Observation of $B_s^0 \to \eta_c\phi$ and evidence for $B_s^0 \to \eta_c\pi^+\pi^-$ decays at LHCb

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Physics motivation

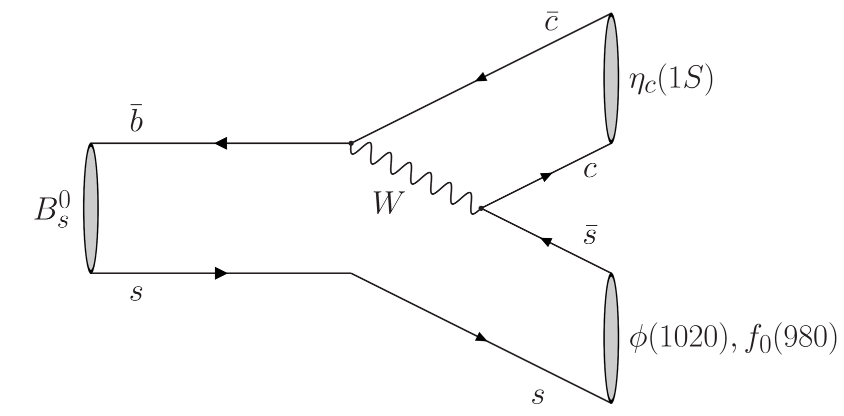
- CP-violating phase ϕ_s, interference between direct decay and mixing in $b \to c\bar{c}s$ transitions:

$$\phi_s = -0.0367^{+0.0007}_{-0.0008} \text{ rad (SM global fit [1])}$$

- Precision limited by statistical uncertainty until the end of the LHCb upgrade with "golden" channel $B_s^0 \to J/\psi\phi$:

$$\phi_s = -0.030 \pm 0.033 \text{ rad [2]}$$

- $B_s^0 \to \eta_c\phi$ and $B_s^0 \to \eta_c\pi^+\pi^-$ decays can also provide measurements of ϕ_s.
- LHC run 1 statistics not sufficient with these decays:
  $\Rightarrow$ first measurement of their braching fractions is performed.



Analysis strategy

$$\mathcal{B}_{\text{meas}}(B_s^0 \to \eta_c X) = \frac{N^{\text{fit}}_{\eta_c}}{N^{\text{fit}}_{J/\psi}} \times \mathcal{B}(B_s^0 \to J/\psi X) \times \frac{\mathcal{B}(J/\psi \to 4h, p\bar{p})}{\mathcal{B}(\eta_c \to 4h, p\bar{p})} \times \frac{\varepsilon_{(J/\psi)}}{\varepsilon_{(\eta_c)}}$$

- External branching fractions (BR) from Particle Data Group [3].
- $B_s^0 \to \eta_c(\to p\bar{p}, K^+K^-\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-K^+K^-)\phi(\to K^+K^-)$.
- $B_s^0 \to \eta_c(\to p\bar{p})\pi^+\pi^-$.
- Normalized to $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$, J/ψ reconstructed into same states as η_c.
- Fit procedure:
  1) Separate signal and background: unbinned extended maximum likelihood fit (UML),
  2) Disentangle η_c and J/ψ from non-resonant (NR) background component: weighted UML.
- Simultaneous fit to improve senstivity in $\mathcal{B}(B_s^0 \to \eta_c\phi)$
- Need to compute efficiencies $\varepsilon_{(J/\psi)}$ and $\varepsilon_{(\eta_c)}$.

