Angular analyses of B meson decays to two vector mesons

H.Luo – University of Edinburgh
On behalf of the LHCb Collaboration

Les Rencontres de Physique de la Valleé d'Aoste

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Introduction

- Charmless b-hadron decays:

  1. Amplitude analysis of $B^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ decays: LHCb-PAPER-2015-006 (to be published soon)

  2. CP asymmetries and polarisation fractions in $B_s^0 \to K^{*0}\overline{K}^{*0}$ decays: LHCb-PAPER-2014-068 (to be published soon)

Amplitude analysis of $B^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ decays and first observation of $B^0 \to \rho^0\rho^0$

Based on full RunI dataset, $3\,\text{fb}^{-1}$
LHCb-PAPER-2015-006

Motivations

- $B^0 \to \rho\rho$ decays provide powerful constraint to the CKM angle α
- Babar and Belle found evidence for the colour-suppressed $B^0 \to \rho^0(\pi^+\pi^-)\rho^0(\pi^+\pi^-)$ decay
- Large longitudinal polarization fraction (f_L) difference in the BaBar and Belle experiments due to signal size

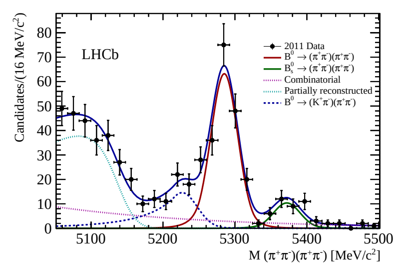
Aims

Measure the branching ratio with respect to $B_d^0 \to \phi K^*(892)$
Determine the longitudinal polarization fraction:

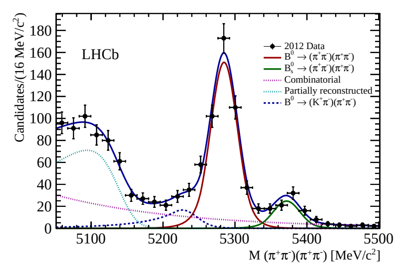
$$f_L = \frac{|A^0_{\rho\rho}|^2}{|A^0_{\rho\rho}|^2 + |A^{\parallel}_{\rho\rho}|^2 + |A^{\perp}_{\rho\rho}|^2}$$

Analysis

- Simultaneous fit to the $B^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ final state for the 2011 and 2012 data sets
- Signal yields are $185 \pm 15 \pm 4$ and $449 \pm 24 \pm 7$ respectively
- *sPlot* technique is used to statistically subtract the background

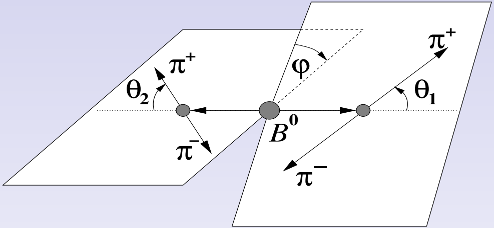


2011



2012

Angular analysis



- A rich resonance structure, ρ^0, ω, $f_0(980)$ and $f_2(1270)$, contribute to the $B^0 \to (\pi^+\pi^-)(\pi^-\pi^+)$ decay
- $B^0 \to \rho^0(\pi^+\pi^-)\rho^0(\pi^+\pi^-)$ $(P \to VV)$ needs angular analysis to disentangle the helicity structure
- The differential decay rate includes $\rho\rho$, $\rho\omega$, $\rho(\pi\pi)$, $\rho f(980)$, $(\pi\pi)(\pi\pi)$, ρf_2 and $a_1\pi$, 11 terms in total

results

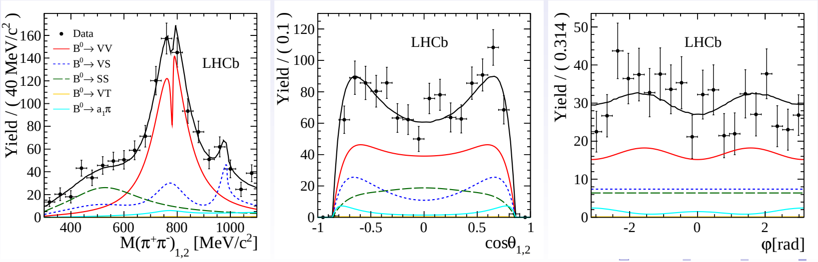
- The $B^0 \to \rho^0(\pi^+\pi^-)\rho^0(\pi^+\pi^-)$ decay longitudinal fraction is measured to be consistent with Babar results $(0.75^{+0.12}_{-0.15})$:

$$f_L = \frac{|A^0_{\rho\rho}|^2}{|A^0_{\rho\rho}|^2 + |A^{\parallel}_{\rho\rho}|^2 + |A^{\perp}_{\rho\rho}|^2} = 0.745^{+0.048}_{-0.058} \pm 0.033$$

