Measuring CP violating phase in beauty baryon decays

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One of the outstanding problems in physics is to explain the baryon-anti-baryon asymmetry observed in nature. According to the well-known Sakharov criterion for explaining the observed baryon-anti-baryon asymmetry, it is essential that CP violation exist in the baryon sector. However, CP violation has only been observed in mesons decays and is yet to be convincingly demonstrated in baryon decays. A critical test of the standard model (SM) goes beyond just observing CP violation in baryons and requires that it be measured in baryon decays as well, in order to verify that it agrees with the measurement using meson decays. In this letter we propose a new method to measure CP violating phase in b-baryons, using interference arising implicitly due to Bose symmetry considerations of the decaying amplitudes.

The proposal to observe CP violation in Σ-baryon decays [1] was first made by Okubo in 1957, much before the first observation of CP violation in 1964 by Fitch and Cronin using neutral K-mesons. CP violation has since been observed in B-meson and D-mesons as well. CP violating phases have been measured accurately in $B-$meson decays and the measurements are found consistent within the standard model (SM) and in agreement the Kobayashi-Maskawa hypothesis.

One of the well-known Sakharov conditions [2, 3] to explain baryon-anti-baryon asymmetry in the universe, is the existence of CP violation. The observation of CP -violation in baryon decays is thus of great interest as it would provide a direct probe of matter-antimatter asymmetry or the dominance of baryon over anti-baryon observed in the universe. However, CP violation has only been observed in mesons decays and is yet to be convincingly demonstrated [4–13] in baryon decays. It is well-known that the largest weak phases within the SM appear in $b \rightarrow u$ and $t \rightarrow d$ transitions. It is thus obvious that it would be easiest to observe CP violation in b-baryons and one must explore the weak decays of the anti-triplet ($\bar{3}$) beauty baryons.

While there is no reason to expect a disagreement between CP violating phases measured using baryons and that using mesons, within the SM, it nevertheless remains imperative, that a clean measurement of the weak phase also be performed in baryons decays. A comparison of the measurements of CP violation in meson and baryon decays would provide a critical probe of physics beyond the SM. Unfortunately, measurement of CP violation in baryon decays is not straight forward. It is well-known that for CP violation to be observed the amplitude must have two contributions with both having different strong phases and weak phases. However, in order to *measure CP violating phase* using the decay(s) of any particle(s) one must satisfy certain further conditions. One of the critical requirements to measure any phase is that

amplitudes interfere. In the case of neutral B-mesons mixing between particle and antiparticle allows for two distinct amplitudes to interfere, with one amplitude corresponding to direct decay and the other to decay via mixing. This results in the well-known time dependent CP violation. However, baryon number conservation forbids oscillations between baryons and anti-baryons disallowing such time dependent mixing and consequent interference of two amplitudes. It is also essential that at least one of the decay amplitudes be re-parametrization invariant [14, 15] such that the CP violating phase to be measured can be uniquely defined. Inability to satisfy this condition results in fewer independent observables than necessary to measure the weak phase. The methods to measure the phase β and α without approximations, in B-mesons satisfy all these conditions.

Interestingly, the phase γ can be measured, without the need for meson mixing. Interference of two decay amplitudes arises from decay to the same final state via intermediate D^0 and $\bar{D}^0$ decays. The only proposal [16] to measure weak phase using baryons is a straightforward extension of this method used in mesons, to achieve interference of two amplitudes. Unfortunately, the b-quark decay of the Λ_b baryons results in only one final state quarks of the four-quark weak decay vertex to be part of the final state baryon, the other two quark-antiquark are part of the neutral D meson. Therefore, the measurement may not necessarily be considered as a measurement of CP violation in baryons. A proposal to measure CP violating weak phase in baryon decays that is not a straightforward extension of the approach used in meson decays and one that *relies on processes specific to baryons* is still missing.

