B_s–$\overline{B}_s$ Mixing Phase at LHCb

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July 7, 2006
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On behalf of the LHCb collaboration

- B_s–$\overline{B}_s$ mixing
- Monte Carlo sensitivity studies:
  - ☆ B_s–$\overline{B}_s$ mixing phase ϕ_s from $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions

(sb) Unitarity Triangle

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\equiv V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

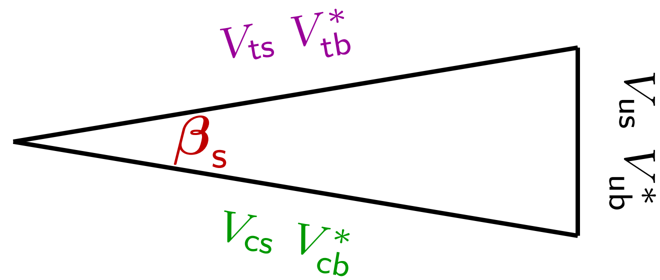
- V_{CKM} unitary
  - $\rightarrow$ 3 angles
  - $\rightarrow$ 1 complex phase $\Rightarrow$ $\not{C}\not{P}$

(sb) orthogonality relation:

$$\underbrace{V_{us}V_{ub}^*}_{\mathcal{O}(\lambda^4)} + \underbrace{V_{cs}V_{cb}^*}_{\mathcal{O}(\lambda^2)} + \underbrace{V_{ts}V_{tb}^*}_{\mathcal{O}(\lambda^2)} = 0$$

with Wolfenstein's parameterization

$\rightarrow$ squashed (sb) triangle



$$\Rightarrow \beta_s \equiv \chi \equiv \arg\left[-\frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*}\right] \approx \lambda^2\eta + \mathcal{O}(\lambda^4) \approx \arg(V_{ts}) - \pi$$

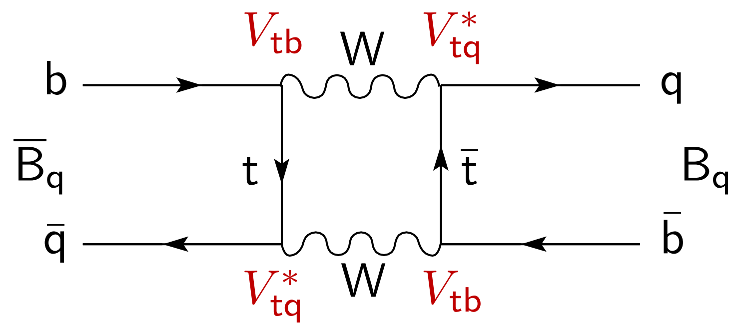
Measurement of β_s for study of $\not{C}\not{P}$ in B_s–$\overline{B}_s$ system $\Leftrightarrow$ β for B_d–$\overline{B}_d$ system

B_q–$\overline{B}_q$ Mixing

Quark mixing $\rightarrow$ neutral B_q ($q \in \{d, s\}$) not eigenstates of weak interaction

B_q–$\overline{B}_q$ oscillations ($|\Delta F| = 2$)

Standard Model (SM) box diagrams



Mass eigenstates differ from flavor ones due to off-diagonal terms in $\mathcal{H}_{\rm eff}$
$\rightarrow$ propagate with measurable different masses ($M_{\rm L,H}$) and lifetimes ($1/\Gamma_{\rm L,H}$)

Notations:

- $|B_{L/H}\rangle = p|B_q\rangle \pm q|\overline{B}_q\rangle$
- oscillation frequency: $\Delta M_q = M_H - M_L$
- B_q–$\overline{B}_q$ mixing phase: ϕ_q
- width difference: $\Delta\Gamma_q = \Gamma_L - \Gamma_H$, average: $\Gamma_q = (\Gamma_L + \Gamma_H)/2$

B_s–$\overline{B}_s$ Mixing Phase

CP-violating phase = phase difference between off-diagonal terms of $\mathcal{H}_{\rm eff}$:

$\phi_{M/\Gamma} = \arg\left[-\frac{M_{12}^{(q)}}{\Gamma_{12}^{(q)}}\right]$. Contributions:

- $M_{12}^{(q)}$: virtual intermediate states $\Rightarrow$ sensitive to New Physics (NP)
- $\Gamma_{12}^{(q)}$: physical (i.e. on-shell) states $\Rightarrow$ insensitive to NP

$\Rightarrow$ for B_s system $\phi_{M/\Gamma}^{\rm SM} \approx \phi_s^{\rm SM} \approx -2\beta_s \approx -2\lambda^2\eta \sim \mathcal{O}(-0.04)$ rad with

- $\arg\left[M_{12}^{(s)}\right] \stackrel{\rm SM}{=} \phi_s^{\rm SM} = 2\arg[V_{ts}^* V_{tb}]$
- $\arg\left[-\Gamma_{12}^{(s)}\right] \stackrel{\rm SM}{=} 2\arg(V_{cb} V_{cs}^*) + \mathcal{O}(\lambda^2) \rightarrow$ real to $\mathcal{O}(\lambda^6)$

If NP contributions to B_s–$\overline{B}_s$ mixing phase $\Rightarrow \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP}$

…ϕ_s not yet measured, interesting probe of NP ! And NP CP-violating phase in B_s–$\overline{B}_s$ mixing unconstrained, even with ΔM_s measurement from CDF !

