$B^0_{s,d} \to \phi\phi$ branching fractions & angular analysis of $B^0_s \to \phi K^+ K^-$

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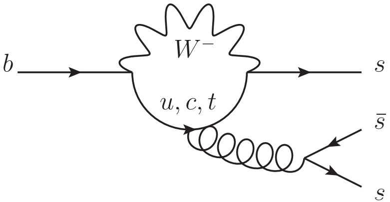
PPE Christmas Meeting
19th Dec 2016

Photo: Phi Phi, Thailand

$b \to s\bar{s}s$ transitions

- Flavour-changing neutral current
- Forbidden at tree-level
  - Dominant diagram is a penguin
  - Sensitive to new particles in the loop
- Possible source of BSM CPV
- Studied in:
  - $B^0 \to \phi K^0_S$
  - $B^0 \to \phi K^{*0}$
  - $B^0_s \to \phi\phi$
  - $\Lambda_b \to \Lambda\phi$
- Results so far consistent with SM :(



A sensitive penguin, sitting down

Outline

1. Measurement of the $B_s^0 \to \phi\phi$ branching fraction and search for $B^0 \to \phi\phi$.
    - LHCb-PAPER-2015-028
    - arXiv:1508.00788
    - JHEP 10 (2015) 053

2. Observation of $B_s^0 \to \phi f_2'(1525)$ and angular analysis of $B_s^0 \to \phi K^+K^-$.
    - In preparation

Event selection

Common selection strategy for both analyses:

- Full Run 1 dataset: 3 fb^{-1} of pp collisions at $\sqrt{s} = 7$ and 8 TeV
- Cut-based pre-selection using track quality, vertex quality, isolation criteria and kinematic information
- Hadron PID requirements to suppress misidentified backgrounds
- Vetoes under different mass hypotheses to remove specific backgrounds
- Multivariate Analysis to reduce combinatorial background

$B_s^0 \to \phi\phi$ branching fraction

Introduction

Motivation:

- Important normalisation channel for other charmless b decays
- Theory predictions in the range $(1.3 \text{ to } 2.0) \times 10^{-5}$
  - Large QCD uncertainties
- Previously measured by CDF using $B_s^0 \to J/\psi\phi$ for normalisation
  - $\mathcal{B}(B_s^0 \to \phi\phi) = (1.91 \pm 0.26\,(\text{stat}) \pm 0.16\,(\text{syst})) \times 10^{-5}$.
  - Large statistical error: LHCb can do better

This analysis:

- Measure the $B_s^0 \to \phi\phi$ branching fraction
  - Use $\phi \to K^+K^-$
- Normalise to $B^0 \to \phi K^{\star 0}$
  - Differs by spectator quark
  - Use $\phi \to K^+K^-$ and $K^{\star 0} \to K^+\pi^-$
  - Cancellation of some systematics

Branching fraction calculation

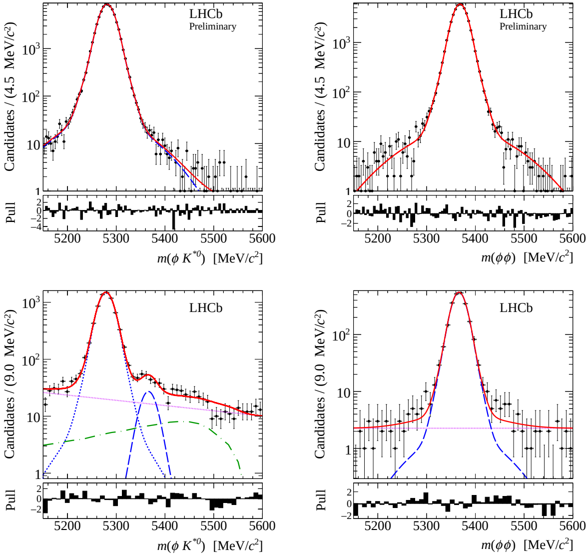
$$\frac{\mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(B^0 \to \phi K^\star)} = \frac{N_{B_s^0 \to \phi\phi}}{N_{B^0 \to \phi K^\star}} \frac{\varepsilon_{\phi K^\star}}{\varepsilon_{\phi\phi}} \frac{\mathcal{B}(K^\star \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \frac{f_d}{f_s}$$

