Measurements of the CP-violating phase ϕ_s at LHCb

Jeroen van Leerdam
On behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects

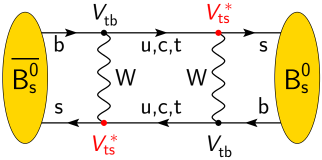
14 October 2013

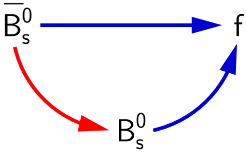
Outline

- Introduction
- Measurements
- Ongoing work
- Conclusion

Measurements of ϕ_s

CP violation in the interference between "mixed" and "unmixed" decays



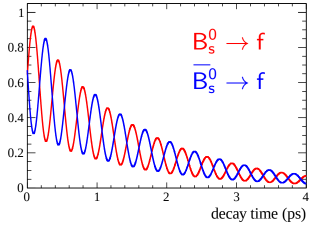


$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} \equiv \eta_f \left|\frac{q}{p}\right| \left|\frac{\overline{A}_{\bar{f}}}{A_f}\right| e^{-i\,\phi_s}$$

CP-violation parameter λ_f contains

- CP violation in mixing
- CP violation in decay
- CP violation in interference between "mixed" and "unmixed" decays

ϕ_s is sensitive to physics beyond the Standard Model
that affects the loops in mixing and/or decay

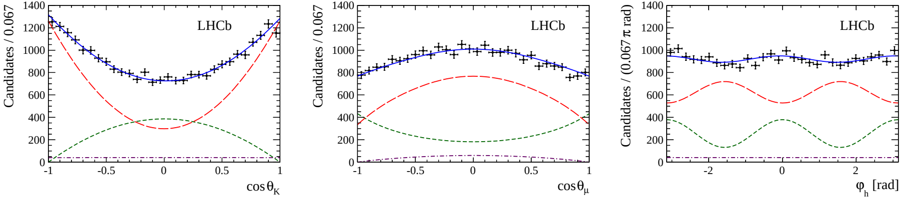


ϕ_s is determined from decay-time distributions

- amplitude of oscillations
- relative contributions of heavy and light $B_s^0/\overline{B}_s^0$ eigenstates to exponential decay

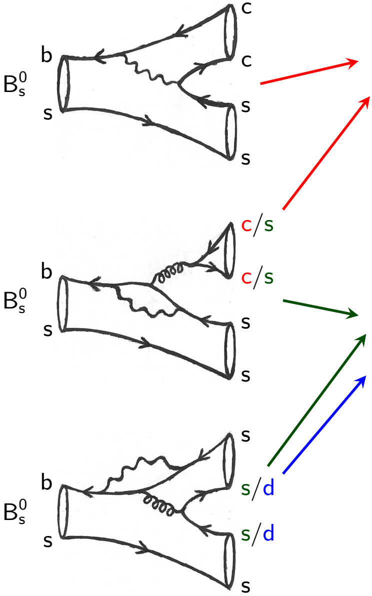
  → see also talk by R. Knegjens on effective lifetimes

Use decay-angle distributions (and h^+h^- invariant masses)
to separate contributions from intermediate resonant and polarization states



$B_s^0 \to J/\psi K^+K^-$ (PRD **87** (2013) 112010)

Decays



$B_s^0 \to J/\psi(\to \mu^+\mu^-)\,\phi(\to K^+K^-)$
$B_s^0 \to J/\psi(\to \mu^+\mu^-)\,f_0(\to \pi^+\pi^-)$

- dominated by tree-level amplitude
- sensitive to non-Standard Model CP violation induced by mixing
- $\phi_s^{c\bar{c}s} \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ in SM

CKMfitter, PRD **84**, 033005 (2011)

$B_s^0 \to \phi(\to K^+K^-)\,\phi(\to K^+K^-)$
$B_s^0 \to K^{*0}(\to K^+\pi^-)\,\overline{K^{*0}}(\to K^-\pi^+)$

- sensitive to non-Standard Model CP violation induced by mixing and/or decay
- $\phi_s^{\phi\phi} \approx 0$ and $\phi_s^{K^*K^*} \approx 0$ in SM

