The sensitivity for ϕ_s at LHCb

Peter Fauland

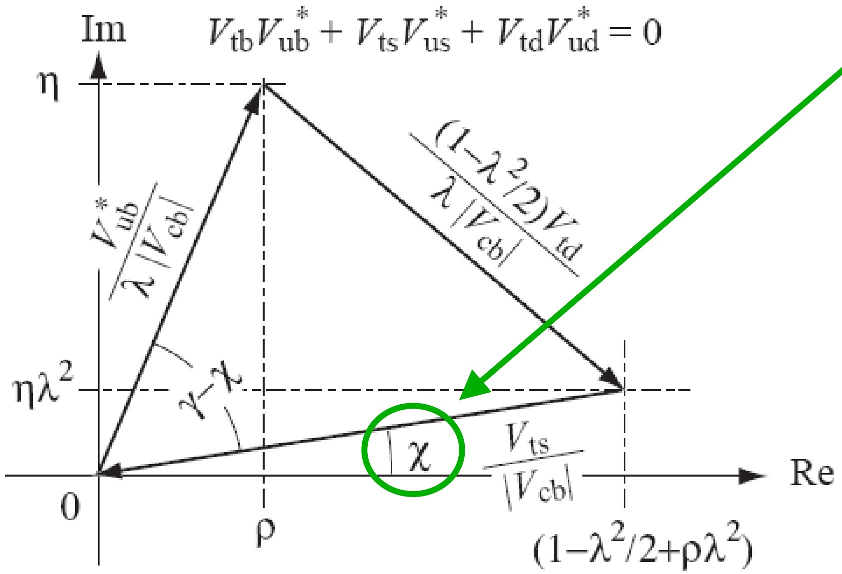
(for the **LHCb** collaboration)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

ϕ_s in the standard model

Wolfenstein parameterization of the CKM matrix ($\lambda \equiv V_{us}$, **A**, ρ, η) ⇨

$$\chi = \arg(V_{ts}) - \pi = \lambda^2 \eta$$



$$\beta = -\arg(V_{td})$$

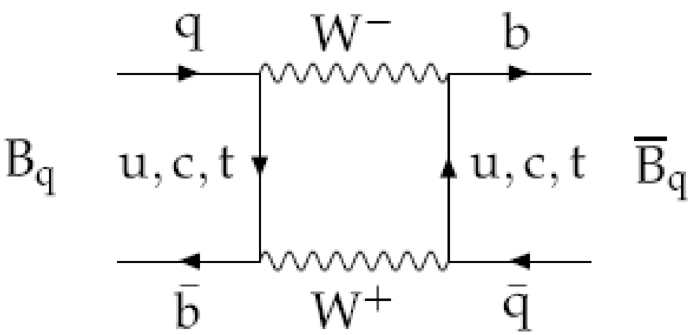
Thus χ in the B_s system corresponds to β in the B_d system (therefore χ is also referred to as β_s)

B_d-system well measured, but

B_s-system (ΔM_s, $\Delta\Gamma_s$, χ, $|p/q|$) not fully explored

ϕ_s in the standard model

$B_q^0 - \overline{B}_q^0$ Mixing : Standard model box diagrams (ΔF=2 transitions)



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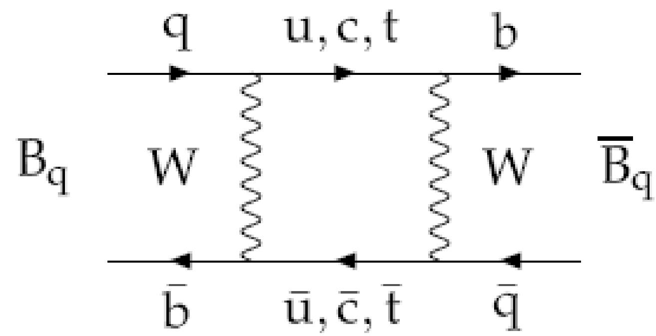


B_q^0 Mixing phase ≡ $\phi_q = 2\arg[V_{tq}^* V_{tb}]$ ⟹ $\phi_d = 2\beta$

$\phi_s = -2\chi$

If only SM box diagrams

If NP contributions in B_s mixing ⟹ $\phi_s = \phi_s^{SMbox} + \phi_s^{NP}$ and $\phi_s \neq -2\chi$

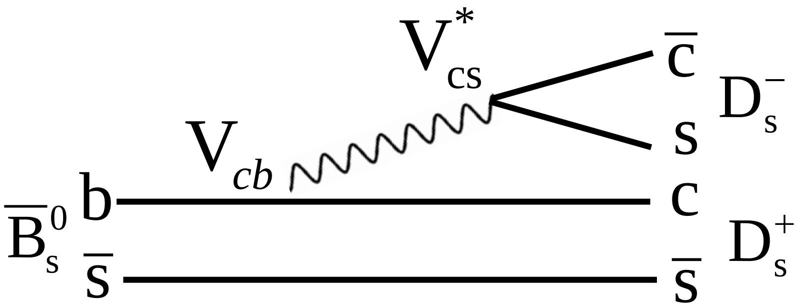
Measuring ϕ_s at LHCb

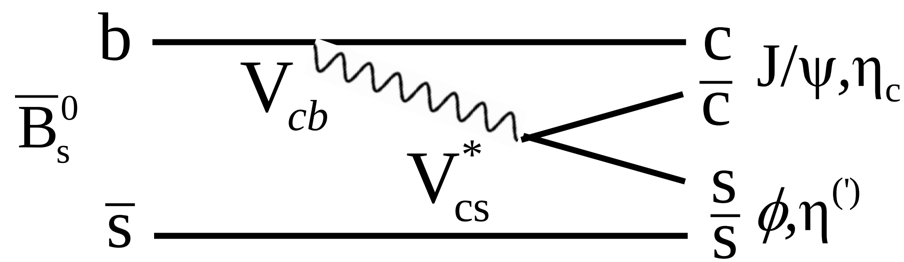
Thus : measure the B_s mixing phase ϕ_s and see if it agrees with SM expectation from the box diagrams (check if $\phi_s \leftrightarrow -2\chi = -2\lambda^2\eta \cong -0.04$)

