# Charmless three-body B-meson decays

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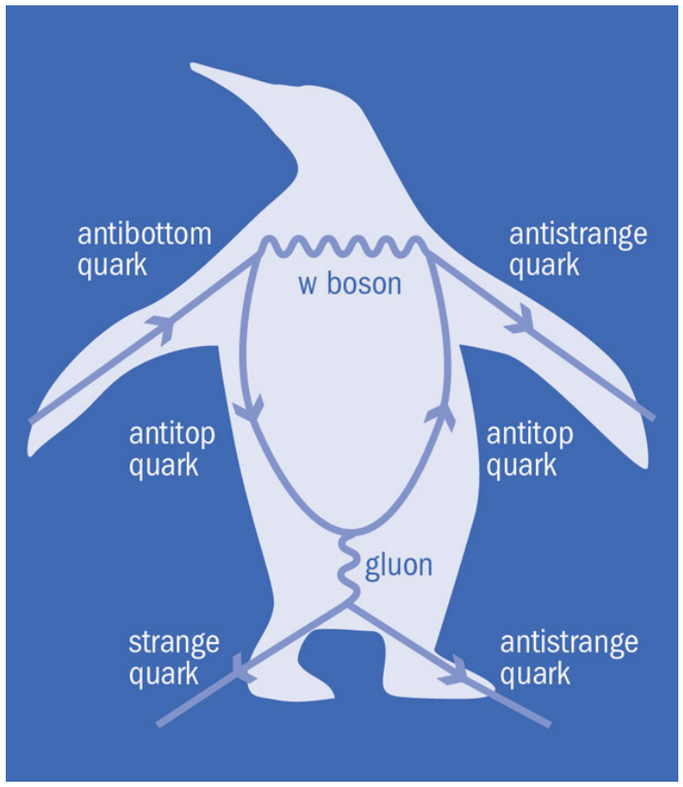
*ICHEP 2018, Seoul*

# Why charmless decays?

- Suppressed in the Standard Model:
  loop and tree diagrams of a similar magnitude

- $b \to s$ and $b \to d$ loop diagrams carry a *different* weak phase to those in the tree diagrams

- Different strong and weak phases can lead to large CP-violation in decay



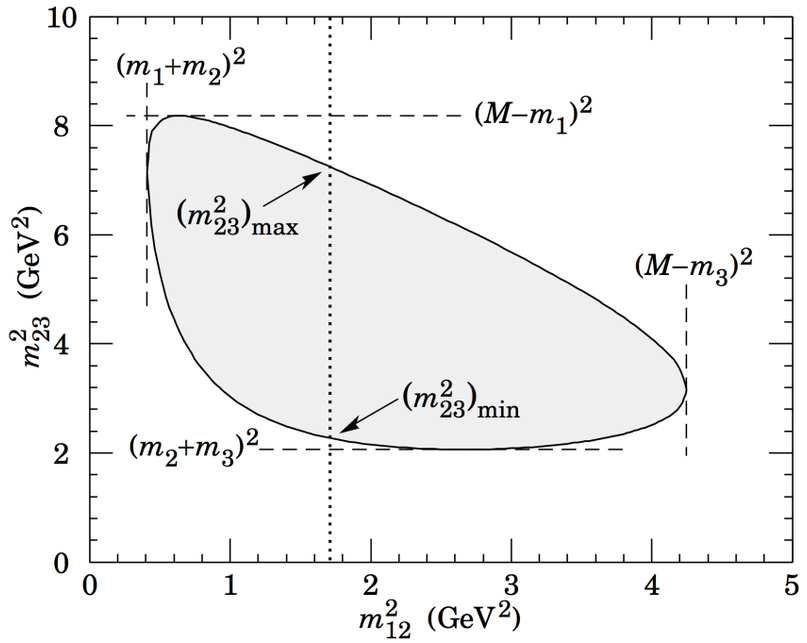

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B} \to \overline{f}) - \Gamma(B \to f)}{\Gamma(\overline{B} \to \overline{f}) + \Gamma(B \to f)}$$

$$= \frac{2|A_1||A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1||A_2| \cos\delta \cos\phi},$$

- Inputs to constrain CKM angles, in particular, determinations of $\gamma$ sensitive to new physics

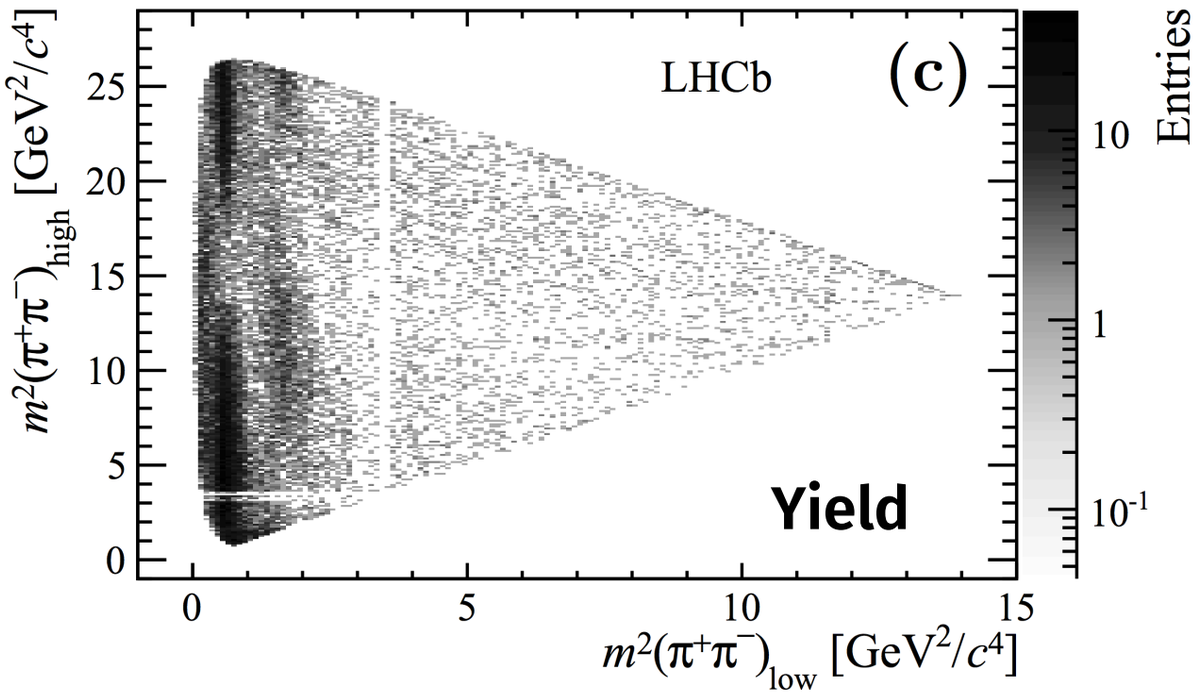
# Why multibody decays?

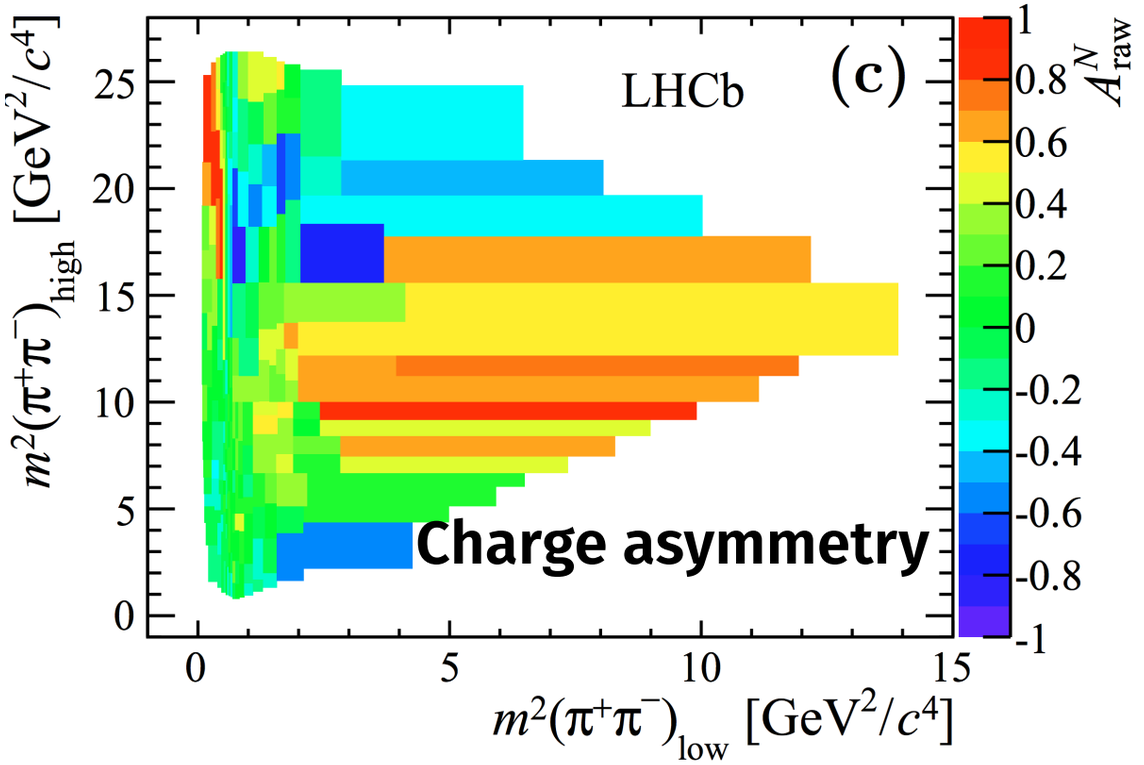
- Intermediate resonances and short distance QCD effects result in a strong phase variation across the *Dalitz* plot




**CPV in decay!**

$B^+ \to \pi^+\pi^+\pi^-$ data (Phys. Rev. D 90, 112004 (2014)):



# The $B \to K^0_S h^+ h^-$ decays (3 fb$^{-1}$)

$(h \in [\pi, K])$

- Central to many proposed new-physics sensitive measurements using hadronic decays:

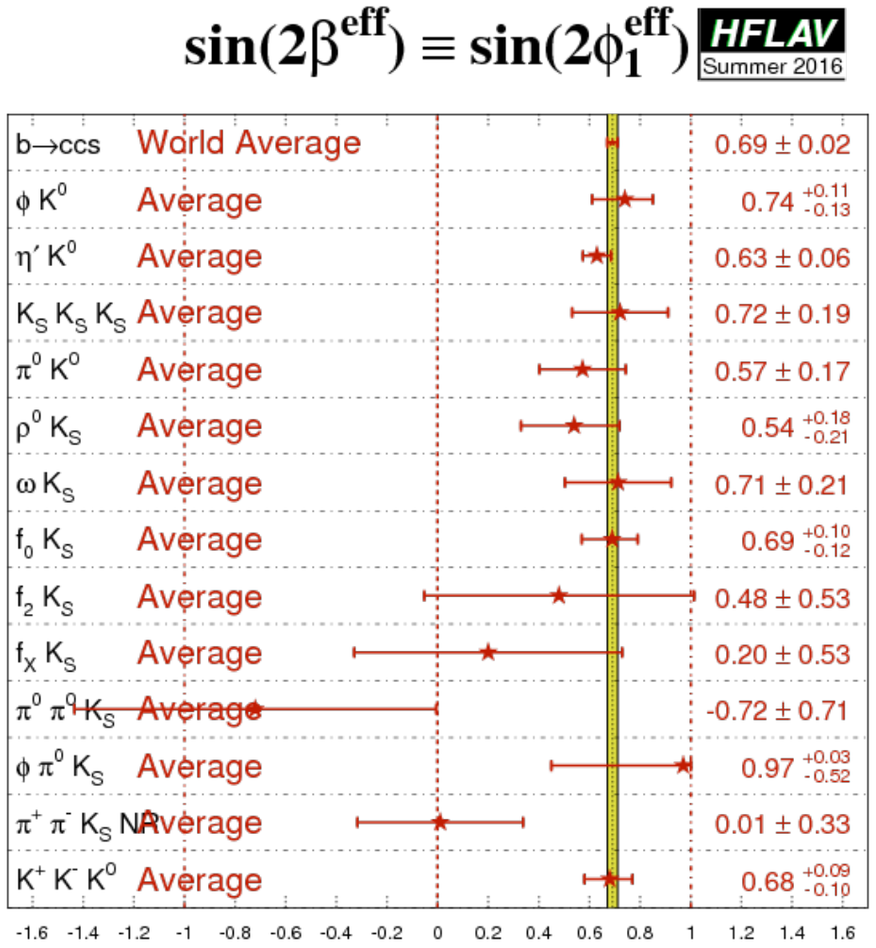
  - $\beta_{\text{eff}}$ in $B^0 \to \phi K^0_S$ and $B^0 \to \rho^0 K^0_S$ decays expected to be similar to that in $b \to c\bar{c}s$ in the SM

*(PLB 407 (1997) 61, arXiv:hep-ph/9704277),*

*(PLB 620 (2005) 143, arXiv:hep-ph/0505075)*

...and similarly for the $B^0_s$ decays

*(PRL 100 (2008) 031802, arXiv:hep-ph/0703137)*



# The $B \to K^0_S h^+ h^-$ decays

- Potential to measure $\gamma$ when combined with other charmless decay modes:
  - Gives relative $B^0, \overline{B}^0$ phase in a measurement using $B^0 \to K^{*-}\pi^+$

    *(Phys.Rev. D74 (2006) 051301, arXiv:hep-ph/0601233)*

  - A similar analysis with $B^0_s$ decays, using $B^0_s \to K^0_S \pi^+ \pi^-$ , can obtain a clean measurement of $\gamma$, without the need for time-dependence

    *(Phys.Lett.B645:201-203,2007, arXiv:hep-ph/0602207), (Phys.Rev.D75:014002,2007, arXiv:hep-ph/0608243)*

  - Instead of isospin, one can also relate decays via U-spin/SU(3)

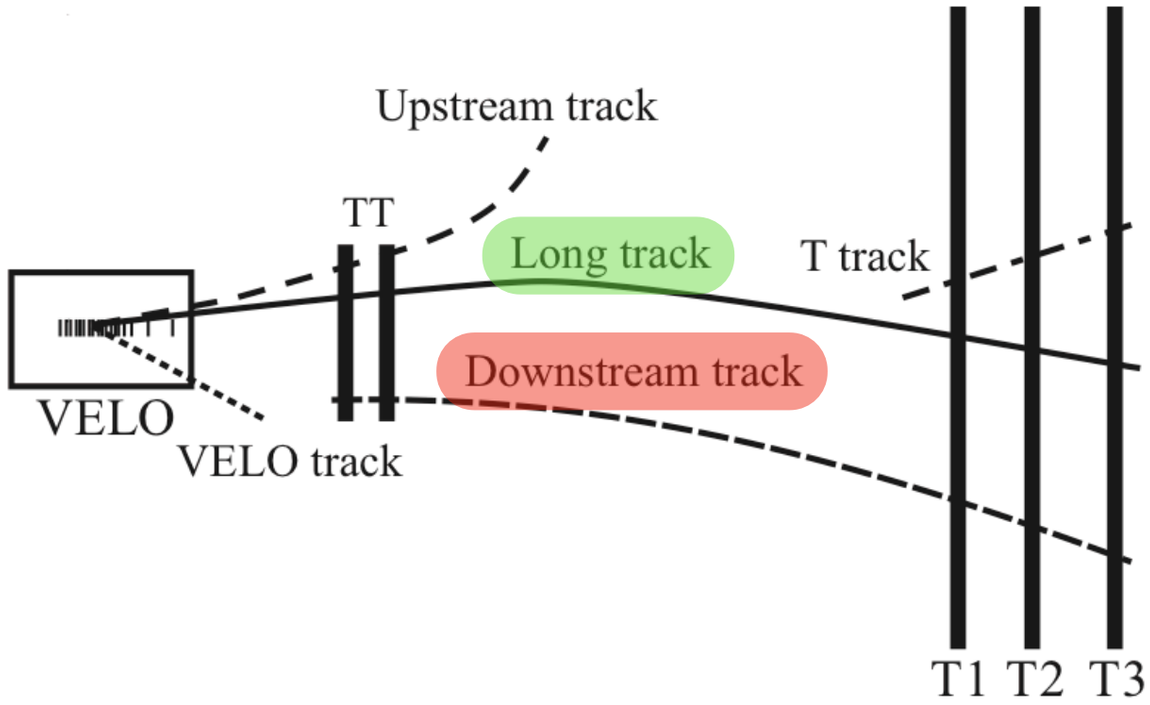
    *(JHEP04 (2015) 154, arXiv:1503.00737), (Phys. Rev. D 89, 074043 (2014), arXiv:1402.2909)*

- $B^0$ decays first observed by B-factories, previous measurements by LHCb have been observations of $B^0_s$ decays and branching fraction measurements *(JHEP. 10 (2013) 143, arXiv:1307.7648)*

**Out of all $B^0$ and $B^0_s$ decays, $B^0_s \to K^0_S K^+ K^-$ remained unobserved**

# A note about $K^0_S$ mesons at LHCb

- $K^0_S$ mesons are long lived, $\tau_{K^0_S} \sim 90$ ps, and therefore many decay *downstream* of the vertex locator acceptance




**Here:**
**DD:LL ~ 2:1**

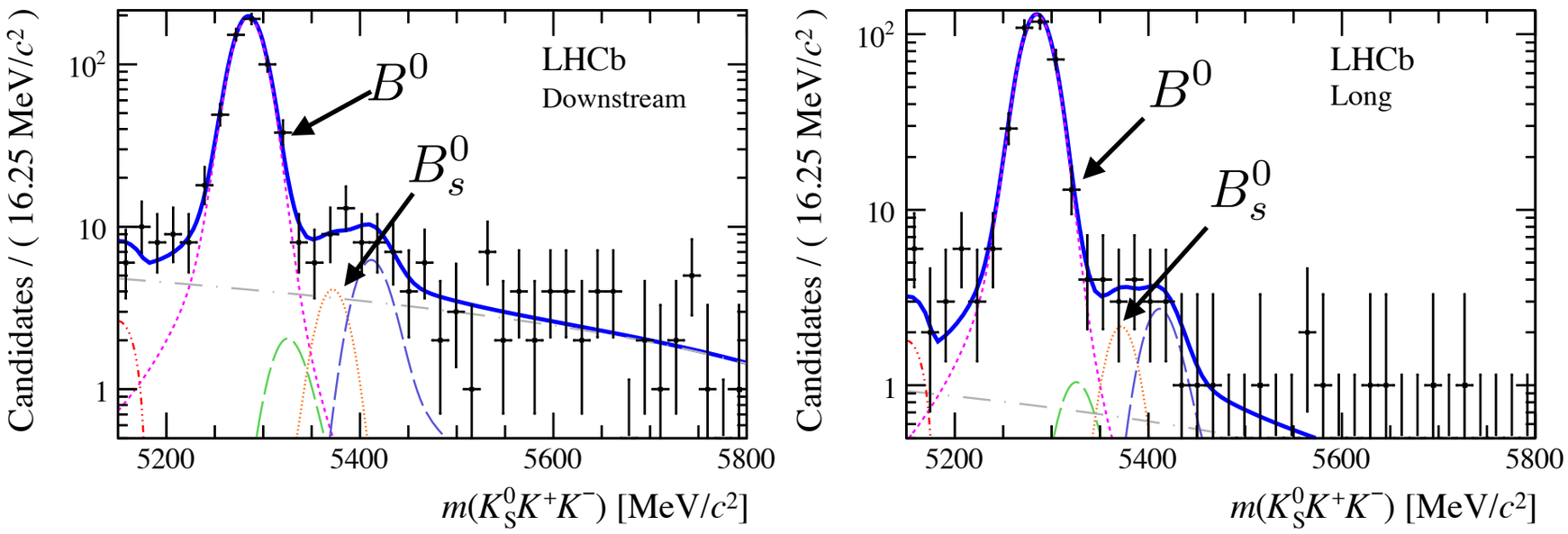
- Those reconstructed with *downstream* or *long* pion tracks have efficiencies calculated separately, but enter a simultaneous fit and are combined for the final measurements

# $B \to K^0_S h^+ h^-$ branching fractions

**JHEP (2017) 2017:027 / arXiv:1707.01665**

- Update of previous result to the full Run 1 LHCb dataset (3 $fb^{-1}$)
- Boosted decision-tree classifier trained to reduce combinatorial background - requirement optimised separately for favoured and suppressed decays
- Charged particle ID used to separate final states

