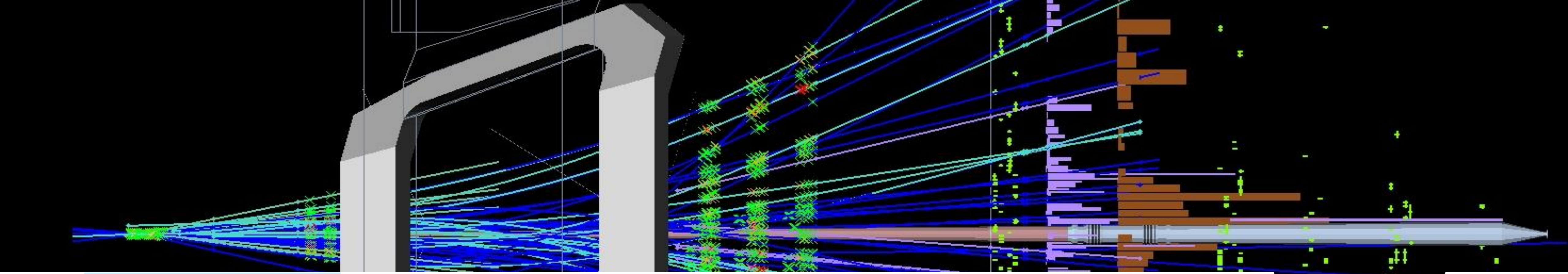


CP violation in charmless multi-body beauty decays

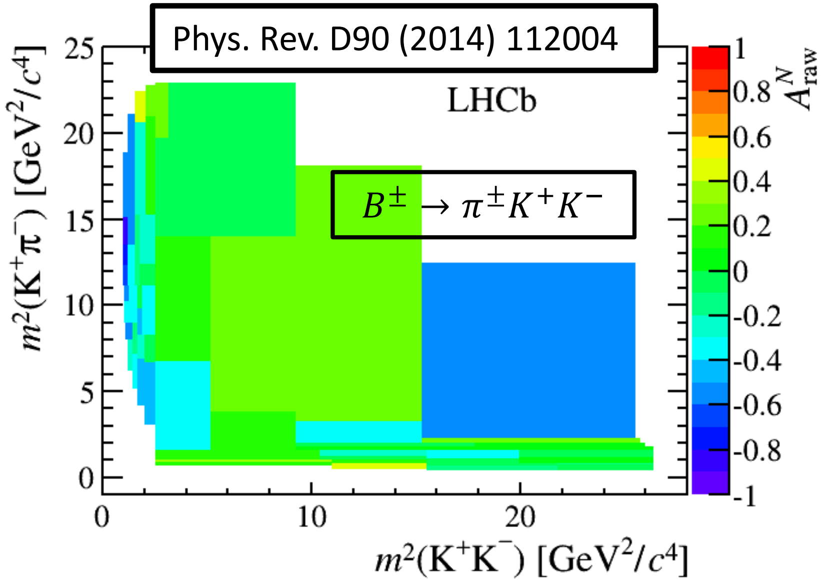
Cayo Costa Sobral, on behalf of the LHCb collaboration

XXXIII Rencontres de Physique de la Vallée d'Aoste – 12/03/2019

Charmless multi-body decays

- Tree-level $b \to u$ transitions are comparable to loop-level $b \to s, d$ amplitudes
  - Potential new physics in loops
  - Potential for large CP violation (CPV) in tree-penguin interference
  - Tests/input to QCD

- Multi-body decays can proceed via a number of intermediate states
  - Resonant + non-resonant contributions can interfere → variation in phase
  - CP asymmetry (A_{CP}) as a function of phase-space (+ phase-space integrated A_{CP})
  - Many techniques available: Amplitude analyses, binned phase-space asymmetries, triple-product asymmetries



Charmless multi-body decays

- LHCb is able to study the whole family of b-hadrons: $B^0, B^{\pm}, B_s^0, \Lambda_b^0$, etc...

- **Some recent results:**
- Amplitude analysis of the $B^0 \to K^{*0}\overline{K}^{*0}$ decay and measurement of its relative branching fraction with the $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay [LHCb-PAPER-2019-004, in preparation]

- Study of the $B^0 \to \rho(770)^0 K^*(892)^0$ mode with an amplitude analysis of $B^0 \to (\pi^{\pm}\pi^{\mp})(K^+\pi^-)$ decays [arxiv:1812.07008, submitted to JHEP]

- Measurement of CP asymmetries in charmless four-body Λ_b^0 and Ξ_b^0 decays [LHCb-PAPER-2018-044, in preparation]

Focus today

- Amplitude analysis of $B^{\pm} \to \pi^{\pm}K^+K^-$ decays [LHCb-PAPER-2018-051, in preparation]

- Amplitude analysis of $B_s^0 \to K_S^0 K^{\pm}\pi^{\mp}$ decays [arxiv:1902.07955, submitted to JHEP]

Isobar model

- Amplitude analyses (AA) are usually carried out via the "isobar model" – full decay amplitude as coherent sum of individual amplitudes

$$\mathcal{A}(m_{ij}^2, m_{jk}^2) = \sum_{r=1}^{N} c_r\, F_r(m_{ij}^2, m_{jk}^2)$$

— c_r – complex coefficient describing relative contribution of the different intermediate states

— F_r – describes the dynamics of the intermediate states (lineshape + angular distribution)

— Extract from the fit: $\mathbf{Re}(\boldsymbol{c_r}), \mathbf{Im}(\boldsymbol{c_r})$ or $|\boldsymbol{c_r}|, \mathbf{arg}(\boldsymbol{c_r})$

  — And the corresponding values for $\bar{\boldsymbol{c}}_{\boldsymbol{r}}$, the coefficient of the charge conjugate decay

— Other quantities are derived from these e.g. branching fractions, A_{CP}

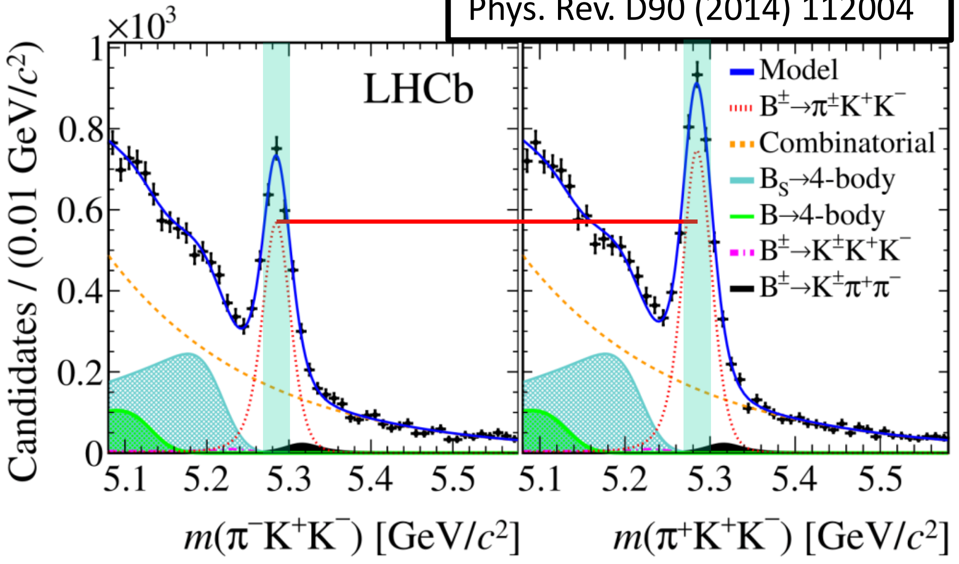
$$A_{CP} = \frac{|\bar{c}_r|^2 - |c_r|^2}{|\bar{c}_r|^2 + |c_r|^2}$$

Fit fraction: $$FF_r = \frac{\iint |c_r F_r|^2 \, dm_{ij}^2 dm_{jk}^2}{\iint |\mathcal{A}|^2 \, dm_{ij}^2 dm_{jk}^2}$$

