Prospect for Measurement of CP-violation phases with B_s decays at future Z factories

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CEPC Workshop 2024

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Introduction

Physics motivation

- CKM parameter:
  - In neutral B meson decays to a final state the interference between the amplitude for the direct decay and the amplitude for decay after oscillation, leads to a time-dependent CP-violating asymmetry between the decay time distributions of B and anti-B mesons.
  - $\phi_s = -arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
  - $\gamma = arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$
  - Contributions from physics beyond the SM could lead to much larger values of ϕ_s, insensitive to γ.
- B_s decay parameters:
  - $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H, \Gamma_s \equiv (\Gamma_L + \Gamma_H)/2.$
  - Able to be calculated with heavy quark expansion (HEQ) theory.

ϕ_s MEASUREMENTS WITH $B_s \to J/\psi\phi$

Measurement of ϕ_s ($\Delta\Gamma$, Γ_s) in experiments

Extract the observables $\phi_s, \Gamma_s, \Delta\Gamma_s$ from the time dependent angular distribution.

$$\frac{d^4\Gamma(B_s \to J/\psi\phi)}{dtd\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega),$$

where

$$h_k(t|B_s) = N_k e^{-\Gamma_s t} \left[a_k \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_k \sinh(\frac{1}{2}\Delta\Gamma_s t) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right]$$

$$h_k(t|\bar{B}_s) = N_k e^{-\Gamma_s t} \left[a_k \cosh(\frac{1}{2}\Delta\Gamma_s t) + b_k \sinh(\frac{1}{2}\Delta\Gamma_s t) - c_k \cos(\Delta m_s t) - d_k \sin(\Delta m_s t) \right]$$

$f_k(\Omega)$: amplitude function.

$b_k \sim \pm |\lambda| \cos(\phi_s)$, $d_k \sim \pm |\lambda| \sin(\phi_s)$

Projection to future Z-factories

$\sigma(\phi_s) \propto 1/\sqrt{N_{\text{eff}}}$

- $N_{\text{eff}} \propto N_{b\bar{b}}$
- $N_{\text{eff}} \propto$ Efficiency
- $N_{\text{eff}} \propto$ Tagging power
- $\sigma_{\phi_s} \propto 1/e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}$

Define:

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

Then: $\sigma(\phi_s, FE) = \xi_{FE} \times \frac{\sigma(\phi_s, EE)}{\xi_{EE}}$

ξ for LHCb Run2 and LHCb on HL-LHC

Numbers are quoted from *Eur.Phys.J.C79(2019)706*

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

- $N_{b\bar{b}} \times \varepsilon \times Br = 11700$. Avoid considering the efficiency on LHCb.
  - $\mathscr{L}_{\text{int}} = 1.9\text{fb}^{-1}$,$b\bar{b}$ cross-section:$144\,\mu\text{b}$,$Br = 20\% \times 0.001 \times 0.06 \times 0.5$.
  - $\varepsilon = 7\%$, where the $b\bar{b}$ is already in the acceptance, reasonable estimation.
- Tagging power $p = 4.73\%$.
- Decay time resolution: 45.5 fs.

ξ:

- $\xi_{\text{LHCb}} = 0.018$,$\sigma(\phi_s, \text{LHCb}) = 0.041\text{rad}$.
- $\xi_{\text{LHCb}} = 0.0014$, $\sigma(\phi_s, \text{HL-LHCb}) = \xi_{\text{HL-LHCb}} \times \sigma(\phi_s, \text{lhcb})/\xi_{\text{LHCb}} = 3.3\ \text{mrad}$ (HL-LHC: $N_{\text{HL-LHCb}} = N_{\text{LHCb}} \times \frac{300\ \text{fb}^{-1}}{1.9\ \text{fb}^{-1}}$)

ξ for CEPC (Statistics)

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

- Tera-Z: 0.152×10^{12},10-Tera-Z:1.52×10^{12}
- $Br = 20\% \times 0.001 \times 0.06 \times 0.5 \times 2$. ($J/\psi$ can also be reconstructed from e^+e^- on CEPC)

ξ for CEPC (Efficiency)

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

Reconstruction:

- Assume that we can distinguish $b\bar{b}$ events from other events.
- Assume that we have perfect ability to distinguish leptons with hadrons.
- ϕ candidates: $1.017 - 1.023\,\mathrm{GeV}/c^2$, two hadron tracks.
- J/ψ candidates: $3.07 - 3.14\,\mathrm{GeV}/c^2$, two lepton tracks.
- B_s^0 candidates: $5.28 - 5.46\,\mathrm{GeV}/c^2$, combination of all J/ψ ϕ candidates.

