Study of charmonium decays to $K^0_S K\pi$ in $B \to (K^0_S K\pi)K$

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Introduction

□ Charmonium decays, such as J/ψ or η_c decays, address relevant questions in the light meson spectroscopy sector where the issues related to the existence of gluonium or molecular states has not been yet solved.

□ One of the still relevant issue is related to the structure of the $K\pi$ S-wave and its resonant composition which has large uncertainties.

□ These uncertainties propagate in significant systematic uncertainties in the recent observation of new exotic states in the high statistics amplitude analyses of heavy flavor decays.

□ In the present analysis we perform new measurements using η_c decays produced in the decay of B^+ mesons.

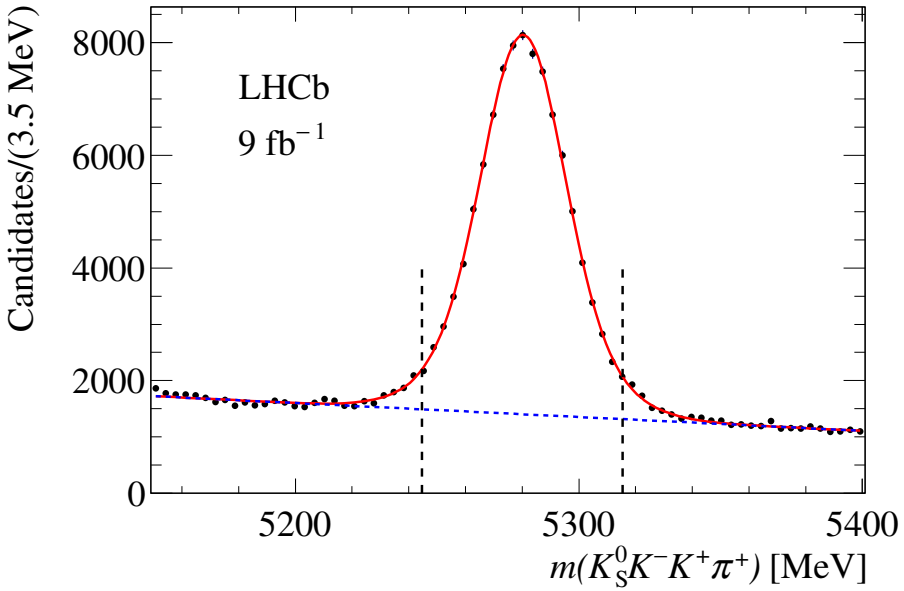
Aaij, R. et.al. [LHCb] Study of charmonium decays to $K^0_S K\pi$ in the $B \to (K^0_S K\pi)K$ channels, Phys. Rev. D ***108****, no.3, 032010 (2023) [arXiv:2304.14891 [hep-ex]].*

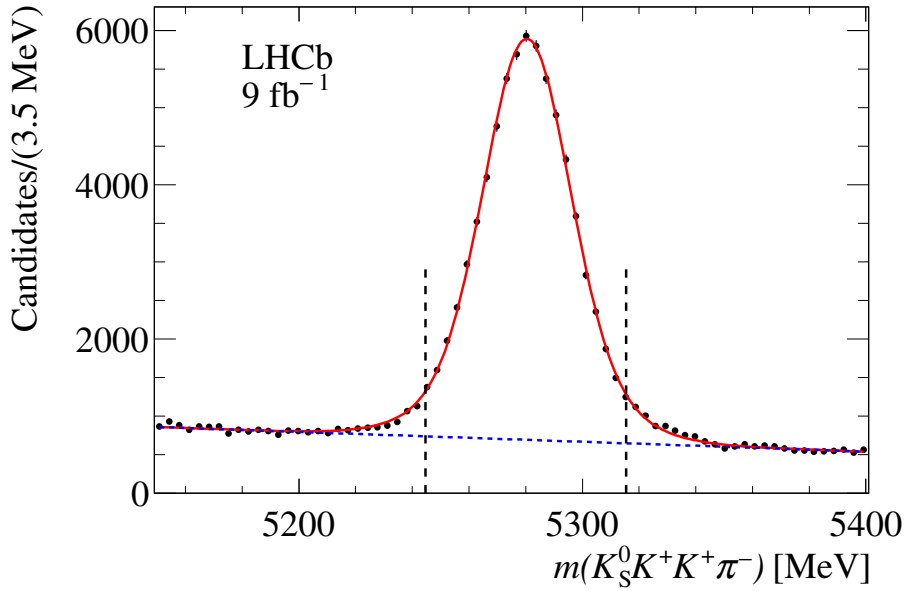
□ Previous studies of η_c decays have been performed by BaBar with the η_c produced in two-photon interactions.

B^+ decay modes

- In this analysis we study the $K^0_S K\pi$ system in the B^+ decays

$$B^+ \to (K^0_S K^- \pi^+) K^+, \qquad B^+ \to (K^0_S K^+ \pi^-) K^+, \quad +c.c.$$



