

Charmless B decays

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on behalf of the LHCb Collaboration

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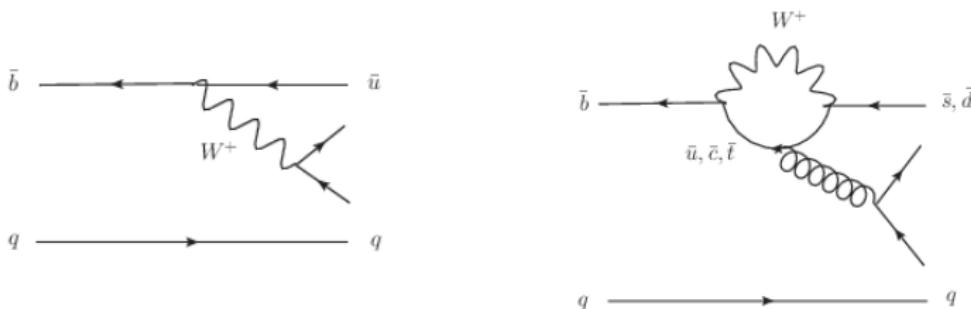
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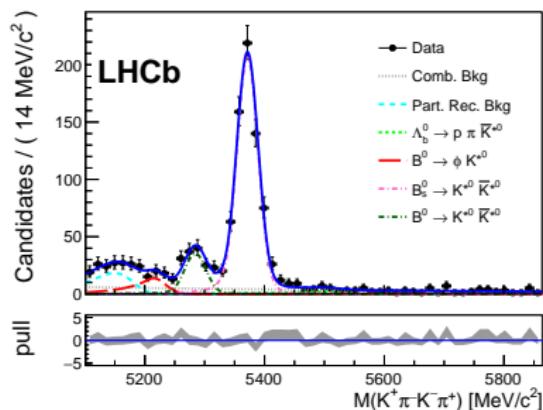
Conclusions

- Charmless hadronic b decays are suppressed in the Standard Model
- They proceed through $b \rightarrow u$ transitions and $b \rightarrow s, d$ transitions
- The respective tree and penguin amplitudes are of similar size, allowing for possible CP violating asymmetries in the interference
- New particles not described in the Standard Model may contribute with additional amplitudes
- These processes could provide additional sources of CP violation that might explain the observed baryon asymmetry
- We present recent results on angular analyses of $B \rightarrow VV$ decays and searches for very suppressed decay modes



CP asymmetries and polarisation fractions in $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$

- "Measurement of CP asymmetries and polarisation fractions in $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$ decays"¹
 - Possible field for precision tests of the SM predictions, when considered in association with $B^0 \rightarrow K^{*0} \bar{K}^{*0}$
 - $B \rightarrow VV$ decay, need of angular analysis. When a scalar meson is allowed, six independent helicities contribute
 - First observed at LHCb, with a remarkably low longitudinal polarisation fraction²
-
- Untagged and time-integrated angular analysis is performed with $1fb^{-1}$
 - 697 $B_s^0 \rightarrow K^+ \pi^- K^- \pi^+$ decays are obtained
 - The $K\pi$ pairs are selected in a $150MeV/c^2$ window around the $K^*(892)^0$ mass



¹arXiv:1503.05362 [hep-ex]

²Phys. Lett. B709 (2012) 50

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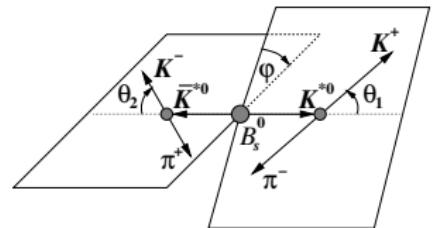
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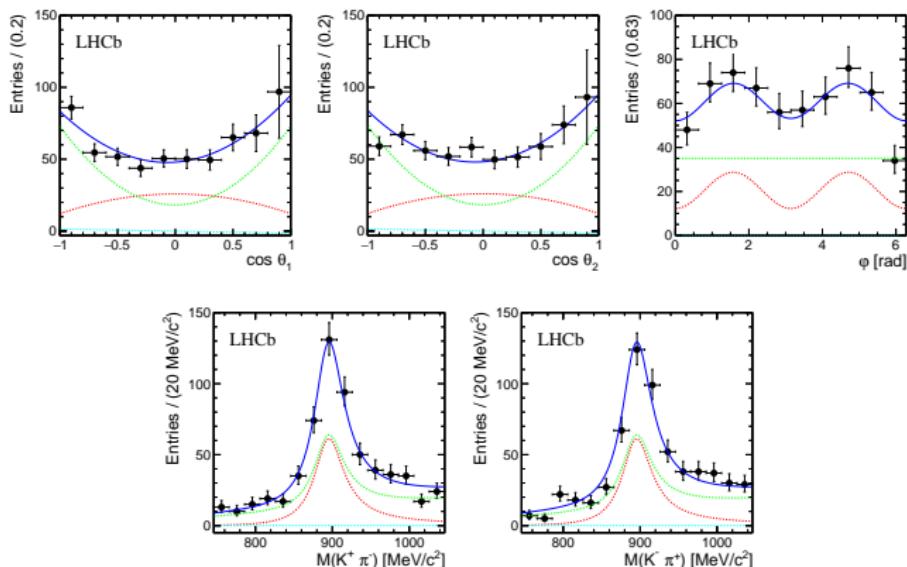
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- Five-dimensional fit to the three helicity angles and to the invariant mass of the two $K\pi$ pairs
- The low polarisation of the vector-vector decay is confirmed, $f_L = 0.201 \pm 0.057 \pm 0.040$
- A large S-wave contribution is found



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- Triple products are T -odd observables having the generic structure $v_1 \cdot (v_2 \times v_3)$ where v_i is the spin or momentum of a final-state particle.
- Assuming CPT conservation, Triple Products Asymmetries are CP violating quantities
- Triple products are also meaningful when one of the final particles is a scalar meson

$$A_{T,D}^{(i)} = \frac{\Gamma(S_i(\theta_1,\theta_2,\varphi) > 0) - \Gamma(S_i(\theta_1,\theta_2,\varphi) < 0)}{\Gamma(S_i(\theta_1,\theta_2,\varphi) > 0) + \Gamma(S_i(\theta_1,\theta_2,\varphi) < 0)}$$

- The main systematic uncertainty is associated to the angular acceptance correction

Asymmetry	Value
A_T^1	$0.003 \pm 0.041 \pm 0.009$
A_T^2	$0.009 \pm 0.041 \pm 0.009$
A_T^3	$0.019 \pm 0.041 \pm 0.008$
A_T^4	$-0.040 \pm 0.041 \pm 0.008$
A_D^1	$-0.061 \pm 0.041 \pm 0.012$
A_D^2	$0.081 \pm 0.041 \pm 0.008$
A_D^3	$-0.079 \pm 0.041 \pm 0.023$
A_D^4	$-0.081 \pm 0.041 \pm 0.010$