B_q–$\overline{B}_q$ Mixing Observables in SM

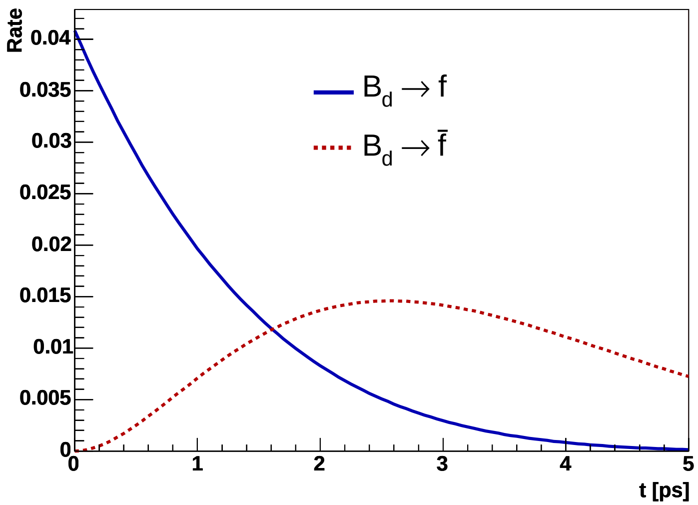
B_d system: well measured

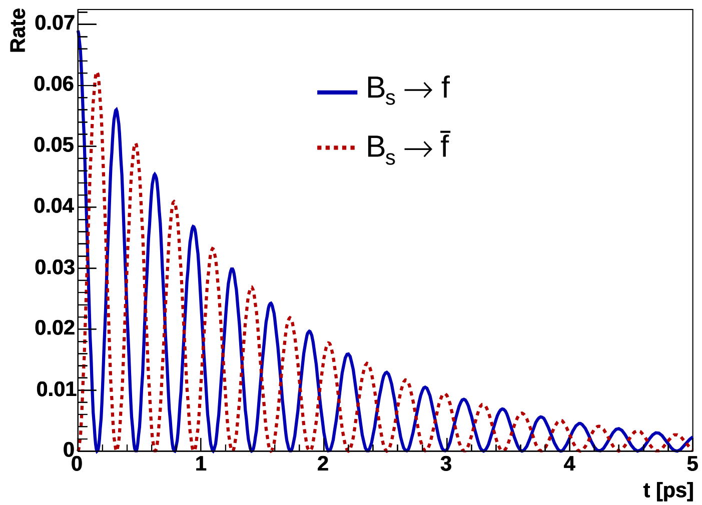
- $\Delta M_d = 0.5 \text{ ps}^{-1}$
- $\Delta\Gamma_d/\Gamma_d \sim 0$
- $\phi_d^{SM} \approx 2\beta = (0.76 \pm 0.04)$ rad

B_s system: partially explored

- $\Delta M_s \sim 17.3 \text{ ps}^{-1}$ (CDF)
- $\Delta\Gamma_s/\Gamma_s \sim 10\%$
- $\phi_s^{SM} \approx -2\beta_s \sim \mathcal{O}(-0.04)$ rad

Probability for B_d (left) or B_s (right) to decay to a flavor-specific final state





We need to extract ΔM_s from the fast B_s–$\overline{B}_s$ oscillations to probe ϕ_s

$\Rightarrow$ prerequisite for time-dependent CP measurement

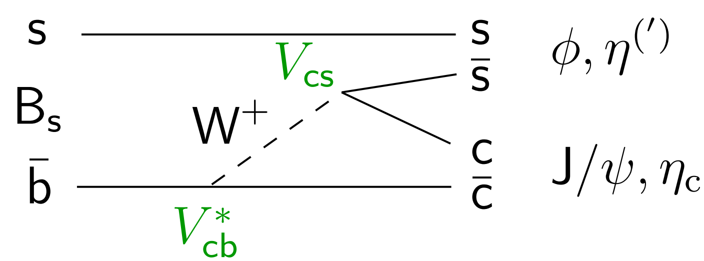
$\bar{b} \to \bar{c}c\bar{s}$ Quark-Level Transitions

B_s decays through $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions

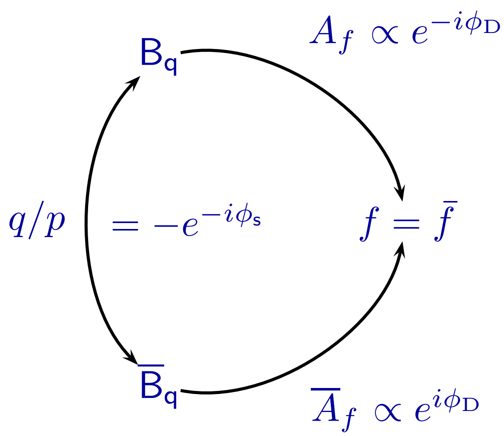
- decays to CP eigenstates ($\eta_f = \pm 1$)
- penguins doubly-Cabibbo suppressed

  $\Rightarrow$ no direct $\not{CP}$

Amplitudes (A_f) dominated by 1 tree $\phi_D \equiv -\arg[V_{cb}^* V_{cs}] \approx 0$



Assuming no $\not{CP}$ in the mixing ($|q/p| = 1$), we still have mixing-induced $\not{CP}$



$\rightarrow$ phase mismatch between ϕ_s and phase of decay amplitudes ratio: $\phi_s - 2\phi_D \approx \phi_s$

[$q/p = -e^{-i\phi_s}$, $\overline{A}_f / A_f = -\eta_f e^{i2\phi_D}$, $\varphi_{CP} = \pi$ (B_s CP phase)]

$\Rightarrow$ can directly determine ϕ_s from a time-dependent CP measurement

Channels for ϕ_s Determination

Decay channels considered to assess LHCb sensitivity to ϕ_s:

- admixture of CP eigenstates ($\eta_f = +1, -1, +1$)
  - $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
    - large event yield, angular analysis required to disentangle final states
- CP-even eigenstates ($\eta_f = +1$): no angular analysis needed, low yields
  - $B_s \to \eta_c(\pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-K^+K^-, K^+K^-K^+K^-)\phi(K^+K^-)$
  - $B_s \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$
  - $B_s \to D_s^+(K^+K^-\pi^+)D_s^-(K^+K^-\pi^-)$: penguin pollution from FSI?

