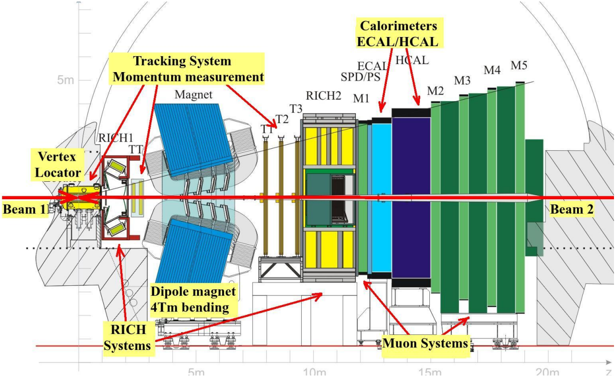
Determination of $\mathcal{CP}$-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decay

V. Batozskaya[1] on behalf of LHCb collaboration

[1]National Centre for Nuclear Research, Warsaw, Poland

XXII Cracow Epiphany Conference
7-9 January 2016

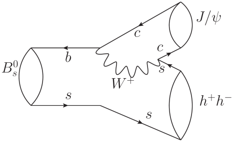
Large Hadron Collider beauty Detector



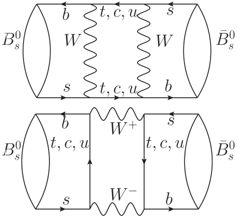
- Single-arm forward spectrometer covering range: $2<\eta<5$ ($10< \theta <300$ (250) mrad)
- Momentum resolution: $\Delta p/p = 0.4\%$ at 5 GeV/c to 0.6% at 100 GeV/c
- Impact parameter resolution: 20 μm for high P_T tracks
- $\mathcal{L} = 3$ fb^{-1}, collected in 2011-2012 at $\sqrt{s} = 7$-8 TeV

Violation of the $\mathcal{CP}$ symmetry

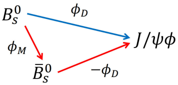
Three mechanisms of $\mathcal{CP}$ violation exist:



- Direct (in decay amplitudes)
- Mixing (indirect)
  - Described by phenomenological Schrödinger equation:
    $$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}=\left(\mathbf{M}-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B_s^0(t)\rangle\\|\bar{B}_s^0(t)\rangle\end{pmatrix}$$
  - Solutions give two mass eigenstates: B_H and B_L
    $|B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$
    $|B_H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$
  - Mixing parameters
    $\Delta m_s = M_H - M_L \qquad \Delta\Gamma_s = \Gamma_L - \Gamma_H$
    $\Gamma_s = \frac{\Gamma_L+\Gamma_H}{2} \qquad \phi_{12} = \arg(-M_{12}/\Gamma_{12})$



- Interference between direct decays and decays with mixing



In the Standard Model $\mathcal{CP}$ violation is described by the CKM matrix

Phase ϕ_s

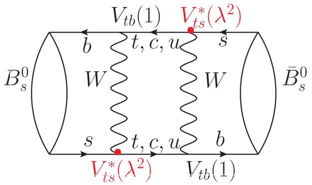
Due to interference between direct decays (D) and decay with mixing (M) we can to measure the value of ϕ_s

$$\phi_s = \Phi_M - 2\Phi_D = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

- from mixing:
  $\phi^M = 2\arg(V_{ts}V_{tb}^*)$
- from direct decays:
  $\phi^D = \arg(V_{cs}V_{cb}^*)$
  - If new particles are exchanged in box diagram, then value of ϕ^M will be different than SM prediction
    $\phi_s = \phi_s^{SM} + \phi_s^{NP}$

