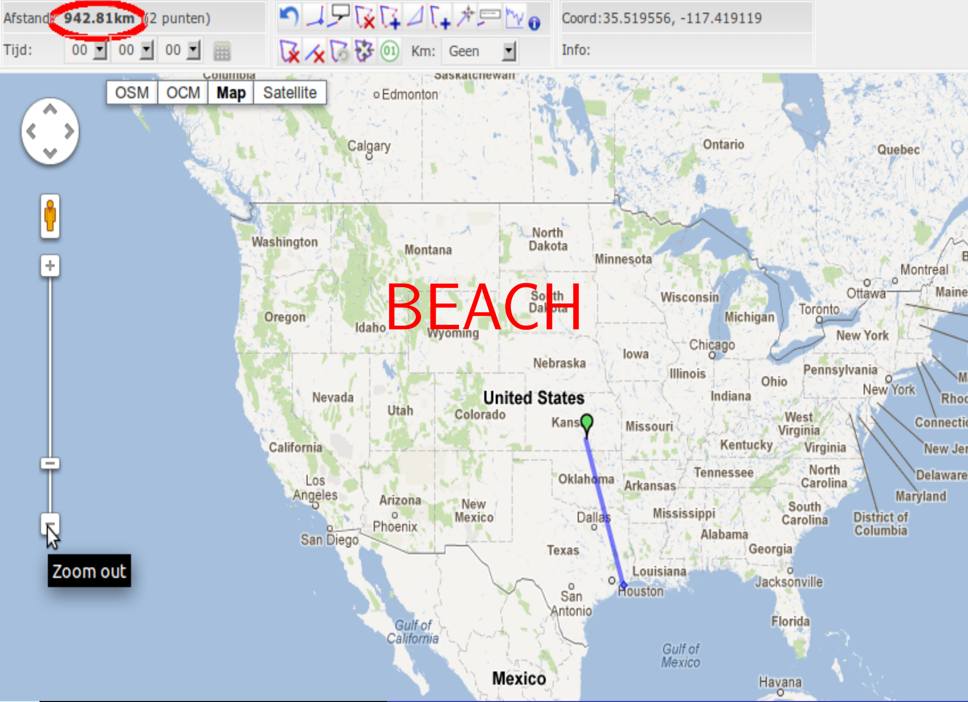
CP violating phases in neutral meson oscillations

BEACH 2012, Wichita, Kansas

Daan van Eijk

On behalf of the LHCb collaboration

July 24 2012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Jacksonville
Florida
Gulf of California
Gulf of Mexico
Mexico
Havana

Outline

LHCb

- LHCb detector and performance

ϕ_s analysis

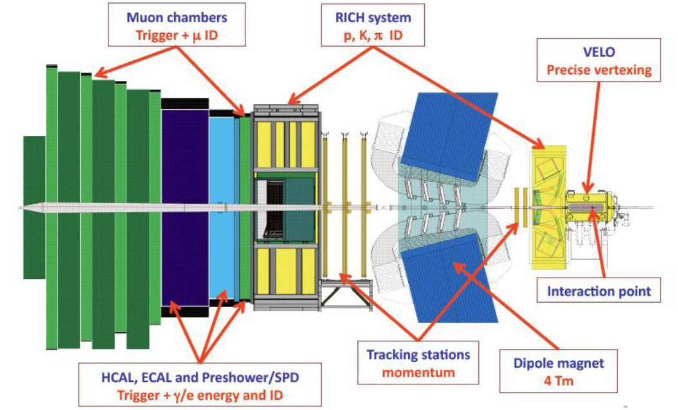
- ϕ_s measurement from $B_s^0 \to J/\psi\,\varphi$ decays
- Phase ambiguity
- ϕ_s measurement from $B_s^0 \to J/\psi\,\pi\,\pi$ decays
- $B_s^0 \to J/\psi\,\overline{K}^{*0}$ (estimate penguin contributions to $B_s^0 \to J/\psi\,\varphi$)

Other analyses

- $a_{\rm sl}^s$ measurement
- $B_s^0 \to \varphi\,\varphi$ (triple-product asymmetries)

The LHCb detector

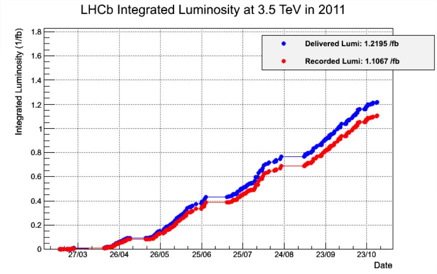
- LHCb is one of the 4 large LHC experiments at CERN
- Single arm forward spectrometer: $2 < \eta < 5$
- Dedicated to heavy flavour physics
- Dimensions: 20 m x 10 m x 10 m

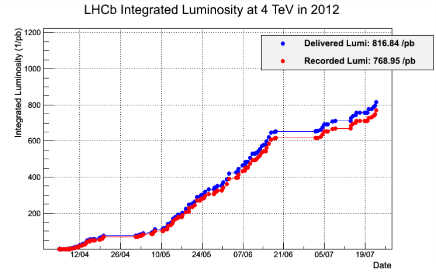


LHCb performance

Integrated luminosity

- 2010: $\sim 37\,\text{pb}^{-1}$
- 2011: $\sim 1\,\text{fb}^{-1}$
- 2012: $\sim 0.77\,\text{fb}^{-1}$, expect about $2.2\,\text{fb}^{-1}$ at the end of the 2012 run

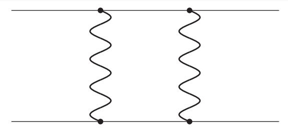




Search for New Physics at LHCb

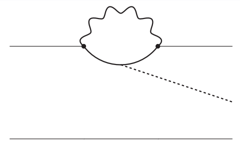
- Indirect search for New Physics (NP) via precision measurements in loop-mediated processes
  - Rare decays → see talk by D. Hutchcroft, Thursday, 10:00
  - CP violation → topic of this talk

Box diagrams



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

Penguin diagrams



- $B_s^0 \to \varphi\,\varphi$
- $B_s^0 \to J/\psi\overline{K}^{*0}$

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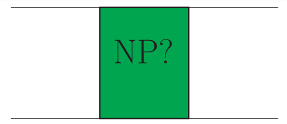

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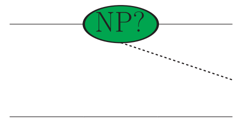


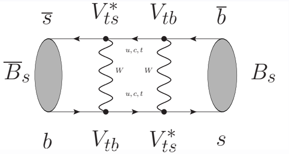
- $B_s^0 \to \varphi\,\varphi$
- $B_s^0 \to J/\psi \overline{K}^{*0}$

