Sensitivities to the B_s^0–$\overline{B_s^0}$ Mixing Parameters using $\bar{b} \rightarrow \bar{c}c\bar{s}$ Quark Transitions at LHCb

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- B_s^0–$\overline{B_s^0}$ Mixing
- Physics Motivations
- Likelihood, Physics Models
- Expected Sensitivities & Conclusions

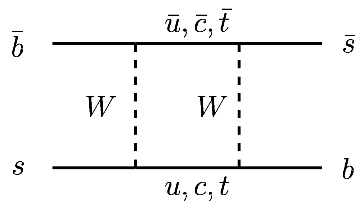
B_s^0–$\overline{B_s^0}$ System

The B_s^0–$\overline{B_s^0}$ system will serve to test the Standard Model (SM) description of CP violation, based on the CKM picture

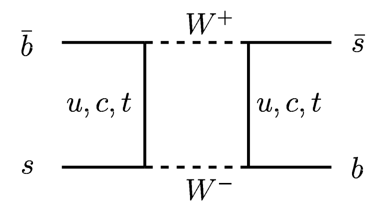
- The $\hat{V}_{\mathrm{CKM}}$ matrix contains 4 independent weak phases $\beta^{(bd)} \equiv \beta_d$, $\gamma^{(bd)} \equiv \gamma_d$, $\beta^{(sd)} \equiv \chi'$ and $\beta^{(bs)} \equiv \beta_s \equiv \chi$
- These phases are in what we are interested in a CP-violating experiment
- The squashed (bs) triangle is relevant for the B_s^0 system

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0\,, \quad \beta^{(bs)} \equiv \arg\left(-V_{cb} V_{cs}^* / V_{tb} V_{ts}^*\right)$$

where $V_{tb}^* V_{ts}$ controls B_s^0–$\overline{B_s^0}$ oscillations



B_s^0–$\overline{B_s^0}$ mixing
$\Delta B = 2$ transition



- The B_s^0–$\overline{B_s^0}$ weak mixing phase ϕ_s is expected to be small in the SM

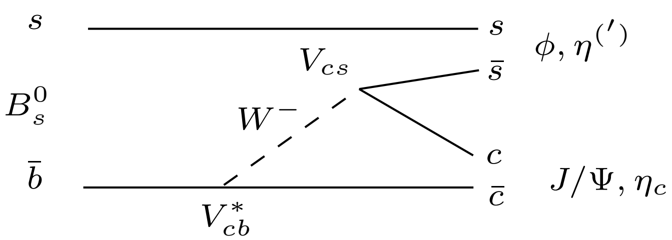
$$\phi_s \equiv 2 \arg\left[V_{ts}^* V_{tb}\right] \approx -2\lambda^2 \eta \approx -2\chi \sim \mathcal{O}(-0.04)$$

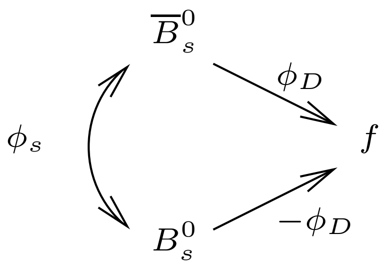
where $\lambda \equiv \sin(\theta_{\mathrm{C}})$ and η are Wolfenstein's parameters

$\bar{b} \to \bar{c}c\bar{s}$ Quark Transitions

- B_s^0 decays into CP self-conjugate final states caused by $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions
  - $B_s^0 \to J/\psi\phi$: admixture of CP eigenstates ($\eta_{J/\psi\phi} = +1, -1, +1$)
  - $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta^{(\prime)}$: pure CP-even eigenstates

Decays dominated by only one CKM phase $\arg[V_{cb}^* V_{cs}] \equiv -\phi_D$ (penguin diagrams suppressed)

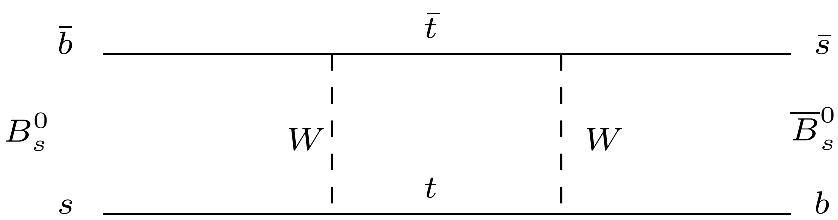


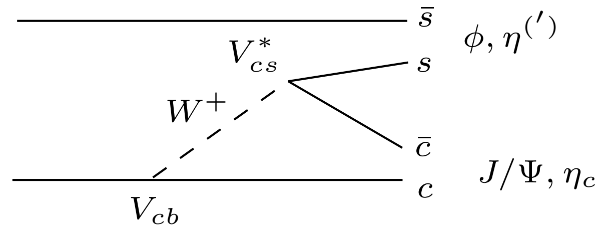


Due to the mixing, the flavor states B_s^0–$\overline{B_s^0}$ can either remain unchanged and decay to f, or oscillate into each other, ...

