Measurement of the $B_s^0 \to \phi\phi$ branching fraction and angular analysis of $B_{(s)}^0 \to \phi\pi^+\pi^-$

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Introduction & Motivation

$B_{(s)}^0 \to \phi\phi$ and $\phi\pi^+\pi^-$ ($m_{\pi^+\pi^-} < m_{D^0}$) are dominated by $b \to s$ transitions.
These proceed via loop-level diagrams and are sensitive to New Physics.

$B_s^0 \to \phi\phi$:

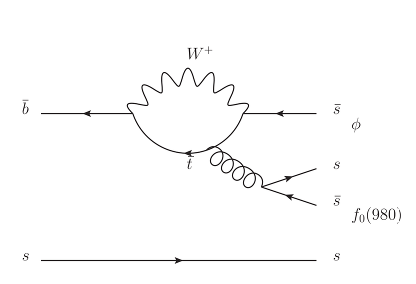
- **Important normalisation channel** for other charmless b-hadron decays.
- **Measure branching fraction (BF).**
- Use $B^0 \to \phi K^*(892)^0$ for normalisation.

$B^0 \to \phi\phi$:

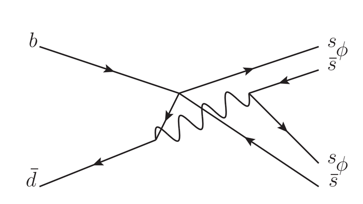
- **Unobserved** and highly suppressed in SM.
- BF could be **enhanced by New Physics**.
- Perform a search using CL_s method.

$B^0 \to \phi\pi^+\pi^-$ and $B_s^0 \to \phi\pi^+\pi^-$:

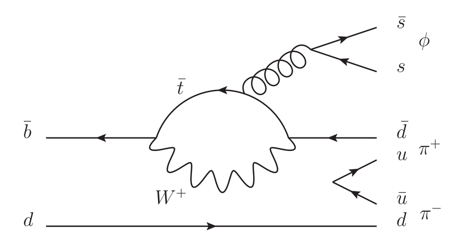
- **Previously unobserved.**
- Measure **inclusive BF** $0.4 < m_{\pi^+\pi^-} < 1.6$ GeV.
- Use $B_s^0 \to \phi\phi$ for normalisation.
- **Amplitude analysis** to extract **exclusive BFs** for $B_s^0 \to \phi\rho^0$, $B_s^0 \to \phi f_0(980)$ and $B_s^0 \to \phi f_2(1270)$.
- **Prospects:** future measurements of CP violation can be made using $B_s^0 \to \phi\pi^+\pi^-$.
  - No need for angular analysis with $B_s^0 \to \phi f_0(980)$.
  - Expect **large asymmetries** in $B_s^0 \to \phi\rho^0$.



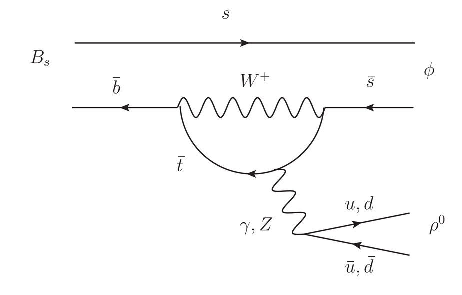
$B_s^0 \to \phi\phi$ and $\phi f_0(980)$ strong penguin.



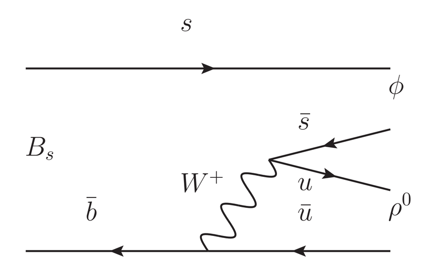
$B^0 \to \phi\phi$ non-factorisable diagram.



$B^0 \to \phi\pi^+\pi^-$ strong penguin.



$B_s^0 \to \phi\rho^0$ electroweak penguin.