In this letter we propose a new approach to measure CP violating weak phase in baryon decays using interference arising due to Bose symmetry considerations of the decaying amplitudes. We start by exploring the weak decays of the anti-triplet $\bar{3}$ beauty baryons which

have been studied earlier in Ref. [17, 18] and where large *CP* violation may be expected. As mentioned earlier for weak-phases to be measurable, the additional criterion of re-parametrization invariance must also hold. This re-parametrization condition is severely restrictive for the weak decay of $\bar{3}$ *b*-baryon and we find that even when the interference criterion due to Bose symmetry holds, measurement of the weak phase is not possible in most cases since re-parametrization invariance of the amplitude does not hold. Considering all the weak decay modes of the $\bar{3}$ *b*-baryons we find one mode namely, $\Xi_b \rightarrow \Sigma'(1385)\pi$, where it is possible to measure the *CP* violating weak phase.

We show in detail how the weak phase can be measured using the decay $\Xi_b \rightarrow \Sigma'\pi$, where Σ' is the $J^P = \frac{3}{2}^+$ decuplet baryon resonance corresponding to $\Sigma'(1385)$. We consider the decays $\Xi_b^- \rightarrow \Sigma'^0(1385)\pi^-$ and $\Xi_b^- \rightarrow \Sigma'^-(1385)\pi^0$ depicted in Fig. 1. Note that Ξ_b^- is an isospin 1/2 state of *bsd* quarks. We will refer to $\Sigma'(1385)$ simply as Σ henceforth. The subsequent strong-decays of the $\Sigma^0 \rightarrow \Lambda^0\pi^0$ and $\Sigma^- \rightarrow \Lambda^0\pi^-$ result in the identical final state $\Xi_b^- \rightarrow \Lambda^0\pi^-\pi^0$ for both the decay modes. The $\Lambda^0\pi^-\pi^0$ Dalitz plot would depict both these decays and have special properties under exchange of the two-pions. The interference between these two modes would arise implicitly from Bose symmetry correlations even though the two decay modes do not effectively interfere on the Dalitz plot. The $\pi^-\pi^0$ can either be in a $|1,-1\rangle$ or $|2,-1\rangle$ isospin state. Since, the two π-bosons are identical under isospin their total wave-function must be symmetric. This necessitates that the two pions in the odd isospin state $|1,-1\rangle$ must be anti-symmetric under spatial exchange, whereas, the two pions of even isospin state $|2,-1\rangle$ must be symmetric under spatial exchange. The Λ^0 is an isospin $|0,0\rangle$ state, hence, the combined isospin of the final $\Lambda^0\pi^-\pi^0$ state must be identical to the isospin of the two pion state, which can either be a $|2,-1\rangle$ or $|1,-1\rangle$. Isolating the $\pi^-\pi^0$ symmetric state which has isospin $|2,-1\rangle$, would thus be equivalent to isolating the $\Delta I = 3/2$ changing contribution to the decay, which cannot arise from the penguin diagram and must have a pure $b \rightarrow u$ weak phase.

Unlike, the previous proposal to measure γ in Λ_b decay, our approach ensures that all four quarks of the weak decay vertex are part of the initial and final state baryons, in at least one the contributing amplitudes. The other contributing amplitude also has a minimum of three quarks of the weak decay vertex that are part of the initial or final state baryons. The *CP* violating weak phase measured using *b*-baryons with in our approach is free from any hadronic uncertainty and relies on reliable theoretical inputs such as isospin and vanishingly small electro-weak penguin contributions in $\Delta S = 0$ $b \rightarrow d$ decays.

We consider the decay in the Gottfried-Jackson frame with Ξ_b moving in the $+\hat{z}$ axis, with the two pions going
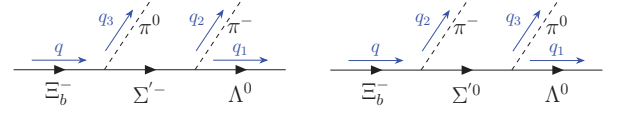

FIG. 1. Feynman diagrams contributing to the quasi two body decay $\Xi_b^-(q) \rightarrow \Lambda^0(q_1)\pi^-(q_2)\pi^0(q_3)$ via the $J^P = \frac{3}{2}^+$, $\Sigma'(1385)$ baryon resonance.

