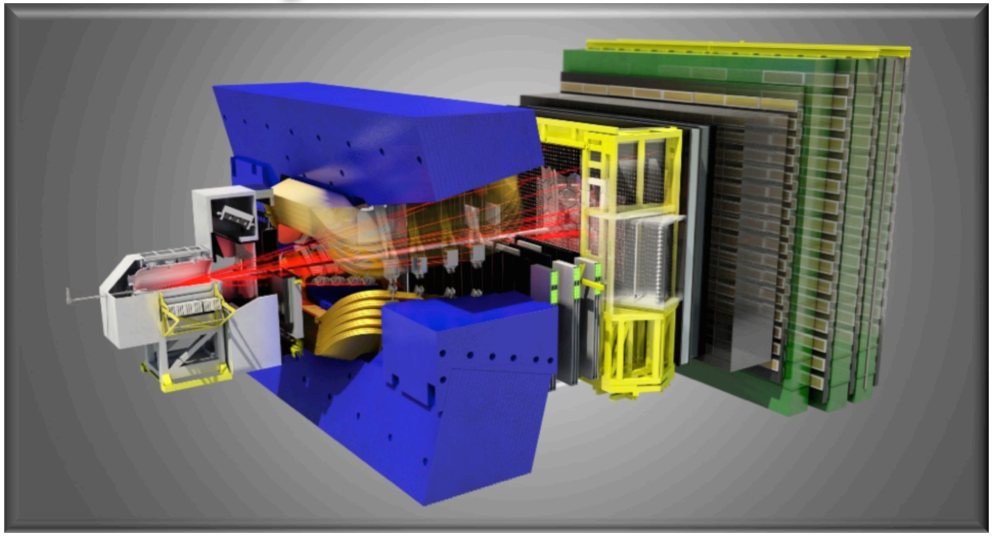
*10th International Workshop on the CKM Unitarity Triangle (CKM 2018)*
*Heidelberg, September 17-21, 2018*

# Dalitz plot analyses of $B^0_{(s)} \to K_S h^+ h'^-$ decays in *LHCb* ( $h^{(\prime)} = K / \pi$ )

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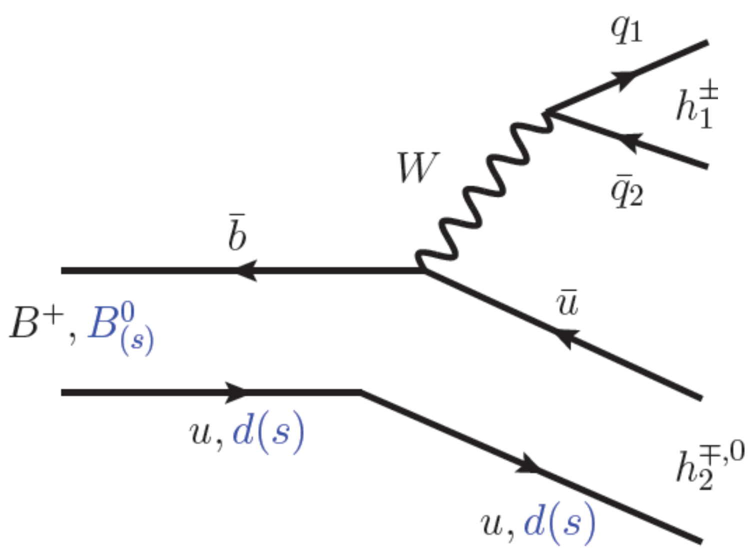
# Outline

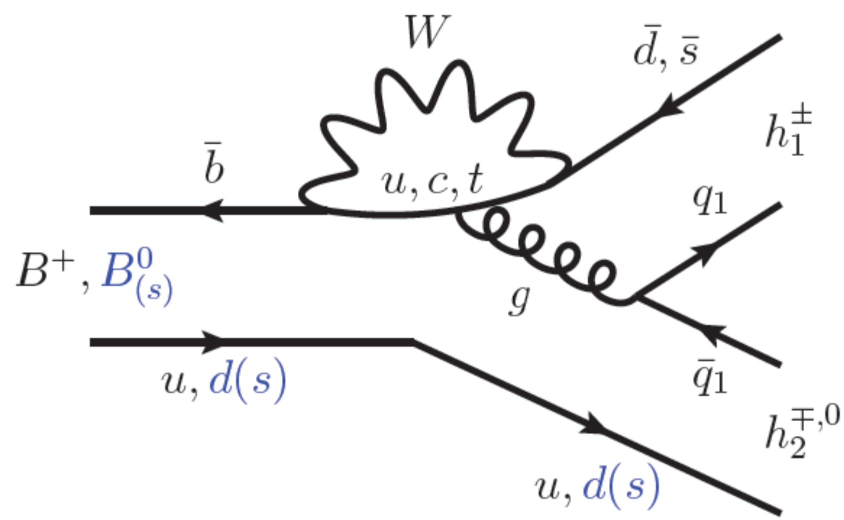
- General introduction
- Update of **$B^0_{(s)} \rightarrow K_S h^+ h'^-$ branching fractions** [JHEP 11 (2017) 027]
- **Amplitude analysis of $B^0 \rightarrow K_S \pi^+ \pi^-$ decays** and first observation of CP asymmetry in $B^0 \rightarrow K^*(892)^+ \pi^-$ [PRL. 120, 261801 (2018)]
- Conclusions, status and plans for Dalitz plot analyses of other $B^0_{(s)} \rightarrow K^0 h^+ h'^-$ decay modes

# General introduction

# Motivations (I)

- In LHCb
  - Large $b\bar{b}$ production cross section
  - Simultaneous analysis of $B^0_s$ and $B^0_d$ decays to $K_S h^+ h'^-$ ($h^{(')}$ = K / π)
- Transitions mediated by b → u (tree) and/or b → d,s (penguin) diagrams

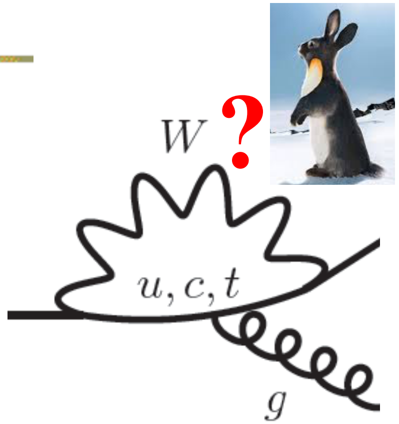



- Comparable amplitudes → interference that may result in large CP-violation effects
- In particular, these modes give access to the CKM angles $\beta$ ($K_S\pi^+\pi^-$, $K_S K^+ K^-$), $\beta_s$ ($B^0_s$ decays ), and γ (e.g., see talks from E. Bertholet and B. Bhattacharya)

# Motivations (II)

- New physics contributions may be present in loops and could significantly alter measured observables




**Comparison of measurements with standard model (SM) predictions may indicate new physics (NP) contributions and in any case constrain the parameter space of NP models**

- Challenge: small theoretical & experimental uncertainties for powerful comparison

- Dalitz-plot analyses allow to:
  - disentangle between intermediate (non) resonant contributions
  - measure their specific observables
  - measure phases between these contributions with no trigonometric ambiguities

**Access to many observables!**

# General strategy

Proceed in steps of increasing complexity, as allowed by the available dataset.