CP violating phase ϕ_s in $B_s^0 \to J/\psi\,\varphi$

- The final state $J/\psi\,\varphi$ is accessible to both B_s^0 and $\overline{B}_s^0$: Interference between decays with and without mixing
- Interference measured through weak phase ϕ_s
- $\phi_s = \phi_M - 2\phi_{c\bar{c}s}$

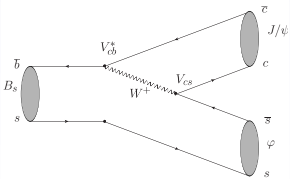
Mixing phase

- $\phi_M^{SM} = \arg\left(V_{tb}V_{ts}^*\right)^2 = -2\,\beta_s$



Decay phase

- $\phi_{c\bar{c}s}^{SM} = \arg(V_{cb}V_{cs}^*) \approx 0$
  $+$ small penguin contribution



- Standard Model (SM) prediction is small: $\phi_s^{SM} = -2\,\beta_s \approx -0.04$

(arXiv: 1102.4274)

CP violating phase ϕ_s in $B_s^0 \to J/\psi\,\varphi$

- The final state $J/\psi\,\varphi$ is accessible to both B_s^0 and $\overline{B}_s^0$: Interference between decays with and without mixing
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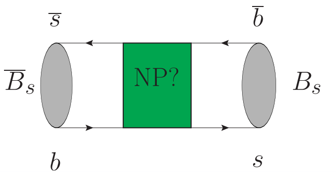
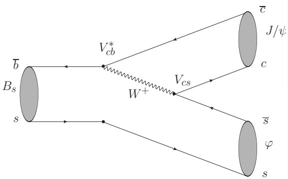




- Standard Model (SM) prediction is small: $\phi_s^{SM} = -2\,\beta_s \approx -0.04$

(arXiv: 1102.4274)

- NP models: $\phi_s \to \phi_s^{SM} + \Delta\phi^{NP}$

How to measure ϕ_s?

CP asymmetry

- If the final state is a CP eigenstate with eigenvalue η_f, the CP asymmetry is defined as

$$A_{CP} \equiv \frac{\Gamma(\overline{B}_s^0 \to f) - \Gamma(B_s^0 \to f)}{\Gamma(\overline{B}_s^0 \to f) + \Gamma(B_s^0 \to f)} \sim \eta_f \sin\phi_s \sin(\Delta m_s t)$$

- Δm_s is the $B_s^0 - \overline{B}_s^0$ mixing frequency

Requirements to measure A_{CP}

- Need to tag initial flavour of B meson (B_s^0 or $\overline{B}_s^0$)
- In the case of $B_s^0 \to J/\psi\,\varphi$ decays: Admixture of CP even and CP odd states $\to$ Need to disentangle
- Detector effects dilute the CP asymmetry:
  - Decay-time resolution (σ_t)
  - Mistag probability (w)

$$A_{CP} \sim (1-2w)\exp(-0.5\Delta m_s^2\sigma_t^2)\,\eta_f\,\sin\phi_s\,\sin(\Delta m_s t)$$

- Strength of LHCb: good decay-time resolution and tagging power

Angular analysis

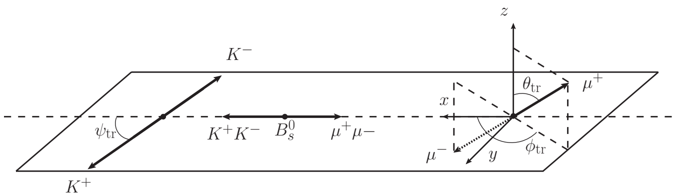
Spin states

- B_s^0 is spin 0, decays to J/ψ (spin 1) and φ (spin 1)
- $B_s^0 \to J/\psi\,\varphi$ is admixture of CP even and odd states
    - $\mathrm{CP}|J/\psi\,\varphi\rangle = (-1)^L|J/\psi\,\varphi\rangle$
- $L = 0$ and $L = 2$ states are CP even, $L = 1$ is CP odd

Transversity basis

Three transversity amplitudes and associated phases

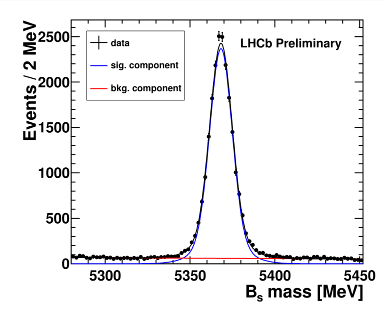
- CP even: $A_{||}$ and A_0, CP odd: $A_{\perp}$
- Use transversity angular distributions (ψ, θ, ϕ) to statistically disentangle CP even and CP odd components



$B_s^0 \to J/\psi\,\varphi$ analysis

Selection

- Dataset with $1.0\,\mathrm{fb}^{-1}$ of integrated luminosity
- Cut-based selection: 21200 $B_s^0 \to J/\psi\,\varphi$ candidates
- Decay time cut $t > 0.3\,\mathrm{ps}$ removes most of the combinatorial background, losing little sensitivity to ϕ_s



Parameters and observables

- Observables: (decay time t, invariant mass $m_{B_s^0}$, decay angles $\cos\psi, \cos\theta, \phi$, tag decision q, event-by-event mistag probability w)
- Simultaneous fit to all observables
- Physics parameters: (average decay time Γ_s, decay time difference $\Delta\Gamma_s$, ϕ_s, transversity amplitudes and corresponding phases)

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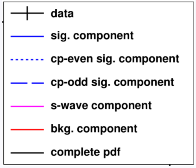
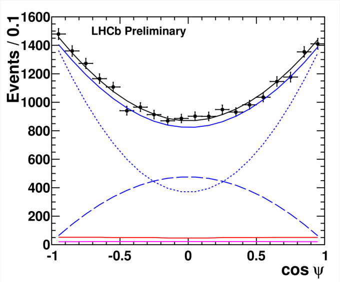
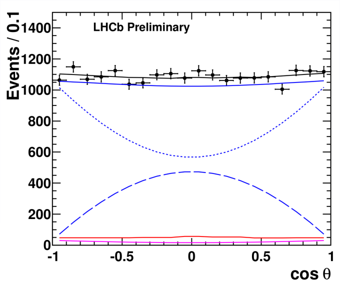
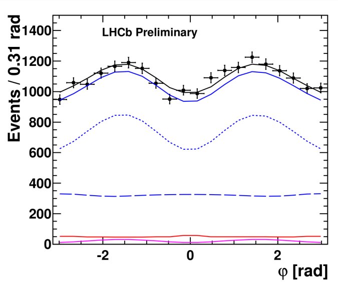
$B_s^0 \to J/\psi\,\varphi$ angular analysis

