Rencontres de Blois 2014

Hadronic b decays and the Unitarity triangle angle γ at LHCb

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on behalf of the LHCb collaboration

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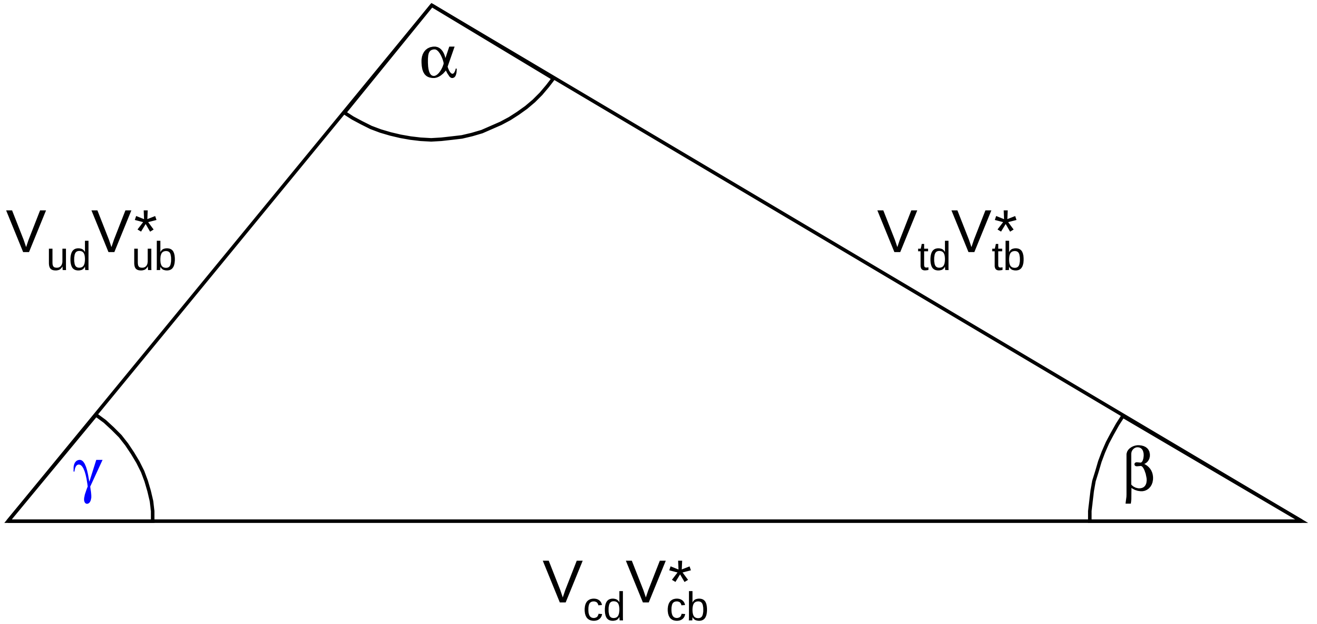
Outline

1. $B^{\pm} \to D[K_S^0\pi^+\pi^-]K^{\pm}$
2. $B^{\pm} \to D[K_S^0K^{\pm}\pi^{\pm}]K^{\pm}$
3. $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$
4. $\Lambda_b^0 \to \bar{K}^0 p\pi^-$

$$\phi_3 = \gamma \equiv -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



γ from B Decays

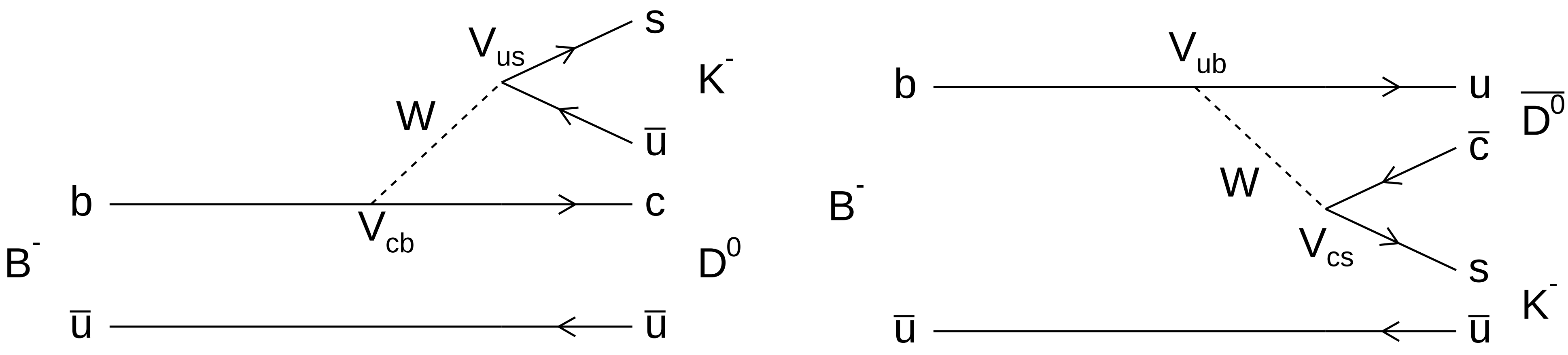
Theoretically cleanest Standard Model measurement of γ from $B \to DK$ decays

$|\delta\gamma| \lesssim \mathcal{O}(10^{-7})$ from electroweak corrections: J. Brod and J. Zupan, JHEP **1401** (2014) 051

When D^0 and $\bar{D}^0$ decay to the same final state, f

Interference between the dominant $b \to c\bar{u}s$ with the corresponding DCS $b \to u\bar{c}s$

$$A_{B^-} \propto A_f \quad + \quad r_B e^{i(\delta_B - \gamma)} \bar{A}_f$$



Amplitude ratio: $r_B = |A(B \to \bar{D}K)| \div |A(B \to DK)|$

Strong phase difference between $A(B \to \bar{D}K)$ and $A(B \to DK)$: δ_B

GGSZ Method

Measure r_B, δ_B and γ, through interference in the Dalitz plot of D decays to CP eigenstates

A. Bondar, Proceedings of BINP Special Analysis Meeting on Dalitz Analysis, 24-26 Sep. 2002, unpublished

A. Giri, Y. Grossman, A. Soffer, J. Zupan, Phys. Rev. D **68** (2003) 054018

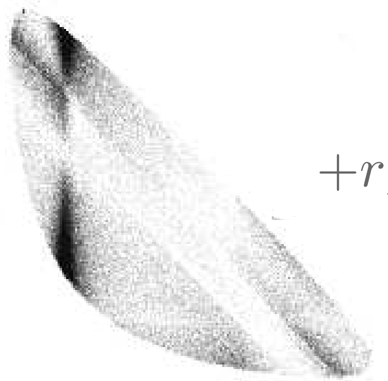
eg. $D^0 \to K^0_S \pi^+ \pi^-$ and $\bar{D}^0 \to K^0_S \pi^+ \pi^-$

Dalitz plots defined as scatterplot of $m^2_+(K^0_S \pi^+)$ vs $m^2_-(K^0_S \pi^-)$

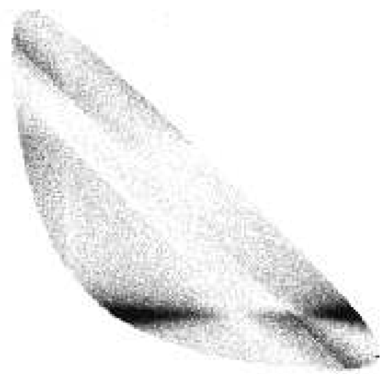
Contains complete quantum information of the decay including phase relationships

$$|A(B^- \to DK^-)|^2 = | A_{D^0} + r_B e^{i(\delta_B - \gamma)} A_{\bar{D}^0} |^2$$

$= |$



$+ r_B e^{i(\delta_B - \gamma)}$



$|^2$

$B^{\pm} \to D[K_S^0\pi^+\pi^-]K^{\pm}$

First model-dependent measurement of γ from LHCb using the GGSZ method

Integrated data sample of 1 fb^{-1} recorded at centre-of-mass energy of 7 TeV

Due to the long K_S^0 lifetime, data divided in 2 depending on K_S^0 reconstruction

- “Long”: Pion tracks located within the silicon vertex detector
- “Downstream”: K_S^0 decayed beyond the silicon vertex detector

Most dangerous background is $B^{\pm} \to D[K_S^0\pi^+\pi^-]\pi^{\pm}$ where $\pi^{\pm}$ was misidentified as $K^{\pm}$

- Excellent RICH PID performance supresses this by $\mathcal{O}(10^2)$ for minimal signal loss

Partially reconstructed backgrounds

- Mostly contains real $D[K_S^0\pi^+\pi^-]$ decays, but involve processes with additional particles
- eg. $B^{\pm} \to D\rho^{\pm}$, $B^{\pm} \to D^*h^{\pm}$ where $h = K$ or π