ξ for CEPC (Efficiency)

Extraction of ϕ_s require a clean background.

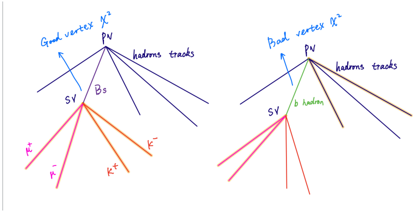
The number of background events are 1.7×10^5 times larger than the number of signal events.

In pure background (from simulation):

- The probability to find a J/ψ candidate is 0.4%.
- The probability to find a ϕ candidate is 3.6%.
- The probability to get a B_s^0 candidate from $J/\psi\,\phi$ combination is 4.6%.
- Total: 6.7×10^{-6}.

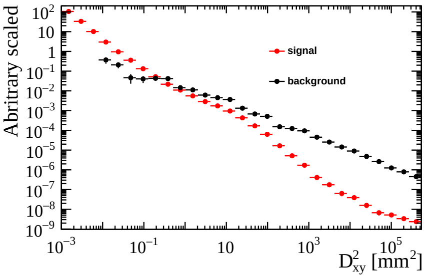
The background is of same magnitude with the signal.

Vertex χ^2: reject background.



$\varepsilon = 75\%$ with 1% background level.

Signal χ^2 distribution:



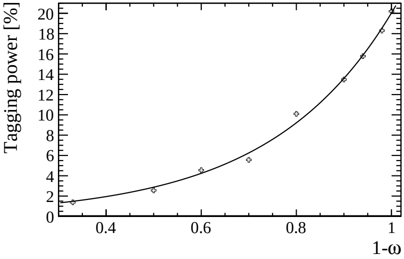
- Background: very large spread χ^2 distribution.
- $\chi^2 < 0.1$ keeps 95% of the signal and reject 99.2% of the background.

ξ for CEPC (Tagging power)

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

20% of the tagging power can be easily achieved with a naive algorithm and with assumption of perfect pid. (Same side + Opposite side algorithm)

Dependence on particle identification:



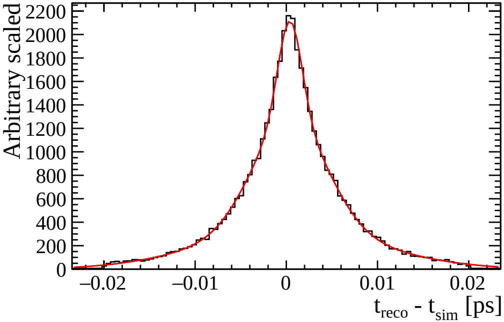
Corretly identification rate:$1-\omega$, misidentification probability: $\omega/2$

Considering the particle identification from the detector simulation, the tagging power is:

- Intrinsic tagging power (without considering the effects from the readout electronics): 19.1%.
- Realistic/conservative tagging power (if the particle identification resolution is degraded by 30% with respect to the intrinsic case): 17.4%.

ξ for CEPC (Time resolution)

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$



Obtained from detector simulation.