Extraction of ΔM_s using flavor-specific control channel:

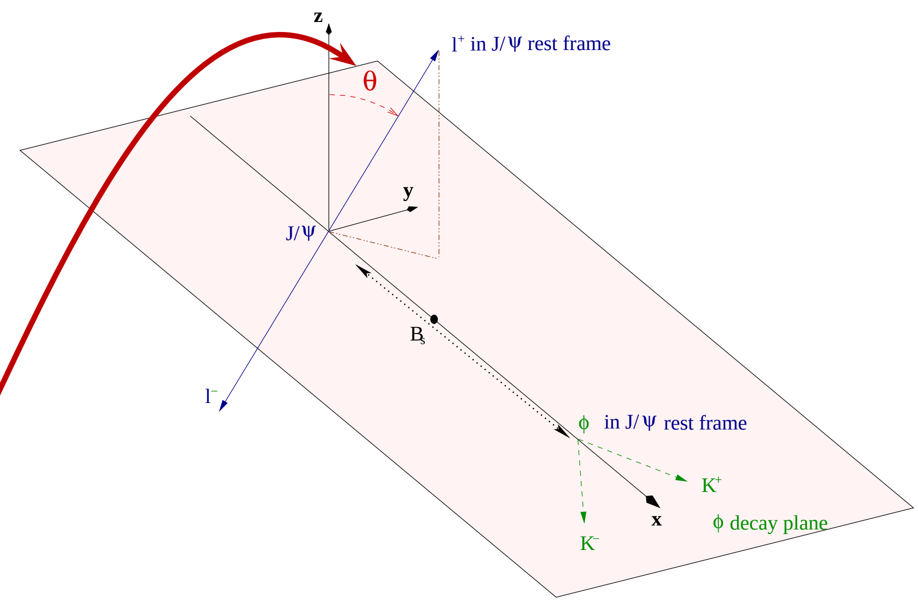
- $B_s \to D_s^-(K^+K^-\pi^-)\pi^+$, $\overline{B}_s \to D_s^+(K^+K^-\pi^+)\pi^-$

$B_s \to J/\psi\phi$ Angular Analysis

Final state $f = \mathrm{J}/\psi\phi$ is an admixture of CP eigenstates

- $f = 0, \|$: CP-even, $\eta_f = +1$, $f = \perp$: CP-odd, $\eta_f = -1$

$\Rightarrow$ disentangle states using polarization amplitudes $A_f(t)$



CP-odd fraction ($t = 0$):

$$R_{\mathrm{T}} \equiv \frac{|A_\perp|^2}{\sum_{f=0,\|,\perp} |A_f|^2} \sim \mathcal{O}(0.2)$$

Transversity basis, one-angle θ distribution:

$$\frac{\mathrm{d}\,\Gamma[\mathrm{B_s(t)} \to \mathrm{f}]}{\mathrm{d}\cos\theta} \propto \left(|A_0(t)|^2 + |A_\|(t)|^2\right) \frac{3}{8}\left(1+\cos^2\theta\right) + |A_\perp(t)|^2\, \frac{3}{4}\left(1-\cos^2\theta\right)$$

LHCb Full MC Simulation

Realistic full MC simulation:

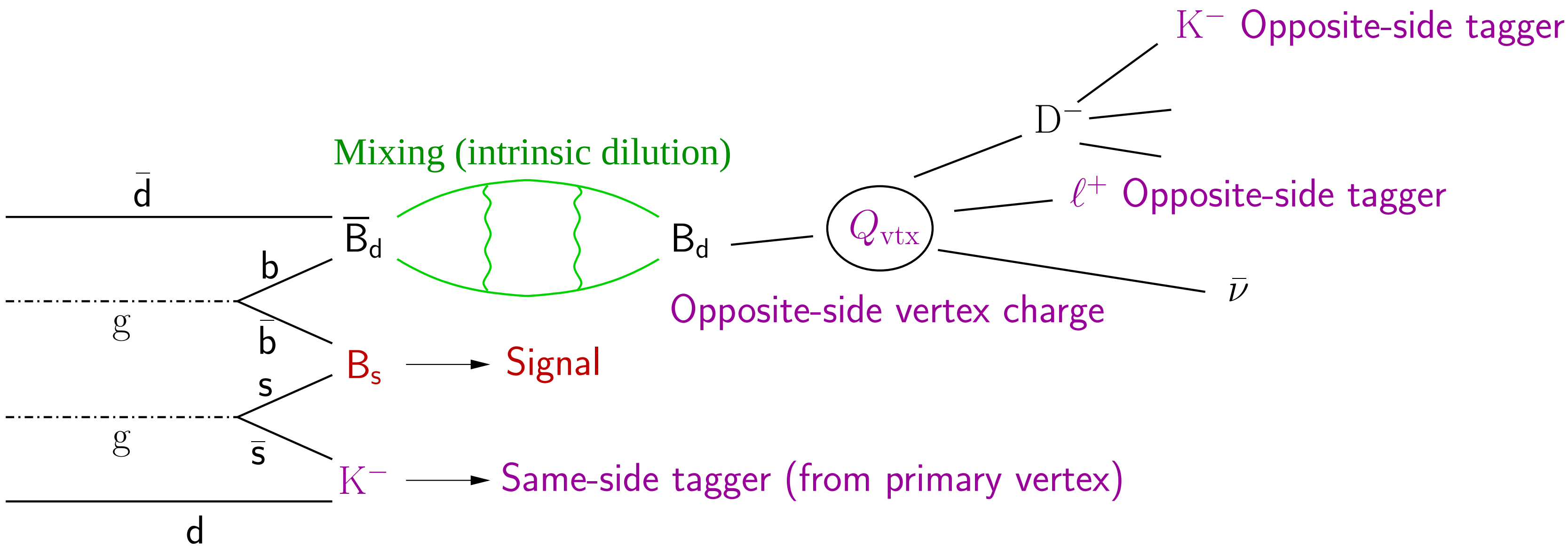
- generation of $\mathrm{p}-\mathrm{p}$ collisions (with pile-up) at $\sqrt{s} = 14\ \mathrm{TeV}$
- detector response, material description, effects of previous crossings
- full pattern recognition, trigger, tagging, off-line event selections