Combinatorial

- Supressed by B candidate displacement from primary pp interaction vertex

Yield Extraction

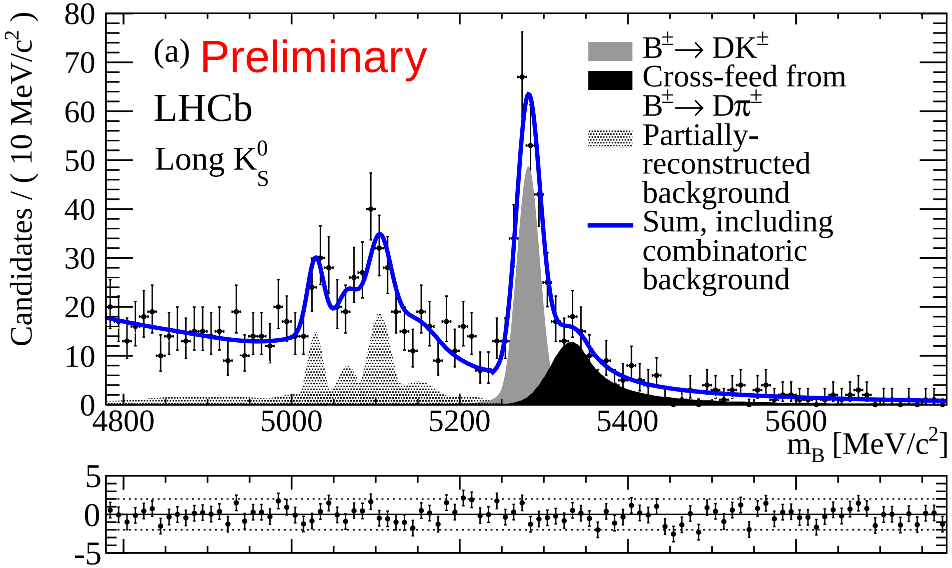
Analysis performed in 2 stages

Determine signal yield from fit to the $B^{\pm}$ candidate mass

Gives the signal and background fractions for the subsequent Dalitz analysis

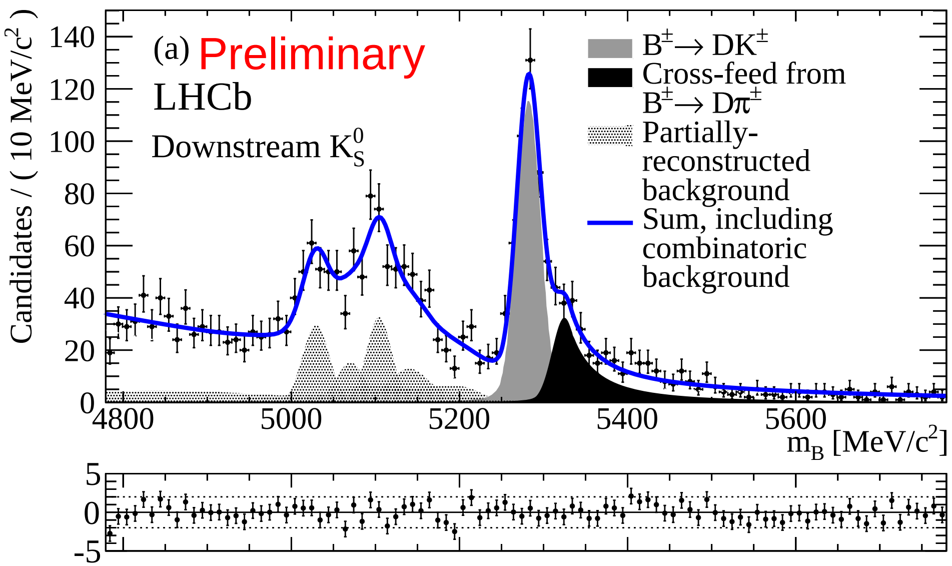
Perform fit simultaneously with control sample $B^{\pm} \to D[K_S^0\pi^+\pi^-]\pi^{\pm}$

“Long” K_S^0



$B^{\pm} \to DK^{\pm}$ yield: 217 ± 17 events

“Downstream” K_S^0



$B^{\pm} \to DK^{\pm}$ yield: 420 ± 27 events

Dalitz Amplitude

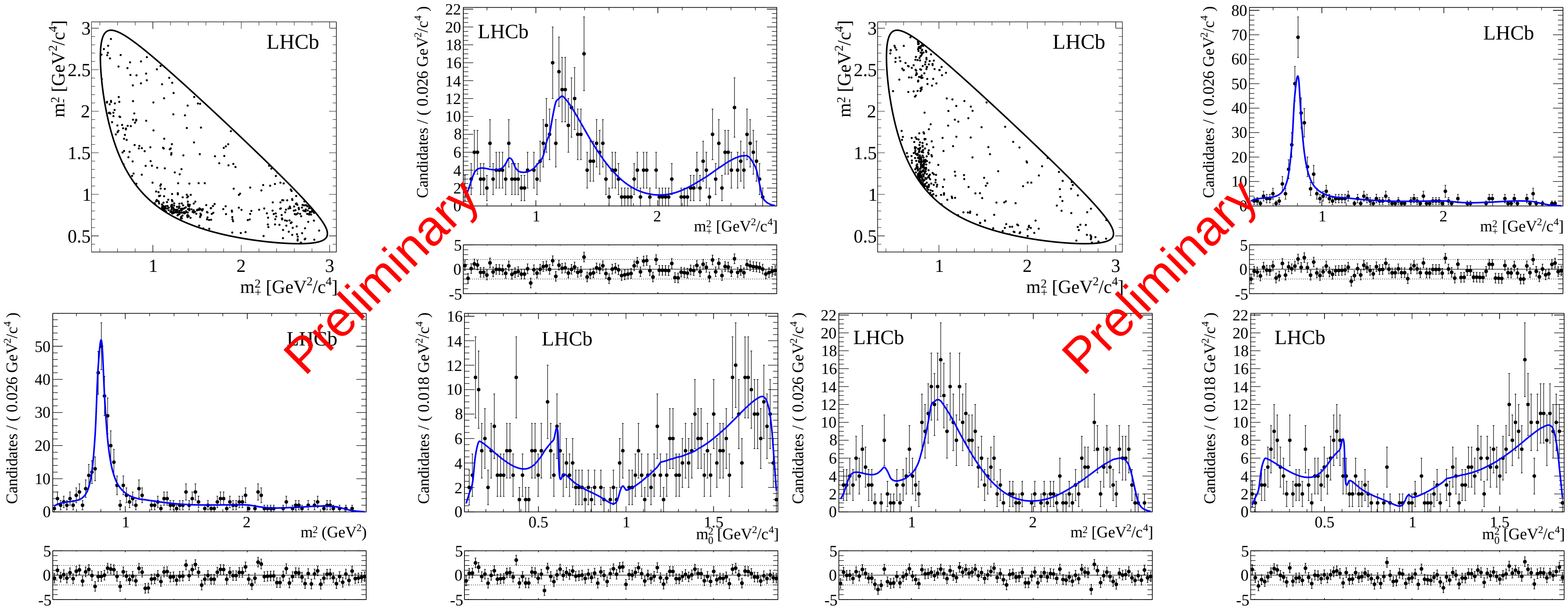
Amplitude model fixed to that determined by the BaBar Collaboration

P. del Amo Sanchez *et al*. (BaBar Collab.), Phys. Rev. Lett. 105 (2010) 081803

Restrict fit region to $\sim 3\sigma$ around B^+ mass

γ manifests as a difference in the structure between these 2 Dalitz plots

$B^- \rightarrow DK^-$ $\qquad\qquad$ $B^+ \rightarrow DK^+$



Results

Technical detail: Instead of fitting for r_B, δ_B and γ directly

Fit for transformed parameters

$$x_{\pm} \equiv r_B \cos(\delta_B \pm \gamma)$$

$$y_{\pm} \equiv r_B \sin(\delta_B \pm \gamma)$$

Preliminary Results

$$x_+ = -0.084 \pm 0.045 \pm 0.009 \pm 0.003$$

$$y_+ = -0.032 \pm 0.048 \pm 0.009 \pm 0.007$$

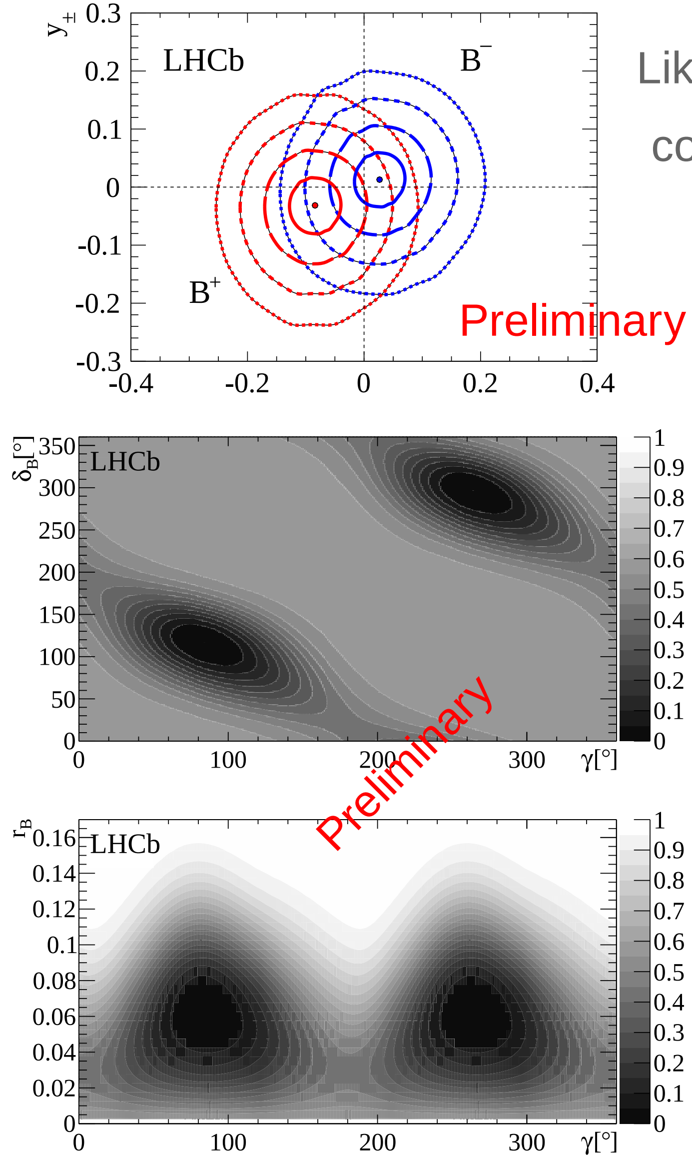
$$x_- = +0.027 \pm 0.044^{+0.010}_{-0.008} \pm 0.001$$