Mass fits

- Fit to simulation for signal shape
- Fit to data with background components for yields
- Subtract s-wave from yields

$B_s^0 \to \phi\phi \quad 2212 \pm 47 \pm 50$
$B^0 \to \phi K^\star \quad 5026 \pm 65 \pm 107$

Uncertainties: $\pm$ statistical $\pm$ s-wave



Efficiencies

Generator efficiency from generator statistics

$$\frac{\varepsilon_{\phi K*}^{\text{gen}}}{\varepsilon_{\phi\phi}^{\text{gen}}} = \frac{(18.69 \pm 0.034)\%}{(17.09 \pm 0.031)\%} = 1.094 \pm 0.004$$

Selection efficiency from simulation

$$\frac{\varepsilon_{\phi K*}^{\text{sel}}}{\varepsilon_{\phi\phi}^{\text{sel}}} = \frac{(1.86 \pm 0.006)\%}{(2.39 \pm 0.013)\%} = 0.778 \pm 0.006$$

Particle identification efficiency from data-driven method

$$\frac{\varepsilon_{\phi K*}^{\text{PID}}}{\varepsilon_{\phi\phi}^{\text{PID}}} = \frac{(84.9 \pm 0.1)\%}{(90.7 \pm 0.2)\%} = 0.936 \pm 0.001$$

Total ratio:

$$\frac{\varepsilon_{\phi K*}}{\varepsilon_{\phi\phi}} = \frac{\varepsilon_{\phi K*}^{\text{gen}}}{\varepsilon_{\phi\phi}^{\text{gen}}} \frac{\varepsilon_{\phi K*}^{\text{sel}}}{\varepsilon_{\phi\phi}^{\text{sel}}} \frac{\varepsilon_{\phi K*}^{\text{PID}}}{\varepsilon_{\phi\phi}^{\text{PID}}} = 0.796 \pm 0.007$$

Result

Relative branching fraction:

$$\frac{\mathcal{B}(B_s^0 \to \phi\phi)}{\mathcal{B}(B^0 \to \phi K^*)} = 1.82 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst}) \pm 0.11\,(f_s/f_d)$$

Absolute branching fraction:

$$\mathcal{B}(B_s^0 \to \phi\phi) = (1.82 \pm 0.05 \pm 0.07 \pm 0.11\,(f_s/f_d) \pm 0.12\,(\text{norm})) \times 10^{-5}$$

Total uncertainty: $\pm 0.18 \times 10^{-5}$ ($\pm 9.6\%$)

Theoretical predictions

BF ($\times 10^{-6}$)	Approach
$19.5 \pm 1.0^{+13.0}_{-8.0}$	QCD factorisation
13.1	QCD factorisation
$16.7^{+2.6\,+11.3}_{-2.1\,-8.8}$	QCD factorisation
$16.7^{+8.9}_{-7.1}$	pQCD

Previous result from CDF:

$$(1.91 \pm 0.26 \pm 0.16) \times 10^{-5}$$

Factor 5 reduction in statistical error :)

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

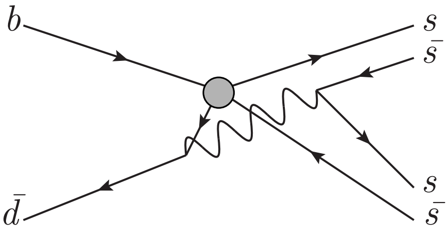
Introduction

Motivation:

- Unobserved and highly suppressed
- Theory predictions in the range $(0.1 \text{ to } 3) \times 10^{-8}$
- Previous limit from BaBar
  - $\mathcal{B}(B^0 \to \phi\phi) < 2.0 \times 10^{-7}$ 90 % CL

This analysis:

- Search for $B^0 \to \phi\phi$
- Normalise to $B_s^0 \to \phi\phi$
  - Same final state
  - Cancellation of many systematics
- Improve the limit on its branching fraction



Don't ask

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

Fit two PDFs to data

- P_{s+b} with a B_d component,
- P_b without.