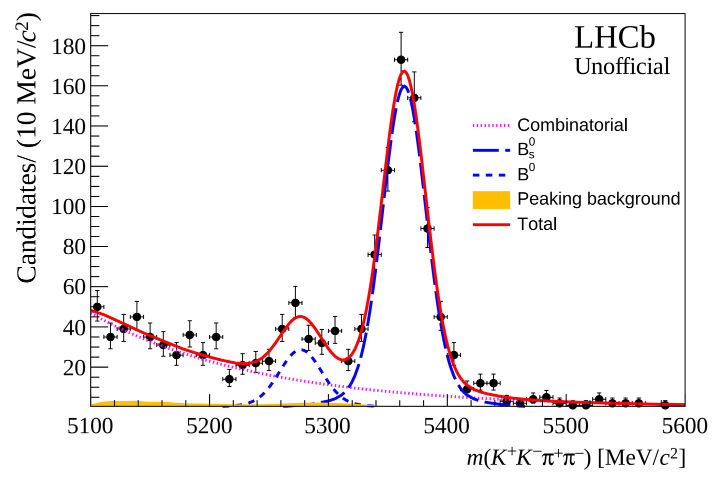
$B_s^0 \to \phi\rho^0$ tree-level diagram.

Event Selection

Full Run 1 dataset: 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV

- Well-reconstructed tracks selected with $p_T > 500$ MeV/c.
- Require significant displacement from the primary vertex.
- $K^\pm$ and $\pi^\pm$ identified using Ring-Imaging Cherenkov Detectors.
- K^+K^- pairs form ϕ candidates.
- $K^+\pi^-$ pairs form K^* candidates.
- Mass vetoes remove specific open charm backgrounds.
- Combinatorial background reduced using a Boosted Decision Tree, taking into account displacement of the $B_{(s)}^0$ from the primary vertex, kinematic information and track isolation.

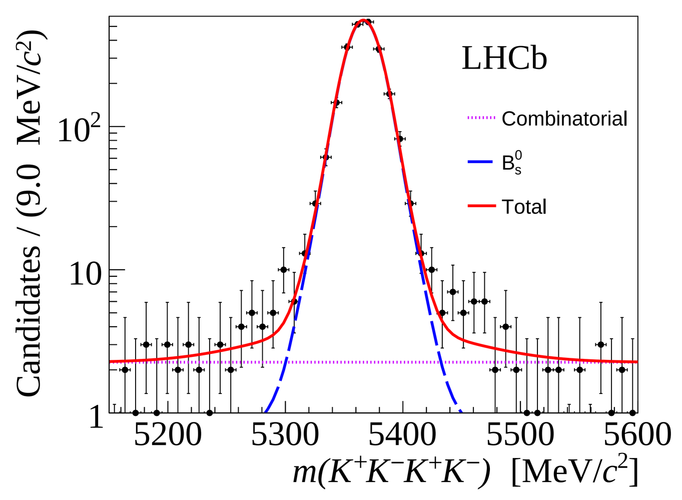
$B_{(s)}^0 \to \phi\pi^+\pi^-$ Mass Fit



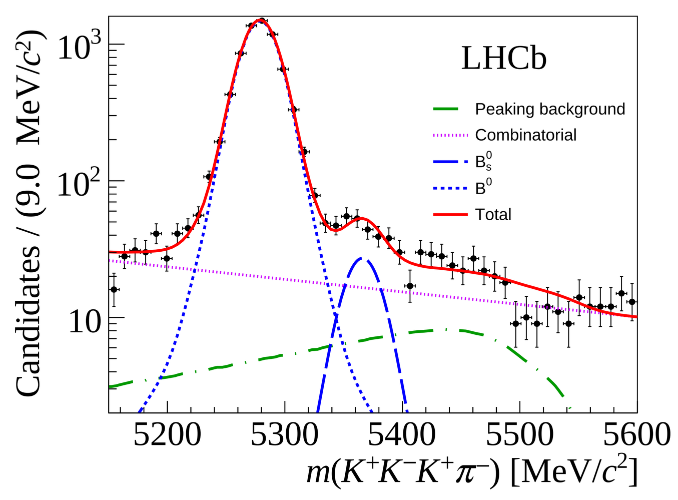
Fit to the $K^+K^-\pi^+\pi^-$ invariant mass spectrum.

