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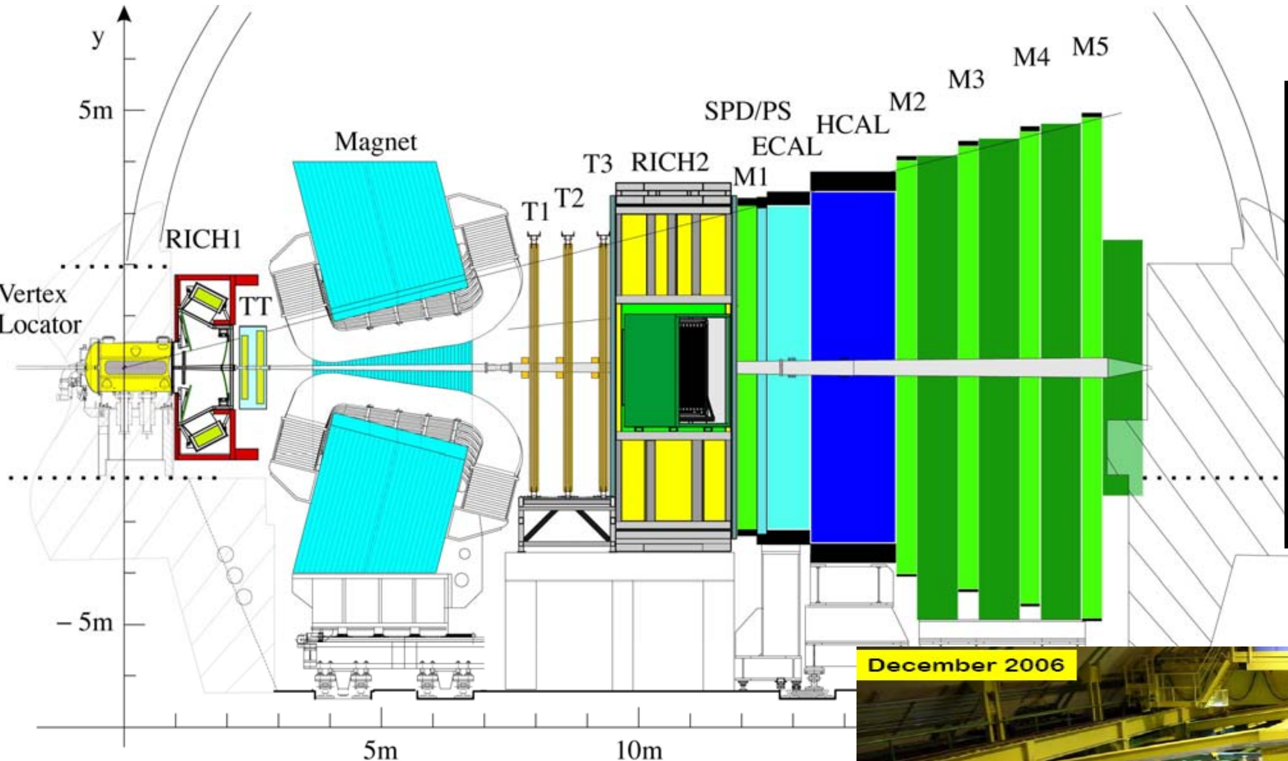
The sensitivity to ϕ_s and $\Delta\Gamma_s$ at LHCb

Jeroen van Hunen

(for the LHCb collaboration)

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

The LHCb experiment

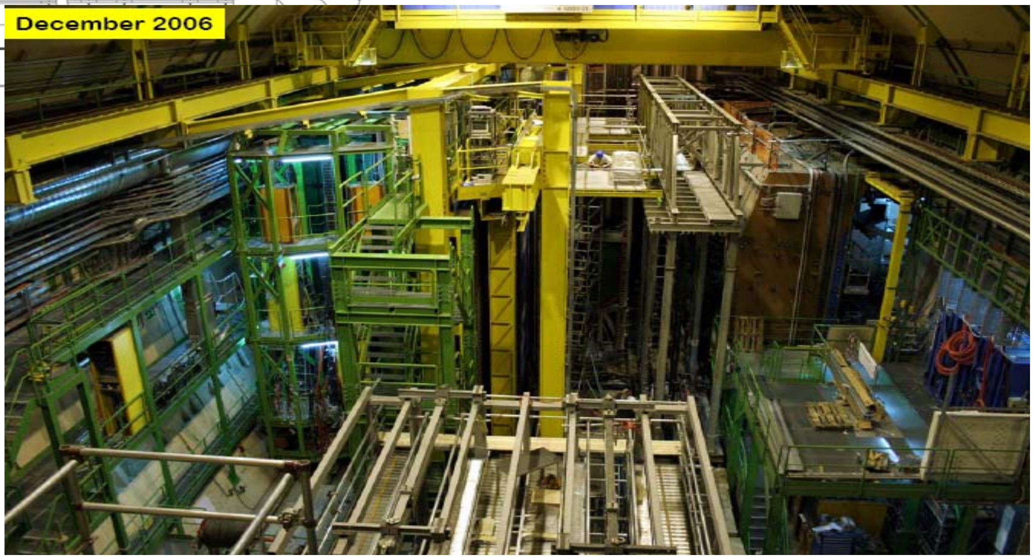


LHCb

Single arm spectrometer with :