- The eight CP-violating quantities are **compatible** with the SM expectation, within 2σ
- The branching fraction has also been updated,
 $\mathcal{B}(B_s^0 \rightarrow K^{*0} \bar{K}^{*0}) = (10.8 \pm 2.1(\text{stat.}) \pm 1.4(\text{syst.}) \pm 0.6(f_d/f_s)) \times 10^{-6}$,
in **agreement** with the theoretical prediction and with the previous result

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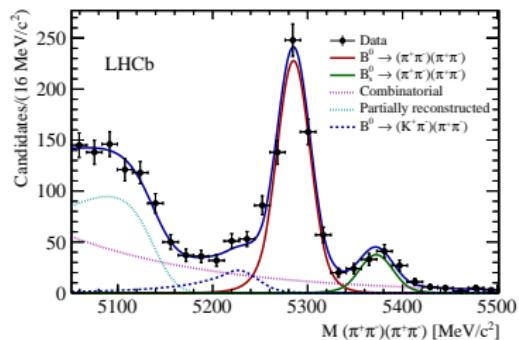
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Amplitude analysis of $B^0 \rightarrow \rho^0 \rho^0$

- "Observation of the $B^0 \rightarrow \rho^0 \rho^0$ decay from an amplitude analysis of $B^0 \rightarrow (\pi^+ \pi^-)(\pi^+ \pi^-)$ decays"¹
- Measurements of the $B^0 \rightarrow \rho^0 \rho^0$ branching fraction and longitudinal polarization can be used as inputs in the determination of α_{CKM}
- The BaBar² and Belle³ experiments reported evidence for the decay. Each experiment measured f_L with a difference at the level of 2σ
- In addition, Belle reported a hint of $B^0 \rightarrow \rho^0 f_0(980)$ decays
- $B^0 \rightarrow \phi K^*(892)^0$ as normalization channel
- Untagged and time-integrated analysis with $3fb^{-1}$
- The two $\pi^+ \pi^-$ pairs are selected in the low invariant mass range (< 1100 MeV/c 2)
- 185 (449) events of $B^0 \rightarrow (\pi^+ \pi^-)(\pi^+ \pi^-)$ in 2011 (2012)



¹Phys. Lett. B747 (2015) 468, arXiv:1503.07770 [hep-ex]

²Phys. Rev. D 76 (2007) 011104

³Phys. Rev. D 89 (2014) 072008

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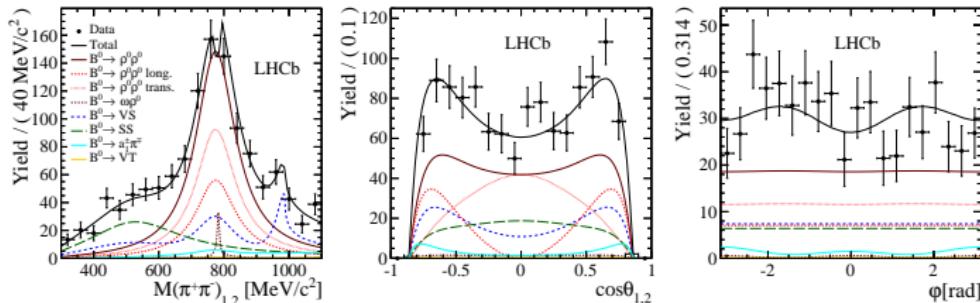
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- Amplitude analysis using two-body mass spectra and angular variables
- 11 amplitudes included in the fit
- $f_L = 0.745^{+0.048}_{-0.058} \pm 0.034$, **consistent** with BaBar measurement
- Systematics highly dominated by the knowledge of the $f_0(500)$ resonance



- First observation of $B^0 \rightarrow \rho^0 \rho^0$
- $\mathcal{B}(B^0 \rightarrow \rho^0 \rho^0) = (0.94 \pm 0.17(stat) \pm 0.09(syst) \pm 0.06(norm)) \times 10^{-6}$, **in agreement** with previous results
- No evidence for the $B^0 \rightarrow \rho^0 f_0(980)$ decay,
 $\mathcal{B}(B^0 \rightarrow \rho^0 f_0(980)) \times \mathcal{B}(f_0(980) \rightarrow \pi^+ \pi^-) < 0.81 \times 10^{-6}$

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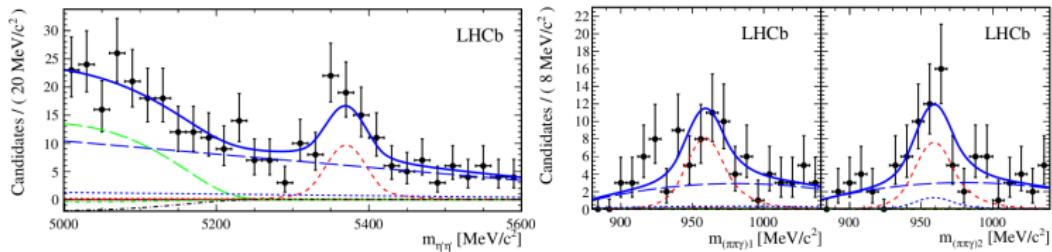
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Observation of $B_s^0 \rightarrow \eta'\eta'$

- "Observation of the $B_s^0 \rightarrow \eta'\eta'$ decay"¹
- Expected to have a relatively large branching fraction, between 14×10^{-6} and 50×10^{-6}
- The $\eta'\eta'$ final state is a pure CP eigenstate. May be used to investigate time-dependent CP asymmetries
- The first observation of the decay is presented, using $3fb^{-1}$ of data



- We observe $36.4 \pm 7.8(\text{stat}) \pm 1.6(\text{syst})$ $B_s^0 \rightarrow \eta'\eta'$ decays corresponding to a significance of 6.4 standard deviations
- $B^\pm \rightarrow \eta' K^\pm$ as normalization channel
- $\mathcal{B}(B_s^0 \rightarrow \eta'\eta') = [3.31 \pm 0.64(\text{stat}) \pm 0.28(\text{syst}) \pm 0.12(\text{norm})] \times 10^{-5}$, in agreement with the theoretical predictions

¹arXiv:1503.07483 [hep-ex]