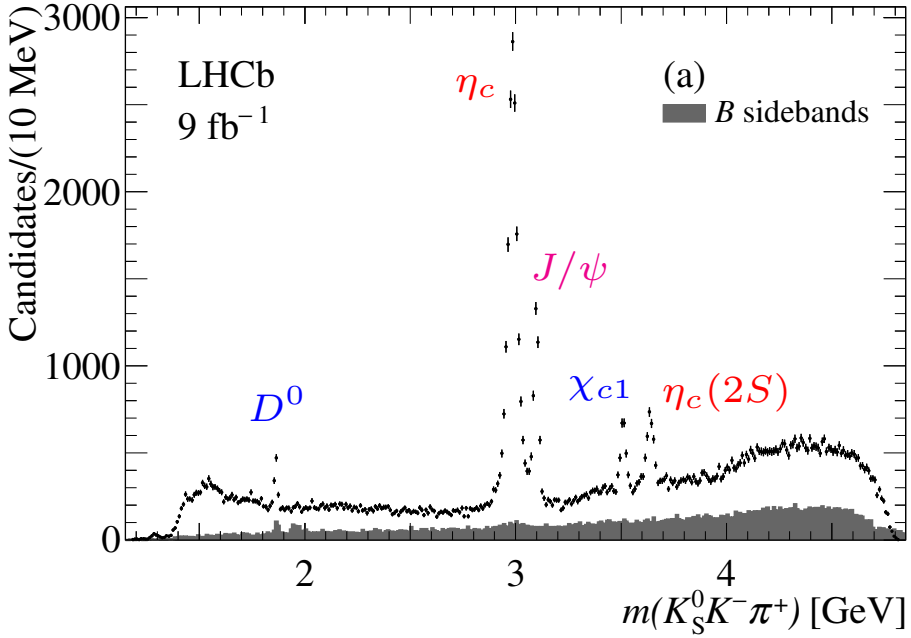


- A total of 340×10^6 candidates. Signals selected by TMVA analyses using 10 variables.
- Reconstructed a total of 74150 $B^+ \to K^0_S K^- \pi^+ K^+$ and 58460 $B^+ \to K^0_S K^+ \pi^- K^+$ events.

$K^0_S K\pi$ mass spectra

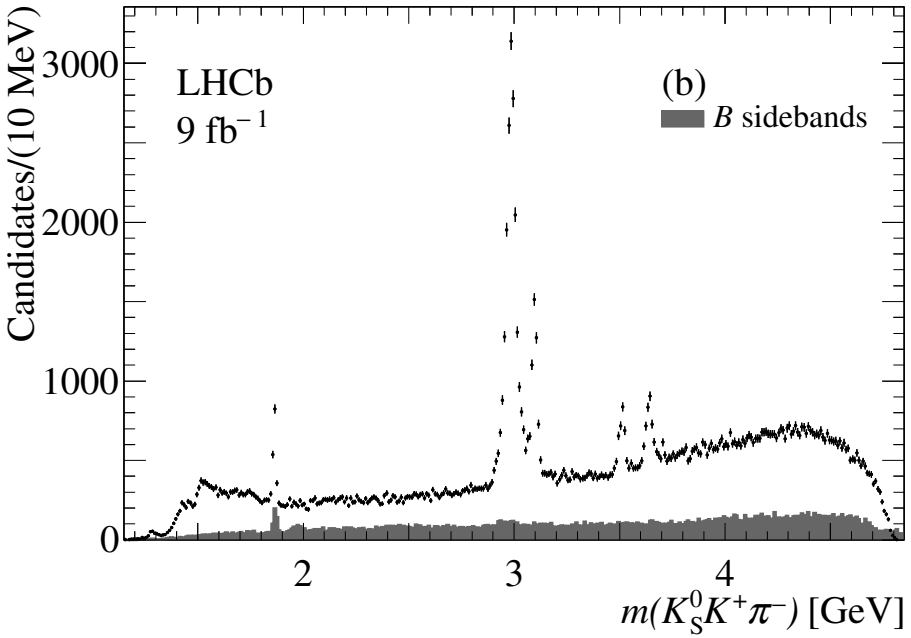
- The $K^0_S K\pi$ mass spectra show rich production of charmonium resonances.
- Structures at threshold. $D^0 \to K^0_S K^- \pi^+$, η_c, J/ψ, χ_{c1}, $\eta_c(2S)$ signals.

$B^+ \to K^0_S K^- \pi^+ K^+$



$B^+ \to K^0_S K^+ \pi^- K^+$

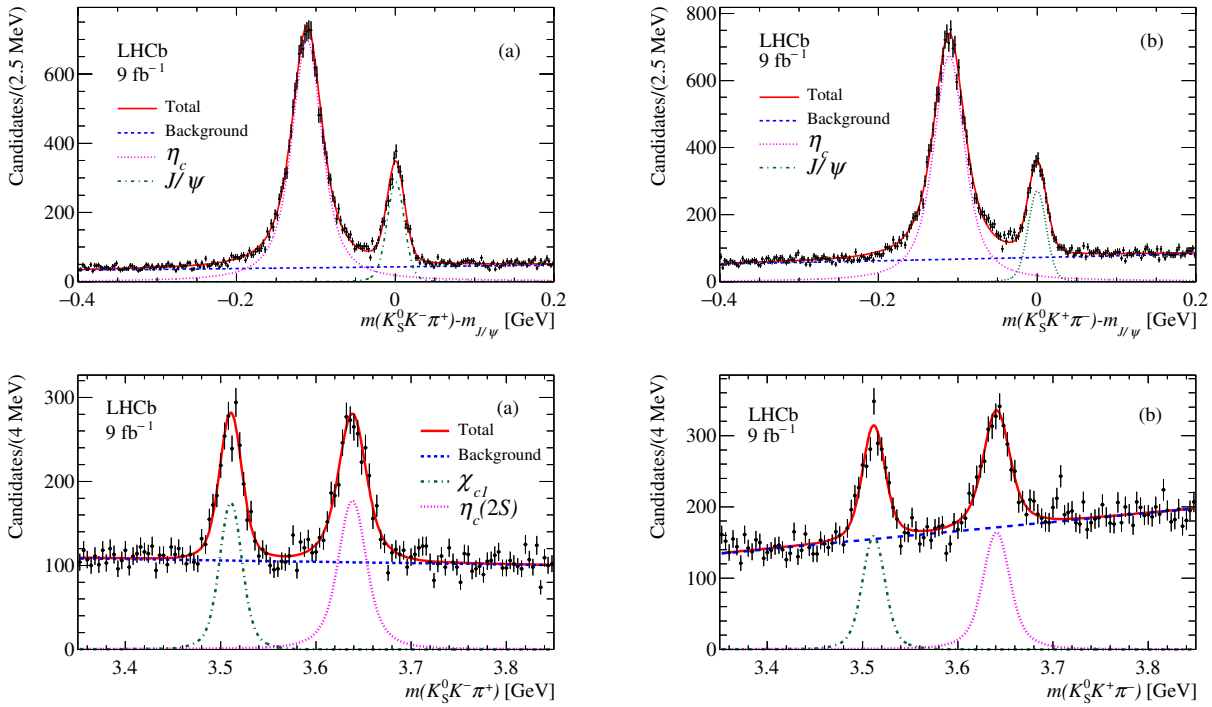
(two combinations per event)



Measurement of the charmonium parameters

- The charmonium modeled by a simple Breit-Wigner convolved with the experimental resolutions.
- Binned fits to the $K^0_S K^\pm \pi^\mp$ mass spectra.