$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

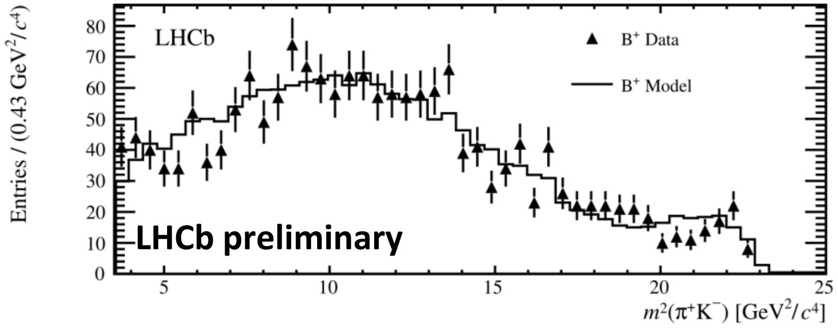
- Previously studied by LHCb [Phys. Rev. D90 (2014) 112004]
  - Inclusive $A_{CP} = -0.123 \pm 0.017 \pm 0.012 \pm 0.007$
  - Phase-space regions with even larger A_{CP}
  - Model independent – no information on contributing intermediate states
- First amplitude analysis of this channel
  - Using 2011+2012 data corresponding to 3.0fb^{-1}
  - Follow up to binned A_{CP} measurement
  - 2052 B^{+} and 1566 B^{-} signal candidates in the fit region
- Signal PDF includes:
  - Resonant contributions from $K^{*}(892)^{0}, K_0^{*0}(1430)$ in $K\pi$ and $\rho(1450), f_2(1270), \phi(1020)$ in KK
  - A single-pole form factor to describe non-resonant $K\pi$ contribution
  - Dedicated amplitude for $\pi\pi \leftrightarrow KK$ rescattering

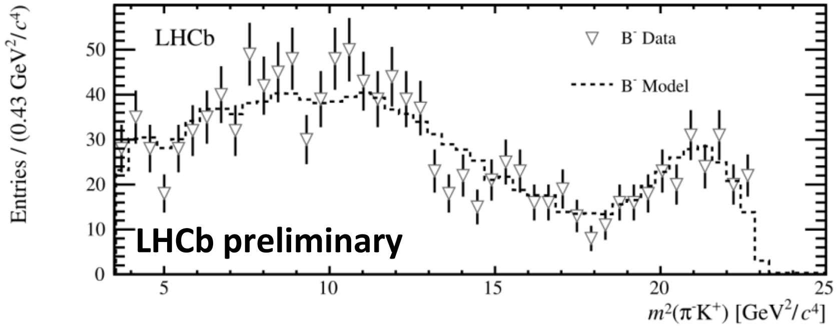
Phys. Rev. D90 (2014) 112004



$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

- Single-pole form factor provides better description than resonant contributions tested such as κ
  - Form factor of the form $(1 + m_{\pi K}^2/\Lambda^2)^{-1}$, $\Lambda = 1\text{GeV}$
  - Proposed in [Phys. Rev. D 92 (2015) 054010]
- Destructive interference pattern at high $m_{\pi K}^2$ is described by combination of $\rho(1450)$ and $f_2(1270)$
- $\pi\pi \leftrightarrow KK$ rescattering amplitude based on Pelaez and Yndurain [Phys. Rev. D 71 (2005) 074016]
  - Rescattering in the region $1.0 < m_{KK}^2 < 1.5\ \text{GeV}/c^2$ (see next slide)
  - $\mathcal{A}_{rescatt} = \mathcal{A}_{source} \cdot f_{scattering}$, with $\mathcal{A}_{source} = (1 + m_{KK}^2/\Lambda^2)^{-1}$
  - $f_{scattering} = \sqrt{1-\eta^2} e^{2i\delta}$ is the off-diagonal term in the $\pi\pi - KK$ coupled channel S-matrix





LHCb-PAPER-2018-051 (in preparation)

$B^{\pm} \to \pi^{\pm} K^{+} K^{-}$

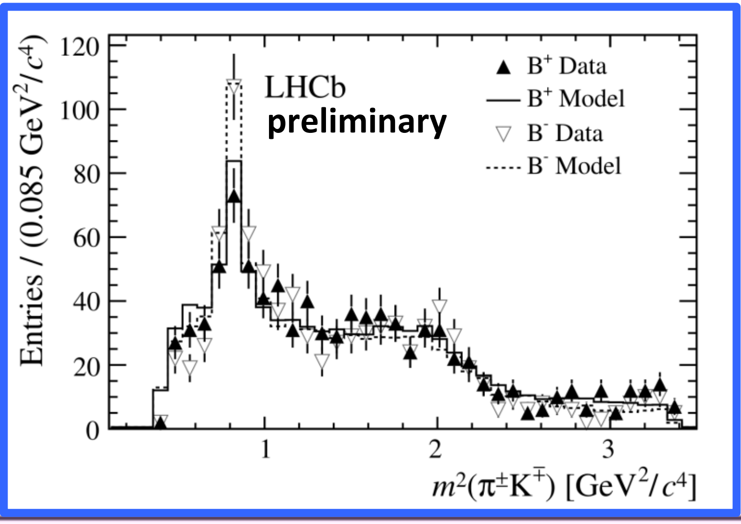
- Fit results:

LHCb preliminary

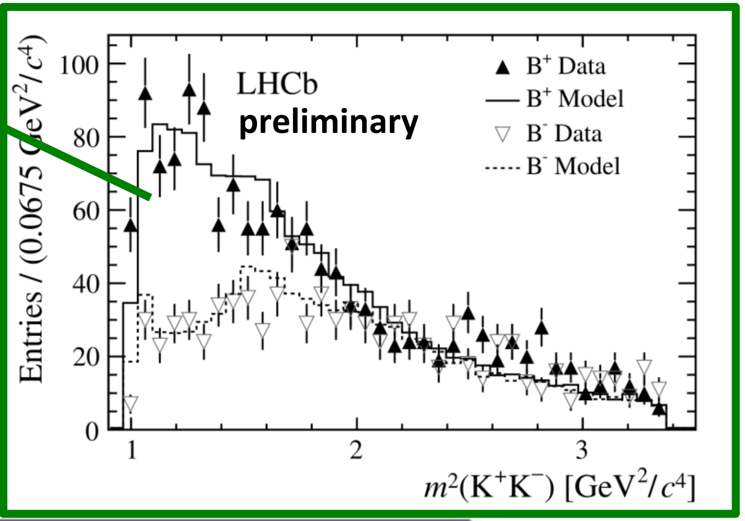
Contribution	Fit Fraction(%)	A_{CP}(%)	Amplitude (B^+/B^-)	Phase[^{o}] (B^+/B^-)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$12.3 \pm 8.7 \pm 4.5$	$0.94 \pm 0.04 \pm 0.02$ / $1.06 \pm 0.04 \pm 0.02$	0 (fixed)
$K_0^{*0}(1430)$	$4.5 \pm 0.7 \pm 1.2$	$10.4 \pm 14.9 \pm 8.8$	$0.74 \pm 0.09 \pm 0.09$ / $0.82 \pm 0.09 \pm 0.10$	$-176 \pm 10 \pm 16$ / $136 \pm 11 \pm 21$
Single-Pole Form Factor	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$	$2.19 \pm 0.13 \pm 0.17$ / $1.97 \pm 0.12 \pm 0.20$	$-138 \pm 7 \pm 5$ / $166 \pm 6 \pm 5$
$\rho(1450)$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$	$2.14 \pm 0.11 \pm 0.07$ / $1.92 \pm 0.10 \pm 0.07$	$-175 \pm 10 \pm 15$ / $140 \pm 13 \pm 20$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$26.7 \pm 10.2 \pm 4.8$	$0.86 \pm 0.09 \pm 0.07$ / $1.13 \pm 0.08 \pm 0.05$	$-106 \pm 11 \pm 10$ / $-128 \pm 11 \pm 14$
rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$	$1.91 \pm 0.09 \pm 0.06$ / $0.86 \pm 0.07 \pm 0.04$	$-56 \pm 12 \pm 18$ / $-81 \pm 14 \pm 15$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.09$	$9.8 \pm 43.6 \pm 26.6$	$0.20 \pm 0.07 \pm 0.02$ / $0.22 \pm 0.06 \pm 0.04$	$-52 \pm 23 \pm 32$ / $107 \pm 33 \pm 41$