- Mass fit to find signal yields of B^0 and $B_s^0 \to \phi\pi\pi$
- Weights calculated using the sPlot technique [12].
- B^0 peak contains 120 ± 17 events
- $B^0 \to \phi\pi\pi$ **is observed with a significance of 6σ.**
- B_s^0 peak contains 695 ± 30 events
- $B_s^0 \to \phi\pi\pi$ **is observed with a significance of 20σ.**
- **First observation** of these modes.
- NB: quoted significances do not account for systematics.

$B_s^0 \to \phi\phi$ Branching Fraction



Fit to the $K^+K^-K^+K^-$ invariant mass spectrum.



Fit to the $K^+K^-K^+\pi^-$ invariant mass spectrum.

$$\frac{\mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(B^0 \to \phi K^*)} = \frac{N_{\phi\phi}}{N_{\phi K^*}} \frac{\varepsilon_{\phi K^*}}{\varepsilon_{\phi\phi}} \frac{\mathcal{B}(K^* \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \frac{f_d}{f_s}$$

- **Mass fits** to extract the signal yields: $N_{\phi\phi} = 2309 \pm 49$ and $N_{\phi K^*} = 6680 \pm 86$.
- **S-wave subtraction** using fractions from previous LHCb analyses [1, 2].
- Efficiencies (ε) calculated using Monte-Carlo and data-driven methods.
- Fragmentation fractions (f) from previous LHCb analyses [3].
- $\mathcal{B}(B^0 \to \phi K^*)$ from average of BaBar and Belle results [4, 5].

$$\mathcal{B}(B_s^0 \to \phi\phi) = (1.84 \pm 0.05(\text{stat}) \pm 0.07(\text{syst}) \pm 0.11(f_s/f_d) \pm 0.12(\text{norm})) \times 10^{-5}$$

- **Statistical uncertainty 5 times smaller** than previous best measurement.
- CDF: $(1.91 \pm 0.26 \pm 0.16) \times 10^{-5}$ [6].
- Overall improvement in relative error: $\pm 9.7\%$ compared to $\pm 16\%$.
- **Dominant systematics:** normalisation ($\pm 6.4\%$), f_s/f_d ($\pm 5.8\%$) and S-wave ($\pm 3.1\%$).

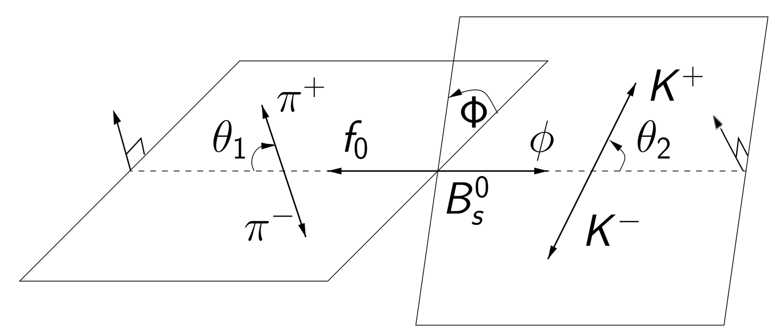
Angular Analysis

An unbinned maximum-likelihood fit is made to $m_{\pi^+\pi^-}$ and decay angles.

