B_s^0 mass difference ΔM_s and mixing phase ϕ_s at LHCb

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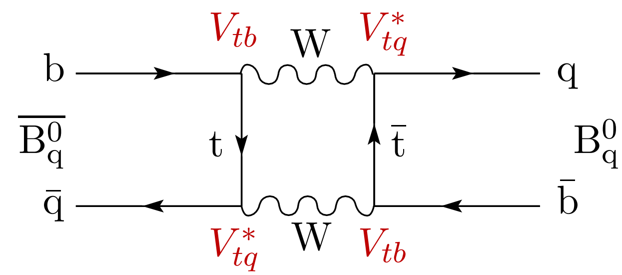
On behalf of the LHCb collaboration

- $B_s^0 - \overline{B_s^0}$ mixing
- LHCb full Monte Carlo simulation
- Sensitivity studies
- ΔM_s from $B_s^0 \to D_s\pi$
- ϕ_s from $B_s^0 \to J/\psi\ \phi$ and $\bar{b} \to \bar{c}c\bar{s}$ transitions to pure CP eigenstates

$B_s^0 - \overline{B_s^0}$ *mixing*

Neutral B_q^0 are *not* eigenstates of the weak interaction

$\longrightarrow$ "mixing": particle–anti-particle oscillations ($|\Delta B = 2|$)



Time evolution of B_q^0 and $\overline{B_q^0}$

$$i\frac{d}{dt}\begin{pmatrix} B_q^0(t) \\ \overline{B_q^0}(t) \end{pmatrix} = \underbrace{(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma})}_{\mathcal{H}_{\rm eff}} \begin{pmatrix} B_q^0(t) \\ \overline{B_q^0}(t) \end{pmatrix} \Longrightarrow$$

Physical (mass) eigenstates

$$|B_{L/H}\rangle = p|B_q^0\rangle \pm q|\overline{B_q^0}\rangle$$

B_s^0 ~~CP~~ phase $\phi = \arg\left(-M_{12}^{(s)}/\Gamma_{12}^{(s)}\right) \approx 2\arg[V_{ts}^* V_{tb}] \sim -2\lambda^2\eta = \mathcal{O}(-0.04)$ rad in SM

where $\arg(-\Gamma_{12}^{(s)}) = 2\arg(V_{cb}V_{cs}^*) + \mathcal{O}(\lambda^2)$ suppressed contributions $\rightarrow \arg(-\Gamma_{12}^{(s)}) \simeq 0$

- $M_{12}^{(s)}$: virtual intermediate states $\Rightarrow$ sensitive to New Physics
- $\Gamma_{12}^{(s)}$: on-shell contributions $\Rightarrow$ *insensitive* to New Physics

En route for NP with $B_s^0 - \overline{B_s^0}$ mixing?

Mixing observables

$B_d^0 - \overline{B_d^0}$ (well measured) versus $B_s^0 - \overline{B_s^0}$ (*Terra incognita*) in SM

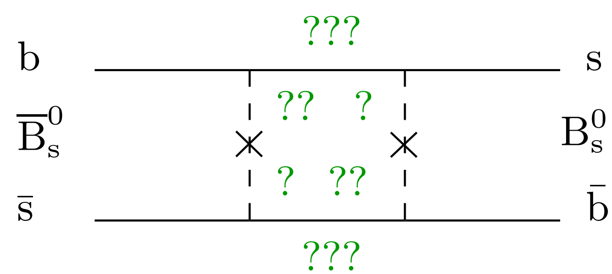
- $\Delta M_d \sim 0.5\ \mathrm{ps}^{-1}$
- $\Delta\Gamma_d/\Gamma_d \sim 0$
- $\phi_d \overset{\mathrm{SM}}{\equiv} 2\arg\left[V_{\mathrm{td}}^* V_{\mathrm{tb}}\right] \approx 2\beta = \mathcal{O}(0.8)\ \mathrm{rad}$

- $\Delta M_s \sim 20\ \mathrm{ps}^{-1} \sim 40$ times faster than B_d^0!
- $\Delta\Gamma_s/\Gamma_s \sim 10\%$
- $\phi_s \overset{\mathrm{SM}}{\equiv} 2\arg\left[V_{\mathrm{ts}}^* V_{\mathrm{tb}}\right] \approx -2\beta_s = \mathcal{O}(-0.04)\ \mathrm{rad}$

Oscillation frequency ΔM_s measurement

- ☆ constrain V_{td}: $\frac{\Delta M_s}{\Delta M_d} \propto \frac{m_{B_s^0}}{m_{B_d^0}} \xi^2 \frac{|V_{\mathrm{ts}}|^2}{|V_{\mathrm{td}}|^2}$ $\longrightarrow$ theoretical errors from ΔM_q partly cancel in ratio
- ☆ ΔM_s beyond SM prediction ($\Delta M_s^{\mathrm{SM}} > 14.5\ \mathrm{ps}^{-1}$ at 95%): $\Delta M_s = \Delta M_s^{\mathrm{SM}} + \Delta M_s^{\mathrm{NP}}$?
- ☆ prerequisite for time-dependent CP-asymmetries!