$B^+ \to K^0_S K^+ K^- \pi^+$ $\qquad$ $B^+ \to K^0_S K^+ K^+ \pi^-$



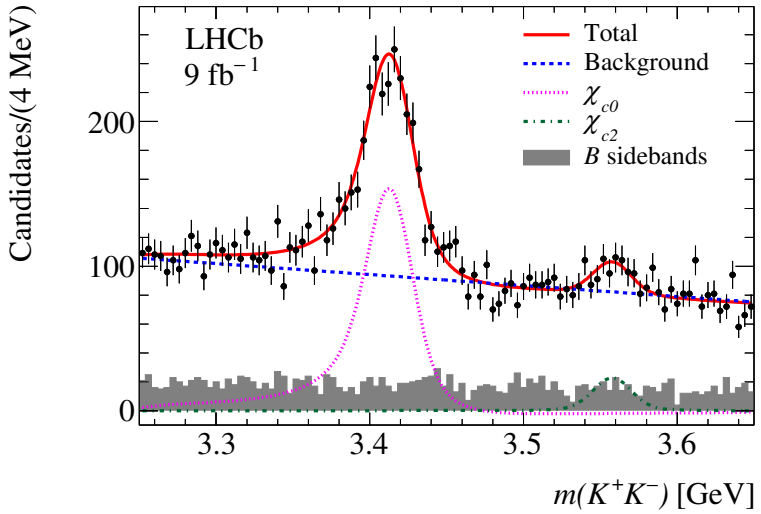
- Fitted charmonium parameters and inverse-variance-weighted averages of the two B^+ decays.

Resonance.	mass (MeV)	width (MeV)	Yield
η_c	$2985.01 \pm 0.17 \pm 0.89$	$29.7 \pm 0.5 \pm 0.2$	34910 ± 283
J/ψ	$-0.54 \pm 0.08 \pm 0.45$	0.0929 (fixed)	6696 ± 106
$\eta_c(2S)$	$3637.90 \pm 0.54 \pm 1.40$	$10.77 \pm 1.62 \pm 1.08$	3680 ± 128
χ_{c1}	$3509.84 \pm 0.69 \pm 0.64$	0.88 (fixed)	2760 ± 86

First observation of $B^+ \to \chi_{c0}(\to K^+K^-)K^0_S\pi^+$

- The $B^+ \to \chi_{c0}K$ decay is expected to be zero in simple factorization models (M. Neubert and B. Stech, Adv. Ser. Direct. High Energy Phys. **15**, 294 (1998)).
- We perform a fit to the K^+K^-, where the χ_c are described by relativistic Breit-Wigner functions, free parameters for the χ_{c0} and fixed to PDG for the χ_{c2}.
- An incoherent fit returns shifted χ_{c0} parameters (≈ 5 MeV) with respect to PDG.
- We allow interference of the χ_{c0} with background and obtain

Final state	p-value (%)	Res.	mass	width	Yield	PDG mass	PDG width
Total	27.9	χ_{c0}	3413.6 ± 1.3	12.8 ± 2.8	1924 ± 89	3414.71 ± 0.3	10.5 ± 0.8
		χ_{c2}	3556.17 (fixed)	2.0 (fixed)	186 ± 33	3556.17 ± 0.07	2.0 ± 0.11



- The interference phase is found to be $\phi = -1.290 \pm 0.073$. χ_{c2} significance: 4.6σ.

First measurements of branching fractions

□ We use the PDG η_c and J/ψ branching fractions

$$\mathcal{B}(B^+ \to \eta_c K^+) \cdot \mathcal{B}(\eta_c \to K^0_S K^\pm \pi^\mp) = 2.7 \pm 0.6 \times 10^{-5},$$
$$\mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to K^0_S K^\pm \pi^\mp) = 5.71 \pm 0.52 \times 10^{-6}.$$