In the SM the phase ϕ_s^{SM} is small and very well predicted **[PRD 84 (2011) 033005]**:

$$\phi_s = -0.0363^{+0.0012}_{-0.0014}\ \text{rad}$$



The measurement ϕ_s is crucial in LHCb from $B_s^0 \to J/\psi\phi$ decays

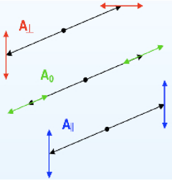
$B_s^0 \rightarrow J/\psi\phi$ decay

$B_s^0 \longrightarrow J/\psi \quad \phi$

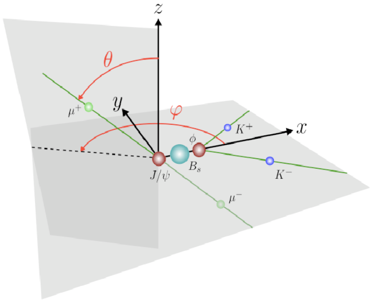
↑ pseudoscalar — vectors

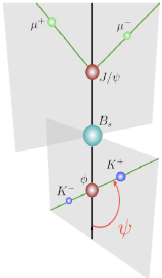
Three final states with relative orbital momentum $(\mathcal{CP}|J/\psi\phi\rangle = (-1)^L|J/\psi\phi\rangle)$:

- $\mathcal{CP}$-even: L $= 0,2 \rightarrow A_0, A_{\parallel}, \delta_0, \delta_{\parallel}$
- $\mathcal{CP}$-odd: L$=1 \rightarrow A_{\perp}, \delta_{\perp}$



The variuos components of $\mathcal{CP}$ can be separated statistically by measurement of three angles:





- θ and φ - polar and azimuthal angles which describe μ^+ direction (in the rest frame of J/ψ)
- ψ - angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ (in the rest frame of ϕ)

Decay rate of $B_s^0 \to J/\psi\phi$ decays

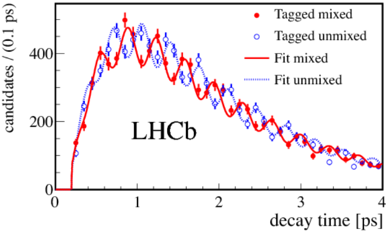
$$\frac{d^4 W(B_s^0 \to J/\psi\phi)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \equiv \frac{d^4 W}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)$$

- Time dependent part: $h_k(t)$
  - $A_0, A_{\|}, A_{\perp}, A_S$
  - $\phi_s, \Gamma_s, \Delta\Gamma_s, \Delta m_s$
- Angular dependent part: $f_k(\Omega)$
  - ψ, θ, φ

The phase ϕ_s measurement in $B_s^0 \to J/\psi\phi$ in LHCb

[NJP 15 (2013) 053021]

- Trigger and selection of $B_s^0 \to J/\psi\phi$ events
- Measurement of mass, proper time and angular variables value
- Determination of an initial flavour

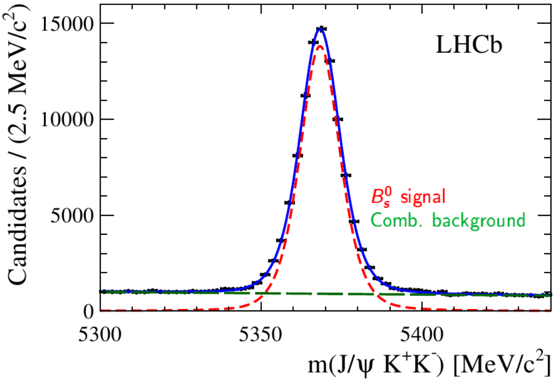


- Simultaneous fitting function of 12 physical observables:

$$\frac{d^4 W(B_s^0 \to J/\psi\phi)}{dt d\cos\theta d\varphi d\cos\psi} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, A_0, A_\parallel, A_\perp, A_S, \delta_0, \delta_\perp, \delta_\parallel, \delta_S)$$

$B_s^0 \to J/\psi(\mu\mu)\phi$ decay in LHCb

[PRL 114 (2015) 041801]

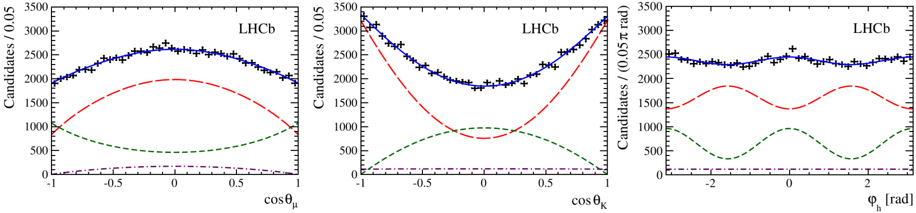


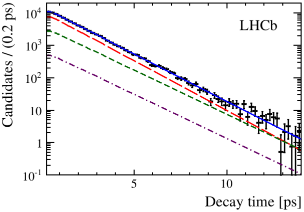
- $\mathcal{L}$=3 fb^{-1} (2011+2012)
- N_{sig} = 95 690±350

