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], Pavel Pakhlov[1,2], Alexander Bondar[3,4]

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

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Talk plan

- Sensitivity assessment of the New Physics (NP) search method in $B \to \phi K_S$ decay
- Development of a new method for NP search in the $B^+ \to K^+K^+K^-$ mode, comparison of accuracy with $B \to \phi K_S$
- Testing the possibility of determining the nature of direct CP violation in $B^+ \to K^+K^+K^-$ based on LHCb results

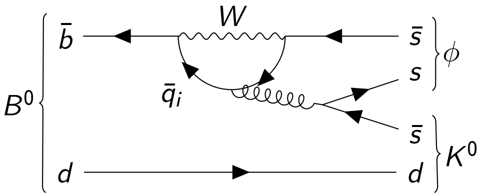
NP in $B \to \phi K_S$

- The B mesons region is very promising for 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

$B \to \phi K_S$ decay amplitudes

Let us derive the CP violation parameters in $B \to \phi K_S$

$$A(B^0 \to \phi K^0) = 1 + re^{i(\delta+\varphi)},$$
$$\bar{A}(\bar{B}^0 \to \phi \bar{K}^0) = 1 + re^{i(\delta-\varphi)},$$



here r — NP or SM pollution amplitude,
δ, φ — relative strong and weak phases

CP violation parameters

Defining time-dependent CP 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

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

where

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

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

Allowed regions (CL = 90%)

Using decay amplitudes, we derive

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

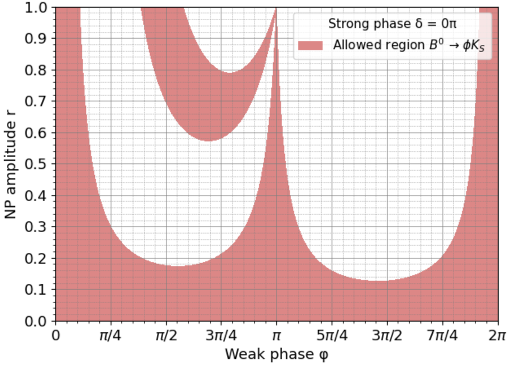
$$A_{\phi K_S} = \frac{2r\sin\delta\sin\varphi}{1 + r^2 + 2r\cos\delta\cos\varphi}.$$

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

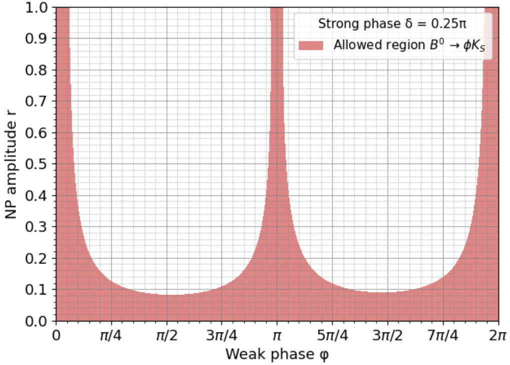
$$\frac{|\sin 2\beta_{\text{eff}} - \sin 2\beta|^2}{(\sigma_{\sin 2\beta_{\text{eff, exp}}})^2} + \frac{|A_{\phi K_S} - 0|^2}{(\sigma_{A_{\phi K_S},\text{ exp}})^2} < 1.65^2 \quad (1.65 \text{ for } 90\% \text{ CL})$$

Allowed regions (CL = 90%)