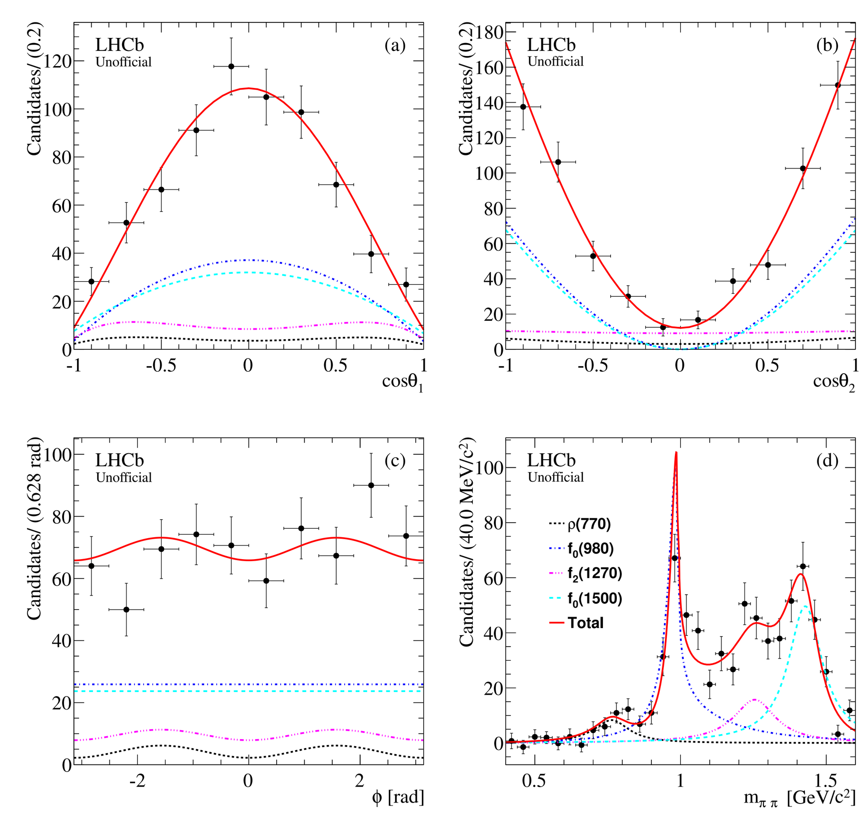
The fit model can be expressed as:

$$\frac{d^4\Gamma}{dm d\Phi d\theta_1 d\theta_2} \propto \sum_i K_i \, \mathcal{M}_i(m) \, f_i(\Phi, \theta_1, \theta_2) \, d\Phi_4$$

- K_i are helicity amplitude terms.
- $\mathcal{M}_i$ are resonance shapes.
- f_i are decay angle distributions.
- $d\Phi_4$ is a phase-space term.



- Decay angles defined in the **helicity basis**.
- Particle momenta reconstructed in the decay frames of their immediate parents.
- Φ is angle between the decay planes.
- θ_1 is between the π^+ and the $\pi^+\pi^-$ parent.
- θ_2 is between the K^+ and the ϕ.



Projections of the fit on $m_{\pi^+\pi^-}$ and the helicity angles.

- Several amplitude fits were tried with different resonant components.
- For the high-mass region, $f_0(1500)$ was favoured over $f_2(1430)$.
- Ambiguity over the presence of the $f_0(1370)$.
- Therefore an exclusive BF is not quoted for the high-mass contribution.
- $B_s^0 \to \phi f_0(980)$ **has a significance of 8σ.**
- $B_s^0 \to \phi f_2(1270)$ **has a significance of 5σ.**
- The significance of $B_s^0 \to \phi\rho^0$ is 4.5σ, therefore an upper limit is set.

- **First observation** of $B_s^0 \to \phi f_0(980)$ and $B_s^0 \to \phi f_2(1270)$

Search for $B^0 \to \phi\phi$

Significance of a B^0 peak in the $\phi\phi$ mass fit is $< 2\sigma$.

A limit is set using the CLs method [7].

