Search for New Physics in CP Violation in $b \to c\bar{c}s$ and $b \to s\bar{s}s$ Amplitudes Interference

Dmitry Gavrilov[1,2,3], Pavel Pakhlov[2,3], Alexander Bondar[4,5]

[1] *Moscow Institute of Physics and Technology (MIPT)*
[2] *Lebedev Physical Institute of the Russian Academy of Sciences (LPI RAS)*
[3] *Higher School of Economics (HSE)*
[4] *Budker Institute of Nuclear Physics (BINP)*
[5] *Novosibirsk State University (NSU)*

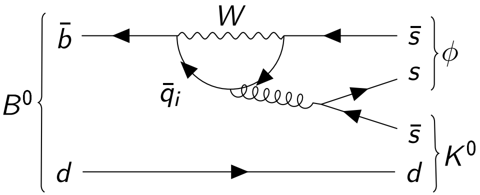
November 1, 2024
AYSS-2024

Introduction

- The B mesons region is very promising for New Physics (NP) searches
- One of the most encouraging channels is a penguin-dominated $B \to \phi K_S$ decay $(b \to s\bar{s}s)$
- Standard Model (SM) predicts $S = \sin 2\beta$ and $A = 0$ in CP asymmetry; deviations may signal about NP

$B \to \phi K$ amplitudes

Let us derive the CP violation parameters



$$\begin{aligned} A(B^0 \to \phi K^0) &= 1 + re^{i(\delta+\phi)}, \\ \bar{A}(\bar{B}^0 \to \phi \bar{K}^0) &= 1 + re^{i(\delta-\phi)}, \end{aligned} \tag{1}$$

where r is NP or SM pollution; δ, ϕ – relative strong and weak phases

CP violation parameters

Defining asymmetry as

$$a_{\phi K_S}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to \phi K_S) - \Gamma(B^0(t) \to \phi K_S)}{\Gamma(\bar{B}^0(t) \to \phi K_S) + \Gamma(B^0(t) \to \phi K_S)},$$

we obtain

$$a_{\phi K_S}(t) = S_{\phi K_S} \cdot \sin(\Delta m t) + A_{\phi K_S} \cdot \cos(\Delta m t),$$

here

$$S_{\phi K_S} \equiv \sin 2\beta_{\rm eff} = \mathrm{Im}\left[e^{2i\beta}\frac{\bar{A}(\bar{B}^0 \to \phi \bar{K}^0)}{A(B^0 \to \phi K^0)}\right],$$

$$A_{\phi K_S} = \frac{|\lambda_{\phi K_S}|^2 - 1}{|\lambda_{\phi K_S}|^2 + 1}, \qquad |\lambda_{\phi K_S}| = \left|\frac{\bar{A}(\bar{B}^0 \to \phi \bar{K}^0)}{A(B^0 \to \phi K^0)}\right|$$

Excluded regions (CL = 90%)

Using amplitudes (1), we derive

$$\sin 2\beta_{\text{eff}} = \frac{1 + r^2\cos 2\phi + 2r\cos\phi\cos\delta}{1 + r^2 + 2r\cos(\delta+\phi)}\sin 2\beta - \frac{r^2\sin 2\phi + 2r\sin\phi\cos\delta}{1 + r^2 + 2r\cos(\delta+\phi)}\cos 2\beta,$$

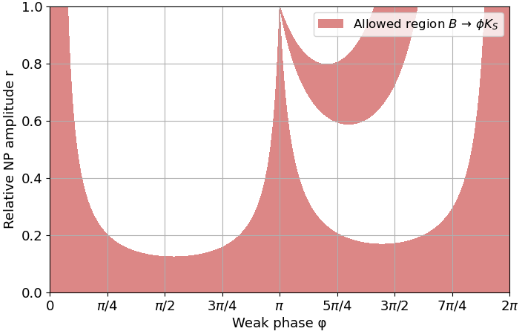
$$A_{\phi K_S} = \frac{2r\sin\delta\sin\phi}{1 + r^2 + 2r\cos\delta\cos\phi}.$$

$$\text{Belle [1], BaBar [2]:} \begin{cases} \sin 2\beta_{\text{eff, exp}} = 0.74^{+0.11}_{-0.13}, \\ A_{\phi K_S,\ \text{exp}} = -0.01 \pm 0.14. \end{cases} \qquad (2)$$

