Time-dependent CP asymmetries in Bs decays at LHCb

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Layout

- Introduction
- Time-dependent CP asymmetries
- LHCb Spectrometer
- LHCb sensitivity
- Conclusions

In the Standard Model (SM):

Corollary

One single phase source of CP violation in flavour changing processes

Conclusion

1. *3 up-type quarks, 3 down-type quarks*
2. *Unitarity requirement imposes constraints on elements*
3. *strong predictive power*

Many New Physics models

1. introduce many new CP-violation phases
2. require approximate CP symmetry
3. violate CP only in mixing amplitudes

Why search for New Physics in CP asymmetries?

1. CKM mechanism can not explain observed baryogenesis
2. strong CP problem: why CP is so small in strong interactions? ($\theta_{\mathrm{CP}} \lesssim 10^{-10}$)

How to observe New Physics in experiments:

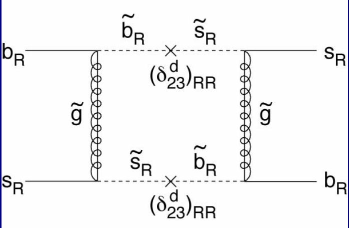
$$\mathcal{A}_{\mathrm{CP}}(t) = -\frac{\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta M_s t) + \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix-ind}} \sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma_s} \sinh(\Delta\Gamma_s t/2)}$$

1. single phase in CKM describes all SM CP violation
   - $\Rrightarrow$ SM predicts $\mathrm{CP}(\mathrm{B}_s \to J/\Psi \mathrm{K}_s) = \mathrm{CP}(\mathrm{B} \to \phi \mathrm{K}_s)$
2. SM predicts many CP violating observables are small
   - $\Rrightarrow$ observation of deviations from zero constrain new physics $\mathrm{CP}(\mathrm{B}_s \to J/\Psi\ \phi), \mathrm{CP}(\mathrm{B}_s \to \phi\phi)$

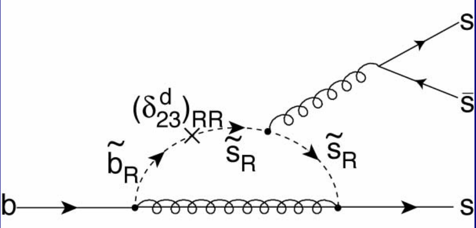
New Physics from B_s decays

Contribution from NP to CP asymetries through loop-diagrams:

Mixing diagram
(exchange of gluinos)



Penguin diagram



For $B_s \rightarrow J/\Psi\ \phi$

$$\phi_s(B_s \rightarrow J/\Psi\ \phi) = 2\arg(V_{ts}^* V_{tb}) = -2\chi = -0.035$$

For $B_s \rightarrow \phi\phi$, $\phi_s \approx 2\arg(V_{ts}^* V_{tb}) - \arg(V_{tb} V_{ts}^* / V_{tb}^* V_{ts}) = -2\chi + 2\chi = 0$
With NP, $\phi_s(B_s \rightarrow \phi\phi) \approx \phi_s^{NP}$.

Time-dependent CP asymmetries (I)

$b \to c\bar{c}s$ decays into CP-even eigenstates:

- $\mathrm{B}_s \to J/\Psi\ \eta$
- $\mathrm{B}_s \to \eta_c\ \phi$
- $\mathrm{B}_s \to \mathrm{D}_s\mathrm{D}_s$
- $\mathrm{B}_s \to \mathrm{D}_s\pi$

admixture of CP eigen states:

- $\mathrm{B}_s \to \phi\phi$
- $\mathrm{B}_s \to J/\Psi\ \phi$

Measure:

$$\mathrm{A_{CP}}(t) = -\frac{\eta_f \sin\phi_s \sin(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2) - \eta_f \cos\phi_s \sinh(\Delta\Gamma_s t/2)}$$

Where

$$\begin{aligned} \Delta m_s &= M_H - M_L \\ \Delta\Gamma_s &= \Gamma_L - \Gamma_H \\ \eta_f &= 1(-1)\ \mathrm{CP-even(CP-odd)} \end{aligned}$$

New Physics contributions to CP

Usually, NP parameterized in 2 different ways:

$$\begin{aligned} \mathrm{M}_{12} &= \mathrm{M}_{12}^{\mathrm{SM}} r_s^2 e^{i\phi_s} \\ &\equiv \mathrm{M}_{12}^{\mathrm{SM}} (1 + h_s e^{2i\sigma}) \end{aligned}$$