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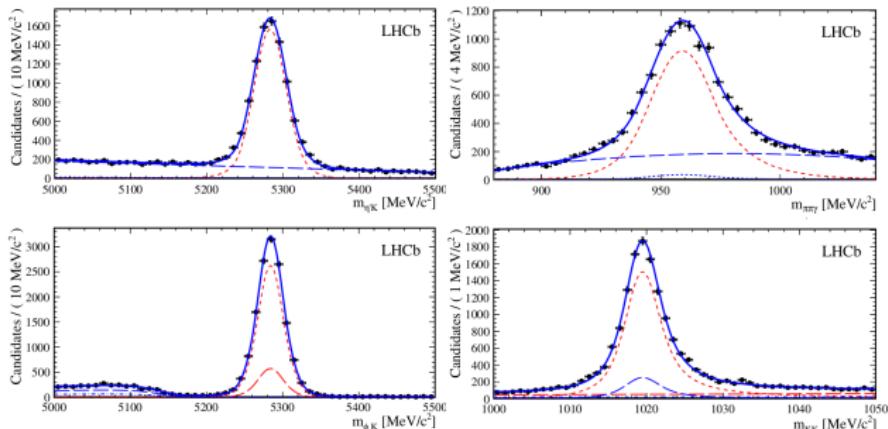
- CP asymmetries of $B^\pm \rightarrow \eta' K^\pm$ and $B^\pm \rightarrow \phi K^\pm$ are also measured:

$$\mathcal{A}^{CP} = \frac{\Gamma^- - \Gamma^+}{\Gamma^- + \Gamma^+}$$

- Under the assumption that the asymmetries are small:

$$\mathcal{A}_{raw,k}^{CP} = \mathcal{A}^{CP} + \mathcal{A}_{D,k} \mathcal{A}_P$$

- Production and detection asymmetries obtained using $B^\pm \rightarrow J/\psi K^\pm$ decays



- $\mathcal{A}^{CP}(B^\pm \rightarrow \eta' K^\pm) = [-0.2 \pm 1.2(stat) \pm 0.1(syst) \pm 0.6(norm)] \times 10^{-2}$
- $\mathcal{A}^{CP}(B^\pm \rightarrow \phi K^\pm) = [+1.7 \pm 1.1(stat) \pm 0.2(syst) \pm 0.6(norm)] \times 10^{-2}$
- **Compatible** with the hypothesis of CP symmetry and with the SM predictions

Search for $\Lambda_b^0 \rightarrow \Lambda\eta^{(\prime)}$

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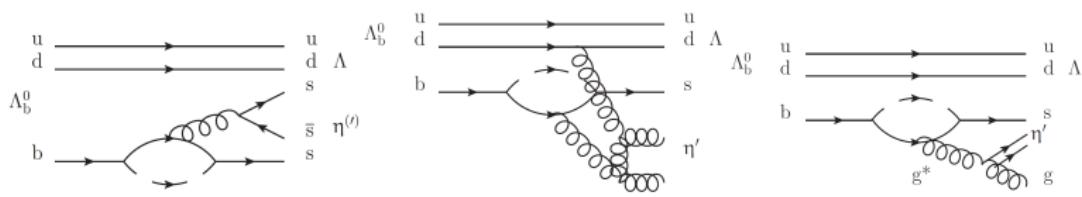
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- "Search for the $\Lambda_b^0 \rightarrow \Lambda\eta'$ and $\Lambda_b^0 \rightarrow \Lambda\eta$ decays with the LHCb detector"¹
- Decays of b-baryons to final states containing η or η' mesons have not yet been observed
- The branching fractions have been estimated to be in the range $(1.8 - 19.0) \times 10^{-6}$, depending on the model used to calculate the hadronic form factors



- The interference between diagrams cancel in such a way that the branching fractions for the η and η' decays are expected to be similar
- $B^0 \rightarrow K_S^0 \eta'$ as normalization channel
- Λ 's are labelled according to where in the detector the decay occurs, Downstream or Long

¹arXiv:1505.03295 [hep-ex]

Search for $\Lambda_b^0 \rightarrow \Lambda\eta^{(\prime)}$

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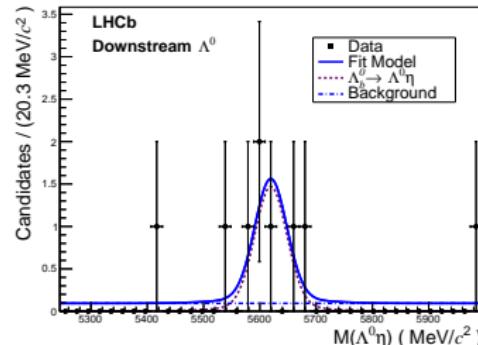
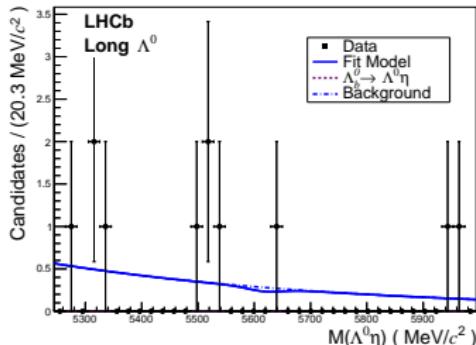
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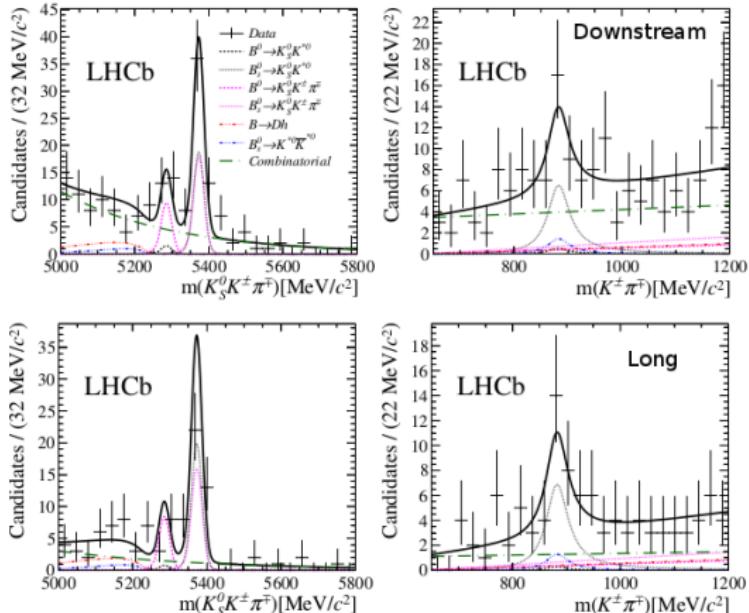
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- No significant signal is observed for the $\Lambda_b^0 \rightarrow \Lambda\eta'$ channel, and so an upper limit is placed, $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\eta') < 3.1 \times 10^{-6}$ at 90% CL
- Evidence is seen for the presence of the $\Lambda_b^0 \rightarrow \Lambda\eta$ decay with a signal yield of 5.3 ± 3.8 candidates, and a significance of 3.0σ ,
 $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\eta) = (9.3^{+7.3}_{-5.3}) \times 10^{-6}$
- Our results favour the branching fractions calculated using the pole model to estimate the hadronic form factors
- Our results are inconsistent with the prediction for $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda\eta')$ obtained by neglecting the anomalous contribution to the decay amplitude, indicating that a gluonic component of the η' wavefunction should be present