Proper decay time: $t = \frac{m l_{xy}}{p_{\mathrm{T}}}$

Fit with sum of three gaussian.

$$\sigma_{\text{eff}} = \sqrt{-\frac{2}{\Delta m_s^2} \ln(\sum_i f_i e^{-\frac{1}{2}\sigma_i^2 \Delta m_s^2})} = 4.7\,\text{fs}.$$

(Reminder LHCb: 45 fs)

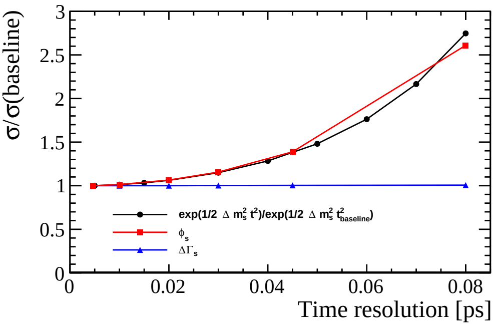
The excellect time resolution benefits from the precise vertex reconstruction and large energy of B_s.

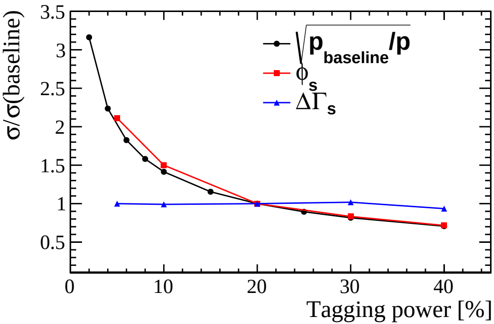
ξ for CEPC (Summary)

Putting all the components together: $\xi_{\text{CEPC}} = 0.0019$ (Tera-Z), $\sigma(\phi_s, \text{CEPC}) = 4.3\text{mrad}$.

	LHCb(HL-LHC)	CEPC(Tera-Z)	CEPC/LHCb
$b\bar{b}$ statics	43.2×10^{12}	0.152×10^{12}	1/284
Acceptance×efficiency	7%	75%	10.7
Br	6×10^{-6}	12×10^{-6}	2
Flavour tagging (perfect pid)	4.7%	20%	4.3
Time resolution $(\exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^{2}{}^2)$	0.52	1	1.92
scaling factor ξ	0.0014	0.0019	0.8
$\sigma(\phi_s)$	3.3 mrad	4.3 mrad	
Flavour tagging (realistic/conservative pid)	4.7%	17.3%	3.7
$\sigma(\phi_s)$	3.3 mrad	4.6 mrad	

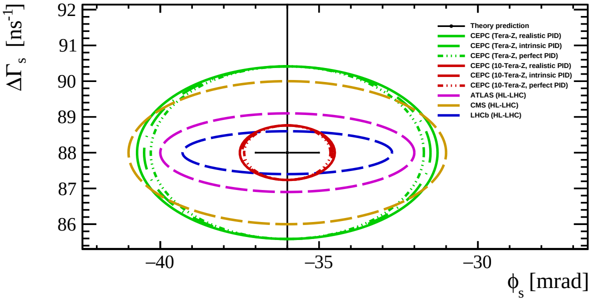
Impact from time resolution and flavour tagging





- Time resolution and tagging power dependence for observables.
- ϕ_s resolution has potential to be improved with better tagging power.
- $\Delta\Gamma_s$(and also Γ_s) has weak dependence: lose the factor of 4.3×1.92.

Results



- Black point: SM global fit (CKMfitter group/UTfit collaboration) + HQE (Proc.Int.Sch.Phys.Fermi 137(1998)329,Adv.Ser.Direct.High Energy Phys.15(1998)239) prediction.
- ATLAS and CMS results are from ATL-PHYS-PUB-2018-041 and CMS-PAS-FTR-18-041.

Penguin control for β_s

Penguin pollution

If the penguin diagram is considered in the B_s decay, the relation between ϕ_s and β_s should be corrected as

$$\phi_s = -2\beta_s + \Delta\phi_s(a, \theta). \tag{1}$$

The shift $\Delta\phi_s$ could be expressed as

$$\tan(\Delta\phi_s) = \frac{2\epsilon a \cos\theta \sin\gamma + \epsilon^2 a^2 \sin(2\gamma)}{1 + 2\epsilon a \cos\theta \cos\gamma + \epsilon^2 a^2 \cos(2\gamma)}, \tag{2}$$

where a and θ are penguin parameters, $\epsilon = \lambda^2/(1-\lambda^2)$ is defined through a Wolfenstein parameter λ, and γ is the angle γ of the Unitarity Triangle.