$$y_- = +0.013 \pm 0.048^{+0.008}_{-0.006} \pm 0.003$$

Uncertainties

1: statistical, 2: systematic, 3: model

Convert to γ, negligible D^0 mixing effect



Likelihood contours

Residual confidence level

Results

LHCb: 1 fb^{-1}

Preliminary Results

$\gamma = (84^{+49}_{-42})^\circ$

Belle: 657M $B\bar{B}$ pairs

PRD **81** (2010) 112002

$\gamma = (78^{+14}_{-15})^\circ$

Includes $B \to D^{(*)}K$

BaBar: 468M $B\bar{B}$ pairs

PRL 105 (2010) 121801

$\gamma = (68 \pm 15)^\circ$

Includes $B \to D^{(*)}K^{(*)}$

Includes $D \to K^0_S K^+ K^-$

There are also model-independent binned Dalitz measurements with input from CLEO

J. Libby *et al*. (CLEO Collab.) Phys. Rev. D. **82** (2010) 112006

LHCb: 1 fb^{-1}

PLB **718** (2012) 43

$\gamma = (44^{+43}_{-38})^\circ$

Includes $D \to K^0_S K^+ K^-$

Belle: 772M $B\bar{B}$ pairs

PRD **85** (2012) 112014

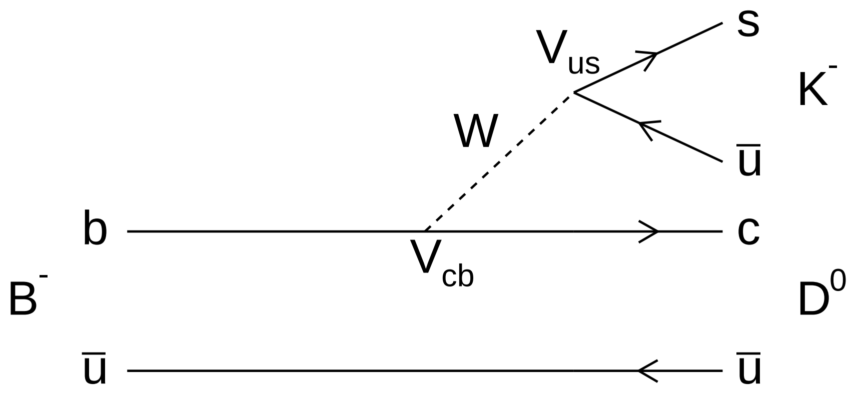
$\gamma = (77 \pm 16)^\circ$

γ solution consistent with Standard Model chosen

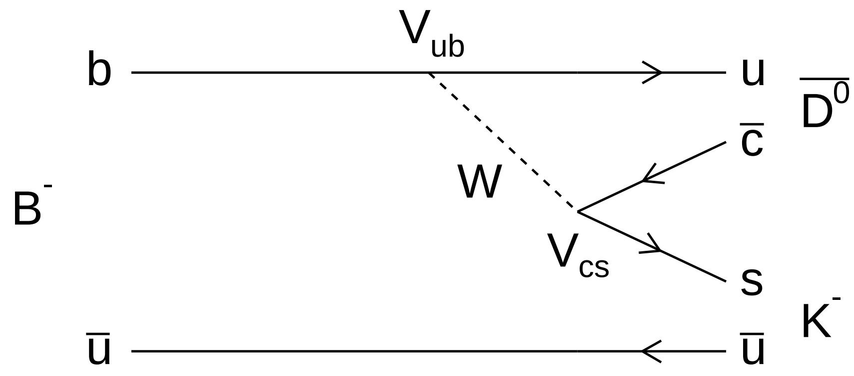
Uncertainties comparable

ADS-Like Adaptation

Colour-favoured

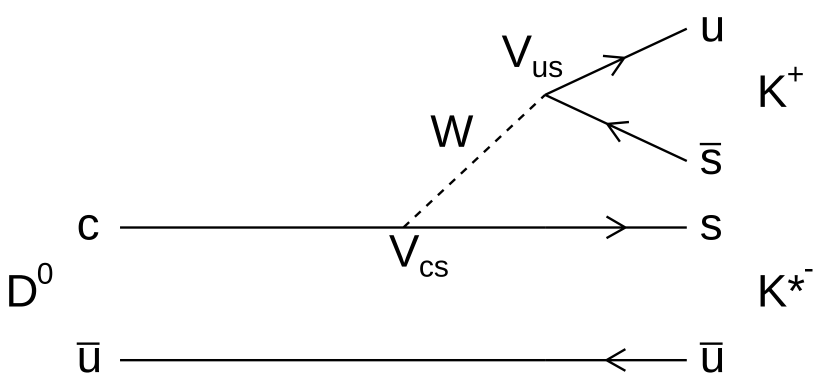


Colour-suppressed

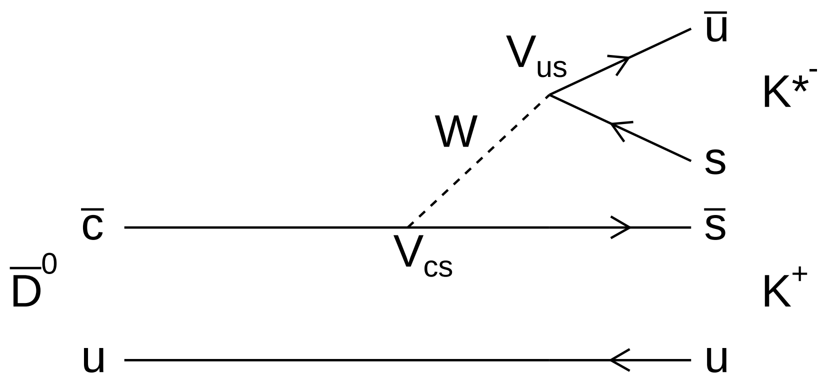


Difference in magnitudes mean that resulting asymmetries tend to be small, however

$K^*(892)^-$ from spectator (suppressed)



$K^*(892)^-$ from W (favoured)



Amplitudes of similar magnitude can enhance the effect of CP asymmetries

D. Atwood, I. Dunietz, A. Soni, Phys. Rev. Lett. **78** (1997) 3257

ADS Method

Singly Cabibbo Suppressed (SCS) D decays across the Dalitz plot

Y. Grossman, Z. Ligeti and A. Soffer, Phys. Rev D **67** (2003) 071301

Consider $B^- \to DK^-$ followed by $D \to K^0_S K^+ \pi^-$

For a given B charge, 2 possibilities for kaon charge configuration

Charged kaons with Opposite Sign (OS)

$$\Gamma^-_{\rm OS} \propto r_B^2 + {r_D}^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma + \delta_f)$$

Charged kaons with Same Sign (SS)

$$\Gamma^-_{\rm SS} \propto 1 + r_B^2 {r_D}^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma - \delta_f)$$

Amplitude ratio: $r_D = |A(D^0 \to K^0_S K^+ \pi^-)| \div |A(\bar{D}^0 \to K^0_S K^+ \pi^-)|$

3-body decay, so resonant structure varies across the Dalitz plot, $m^2_{K^0_S K}$ vs $m^2_{K^0_S \pi}$

Decay rate in region of a resonance depends on integral of the interference term in that region

Coherence factor κ_f, and average strong phase difference δ_f

ADS Method

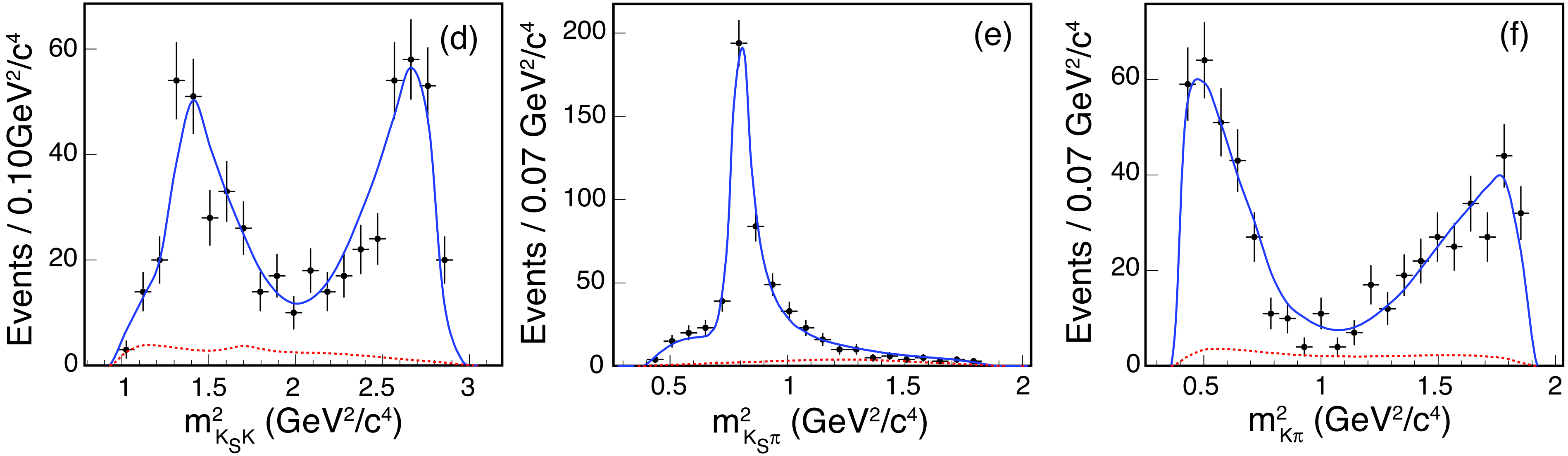
$$\kappa_f e^{-i\delta_f} \propto \int A^*_{K^0_S K^- \pi^+}(m^2_{K^0_S K}, m^2_{K^0_S \pi}) A_{K^0_S K^+ \pi^-}(m^2_{K^0_S K}, m^2_{K^0_S \pi}) dm^2_{K^0_S K} dm^2_{K^0_S \pi}$$

$K^0_S K^- \pi^+$ and $K^0_S K^+ \pi^-$ are flavour non-specific final states

Correlated $D^0 \bar{D}^0$ pairs can tag the D flavour

Amplitudes measured by the CLEO Collaboration

J. Insler *et al*. (CLEO Collab.) Phys. Rev. D. **85** (2012) 092016



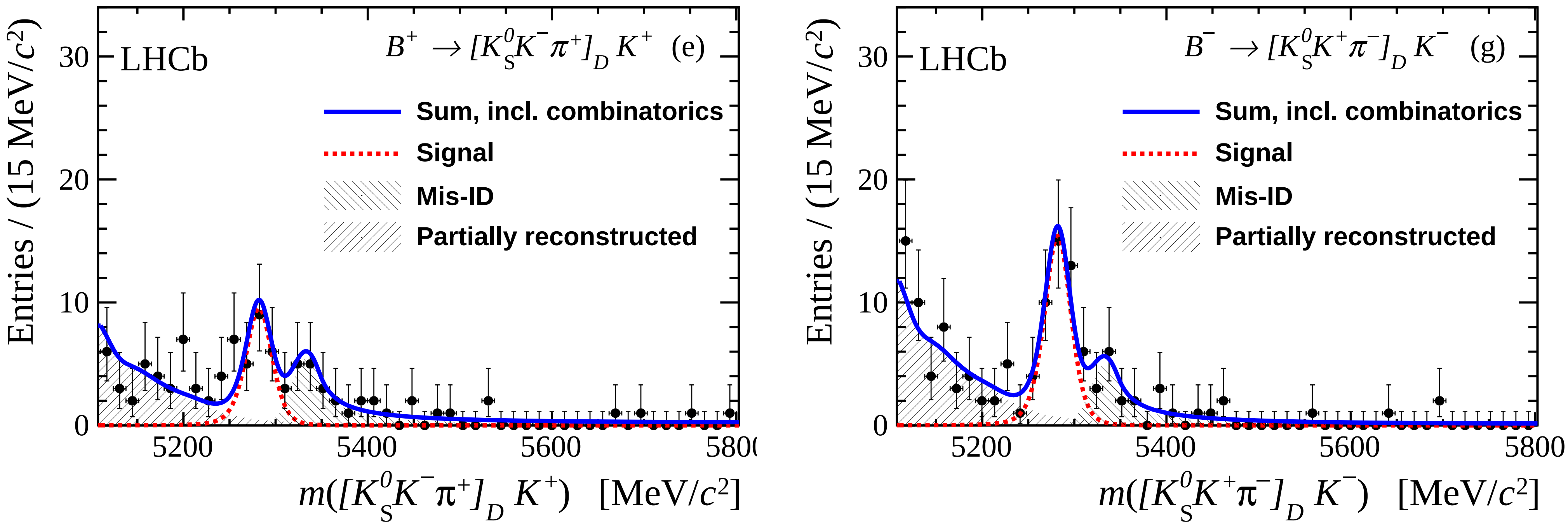
Results

World's first measurement of γ using SCS $D \to K_S^0 K^+ \pi^-$ decays

Full LHCb data sample of 3 fb^{-1}: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