- "Mixing-induced" CP violation arises from a phase mismatch (ϕ_{CKM}) between the weak mixing phase $\phi_s \equiv 2\arg[V_{ts}^* V_{tb}]$ and the tree phase $\phi_D \equiv \arg[V_{cb}V_{cs}^*]$

$$\phi_{CKM} = \phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$$





- $\phi_s \approx -2\chi \leftrightarrow$ *strange* counterpart of $\sin(2\beta_d)$ measurement for B_d^0 ($\phi_d \approx 2\beta_d$)

CP Asymmetry and Tagging

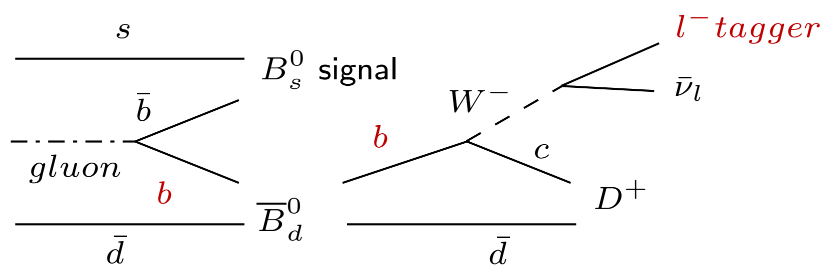
- The study of CP violation implies the measurement of the time-dependent decay asymmetry $\mathcal{A}_{\rm CP}^{obs}(t)$ between the $\overline{B_s^0}$ and the B_s^0

$$\mathcal{A}_{\rm CP}^{obs}(t) \equiv \frac{R\left(\overline{B_s^0}(t) \to f\right) - R\left(B_s^0(t) \to f\right)}{R\left(B_s^0(t) \to f\right) + R\left(\overline{B_s^0}(t) \to f\right)}$$

with t the proper time, R the observed decay rates and $f = \bar{f}$

- When a signal B is observed, we need to know the initial flavor of the reconstructed mesons $\Rightarrow$ flavor tagging

  - *opposite-side* tagging: identify the b-hadron containing the other b



  - *same-side* tagging: use the companion of the b quark in the signal B

- The tagging procedure does not always give an answer: tagging efficiency ε_{tag}
- Even if there is a tag, our identification could be incorrect: wrong tag ω

$\Rightarrow$ The tagging will *dilute* the theoretical asymmetry $\mathcal{A}_{\rm CP}^{th}(t)$ with a factor D

$$\mathcal{A}_{\rm CP}^{obs}(t) = D \cdot \mathcal{A}_{\rm CP}^{th}(t)$$

which reduces to $D = (1 - 2\omega)$ for a perfect resolution and no background

Physics Motivations of $\bar{b} \to \bar{c}c\bar{s}$ Transitions

- The mixing-induced CP asymmetry for a given CP eigenstate (with eigenvalue η_f) directly measures ϕ_s (tree phase $\phi_D \approx 0$)

$$\mathcal{A}^{th}_{\rm CP}(t) = \frac{-\eta_f \sin(\phi_s) \sin(\Delta M_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f \cos(\phi_s) \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$

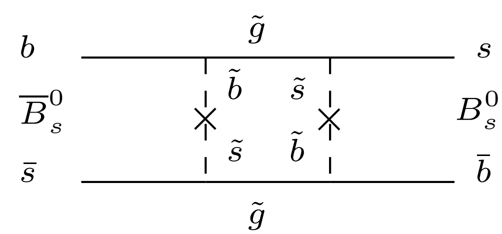
  where $\Delta M_s \equiv M_{\rm H} - M_{\rm L}$ and $\Delta\Gamma_s \equiv \Gamma_{\rm L} - \Gamma_{\rm H}$ are the mass and decay width differences of the physical (mass) eigenstates $\left|B_{\rm L/H}\right\rangle = p\left|B^0_s\right\rangle \pm q\left|\overline{B^0_s}\right\rangle$

- Physics Motivations : measure the mixing parameters
  - extract $\Delta M_s \sim \mathcal{O}(20)\,{\rm ps}^{-1}$ and $\Delta\Gamma_s/\Gamma_s \sim \mathcal{O}(10\%)$, with $\Gamma_s \equiv (\Gamma_{\rm H} + \Gamma_{\rm L})/2$ the average decay width ($\tau_{B^0_s} = 1/\Gamma_s = 1.46$ ps)
  - probe the B^0_s–$\overline{B^0_s}$ weak mixing phase ϕ_s, expected to be small in the SM $\sim \mathcal{O}(-0.04)$

$\Rightarrow$ B^0_s system represents a prime candidate for the discovery of New Physics

SUSY contributions (mainly induced by gluino exchange) to the B^0_s–$\overline{B^0_s}$ transitions could drastically change the SM predictions (hep-ph/0311361):

