Measuring CP violating phase in beauty baryon decays

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THE UNIVERSITY of MISSISSIPPI

Dedicated in memory of Sheldon Stone.

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Work in collaboration with

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Phys. Rev. Lett. 128, 081803

Presented on behalf of Shibasis Roy

Our paper & talk is dedicated to the memory of Sheldon Stone.

He went through the draft of our draft even while he was in hospital and provided useful comments; such was his love for physics. His forthright attitude and recognition of good physics won him support from many physicists. His presence will forever be missed.

Why measure CP violation in Baryons?

- *One of the outstanding problem in physics is to explain the baryon-anti-baryon asymmetry on nature which requires CP violation.*
- *For Sakharov conditions to hold CP violation must be observed in Baryons at least within the SM. Even though the earliest proposal to observe CP violation was made in 1957 by Okubo for Baryons, no CP violation seen in Baryons so far.*
- *We must also measure weak phase(s) in Baryon decays and compare it with that measured in mesons to test SM. Any disagreement in the two measurements would point to New Physics.*
- *With in SM the largest CP violation should be expected in the anti-triplet $\overline{3}$ B-Baryons.*
- *Clean measurement of weak phases has only been possible in B mesons but not in K or D mesons. No reason clean measurements will necessarily be possible in Baryons.*

Measurement of CP violating phase in Baryon decays is not quite simple. Many hurdles

In order to measure any CP violating one must satisfy certain further conditions.

- *Well-known that for CP violation to be observed the amplitude must have two contributions with both having different strong phases and weak phases.* ***Interference must***

  In neutral B-mesons mixing between particle and antiparticle allows for two distinct amplitudes to interfere.

  $$B^0 \longrightarrow f, \qquad B^0 \rightarrow \bar{B}^0 \rightarrow f$$

  Time dependent mixing

  Baryon number conservation forbids oscillations between baryons and anti-baryons disallowing such interference of two amplitudes

- *At least one of the decay amplitudes be re-parametrization invariant such that the CP violating phase to be measured can be uniquely defined*

David London, Nita Sinha and R. S., Phys. Rev. D60, 074020 (1999)
M. Imbeault, D. London, C. Sharma, N. Sinha and R. S., Phys. Lett. B 653, 254 (2007)

The decay $\Xi_b^- \to \Sigma'^0\pi^- / \Sigma'^-\pi^0 \to \Lambda^0\pi^-\pi^0$

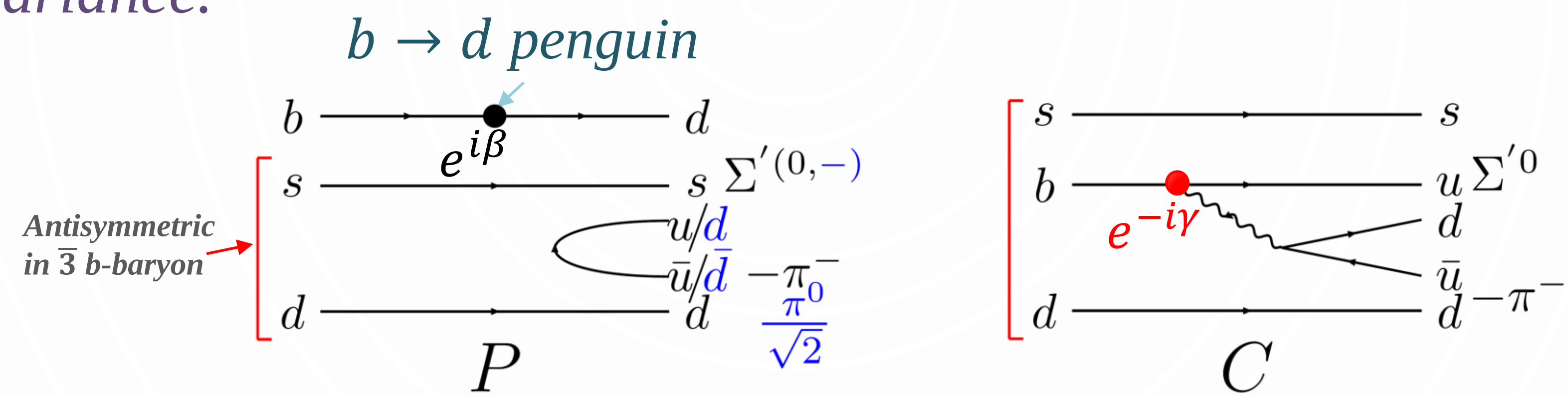
Consider $\Xi_b^- \to \Sigma'^0\pi^- / \Sigma'^-\pi^0$, $\Sigma'(1385)$ *is decuplet* $J^P = \frac{3}{2}^+$