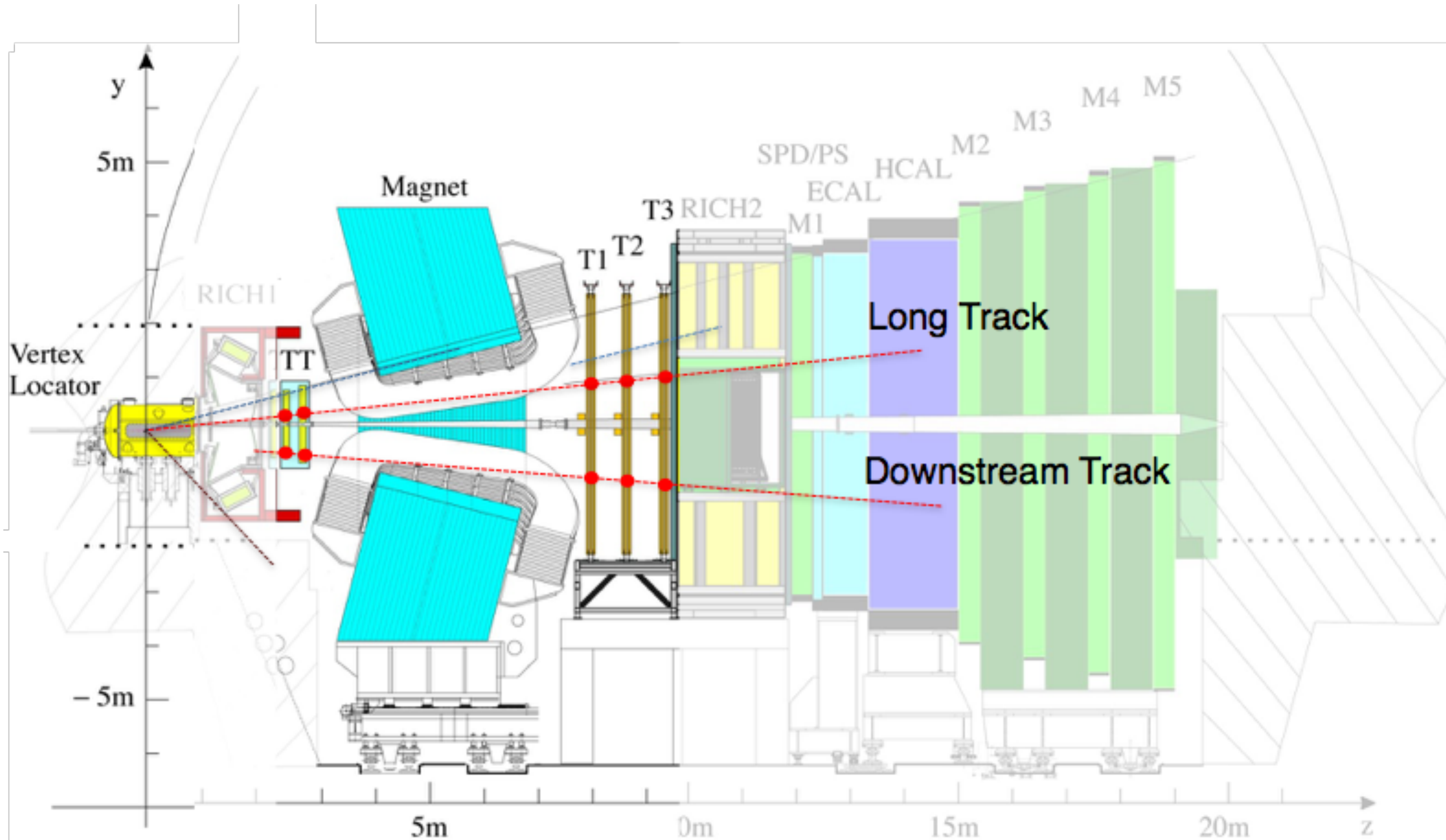
- First, measure branching fractions to prepare, and provide input for, the Dalitz-plot analyses of all $B^0_{(s)} \to K_S h^+ h'^-$ modes
- Time-integrated Dalitz-plot analyses, with no flavour tagging

Larger data sample → more complete model giving access to more observables

- Full time-dependent Dalitz-plot analyses, giving access to CKM phases

# $K_S$ reconstruction

- $K_S$ mesons are reconstructed via their decay to $\pi^+\pi^-$, either two "Long" or two "Downstream" $\pi$ tracks (2 $K_S$ "categories")



# Updated branching fraction measurements of

# $B^0_{(s)} \to K_S h^+ h'^-$

**(with 3 $fb^{-1}$)**

**[JHEP 11 (2017) 027]**

# Introduction of the analysis

$B_{d,s} \rightarrow K_S h^+ h^{-\prime}$, with $h^{(\prime)} = K / \pi \rightarrow$ 8 decays (6, considering $K_S K^{\pm}\pi^{\mp}$)

| | | | |
|---|---|---|---|
| $B_d \rightarrow K_S \pi^+ \pi^-$ | $B_d \rightarrow K_S K^+ \pi^-$ | $B_d \rightarrow K_S K^- \pi^+$ | $B_d \rightarrow K_S K^+ K^-$ |
| $B_s \rightarrow K_S \pi^+ \pi^-$ | $B_s \rightarrow K_S K^+ \pi^-$ | $B_s \rightarrow K_S K^- \pi^+$ | $B_s \rightarrow K_S K^+ K^-$ |