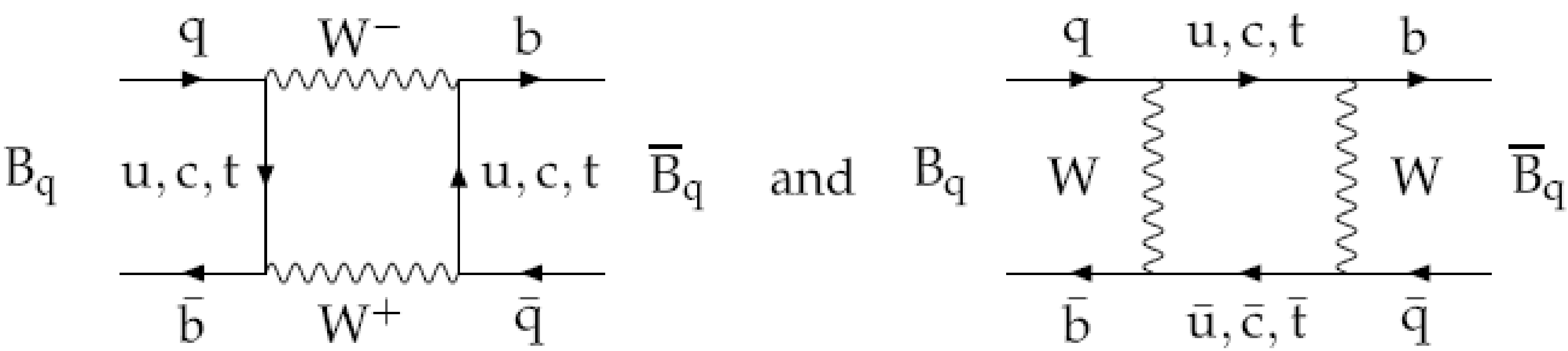
- good vertexing/tracking for reconstruction of the primary and B-decay vertices.
- good mass resolution and particle identification

LHCb under construction. It's real!



ϕ_s in the Standard Model

$B^0_q - \overline{B}^0_q$ mixing : Standard Model box diagrams



B^0_q mixing phase $\equiv$ $\phi_q = 2\arg[V^*_{tq} V_{tb}]$ $\Longrightarrow$ $\phi_d = 2\beta$

$\phi_s = -2\chi$

If only SM box diagrams

If NP contributions in B_s mixing $\Rightarrow$ $\phi_s = \phi_s^{SMbox} + \phi_s^{NP}$ 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 $\phi_s \leftrightarrow -2\chi = -2\lambda^2\eta \cong -0.04$)

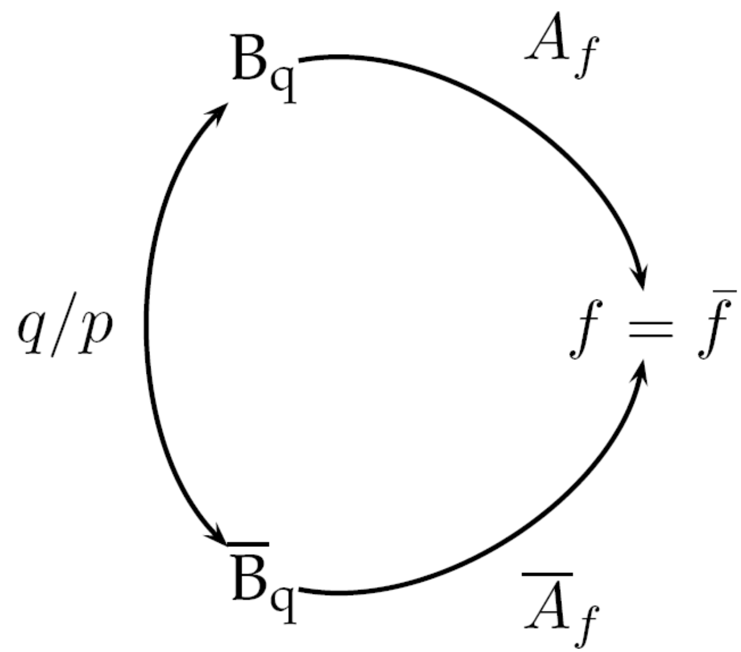
These B_s-decays have been used to determine the LHCb sensitivity to ϕ_s :

$B_s \to J/\psi(\mu^-\mu^+)\phi(K^+K^-)$	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
$B_s \to D_s(K^+K^-\pi^-)\ D_s(K^+K^-\pi^+)$	CP-even eigenstate
$B_s \to D_s^-(K^+K^-\pi^-)\pi^+$	Flavour-specific decay (control channel needed for determination of ΔM_s and the wrong tag fraction)

CP asymmetry in $B_s \rightarrow \bar{c}c\bar{s}s$ decays

$$\mathcal{A}_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \rightarrow f] - \Gamma[B_s(t) \rightarrow f]}{\Gamma[\overline{B}_s(t) \rightarrow f] + \Gamma[B_s(t) \rightarrow f]}$$

