Measurement of the accuracy and mixing-induced CP-violating parameters of $B_s \to \phi\gamma$ at Tera Z

Hengyu Wang (IHEP)

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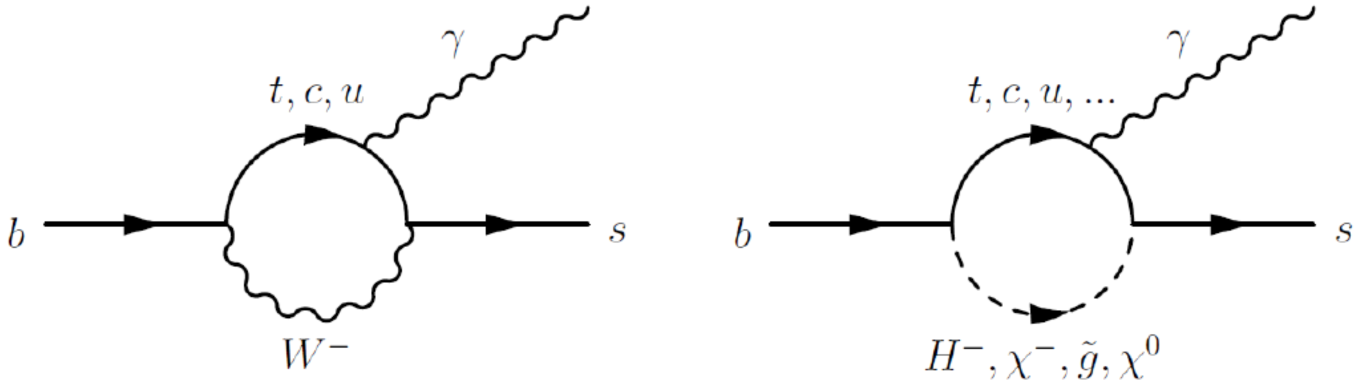
Content

- Motivation: Precision measurement & test SM
- CEPC detector and samples
- Event Selection
- Physics result: Accuracy & CP-violating parameters

Photon polarization in $b \to s\gamma$

- This transition occurs in the SM through one-loop W boson exchanges.
- In the SM, the $b \to s\gamma$ photon is emitted predominantly with left-handed helicity (right-handed in $\bar{b} \to \bar{s}\gamma$)
- The exchange of new virtual particles in the loop could modify the decay rates the and the helicity structure of the vertex
- Such a significant right-handed contribution would be a clear signature of New Physics



The $b \to s\gamma$ penguin diagram mediated by SM particles (left) and new physics particles (right)

$B_s^0/\overline{B_s^0}$ mixing and CP-violating

- The right-handed component can be observed by effects of mixing-induced CP asymmetries and time-dependent decay rate of B_s^0 and $\overline{B_s^0}$ decays.
- The rate

$$P(t) \propto e^{\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right]$$

There are three observables:

$A^{\Delta} = \sin(2\psi)$, where $\tan(\psi) = \frac{|A(\overline{B_s^0}\to\phi\gamma_R)|}{|A(B_s^0\to\phi\gamma_L)|}$

$S \simeq \sin(2\psi)\sin(\varphi)$, where $\varphi = \varphi_s - \varphi_R - \varphi_L$ is weak phase angle

C characterize direct CP violation

- The SM predictions for A, C, S in the $B_s^0 \to \phi\gamma$ decay are close to zero

$$A_{SM}^{\Delta} = 0.047^{+0.029}_{-0.025}$$

$$S_{SM} = 0 \pm 0.02$$

$$C_{SM} \simeq 0.005 \pm 0.005$$

- The observable A and S are sensitive to the ratio of helicity amplitudes (photon polarization) and weak phases, while C is related to CP violation.

CEPC advantages

CEPC advantages

- Clean collision environment
- High statistics b hadrons
- Much higher b quark boost
- Good VTX/tracking and PID system

Numerical values used to estimate the signal statistics at Tera-Z.

$f(b \to B^0)$	0.404 ± 0.007
$f(b \to B_s^0)$	0.101 ± 0.008
$Br(B_s^0 \to \phi\gamma)$	$(3.4 \pm 0.4) \times 10^{-5}$
$Br(\phi \to K^+K^-)$	$(49.1 \pm 0.5\ )\,\%$

Table 1. Expected yields of b-hadrons at Belle II, LHCb Upgrade II, and CEPC Tera-Z.

b-hadrons	Belle II	LHCb ($300\ fb^{-1}$)	CEPC($100\ ab^{-1}$)
$B^0, \bar{B}^0$	5.4×10^{10} ($50\ ab^{-1}$ on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} ($50\ ab^{-1}$ on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B_s^0, \bar{B}_s^0$	6.0×10^{8} ($5\ ab^{-1}$ on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.4×10^{8}
$\Lambda_b^0, \bar{\Lambda}_b^0$	-	2×10^{13}	1.0×10^{11}

Reference Detector and Samples

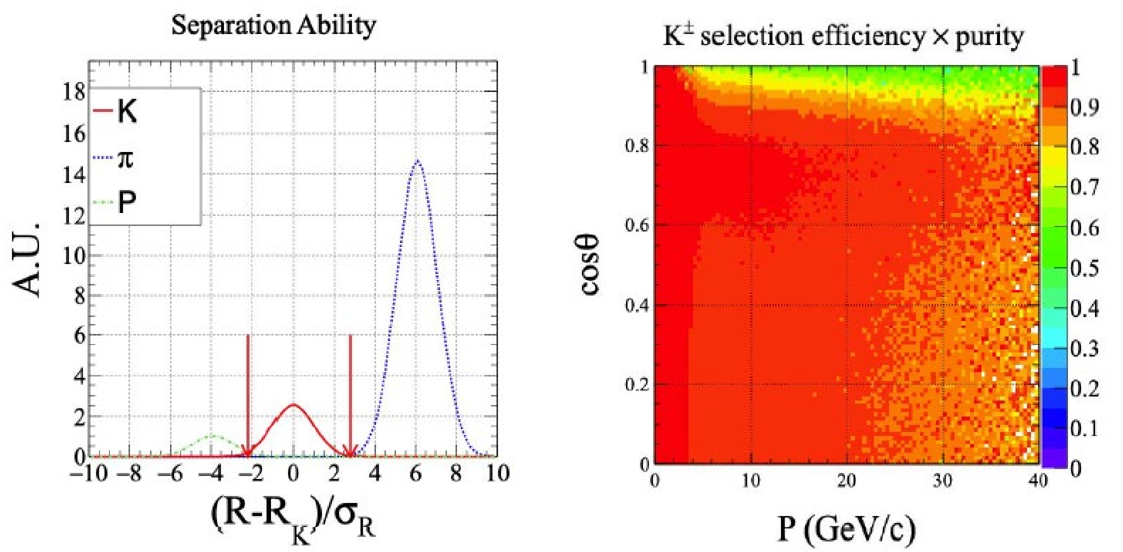
Fast Simulation

Detector performance

Vertex : $\sigma_{r\phi} = 5 \oplus \frac{10}{p(GeV)\sin^{\frac{3}{2}}\theta}(\mu m)$

Tracker : $\sigma_{\frac{1}{p_T}} = 2\times 10^{-5} \oplus \frac{0.001}{p(GeV)\sin^{\frac{3}{2}}\theta}$