- Determine angular acceptance from MC
- CP odd S-wave amplitude included, parameterized by fraction f_S and phase δ_S









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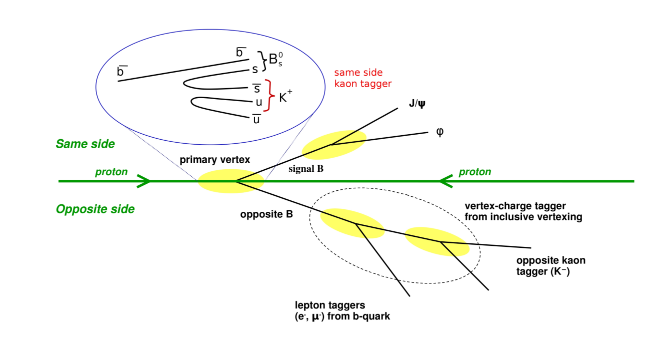
Tagging

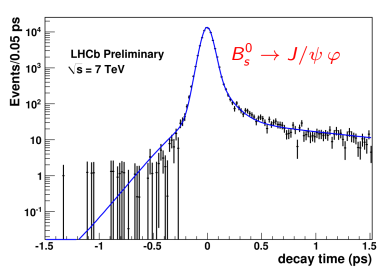


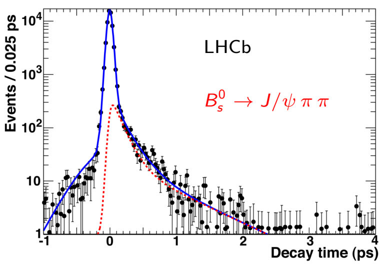
- Sensitivity to ϕ_s comes from information on the flavour of the produced B_s^0 meson
- Flavour indicated by tag decision $q = \pm 1$, with per-event mistag probability w_i
- Effective tagging power $Q = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}}(1 - 2w)^2$
- Only Opposite Side (OS) tagger is used, $Q = (2.29 \pm 0.27)\%$

arXiv: 1202.4979

Decay-time resolution

- Determined from prompt J/ψ candidates that decay at $t \sim 0$
- Effective decay-time resolution for $B_s^0 \to J/\psi\,\varphi$: $\sigma_{\text{eff.}} = 45\,\text{fs}$
- Effective decay-time resolution for $B_s^0 \to J/\psi\pi\pi$: $\sigma_{\text{eff.}} = 40\,\text{fs}$





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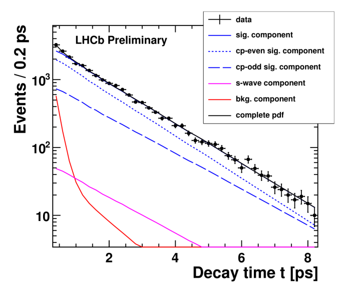
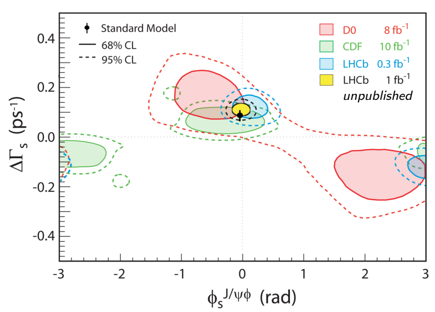
arXiv: 1204.5675

Preliminary results for $B_s^0 \rightarrow J/\psi\,\varphi$ analysis



Parameter	Value	Stat.	Syst
$\Gamma_s\ [\mathrm{ps}^{-1}]$	0.6580	0.0054	0.0066
$\Delta\Gamma_s\ [\mathrm{ps}^{-1}]$	0.116	0.018	0.006
ϕ_s	-0.001	0.101	0.027
$\lvert A_0(0)\rvert^2$	0.523	0.007	0.024
$\lvert A_\perp(0)\rvert^2$	0.246	0.010	0.013
f_S	0.022	0.012	0.007
$\delta_\parallel$	[2.81,3.47]		0.13
$\delta_\perp$	2.90	0.36	0.07
δ_S	2.90	0.36	0.08

First observation of non-zero $\Delta\Gamma_s$ at $> 5\sigma$



Dominating systematics

- Neglecting (possible) CP violation in mixing and CP violation in decay
- Angular acceptance
- Decay-time acceptance

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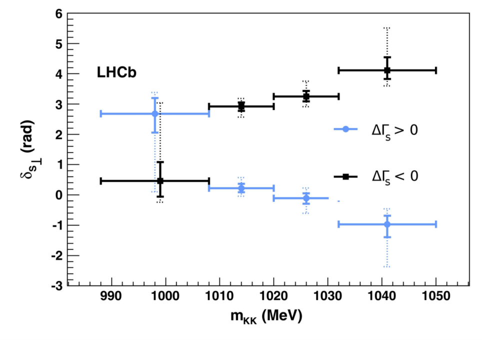
Resolving the ambiguity

- The fitted solution is ambiguous:
- $(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp, \delta_S) \rightarrow (\pi - \phi_s, -\Delta\Gamma_s, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$

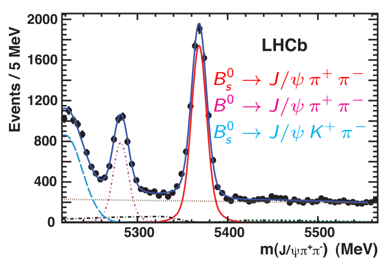


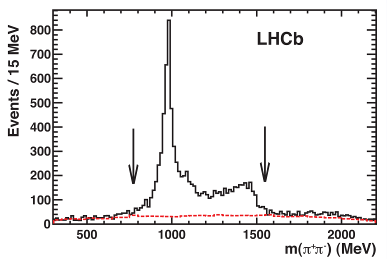
- As KK invariant mass passes through the $\varphi(1020)$ resonance:
  - S-wave amplitude constant: δ_S expected to increase slowly
  - P-wave amplitude Breit-Wigner: $\delta_\perp$ expected to rise quickly
- Physical solution: falling trend of $\delta_{S\perp} = \delta_S - \delta_\perp$ as a function of KK invariant mass: $\Delta\Gamma_s > 0$ ($4.7\,\sigma$ significance)

arXiv: 1202.4717

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

- $b \to c\bar{c}s$ transition, sensitive to ϕ_s
- Smaller BR than $B_s^0 \to J/\psi\,\varphi$
- Final state $J/\psi\,\pi^+\pi^-$ is $> 97.7\%$ CP odd at 95% C.L. *(arXiv: 1204.5643)*
  - No angular analysis needed