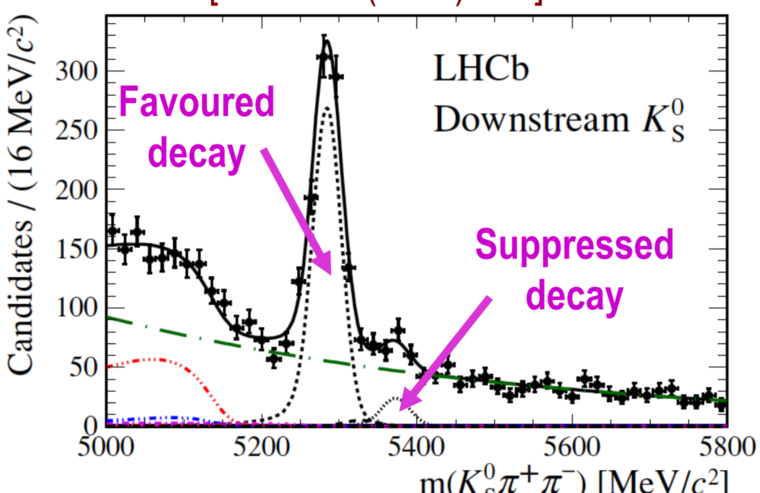
Favoured

Observed

~~Observed~~

(in previous LHCb analysis ($1 fb^{-1}$))

Previous LHCb analysis ($1 fb^{-1}$)
[JHEP 10 (2013) 143]




- Observed $B_s \rightarrow K_S \pi^+ \pi^-$.
- Confirmed $B_d \rightarrow K_S K^{\pm} \pi^{\pm}$.
- Observed $B_s \rightarrow K_S K^{\pm} \pi^{\pm}$.

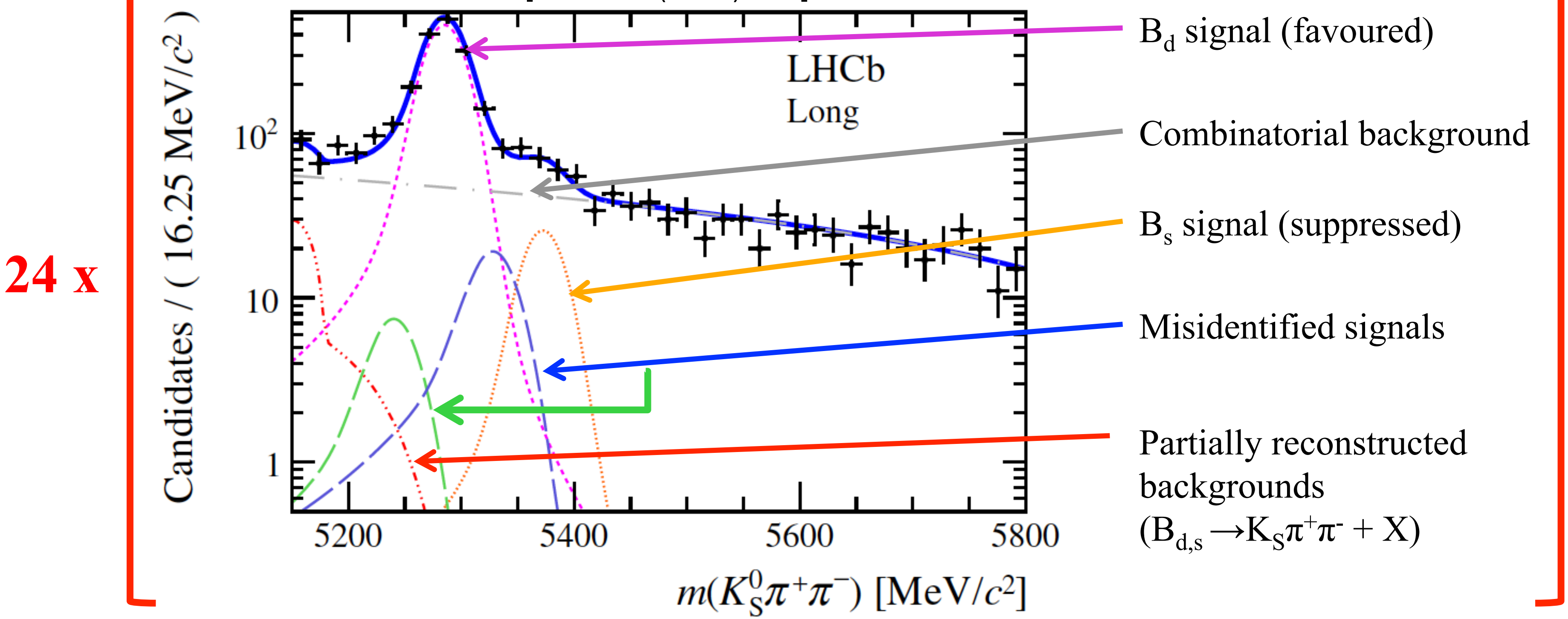
- Goals of the analysis using $3 fb^{-1}$:
  - update measurement of BFs
  - search for $B_s \rightarrow K_S K^+ K^-$
- Dataset divided into:
  - 4 final states
  - 2 $K_S$ reconstruction categories
  - 3 data-taking periods

→ **24 invariant-mass distributions**

# Analysis strategy

- Simultaneous fit of the 24 invariant mass spectra

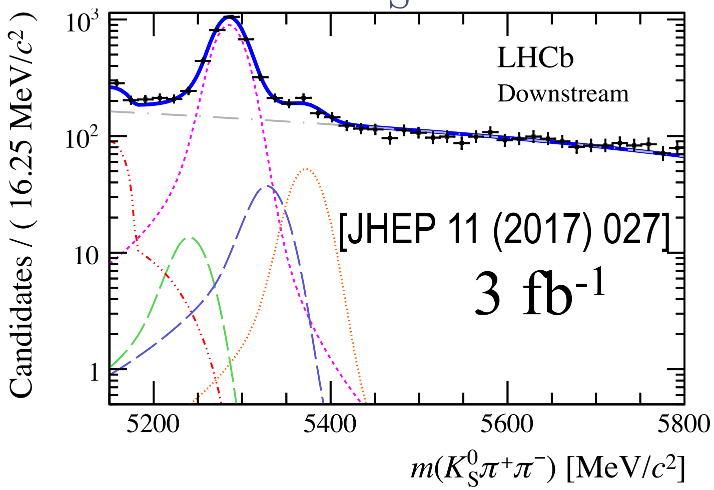
[JHEP 11 (2017) 027]