R. Aaij *et al.* (LHCb Collab.) Phys. Lett. B **733** (2014) 36

$\Gamma^+_{\rm OS} \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_f \cos(\delta_B + \gamma + \delta_f)$ $\Gamma^-_{\rm OS} \propto r_B^2 + r_D^2 + 2 r_B r_D \kappa_f \cos(\delta_B - \gamma + \delta_f)$

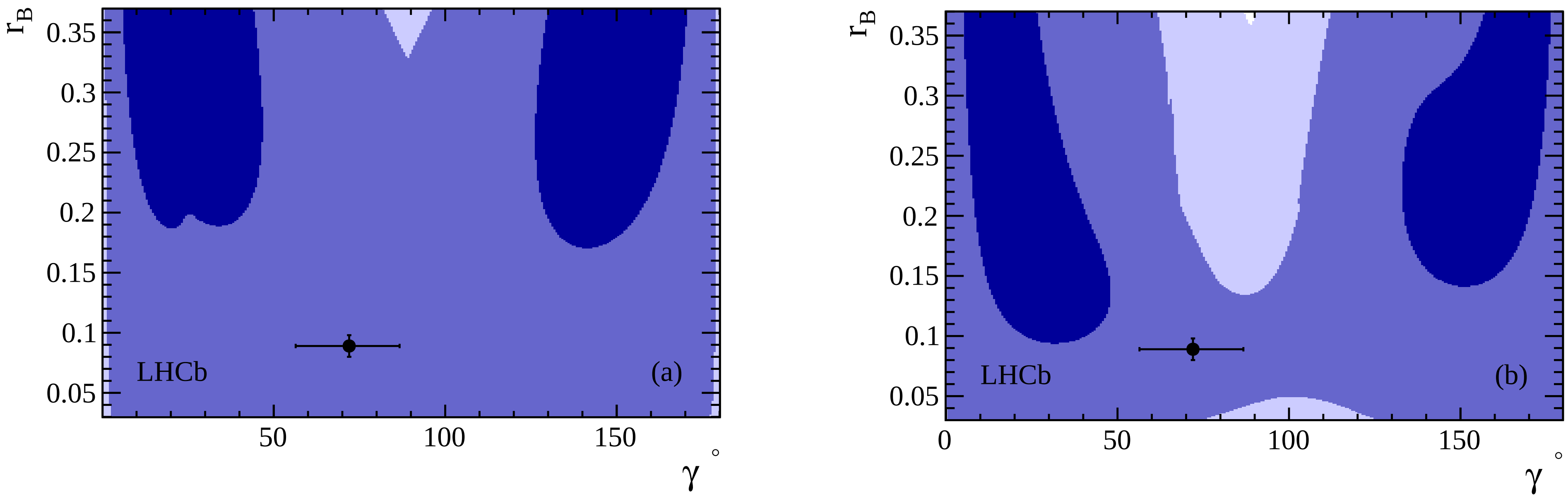


γ manifests as a difference in the rates when 2 kaons have opposite charge

Results

γ constraint accounting for D^0 mixing effects, contours represent change in likelihood

Whole Dalitz plot $\qquad$ $K^*(892)$ region



$n\sigma$ contours with $n = 1$ (dark blue), $n = 2$ (medium blue) and $n = 3$ (light blue)

Data point: LHCb average from other $B \to DK$ modes
R. Aaij *et al.* (LHCb Collab.) Phys. Lett. B **726** (2013) 151

Agreement within 2σ

Constraint tighter in $K^*(892)$ region because coherence factor is larger

$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

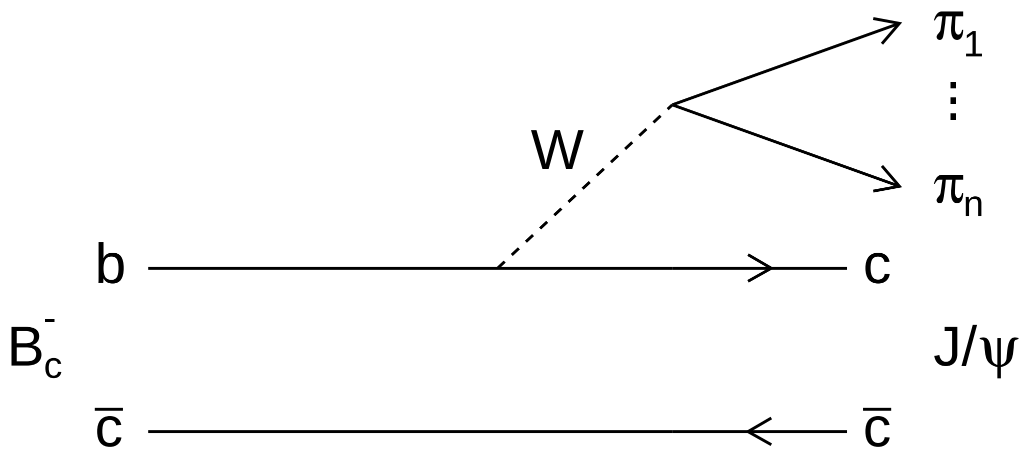
B_c^- $(b\bar{c})$ the only meson containing 2 heavy quarks of different flavour

Test of QCD factorisation

- Form factor of $B_c \to J/\psi W^*$
- Spectral fragmentation of the W^* into $n\pi$

Measure ratio of branching fractions

$$R_{5\pi} = \frac{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}$$



Predictions range from 0.95 to 1.1

- A. V. Luchinsky, Phys. Rev. D **86** (2012) 074024

Results

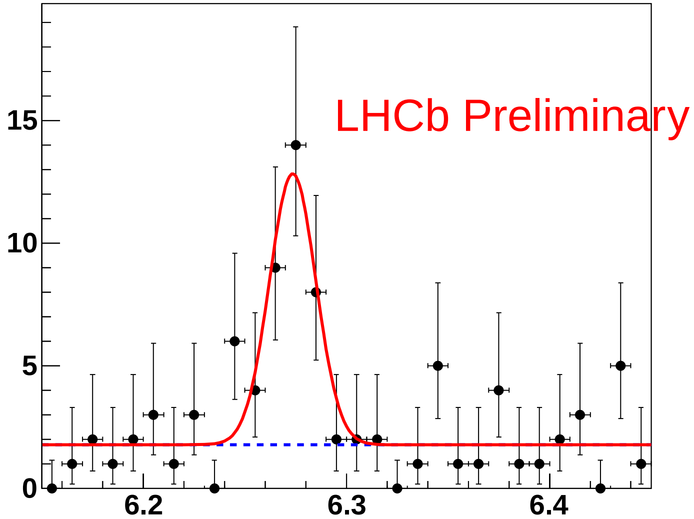
World's first measurement

Full LHCb data sample of 3 fb^{-1}: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV
R. Aaij *et al*. (LHCb Collab.), arXiv:1404.0287 (2014)

J/ψ reconstructed in di-muon channel

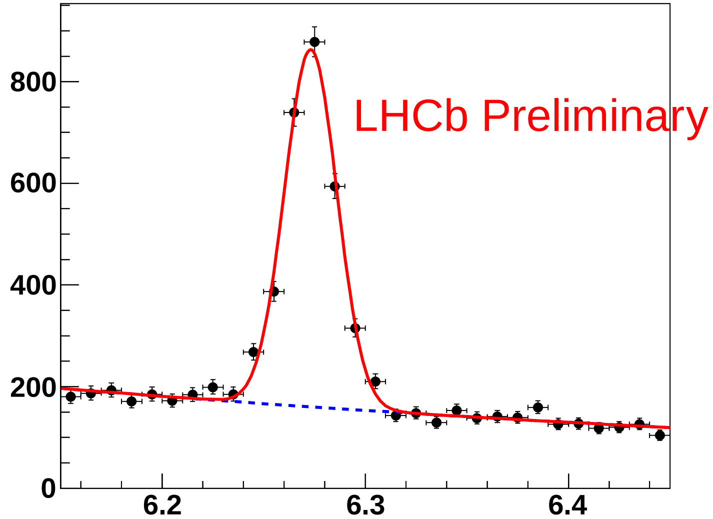
5 pion distribution generated according to various QCD factorisation models

$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$



Yield: 32 ± 8 events

$B_c^+ \to J/\psi \pi^+$



Yield: 2271 ± 63 events

4.5σ significance

Results

Efficiency ratio from MC

$$\frac{\epsilon(B_c^+ \to J/\psi\pi^+)}{\epsilon(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)} = 123.8 \pm 5.6$$

Error from MC statistics only

Ratio of brancing fractions

$$R_{5\pi} = \frac{N(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)}{N(B_c^+ \to J/\psi\pi^+)} \times \frac{\epsilon(B_c^+ \to J/\psi\pi^+)}{\epsilon(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)} = 1.74 \pm 0.44 \pm 0.24$$