- Γ_s and $\Delta\Gamma_s$ constrained from $B_s^0 \to J/\psi\,\varphi$ analysis
- Δm_s constrained from LHCb measurement *(arXiv: 1112.4311)*
- $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$

arXiv: 1204.5675

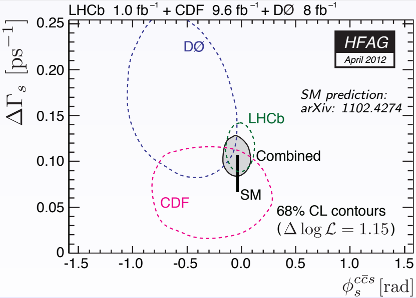
ϕ_s combinations

LHCb simultaneous fit of $B_s^0 \to J/\psi\,\varphi$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$ (preliminary)

$\phi_s = -0.002 \pm 0.083\,(\mathrm{stat.}) \pm 0.027\,(\mathrm{syst.})$ *LHCb-CONF-2012-002*

Global ϕ_s combination (HFAG)

$\phi_s = -0.044^{+0.090}_{-0.085}, \quad \Delta\Gamma_s = 0.105 \pm 0.015\,\mathrm{ps}^{-1}$ *arXiv: 1207.1158*

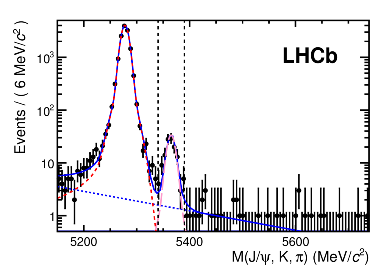


ATLAS results (ICHEP 2012)

- $\phi_s = 0.22 \pm 0.41\,(\mathrm{stat.}) \pm 0.10\,(\mathrm{syst.})$
- $\Delta\Gamma_s = 0.053 \pm 0.021\,(\mathrm{stat.}) \pm 0.008\,(\mathrm{syst.})\,\mathrm{ps}^{-1}$

Penguin contributions: $B_s^0 \to J/\psi\,\overline{K}^{*0}$ analysis

- Analysis of this channel can help to control penguin contributions to ϕ_s (*Phys. Rev. D, vol 79, 014005, Jan 2009*)
- First step: branching ratio measurement
- Branching ratio is related to $\mathcal{B}(B_d^0 \to J/\psi\,K^{*0})$ assuming that the light quark (s, d) is a spectator quark of the b-decay



- LHCb result: $370\,\mathrm{pb}^{-1}$, 114 signal events
- $\mathcal{B}(B_s^0 \to J/\psi\,\overline{K}^{*0}) = (4.42^{+0.46}_{-0.44}\,(\mathrm{stat.}) \pm 0.80\,(\mathrm{syst.})) \times 10^{-5}$

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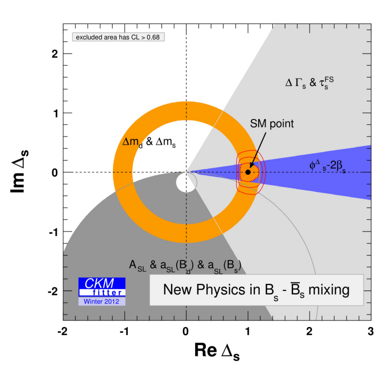
Implications for New Physics



- $M_{12}^q \equiv M_{12}^{\mathrm{SM},q} \Delta_q$
- $\Delta_q \equiv |\Delta_q| e^{i\phi_q^\Delta}, \quad q = d, s$
- Discrepancy with D0 A_{SL} measurement
- Need independent (LHCb) measurement

arXiv: 1203.0238v2

CP violation in mixing: $a^s_{\rm sl}$ measurement (preliminary)

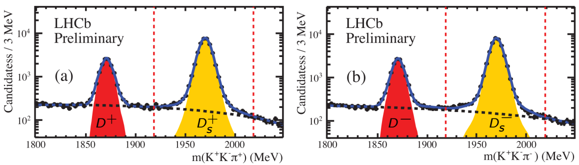
B^0_s mixing:

$$\phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Observable:

$$a^s_{\rm sl} = \frac{\Gamma(\overline{B}^0_s(t)\to f) - \Gamma(B^0_s(t)\to \overline{f})}{\Gamma(\overline{B}^0_s(t)\to f) + \Gamma(B^0_s(t)\to \overline{f})} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_{M/\Gamma}$$

- SM prediction: $a^s_{\rm sl} = (1.9 \pm 0.3)\times 10^{-5}$ *(arXiv: 1205.1444)*
- Use as final state $D^\pm_s X \mu^\mp \overset{(-)}{\nu}$, $D^\pm_s \to \varphi\pi^\pm$



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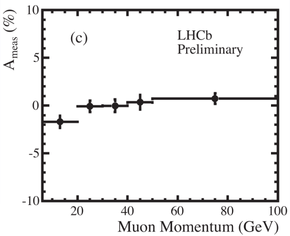
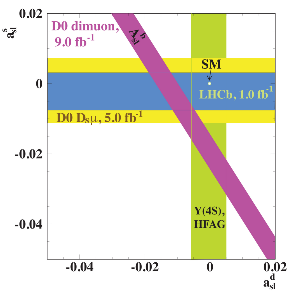
CP violation in mixing: $a^s_{\rm sl}$ measurement (preliminary)

$$A_{\rm meas} = \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a^s_{\rm sl}}{2} + \left[a_{\rm p} - \frac{a^s_{\rm sl}}{2}\right] \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t}\cosh\frac{\Delta\Gamma_s t}{2}\epsilon(t)dt}$$

- Time-integrated measurement:
  - Effect of small production asymmetry eliminated due to large Δm_s
- Detection asymmetries estimated from calibration samples
- Residual detector asymmetries averaged out using magnet-up and magnet-down data (roughly equal-sized datasets)

$a^s_{\rm sl} = (-0.24 \pm 0.54 \pm 0.33)\%$





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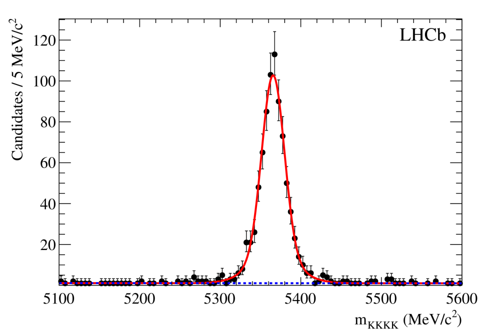
$B_s^0 \to \varphi\,\varphi$ analysis