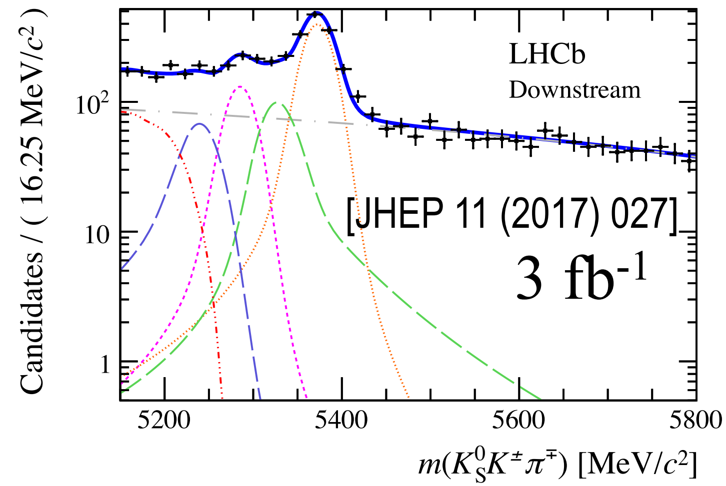

- Shapes taken from Monte-Carlo, except for combinatorial background
- $B_d$ and $B_s$ masses and widths from fit to data
- Gaussian constraints on yields of misidentified signal and partially reconstructed background
- Fast Monte-Carlo developed for partially reconstructed background modelling

# Results

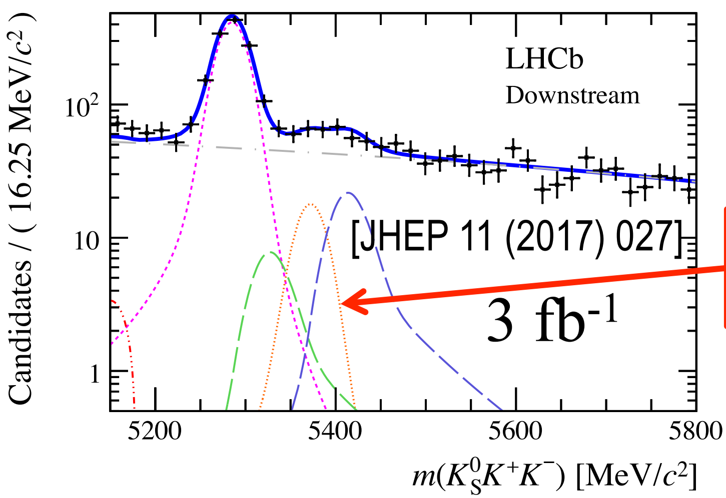
$B^0 \to K^0_S \pi^+ \pi^-$




$B^0_{(s)} \to K^0_S K^\pm \pi^\mp$




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




Five BFs are measured relative to that of $B^0 \to K_S\pi^+\pi^-$

All are compatible with previous results

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} \in [0.008 - 0.051] \text{ at } 90\% \text{ confidence level}$$

Significance: 2.5σ

# **Amplitude analysis of $B^0 \rightarrow K_S\pi^+\pi^-$ decays**

## and first observation of CP asymmetry in $B^0 \rightarrow K^*(892)^+\pi^-$

**(using 3 $fb^{-1}$)**

**[PRL. 120, 261801 (2018)]**

# Isobar model and formalism

- Intermediate resonances in P → 1 2 3 appear as structures in the Dalitz plot, characterized by their mass, width and spin

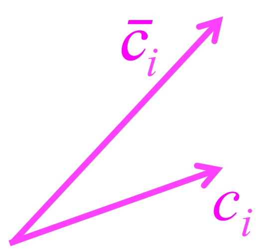
- Parameterization of amplitudes (isobar model):

$A = \Sigma\, c_i F_i (m^2_{13}, m^2_{23})$ B decays

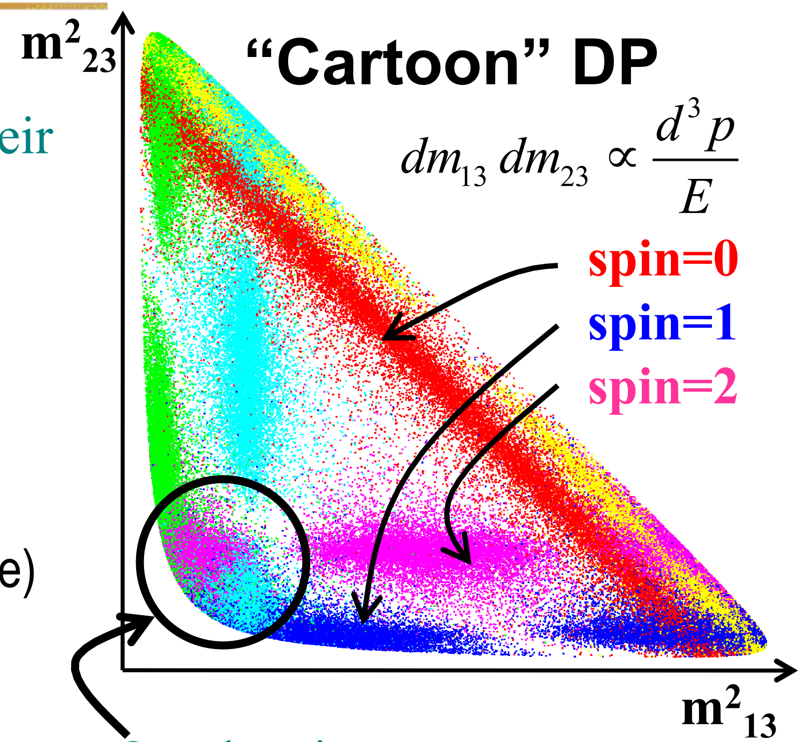
$\bar{A} = \Sigma\, \bar{c}_i F_i (m^2_{23} m^2_{13})$ $\bar{B}$ decays

complex coeffs. CP-violating | decay dynamics (e.g. Breit-Wigner) CP-conserving | ($i$ = intermediate state)

Directly extracted parameters: isobar coefficients $c_i$
Many observables ($A_{CP}$, BFs, …) are derived from these