$\sin(\phi_s) \sim \mathcal{O}(-1)$, $\Delta M_s = (10 - 10^4)\,{\rm ps}^{-1}$



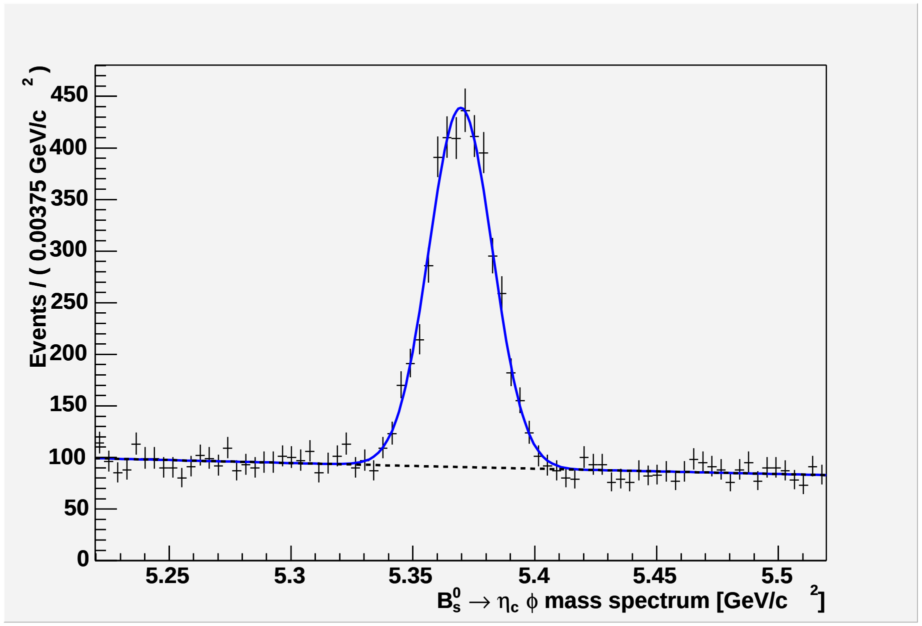
Sensitivity Studies

- The sensitivities of LHCb to the CP B_s^0 observables are assessed by the use of fast *toy* Monte Carlo (MC) experiments using
  - $B_s^0 \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$
  - $B_s^0 \to \eta_c(2\pi 2K, 4\pi)\phi(K^+K^-)$
  - $B_s^0 \to J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$
- The parameterizations used are obtained from the study of fully simulated and reconstructed MC events (see talk of Benjamin Carron)
  - the computed per-event lifetime error σ_t is used in the fast simulation such that an experimental uncertainty is assigned to each generated event
  - The tagging efficiency ε_{tag} and the mistag probability ω are taken from the full MC
- For $B_s^0 \to J/\psi\phi$, the so-called transversity angle θ_{tr} is introduced to take into account the angular distribution of the two vectors in the final state
- Physics parameters: extracted using an "unbinned extended maximum" likelihood fit to the proper time and mass distributions (and to $\cos(\theta_{tr})$ for $J/\psi\phi$)
- The fit is simultaneously maximized with the control sample $B_s^0 \to D_s^-\pi^+$ which allows the determination of ΔM_s, ω and $\Delta\Gamma_s$

Likelihood (1)

$$\mathcal{L} = \prod_{i \in B_s^0 \to f}^{N_{obs}} \left[f^{sig}(m^i) R^{sig}(t^i_{rec}, \sigma^i_t) + (1 - f^{sig}(m_i)) R^{bkg}(t^i_{rec}) \right]$$

- Sig and bkg probabilities (f^{sig}, f^{bkg}) of an event are based on its reconstructed mass
  - gaussian shape for the signal
  - exponential shape for the background



$B_s^0 \to \eta_c \phi$ mass distribution (with $\mathcal{L}$ fit projection superimposed)

Annual yield = 3k
$B/S = 0.8$
Mass resolution $\sigma_{B_s^0} = 13\mathrm{MeV/c^2}$
True B_s^0 mass $= 5369.6\mathrm{MeV/c^2}$
Bkg $\mu_{bkg} = -0.6\mathrm{MeV/c^2}$

Likelihood (2)