ECAL : $\frac{\sigma_E}{E} = \frac{17.1\%}{\sqrt{E}} \oplus 0.01$



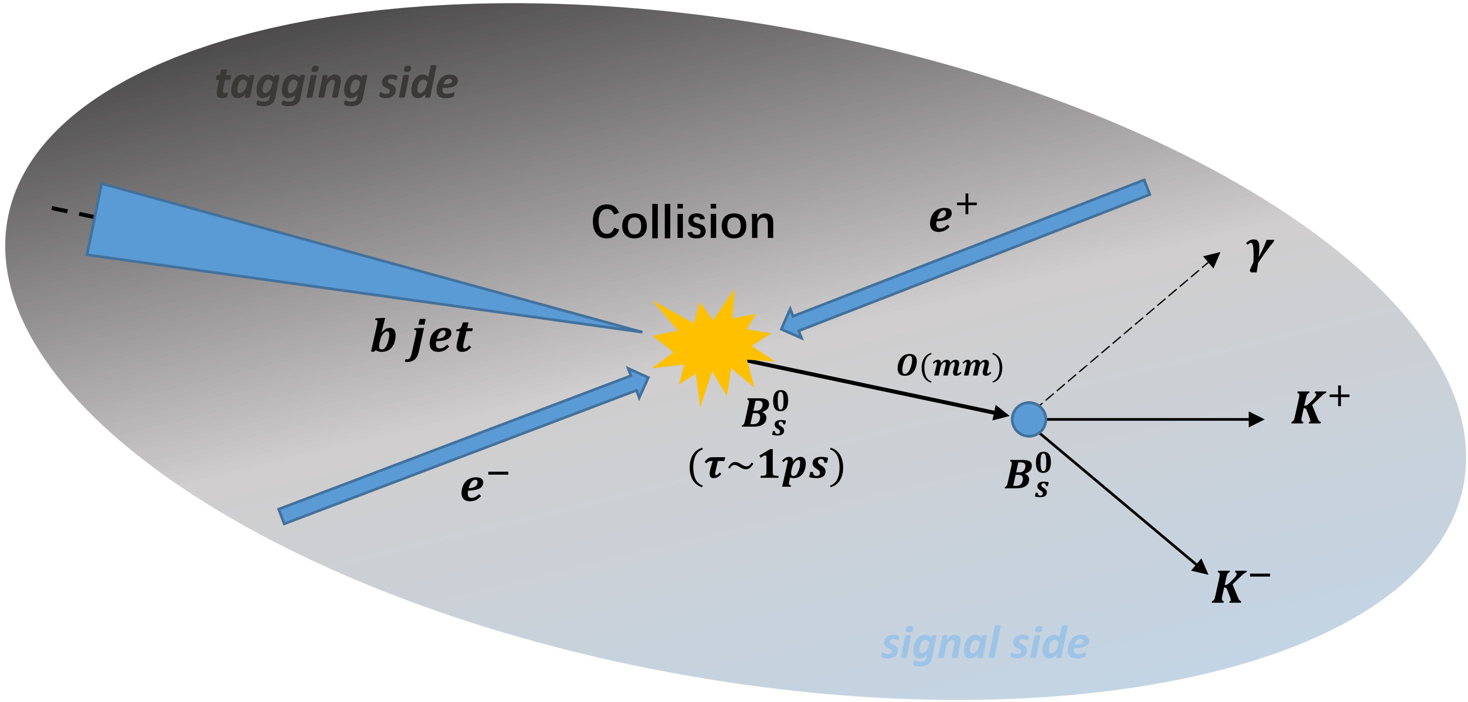
PID performance from CEPC CDR

Events	$B_s^0 \to \phi(\to K^+K^-)\gamma$	$z \to d\bar{d}$	$z \to u\bar{u}$	$z \to s\bar{s}$	$z \to c\bar{c}$	$z \to b\bar{b}$
yield	1.04524e+06	6.4944e+11	4.5797e+11	6.4944e+11	4.9323e+11	6.1992e+11
samples	223521	1.9967e+08	1.9999e+08	1.9999e+08	1.9981e+08	1.99869e+08
weights	4.67625	3252.57	2289.96	3247.36	2468.49	3101.63

Generated by Pythia8

Generated by Whizard 1.95

Topology of $B_s^0 \to \phi\gamma$ decay



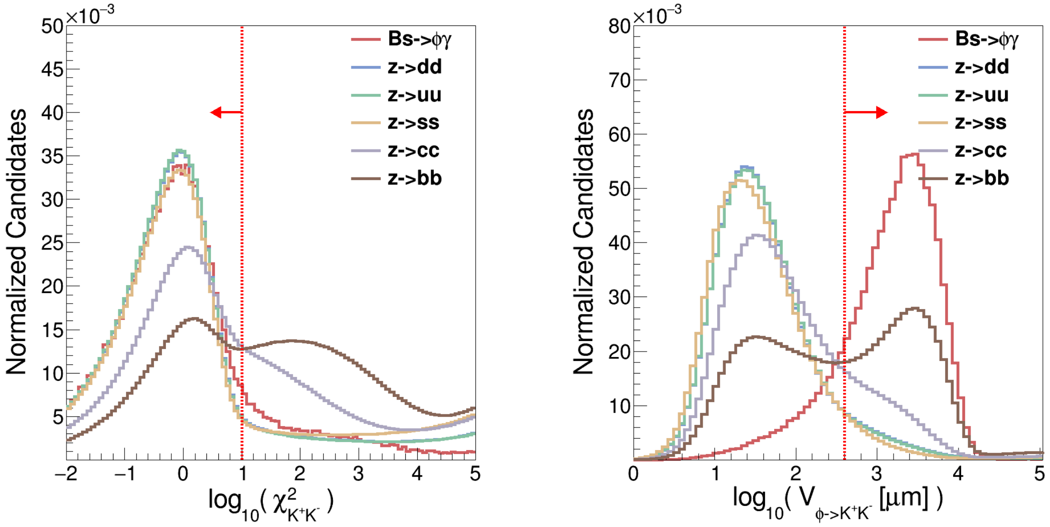
The topology of $B_s^0 \to \phi\gamma$ decay at Z-pole

- Signal side : event selection
- Tagging side: used for b jet tagging;
- B_s^0 mesons are produced through the hadronization of b quark.
- B_s^0 lifetime ~ ps, flight length ~ mm

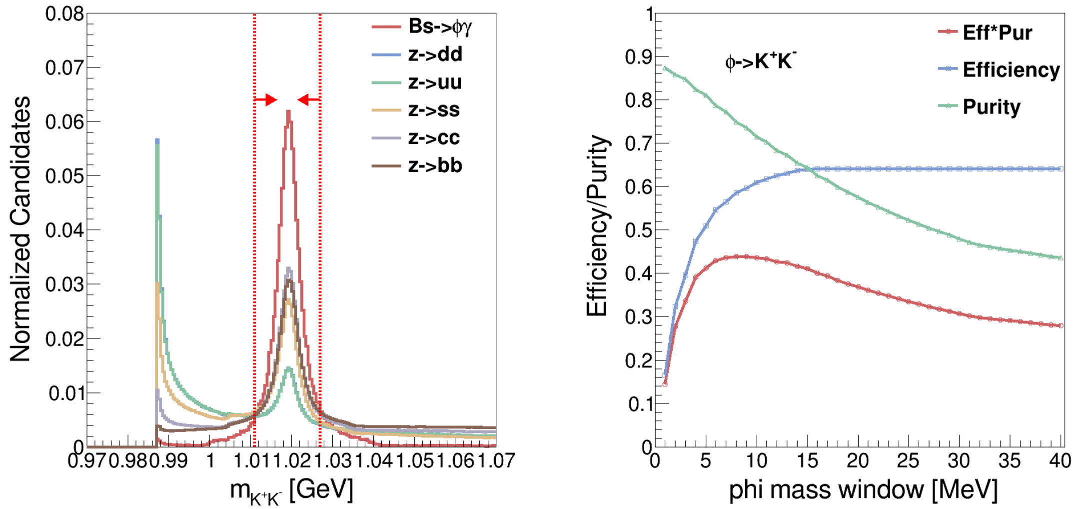
Reconstruction of $\phi \rightarrow K^+K^-$

Event selection strategy

1. Reconstruct charged tracks and select the K^+K^- pair
2. $\log_{10}\chi^2 < 1$: eliminate bad fited vertex.
3. $\log_{10}V_{\phi\rightarrow K^+K^-} > 2.6$: eliminate QCD background.



Normalized χ^2 (left) and $V_{\phi\rightarrow K^+K^-}$ (right) of signal and background distributions.



Reconstructed ϕ candidates mass distribution (left) and the overall efficiency andpurity distribution (right)

Selected ϕ : $1.011 < m_{K^+K^-} < 1.027GeV$

➢ $Eff = 63.6\%$ & $pur = 74.9\%$

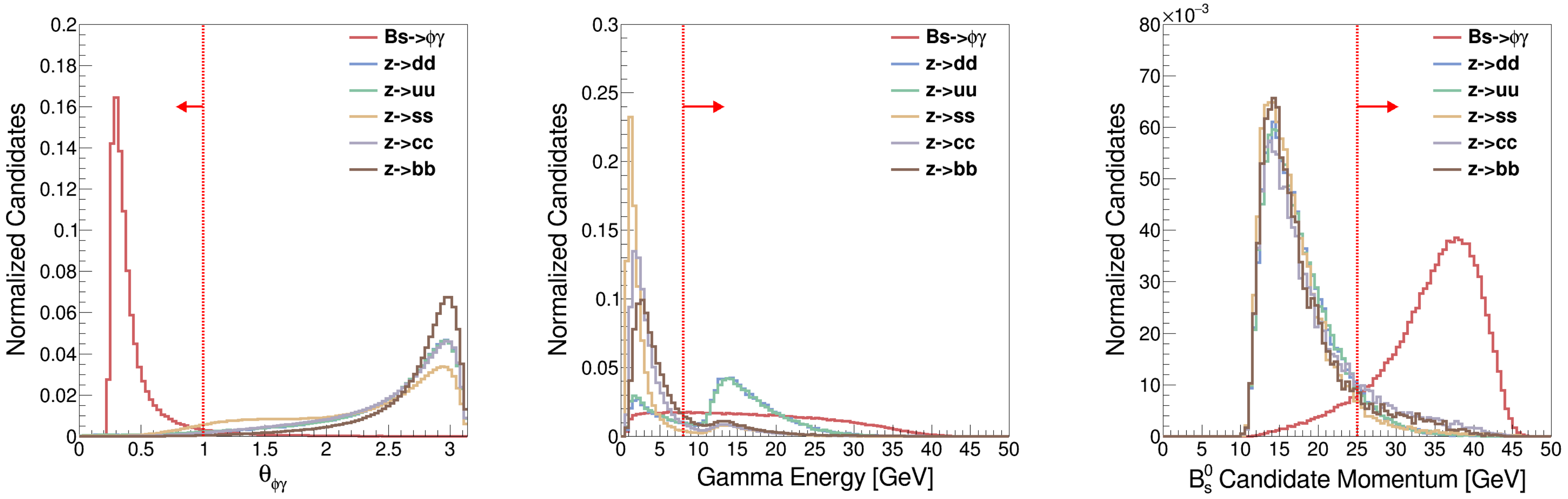
Reconstruction of $B_s^0 \to \phi\gamma$