In $\mathrm{B}_s \to J/\Psi\ \phi$,

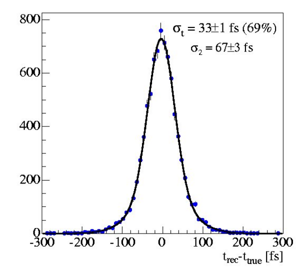
$$\begin{aligned} \phi_s(\mathrm{B}_s \to J/\Psi\ \phi) &= \phi_s^{\mathrm{SM}}(\mathrm{B}_s \to J/\Psi\ \phi) - \arg[1 + h_s e^{2i\sigma_s}] \\ \Delta m_s &= \Delta m_s^{\mathrm{SM}} \left|1 + h_s e^{2i\sigma}\right| \\ \Delta\Gamma_s &= \left|\Delta\Gamma_s^{SM}\right| \cos^2[\arg(1 + h_s e^{2i\sigma})] \end{aligned}$$

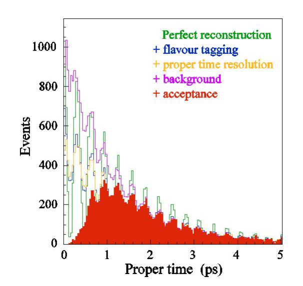
In MFV, $\sigma_s = 0 \mod \pi/2$,
but *e.g.* in NMFV, $\sigma_s \neq 0$ is allowed…

Decay rate R:

$$R(t,r) \propto \frac{e^{-\Gamma_s t}}{2}\left\{\cosh\frac{\Delta\Gamma_s t}{2} + rD\cos(\Delta m_s t)\right\}$$

Use $B_s \rightarrow D_s\pi$ to determine Δm_s





In 1 year of LHCb running:

- $B_s \rightarrow D_s\pi$ Yield: 140k,
- B/S <0.05,
- Statistical accuracy: $\sigma(\Delta m_s) = 0.006\ \mathrm{ps}^{-1}$

Note: Sensitivity will be limited by systematics.

Time-dependent CP asymmetries in $B_s \to J/\Psi\ \phi$

For $B_s \to J/\Psi\ \phi$:

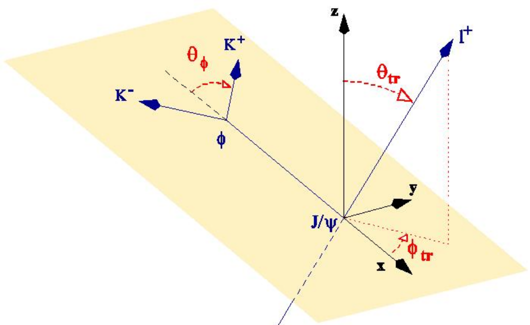
$$A_{CP} = \frac{\Gamma(\bar{B}_s \to J/\Psi\ \phi) - \Gamma(B_s \to J/\Psi\ \phi)}{\Gamma(\bar{B}_s \to J/\Psi\ \phi) + \Gamma(B_s \to J/\Psi\ \phi)}$$

Note that

- $J/\Psi\ \phi$ final state composed of CP-even and CP-odd states:

$$\frac{d\Gamma}{dc} \propto \left[|A_0|^2 + |A_{||}|^2\right] \frac{3}{8}(1 + c^2) + |A_\perp|^2 \frac{3}{4}(1 - c^2)$$

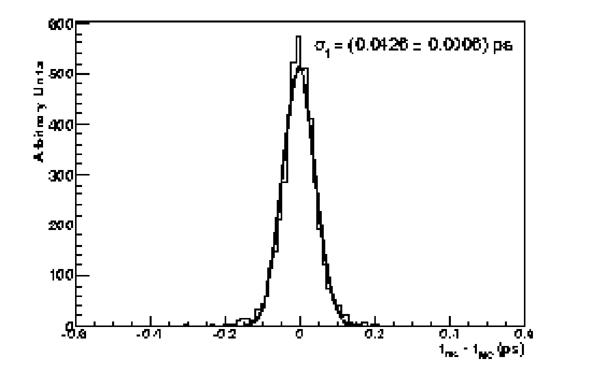
with $c = \cos\Theta_{tr}$, $A_{||}$, A_0 the CP-even components and $A_\perp$ the CP-even component. Separate components with Θ_{tr} angle analysis:



CP-violation in the decay $B_s \to \phi\phi$

- angular analysis determines CP-even/odd components
- 2 Kaon pairs observe Bose-statistics: treat them symmetrically