$K^0_S K^+ K^-$ **(tight)**

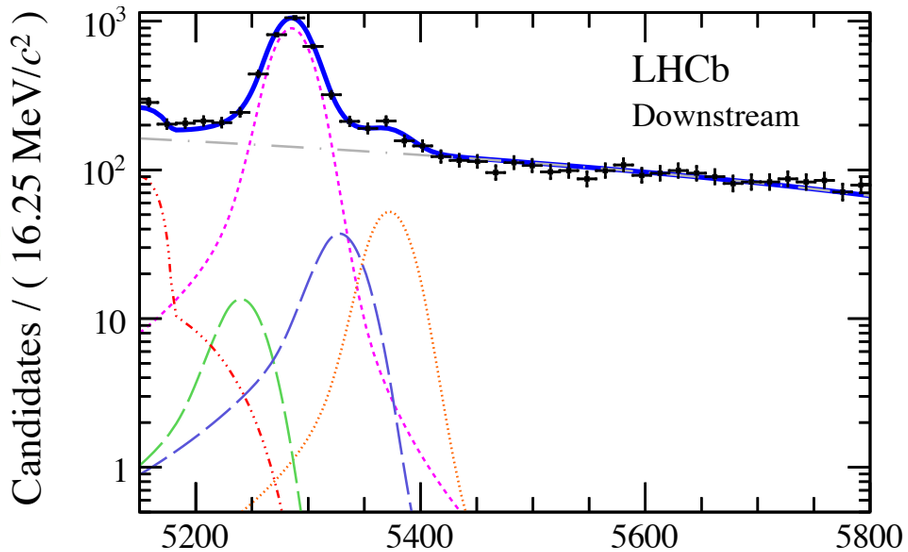


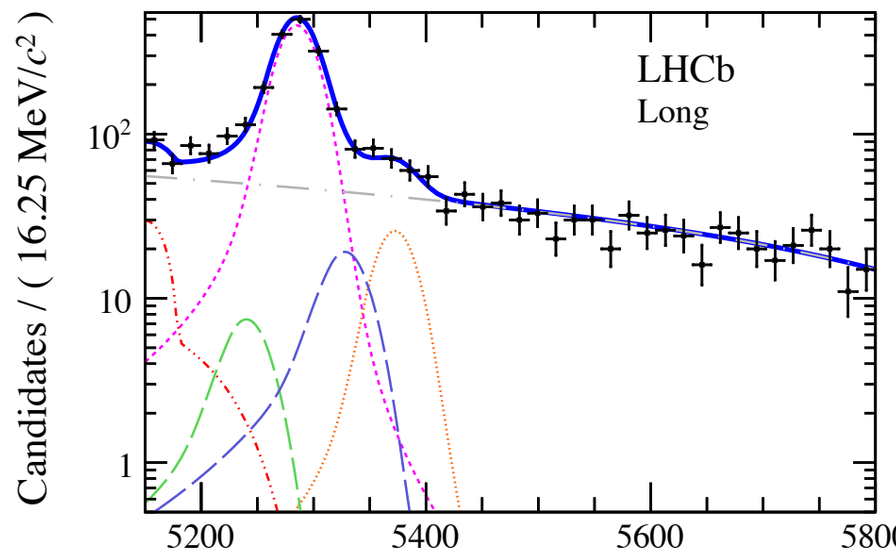

- Unfortunately no $B^0_s \to K^0_S K^+ K^-$ signal observed (19 ± 7 candidates, 2.5σ)

# $B \to K^0_S h^+ h^-$ branching fractions

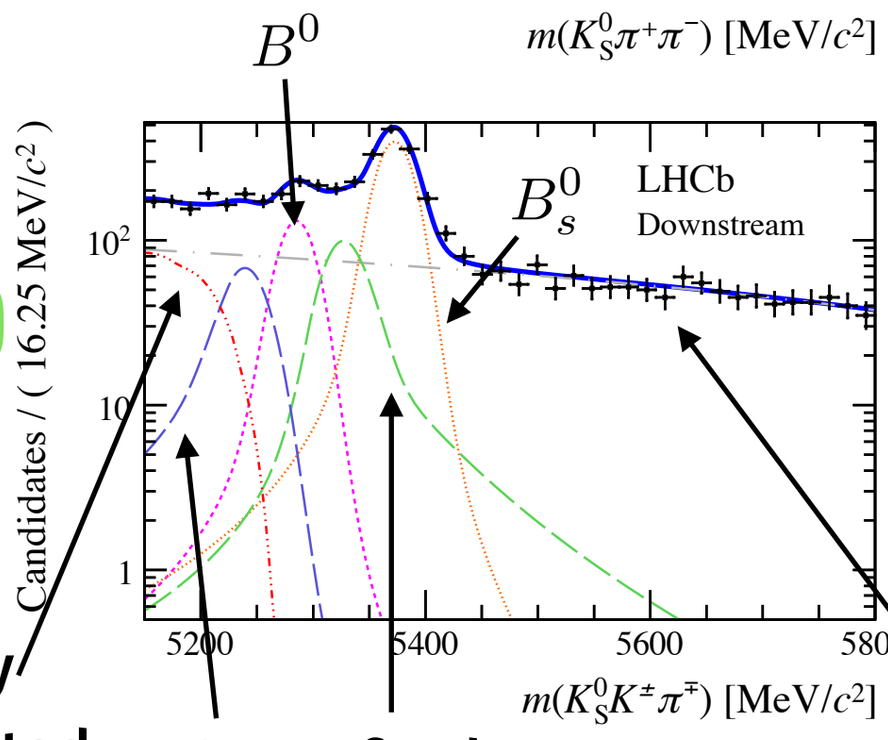
- Other final states (loose selection criteria):

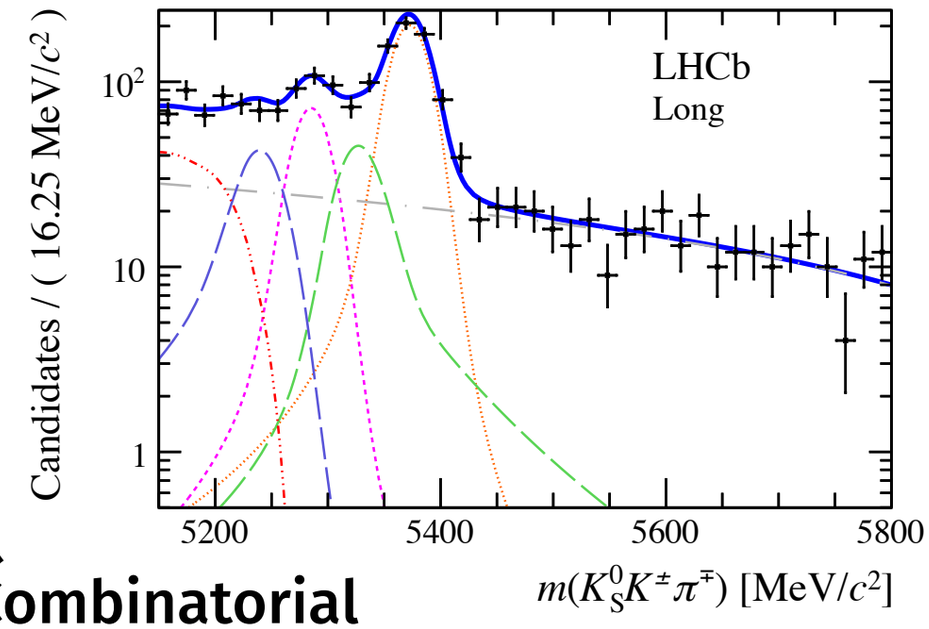
$K^0_S \pi^+ \pi^-$




$K^0_S K^\pm \pi^\mp$



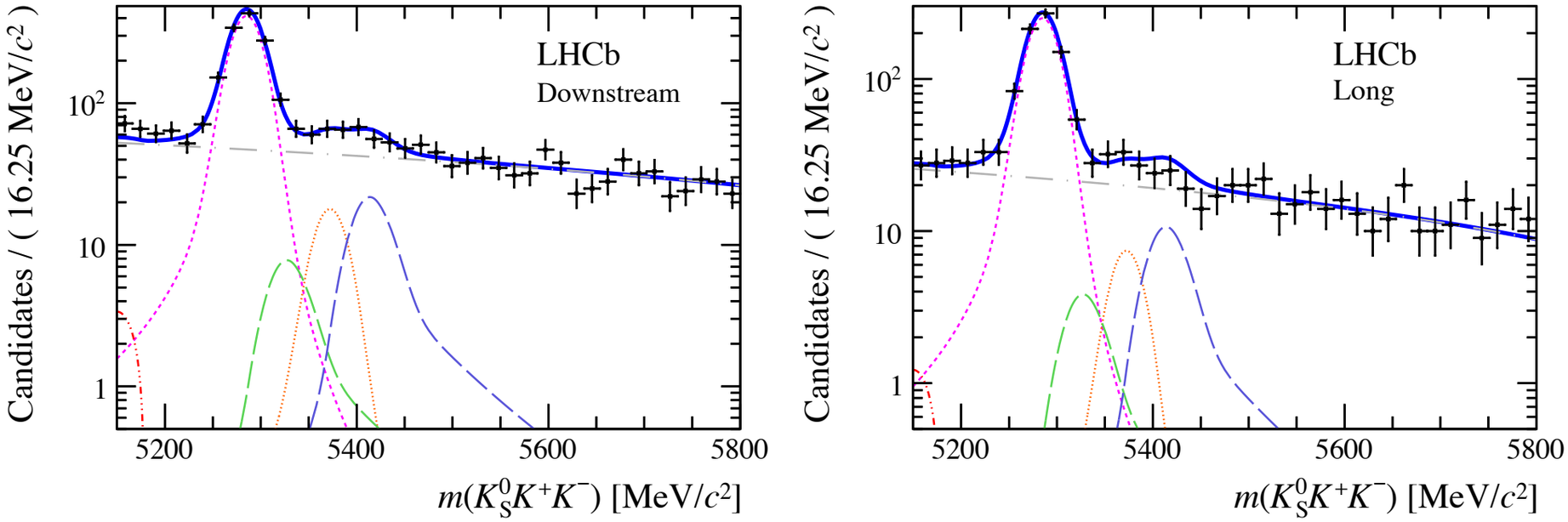



JHEP (2017) 2017:027 / arXiv:1707.01665

# $B \to K^0_S h^+ h^-$ branching fractions

- Other final states (loose selection criteria):

$K^0_S K^+ K^-$ **(loose)**




- Efficiency description based on simulated data, with data-driven corrections for particle ID and hardware trigger efficiencies, calculated as a function of the phase-space position