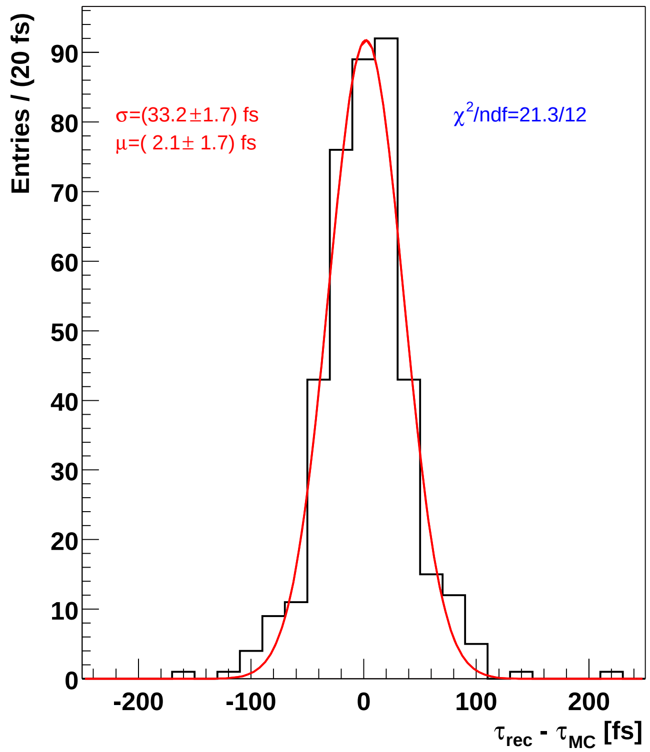
$$\mathcal{L} = \prod_{i \in B_s^0 \to f}^{N_{obs}} \left[f^{sig}(m^i) R^{sig}(t^i_{rec}, \sigma^i_t) + (1 - f^{sig}(m_i)) R^{bkg}(t^i_{rec}) \right]$$

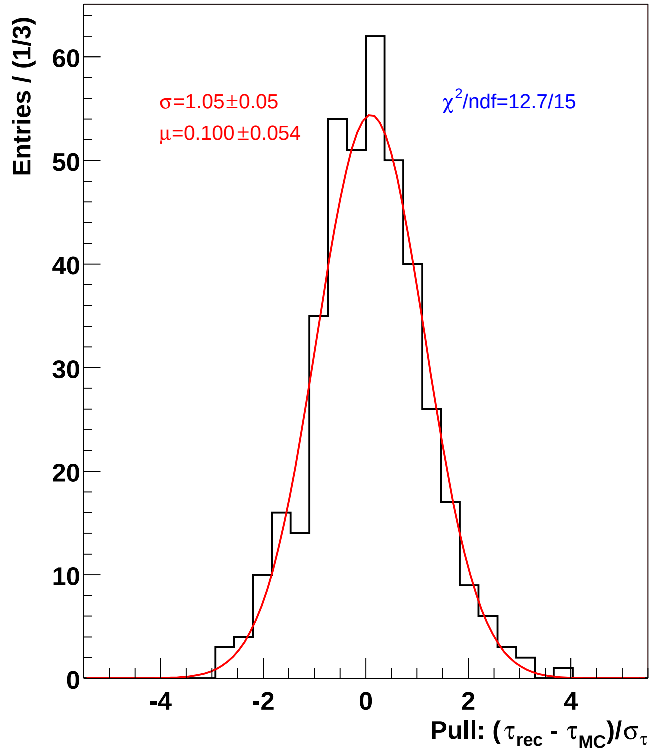
- R^{sig}: observed signal decay rate

$$R^{sig}(t^i_{rec}, \sigma^i_t | \vec{\alpha}) = A(t^i_{true}) \left[(1-\omega)\Gamma_{B \to f}(t^i_{true}, \vec{\alpha}) + \omega \Gamma_{\overline{B} \to f}(t^i_{true}, \vec{\alpha}) \right] \otimes Res(t^i_{rec} - t^i_{true}, s_1 \sigma^i_t, \mu_1 \sigma^i_t)$$

  - Γ: analytical decay rates
  - $\vec{\alpha} = (\Delta M_s, \Delta\Gamma_s, ...)$: physics parameters
  - Res: Gaussian resolution scaled with σ^i_t
  - A: flat acceptance
- R^{bkg}: background decay rate, exponential shape
  - For $B_s^0 \to D_s^- \pi^+$, $\tau_{bkg} \approx \tau_{B_s^0}/2$
- For $B_s^0 \to J/\psi\phi$, the signal likelihood is given by the sum of the CP-even and CP-odd components, including the corresponding θ_{tr} contribution

$B_s^0 \to \eta_c \phi$ Proper Time – Full Monte Carlo Simulation





B_s^0 proper time τ resolution:
$\sigma \sim 33$ fs
$\tau = m_{B_s^0}\, \vec{p}_{B_s^0} \cdot \vec{L} / \left|\vec{p}_{B_s^0}\right|^2$
$\vec{L} = \vec{x}_S - \vec{x}_P$ decay length

Pull: ~ 1
σ_τ: computed per-event error on τ using the tracks covariance matrices

Physics Model: $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$

- $f = \eta_c\phi, J/\psi\eta$ CP-even eigenstates: $(\mathcal{CP})|f\rangle = \eta_f\,|f\rangle$, $\eta_f = +1$
- Observed transition rates of initially pure B_s^0 and $\overline{B_s^0}$ states (perfect resolution, no bkg)

$$R\left(B_s^0(t) \to f\right) = |A_f(0)|^2\,\frac{e^{-\Gamma_s t}}{2} \times \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f\cos(\phi_s)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + D\,\eta_f\sin(\phi_s)\sin\left(\Delta M_s t\right)\right]$$