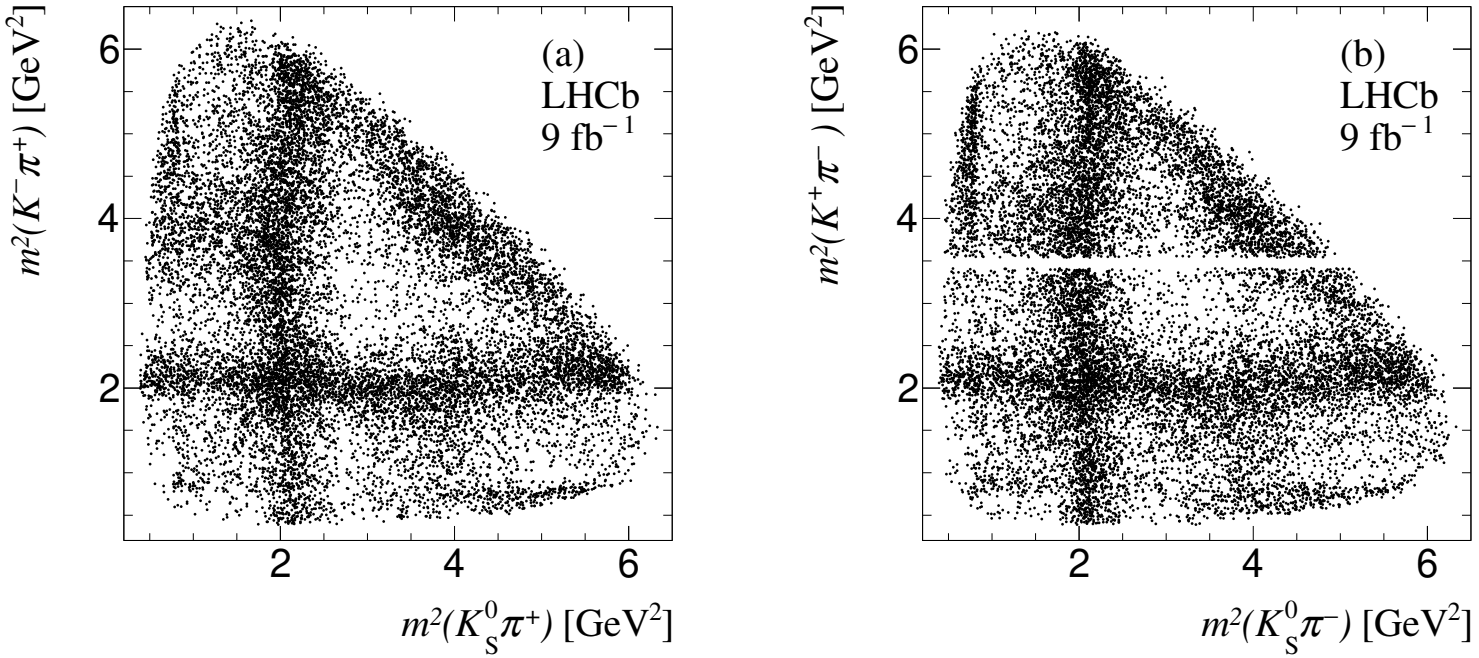
to convert relative to absolute branching fractions.

□ Measured branching fractions.

Final state	$\mathcal{B}$ ($\times 10^{-5}$)
	η_c as reference
$B^+ \to K^0 K^+ K^- \pi^+$	$32.28 \pm 0.33 \pm 1.97 \pm 7.17$
$B^+ \to K^0 K^+ K^+ \pi^-$	$26.56 \pm 0.31 \pm 0.68 \pm 5.90$
$B^+ \to \chi_{c0} K^0 \pi^+$	$1.38 \pm 0.07 \pm 0.11 \pm 0.32$
$B^+ \to \chi_{c2} K^0 \pi^+$	$0.87 \pm 0.20 \pm 0.08 \pm 0.20$
	J/ψ as reference
$B^+ \to K^0 K^+ K^- \pi^+$	$34.01 \pm 0.74 \pm 0.91 \pm 3.10$
$B^+ \to K^0 K^+ K^+ \pi^-$	$28.01 \pm 0.68 \pm 1.35 \pm 2.55$
$B^+ \to \chi_{c0} K^0 \pi^+$	$1.45 \pm 0.08 \pm 0.11 \pm 0.16$
$B^+ \to \chi_{c2} K^0 \pi^+$	$0.92 \pm 0.21 \pm 0.08 \pm 0.10$

□ The first uncertainty is statistical, the second systematic, the third is due to the PDG uncertainty on the $B \to \eta_c K$ or $B \to J/\psi K$ branching fraction.

The η_c Dalitz plot from $B^+ \to K^0_S K^+ K^- \pi^+$ and $B^+ \to K^0_S K^+ K^+ \pi^-$



- Dominated by uniform constructive horizontal and vertical bands due to $K^*_0(1430)$.
- G-parity relates the final states $\bar{K}^*_0 K$ and $K^*_0 \bar{K}$ and for the I=0 $J^{PC} = 0^{-+}$ η_c resonance.
- G-parity is even and therefore the $\bar{K}^*_0 K$ and $K^*_0 \bar{K}$ bands interfere constructively.
- Removed strong $\bar{D}^0 \to K^+\pi^-$ in $B^+ \to K^0_S K^+ K^+ \pi^-$.
- We perform two η_c Dalitz plot analyses:

(a) Quasi Model Independent (QMI) measurement of the $K\pi$ S-wave .
(b) Isobar model: all the resonances are described by Breit-Wigner functions.

