Time Integrated Analysis of $B_s^0 \to \phi\phi$ at LHCb

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on behalf of the LHCb Collaboration

Rencontres de Moriond 2012

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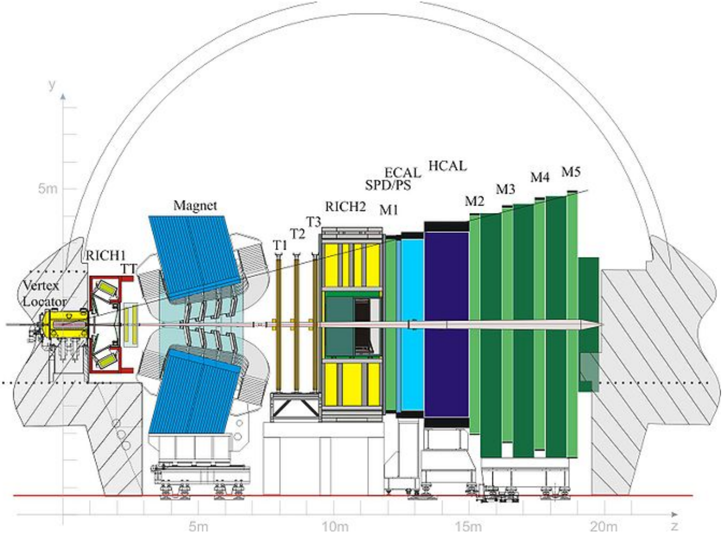
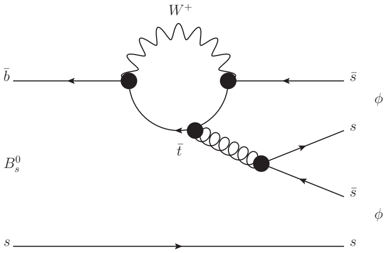
- Triple Product Asymmetries

LHCb Detector



Motivation

- The decay $B_s^0 \to \phi\phi$ proceeds via a Flavour Changing Neutral Current (FCNC) process.
- FCNCs or B flavour mixing allow possible new physics contributions in loop diagrams.
- $\mathcal{CP}$ violating phase $\Phi_s^{\phi\phi}$ accessible, larger dataset needed.
- Using smaller dataset can measure T-violating "triple products", which do not rely on flavour tagging/time.



Data Sample

Analysis presented uses entire dataset collected by LHCb during 2011, 1.0fb^{-1}.
Reconstruct as $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$.

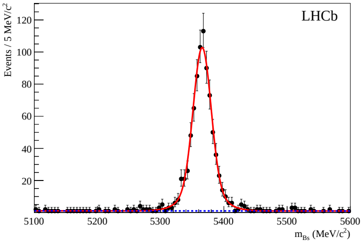
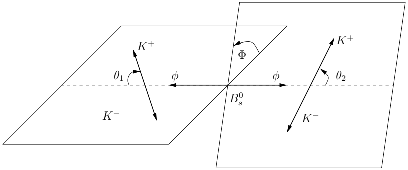


Figure: B_s^0 mass distribution after full offline selection. Fits to a double Gaussian signal(red) and exponential background(blue dotted) are superimposed.

801 ± 29 events observed.
LHCb-Paper-2012-04

Angular Analysis



- P$\rightarrow$VV decay, spin 0 B meson decays to two particles of spin 1.
- Therefore there are 3 possible spin configurations allowed by conservation of orbital angular momentum.
- These correspond to 3 linear polarisation amplitudes, $|A_0|, |A_\perp|, |A_{||}|$.

“Polarisation Puzzle”

- Due to V-A nature of the weak interaction, $f_L \gg f_T$.
- Experimentally confirmed by the B-factories in tree dominated processes e.g. $B_d^0 \to \rho^+\rho^-$.
- However in decays such as $B_d^0 \to \phi K^*(892)$ it was found $f_L \approx f_T$.
- This is sometimes known as the “polarisation puzzle.”