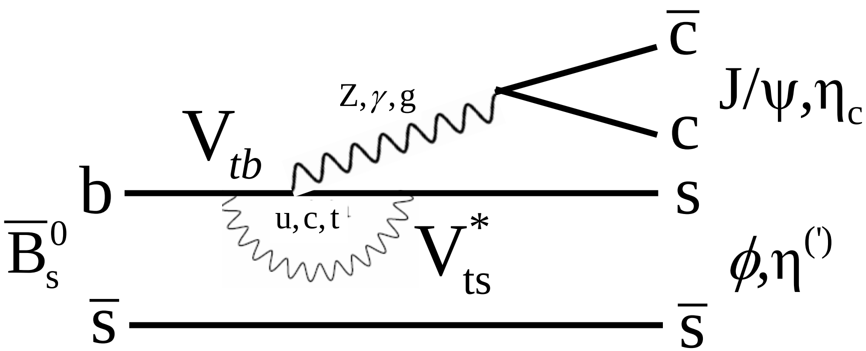
The following B_s-decays have been used to determine the LHCb sensitivity to ϕ_s :

$B_s \to J/\psi(\mu^-\mu^+)\phi(K^+K^-)$	CP-odd and CP-even eigenstates
$B_s \to \eta_c(h^-h^+h^-h^+)\phi(K^+K^-)$	CP-even eigenstate
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\gamma\gamma)$	CP-even eigenstate
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	CP-even eigenstate
$B_s \to J/\psi\ (\mu^-\mu^+)\eta'(\pi^+\pi^-\eta\ (\gamma\gamma))$	CP-even eigenstate
$B_s \to D_s\ (K^+K^-\pi^-)\ D_s\ (K^+K^-\pi^+)$	CP-even eigenstate
$B_s \to D_s\ (K^+K^-\pi^-)\pi^+$	ΔM_s determination, Control Channel

Tree and Penguin Diagrams







The $\bar{b} \to \bar{c}c\bar{s}$ transitions are dominated by a single weak phase : $V_{cs}V^*_{cb}$

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

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

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

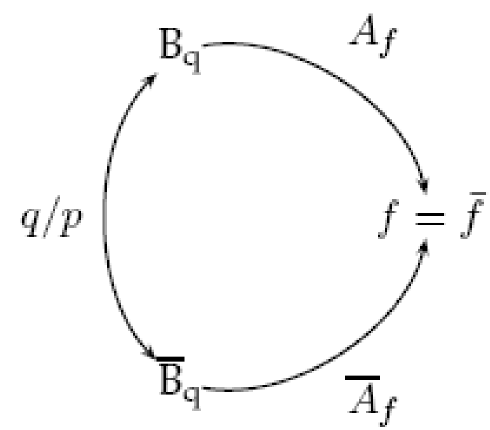
$\sim A\lambda^2(1-\lambda^2/2)$

$\sim A\lambda^4(\rho + i\eta)$

CP asymmetry

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

- CP eigenstates with eigenvalues: $\eta_f = \pm 1$
- $\not{CP}$: interference in mixing and decay (no direct $\not{CP}$)
- $\overline{\rm b} \to \overline{\rm c}{\rm c}\overline{\rm s}$ is dominated by a single weak phase

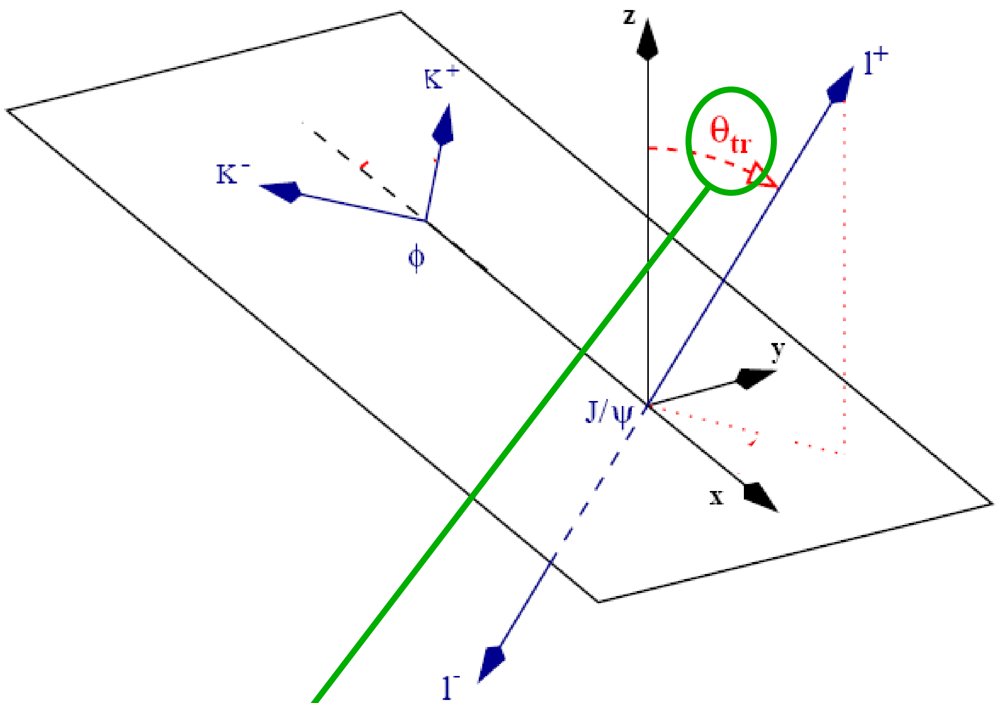


$$\mathcal{A}_{\rm CP}^{\text{mix-ind}}(t) = -\frac{\eta_f \sin\phi_{\rm q} \sin(\Delta M_{\rm q}\, t)}{\cosh(\Delta\Gamma_{\rm q}\, t/2) - \eta_f \cos\phi_{\rm q} \sinh(\Delta\Gamma_{\rm q}\, t/2)}$$

The time dependent CP asymmetry allows us to measure ϕ_s.