Event selection and efficiency correction

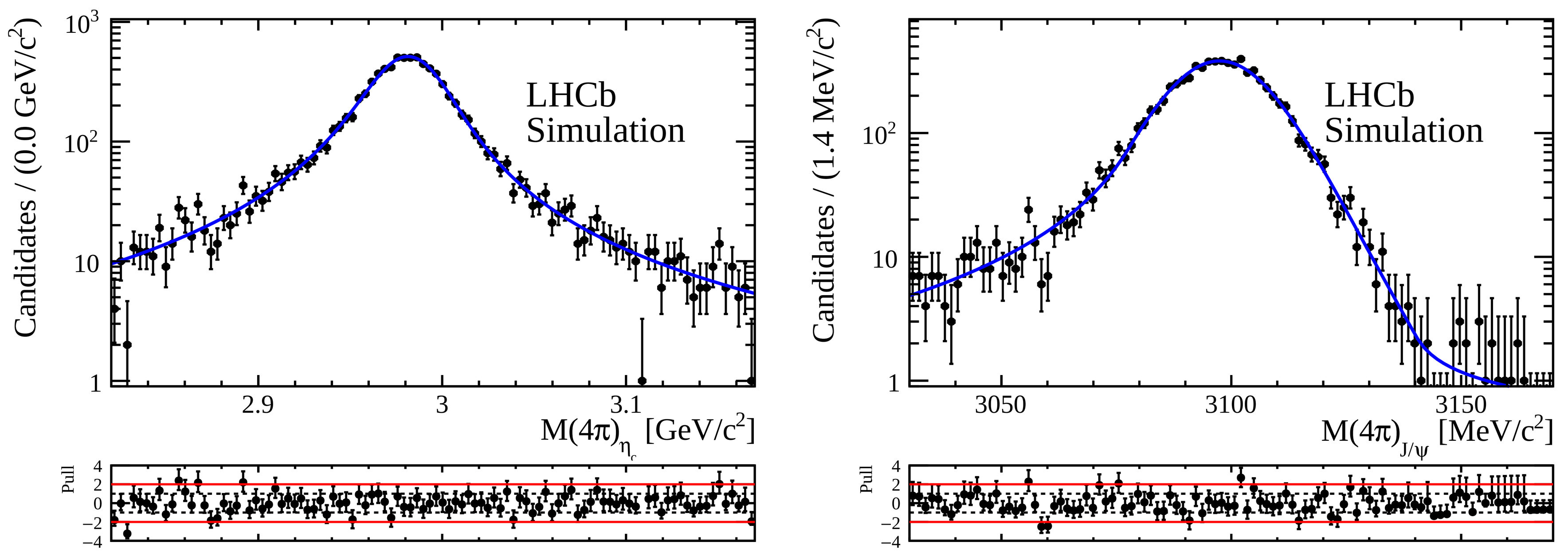
- Full run 1 dataset: 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV and similar selection for all modes
  - Candidates are required to have four(six) good quality high-p_{T} tracks,
  - Consistent with coming from a vertex that is displaced from any primary vertex in the event,
  - Multivariate analysis with a boosted decision tree applied to reduce combinatorial background,
  - Loose particle identification (PID) criteria are applied,
  - Mass veto to remove specific open charm backgrounds.

$$\frac{\varepsilon(J/\psi)}{\varepsilon(\eta_c)} = \frac{\varepsilon(J/\psi)^{\text{geo}}}{\varepsilon(\eta_c)^{\text{geo}}} \times \frac{\varepsilon(J/\psi)^{\text{reco+sel}}}{\varepsilon(\eta_c)^{\text{reco+sel}}} \times \frac{\varepsilon(J/\psi)^{\text{PID}}}{\varepsilon(\eta_c)^{\text{PID}}} \times \mathcal{F}^{\text{lifetime}}_{corr}$$

	$2K2\pi\phi$	$4\pi\phi$	$4K\phi$	$p\bar{p}\phi$	$p\bar{p}\pi^+\pi^-$
$\frac{\varepsilon(J/\psi)}{\varepsilon(\eta_c)}$	1.047 ± 0.011	1.068 ± 0.016	0.962 ± 0.028	1.038 ± 0.009	1.004 ± 0.015

