Charmless hadronic B decays at LHCb

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on behalf of the LHCb Collaboration

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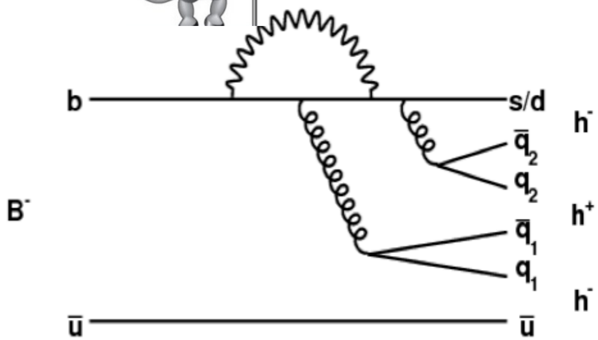
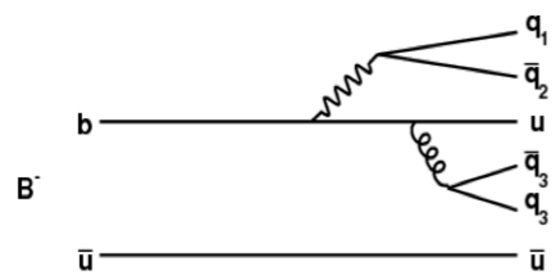
Overview

- Introduction
- Recent results from LHCb
  - Measurement of the branching fraction of the decay $B_s^0 \to K_S^0 K_S^0$
    - Phys. Rev. D 102 (2020) 012011
  - Amplitude analysis of $B^+ \to \pi^+ K^+ K^-$ decays
    - Phys. Rev. Lett. 123 (2019) 231802
  - Amplitude analysis of $B^+ \to \pi^+ \pi^+ \pi^-$ decays
    - Phys. Rev. Lett. 124 (2020) 031801
    - Phys. Rev. D 101 (2020) 012006
  - NEW! Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$ decays
    - LHCb-PAPER-2020-031 (in preparation)
- Conclusion

Rich physics of charmless decays

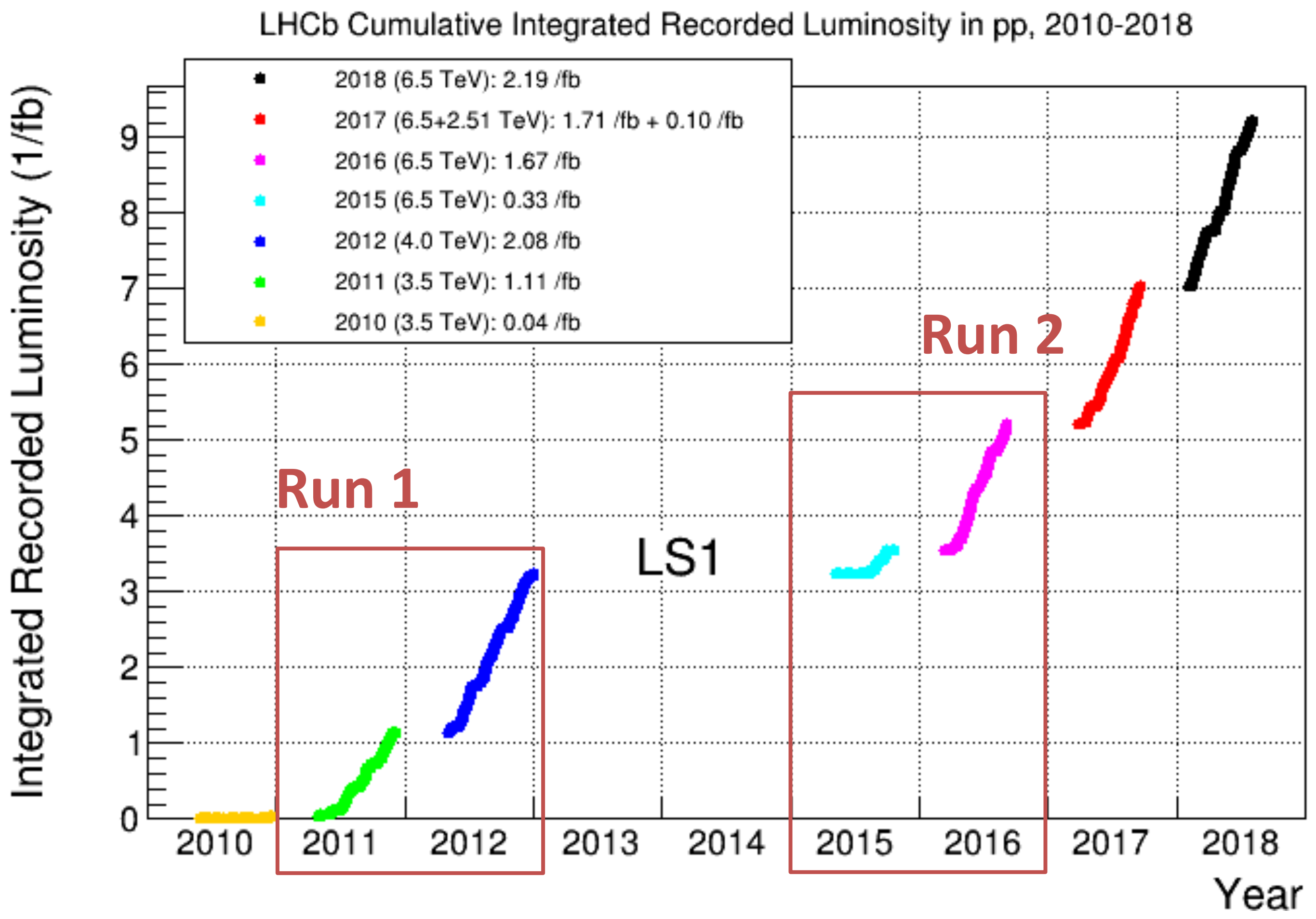
New physics contributions in loops?





- Contributions from both loop (penguin) and tree decay diagrams
- Have comparable magnitude and a relative weak phase (= γ in SM)
- Interference can therefore give rise to *CP* violation
- Important to test the SM by comparing with tree-dominated decays
- Multi-body decays also possess rich resonance structure
- Provides important information for refining models of hadronisation
- Can also lead to very interesting variation of CPV over the phase space, e.g. as seen in $B^+ \to h^+ h'^+ h'^-$ [Phys. Rev. D 90 (2014) 112004]

Data Sample



LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
Integrated Recorded Luminosity (1/fb)
Year
2010
2011
2012
2013
2014
2015
2016
2017
2018
0
1
2
3
4
5
6
7
8
9
Run 1
Run 2
LS1

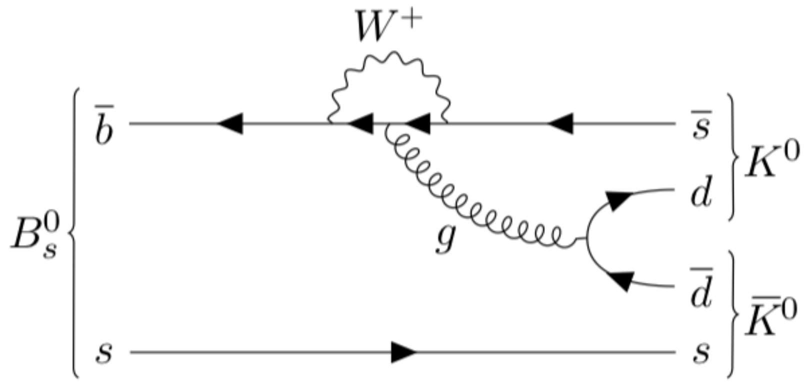
Measurement of the branching fraction of the decay $B_s^0 \to K_S^0 K_S^0$

LHCb-PAPER-2019-030

Published in Phys. Rev. D 102 (2020) 012011

$B_s^0 \to K_S^0 K_S^0$ – introduction

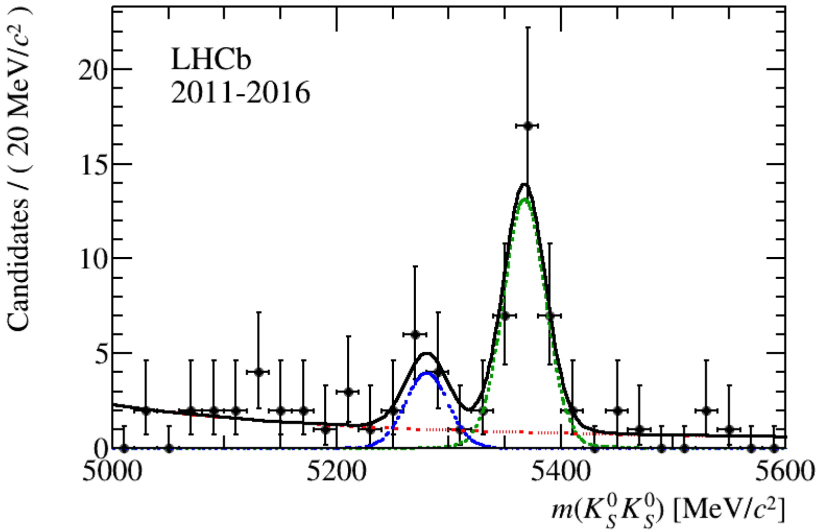
- Decay amplitude is dominated by $b \to s\bar{d}d$ loop transition
- No CPV in decay expected
- Eventually, time-dependent CPV measurement, analogous to that of $B_s^0 \to K^{*0}\overline{K}^{*0}$, can help probe new physics contributions in $\phi_s^{s\bar{d}d}$



- Decay first observed by Belle [PRL 116 (2016) 161801]
- Reported $\mathcal{B}(B_s^0 \to K^0\overline{K}^0) = (19.6\,^{+5.8}_{-5.1} \pm 1.0 \pm 2.0)\times 10^{-6}$
- Around 10x larger than related decay $B^0 \to K^0\overline{K}^0$
- NB that since final states is CP even $\mathcal{B}(B_{(s)}^0 \to K_S^0 K_S^0) = \frac{1}{2}\mathcal{B}(B_{(s)}^0 \to K^0\overline{K}^0)$

- This analysis measures the BF of these $B_{(s)}^0 \to K_S^0 K_S^0$ decays relative to that of $B^0 \to \phi K_S^0$
- $K_S^0 \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays are reconstructed
- Data sample of 5fb^{-1} (2011-6)

$B_s^0 \to K_S^0 K_S^0$ – results



- Very little background survives the selection, which exploits the highly displaced vertices
- Find 32 $B_s^0 \to K_S^0 K_S^0$ decays (6.5σ significance) and 9 $B^0 \to K_S^0 K_S^0$ decays (3.5σ significance), combining all categories
  - Factor $\sim$10 in BFs but f_s/f_d gives factor $\sim$4 in opposite direction

- Simultaneous fit to all data categories used to determine BF:

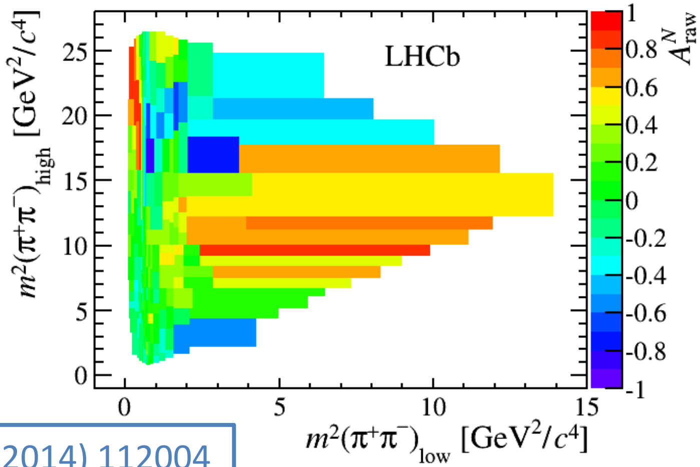
$$\mathcal{B}\left(B_s^0 \to K_S^0 K_S^0\right) = [8.3 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.8(\text{norm}) \pm 0.3(f_s/f_d)]\times 10^{-6}$$