Penguin pollution

Control channels: $B_s^0 \to J/\Psi K^*$: determine the penguin parameters a and θ.

The observables in $B_s^0 \to J/\Psi K^*$ measurements:

$$A^{\mathrm{CP}} = -\frac{2a\sin\theta\sin\gamma}{1-2a\cos\theta\cos\gamma+a^2}, \tag{3}$$

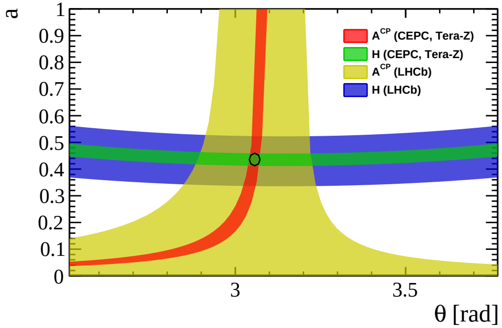
and

$$H = \frac{1-2a\cos\theta\cos\gamma+a^2}{1+2\epsilon a\cos\theta\cos\gamma+\epsilon^2 a^2}, \tag{4}$$

where A^{CP} is the CP asymmetry and H is an observable constructed containing the branching fraction information, assuming the $\mathrm{SU}(3)$ symmetry.

Results

Follow a similar projection method as for ϕ_s and Γ_s:

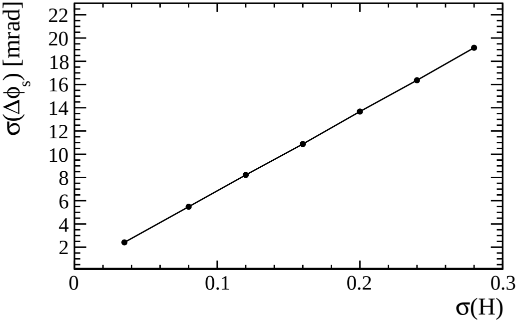


The expected uncertainty of a and θ is obtained by a χ^2 fit, resulting in

$$a = 0.436 \pm 0.023, \theta = 3.057 \pm 0.016^{\circ}.$$

. With an error propagation neglecting the correlation between a and θ, the precision of the penguin shift is estimated as $\sigma(\Delta\phi_s) = 2.4$ mrad.
(note: $\sigma(\Delta\phi_s) = 4.6$ mrad)

SU(3) symmetry violation



- The $\mathrm{SU}(3)$ symmetry does not always hold.
- The rightmost point corresponds to $\sigma(H) = 0.28$ (current theory uncertainty).
- $\sigma(\Delta\phi_s)$ is roughly linearly dependent on $\sigma(H)$.
- Without improved theoretical input, the control of penguin contamination will be far from satisfactory.

γ MEASUREMENTS WITH Bs

γ is extracted by fiting the time distribution:

$$
\begin{aligned}
P_{B_s^0\to D_s^+K^-}(t) &\propto e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - C\cos(\Delta m_s t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_{\bar f}\sin(\Delta m_s t)\right)\\
P_{B_s^0\to D_s^-K^+}(t) &\propto e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C\cos(\Delta m_s t) + D_f\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) - S_f\sin(\Delta m_s t)\right)\\
P_{\bar B_s^0\to D_s^+K^-}(t) &\propto e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + C\cos(\Delta m_s t) + D_{\bar f}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + S_{\bar f}\sin(\Delta m_s t)\right)\\
P_{\bar B_s^0\to D_s^-K^+}(t) &\propto e^{-\Gamma_s t}\left(\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - C\cos(\Delta m_s t) + D_f\sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + S_f\sin(\Delta m_s t)\right)
\end{aligned}
$$

The γ parameters are in the D and S parameters, eg. $D_f = \frac{-2\,r_{D_sK}\,\cos(\delta-(\gamma-2\,\beta_s))}{1+r_{D_sK}^2}$.