- Additional channel [PLB 736 (2014) 186]:
  - $B_s^0 \to J/\psi(\mu\mu)f_0(980)$ where $f_0 \to \pi^+\pi^-$
  - N_{sig} = 27 100±200 (3 fb^{-1})

Angular and decay time distributions

[PRL 114 (2015) 041801]





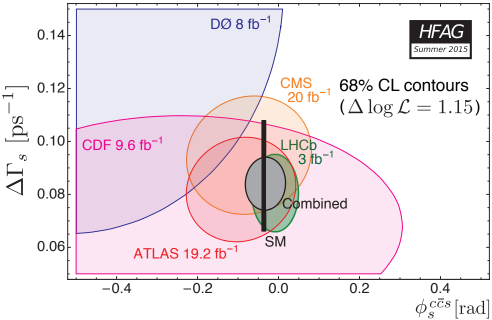
The relative orbital angular momentum of the final states is an admixture of:

- Total fit
- $\mathcal{CP}$-even: L = 0 and 2
- $\mathcal{CP}$-odd: L = 1
- $\mathcal{S}$-wave

The results of the parameters measurement

Standard Model predictions:

- $\phi_s^{c\bar{c}s}$ = -0.0363$^{+0.0012}_{-0.0014}$ rad **[PRD 84 (2011) 033005]**
- $\Delta\Gamma_s$ = 0.087$\pm$0.021 ps^{-1} **[A. Lenz et al, arXiv:1102.4274]**



- LHCb results **[PRL 114 (2015) 041801]**:

$$\phi_s^{c\bar{c}s} = \text{-}0.010\pm0.039 \text{ rad}$$
$$\Delta\Gamma_s = 0.0805\pm0.0091\pm0.0032 \text{ ps}^{-1}$$

- HFAG combination (including D∅ and CDF measurements):

$$\phi_s^{c\bar{c}s} = \text{-}0.034\pm0.033 \text{ rad}$$
$$\Delta\Gamma_s = 0.082\pm0.006 \text{ ps}^{-1}$$

Compatible with SM estimations!

$B_s^0 \to J/\psi(ee)\phi$ decay in LHCb

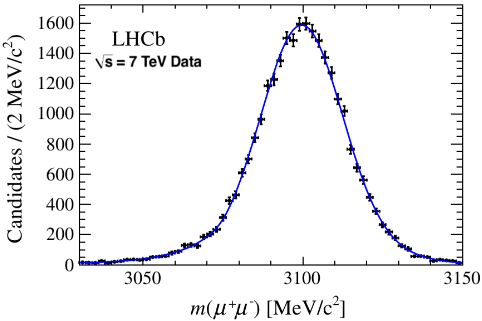
In order to increase the statistics of the data and to improve the accuracy of $\mathcal{CP}$ violating phase ϕ_s measurement, the analysis of e^+e^- mode in $B_s^0 \to J/\psi\phi$ decays is underway

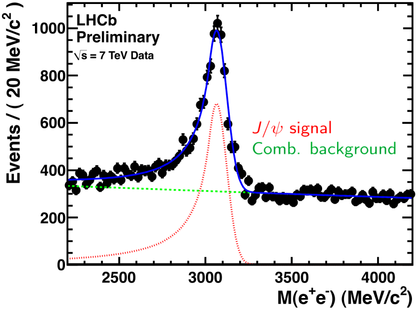
Experimental problems:

- e^+e^- irradiative Bremsstrahlung photons $\Rightarrow$ degradation of the B_s^0 and J/ψ mass resolution;
- Large electromagnetic and hadronic background in the electromagnetic calorimeter;
- Different trigger than in the $\mu\mu$ channel final state

$B_s^0 \to J/\psi(ee)\phi$ decay in LHCb

[PRD 87 (2013) 112010]





- $\mathcal{BR}(J/\psi \to \mu^+\mu^-) = (5.961\pm0.033)\%$
- $\mathcal{BR}(J/\psi \to e^+e^-) = (5.971\pm0.032)\%$
- Estimated yield of e^+e^- channel is $\sim 10\%$ of the leading $B_s^0 \to J/\psi(\mu\mu)\phi(K^+K^-)$ mode