- This is the most precise measurement of this quantity to date
- Furthermore it agrees very well both with Standard Model predictions, in range $(7-13)\times 10^{-6}$, and with the previous Belle measurement
- The ratio of the $B^0$and B_s^0 decays is also found to be compatible with the world average, although in this case has poorer precision
- Largest systematic uncertainties from trigger efficiency

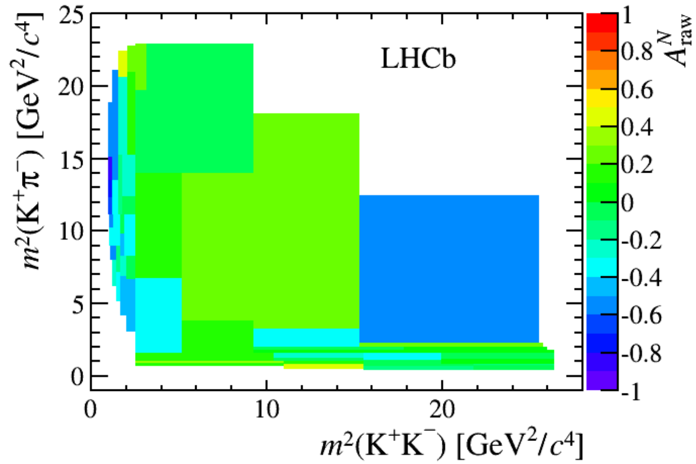
Amplitude analyses of $B^+ \to \pi^+ K^+ K^-$ and $B^+ \to \pi^+ \pi^+ \pi^-$ decays

LHCb-PAPER-2018-051
Published in Phys. Rev. Lett. 123 (2019) 231802
LHCb-PAPER-2019-017
Published in Phys. Rev. D 101 (2020) 012006
LHCb-PAPER-2019-018
Published in Phys. Rev. Lett. 124 (2020) 031801

$B^+ \to \pi^+ h^+ h^-$ – introduction

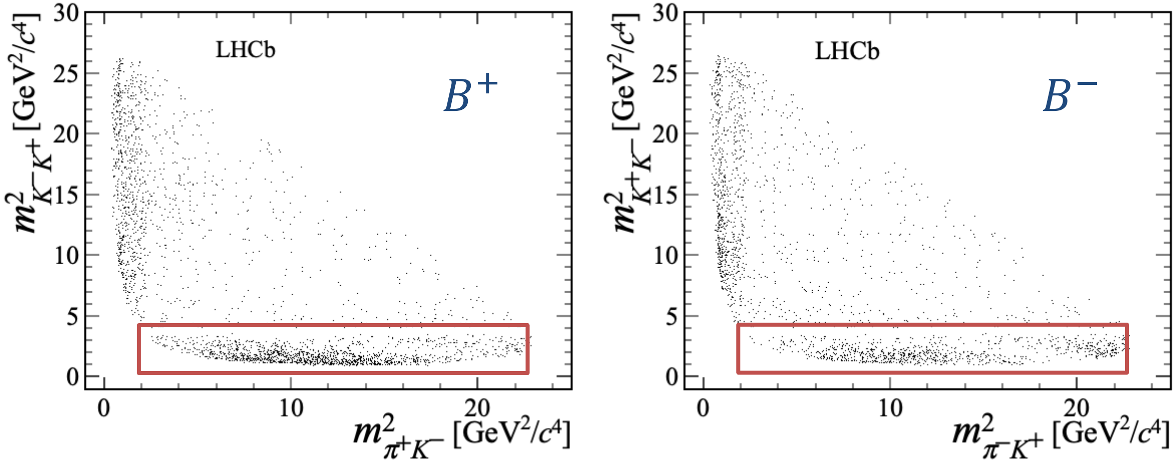


PRD 90 (2014) 112004



- Interesting pattern of very large CP asymmetries seen in model-independent analysis
- Strong motivation for amplitude analysis to shed light on origins
- Pair of decays are coupled through $\pi\pi \leftrightarrow KK$ rescattering processes
- Data sample: 3fb^{-1} (2011-2)

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



Signal yields:
B^+: 2052 ± 102
B^-: $1566 \pm \ \ 84$

Effects from CPV already apparent on inspection

- First amplitude analysis of this decay
- Expect resonances decaying to $K^-\pi^+$
  - Pure penguin decays
- Expect resonances decaying to K^+K^-
  - Contributions from both tree and penguin
  - Do not expect large contributions from ϕ and other $s\bar{s}$ states due to OZI suppression

- S-wave model includes $K_0^*(1430)^0$ resonance and
  - "Single pole" nonresonant amplitude, based on phenomenological description [PRD 92 (2015) 054010]

    $[1 + m^2_{\pi K}/\Lambda^2]^{-1}$

  - "Rescattering" amplitude – single pole multiplied by scattering term [PRD 71 (2005) 074016]

    $\sqrt{1 - v^2}e^{2i\delta}$

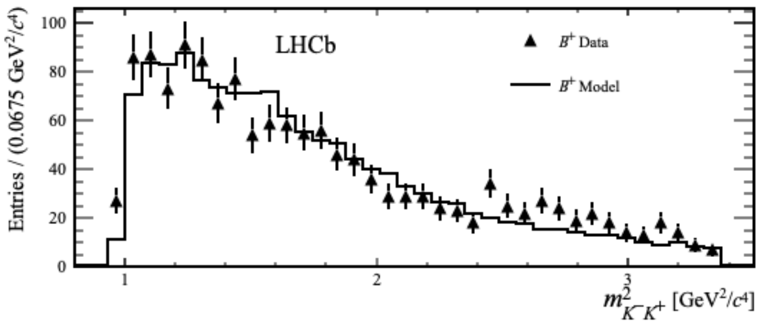
PRL 123 (2019) 231802

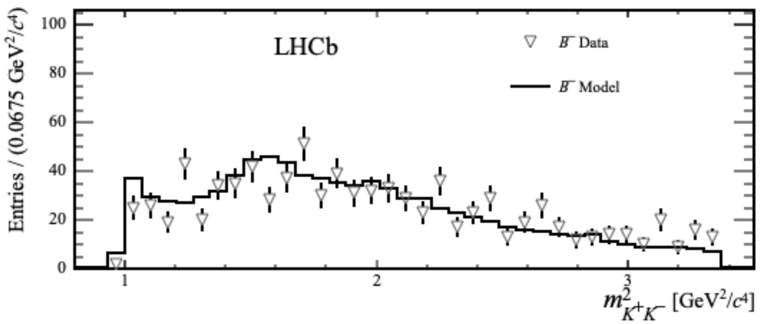
$B^+ \to \pi^+ K^+ K^-$ results

$$A_{CP}^{j} = \frac{|c_j^-|^2 - |c_j^+|^2}{|c_j^-|^2 + |c_j^+|^2}$$

$$FF_j = \frac{\int \left(|c_j^+ F_j|^2 + |c_j^- F_j|^2\right) ds\, dt}{\int (|A^+|^2 + |A^-|^2)\, ds\, dt}$$

	Contribution	Fit Fraction(%)	A_{CP}(%)
$K^-\pi^+$	$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
	$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
	Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
K^+K^-	$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
	$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
	Rescattering	$16.4 \pm 0.8 \pm 1.0$	$\boxed{-66.4 \pm 3.8 \pm 1.9}$
	$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$



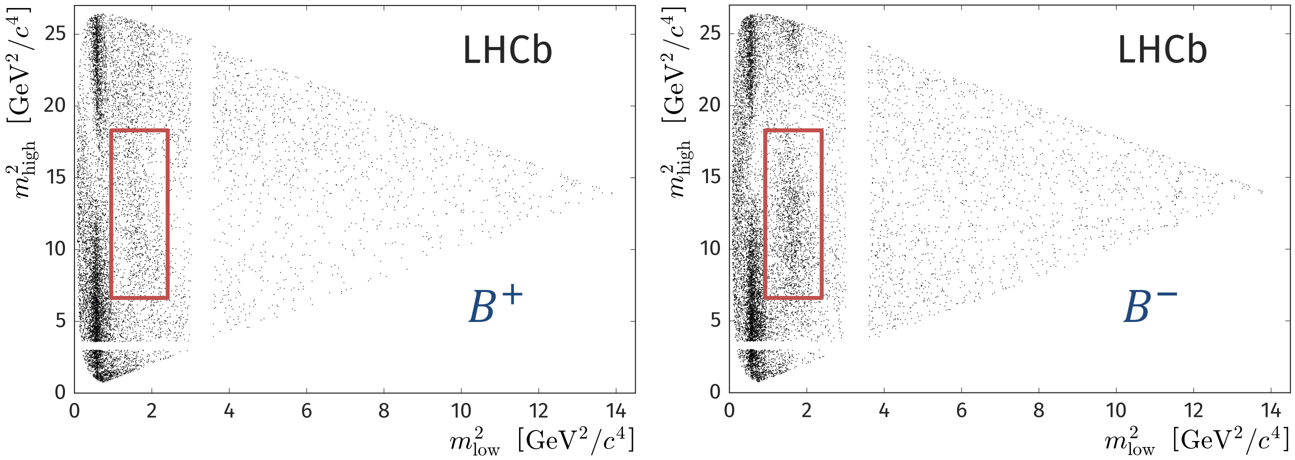


- Largest contribution is nonresonant S-wave
- Very large negative asymmetry at low $m_{K^+K^-}$
  - Largest CPV observation for a single amplitude
  - Consistent with presence of positive asymmetry in coupled mode $B^+ \to \pi^+\pi^+\pi^-$
- Asymmetries in $K^-\pi^+$ consistent with zero
- Inclusion of $\phi(1020)$ improves description of data near threshold – but has rather low significance
- Unexpected large fraction for $B^+ \to \rho(1450)^0\pi^+$
- Addition of Run 2 data sample will help to further scrutinise these regions