$K\pi$ (first three rows); KK (last four rows)

$\phi(1020)$ seen at 3σ level



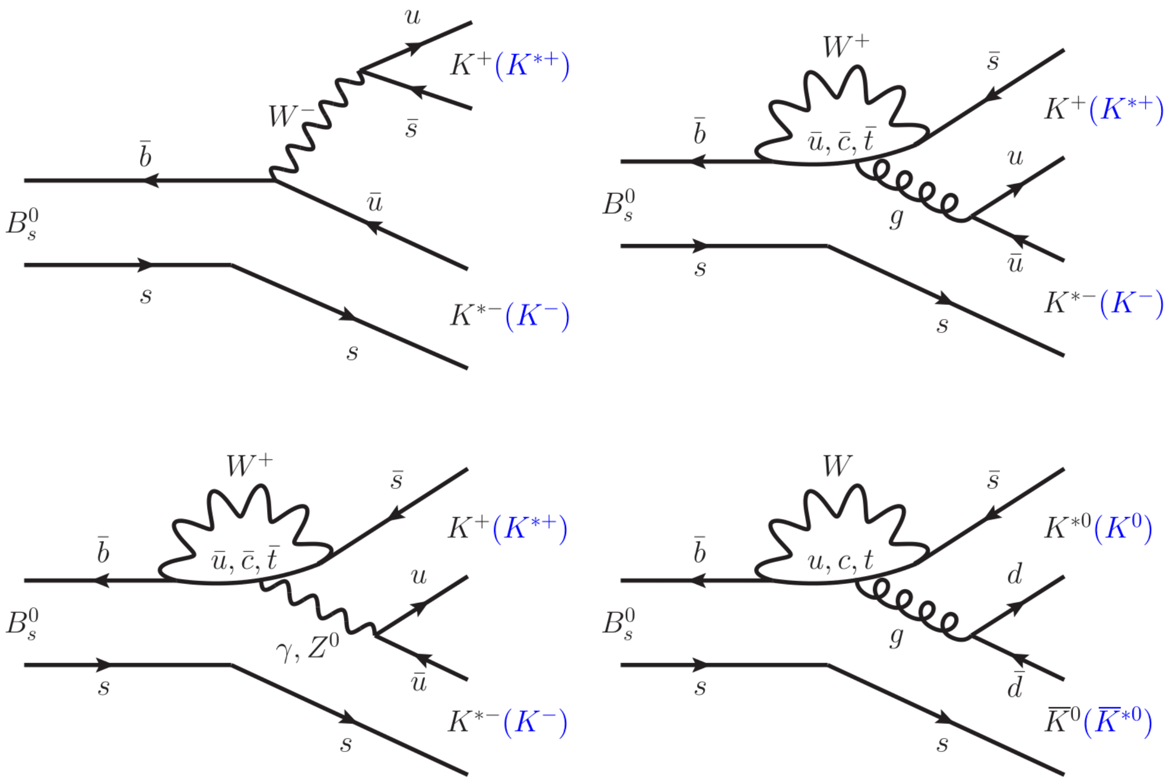
Largest A_{CP} reported for a single amplitude



arxiv:1902.07955

$B_s^0 \to K_S^0 K^\pm \pi^\mp$

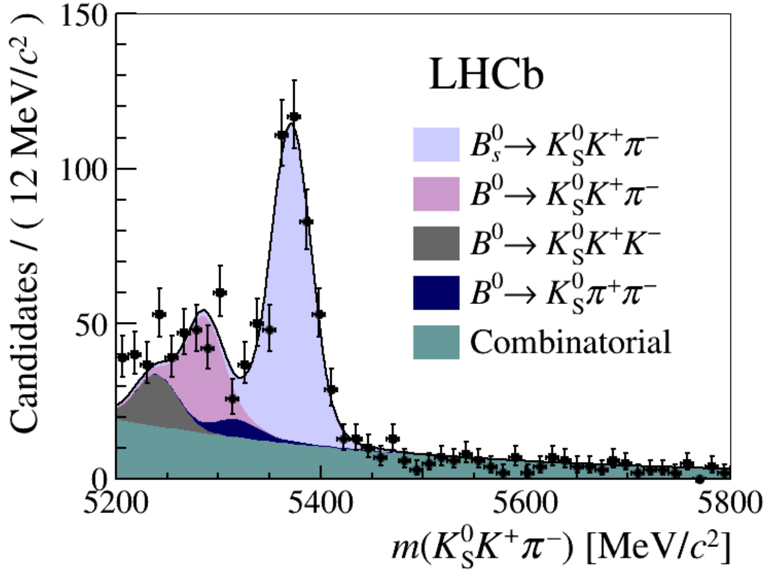
- First amplitude analysis of these decays
  - Untagged, decay-time-integrated
  - Novel approach – simultaneous amplitude fit of two final states
  - Using 3.0fb^{-1} of data (2011+2012)
- The two final states $K_S^0 K^+ \pi^-$ and $K_S^0 K^- \pi^+$ are both accessible by B_s^0 and $\bar{B}_s^0$
- Previously observed by LHCb
  - [JHEP 10 (2013) 143, JHEP 11 (2017) 027]
- Measurements of resonant contributions also performed
  - $B_s^0 \to K^{*\pm} K^\mp$ [New J. Phys. 16 (2014) 123001]
  - $B_s^0 \to K^{*0} K_S^0$ [JHEP 01 (2016) 012]
  - Potential for time-dependent CP violation measurements with larger samples