$\Lambda^0\pi^0$ $\qquad$ $\Lambda^0\pi^-$ $\qquad$ Σ' *mass* m, *width* Γ. Σ' *symmetric state.*

Identical final $\Lambda^0\pi^-\pi^0$ *state*

Why this mode?

Found nothing else that works due to re-parametrization invariance.

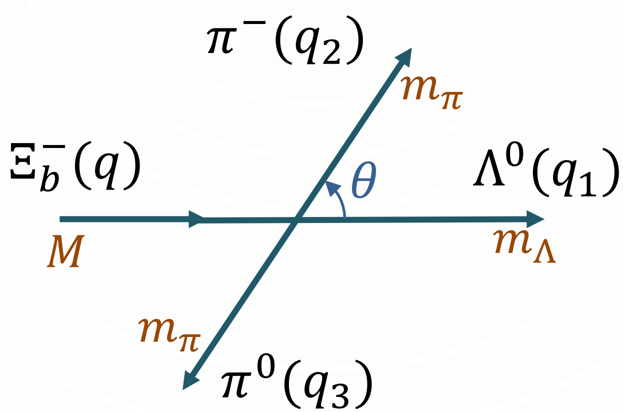


Only penguin diagram P contributes to $\Sigma'^-\pi^0$ *mode, whereas both C (tree) and P diagrams contribute to* $\Sigma'^0\pi^-$*. Due to absence of u-quark in the initial state no exchange (E) diagram exists.*

The CP violating weak phase measured within our approach is based only on experimentally measured observables and hence free from any hadronic uncertainty

Assumptions: reliable theoretical inputs.

1. *Isospin*
2. *vanishingly small electroweak penguin contributions in $\Delta S = 0$, $b \rightarrow d$ transitions.*

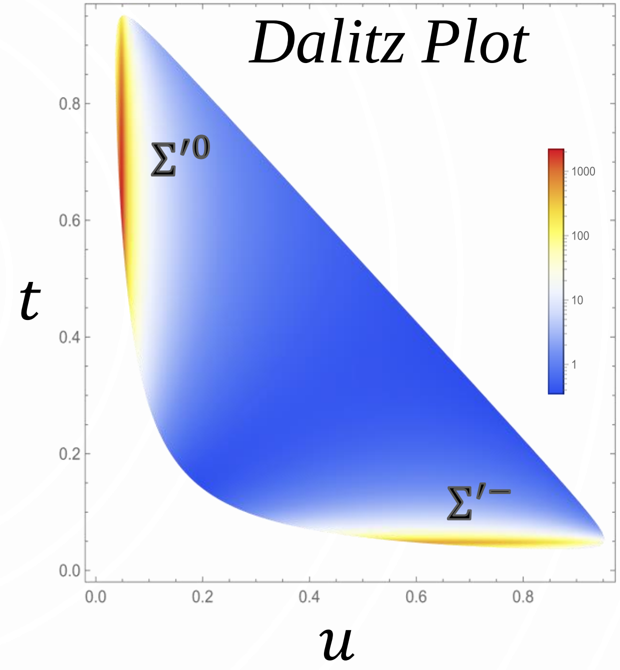


Gottfried-Jackson frame

Dalitz Plot of three body decay

Three body decays are best studied in terms of Mandelstam variables s, t, u *with graphical representation on Dalitz plot*

$$s \equiv (q_2 + q_3)^2 = (q - q_1)^2$$
$$t \equiv (q_1 + q_3)^2 = (q - q_2)^2$$
$$u \equiv (q_1 + q_2)^2 = (q - q_3)^2$$
$$t = x + y\cos\theta$$
$$u = x - y\cos\theta$$
$$x = \frac{M^2 + m_\Lambda^2 + 2\,m_\pi^2 - s}{2}$$
$$y = \frac{\sqrt{s - 4m_\pi^2}}{2\sqrt{s}}\sqrt{\lambda(M^2, m_\Lambda^2, s)}$$



Clearly the Σ' *resonances don't overlap on the Dalitz plot, so why bother at all to consider the strong decay of* Σ'*?*

Implicit Interference due to Bose symmetry

New method to measure CP violating phase, using interference arising implicitly due to Bose symmetry considerations of the decaying amplitudes.