First observation of $B_s^0 \rightarrow K_S^0 K^*(892)^0$

- “First observation of the decay $B_s^0 \rightarrow K_S^0 K^*(892)^0$ ”¹
- Analysis performed with 1fb^{-1} of data
- $B^0 \rightarrow K_S^0 \pi^+ \pi^-$ as normalization channel
- 21 ± 6 (25 ± 6) events for Downstream (Long)



- $B_s^0 \rightarrow K_S^0 K^*(892)^0$ observed for the first time, with 7.1σ
- $\mathcal{B}(B_s^0 \rightarrow K_S^0 K^*(892)^0) = (10.9 \pm 2.5(\text{stat}) \pm 1.0(\text{syst}) \pm 0.5(f_s/f_d) \pm 0.4(\text{norm})) \times 10^{-6}$
- For the $B^0 \rightarrow K_S^0 K^*(892)^0$ an upper limit is determined,
 $\mathcal{B}(B^0 \rightarrow K_S^0 K^*(892)^0) = (0.15 \pm 0.25(\text{stat}) \pm 0.05(\text{syst}) \pm 0.01(\text{norm})) \times 10^{-6}$,
 $< 0.64(0.69)) \times 10^{-6}$ at 90% (95%) CL

¹arXiv:1506.08634 [hep-ex]

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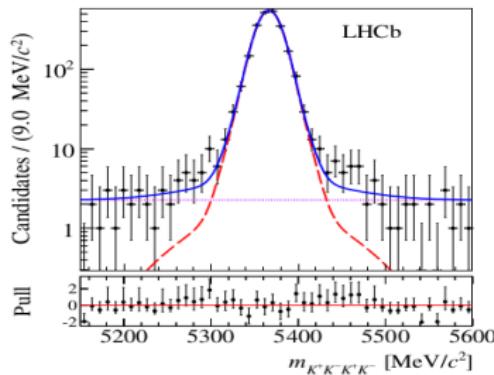
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Measurement of $B_s^0 \rightarrow \phi\phi$ BF NEW!!

- "Measurement of the $B_s^0 \rightarrow \phi\phi$ branching fraction"¹ (in preparation)
- The decay $B^0 \rightarrow \phi K^*(892)^0$ is used for normalization
- $\mathcal{B}(B_s^0 \rightarrow \phi\phi) = [1.84 \pm 0.05(\text{stat}) \pm 0.07(\text{syst}) \pm 0.11(f_s/f_d) \pm 0.12(\text{norm})] \times 10^{-5}$,
in agreement with theory predictions and previous results



- In addition, a search for the unobserved decay $B^0 \rightarrow \phi\phi$ is made
- The statistical significance of the fitted B^0 signal is less than 2σ , hence a limit on the branching fraction is placed, using the CL_s method,
 $\mathcal{B}(B^0 \rightarrow \phi\phi) < 3.4 \times 10^{-8}$

¹LHCb-PAPER-2015-028

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- The latest charmless B decays results from LHCb have been presented
- Three channel decays observed for the first time, $B^0 \rightarrow \rho^0 \rho^0$, $B_s^0 \rightarrow \eta' \eta'$ and $B_s^0 \rightarrow K_S^0 K^*(892)^0$
- Evidence for the $\Lambda_b^0 \rightarrow \Lambda \eta$ decay
- Solved the discrepancy between BaBar and Belle about the $B^0 \rightarrow \rho^0 \rho^0$ longitudinal polarization, and no observation of the $B^0 \rightarrow \rho^0 f_0(980)$
- Confirmed the low longitudinal polarization in $B_s^0 \rightarrow K^*(892)^0 \bar{K}^*(892)^0$, found a very large S-wave contribution and the measurements of the CP-violating asymmetries compatible with the Standard Model
- Measurement of the $B_s^0 \rightarrow \phi \phi$ branching fraction, and no evidence of the $B^0 \rightarrow \phi \phi$ decay
- The final conclusion of the presentation is that, unfortunately, **no deviations from the SM are seen**, neither in the $B \rightarrow VV$ angular analysis nor in the branching fraction measurements from several decay channels

Thanks for your attention!

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Backup Slides

CP asymmetries and polarisation fractions in $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$

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- Untagged time-integrated terms used, under the assumption of no CP violation