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



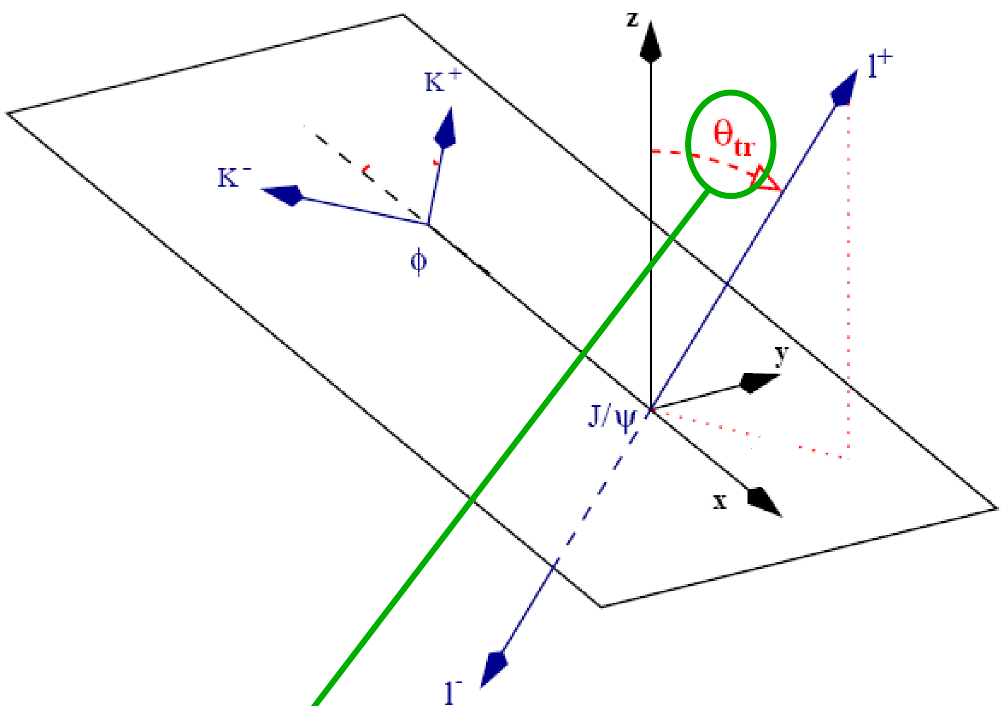
$$\mathcal{A}_{CP}^{\text{mix-ind}}(t) = -\frac{\eta_f \sin\phi_s \sin(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t/2) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s\, t/2)}$$

The time-dependent CP asymmetry allows us to measure ϕ_s and $\Delta\Gamma_s$

(but also untagged events give a sensitivity to $\phi_s \Rightarrow \cos(\phi_s)$ term)

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

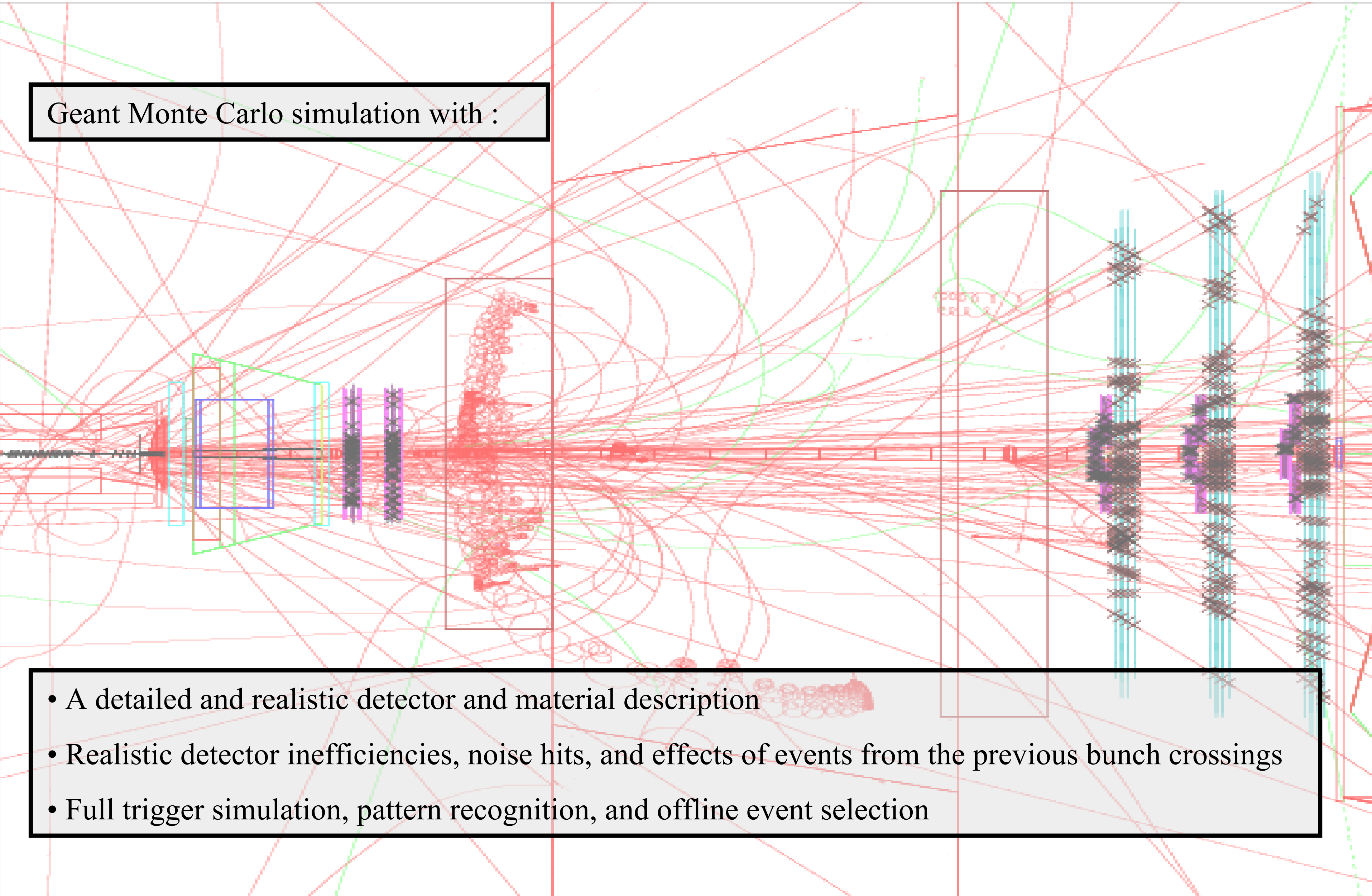
$R_T = 0.5 \to$ maximum dilution
(but still sensitivity to ϕ_s since odd and even contributions have different θ_{tr} distribution)