Determination of: $\phi_s = \underbrace{\phi^{\mathrm{SM}}}_{\mathcal{O}(-0.04)} + \phi^{\mathrm{NP}}$?



LHCb full MC simulation

Estimate LHCb performances in reconstructing b-decays

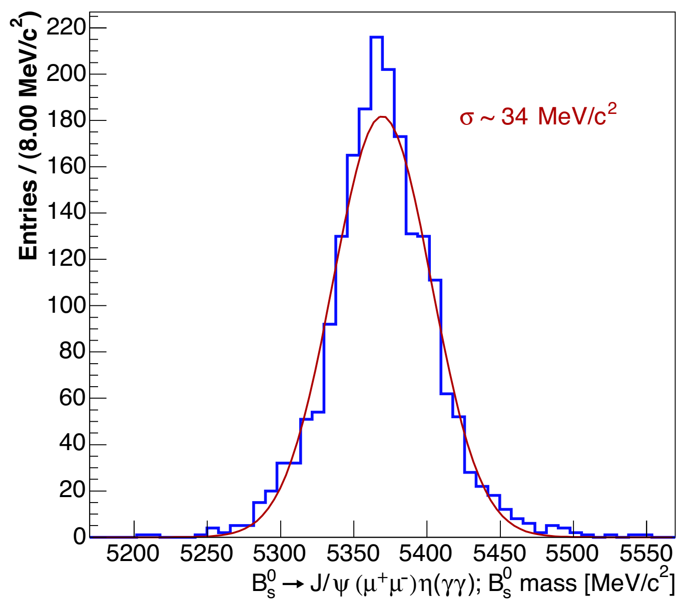
- time-dependent asymmetry and ΔM_s measurements strongly depend on:
  - proper-time resolution: must be good enough to resolve fast $\mathrm{B_s^0} - \overline{\mathrm{B_s^0}}$ oscillations
  - tagging: knowledge of initial b-hadron flavour, dilution of CP-asymmetries (wrong tag)
- decay channels selection (yields, trigger efficiencies), background sources / levels

Full MC simulation main steps:

- `Pythia`: generation of $\mathrm{p}-\mathrm{p}$ collisions at $\sqrt{s} = 14\ \mathrm{TeV}$ (including pile-up)
- `Geant`: detector response, spill-over and tracking through material
- on/offline pattern recognition, full trigger chain, tagging, offline selections, ...

Full MC performances

$B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$: $\sigma_m \sim 34$ MeV/c^2



- mass resolutions
  - ~ 15 MeV/c^2 for charged final states
  - $\sim 30 - 70$ MeV/c^2 when involving γ(s)
- vertex
  - primaries $\sigma_z \sim 50\ \mu$m
  - b-decay vertices $\sigma_z < 200\ \mu$m
- proper-time
  - $\sigma_\tau \sim 30 - 40$ fs

Flavour tagging power: $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}}(1 - 2\omega_{\text{tag}})^2$

- for $B_s^0 \to$ 2003 MC: $\varepsilon_{\text{eff}} \sim 6\%$, 2004 MC (neural network): $\varepsilon_{\text{eff}} \sim 7 - 9\%$

Presentation results based on:

- for ΔM_s: studies with 2003 MC data (re-opt. TDR CERN/LHCC 2003-030)
- for ϕ_s: new study with recent MC data
  $\longrightarrow$ improved tagging, L1 trigger, high-level trigger design (~ 2 kHz), ...

Sensitivity to mixing observables

Statistical sensitivities to mixing observables assessed using fast MC

- generate event samples with LHCb expected statistics
- characteristics of samples taken from full simulation (resolutions, acceptance, tagging)
- background levels from fully-simulated inclusive $\mathrm{b\bar{b}}$ events

Unbinned maximum likelihood fits to proper-time to extract expected statistical uncertainties

$$\mathcal{L} = \prod_i \left[f_i^{\mathrm{sig}} \mathcal{R}_i^{\mathrm{sig}} + (1 - f_i^{\mathrm{sig}}) \mathcal{R}_i^{\mathrm{bkg}} \right]$$