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}, f_T = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2}.$$

Angular Analysis Results

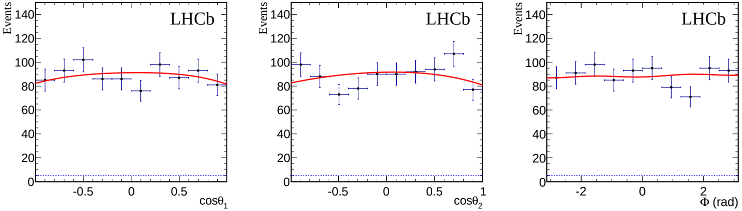
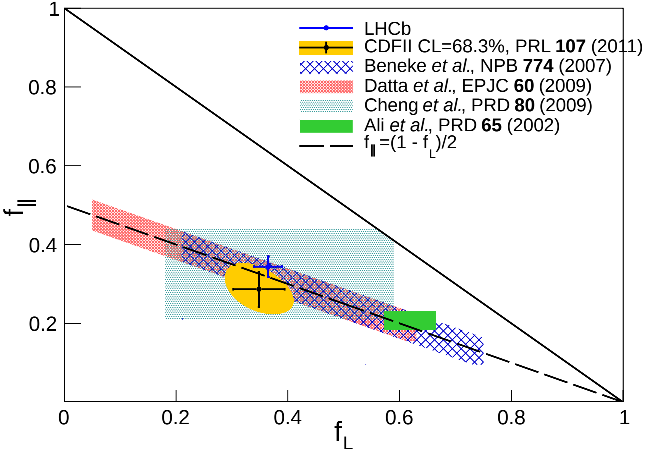


Figure: Angular distributions(points) and fit projections for signal(red) and background(blue).

The polarisation amplitudes and strong phase are measured, using the constraint $|A_{||}|^2 = 1 - |A_0|^2 - |A_\perp|^2$.

$$
\begin{array}{lcllll}
|A_0|^2 & = & 0.365 & \pm 0.022\,(\text{stat}) & \pm 0.012 & (\text{syst}) \\
|A_\perp|^2 & = & 0.291 & \pm 0.024\,(\text{stat}) & \pm 0.010 & (\text{syst}) \\
|A_{||}|^2 & = & 0.344 & \pm 0.024\,(\text{stat}) & \pm 0.014 & (\text{syst}) \\
\cos(\delta_{||} - \delta_0) & = & \text{-}0.844 & \pm 0.068\,(\text{stat}) & \pm 0.029 & .\,(\text{syst})
\end{array}
$$

Angular Analysis Comparison



[1] http://www-cdf.fnal.gov/physics/new/bottom/110331.blessed-BsphiphiCPV/

Triple Product Asymmetries

- Scalar triple products of three momentum (e.g. $sin\psi = \vec{p_1} \cdot \vec{p_2} \times \vec{p_3}$) or spin vectors are odd under time reversal.
- **Non-zero** triple product asymmetries can either be due to a T-violating phase or a T-conserving phase and final-state interactions.
- The former case implies, assuming $\mathcal{CPT}$ conservation, that $\mathcal{CP}$ is violated.

We define our triple products as:

$$U = \sin(2\Phi)$$
$$V = \sin(\pm\Phi)$$
$$A_u \equiv \frac{\Gamma(U>0) - \Gamma(U<0)}{\Gamma(U>0) + \Gamma(U<0)}.$$
$$A_v \equiv \frac{\Gamma(V>0) - \Gamma(V<0)}{\Gamma(V>0) + \Gamma(V<0)}.$$

Where positive sign in $\sin(\pm\Phi)$ is taken if $\cos\theta_1 \cos\theta_2 \geq 0$.

[2] M. Gronau, J. Rosner. "TRIPLE PRODUCT ASYMMETRIES IN K,$D_{(s)}$ AND $B_{(s)}$ DECAYS."