back to back with the $\pi^-(q_2)$ at an angle θ to the $\Lambda^0(q_1)$. In this frame (see Fig. 2) $\vec{q_2} + \vec{q_3} = 0$. We define $s \equiv (q_2 + q_3)^2 = (q - q_1)^2$, $t \equiv (q_1 + q_3)^2 = (q - q_2)^2$ and $u \equiv (q_1 + q_2)^2 = (q - q_3)^2$. t and u can be written as

$$t = x + y\cos\theta \tag{1}$$
$$u = x - y\cos\theta \tag{2}$$

where

$$x = \frac{M^2 + m_\Lambda^2 + 2m_\pi^2 - s}{2} \tag{3}$$

$$y = \frac{\sqrt{s - 4m_\pi^2}}{2\sqrt{s}} \lambda^{1/2}(M^2, m_\Lambda^2, s), \tag{4}$$

and $\lambda(M^2, m_\Lambda^2, s) = (M^4 + m_\Lambda^4 + s^2 - 2M^2m_\Lambda^2 - 2M^2s - 2m_\Lambda^2s)$. M is the mass of the Ξ_b baryon, m_Λ is the mass of the Λ^0 and m_π is the mass of the pions.

The matrix element for the weak-decay $\Xi_b^- \rightarrow \Sigma^{(-,0)}\pi^{(0,-)}$ is given by

$$\mathcal{M}(\Xi_b \rightarrow \Sigma\pi) = -iq_\mu^\pi \bar{u}_\Sigma^\mu(a + b\gamma_5)u_{\Xi_b}, \tag{5}$$

where, u_Σ^μ is the Rarita-Schwinger spinor for the spin-$3/2$ decuplet and hence a Lorentz index, q_μ^π is the momentum of the π, and u_{Ξ_b} is the spinor of the Ξ_b. The two coefficients a and b depend on the CKM elements and flavor structure specific to the decay mode. It may be noted that a and b are related to the P and D wave decay amplitudes respectively. The Σ baryon subsequently decays via strong-interaction to a Λ^0-baryon and a pion with the matrix element for the decay being given by,

$$\mathcal{M}(\Sigma \rightarrow \Lambda^0\pi) = ig_{\Sigma\Lambda\pi}q_\mu^\pi \bar{u}_\Lambda u_\Sigma^\mu, \tag{6}$$

where, $g_{\Sigma\Lambda\pi}$ is the invariant coupling for the decay. The decay for the conjugate modes, $\Xi_b^+ \rightarrow \Sigma^{(+,0)}\pi^{(0,+)}$ can be
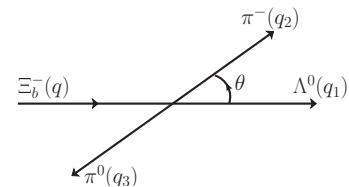

FIG. 2. Jackson frame in which $\Xi_b^-(q)$ decays to three bodies $\Lambda^0(q_1)$, $\pi^-(q_2)$ and $\pi^0(q_3)$.

described analogously except that it would be described by new coefficients $\bar{a}$ and $\bar{b}$ that are related to a and b by reversing the respective weak phases. The propagator of the $\Sigma(1385)$ baryon has the form [19]

$$\Pi^{\mu\nu}(k) = -\frac{(\slashed{k}+m)}{(k^2-m^2+im\Gamma)}\Big(g^{\mu\nu} - \frac{2}{3}\frac{k^\mu k^\nu}{m^2}$$
$$-\frac{1}{3}\gamma^\mu\gamma^\nu + \frac{1}{3m}(k^\nu\gamma^\mu - k^\mu\gamma^\nu)\Big), \quad (7)$$

corresponding to that of a spin-$3/2$ fermion with the four-momentum k, mass m and width Γ.