**JHEP (2017) 2017:027 / arXiv:1707.01665**

# $B \to K^0_S h^+ h^-$ branching fractions

- Branching fractions measured relative to $B^0 \to K^0_S \pi^+ \pi^-$ :

$$
\begin{aligned}
\mathcal{B}(B^0 \to \overline{(}K^0 K^\pm \pi^\mp) &= (6.1 \pm 0.5 \pm 0.7 \pm 0.3) \times 10^{-6}, \\
\mathcal{B}(B^0 \to K^0 K^+ K^-) &= (27.2 \pm 0.9 \pm 1.6 \pm 1.1) \times 10^{-6}, \\
\mathcal{B}(B^0_s \to K^0 \pi^+ \pi^-) &= (9.5 \pm 1.3 \pm 1.5 \pm 0.4) \times 10^{-6}, \\
\mathcal{B}(B^0_s \to \overline{(}K^0 K^\pm \pi^\mp) &= (84.3 \pm 3.5 \pm 7.4 \pm 3.4) \times 10^{-6}, \\
\mathcal{B}(B^0_s \to K^0 K^+ K^-) &\in [0.4 - 2.5] \times 10^{-6} \ \text{at } 90\% \text{ C.L.}, \\
&\quad \text{Using Feldman-Cousins method}
\end{aligned}
$$

*(Phys. Rev. D 57 3873-3889 (1998), arXiv:physics/9711021)*

- Dominant systematics arise from the combinatorial background model, and the knowledge of the hardware trigger efficiencies

- Measurements are valuable for obtaining quasi-two-body branching fractions from future amplitude analyses of these modes



**JHEP (2017) 2017:027 / arXiv:1707.01665**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$ (3 fb$^{-1}$)

**Phys. Rev. Lett. 120 261801 (2018) / arXiv:1712.09320 (to appear in PRL)**

- Previous measurement by B-factories found a hint of CP violation in $\overline{B}^0 \to K^{*-}\pi^+$

  - $\overline{B}^0 \to K^{*-}(K^-\pi^0)\pi^+$ (BaBar, *Phys. Rev. D 83, 112010 (2011)/arXiv:1105.0125*)

$$A_{CP} = -0.29 \pm 0.11 \pm 0.02$$

  - $\overline{B}^0 \to K^{*-}(K^0_S\pi^-)\pi^+$ (BaBar, *Phys. Rev. D 80 12001 (2009)/arXiv:0905.3615*)

$$A_{CP} = -0.20 \pm 0.10 \pm 0.01 \pm 0.01$$

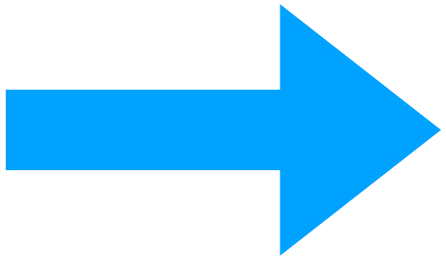
  - $\overline{B}^0 \to K^{*-}(K^0_S\pi^-)\pi^+$ (Belle, *Phys. Rev. D 79 072004 (2009)/arXiv:0811.3665*)

$$A_{CP} = -0.21 \pm 0.11 \pm 0.05 \pm 0.05$$

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

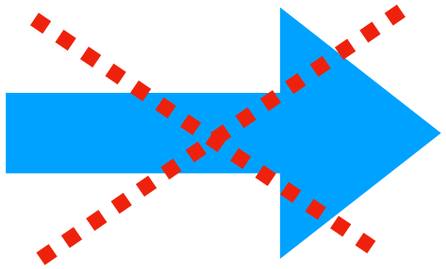
- Here: time-integrated analysis - first step towards measuring $\beta_{\rm eff}$ in this mode
- Decay proceeds via numerous intermediate resonances
- No tagging or time-dependence, but can exploit the quasi-flavour specific decay of $B^0$ :

$$B^0 \to K^{*+}\pi^-$$
$$(\bar{b}d) \quad (u\bar{s}) \quad (d\bar{u})$$



**Favoured**

$$\overline{B}^0 \to K^{*+}\pi^-$$
$$(b\bar{d}) \quad (u\bar{s}) \quad (d\bar{u})$$



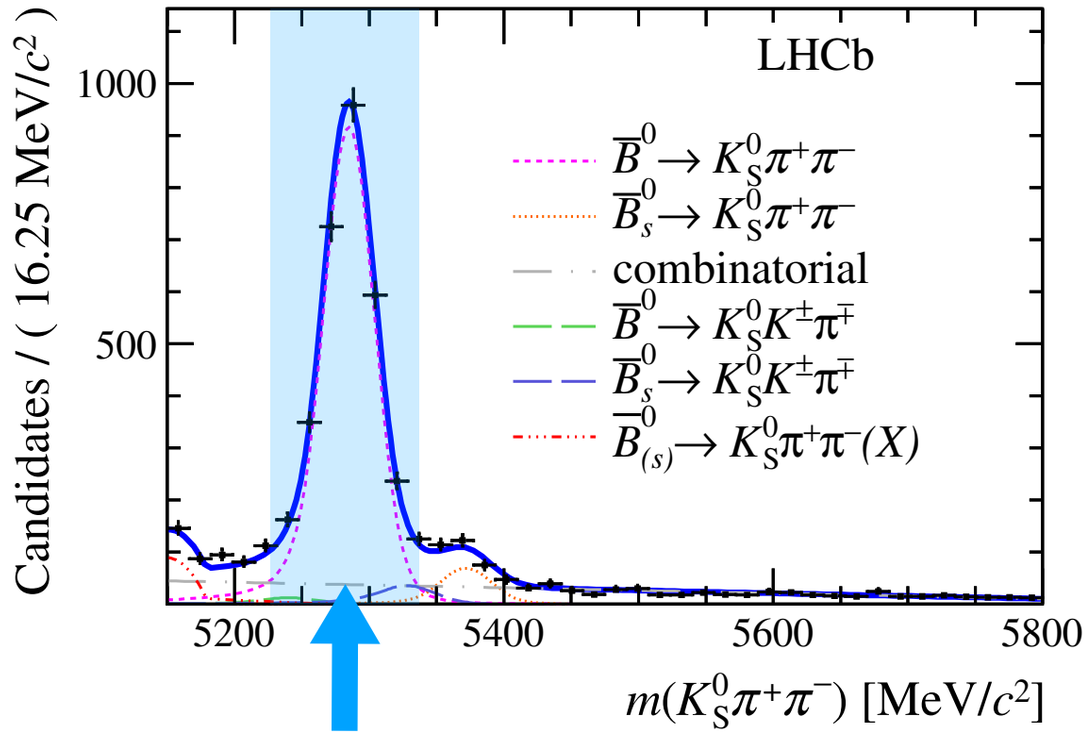
**Suppressed**



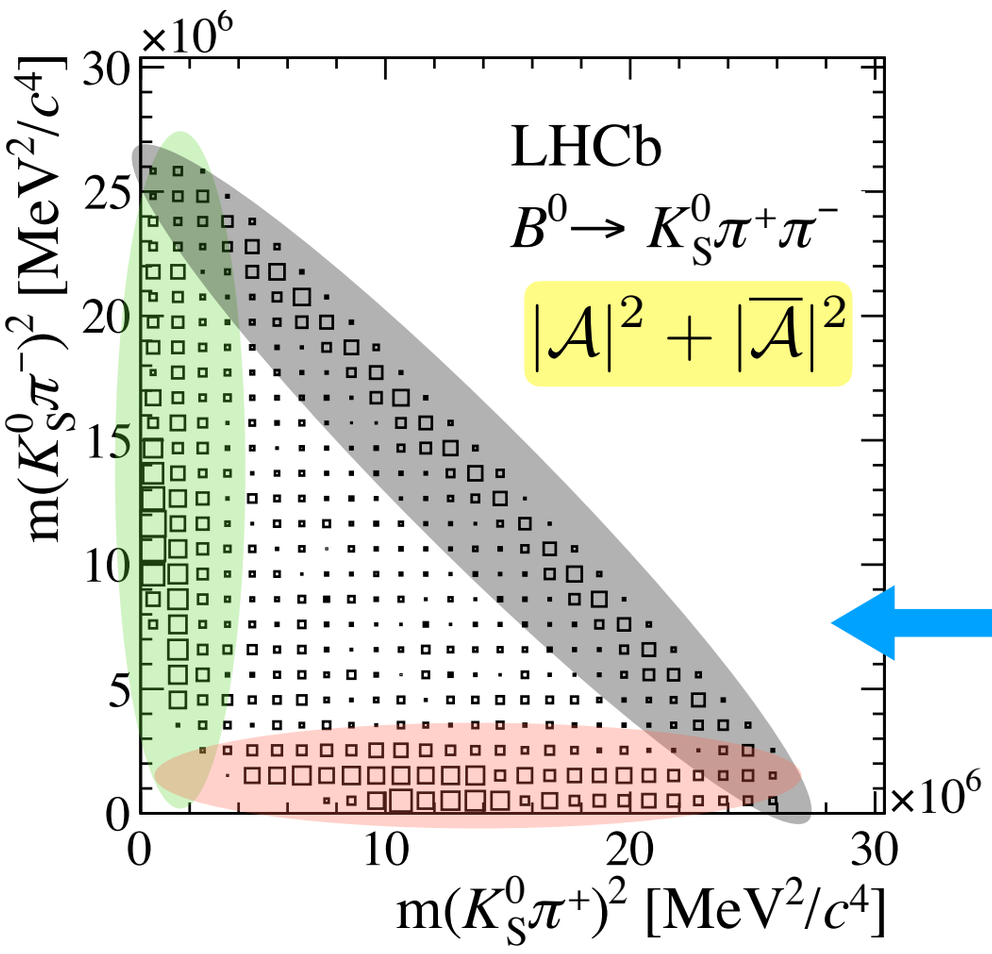
**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Amplitude analysis of $\overline{B}^0 \to K^0_S\pi^+\pi^-$

- Model $K^0_S\pi^+\pi^-$ spectrum to extract signal yield and background contributions - very low background contamination!
- Fit amplitude model to two-dimensional Dalitz plot:




**Dalitz plot fit region (~3200 candidates)**




**Sum over all $K^0_S$ categories and running periods**



Phys. Rev. Lett. 120 261801 / arXiv:1712.09320

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- Amplitude model - sum over individual resonant contributions, in terms of invariant-mass pairs squared: $s^+ \equiv m^2_{K^0_S \pi^+}$ , $s^- \equiv m^2_{K^0_S \pi^-}$