Measurements (Tevatron) $\to$
$R_T \cong 0.2$

(full angular analysis, i.e. with 3 angles, started)

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

The LHCb MC simulation



Geant Monte Carlo simulation with :

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

Results on the event selections

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

In summary (important for the sensitivity to ϕ_s) :

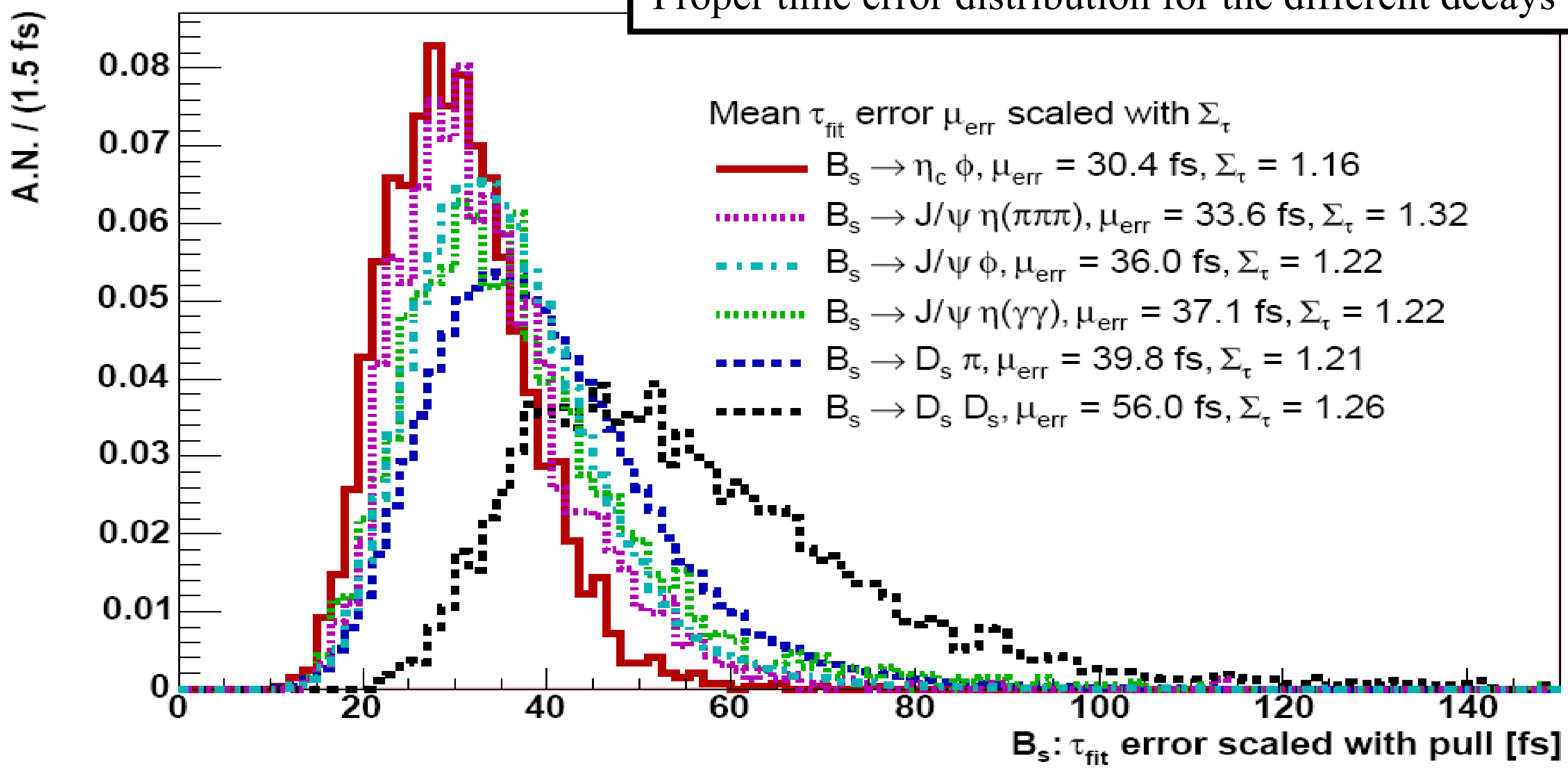
$B_s \to J/\psi\phi$: Large yield, but mixture of CP-odd and CP-even eigenstates

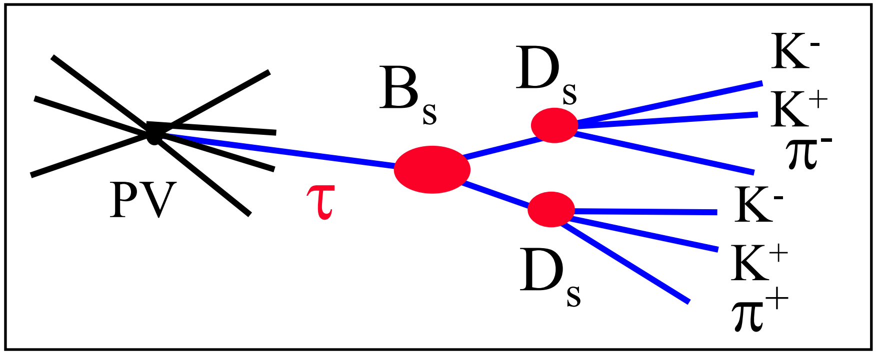
$B_s \to J/\psi\eta$, $B_s \to \eta_c\phi$: Low yield, high background, but CP-even