PRD 101 (2020) 012006

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

The $\rho(770)^0$ and S-wave dominate



Signal yield:
$20\,600 \pm 1600$

~82% pure

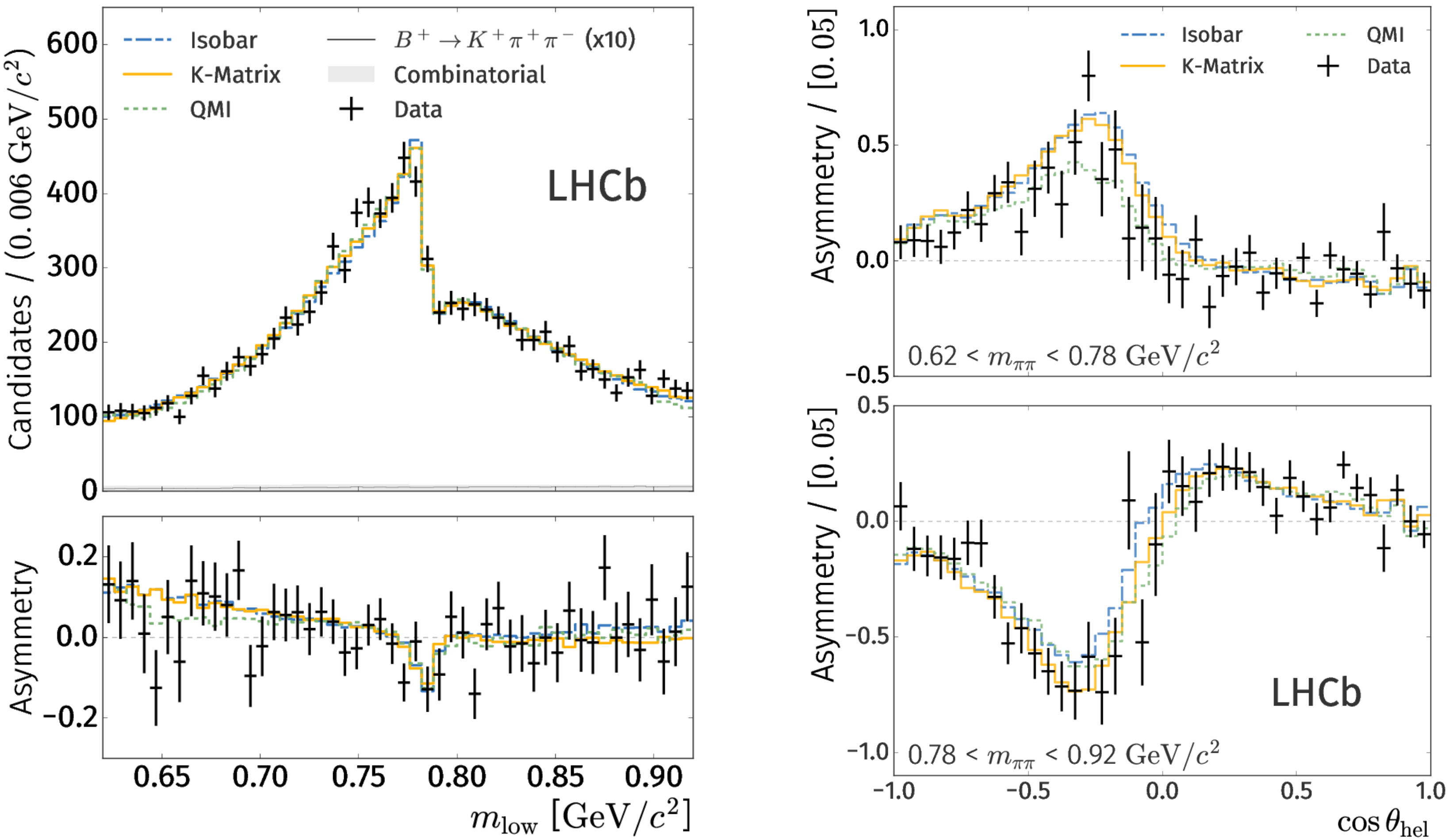
Effects from CPV again quite clear

- First amplitude analysis of this decay at LHCb
- Previous analysis by BaBar had signal yield ~1200 and ~30% purity [PRD 79 (2009) 072006]
  - No evidence for CPV but some intriguingly large central values

- Decay amplitude must be symmetrised under exchange of identical pions:
  $$A(s,t) \equiv A(t,s)$$
- Dalitz plot can be folded along $s = t$

PRL 124 (2020) 031801

$\rho(770)^0$ & $\omega(782)$ region

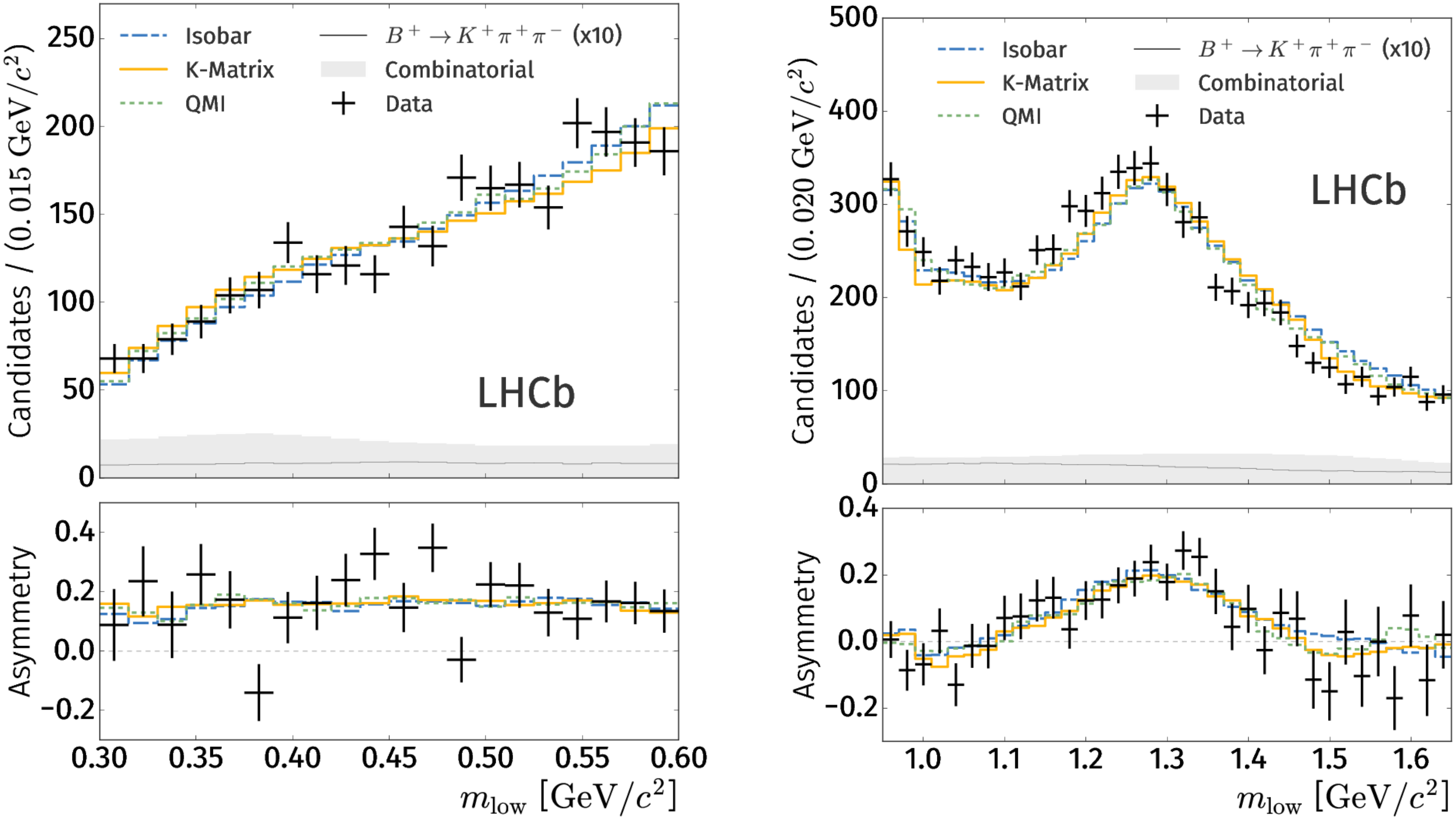


Significant asymmetries in interference between the P-wave and S-wave

Cancel when integrating over phasespace – both $\rho(770)^0$ & $\omega(782)$ have ~ 0 Q2B A_{CP}

PRL 124 (2020) 031801

Low mass & $f_2(1270)$ regions



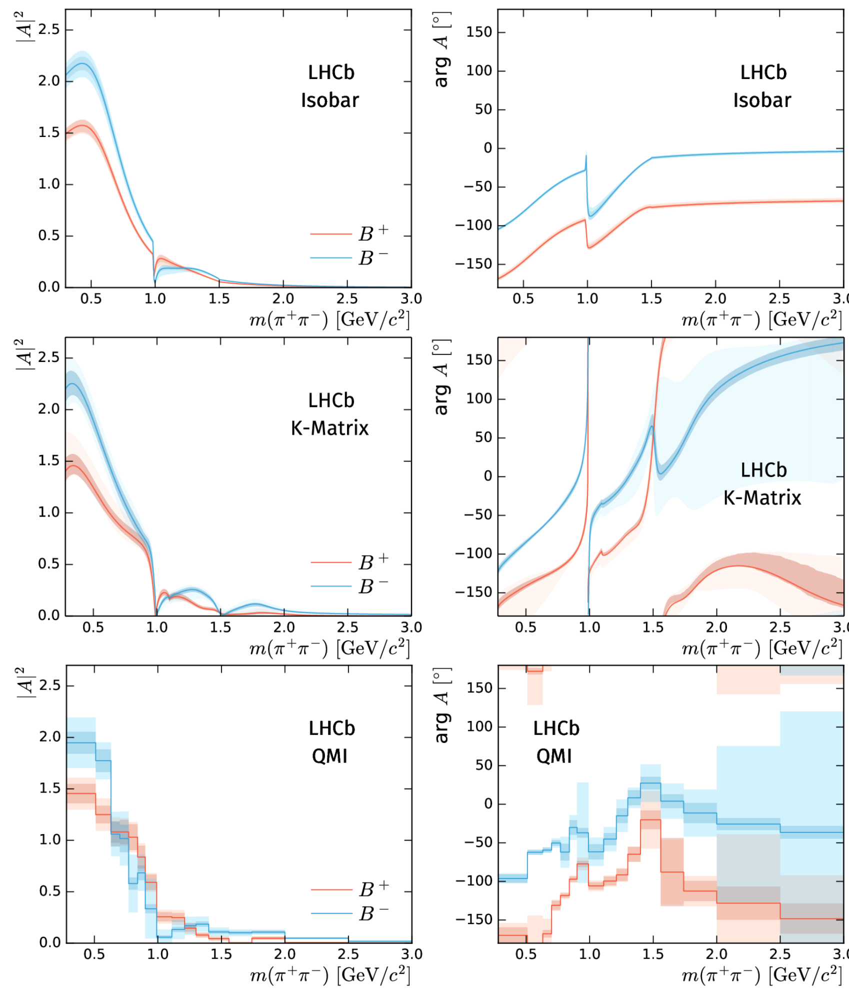
Significant positive asymmetries in the $f_2(1270)$, ~40%, and S-wave, ~15%

First CPV to be observed involving a tensor state

PRD 101 (2020) 012006

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

- Very good consistency between the three S-wave modelling approaches in both magnitude and phase behaviour
- Clear positive asymmetry at low dipion mass
- Asymmetry rapidly changes sign around $K\bar{K}$ threshold
- Exciting to see what new insights and additional precision Run 2 data will bring to these analyses



Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$ decays

LHCb-PAPER-2020-031

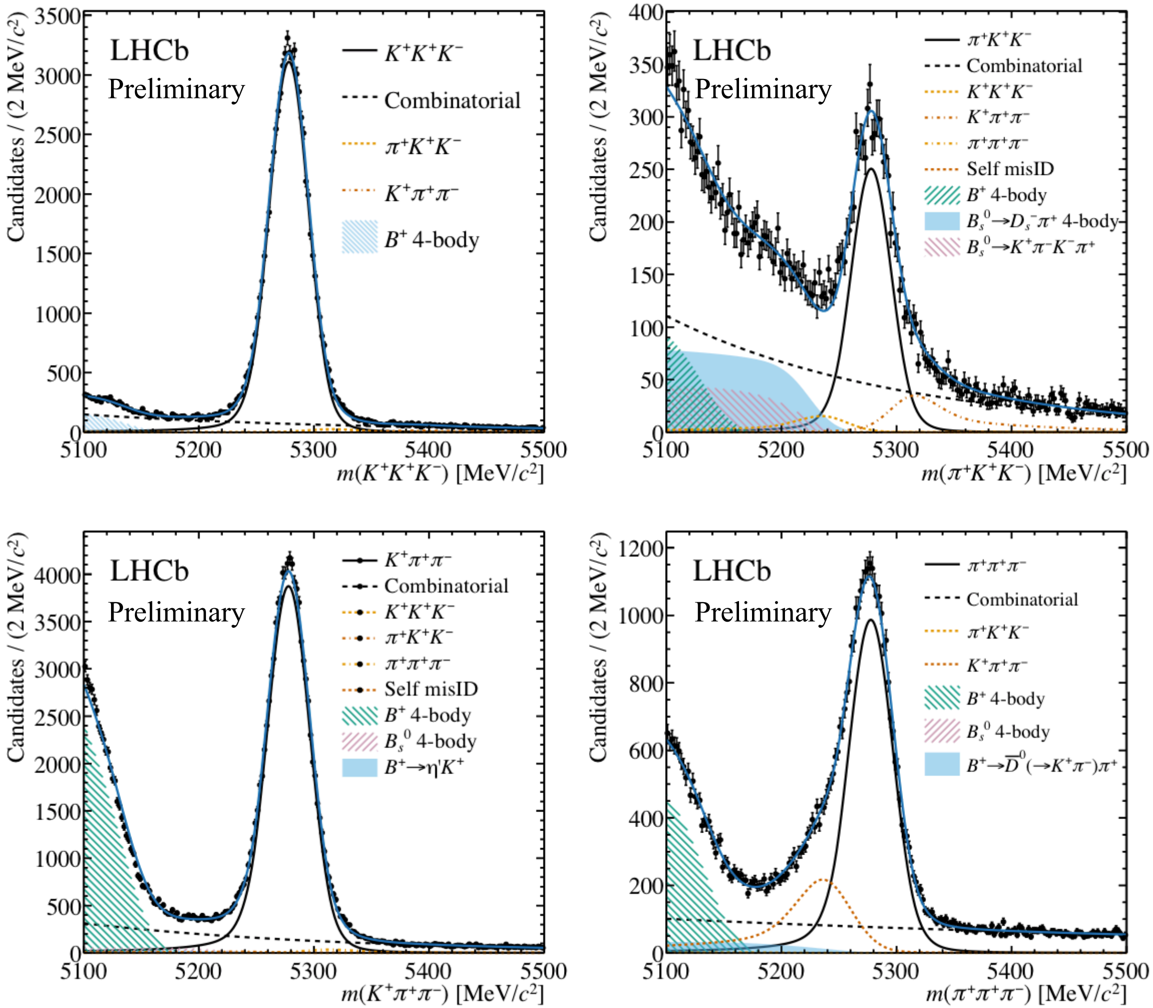
(in preparation)

$B^+ \to h^+ h'^+ h'^-$ branching fractions

- Increasingly precise measurements of quasi-two-body CP asymmetries and fit fractions coming from amplitude analyses
- To convert fit fractions into branching fractions, for comparison with theory predictions, need precise knowledge of the three-body branching fractions
- Current precision ranges from 4 – 9% (as shown below)
- Use LHCb Run 1 data sample to improve upon these

Mode	PDG average branching fraction (10^{-6})
$B^+ \to K^+K^+K^-$	34.0 ± 1.4
$B^+ \to \pi^+K^+K^-$	5.2 ± 0.4
$B^+ \to K^+\pi^+\pi^-$	51.0 ± 2.9
$B^+ \to \pi^+\pi^+\pi^-$	15.2 ± 1.4

$B^+ \to h^+ h'^+ h'^-$ fit results

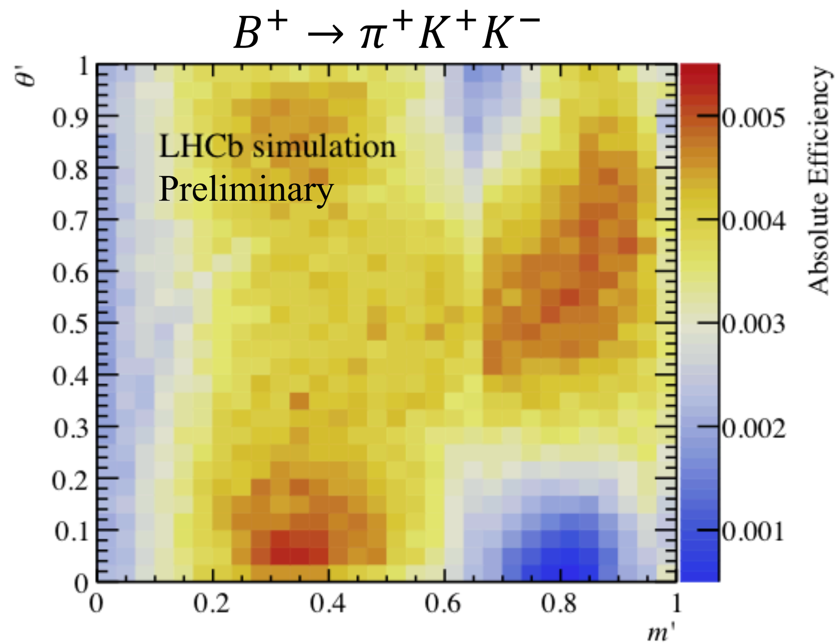


- Signal yields extracted from a simultaneous fit to all four channels
- Allows to constrain cross-feed between the signal channels due to particle mis-ID
- Intermediate charm decays removed with invariant mass vetoes

Channel	Fit yield
$B^+ \to K^+K^+K^-$	$69\,310 \pm 280$
$B^+ \to \pi^+K^+K^-$	$5\,760 \pm 140$
$B^+ \to K^+\pi^+\pi^-$	$94\,950 \pm 430$
$B^+ \to \pi^+\pi^+\pi^-$	$25\,480 \pm 200$

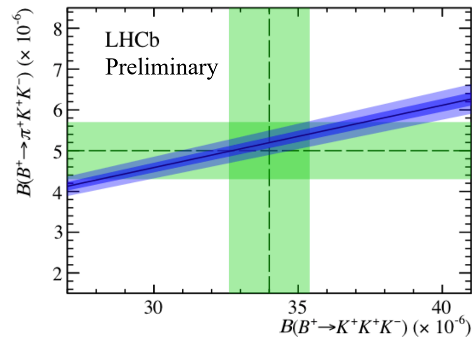
$B^+ \to h^+ h'^+ h'^-$ branching fractions

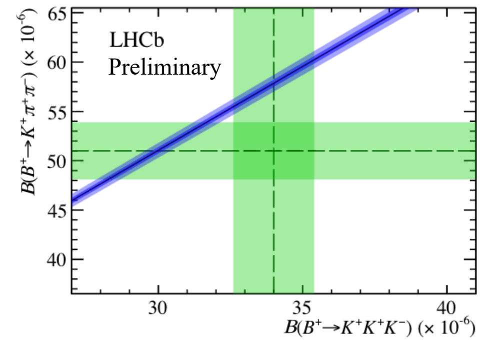
- Determination of relative branching fractions requires understanding:
  - signal distribution in the 3-body phasespace
  - efficiency variation over the same
- Signal distribution extracted using sPlot approach [NIM A 555 (2005) 356]
- Efficiency determined from simulation with corrections from data control samples for
  - Particle identification
  - Tracking
  - Hardware trigger
  - Production kinematics
  - Track multiplicity



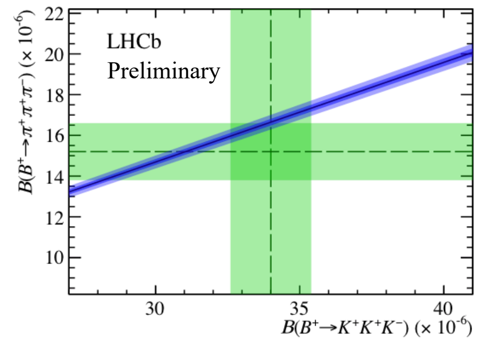
$B^+ \to h^+ h'^+ h'^-$ branching fractions

- Preliminary results for relative branching fractions determined
- Results are systematically limited
- Largest sources of systematic uncertainty from background modelling and hardware trigger efficiency determination





- Figures show comparison with current WA results
- Significant improvement in precision obtained
  - e.g., using these results and fit fraction from $B^+ \to \pi^+\pi^+\pi^-$ amplitude analysis, precision on $\mathcal{B}(B^+ \to \rho^0\pi^+)$ improves from 16% to 6%



$$\begin{aligned}
\mathcal{B}(B^+\to\pi^+K^+K^-)/\mathcal{B}(B^+\to K^+K^+K^-) &= 0.151 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst})\,,\\
\mathcal{B}(B^+\to K^+\pi^+\pi^-)/\mathcal{B}(B^+\to K^+K^+K^-) &= 1.703 \pm 0.011\,(\text{stat}) \pm 0.022\,(\text{syst})\,,\\
\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)/\mathcal{B}(B^+\to K^+K^+K^-) &= 0.488 \pm 0.005\,(\text{stat}) \pm 0.009\,(\text{syst})\,.
\end{aligned}$$

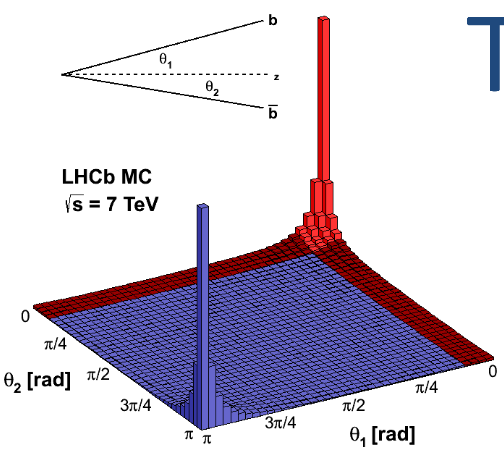
Summary

- Measurement of the branching fraction of the decay $B_s^0 \to K_S^0 K_S^0$
  - Phys. Rev. D 102 (2020) 012011
  - Most precise measurement of this decay to date
- Amplitude analyses of $B^+ \to \pi^+ K^+ K^-$ and $B^+ \to \pi^+ \pi^+ \pi^-$ decays
  - Phys. Rev. Lett. 123 (2019) 231802
  - Phys. Rev. Lett. 124 (2020) 031801 & Phys. Rev. D 101 (2020) 012006
  - Large CP asymmetries observed in several amplitudes, including
    - Largest CP asymmetry for a single amplitude
    - First observation of CPV in decay involving tensor state
    - First observation of CPV in interference between two quasi-two-body decays
- Measurement of the relative branching fractions of $B^+ \to h^+ h'^+ h'^-$ decays

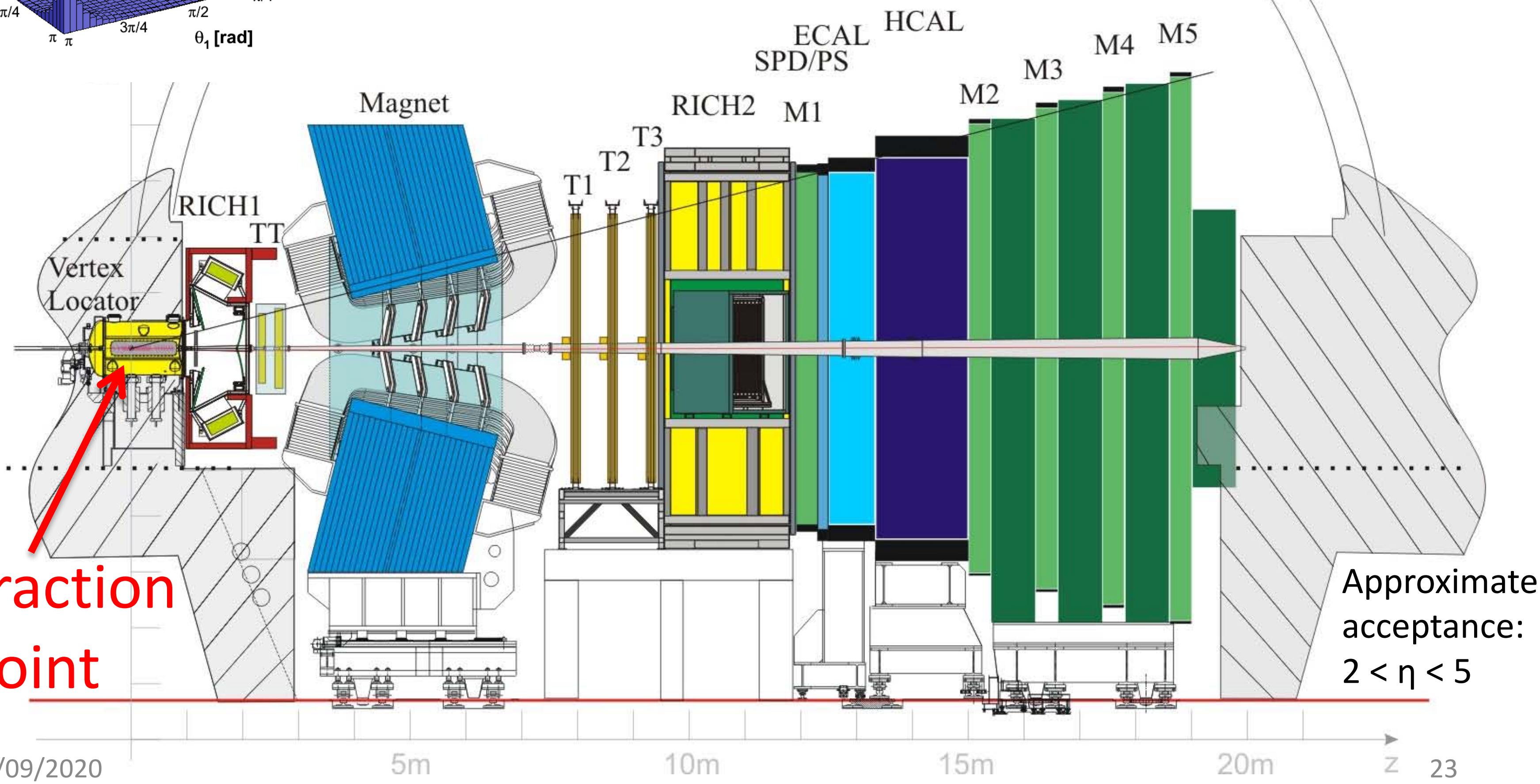
  - LHCb-PAPER-2020-031 (in preparation)
  - Significant improvement in precision wrt world averages obtained
- Exciting prospects for improved understanding of CPV with LHCb upgrade data