Triple Product Results

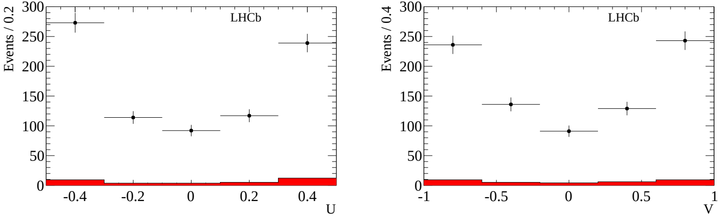


Figure: U & V distributions for data(black) and background(red).

The triple product asymmetries in this mode are measured to be:

$$A_U = \text{-0.055} \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$A_V = 0.010 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst}).$$

Systematic Uncertainties

Systematics uncertainties are considered from several sources.

Angular Analysis:

Source	$\|A_0\|^2$	$\|A_\perp\|^2$	$\|A_{\|\|}\|^2$	$\cos\delta_{\|\|}$
S-wave	0.007	0.005	0.012	0.001
Time acceptance	0.006	0.006	0.002	0.007
Angular acceptance	0.007	0.006	0.006	0.028
Trigger category	0.003	0.002	0.001	0.004
Background model	0.001	-	0.001	0.003
Total	0.012	0.010	0.014	0.029

Triple Product Analysis:

Source	A_U	A_V	Chosen uncertainty
Angular acceptance	0.009	0.006	0.009
Time acceptance	0.006	0.014	0.014
Fit model	0.004	0.005	0.005
Total			0.018

Conclusion

- Polarisation amplitudes, triple products and a strong phase have been measured, using a time integrated method, in $B_s^0 \to \phi\phi$.
- These are currently the most precise measurements of these parameters for this decay.
- Results are consistent with earlier measurements by LHCb[3] and CDF[4].
- Triple product asymmetries are consistent with no T-violation, hence no $\mathcal{CP}$-violation from $\mathcal{CPT}$.
- Paper soon to be submitted to Phys. Lett. B.

[3] Study of Triple Product Asymmetries in $B_s \to \phi\phi$ decays. LHCb-CONF-2011-052.

[4] Measurement of Polarization and Search for CP-Violation in $B_s^0 \to \phi\phi$ Decays. FERMILAB-PUB-11-345-E

END.

The angular functions in the helicity basis are given

$$
\begin{aligned}
f_1(\theta_1, \theta_2, \Phi) &= 4\cos^2\theta_1\cos^2\theta_2 \\
f_2(\theta_1, \theta_2, \Phi) &= \sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi) \\
f_3(\theta_1, \theta_2, \Phi) &= \sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi) \\
f_4(\theta_1, \theta_2, \Phi) &= -2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi \\
f_5(\theta_1, \theta_2, \Phi) &= \sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi \\
f_6(\theta_1, \theta_2, \Phi) &= -\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi.
\end{aligned}
$$

The time dependent functions are

$$
\begin{aligned}
K_1(t) &= \frac{1}{2} A_0^2 [(1+\cos\phi_s) e^{-\Gamma_L t} + (1-\cos\phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin\phi_s] \\
K_2(t) &= \frac{1}{2} A_{\|}^2 [(1+\cos\phi_s) e^{-\Gamma_L t} + (1-\cos\phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin\phi_s] \\
K_3(t) &= \frac{1}{2} A_{\perp}^2 [(1-\cos\phi_s) e^{-\Gamma_L t} + (1+\cos\phi_s) e^{-\Gamma_H t} \mp 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin\phi_s] \\
K_4(t) &= |A_{\|}||A_{\perp}|[\pm e^{-\Gamma_s t} \{\sin\delta_1 \cos(\Delta m_s t) - \cos\delta_1 \sin(\Delta m_s t) \cos\phi_s\} \\
&\quad - \frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \cos\delta_1 \sin\phi_s] \\
K_5(t) &= \frac{1}{2} |A_0||A_{\|}| \cos(\delta_2 - \delta_1) \\
&\quad [(1+\cos\phi_s) e^{-\Gamma_L t} + (1-\cos\phi_s) e^{-\Gamma_H t} \pm 2 e^{-\Gamma_s t} \sin(\Delta m_s t) \sin\phi_s] \\
K_6(t) &= |A_0||A_{\perp}|[\pm e^{-\Gamma_s t} \{\sin\delta_2 \cos(\Delta m_s t) - \cos\delta_2 \sin(\Delta m_s t) \cos\phi_s\} \\
&\quad - \frac{1}{2}(e^{-\Gamma_H t} - e^{-\Gamma_L t}) \cos\delta_2 \sin\phi_s]
\end{aligned}
$$