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



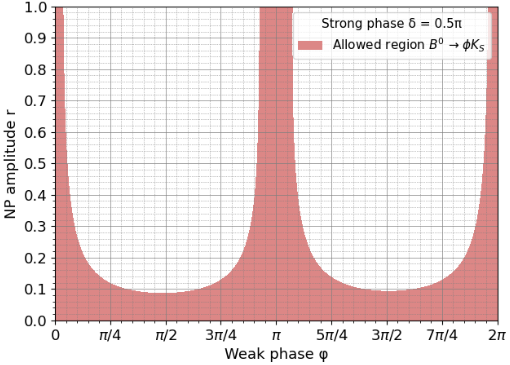
(a) $\delta = 0$



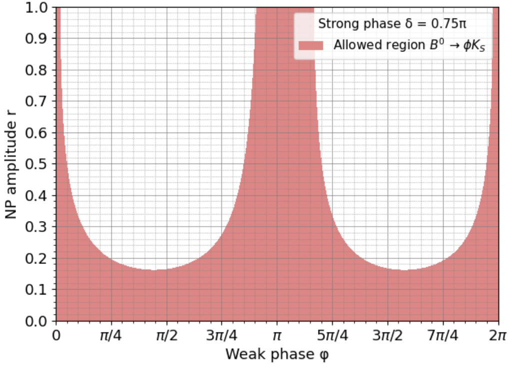
(b) $\delta = \frac{\pi}{4}$

Allowed regions (CL = 90%)

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



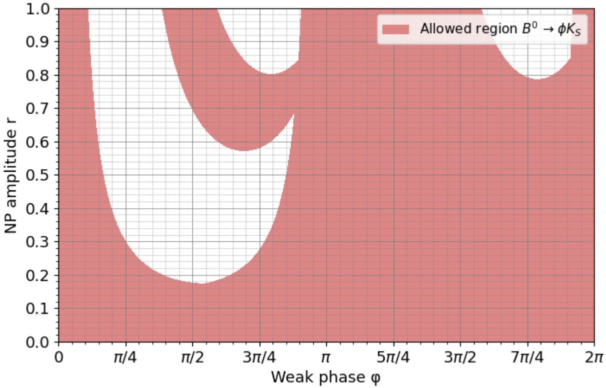
(c) $\delta = \frac{\pi}{2}$



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

Allowed 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**

CP violation in $B^+ \to \phi K^+$

Isospin-conjugated to the $B^0 \to \phi K_S$ mode, it has the same amplitudes?

We can assume that $A_{\phi K_S} = A_{\phi K^+}$

At present, A_{CP} in the $B^+ \to \phi K^+$ channel has been measured only by the BaBar:

$$A_{CP}(B^+ \to \phi(1020)K^+) \equiv A_{\phi K^+,\,\mathrm{exp}} = (12.8 \pm 4.4 \pm 1.3)\%.$$

The detected direct CP violation differs from 0 by 2.8 standard deviations

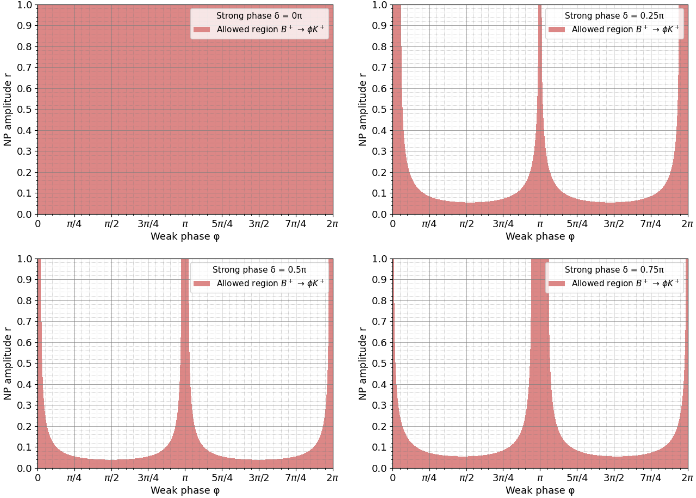
It is unclear why other collaborations (Belle, Belle II, LHCb) have not made similar measurements

CP violation in $B^+ \to \phi K^+$

Let us check what accuracy we could achieve with such measurements:

$$\frac{\left|A_{\phi K^+} - 0\right|^2}{(\sigma_{A_{\phi K^+},\ \mathrm{exp}})^2} < 1.65^2$$

New measurements would be very useful!

