the $\rho \to \pi\pi$ vector resonance, 6 interfering modes contributes in the Dalitz plot of the 3-bodies decay. Moreover, both Tree and Penguin transitions

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contribute to each mode. Using isospin constraints, it has been shown [1] that the proper-time evolution of the tagged Dalitz distributions of the 3-bodies decay, provides enough information to determine simultaneously the angle α and the relative amplitudes and strong phases between all transition processes.

The method requires an accurate knowledge of both the phenomenological inputs (parametrization of the rho line-shape) and the experimental acceptances.

2.2. Selection of the $B \to \pi^+\pi^-\pi^0$

The hard spectrum of the neutral pion, together with the vertex constrains of the charged pions pair means that the decay can be well isolated from the combinatorial background, even in the high multiplicity environment of the LHC. A performant background rejection is obtained thanks to a multivariate selection combining several variables based on the identification of neutral and charged pions, the kinematics of the process or the displaced vertex of the B decay. The expected performance of the selection has been estimated using the full reconstruction and pattern recognition of 1 million of simulated pp collisions producing the $B \to \pi^+\pi^-\pi^0$ decay in the LHCb acceptance.

This accumulated statistics almost represents 10 days of data taking with the nominal LHCb luminosity of 2×10^{32} cm^{-2}s^{-1}. About 1300 events pass the trigger and selection criteria. The corresponding expected annual yield (10^7 s) is 14 k reconstructed $B \to \pi^+\pi^-\pi^0$ decays with an overall efficiency $\varepsilon_{\rm acc} \times \varepsilon_{\rm trig} \times \varepsilon_{\rm sel} = 7 \times 10^{-4}$.

The mass and proper time resolutions of the selected $B \to \pi^+\pi^-\pi^0$ candidates, respectively $\sigma_M = 60\,{\rm MeV}/c^2$ and $\sigma_\tau = 50\,{\rm fs}$, are dominated by the energy resolution of the electromagnetic calorimeter.

The proper-time-dependent and the Dalitz-position-dependent acceptance of the selection are illustrated in Fig. 1. As can be seen, the low proper-time region and the lower Dalitz corner regions are depopulated, due to the large impact parameter required for the $\pi^\pm$ and the large transverse energy required for the π^0, respectively.

The tagging efficiency has been evaluated to be $\varepsilon = 40\%$ and the wrong tag fraction $\omega = 31\%$, leading to an effective tagging power $\varepsilon_{\rm eff} = \varepsilon(1-2\omega)^2 = 5.8\%$.

The background contamination has been estimated with the simulation of 33 millions of inclusive pp collision producing the B flavor in the final state. This corresponds to about 15 minutes of LHCb data taking. In addition to this generic $B\overline{B}$ background, the possible contamination from the specific, low branching ratio, charmless B decays have been studied using dedicated

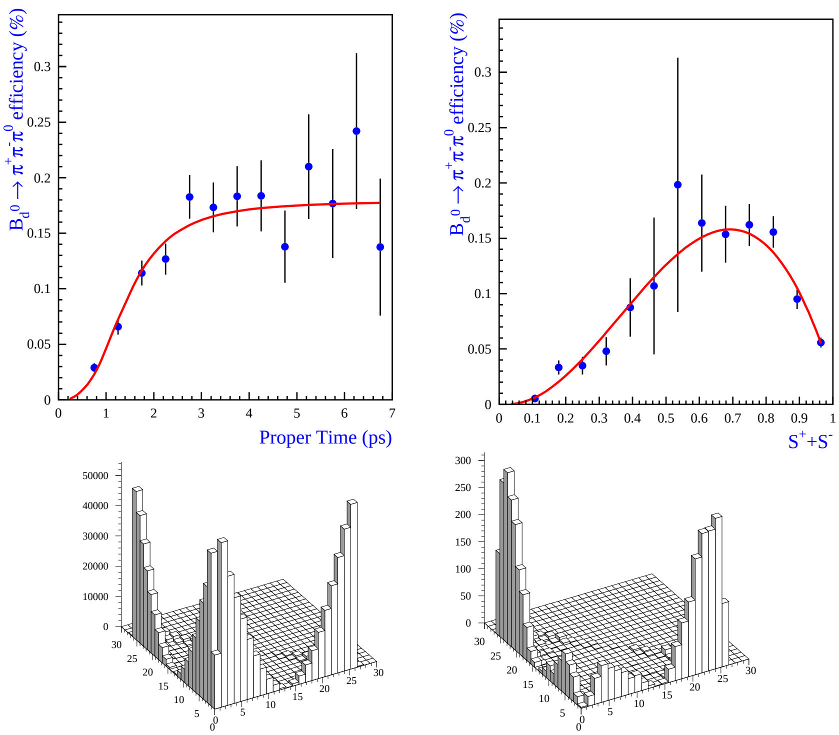

Fig. 1. Selection efficiency as a function of the proper time (left top) and as a function of the sum of the Dalitz coordinates (right top). The 2-dimensional histograms display the Dalitz distribution before (left bottom) and after (right bottom) the selection is applied.

