Charmless B decays at LHCb

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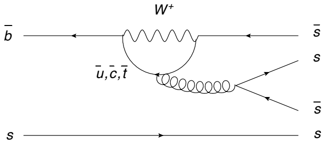
Outline

1. $B^0_{(s)} \to \phi\phi$ branching ratio
   - JHEP 10 (2015) 053
2. First observation of $B^0_s \to \eta'\eta'$
   - Phys. Rev. Lett. **115** (2015) 051801
3. First observation of $B^0 \to \rho^0\rho^0$
   - Phys. Lett **B747** (2015) 468
4. Summary

Introduction

Why charmless B decays?

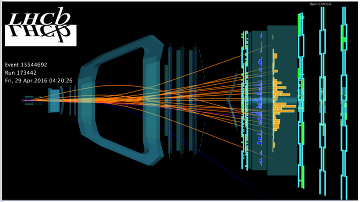
- $|V_{ub}|$ is small: significant loop contributions
- FCNC: forbidden at tree level
- Sensitive to contributions beyond the SM



Why LHCb?

- Full spectrum of B hadrons: B^0, B^0_s, B^+, B^+_c, Λ^0_b, etc.
- Very large production x-section

  $75.3 \pm 5.4 \pm 13$ μb @ 7 TeV (Phys. Lett. **B694** (2010) 209)
- Excellent trigger, tracking and PID



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Motivation: $B^0_{(s)} \to \phi\phi$ branching fraction

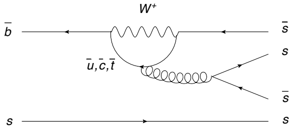
Measurement of the $B^0_s \to \phi\phi$ branching fraction

- Key decay for *CP* violation studies
- Important normalisation mode
- Theoretical predictions $1.5 - 2.0 \times 10^{-5}$
- Previous measurement: $1.91 \pm 0.31 \times 10^{-5}$ (CDF: PRL **95** (2005) 031801)

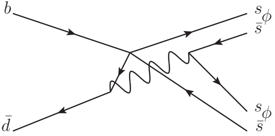
Search for $B^0 \to \phi\phi$ decays

- Highly suppressed in the SM
- SM predictions $1 - 30 \times 10^{-9}$
- Could be enhanced in BSM models 10^{-7}
- Previous limit: $< 2.0 \times 10^{-7}$ (Belle: PRL **101** (2008) 201801)

$B^0_s \to \phi\phi$ diagram



$B^0 \to \phi\phi$ diagram



$B^0_{(s)} \to \phi\phi$ measurement overview (3 fb^{-1} Run 1 data)

The $B^0_s \to \phi\phi$ branching fraction is determined w.r.t. $B^0 \to \phi K^{*0}$

$$\frac{\mathcal{B}(B^0_s \to \phi\phi)}{\mathcal{B}(B^0 \to \phi K^{*0})} = \frac{N_{\phi\phi}}{N_{\phi K^{*0}}} \frac{\varepsilon^{sel}_{\phi K^{*0}}}{\varepsilon^{sel}_{\phi\phi}} \frac{\mathcal{B}(\phi \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \cdot \frac{f_d}{f_s}$$

- Efficiencies determined from MC, apart from PID determined from charm decays
- f_s/f_d hadronisation probability to B^0_s/B^0 mesons

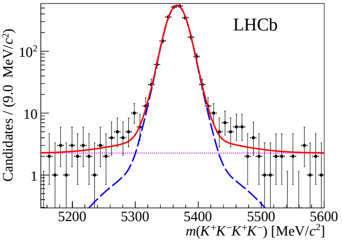
- Selection: trigger, pre-selection, boosted decision tree, particle ID
- Vetoes against $\phi\phi \leftrightarrow \phi K^{*0}$ cross feed and D^+ and D^+_s decays