Event selection strategy

1. $\theta_{\phi\gamma} < 1$: eliminate random $\phi\gamma$ pairs
2. $E_\gamma > 8\ GeV$ & $p_{B_s^0} > 25\ GeV$: Selected γ & B_s^0 with high energy.

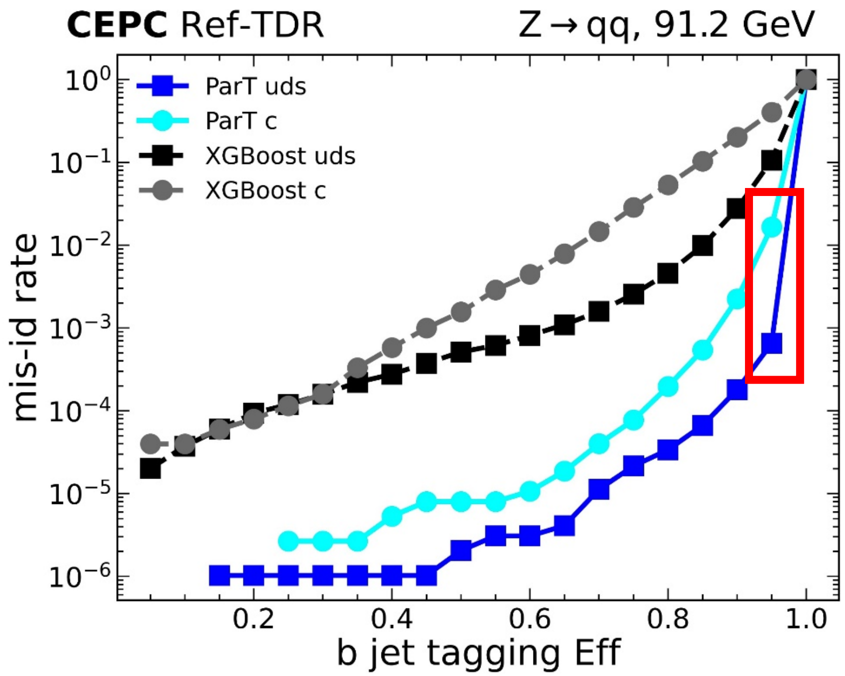
Selected B_s^0 : $5.187 < m_{\phi\gamma} < 5.547 GeV$

- $Eff = 43.9\%$ & $pur = 11.1\%$

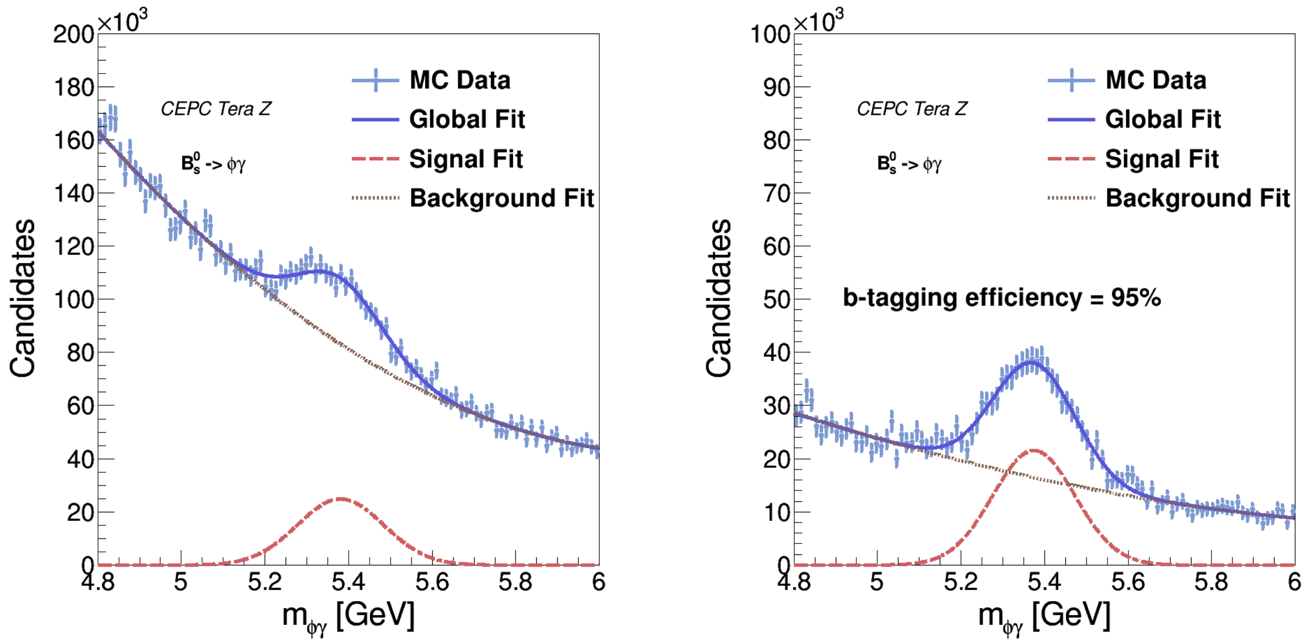


Normalized signal and background distributions for $\theta_{\phi\gamma}$, E_γ, and $E_{B_s^0}$

b-jet tagging



b-jet efficiency ~ 95% with mis-id rate of only 0.1% from light quark jets



The distribution of the invariant mass of the reconstructed B_s^0 candidates before (left) and after (right) applying b-tagging With a b-tagging efficiency of 95%. $\sigma_{m(left)} = 98MeV$, $\sigma_{m(right)} = 95MeV$

Selected B_s^0 : $5.187 < m_{\phi\gamma} < 5.547GeV$

- $Efficiency$: $43.9\% \rightarrow 41.7\%$
- $purity$: $11.1\% \rightarrow 43.1\%$
- Accuracy : 0.443% → 0.237%

Event Selection

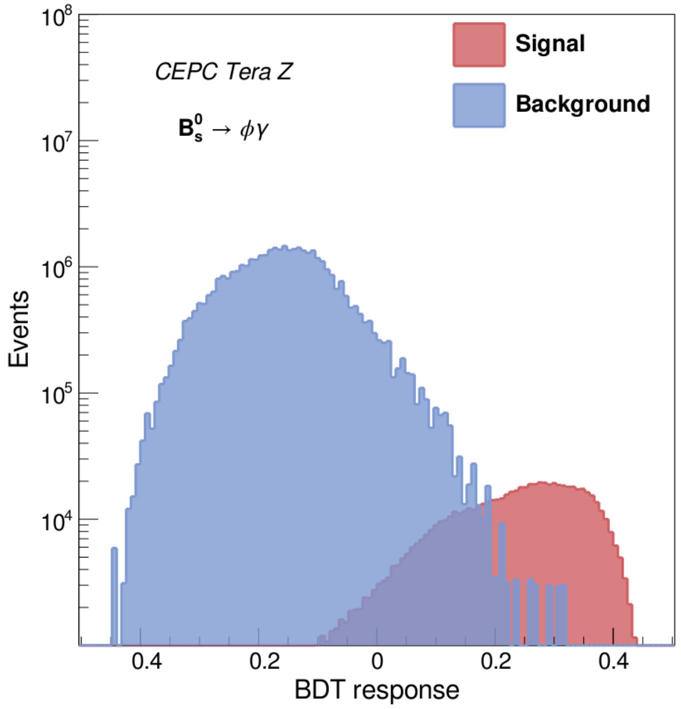
Signal : Candidates $Bs \to \phi(\to K^+K^-)\gamma$; Background : exclusive $z \to q\bar{q}$
Reconstruction : K^+K^- & γ $repeatedly\ paired$