- f_i^{sig}: signal probability based on reconstructed mass; $\mathcal{R}_i^{\mathrm{sig}}$, $\mathcal{R}_i^{\mathrm{bkg}}$: signal, bkg decay rates
- rates convoluted with proper-time resolution and weighted with acceptance
- proper-time resolution based on per-candidate computed errors from full MC

$B_s^0 \to D_s\pi$ *reconstruction*

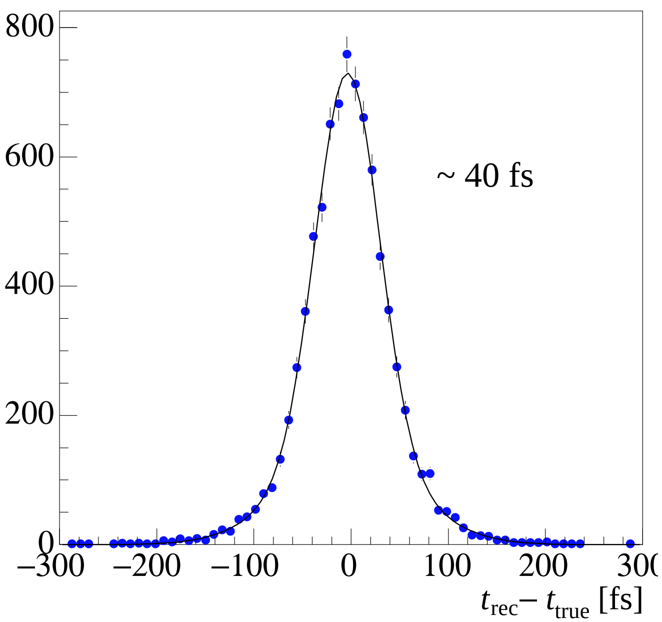
ΔM_s measurement with $B_s^0 \to D_s^- \pi^+$: flavour specific decay

- flavour asymmetry $\mathcal{A}_f^{obs}(t) = -D \cdot \frac{\cos(\Delta M_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2})}$, $D = (1-2w)$ if perfect resolution

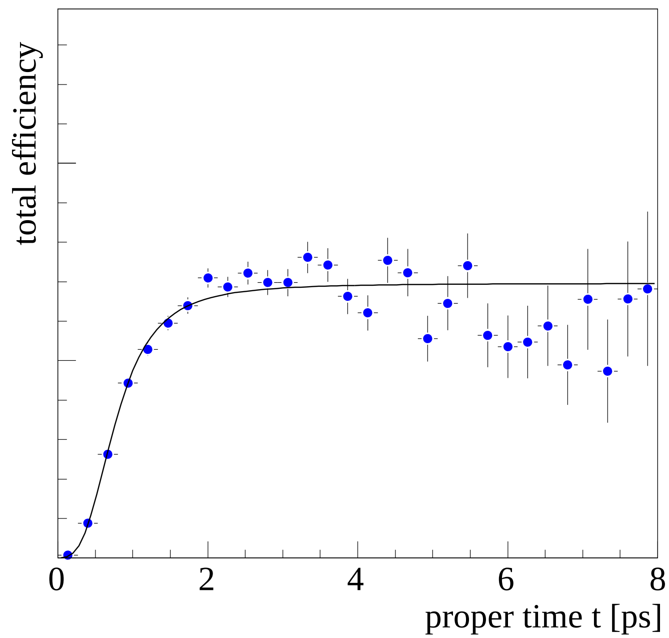
Full MC study (LHCb 2003-127)

- reconstructed with $D_s \Rightarrow KK\pi$ mode, expect ~ 80 k events per year (2 fb^{-1})
- $B/S \sim 0.3$ from fully-simulated inclusive $b\bar{b}$ events

Proper time resolution ~ 40 fs



Acceptance (proper-time efficiency)

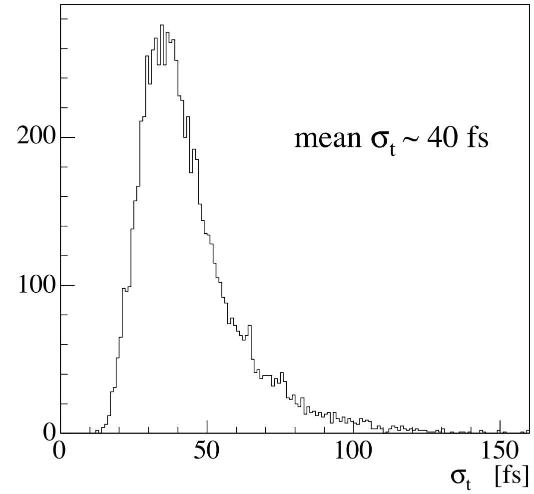


$\Rightarrow$ characteristics from full MC used as inputs for toy studies (LHCb 2003-103)