- The BR of the $B^0 \to \rho^0(\pi^+\pi^-)\rho^0(\pi^+\pi^-)$ decay and upper limit of the $B^0 \to \rho f_0(980)$ decay are measured to be:

$$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17 \pm 0.08 \pm 0.06(B^0_d \to \phi K^*(892))) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to \rho f_0(980)) \times (f_0(980) \to \pi^+\pi^-) < 0.76 \times 10^{-6}$$



Measurement of CP asymmetries and polarisation fractions in $B_s^0 \to K^{*0}\bar{K}^{*0}$ decays

Based on $1\,\mathrm{fb}^{-1}$ dataset

LHCb-PAPER-2014-068

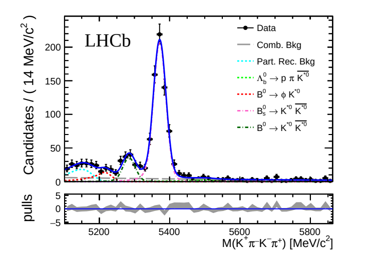
Motivations

- It is sensitive to physics beyond the SM via the appearance of unexpected angular distributions or CP violating phases
- Previous analysis (35pb^{-1}) show lower longitudinal polarisation fraction than the QCD prediction

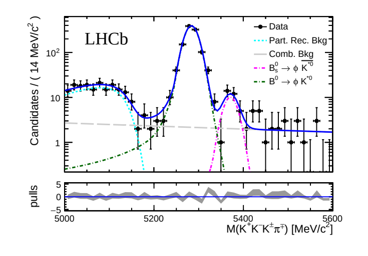
Aims

Measure the Triple Product Asymmetries (TPA)
Determine the polarisation fractions for the vector mode
Measure the $B_s^0 \to K^{*0}\bar{K}^{*0}$ branching ratio with respect to the $B_d^0 \to \phi K^*(892)$ decay

Analysis



$B_s^0 \to K^+\pi^-K^-\pi^+$



$B_d^0 \to \phi K^*(892)$

- A total of 697 ± 31 $B_s^0 \to K^+\pi^-K^-\pi^+$ events is obtained
- Similar selection cuts obtain a signal yields of 1049 ± 33 $B_d^0 \to \phi K^*(892)$ events
- With angular analysis, the $B_s^0 \to K^{*0}\bar{K}^{*0}$ branching fraction is measured to be:

$$\mathcal{B}(B_s^0 \to K^{*0}\bar{K}^{*0}) =$$
$$(10.5 \pm 1.8 \pm 1.1 \pm 0.6(f_d/f_s)) \times 10^{-6}$$

- Main systematic uncertainties are from the trigger efficiency and branching ratio error of the reference decay

TP asymmetries

- Using the events within a $\pm 30\mathrm{MeV}/c^2$ of the nominal B_s^0 mass and upper mass sideband events as background, the results are

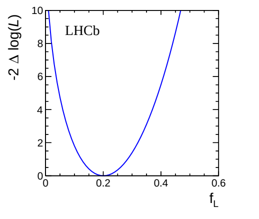
Asymmetry	Value	Asymmetry	Value
A_T^1	$0.003 \pm 0.041 \pm 0.009$	A_D^1	$-0.061 \pm 0.041 \pm 0.012$
A_T^2	$0.009 \pm 0.041 \pm 0.009$	A_D^2	$0.081 \pm 0.041 \pm 0.008$
A_T^3	$0.019 \pm 0.041 \pm 0.008$	A_D^3	$-0.079 \pm 0.041 \pm 0.023$
A_T^4	$-0.040 \pm 0.041 \pm 0.008$	A_D^4	$-0.081 \pm 0.041 \pm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

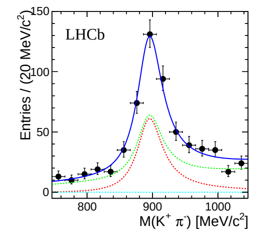
$A^i_{T,D}$ are asymmetry quantities related to the CP-odd amplitude $A_\perp$ and A_s^+, meaning of the asymmetries are in backup