Events	*Signal*	Background				Accuracy
CutChain	$Bs \to \phi(\to K^+K^-)\gamma$	$z \to d\bar{d}, u\bar{u}, s\bar{s}$	$z \to c\bar{c}$	Remaining $z \to b\bar{b}$	S/B(%)	$\sqrt{S+B}/S$
	1.04e+6	1.76e+12	4.90e+11	6.20e+11	3.63E-5	162
K+K– Pair Selection	1.04e+06	6.37e+11	2.38e+11	3.66e+11	8.39e-05	107
$log10(\chi^2)$ < 1	9.98e+05	5.64e+11	1.91e+11	2.43e+11	1.00e-04	100
$log10$ $(V_{\phi\to KK}/\mu m)$> 2.6	7.77e+05	6.33e+10	4.81e+10	1.39e+11	3.10e-04	64.5
$1.011 < m_{K^+K^-} < 1.027\ GeV$	6.84e+05	7.39e+09	8.24e+09	2.16e+10	1.84e-03	28.2
$\theta_{\phi\gamma} < 1.0$	6.61e+05	4.90e+08	2.21e+08	1.68e+08	7.52e-02	4.49
$E_\gamma > 8GeV$	5.07e+05	1.81e+08	3.68e+07	3.80e+07	1.99e-01	3.15
$P_{B_S} > 25\ GeV$	4.59e+05	1.22e+07	4.85e+06	3.27e+06	2.25e+00	0.994
5.187 < $m_{\phi\gamma}$<5.547 GeV	4.16e+05	1.84e+06	8.16e+05	4.93e+05	1.32e+01	0.454
B–tagging $(\varepsilon_{b,c,dus\to b} = 95\%, 1.660\%, 0.065\%)$	3.96e+05	1.20e+03	1.36e+04	4.68e+05	8.19e+01	0.237

BDT training

Pre-selection strategy

1. $log10(\chi^2)$ < 1
2. $log10(V_{\phi\to KK}/\mu m)$> 2.1
3. $1.01 \ < m_{K^+K^-} < 1.07\ GeV$
4. $\theta_{\phi\gamma} < 1.5$
5. $E_\gamma > 5\ GeV$
6. $P_{B_S} > 10\ GeV$
7. 5.0 < $m_{\phi\gamma}$<5.7 GeV
8. B−tagging($\varepsilon_{b,c,dus\to b} = 95\%, 1.660\%, 0.065\%$)



BDT response distributions compared for signal and background after pre-selection and b-tagging.

- ➢ **BDT Response > 2.3 : Accuracy = 0.156%**

Event Selection

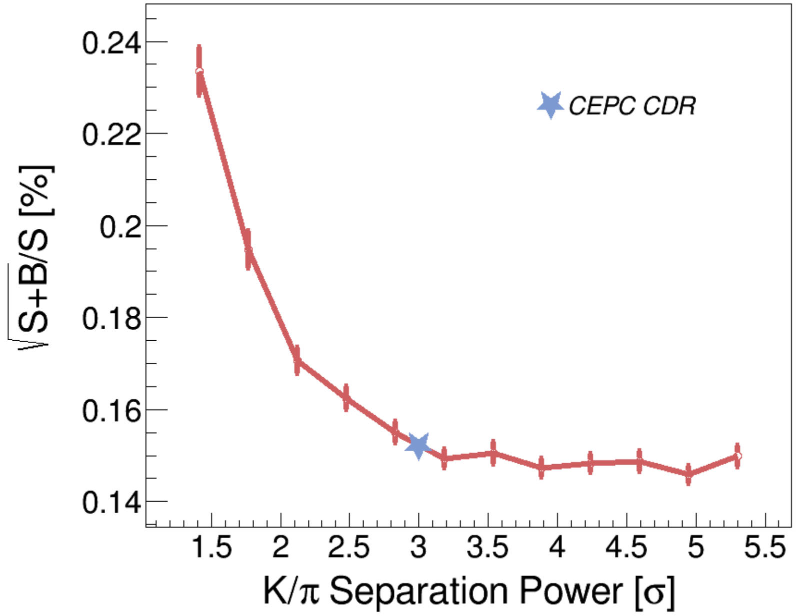
Signal : Candidates $Bs \to \phi(\to K^+K^-)\gamma$; Background : exclusive $z \to q\bar{q}$
Reconstruction : K^+K^- & γ *repeatedly paired*

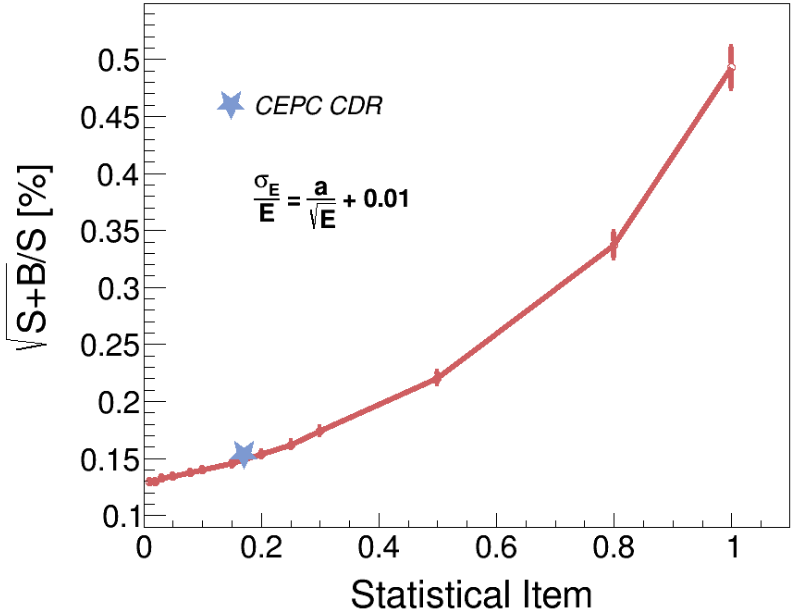
Accuracy = 0.156%$\pm$0.0025%

Events	*Signal*	Background				Accuracy
CutChain	$Bs \to \phi(\to K^+K^-)\gamma$	$z \to d\bar{d}, u\bar{u}, s\bar{s}$	$z \to c\bar{c}$	Remaining $z \to b\bar{b}$	S/B(%)	$\sqrt{S+B}/S$
	1.04e+6	1.76e+12	4.90e+11	6.20e+11	3.63E-5	162
K+K− Pair Selection	1.04e+06	6.37e+11	2.38e+11	3.66e+11	8.39e-05	107
$\log10(\chi^2)$ < 1	9.98e+05	5.64e+11	1.91e+11	2.43e+11	1.00e-04	100
$\log10(V_{\phi\to KK}/\mu m)$> 2.1	9.23e+05	1.46e+11	8.53e+10	1.71e+11	2.30e-06	68.7
$1.01 < m_{K^+K^-} < 1.07\ GeV$	8.89e+05	3.89e+10	2.09e+10	4.17e+10	8.75e-06	35.9
$\theta_{\phi\gamma} < 1.5$	8.77e+05	5.54e+09	2.05e+09	1.86e+09	9.29e-05	11.1
$E_\gamma > 5\ GeV$	7.43e+05	2.00e+09	4.07e+08	4.10e+08	2.64e-04	7.13
$P_{B_S} > 10\ GeV$	7.39e+05	1.51e+09	2.79e+08	2.40e+08	3.64e-04	6.10
5.0 < $m_{\phi\gamma}$<5.7 GeV	7.32e+05	5.67e+08	9.98e+07	8.48e+07	9.74e-04	3.75
B−tagging ($\varepsilon_{b,c,dus\to b} = 95\%, 1.660\%, 0.065\%$)	6.96e+05	3.68e+05	1.66e+06	8.06e+07	8.42e-03	1.31
BDT Response > 0.23	4.65e+5	273	4.96e+3	5.60e+4	759	0.156

Detector Performance Dependence

- K/π 3σ separation power → Accuracy = 0.156%
- $ECAL\ resolution$: 17% → Accuracy = 0.156% CEPC CRD
- $ECAL\ resolution$: 3% → Accuracy = 0.133% CEPC Ref-TDR





Dependency $B_s^0 \to \phi\gamma$ measurement accuracy on PID performance (left) and ECAL resolution (right)