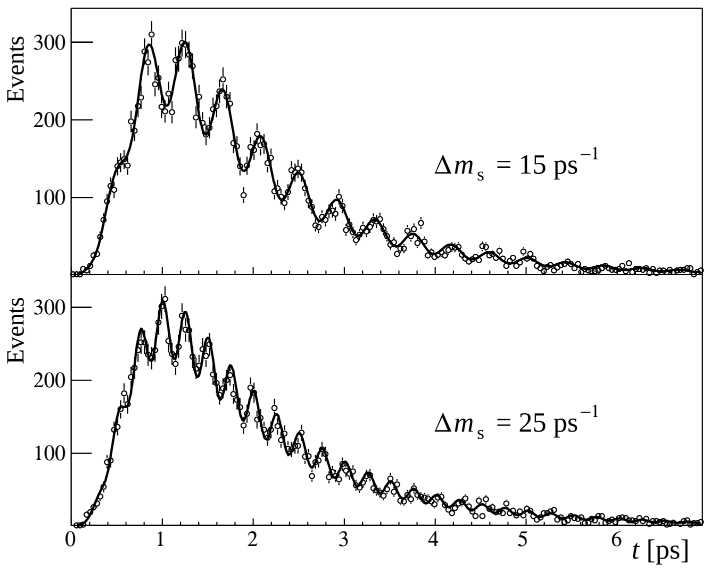
B_s^0 *oscillation frequency with* $B_s^0 \to D_s\pi$

Unbinned likelihood fit:

- rates weighted with acceptance, tagging dilution
- proper-time error σ_t obtained from full MC
  $\to$ uncertainty to generated events
- $\Delta\Gamma_s/\Gamma_s = 0.1$



Once oscillations observed, precise value of ΔM_s obtained: uncertainty $\sim 0.06\%$ (2 fb^{-1})



Decay rate for unmixed B_s^0

Statistical precision on ΔM_s after 1 year (2 fb^{-1})

ΔM_s [ps^{-1}]	15	20	25	30
$\sigma(\Delta M_s)$ [ps^{-1}]	0.009	0.011	0.013	0.016

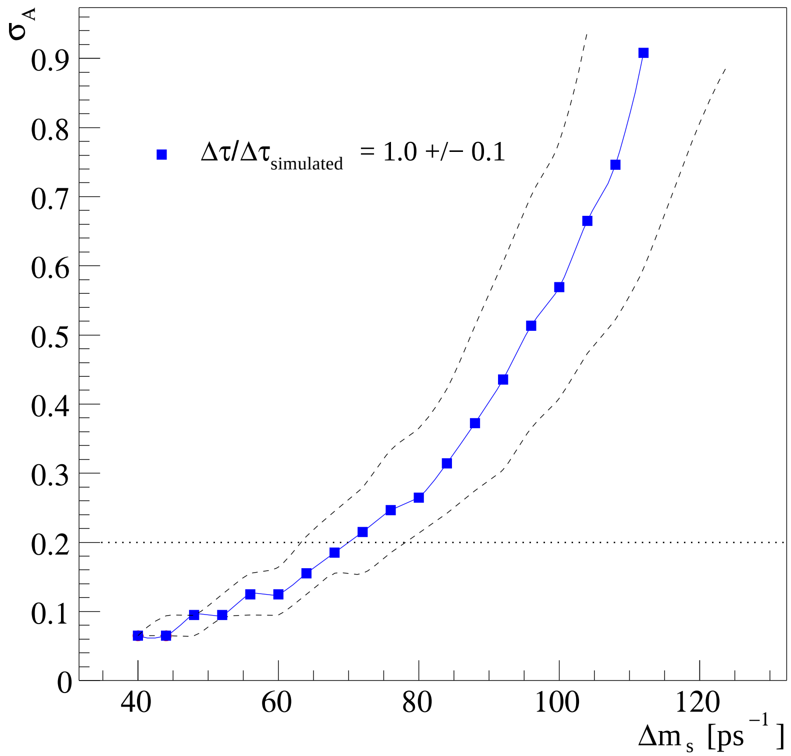
- $\sigma(\Delta M_s)$ will probably be dominated by systematics, e.g. t scale

  $\to$ even if $\sigma_{\text{sys}} \sim 10 \cdot \sigma_{\text{stat}}$, uncertainty $< 1\%$

ΔM_s *sensitivity limit*

'Amplitude method' used to evaluate maximum value of ΔM_s measurable (2 fb^{-1})

$\longrightarrow$ fit factor A in front of $\cos(\Delta M_s t)$ term in asymmetry for different ΔM_s values