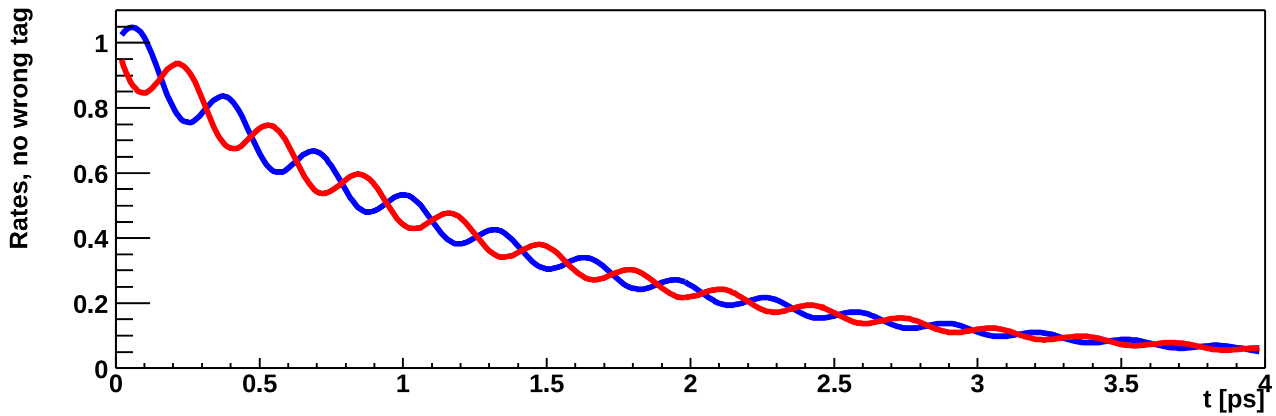
$$R\left(\overline{B_s^0}(t) \to f\right) = |A_f(0)|^2\,\frac{e^{-\Gamma_s t}}{2} \times \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \eta_f\cos(\phi_s)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - D\,\eta_f\sin(\phi_s)\sin\left(\Delta M_s t\right)\right]$$

  - $A_f(0) \equiv A\left(B_s^0 \to f\right)$: instantaneous decay amplitude
  - $D = (1-2\omega)$: dilution factor
- We get the corresponding analytical transition rates Γ by setting $\omega = 0$ (i.e. no wrong tag) in the observed decay rates R

$B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$ Decay Rates

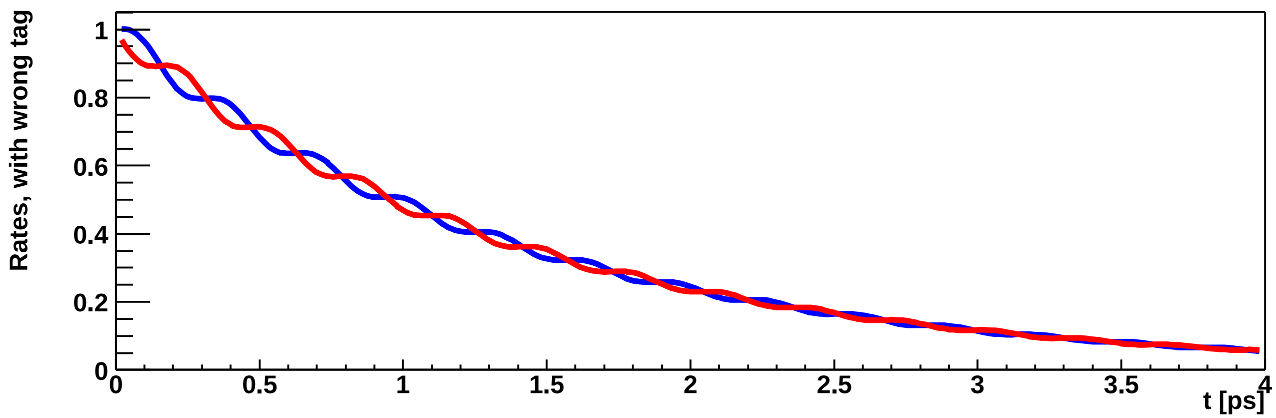
Decay rates for $B_s^0 \to \eta_c\phi$ and $B_s^0 \to J/\psi\eta$ in case of a perfect resolution

- Blue: initial pure $\overline{B_s^0}$, Red: initial pure B_s^0
- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta\Gamma_s/\Gamma_s = 0.1$, $\sin(\phi_s) = -0.1$ (nominal $\sin(\phi_s) = -0.04$)