Fit models

- B_s^0, B_d^0: Hypatia [4]
- Mis-ID background $p\bar{p}K^+\pi^-$: Crystal-Ball [5]
- Combinatorial background: exponential
- ϕ: Relativistic Breit-Wigner (BW) $\otimes$ Gaussian
- Non resonant K^+K^-: linear



- Simultaneous amplitude fit model: $\mathrm{PDF}^{\mathrm{reco}}(m) = \mathrm{PDF}^{\mathrm{phys}}(m) \otimes R(m)$
  - R: Hypatia [4] (detector resolution function)
  - $\mathrm{PDF}^{\mathrm{phys}}$: $f_{\eta_c}F_{\eta_c} + f_{\mathrm{SnoI}}F_{\mathrm{SnoI}} + f_{\mathrm{SI}}F_{\mathrm{SI}} + 2\sqrt{f_{\eta_c}f_{\mathrm{SI}}}F_{\mathrm{Interf}} + f_{J/\psi}F_{J/\psi}$
  - η_c: $F_{\eta_c}(m) = |BW(m)|^2$
  - J/ψ: Dirac function
  - S-waves non-interfering and interfering components: exponential $\exp(-\kappa_{\mathrm{SnoI}}m)$ and $\exp(-\kappa_{\mathrm{SI}}m)$
  - Interference term: $F_{\mathrm{Interf}}(m) = \Re\left(\exp(-\frac{1}{2}\kappa_{\mathrm{SI}}m)BW^*\right)$
- Due to the limited size and the small expected contribution of the NR $p\bar{p}$ component, corresponding interference amplitudes are neglected.

Systematic uncertainties

- Dominated by external BR:

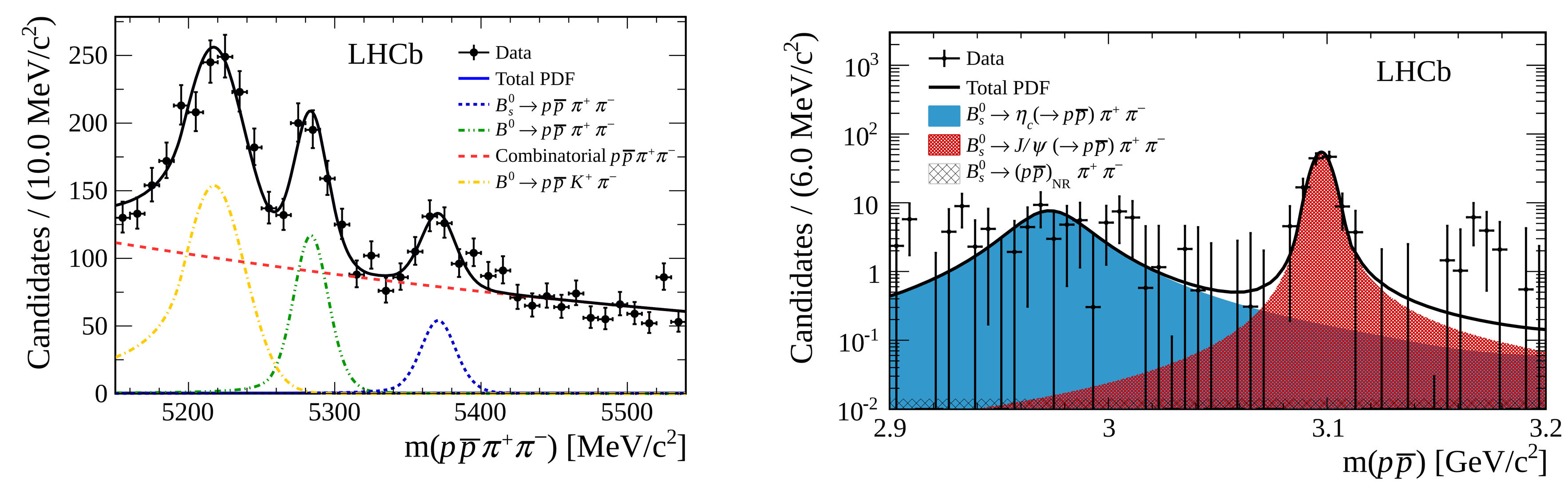
Source (%)	$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-)$	$\mathcal{B}(B_s^0 \to \eta_c\phi)$
Fixed PDF parameters	5.7	1.4
Efficiencies	3.4	0.8
Fit bias	1.7	1.4
Resolution model	0.6	4.4
Acceptance $(4h)$	n/a	1.6
$\phi(1020)$ barrier radius	n/a	1.6
Non-resonant $p\bar{p}$	n/a	1.0
Quadratic sum	6.8	5.4
External branching fractions	16.4	12.6