$|c_i| \neq |\bar{c}_i|$
$\Rightarrow$ CP violation in decay



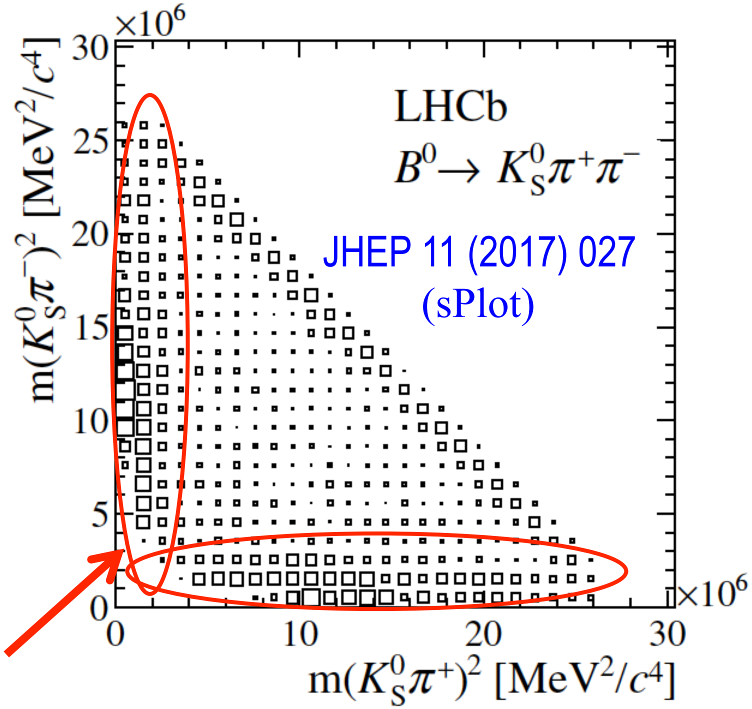

Overlapping resonant contributions
→ interference
→ access to relative phases with no ambiguity such as $\sin 2\beta_{\rm eff} = \sin(180° - 2\beta_{\rm eff})$ (time dependent analysis)

# Introduction of the analysis

- This mode contains intermediate states such as $\overline{B}^0 \to K^{*-}\pi^+$, which could shed light on the "K$\pi$ puzzle" (difference between $A_{CP}$ in $\overline{B}^0 \to K^-\pi^+$ and $B^- \to K^-\pi^0$)
Eur. Phys. J. C51 (2007) 55, Phys.Lett. B675 (2009) 59, Phys. Rev.D83 (2011) 034023, Phys. Lett. B682 (2009) 74

- Current statistics do not allow to use flavour tagging (power ~ 5% in LHCb)
→ analysis is time-integrated → involves incoherent sum of $B^0$ and $\overline{B}^0$ amplitudes

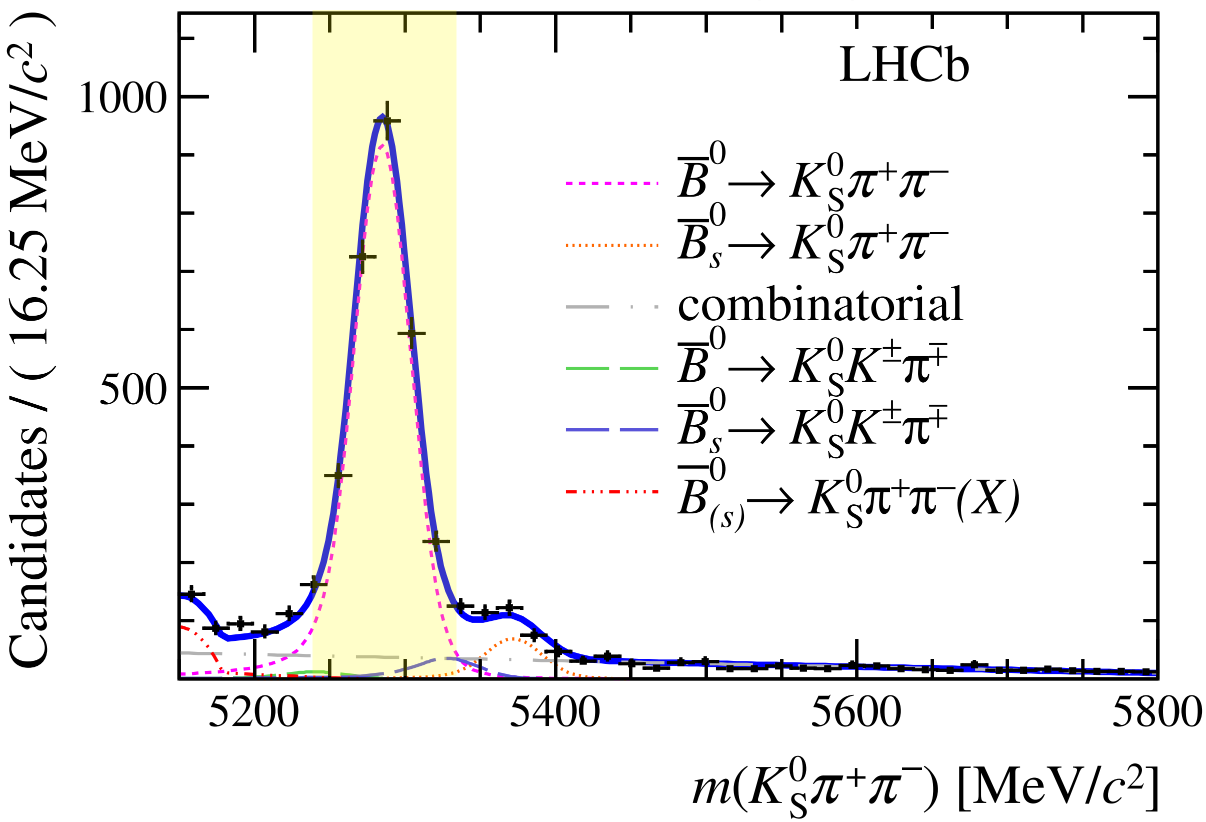
- CKM phases are thus not accessible, but direct CP asymmetries between flavour-specific (FS) states such as $\overline{B}^0 \to K^{*-}\pi^+$ and $B^0 \to K^{*+}\pi^-$ are measured




Flavour-specific states

# Signal and background

[PRL. 120, 261801 (2018)]




- Signal region for the Dalitz-plot fit: ±3σ around nominal mass
- ~3.2K signal events
- Event selection allows to obtain purity of 85-95%
- Backgrounds due to combinatorial (3-13%) and cross-feed (2-3%)

# Signal model and observables

| Resonance | Parameters | Lineshape |
|---|---|---|
| $K^*(892)^-$ | $m_0 = 891.66 \pm 0.26$<br>$\Gamma_0 = 50.8 \pm 0.9$ | RBW |
| Kπ S-wave $(K\pi)_0^-$ | $\mathcal{R}e(\lambda_0) = 0.204 \pm 0.103$<br>$\mathcal{I}m(\lambda_0) = 0$<br>$\mathcal{R}e(\lambda_1) = 1$<br>$\mathcal{I}m(\lambda_1) = 0$ | **EFKLLM** |
| $K_2^*(1430)^-$ | $m_0 = 1425.6 \pm 1.5$<br>$\Gamma_0 = 98.5 \pm 2.7$ | RBW |
| $K^*(1680)^-$ | $m_0 = 1717 \pm 27$<br>$\Gamma_0 = 332 \pm 110$ | Flatté |
| ππ S-wave $f_0(500)$ | $m_0 = 513 \pm 32$<br>$\Gamma_0 = 335 \pm 67$ | **RBW (Bugg model)** |
| $\rho(770)^0$ | $m_0 = 775.26 \pm 0.25$<br>$\Gamma_0 = 149.8 \pm 0.8$ | GS ] |
| $f_0(980)$ | $m_0 = 965 \pm 10$<br>$g_\pi = 0.165 \pm 0.025$ GeV<br>$g_K = 0.695 \pm 0.119$ GeV | Flatté |
| $f_0(1500)$ | $m_0 = 1505 \pm 6$<br>$\Gamma_0 = 109 \pm 7$ | RBW |
| $\chi_{c0}$ | $m_0 = 3414.75 \pm 0.31$<br>$\Gamma_0 = 10.5 \pm 0.6$ | RBW |
| Nonresonant (NR) | | Phase space |