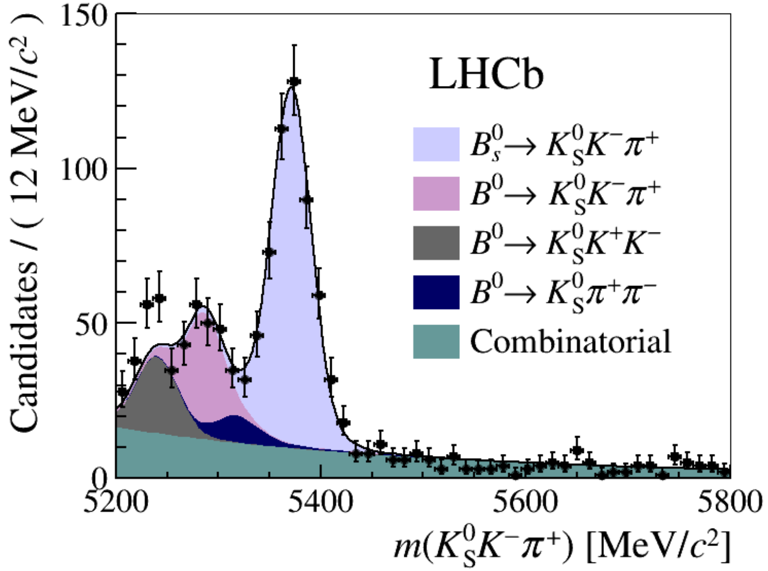


arxiv:1902.07955

$B_s^0 \to K_S^0 K^\pm \pi^\mp$

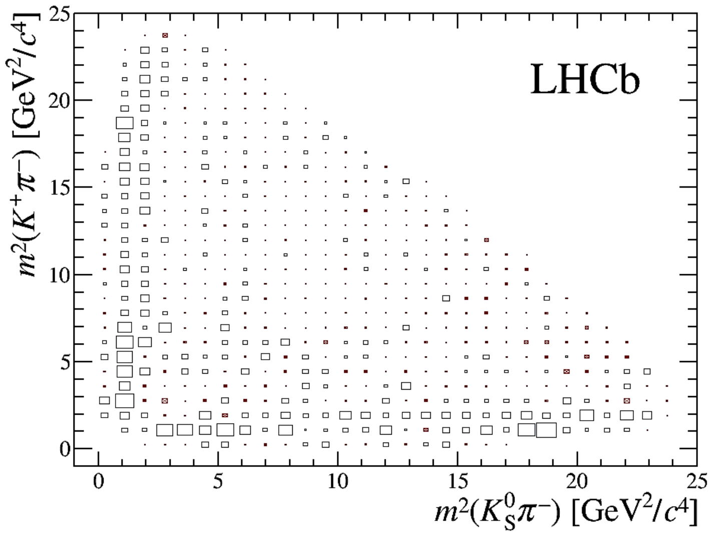
- Event selection follows closely from updated BF measurement [JHEP 11 (2017) 027]
  - Criteria have been reoptimized for an AA
- Data sample divided into 24 sub-samples
  - Four final states: $K_S^0 K^\pm \pi^\mp$, $K_S^0 \pi^+ \pi^-$, $K_S^0 K^+ K^-$
  - Two K_S^0 reconstruction categories
  - Three data-taking periods
- Simultaneous, unbinned, extended maximum-likelihood fit to all sub-samples to extract signal yields
  - Signal yields of $431.1(489.4)$ in $K_S^0 K^+ \pi^- (K_S^0 K^- \pi^+)$ in the region used for the AA

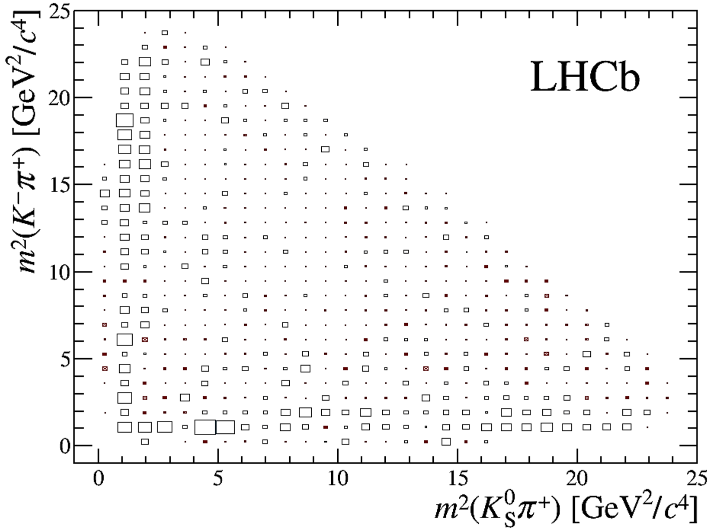




$B_s^0 \to K_S^0 K^\pm \pi^\mp$

- Both B_s^0 and $\bar{B}_s^0$ contribute to each final state f but the two amplitudes need not be the same: $\mathcal{A}_f \neq \bar{\mathcal{A}}_f$
- Untagged analysis means that the B_s^0 and $\bar{B}_s^0$ contributions cannot be untangled
- Amplitude fit is performed using an effective amplitude that is some combination of $\mathcal{A}_f$ and $\bar{\mathcal{A}}_f$
  - Akin to CP-averaged amplitude fits
- Method validated by generating pseudoexperiments with full decay-time-dependent model
  - Amplitude parameters based on expected BFs + range of CP violation hypotheses
  - Effective model results for **fit fractions** are found to be robust



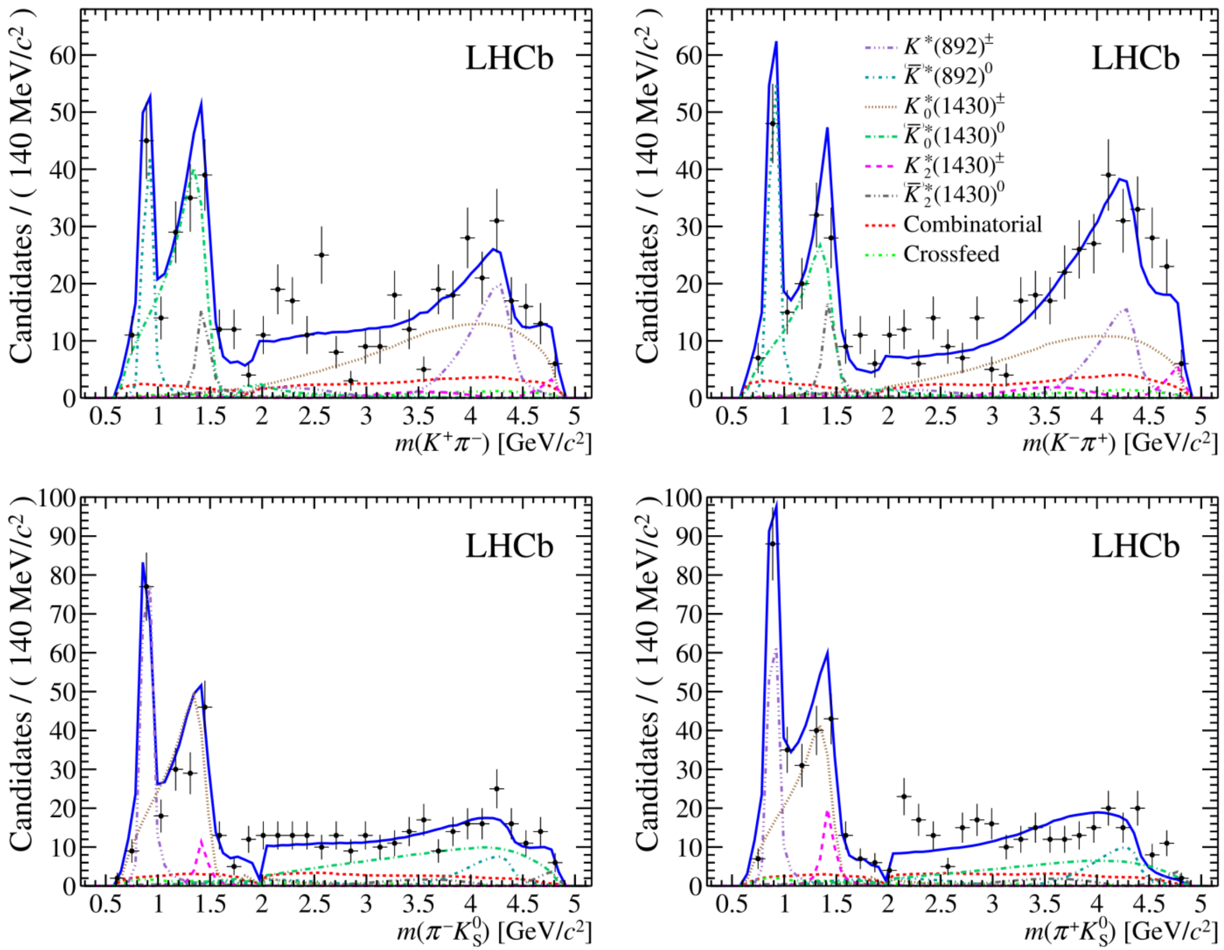


arxiv:1902.07955

$B_s^0 \to K_S^0 K^\pm \pi^\mp$

$K_S^0 K^+ \pi^-$		$K_S^0 K^- \pi^+$	
Resonance	Fit fraction (%)	Resonance	Fit fraction (%)
$K^*(892)^-$	15.6 ± 1.5	$K^*(892)^+$	13.4 ± 2.0
$K_0^*(1430)^-$	30.2 ± 2.6	$K_0^*(1430)^+$	28.5 ± 3.6
$K_2^*(1430)^-$	2.9 ± 1.3	$K_2^*(1430)^+$	5.8 ± 1.9
$K^*(892)^0$	13.2 ± 2.4	$\overline{K}^*(892)^0$	19.2 ± 2.3
$K_0^*(1430)^0$	33.9 ± 2.9	$\overline{K}_0^*(1430)^0$	27.0 ± 4.1
$K_2^*(1430)^0$	5.9 ± 4.0	$\overline{K}_2^*(1430)^0$	7.7 ± 2.8