Uncertainty 1: statistical, 2: systematic

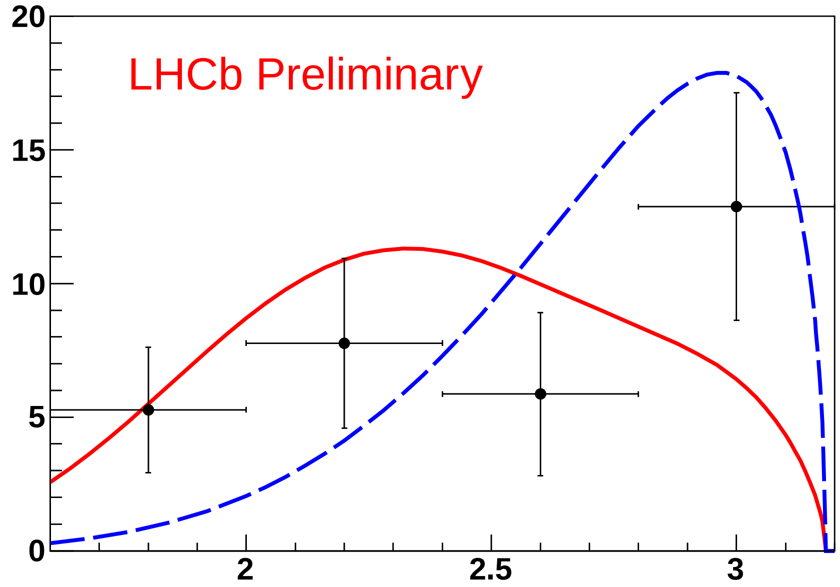
Consistent with theoretical predictions

Consistent with analogous measurements with B^0 and B^+

Dominant systematic uncertainty on 5π model

Affects $\epsilon(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)$

Background-subtracted 5π distribution



Red: Model prediction

Blue: 5-body phase space

Reweight to data distribution

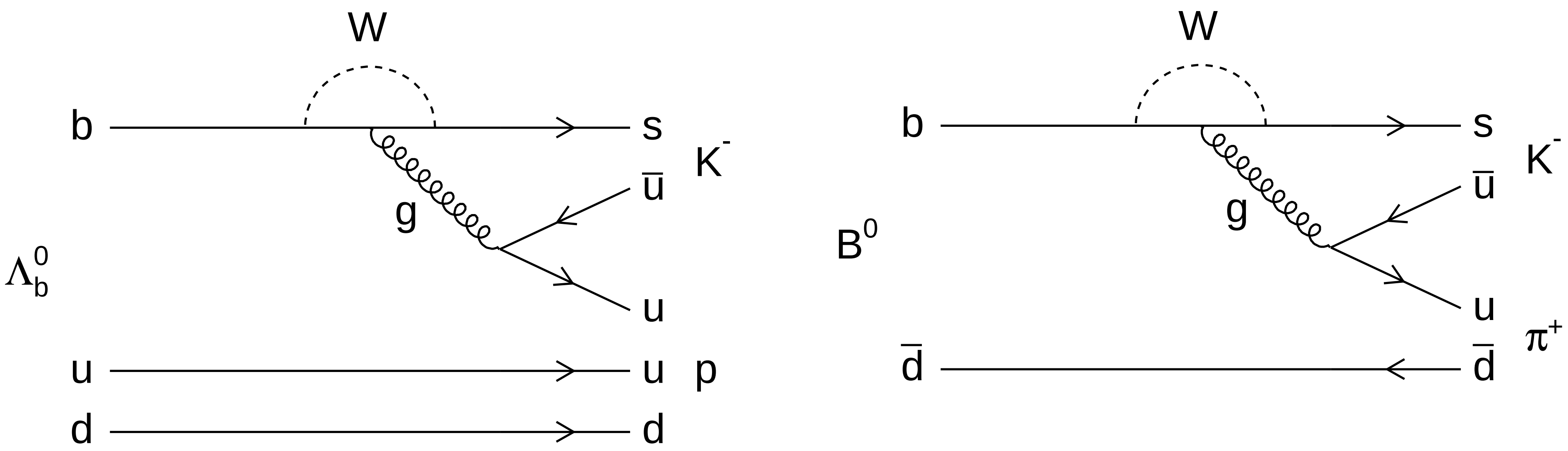
$\Lambda_b^0 \to \bar{K}^0 p \pi^-$

No hadronic charmless 3-body decays yet observed in b baryons

Interesting area to search for CP violating effects

Analogous to large CP violating effects in hadronic charmless 3-body B mesons decays

R. Aaij *et al*. (LHCb Collab.), PRL **111** (2013) 101801; PRL **112** (2014) 011801



Unknown heavy particle in the loop may cause unexpected CP violating effects

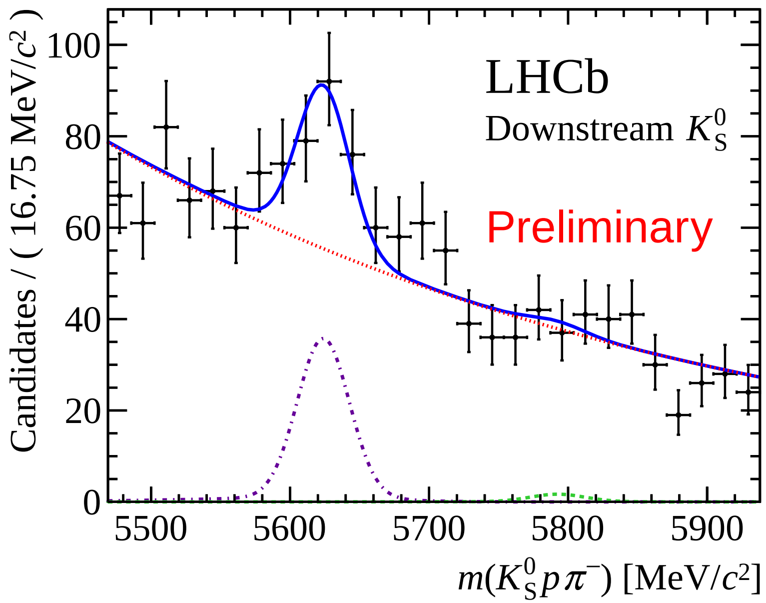
Potential for New Physics

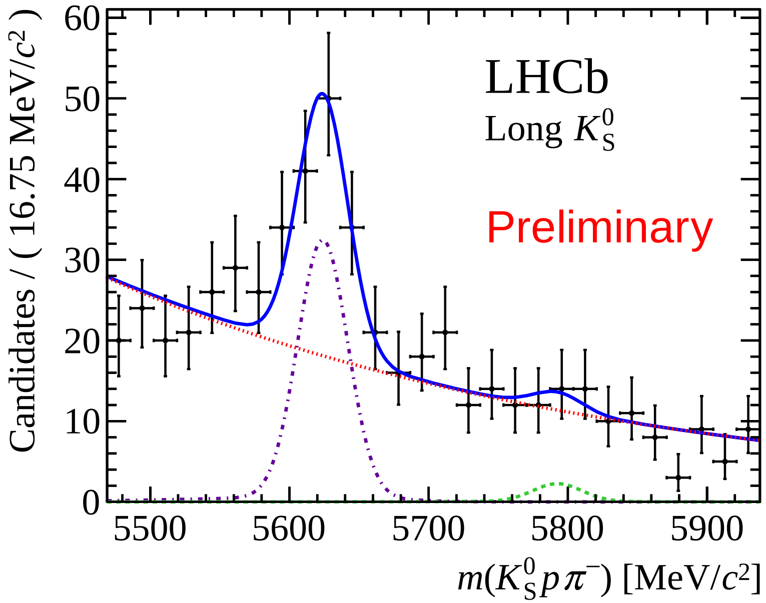
Results

LHCb data sample of $1\ \text{fb}^{-1}$ @ 7 TeV
R. Aaij *et al*. (LHCb Collab.), arXiv:1402.0770 (2014)

Veto significant background from $\Lambda_b^0 \to \Lambda_c^+[pK_S^0]h^-$

$B^0 \to K_S^0\pi^+\pi^-$ used as normalisation channel

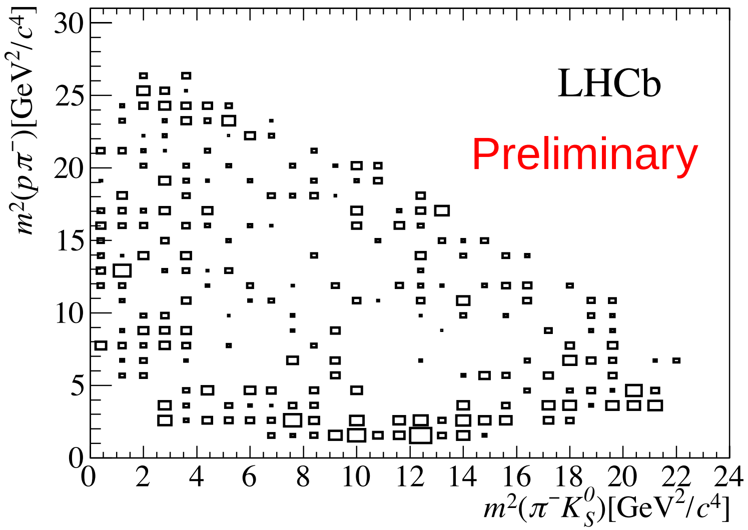




8.6σ significance including systematic uncertainties, first observation

Green curve shows concurrent search for $\Xi_b^0\ (usb)$ baryon, not significant

Results



Background subtracted $\Lambda_b^0 \to \bar{K}^0 p\pi^-$ Dalitz plot

Signal detection efficiency weighted by Dalitz plot

No clear peaking structure except for low $p\pi^-$ mass

Could be from excited nucleon states

$$\mathcal{B}(\Lambda_b^0 \to \bar{K}^0 p\pi^-) = (1.26 \pm 0.19 \pm 0.09 \pm 0.34 \pm 0.05) \times 10^{-5}$$

Uncertainties 1: statistical, 2: systematic, 3: $f_{\Lambda_b^0}/f_d$, 4: $\mathcal{B}(B^0 \to K^0_S \pi^+\pi^-)$

Measure integrated direct CP violation over the Dalitz plot

$$\mathcal{A}_{CP}^{\text{Raw}} = (N_{\bar{f}} - N_f)/(N_{\bar{f}} + N_f)$$

Remove production and detection asymmetries with $\Lambda_b^0 \to \Lambda_c^+[\bar{K}^0 p]\pi^-$ control sample

$\mathcal{A}_{CP}(\Lambda_b^0 \to \bar{K}^0 p\pi^-) = 0.22 \pm 0.13$ (stat) $\pm\, 0.03$ (syst)

Summary

First model-dependent measurement of γ at LHCb using $B^{\pm} \to D[K_S^0 \pi^+ \pi^-] K^{\pm}$

- Consistent with Standard Model expectations
- Similar precision to model independent methods

First ADS-like constraint of γ with $B^{\pm} \to D[K_S^0 K^{\pm} \pi^{\pm}] K^{\pm}$

- Amplitude from CLEO
- γ consistent with other LHCb measurements

First evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

- Branching fraction consistent with expectations from QCD factorisation

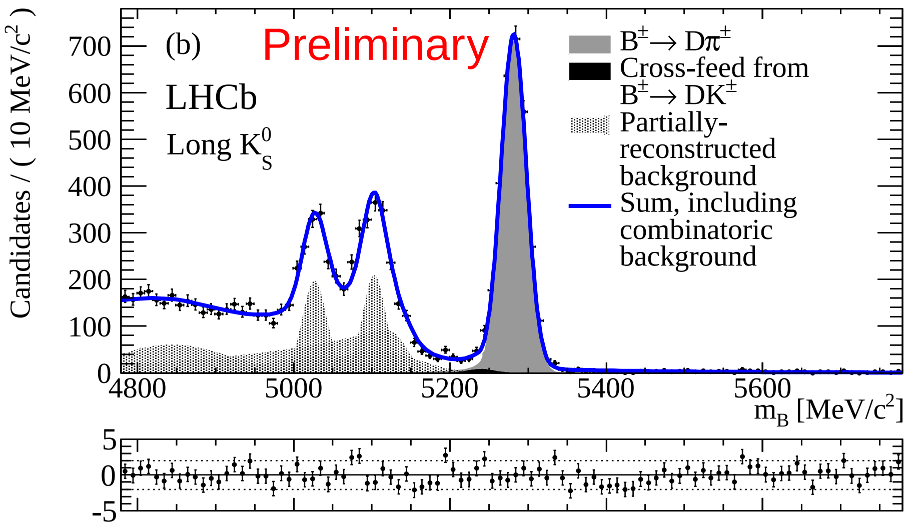
First observation of 3-body hadronic charmless b baryon decays