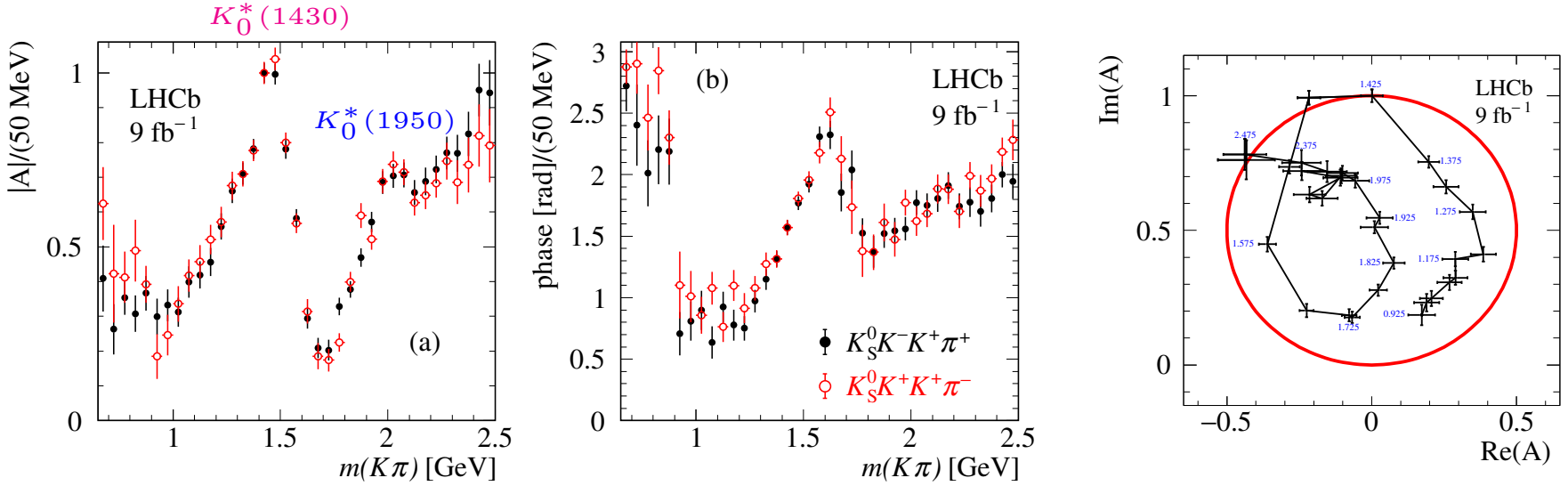
Measurement of the $K\pi$ S-wave

- The $K\pi$ invariant-mass spectrum is divided into 37 equally-spaced mass intervals 50MeV wide, and two new fit parameters are added for each interval: the amplitude and phase of the $K\pi$ S-wave.

- The $K\pi$ S-wave amplitude in bin j is written as

$$A^j_{S-wave} = \frac{1}{\sqrt{2}}(a_j^{K\pi}(m)e^{i\phi_j^{K\pi}(m)} + a_j^{K^0\pi}(m)e^{i\phi_j^{K^0\pi}(m)}),$$

- Plot the $K\pi$ S-wave for $B^+ \to K^0_S K^+ K^- \pi^+$ (black) and $B^+ \to K^0_S K^+ K^+ \pi^-$ (red) data

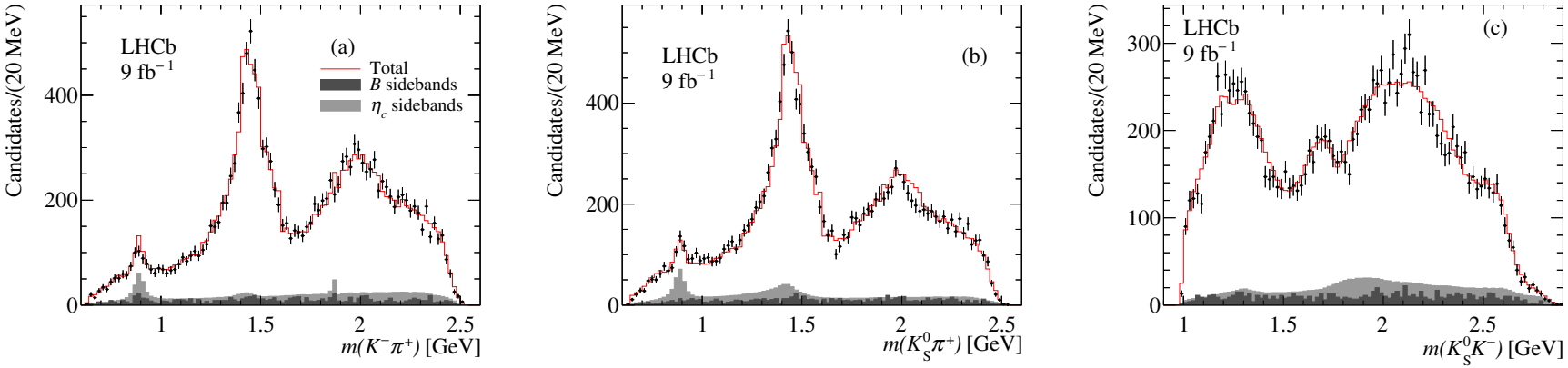


- Perform the inverse-variance-weighted average and plot the Argand diagram.

- Anticlockwise motion. Large loop: $K_0^*(1430)$, smaller loop: $K_0^*(1950)$.

Results from the QMI analysis

- Fit projections for $B^+ \to K^0_S K^+ K^- \pi^+$ data



- $K^*(892)$ signal entirely due to background.
- Inverse-variance-weighted averages from the QMI Dalitz-plot analysis of the η_c decay.

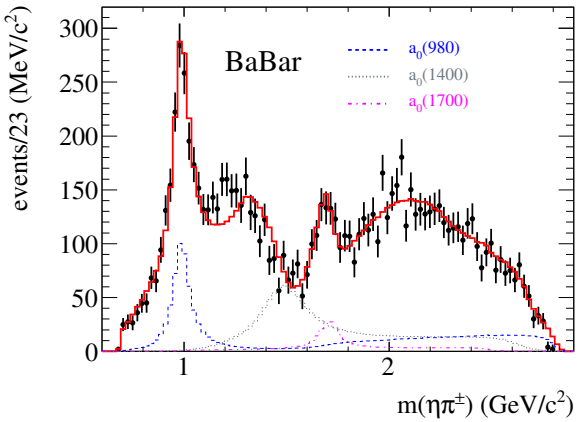
Final state	Fraction [%]	Phase [rad]
$(K\pi)_S K$	$114.4 \pm 1.8 \pm 4.6$	0.
$a_0(1450)\pi$	$1.4 \pm 0.2 \pm 0.4$	$2.31 \pm 0.06 \pm 0.09$
$K^*_2(1430)K$	$17.1 \pm 0.6 \pm 0.7$	$4.32 \pm 0.02 \pm 0.08$
$a_2(1320)\pi$	$0.7 \pm 0.1 \pm 0.4$	$4.20 \pm 0.08 \pm 0.26$
$a_0(980)\pi$	$10.5 \pm 0.4 \pm 0.4$	$-2.97 \pm 0.02 \pm 0.03$
$a_0(1700)\pi$	$1.0 \pm 0.1 \pm 0.1$	$2.04 \pm 0.06 \pm 0.12$
$K^*_2(1980)K$	$3.5 \pm 0.3 \pm 0.9$	$0.06 \pm 0.04 \pm 0.07$
$a_2(1750)\pi$	$0.2 \pm 0.1 \pm 0.1$	$-3.69 \pm 0.15 \pm 0.16$
Sum	$148.8 \pm 2.0 \pm 4.8$	

η_c Dalitz plot analysis using the isobar model

- All the resonances are described by relativistic Breit-Wigner functions.
- After having included all possible known resonances, we introduce an additional contribution, described by a BW pole, with free parameters and label the contribution as $\kappa(2600)$.
- We obtain the following measurement of the resonances parameters.
- Significances estimated using Wilks' theorem.