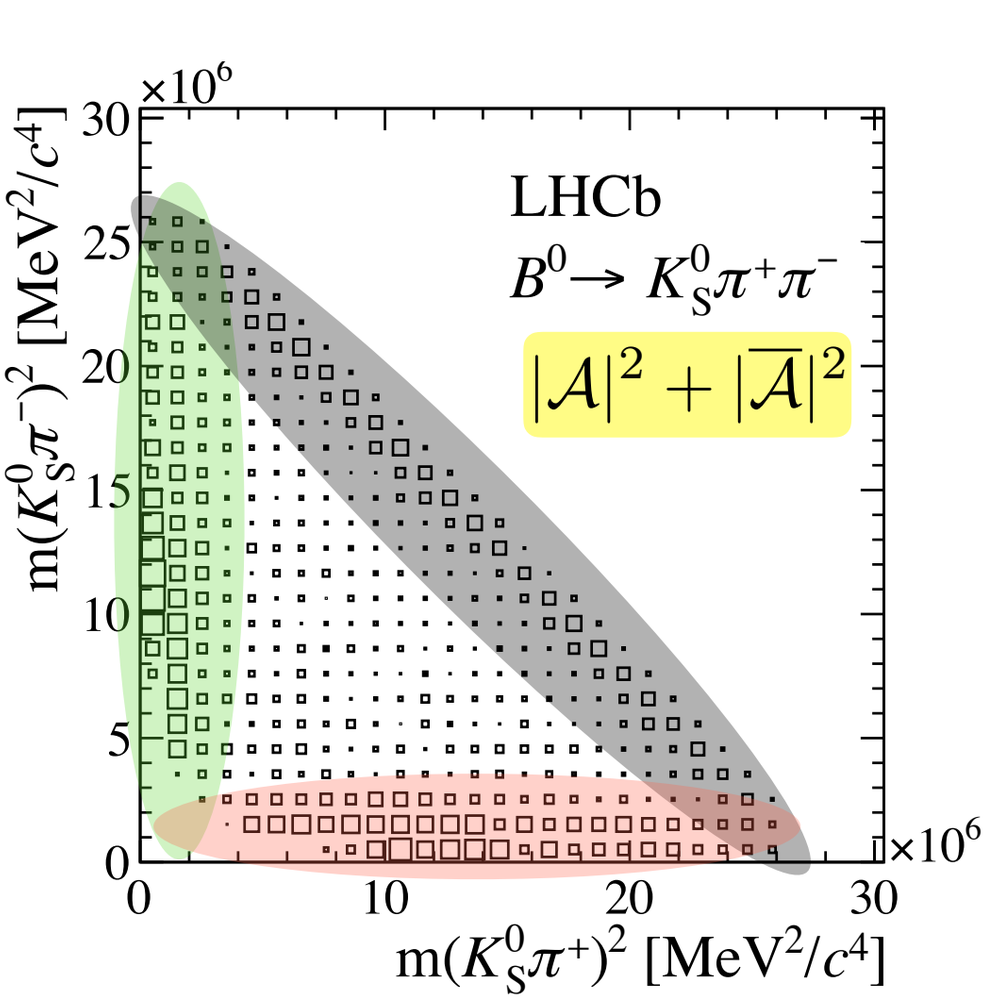
**Total amplitude**

**Resonant component**

$$\mathcal{A} = \sum_j c_j \mathcal{A}_j(s^+, s^-)$$

**Complex 'isobar' coefficient**

- Observed distribution: $|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2$






**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- Form of $\mathcal{A}_j$ given by:

**Mass lineshape in $s^+$ or $s^-$**

**Centrifugal barrier factors (Blatt-Weisskopf)**

$$\mathcal{A}_j(s^+, s^-, L) \propto T(s^+, s^-) \cdot Z(s^+, s^-, L) \cdot X(s^+, s^-, L)$$

**Spin (L) term, proportional to angular momentum eigenfunctions**



**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- **Resonant contributions:** start with what was observed by B-factories, additional components added based on change in log-likelihood, fit quality, or component magnitude

| Component | | Mass model |
|---|---|---|
| Decaying to $K^0_S \pi^\pm$ | $K^*(892)^-$ | Relativistic Breit-Wigner |
| | $(K\pi)^-_0$ | EFKLLM ← (From QCDF, arXiv:0902.3645) |
| | $K^*_2(1430)^-$ | Relativistic Breit-Wigner |
| | $K^*(1680)^-$ | Flatté |
| Decaying to $\pi^+\pi^-$ | $f_0(500)$ | Relativistic Breit-Wigner |
| | $\rho(770)^0$ | Gounaris-Sakurai |
| | $f_0(980)$ | Flatté |
| | $f_0(1500)$ | Relativistic Breit-Wigner |
| | $\chi_{c0}$ | Relativistic Breit-Wigner |

**Plus a flat non-resonant contribution**



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# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- CP asymmetries defined as the asymmetry in the magnitude squared of the complex isobar coefficients

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

and corrected for the $B^0$ production asymmetry of approximately -0.35%

- Fit fractions used to obtain quasi-two-body branching fractions, defined as the relative intensity of a single component

$$FF_j = \frac{\int_{\rm DP} |c_j A_j|^2 ds^+ ds^-}{\int_{\rm DP} |\sum_j c_j A_j|^2 ds^+ ds^-}$$



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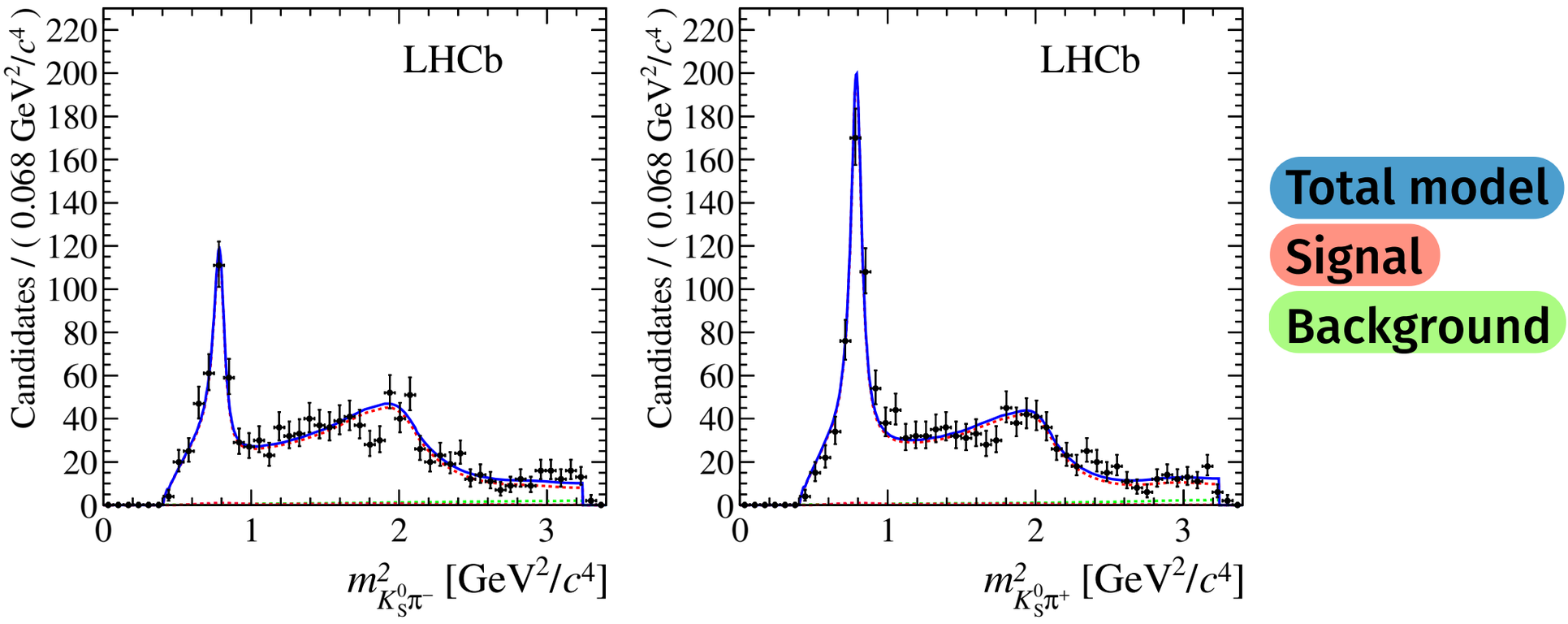
# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- Fit model and data projections:




- After correcting for the efficiency and production asymmetry:

$$\mathcal{A}_{\rm CP}\left(\overline{B}^0 \to K^*(892)^-\pi^+\right) = -0.308 \pm 0.060\ (\text{stat.}) \pm 0.011\ (\text{syst.}) \pm 0.012\ (\text{model.})$$

**Observation of CP violation at > 6σ significance!**



**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- Additional CP asymmetries measured:

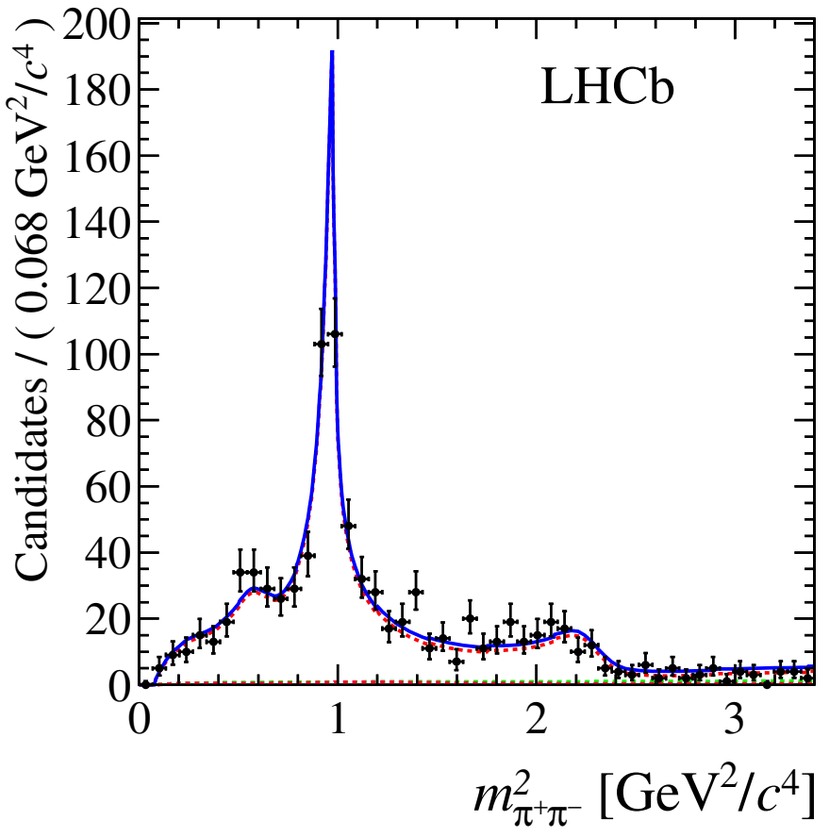
$$\mathcal{A}_{CP}\left(\overline{B}^0 \to (K^0_S\pi^-)_0\pi^+\right) = -0.032 \pm 0.047 \pm 0.016 \pm 0.027$$

$$\mathcal{A}_{CP}\left(\overline{B}^0 \to K^*_2(1430)^-\pi^+\right) = -0.29 \pm 0.22 \pm 0.09 \pm 0.03$$

$$\mathcal{A}_{CP}\left(\overline{B}^0 \to K^*(1680)^-\pi^+\right) = -0.07 \pm 0.13 \pm 0.02 \pm 0.03$$