Ratio of log-likelihoods used as test statistic

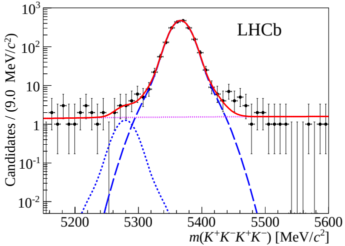
$$R_L = \frac{\mathcal{L}(P_{s+b})}{\mathcal{L}(P_b)}$$

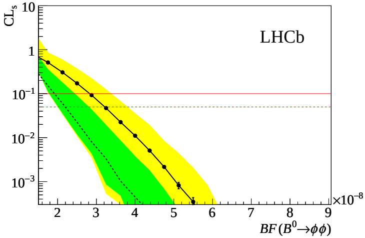
For each point in scan through $\mathcal{B}(B^0 \to \phi\phi)$:

- Calculate $-2 \ln R_L$ from data fit
- Generate toys from P_{s+b} & P_b
- Calculate $-2 \ln R_L$ for each toy
- Take $\text{CL}_{\text{s+b}}$ and CL_{b} as fraction of toys with $-2 \ln R_L$ above the value found in data.

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

Upper limit to 90% C.L. is where $\text{CL}_{\text{s}} = 0.1$.





Upper limit on $\mathcal{B}(B^0 \to \phi\phi)$

Upper limit to 90% C.L.

$$\mathcal{B}(B^0 \to \phi\phi) < 2.8 \times 10^{-8}$$

- Theoretical predictions in range $[0.1, 3.0] \times 10^{-8}$
- Previous result from BaBar: $< 2.0 \times 10^{-7}$ (90% C.L.)
  - Factor of 7 improvement :)

Angular analysis of $B_s^0 \to \phi K^+ K^-$

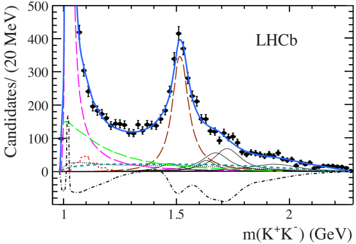
Introduction

Motivation:

- $B_s^0 \to \phi K^+ K^-$ in the region $m\left(K^+K^-\right) < m(D^0)$ is $b \to s\bar{s}s$
- Several K^+K^- resonances, including unobserved $B_s^0 \to \phi f_2'(1525)$
- pQCD predictions:
  - $\mathcal{B}\left(B_s^0 \to \phi f_2'(1525)\right) = \left(3.1^{+1.8}_{-1.4} \pm 0.6\right) \times 10^{-6}$
  - $\mathcal{F}_L = |A_0|^2 / \sum_i |A_i|^2 = \left(75.3^{+3.0+3.5}_{-3.2-1.7}\right)$ %.
- Complementary to tree-level $B_s^0 \to J/\psi K^+ K^-$ analysis

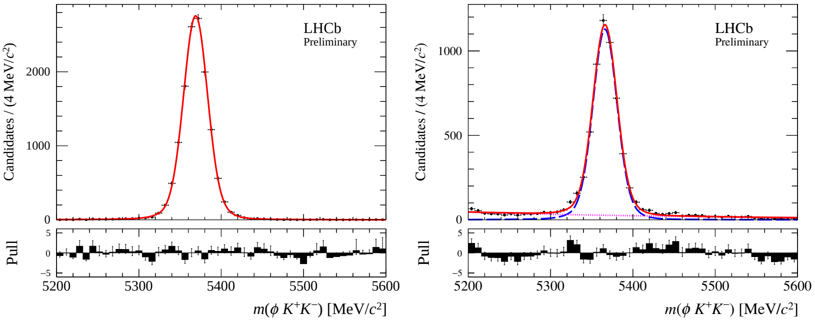
This analysis:

- Amplitude fit in region $m\left(K^+K^-\right) < 1800$ MeV
- First observation of $B_s^0 \to \phi f_2'$
  - Measure branching fraction
  - Measure polarisation amplitudes
- Normalise to $B_s^0 \to \phi\phi$