The matrix element for the two-step decay $\Xi_b^-(q) \to \Sigma^-[\to \Lambda^0(q_1)\pi^-(q_2)]\pi^0(q_3)$ is given by

$$\mathcal{M}_u = \mathcal{M}\Big(\Xi_b^-(q) \to \Sigma^-\big[\to \Lambda^0(q_1)\pi^-(q_2)\big]\pi^0(q_3)\Big) =$$
$$g_{\Sigma\Lambda\pi}\bar{u}(q_1)(a^- + b^-\gamma_5)\Pi^{\mu\nu}(q_{12})u(q)\,q_3^\mu q_2^\nu, \quad (8)$$

where $q_{ij} = q_i + q_j$ and m is the mass of $\Sigma(1385)$ resonance. Similarly, the two-step decay $\Xi_b^-(q) \to \Sigma^0[\to \Lambda^0(q_1)\pi^0(q_3)]\pi^-(q_2)$ is given by

$$\mathcal{M}_t = \mathcal{M}\Big(\Xi_b^-(q) \to \Sigma^0\big[\to \Lambda^0(q_1)\pi^0(q_3)\big]\pi^-(q_2)\Big) =$$
$$g_{\Sigma\Lambda\pi}\bar{u}(q_1)(a^0 + b^0\gamma_5)\Pi^{\mu\nu}(q_{13})u(q)\,q_2^\mu q_3^\nu. \quad (9)$$

The matrix elements $\mathcal{M}_u$ and $\mathcal{M}_t$ are related by isospin. The sum of the matrix element of the two contributing modes must be completely Bose symmetric under the exchange of the two pions and may be written in an explicitly symmetric form as

$$\mathcal{M}\Big(\Xi_b^- \to \Sigma[\Lambda\pi]\pi\Big) = g_{\Sigma\Lambda\pi}\bar{u}(q_1)\Big[(A_e + B_e\gamma_5)$$
$$\big(\Pi^{\nu\mu}(q_{12}) + \Pi^{\mu\nu}(q_{13})\big) + (A_o + B_o\gamma_5)$$
$$\big(\Pi^{\nu\mu}(q_{12}) - \Pi^{\mu\nu}(q_{13})\big)\Big]u(q)q_2^\mu q_3^\nu \quad (10)$$

where A_e, B_e and A_o, B_o are the even and odd parts of the amplitude under the exchange of the two pions and are given by
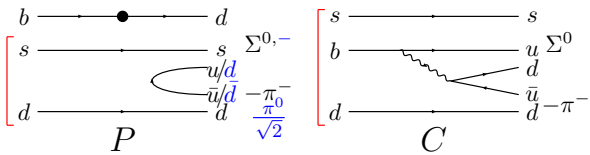
$$A_{e,o} = (a^- \pm a^0)/2$$

FIG. 3. Topological diagrams contributing to decay $\Xi_b^- \to \Sigma\pi$ decays. The blob on the $b \to d$ transition in the diagram on the left corresponds to the $b \to d$ penguin. The red line straddling between the s and d quarks of the initial Ξ_b baryon indicates anti-symmetry of quarks in the initial $\bar{3}$ state. The symmetric wave-function of the $J^P = \frac{3}{2}$ nucleon Σ allows only the above topologies.

$$B_{e,o} = (b^- \pm b^0)/2. \quad (11)$$

The coefficients a^0, a^+, b^0 and b^+ are related (see Fig. 3) to the topological amplitudes [17, 18], which after a phase rotation of $e^{i\gamma}$ may be written as follows

$$a^0 = -\tfrac{1}{2\sqrt{3}}\big(C^\mathsf{P} - P^\mathsf{P}e^{-i\alpha}\big),$$
$$a^- = -\tfrac{1}{2\sqrt{3}}P^\mathsf{P}e^{-i\alpha}$$
$$b^0 = -\tfrac{1}{2\sqrt{3}}\big(C^\mathsf{D} - P^\mathsf{D}e^{-i\alpha}\big),$$
$$b^- = -\tfrac{1}{2\sqrt{3}}P^\mathsf{D}e^{-i\alpha}, \quad (12)$$

where C^P, P^P are related to the topological amplitudes contributing to the P wave with analogous definitions for the D wave. Note that the phase rotation of $e^{i\gamma}$ does not alter any physical observable. Hence,