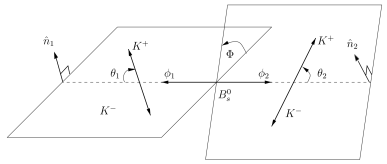
- Pure $b \to s\bar{s}s$ penguin transition
- SM prediction: weak phase $\phi_s' = 0$
- LHCb: so far only untagged analysis, no sensitivity to ϕ_s' yet
- Roughly 800 events observed with $1.0\,\text{fb}^{-1}$

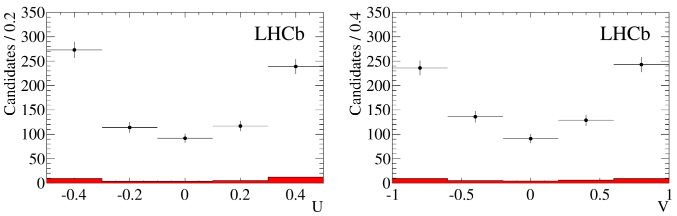


arXiv: 1204.2813

$B_s^0 \to \varphi\,\varphi$ analysis: triple-product asymmetries

- Triple products
  $U = \sin(2\Phi)/2$ and
  $V = \pm\sin(\Phi)$
- Products of three momentum vectors $\to$ CP-odd quantities
- Triple-product asymmetries A_U and A_V consistent with CP conservation





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Summary

- Excellent performance of LHC and LHCb in 2010, 2011 and 2012
- World's best measurement of ϕ_s (both in $B_s^0 \to J/\psi\,\varphi$ decays and in $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays): in agreement with SM prediction
- First observation of non-zero $\Delta\Gamma_s$ ($> 5\sigma$)
- Ambiguity in the sign of $\Delta\Gamma_s$ is resolved: $\Delta\Gamma_s > 0$
- Measurement of $\mathcal{B}(B_s^0 \to J/\psi \overline{K}^{*0})$ performed
- World's best measurement of a_{sl}^s: in agreement with SM prediction
- Triple-product asymmetries in $B_s^0 \to \varphi\,\varphi$ decays show no indications of CP violation
- More data available and being analyzed (already $0.77\,\mathrm{fb}^{-1}$ collected in 2012, expect about $2.2\,\mathrm{fb}^{-1}$ at the end of the run)

Backup

ϕ_s in the Standard Model

$$A_f(t) = A_f(0)[g_+(t) + \lambda_f g_-(t)] \tag{1}$$

$$\lambda_{J/\psi\,\varphi} = \frac{q}{p}\frac{\overline{A}_{J/\psi\,\varphi}}{A_{J/\psi\,\varphi}} \equiv \eta_{J/\psi\,\varphi}\lambda \tag{2}$$

$$\frac{q}{p} \approx -e^{-i\phi_M} \tag{3}$$

$$\frac{\overline{A}_{J/\psi\,\varphi}}{A_{J/\psi\,\varphi}} = -\eta_{J/\psi\,\varphi}\, e^{2i\phi_{c(\bar{c}s)}} \tag{4}$$

$$\lambda = e^{-i\phi_M} e^{2i\phi_{c(\bar{c}s)}} = e^{-i\phi_s} \tag{5}$$

$$\begin{aligned} \phi_s &= \phi_M - 2\phi_{c(\bar{c}s)} \\ &= \arg[(V_{tb}V_{ts}^*)^2] - 2\arg(V_{cb}V_{cs}^*) \\ &= 2\arg\left(\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) \\ &= -2\beta_s \end{aligned} \tag{6}$$

$B_s^0 \to J/\psi\,\varphi$ time-dependent functions

$$
\begin{aligned}
A_1 &= |a_0|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_2 &= |a_{\|}|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_3 &= |a_{\perp}|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_4 &= |a_{\|}||a_{\perp}|e^{-t/\tau}[-\cos(\delta_{\perp} - \delta_{\|}) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_{\perp} - \delta_{\|}) \cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_{\perp} - \delta_{\|}) \cos(\Delta m t)] \\
A_5 &= |a_0||a_{\|}|e^{-t/\tau} \cos(\delta_{\|} - \delta_0)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) + \sin\phi_s \sin(\Delta m t)] \\
A_6 &= |a_0||a_{\perp}|e^{-t/\tau}[-\cos(\delta_{\perp} - \delta_0) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \cos(\delta_{\perp} - \delta_0) \cos\phi_s \sin(\Delta m t) \\
&\quad + \sin(\delta_{\perp} - \delta_0) \cos(\Delta m t)] \\
A_7 &= |a_S|^2 e^{-t/\tau}[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t] \\
A_8 &= |a_S||a_{\|}|e^{-t/\tau}[-\sin(\delta_{\|} - \delta_S) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_{\|} - \delta_S) \cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_{\|} - \delta_S) \cos(\Delta m t)] \\
A_9 &= |a_S||a_{\perp}|e^{-t/\tau} \sin(\delta_{\perp} - \delta_S)[\cosh\left(\frac{\Delta\Gamma}{2}t\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin\phi_s \sin(\Delta m t)] \\
A_{10} &= |a_S||a_0|e^{-t/\tau}[-\sin(\delta_0 - \delta_S) \sin\phi_s \sinh\left(\frac{\Delta\Gamma}{2}t\right) - \sin(\delta_0 - \delta_S) \cos\phi_s \sin(\Delta m t) \\
&\quad + \cos(\delta_0 - \delta_S) \cos(\Delta m t)]
\end{aligned}
$$