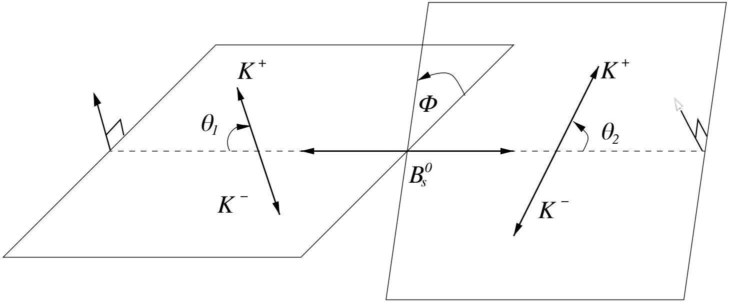
From $B_s^0 \to J/\psi K^+ K^-$

$\phi K^+ K^-$ mass fit



- Used to s-weight the data
- 3990 ± 70 $B_s^0 \to \phi K^+ K^-$ events

Angular distributions



Angular distribution of $P \to (X_1 \to PP)(X_2 \to PP)$ in the helicity basis

$$F(\Phi, \theta_1, \theta_2) = \sum_{\lambda=-J_{\text{min}}}^{+J_{\text{min}}} \mathcal{A}_\lambda Y_{J_1}^{-\lambda}(\pi - \theta_1, -\Phi) Y_{J_2}^{\lambda}(\theta_2, 0)$$

Resonance lineshapes: Relativistic Breit-Wigner

$$T(m|m_0,\Gamma_0) \propto \frac{1}{m_0^2 - m^2 - i m_0 \Gamma(m)},$$

where

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2J+1} \left(\frac{m_0}{m}\right) B_J'(q,q_0)^2,$$

Resonance lineshapes: Flatté

For resonances close to a threshold (e.g. $f_0(980) \to K^+K^-$)

$$T(m|m_0, g_{\pi^+\pi^-}, g_{K^+K^-}) \propto \frac{1}{m_0^2 - m^2 - i m_0 \left(\Gamma_{\pi^+\pi^-}(m) + \Gamma_{K^+K^-}(m)\right)}$$

where

$$\Gamma_{\pi^+\pi^-}(m) = g_{\pi^+\pi^-}\sqrt{\frac{m^2}{4} - m_{\pi^+}^2}$$

and

$$\Gamma_{K^+K^-}(m) = \begin{cases} g_{K^+K^-}\sqrt{\frac{m^2}{4} - m_{K^+}^2} & m > 2m_{K^+} \\ i g_{K^+K^-}\sqrt{m_{K^+}^2 - \frac{m^2}{4}} & m < 2m_{K^-} \end{cases}$$

Time-independent decay rate

$$A(m,\Phi,\theta_1,\theta_2) = \sum_{\text{resonances}} T(m) F(\Phi,\theta_1,\theta_2) \left(\frac{q}{m}\right)^J B'_J(q,q_0) B'_0(p,p_0)$$

$$\Gamma(m,\Phi,\theta_1,\theta_2) = |A(m,\Phi,\theta_1,\theta_2)|^2 pq$$

Time integral

Time-evolution of decay amplitudes from $B_s^0 - \bar{B}_s^0$ mixing:

$$\begin{aligned} A(t) &= A(0)g_+(t) + \frac{q}{p}\bar{A}(0)g_-(t) \\ \bar{A}(t) &= \bar{A}(0)g_+(t) + \frac{p}{q}A(0)g_-(t) \end{aligned}$$

where

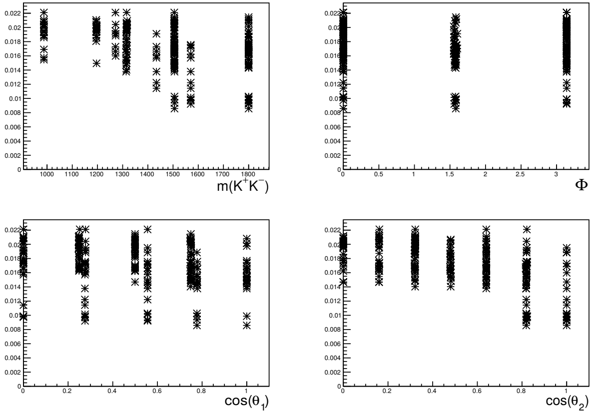
$$g_\pm(t) = \frac{1}{2}\left(e^{-(im_H+\Gamma_H/2)t} \pm e^{-(im_L+\Gamma_L/2)t}\right)$$