$$A_e = -\tfrac{1}{4\sqrt{3}}C^\mathsf{P} \equiv x_\mathsf{P}$$
$$A_o = \tfrac{1}{4\sqrt{3}}C^\mathsf{P} - \tfrac{1}{2\sqrt{3}}P^\mathsf{P}e^{-i\alpha} \equiv -x_\mathsf{P} + z_\mathsf{P}e^{-i\alpha}e^{i\delta_\mathsf{P}}$$
$$B_e = -\tfrac{1}{4\sqrt{3}}C^\mathsf{D} \equiv x_\mathsf{D}$$
$$B_o = \tfrac{1}{4\sqrt{3}}C^\mathsf{D} - \tfrac{1}{2\sqrt{3}}P^\mathsf{D}e^{-i\alpha} \equiv -x_\mathsf{D} + z_\mathsf{D}e^{-i\alpha}e^{i\delta_\mathsf{P}}, \quad (13)$$

where, $\delta_{(\mathsf{P},\mathsf{D})}$, is the strong phase difference between the penguin and the tree contribution for the P and D waves respectively.

The decay rate for the 3-body final state $\Lambda^0\pi^-\pi^0$ will depend on the Mandelstam variables t and u. This can easily be cast in terms of s and $\cos\theta$ using Eqs. (1), (2), (3) and (4). It is obvious to conclude from Fig. 2 that under the exchange of the two pions, $\theta \leftrightarrow \pi - \theta$. The odd (even) part of the amplitude under the exchange of two pions must therefore be proportional to odd (even) powers of $\cos\theta$. Since, Bose correlations are clearly depicted in plots involving $\hat{s} = s/M^2$ and θ, we refer to such plots as correlation-plots. In Fig 4, we show sample correlation-plots for $P^\mathsf{P}/C^\mathsf{P} = 0.6$, $\delta_\mathsf{P} = \pi/3$ and $\alpha = \pi/2$. Plotted are the logarithmic values of the P-wave rates with an arbitrary scale that depends on the choice of $P^\mathsf{P}/C^\mathsf{P}$ and the P-wave rate for the decay $\Xi_b^- \to \Sigma^-\pi^0$. In our calculations we have used $M = 5797$ MeV, $m = 1385$ MeV, $\Gamma = 38$ MeV, $m_\Lambda = 1115$ MeV and $m_\pi = 135$ MeV. The effects of CP violation can be observed as differences between the two plots corresponding to mode and conjugate mode. The effects of Bose correlation are also obvious. The decay $\Xi^- \to \Sigma^-\pi^0$ arises due to pure penguin (See Eqns. (8) and (12)). If there are no Bose correlation effects contributing to the decays, the decays of $\Xi_b^- \to \Sigma^-\pi^0$ and $\bar{\Xi}_b^+ \to \bar{\Sigma}^+\pi^0$ seen on the left of the two plots in Fig. 4 would look identical. However, the Dalitz plots show a marked difference between $\Xi_b^- \to \Sigma^-\pi^0$ and $\bar{\Xi}_b^+ \to \bar{\Sigma}^+\pi^0$ on their respective Dalitz plot, *providing a smoking gun evidence of large Bose correlation effects.* This observation is fundamental to our new approach to measure CP violation. We will show next that *the observed distributions along*
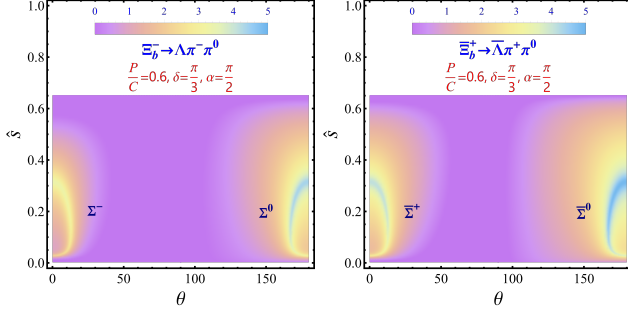
FIG. 4.   Sample correlation-plots for the P-wave contributions for the specified choice of parameters. Plotted are the logarithmic value of the P-wave rates with an arbitrary scale that depends on C. Explicit dependence of the some of the parameters on P-wave is suppressed for simplicity. The contributing intermediate Σ resonances are depicted on the plots. The differences between the two plots arise only due CP violation effects. Similar plots would arise from the D-wave contributions.

these narrow resonances provide enough information to extract all theoretical parameters from experimental data, including the P and D wave contributions respectively.