Fits to the $B^0_s \to \phi\phi$ and $B^0 \to \phi K^{*0}$ mass spectra

BDT cut optimised to maximise the $B^0 \to \phi K^{*0}$ significance

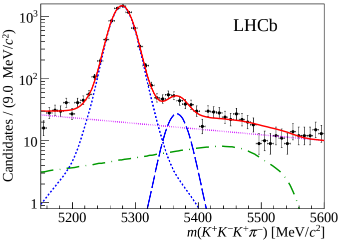
Fit to the $K^+K^-K^+K^-$ spectrum

- Only $B^0_s \to \phi\phi$ and combinatorial
- $N_{B^0_s \to \phi\phi} = 2349 \pm 49$ candidates



Fit to the $K^+K^-K^+\pi^-$ spectrum

- $B^0_{(s)} \to \phi K^{*0}$ signal peaks
- Combinatorial plus $\Lambda^0_b \to \phi p\pi^-$ and $\Lambda^0_b \to \phi pK^-$ peaking backgrounds
- $N_{B^0 \to \phi K^{*0}} = 6680 \pm 86$ candidates



$B^0_s \to \phi\phi$ branching ratio determination

Non-resonant contributions (from angular analysis)

- $B^0_s \to \phi\phi$ S-wave: $2.1 \pm 1.6\%$
- $B^0 \to \phi K^{*0}$ S-wave: $26.5 \pm 1.8\%$
- Corrected for, but dominant systematic uncertainty

Final result

$$\frac{\mathcal{B}(B^0_s \to \phi\phi)}{\mathcal{B}(B^0 \to \phi K^{*0})} = 1.84 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.11\,(f_s/f_d)$$

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

Consistent with previous measurement and $\sim \times 2$ more precise

$B^0 \to \phi\phi$ limit setting

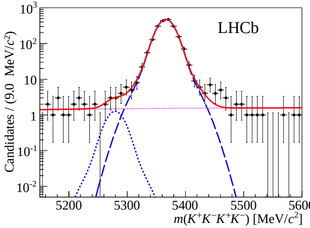
Tighter selection, maximising FoM $= \frac{\varepsilon'_S}{3/2+\sqrt{N'_{bg}}}$

- ε'_S: BDT selection efficiency
- N'_{bg}: estimated background yield
- Signal Yield compatible with zero
  $N_{B^0\to\phi\phi} = 5 \pm 6$ candidates
- Limit set with frequentist approach
  $CL_s = CL_{s+b}/CL_b$

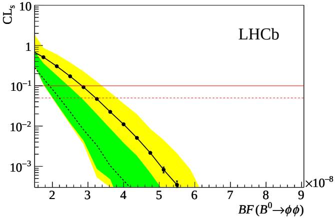
Result: $\mathcal{B}(B^0 \to \phi\phi) < 2.8 \times 10^{-8}$ @ 90%

Seven times better than previous limit and excluding some BSM predictions.

Fit to the $K^+K^-K^+K^-$ spectrum
$B^0_{(s)} \to \phi\phi$ and combinatorial



Expected and measured limit of $B^0 \to \phi\phi$



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4. Summary

Motivation: $B^0_s \to \eta'\eta'$, $B^+ \to \eta' K^+$ & $B^+ \to \phi K^+$

Search for the $B^0_s \to \eta'\eta'$ decay

- Charmless B^0_s decays less studied than B^0 and B^+ decays
- U-spin related decays ($B^+ \to \eta' K^+$ & $B^+ \to \phi K^+$) have large $\mathcal{B}$
- Theoretical predictions $\mathcal{B} \sim 1.4 - 5.0 \times 10^{-5}$
- *CP* eigenstate – time dependent CPV studies similar to $B^0_s \to \phi\phi$