$\pi^-\pi^0$ *either in* $|1,-1\rangle$ *or* $|2,-1\rangle$ *isospin state*

Two pions-bosons are identical bosons under isospin $\Rightarrow$ *total wave function must be symmetric* $\Rightarrow$

- *Odd isospin* $|1,-1\rangle$ *state anti-symmetric under spatial exchange*
- *Even isospin* $|2,-1\rangle$ *state symmetric under spatial exchange.*

Spatial exchange: $t \leftrightarrow u$ *or* $\theta \leftrightarrow \pi - \theta$ *or* $\pi^0 \leftrightarrow \pi^-$

Ξ_b^- is isospin $\frac{1}{2} \Rightarrow$ *isolating symmetric* $\pi^-\pi^0$ *state* $\equiv$ *isolating* $\Delta I = \frac{3}{2}$ *contribution which cannot arise from penguin diagrams*

Bose symmetry considerations require that the two decays not be considered in isolation but together in terms of even and odd contributions to isolate isospin contributions.

The details…

$$\mathcal{M}(\Xi_b \to \Sigma'\pi) = -i\, q_\mu^\pi\, \bar{u}_{\Sigma'}^\mu (a + b\gamma_5) u_{\Xi_b}$$

a: p-wave $\quad$ b: d-wave

$$\mathcal{M}(\Sigma' \to \Lambda\pi) = i g_{\Sigma'\Lambda\pi} q_\mu^\pi\, \bar{u}_\Lambda u_\Sigma^\mu$$

$\bar{u}_{\Sigma'}^\mu$ Rarita-Schwinger spinor , $g_{\Sigma'\Lambda\pi}$ invariant coupling

The propagator of $\Sigma'(1385)$ with mass m and width Γ is

$$\Pi^{\mu\nu}(k) = -\frac{(\not{k} + m)}{(k^2 - m^2 + im\Gamma)}\left(g^{\mu\nu} - \frac{2}{3}\frac{k^\mu k^\nu}{m^2} - \frac{1}{3}\gamma^\mu\gamma^\nu + \frac{1}{3m}(k^\nu\gamma^\mu - k^\mu\gamma^\nu)\right)$$

Matrix element $\mathcal{M}_u$ for decay $\Xi_b^-(q) \to \Sigma'^-[\to \Lambda^0(q_1)\pi^-(q_2)]\pi^0(q_3)$

$$\mathcal{M}_u = g_{\Sigma'\Lambda\pi}\, \bar{u}(q_1)(a^- + b^-\gamma_5)\Pi^{\mu\nu}(q_{12})u(q)q_3^\mu q_2^\nu$$

Matrix element $\mathcal{M}_t$ for decay $\Xi_b^-(q) \to \Sigma'^0[\to \Lambda^0(q_1)\pi^0(q_3)]\pi^-(q_2)$

$$\mathcal{M}_t = g_{\Sigma'\Lambda\pi}\, \bar{u}(q_1)(a^0 + b^0\gamma_5)\Pi^{\mu\nu}(q_{13})u(q)q_2^\mu q_3^\nu$$

p-wave and d-wave amplitudes in terms of the topological amplitudes C and P

$$a^0 = \tfrac{-1}{2\sqrt{3}}\left(C_p - P_p e^{-i\alpha}\right) \qquad a^- = \tfrac{-1}{2\sqrt{3}} P_p e^{-i\alpha}$$

$$b^0 = \tfrac{-1}{2\sqrt{3}}\left(C_d - P_d e^{-i\alpha}\right) \qquad b^- = \tfrac{-1}{2\sqrt{3}} P_p e^{-i\alpha}$$

after phase rotation of $e^{-i\gamma}$

Bose symmetric combination of matrix element written as

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

$$A_{e,o} = \left(a^- \pm a^0\right)/2$$
$$B_{e,o} = \left(b^- \pm b^0\right)/2$$