Statistical uncertainty on amplitude factor A (σ_A) versus ΔM_s

Sensitivity limit:
ΔM_s for which $5 \cdot \sigma_A = 1 = A$

In 1 year, $\geq 5\sigma$ observation of $\mathrm{B_s^0}$ oscillations up to $\Delta M_s = 68\ \mathrm{ps}^{-1}$

$\longrightarrow$ could exclude full SM range

'Immediate' measure of ΔM_s if small: $1/8$ year LHCb running! (0.25 fb^{-1}, $\Delta M_s = 40\ \mathrm{ps}^{-1}$)

CP violation and $\bar{b} \to \bar{c}c\bar{s}$ transitions

- $B_s^0 \to J/\psi\ \phi$: admixture of CP eigenstates ($\eta_{J/\psi\phi} = +1, -1, +1$)

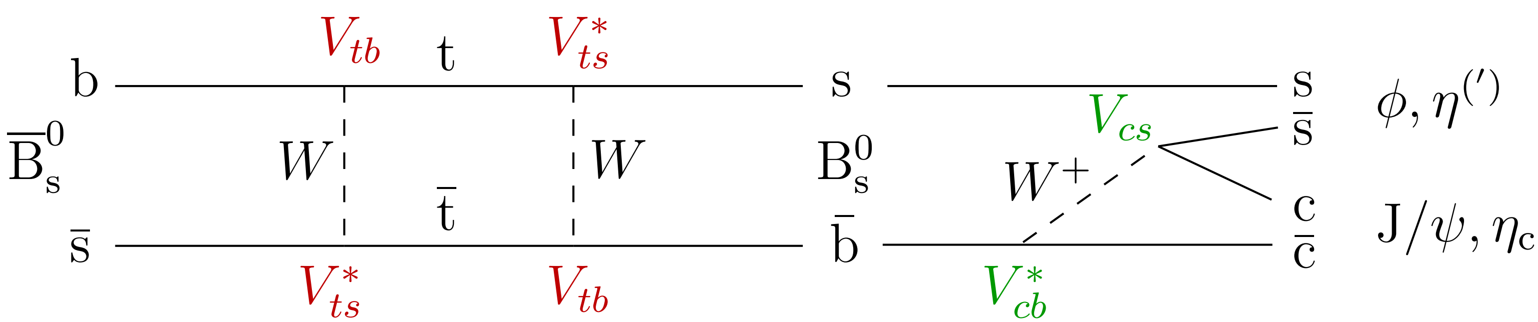
  $\longrightarrow$ one-angle θ_{tr} angular analysis (Phys.Rev. D63 (2001) 114015, hep-ph/0012219)

  \- fraction of CP-odd decays defined as $R_T \equiv |A_\perp(0)|^2 / \sum_{i=0,\parallel,\perp} |A_f(0)|^2 \sim \mathcal{O}(0.2)$

- $B_s^0 \to \eta_c\ \phi$, $B_s^0 \to J/\psi\eta^{(\prime)}$: pure CP-even eigenstates $\longrightarrow$ no angular analysis needed

- Mixing-induced CP violation: phase mismatch $\phi_s - 2\phi_D \approx \phi_s \neq 0, \pi$

"first mix, then decay"



$\longrightarrow$ CP-asymmetry directly measures $\phi_s = \mathcal{O}(-0.04)$ rad (for given $\eta_{f_{CP}}$)

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

Physics model: $\bar{\mathrm{b}} \to \bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}$ *to pure CP eigenstates*

- Final states $f = \eta_c\phi, \mathrm{J}/\psi\eta^{(\prime)}$ CP-even eigenstates: $(\mathcal{CP})|f\rangle = \eta_f\,|f\rangle$, $\eta_f = +1$
- Transition rates of initially pure $\mathrm{B_s^0}$ and $\overline{\mathrm{B_s^0}}$ states (perfect resolution)

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

  - tagging categories: $q = +1, -1$ for $R(\mathrm{B_s^0}, \overline{\mathrm{B_s^0}}(t) \to f)$, $q = 0$ untagged
  - $D = (1 - 2\omega)$: tagging dilution; ω: wrong tag fraction
- Both D and ϕ_s modulate the oscillating term: need a control channel to extract ω $\to \mathrm{B_s^0} \to \mathrm{D_s}\pi$ is used
- Untagged events: access to $\Delta\Gamma_s$ *and* ϕ_s (small sensitivity to ϕ_s, since $\mathcal{O}(\phi_s^2)$ in SM)

Inputs from full MC simulation for ϕ_s study

Decay channels considered to assess LHCb sensitivity to ϕ_s:

- $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$
- $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$: pure CP eigenstate
- $B_s^0 \to \eta_c(\pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-K^+K^-, K^+K^-K^+K^-)\phi(K^+K^-)$: pure CP eigenstate

These channels were studied in the full MC (2004 MC data), and inputs used for toys

Most relevant parameters (yields after high-level trigger):

Parameters	$J/\psi\ \eta(\gamma\gamma)$	$J/\psi\ \eta(\pi^+\pi^-\pi^0)$	$\eta_c\phi$	$J/\psi\ \phi$
Untagged yield [k events] (2 fb^{-1})	8.9	3.1	3	125
B/S	2.0	3.0	0.7	0.3
Mean $\sigma_{t_i^{rec}}$ [fs]	30.4	25.5	26.2	35.8
ω_{tag} / ε_{tag}[%]	35/63	30/62	31/66	33/60

These $\bar{b} \to \bar{c}c\bar{s}$ transitions will be fitted simultaneously with $B_s^0 \to D_s\pi$ sample

ϕ_s likelihood fit strategy

- Generate and fit ~ 250 toy experiments corresponding to 1 year data taking at $2\ \mathrm{fb}^{-1}$
- Unbinned (extended) likelihood fit to $\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}}$

$$\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}} = \prod_{i \epsilon \mathrm{B_s^0} \to f} \mathcal{L}_i^{\bar{b}\to\bar{c}c\bar{s}}(m_i, \theta_{\mathrm{tr}i}, t_i^{rec}, \sigma_{t_i}, q_i)$$

1. Mass distributions fitted to determine signal and background probabilities
2. Sidebands: background parameters determined, acceptance fitted
3. Signal window: physics parameters $\vec{\alpha} = (\Delta\Gamma_s/\Gamma_s, \Delta M_s, \phi_s, \tau_{\mathrm{B_s^0}}(, R_T))$ and wrong tag fraction ω fitted

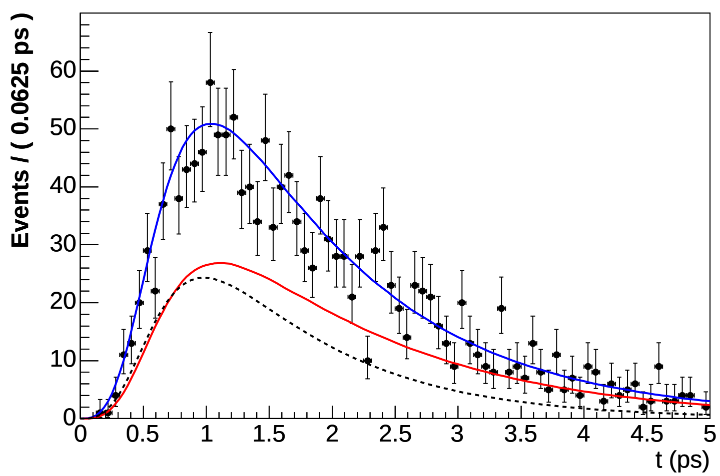
- $\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}}$ simultaneously maximized with likelihood of the $\mathrm{B_s^0} \to \mathrm{D_s}\pi$ control sample

Likelihood: rate parts

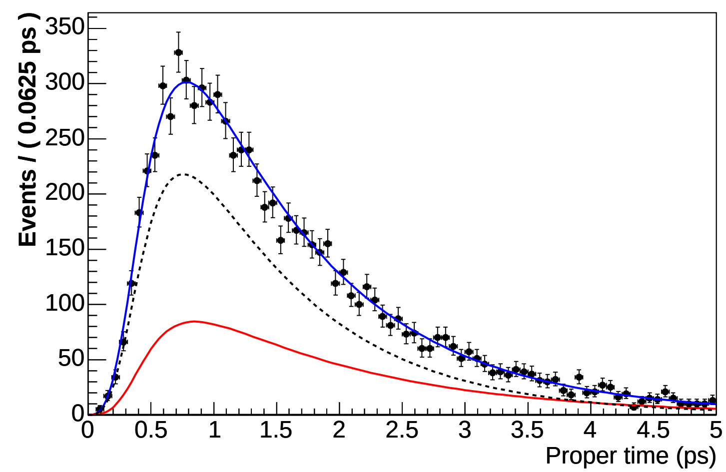
$$\mathcal{L}^{sig}_{t,even}(t_i^{rec}, \sigma_{t_i}, q_i | \overrightarrow{\alpha}, \omega, acc_s) \propto A(t_i^{rec}) \times \left[(1-\omega)\Gamma^{even}_{\mathrm{B^0_s}\to f}(t_i^{true}) + \omega \Gamma^{even}_{\overline{\mathrm{B}}^0_s \to f}(t_i^{true}) \right] \otimes G(t_i^{rec} - t_i^{true}, S\sigma_{t_i}, \mu\sigma_{t_i})$$

$$\mathcal{L}^{bkg}_{t}(t_i^{rec}; \tau_{bkg}, acc_s) \propto A(t_i^{rec}) \times E(t_i^{true}; \tau_{bkg}) \otimes \delta(t_i^{rec} - t_i^{true})$$