CP asymmetry of $B^+ \to \eta' K^+$ and $B^+ \to \phi K^+$ decays

- Predicted to have negligible *CP* violation in the SM
- Tree and loop diagrams of comparable size
  - Sensitive to BSM contributions
  - BaBar, Belle, CLEO: $\mathcal{A}^{CP}(B^+ \to \eta' K^+) = 0.013 \pm 0.017$
  - LHCb: $\mathcal{A}^{CP}(B^+ \to \phi K^+) = 0.022 \pm 0.023$
    BaBar: $\mathcal{A}^{CP}(B^+ \to \phi K^+) = 0.128 \pm 0.046$

$B^0_s \to \eta'\eta'$ selection and fit (3 fb^{-1} Run 1 data)

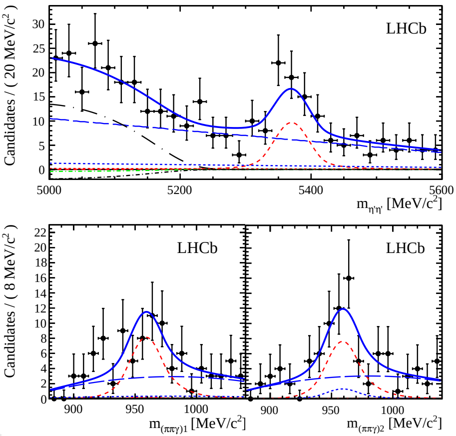
Reconstruction & selection

- Reconstruct decays of $\eta' \to \pi^+\pi^-\gamma$
- Selection with rectangular cuts
- Maximise FoM $= \frac{\varepsilon_S}{5/2+\sqrt{N_{bg}}}$

Fit to the η' η' spectrum

- B^0_s and η' signal peaks
- Combinatorial and partially reconstructed backgrounds

$N_{B^0_s \to \eta'\eta'} = 36.4 \pm 7.8\,(\mathrm{stat}) \pm 1.6\,(\mathrm{syst})$



Signal significance: 6.4 σ

$B^0_s \to \eta'\eta'$ branching ratio determination

$B^+ \to \eta' K^+$ normalisation channel

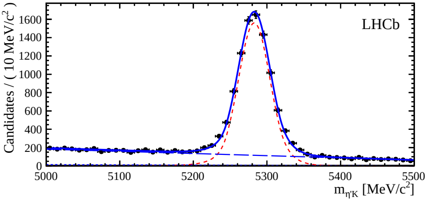
- Reconstruction & selection near identical to $B^0_s \to \eta'\eta'$

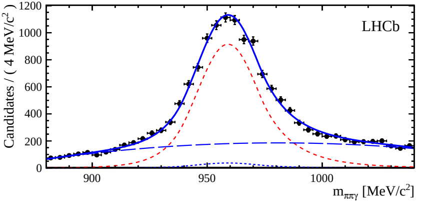
$N_{B^+\to\eta' K^+} = 8672 \pm 114\,(\text{stat})$

Relative efficiency: $\frac{B^0_s\to\eta'\eta'}{B^+\to\eta' K^+}$

- Particle ID, photon & H/W trigger determined from data
- Remaining efficiencies from MC

Signal and combinatorial background





$$\frac{\mathcal{B}(B^0_s\to\eta'\eta')}{\mathcal{B}(B^+\to\eta' K^+)} = 0.47 \pm 0.09\,(\text{stat}) \pm 0.04\,(\text{syst})$$

$$\mathcal{B}(B^0_s \to \eta'\eta') = (3.31 \pm 0.64\,(\text{stat}) \pm 0.28\,(\text{syst}) \pm 0.12\,(\text{norm})) \times 10^{-5}$$

CP asymmetries of $B^+ \to \eta' K^+$ & $B^+ \to \phi K^+$

Raw asymmetries ($\mathcal{A}_{raw}$) from fits

- For small asymmetries: $\mathcal{A}_{raw} = \mathcal{A}^{CP} + \mathcal{A}_{D,k} + \mathcal{A}_P$
- $\mathcal{A}_{D,k} + \mathcal{A}_P$ is identical to that of $B^+ \to J/\psi K^+$