Assuming no CP violation and uniform time acceptance

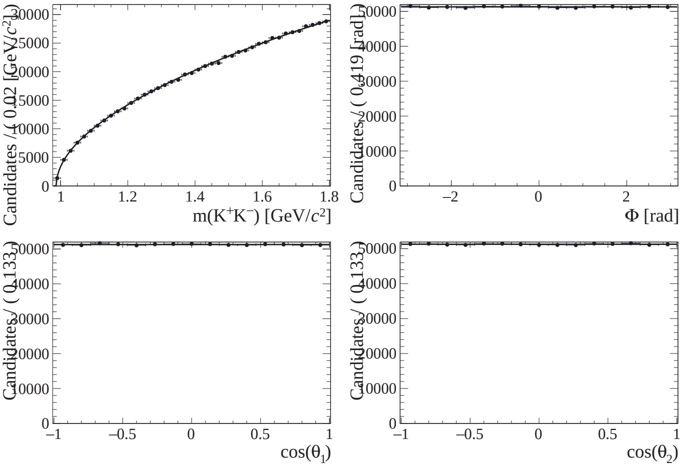
$$\int_0^\infty \Gamma(t) + \bar{\Gamma}(t)dt = \frac{1}{2}\left(|A(0)|^2 + |\bar{A}(0)|^2\right)\left(\frac{1}{\Gamma_H} + \frac{1}{\Gamma_L}\right) + \Re\left(\bar{A}(0)A(0)^*\right)\left(\frac{1}{\Gamma_L} - \frac{1}{\Gamma_H}\right)$$

Acceptance

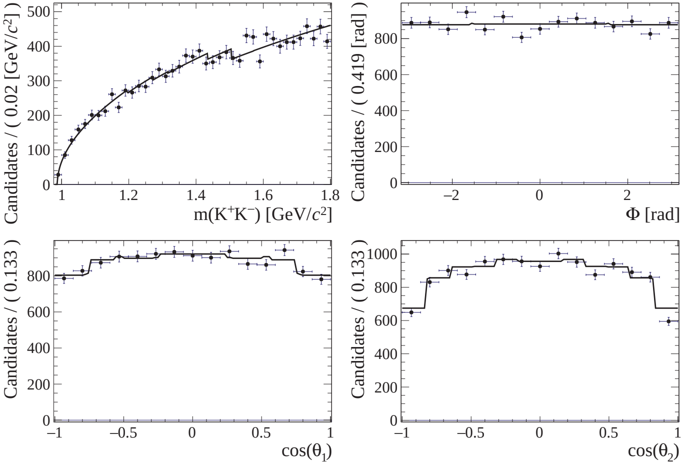
- Adaptively-binned 4D histogram $\to$ bins of equal content
- Denominator: Unbiased generator-level events
- Numerator: Fully-selected simulation



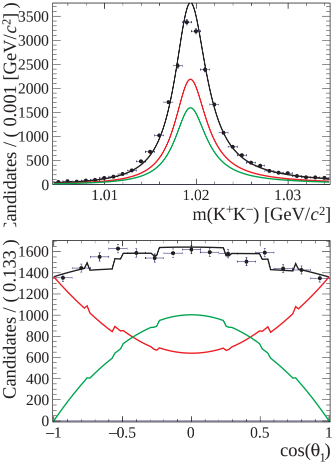
Phase space generator-level sample with $m(KK) < 1800$ MeV



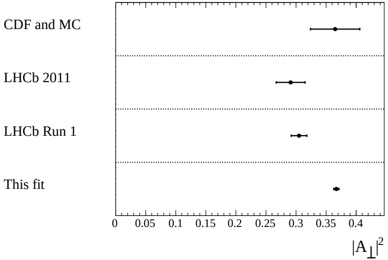
Fully-selected phase space Monte Carlo sample

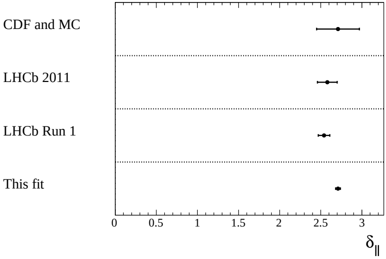


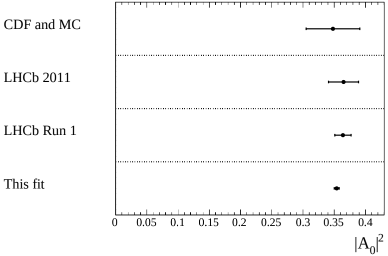
Fully-selected p-wave Monte Carlo sample