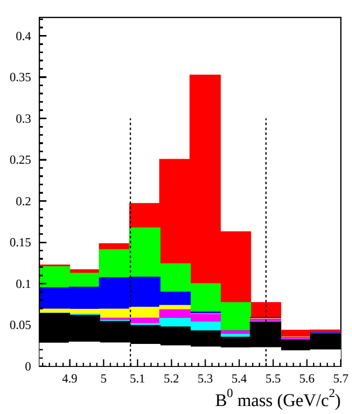

Fig. 2. Accumulated mass spectrum for the selected signal events and various background sources (arbitrary vertical scale). The dotted lines indicate the selection mass window ($\pm$ 200 MeV/c^2).

simulation. It has been concluded that the B/S ratio should not exceed one, a value which has been assumed for the subsequent sensitivity study. Fig. 2 displays the accumulated mass spectrum for the selected signal events and various background sources

2.3. Perspective on α extraction with the $B \to \pi^+\pi^-\pi^0$ analysis

The expected sensitivity on the angle α has been estimated using a toy Monte Carlo method, taking the resolutions, tagging performance and acceptances from the full simulation. Repeated toy experiments are performed, each of which has 10000 signal events, almost corresponding to an accumulated luminosity of $2\,\mathrm{fb}^{-1}$ (*i.e.* one nominal year of LHCb data taking). The background is modeled as a combination of non-resonant, resonant and $B \to K^+\pi^-\pi^0$ contributions, with an overall $B/S = 1$ ratio. The relative fractions for each background contributions are free parameters of the unbinned log-likelihood fit together with the 9D theoretical parameters $\vec{\alpha}$. Several scenario have been considered for the relative values of the Penguin and Tree amplitudes and phases contributing to the final state. The "strong penguin" scenario [2] is used for illustration purpose in the following.

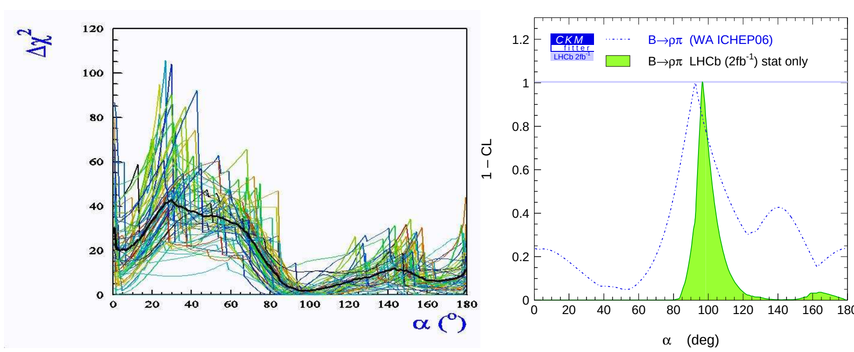

Fig. 3. Left: variation in χ^2 as a function of α for fits to 75 toys experiments superimposed. The averaged $\Delta\chi^2$ is indicated by the thick black curve. Right: confidence level as a function of α for a typical $\rho\pi$ toy experiment (solid curve). The dotted curve corresponds to the current BABAR measurement (including the systematic errors).

The left side of Fig. 3 shows the projections onto α of the variation in χ^2 for fits to 75 toy experiments. A clear minimum is obtained near the input value of $\alpha = 96.5°$ for most of the experiments. The statistical error on the α measurement is below $10°$ for about 90% of the toy experiments. The mean value is $8.5°$. With an accumulated luminosity of 2 fb^{-1}, about 85% of the toy experiments converge to the correct input value for α.

The remaining 15% of the experiments mostly converge to the most dangerous pseudo-mirror solution located near $\frac{3}{2}\pi - \alpha \sim 175°$. In this case the correct solution still corresponds to a deep minimum of the χ^2 curve, as shown on the bottom right curve on Fig. 3. The fraction of the toy experiments converging to the pseudo mirror solution is strongly reduced when more luminosity is accumulated. With $10\,\mathrm{fb}^{-1}$ this fraction is expected to be less than 1%. The right hand side of the Fig. 3 displays the Confidence Level projected onto α for a typical LHCb experiment with an accumulated luminosity of $2\,\mathrm{fb}^{-1}$. The corresponding 1σ interval is $\alpha = (97^{+9}_{-4})°$. The current BABAR measurement (including the systematic errors) is also shown for comparison.