Characteristics of samples from full MC used in toy (fast) MC sensitivity studies to assess sensitivity to mixing observables

- event yields (after full trigger), background levels
- resolutions (mass, proper-time t), t efficiency (acceptance function)
- scale factor of proper-time error $\tau_{\mathrm{fit}}^{\mathrm{err}}$ (wrong error assignments)
- tagging (determination of initial b-meson flavor) performance

Flavor Tagging

- Tagging efficiency ε_{tag}: probability tagging procedure gives an answer
- Wrong tag fraction ω_{tag}: mistag probability when a tag is present



Effect of tagging: dilution of the oscillations with $D = (1 - 2\omega_{\text{tag}})$

$\Rightarrow$ use control sample $B_s \to D_s\pi$ to extract ω_{tag} (and ΔM_s). Rates:

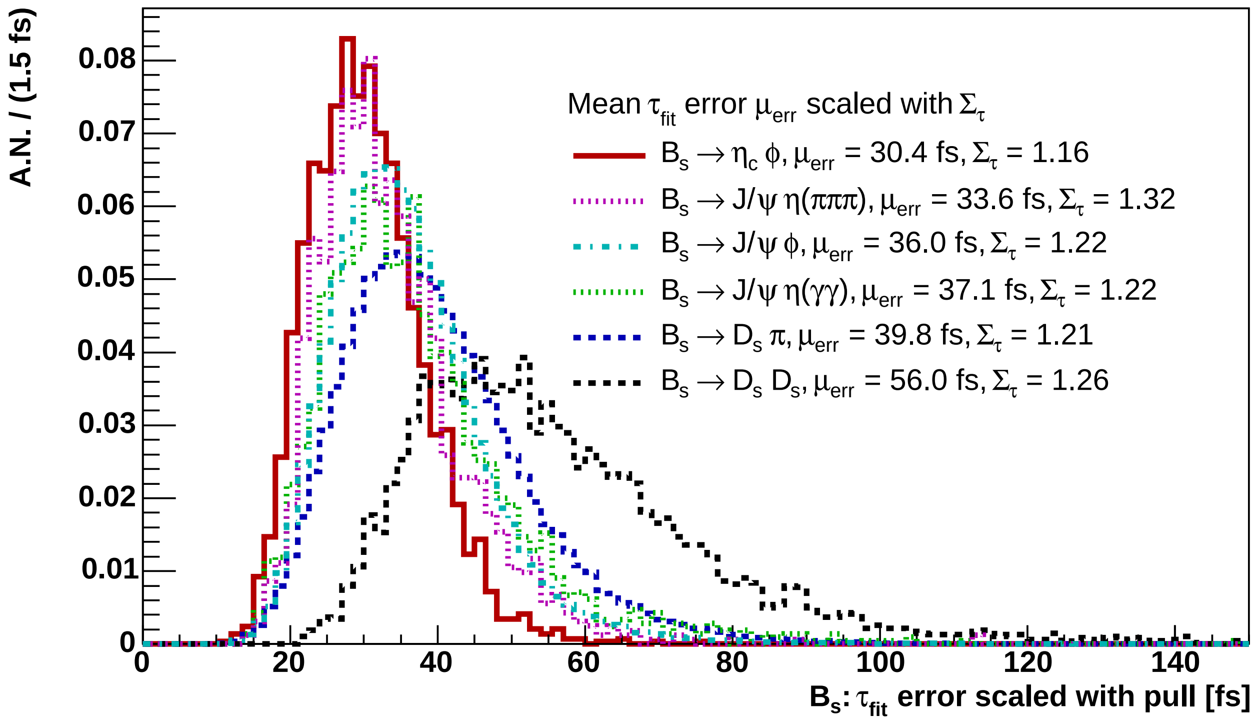
$$R_f\left(t_i^{\text{true}}, r_i; \omega_{\text{tag}}, \vec{\beta}\right) \propto \frac{e^{-\Gamma_s t_i^{\text{true}}}}{2}\left\{\cosh\frac{\Delta\Gamma_s t_i^{\text{true}}}{2} + r_i D \cos\left(\Delta M_s t_i^{\text{true}}\right)\right\}$$

$r_i = +1$ ($r_i = -1$) B_s tagged as unmixed (mixed), $r_i = 0$ untagged ($D = 0$)

Proper-Time Error from Full MC

Excellent proper-time resolution required to resolve fast B_s–$\overline{B}_s$ oscillations

$\Rightarrow$ most channels have a proper-time resolution below 40 fs



Per candidate proper-time errors are used as inputs for toy MC

Full MC Event Selection Results

Parameters	$J/\psi\ \phi$	$\eta_c\ \phi$	$D_s D_s$	$J/\psi\eta(\gamma\gamma)$	$J/\psi\eta(\pi\pi\pi)$	$D_s\pi$
2 fb^{-1} yield [k events]	131	3	4	8.5	3	120
Background level B/S	0.12	0.6	0.3	2.0	3.0	0.4
Mass σ_{B_s} [MeV/c]	14	12	6	34	20	14
Mean $< \tau_{fit}^{err} >$ [fs]	29.5	26.2	44.4	30.4	25.5	32.9
Scale factor Σ_τ	1.22	1.16	1.26	1.22	1.32	1.21
Wrong tag ω_{tag} [%]	33	31	34	35	30	31
Tagging ε_{tag} [%]	57	66	57	63	62	63