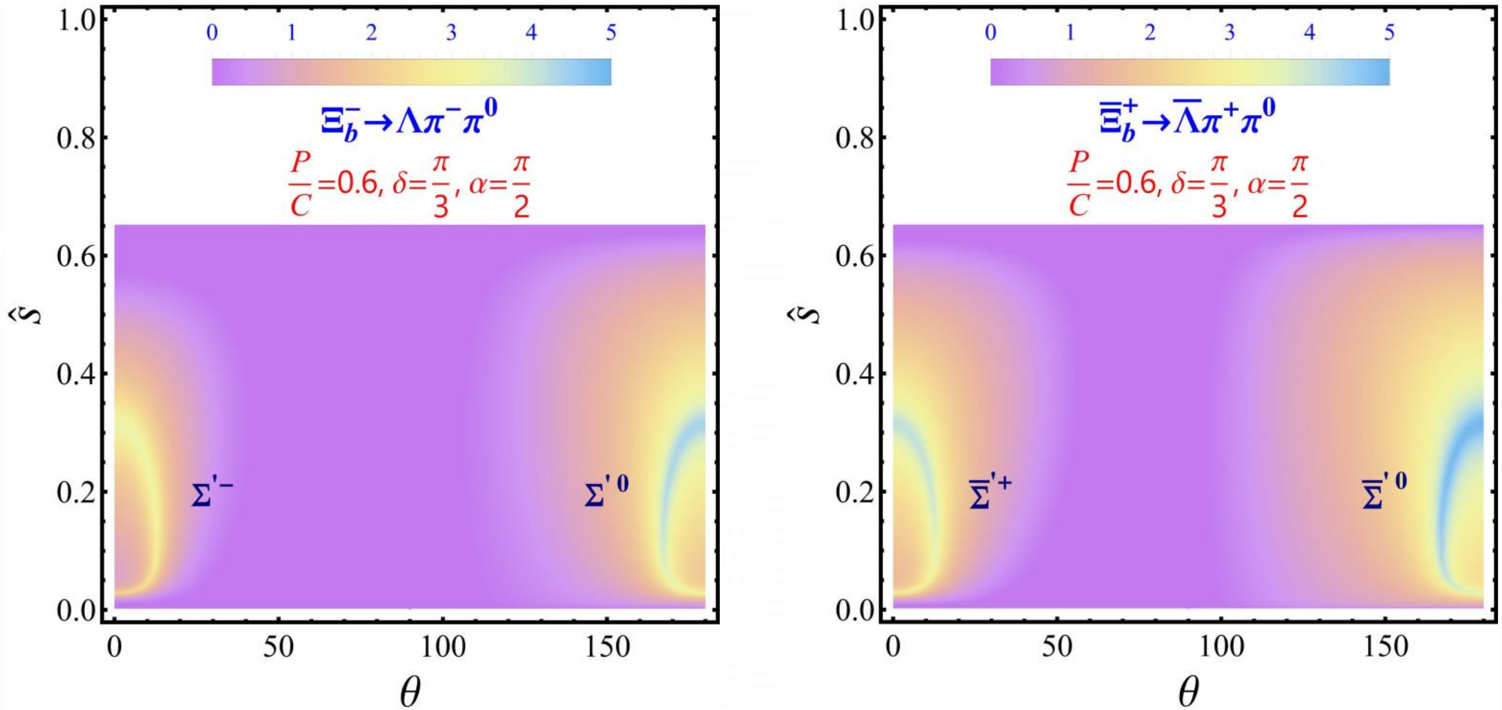
$$A_e = \frac{-1}{4\sqrt{3}}C_p \equiv x_p$$
$$A_o = \frac{1}{4\sqrt{3}}C_p - \frac{1}{2\sqrt{3}}P_p e^{-i\alpha} \equiv -x_p + z_d e^{-i\alpha} e^{i\delta_P}$$
$$B_e = \frac{-1}{4\sqrt{3}}C_d \equiv x_d$$
$$B_o = \frac{1}{4\sqrt{3}}C_d - \frac{1}{2\sqrt{3}}P_d e^{-i\alpha} \equiv -x_d + z_d e^{-i\alpha} e^{i\delta_d}$$

strong phases

x_p, z_p *new variables defined for simplicity*

Shown that it is possible to determine the complex amplitudes A_e, A_o, B_e, B_o using the Dalitz plot distribution. Hence, solve for α and all other theoretical parameters.