		$\cosh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T\cos(\Delta m t)$	$\sinh\left(\frac{\Delta\Gamma}{2}t\right)$	$q_T\sin(\Delta m t)$
$\lvert\mathcal{A}_0(t)\rvert^2$	$\frac{\lvert a_0\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\lvert\mathcal{A}_\parallel(t)\rvert^2$	$\frac{\lvert a_\parallel\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
$\lvert\mathcal{A}_\perp(t)\rvert^2$	$\frac{\lvert a_\perp\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	$+D$	$+S$
$\Im(\mathcal{A}_\parallel^*(t)\mathcal{A}_\perp(t))$	$\frac{\Re(a_\parallel^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
	$\frac{\Im(a_\parallel^* a_\perp)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\Im(\mathcal{A}_0^*(t)\mathcal{A}_\perp(t))$	$\frac{\Re(a_0^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
	$\frac{\Im(a_0^* a_\perp)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
$\Re(\mathcal{A}_0^*(t)\mathcal{A}_\parallel(t))$	$\frac{\Re(a_0^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	1	C	$-D$	$-S$
	$\frac{\Im(a_0^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	0	0	0	0
$\lvert\mathcal{A}_S(t)\rvert^2$	$\frac{\lvert a_S\rvert^2 e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\Im(\mathcal{A}_S^*(t)\mathcal{A}_\perp(t))$	$\frac{\Re(a_S^* a_\perp)e^{-t/\tau}}{1+q_T C}$	0	0	0	0
	$\frac{\Im(a_S^* a_\perp)e^{-t/\tau}}{1+q_T C}$	1	C	D	S
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_0(t))$	$\frac{\Re(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
	$\frac{\Im(a_S^* a_0)e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$
$\Re(\mathcal{A}_S^*(t)\mathcal{A}_\parallel(t))$	$\frac{\Re(a_S^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	C	1	0	0
	$\frac{\Im(a_S^* a_\parallel)e^{-t/\tau}}{1+q_T C}$	0	0	S	$-D$

$B_s^0 \to J/\psi\,\varphi$ angular functions

amplitudes	Angular function
$\lvert a_0\rvert^2$	$2\cos^2\psi\left(1-\sin^2\theta\cos^2\phi\right)$
$\lvert a_{\parallel}\rvert^2$	$\sin^2\psi\left(1-\sin^2\theta\sin^2\phi\right)$
$\lvert a_{\perp}\rvert^2$	$\sin^2\psi\sin^2\theta$
$\Im(a_{\parallel}\,a_{\perp})$	$-\sin^2\psi\sin 2\theta\sin\phi$
$\Re(a_0\,a_{\parallel})$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin^2\theta\sin 2\phi$
$\Im(a_0\,a_{\perp})$	$\frac{1}{2}\sqrt{2}\,\sin 2\psi\sin 2\theta\cos\phi$
$\lvert a_S(t)\rvert^2$	$\frac{2}{3}(1-\sin^2\theta\cos^2\phi)$
$\Re(a_S^*(t)a_{\parallel}(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin^2\theta\sin 2\phi$
$\Im(a_S^*(t)a_{\perp}(t))$	$\frac{1}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\phi$
$\Re(a_S^*(t)a_0(t))$	$\frac{4}{3}\sqrt{3}\cos\psi(1-\sin^2\theta\cos^2\phi)$

Asymmetry

$$A_{CP} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to f)}{\Gamma(\overline{B} \to f) + \Gamma(B \to f)} = \frac{\eta_f \sin\phi_s \sin\Delta m t}{\cosh\frac{\Delta\Gamma t}{2} + \eta_f \cos\phi_s \sinh\frac{\Delta\Gamma t}{2}}$$

$$\begin{aligned}
\Gamma_{B\to f}(t) &= |A_f|^2 (1+|\lambda_f|^2) \frac{e^{-\Gamma t}}{2} \cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - D_f \sinh\frac{\Delta\Gamma t}{2} + C_f \cos\Delta m t - S_f \sin\Delta m t\right) \qquad (7) \\
\Gamma_{B\to \overline{f}}(t) &= |\overline{A}_{\overline{f}}|^2 \left|\frac{q}{p}\right|^2 (1+|\overline{\lambda}_{\overline{f}}|^2) \frac{e^{-\Gamma t}}{2} \cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - \overline{D}_{\overline{f}} \sinh\frac{\Delta\Gamma t}{2} - \overline{C}_{\overline{f}} \cos\Delta m t + \overline{S}_{\overline{f}} \sin\Delta m t\right) \qquad (8) \\
\Gamma_{\overline{B}\to f}(t) &= |A_f|^2 \left|\frac{p}{q}\right|^2 (1+|\lambda_f|^2) \frac{e^{-\Gamma t}}{2} \cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - D_f \sinh\frac{\Delta\Gamma t}{2} - C_f \cos\Delta m t + S_f \sin\Delta m t\right) \qquad (9) \\
\Gamma_{\overline{B}\to \overline{f}}(t) &= |\overline{A}_{\overline{f}}|^2 (1+|\overline{\lambda}_{\overline{f}}|^2) \frac{e^{-\Gamma t}}{2} \cdot \\
&\quad \left(\cosh\frac{\Delta\Gamma t}{2} - \overline{D}_{\overline{f}} \sinh\frac{\Delta\Gamma t}{2} + \overline{C}_{\overline{f}} \cos\Delta m t - \overline{S}_{\overline{f}} \sin\Delta m t\right) \qquad (10)
\end{aligned}$$

where

$$\begin{aligned}
D_f &= \frac{2\,\mathrm{Re}[\lambda_f]}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad S_f = \frac{2\,\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}, \\
\overline{D}_{\overline{f}} &= \frac{2\,\mathrm{Re}[\overline{\lambda}_{\overline{f}}]}{1+|\overline{\lambda}_{\overline{f}}|^2}, \quad \overline{C}_{\overline{f}} = \frac{1-|\overline{\lambda}_{\overline{f}}|^2}{1+|\overline{\lambda}_{\overline{f}}|^2}, \quad \overline{S}_{\overline{f}} = \frac{2\,\mathrm{Im}[\overline{\lambda}_{\overline{f}}]}{1+|\overline{\lambda}_{\overline{f}}|^2}.
\end{aligned} \qquad (11)$$

Selection details

Decay mode	Cut parameter	Stripping 17	Final selection
all tracks	$\chi^2_{\text{track}}/\text{nDoF}$	< 5	< 4
	clone distance	–	> 5000
$J/\psi \to \mu^+\mu^-$	$\Delta\text{LL}\mu\pi$	> 0	> 0
	$min(p_T(\mu^+), p_T(\mu^-))$	–	$> 0.5\,\text{GeV}/c$
	$\chi^2_{\text{vtx}}/\text{nDoF}(J/\psi)$	< 16	< 16
	$\lvert M(\mu^+\mu^-) - M(J/\psi)\rvert$	$< 80\,\text{MeV}/c^2$	$\in [3030,\ 3150]\,\text{MeV}/c^2$
$\phi \to K^+K^-$	$\Delta\text{LL}K\pi$	> -2	> 0
	p_T (K)	$> 500\,\text{MeV}/c$	$> 500\,\text{MeV}/c$
	p_T (ϕ)	$> 1\,\text{GeV}/c$	$> 1\,\text{GeV}/c$
	$M(\phi)$	$\in [980,\ 1050]\,\text{MeV}/c^2$	$\in [1007.46,\ 1031.46]\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}/\text{nDoF}(\phi)$	< 16	< 16
$B^0_s \to J/\psi\,\phi$	$M(B^0_s)$	$\in [5200,\ 5550]\,\text{MeV}/c^2$	$\in [5200,\ 5550]\,\text{MeV}/c^2$
	$\chi^2_{\text{vtx}}/\text{nDoF}(B^0_s)$	< 10	< 10
	$\chi^2_{\text{DTF(B+PV)}}/\text{nDoF}(B^0_s)$	–	< 5
	$\chi^2_{\text{IP}}(B^0_s)$	–	< 25
	$\chi_{\text{IP,next}}(B^0_s)$	–	> 50
	$t(*)$	$> 0.2\,\text{ps}$	$> 0.3\,\text{ps}$