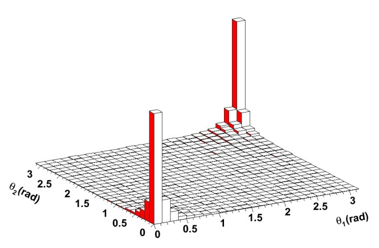
Propertime Resolution:

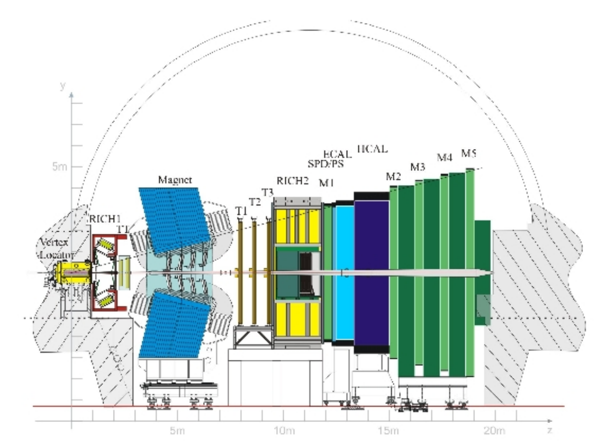


In 1 year of LHCb running:
Yield: 3.1k Events, B/S < 0.8, $\sigma(\phi_s) = 0.11$

Experimental Challenge

- $b\bar{b}$ production cross section: $\sigma(b\bar{b}) = 500\mu\mathrm{b}$
- separate K from π: at LHCb $7\times$ more π as Kaons
- flight distance of B_s meson ($c\tau = 439\mu\mathrm{m}$): ~ 1 cm
- B_s oscillation frequency: $\Delta m_s = 17.8\mathrm{ps}^{-1}$





Trigger:

- $1\mathrm{MHz}$ Level 0 trigger
- $2\mathrm{kHz}$ logging rate

LHCb Sensitivity to ϕ_s

Physics input:

ϕ_s[rad]	$\Delta M_s[\mathrm{ps}^{-1}]$	$\Delta\Gamma_s/\Gamma_s$	$\tau_{B_s^0}$[ps]	R_T
-0.04	17.5	0.15	1.45	0.2

Results from fit to Toy MC data:

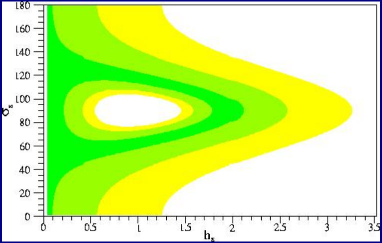
Sensitivity	$J/\Psi\ \eta(\gamma\gamma)$	$J/\Psi\ \eta(3\pi)$	$\eta_c\phi$	$J/\Psi\ \phi$
$\sigma(B_s)$[MeV/c]	34	20	12	14
$\Delta\Gamma_s/\Gamma_s$	0.016	0.019	0.018	0.0079

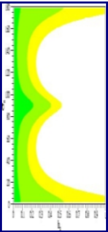
Channel	$\sigma(\phi_s)$[rad]	Weight $(\sigma/\sigma_i)^2$ [%]
$B_s \to J/\eta(3\pi)$	0.14	2.3
$B_s \to D_sD_s$	0.13	2.6
$B_s \to J/\eta(\gamma\gamma)$	0.11	3.9
$B_s \to \eta_c\phi$	0.11	3.9
Combined sensitivity :	0.06	12.7
$B_s \to J/\Psi\ \phi$	0.023	87.3
Total combined sensitivity:	0.022	100.0

Parameterize New Physics as Limit on h_s: $h_s < 0.1$

LHCb Sensitivity to ϕ_s

- $\mathrm{B}_s \to J/\Psi\ \phi$:
  - $\sigma(\phi_s) = 0.023\ \mathrm{rad}$
  - $\sigma(\Delta\Gamma_s/\Gamma_s) = 0.0092$
- including decays into CP-eigen states:
  - relative weight $\sim$ 13%
  - $\sigma(\phi_s) = 0.021$
- constraint on NP:
  - σ_s: phase due to supersymmetry
  - h_s: scale of observable





Conclusions

- SM picture of CP violation incomplete $\rightarrow$ NP needed
- LHCb experiment capable of constraining possible NP
- measurements of CP observables constrain scale of new phases
- ϕ_s from $\mathrm{B}_s \rightarrow J/\Psi\ \phi$ yields $\sigma_\phi = 0.022$ in 2 fb^{-1}
- $\sigma(\phi_s)$ from $\mathrm{B}_s \rightarrow \phi\phi = 0.11$
- improve limits on σ_s, h_s by factor ~ 10