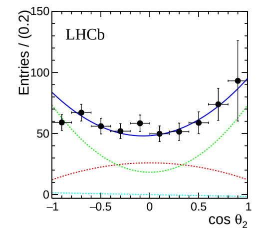
- TPA derived from the the angular distribution of the signal events is measured to be consistent with zero
- Main systematic uncertainty is associated to the angular acceptance correction

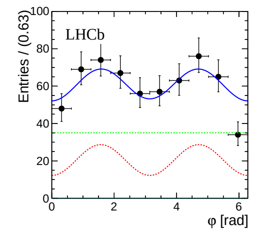
Angular analysis

- Similar helicity basis as the $B^0 \to \rho^0\rho^0$ decay
- The differential decay rate includes $K^{*0}\bar{K}^{*0}$, $K^{*0}K\pi$ and $(K\pi)(K\pi)$
- Measured longitudinal and parallel fractions are $0.201 \pm 0.057 \pm 0.040$ and $0.215 \pm 0.046 \pm 0.015$







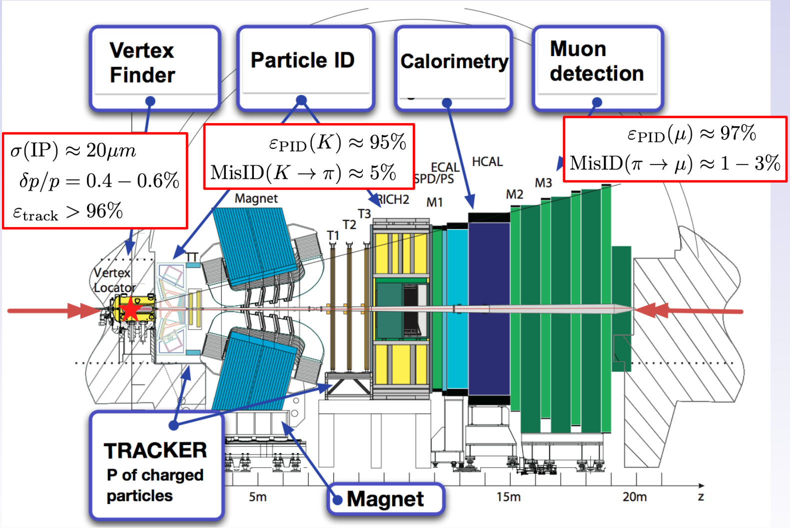


Conclusion

- **First observation** of the $B^0 \to \rho^0\rho^0$ decay, branching ratio is $\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17 \pm 0.08 \pm 0.06(B_d^0 \to \phi K^*(892))) \times 10^{-6}$
- **Large** longitudinal polarisation fraction in the $B^0 \to \rho^0\rho^0$ decay is consistent with the BaBar collaboration $(0.745^{+0.048}_{-0.058} \pm 0.033)$
- An upper limit at 90% confidence level of the $B^0 \to \rho f_0(980)$ is set to 0.76×10^{-6}
- TPA of the $B_s^0 \to K^{*0}\bar{K}^{*0}$ decay is **zero**, compatible with SM prediction
- **Low** longitudinal polarisation of this decay is confirmed
- Branching ratio of the $B_s^0 \to K^{*0}\bar{K}^{*0}$ is measured to be $(10.5 \pm 1.8 \pm 1.1 \pm 0.6(f_d/f_s)) \times 10^{-6}$

Back Up

LHCb detector



Differential decay rate

- Differential decay rate of the $B^0 \to (\pi^+\pi^-)(\pi^-\pi^+)$ decay:

$$d^5\Gamma = \frac{9}{8\pi}\left|\sum_{i=1}^{11} A_i f_i(m_1, m_2, \theta_1, \theta_2, \psi)\right|^2 d\Phi_4(m_1, m_2)$$

where A_i are complex amplitudes, $f_i(m_1, m_2, \theta_1, \theta_2, \psi)$ are the mass-angle distributions