Decay Time Resolution

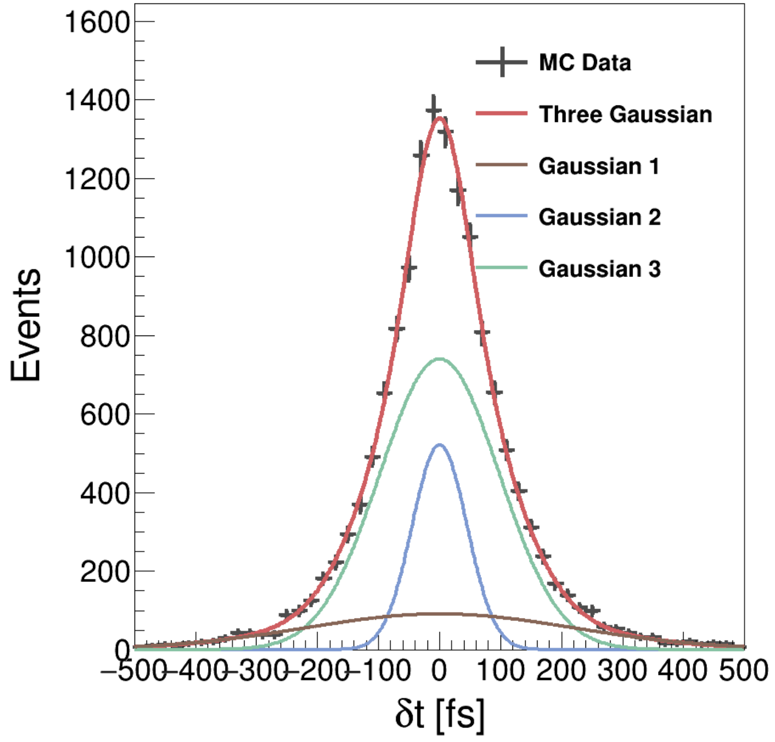
The B_s^0 lifetime can be calculated using the reconstructed vertex position and momentum

$$\tau = \frac{m_s l_{VTX}}{p_s}$$

The resolution of three Gaussian functions can be calculated by

$$\sigma_\tau = \sqrt{-\frac{2}{\Delta m_s^2}\ln(f_1 e^{-\frac{1}{2}\sigma_1^2\Delta m_s^2} + f_2 e^{-\frac{1}{2}\sigma_2^2\Delta m_s^2} + f_3 e^{-\frac{1}{2}\sigma_3^2\Delta m_s^2})},$$

where $\boldsymbol{f}_{123}$ are the fractions, and $\boldsymbol{\sigma}_{123}$ denote the widths of the three Gaussian functions,



Time resolution distribution of B_s^0 candidates from full simulation, the resolution of three Gaussian function is $\boldsymbol{\sigma_\tau = 76fs}$

Acceptance and background fit

$$\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta}\sin h\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right]$$

The effciency as a function of the decay time t is parameterized as

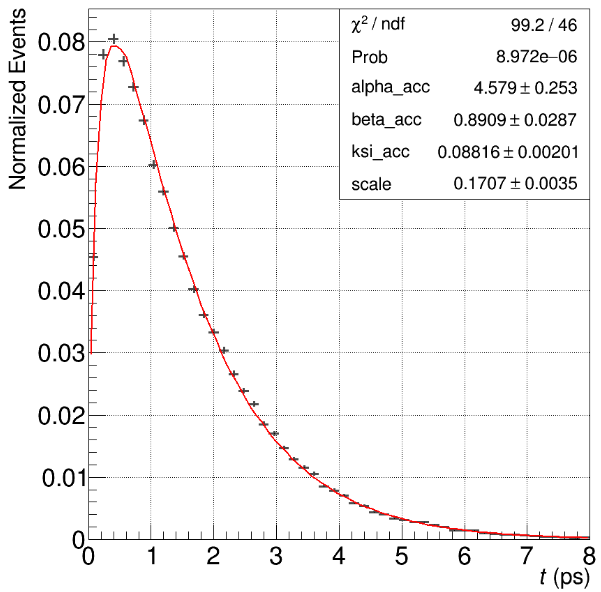
$$A(t) = \frac{\alpha t^{\beta}}{1+\alpha t^{\beta}}(1+\xi t)$$

Signal fit:

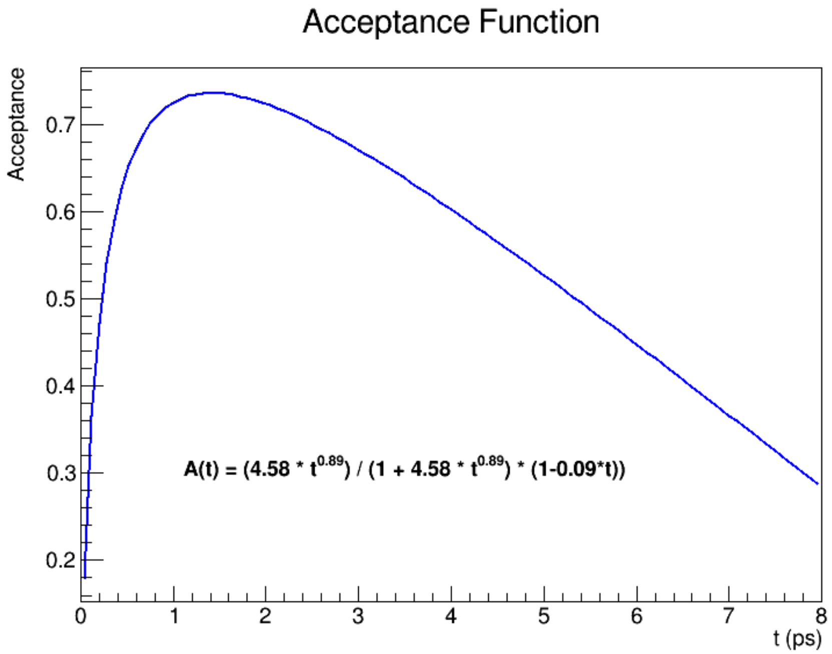
$$F(t) = \Gamma_{B_s^0\to\phi\gamma}(t)\otimes A(t)$$

Background fit：

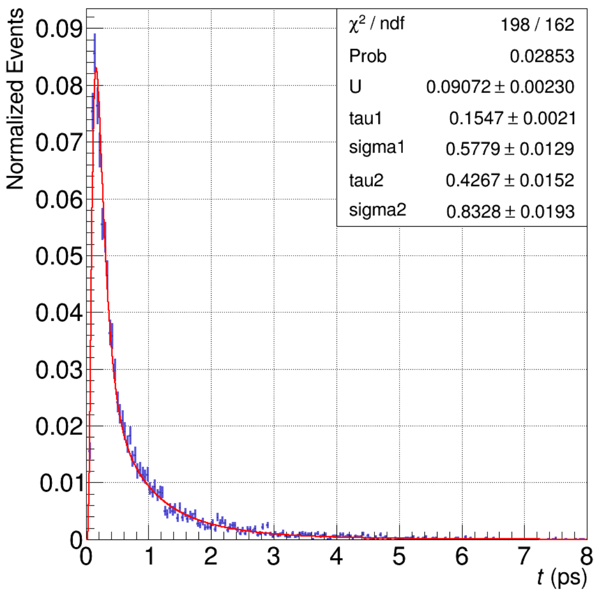
$$F(t) = U\times\{\exp\left(-\frac{1}{2}\times\left(\frac{\ln\frac{t}{\tau 1}}{\sigma 1}\right)^2\right) + 0.2\times\exp\left(-\frac{1}{2}\times\left(\frac{\ln\frac{t}{\tau 2}}{\sigma 2}\right)^2\right)\}$$



Reconstructed signal fited



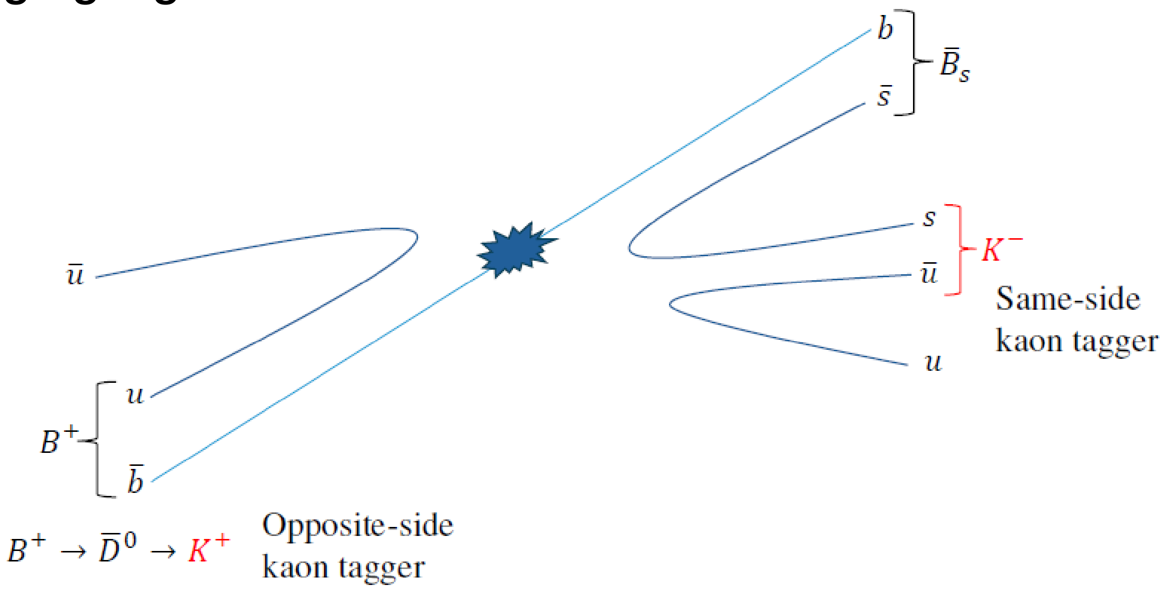
Acceptance function



Reconstructed background fited

$B_s^0/\overline{B_s^0}$ initial flavor tagging

B_s^0 inital flavor can be tagged by B_s^0 initial flavor tagging algorithms



Schematic representation of B_s^0 initial flavor tagging algorithms

- The tagging algorithm record the charge of this two kaon to identify the initial flavor of Bs