Backup Slides

The LHCb detector



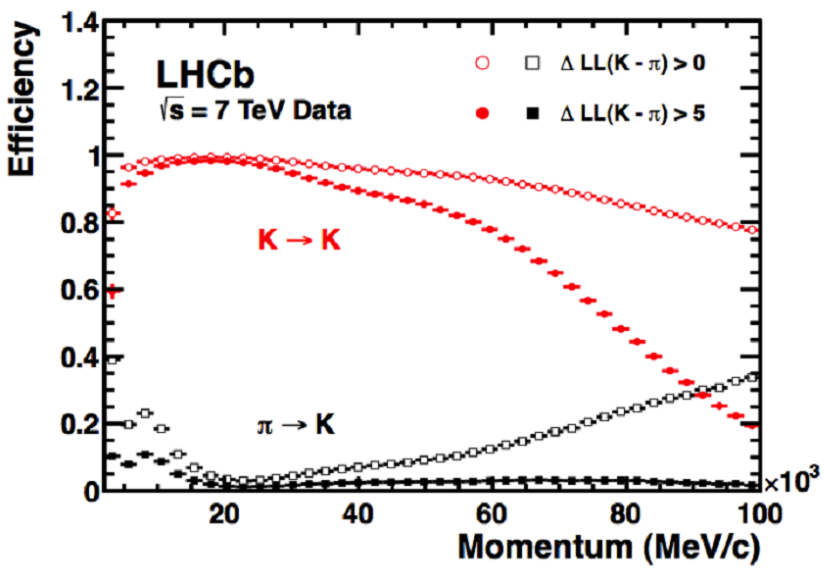
LHCb $\sigma(pp \rightarrow H_b X)$ @ 7 TeV = (72.0 ± 0.3 ± 6.8) μb
LHCb $\sigma(pp \rightarrow H_b X)$ @ 13 TeV = (154.3 ± 1.5 ± 14.3) μb
[Phys. Rev. Lett. 118 (2017) 052002]

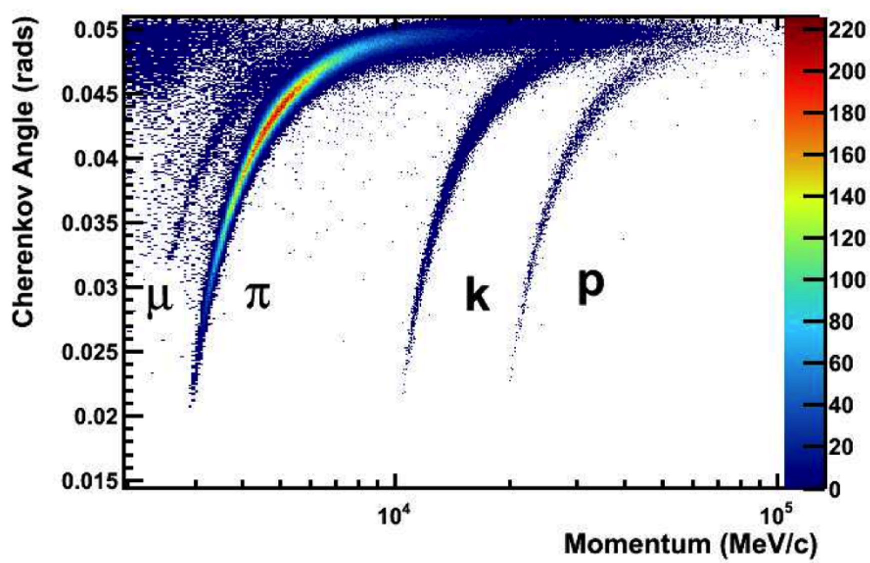


Kaon/pion separation

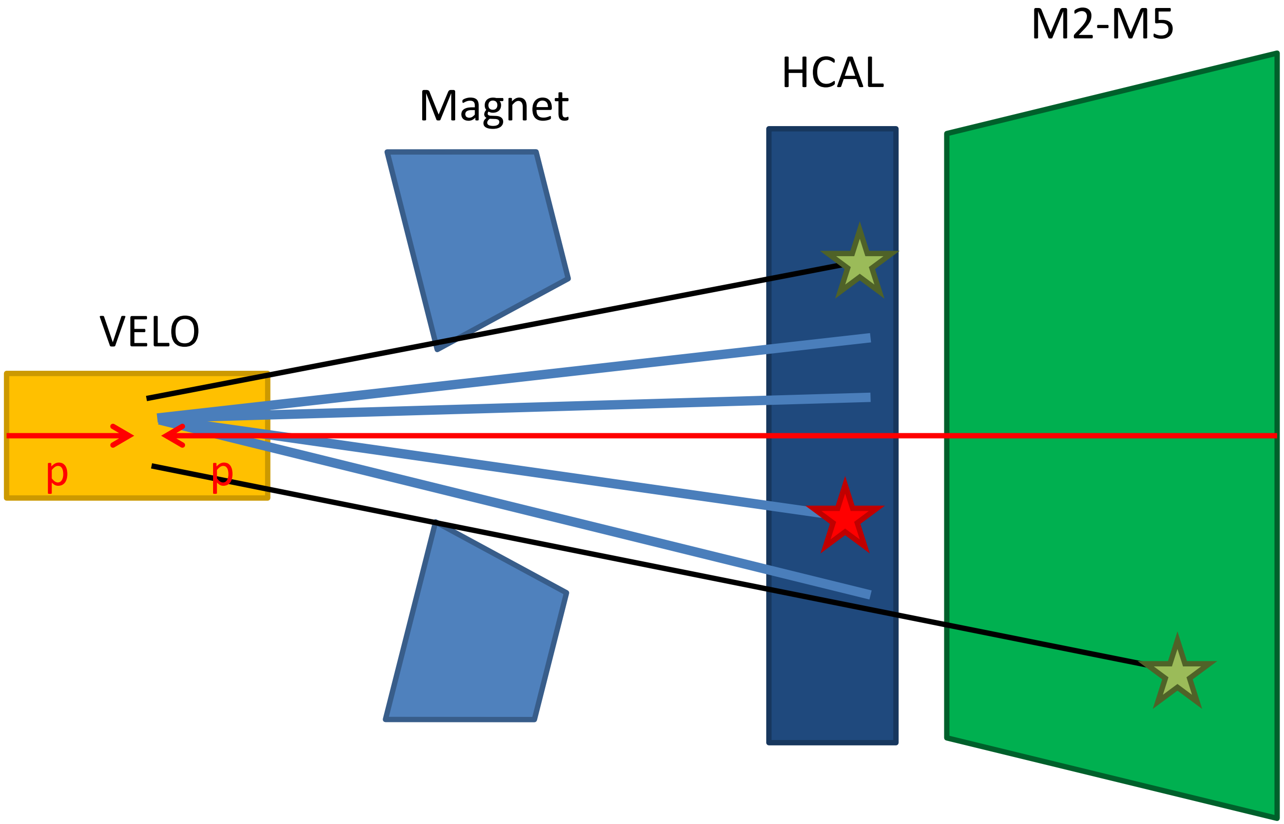
- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Different radiators provide separation over a wide momentum range.

$$\cos\theta = \frac{1}{\beta n}$$





Trigger categories



Trigger On Signal

- Particle from the signal decay fires a trigger line.
- Triggered by HCAL deposits.

Trigger Independent of Signal

- Particle from the rest of the event fires a trigger line.
- Triggered mostly by HCAL deposits or muons.

- Trigger Efficiencies:
  - ~30% efficient for multi-body hadronic
  - ~90% efficient for di-muons

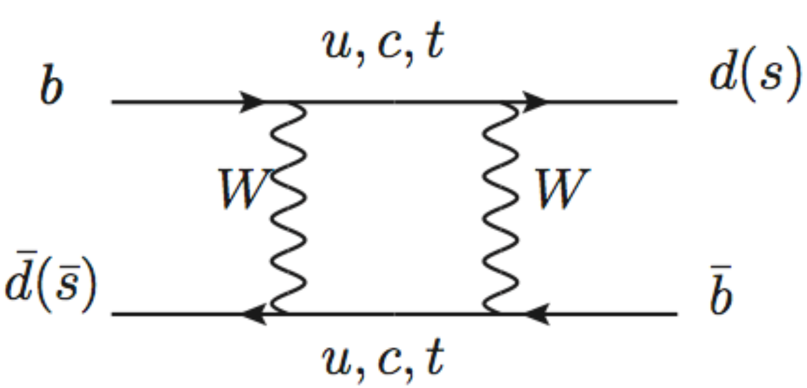
Manifestations of CPV

- **CPV in decay** $|\bar{A}_{\bar{f}}/A_f| \neq 1$
  - The ratio of the amplitudes for the decay of b and $\bar{b}$ hadrons to CP-conjugate final states is not of unit magnitude
  - Only form of CPV possible for B^+ mesons and b-baryons
- **CPV in mixing** $|q/p| \neq 1$
  - Expected to be small for the B meson system
  - Will not discuss this today (although LHCb has made important measurements in last couple of years)

[Phys. Rev. Lett. 114 (2015) 041601]