Angular analysis (CP-odd/CP-even separation)

Complication for: $B_s \to J/\psi(\to \ell^+\ell^-)\ \phi(\to K^+K^-)$



$$R_T \equiv \frac{|A_\perp(0)|^2}{\sum_{f=0,\|,\perp} |A_f(0)|^2}$$

$R_T = 0 \to$ CP even

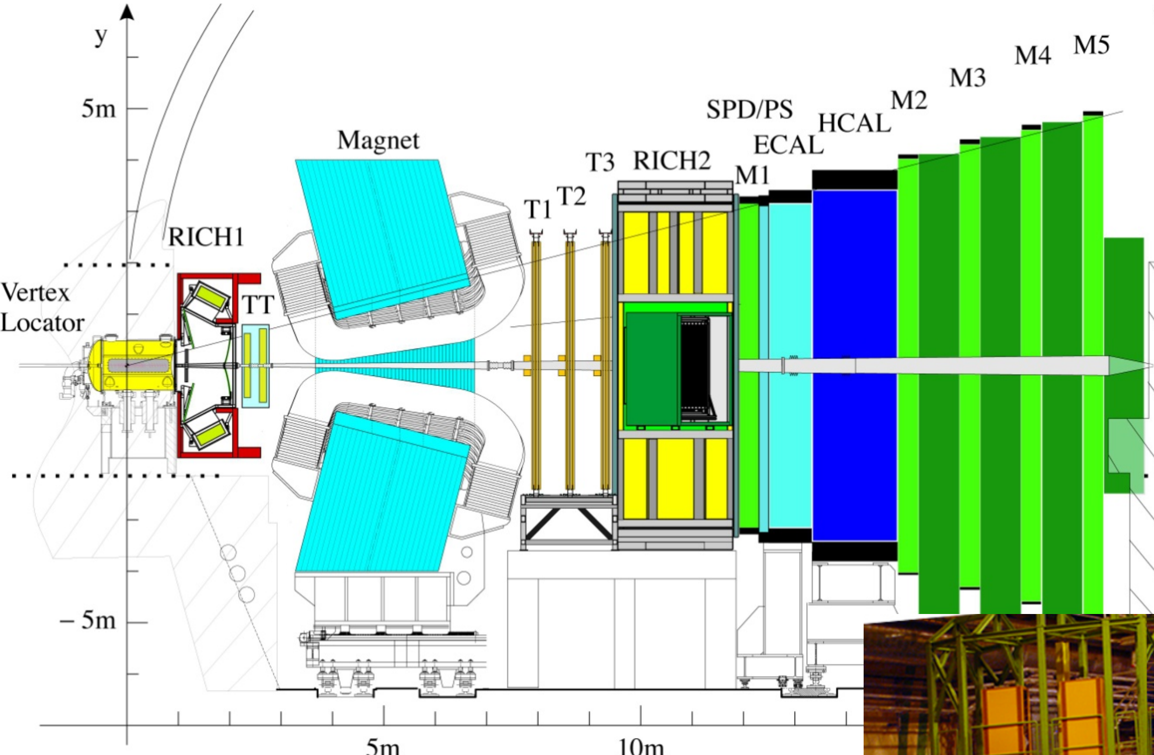
$R_T = 0.5 \to$ maximum dilution

(but still some sensitivity to ϕ_s since odd and even contributions have different θ_{tr} distribution)

Measurements $\to R_T \cong 0.2$

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

The LHCb experiment

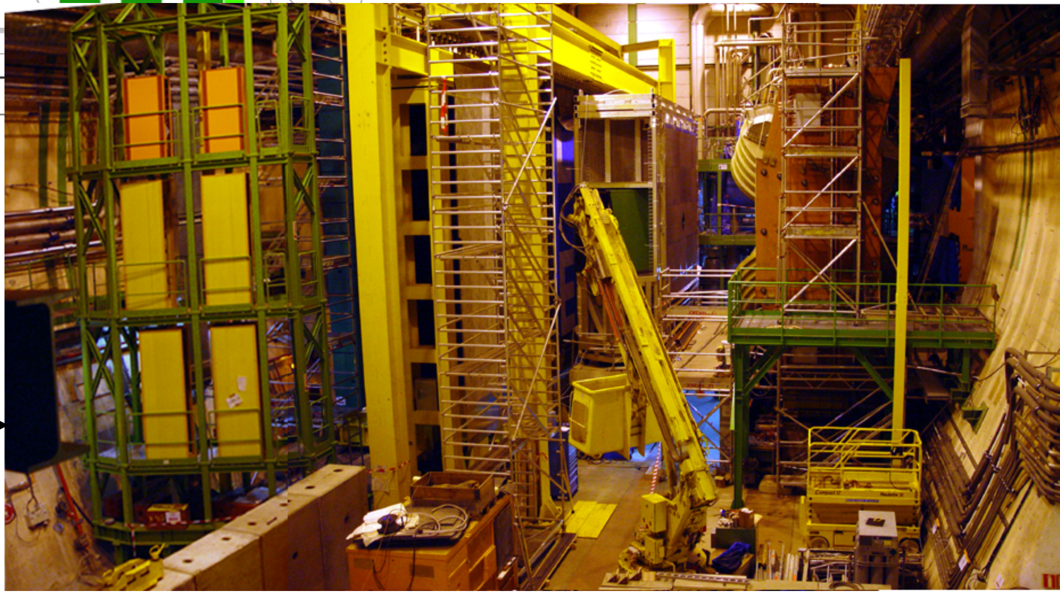


LHCb

Single arm spectrometer with:

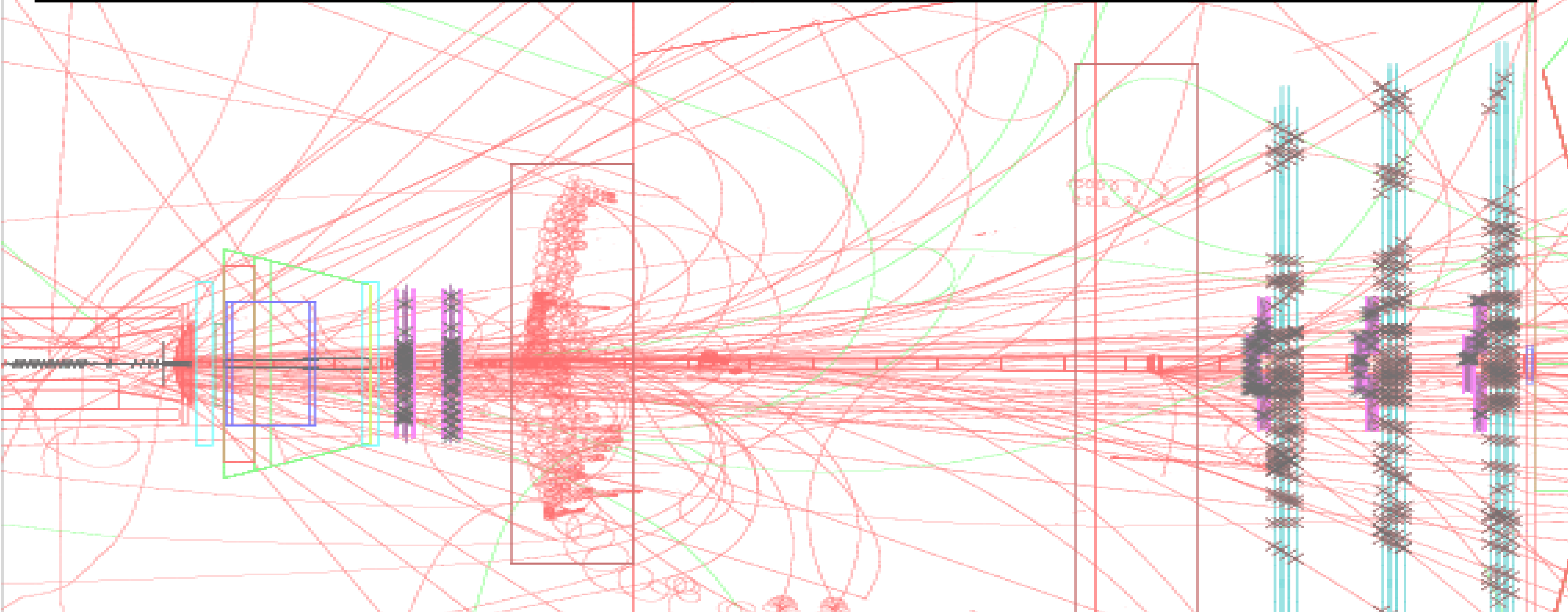
- good vertexing/tracking for reconstruction of the primary and B-decay vertex.
- good particle identification

LHCb under construction. It's real!



The LHCb MC simulation

The results in the next slides have been obtained with the latest (DC04) LHCb Monte Carlo simulation.



- Very detailed and realistic detector and material description
- Full pattern recognition, trigger simulation (also HLT), and offline event selection .
- Realistic detector inefficiencies, noise hits, and effects of events from the previous bunch crossings

Results on the event selections

	Yield (10^3/2 fb^{-1})	B/S	$<\delta_\tau>$ (fs)	σ_{mass} (MeV/c^2)	w_{tag} (%)	ε_{tag} (%)
$B_s \to J/\psi(\mu^-\mu^+)\phi(K^+K^-)$	**131**	**0.12**	**36**	**14**	**33**	**57**
$B_s \to \eta_c(h^-h^+h^-h^+)\phi(K^+K^-)$	**3**	**0.6**	**30**	**12**	**31**	**66**
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\gamma\gamma)$	**8.5**	**2.0**	**37**	**34**	**35**	**63**
$B_s \to J/\psi(\mu^-\mu^+)\ \eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	**3.0**	**3.0**	**34**	**20**	**30**	**62**
$B_s \to J/\psi\ (\mu^-\mu^+)\ \eta'(\pi^+\pi^-\eta\ (\gamma\gamma))$	**2.2**	**2.0**	**32**	**19**	**31**	**64**
$B_s \to D_s(K^+K^-\pi^-)\ D_s(K^+K^-\pi^+)$	**4.0**	**0.3**	**56**	**6**	**34**	**57**
$B_s \to D_s\ (K^+K^-\pi^-)\pi^+$	**120**	**0.4**	**40**	**14**	**31**	**63**

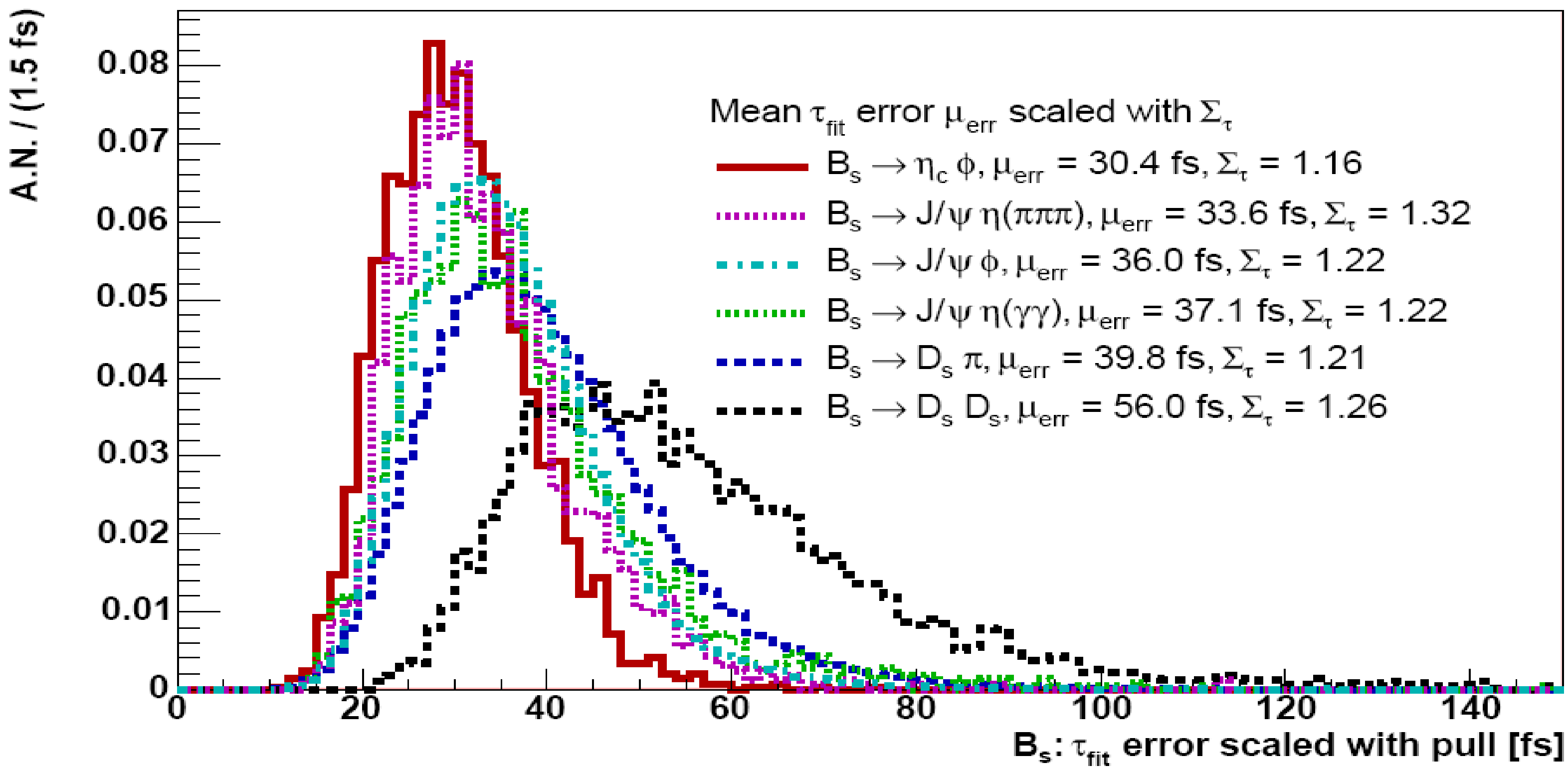
The sensitivity to ϕ_s :