Reconstructed B_s^0 can be categorized into correctly tagged (R), incorrectly tagged(W), and untagged (U) events.

$$\epsilon_{tag} = \frac{R+W}{R+W+U}$$
$$\omega = \frac{W}{R+W}$$
$$\epsilon_{eff} = \epsilon_{tag}(1-2\omega)^2$$

Methods	ϵ_{tag}	ω	ϵ_{eff}
Leading SSK (%)	57.45	19.96	20.73
Leading OSK (%)	72.41	31.36	10.06
Combined (%)	72.12	21.39	23.60

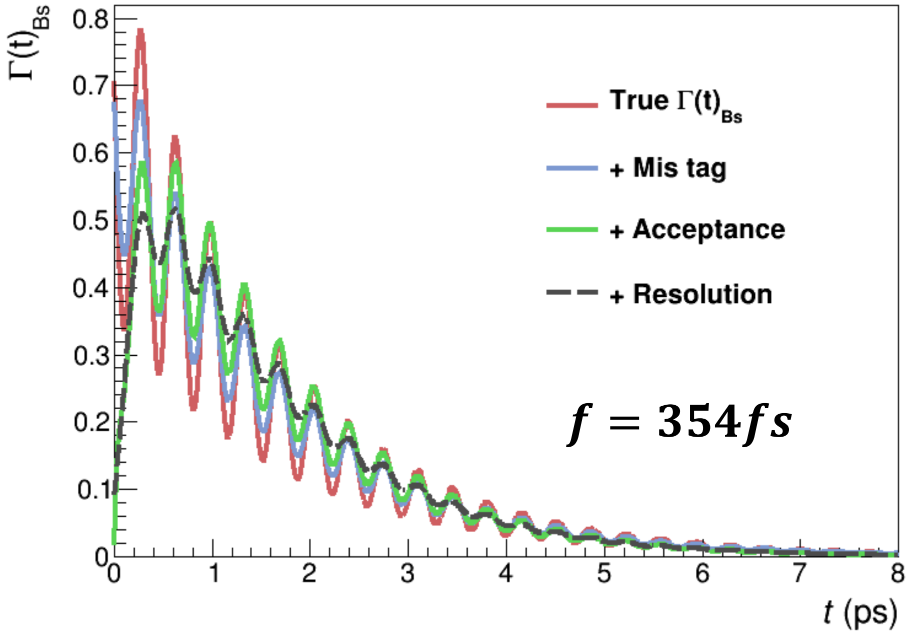
$B_s^0/\overline{B_s^0}$ mixing

$$\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + C\cos(\Delta m_s t) - S\sin(\Delta m_s t)\right]$$

$$\Gamma_{\overline{B_s^0}\to\phi\gamma}(t) \propto e^{\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - C\cos(\Delta m_s t) + S\sin(\Delta m_s t)\right]$$

$$|B^0_{s\,L}\rangle = p|B_s^0\rangle + q|\overline{B_s^0}\rangle$$

$$|B^0_{s\,H}\rangle = p|B_s^0\rangle - q|\overline{B_s^0}\rangle$$



Reconstruction effect, with pre-defined the central value of the LHCb measurement result as the true value

The values of parameters for $B_s^0/\overline{B_s^0}$ mixing, where $\Gamma_s = (\Gamma_L + \Gamma_H)/2$, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Delta m_s = m_H - m_L$

Γ_s	$0.6598 \pm 0.0025\ ps^{-1}$
$\Delta\Gamma_s$	$0.084 \pm 0.005 ps^{-1}$
Δm_s	$17.765 \pm 0.006 ps^{-1}$

LHCb measurement result

$$A^{\Delta}_{\phi\gamma} = -0.67^{+0.37}_{-0.41}(stat) \pm 0.17(syst)$$

$$C^{\Delta}_{\phi\gamma} = 0.11 \pm 0.29(stat) \pm 0.11(syst)$$

$$S_{\phi\gamma} = 0.43 \pm 0.30(stat) \pm 0.11(syst)$$

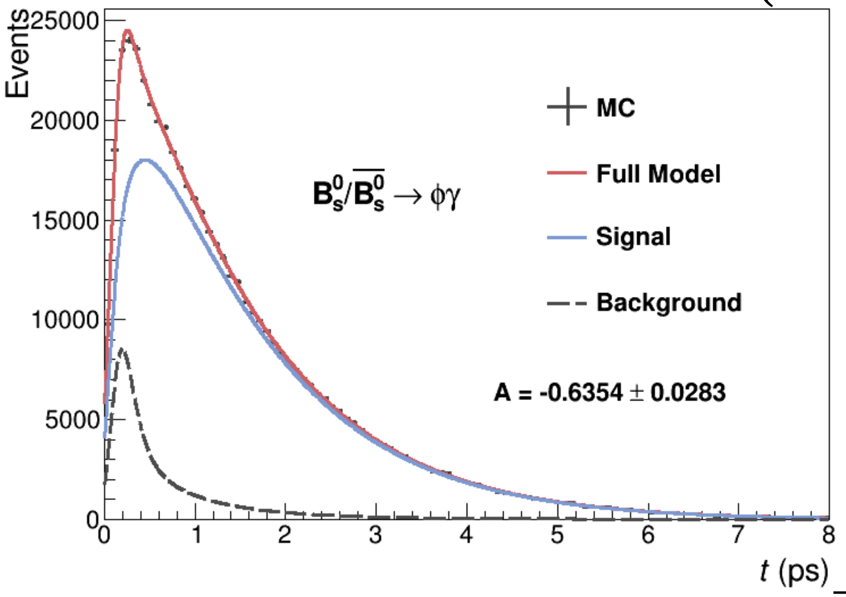
Impact of CP-violating parameter A

Generated A = -0.67

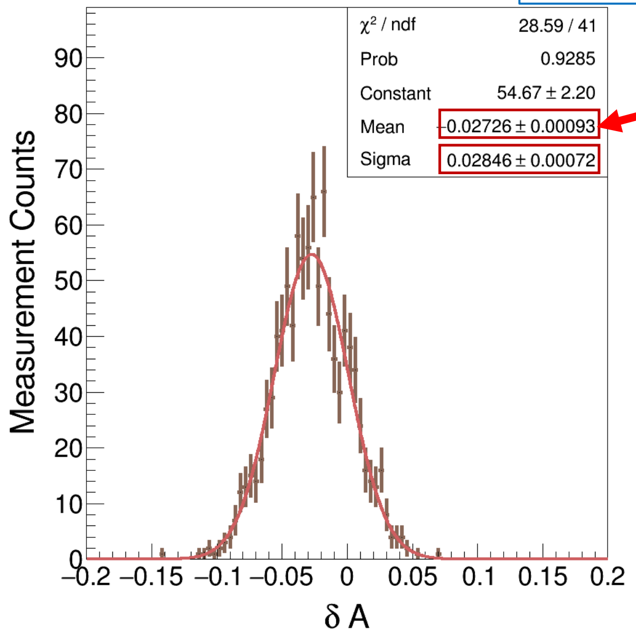
Parameter A can be fitted by flavor untagged B_s^0 decay time

$$\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{\Gamma_s t}[cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta}sinh(\frac{\Delta\Gamma_s t}{2})]$$

$$A^{\Delta} = sin(2\psi), tan(\psi) = \frac{|A\left(\overline{B_s^0}\to\phi\gamma_R\right)|}{|A\left(\overline{B_s^0}\to\phi\gamma_L\right)|}$$



The decay time for flavor-untagged for $B_s^0\overline{B_s^0} \to \phi\gamma$ decays and photon polarization parameter A fit.



bias

The distribution of systematic bias

- Systematic uncertainty = $\sqrt{bias^2 + \sigma_{\delta A}^2}$
- Fit result :

