Prospect for CP-violation phase ϕ_s study in the $B_s \to J/\psi\phi$ channel at future Z factories

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CEPC snowmass discussion

Outline

1. Introduction
2. Prospect for measurement of CPV observables
3. Summary

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.
  - $\phi_s = -arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$
  - SM: small CPV phase-ϕ_s
  - Contributions from physics beyond the SM could lead to much larger values of ϕ_s.
- 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.

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.

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

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

Previous estimation:

	LHCb	CEPC	LHCb(Run 1)
$b\bar{b}$ statics	43.2 * 10^12	0.152 * 10^12	26.64 * 10^9
Acceptance * trigger * Reconstruction	5%	100%	5%
Br($b\bar{b}$ -> Bs)	10% * 2(b and anti-b)	10% * 2	10% * 2
Br(Bs->Jpsi Phi) *Br(Jpsi->ll) *Br(Phi->KK)	0.001 * 0.06 * 0.5	0.001 * 0.12 (ee channel) * 0.5	0.001 * 0.06 * 0.5
Bs->Jpsi(->ll)Phi(->KK) stat			8000 consist with paper
Flavour tagging	4%	15% (to update)	4%
Time resolution	0.67	1	0.67
Total effective statics	0.23 * 10^6	0.27 * 10^6	144

- CEPC
  - Tera-Z.
  - Flavour tagging: 15%.
  - Efficiency: 100%.
- LHCb
  - LHC Run1 data.
  - Efficiency: 5%.
- Conclusion: competitive resolution for Tera-Z and HL-LHCb

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:

- $\xi_{\text{LHCb}} = 0.018$,$\sigma(\phi_s, \text{LHCb}) = 0.041\text{rad}$.
- $\xi_{\text{LHCb}} = 0.0014$, $\sigma(\phi_s, \text{HL-LHCb}) = \xi_{\text{HL-LHCb}} \times \sigma(\phi_s, \text{lhcb})/\xi_{\text{LHCb}} = 3.2\ \text{mrad}$ (HL-LHC: $N_{\text{HL-LHCb}} = N_{\text{LHCb}} \times \frac{300\ \text{fb}^{-1}}{1.9\ \text{fb}^{-1}} \times \frac{14\,\text{TeV}}{13\,\text{TeV}}$)

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.

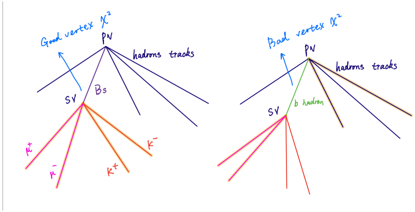
In pure background (from simulation):

- 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.

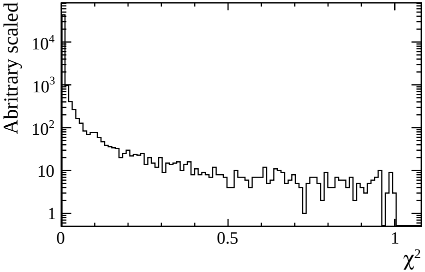
ξ for CEPC (Efficiency)

Vertex χ^2: reject background.



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

Signal χ^2 distribution:



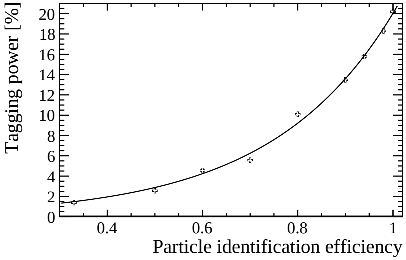
- Background: very large spread χ^2 distribution.
- $\chi^2 < 0.1$ keeps 95% of the signal and reject 99.2% of the background.

ξ for CEPC (Tagging power)

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

Previous study: 20% of the tagging power can be easily with a naive algorith and with assumption of perfect pid.

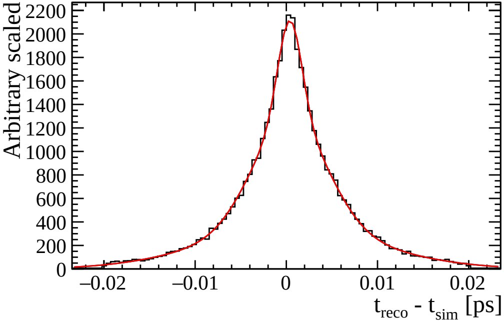
This time: pid effect



Efficiency:$1-\omega$,$p \to \pi$,$p \to K$, misidentification probability $\omega/2$.

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.

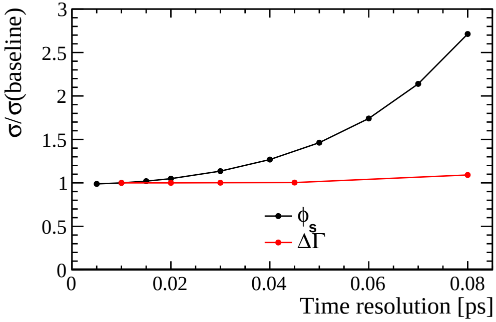
$$\sigma_\text{eff} = \sqrt{-\frac{2}{\Delta m_s^2}\ln(\sum_i f_i e^{-\frac{1}{2}\sigma_i^2 \Delta m_s^2})} = 4.7\,\text{fs}.$$

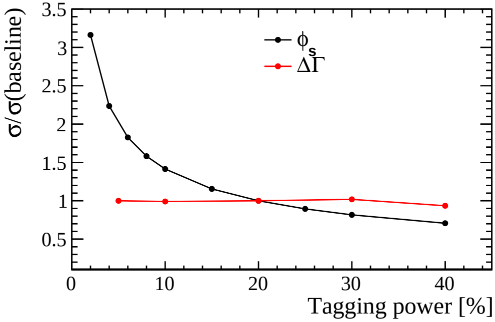
ξ for CEPC (Summary)

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	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	

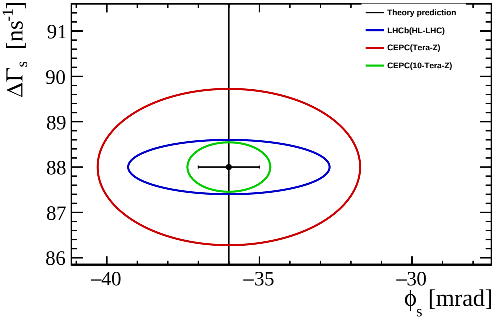
Impact from time resolution and flavour tagging





- Time resolution and tagging power dependence for observables. ($\Delta\Gamma_s$:Toy MC, ϕ_s: analytic, validated with Toy MC)
- 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.
- Circles: expected confidential region.(68% CL)

Summary

- Competitive ϕ_s resolution for CEPC(Tera-Z) and LHCb(HL-LHC).
  - Expected ϕ_s resolution: CEPC(Tera-Z) a little better than LHCb(HL-LHC) $\rightarrow$ a little worse than LHCb(HL-LHC).
  - CEPC has potential to improve the flavour tagging to get better ϕ_s resolution.
- 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.
- Particle identification is critical.
  - We assume perfect distinguish between lepton and hadron.
  - 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!