- Contributions in $m^2_{K^+K_S}$ such as $a_2(1320)^\pm$ were considered but found to be negligible
- Vector and tensor states modelled with Breit—Wigner functions
- $K\pi$ S-wave modelled with LASS lineshape, combines $K_0^*(1430)$ + non-resonant shape
- **$K_0^*(1430)$ contributions observed at $> 10\sigma$ level for the first time**
- **No significant CP violation seen**



$B_s^0 \to K_S^0 K^\pm \pi^\mp$

- Branching fractions can be obtained from the flavour-averaged fit fractions:

$$\mathcal{B}\left(B_s^0 \to K^*(892)^\pm K^\mp; K^*(892)^\pm \to \overset{(-)}{K}{}^0\pi^\pm\right) = (12.4 \pm 0.8 \pm 0.5 \pm 2.7 \pm 1.3) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to (\overset{(-)}{K}{}^0\pi^\pm)_0^* K^\mp\right) = (24.9 \pm 1.8 \pm 0.5 \pm 20.0 \pm 2.6) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to K_2^*(1430)^\pm K^\mp; K_2^*(1430)^\pm \to \overset{(-)}{K}{}^0\pi^\pm\right) = (3.4 \pm 0.8 \pm 0.4 \pm 5.4 \pm 0.4) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to \overset{(-)}{K}{}^*(892)^0 \overset{(-)}{K}{}^0; \overset{(-)}{K}{}^*(892)^0 \to K^\mp\pi^\pm\right) = (13.2 \pm 1.9 \pm 0.8 \pm 2.9 \pm 1.4) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to (K^\mp\pi^\pm)_0^* \overset{(-)}{K}{}^0\right) = (26.2 \pm 2.0 \pm 0.7 \pm 7.3 \pm 2.8) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to \overset{(-)}{K}{}_2^*(1430)^0 \overset{(-)}{K}{}^0; \overset{(-)}{K}{}_2^*(1430)^0 \to K^\mp\pi^\pm\right) = (5.6 \pm 1.5 \pm 0.6 \pm 7.0 \pm 0.6) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to (\overset{(-)}{K}{}^0\pi^\pm)_{\rm NR} K^\mp\right) = (11.4 \pm 0.8 \pm 0.2 \pm 9.2 \pm 1.2 \pm 0.5) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to (K^\mp\pi^\pm)_{\rm NR} \overset{(-)}{K}{}^0\right) = (12.1 \pm 0.9 \pm 0.3 \pm 3.3 \pm 1.3 \pm 0.5) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to K_0^*(1430)^\pm K^\mp; K_0^*(1430)^\pm \to \overset{(-)}{K}{}^0\pi^\pm\right) = (19.4 \pm 1.4 \pm 0.4 \pm 15.6 \pm 2.0 \pm 0.3) \times 10^{-6}$$

$$\mathcal{B}\left(B_s^0 \to \overset{(-)}{K}{}_0^*(1430)^0 \overset{(-)}{K}{}^0; \overset{(-)}{K}{}_0^*(1430)^0 \to K^\mp\pi^\pm\right) = (20.5 \pm 1.6 \pm 0.6 \pm 5.7 \pm 2.2 \pm 0.3) \times 10^{-6}$$

- Largest systematic uncertainty comes from alternative $K\pi$ S-wave parameterisation

- $(K\pi)_0^*$ refers to the total $K\pi$ S-wave

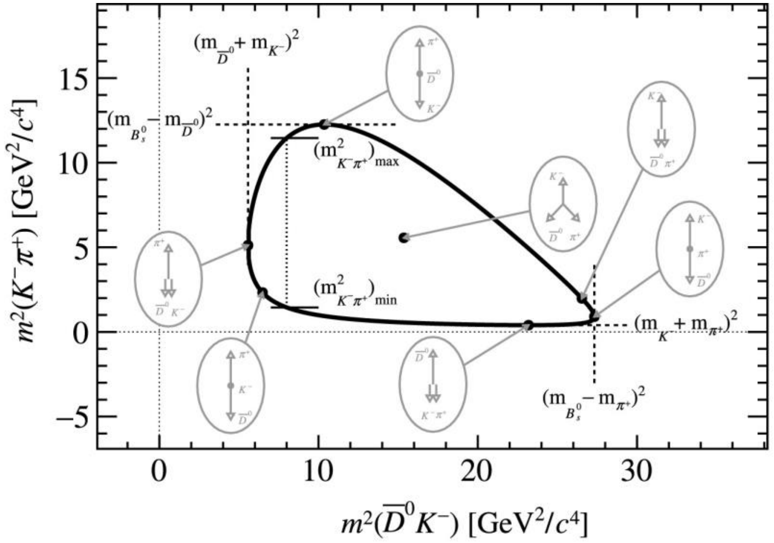
Summary

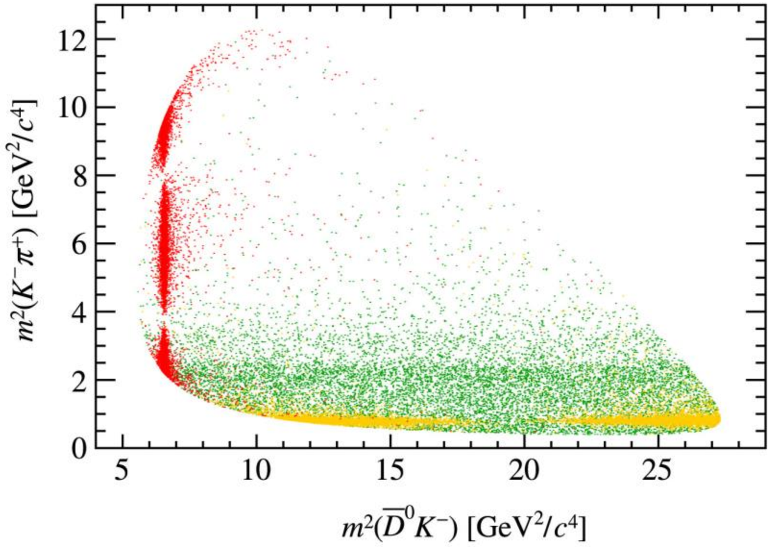
- Charmless multi-body decays are a crucial area for studying CP violation
- LHCb continues to provide many interesting results
  - Motivation for Run 2 analyses + LHCb upgrade
  - Some areas exclusive to LHCb in the near future: B_s^0, b-baryons
- $B^\pm \to \pi^\pm K^+ K^-$ reports largest A_{CP} for a single amplitude
  - Inclusion of rescattering amplitude highlights constructive dialogue between theory and experiment in developing new models
  - Potentially important for channels with larger datasets
  - Size of rescattering hints towards need of coupled-channel analyses
- $B_s^0 \to K_S^0 K^\pm \pi^\mp$ analysis:
  - Observation of $K_0^*(1430)$ states, with $> 10\sigma$ significance
  - Full flavour-tagged, decay-time-dependent analysis only possible following LHCb upgrade

Backup

Comput. Phys. Commun. 231, 198 (2018)