Fully-selected p-wave Monte Carlo sample



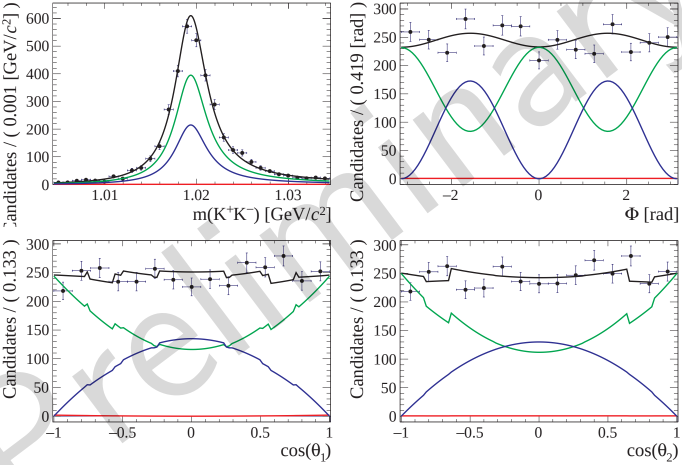




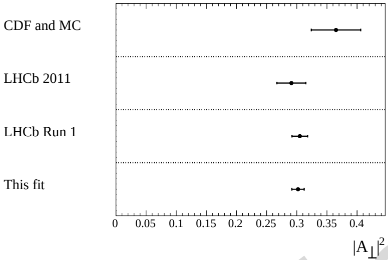
Parameter	Fit result and error	σ from input
$\lvert A_\perp \rvert^2$	0.367 ± 0.004	0.7
$\lvert A_0 \rvert^2$	0.354 ± 0.004	1.5
$\delta_\parallel$	2.71 ± 0.03	0.02

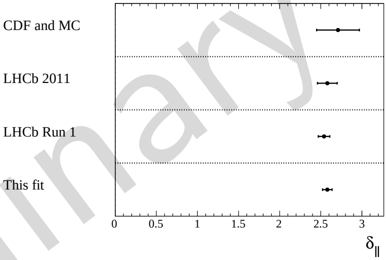
NB: Input values are the CDF results

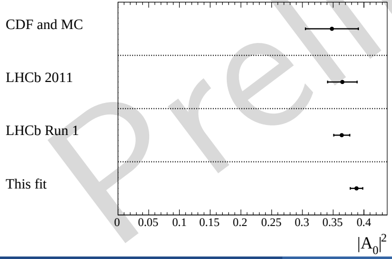
Fit to data in $|m(KK) - m(\phi)| < 15$ MeV



Fit to data in $|m(KK) - m(\phi)| < 15$ MeV

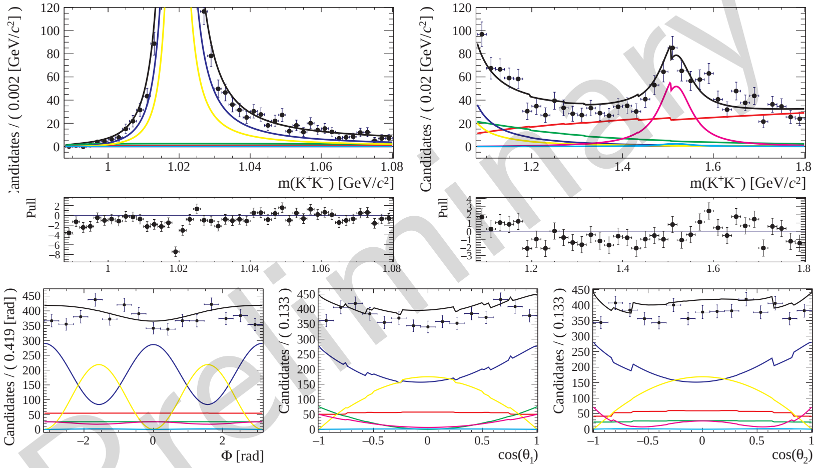






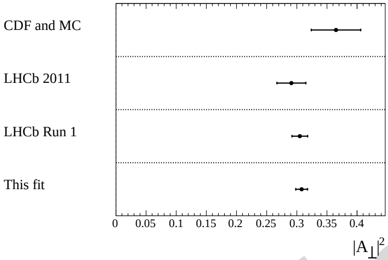
Resonance	Parameter	Result
$f_0(980)$	δ_0^S	-0.7 ± 0.6
$\phi(1020)$	$\lvert A_\perp \rvert^2$	0.30 ± 0.01
	$\lvert A_0 \rvert^2$	0.39 ± 0.01
	$\delta_\parallel^P$	2.58 ± 0.06