Correlation plots −Dalitz in terms of $\hat{s}$ and θ



Logarithmic values of the P−wave rates (arbitrary scale), $\hat{s} = s/M^2$.

Effects of CP violation indicated by differences between the two plots corresponding to mode and conjugate mode.

Differences between $\Xi_b^- \to \Sigma'^- \pi^0$ and $\bar{\Xi}_b^+ \to \bar{\Sigma}'^+ \pi^0$ smoking gun evidence of large Bose correlation effects. No CP violation in this mode!

Bose correlations play a fundamental role in our new approach to measure CP.

Conclusions…

- *Demonstrated that Bose correlations arise from two intermediate decays $\Xi_b^- \to \Sigma^0\pi^-$ and $\Xi_b^- \to \Sigma^-\pi^0$ contributing to final state $\Xi_b^- \to \Lambda^0\pi^-\pi^0$*
- *Similar correlation arise in $\bar{\Xi}_b^+ \to \bar{\Lambda}^0\pi^+\pi^0$*
- *Weak phase α can be measured using*
  - *'even' and 'odd' contributions to the amplitudes under pion exchange*
  - *Comparing mode and conjugate mode correlation plots.*
- *The $\Delta S = -1$ transition $\Xi_b^- \to \Xi'\pi$ can be used to measure the phase γ in a similar fashion.*
  - *Unfortunately, $b \to s$ modes receive contribution from the electroweak penguin resulting in pollution of the measured phase. However, the pollution can be estimated using a theoretical relation between the C and the P_{EW}. Upcoming paper…*
- *Idea can be applied to Charm baryon decays as well.*

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Amplitudes from Dalitz-correlation plot

Numerator of decay rate N_Γ, for mode and conjugate mode has the form:

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

all masses and momenta normalized to M,

$$c_n(\hat{s}) = f_n^{(1)}(\hat{s})|A_e|^2 + f_n^{(2)}(\hat{s})|B_e|^2 + f_n^{(3)}(\hat{s})|A_o|^2 + f_n^{(4)}(\hat{s})|B_o|^2$$

$$d_n(\hat{s}) = g_n^{(1)}(\hat{s})\mathrm{Re}(A_e A_o^*) + g_n^{(2)}(\hat{s})\mathrm{Re}(B_e B_o^*) + g_n^{(3)}(\hat{s})\mathrm{Im}(A_e A_o^*) + g_n^{(4)}(\hat{s})\mathrm{Im}(B_e B_o^*)$$

For a given choice of $\hat{s}$, $f_n^{(i)}$ and $g_n^{(i)}$ are just numbers. Drop explicit dependence on $\hat{s}$. Fit as function of θ to solve for

$c_0, c_1, c_2, c_3, d_0, d_1, d_2, d_3 \Rightarrow |A_e|^2, |A_o|^2, |B_e|^2, |B_o|^2, \mathrm{Re}(A_e A_o^*), \mathrm{Re}(B_e B_o^*), \mathrm{Im}(A_e A_o^*), \mathrm{Im}(B_e B_o^*)$.

Minimum data in 8 bins needed.

Identical analysis for conjugate mode to obtain

$|\bar{A}_e|^2, |\bar{A}_o|^2, |\bar{B}_e|^2, |\bar{B}_o|^2$ & $\mathrm{Re}(\bar{A}_e \bar{A}_o^*), \mathrm{Re}(\bar{B}_e \bar{B}_o^*), \mathrm{Im}(\bar{A}_e \bar{A}_o^*), \mathrm{Re}(\bar{B}_e \bar{B}_o^*)$