- No evidence for direct CP at this time

Backup

$B^{\pm} \to D[K^0_S\pi^+\pi^-]\pi^{\pm}$

"Long" K^0_S



"Downstream" K^0_S

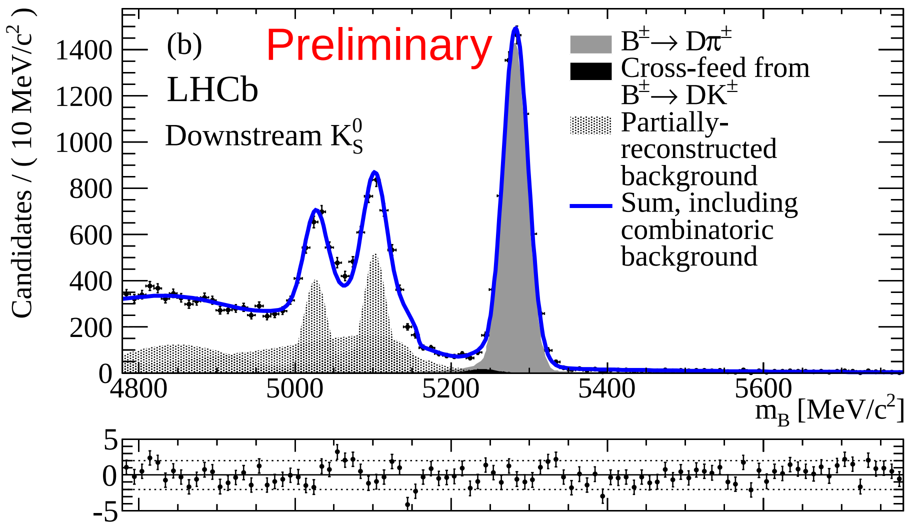


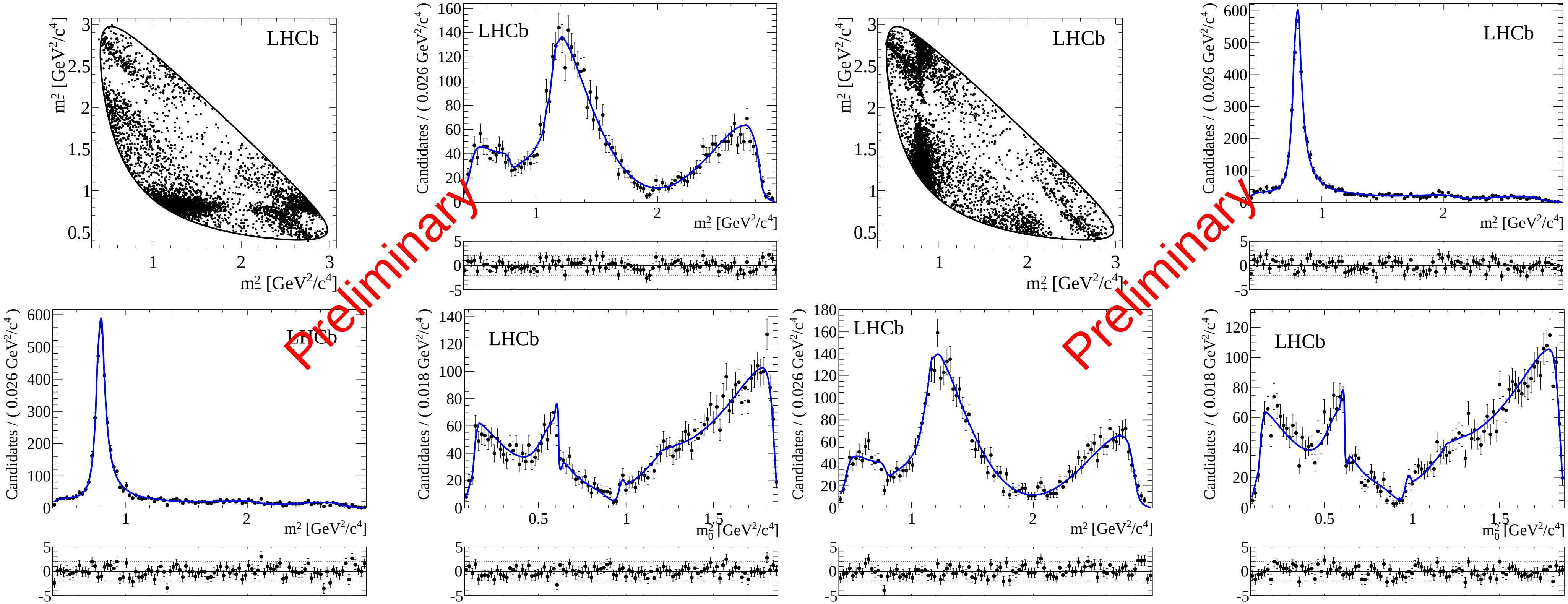
Table 1: Fitted signal and background yields in the signal invariant mass region ($|B$ mass after refit - world average$| < 50\,\mathrm{MeV}/c^2$) for components contributing to the *CP* fit.

Fit component	$B^{\pm} \to DK^{\pm}$, *long*	$B^{\pm} \to DK^{\pm}$, *downstream*
Signal	217±17	420±27
Cross-feed background (from $B^{\pm} \to D\pi^{\pm}$)	35.9±0.7	76±1
Combinatoric D background	5^{+7}_{-3}	31^{+11}_{-9}
Random Dh background	28^{+5}_{-8}	45^{+18}_{-19}
$D^*\pi$ background	0.36±0.08	6±7
$D\rho$ background	2.2±0.5	4±11
$B_s \to DK^*$ background	0.9±0.2	4±2

Fit component	$B^{\pm} \to D\pi^{\pm}$, *long*	$B^{\pm} \to D\pi^{\pm}$, *downstream*
Signal	2906±56	5960±80
Cross-feed background (from $B^{\pm} \to DK^{\pm}$)	27±2	53±3
Combinatoric D background	15^{+19}_{-10}	99^{+36}_{-27}
Random Dh background	76^{+15}_{-22}	146^{+33}_{-41}
$D^*\pi$ background	6.6±0.4	22.0±0.7

$B^{\pm} \to D[K^0_S \pi^+ \pi^-]\pi^{\pm}$

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



$B^{\pm} \to D[K_S^0\pi^+\pi^-]K^{\pm}$

	Description		$\delta x_-(\times 10^{-3})$	$\delta y_-(\times 10^{-3})$	$\delta x_+(\times 10^{-3})$	$\delta y_+(\times 10^{-3})$
(a)	K-matrix 1st solution		-0.132	0.044	0.250	-2.346
(b)	K-matrix 2nd solution		-0.086	-0.339	0.122	-0.528
(c)	Remove slowly varying part in P-vector		-0.144	-0.317	0.097	-0.762
(d)	Generalised LASS $\to$ relativistic Breit-Wigner		-0.713	-1.846	3.042	6.584
(e)	Gounaris-Sakurai $\to$ relativistic Breit-Wigner		0.077	-0.849	0.145	0.818
(f)	$K^\star(1680)$	$m+\delta m$	-0.063	-0.561	0.181	0.256
(g)	$K^\star(1680)$	$m-\delta m$	-0.128	-0.161	-0.098	-1.104
(h)	$K^\star(1680)$	$\Gamma+\delta\Gamma$	-0.059	-0.365	-0.048	-0.423
(i)	$K^\star(1680)$	$\Gamma-\delta\Gamma$	-0.158	-0.333	0.273	-0.489
(j)	$f_2(1270)$	$m+\delta m$	-0.106	-0.346	0.096	-0.464
(k)	$f_2(1270)$	$m-\delta m$	-0.102	-0.351	0.085	-0.456
(l)	$f_2(1270)$	$\Gamma+\delta\Gamma$	-0.102	-0.344	0.081	-0.467
(m)	$f_2(1270)$	$\Gamma-\delta\Gamma$	-0.105	-0.351	0.097	-0.453
(n)	$K_2^\star(1430)$	$m+\delta m$	-0.082	-0.355	0.078	-0.421
(o)	$K_2^\star(1430)$	$m-\delta m$	-0.125	-0.342	0.106	-0.498
(p)	$K_2^\star(1430)$	$\Gamma+\delta\Gamma$	-0.100	-0.369	0.071	-0.432
(q)	$K_2^\star(1430)$	$\Gamma-\delta\Gamma$	-0.109	-0.328	0.112	-0.489
(r)	$r_{\rm BW} = 0.0\,{\rm GeV}^{-1}$		-0.154	-0.385	-0.116	-0.338
(s)	$r_{\rm BW} = 3.0\,{\rm GeV}^{-1}$		-0.308	-0.281	1.225	-0.386
(t)	Add $K^\star(1410)$ and $\rho(1450)$		-0.124	-0.286	0.023	-0.701

Table 2: Summary of the model related systematic uncertainties for each alternative model.

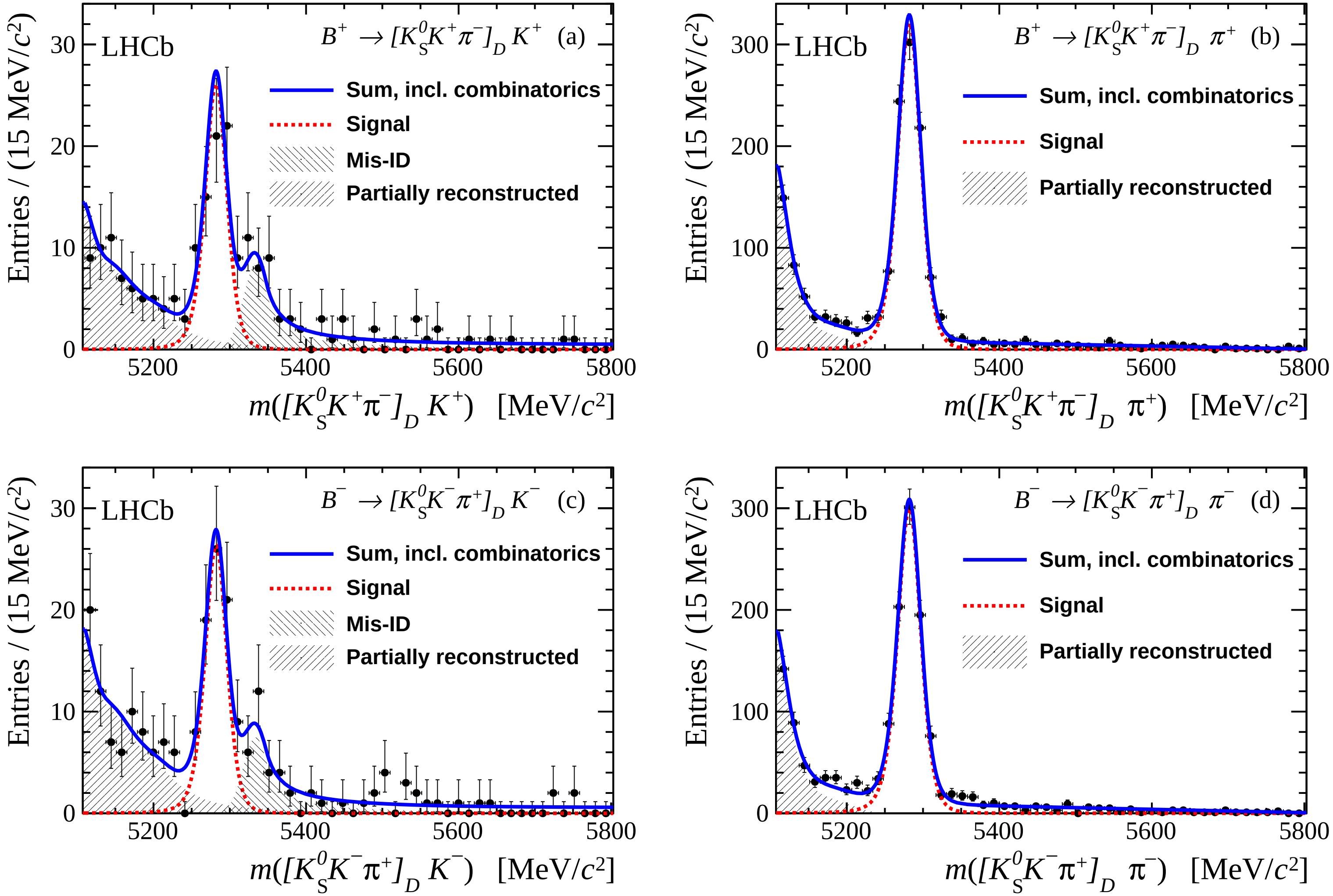
$B^{\pm} \rightarrow D[K^0_S \pi^+ \pi^-]K^{\pm}$