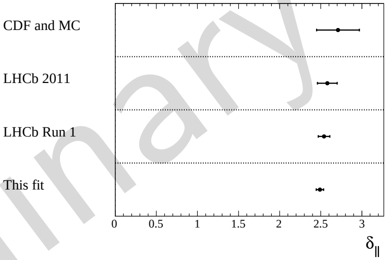
Fit to data

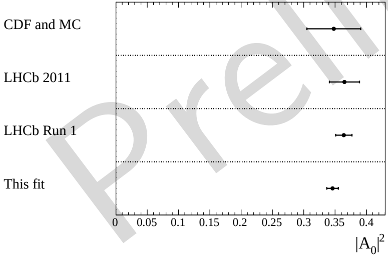


Note: probably a normalisation error in the plotting

Fit to data







Resonance	Parameter	Result
$f_0(980)$	δ_0	-0.60 ± 0.13
$\phi(1020)$	$\lvert A_\perp\rvert^2$	0.31 ± 0.01
	$\lvert A_0\rvert^2$	0.346 ± 0.009
	$\delta_\parallel$	2.49 ± 0.04
$f_2'(1525)$	$\lvert A_\perp\rvert^2$	0.04 ± 0.02
	$\lvert A_0\rvert^2$	0.79 ± 0.04
	$\delta_\perp$	1.82 ± 0.25
	δ_0	0.52 ± 0.18
	$\delta_\parallel$	-1.61 ± 0.26

Summary

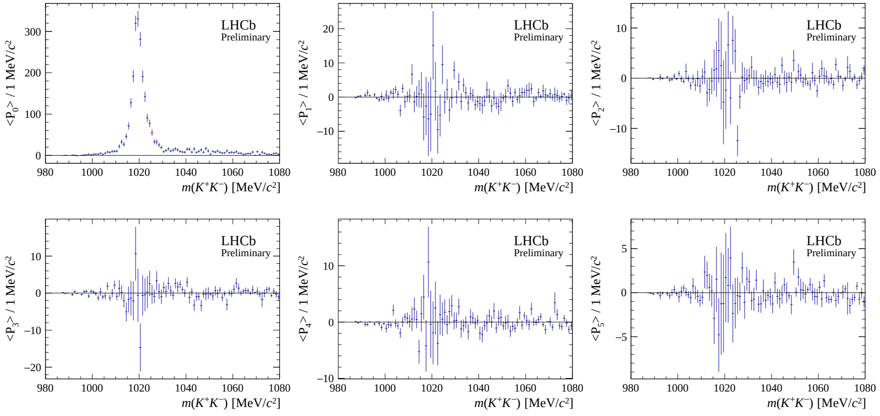
- Improved measurement of $\mathcal{B}(B_s^0 \to \phi\phi)$
- Improved upper limit on $\mathcal{B}(B^0 \to \phi\phi)$
- Angular analysis of $B_s^0 \to \phi K^+ K^-$ in progress
    - First observation of $B_s^0 \to \phi f_2'$
    - Measure branching fraction and polarisation

Backup

Legendre moments

- $\langle P_0 \rangle$ The s-weighted event distribution.
- $\langle P_1 \rangle$ The interference of the sum of S & P-wave and P & D-wave amplitudes.
- $\langle P_2 \rangle$ The sum of the P-wave, D-wave and the interference of S & D-wave amplitudes.
- $\langle P_3 \rangle$ The interference between P & D-wave amplitudes.
- $\langle P_4 \rangle$ The D-wave amplitude.
- $\langle P_5 \rangle$ The F-wave amplitude.

Legendre moments: $m(K^+K^-) < 1.08$ GeV



Legendre moments: $1.08 < m(K^+K^-) < 1.80$ GeV