3. α from $B_{d(u)} \to \rho\rho$ SU(2)-related modes

3.1. The method

The B_d decay into the vector mesons pair $\rho^+\rho^-$ decays has been measured to be an almost pure CP-eigenstates [3]. Due to the non negligible Penguin contribution, the time-dependent asymmetry reads :

$$A^{+-}_{\rho\rho}(\tau) = C^{+-}_{\rho\rho}\cos(\Delta m\tau) - S^{+-}_{\rho\rho}\sin(\Delta m\tau)\,,$$

where $S^{+-}_{\rho\rho} = \sqrt{1-(C^{+-}_{\rho\rho})^2}\,\sin[2(\alpha+\Delta\alpha)]$. It has been shown [5] that measuring the branching ratio of the SU(2)-related modes, $B_u \to \rho^+\rho^0$ and $B_d \to \rho^0\rho^0$, allows to put a constraint on the $\Delta\alpha$ deviation. This gives access to α determination up to a eight-fold ambiguities. Moreover, the time-dependent asymmetry of the $B_d \to \rho^0\rho^0$ decay could provide the additional information that allows to reduce the degeneracy of the mirror solutions.

3.2. Selections expected performance

The $B_d \to \pi^+\pi^-\pi^0$ multivariate selection has been extended to the 4-bodies decays for the $B_d \to \rho^+(\pi^-\pi^0)\rho^-(\pi^-\pi^0)$, $B_u \to \rho^+(\pi^-\pi^0)\rho^0(\pi^-\pi^-)$, and $B_d \to \rho^0(\pi^-\pi^-)\rho^0(\pi^+\pi^-)$ modes. The performances, summarized in Table I, are essentially driven by the number of neutral pions in the final states.

The expected annual yield of reconstructed $B_d \to \rho^+\rho^-$ events is 2000 events. Due to this relatively small yield combined with the low tagging performance related to the hadronic production of the neutral B, several years of LHCb data taking will be necessary to get a competitive measurement of the $C^{+-}_{\rho\rho}$ and $S^{+-}_{\rho\rho}$ observables with respect to the current B factories achievement.

TABLE I

Performance of the LHCb selection for the $B_d \to \rho\rho$ SU(2)-related modes.

Mode	Branching ratio $\times 10^6$ [3]	Selection efficiency	Annual yield $2\,\mathrm{fb}^{-1}$	B/S	σ_M MeV/c^2	σ_τ fs
$B_d \to \rho^+\rho^-$	23.1 ± 3.3	0.01%	2000	< 5	80	85
$B_u \to \rho^+\rho^0$	18.2 ± 3.0	0.045%	7000	~ 1	52	47
$B_d \to \rho^0\rho^0$	1.2 ± 0.5	0.16%	1200	< 5	16	32

The main contribution of LHCb to the $\rho\rho$ analysis could be the improvement of the measurement of the $\rho^0\rho^0$ mode, as discussed in the next subsection.

3.3. Perspective on α extraction

In order to evaluate the contribution of LHCb in the extraction of α, the following assumptions have been made about the $B_d \to \rho^0\rho^0$ decay. Firstly, the Branching Ratio ($\mathrm{BR} = 1.2 \times 10^{-6}$) is assumed to be the central value of the current B factories measurement [3]. It is moreover assumed that LHCb will reach a 20% relative uncertainty on this measurement (current error is 40%). The value of the time-independent and time-dependent parameters of the asymmetry, $C^{00}_{\rho\rho}$ and $S^{00}_{\rho\rho}$, are assumed to match their preferred value extracted from the global fit of the current data [4], *i.e.* $(C^{00}_{\rho\rho}, S^{00}_{\rho\rho}) = (0.51, -0.30)$. Eventually, LHCb is assumed to reach the resolution $\sigma_{C/S} = 0.4$ on both the parameters with an integrated luminosity of $2\,\mathrm{fb}^{-1}$. This value is based on the rescaling of the expected LHCb performance for the asymmetry measurement of the $B \to \pi^+\pi^-$ decay.

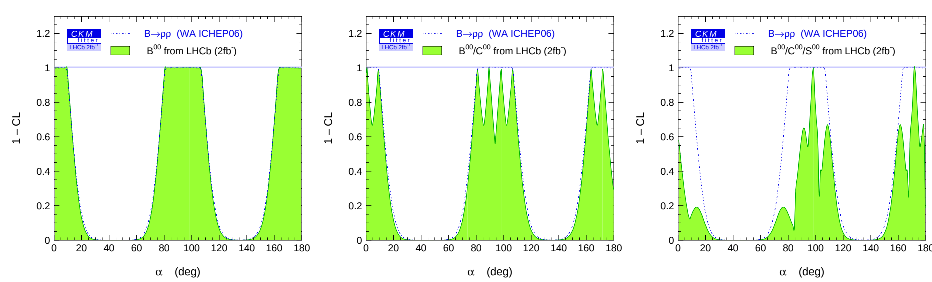

Fig. 4. Confidence level as a function of α when including the expected LHCb contributions to the knowledge of the $B_d \to \rho^0\rho^0$ decay.