Results

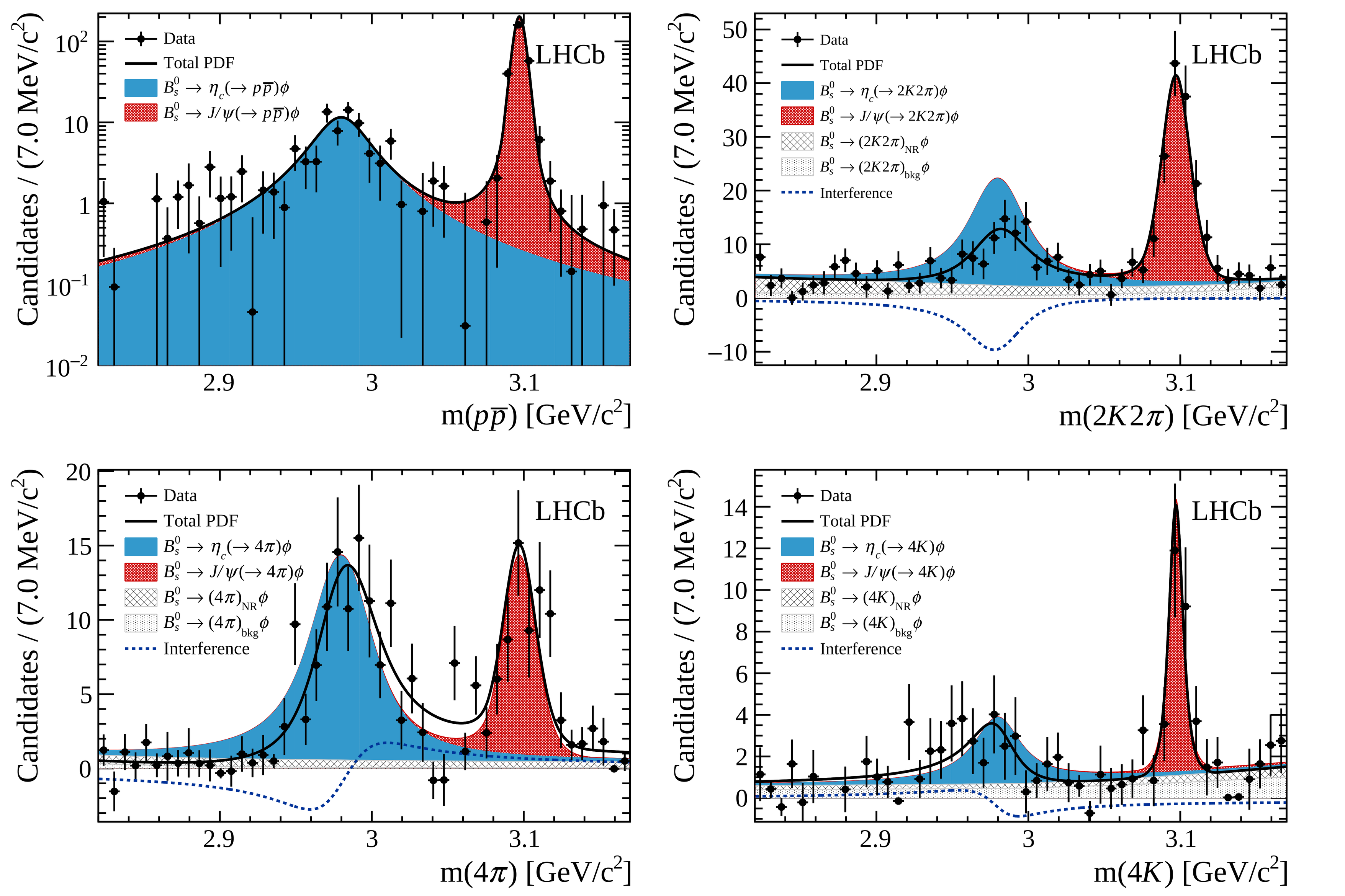
- Yields from the fit to $p\bar{p}\pi^+\pi^-$ and from the 2D fits to $p\bar{p}(4h)K^+K^- \times K^+K^-$:

Mode	Yield: $B_s^0 \to$ Mode	$B_d^0 \to$ Mode	Combinatorial	$B_d^0 \to p\bar{p}K^+\pi^-$
$p\bar{p}\pi^+\pi^-$	179 ± 32	384 ± 43	3261 ± 119	897 ± 69
$p\bar{p}\phi$	447 ± 24	13 ± 7	43 ± 17	11 ± 14
$p\bar{p}K^+K^-$	10 ± 11	-4 ± 5	106 ± 19	11 ± 14
$2K2\pi\phi$	586 ± 34	7 ± 17	419 ± 39	n/a
$2K2\pi K^+K^-$	86 ± 21	18 ± 16	329 ± 33	n/a
$4\pi\phi$	502 ± 33	77 ± 23	380 ± 43	n/a
$4\pi K^+K^-$	111 ± 25	67 ± 24	599 ± 43	n/a
$4K\phi$	151 ± 15	6 ± 5	44 ± 13	n/a
$4KK^+K^-$	-3 ± 4	-10 ± 9	44 ± 11	n/a

- $B_s^0 \to p\bar{p}\pi^+\pi^-$: distribution of $p\bar{p}\pi^+\pi^-$ and $p\bar{p}$ invariant-mass obtained with $_s\mathcal{P}lot$ [6]:



- $B_s^0 \to p\bar{p}(4h)\phi$: distribution of $p\bar{p}$ and each $4h$ invariant-mass spectra obtained with $_s\mathcal{P}lot$ [6]:



- Final results: First observation of the decay $B_s^0 \to \eta_c\phi$ and evidence for $B_s^0 \to \eta_c\pi^+\pi^-$

$$\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53 \pm 0.27 \pm 0.63) \times 10^{-4},$$
$$\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59 \pm 0.12 \pm 0.29) \times 10^{-4}.$$

- Uncertainties: statistical, systematic and limited knowledge of external BR, respectively.

[1] CKMfitter Group, J. Charles et al., "CP violation and the CKM matrix: Assessing the impact of the asymmetric B factories", Eur. Phys. J. C41 (2005) 1.
[2] HFAG, Amhis, Y. and others, "Averages of b-hadron, c-hadron, and τ-lepton", 2014 arXiv:1412.7515.
[3] Particle Data Group, C. Patrignani et al., "Review of particle physics", Chin. Phys. C40 (2016) 100001.
[4] D. Martinez Santos and F. Dupertuis, "Mass distributions marginalized over per-event errors", Nucl. Instrum. Meth. A764 (2014) 150, arXiv:1312.5000.
[5] T. Skwarnicki, "A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances", PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.
[6] M. Pivk and F.R. Le Diberder, "sPlot: A statistical tool to unfold data distributions", Nucl.Instrum.Meth. A555 (2005) 356 arXiv:physics/0402083.