EFKLLM: $$F_j(m) = F(m)\left(\frac{\lambda_0}{m^2} + \lambda_1\right)$$

Phys. Rev. D79 (2009) 094005

- Baseline model inspired by analysis from B-factories
  [Phys. Rev. D79 (2009) 072004, Phys. Rev. D80 (2009) 112001]
- Evaluated by add/remove algorithm
- Critical role of the (Kπ) S-wave
  →EFKLLM model
- From the raw asymmetry:

$$\mathcal{A}_{\rm raw} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2}$$

is derived the CP asymmetry:

$$\mathcal{A}_{CP} = \mathcal{A}_{\rm raw} - \mathcal{A}_\Delta$$
$$\mathcal{A}_\Delta = \mathcal{A}_P(B^0) + \mathcal{A}_D(\pi)$$

(-0.35 ± 0.81)% (0 ± 0.25)%

[$D_s^+$,PRL 110 (2013) 221601, PLB 713 (2012) 186]

- Fit fractions (CP averaged):

$$\mathcal{F}_i = \frac{\iint_{\rm DP} |c_i F_i(s_+, s_-)|^2 \, ds_+ ds_-}{\iint_{\rm DP} \left|\sum_j c_j F_j(s_+, s_-)\right|^2 ds_+ ds_-}$$

# Results: fit fractions

[PRL. 120, 261801 (2018)]

| | | |
|---|---|---|
| $\mathcal{F}(K^*(892)^-\pi^+)$ | $=$ | $9.43 \pm 0.40 \pm 0.33 \pm 0.34$ % |
| $\mathcal{F}((K\pi)_0^-\pi^+)$ | $=$ | $32.7 \pm 1.4 \pm 1.5 \pm 1.1$ % |
| $\mathcal{F}(K_2^*(1430)^-\pi^+)$ | $=$ | $2.45\ ^{+0.10}_{-0.08} \pm 0.14 \pm 0.12$ % |
| $\mathcal{F}(K^*(1680)^-\pi^+)$ | $=$ | $7.34 \pm 0.30 \pm 0.31 \pm 0.06$ % |
| $\mathcal{F}(f_0(980)K^0_S)$ | $=$ | $18.6 \pm 0.8 \pm 0.7 \pm 1.2$ % |
| $\mathcal{F}(\rho(770)^0K^0_S)$ | $=$ | $3.8\ ^{+1.1}_{-1.6} \pm 0.7 \pm 0.4$ % |
| $\mathcal{F}(f_0(500)K^0_S)$ | $=$ | $0.32\ ^{+0.40}_{-0.08} \pm 0.19 \pm 0.23$ % |
| $\mathcal{F}(f_0(1500)K^0_S)$ | $=$ | $2.60 \pm 0.54 \pm 1.28 \pm 0.60$ % |
| $\mathcal{F}(\chi_{c0}K^0_S)$ | $=$ | $2.23\ ^{+0.40}_{-0.32} \pm 0.22 \pm 0.13$ % |
| $\mathcal{F}(K^0_S\pi^+\pi^-)^{\rm NR}$ | $=$ | $24.3 \pm 1.3 \pm 3.7 \pm 4.5$ % |

stat. syst. model

Results in agreement with the measurements from the B factories (for components that can be compared)

- The resonances $K^*(1680)$ and $f_0(1500)$ were not included in this mode by B-factories

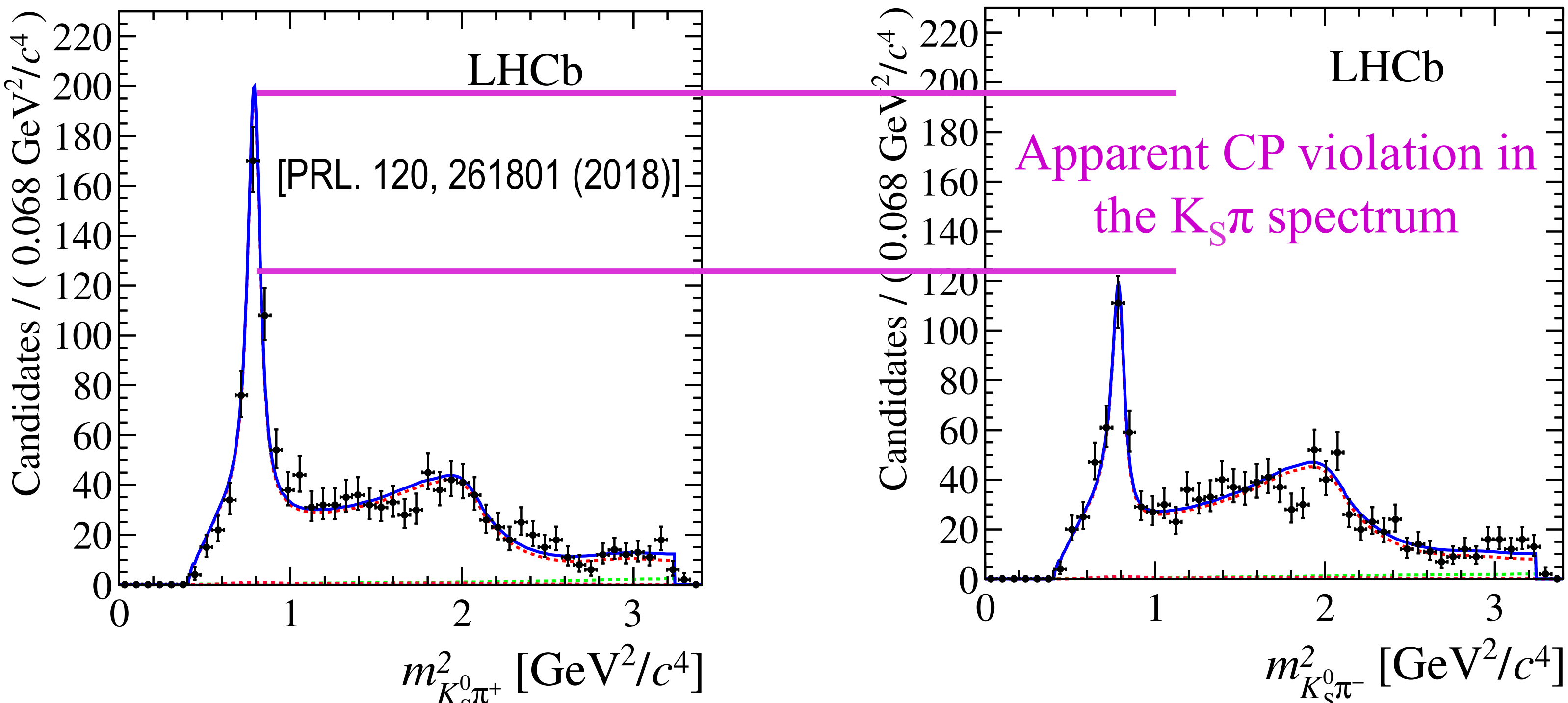
Belle PRD 79 (2009) 072004, BaBar PRD 80 (2009) 112001