- $\vec{\alpha} = (\Delta\Gamma_s/\Gamma_s, \Delta M_s, \phi_s, \tau_{\mathrm{B^0_s}}(, R_T))$: vector of physics parameters



$\mathrm{B^0_s} \to \eta_c\ \phi$ *lifetime*



$\mathrm{B^0_s} \to \mathrm{J}/\psi\eta(\gamma\gamma)$ *lifetime*

Signal: red, Background: black, Total: blue

ϕ_s *sensitivities*

Physics input values

ϕ_s [rad]	ΔM_s [ps^{-1}]	$\Delta\Gamma_s/\Gamma_s$	$\tau_{B_s^0}$ [ps]	R_T
-0.04	20.0	0.1	1.472	0.2

Fit results $(2\ \text{fb}^{-1})$

Sensitivity	$J/\psi\ \eta(\gamma\gamma)$	$J/\psi\ \eta(3\pi)$	$\eta_c\phi$	$J/\psi\ \phi$
$\sigma(\Delta\Gamma_s/\Gamma_s)$	0.019	0.024	0.025	0.011

$\sigma(R_T) = 0.0047$

Channels	$\boldsymbol{\sigma(\phi_s)}$ [rad]	Weight $(\sigma/\sigma_i)^2$ [%]
$B_s^0 \to J/\psi\ \eta(\gamma\ \gamma)$	0.112	6.4
$B_s^0 \to J/\psi\ \eta(\pi^+\ \pi^-\ \pi^0)$	0.148	3.6
$B_s^0 \to \eta_c\ \phi$	0.106	7.1
Combined three pure CP eigenstates channels	0.068	17.1
$B_s^0 \to J/\psi\ \phi$	0.031	82.9
Combined all four CP eigenstates channels	0.028	100.0

Contribution from pure CP eigenstates: $\sim 17\%$

With $10\ \text{fb}^{-1}$ (5 years): $\sigma(\phi_s) \sim 0.013$ rad $\longrightarrow$ $\sim 3\sigma$ for $\phi_s = -0.04$ rad (SM)

Outlook

ΔM_s with $B_s^0 \to D_s\pi$

- very good precision after 1 year LHCb. If SM ΔM_s, do not need $2\ \mathrm{fb}^{-1}$ to measure it
- could exclude full SM range in 1 year

ϕ_s with $B_s^0 \to J/\psi\phi(K^+K^-)$, $B_s^0 \to J/\psi\eta(\gamma\gamma, \pi^+\pi^-\pi^0)$, $B_s^0 \to \eta_c(4h)\phi(K^+K^-)$

- 3σ measurement within 5 year for SM ϕ_s, $\sim 17\%$ contribution from pure CP eigenstates
- $\geq 5\sigma$ after 1 year if $\phi_s \sim -0.2$ rad
- other channels could be added: $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$, $B_s^0 \to J/\psi\eta'$
- lifetime unbiased selections and trigger to be explored (flat proper-time efficiency)

$\Rightarrow$ $B_s^0 - \overline{B_s^0}$ represents a sensitive probe for New Physics $\Leftarrow$

BACK-UP SLIDES

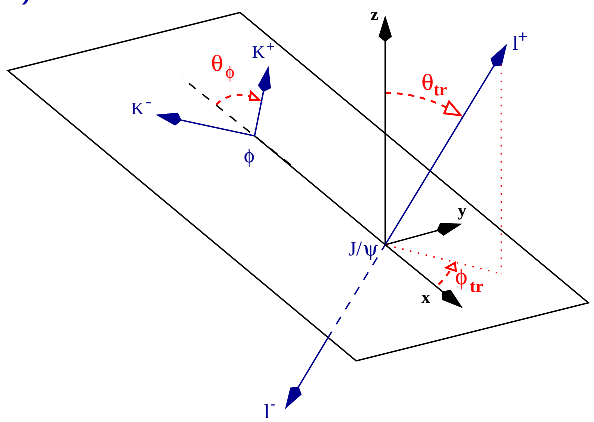
Physics model: $\mathrm{B_s^0} \to \mathrm{J}/\psi\ \phi$