Resonance	Mass (MeV)	Γ (MeV)	$\Delta(2log\mathcal{L})$	Significance ($n\sigma$)
$K_0^*(1430)$	$1493 \pm 4 \pm 7$	$215 \pm 7 \pm 4$		
$K_0^*(1950)$	$1980 \pm 14 \pm 19$	$229 \pm 26 \pm 16$	316	17.8
$a_0(1700)$	$1736 \pm 10 \pm 12$	$134 \pm 17 \pm 61$	161	12.7
$\kappa(2600)$	$2662 \pm 59 \pm 201$	$480 \pm 47 \pm 72$	1338	36.6

- The fit requires the presence of $a_0(1700)^- \to K_S^0 K^-$, first observed by BaBar ($a_0(1700)^- \to \eta\pi^-$) in the Dalitz plot analysis of $\eta_c \to \eta\pi^+\pi^-$ *(J. P. Lees et al., Phys. Rev. D **104**, 072002 (2021),[arXiv:2106.05157])*



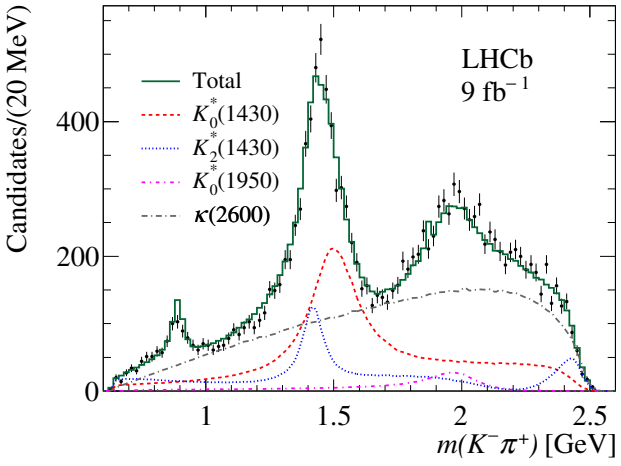
- We test the presence of the low mass $\kappa(800)$ with parameters fixed to PDG values. We obtain a $\Delta(2log\mathcal{L})$=6.6 for the difference of two parameters. This corresponds to a significance of 1.8σ.

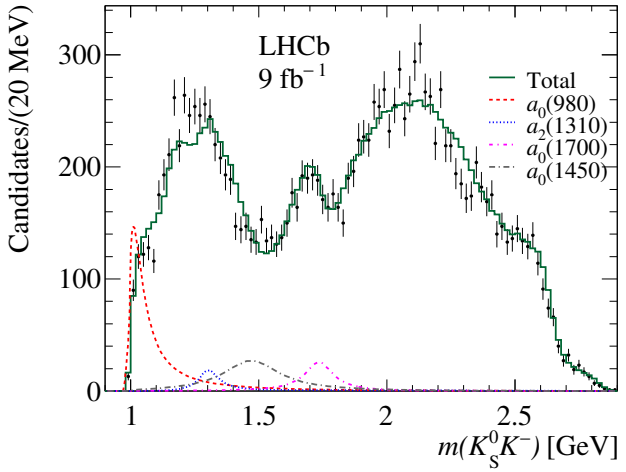
η_c isobar model average results

□ Inverse-variance-weighted averages from $B^+ \to K^0_S K^+ K^- \pi^+$ and $B^+ \to K^0_S K^+ K^+ \pi^-$ data.

Final state	Fraction (%)	Phase
$K_0^*(1430)\bar{K}$	$33.4 \pm 0.9 \pm 2.0$	0.
$a_0(980)^-\pi^+$	$5.1 \pm 0.5 \pm 0.8$	$-3.38 \pm 0.06 \pm 0.08$
$K_2^*(1420)\bar{K}$	$14.6 \pm 0.7 \pm 0.8$	$3.54 \pm 0.02 \pm 0.07$
$a_2(1310)^-\pi^+$	$1.1 \pm 0.1 \pm 0.2$	$-2.89 \pm 0.08 \pm 0.18$
$K_0^*(1950)\bar{K}$	$3.7 \pm 0.3 \pm 0.2$	$-0.44 \pm 0.04 \pm 0.45$
$a_0(1700)^-\pi^+$	$1.1 \pm 0.2 \pm 0.2$	$1.05 \pm 0.06 \pm 0.15$
$a_0(1450)^-\pi^+$	$2.6 \pm 0.3 \pm 0.5$	$-4.82 \pm 0.06 \pm 0.13$
$a_2(1750)^-\pi^+$	$0.3 \pm 0.1 \pm 0.1$	$2.33 \pm 0.12 \pm 0.11$
$\kappa(2600)\bar{K}$	$61.8 \pm 2.4 \pm 5.4$	$-0.37 \pm 0.03 \pm 0.09$
Sum	$123.7 \pm 2.7 \pm 4.7$	

□ Fit projections.