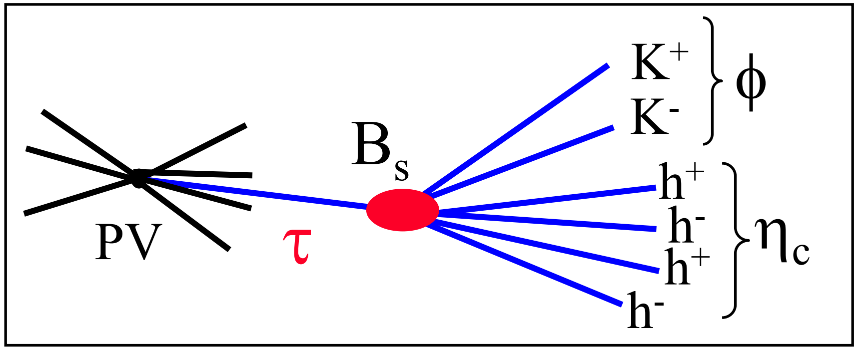
$B_s \to D_sD_s$: Low yield, worse proper time resolution, but CP-even

Results on the event selections

Proper time error distribution for the different decays







Toy MC

The sensitivities for ϕ_s and $\Delta\Gamma_s$ are determined by making use of a fast parameterized MC. The results on the event selections from the full LHCb MC are used as input.

The CP parameters are extracted by performing a likelihood fit to the mass and the tagged and untagged proper-time distributions (and for $B_s \to J/\psi\phi$ to the transversity angle, θ_{tr}).

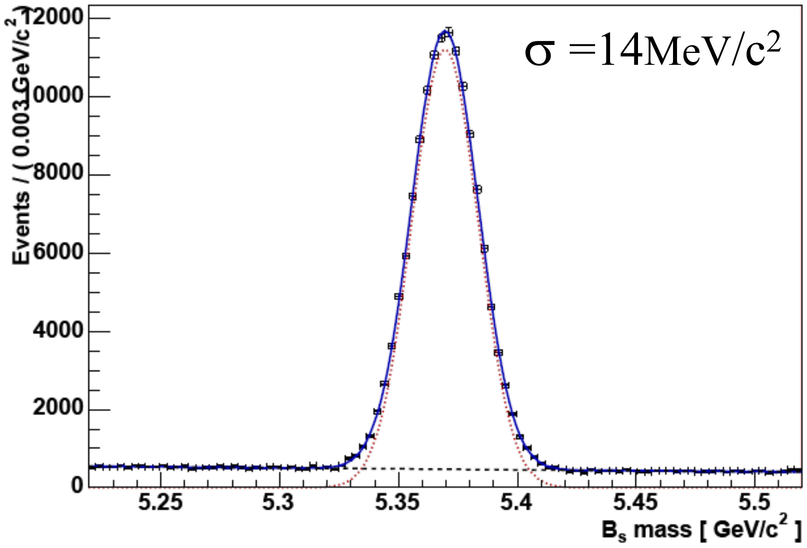
The likelihood for the signal $\bar{b} \to \bar{c}c\bar{s}$ transitions is simultaneously maximized with the control sample ($B_s \to D_s\pi$). The wrong tag fraction (w_{tag}) is assumed to be the same for the control and signal sample.

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

Standard model values are used as input

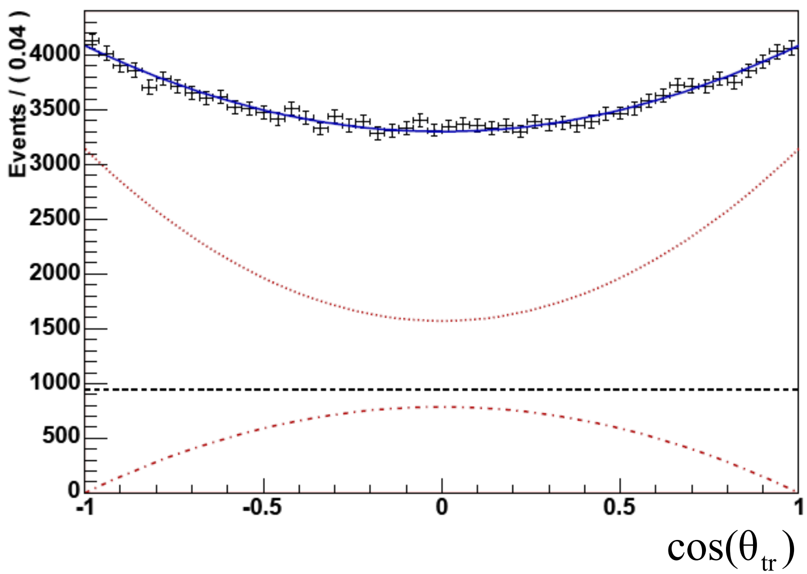
Performed ~200 toy experiments, where each experiment represents $2\mathrm{fb}^{-1}$ (10^7 seconds at $2\times10^{32}\mathrm{cm}^2\mathrm{s}^{-1}$). The RMS of the ϕ_s distribution is given as the sensitivity.