Summary

- Using LHCb data collected in Run I (3 fb^{-1}):
  - ≈96 000 $B_s^0 \to J/\psi(\mu\mu)\phi(KK)$ signal candidates were selected
  - ϕ_s and $\Delta\Gamma_s$ were measured with the best world accuracy

$$\phi_s^{c\bar{c}s} = -0.010 \pm 0.039 \text{ rad}$$

$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}$$

  - All mesurements are in agreement with the Standard Model predictions and with the results of other experiments
- $B_s^0 \to J/\psi(ee)\phi(K^+K^-)$ decays is underway:
  - Estimated number of signal events is ≈10 000 for 3 fb^{-1} (2011+2012 data)
  - e^+e^- channel could bring ∼ 10% of the leading $B_s^0 \to J/\psi(\mu\mu)\phi(K^+K^-)$ mode statistics
- Future estimations for LHCb: [LHCb-PUB-2014-040]

Decay mode $\sigma_{stat}(\phi_s)$ [rad]	Run I (3 fb^{-1}) (2010-2012)	Run II (8 fb^{-1}) (2015-2018)	LHCb upgrade (+2024, 46 fb^{-1})	Theory limit
$B_s^0 \to J/\psi K^+K^-$	0.049	0.025	0.009	∼0.003

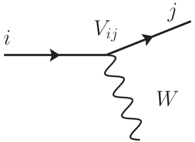
Thank you for your attention

Backups

CKM - quark mixing matrix

The Cabibbo-Kobayashi-Maskawa matrix is a 3×3 unitary matrix which consists of information about flavour changing weak decays

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} \leftrightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

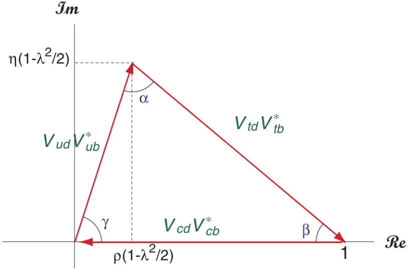


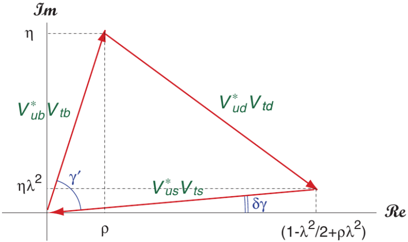
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda \approx 0.22$

CKM - quark mixing matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$





$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\Downarrow d \to s$$

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \Longrightarrow$$

$$V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0$$

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \equiv \delta\gamma$$

Can be measured in the decay of $B_s^0 \to J/\psi\phi$: $(\bar{b}s) \to (c\bar{c})(s\bar{s})$

The $B_s^0 \to J/\psi\phi$ decays

The amplitude for $\bar{b} \to \bar{c}c\bar{s}$ decay maybe expressed as a combination of:

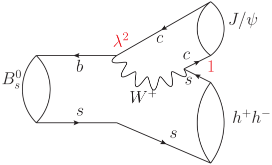
- a tree amplitude (A_T)
- the penguin amplitude (P_u, P_c, P_t)

$$\mathbf{A} = V_{cs}V_{cb}^{*}A_T + V_{us}V_{ub}^{*}P_u + V_{cs}V_{cb}^{*}P_c + V_{ts}V_{tb}^{*}P_t$$

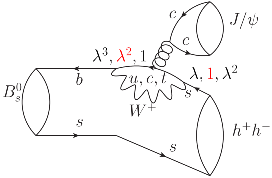
$$= \underline{V_{cs}V_{cb}^{*}(A_T + P_c - P_t)} + V_{us}V_{ub}^{*}(P_u - P_t)$$

where $V_{ts}V_{tb}^{*} = -V_{us}V_{ub}^{*} - V_{cs}V_{cb}^{*}$

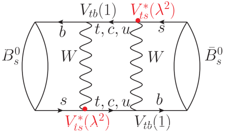
- $V_{cs}V_{cb}^{*} \sim A\lambda^2(1-\lambda^2/2)$ and $V_{us}V_{ub}^{*} \sim A\lambda^4(\rho + i\eta)$,
- the $B_s^0 \to J/\psi\phi$ decay amplitude is dominated by one weak phase $\Phi_D = arg(V_{cs}V_{cb}^{*})$