Measure the difference in asymmetry

$$\mathcal{A}^{CP}(\text{signal}) - \mathcal{A}^{CP}(B^+ \to J/\psi K^+) = \mathcal{A}_{\text{raw}}(\text{signal}) - \mathcal{A}_{\text{raw}}(B^+ \to J/\psi K^+)$$

Adding the control mode asymmetry ($\mathcal{A}^{CP}(B^+ \to J/\psi K^+)$)

$$\mathcal{A}^{CP}(B^+ \to \eta' K^+) = (-0.2 \pm 1.2\,(\text{stat}) \pm 0.1\,(\text{syst}) \pm 0.6\,(\text{norm})) \times 10^{-2}$$
$$\mathcal{A}^{CP}(B^+ \to \phi K^+) = (+1.7 \pm 1.1\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.6\,(\text{norm})) \times 10^{-2}$$

Most precise results to date and compatible with *CP* conservation

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4. Summary

Motivation: Amplitude analysis of $B^0 \to \rho^0\rho^0$

Used in measurement of CKM angle α

- Combined analysis of $B^0 \to \rho^+\rho^-$, $B^+ \to \rho^+\rho^0$ and $B^0 \to \rho^0\rho^0$
  - Measures $\beta + \gamma = \pi - \alpha$
- LHCb ideal place to measure $B^0 \to \rho^0\rho^0$

Experimental status

- Belle and BaBar found evidence for $B^0 \to \rho^0\rho^0$
- $\mathcal{B} = (0.97 \pm 0.24) \times 10^{-6}$ (Phys. Rev. D **89** (2014) 119903, Phys. Rev. D **78** (2008) 071104)
- Tension between measured values of the longitudinal polarisation
  - Belle $f_L = 0.21^{+0.22}_{-0.26}$
  - BaBar $f_L = 0.75^{+0.12}_{-0.15}$

$B^0 \to \rho^0\rho^0$ measurment overview (3 fb^{-1} Run 1 data)

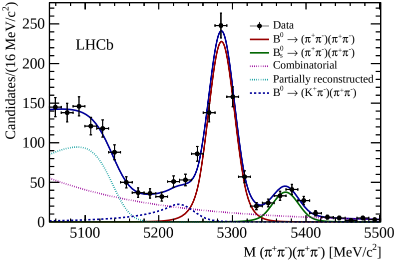
Selection of $B^0 \to \pi^+\pi^-\pi^+\pi^-$

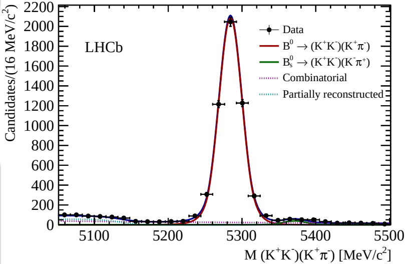
- Combine two $\pi^+\pi^-$ pairs consistent with B^0 decays
- Pre-selection, BDT and particle ID
- Vetoes against J/ψ, χ_{c0}, χ_{c2} and D^0 two-body decays and the low mass region of three-body combinations

$N_{B^0 \to \pi^+\pi^-\pi^+\pi^-} = 634 \pm 29$
$N_{B^0_s \to \pi^+\pi^-\pi^+\pi^-} = 101 \pm 13$
$B^0_s \to \pi^+\pi^-\pi^+\pi^-$ significance: $> 10\ \sigma$

Normalisation channel: $B^0 \to \phi K^{*0}$

- Resonant fraction determined from angular analysis





Amplitude model for the $B^0 \to \pi^+\pi^-\pi^+\pi^-$ decays

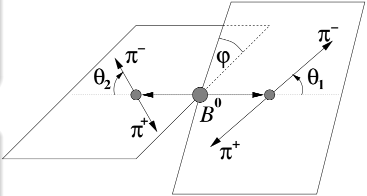
Amplitude variables

- Invariant mass $m_{1,2}(\pi^+\pi^-)$ and angles $\theta_{1,2}$ and ϕ
- Extracted with *sPlot* technique