The mass and θ_{tr} distributions



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

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

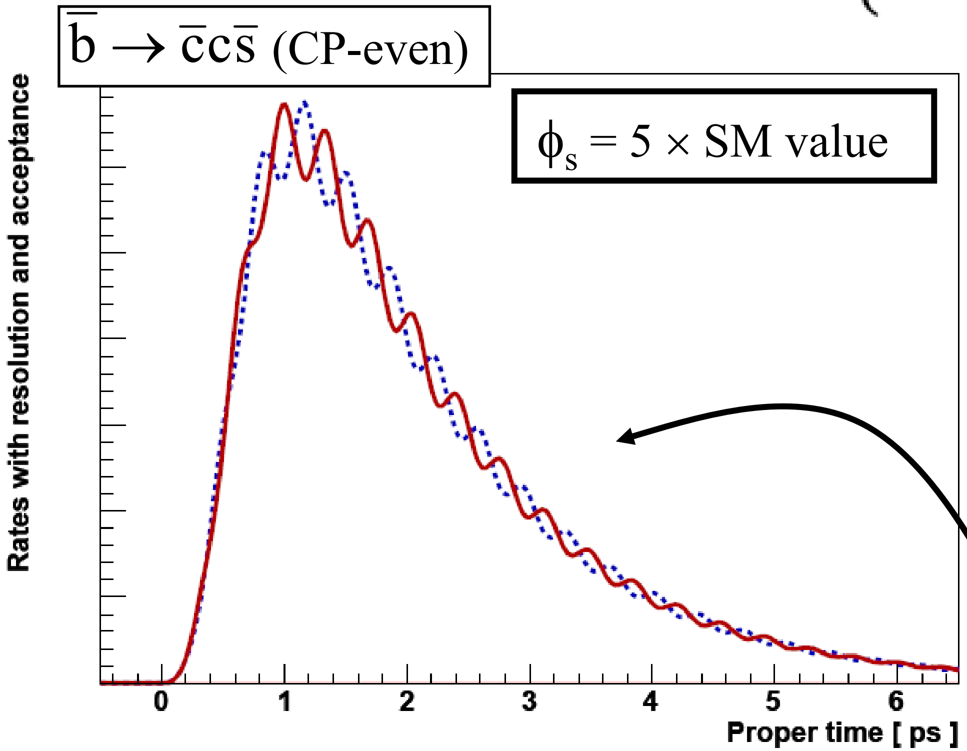


Projection of the likelihood on the transversity angle distribution for $B_s \to J/\psi\phi$.

Blue=total, red dotted = CP-even, red dashed =CP-odd, black=background (is assumed to be independent of $\cos(\theta_{tr})$).

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) = $1\text{-}2w_{tag}$

But $\Rightarrow$ also sensitivity to ϕ_s with untagged events (w_{tag}=0.5, D=0) from the $\cos(\phi_s)$ term, especially if ϕ_s is large.

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)

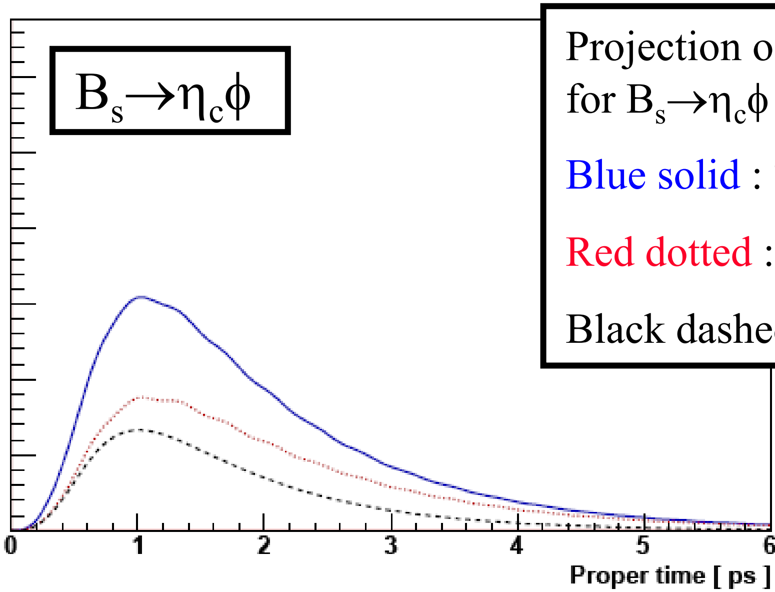
The tagged proper time distributions

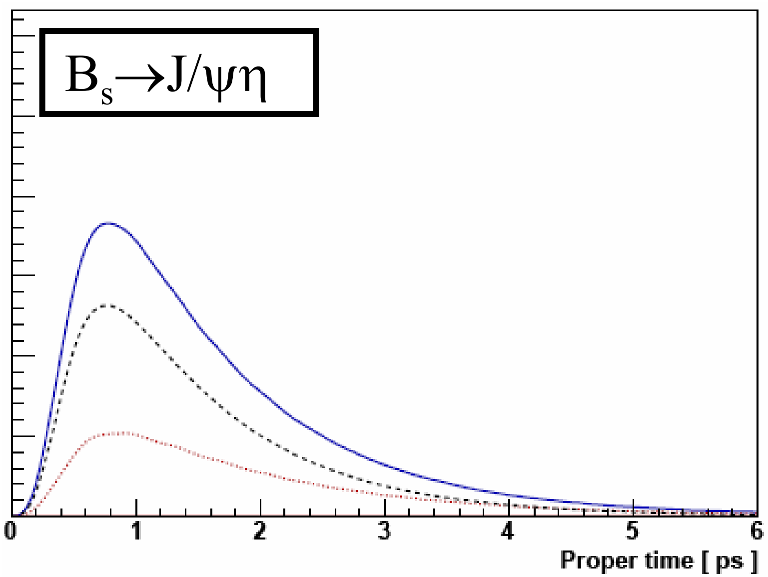
Projection of the likelihood on the proper time distribution for $B_s \to \eta_c \phi$ and $B_s \to J/\psi \eta$ (now with SM parameters)

Blue solid : Total

Red dotted : Signal

Black dashed : Background





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

$B_s \to J/\psi \eta$: larger background, worse proper time resolution $\Rightarrow$ flattens the wiggles

Likelihood for the proper time distribution includes (from full MC) :

- acceptance function
- per-event-error for the decay time
- tagging performance
- exponential background function