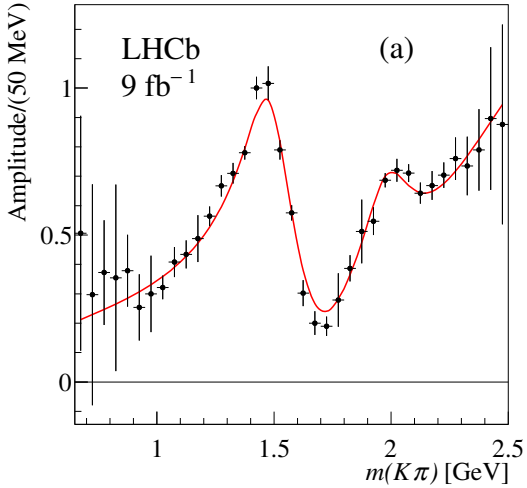


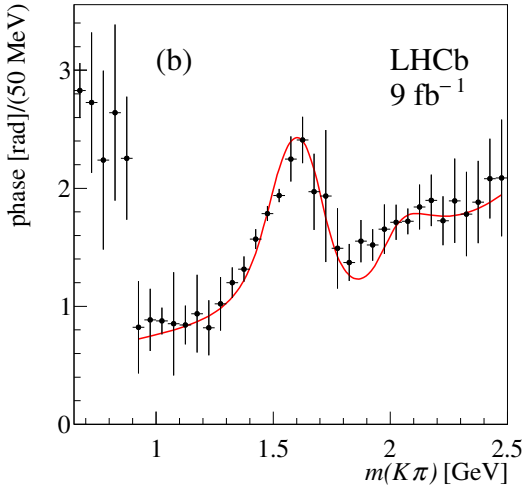
Consistency test with the results from QMI analysis

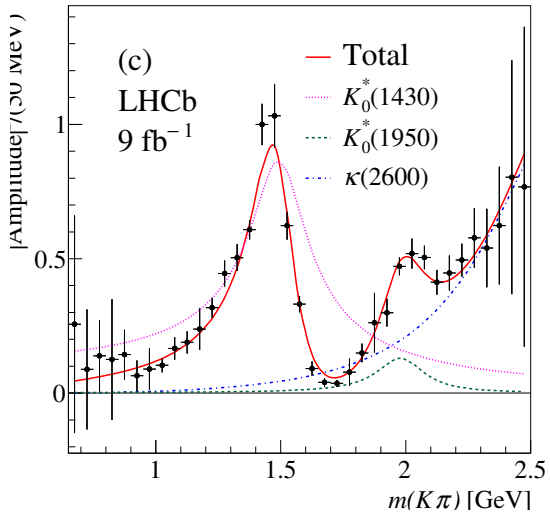
- We test the consistency between the $K\pi$ $\mathcal{S}-$wave model obtained from the QMI analysis with that obtained from the isobar model analysis.
- In the isobar model the $K\pi$ $\mathcal{S}-$wave is described in terms of $K_0^*(1430) + K_0^*(1950) + \kappa(2600)$.
- We perform a χ^2 fit to the QMI $K\pi$ $\mathcal{S}-$wave amplitude and phase using the model:

$$f(m) = c_1 BW_{K^*(1430)}(m)e^{i\phi_1} + c_2 BW_{K^*(1950)}(m)e^{i\phi_2} + c_3 BW_{\kappa(2600)}(m)e^{i\phi_3}$$

- All the resonances have parameters fixed to the results from the isobar model analysis.



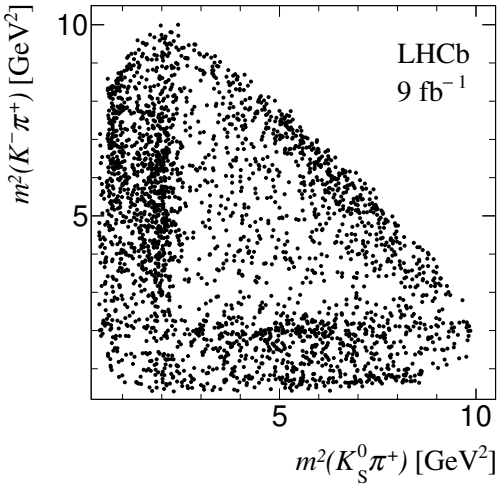




- The fit has a p-value of 40%
- **Similar to the $f_0(980)/\sigma$ interference observed in the $\pi\pi$ final state.**

First Dalitz plot analysis of $\eta_c(2S)$ in $B^+ \to K^0_S K^+ K^- \pi^+$

□ $\eta_c(2S)$ Dalitz plot and fit results

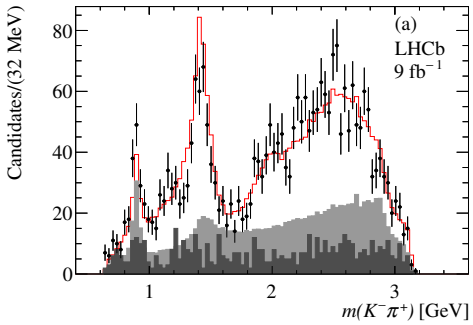


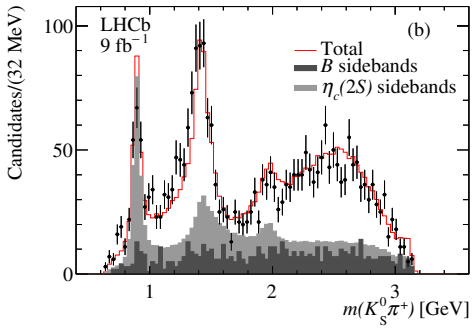
Final state	Fraction(%)	Phase
$K_0^*(1430)K$	$25.5 \pm 3.3 \pm 2.3$	0.
$K_2^*(1430)K$	$24.5 \pm 3.3 \pm 2.5$	$3.10 \pm 0.11 \pm 0.06$
$K_0^*(1950)K$	$3.7 \pm 1.3 \pm 0.6$	$-0.82 \pm 0.17 \pm 0.09$
$a_0(1700)^-\pi^+$	$1.7 \pm 1.1 \pm 0.3$	$1.22 \pm 0.32 \pm 0.19$
$a_0(1450)^-\pi^+$	$7.8 \pm 1.9 \pm 0.9$	$1.86 \pm 0.14 \pm 0.11$
$a_2(1750)^-\pi^+$	$4.9 \pm 1.4 \pm 0.6$	$-1.75 \pm 0.15 \pm 0.04$
$\kappa(2600)K$	$124.2 \pm 9.0 \pm 5.4$	$-0.91 \pm 0.10 \pm 0.07$
Sum	192.3 ± 10.9	

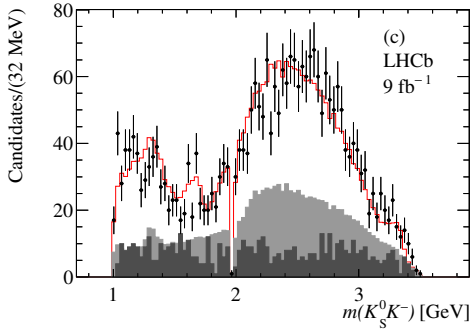
□ Similar to that from the η_c with larger phase space.