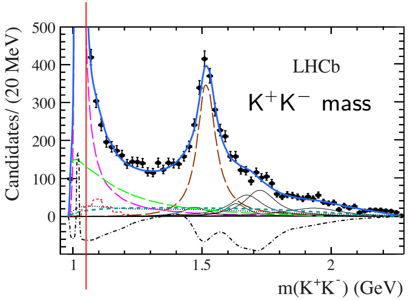
---

also expected:
$B_s^0 \to \psi(2S)\,\phi$; $B_s^0 \to J/\psi\,\eta^{(\prime)}$; $B_s^0 \to D_s^+ D_s^-$

Outline

- Introduction
- Measurements
  - $B_s^0 \to J/\psi\, K^+K^-$ and $B_s^0 \to J/\psi\, \pi^+\pi^-$
  - $B_s^0 \to \phi\, \phi$
  - $B_s^0 \to K^{*0}\, \overline{K^{*0}}$
- Ongoing work
- Conclusion

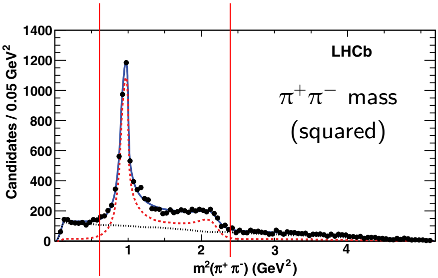
$B_s^0 \to J/\psi\, K^+K^-$ (PRD **87** (2013) 072004)



ϕ_s analysis:
0.99–1.05 GeV$/c^2$ K^+K^--mass window

- mass region dominated by $\phi(1020)$
- small S-wave component

$B_s^0 \to J/\psi\, \pi^+\pi^-$ (PRD **86** (2012) 052006)



ϕ_s analysis:
0.60–2.40 GeV$^2/c^4$ $\pi^+\pi^-$-mass window

- mass region dominated by $f_0(980)$
- fraction of CP-odd components > 0.977 at 95% C.L.

$B_s^0 \to J/\psi\, h^+h^-$

PRD **87** (2013) 112010; PLB **713** (2012) 378

Analysis on 1 fb^{-1} of data from 2011 (update with full 3 fb^{-1} planned)

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

$\approx 28,000$ signal events

$$\phi_s^{c\bar{c}s} = 0.07 \pm 0.09 \pm 0.01 \text{ rad}$$

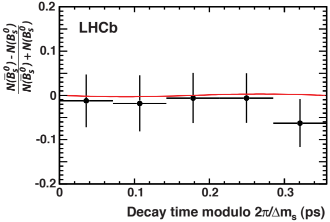
$$\Delta\Gamma_s = 0.100 \pm 0.016 \pm 0.003 \text{ ps}^{-1}$$

$$\Gamma_s = 0.663 \pm 0.005 \pm 0.006 \text{ ps}^{-1}$$

$B_s^0 \to J/\psi\, \pi^+\pi^-$

$7,421 \pm 105$ signal events

$$\phi_s^{c\bar{c}s} = -0.14^{+0.17}_{-0.16} \pm 0.01 \text{ rad}$$



- Assume ϕ_s does not depend on decay channel (or intermediate state)
- Combination for $B_s^0 \to J/\psi\, h^+h^-$ channels gives

$$\phi_s^{c\bar{c}s} = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1}$$

$$\Gamma_s = 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1}$$

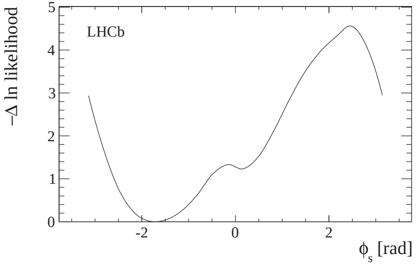
$B_s^0 \to \phi\,\phi$

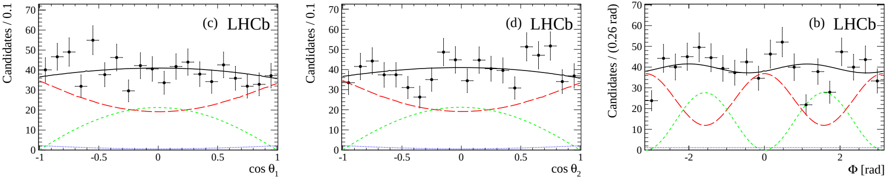
PRL **110** (2013) 241802

Analysis on 1 fb^{-1} of data from 2011 (update with full 3 fb^{-1} planned)