No wrong tag ω

$\longrightarrow$ perfect tagging



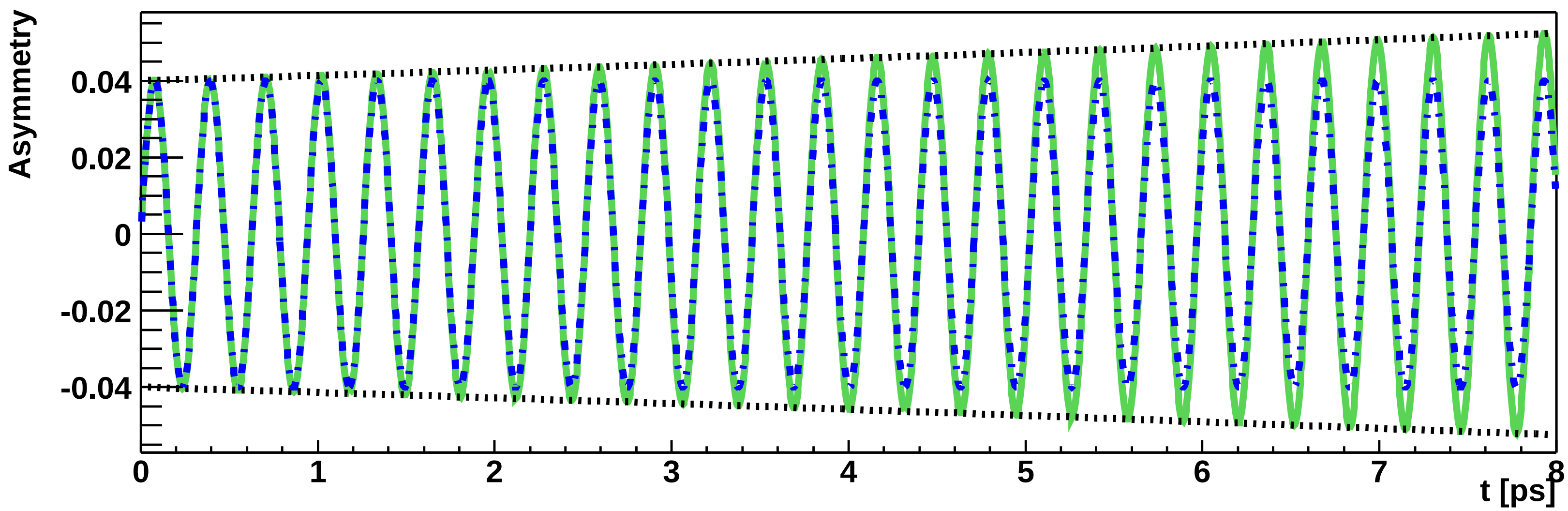
With wrong tag $\omega = 0.3$

$\longrightarrow$ wiggles are flattened

$B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$: *Asymmetry*

Asymmetry $\mathcal{A}_{\rm CP}(t)$ for $B_s^0 \to \eta_c\phi$ and $B_s^0 \to J/\psi\eta$ in case of a perfect resolution

- Solid green: $\mathcal{A}_{\rm CP}$ with no mistag ω=0
- Dotted black: envelope due to non-zero $\Delta\Gamma_s$
- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta\Gamma_s/\Gamma_s = 0.1$, $\sin(\phi_s) = -0.04$ (nominal parameters)



- Dashed blue: $\mathcal{A}_{\rm CP}$ with $\omega = 0$ and $\Delta\Gamma_s = 0$

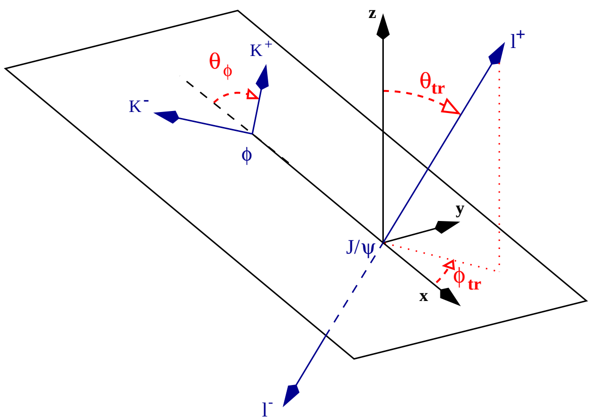
$\to$ oscillation amplitude given by $A_{mix} = -\eta_f \sin(\phi_s)$

Physics Model: $B_s^0 \to J/\psi\phi$

- In $B_s^0 \to J/\psi\phi$, the final state f is an admixture of CP eigenstates
  - ☆ $f = 0, \|$: CP-even configuration, $\eta_f = +1$, $f = \perp$: CP-odd configuration, $\eta_f = -1$
- Linear polarization amplitudes corresponding to the different configurations are introduced (hep-ph/9804293, hep-ph/0012219): $A_f(t), \quad \text{for } f = 0, \|, \perp$
  - ☆ The fraction of CP-odd decays is defined as $R_T \equiv |A_\perp(0)|^2 / \sum_{i=0,\|,\perp} |A_f(0)|^2 \sim \mathcal{O}(0.2)$
- Each of the $|A_f(t)|^2$ corresponds to an *ordinary* decay rate of a pure CP eigenstate for a $\bar{b} \to \bar{c}c\bar{s}$ transition (for a given η_f eigenvalue)
- The one-angle θ_{tr} distribution enables us to disentangle the different CP eigenstates

$$\frac{d\Gamma(t)}{d(\cos(\theta_{tr}))} \propto \left[|A_0(t)|^2 + \left|A_\|(t)\right|^2\right] \frac{3}{8}(1+\cos^2\theta_{tr}) + |A_\perp(t)|^2 \frac{3}{4}\sin^2\theta_{tr}$$