□ We only use the isobar model Dalitz plot analysis with all the resonances parameters fixed to that obtained in the η_c analysis.

□ Fit projections

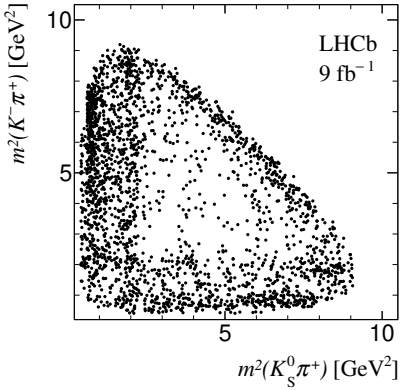


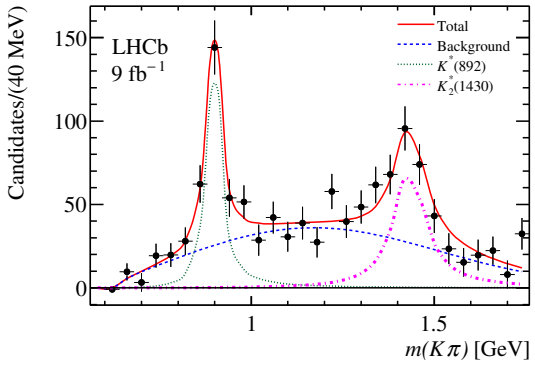


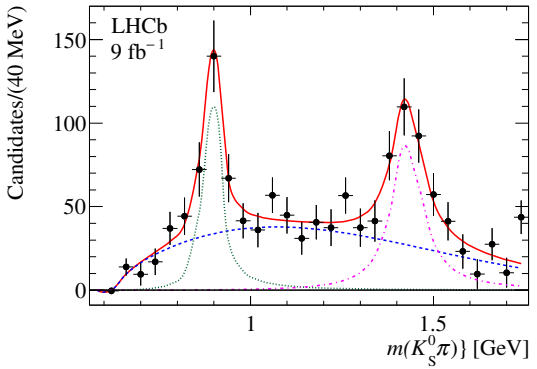


Study of $\chi_{c1} \to K^0_S K^\pm \pi^\mp$

□ χ_{c1} Dalitz plot for $B^+ \to K^0_S K^+ K^- \pi^+$ data. Dominated by K^* resonances.







□ Fit to the background subtracted $K\pi$ mass spectra using two relativistic Breit-Wigner functions to describe the $K^*(892)$ and $K^*_2(1430)$ resonances. Summed over the two B^+ decay modes.

□ The fractional $K^*(892)$ and $K^*_2(1430)$ contributions are converted into $\chi_{c1} \to K^* \bar{K}$ branching fractions by multiplying by the known χ_{c1} branching fraction

$$\mathcal{B}(\chi_{c1} \to \bar{K}^0 K^+ \pi^-) = (7.0 \pm 0.6) \times 10^{-3},$$

and correcting for unseen K^* decay modes.

□ Inverse-variance-weighted branching fractions averages.

Decay mode	Fraction	Branching fraction ($\times 10^{-3}$)
$\mathcal{B}(\chi_{c1} \to K^*(892)^0 \bar{K}^0)$	$0.099 \pm 0.012 \pm 0.004$	$1.04 \pm 0.13 \pm 0.04 \pm 0.09$
$\mathcal{B}(\chi_{c1} \to K^*_2(1430)^0 \bar{K}^0)$	$0.111 \pm 0.015 \pm 0.005$	$1.17 \pm 0.16 \pm 0.05 \pm 0.10$
$\mathcal{B}(\chi_{c1} \to K^*(892)^+ K^-)$	$0.112 \pm 0.016 \pm 0.013$	$1.18 \pm 0.17 \pm 0.14 \pm 0.10$
$\mathcal{B}(\chi_{c1} \to K^*_2(1430)^+ K^-)$	$0.143 \pm 0.018 \pm 0.006$	$1.61 \pm 0.19 \pm 0.19 \pm 0.14$

Summary

□ In this analysis we study the B^+ decay to $K^0_S K K \pi$ and obtain the following results.

- (a) Precise measurements of the η_c and $\eta_c(2S)$ parameters
- (b) High statistics and high purity Dalitz plot analysis of η_c decay using the QMI and isobar model approaches.
- (c) Improved measurement of the $K\pi$ S-wave from the η_c decay described by an alternative model.
- (d) Established the existence of the $K^*_0(1950)$ and $a_0(1700)$ resonances.
- (e) First Dalitz plot analysis of $\eta_c(2S) \to K^0_S K^{\pm}\pi^{\mp}$.
- (f) Improved measurements of the $\chi_{c1} \to K^* K$ branching fractions.
- (g) First measurement of the $B^+ \to K^0_S K^- \pi^+ K^+$ and $B^+ \to K^0_S K^+ \pi^- K^+$ branching fractions.
- (h) Measurement of the B^+ to η_c, J/ψ, $\eta_c(2S)$ and χ_{c1} branching fractions.
- (i) First observation of the decay $B^+ \to \chi_{c0} K^0_S \pi^+$