Backup

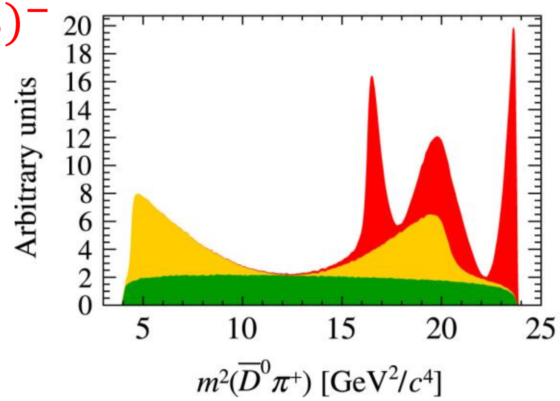


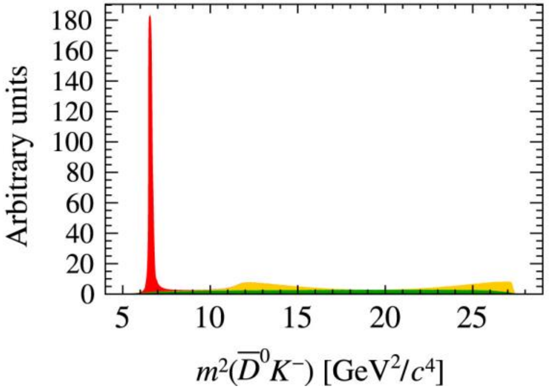


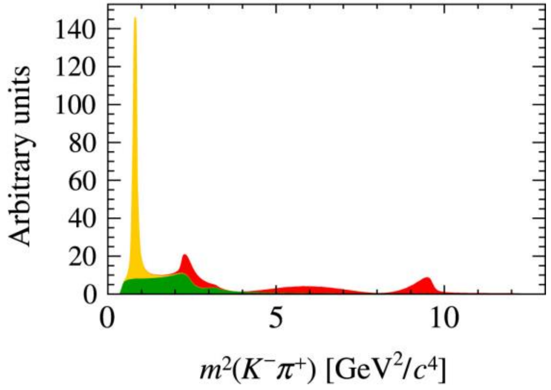
$K\pi$ S-wave

$K^*(892)$

$D^*_{s2}(2573)^-$

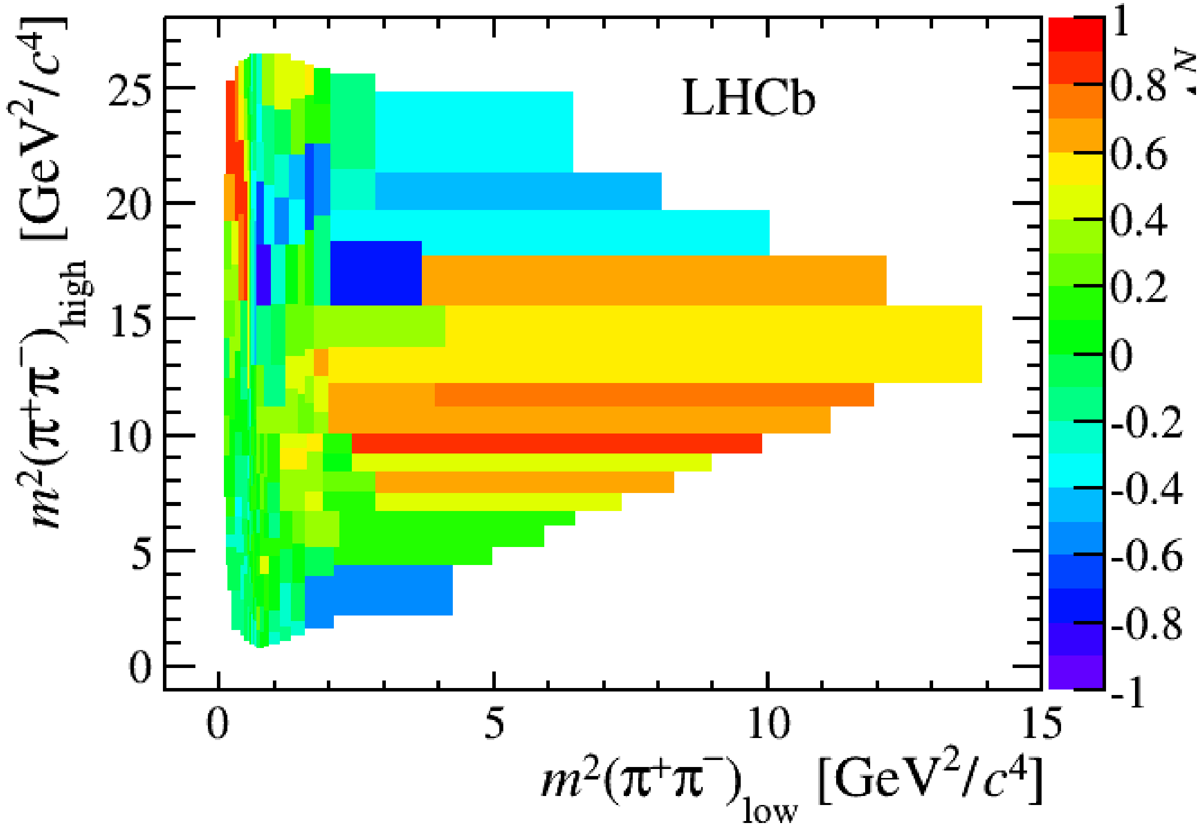


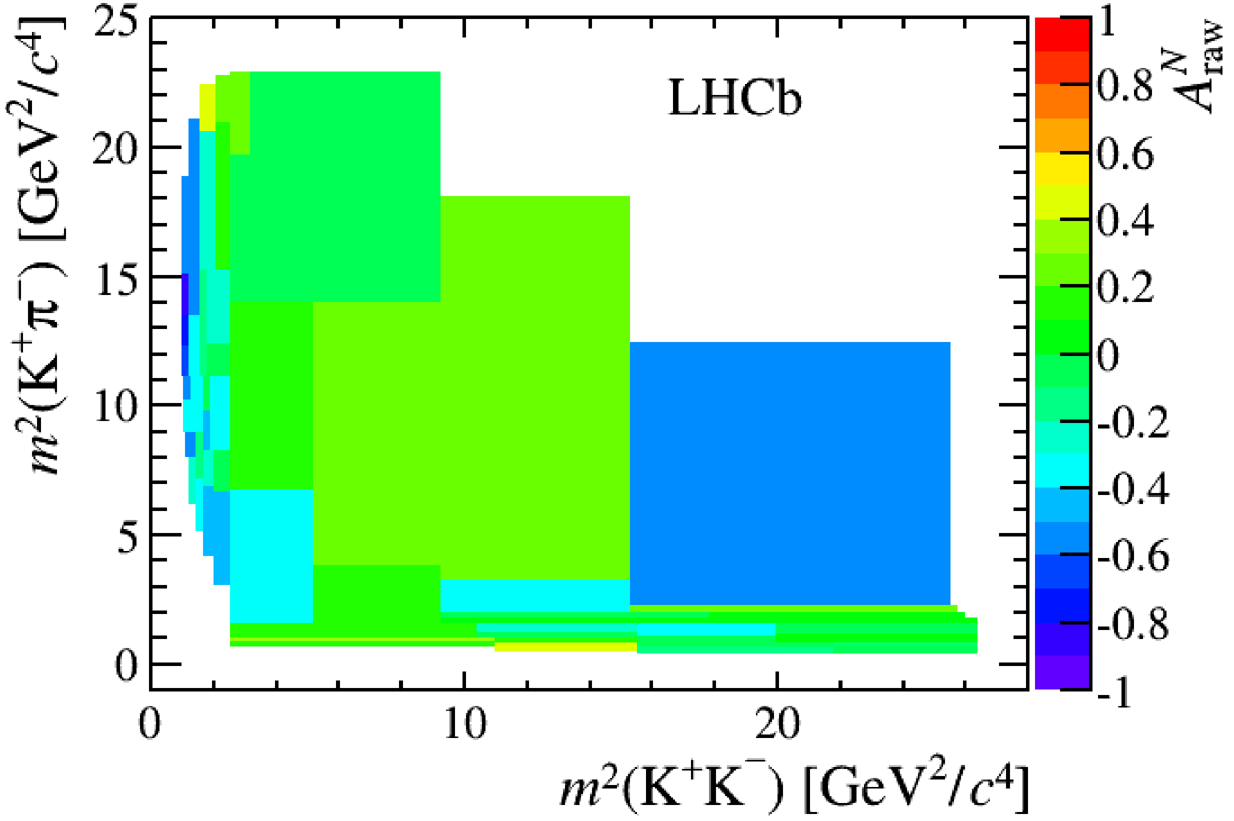




Phys. Rev. D90 (2014) 112004

Backup





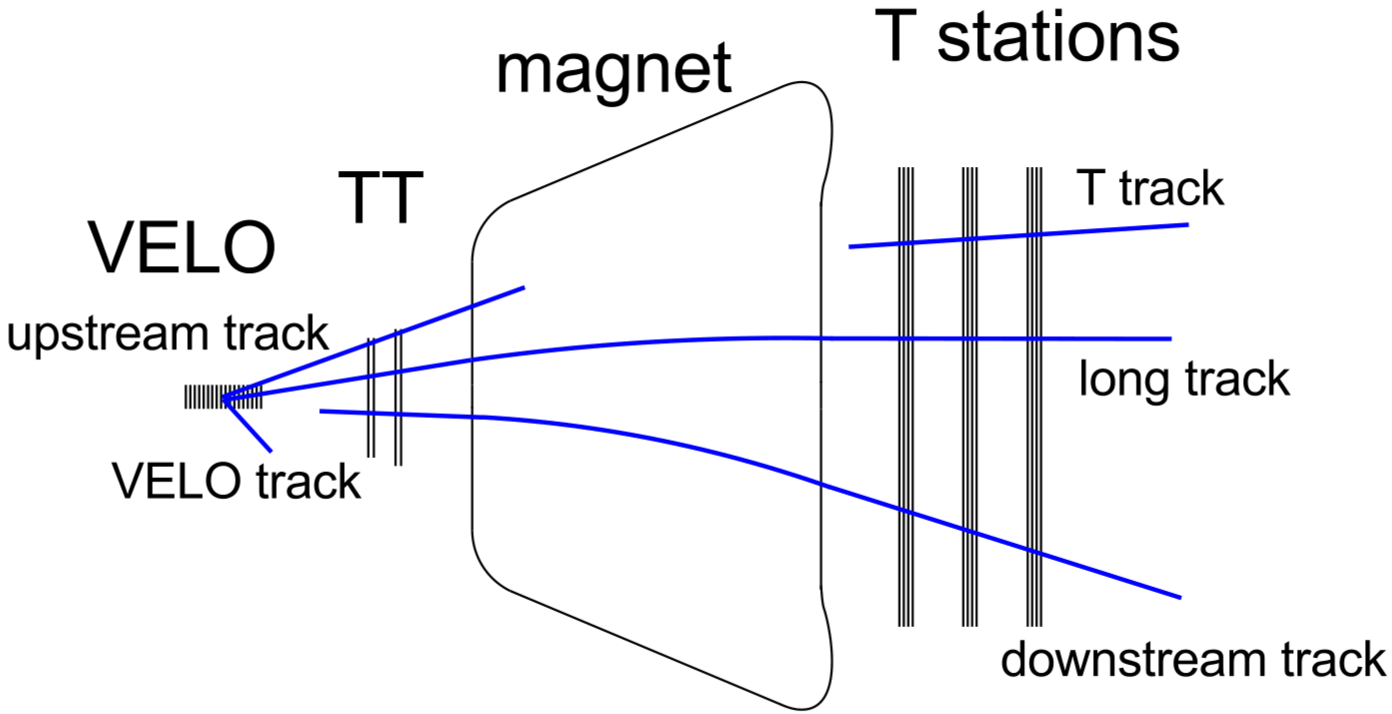
Backup

- Previous $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ measurements:

	$\mathcal{BF}$	A_{CP}
BaBar	$(5.0 \pm 0.5 \pm 0.5) \times 10^{-6}$	–
LHCb	–	$-0.123 \pm 0.017 \pm 0.012 \pm 0.007$
Belle	$(5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$	$-0.170 \pm 0.073 \pm 0.017$

BaBar [Phys. Rev. Lett. 99 (2007) 221801]
LHCb [Phys. Rev. D90 (2014) 112004]
Belle [Phys. Rev. D96 (2017) 031101]

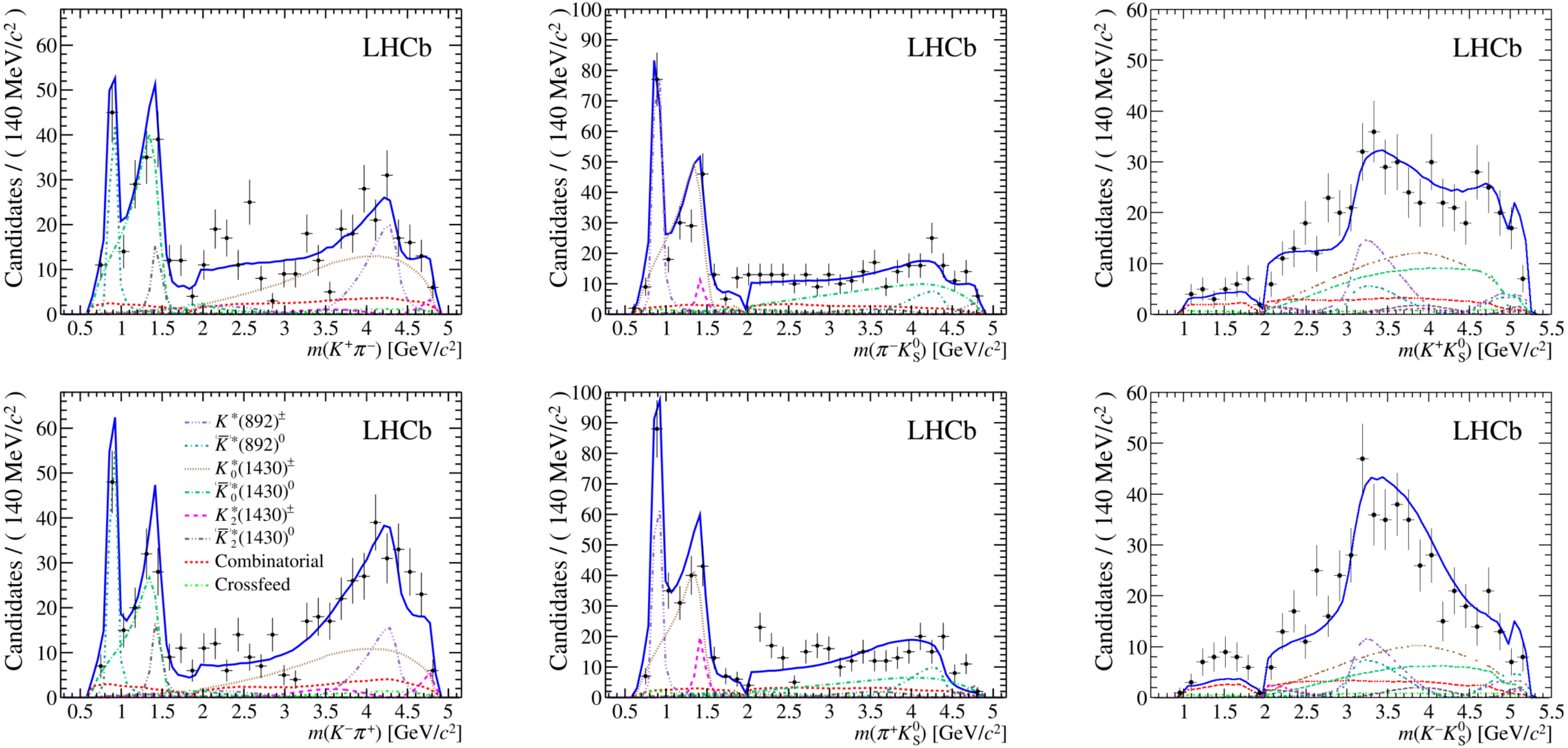
Backup



JINST 10 (2015) P02007