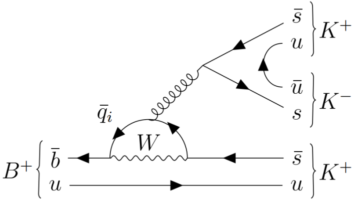


NP in amplitudes interference

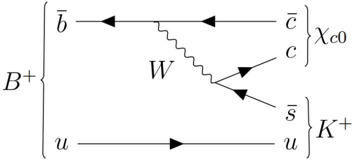
- A new method for NP searching in $B^+ \to K^+K^+K^-$ decay is developed
- The method uses interference between penguin $b \to s\bar{s}s$ and tree $b \to c\bar{c}s$ diagrams
- There is the scalar resonance $\chi_{c0}(1P)$ in tree amplitude
- The process's **strong phase changes near the resonance pole**

$\chi_{c0}(1P)$	$I^G(J^{PC}) = 0^+(0^{++})$
$\chi_{c0}(1P)$ MASS	3414.71 ± 0.30 MeV
$\chi_{c0}(1P)$ WIDTH	10.5 ± 0.8 MeV (S = 1.1)

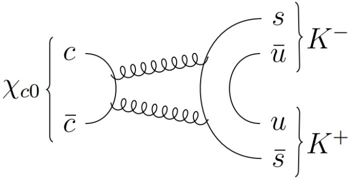
$B^+ \to \chi_{c0}K^+ \to K^+K^-K^+$ amplitudes



(a) $B^+ \to K^+K^+K^-$ (penguin)



(b) $B^+ \to \chi_{c0}K^+$ (tree)



(c) $\chi_{c0} \to K^+K^-$

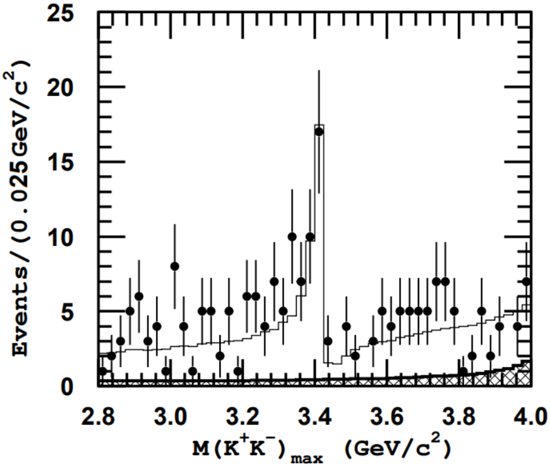
$$|A|^2 = \left| \underbrace{1 + re^{i(\delta \pm \varphi)}}_{penguin} + \underbrace{ae^{i\delta_T}\left[A_{BW}(m_{13}^2) + A_{BW}(m_{23}^2)\right]}_{tree} \right|^2, \quad A_{BW}(m_{ij}^2) = \frac{m_0\Gamma_0}{(m_0^2 - m_{ij}^2) - im_0\Gamma_0}$$

$B^+ \to K^+K^+K^-$ (Belle data)

Here is how K^+K^- invariant masses look like ($140\ \text{fb}^{-1}$, Belle)

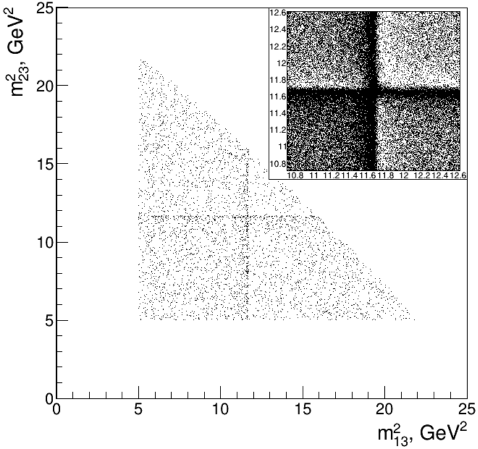
The interference pattern of the substrate and χ_{c0} resonance is clearly visible

We choose such parameters of functions for MC so that the projections are similar to this picture



Dalitz plot (MC)

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



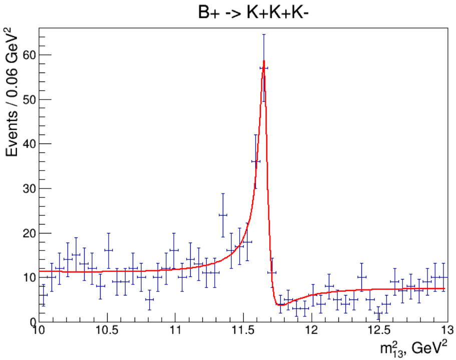
We perform toy Monte Carlo to get data-like distributions