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

**Sensitivity due to interference with quasi-flavour-specific contributions**






**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- CP conserving fit fractions:

$$
\begin{aligned}
\mathcal{F}(K^*(892)^-\pi^+) &= 9.43 \pm 0.40 \pm 0.33 \pm 0.34\,\%, \\
\mathcal{F}((K\pi)^-_0\pi^+) &= 32.7 \pm 1.4 \pm 1.5 \pm 1.1\,\%, \\
\mathcal{F}(K^*_2(1430)^-\pi^+) &= 2.45\,^{+\,0.10}_{-\,0.08} \pm 0.14 \pm 0.12\,\%, \\
\mathcal{F}(K^*(1680)^-\pi^+) &= 7.34 \pm 0.30 \pm 0.31 \pm 0.06\,\%, \\
\mathcal{F}(f_0(980)K^0_S) &= 18.6 \pm 0.8 \pm 0.7 \pm 1.2\,\%, \\
\mathcal{F}(\rho(770)^0 K^0_S) &= 3.8\,^{+\,1.1}_{-\,1.6} \pm 0.7 \pm 0.4\,\%, \\
\mathcal{F}(f_0(500)K^0_S) &= 0.32\,^{+\,0.40}_{-\,0.08} \pm 0.19 \pm 0.23\,\%, \\
\mathcal{F}(f_0(1500)K^0_S) &= 2.60 \pm 0.54 \pm 1.28 \pm 0.60\,\%, \\
\mathcal{F}(\chi_{c0}K^0_S) &= 2.23\,^{+\,0.40}_{-\,0.32} \pm 0.22 \pm 0.13\,\%, \\
\mathcal{F}(K^0_S\pi^+\pi^-)^{\rm NR} &= 24.3 \pm 1.3 \pm 3.7 \pm 4.5\,\%,
\end{aligned}
$$

**Dominated by S-wave and non-resonant**

- Systematics arise from:
  - Signal yield
  - Variation of signal efficiency and background over the Dalitz plot
  - Fixed model parameters
  - S-wave model
  - Marginal model contributions

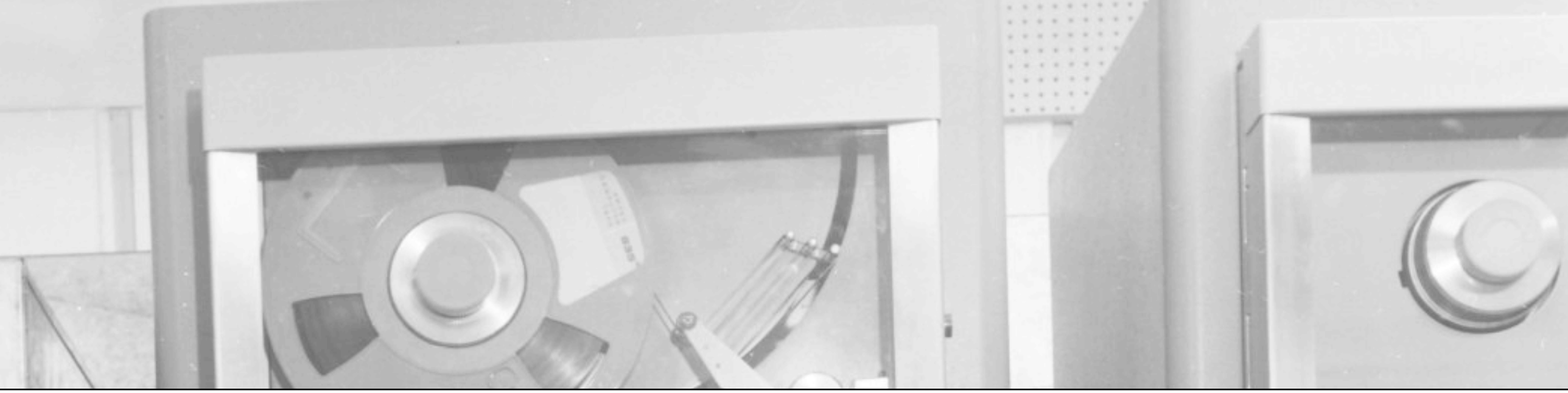


**Phys. Rev. Lett. 120 261801 / arXiv:1712.09320**

# Summary

- LHCb has updated the branching fraction measurements of the $B \to K^0_S h^+ h^-$ decays, using the full Run 1 dataset
    - These improve precision on branching fractions of the intermediate quasi-two-body decays, particularly of $B^0_s$ mesons
    - Still no observation of the elusive $B^0_s \to K^0_S K^+ K^-$ decay!

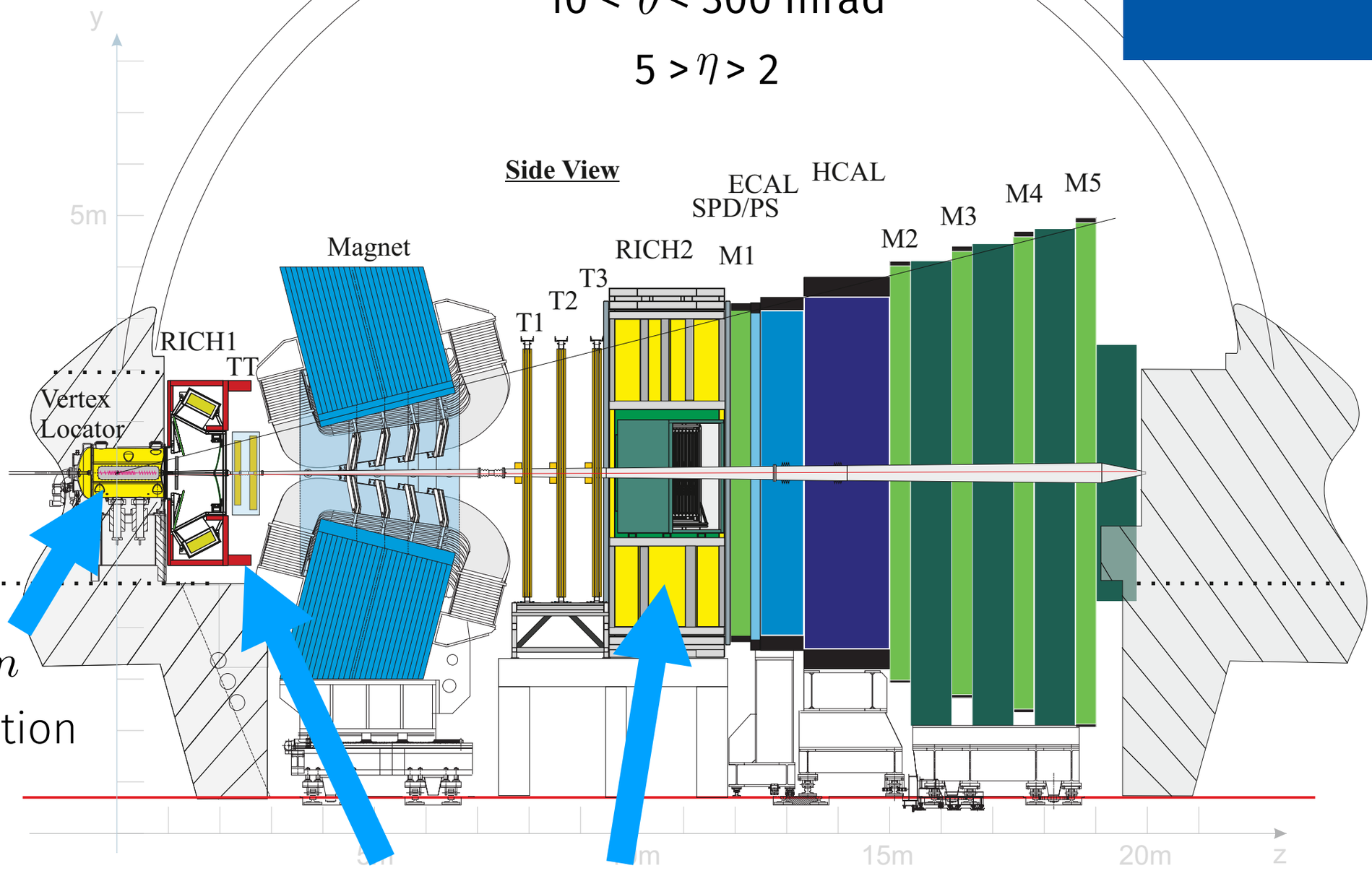
- CP violation in the $\overline{B}^0 \to K^{*-}\pi^+$ decay has been observed for the first time at a level exceeding 6σ significance
    - Central value is consistent with B-factory measurements
    - Additional CP asymmetries and fit fractions measured in the resonances contributing to the $\overline{B}^0 \to K^0_S \pi^+ \pi^-$ phase space