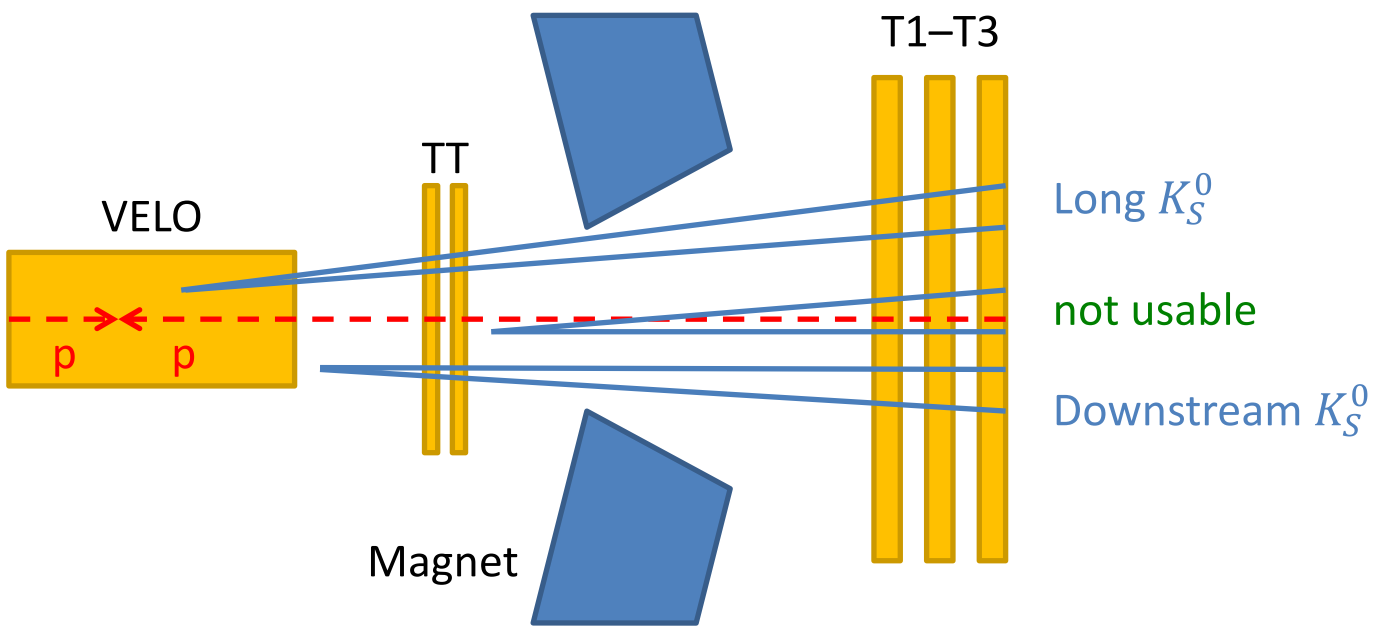
[Phys. Rev. Lett. 117 (2016) 061803]

- **Mixing-induced CPV** $\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$
  - The ratio of the amplitudes for decays with and without mixing is not real
  - Investigated for both B^0 and B_s^0 decays - requires time-dependent analyses
  - Have heard much about this earlier in the session



K_S^0 reconstruction

- $K_S^0 \to \pi^+\pi^-$ reconstructed in two categories: Long (w/ VELO info) & Downstream (w/o)
- Data samples split into Run 1 / Run 2 & Long+Long (LL) / Long+Downstream (LD) categories
  - The ϕ meson in control channel is always Long category, while the K_S^0 can be either category
  - One signal K_S^0 required to be Long category, while the second can be either category
- Trigger efficiency steadily improved, particularly for Downstream, over data-taking period
  - But overall efficiency still low – signal mode efficiency ~30x smaller than normalisation mode



$B_s^0 \to K_S^0 K_S^0$ detailed fit results

Table 1: Results of the simultaneous fit to the invariant mass of the $K_S^0 K_S^0$ system. The fit results for $\mathcal{B}$ and f_{B^0/B_s^0} are shared among all data categories. The given uncertainties are statistical only. The normalization constant α and the corresponding normalization channel yields N_{norm} are shown for reference.

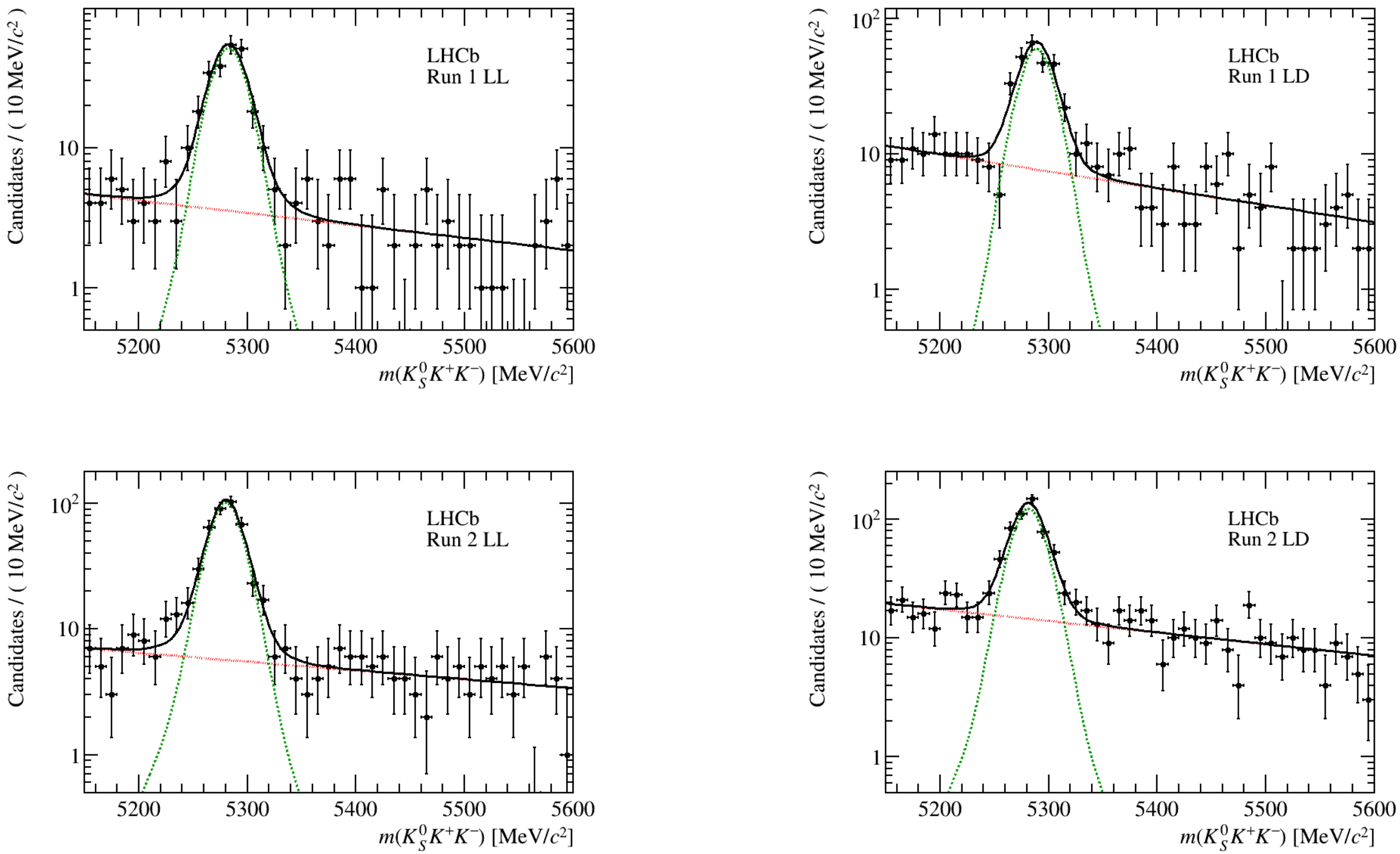
Parameter	Run 1 LL	Run 1 LD	Run 2 LL	Run 2 LD	Status
$\mathcal{B}$ $(\times 10^{-6})$		8.3 ± 1.6			Free
f_{B^0/B_s^0}		0.30 ± 0.13			Free
$N_{B_s^0}$	4.3 ± 1.0	2.1 ± 0.5	12.8 ± 2.7	12.4 ± 2.7	$\mathcal{B}/\alpha$
N_{B^0}	1.3 ± 0.5	0.63 ± 0.26	3.8 ± 1.5	3.7 ± 1.5	$f_{B^0/B_s^0} \times \mathcal{B}/\alpha$
N_{bkg}	10.4 ± 3.5	3.5 ± 2.2	7.2 ± 3.0	13 ± 4	Free
α $(\times 10^{-6})$	1.90 ± 0.21	3.9 ± 0.5	0.65 ± 0.05	0.66 ± 0.05	Gaussian constr.
N_{norm}	179 ± 18	178 ± 22	316 ± 25	400 ± 31	Included in α

$B_s^0 \to K_S^0 K_S^0$ systematic uncertainties

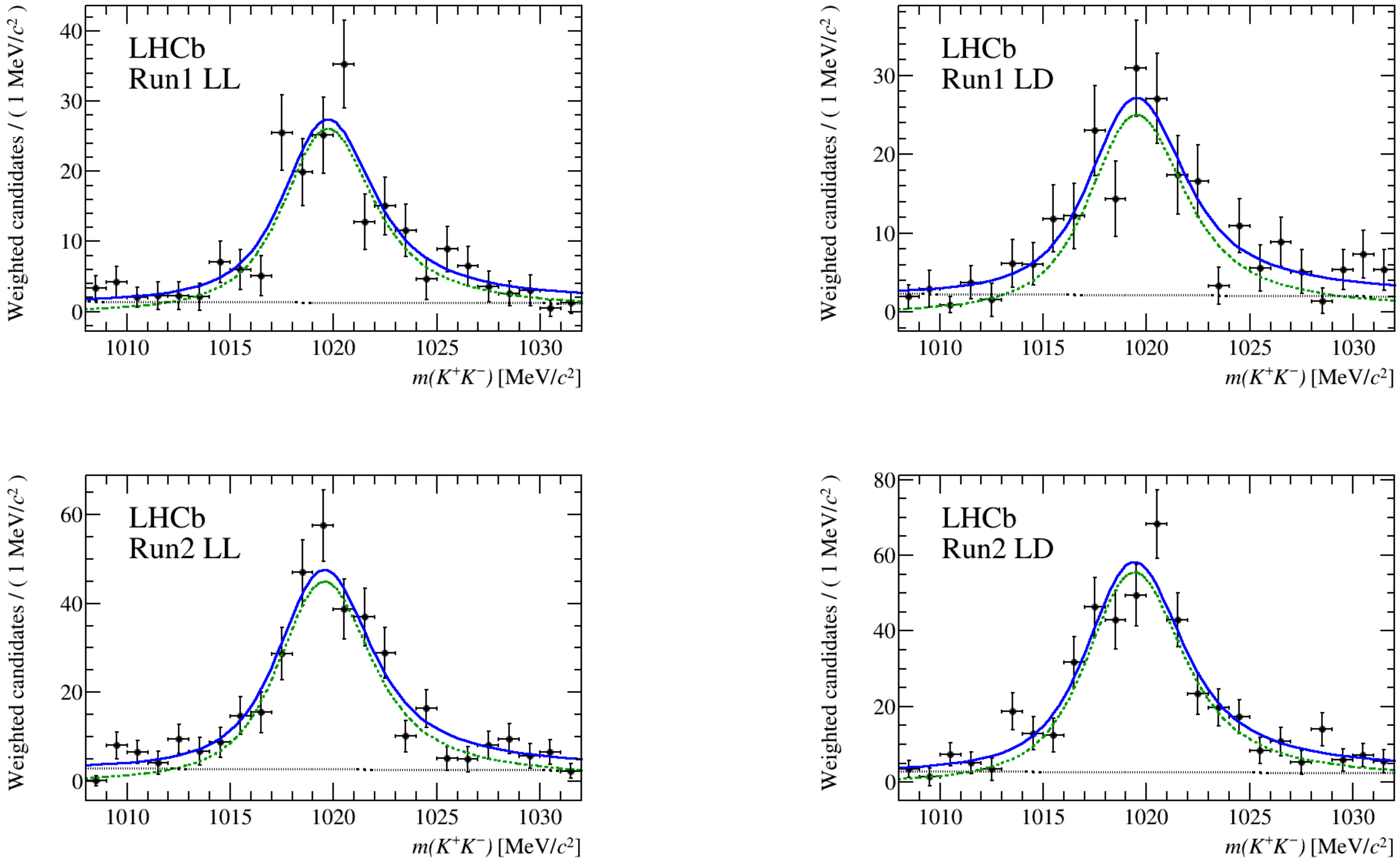
Table 2: All systematic uncertainties on the $B_s^0 \to K_S^0 K_S^0$ branching fraction, presented as relative measurements. The last row shows the combined systematic uncertainty for each data sample.