Main components

- $B^0 \to VV$: $B^0 \to \rho^0\rho^0$ & $B^0 \to \rho^0\omega$
- $B^0 \to VS$: $B^0 \to \rho^0 f_0(980)$ & ρ^0 + $(\pi^+\pi^-)_0$
- $B^0 \to VT$: $B^0 \to \rho^0 f_2(1270)$
- Contamination from $B^0 \to a_1^{\pm}\pi^{\pm}$

Definition of angles



Differential decay rate

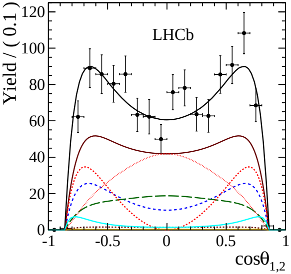
$$\frac{d^5(\Gamma + \bar{\Gamma})}{d\cos\theta_1\, d\cos\theta_2\, d\varphi\, dm_1^2\, dm_2^2}$$

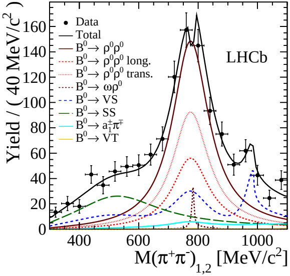
Results of the amplitude analyssis

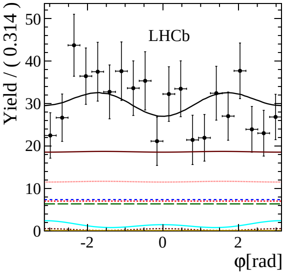
Fit results

Fraction of $B^0 \to \rho^0\rho^0$:
$P(B^0 \to \rho^0\rho^0) = 0.619 \pm 0.072\,(\text{stat}) \pm 0.049\,(\text{syst})$

Longitudinal polarisation:
$f_L = 0.745^{+0.048}_{-0.058}\,(\text{stat}) \pm 0.034\,(\text{syst})$







Branching ration determination

Efficiency corrections

- Integrated across the phase space, taking amplitude model into account
- Accounting for MC and data differences

Final result

Approximately 390 $B^0 \to \rho^0\rho^0$ candidates observed

Signal significance 7.1 σ

$$\frac{\mathcal{B}(B^0 \to \rho^0\rho^0)}{\mathcal{B}(B^0 \to \phi K^{*0})} = 0.094 \pm 0.017\,(\text{stat}) \pm 0.009\,(\text{syst})$$

$$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.06\,(\text{norm})) \times 10^{-6}$$

No evidence found for $B^0 \to \rho^0 f_0(980)$

Consistent with previous measurement and $\sim \times 12$ more precise

Summary

1. $B^0_{(s)} \to \phi\phi$ branching ratio
   - Key decay mode for CPV studies
   - $\mathcal{B}(B^0_s \to \phi\phi) = (1.84 \pm 0.18) \times 10^{-5}$
   - $\mathcal{B}(B^0 \to \phi\phi) < 2.8 \times 10^{-8}$ @ 90%

2. First observation of $B^0_s \to \eta'\eta'$ (6.4σ)
   - First step towards CPV studies of $B^0_s \to \eta'\eta'$
   - $\mathcal{B}(B^0_s \to \eta'\eta') = (3.31 \pm 0.71) \times 10^{-5}$
   - $\mathcal{A}^{CP}(B^+ \to \eta' K^+) = (-0.2 \pm 1.3) \times 10^{-2}$
   - $\mathcal{A}^{CP}(B^+ \to \phi K^+) = (+1.7 \pm 1.3) \times 10^{-2}$

3. First observation of $B^0 \to \rho^0\rho^0$ (7.1σ)
   - Used for measuring CKM angle α
   - $\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.20) \times 10^{-6}$
   - Longitudinal polarisation $f_L = 0.745^{+0.059}_{-0.067}$