$\Rightarrow$ results used as inputs to parameterize toy MC

Sensitivities to mixing observables assessed using fast MC

- perform ~ 225 toy experiments each with statistics corresponding to 2 fb^{-1} (10^7 s at LHCb nominal $\mathcal{L} = 2 \times 10^{32}$ $cm^{-2}s^{-1}$)
- sensitivity to parameter = rms of error distribution from likelihood fit

Toy MC

Mixing parameters extracted by performing a likelihood fit to:

- mass distributions $\longrightarrow$ determine signal / background probabilities
- proper-time distributions: including acceptance, tagging, $\tau_{\text{fit}}^{\text{err}}$
- transversity angle θ for $B_s \to J/\psi\phi$

Principal fitted parameters: $\vec{\alpha} = (\Delta\Gamma_s, \Gamma_s, \phi_s, \Delta M_s)$, R_T, ω_{tag}

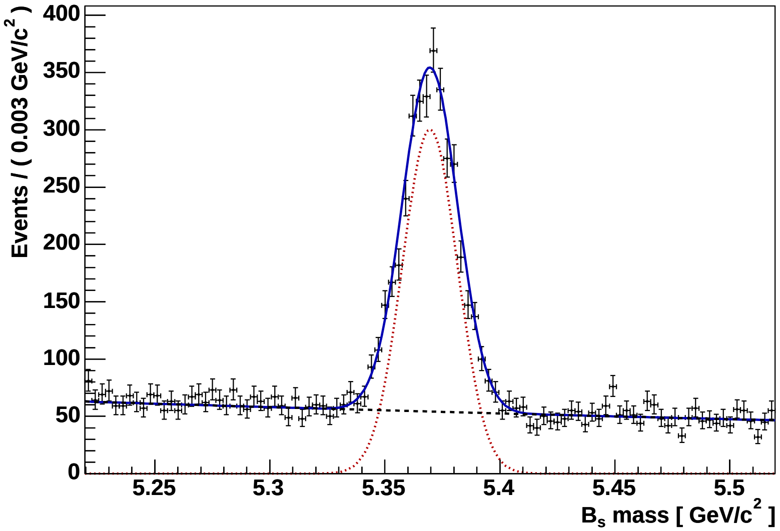
$\mathcal{L}^{\bar{b}\to\bar{c}c\bar{s}}$ simultaneously maximized with control sample ($B_s \to D_s\pi$)

Assumed same tagging performance (taken from signal) for $\bar{b} \to \bar{c}c\bar{s}$ and control samples

Nominal SM inputs used:

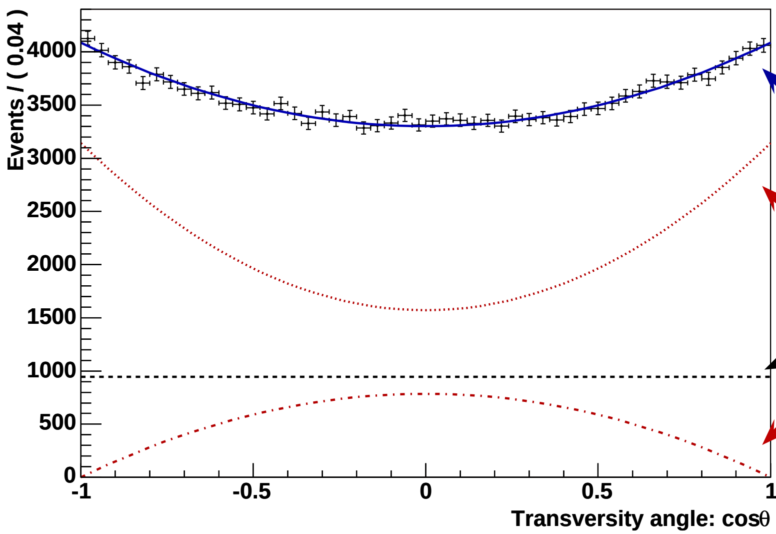
- $M_{B_s} = 5369.6$ MeV/c^2
- $\Delta M_s = 17.5$ ps^{-1}
- $\phi_s = -0.04$ rad
- $\Delta\Gamma_s/\Gamma_s = 0.15$
- $\tau_s = 1/\Gamma_s = 1.45$ ps
- $R_T = 0.2$, for $B_s \to J/\psi\phi$

Mass and Angular Models



Likelihood projection onto mass distribution for $B_s \to \eta_c \phi$

- signal: Gaussian
- background: exponential



Likelihood projection onto transversity angle distribution for $B_s \to J/\psi\phi$

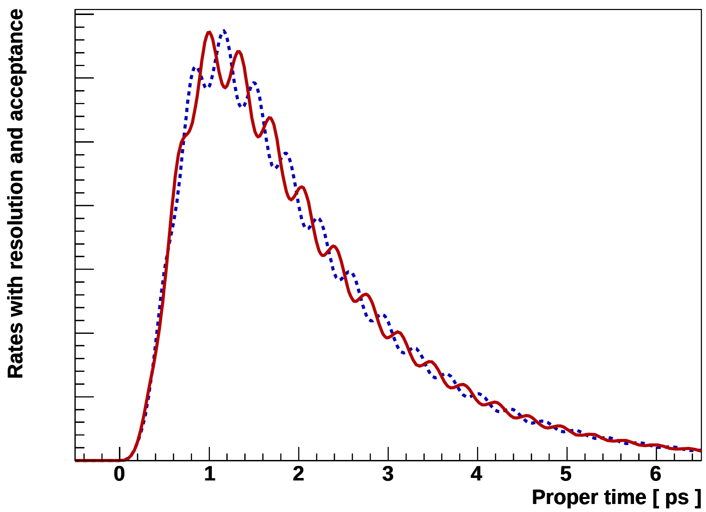
- total
- CP even
- CP odd
- background (assumed to be flat)