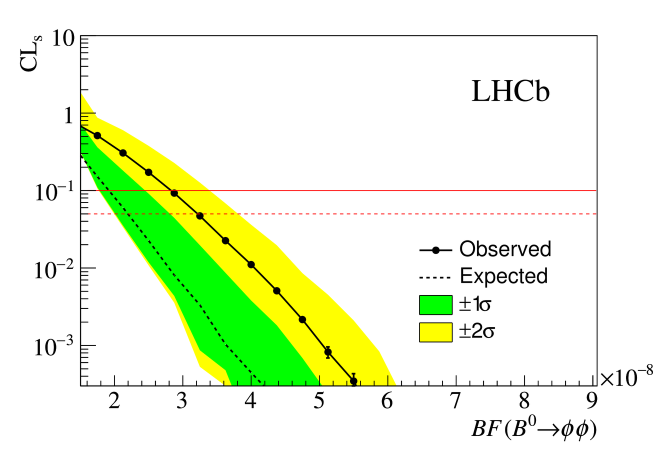
- Fit two PDFs: P_{s+b} (with B^0) and P_b (no B^0).
- Ratio of log-likelihoods (R_L) used as test statistic.

At each point in a scan through $\mathcal{B}(B^0 \to \phi\phi)$:

- Calculate R_L from data fit and from toys generated from P_{s+b} & P_b,
- Take CL_{s+b} and CL_b as fraction of toys with $-2 \ln R_L$ above the value found in data.

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b}$$

- Upper limit at 90% C.L. is where $\text{CL}_s = 0.1$.



Result of CL_s scan. Upper limit at 90% (95%) C.L. is where the black line crosses the solid (dotted) red line.

$$\mathcal{B}(B^0 \to \phi\phi) < 2.8 \times 10^{-8} \text{ (90\% C.L.)}$$

- **7 times tighter** than previous best limit.
- BaBar: 2.0×10^{-7} (90% C.L.) [8].
- SM predictions: $(0.1 \text{ to } 3) \times 10^{-8}$ [9, 10, 11].

$B_{(s)}^0 \to \phi\pi^+\pi^-$ Branching Fractions

$$\frac{\mathcal{B}(B^0 \to \phi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \phi\phi)} = \frac{N_{\phi\pi\pi}}{N_{\phi\phi}} \frac{\varepsilon_{\phi\phi}}{\varepsilon_{\phi\pi\pi}} \mathcal{B}(\phi \to K^+K^-) \frac{f_s}{f_d}$$

$$\frac{\mathcal{B}(B_s^0 \to \phi X \to \phi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \phi\phi)} = \frac{N_{\phi X}}{N_{\phi\phi}} \frac{\varepsilon_{\phi\phi}}{\varepsilon_{\phi\pi\pi}} \mathcal{B}(\phi \to K^+K^-)$$

Inclusive BFs in the range $0.4 < m_{\pi^+\pi^-} < 1.6$ GeV are measured to be:

$$\mathcal{B}(B^0 \to \phi\pi^+\pi^-) = (1.58 \pm 0.18(\text{stat}) \pm 0.35(\text{syst}) \pm 0.13(\text{norm})) \times 10^{-7}$$

$$\mathcal{B}(B_s^0 \to \phi\pi^+\pi^-) = (3.37 \pm 0.20(\text{stat}) \pm 0.16(\text{syst}) \pm 0.34(\text{norm})) \times 10^{-6}$$

Exclusive BFs are measured to be

$$\mathcal{B}(B_s^0 \to \phi f_0(980) \to \phi\pi^+\pi^-) = (1.12 \pm 0.16(\text{stat})^{+0.07}_{-0.14}(\text{syst}) \pm 0.11(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(B_s^0 \to \phi f_2(1270) \to \phi\pi^+\pi^-) = (0.55 \pm 0.10(\text{stat})^{+0.18}_{-0.05}(\text{syst}) \pm 0.06(\text{norm})) \times 10^{-6}$$

$$\mathcal{B}(B_s^0 \to \phi\rho^0) < 4 \times 10^{-7} \text{ (90\% C.L.)}$$

References

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