Table 3: Selection criteria for $B^0_s \to J/\psi\,\phi$ candidates in Stripping17 and final selection. (*) the cut on decay time performed in the stripping is on the "OfflineVertexFitter" decay time, while the one performed offline is on the DecayTreeFitter decay time. See the text for more details.

Decay-time acceptance

$$\epsilon = \frac{N^{\mathrm{sig}}_{\mathrm{unbiased\&\&biased}}}{N^{\mathrm{sig}}_{\mathrm{unbiased}}}$$

Decay-time resolution

- Dilution $D = \exp\left(-\Delta m_s^2 \sigma_t^2/2\right)$, effective power $\mathcal{P} = \mathcal{D}^2$

$$R(t,\sigma_t) = \sum_{i=1}^{3} f_i \frac{1}{\sqrt{2\,\pi} s_i \sigma_t} \exp\left(-\frac{(t-d)^2}{2(s_i\,\sigma_t)^2}\right) \quad , \qquad (12)$$

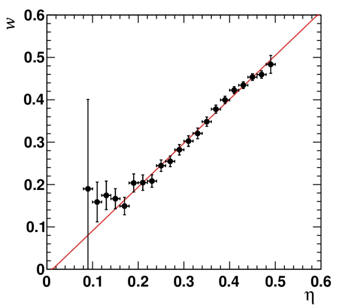
- If the resolution model is the sum of j Gaussians, the effective power becomes $\mathcal{P} = [\sum_j f_j \exp(-\Delta m_s^2 \sigma_j^2/2)]^2$.
- When using a per-event decay-time error $\sigma_{j,e}$, the average power of the model is $\langle\mathcal{P}\rangle = \sum_e \mathcal{P}_e/N$, where $\mathcal{P}_e$ is the per-event power.
- Convert this three Gaussian model back to single Gaussian with same effective power:
- $d = 0$ and scale factor $S_{\sigma_t} = 1.45 \pm 0.06$

Tagging

$$\sigma(A_{CP}) = \frac{1}{D_{\text{eff}}}\sigma(A_{\text{observed}}) \propto \frac{1}{D_{\text{eff}}}\frac{1}{\sqrt{\epsilon_T N}} = \frac{1}{\sqrt{\epsilon_T D_{\text{eff}}^2 N}} \equiv \frac{1}{\sqrt{QN}} \quad (13)$$

$$D_{\text{eff}}^2 = \frac{1}{N}\sum D_i^2 = \frac{1}{N}\sum_{i\in\text{tagged}} (1-2w_i)^2 \equiv (1-2w_{\text{eff}})^2 \quad (14)$$

- Calibrate mistag probability using self-tagging decay $B^+ \to J/\psi K^+$
- $w_i = p_0 + p_1(\eta - <\eta>)$
- Float p_0 and p_1 within their errors in fits



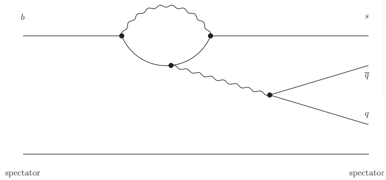
Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Production asymmetry (± 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay (± 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

Penguins

$$A(\bar{b} \to \bar{c}c\bar{s}) = V_{cs}V_{cb}^*(T_c + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t$$
$$= V_{cs}V_{cb}^*(T_c + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t)$$

The second term in Eq. 15 is doubly Cabibbo-suppressed with respect to the first term ($|V_{us}V_{ub}^*| \sim \lambda^4$ versus $|V_{cs}V_{cb}^*| \sim \lambda^2$). The first term, proportional to $V_{cs}V_{cb}^*$, includes both tree and penguin contributions, but these penguin contributions have the same phase as the tree contribution and thus do not change the value of ϕ_s.



$$A(\bar{b} \to \bar{c}c\bar{d}) = V_{cd}V_{cb}^*(T_c + P_c - P_t) + V_{ud}V_{ub}^*(P_u - P_t)$$

In this case, however, the second term, $V_{ud}V_{ub}^*(P_u - P_t)$, is not Cabibbo suppressed with respect to the first term, since both $|V_{ud}V_{ub}^*|$ and $|V_{cd}V_{cb}^*|$ are of order λ^3. This means that the relative size of the first term with respect to the second term, $\frac{P_u - P_t}{T_c + P_c - P_t}$ can be determined by analyzing $B_s^0 \to J/\psi\overline{K}^{*0}$ decays.

$B_s^0 \to J/\psi\, \overline{K}^{*0}$ analysis

- Branching ratio is related to $\mathcal{B}(B_d^0 \to J/\psi\, K^{*0})$ assuming that the light quark (s, d) is a spectator quark of the b-decay

$$\mathcal{B}(B_s^0 \to J/\psi\, \overline{K}^{*0}) \sim \frac{|V_{cd}|^2}{|V_{cs}|^2} \times \mathcal{B}(B_d^0 \to J/\psi\, K^{*0}) = (6.5 \pm 1.0) \times 10^{-5}$$

- Angular analysis:

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} = 0.503^{+0.075}_{-0.078}\,(\mathrm{stat.}) \pm 0.021\,(\mathrm{syst.})$$

$$f_\parallel = \frac{|A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} = 0.187^{+0.099}_{-0.080}\,(\mathrm{stat.}) \pm 0.022\,(\mathrm{syst.})$$

$B_s^0 \to \varphi\,\varphi$ analysis

- Triple-product asymmetries:

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

- $A_U = \frac{N_+ - N_-}{N_+ + N_-}$
- $N_+(N_-)$ is the number of events with $U > 0 (U < 0)$
- $A_V = \frac{M_+ - M_-}{M_+ + M_-}$
- $M_+(M_-)$ is the number of events with $V > 0 (V < 0)$
- $U = \sin(2\Phi)/2$, $V = \pm\sin(\Phi)$, with Φ the angle between the KK decay planes
- Positive sign in V if the T even quantity $\cos\theta_1 \cos\theta_2 \geq 0$
- θ_i angle of K^+ with B decay axis