- On the other hand, we see no significant sign of $f_2(1270)$
- Alternative LASS modelling for the S-wave has been examined and resulted in:

$$-2\Delta \ln \mathcal{L} = 85$$

- No systematic uncertainty is assigned to the choice of the $K\pi$ S-wave model
- Dominant model uncertainty is related to the $\pi\pi$ S-wave model

# Results: CP asymmetries




FS:

$$\mathcal{A}_{CP}(K^*(892)^-\pi^+) = -0.308 \pm 0.060 \pm 0.011 \pm 0.012$$
$$\mathcal{A}_{CP}((K\pi)_0^-\pi^+) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027$$
$$\mathcal{A}_{CP}(K_2^*(1430)^-\pi^+) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03$$
$$\mathcal{A}_{CP}(K^*(1680)^-\pi^+) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03$$

~~FS~~:

$$\mathcal{A}_{CP}(f_0(980)K^0_S) = 0.28 \pm 0.27 \pm 0.05 \pm 0.14$$

(stat. — syst. — model)

[PRL. 120, 261801 (2018)]

First observation of *CP* violation in $B^0 \to K^*(892)\pi$ with ~ 6σ

Consistent with SM predictions* and previous world average:

$$\mathcal{A}(K^*(892)\pi) = -0.23 \pm 0.06$$

*[JHEP09 (2008) 038; PRD78 034011 (2008), PRD91, 014011 (2015)]

# Summary, status and prospects

- An updated measurement of the $B^0_{(s)} \rightarrow K_S h^+ h'^-$ BFs with 3 $fb^{-1}$ is available
  → Only mode that is not yet observed: $B_s \rightarrow K_S K^+ K^-$ (significance: 2.5 $\sigma$)

- **First amplitude analysis of** $B^0 \rightarrow K_S \pi^+ \pi^-$ decays in a hadron collider
  → First observation (6 $\sigma$) of direct CP violation in $B^0 \rightarrow K^{*+}(892)\pi^-$

- Upcoming Dalitz-plot analyses
  - About to be published with Run-I (3 $fb^{-1}$):
    - $B_s \rightarrow K_S K^{\pm} \pi^{\mp}$ time-integrated, untagged — **First ever**
  - Analyses under way using Run-II data
    - $B^0 \rightarrow K_S K^+ K^-$ time-dependent (+ search for $B_s \rightarrow K_S K^+ K^-$ decays)
    - $B^0 \rightarrow K_S \pi^+ \pi^-$ time-dependent
    - $B_s \rightarrow K_S \pi^+ \pi^-$ time-integrated, untagged — **First ever**

> Run-II dataset (and beyond) will provide unprecedented insights for these modes

# Extras

# Measured branching fractions

BF of $B^0_{(s)} \to K_S h^+ h'^-$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.128 \pm 0.017\,(\text{stat.}) \pm 0.009\,(\text{syst.}),$$

$$\frac{\mathcal{B}(B^0 \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.385 \pm 0.031\,(\text{stat.}) \pm 0.023\,(\text{syst.}),$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S \pi^+\pi^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 0.29 \pm 0.06\,(\text{stat.}) \pm 0.03\,(\text{syst.}) \pm 0.02\,(f_s/f_d),$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} = 1.48 \pm 0.12\,(\text{stat.}) \pm 0.08\,(\text{syst.}) \pm 0.12\,(f_s/f_d),$$

$$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)} \in [0.004; 0.068] \text{ at } 90\% \text{ CL}.$$

Using world average for $B^0 \to K_S\pi^+\pi^-$

$$\mathcal{B}(B^0 \to K^0 K^\pm \pi^\mp) = (6.4 \pm 0.9 \pm 0.4 \pm 0.3) \times 10^{-6},$$

$$\mathcal{B}(B^0 \to K^0 K^+ K^-) = (19.1 \pm 1.5 \pm 1.1 \pm 0.8) \times 10^{-6},$$

$$\mathcal{B}(B^0_s \to K^0 \pi^+\pi^-) = (14.3 \pm 2.8 \pm 1.8 \pm 0.6) \times 10^{-6},$$

$$\mathcal{B}(B^0_s \to K^0 K^\pm \pi^\mp) = (73.6 \pm 5.7 \pm 6.9 \pm 3.0) \times 10^{-6},$$

$$\mathcal{B}(B^0_s \to K^0 K^+ K^-) \in [0.2; 3.4] \times 10^{-6} \text{ at } 90\% \text{ CL},$$