Tree diagram



Penguin diagram



In the SM, the B_s^0 meson may change into $\bar{B}_s^0$ and vice versa through box diagrams
$\Phi_M = 2arg(V_{ts}V_{tb}^{*})$

The angle measurements

The differential decay rates:

$$\frac{d^4 W(B_s^0 \to J/\psi\phi)}{dt d\cos\theta d\varphi d\cos\psi} \equiv \frac{d^4 W}{dt d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega) \qquad \frac{d^4 W(\bar{B}_s^0 \to J/\psi\phi)}{dt d\cos\theta d\varphi d\cos\psi} \equiv \frac{d^4 \bar{W}}{dt d\Omega} \propto \sum_{k=1}^{10} \bar{h}_k(t) f_k(\Omega)$$

k	$h_k(t)$	$\bar{h}_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\|A_0(t)\|^2$	$\|\bar{A}_0(t)\|^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\|A_\parallel(t)\|^2$	$\|\bar{A}_\parallel(t)\|^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\|A_\perp(t)\|^2$	$\|\bar{A}_\perp(t)\|^2$	$\sin^2\psi\sin^2\theta$
4	$\|A_S(t)\|^2$	$\|\bar{A}_S(t)\|^2$	$\frac{4}{3}\sin^2\theta$
5	$\Im\{A_\parallel^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_\parallel^*(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
6	$\Re\{A_0^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_0^*(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
7	$\Im\{A_0^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_0^*(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$
8	$\Re\{A_S^*(t)A_\parallel(t)\}$	$\Re\{\bar{A}_S^*(t)\bar{A}_\parallel(t)\}$	$-\frac{2}{3}\sqrt{6}\sin\psi\sin 2\theta\cos\varphi$
9	$\Im\{A_S^*(t)A_\perp(t)\}$	$\Im\{\bar{A}_S^*(t)\bar{A}_\perp(t)\}$	$\frac{2}{3}\sqrt{6}\sin\psi\sin 2\theta\sin\varphi$
10	$\Re\{A_S^*(t)A_0(t)\}$	$\Re\{\bar{A}_S^*(t)\bar{A}_0(t)\}$	$\frac{8}{3}\sqrt{3}\sin^2\theta\cos\psi$

for particles ⇑ for antiparticles ⇑

Amplitudes for $B_s^0 \to J/\psi\phi$

$$|A_0(t)|^2 = |A_0|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right]$$

$$|A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right]$$

$$|A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right]$$

$$|A_S(t)|^2 = |A_S|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\phi_s \sin(\Delta m_s t)\right]$$

$$\Im\{A_\parallel^*(t)A_\perp(t)\} = |A_\parallel||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_\parallel)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_\parallel)\cos\phi_s \sin(\Delta m_s t)\right]$$

$$\Re\{A_0^*(t)A_\parallel(t)\} = |A_0||A_\parallel|e^{-\Gamma_s t}\cos(\delta_\parallel - \delta_0)\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\phi_s \sin(\Delta m_s t)\right]$$

$$\Im\{A_0^*(t)A_\perp(t)\} = |A_0||A_\perp|e^{-\Gamma_s t}\left[-\cos(\delta_\perp - \delta_0)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin(\delta_\perp - \delta_0)\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_0)\cos\phi_s \sin(\Delta m_s t)\right]$$

$$\Re\{A_S^*(t)A_\parallel(t)\} = |A_S||A_\parallel|e^{-\Gamma_s t}\left[-\sin(\delta_\parallel - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\delta_\parallel - \delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel - \delta_S)\cos\phi_s \sin(\Delta m_s t)\right]$$

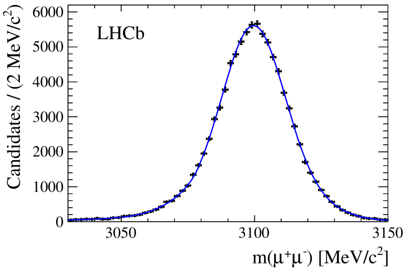
$$\Im\{A_S^*(t)A_\perp(t)\} = |A_S||A_\perp|e^{-\Gamma_s t} - \sin(\delta_\perp - \delta_S)\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\phi_s \sin(\Delta m_s t) - \sin\phi_s \sin(\Delta m_s t)\right]$$