arxiv:1902.07955

Backup



Backup

arxiv:1902.07955

Resonance	Yields	Bkg.	Eff.	Fit bias	Add. res.	Fixed par.	Alt. model	Method	Total
	Fit fraction (%) uncertainties								
$K^*(892)^-$	0.2	0.2	0.5	0.2	–	0.7	5.4	3.1	6.3
$K_0^*(1430)^-$	0.1	0.2	0.6	0.3	0.1	2.1	22.0	2.9	22.3
$K_2^*(1430)^-$	0.1	0.1	0.3	0.6	0.1	1.8	2.2	0.2	2.9
$K^*(892)^0$	0.2	0.2	0.4	0.9	–	0.3	7.0	2.0	7.4
$K_0^*(1430)^0$	0.2	0.3	0.9	0.4	0.1	4.4	3.3	1.3	5.7
$K_2^*(1430)^0$	0.1	0.3	0.7	1.3	0.2	4.4	3.6	1.0	6.0
$K^*(892)^+$	0.4	0.1	0.6	0.5	0.1	0.7	1.1	0.7	1.8
$K_0^*(1430)^+$	0.5	0.4	0.7	0.8	0.2	6.4	13.0	4.5	15.2
$K_2^*(1430)^+$	0.1	0.2	0.4	0.2	0.1	4.1	4.5	3.2	6.9
$\overline{K}^*(892)^0$	0.4	0.3	0.4	0.2	0.2	0.5	3.0	7.9	8.5
$\overline{K}_0^*(1430)^0$	0.4	0.4	0.6	0.8	0.7	0.9	3.9	5.4	6.8
$\overline{K}_2^*(1430)^0$	0.1	0.2	0.4	0.8	0.1	1.0	5.5	2.7	6.3