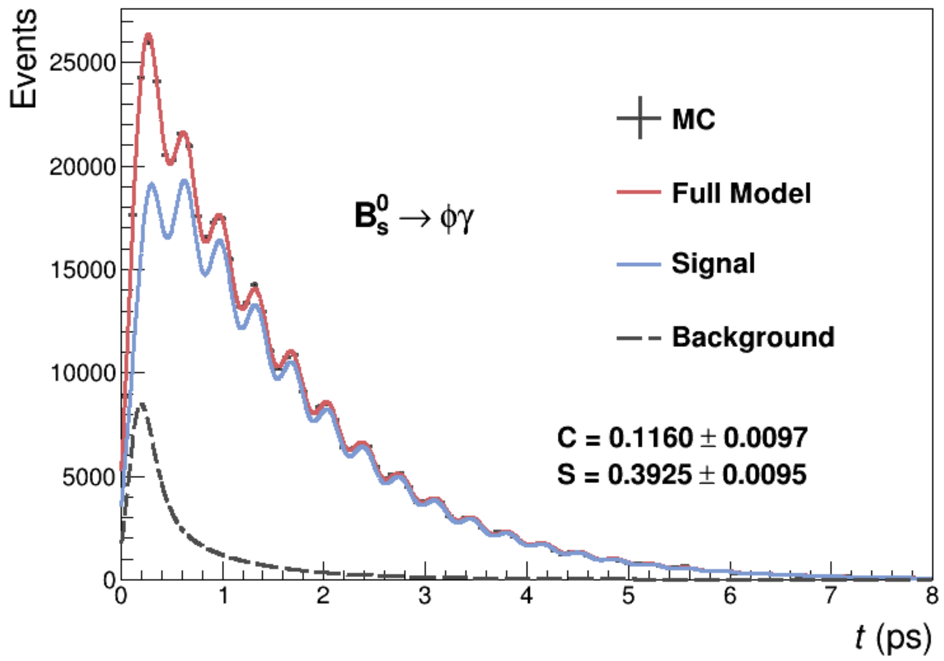
$$A_{\phi\gamma}^{\Delta} = -0.67 \pm 0.028(stat) \pm 0.041(syst)$$

Impact of parameters C and S

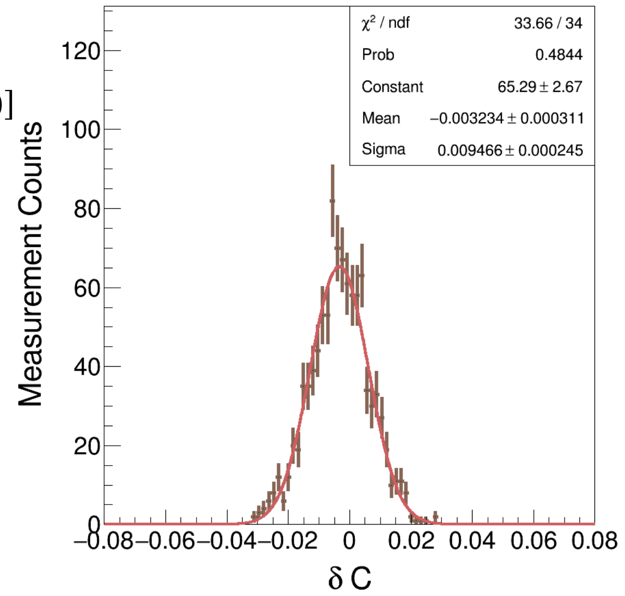
Generated C = 0.11
Generated S = 0.43

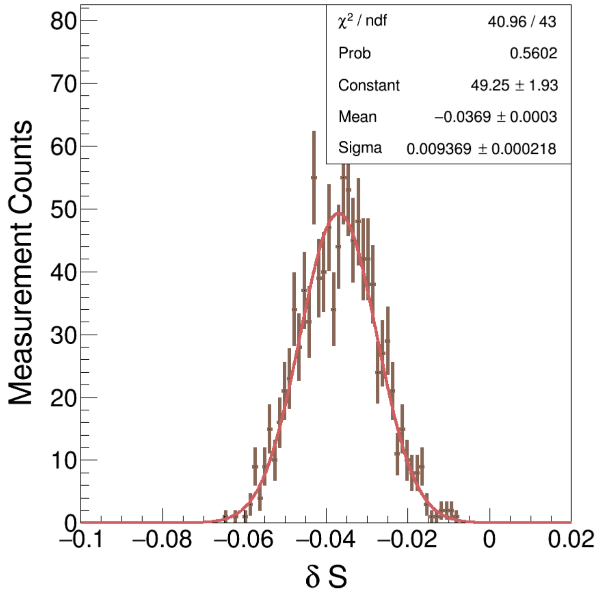
Parameter C and S can be fitted by flavor tagged B_s^0 decay time

$$\Gamma_{B_s^0\to\phi\gamma}(t) \propto e^{\Gamma_s t}\left[cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - A^{\Delta} sin\,h\left(\frac{\Delta\Gamma_s t}{2}\right) + C\,cos(\Delta m_s t) - S\,sin(\Delta m_s t)\right]$$



The decay time for flavor tagged for $B_s^0 \to \phi\gamma$ decays and photon polarization parameter C and S fit with a different decay time resolution.

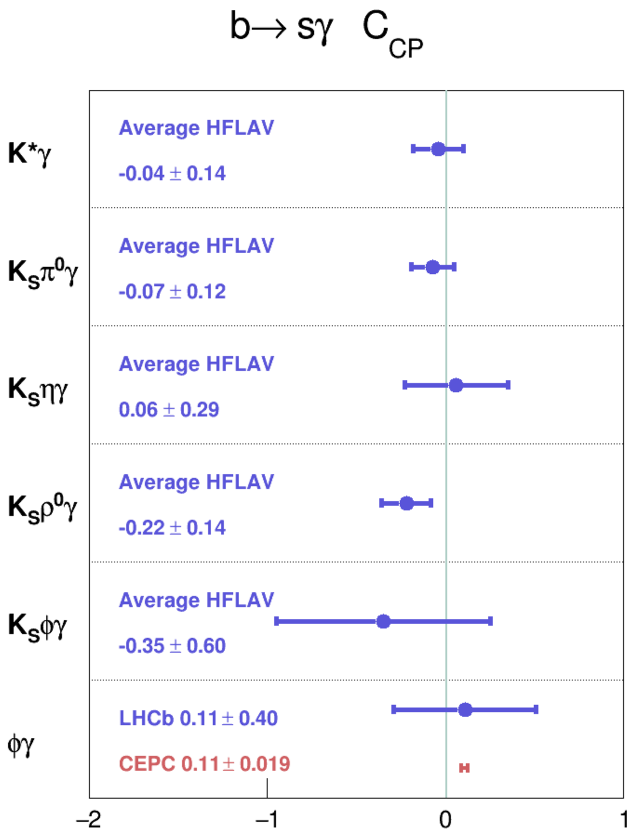


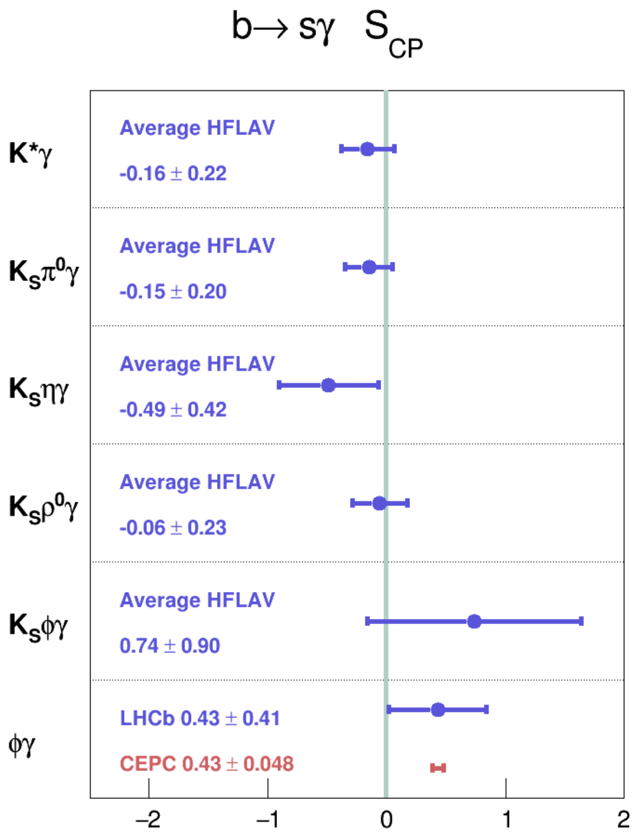


- Fit result :

$$C^{\Delta}_{\phi\gamma} = 0.11 \pm 0.0097(stat) \pm 0.0092(syst)$$
$$S_{\phi\gamma} = 0.43 \pm 0.0095(stat) \pm 0.0384(syst)$$

Impact of parameters C and S

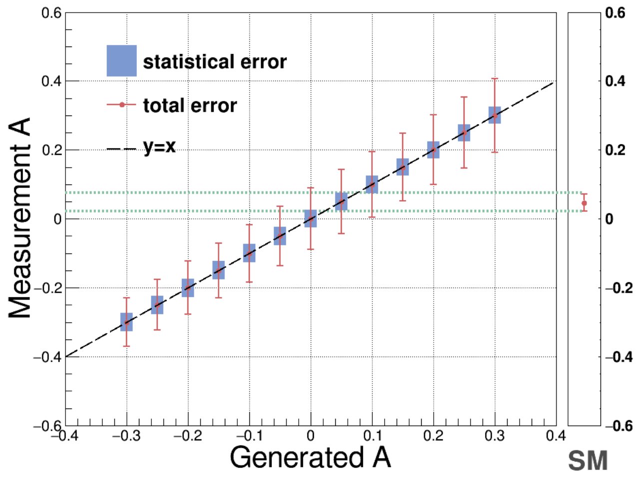




Summary of the S_{CP} and C_{CP} measurements in $b \rightarrow s\gamma$ transitions. the current measurement result of b factory are shown in bule, the result of CEPC Tera-Z is shown in red.