- Final state f is an admixture of CP eigenstates
  - $f = 0, \|$: CP-even, $\eta_f = +1$, $f = \perp$: CP-odd, $\eta_f = -1$
- Linear polarization amplitudes: $A_f(t)$
  - fraction of CP-odd decays defined as $R_T \equiv |A_\perp(0)|^2 / \sum_{i=0,\|,\perp} |A_f(0)|^2 \sim \mathcal{O}(0.2)$
  - $R_T = (0.2 \pm 0.1)$, CDF: Phys.Rev.Lett. 94 (2005) 101803 (hep-ex/0412057)
- The one-angle θ_{tr} distribution enables to disentangle the different CP eigenstates

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

(Phys.Rev. D63 (2001) 114015, hep-ph/0012219)

Transversity angle θ_{tr}: angle between positive lepton from the J/ψ and the normal to the ϕ decay plane, in the J/ψ rest frame



Parameter scans

Scans: input values to nominal, except for parameter under study ($2\ \mathrm{fb}^{-1}$)

$\sigma(\phi_s)$ [rad]	Nominal	$\Delta M_s = 15\mathrm{ps}^{-1}$	$\Delta M_s = 25\mathrm{ps}^{-1}$	$\Delta\Gamma_s/\Gamma_s = 0.2$	$R_T = 0$	$R_T = 0.5$
$\mathrm{J}/\psi\ \eta(\gamma\gamma)$	**0.112**	0.102	0.126	0.099	–	–
$\mathrm{J}/\psi\ \eta(3\pi)$	**0.148**	0.136	0.161	0.139	–	–
$\eta_c\phi$	**0.106**	0.100	0.113	0.097	–	–
$\mathrm{J}/\psi\ \phi$	**0.031**	0.028	0.034	0.030	0.021	0.062

- sensitivity to ϕ_s increases by $\sim 10\%$ per $5\ \mathrm{ps}^{-1}$ step in ΔM_s
- $R_T = 0$: pure CP eigenstate limit for $\mathrm{B}_s^0 \to \mathrm{J}/\psi\ \phi$, $\sigma(\phi_s)$ 1.5 times better w.r.t nominal
- $R_T = 0.5$: $\sigma(\phi_s)$ gets 2 times worse for equal CP-even and CP-odd fractions

Good precision for larger $\phi_s \sim -0.2$ rad: more than 5σ in one year

Total $\bar{\mathrm{b}} \to \bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}$ *likelihood*

$$\mathcal{L}_{tot}^{\bar{\mathrm{b}}\to\bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}} = \prod_{i\epsilon \mathrm{B_s^0}\to f} \mathcal{L}_i^{\bar{\mathrm{b}}\to\bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}}(m_i, \theta_{\mathrm{tr}i}, t_i^{rec}, \sigma_{t_i}, q_i)$$

$$\begin{aligned}\mathcal{L}_i^{\bar{\mathrm{b}}\to\bar{\mathrm{c}}\mathrm{c}\bar{\mathrm{s}}}(m_i, \theta_{\mathrm{tr}i}, t_i^{rec}, \sigma_{t_i}, q_i) \quad = \quad & \mathcal{L}_m^{sig}(m_i)\Big[R_T \mathcal{L}_{\theta_{\mathrm{tr}}}^{sig,odd}(\theta_{\mathrm{tr}i})\mathcal{L}_{t,odd}^{sig}(t_i^{rec}, \sigma_{t_i}, q_i) \\ & + (1-R_T)\mathcal{L}_{\theta_{\mathrm{tr}}}^{sig,even}(\theta_{\mathrm{tr}i})\mathcal{L}_{t,even}^{sig}(t_i^{rec}, \sigma_{t_i}, q_i)\Big] \\ & \times \mathcal{L}_m^{bkg}(m_i)\mathcal{L}_{\theta_{\mathrm{tr}}}^{bkg}(\theta_{\mathrm{tr}i})\mathcal{L}_t^{bkg}(t_i^{rec})\end{aligned}$$

- $\mathcal{L}_m^{sig}(m_i), \mathcal{L}_m^{bkg}(m_i)$: signal, background probabilities based on the reconstructed mass m_i
  - Gaussian for signal, exponential for background
- $\mathcal{L}_t^{sig}(t_i^{rec}, \sigma_{t_i}, q_i), \mathcal{L}_t^{bkg}(t_i^{rec})$: signal, background decay rates
- $\mathcal{L}_{\theta_{\mathrm{tr}}}^{sig}(\theta_{\mathrm{tr}i}), \mathcal{L}_{\theta_{\mathrm{tr}}}^{bkg}(\theta_{\mathrm{tr}i})$: angular parts for $\mathrm{B_s^0} \to \mathrm{J}/\psi\ \phi$ with transversity angle $\theta_{\mathrm{tr}i}$