LHCb-PAPER-2018-044 (in preparation)

Backup – $\Lambda_b^0, \Xi_b^0 \rightarrow$ 4-body

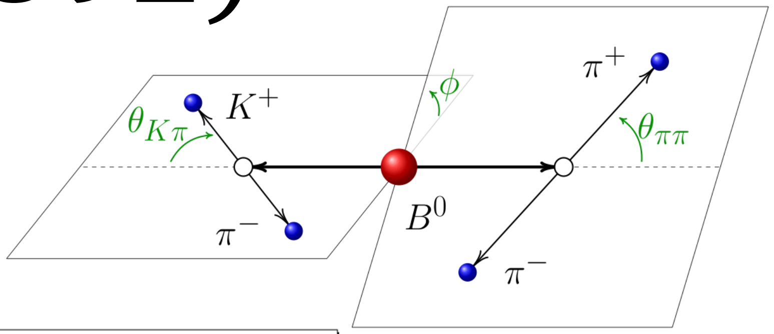
- CP violation search in 6 modes
- Measure difference in A_{CP} between charmless decay and decay with intermediate charm baryon
  - Cancel out detector+production charge asymmetries
- 18 CP asymmetries considered:
  - Inclusive A_{CP} of the six modes
  - A_{CP} in low two-body mass regions in the large-yield channels
  - A_{CP} in regions containing specific intermediate baryonic/mesonic resonances
- No significant CP violation observed
  - Contrast with evidence (3.3σ) seen previously in $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ using triple-product asymmetries
    - [Nature Physics 13 (2017) 391]

$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.1 \pm 2.5 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (3.2 \pm 1.1 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (-6.9 \pm 4.9 \pm 0.8)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+K^-) = (0.2 \pm 1.8 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) = (-16.8 \pm 10.4 \pm 0.6)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) = (-6.8 \pm 8.0 \pm 0.8)\,\%$$

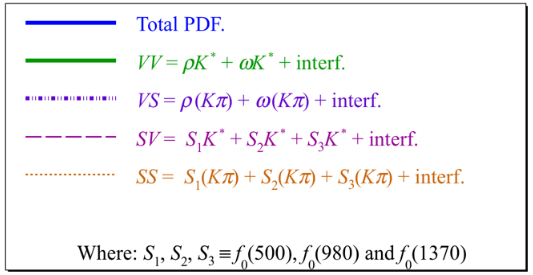
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (3.7 \pm 4.1 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (3.5 \pm 1.5 \pm 0.5)\,\%$$
$$\Delta\mathcal{A}^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) = (2.7 \pm 2.3 \pm 0.6)\,\%$$

LHCb preliminary

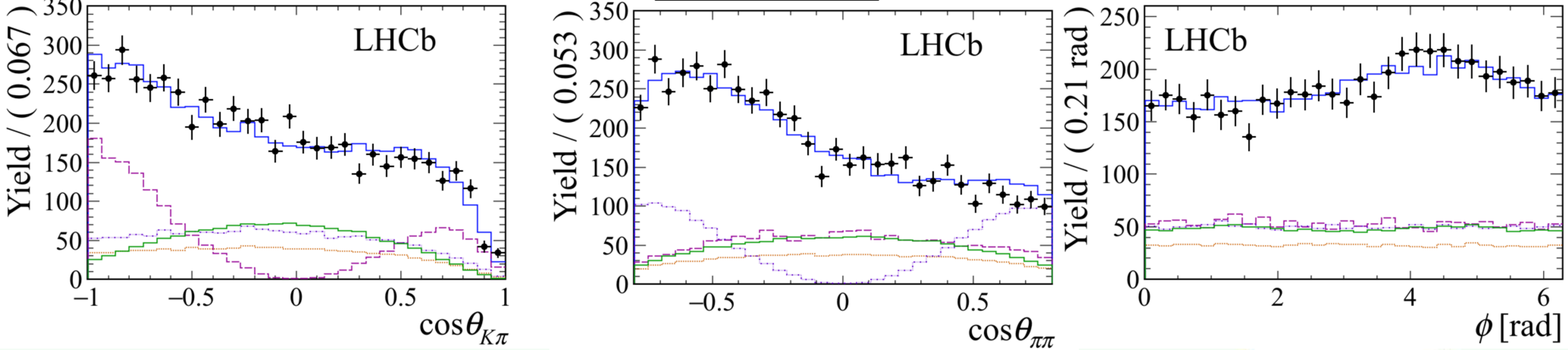
$Backup - B^0 \to \rho(770)^0 K^*(892)^0$



- First AA of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$
  - $300 < m(\pi^+\pi^-) < 1100\ \mathrm{MeV}/c^2$
  - $750 < m(K^+\pi^-) < 1200\ \mathrm{MeV}/c^2$
- Fit model includes 10 decay channels = 14 amplitudes
  - Each Vector-Vector wave contributes 3 amplitudes
  - GPU-based fit framework to deal with high-dimensionality



B^0 fit shown



$Backup - B^0 \rightarrow \rho(770)^0 K^*(892)^0$

arxiv:1812.07008

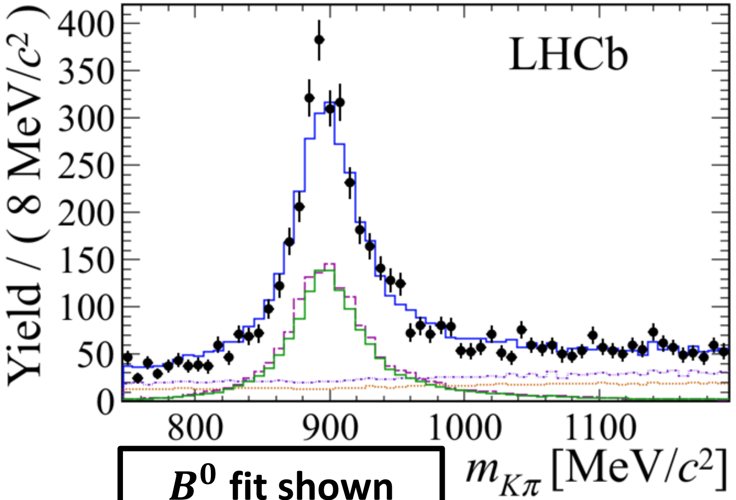
- Particularly small longitudinal polarisation fraction and significant direct CP asymmetry measured for $B^0 \rightarrow \rho(770)^0 K^*(892)^0$

$$\tilde{f}^0_{\rho K^*} = 0.164 \pm 0.015 \pm 0.022 \quad \text{and} \quad \mathcal{A}^0_{\rho K^*} = -0.62 \pm 0.09 \pm 0.09$$

$> 5\sigma$

- Parameters for $B^0 \rightarrow \omega K^{*0}$ also determined

$$\tilde{f}^0_{\omega K^*} = 0.68 \pm 0.17 \pm 0.16 \quad \text{and} \quad \mathcal{A}^0_{\omega K^*} = -0.13 \pm 0.27 \pm 0.13$$



B^0 fit shown