$\bar{b} \to \bar{c}c\bar{s}$ Signal Decay Rates

Decay rates of initially pure B_s and $\overline{B}_s$ states (perfect resolution)

$$R_f\,(t_i, q_i; \omega_{\text{tag}}, \vec{\alpha}) \quad \propto \quad e^{-\Gamma_s t_i} \left\{ \cosh \frac{\Delta\Gamma_s\, t_i}{2} - \eta_f \cos\phi_s \,\sinh \frac{\Delta\Gamma_s\, t_i}{2} + \eta_f\, q_i\, D \sin\phi_s\, \sin\left(\Delta M_s\, t_i\right) \right\}$$

$q_i = +1\ (-1)$ if tagged as B_s ($\overline{B}_s$) at production, $q_i = 0$ if untagged ($D = 0$)



- Tagging dilution $D \longrightarrow$ need control channel to extract ω_{tag} to determine ϕ_s from sine term

- Still access to ϕ_s for untagged events

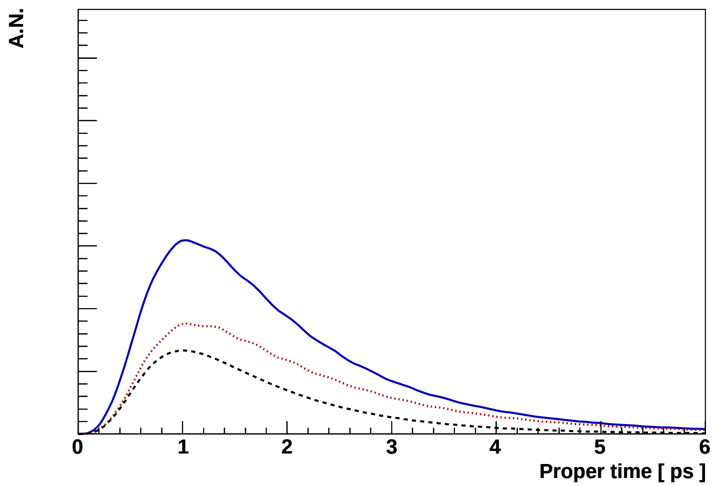
$\Leftarrow$ rates (CP even) with ϕ_s $5\times$ SM, with proper-time acceptance, ω_{tag}, and t resolution

Red solid (blue dashed) line: initially tagged as B_s ($\overline{B}_s$)

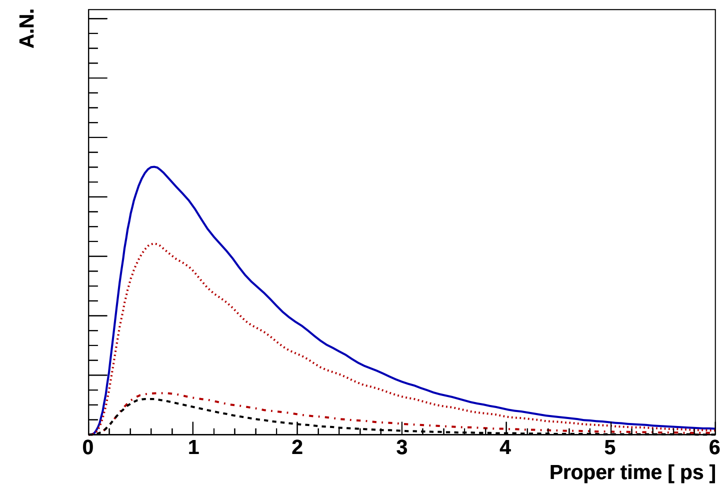
Proper-Time Distributions

Likelihood projection onto proper-time distribution (tagged as B_s)

$B_s \rightarrow \eta_c \phi$



$B_s \rightarrow J/\psi \phi$



Total: blue solid line. Background: black line.
Signal: dotted red line (CP even), dashed-dotted red line (CP odd).

Proper-time model includes:

- proper-time acceptance and per-event proper-time errors
- tagging performance $\rightarrow$ dilutes oscillations
- exponential background shape $\rightarrow$ flattens wiggles

Sensitivities to a SM ϕ_s

Combined expected statistical errors on ϕ_s for the different $\bar{b} \to \bar{c}c\bar{s}$ quark-level transitions to CP eigenstates, with $2\,\text{fb}^{-1}$ at LHCb:

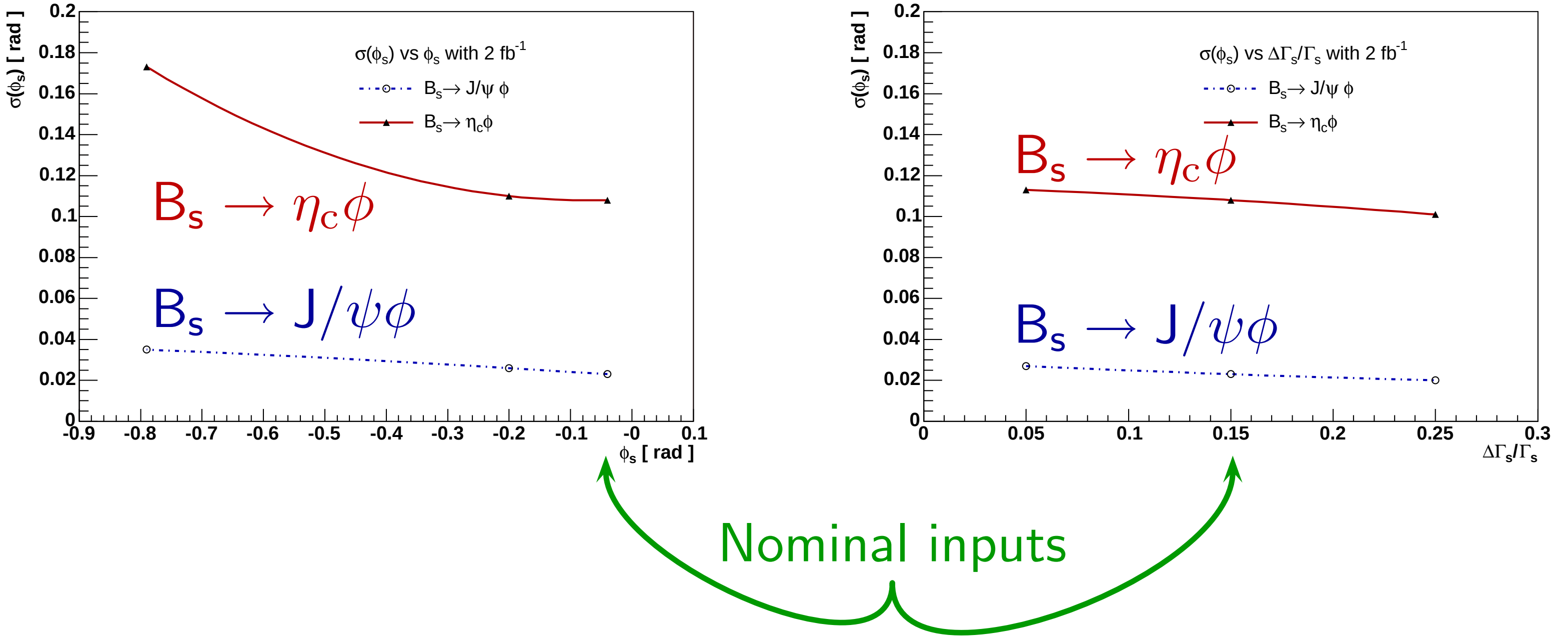
Channels	$\sigma(\phi_s)$ [rad]	Weight $(\sigma/\sigma_i)^2$ [%]
$B_s \to J/\psi\ \eta(\pi^+\ \pi^-\ \pi^0)$	0.142	2.3
$B_s \to D_s D_s$	0.133	2.6
$B_s \to J/\psi\ \eta(\gamma\ \gamma)$	0.109	3.9
$B_s \to \eta_c \phi$	0.108	3.9
Combined (pure CP eigenstates)	**0.060**	**12.7**
$B_s \to J/\psi\phi$	0.023	87.3
Combined (all CP eigenstates)	**0.022**	**100.0**

Combined sensitivity with $10\,\text{fb}^{-1}$ at LHCb: $\sigma(\phi_s) = \pm 0.0098\,\text{rad}$ (statistical)

$\Rightarrow \sim 4\,\sigma$ measurement for a SM ϕ_s and $10\,\text{fb}^{-1}$

Dependence of Sensitivity to ϕ_s on ϕ_s and $\Delta\Gamma_s/\Gamma_s$

$\sigma(\phi_s)$ vs ϕ_s | $\sigma(\phi_s)$ vs $\Delta\Gamma_s/\Gamma_s$



Very small dependence on ϕ_s value for $B_s \to J/\psi\phi$

Does not depend on sign of ϕ_s for:

- pure CP eigenstates
- $B_s \to J/\psi\phi$ and one-angle angular analysis

Not very sensitive to $\Delta\Gamma_s/\Gamma_s$ value

Better sensitivity for larger $\Delta\Gamma_s/\Gamma_s$ $\to$ better separation between Γ_L (short lived, CP even) and Γ_H (long lived, CP odd) eigenstates

Conclusions

Combined statistical sensitivity to ϕ_s is 0.022 rad with $2\,\text{fb}^{-1}$:

- dominated by $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- substantial $\sim 13\,\%$ contribution from pure CP eigenstates

$\Rightarrow$ ϕ_s still unknown, LHCb will be able to have first results already in 2008

For a SM $\phi_s = -0.04$ rad: $\sim 2\,\sigma$ measurement with $2\,\text{fb}^{-1}$, and able to detect sizable NP effects.

$\Rightarrow$ New Physics may be hiding in B_s–$\overline{B}_s$ mixing !?! $\Leftarrow$

BACK-UP SLIDES

Sensitivities to Physics Parameters

Expected statistical errors on other physics parameters ($2\,\text{fb}^{-1}$ at LHCb)

Parameter	Sensitivity	Channel
ϕ_s [rad]	0.022	$J/\psi\phi$, $\eta_c\phi$, $J/\psi\eta(\gamma\gamma)$, $J/\psi\eta(\pi\pi\pi)$, D_sD_s
$\Delta\Gamma_s/\Gamma_s$	0.0092	$J/\psi\phi$
ΔM_s [ps^{-1}]	0.007	$D_s\pi$
ω_{tag}	0.0036	$D_s\pi$
R_T	0.00040	$J/\psi\phi$

Results for ΔM_s and ω_{tag} are from likelihood fit to $B_s \to D_s\pi$ alone

Precise value of ΔM_s: uncertainty $\sim 0.04\,\%$

Nominal SM inputs used:

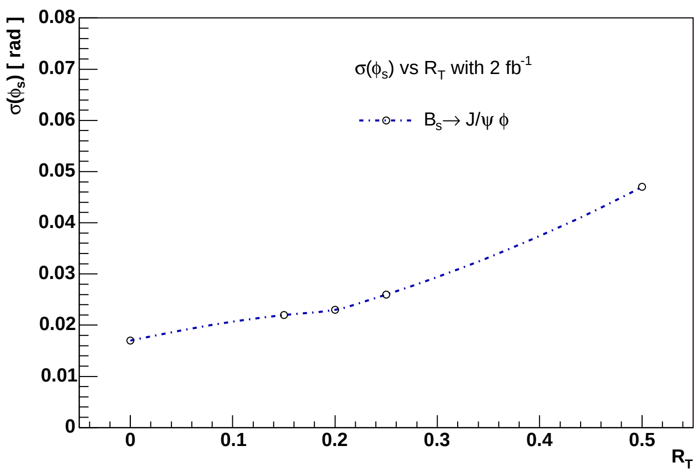
- $M_{B_s} = 5369.6\,\text{MeV}/c^2$
- $\Delta M_s = 17.5\,\text{ps}^{-1}$
- $\phi_s = -0.04\,\text{rad}$
- $\Delta\Gamma_s/\Gamma_s = 0.15$
- $\tau_s = 1/\Gamma_s = 1.45\,\text{ps}$
- $R_T = 0.2$, for $B_s \to J/\psi\phi$