- 880 ± 31 signal events
- $\phi_s^{\phi\phi} \in [-2.46, -0.76]$ rad (68% C.L.)

$$F_L = 0.329 \pm 0.033 \pm 0.017$$
$$F_\perp = 0.358 \pm 0.046 \pm 0.018$$
$$\delta_1 = +2.19 \pm 0.44 \pm 0.12$$
$$\delta_2 = -1.47 \pm 0.48 \pm 0.10$$



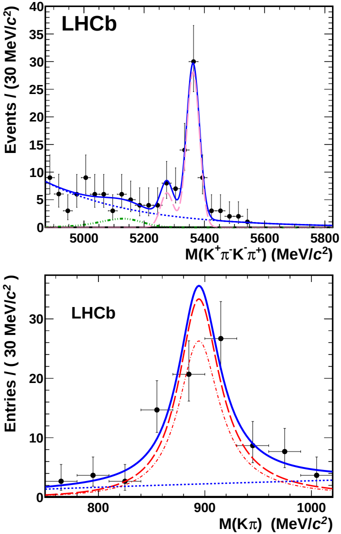


$B_s^0 \to K^{*0}\,\overline{K^{*0}}$

Analysis on 35 pb^{-1} of data from 2010
(update with 1 fb^{-1} (2011) planned, working on time-dependent analysis with 3 fb^{-1})

- first observation
- angular analysis
- 50 ± 8 signal events
- $F_L = 0.31 \pm 0.12 \pm 0.04$
  $F_\perp = 0.38 \pm 0.11 \pm 0.04$

Update will also contain triple-product asymmetries



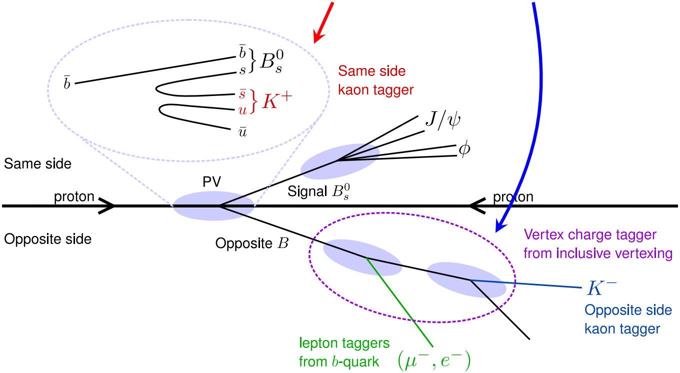
Outline

- Introduction
- Measurements
- Ongoing work
  - Flavour tagging
  - Invariant h^+h^--mass modelling
  - Polarization-dependent CP violation
- Conclusion

Flavour tagging

Improving several experimental aspects – one example is flavour tagging

- Can we increase the effective fraction of perfectly tagged events ($\varepsilon\langle\mathcal{D}^2\rangle \approx 3\%$)?
- Statistical uncertainty on ϕ_s approximately proportional to $1/\sqrt{\varepsilon\langle\mathcal{D}^2\rangle}$
- Improvements for both same-side and opposite-side tagging

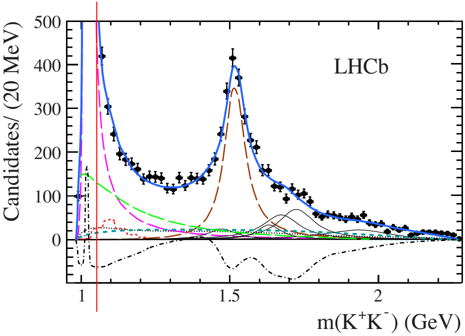


- neural net-based algorithms
- reoptimization

Invariant h^+h^--mass modelling

In addition to decay time and decay angles, should we also model the h^+h^- mass(es)?