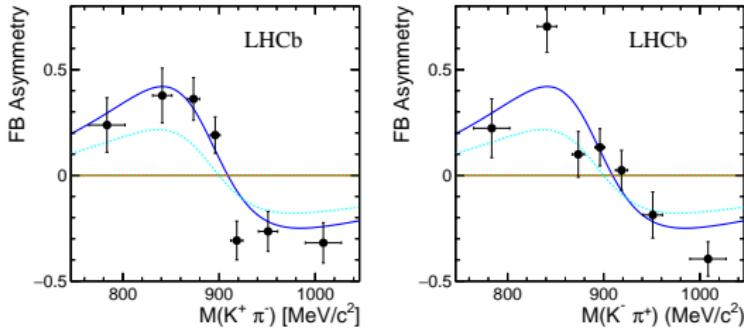
n	K_n	F_n
1	$\frac{1}{\Gamma_L} A_0 ^2 \mathcal{M}_1(m_1) ^2 \mathcal{M}_1(m_2) ^2$	$\cos^2 \theta_1 \cos^2 \theta_2$
2	$\frac{1}{\Gamma_L} A_\parallel ^2 \mathcal{M}_1(m_1) ^2 \mathcal{M}_1(m_2) ^2$	$\frac{1}{2} \sin^2 \theta_1 \sin^2 \theta_2 \cos^2 \varphi$
3	$\frac{1}{\Gamma_H} A_\perp ^2 \mathcal{M}_1(m_1) ^2 \mathcal{M}_1(m_2) ^2$	$\frac{1}{2} \sin^2 \theta_1 \sin^2 \theta_2 \sin^2 \varphi$
4	$\frac{1}{\Gamma_L} A_\parallel A_0 \cos \delta_\parallel \mathcal{M}_1(m_1) ^2 \mathcal{M}_1(m_2) ^2$	$\frac{1}{2\sqrt{2}} \sin 2\theta_1 \sin 2\theta_2 \cos \varphi$
5	0	$-\frac{1}{2\sqrt{2}} \sin 2\theta_1 \sin 2\theta_2 \sin \varphi$
6	0	$-\frac{1}{2} \sin^2 \theta_1 \sin^2 \theta_2 \sin 2\varphi$
7	$\frac{1}{2} \left(\frac{ A_\perp^+ ^2}{\Gamma_H} + \frac{ A_\perp^- ^2}{\Gamma_L} \right) \mathcal{M}_1(m_1) ^2 \mathcal{M}_0(m_2) ^2$	$\frac{1}{3} \cos^2 \theta_1$
8	$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_0 \mathcal{R}e(e^{i\delta_s^-} \mathcal{M}_1^*(m_2) \mathcal{M}_0(m_2)) \mathcal{M}_1(m_1) ^2$	$-\frac{2}{\sqrt{3}} \cos^2 \theta_1 \cos \theta_2$
9	$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_\parallel \mathcal{R}e(e^{i(\delta_s^- - \delta_\parallel)} \mathcal{M}_1^*(m_2) \mathcal{M}_0(m_2)) \mathcal{M}_1(m_1) ^2$	$-\frac{1}{\sqrt{6}} \sin 2\theta_1 \sin \theta_2 \cos \varphi$
10	$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_H} A_s^+ A_\perp \mathcal{I}m(e^{i(\delta_\perp - \delta_s^+)} \mathcal{M}_0^*(m_2) \mathcal{M}_0(m_2)) \mathcal{M}_1(m_1) ^2$	$\frac{1}{\sqrt{6}} \sin 2\theta_1 \sin \theta_2 \sin \varphi$
11	$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_{ss} \mathcal{R}e(e^{i(\delta_s^- - \delta_{ss})} \mathcal{M}_0^*(m_1) \mathcal{M}_1(m_1)) \mathcal{M}_0(m_2) ^2$	$\frac{2}{3\sqrt{3}} \cos \theta_1$
12	$\frac{1}{2} \left(\frac{ A_\perp^+ ^2}{\Gamma_H} + \frac{ A_\perp^- ^2}{\Gamma_L} \right) \mathcal{M}_0(m_1) ^2 \mathcal{M}_1(m_2) ^2$	$\frac{1}{3} \cos^2 \theta_2$
13	$-\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_0 \mathcal{R}e(e^{i\delta_s^-} \mathcal{M}_1^*(m_1) \mathcal{M}_0(m_1)) \mathcal{M}_1(m_2) ^2$	$-\frac{2}{\sqrt{3}} \cos \theta_1 \cos^2 \theta_2$
14	$-\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_\parallel \mathcal{R}e(e^{i(\delta_s^- - \delta_\parallel)} \mathcal{M}_1^*(m_1) \mathcal{M}_0(m_1)) \mathcal{M}_1(m_2) ^2$	$\frac{1}{\sqrt{6}} \sin \theta_1 \sin 2\theta_2 \cos \varphi$
15	$\frac{1}{\sqrt{2}} \frac{1}{\Gamma_H} A_s^+ A_\perp \mathcal{I}m(e^{i(\delta_\perp - \delta_s^+)} \mathcal{M}_0^*(m_1) \mathcal{M}_0(m_1)) \mathcal{M}_1(m_2) ^2$	$-\frac{1}{\sqrt{6}} \sin \theta_1 \sin 2\theta_2 \sin \varphi$
16	$-\frac{1}{\sqrt{2}} \frac{1}{\Gamma_L} A_s^- A_{ss} \mathcal{R}e(e^{i(\delta_s^- - \delta_{ss})} \mathcal{M}_0^*(m_2) \mathcal{M}_1(m_2)) \mathcal{M}_0(m_1) ^2$	$-\frac{2}{3\sqrt{3}} \cos \theta_2$
17	$\left(\frac{ A_\perp^+ ^2}{\Gamma_H} - \frac{ A_\perp^- ^2}{\Gamma_L} \right) \mathcal{R}e(\mathcal{M}_1^*(m_1) \mathcal{M}_0^*(m_2) \mathcal{M}_0(m_1) \mathcal{M}_1(m_2))$	$-\frac{1}{3} \cos \theta_1 \cos \theta_2$
18	$\frac{1}{\Gamma_L} A_{ss} ^2 \mathcal{M}_0(m_1) ^2 \mathcal{M}_0(m_2) ^2$	$\frac{1}{9}$
19	$\frac{1}{\Gamma_L} A_{ss} A_0 \mathcal{R}e(e^{i\delta_{ss}} \mathcal{M}_1^*(m_1) \mathcal{M}_1^*(m_2) \mathcal{M}_0(m_1) \mathcal{M}_0(m_2)) $	$-\frac{2}{3} \cos \theta_1 \cos \theta_2$
20	$\frac{1}{\Gamma_L} A_{ss} A_\parallel \mathcal{R}e(e^{i(\delta_{ss} - \delta_\parallel)} \mathcal{M}_1^*(m_1) \mathcal{M}_1^*(m_2) \mathcal{M}_0(m_1) \mathcal{M}_0(m_2)) $	$-\frac{\sqrt{2}}{3} \sin \theta_1 \sin \theta_2 \cos \varphi$
21	0	$\frac{\sqrt{2}}{3} \sin \theta_1 \sin \theta_2 \sin \varphi$

CP asymmetries and polarisation fractions in $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$

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- Forward-backward asymmetry for K^{*0} mesons



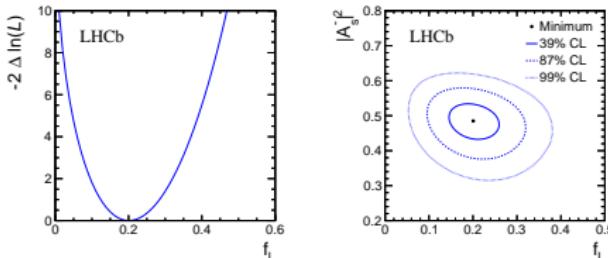
- Results of the fit

Parameter	Value
f_L	$0.201 \pm 0.057 \pm 0.040$
f_{\parallel}	$0.215 \pm 0.046 \pm 0.015$
$ A_s^+ ^2$	$0.114 \pm 0.037 \pm 0.023$
$ A_s^- ^2$	$0.485 \pm 0.051 \pm 0.019$
$ A_{ss} ^2$	$0.066 \pm 0.022 \pm 0.007$
δ_{\parallel}	$5.31 \pm 0.24 \pm 0.14$
$\delta_{\perp} - \delta_s^+$	$1.95 \pm 0.21 \pm 0.04$
δ_s^-	$1.79 \pm 0.19 \pm 0.19$
δ_{ss}	$1.06 \pm 0.27 \pm 0.23$

CP asymmetries and polarisation fractions in $B_s^0 \rightarrow K^{*0} \bar{K}^{*0}$

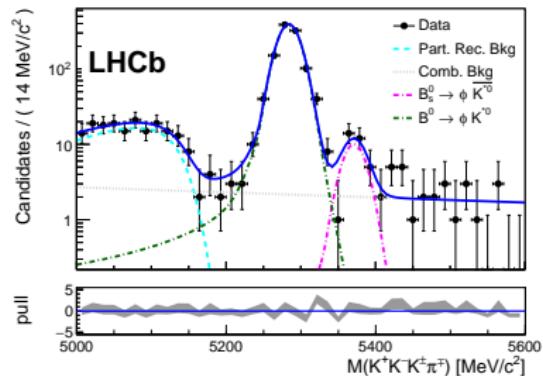
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- (Left) Profile likelihood for f_L . (Right) Regions corresponding to $\Delta\mathcal{L} = 0.5, 2$ and 4.5 (39%, 87% and 99% confidence level) in the $|A_S^-|^2 - f_L$ plane