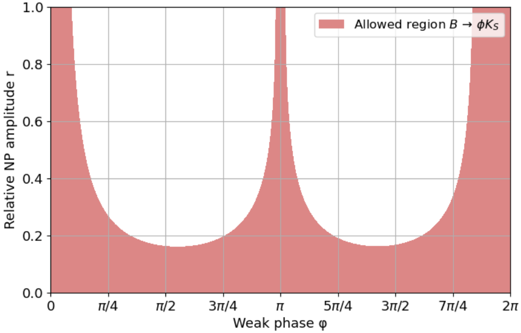
$$\boxed{\frac{|\sin 2\beta_{\text{eff}} - \sin 2\beta|^2}{(\sigma_{\sin 2\beta_{\text{eff, exp}}})^2} + \frac{|A_{\phi K_S} - 0|^2}{(\sigma_{A_{\phi K_S},\ \text{exp}})^2} < 1.65^2} \qquad (1.65 \text{ for } 90\% \text{ CL})$$

Excluded regions (CL = 90%)

$$\frac{\left|\sin 2\beta_{\text{eff}} - \sin 2\beta\right|^2}{(\sigma_{\sin 2\beta_{\text{eff}},\ \text{exp}})^2} + \frac{\left|A_{\phi K_S} - 0\right|^2}{(\sigma_{A_{\phi K_S},\ \text{exp}})^2} < 1.65^2$$



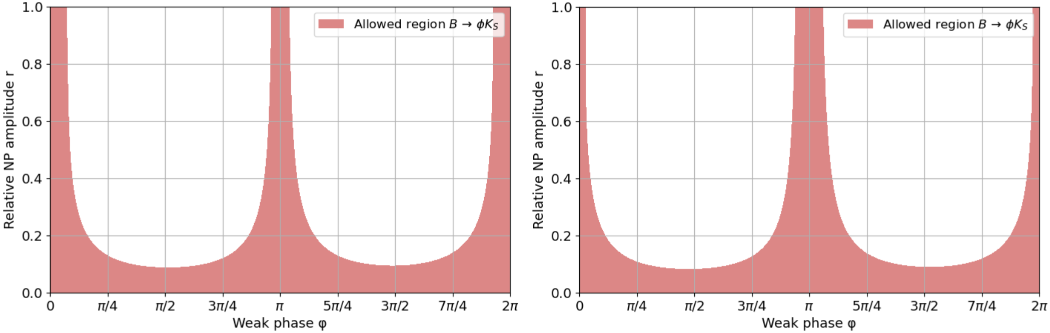
(a) $\delta = 0$



(b) $\delta = \frac{\pi}{4}$

Excluded regions (CL = 90%)

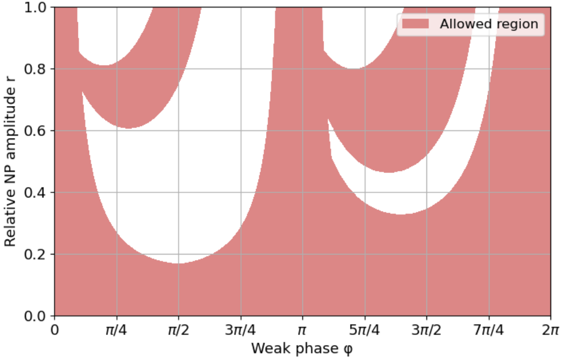
$$\frac{\left|\sin 2\beta_{\text{eff}} - \sin 2\beta\right|^2}{(\sigma_{\sin 2\beta_{\text{eff}},\ \text{exp}})^2} + \frac{\left|A_{\phi K_S} - 0\right|^2}{(\sigma_{A_{\phi K_S},\ \text{exp}})^2} < 1.65^2$$



(a) $\delta = \frac{\pi}{2}$ (b) $\delta = \frac{3\pi}{4}$

Excluded regions (CL = 90%)

Excluded regions with any strong phase $\delta \in [0, \pi)$:

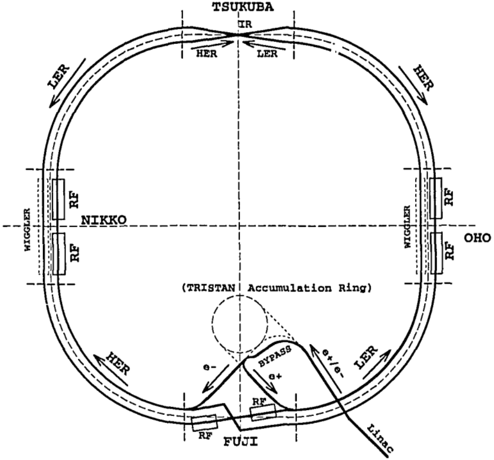


Taking into account the absence of restrictions on the strong phase of the process, **the sensitivity of $B \to \phi K_S$ to NP significantly decreases**

NP in amplitudes interference

- A new method for NP searching in $B^+ \to K^+ K^+ K^-$ decay is being proposed
- The method uses interference between penguin $b \to s\bar{s}s$ and tree $b \to c\bar{c}s$ diagrams
- There is the scalar resonance $\chi_{c0}(1P)$ in tree amplitude with a width of 10 MeV
- The process's strong phase changes near the resonance pole

The Belle detector



The Belle detector had been operating at the KEKB asymmetric-energy e^+e^- collider (Tsukuba, Japan) with a center-of-mass energy at the $\Upsilon(4S)$ resonance (≈ 10.58 GeV)

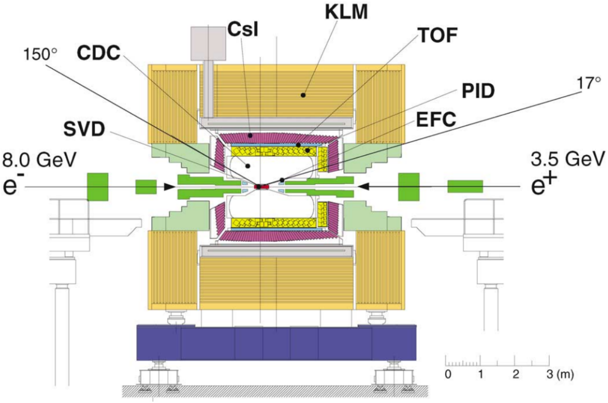
$$\text{Beam energies:} \begin{cases} e^- \text{ — } 8.0 \text{ GeV}, \\ e^+ \text{ — } 3.5 \text{ GeV}. \end{cases}$$

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

The Belle detector

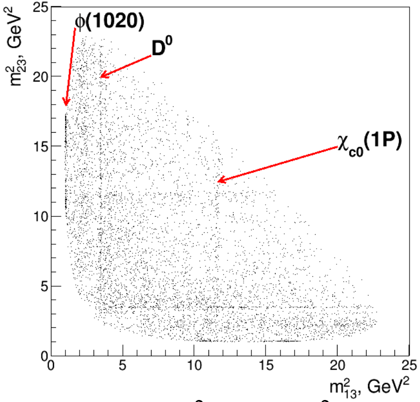
We simulate Belle 711 fb^{-1} with an energy at the $\Upsilon(4S)$ resonance

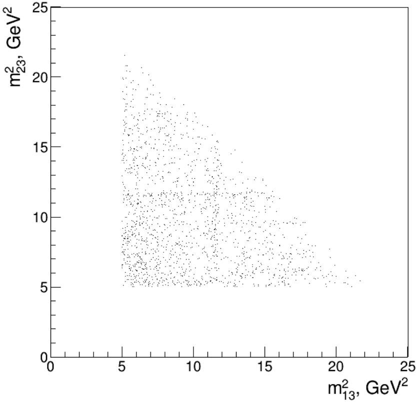
$\approx 770 \cdot 10^6$ $B\bar{B}$ pairs



$B \to KKK$ Dalitz plot (real data)

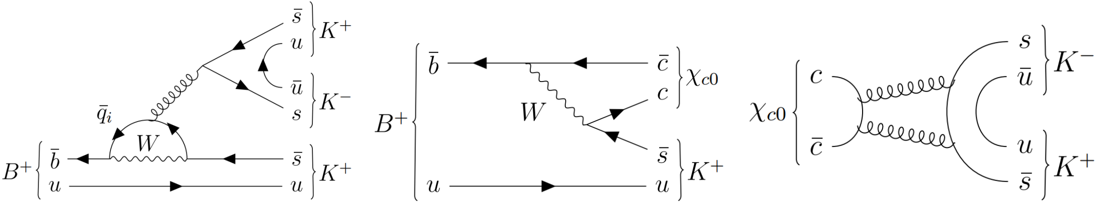
Let us see what real Belle $B \to KKK$ data looks like