Solution of amplitudes, strong &weak phase

$$r_0 = |A_e|^2 = |\bar{A}_e| = x_p^2$$

$$r_1 = |A_o|^2 + |\bar{A}_o| = 2x_p^2 + 2z_p^2 - 4x_p z_p \cos\delta_p \cos\alpha$$

$$r_2 = |A_o|^2 - |\bar{A}_o| = -4x_p z_p \sin\delta_p \sin\alpha$$

$$r_3 = \mathrm{Re}\left(A_e A_o^* - \bar{A}_e \bar{A}_o^*\right) = 2x_p z_p \sin\delta_p \sin\alpha$$

$$r_4 = \mathrm{Im}\left(A_e A_o^* - \bar{A}_e \bar{A}_o^*\right) = 2x_p z_p \cos\delta_p \sin\alpha$$

$$r_5 = \mathrm{Re}\left(A_e A_o^* + \bar{A}_e \bar{A}_o^*\right) = -x_p^2 + 2x_p z_p \cos\delta_p \sin\alpha$$

$$r_6 = \mathrm{Im}\left(A_e A_o^* - \bar{A}_e \bar{A}_o^*\right) = -2x_p z_p \sin\delta_p \cos\alpha$$

Solve for all p-wave amplitudes and phases.

$$\boxed{\tan\alpha = -\frac{r_3}{r_6} = \frac{r_2}{2\,r_6}}$$

$$x_p^2 = r_0$$

$$\tan\delta_p = r_3/r_4$$

$$z_p^2 = \frac{(r_3^2 + r_4^2)(r_3^2 + r_6^2)}{4\,r_0 r_3^2}$$

Constraints:

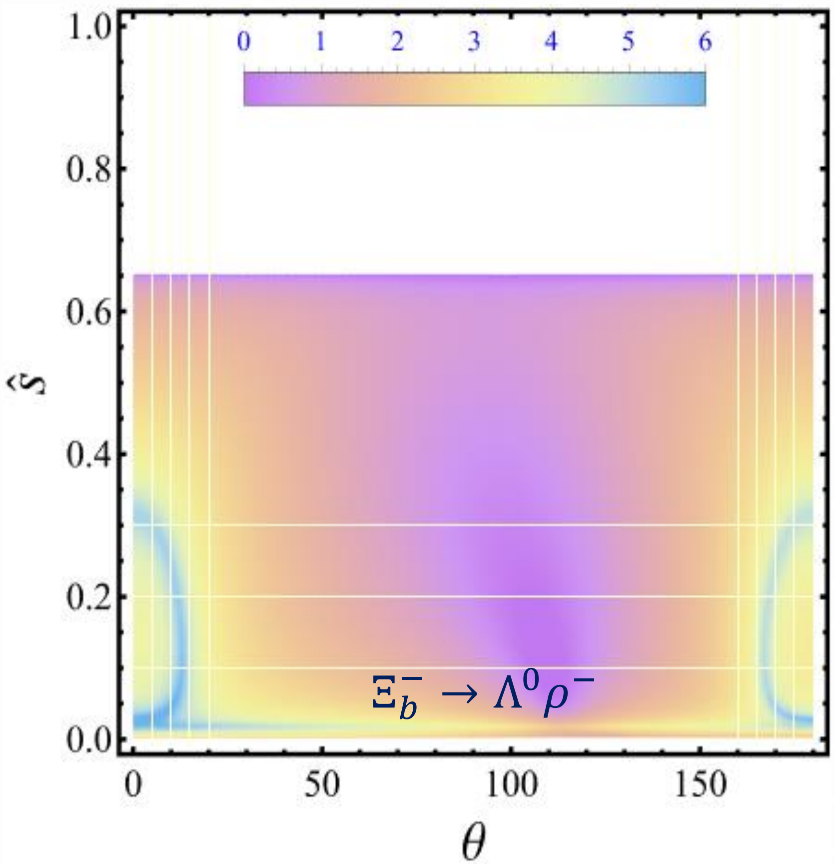
$$r_3^2 + r_4^2 + r_5^2 + r_6^2 = 2\,r_0 r_1$$

$$r_3 r_5 + r_4 r_6 = r_0 r_2$$

$$r_2 = -2\,r_3$$

Identical solutions for d-wave

Complicated Dalitz plot in reality…



The observed Dalitz plot several contributing resonances.

- *Heavier $\Sigma^{(\prime)}$ states have a similar decay dynamics, same weak phase α, but the relevant amplitudes and strong phases would differ. These resonances are not a cause for concern suitable binning cuts required.*
- *Only interference with the decay mode like $\Xi_b^- \to \Lambda^0 \rho^- \to \Lambda^0 \pi^- \pi^0$ need a closer look. Have 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*

Enough information on Dalitz plot to remove pollution from other resonance effects without diluting sample…

Upcoming paper…