- (Left) Relevant quantities in the \mathcal{B} calculation. (Right) Invariant mass of the normalization channel

$N_{B_s^0}$	$697 \pm 31 \pm 11$
N_{B^0}	$1049 \pm 33 \pm 7$
$\kappa_{B^0 \rightarrow \phi K^{*0}} / \kappa_{B_s^0 \rightarrow K^{*0} \bar{K}^{*0}}$	$0.453 \pm 0.059 \pm 0.040$
$\varepsilon_{B^0 \rightarrow \phi K^{*0}} / \varepsilon_{B_s^0 \rightarrow K^{*0} \bar{K}^{*0}}$	$1.30 \pm 0.17 \pm 0.07$

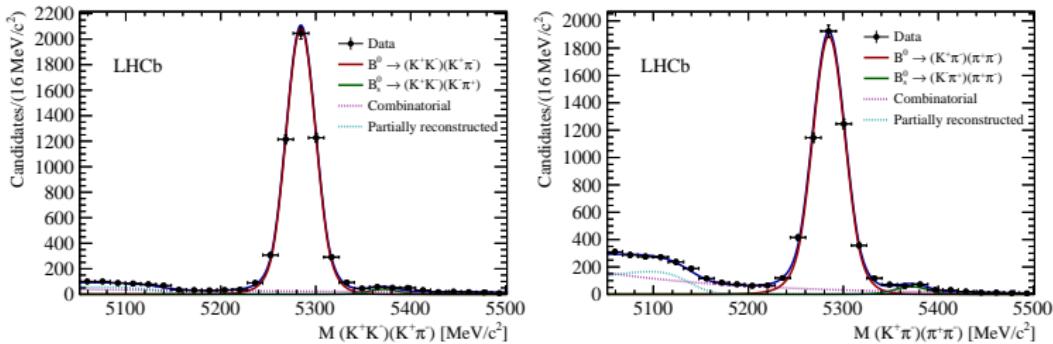


Amplitude analysis of $B^0 \rightarrow \rho^0 \rho^0$

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- Reconstructed invariant mass of the normalization (left) and the PID misidentification control (right) channels



- Yields from the simultaneous fit

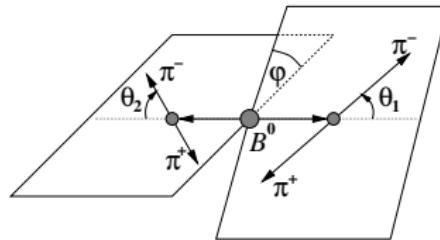
Decay mode	Signal yields 2011	Signal yields 2012
$B^0 \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)$	$185 \pm 15 \pm 4$	$449 \pm 24 \pm 7$
$B^0 \rightarrow (K^+\pi^-)(\pi^+\pi^-)$	$1610 \pm 42 \pm 5$	$3478 \pm 62 \pm 10$
$B^0 \rightarrow (K^+K^-)(K^+\pi^-)$	$1513 \pm 40 \pm 8$	$3602 \pm 62 \pm 10$
$B_s^0 \rightarrow (\pi^+\pi^-)(\pi^+\pi^-)$	$30 \pm 7 \pm 1$	$71 \pm 11 \pm 1$
$B_s^0 \rightarrow (K^-\pi^+)(\pi^+\pi^-)$	$40 \pm 10 \pm 3$	$96 \pm 14 \pm 6$
$B_s^0 \rightarrow (K^+K^-)(K^-\pi^+)$	$42 \pm 10 \pm 3$	$66 \pm 13 \pm 4$

Amplitude analysis of $B^0 \rightarrow \rho^0 \rho^0$

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- Helicity angles for the $(\pi^+ \pi^-)(\pi^+ \pi^-)$ system



- Amplitudes, A_i , CP eigenvalues, η_i and mass-angle distributions, f_i of the $B^0 \rightarrow \rho^0 \rho^0$ model

A_i	η_i	f_i
$A_{\rho\rho}^0$	1	$M_\rho(m_1)M_\rho(m_2)\cos\theta_1\cos\theta_2$
$A_{\rho\rho}^+$	1	$M_\rho(m_1)M_\rho(m_2)\frac{1}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\varphi$
$A_{\rho\rho}^\perp$	-1	$M_\rho(m_1)M_\rho(m_2)\frac{i}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\varphi$
$A_{\rho\omega}^0$	1	$\frac{1}{\sqrt{2}}[M_\rho(m_1)M_\omega(m_2)+M_\omega(m_1)M_\rho(m_2)]\cos\theta_1\cos\theta_2$
$A_{\rho\omega}^1$	1	$\frac{1}{\sqrt{2}}[M_\rho(m_1)M_\omega(m_2)+M_\omega(m_1)M_\rho(m_2)]\frac{1}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\varphi$
$A_{\rho\omega}^\perp$	-1	$\frac{1}{\sqrt{2}}[M_\rho(m_1)M_\omega(m_2)+M_\omega(m_1)M_\rho(m_2)]\frac{i}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\varphi$
$A_{\rho(\pi\pi)_0}$	-1	$\frac{3}{\sqrt{6}}[M_\rho(m_1)M_{(\pi\pi)_0}(m_2)\cos\theta_1+M_{(\pi\pi)_0}(m_1)M_\rho(m_2)\cos\theta_2]$
$A_{\rho f(980)}$	-1	$\frac{1}{\sqrt{6}}[M_\rho(m_1)M_{f(980)}(m_2)\cos\theta_1+M_{f(980)}(m_1)M_\rho(m_2)\cos\theta_2]$
$A_{(\pi\pi)_0(\pi\pi)_0}$	1	$M_{(\pi\pi)_0}(m_1)M_{(\pi\pi)_0}(m_2)\frac{1}{3}$
$A_{\rho f_2}^0$	-1	$\sqrt{\frac{5}{24}}[M_\rho(m_1)M_{f_2}(m_2)\cos\theta_1(3\cos^2\theta_2-1)+M_{f_2}(m_1)M_\rho(m_2)\cos\theta_2(3\cos^2\theta_1-1)]$
$A_{a_1\pi}^{S^+}$	1	$\frac{1}{\sqrt{8}}\sum_{ijkl}\frac{1}{\sqrt{3}}M_{a_1}(m_{ijkl})M_\rho(m_{ij})[\cos\alpha_{kl}\cos\beta_{ik}+\sin\alpha_{kl}\sin\beta_{ik}\cos\Phi_{kl}]$

Amplitude analysis of $B^0 \rightarrow \rho^0 \rho^0$

Charmless B
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• Results of the fit to the angular and two-body invariant mass distribution