The transversity angle θ_{tr} corresponds to the angle between the positive lepton from the J/Ψ and the ϕ decay plane, in the J/Ψ rest frame



Physics Model: $B_s^0 \to D_s^- \pi^+$

- The decay $B_s^0 \to D_s^- \pi^+$ is flavor specific in which a single tree diagram contributes
  - B_s^0 decays instantaneously as $f = D_s^- \pi^+$ and $\overline{B_s^0}$ instantaneously as $D_s^+ \pi^-$
  - No expected CP violation in $B_s^0 \to D_s^- \pi^+$
- Analytical decay rates with a possible mistag probability ω

$$R_f(t) = R_{B_s^0 \to f}(t) \quad = \quad |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + (1-2\omega)\cos(\Delta M_s t)\right]$$

$$\overline{R}_f(t) = R_{\overline{B_s^0} \to f}(t) \quad = \quad |A_f(0)|^2 \frac{e^{-\Gamma_s t}}{2} \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - (1-2\omega)\cos(\Delta M_s t)\right]$$

- Observed flavor asymmetry $\mathcal{A}_f^{obs}$

$$\mathcal{A}_f^{obs}(t) \quad = \quad D \cdot \mathcal{A}_f^{th}(t)$$

with the theoretical flavor asymmetry $\mathcal{A}_f^{th}$

$$\mathcal{A}_f^{th}(t) \quad \equiv \quad \frac{\overline{R}_f(t) - R_f(t)}{\overline{R}_f(t) + R_f(t)} = -\frac{\cos(\Delta M_s t)}{\cosh\left(\frac{\Delta\Gamma_s t}{2}\right)}$$

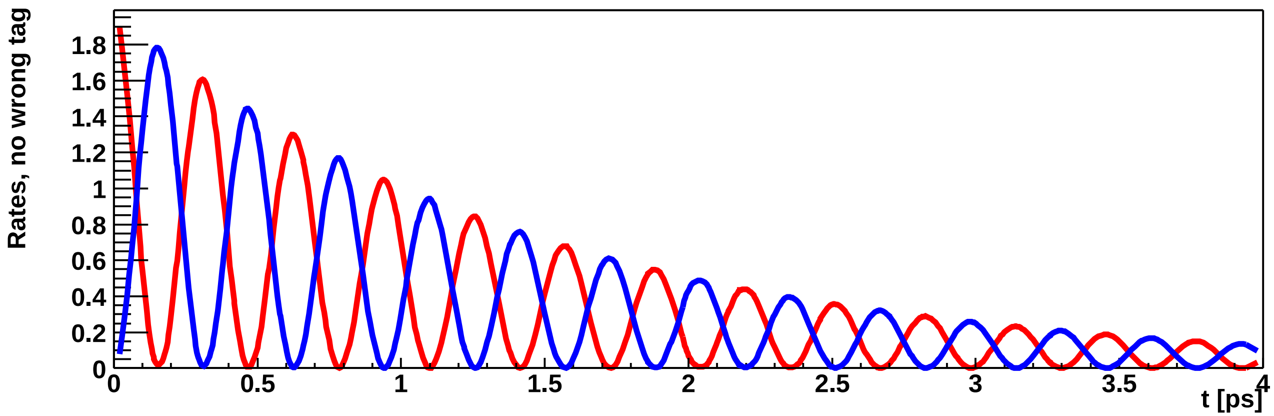
where the dilution factor D reduces to $D = (1-2w)$ in case of a perfect resolution

- $B_s^0 \to D_s^- \pi^+$ allows the extraction of the parameters ΔM_s, $\Delta\Gamma_s$ and ω