The resulting performance on the α extraction are illustrated on Fig. 4. As can be seen on the left curve, the improvement of the branching ratio measurement would not provide a significant impact on α with respect to the current constraint. Measuring in addition the time-independant asymmetry $C^{00}_{\rho\rho}$ will allow to distinguish the 8-fold mirror solutions. However, the global constraint is almost unchanged.

Eventually, the measurement of the time-dependant asymmetry results in a significant improvement of the constraint, thanks to the reduction of the mirror solution degeneracy. The resulting uncertainty on α is $(97^{+15.2}_{-12.8})^\circ$. The resolution improvement will, however, be strongly dependent on the central value of the measured $(C^{00}_{\rho\rho},S^{00}_{\rho\rho})$.

4. Conclusions

Two complementary approaches have been studied for the extraction of the angle α with LHCb.

- **The time dependent analysis of the $B_d \to (\rho\pi)^0$ Dalitz decay.** This method allows, in principle, a clean extraction of the angle α free of ambiguities in the $[0., \pi]$ range but with dangerous pseudo-mirror solutions. With $2\,\mathrm{fb}^{-1}$ integrated, LHCb could provide a determination of α with a statistical error below 10°. Studies of the potential systematic uncertainties indicate that an accurate control of both the experimental distortions (acceptance and tagging performance) and the phenomenological inputs (ρ line-shape parametrisation) is required. This ambitious analysis, challenging in the hadronic environment of LHC, will probably require a long period to be performed accurately.
- **The SU(2) analysis of the $B_d \to \rho\rho$ modes.** This method provides a measurement of α up to a 8-fold ambiguities. Several years of LHCb data taking will be needed to get a competitive measurement of the time-dependent asymmetry in the $B_d \to \rho^+\rho^-$ decay with respect to the current B factories achievement. The main contribution of LHCb to the $B \to \rho\rho$ analysis could be the improvement of the measurements in the $\rho^0\rho^0$ mode. In particular, the determination of the currently unmeasured time-dependent parameter of the decay asymmetry, will allow to reduce the degeneracy between the mirror solutions. An improvement on the α measurement down to the 15° precision could be achieved with an integrated luminosity of $2\,\mathrm{fb}^{-1}$.

Fig. 5 displays a tentative sketch of the constraint on α when $2\,\mathrm{fb}^{-1}$ of LHCb data will be accumulated at the end of this decade. The combined constraint including the LHCb contributions to the $\rho\pi$ and $\rho\rho$ (and marginally $\pi\pi$) analysis is shown. The corresponding 1σ interval is $\alpha = (97^{+5.9}_{-3.8})^\circ$.

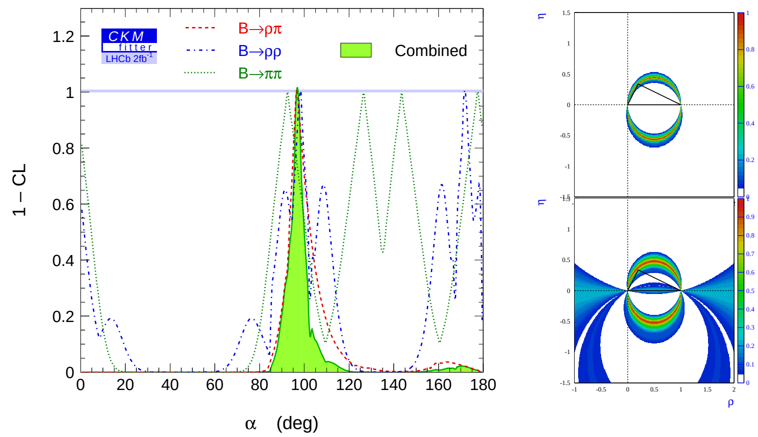

Fig. 5. Perspective on the α sensitivity when the contributions from $2\,\mathrm{fb}^{-1}$ of LHCb data are included. The dashed curve indicate the expected constraint from the $\rho\pi$ Dalitz analysis using the LHCb data . The dash-dotted curve is the constraint from the world averaged $\rho\rho$ data including the expected LHCb contribution to the $\rho^0\rho^0$ mode. The dotted curve is the constraint from the world averaged $\pi\pi$ data including the (marginal) LHCb contribution to the measurement of the $\pi^+\pi^-$ asymmetry. The shaded curve is the combined constraint.

During the LHCb era, the precision of the α extraction could thus reach the few degrees level. The theoritical limitations of the analysis such as SU(2)-breaking effects or electroweak Penguin contribution could then be an issue.

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