Source of uncertainty	$\delta x_-(\times 10^{-3})$	$\delta y_-(\times 10^{-3})$	$\delta x_+(\times 10^{-3})$	$\delta y_+(\times 10^{-3})$
Combinatoric D yield estimate	1.0	4.3	2.7	4.9
Inclusion of semileptonic background	3.1	2.8	0.63	3.2
Charged kaon detection asymmetry	0.022	0.030	0.0041	0.025
Amplitudes for backgrounds				
Combinatoric D	3.5	3.4	4.7	6.4
Random Dh	0.10	0.16	0.066	0.16
B_s partially-reconstructed	0.59	0.59	0.15	0.73
$r_{B^{\pm}\rightarrow D\pi^{\pm}}$	1.8	1.9	1.6	1.1
Efficiency over the phase space	5.7	0.35	6.9	0.31
CP fit bias	5.7	5.1	-1.3	2.6
Total experiment or fit related	$^{+9.6}_{-7.7}$	$^{+8.2}_{-6.4}$	$^{+9.0}_{-9.1}$	$^{+9.2}_{-8.8}$
Total model related	0.9	2.5	3.3	7.4

Table 3: Summary of absolute values of systematic uncertainties.

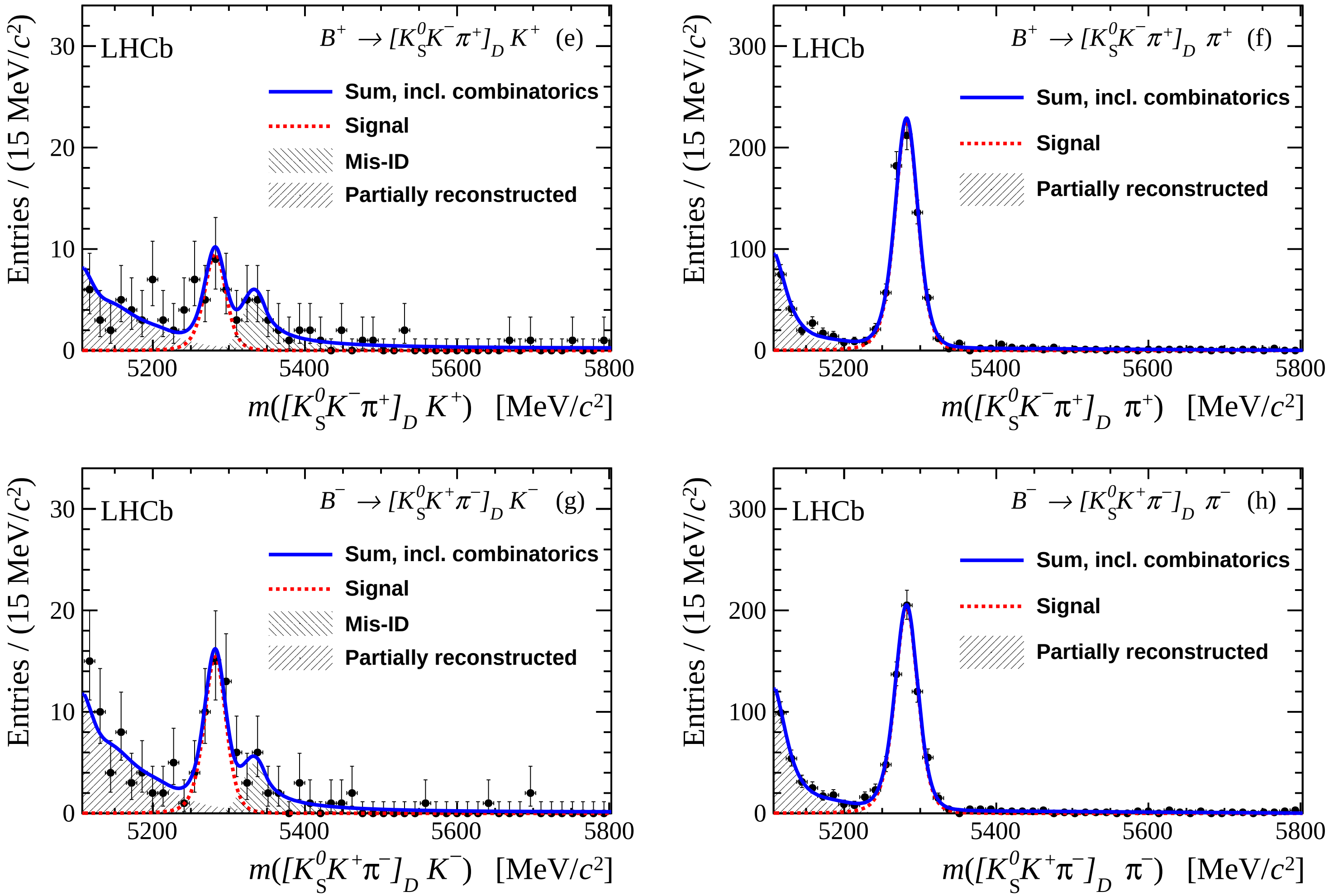
$B^{\pm} \to D[K^0_S K^{\pm}\pi^{\pm}]K^{\pm}$

SS candidates



$B^{\pm} \to D[K_S^0 K^{\pm}\pi^{\pm}]K^{\pm}$

OS candidates



$B^\pm \to D[K^0_S K^\pm \pi^\pm] K^\pm$

Table 1: Signal yields and their statistical uncertainties derived from the fit to the whole Dalitz plot region, and in the restricted region of phase space around the $K^*(892)^\pm$ resonance.

	Whole Dalitz plot		$K^*(892)^\pm$ region	
Mode	$DK^\pm$	$D\pi^\pm$	$DK^\pm$	$D\pi^\pm$
SS	145 ± 15	1841 ± 47	97 ± 12	1365 ± 38
OS	71 ± 10	1267 ± 37	26 ± 6	553 ± 24

Table 2: Results for the observables measured in the whole Dalitz plot region, and in the restricted region of phase space around the $K^*(892)^\pm$ resonance. The first uncertainty is statistical and the second is systematic. The corrections for production and detection asymmetries are applied, as is the efficiency correction defined in Eq. (5).

Observable	Whole Dalitz plot	$K^*(892)^\pm$ region
$\mathcal{R}_{\text{SS/OS}}$	$1.528 \pm 0.058 \pm 0.025$	$2.57 \pm 0.13 \pm 0.06$
$\mathcal{R}_{DK/D\pi,\text{ SS}}$	$0.092 \pm 0.009 \pm 0.004$	$0.084 \pm 0.011 \pm 0.003$
$\mathcal{R}_{DK/D\pi,\text{ OS}}$	$0.066 \pm 0.009 \pm 0.002$	$0.056 \pm 0.013 \pm 0.002$
$\mathcal{A}_{\text{SS},\ DK}$	$0.040 \pm 0.091 \pm 0.018$	$0.026 \pm 0.109 \pm 0.029$
$\mathcal{A}_{\text{OS},\ DK}$	$0.233 \pm 0.129 \pm 0.024$	$0.336 \pm 0.208 \pm 0.026$
$\mathcal{A}_{\text{SS},\ D\pi}$	$-0.025 \pm 0.024 \pm 0.010$	$-0.012 \pm 0.028 \pm 0.010$
$\mathcal{A}_{\text{OS},\ D\pi}$	$-0.052 \pm 0.029 \pm 0.017$	$-0.054 \pm 0.043 \pm 0.017$

$B^\pm \to D[K^0_S K^\pm \pi^\pm] K^\pm$

Table 3: Absolute values of systematic uncertainties, in units of 10^{-2}, for the fit to the whole Dalitz plot.

Observable	Eff. correction	Fit PDFs	Prod. and det. asymms.	PID	Total
$\mathcal{R}_{\mathrm{SS/OS}}$	2.40	0.50	–	0.01	2.45
$\mathcal{R}_{DK/D\pi,\,\mathrm{SS}}$	0.01	0.38	–	0.02	0.38
$\mathcal{R}_{DK/D\pi,\,\mathrm{OS}}$	0.01	0.19	–	0.01	0.19
$\mathcal{A}_{\mathrm{SS},\,DK}$	0.14	0.44	1.71	0.01	1.78
$\mathcal{A}_{\mathrm{OS},\,DK}$	0.36	2.13	0.99	0.01	2.37
$\mathcal{A}_{\mathrm{SS},\,D\pi}$	0.02	0.05	0.99	< 0.01	0.99
$\mathcal{A}_{\mathrm{OS},\,D\pi}$	0.03	0.10	1.71	< 0.01	1.72

Table 4: Absolute values of systematic uncertainties, in units of 10^{-2}, for the fit in the restricted region.