- The uncertainties at CEPC Tera-Z are significantly improved compared to the B-factories.

Sensitivity of NP



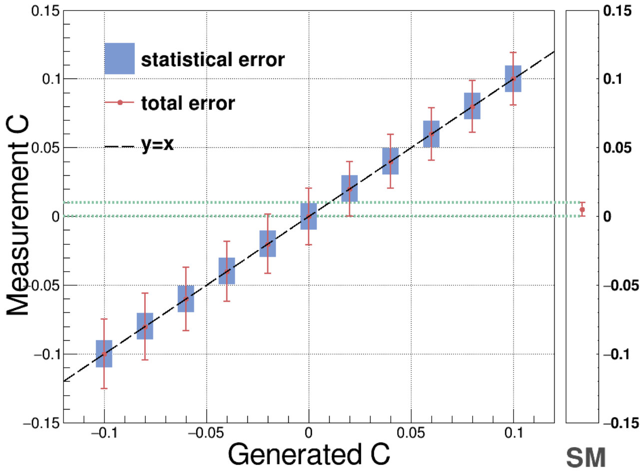
The measurement result relies on preassigned input value.

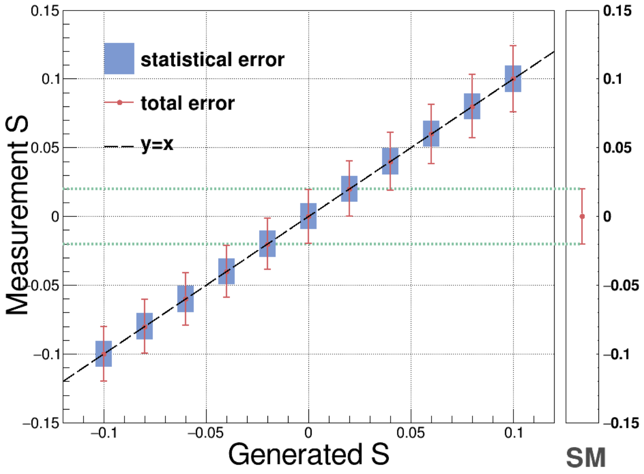
- The 1σ sensitive boundary for new physics are

$$A^{\Delta}_{\phi\gamma} < -0.1 \ or \ A^{\Delta}_{\phi\gamma} > 0.2$$

$$C_{\phi\gamma} < -0.04 \ or \ C_{\phi\gamma} > 0.04$$

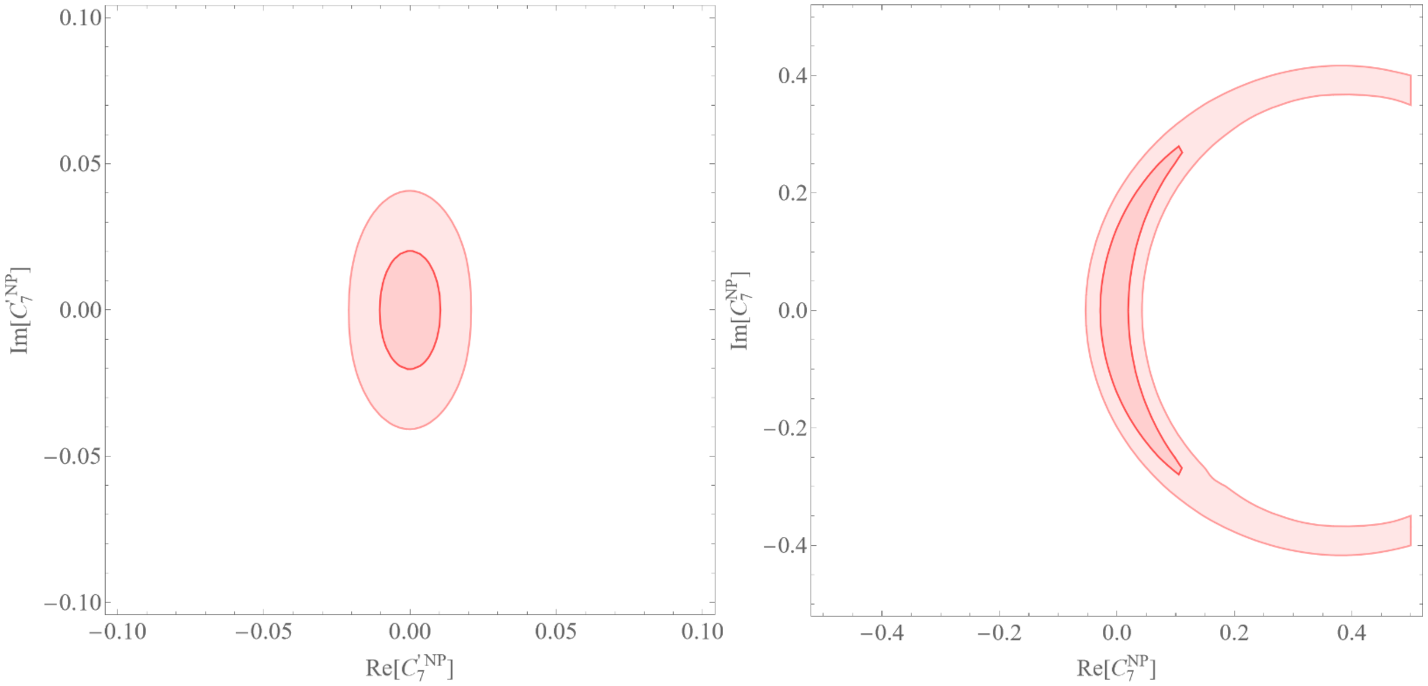
$$S_{\phi\gamma} < -0.04 \ or \ S_{\phi\gamma} > 0.04$$





Sensitivity of A, C, S. The blue rectangular area represents the statistical uncertainty, while the red solid line indicates the total uncertainty, which combined systematic uncertainty and the statistical uncertainty, the green area shows the predicted range by SM.

Constraints on new physics



Constraints on new physics of the $C_7^{\prime NP}$ (left) and the C_7^{NP} (right) . The 1σ and 2σ frequentist bound are shown in lighter part and darker part.

$$A_{CP}^{\Delta} \simeq \frac{2Re\left(e^{-i\phi_s} C_7 C_7'\right)}{|C_7|^2 + |C_7'|^2}$$

$$S_{CP} \simeq \frac{2Im\left(e^{-i\phi_s} C_7 C_7'\right)}{|C_7|^2 + |C_7'|^2}$$

- **CPV is very sensitive to the new physics of C_7'.**
- **Constraints from other channels such as $B_s^0 \to \phi ll$ will further improve the constraints.**

Conclusion

- The accuracy of $B_s^0 \to \phi\gamma$ at CEPC Z pole is $0.156\% \pm 0.0025\%$, which achieves an improvement of two orders of magnitude compared to existing measurements.
- The predicted value of A, C, and S at CEPC are

$$A^{\Delta}_{\phi\gamma} = -0.67 \pm 0.0283(stat) \pm 0.0408(syst)$$

$$C^{\Delta}_{\phi\gamma} = 0.11 \pm 0.0097(stat) \pm 0.0092(syst)$$

$$S_{\phi\gamma} = 0.43 \pm 0.0095(stat) \pm 0.0384(syst)$$

- The 1σ sensitive boundary for new physics are

$$A^{\Delta}_{\phi\gamma} < -0.1 \; or \; A^{\Delta}_{\phi\gamma} > 0.2$$

$$C_{\phi\gamma} < -0.04 \; or \; C_{\phi\gamma} > 0.04$$

$$S_{\phi\gamma} < -0.04 \; or \; S_{\phi\gamma} > 0.04$$

- CPV is very sensitive to the new physics of C_7'

Thanks !!!