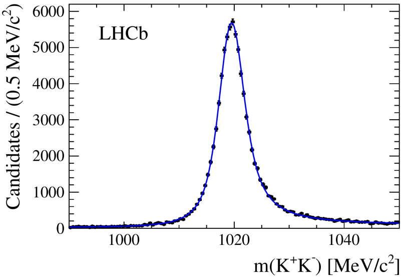
$$\Re\{A_S^*(t)A_0(t)\} = |A_S||A_0|e^{-\Gamma_s t}\left[-\sin(\delta_0 - \delta_S)\sin\phi_s \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos(\delta_0 - \delta_S)\cos(\Delta m_s t) - \sin(\delta_0 - \delta_S)\cos\phi_s \sin(\Delta m_s t)\right]$$

Trigger and selection

- Reconstructed as $B_s^0 \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$
- Trigger: Muons from $J/\psi \to \mu^+\mu^-$
- Selection based on Boosted Decision Tree
  trained on Simulation (Signal) and Data (Background)
- Event yield: 95 690±350 signal candidates

[PRD 87 (2013) 112010]



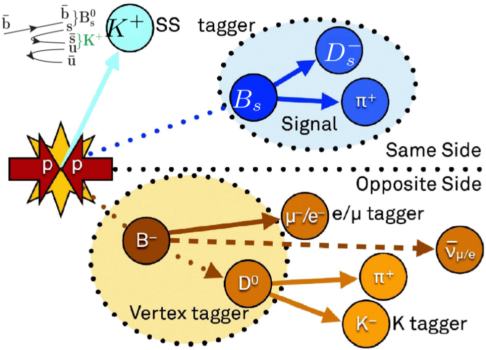


- Mass model:
  - Sum of two CB function

- Mass model:
  - P-wave: RBW⊗Gauss function
  - S-wave: polynomial function

The flavour tagging of initial B_s^0

- Since B_s^0 and $\bar{B}_s^0$ mixing we need to tag the initial flavour state
- In LHCb is used two types of tagging:
  - same side - charge kaon which is correlated with B_s^0
  - opposite side - charge lepton or kaon from second B decay
- To check the tagging algorithm similar and self tagging decays to signal are used:
  $B^+ \to J/\psi K^+$ for OS and
  $B_s^0 \to D_s^- \pi^+$ for SS



- Estimated the efficiency of the algorithm:
  - tagging efficiency ϵ_{tag}
  - corrected mistag probability ω
  - total efficiency $\epsilon_{eff} = \epsilon_{tag}(1\text{-}2\omega)^2 = (3.73 \pm 0.15)\%$ for $B_s^0 \to J/\psi(\mu\mu)\phi$

The results of the parameters measurement

$\mathcal{CP}$ violation measurements in Run I data from LHCb, ATLAS and CMS:

Measurement of ϕ_s in $b \to c\bar{c}s$ modes:

- LHCb ($B_s^0 \to J/\psi K^+K^-$, $B_s^0 \to J/\psi \pi^+\pi^-$, 3 fb^{-1}): $\phi_s^{c\bar{c}s}$=-0.010±0.039 rad
- ATLAS ($B_s^0 \to J/\psi K^+K^-$, 19.2 fb^{-1}): $\phi_s^{c\bar{c}s}$=-0.094±0.083±0.033 rad
- CMS ($B_s^0 \to J/\psi K^+K^-$, 19.7 fb^{-1}): $\phi_s^{c\bar{c}s}$=-0.075±0.097±0.031 rad

Measurement of $\Delta\Gamma_s$ in $B_s^0 \to J/\psi K^+K^-$ modes:

- LHCb (3 fb^{-1}): $\Delta\Gamma_s$=0.0805±0.0091±0.0032 ps^{-1}
- ATLAS (19.2 fb^{-1}): $\Delta\Gamma_s$=0.082±0.011±0.007 ps^{-1}
- CMS (19.7 fb^{-1}): $\Delta\Gamma_s$=0.095±0.013±0.007 ps^{-1}