Results on the sensitivity to ϕ_s

Channels (sensitivity to ϕ_s with 2 fb^{-1})	$\sigma(\Phi_s)[rad]$	$Weight\left(\sigma / \sigma_i\right)^2 [\%]$
$B_S \to D_S(K^+K^-\pi)D_S(K^+K^-\pi^+)$	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	100.0

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

Additional studies ongoing : $B_S \to J/\Psi\eta'(\pi^+\pi^-\eta(\gamma\gamma))$ $B_S^0 \to J/\Psi(\mu^+\mu^-)\eta'(\rho^0(\pi^+\pi^-)\gamma)$

The sensitivity to B_s mixing parameters

Parameter	Sensitivity with 2 fb^{-1}	Channels
ϕ_s	**0.021 rad**	**$B_s \to J/\psi\phi$, $B_s \to \eta_c\phi$, $B_s \to J/\psi\eta$, $B_s \to D_sD_s$**
$\Delta\Gamma_s/\Gamma_s$	**0.0092**	**$B_s \to J/\psi\phi$**
R_T	**0.00040**	**$B_s \to J/\psi\phi$**
Δm_s	**0.007 ps^{-1}**	**$B_s \to D_s\pi^+$**
w_{tag}	**0.0036**	**$B_s \to D_s\pi^+$**

Control channel only

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

Input to the likelihood fit

Results on the sensitivity to ϕ_s

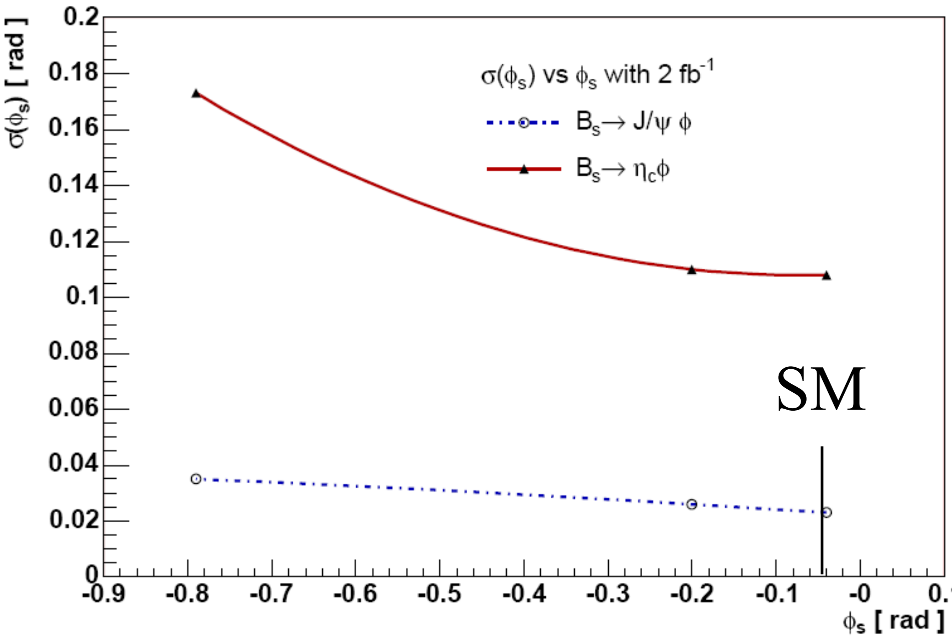
The effect on the sensitivity of a degraded (Σ_τ+10%) or improved (Σ_τ-10%) proper time resolution.

And the effect of a larger B/S

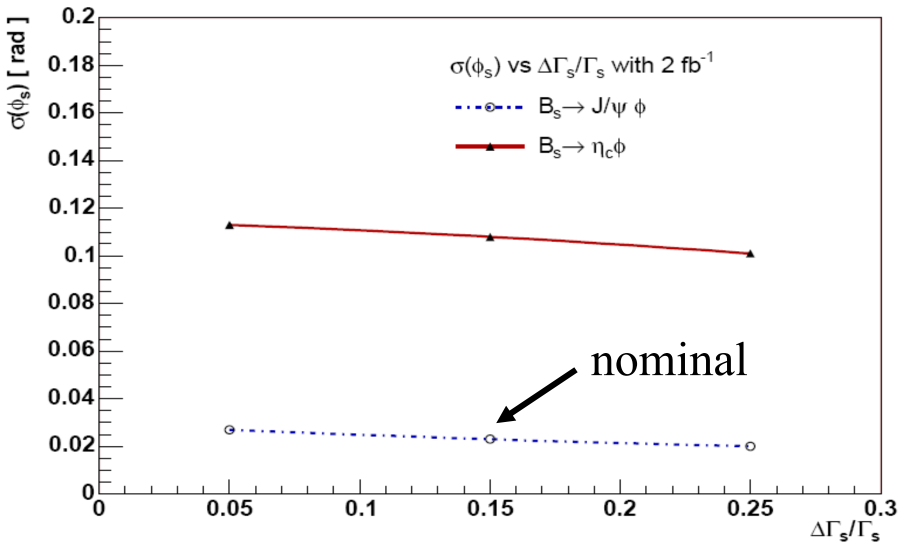
Scan	$\sigma(\phi_s)$ [rad] $B_s \to J/\psi\, \phi$	$\sigma(\phi_s)$ [rad] $B_s \to \eta_c\, \phi$
Nominal	0.023	0.108
$\Sigma_\tau + 10$ %	0.025	0.108
$\Sigma_\tau - 10$ %	0.023	0.103
$B/S \times 2$	0.025	0.118

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)