# Backup

$10 < \theta < 300$ mrad

$5 > \eta > 2$



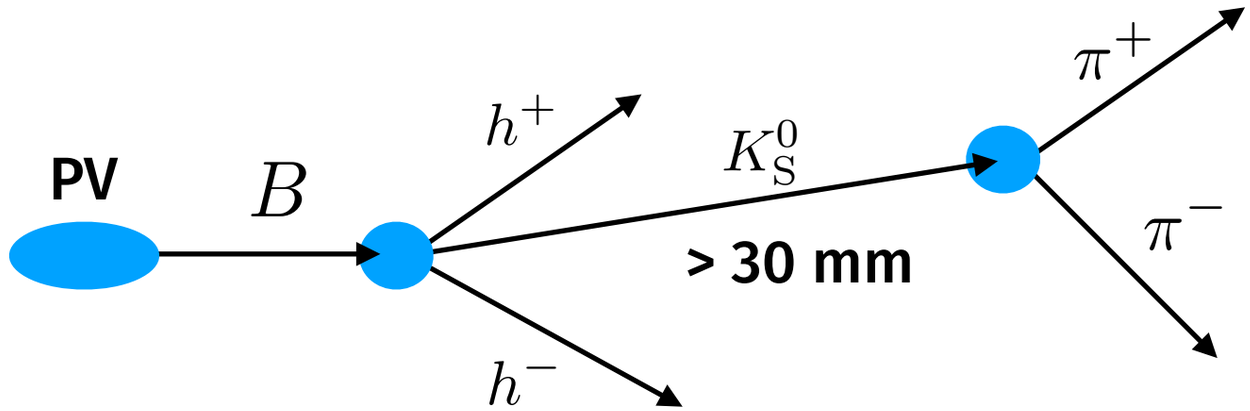

$\sim 20\ \mu m$

IP resolution

Separation of charged hadron species via Cherenkov radiation

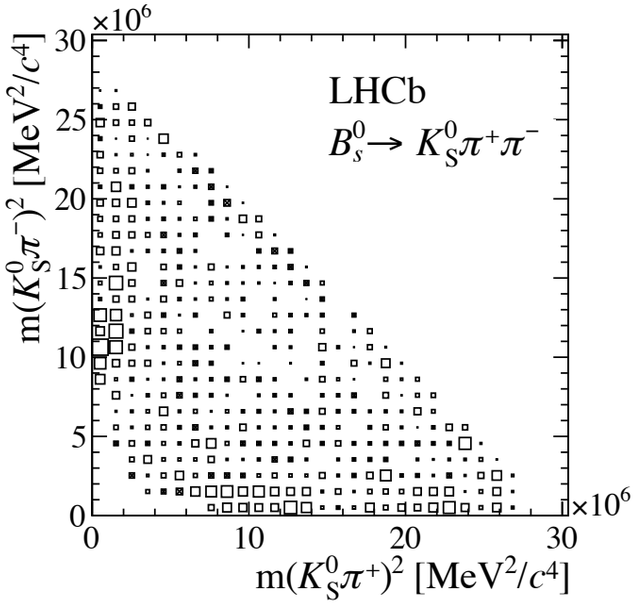
# $B \to K^0_S h^+ h^-$ selection

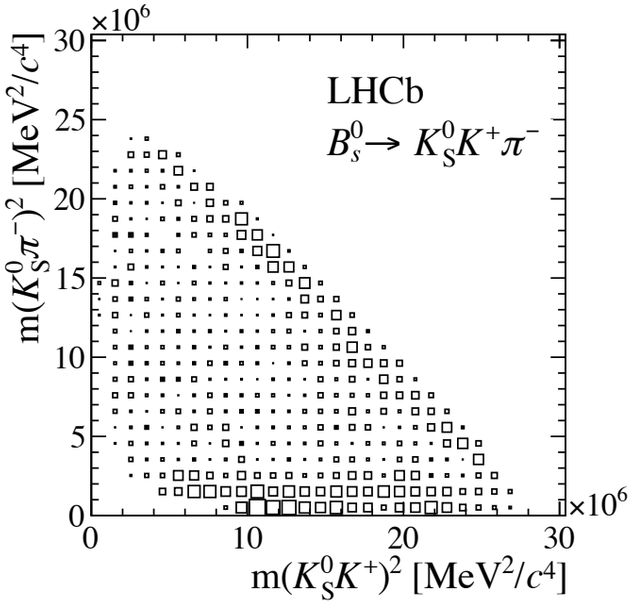
- B candidate formed by combining a $K^0_S$ formed from good quality high momentum tracks, not from the primary vertex, and two oppositely charged tracks that result in a B with high momentum, a good vertex quality, and consistent with a primary vertex

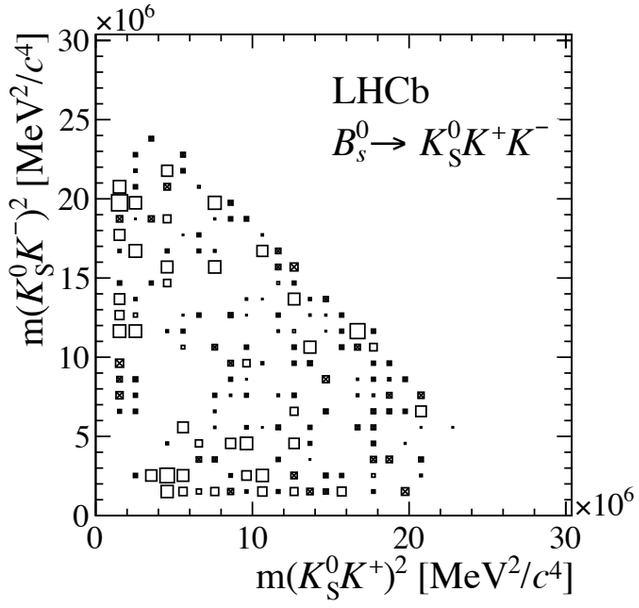


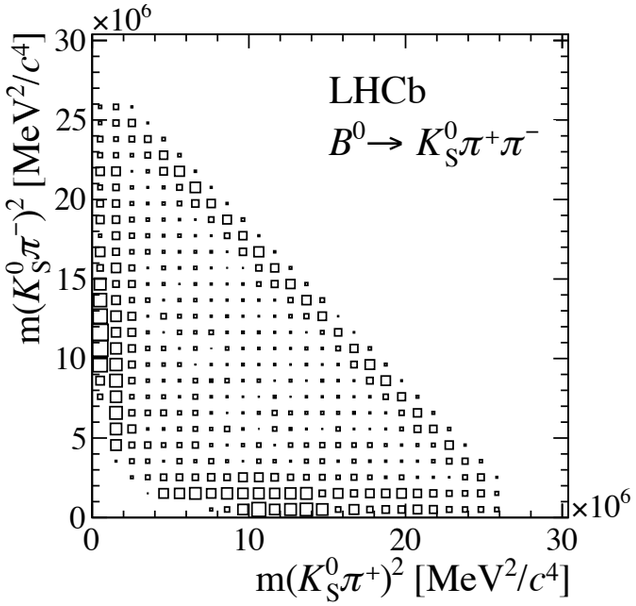

- A further requirement on the B candidate and $K^0_S$ vertex distance rejects four-body background
- A boosted decision-tree is trained using kinematic and vertex information, along with the transverse momentum asymmetry of the candidate with respect to the rest of the event