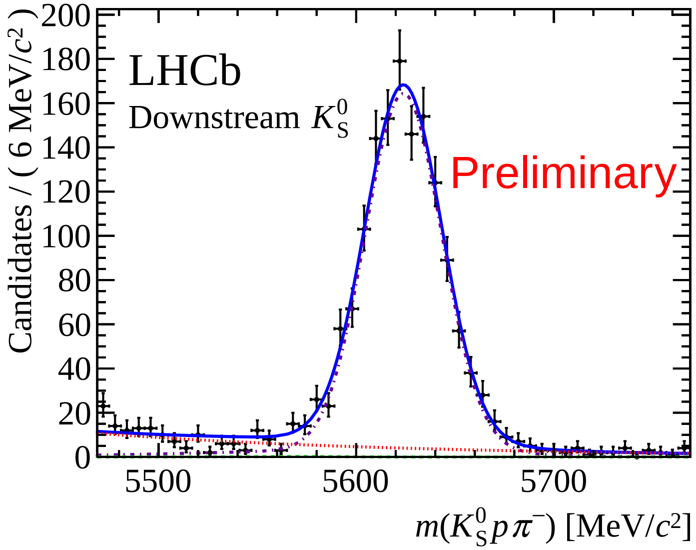
Observable	Eff. correction	Fit PDFs	Prod. and det. asymms.	PID	Total
$\mathcal{R}_{\mathrm{SS/OS}}$	6.08	0.53	–	0.01	6.10
$\mathcal{R}_{DK/D\pi,\,\mathrm{SS}}$	0.01	0.25	–	0.02	0.25
$\mathcal{R}_{DK/D\pi,\,\mathrm{OS}}$	0.01	0.21	–	0.01	0.21
$\mathcal{A}_{\mathrm{SS},\,DK}$	0.13	2.27	1.71	0.01	2.85
$\mathcal{A}_{\mathrm{OS},\,DK}$	0.04	2.38	0.99	0.01	2.57
$\mathcal{A}_{\mathrm{SS},\,D\pi}$	0.04	0.17	0.99	< 0.01	1.00
$\mathcal{A}_{\mathrm{OS},\,D\pi}$	0.06	0.09	1.71	< 0.01	1.72

$B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

Table 2: Relative systematic uncertainties for the ratio $R_{5\pi}$. The total uncertainty is the quadratic sum of the individual components.

Source	Uncertainty [%]
Fit model	6.6
Decay model	
$m_{3\pi^+2\pi^-}$ reweighting	7.7
$\psi(2S)$ mass veto	3.1
Data-simulation agreement	
Hadron interactions	4×2.0
Track quality selection	4×0.6
Trigger	1.1
Pion identification	0.7
Selection variables	1.0
B_c^+ lifetime	0.9
Stability for various data taking conditions	2.5
Acceptance	0.8
Total	13.9

$\Lambda_b^0 \rightarrow \Lambda_c^+[\bar{K}^0 p]\pi^-$



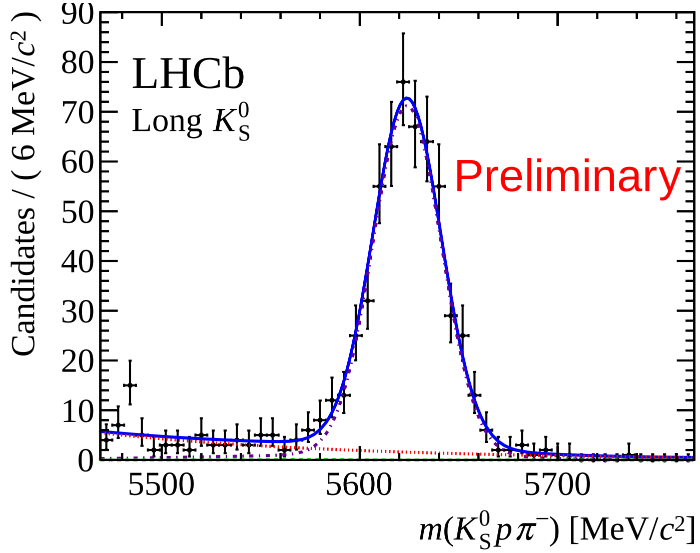


Table 1: Fitted yields and efficiency for each channel, separated by K^0_S type. Yields are given with both statistical and systematic uncertainties, whereas for the efficiencies only the uncertainties due to the limited Monte Carlo sample sizes are given. The three rows for the $B^0 \rightarrow K^0_S\pi^+\pi^-$ decay correspond to the different BDT selections for charmless signal modes and the channels containing Λ_c^+ or D_s^- hadrons.

Mode	Downstream		Long	
	Yield	Efficiency ($\times 10^{-4}$)	Yield	Efficiency ($\times 10^{-4}$)
$\Lambda_b^0 \rightarrow K^0_S p\pi^-$	$106.1 \pm 21.5 \pm 3.7$	5.40 ± 0.12	$90.9 \pm 14.6 \pm 1.0$	2.26 ± 0.06
$\Lambda_b^0 \rightarrow K^0_S pK^-$	$11.5 \pm 10.7 \pm 1.2$	5.34 ± 0.11	$19.6 \pm 8.5 \pm 0.8$	2.87 ± 0.07
$\Xi_b^0 \rightarrow K^0_S p\pi^-$	$5.3 \pm 15.7 \pm 0.7$	5.35 ± 0.10	$6.4 \pm 8.5 \pm 0.5$	2.67 ± 0.07
$\Xi_b^0 \rightarrow K^0_S pK^-$	$10.5 \pm 8.8 \pm 0.5$	6.12 ± 0.10	$6.3 \pm 5.6 \pm 0.4$	2.91 ± 0.07
$\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^0_S)\pi^-$	$1391.6 \pm 39.6 \pm 24.8$	4.85 ± 0.09	$536.8 \pm 24.6 \pm 3.5$	1.71 ± 0.05
$\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pK^0_S)K^-$	$70.0 \pm 10.3 \pm 3.3$	4.69 ± 0.07	$37.4 \pm 7.1 \pm 2.7$	1.66 ± 0.03
$\Lambda_b^0 \rightarrow D_s^- p$	$6.3 \pm 5.1 \pm 0.6$	2.69 ± 0.05	$6.5 \pm 3.7 \pm 0.2$	0.89 ± 0.03
$B^0 \rightarrow K^0_S\pi^+\pi^-$ ($K^0_S ph$)	$913.5 \pm 45.0 \pm 12.2$	5.57 ± 0.09	$495.7 \pm 31.8 \pm 7.5$	2.86 ± 0.06
$B^0 \rightarrow K^0_S\pi^+\pi^-$ ($\Lambda_c^+ h$)	$1163.8 \pm 60.7 \pm 18.8$	7.38 ± 0.11	$589.0 \pm 33.3 \pm 17.3$	3.27 ± 0.06
$B^0 \rightarrow K^0_S\pi^+\pi^-$ ($D_s^- p$)	$1317.8 \pm 77.1 \pm 25.7$	7.76 ± 0.11	$614.1 \pm 38.3 \pm 14.8$	3.47 ± 0.07

$\Lambda_b^0 \to \bar{K}^0 p\pi^-$

Control sample $B^0 \to K^0\pi^+\pi^-$ with selection criteria of $\Lambda_b^0 \to \bar{K}^0 p\pi^-$

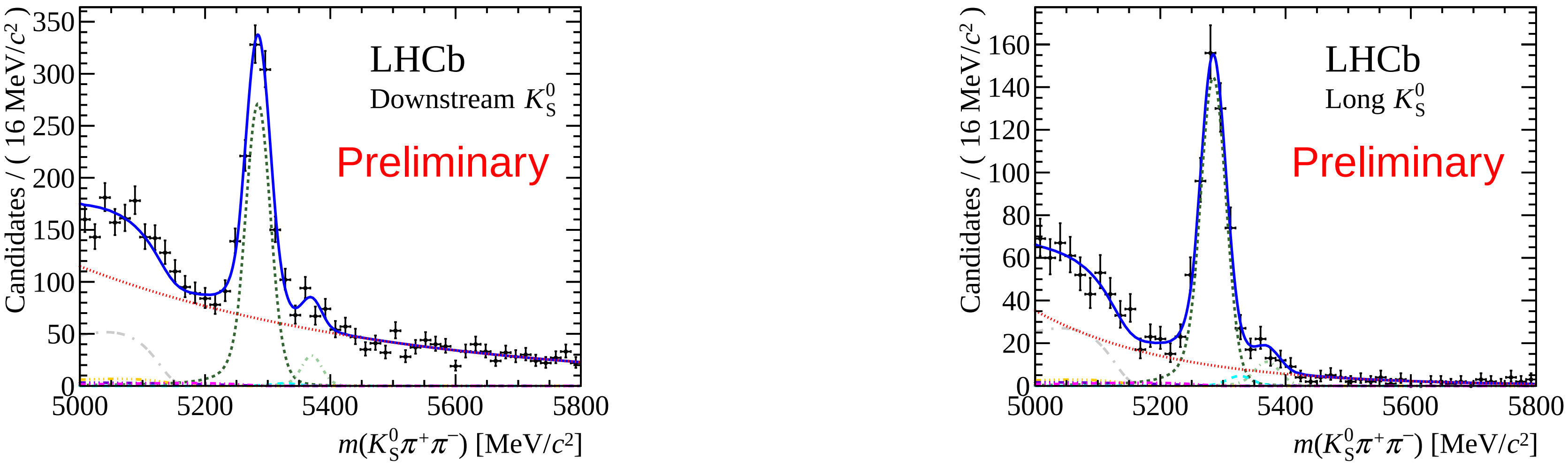


Table 2: Relative systematic uncertainties on the branching fraction ratios (%) with respect to $B^0 \to K_S^0\pi^+\pi^-$ decays. The total is obtained from the sum in quadrature of all contributions except that from knowledge of the fragmentation fractions.

Downstream	Simulation	$\Delta_{\rm PHSP}$	PID	Fit model	Fit bias	Vetoes	Total	$f_{\Lambda_b^0}/f_d$
$\mathcal{B}(\Lambda_b^0 \to K_S^0 p\pi^-)$	6	4	6	1	<1	3	10	27
$\mathcal{B}(\Lambda_b^0 \to K_S^0 pK^-)$	6	58	2	8	4	4	59	27
$\mathcal{B}(\Xi_b^0 \to K_S^0 p\pi^-)$	4	64	6	12	7	–	66	–
$\mathcal{B}(\Xi_b^0 \to K_S^0 pK^-)$	4	47	2	4	3	–	47	–
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-)$	5	–	6	2	<1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-)$	5	–	4	5	<1	1	8	27
$\mathcal{B}(\Lambda_b^0 \to D_s^-(\to K_S^0K^-)p)$	6	–	6	7	6	–	12	27
Long								
$\mathcal{B}(\Lambda_b^0 \to K_S^0 p\pi^-)$	6	3	4	2	1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to K_S^0 pK^-)$	6	42	4	4	1	1	43	27
$\mathcal{B}(\Xi_b^0 \to K_S^0 p\pi^-)$	5	47	5	8	2	–	49	–
$\mathcal{B}(\Xi_b^0 \to K_S^0 pK^-)$	5	37	5	6	4	–	39	–
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)\pi^-)$	6	–	4	3	<1	<1	8	27
$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+(\to pK_S^0)K^-)$	5	–	6	8	1	<1	11	27
$\mathcal{B}(\Lambda_b^0 \to D_s^-(\to K_S^0K^-)p)$	6	–	8	4	2	–	11	27