Results on Sensitivity to ϕ_s

Scan	$\sigma(\phi_s)$ [rad] $B_s \to J/\psi\phi$	$\sigma(\phi_s)$ [rad] $B_s \to \eta_c\phi$
Nominal	0.023	0.108
$\Sigma_\tau + 10\,\%$	0.025	0.108
$\Sigma_\tau - 10\,\%$	0.023	0.103
$B/S \times 2$	0.025	0.118

- Effect of worse proper-time resolution (i.e. $\pm 10\%$ scale factor Σ_τ)
- Effect of larger B/S

$\sigma(\phi_s)$ vs R_T for $B_s \to J/\psi\phi$



Very sensitive to R_T (nominal $=$ 0.2):

- $R_\mathrm{T} = 0.0$: CP-even limit
- $R_\mathrm{T} = 0.5$: maximal dilution but still sensitive because very distinctive angular distributions

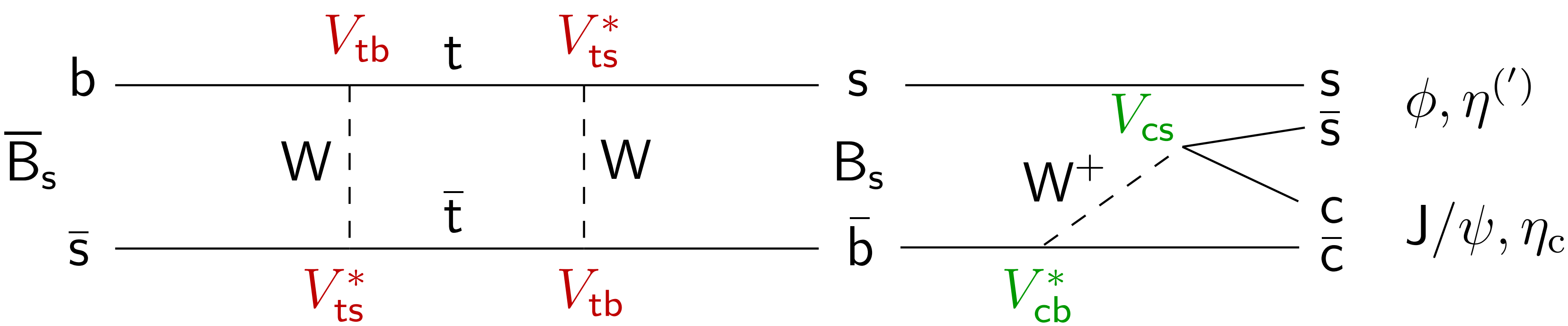
CP Asymmetry

CP asymmetry for decays to self-conjugated eigenstates ($f = \bar{f}$):

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{\Gamma[\overline{\mathrm{B}}_{\mathrm{q}}(t) \to f] - \Gamma[\mathrm{B}_{\mathrm{q}}(t) \to f]}{\Gamma[\overline{\mathrm{B}}_{\mathrm{q}}(t) \to f] + \Gamma[\mathrm{B}_{\mathrm{q}}(t) \to f]}$$

Mixing-induced CP asymmetry for $\bar{\mathrm{b}} \to \bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}$ quark-level transitions (for a given η_f eigenstate):

$$\mathcal{A}_{\mathrm{CP\,B_s}}^{\text{mix-ind}}(t) = -\frac{\eta_f \sin\phi_{\mathrm{q}} \sin(\Delta M_{\mathrm{q}}\, t)}{\cosh(\Delta\Gamma_{\mathrm{q}}\, t/2) - \eta_f \cos\phi_{\mathrm{q}} \sinh(\Delta\Gamma_{\mathrm{q}}\, t/2)}$$



$\bar{b} \longrightarrow \bar{c}c\bar{s}$ Likelihood

$$\mathcal{L}^{\bar{b}\rightarrow\bar{c}c\bar{s}} = \frac{e^{-(N_{\rm sig}+N_{\rm bkg})}}{N_{\rm obs}!} \prod_{i\epsilon B_s\rightarrow f}^{N_{\rm obs}} \mathcal{L}_i^{\bar{b}\rightarrow\bar{c}c\bar{s}}(m_i, \theta_i, t_i^{\rm rec}, \tau_i^{\rm err}, q_i)$$

$$\begin{aligned}\mathcal{L}_i^{\bar{b}\rightarrow\bar{c}c\bar{s}}(m_i, \theta_i, t_i, \tau_i^{\rm err}, q_i) \quad = \quad & N_{\rm sig}\,\mathcal{L}_m^{\rm sig}(m_i)\Big[R_{\rm T}\mathcal{L}_{\theta,\rm odd}^{\rm sig}(\theta_i)\mathcal{L}_{t,\rm odd}^{\rm sig}(t_i^{\rm rec}, \tau_i^{\rm err}, q_i) \\ & + (1-R_{\rm T})\mathcal{L}_{\theta,\rm even}^{\rm sig}(\theta_i)\mathcal{L}_{t,\rm even}^{\rm sig}(t_i^{\rm rec}, \tau_i^{\rm err}, q_i)\Big] \\ & + N_{\rm bkg}\,\mathcal{L}_m^{\rm bkg}(m_i)\mathcal{L}_\theta^{\rm bkg}(\theta_i)\mathcal{L}_t^{\rm bkg}(t_i^{\rm rec})\end{aligned}$$