We apply cut $m_{ij}^2 > 5$ GeV^2 due to complex resosances structure

$B \to \chi_{c0} K \to KKK$ amplitudes

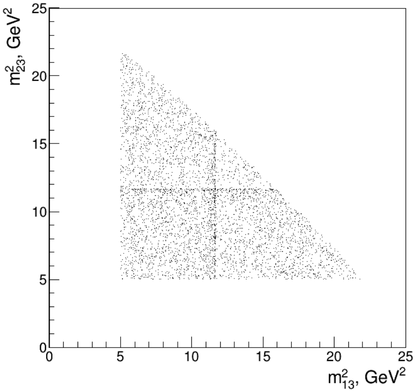


(a) $B^+ \to K^+K^+K^-$ penguin (b) $B^+ \to \chi_{c0}K^+$ tree (c) $\chi_{c0} \to K^+K^-$

$$|A|^2 = \left| \underbrace{1 + re^{i(\delta \pm \phi)}}_{penguin} + \underbrace{ae^{i\gamma}\left[A_{BW}(m_{13}^2) + A_{BW}(m_{23}^2)\right]}_{tree} \right|^2, \quad A_{BW}(m_{ij}^2) = \frac{m_0\Gamma_0}{(m_0^2 - m_{ij}^2) - im_0\Gamma_0}$$

Dalitz plot (MC)

$$|A|^2(m_{13}^2, m_{23}^2) = \left|1 + re^{i(\delta \pm \phi)} + ae^{i\gamma}\left[A_{BW}(m_{13}^2) + A_{BW}(m_{23}^2)\right]\right|^2$$

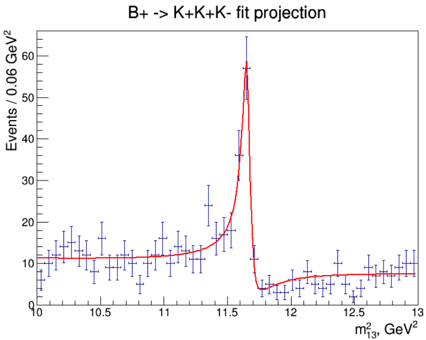


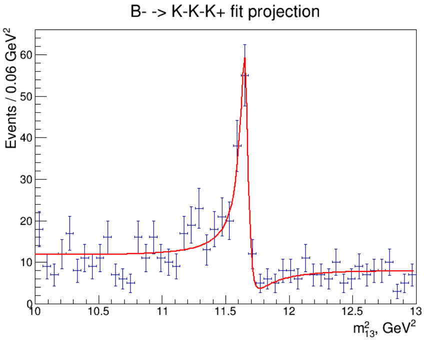
Generation parameters:
$a = 1.93$
$\gamma = 1.94\pi$
$r = 0$

We extract NP amplitude r by fitting generated Dalitz plot for both B^+ and B^- at the same time

Dalitz fit projections (MC)

$$|A|^2 = \left|1 + re^{i(\delta \pm \phi)} + ae^{i\gamma}\left[A_{BW}(m_{13}^2) + A_{BW}(m_{23}^2)\right]\right|^2$$





Fit sample:

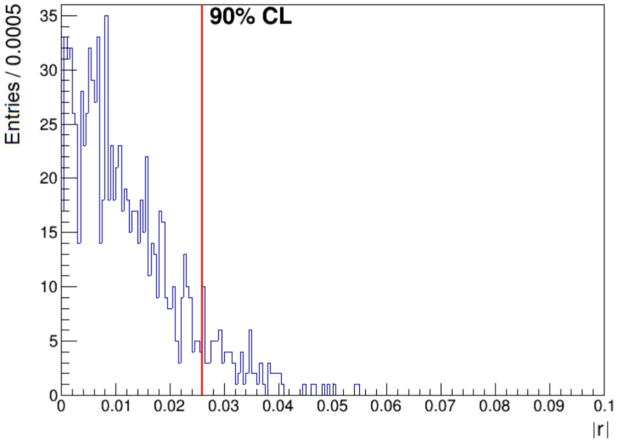
$a = 1.97 \pm 0.08$
$\gamma = 1.92\pi \pm 0.02\pi$
$\boxed{r = 0.024} \pm 0.017$
$\delta = \pi/4$ (fixed)
$\phi = \pi/4$ (fixed)