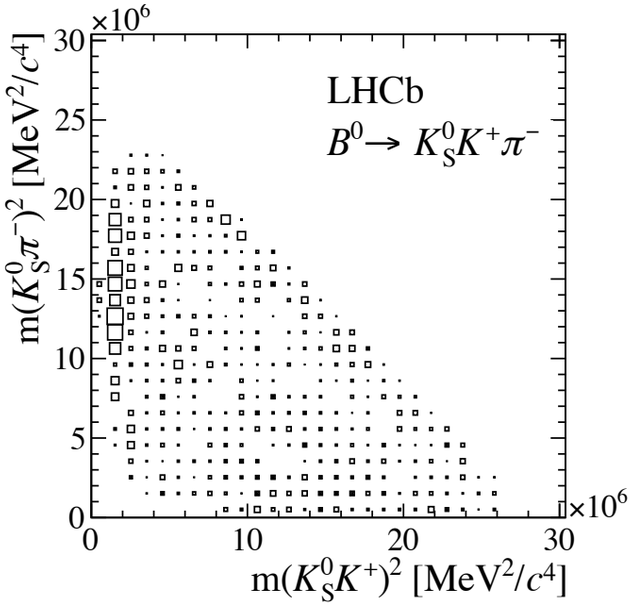
# $B \to K^0_S h^+ h^-$ Dalitz plots

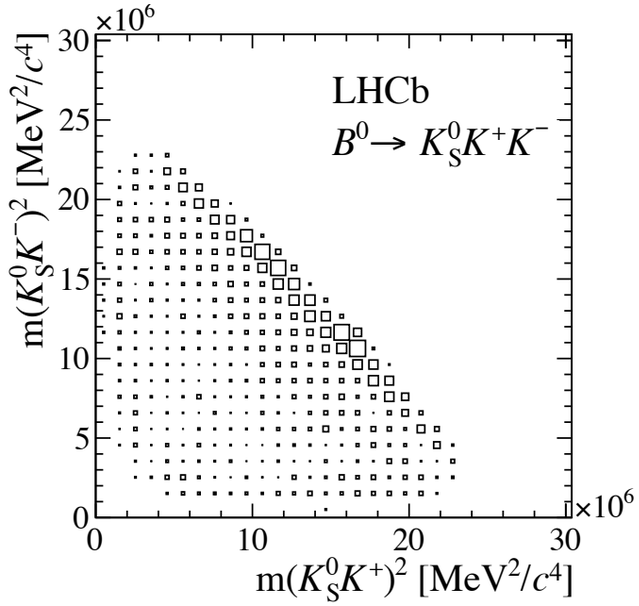



**Background subtracted**

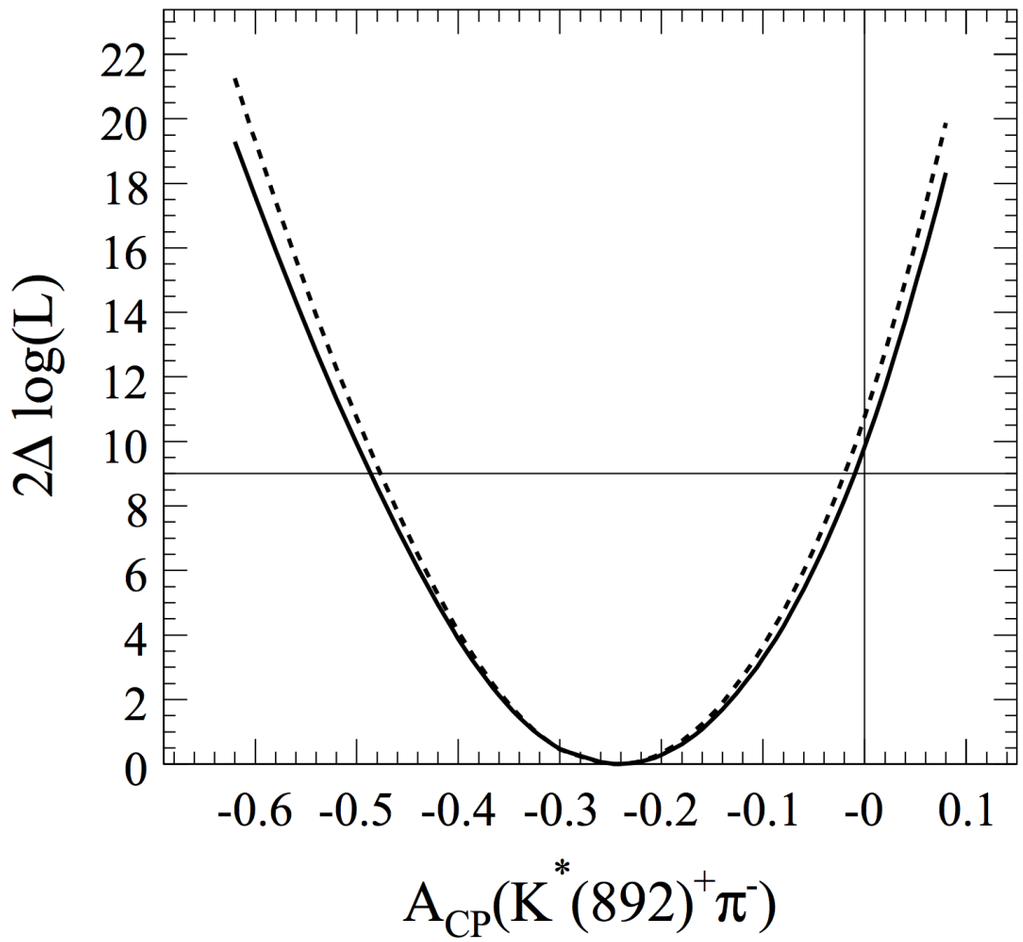


**JHEP (2017) 2017:027 / arXiv:1707.01665**

# Amplitude analysis of $\overline{B}^0 \to K^0_S \pi^+ \pi^-$

- Combination of BaBar results for $\mathcal{A}_{CP}(B^0 \to K^*(892)^+ \pi^-)$

  *(Phys. Rev. D 83, 112010 (2011)/arXiv:1105.0125)*




$-0.24 \pm 0.07 \pm 0.02$

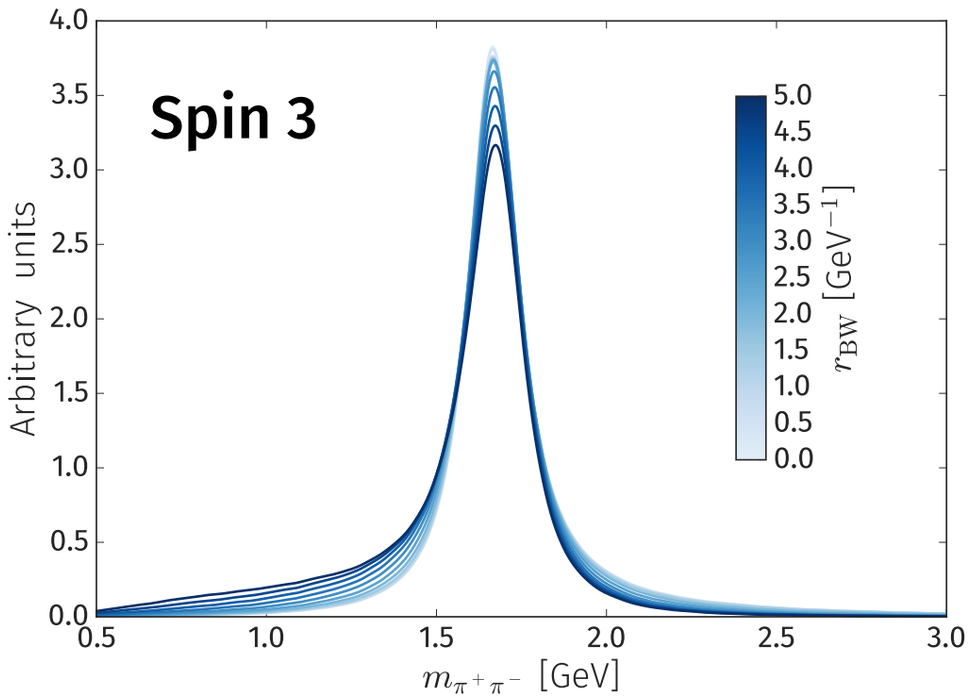
**(3σ)**



**LHCB-PAPER-2017-033 / arXiv:1712.09320**

# Amplitude model

## Blatt-Weisskopf barrier factors



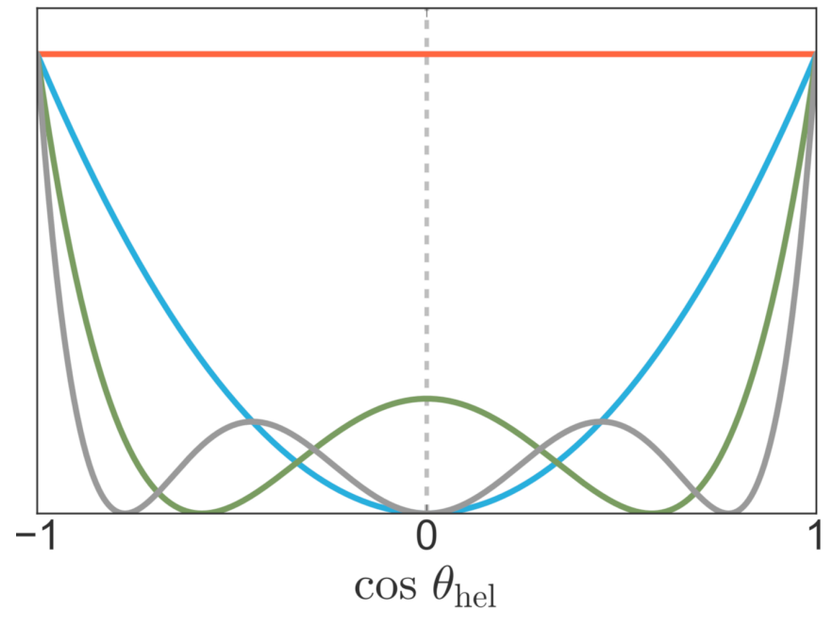

$$L=0 \;:\; X(z) \;=\; 1\,,$$

$$L=1 \;:\; X(z) \;=\; \sqrt{\frac{1+z_0^2}{1+z^2}}\,,$$

$$L=2 \;:\; X(z) \;=\; \sqrt{\frac{z_0^4+3z_0^2+9}{z^4+3z^2+9}}\,,$$

$$L=3 \;:\; X(z) \;=\; \sqrt{\frac{z_0^6+6z_0^4+45z_0^2+225}{z^6+6z^4+45z^2+225}}$$

## Spin terms




$$L=0 \;:\; Z(\vec{p},\vec{q}) \;=\; 1,$$

$$L=1 \;:\; Z(\vec{p},\vec{q}) \;=\; -2\,\vec{p}\cdot\vec{q},$$

$$L=2 \;:\; Z(\vec{p},\vec{q}) \;=\; \frac{4}{3}\left[3(\vec{p}\cdot\vec{q})^2-(|\vec{p}||\vec{q}|)^2\right],$$

$$L=3 \;:\; Z(\vec{p},\vec{q}) \;=\; -\frac{24}{15}\left[5(\vec{p}\cdot\vec{q})^3-3(\vec{p}\cdot\vec{q})(|\vec{p}||\vec{q}|)^2\right]$$

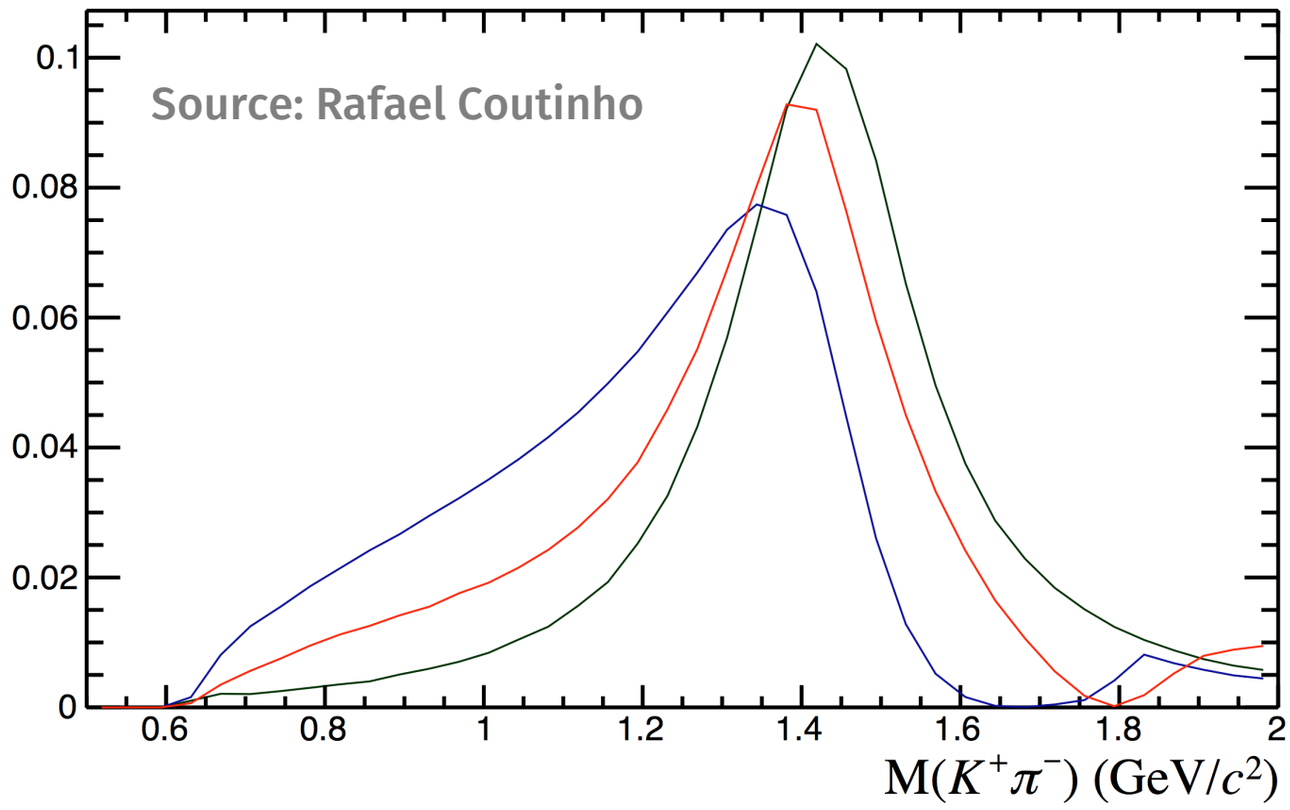
# $K\pi$ S-wave

**EFKLLM:** $T_j(s) = F(s)\left(\frac{c_0}{s} + c_1\right)$
arXiv:0902.3645

**Form factor from QCDF**

**Left free**

Toy simulation using Laura++ package
arXiv:1711.09854




**Slowly varying component**

**RBW-like**

**LASS:**

$$T_j(s) = \frac{\sqrt{s}}{q\cot\delta_B - iq} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{(m_0^2 - s) - im_0\Gamma_0\frac{q}{\sqrt{s}}\frac{m_0}{q_0}}$$

$$\cot\delta_B = \frac{1}{aq} + \frac{1}{2}rq$$

Nucl. Phys. B296 (1988) 493

**Left free**

**EFKLLM is preferred over LASS by 43 units of log-likelihood**