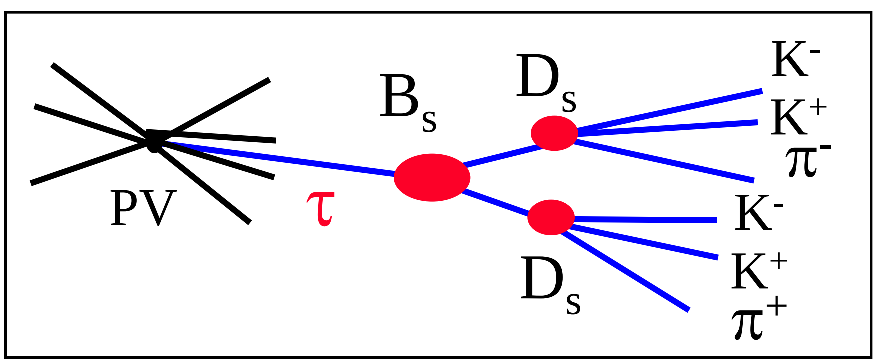
$B_s \to J/\psi\phi$: Large yield, but mixture of CP-odd and CP-even eigenstates.

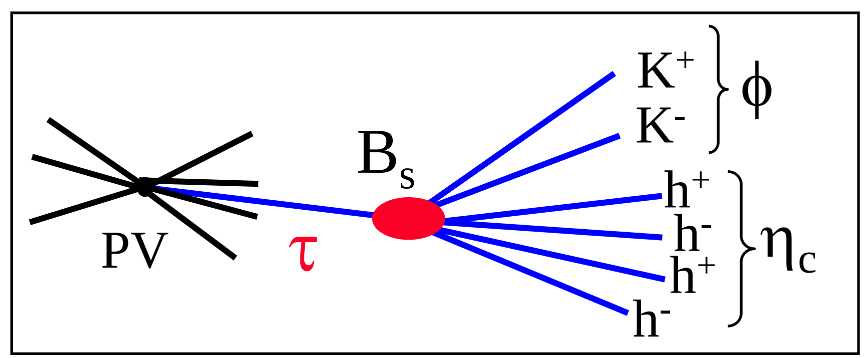
$B_s \to J/\psi\eta^{(\prime)}$, $B_s \to \eta_c\phi$: Low yield, high background, but CP-even.

$B_s \to D_sD_s$: Low yield, worse proper time resolution, but CP-even (FSI?)

Results on the event selections







Toy MC: modeling the events

The Sensitivity is determined by making use of a fast parameterized MC. As input the results from the full LHCb MC are used.

The CP parameters are extracted by performing a likelihood fit to the mass and proper time distributions (and to the transversity angle for $B_s \to J/\psi\phi$).

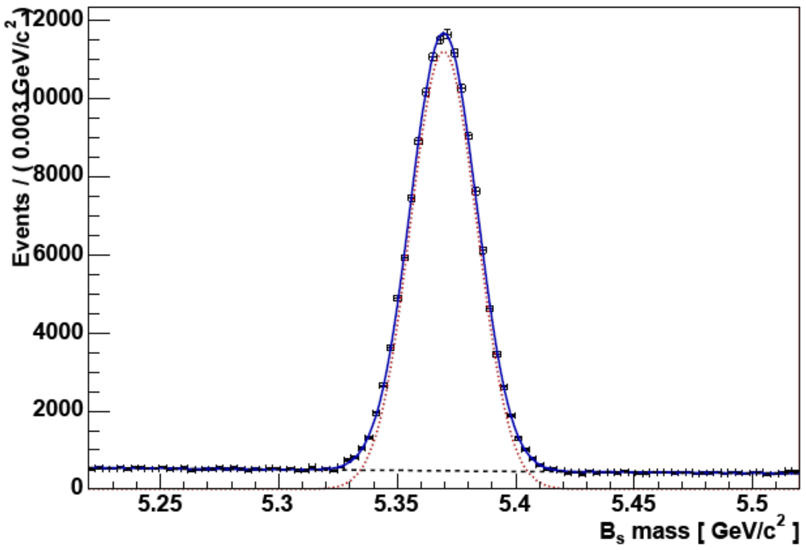
The likelihood for the signal $\bar{b} \to \bar{c} c \bar{s}$ transitions is simultaneously optimized with the control sample ($B_s \to D_s\pi$). The tagging performance is assumed to be the same for the control and signal sample. The statistical uncertainty of control channel is thus included.

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

Perform ~200 toy experiments, where each experiment represents ~one LHCb year of data taking (2fb^{-1} at $2\times10^{32}\mathrm{cm^2 s^{-1}}$). The RMS of the ϕ_s distribution is given as the sensitivity.