Ensemble of fits (MC)

For many $\begin{cases} \delta \in [0, \pi), \\ \phi \in [0, 2\pi), \end{cases}$
we perform 1000 simulations and fits to get 90% error of r extraction

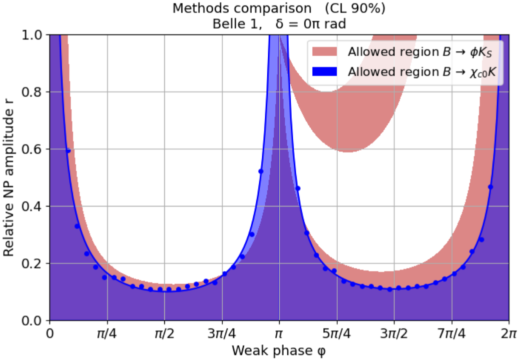
Thus, we obtain $\boxed{r_{\text{ext. error}} = 0.026}$ $(\delta = \pi/4, \ \phi = \pi/4)$

We scan 4 δ and 50 ϕ phases, so we perform $4 \cdot 50 \cdot 1000 = 200000$ fits

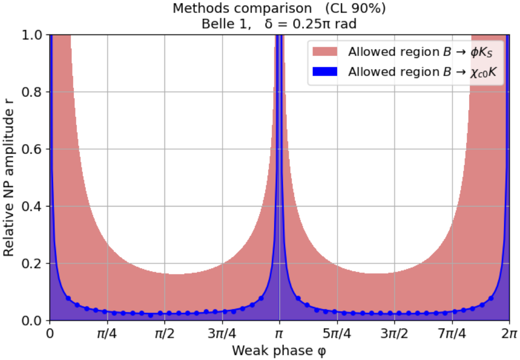


Methods comparison (CL = 90%)

We compare methods by imposing $B \to KKK$ extraction errors on $B \to \phi K$ regions

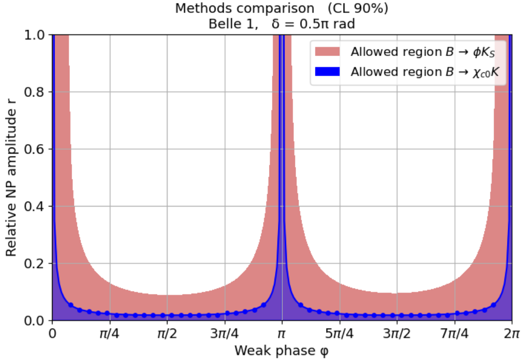


(a) $\delta = 0$

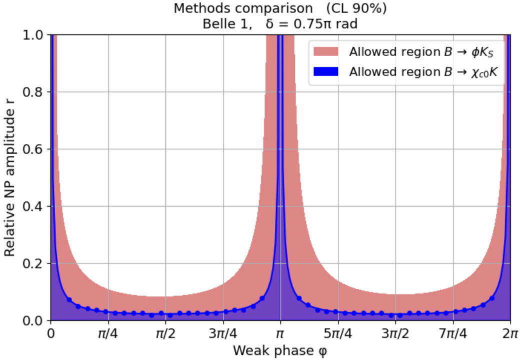


(b) $\delta = \frac{\pi}{4}$

Methods comparison (CL = 90%)



(a) $\delta = \frac{\pi}{2}$



(b) $\delta = \frac{3\pi}{4}$

The $B \to KKK$ method has **a significant advantage when** $\delta \neq 0$?

Conclusions

- The New Physics extraction in $B \to \phi K_S$ decay has a sufficient drawback
- New NP extraction method in $B^+ \to K^+K^+K^-$ is proposed
- We expect better sensitivity thanks to $\chi_{c0}(1P)$ resonance
- The method could be used on Belle II and LHCb experiments

References

[1] Y. Nakahama et al.
Measurement of CP violating asymmetries in $B^0 \to K^+K^-K^0_S$ decays with a time-dependent Dalitz approach
PhysRevD.82.073011

[2] J. P. Lees et al.
Study of CP violation in Dalitz-plot analyses of $B^0 \to K^+K^-K^0_S$, $B^+ \to K^+K^-K^+$, and $B^+ \to K^0_S K^0_S K^+$
PhysRevD.85.112010