Angular Analysis

In order to disentangle different $\mathcal{CP}$ states an angular analysis is needed. The time dependent differential cross section is given

$$\frac{d^4\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi dt} \propto \sum_{n=1}^{6} K_n(t) f_n(\theta_1, \theta_2, \Phi),$$

K_n are parts describing time evolution and f_n are angular distributions. Integrating over all time, assuming $\phi_s = 0$ and equal numbers of B_s and $\bar{B}_s$ at production.

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto |A_0|^2 f_1 + |A_\parallel|^2 f_2 + |A_\perp|^2 f_3 + |A_0||A_\parallel| f_5 \cos(\delta_\parallel).$$

Triple Product Asymmetries

- TPA given $A_{TP}^{\|,0} \propto \frac{\Im(A_{\perp} A^{*}_{\|,0})}{\Sigma |A_{\lambda}|^2}$.
- Without carrying out an angular fit we can calculate TP from U and V distributions.

$$
\begin{aligned}
U &= \sin\left(2\Phi\right) \\
V &= \sin\left(\pm\Phi\right) \\
A_u &\equiv \frac{\Gamma(\sin 2\Phi > 0) - \Gamma(\sin 2\Phi < 0)}{\Gamma(\sin 2\Phi > 0) + \Gamma(\sin 2\Phi < 0)}. \\
A_v &\equiv \frac{\Gamma(\sin(\pm\Phi) > 0) - \Gamma(\sin(\pm\Phi) < 0)}{\Gamma(\sin(\pm\Phi) > 0) + \Gamma(\sin(\pm\Phi) < 0)}.
\end{aligned}
$$

Where positive sign in $\sin\left(\pm\Phi\right)$ is taken if $\cos\theta_1 \cos\theta_2 \geq 0$.

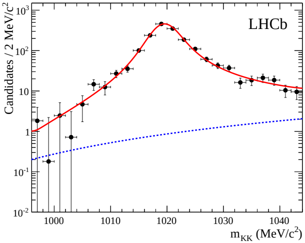


Figure: ϕ mass distribution for the $B_s^0 \to \phi\phi$ data without a ϕ mass cut applied. The background has been removed using the sPlot technique. There are two entries per B_s^0 candidate. The red curve shows a relativistic Relativistic Breit-Wigner. The S-wave component is shown by the dotted line.

Cut	Value
Track χ^2/ndf	$<\ 5$
Track p_T	$> 500\ MeV/c$
Track IP χ^2	$>\ 21$
$\Delta\ln\mathcal{L}_{K\pi}$	> 0
$\lvert M_\phi - M_\phi^{PDG}\rvert$	$<\ 12\ MeV/c^2$
$p_T^{\phi1}, p_T^{\phi2}$	$> 900\ MeV/c$
$p_T^{\phi1}\ \times\ p_T^{\phi2}$	$> 2\ \mathrm{GeV}^2/\mathrm{c}^2$
ϕ vertex χ^2/ndf	$<\ 24$
B_s^0 vertex χ^2/ndf	$<\ 7.5$
B_s^0 FD χ^2	$>\ 270$
B_s^0 IP χ^2	$<\ 15$

Selection criteria for $B_s^0 \to \phi\phi$. The abbreviations IP and FD stand for Impact Parameter and Flight Distance respectively. $P_T^{\phi1}$ and $P_T^{\phi2}$ refer to the transverse momentum of the two ϕ candidates.