The numerator of the decay rate N_Γ for both the mode and conjugate mode are worked out to have the complicated form:

$$N_\Gamma = \sum_{n=0}^{4} c_n(\hat{s})\cos 2n\theta + \sum_{n=0}^{3} d_n(\hat{s})\cos(2n+1)\theta, \quad (14)$$

where, all masses and momenta are normalized to M, the Ξ_b mass for simplicity, and

$$c_n(s) = \left(f_n^{(1)}(\hat{s})|A_e|^2 + f_n^{(2)}(\hat{s})|B_e|^2\right.$$
$$\left. + f_n^{(3)}(\hat{s})|A_o|^2 + f_n^{(4)}(\hat{s})|B_o|^2\right) \quad (15)$$
$$d_n(\hat{s}) = \left(g_n^{(1)}(\hat{s})\mathrm{Re}(A_e A_o^*) + g_n^{(2)}(\hat{s})\mathrm{Re}(B_e B_o^*)\right.$$
$$\left. + g_n^{(3)}(\hat{s})\mathrm{Im}(A_e A_o^*) + g_n^{(4)}(\hat{s})\mathrm{Im}(B_e B_o^*)\right). \quad (16)$$

The coefficients $f_n^{(i)}$ and $g_n^{(i)}$ are functions of $\hat{s}$ and are easily computed in terms of kinematic factors. For a given choice of $\hat{s}$, $f_n^{(i)}$ and $g_n^{(i)}$ are just numbers. We henceforth drop explicit dependence on $\hat{s}$, since our solutions are valid for all $\hat{s}$. The numerator of the decay rate given in Eq. (14) can be fitted as a function of θ to obtain coefficients c_n and d_n. Having obtained c_0, c_1, c_2 and c_3 it is obvious that $|A_e|^2$, $|A_o|^2$, $|B_e|^2$ and $|B_o|^2$ can easily be obtained. Similarly, $\mathrm{Re}(A_e A_o^*)$, $\mathrm{Re}(B_e B_o^*)$, $\mathrm{Im}(A_e A_o^*)$ and $\mathrm{Im}(B_e B_o^*)$ can be solved using d_0, d_1, d_2 and d_3. In order to solve for the amplitudes and their interference, one must have a minimum of 8-bins in θ and $\hat{s}$ involving both the resonances contributing to the process. Experimental procedure used in an actual analysis can be more refined. An identical analysis of the decay rate for the conjugate process would enable us to solve for $|\overline{A}_e|^2$, $|\overline{A}_o|^2$, $|\overline{B}_e|^2$, $|\overline{B}_o|^2$ and $\mathrm{Re}(\overline{A}_e \overline{A}_o^*)$,

$\mathrm{Re}(\overline{B}_e \overline{B}_o^*)$, $\mathrm{Im}(\overline{A}_e \overline{A}_o^*)$ and $\mathrm{Im}(\overline{B}_e \overline{B}_o^*)$. Having solved the values of these amplitudes and their interference, our aim is to solve for the weak phase α and the amplitudes $x_{\mathsf{P,D}}$ and $z_{\mathsf{P,D}}$ defined in Eq. (13) and the strong phases $\delta_{\mathsf{P,D}}$. In order to obtain the solutions for the P-wave parameters we define new intermediate observables r_i:

$$r_0 = |A_e|^2 = |\overline{A}_e|^2 = x_{\mathsf{P}}^2$$
$$r_1 = |A_o|^2 + |\overline{A}_o|^2 = 2x_{\mathsf{P}}^2 + 2z_{\mathsf{P}}^2 - 4x_{\mathsf{P}}z_{\mathsf{P}}\cos\delta_{\mathsf{P}}\cos\alpha$$
$$r_2 = |A_o|^2 - |\overline{A}_o|^2 = -4\,x_{\mathsf{P}}z_{\mathsf{P}}\sin\delta_{\mathsf{P}}\sin\alpha$$
$$r_3 = \mathrm{Re}(A_e A_o^* - \overline{A}_e \overline{A}_o^*) = 2x_{\mathsf{P}}z_{\mathsf{P}}\sin\delta_{\mathsf{P}}\sin\alpha$$
$$r_4 = \mathrm{Im}(A_e A_o^* - \overline{A}_e \overline{A}_o^*) = 2x_{\mathsf{P}}z_{\mathsf{P}}\cos\delta_{\mathsf{P}}\sin\alpha$$
$$r_5 = \mathrm{Re}(A_e A_o^* + \overline{A}_e \overline{A}_o^*) = -2x_{\mathsf{P}}^2 + 2x_{\mathsf{P}}z_{\mathsf{P}}\cos\delta_{\mathsf{P}}\cos\alpha$$
$$r_6 = \mathrm{Im}(A_e A_o^* + \overline{A}_e \overline{A}_o^*) = -2x_{\mathsf{P}}z_{\mathsf{P}}\sin\delta_{\mathsf{P}}\cos\alpha. \quad (17)$$

We find the solutions in terms of r_i to be,

$$x_{\mathsf{P}}^2 = r_0$$
$$\tan\delta_{\mathsf{P}} = r_3/r_4$$
$$\tan\alpha = -r_3/r_6 = r_2/(2r_6)$$
$$z_{\mathsf{P}}^2 = \frac{(r_3^2 + r_4^2)(r_3^2 + r_6^2)}{4r_0 r_3^2} \quad (18)$$

Since, all the r_i are not independent, we find the relations:

$$r_3^2 + r_4^2 + r_5^2 + r_6^2 = 2r_0 r_1$$
$$r_3 r_5 + r_4 r_6 = r_0 r_2 \quad (19)$$
$$r_3 = -2r_2 \quad (20)$$

The solutions for the D-wave parameters can be obtained similarly. It is noted that both the P and D wave contributions must result in the measurement of the same weak phase α. We hence have two independent measurements of α corresponding to the two partial waves.

The observed Dalitz plot must have a more complicated structure with several resonances, and one may wonder if our approach to measure the weak phase would be possible. The contribution from heavier Σ states have a similar decay dynamics with the same weak phase α, but the relevant amplitudes and strong phases would differ. While these resonances are not a cause for concern suitable binning cuts would easily remove their contributions without losing relevant signal sample. Only the interference with the decay mode $\Xi_b^- \to \Lambda^0 \rho^- \to \Lambda^0 \pi^- \pi^0$, and modes involving heavier ρ-like resonances, instead of ρ, need a closer look. It is interesting to note that $\Xi_b^- \to \Lambda^0 \rho^-$ has a different $\hat{s}$ dependence in the overlap region and contributes only to the odd part of the amplitude. Once data is available in several more $\hat{s}$ bins, such interference effects can easily be isolated using the Dalitz distribution [20]. One does not need to impose cuts to remove the $\Xi_b^- \to \Lambda^0 \rho^-$ contributions.

We have demonstrated that Bose correlations arise from two intermediate decays $\Xi_b^- \to \Sigma^0 \pi^-$ and $\Xi_b^- \to \Sigma^- \pi^0$ contributing to the final state $\Xi_b^- \to \Lambda^0 \pi^- \pi^0$. Similar Bose correlations arise in the decay to conjugate final state $\bar{\Xi}_b^+ \to \bar{\Lambda}^0 \pi^+ \pi^0$. We explicitly show that the weak phase α can be measured using both even and odd contributions to the amplitudes under pion exchange and comparing the mode and conjugate-mode correlation-plots. Naively, one may be tempted to incorrectly assume that Bose correlation effects are too small to be observed. However, we have shown numerically and explicitly that such correlations are sizable providing an unequivocal approach to measuring CP violation in baryon decays. *The significant difference between the pure penguin decays of $\Xi_b^- \to \Sigma^- \pi^0$ and $\bar{\Xi}_b^+ \to \bar{\Sigma}^+ \pi^0$ on their respective Dalitz plot is a smoking gun evidence of large Bose correlation effects.* Our new approach to measure CP violation critically depends on such Bose correlations. Interestingly, inexplicably large CP violation effects are observed in the Dalitz plot of three body B-meson decays; we conjecture that these arise due to Bose correlations on the Dalitz plot.

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