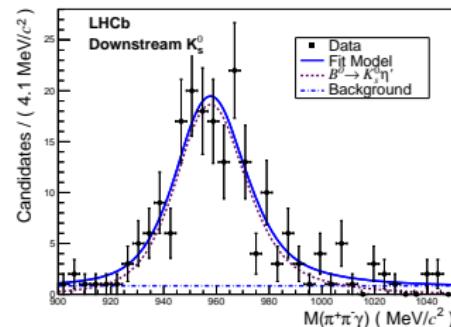
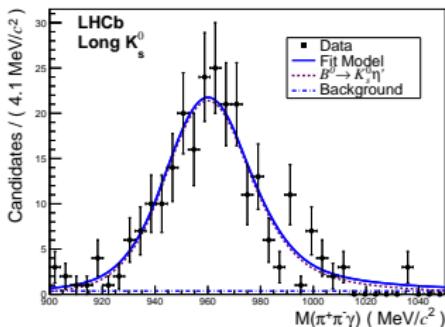
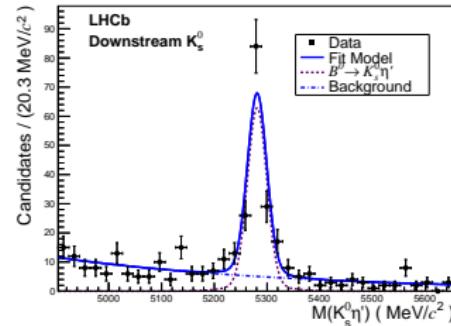
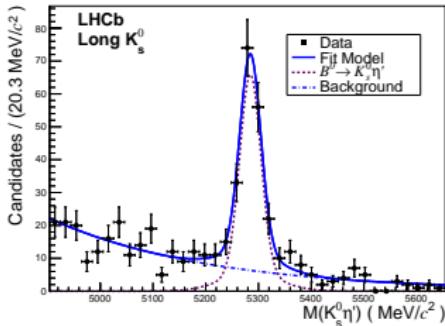
Parameter	Definition	Fit result
f_L	$ A_{\rho\rho}^0 ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.745^{+0.048}_{-0.058} \pm 0.034$
f_\parallel^\perp	$ A_{\rho\rho}^\perp ^2/(A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.50 \pm 0.09 \pm 0.05$
$\delta_\parallel - \delta_0$	$\arg(A_{\rho\rho}^\parallel A_{\rho\rho}^{0*})$	$1.84 \pm 0.20 \pm 0.14$
$F_{\rho(\pi\pi)_0}$	$ A_{\rho(\pi\pi)_0} ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.30^{+0.11}_{-0.09} \pm 0.08$
$F_{\rho f(980)}$	$ A_{\rho f(980)} ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.29^{+0.12}_{-0.09} \pm 0.08$
$F_{\pi\pi(0)(\pi\pi)_0}$	$ A_{\pi\pi(0)(\pi\pi)_0} ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.21^{+0.06}_{-0.04} \pm 0.08$
$\delta_\perp - \delta_{\rho(\pi\pi)_0}$	$\arg(A_{\rho\rho}^\perp A_{\rho(\pi\pi)_0}^*)$	$-1.13^{+0.33}_{-0.22} \pm 0.24$
$\delta_\perp - \delta_{\rho f(980)}$	$\arg(A_{\rho\rho}^\perp A_{\rho f(980)}^*)$	$1.92 \pm 0.24 \pm 0.16$
$\delta_{(\pi\pi)_0(\pi\pi)_0} - \delta_0$	$\arg(A_{(\pi\pi)_0(\pi\pi)_0} A_{\rho\rho}^{0*})$	$3.14^{+0.36}_{-0.38} \pm 0.39$
$F_{\rho\omega}$	$(A_{\rho\omega}^0 ^2 + A_{\rho\omega}^\parallel ^2 + A_{\rho\omega}^\perp ^2)/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.025^{+0.048}_{-0.022} \pm 0.020$
$f_L^{\rho\omega}$	$ A_{\rho\omega}^0 ^2/(A_{\rho\omega}^0 ^2 + A_{\rho\omega}^\parallel ^2 + A_{\rho\omega}^\perp ^2)$	$0.70^{+0.23}_{-0.60} \pm 0.13$
$f_\parallel^{\rho\omega'}$	$ A_{\rho\omega}^\parallel ^2/(A_{\rho\omega}^\parallel ^2 + A_{\rho\omega}^\perp ^2)$	$0.97^{+0.69}_{-0.56} \pm 0.15$
$\delta_0^{\rho\omega} - \delta_0$	$\arg(A_{\rho\omega}^0 A_{\rho\rho}^{0*})$	$-2.56^{+0.76}_{-0.92} \pm 0.22$
$\delta_\parallel^{\rho\omega} - \delta_0$	$\arg(A_{\rho\omega}^\parallel A_{\rho\rho}^{0*})$	$-0.71^{+0.71}_{-0.67} \pm 0.32$
$\delta_\perp^{\rho\omega} - \delta_{\rho(\pi\pi)_0}$	$\arg(A_{\rho\omega}^\perp A_{\rho(\pi\pi)_0}^*)$	$-1.72 \pm 2.62 \pm 0.80$
$F_{\rho f_2}^0$	$ A_{\rho f_2}^0 ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$0.01^{+0.04}_{-0.02} \pm 0.03$
$\delta_{\rho f_2}^0 - \delta_{\rho(\pi\pi)_0}$	$\arg(A_{\rho f_2}^0 A_{\rho(\pi\pi)_0}^*)$	$-0.56 \pm 1.48 \pm 0.80$
$F_{a_1\pi}^{S+}$	$ A_{a_1\pi}^{S+} ^2/(A_{\rho\rho}^0 ^2 + A_{\rho\rho}^\parallel ^2 + A_{\rho\rho}^\perp ^2)$	$1.4^{+1.0+1.2}_{-0.7-0.8}$
$\delta_{a_1\pi}^{S+} - \delta_{\rho(\pi\pi)_0}$	$\arg(A_{a_1\pi}^{S+} A_{\rho(\pi\pi)_0}^*)$	$-0.09^{+0.30}_{-0.36} \pm 0.38$

Search for $\Lambda_b^0 \rightarrow \Lambda\eta^{(\prime)}$

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- Mass distribution of the selected $B^0 \rightarrow K_S^0\eta'(\eta' \rightarrow \pi^+\pi^-\gamma)$ candidates (top) and of the reconstructed η' mesons (bottom), in the Long (left) and Downstream (right) categories