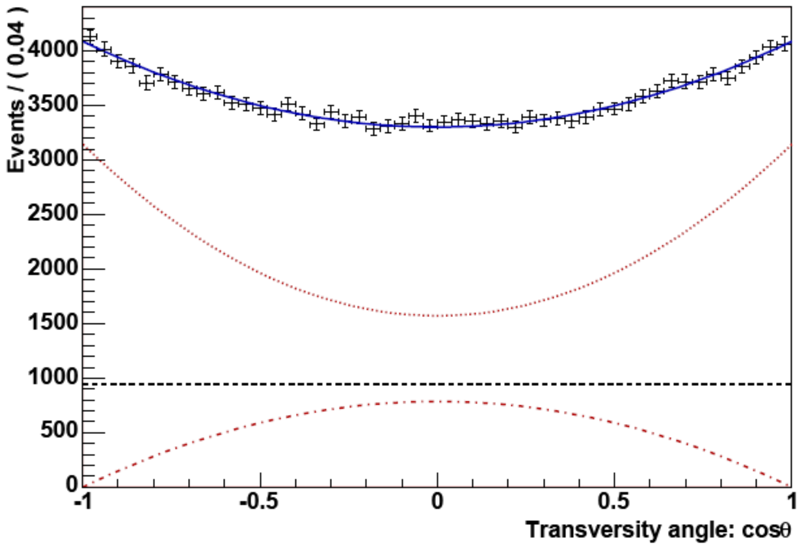
Standard model values are used as input

Modeling the mass and θ_{tr} distributions



Projection of the likelihood on mass distribution for $B_s \rightarrow J/\psi\phi$.

The mass peak is modeled by an exponential (background) and a Gaussian (signal).

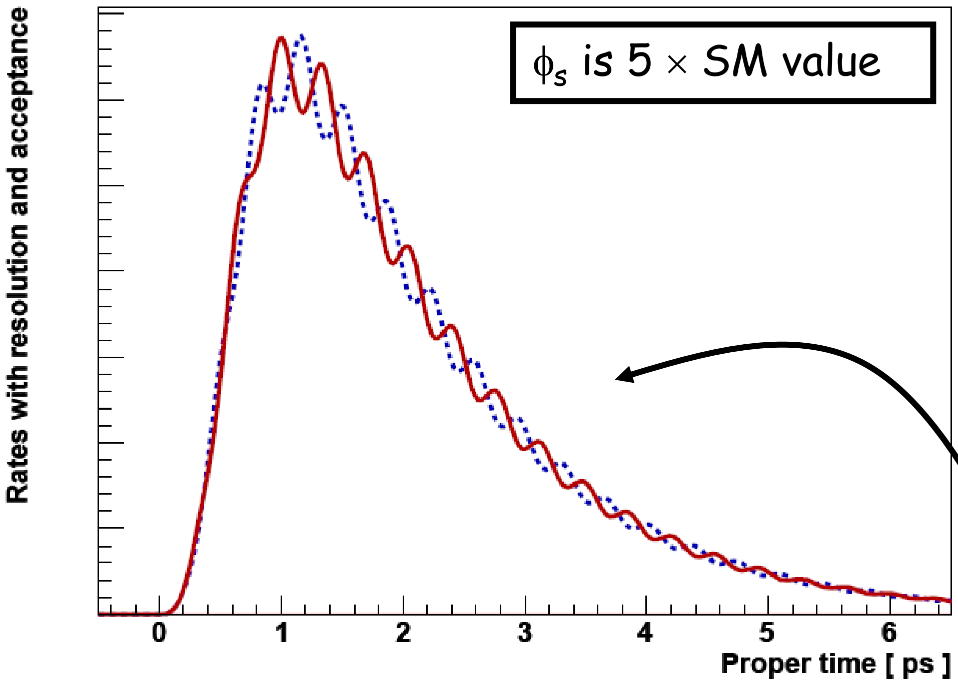


Projection of the likelihood on the transversity angle distribution for $B_s \rightarrow J/\psi\phi$.

Blue=total, red dotted = CP-even, red dashed =CP-odd, black=background (is assumed to be independent on θ_{tr}.

Modeling the tagged proper time distributions

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



- Sensitivity to ϕ_s depends on D (tagging dilution factor) = $1\text{-}2w_{tag}$

  But ⇒ also sensitivity if we have untagged events (w_{tag}=0.5, D=0) trough $\cos(\phi_s)$ term

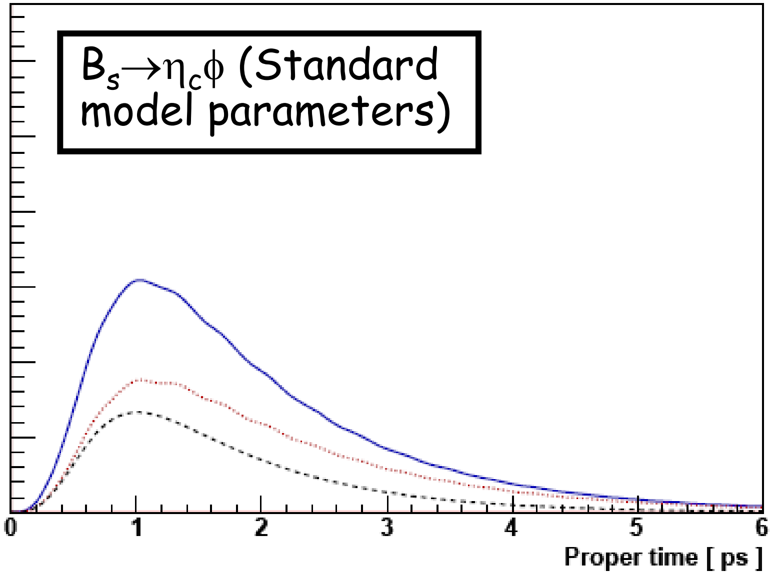
Include:

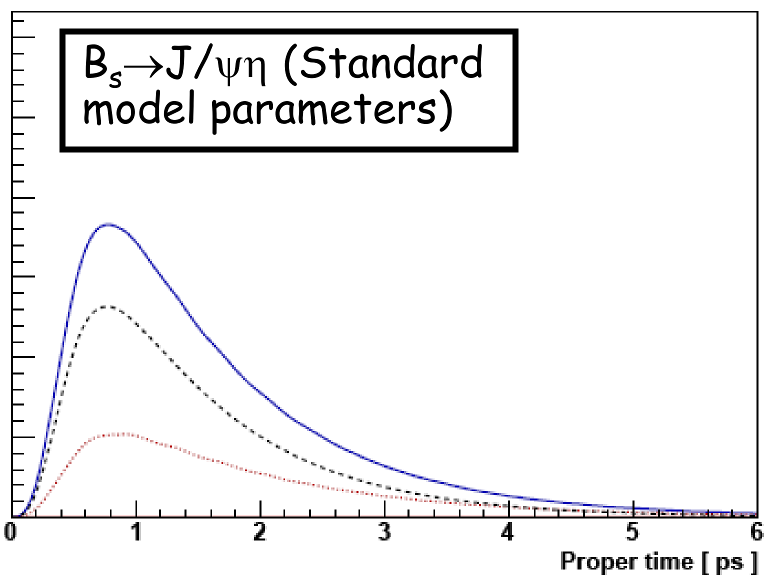
- Trigger and Selection bias on τ
- Proper time resolution

- Red solid line : tagged as initially B_s^0
- Blue dashed : tagged as initially $\overline{B}_s^0$

(Wrong tag fraction is included)

Modeling the tagged proper time distributions





Projection of the likelihood on the proper time distribution

Blue solid : Total

Red dotted : Signal

Black dashed : Background

$B_s \to \eta_c \phi$: better proper time resolution $\Rightarrow$ wiggles in the signal are visible

$B_s \to J/\psi \eta$: higher background $\Rightarrow$ flattens the wiggles

Likelihood for the proper time distribution includes:

- acceptance function (full MC)
- per-event-error for the proper time (full MC)
- tagging performance
- exponential background function

Results on the sensitivity to ϕ_s

The LHCb sensitivity for ϕ_s with 2 fb^{-1}

Channels	$\sigma(\Phi_s)[rad]$	$Weight\left(\sigma/\sigma_i\right)^2[\%]$
$B_S \to D_S(K^+K^-\pi)D_S(K^+K^-\pi^+)$	0.133	2.6
$B_S \to J/\Psi(\mu^+\mu^-)\eta(\pi^+\pi^-\pi^0(\gamma\gamma))$	0.142	2.8
$B_S \to J/\Psi(\mu^+\mu^-)\eta(\gamma\gamma)$	0.109	3.9
$B_S \to \eta_C(h^-h^+h^-h^+)\Phi(K^+K^-)$	0.108	3.9
Combined sensitivity for pure CP eigenstates	0.059	13.2
$B_S \to J/\Psi(\mu^+\mu^-)\Phi(K^+K^-)$	0.023	86.8
Combined sensitivity for all CP eigenstates	0.021	100.00

An additional study (Sergio Jimenez Otero), but $\Delta\Gamma_s/\Gamma_s$ = 0.10, Δm_s=20ps^{-1}	
$B_s \to J/\psi\eta'(\pi^+\pi^-\eta\ (\gamma\gamma))$	$\sigma(\phi_s)$= 0.20 rad

Total LHCb sensitivity with 10 fb^{-1} : 0.01 rad =0.6 degrees (but statistical uncertainty only)

The sensitivity for ϕ_s, ΔM_s, $\Delta\Gamma_s/\Gamma_s$, R_T, w_{tag} with $2fb^{-1}$

Parameter	Sensitivity	Channel
ϕ_s [rad]	0.021	$J/\psi\,\phi$, $\eta_c\,\phi$, $J/\psi\,\eta\,(\gamma\,\gamma)$, $J/\psi\,\eta\,(\pi\,\pi\,\pi)$, $D_s\,D_s$
$\Delta\Gamma_s/\Gamma_s$	0.0092	$J/\psi\,\phi$
ΔM_s [ps^{-1}]	0.007	$D_s\,\pi$ (alone)
ω_{tag}	0.0036	$D_s\,\pi$ (alone)
R_T	0.00040	$J/\psi\,\phi$

Only Control sample used, no signal.

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

Input to the likelihood fit

Results on the sensitivity to ϕ_s

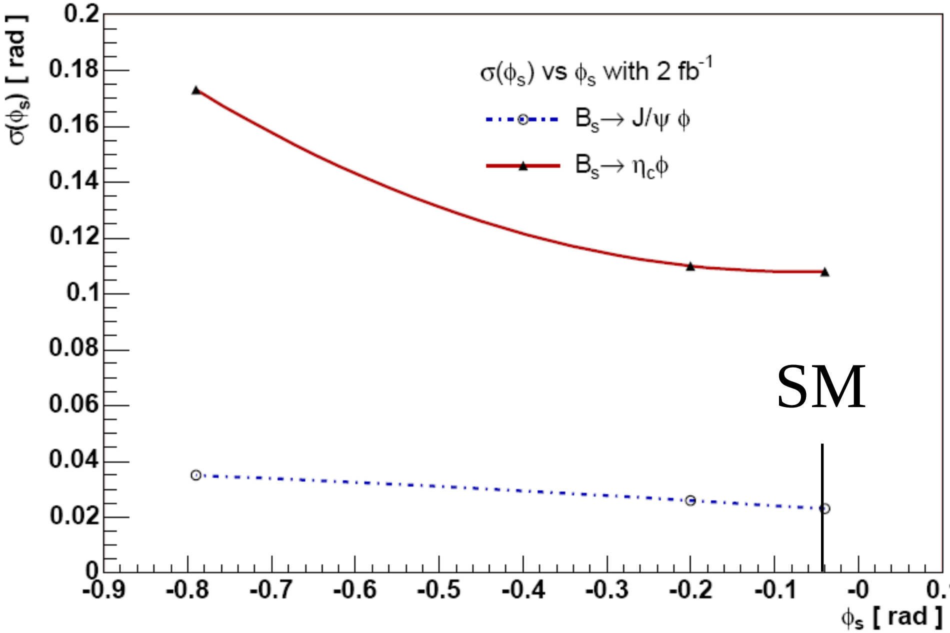
The effect of an improved or degraded proper time resolution (Σ_τ).