# BABAR signal model

$B^0 \to K_S \pi^+ \pi^-$

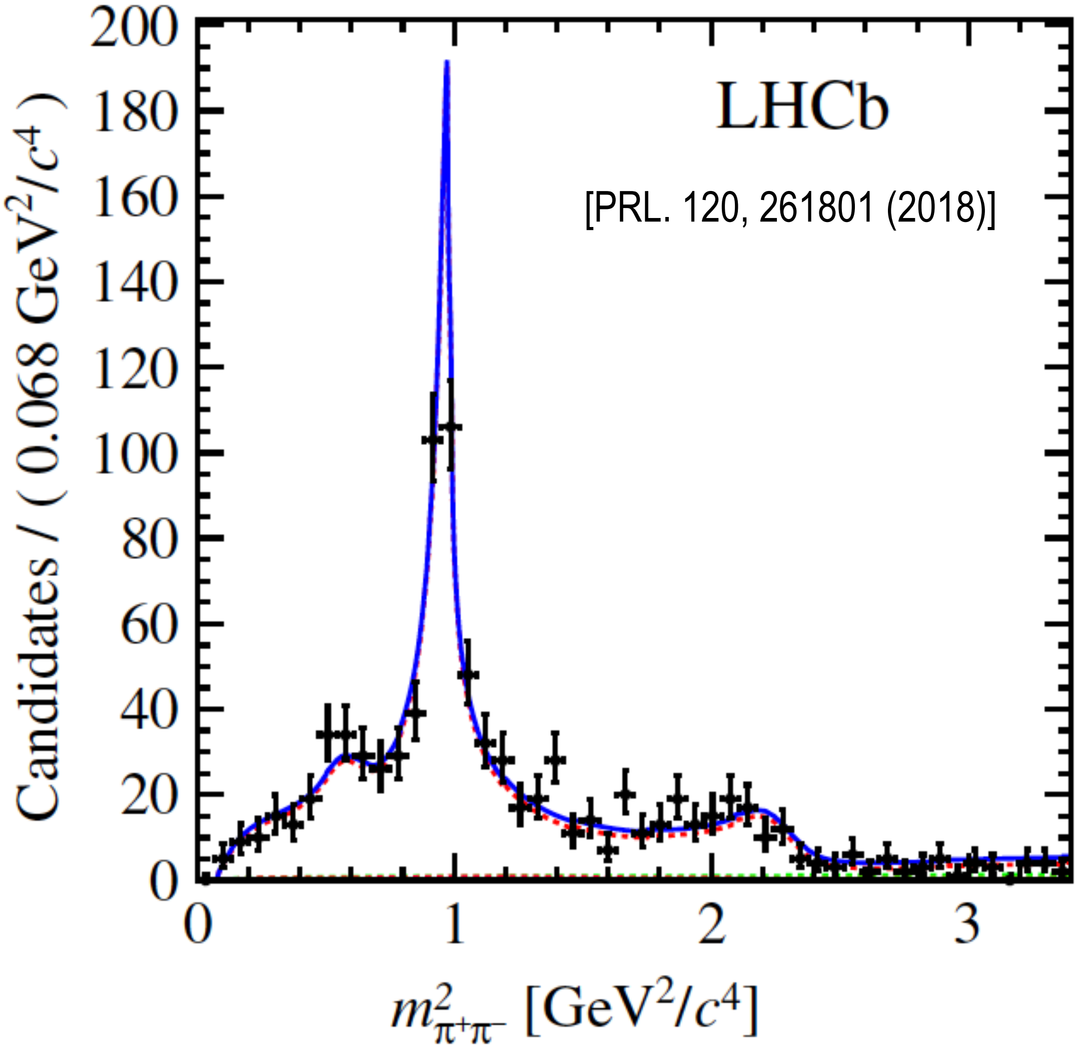
PRD 80, 112001 (2009)

TABLE I. Parameters of the DP model used in the fit. Values are given in MeV/($c^2$), unless mentioned otherwise. The mass and width for the $f_X(1300)$ are averaged from results in $B^+ \to K^+\pi^-\pi^+$ Dalitz analyses [27,28].

| Resonance | Parameters | Line shape | Ref. for Parameters |
|---|---|---|---|
| $f_0(980)$ | $m_0 = 965 \pm 10$<br>$g_\pi = 165 \pm 18$<br>$g_K = 695 \pm 93$ | Flatté | [31] |
| $\rho^0(770)$ | $m_0 = 775.5 \pm 0.4$<br>$\Gamma_0 = 146.4 \pm 1.1$<br>$r = 5.3^{+0.9}_{-0.7}$ (GeV/$c$)$^{-1}$ | GS | [32] |
| $K^{*+}(892)$<br>$K^{*-}(892)$ | $m_0 = 891.66 \pm 0.26$<br>$\Gamma_0 = 50.8 \pm 0.9$<br>$r = 3.6 \pm 0.6$ (GeV/$c$)$^{-1}$ | RBW | [32] |
| $(K\pi)_0^{*+}$<br>$(K\pi)_0^{*-}$ | $m_0 = 1415 \pm 3$<br>$\Gamma_0 = 300 \pm 6$<br>$m_{K\pi}^{\mathrm{cutoff}} = 1800$<br>$a = 2.07 \pm 0.10$ (GeV/$c$)$^{-1}$<br>$r = 3.32 \pm 0.34$ (GeV/$c$)$^{-1}$ | LASS | [27] |
| $f_2(1270)$ | $m_0 = 1275.4 \pm 1.1$<br>$\Gamma_0 = 185.2^{+3.1}_{-2.5}$<br>$r = 3.0$ (GeV/$c$)$^{-1}$ | RBW | [32] |
| $f_X(1300)$ | $m_0 = 1471 \pm 7$<br>$\Gamma_0 = 97 \pm 15$ | RBW | [27,28] |
| NR decays | | flat phase space | |
| $\chi_{c0}$ | $m_0 = 3414.75 \pm 0.35$<br>$\Gamma_0 = 10.4 \pm 0.7$ | RBW | [32] |

# $m^2(\pi\pi)$

$B^0 \to K_S\pi^+\pi^-$



# Analysis strategy

$B^0 \rightarrow K_S\pi^+\pi^-$

- Define a signal window around $B^0$ signal peak (3 standard deviations of the resolution model) in the invariant mass spectrum of $K_S\pi\pi$ candidates
- Determine from the mass fit the signal fraction and build the distribution of combinatorial backgrounds in the DP of $B^0 \rightarrow K_S\pi\pi$, from the RHSB.
- Determine, in addition, from the invariant mass distribution fits, the empirical data-driven $B_s \rightarrow K_S K\pi$ DP distribution to model the cross-feed background component in the $B^0 \rightarrow KS\pi\pi$ DP.
- Obtain the histogram of the whole selection efficiency variation across the DP, evaluated from simulated events.
- Fit simultaneously the six category data samples and educate the final model by adding relevant new contributions to the baseline and decide on the basis of a tentatively objective algorithm to keep the resonance or not.

# Systematic uncertainties

$B^0 \rightarrow K_S\pi^+\pi^-$

- Quantified effects from:
  - biases related to the Dalitz fit to the data,
  - the fraction of signal/background extracted from the mass fit,
  - uncertainties on the selection and tracking efficiency across the SDP,
    ➔dominant (MC statistics)
  - uncertainty on the combinatorial background across the SDP.

- Signal model uncertainties
  - Fixed parameters of the line shapes
  - Addition /removal of marginal components to the nominal model
  - alternative models for the $\pi\pi$ $S$-wave
    ➔dominant