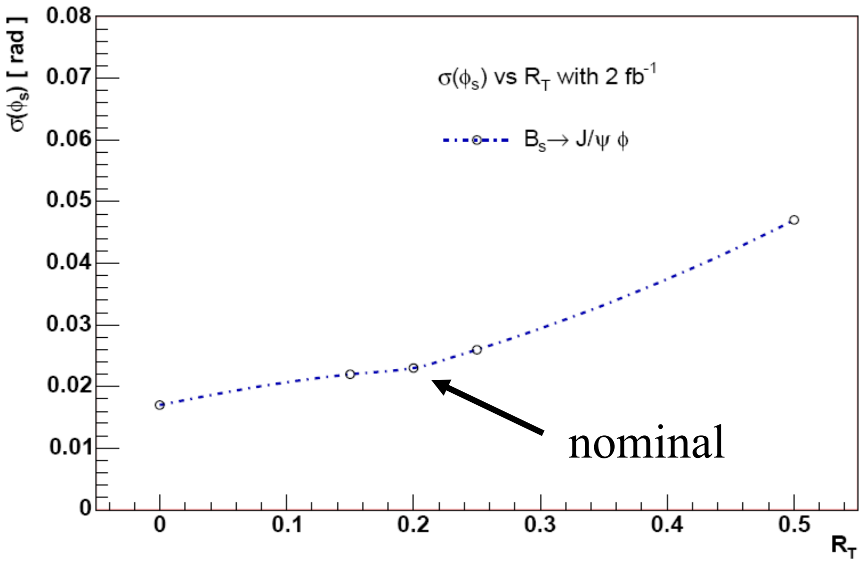


Results on the sensitivity to ϕ_s



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

$\Rightarrow$ Not very sensitive to $\Delta\Gamma_s/\Gamma_s$.



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

$\Rightarrow$ Sensitive to R_T, but we still have a reasonable sensitivity if maximum dilution, i.e. R_T=0.5.

(full angular analysis will reduce dependence)

Possible improvements for the sensitivity study

- Include the $J/\psi \to e^+e^-$ events : ~20% increase of event yields
- Full angular analysis for $B_s \to J/\psi\phi$
- Include additional B_s decays ($J/\Psi\eta'(\pi^+\pi^-\eta(\gamma\gamma))$, $J/\Psi(\mu^+\mu^-)\eta'(\rho^0(\pi^+\pi^-)\gamma)$)
- Perform a combined fit with all signal channels
- Study the systematic uncertainty
- Optimize the use of the control sample ($B_s \to D_s\pi$) for the determination of the tagging performance of the signal samples ($B_s \to J/\psi\phi$, etc.) by defining sub-samples with similar tagging performance.
- …

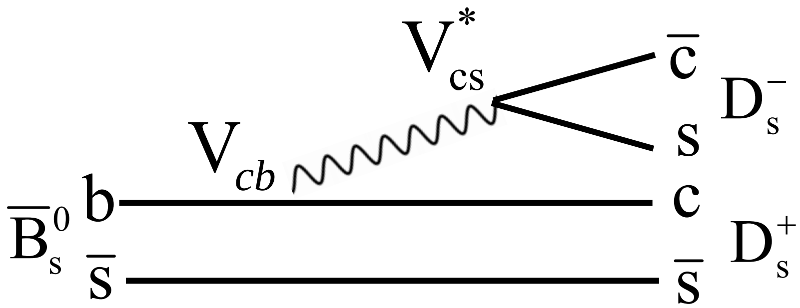
Conclusions

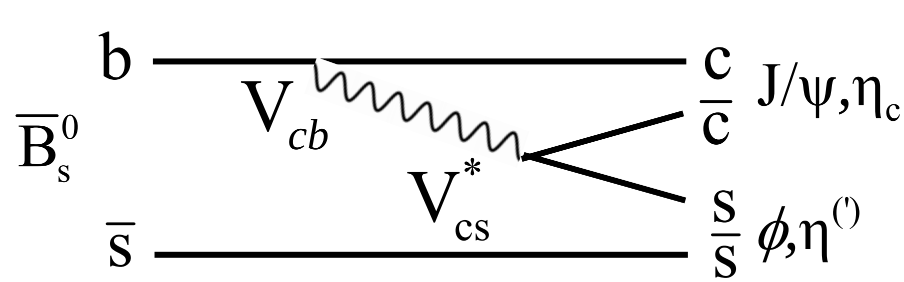
The value of ϕ_s is not known precisely

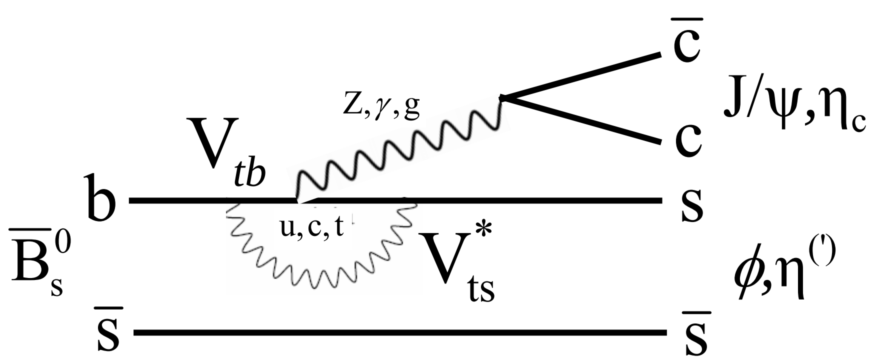
- The LHCb sensitivity for ϕ_s is 0.02 rad (~1.2 degrees) for 2 fb^{-1}
- Small dependence of the sensitivity on $\Delta\Gamma_s/\Gamma_s$ and ϕ_s
- After a few years of data LHCb will be able to measure also a SM ϕ_s
- Already with a small data sample (0.2 fb^{-1}) we have interesting results on ϕ_s

We aim for a ϕ_s result in 2008!

Backup: Tree and Penguin Diagrams







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

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

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

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

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

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