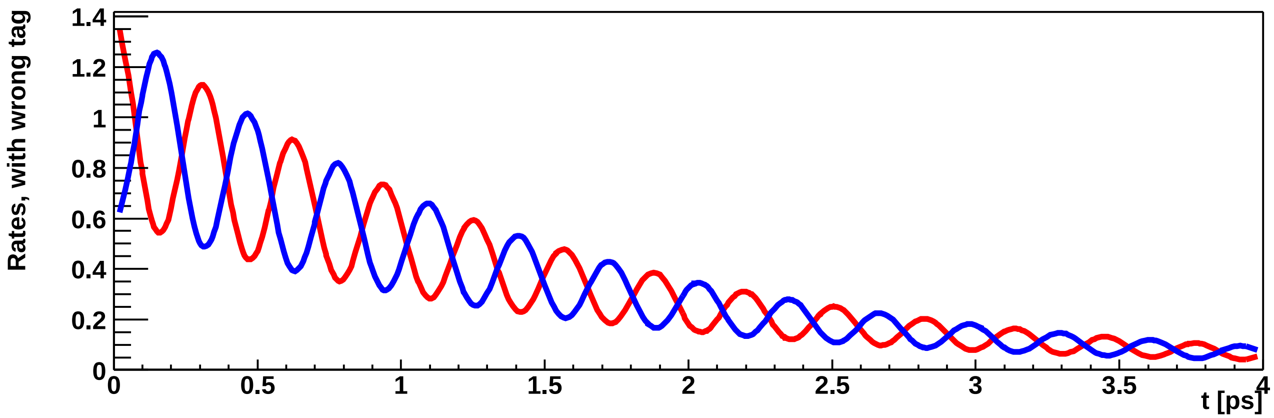
$B_s^0 \to D_s^- \pi^+$ Decay Rates

$B_s^0 \to D_s^- \pi^+$ decay rates $\Gamma(t)$ in case of a perfect resolution

- Rates $\to$ Blue: initial pure $\overline{B_s^0}$, Red: initial pure B_s^0, Dashed green: no tag ($\omega = 0.5$)
- $\Delta M_s = 20\text{ps}^{-1}$, $\Delta\Gamma_s/\Gamma_s = 0.1$ (nominal parameters)



No wrong tag $\omega = 0$



With wrong tag $\omega = 0.3$

$\to$ $\omega \neq 0$: raise of $\overline{B_s^0}$ and B_s^0 starting points

$\to$ attenuation of the oscillations

Toy Monte Carlo Setup

- For every signal channel, events are generated with the following physics parameters
  - $\Delta M_s = 20\text{ps}^{-1}$
  - $\Delta\Gamma_s/\Gamma_s = 0.1$
  - $1/\Gamma_s = 1.46\text{ps}$
  - $\sin(\phi_s) = -0.04$
  - $R_T = 0.2$, for $B_s^0 \to J/\psi\phi$
  - ω and ε_{tag} taken from the full MC, e.g. $\omega = 30\%$ and $\varepsilon_{tag} = 55\%$ for $B_s^0 \to \eta_c\phi$
- The sig/bkg probabilities were obtained using parameterizations from the full MC

Decay channel	N_s	B/S	Window $[\text{MeV}/c^2]$	$\sigma_{B_s^0}$ $[\text{MeV}/c^2]$
$B_s^0 \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$	100 k	0.3	± 50	15
$B_s^0 \to \eta_c(2\pi 2K, 4\pi)\phi(K^+K^-)$	3 k	0.8	± 45	13
$B_s^0 \to J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$	7 k	1.6	± 90	33
$B_s^0 \to D_s^-\pi^+$	80 k	0.5	± 50	13

B/S: 90% CL upper limit on the background level from inclusive $b\bar{b}$ events (dominant source)

- For each signal channel, 1000 toy experiments each corresponding to one year of data taking at LHCb are generated

Expected Sensitivities & Conclusions

- Expected statistical precisions for one year of LHCb data taking (preliminary)

Sensitivity	$\sigma(\Delta M_s)$ [ps^{-1}]	$\sigma(\Delta\Gamma_s/\Gamma_s)$	$\sigma(\phi_s)$ [rad]
$B_s^0 \to J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$	0.024	0.018	0.064
$B_s^0 \to \eta_c(2\pi 2K, 4\pi)\phi(K^+K^-)$	0.017	0.031	0.153
$B_s^0 \to J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$	0.023	0.024	0.154
Combined ϕ_s sensitivity: $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$			0.109
Combined ϕ_s sensitivity: $B_s^0 \to \eta_c\phi$, $B_s^0 \to J/\psi\eta$, $B_s^0 \to J/\psi\phi$			0.055

- The following $\bar{b} \to \bar{c}c\bar{s}$ decays to pure CP eigenstates are currently under study at LHCb to increase the sensitivity to ϕ_s
  - ☆ $B_s^0 \to J/\Psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0)$
  - ☆ $B_s^0 \to J/\Psi(\mu^+\mu^-)\eta^{'}(\pi^+\pi^-\eta(\gamma\gamma))$
  - ☆ $B_s^0 \to J/\Psi(\mu^+\mu^-)\eta^{'}(\pi^+\pi^-\gamma)$
- Statistical sensitivity to ϕ_s after five years of LHCb data taking $\to \sigma(\phi_s) \sim 0.025$, with $\phi_s \sim \mathcal{O}(-0.04)$ in the SM
  - ☆ if ϕ_s (and/or ΔM_s) large compared to the SM expectation $\to$ New Physics (SUSY, ...)