And the effect of a larger B/S

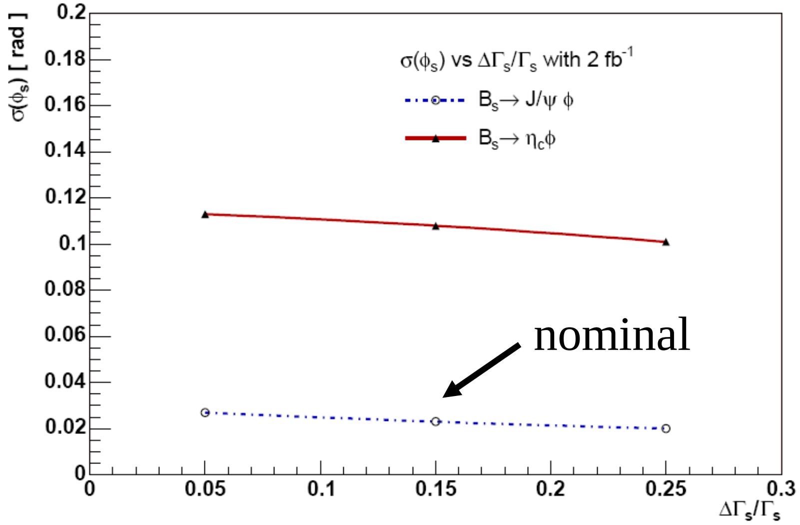
Scan	$\sigma(\phi_s)$ [rad] $B_s \to J/\psi\,\phi$	$B_s \to \eta_c\,\phi$
Nominal	0.023	0.108
$\Sigma_\tau + 10\ \%$	0.025	0.108
$\Sigma_\tau - 10\ \%$	0.023	0.103
$B/S \times 2$	0.025	0.118

Dependence of the ϕ_s sensitivity on ϕ_s

(It has been checked that the sensitivity does not depend on the sign of ϕ_s)



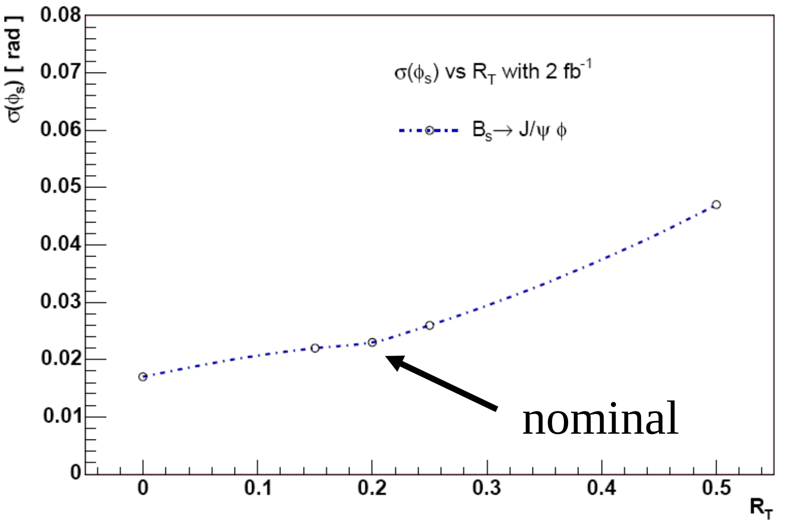
Results on the sensitivity to ϕ_s



Dependence of the ϕ_s sensitivity on $\Delta\Gamma_s/\Gamma_s$.

The world average is 0.14±0.06.

⇒ not very sensitive to $\Delta\Gamma_s/\Gamma_s$.



Dependence of the ϕ_s sensitivity on the CP-odd fraction (R_T) .

The world average is 0.167±0.041.

⇒ very sensitive to R_T, but we still have a reasonable sensitivity if maximum dilution (i.e. R_T=0.5)

Possible improvements for the sensitivity at LHCb

- Include the $J/\psi \to e^+e^-$ events : ~20% increase of event yields
- Full angular analysis for $B_s \to J/\psi\phi$
- Perform a combined fit with all signal channels
- Study the systematic uncertainty (extract proper time resolution from data)
- Optimize the use of the control sample ($B_s \to D_s\pi$) for the determination of the tagging performance of the signal samples ($B_s \to J/\psi\phi$, $B_s \to \eta_c\phi$, $B_s \to J/\psi\eta^{(')}$, $B_s \to D_sD_s$) (define sub-samples with the similar tagging performance)

Conclusions

The value of ϕ_s is unknown!

- The LHCb sensitivity for ϕ_s is 0.02 rad for 2 fb^{-1}
- Small dependence of the sensitivity on $\Delta\Gamma_s/\Gamma_s$ and ϕ_s .
- After a few years of data LHCb will be able to measure also a SM ϕ_s.
- Already with a small data sample (~0.2 fb^{-1}) we will have interesting results on ϕ_s. We aim for a ϕ_s result in 2008!

Thank you …

Backup slides

$$R\left(\mathrm{B_s}(t) \to f\right) = \left(1-\omega_{\mathrm{tag}}\right)\cdot\Gamma\left(\mathrm{B_s}(t)\to f\right) + \omega_{\mathrm{tag}}\cdot\Gamma\left(\overline{\mathrm{B}}_{\mathrm{s}}(t)\to f\right)$$

$$R\left(\overline{\mathrm{B}}_{\mathrm{s}}(t) \to f\right) = \omega_{\mathrm{tag}}\cdot\Gamma\left(\mathrm{B_s}(t)\to f\right) + \left(1-\omega_{\mathrm{tag}}\right)\cdot\Gamma\left(\overline{\mathrm{B}}_{\mathrm{s}}(t)\to f\right)$$

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

$$R[\overline{\mathrm{B}}_{\mathrm{s}}(t)\to f] = N_f\,|A_f^{(\mathrm{s})}(0)|^2\,e^{-\Gamma_{\mathrm{s}}t}\left\{\cosh\frac{\Delta\Gamma_{\mathrm{s}}\,t}{2} - \eta_f\cos\phi_{\mathrm{s}}\,\sinh\frac{\Delta\Gamma_{\mathrm{s}}\,t}{2} - \eta_f\,D\,\sin\phi_{\mathrm{s}}\,\sin(\Delta M_s\,t)\right\}.$$