Systematic uncert.	Run 1, LL	Run 1, LD	Run 2, LL	Run 2, LD
Fit bias	0.059	0.059	0.059	0.059
Fit model choice	0.022	0.033	0.015	0.013
Fit model parameters	0.026	0.026	0.026	0.026
BDT	0.023	0.040	0.014	0.031
PID	0.007	0.008	0.026	0.026
Hardware trigger	0.063	0.062	0.063	0.062
Software trigger	0.065	0.106	0.008	0.026
Trigger misconfig.	—	—	0.007	0.004
$\pi^\pm/K^\pm$ hadronic interaction	0.005	0.005	0.005	0.005
VELO misalignment	0.008	0.008	0.008	0.008
Total	0.116	0.149	0.097	0.103

$B_s^0 \to K_S^0 K_S^0$ control channel fits



$B_s^0 \to K_S^0 K_S^0$ control channel fits



$B^+ \to \pi^+ h^+ h^-$ – amplitude formalism

- Both analyses use “isobar model” to form the total amplitude

$$F_j(m_{13}^2, m_{23}^2) \propto R(m_{13}) \cdot T(\vec{p}, \vec{q}) \cdot X(p \cdot r_{BW}^P) \cdot X(q \cdot r_{BW}^R)$$

$$A^{\pm}(m_{13}^2, m_{23}^2) = \sum_j \boxed{c_j^{\pm}} \boxed{F_j(m_{13}^2, m_{23}^2)}$$

CP violating

$$\boxed{c_j^{\pm} = (x \pm \delta x) + i(y \pm \delta y)}$$

- In addition, the $B^+ \to \pi^+\pi^+\pi^-$ analysis uses two alternative approaches to describe the $\pi^+\pi^-$ S-wave amplitude
  - K-matrix formalism:
    - Includes effects of rescattering between 2-body system
    - Preserves 2-body unitarity
    - Produced initial states are propagated to the observed final state by the K-matrix
  - Quasi-model-independent approach:
    - Dipion mass spectrum divided into bins
    - Each bin has independent magnitude and phase that are free to vary

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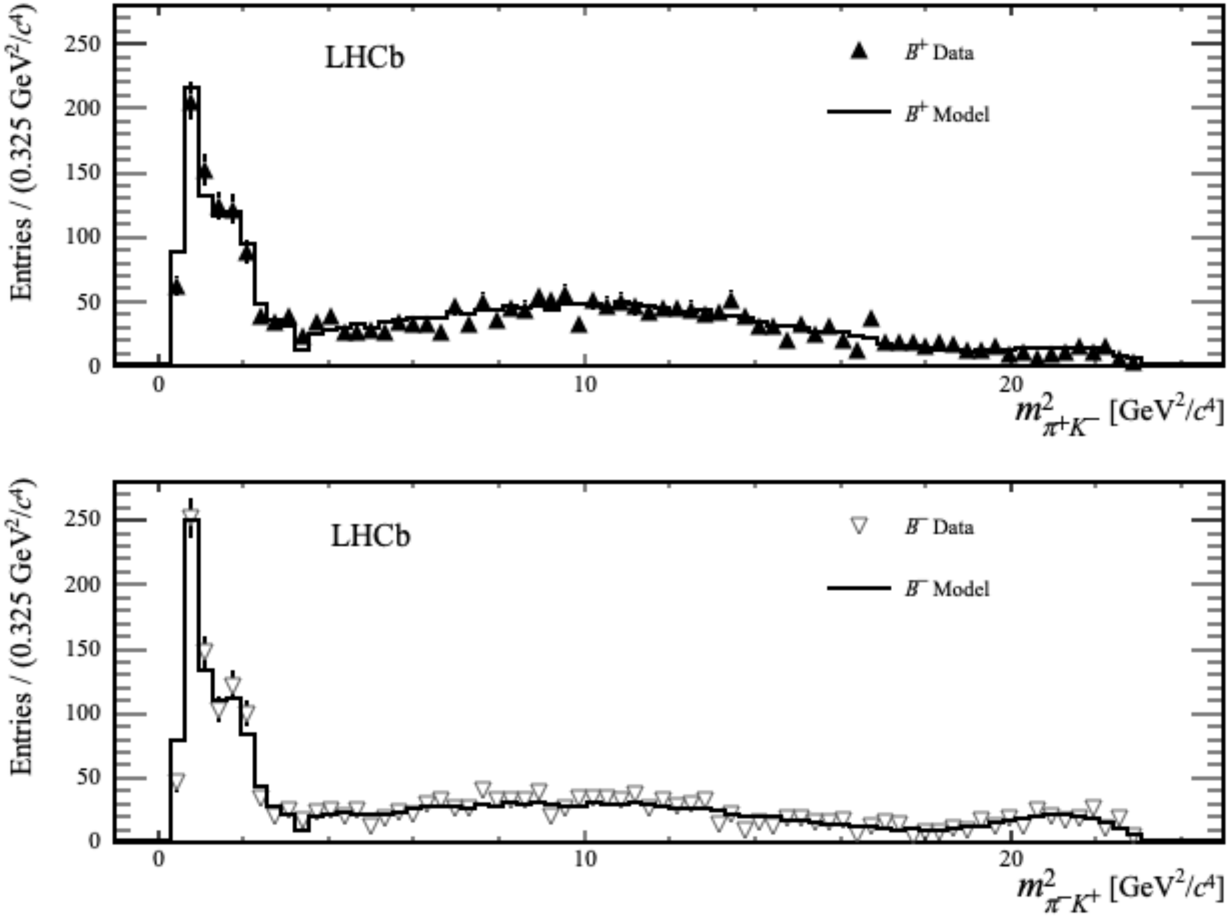
$B^+ \to \pi^+ K^+ K^-$ results



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

Fit fractions (%) The $\rho(770)^0$ and S-wave dominate

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$55.5 \pm 0.6 \pm 0.4 \pm 2.5$	$56.5 \pm 0.7 \pm 1.5 \pm 3.1$	$54.8 \pm 1.0 \pm 1.9 \pm 1.0$
$\omega(782)$	$0.50 \pm 0.03 \pm 0.01 \pm 0.04$	$0.47 \pm 0.04 \pm 0.01 \pm 0.03$	$0.57 \pm 0.10 \pm 0.12 \pm 0.12$
$f_2(1270)$	$9.0 \pm 0.3 \pm 0.7 \pm 1.4$	$9.3 \pm 0.4 \pm 0.6 \pm 2.4$	$9.6 \pm 0.4 \pm 0.7 \pm 3.9$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 0.2 \pm 1.9$	$10.5 \pm 0.7 \pm 0.8 \pm 4.5$	$7.4 \pm 0.5 \pm 3.9 \pm 1.1$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.1 \pm 0.3$	$1.5 \pm 0.1 \pm 0.1 \pm 0.4$	$1.0 \pm 0.1 \pm 0.5 \pm 0.1$
S-wave	$25.4 \pm 0.5 \pm 0.5 \pm 3.6$	$25.7 \pm 0.6 \pm 2.6 \pm 1.4$	$26.8 \pm 0.7 \pm 2.0 \pm 1.0$

A_{CP} (%) Significant positive asymmetries in the $f_2(1270)$ and S-wave

Component	Isobar	K-matrix	QMI
$\rho(770)^0$	$+0.7 \pm 1.1 \pm 0.6 \pm 1.5$	$+4.2 \pm 1.5 \pm 2.6 \pm 5.8$	$+4.4 \pm 1.7 \pm 2.3 \pm 1.6$
$\omega(782)$	$-4.8 \pm 6.5 \pm 1.3 \pm 3.5$	$-6.2 \pm 8.4 \pm 5.6 \pm 8.1$	$-7.9 \pm 16.5 \pm 14.2 \pm 7.0$
$f_2(1270)$	$+46.8 \pm 6.1 \pm 1.5 \pm 4.4$	$+42.8 \pm 4.1 \pm 2.1 \pm 8.9$	$+37.6 \pm 4.4 \pm 6.0 \pm 5.2$
$\rho(1450)^0$	$-12.9 \pm 3.3 \pm 3.6 \pm 35.7$	$+9.0 \pm 6.0 \pm 10.8 \pm 45.7$	$-15.5 \pm 7.3 \pm 14.3 \pm 32.2$
$\rho_3(1690)^0$	$-80.1 \pm 11.4 \pm 7.8 \pm 24.1$	$-35.7 \pm 10.8 \pm 8.5 \pm 35.9$	$-93.2 \pm 6.8 \pm 8.0 \pm 38.1$
S-wave	$+14.4 \pm 1.8 \pm 1.0 \pm 1.9$	$+15.8 \pm 2.6 \pm 2.1 \pm 6.9$	$+15.0 \pm 2.7 \pm 4.2 \pm 7.0$