LHCb trigger

- Trigger important:
- σ_{bb} is less than 1 % of total inelastic cross section
- BR of interesting B decays $< 10^{-5}$

- b-hadrons long-lived:
  - Separate primary and secondary vertices
- b-hadrons have large mass:
  - Decay products with high p_T

- L0: Search for high p_T μ, e, γ and hadron candidates
- HLT: Software trigger
- HLT1: L0 confirmation
- HLT2: Global event reconstruction
  - Inclusive and exclusive selections

Trigger scheme

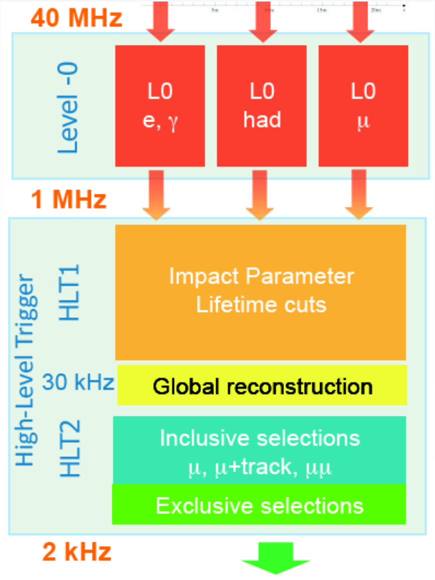
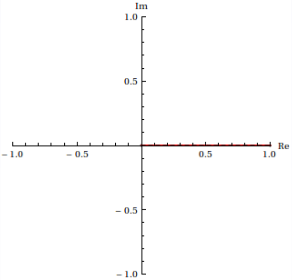
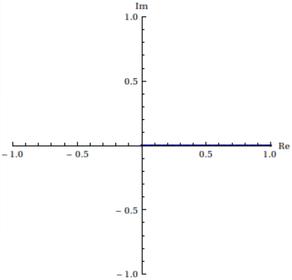


Illustration of time-dependent CP violation

$$A_{CP} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to f)}{\Gamma(\overline{B} \to f) + \Gamma(B \to f)} = \frac{|A(\overline{B} \to f)|^2 - |A(B \to f)|^2}{|A(\overline{B} \to f)|^2 + |A(B \to f)|^2}$$





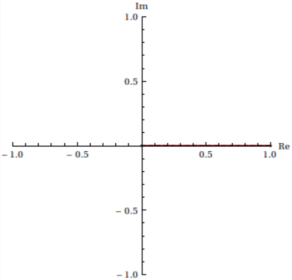
$\Gamma(B \to f) \propto$
$e^{-\Gamma t} \left|\cos\frac{\Delta m t}{2} + e^{-i\phi_{\mathrm{weak}}} \sin\frac{\Delta m t}{2}\right|^2$

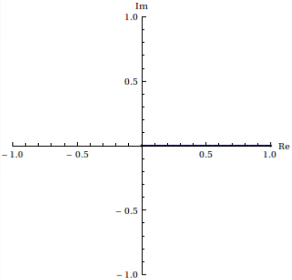
$\Gamma(\overline{B} \to f) \propto$
$e^{-\Gamma t} \left|\cos\frac{\Delta m t}{2} + e^{+i\phi_{\mathrm{weak}}} \sin\frac{\Delta m t}{2}\right|^2$

$\Delta\Gamma = 0$

Visualization of time-dependent CP asymmetry

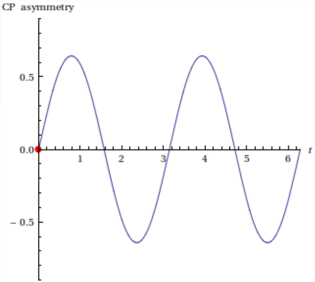
$B \to f$

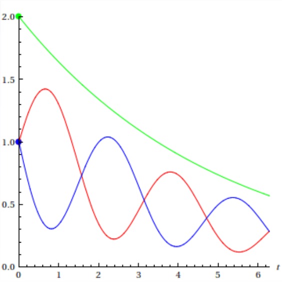




$\overline{B} \to f$

Asymmetry





Decay

$\Delta\Gamma = 0$

CP violation in mixing: a_{sl}^s measurement

B_s^0 mixing

Hamiltonian:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \overline{B}_s^0 \end{pmatrix}$$

Eigenstates:

$$\begin{aligned} M_L, M_H &: \quad \Delta m_s = M_H - M_L \\ \Gamma_L, \Gamma_H &: \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H \end{aligned}$$

$$\phi_{M/\Gamma} = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

Observable:

$$a_{\mathrm{sl}}^s = \frac{\Gamma(\overline{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \overline{f})}{\Gamma(\overline{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \overline{f})} = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_{M/\Gamma} \qquad (15)$$

- SM prediction: $a_{\mathrm{sl}}^s = (1.9 \pm 0.3) \times 10^{-5}$ *(arXiv: 1205.1444)*

KEY ELEMENTS OF THE ANALYSIS

- B_s production asymmetry does not affect the measurement (fast oscillations suppress this effect by 0.2% of the ~1% initial asymmetry)
- Prompt D_s have negligible asymmetry (~0.3%) and represent a small fraction of the signal
- Backgrounds are small and have negligible asymmetries
- We have MAGNET UP and MAGNET DOWN data samples of almost equal size, which allow to average out residual charge asymmetries in detection efficiency.

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Note: Small means ~ 1%

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ANALYSIS METHOD

PHILOSOPHY: DATA DRIVEN ANALYSIS, ALL CORRECTIONS ARE DERIVED FROM DATA, WITH TWO INDEPENDENT METHODS, WHENEVER POSSIBLE.

- Determination of the signal yields $D_s^{\pm}\mu^{\mp}, D_s^{\pm} \to \varphi\pi^{\pm}$ with 2011 full data set: 447 pb^{-1} collected with magnet polarity UP and 595 pb^{-1} collected with magnet polarity DOWN
- $\varphi \to K^+K^-$ mass cut provides almost equal kaon momentum spectra.
- Detailed analysis of background sources, mostly data based on data.
- Efficiency ratio derived from calibration samples, can be expressed as

$$\epsilon(D_s^-\mu^+) = \epsilon_{\rm id}(\mu^+) \times \epsilon_{\rm Trigger}(D_s^-\mu^+)\,,$$

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