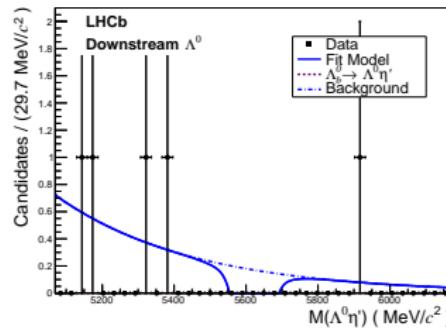
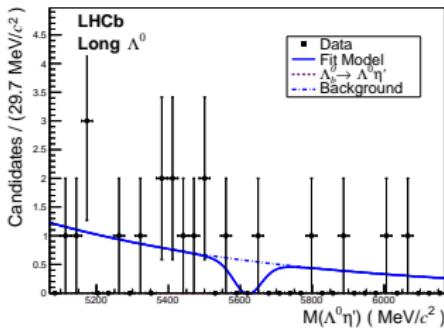
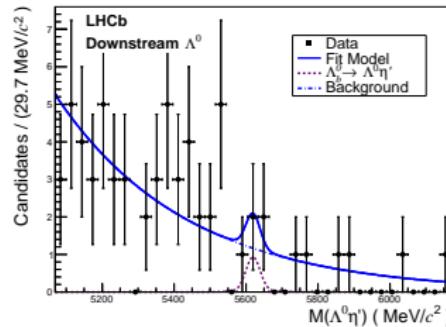
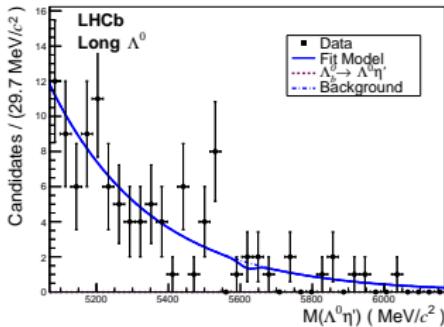


Search for $\Lambda_b^0 \rightarrow \Lambda\eta^{(\prime)}$

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- Mass distribution of the selected $\Lambda_b^0 \rightarrow \Lambda\eta'(\eta' \rightarrow \pi^+\pi^-\gamma)$ candidates (top) and of the selected $\Lambda_b^0 \rightarrow \Lambda\eta'(\eta' \rightarrow \pi^+\pi^-\eta)$ (bottom), in the Long (left) and Downstream (right) categories



Search for $\Lambda_b^0 \rightarrow \Lambda\eta^{(\prime)}$

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• Components contributing to the \mathcal{B} calculation

Factor	$\Lambda\eta'(\pi^+\pi^-\gamma)$		$\Lambda\eta'(\pi^+\pi^-\eta)$		$\Lambda\eta(\pi^+\pi^-\pi^0)$	
	L	D	L	D	L	D
$\epsilon_{\text{tot}}(B^0)/\epsilon_{\text{tot}}(\Lambda_b^0)$	2.3 ± 0.1	1.55 ± 0.08	7.4 ± 0.6	9.5 ± 1.4	4.6 ± 0.3	3.4 ± 0.2
$f_B/f_{\Lambda_b^0}$		2.5 ± 0.2		2.5 ± 0.2		2.5 ± 0.2
$1/C_\gamma$		1 (fixed)		0.95 ± 0.04		1.13 ± 0.04
$0.5 \cdot \mathcal{B}(K_s^0)/\mathcal{B}(\Lambda)$		0.541 ± 0.004		0.541 ± 0.004		0.541 ± 0.004
$\mathcal{B}(\eta')/\mathcal{B}(\eta^{(\prime)})$		1 (fixed)		1.71 ± 0.05		1.31 ± 0.03
α	3.1 ± 0.3	2.1 ± 0.2	17.7 ± 2.3	22.8 ± 4.0	9.5 ± 1.2	7.0 ± 0.8

First observation of $B_s^0 \rightarrow K_S^0 K^*(892)^0$

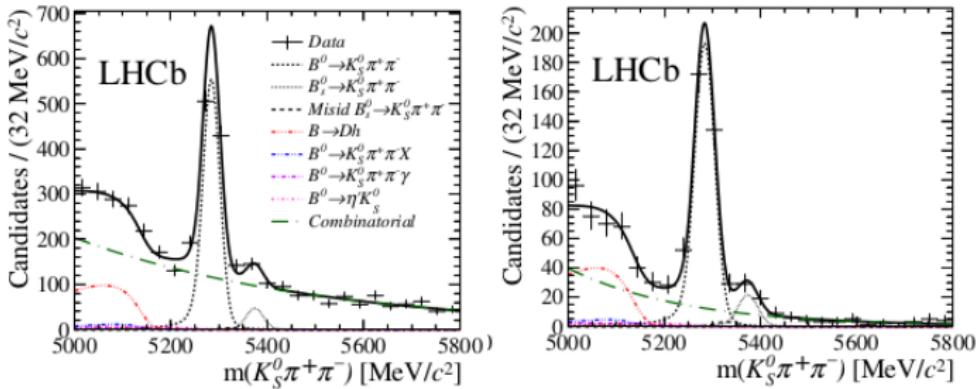
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- Signal yields obtained from the fits to the $K_S^0 K^\pm \pi^\mp$ and $K_S^0 \pi^+ \pi^-$ mass distributions and corresponding efficiencies

Decay	Downstream		Long	
	Yield	Efficiency (%)	Yield	Efficiency (%)
$B_s^0 \rightarrow K_S^0 K^{*0}$	21 ± 6	0.0174 ± 0.0012	25 ± 6	0.0121 ± 0.0008
$B_s^0 \rightarrow K_S^0 K^{*0}$	2 ± 3	0.0183 ± 0.0013	1 ± 2	0.0125 ± 0.0009
$B_s^0 \rightarrow K_S^0 \pi^+ \pi^-$	828 ± 41	0.0336 ± 0.0010	341 ± 23	0.0117 ± 0.0009

- Distributions of $K_S^0 \pi^+ \pi^-$ mass for Downstream (left) and Long (right) categories

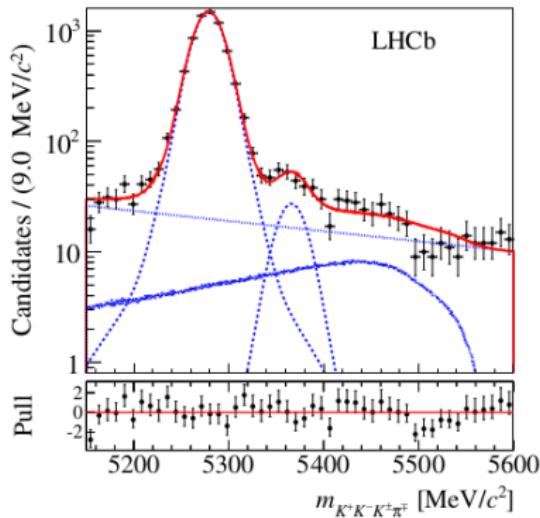


Measurement of $B_s^0 \rightarrow \phi\phi$ BF

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- Invariant mass distribution of $K^+K^-K^\pm\pi^\mp$ decays, used for the normalization



Measurement of $B_s^0 \rightarrow \phi\phi$ BF

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- (Left) The $K^+K^-K^+K^-$ invariant mass with a $B^0 \rightarrow \phi\phi$ component included. (Right) Results of the CL_s scan as a function of the $B^0 \rightarrow \phi\phi$ branching fraction