Projection to future Z-factories

$\sigma(\gamma) \propto 1/\sqrt{N_{\text{eff}}}$

- $N_{\text{eff}} \propto N_{b\bar{b}}$
- $N_{\text{eff}} \propto$ Efficiency
- $N_{\text{eff}} \propto$ Tagging power
- $\sigma_\gamma \propto 1/e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}$

Use the similar equation as for ϕ_s to estimate the resolution of γ.

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

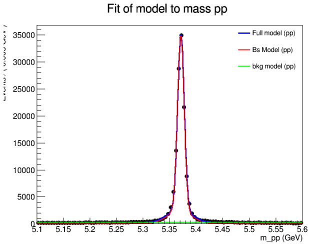
- Stat:

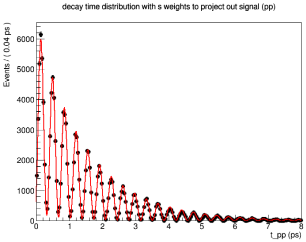
$$\begin{aligned}
&N_{exp}(Z \to b\bar{b} \to B_s^0(\to D_s^-(\to K^-K^+\pi^-)K^+)X) \\
&= 10^{12} \times \mathscr{B}(Z \to b\bar{b}) \times \mathscr{B}(\bar{b} \to B_s^0) \times \mathscr{B}(B_s^0 \to D_s^- K^+) \times \mathscr{B}(D_s^- \to K^-K^+\pi^-) \\
&= 149804 \qquad (5)
\end{aligned}$$

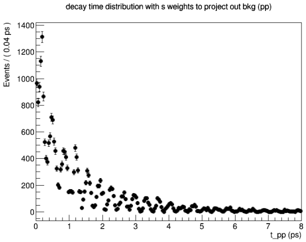
- For the specific $D_s^- \to K^-K^+\pi^-$ subdecay in the signal samples, the events of $B2DK$ in total should be:

$$\begin{aligned}
&N_{exp}(B_s^0 \to D_s^{\mp}(KK\pi)K^{\pm}) \\
&= N_{exp}(B_s^0 \to D_s^+(KK\pi)K^-) + N_{exp}(B_s^0 \to D_s^-(KK\pi)K^+) \\
&+N_{exp}(\bar{B}_s^0 \to D_s^+(KK\pi)K^-) + N_{exp}(\bar{B}_s^0 \to D_s^-(KK\pi)K^+) \\
&= 4 \times N_{exp}(Z \to b\bar{b} \to B_s^0(\to D_s^-(\to K^-K^+\pi^-)K^+)X) \\
&= 599216 \qquad (6)
\end{aligned}$$

Parameters extraction at MC Truth level







- Perfect flavour tagging and time resolution.
- Resolution: $\sigma(\gamma) = 0.35°$.

Time resolution and falvour tagging

$$\xi = 1/\left(\sqrt{N_{b\bar{b}} \times \varepsilon \times Br} \times \sqrt{p} \times \exp(-\frac{1}{2}\Delta m_s^2 \sigma_t^2)\right)$$

- Temporarily ignore the time resolution effects, considering the time resolution of B_s is excellent (from $B_s \to J/\psi\phi$ study).
- Tagging power: 40%
- Resulting $\sigma(\gamma) = 0.55°$
- Expection from HL-LHC LHCb: $\sigma(\gamma) = 0.35°$.

Summary

Summary

- Competitive ϕ_s resolution for CEPC(Tera-Z) and LHCb(HL-LHC).
  - Expected ϕ_s resolution: CEPC(Tera-Z) is a little worse than LHCb(HL-LHC).
  - CEPC has potential to improve the flavour tagging to get better ϕ_s resolution with better algorithm.
- Only in the 10-Tera-Z configuration, can Z factories be competitive to the LHCb(HL-LHC) for $\Delta\Gamma_s$ and Γ_s measurements.
- Expect good resolution for γ, but more to investigate.
- Particle identification is critical.
  - Hadron pid is not used in reconstruction. With the information, a better efficiency is expected.
  - Tagging power drop fast with particle misidentification.
- Vertex reconstruction is critical for background suppression.

Thank you for your attention!