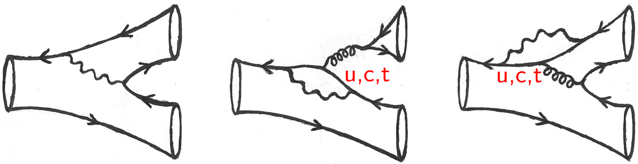
- $B_s^0 \to J/\psi K^+K^-$ analysis is done in $\phi(1020)$ region (in bins of the K^+K^- mass)
- What would we gain by modelling the K^+K^- mass distribution?
- What would we learn from other resonances?
- Modified time-dependent Dalitz analysis with time, helicity angles and m_{KK} described by Zhang and Stone (PLB **719** (2013) 383)



Should the model also depend on orbital angular momenta?
(barrier factors, momentum dependence of wave function)

Polarization-dependent CP violation

- We usually only consider dominant (Standard Model) amplitudes:
  - tree-level for $B_s^0 \to J/\psi\, h^+ h^-$
  - $\mathcal{O}(\lambda^2)$ for $B_s^0 \to \phi\,\phi$ and $B_s^0 \to K^{*0}\,\overline{K^{*0}}$ (where $\lambda \equiv |V_{us}|$)
- But CP violation is small... For a precise measurement we may also have to consider suppressed penguin amplitudes ($\longrightarrow \mathcal{O}(\lambda^4)$ in Standard Model)
- And contributions with new weak phases may be introduced in the decay



- Previous measurements assumed that
  CP violation is the same for all polarization (and resonant) states
- A consequence of multiple amplitudes is that (in general)
  CP violation depends on the intermediate state

Polarization-dependent CP violation

Corrections to ϕ_s

CP-violation parameter λ_k depends on intermediate state k:

$$\lambda_k \equiv \frac{q}{p}\frac{\overline{A}_k}{A_k} \approx \eta_k \, e^{-i\,\phi_s^{\text{dom}}} \frac{1 + r\,R_k\,e^{i\,\delta_k}\,e^{+i\,\theta}}{1 + r\,R_k\,e^{i\,\delta_k}\,e^{-i\,\theta}}$$

where

- ϕ_s^{dom} is ϕ_s if there were only the dominant amplitudes
- $R_k\,e^{i\,\delta_k}\,e^{\pm i\,\theta}$ is the "ratio of suppressed and dominant amplitudes" for $\overline{B}_s^0$ (B_s^0) (with strong phase δ_k and weak phase θ)
- r is the magnitude of ratio of CKM elements

- Corrections to measured ϕ_s, polarization dependent in general
- Constant correction to measured λ_k if amplitudes ratio polarization independent: $R_k\,e^{i\,\delta_k}\,e^{\pm i\,\theta} \to R\,e^{i\,\delta}\,e^{\pm i\,\theta}$
- No correction ($\lambda \equiv \frac{1}{\eta_k}\lambda_k \approx e^{-i\,\phi_s^{\text{dom}}}$) if:
  - magnitude of CKM-elements ratio small: $r \to 0$
  - or magnitude of amplitudes ratio small: $R_k \to 0$
  - or no weak phase in ratio of amplitudes: $\theta \to 0$

Polarization-dependent CP violation

Experimental approaches

- $B_s^0 \to \phi\,\phi$: Studying possibility to directly measure theoretical parameters in expressions for λ_k (independent parameters for intermediate states)
  $\to$ Bhattacharya, Datta, Duraisamy, London, PRD **88** (2013) 016007
  $\to$ talk by B. Bhattacharya on Wednesday

- $B_s^0 \to J/\psi\,K^+K^-$: Planning to measure observables: independent $\lambda_k \equiv |\lambda_k|\,e^{-i\,\phi_s^k}$ for intermediate states
  $\to$ Bhattacharya, Datta, London, Int. J. Mod. Phys. **A28** (2013) 1350063

- Extract interesting physics from $B_s^0 \to J/\psi\,K^+K^-$ parameters in separate analysis, using also
  - $B_s^0 \to J/\psi\,\overline{K^{*0}}$ (U-spin related) $\to$ Faller, Fleischer, Mannel, PRD **79** (2009) 014005
  - perturbative QCD calculations $\to$ Liu, Wang, Xie, arXiv:1309.0313 [hep-ph]
  - ...