Good agreement between the three approaches

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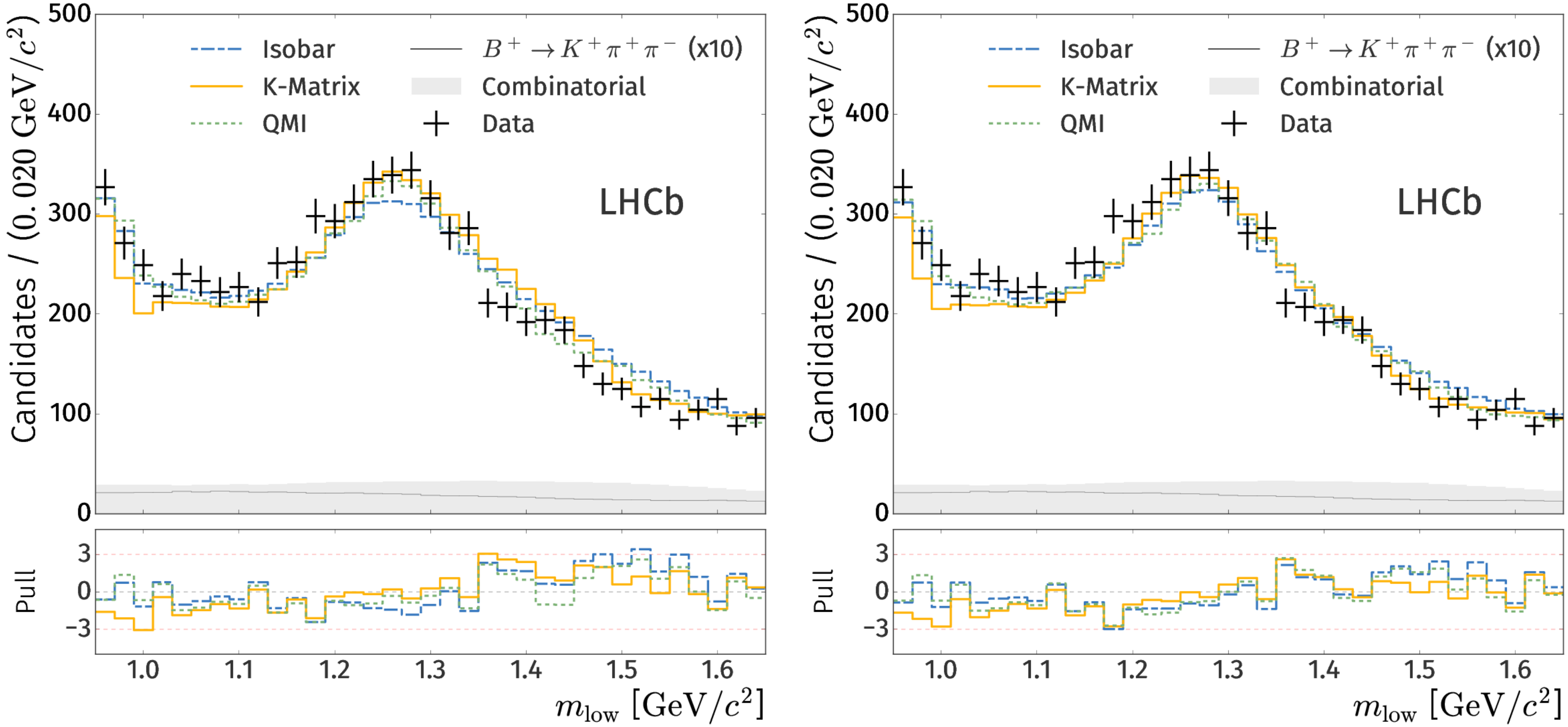
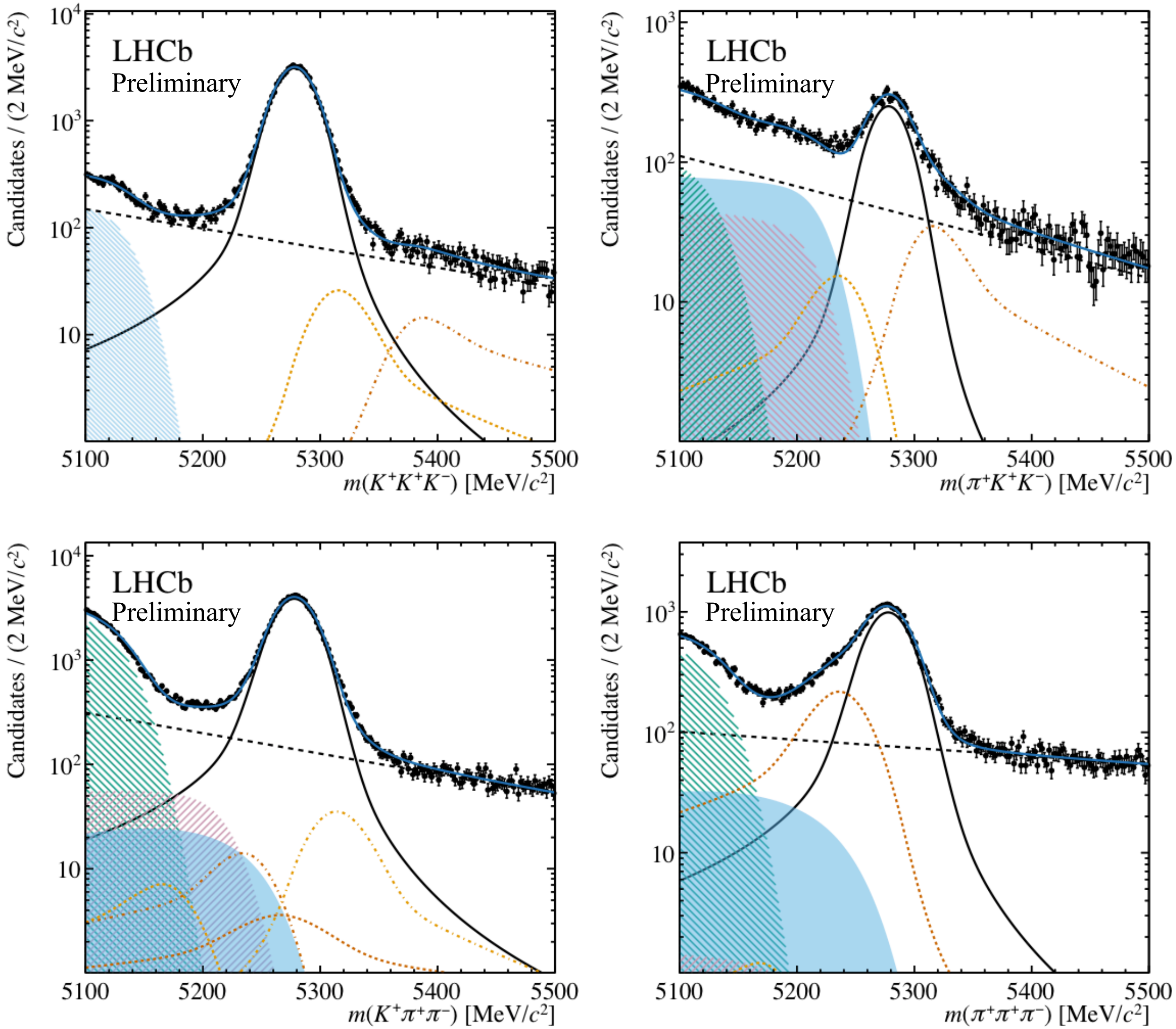
$f_2(1270)$ region modelling



Alternative models with (left) freely varied $f_2(1270)$ resonance parameters and (right) additional spin-2 component with mass and width parameters floating

$B^+ \to h^+ h'^+ h'^-$ fit results



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$B^+ \to h^+ h'^+ h'^-$ systematic uncertainties

Table 6: Absolute systematic uncertainties. All values are given multiplied by 100.

$\mathcal{B}$ ratio	Model I	Model II	Model III	Fit bias	Fixed params	L0 TOS	L0 TIS	Tracking	Kinematics	MVA	Veto	Binning	MC stats	PID
$\frac{\mathcal{B}(B^+\to\pi^+K^+K^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.04	0.55	0.50	0.01	0.11	0.20	0.12	0.01	0.01	0.03	0.05	0.05	0.03	0.08
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.1	1.0	1.2	0.0	0.7	0.8	0.4	0.2	0.2	0.6	0.5	0.1	0.3	0.4
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.05	0.02	0.72	0.02	0.24	0.23	0.19	0.13	0.10	0.16	0.12	0.36	0.11	0.16
$\frac{\mathcal{B}(B^+\to K^+K^+K^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	2	24	19	1	5	9	5	0	0	1	2	2	1	4
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	2	32	40	1	10	9	9	1	1	2	3	3	2	6
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	1	12	14	0	3	3	3	1	0	0	1	1	1	2
$\frac{\mathcal{B}(B^+\to K^+K^+K^-)}{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}$	0.0	0.4	0.4	0.0	0.2	0.3	0.1	0.1	0.1	0.2	0.2	0.0	0.1	0.1
$\frac{\mathcal{B}(B^+\to\pi^+K^+K^-)}{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}$	0.04	0.23	0.23	0.01	0.17	0.07	0.07	0.01	0.01	0.01	0.03	0.02	0.02	0.05
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}$	0.04	0.23	0.23	0.01	0.17	0.01	0.10	0.04	0.02	0.01	0.06	0.20	0.06	0.04
$\frac{\mathcal{B}(B^+\to K^+K^+K^-)}{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}$	0.2	0.1	3.1	0.1	0.9	1.0	0.8	0.5	0.4	0.7	0.5	1.5	0.5	0.6
$\frac{\mathcal{B}(B^+\to\pi^+K^+K^-)}{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}$	0.1	1.1	1.5	0.0	0.3	0.3	0.3	0.1	0.0	0.0	0.1	0.1	0.1	0.2
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}$	0.5	2.7	2.8	0.1	2.0	0.1	1.2	0.5	0.2	0.1	0.8	2.4	0.7	0.5

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$B^+ \to h^+ h'^+ h'^-$ preliminary results

$\mathcal{B}$ ratio	Value
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$0.151 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$1.703 \pm 0.011\,(\text{stat}) \pm 0.022\,(\text{syst})$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ K^+ K^-)$	$0.488 \pm 0.005\,(\text{stat}) \pm 0.009\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$6.61 \pm 0.17\,(\text{stat}) \pm 0.33\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$11.27 \pm 0.29\,(\text{stat}) \pm 0.54\,(\text{syst})$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ K^+ K^-)$	$3.23 \pm 0.09\,(\text{stat}) \pm 0.19\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.587 \pm 0.004\,(\text{stat}) \pm 0.008\,(\text{syst})$
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.0888 \pm 0.0023\,(\text{stat}) \pm 0.0047\,(\text{syst})$
$\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)$	$0.2867 \pm 0.0029\,(\text{stat}) \pm 0.0045\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$2.048 \pm 0.020\,(\text{stat}) \pm 0.040\,(\text{syst})$
$\mathcal{B}(B^+ \to \pi^+ K^+ K^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$0.310 \pm 0.008\,(\text{stat}) \pm 0.020\,(\text{syst})$
$\mathcal{B}(B^+ \to K^+ \pi^+ \pi^-)/\mathcal{B}(B^+ \to \pi^+ \pi^+ \pi^-)$	$3.488 \pm 0.035\,(\text{stat}) \pm 0.053\,(\text{syst})$

$B^+ \to h^+ h'^+ h'^-$ correlations

Table 8: Statistical correlations between the measured branching fraction ratios.

	$\frac{\pi^+K^+K^-}{K^+K^+K^-}$	$\frac{K^+\pi^+\pi^-}{K^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{K^+K^+K^-}$	$\frac{K^+\pi^+\pi^-}{\pi^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{\pi^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{K^+\pi^+\pi^-}$
$\frac{\mathcal{B}(B^+\to\pi^+K^+K^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	—	0.16	0.10	−0.96	−0.92	−0.01
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.16	—	0.32	0.12	−0.03	−0.34
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.10	0.32	—	−0.01	0.31	0.78
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	−0.96	0.12	−0.01	—	0.92	−0.08
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	−0.92	−0.03	0.31	0.92	—	0.32
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}$	−0.01	−0.34	0.78	−0.08	0.32	—

Table 9: Systematic correlations between the measured branching fraction ratios.

	$\frac{\pi^+K^+K^-}{K^+K^+K^-}$	$\frac{K^+\pi^+\pi^-}{K^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{K^+K^+K^-}$	$\frac{K^+\pi^+\pi^-}{\pi^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{\pi^+K^+K^-}$	$\frac{\pi^+\pi^+\pi^-}{K^+\pi^+\pi^-}$
$\frac{\mathcal{B}(B^+\to\pi^+K^+K^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	—	−0.27	0.15	−0.96	−0.97	0.38
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	−0.27	—	0.34	0.53	0.35	−0.72
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+K^+K^-)}$	0.15	0.34	—	−0.02	0.10	0.38
$\frac{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	−0.96	0.53	−0.02	—	0.96	−0.54
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to\pi^+K^+K^-)}$	−0.97	0.35	0.10	0.96	—	−0.27
$\frac{\mathcal{B}(B^+\to\pi^+\pi^+\pi^-)}{\mathcal{B}(B^+\to K^+\pi^+\pi^-)}$	0.38	−0.72	0.38	−0.54	−0.27	—

Improvement in $B^+ \to \rho^0\pi^+$ branching fraction

- I now show a worked example to highlight the improvement in precision in quasi-two-body BFs when combining these results with the recent amplitude analyses – NB this is a personal calculation using the available results shown

- HFLAV average for $\mathcal{B}(B^+ \to \rho^0\pi^+) = (8.3^{+1.2}_{-1.3})\times 10^{-6}$
  - **Relative uncertainty of 16%**

- HFLAV average for $\mathcal{B}(B^+ \to K^+K^+K^-) = (34.0 \pm 1.0)\times 10^{-6}$
- Our preliminary $\pi\pi\pi/KKK$ ratio is 0.488 ± 0.010 [LHCb-PAPER-2020-031]
- Fit-fraction result (isobar) from $B^+ \to \pi^+\pi^+\pi^-$ amplitude analysis is $FF(\rho^0\pi^+) = (55.5 \pm 2.6)\%$ [LHCb-PAPER-2019-017]

- Combining these numbers

$$\mathcal{B}(B^+ \to \rho^0\pi^+) = \mathcal{B}(B^+ \to K^+K^+K^-) \cdot R\left({}^{\pi\pi\pi}/_{KKK}\right) \cdot FF(\rho^0\pi^+)$$
$$= (9.2 \pm 0.5)\times 10^{-6}$$

  - **Relative uncertainty of 6%**