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

TP and direct CP asymmetries

$$
\begin{aligned}
A_T^1 &= \frac{2\sqrt{2}}{\pi}\frac{1}{D}\int \Im(\mathcal{A}_\perp \mathcal{A}_0^*)\,\mathrm{d}t, \\
A_T^2 &= -\frac{4}{\pi}\frac{1}{D}\int \Im(\mathcal{A}_\perp \mathcal{A}_\parallel^*)\,\mathrm{d}t \\
A_T^3 &\equiv \frac{\Gamma((\cos\theta_1+\cos\theta_2)\sin\varphi>0)-\Gamma((\cos\theta_1+\cos\theta_2)\sin\varphi<0)}{\Gamma((\cos\theta_1+\cos\theta_2)\sin\varphi>0)+\Gamma((\cos\theta_1+\cos\theta_2)\sin\varphi<0)} \\
&= \frac{32}{5\pi\sqrt{3}}\frac{1}{\mathcal{D}}\int \Im\left(\left(\mathcal{A}_\perp \mathcal{A}_s^{-*} - \bar{\mathcal{A}}_\perp \bar{\mathcal{A}}_s^{-*}\right)\mathcal{M}_1(m)\mathcal{M}_0^*(m)\right)\mathrm{d}m \\
A_T^4 &\equiv \frac{\Gamma(\sin\varphi>0)-\Gamma(\sin\varphi<0)}{\Gamma(\sin\varphi>0)+\Gamma(\sin\varphi<0)} \\
&= \frac{3\pi}{4\sqrt{2}}\frac{1}{\mathcal{D}}\int \Im\left(\left(\mathcal{A}_\perp \mathcal{A}_{ss}^{*} - \bar{\mathcal{A}}_\perp \bar{\mathcal{A}}_{ss}^{*}\right)\mathcal{M}_1(m)\mathcal{M}_0^*(m)\right)\mathrm{d}m
\end{aligned}
$$

TP and direct CP asymmetries

$$A_D^{(1)} \equiv \frac{\Gamma(\cos\theta_1\cos\theta_2(\cos\theta_1-\cos\theta_2)>0)-\Gamma(\cos\theta_1\cos\theta_2(\cos\theta_1-\cos\theta_2)<0)}{\Gamma(\cos\theta_1\cos\theta_2(\cos\theta_1-\cos\theta_2)>0)+\Gamma(\cos\theta_1\cos\theta_2(\cos\theta_1-\cos\theta_2)<0)}$$

$$= \frac{\sqrt{2}}{5\sqrt{3}}\frac{1}{\mathcal{D}}\left[9\int \Re\left((\mathcal{A}_s^+\mathcal{A}_0^* - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_0^*)\mathcal{M}_0(m)\mathcal{M}_1^*(m)\right)\mathrm{d}m + 5\int \Re\left((\mathcal{A}_s^+\mathcal{A}_{ss}^* - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_{ss}^*)\mathcal{M}_1(m)\mathcal{M}_0^*(m)\right)\mathrm{d}m\right]$$

$$A_D^{(2)} \equiv \frac{\Gamma((\cos\theta_1-\cos\theta_2)\cos\varphi>0)-\Gamma((\cos\theta_1-\cos\theta_2)\cos\varphi<0)}{\Gamma((\cos\theta_1-\cos\theta_2)\cos\varphi>0)+\Gamma((\cos\theta_1-\cos\theta_2)\cos\varphi<0)}$$

$$= -\frac{32}{5\pi\sqrt{3}}\frac{1}{\mathcal{D}}\int \Re\left((\mathcal{A}_s^+\mathcal{A}_\parallel^* - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_\parallel^*)\mathcal{M}_0(m)\mathcal{M}_1^*(m)\right)\mathrm{d}m$$

$$A_D^{(3)} \equiv \frac{\Gamma((\cos\theta_1-\cos\theta_2)>0)-\Gamma((\cos\theta_1-\cos\theta_2)<0)}{\Gamma((\cos\theta_1-\cos\theta_2)>0)+\Gamma((\cos\theta_1-\cos\theta_2)<0)}$$

$$= \frac{2\sqrt{2}}{5\sqrt{3}}\frac{1}{\mathcal{D}}\left[3\int \Re\left((\mathcal{A}_s^+\mathcal{A}_0^* - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_0^*)\mathcal{M}_0(m)\mathcal{M}_1^*(m)\right)\mathrm{d}m + 5\int \Re\left((\mathcal{A}_s^+\mathcal{A}_{ss}^* - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_{ss}^*)\mathcal{M}_1(m)\mathcal{M}_0^*(m)\right)\mathrm{d}m\right]$$

$$A_D^{(4)} \equiv \frac{\Gamma((\cos^2\theta_1-\cos^2\theta_2)>0)-\Gamma((\cos^2\theta_1-\cos^2\theta_2)<0)}{\Gamma((\cos^2\theta_1-\cos^2\theta_2)>0)+\Gamma((\cos^2\theta_1-\cos^2\theta_2)<0)}$$

$$= \frac{1}{\mathcal{D}}\Re\left(\mathcal{A}_s^+\mathcal{A}_s^{-*} - \bar{\mathcal{A}}_s^+\bar{\mathcal{A}}_s^{-*}\right)$$