- preliminary studies on 1 fb^{-1} show that $B_s^0 \to J/\psi\,K^+K^-$ measurement is feasible:

$$\phi_s = 0.07 \pm 0.09 \longrightarrow \begin{cases} \phi_s^0 = \ldots \pm 0.10;\ \phi_s^{\parallel} = \ldots \pm 0.12;\ \phi_s^{\perp} = \ldots \pm 0.15 \\ \phi_s^S = \ldots \pm 0.16 \end{cases}$$

Outline

- Introduction
- Measurements
- Ongoing work
- Conclusion

Conclusion

- $B_s^0 \to J/\psi\, h^+h^-$ and $B_s^0 \to \phi\,\phi$ measurements of ϕ_s with 1 fb^{-1} from 2011:
  - $\phi_s^{c\bar{c}s} = (0.01 \pm 0.07 \pm 0.01)$ rad
  - $\phi_s^{\phi\phi} \in [-2.46, -0.76]$ rad (68% C.L.)

  updates planned with the full 3 fb^{-1} data set
- $B_s^0 \to K^{*0}\,\overline{K^{*0}}$ amplitude analysis with 1 fb^{-1} planned, working on time-dependent analysis with 3 fb^{-1}
- Working on several experimental and modelling improvements, specifically on models which incorporate resonance- and polarization-dependent CP violation

Additional information

Products of decay amplitudes

$$A_i(t)^* A_j(t) = A_i^* A_j \, \frac{\left(1+\left|\frac{q}{p}\right|^2\right)^2}{4\left|\frac{q}{p}\right|^2} \, (1 - q_{\mathrm{flav}}\, C_{\mathrm{m}})\; e^{-\Gamma_{\mathrm{s}}\, t}$$

$$\times \Big[\left(P_{ij}^{+} + P_{ij}^{-}\, C_{\mathrm{m}}\right) \cosh\left(\tfrac{1}{2}\Delta\Gamma_{\mathrm{s}}\, t\right) + q_{\mathrm{flav}} \left(P_{ij}^{-} + P_{ij}^{+}\, C_{\mathrm{m}}\right) \cos\left(\Delta m_{\mathrm{s}}\, t\right)$$

$$+ \left(P_{ij}^{\Re}\, D_{\mathrm{m}} + P_{ij}^{\Im}\, S_{\mathrm{m}}\right) \sinh\left(\tfrac{1}{2}\Delta\Gamma_{\mathrm{s}}\, t\right) + q_{\mathrm{flav}} \left(P_{ij}^{\Im}\, D_{\mathrm{m}} - P_{ij}^{\Re}\, S_{\mathrm{m}}\right) \sin\left(\Delta m_{\mathrm{s}}\, t\right) \Big]$$

$$P_{ij}^{+} = \tfrac{1}{2}\left[1 + \left(\frac{\overline{A}_i}{A_i}\right)^* \frac{\overline{A}_j}{A_j}\right] \longrightarrow \tfrac{1}{2}\left(1 + \left|\frac{\overline{A}_i}{A_i}\right|^2\right) \quad \text{for } i = j$$

$$P_{ij}^{-} = \tfrac{1}{2}\left[1 - \left(\frac{\overline{A}_i}{A_i}\right)^* \frac{\overline{A}_j}{A_j}\right] \longrightarrow \tfrac{1}{2}\left(1 - \left|\frac{\overline{A}_i}{A_i}\right|^2\right)$$

$$P_{ij}^{\Re} = \tfrac{1}{2}\left[\left(\frac{\overline{A}_i}{A_i}\right)^* + \frac{\overline{A}_j}{A_j}\right] \longrightarrow \Re\left(\frac{\overline{A}_i}{A_i}\right)$$

$$P_{ij}^{\Im} = i \cdot \tfrac{1}{2}\left[\left(\frac{\overline{A}_i}{A_i}\right)^* - \frac{\overline{A}_j}{A_j}\right] \longrightarrow \Im\left(\frac{\overline{A}_i}{A_i}\right)$$

$$C_{\mathrm{m}} = \frac{1-\left|\frac{q}{p}\right|^2}{1+\left|\frac{q}{p}\right|^2} \qquad D_{\mathrm{m}} = -\frac{2\,\Re\left(\frac{q}{p}\right)}{1+\left|\frac{q}{p}\right|^2} \qquad S_{\mathrm{m}} = \frac{2\,\Im\left(\frac{q}{p}\right)}{1+\left|\frac{q}{p}\right|^2}$$

$$\nu_{\mathrm{N}} = -C_{\mathrm{m}} \quad (\mathrm{B_s^0}\text{–}\overline{\mathrm{B}}{}_{\mathrm{s}}^0 \text{ normalization asymmetry})$$