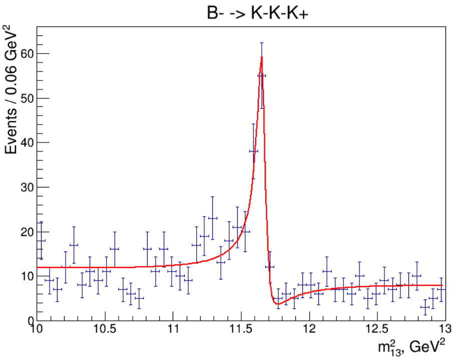
Generation parameters:
$a = 1.93 \quad (\pm 0.18)$
$\delta_T = 1.94\pi \quad (\pm 0.06\pi)$
$r = 0$

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

Dalitz fit projections (MC)

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





Fit sample:

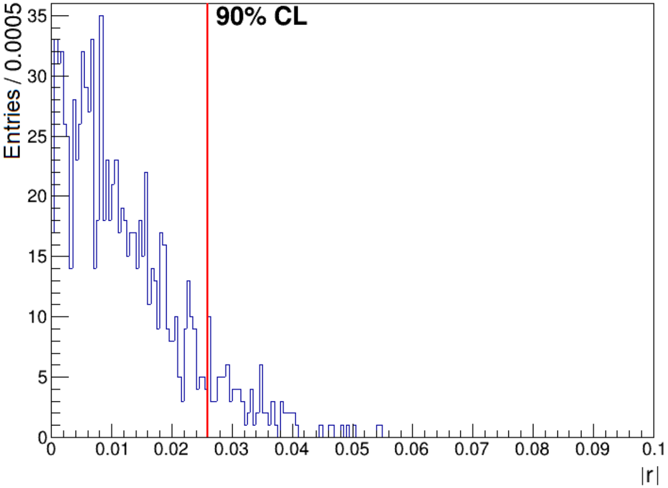
$a = 1.99 \pm 0.08$
$\delta_T = 1.92\pi \pm 0.02\pi$
$r = 0.024 \pm 0.017$
$\delta = \pi/4$ (fixed)
$\varphi = \pi/4$ (fixed)

Ensemble of fits (MC)

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

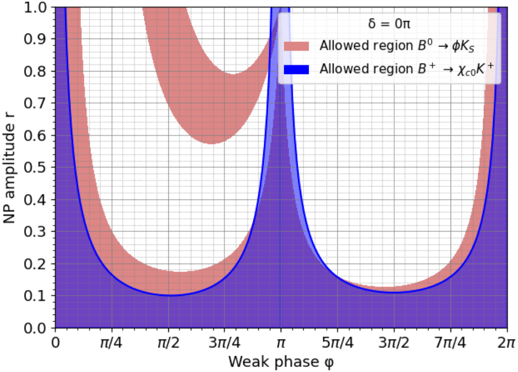
Thus, we obtain $r_{\text{ext. error}} = 0.026$ $(\delta = \pi/4,\ \varphi = \pi/4)$

We scan 8 δ and 50 φ phases, so we perform $8 \cdot 50 \cdot 1000 = 400000$ fits

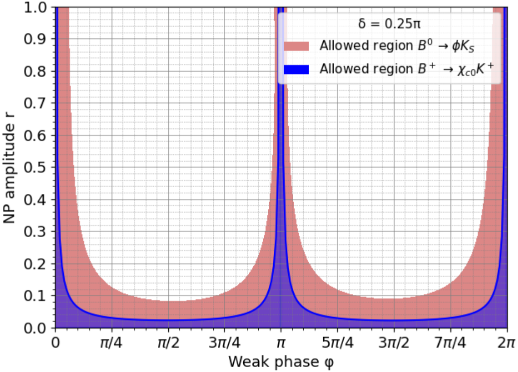


Methods comparison (CL = 90%)

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

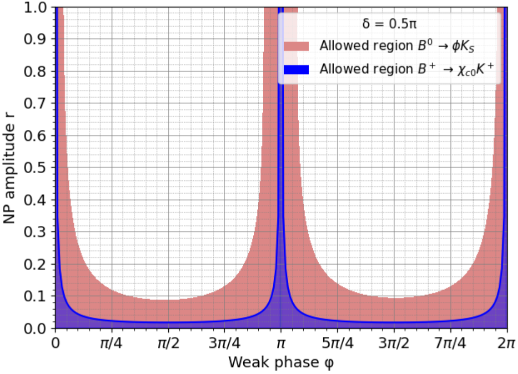


(a) $\delta = 0$

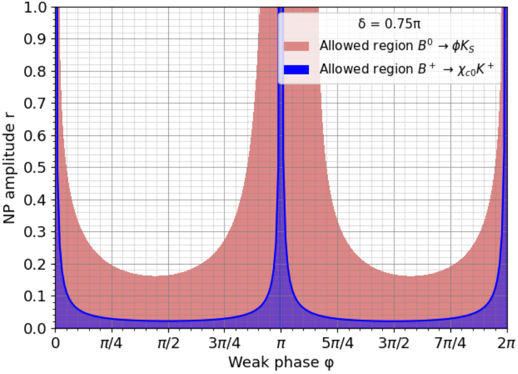


(b) $\delta = \frac{\pi}{4}$

Methods comparison (CL = 90%)



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



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

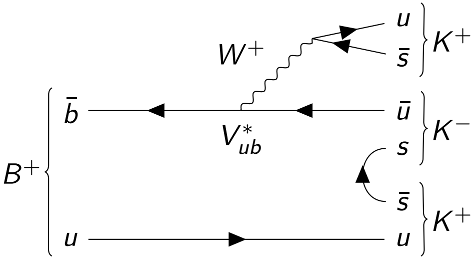
The $B \to KKK$ **method has a significant advantage** when $\delta \neq 0$

$b \to u$ contribution in $B^+ \to K^+K^+K^-$ decay

According to the latest measurement by the LHCb collaboration,

$$A_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.037 \pm 0.002 \pm 0.002 \pm 0.003 \qquad (8.5\sigma)$$

In the Standard Model there is an amplitude $b \to u$ that leads to CP violation



$$V_{ub} \approx |V_{ub}| e^{-i\gamma}$$

The same formulas, but $\varphi = \gamma$,

$$\text{где } \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \approx 66^\circ$$

It is necessary to have a way to determine the nature of the CP violation

$b \to u$ contribution in $B^+ \to K^+K^+K^-$ decay

Goal: extract the weak phase φ and compare it with that in SM

Consider the case where either $b \to u$ or NP is present

We perform Monte Carlo simulation for r, δ such that $A_{CP} \approx A_{CP\ \mathrm{LHCb}}$

- $r_{true} = 0.022$,
- $\delta_{true} = 1.375\pi$,
- $\varphi_{true} = \gamma = 0.368\pi$,
- $a_{true} = 1.930$,
- $\delta_{T,\ true} = 1.940\pi$,

- $r_{fit} = 0.024 \pm 0.002$,
- $\delta_{fit} = 1.37\pi^{+0.05\pi}_{-0.04\pi}$,
- $\varphi_{fit} = 0.39\pi^{+0.09\pi}_{-0.05\pi}$,
- $a_{fit} = 1.950 \pm 0.012$,
- $\delta_{T,\ fit} = 1.940\pi \pm 0.004$.

$\delta = 9\pi/8$	$10\pi/8$	$11\pi/8$	$12\pi/8$	$13\pi/8$	$14\pi/8$	$15\pi/8$
$\varphi_{error} = 0.04\pi$	0.07π	0.05π	0.04π	0.05π	0.06π	0.03π

The accuracy is high enough for precision verification of the Standard Model

Findings

- "Golden" mode $B \to \phi K_S$ has a significant disadvantage
- A new method for finding NP in $B^+ \to K^+K^+K^-$ is developed
- The method provides better sensitivity to NP thanks to the $\chi_{c0}(1P)$ resonance
- The new method has potential for use at LHCb