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## RADIATIVE PENGUIN $B^0 \rightarrow K^* \gamma$ AND $B_s^0 \rightarrow \phi \gamma$ DECAYS IN LHCb EXPERIMENT

The LHCb experiment at the Large Hadron Collider (LHC) is dedicated to studies of rare phenomena in  $b$ - and  $c$ -decays. These studies provide a possibility to precision tests of the Standard Model and discover the evidences of New Physics. We report recent measurements of radiative penguin rare decays  $B^0 \rightarrow K^* \gamma$  and  $B_s^0 \rightarrow \phi \gamma$  using  $1 \text{ fb}^{-1}$  of data taken at  $\sqrt{s} = 7 \text{ TeV}$  with the LHCb detector. Radiation level measurements for the silicon inner tracker operation and measurements of integrated luminosity with the Radiation Monitoring System, developed at Kiev Institute for Nuclear Research, are discussed.

**Keywords:** LHC, LHCb experiment, CP violation,  $B_s^0$ -meson, radiative decay, radiation monitoring system.

### Introduction

Flavor changing neutral current (FCNC) processes are highly suppressed in the standard model (SM) and thus constitute a stringent test of the current description of particle physics. Measurements of FCNCs provide sensitivity to the contributions of heavy virtual particles in the loop diagram. Loop diagrams are well described theoretically and easily accessible experimentally through many observables which we can measure, e.g. branching fractions, CP and isospin asymmetries and photon polarization. Thus, studies of the rare  $B$ -decays can yield powerful constraints on many New Physics scenarios, including models with supersymmetry.

### Large Hadron Collider beauty

The LHCb detector [1] is a single-arm forward spectrometer at the LHC covering the pseudo-rapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  or  $c$  quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the  $pp$  interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream. The combined

tracking system has a momentum resolution  $\Delta p/p$  that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and an impact parameter (IP) resolution of 20  $\mu\text{m}$  for tracks with high transverse momentum ( $p_T$ ). Charged hadrons are identified using two ring-imaging Cherenkov detectors (RICH). Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction.

### Radiative penguin $B^0 \rightarrow K^* \gamma$ and $B_s^0 \rightarrow \phi \gamma$ decays

In the SM, the decays  $B^0 \rightarrow K^* \gamma$  and  $B_s^0 \rightarrow \phi \gamma$  proceed at leading order through the electromagnetic penguin transitions,  $b \rightarrow s \gamma$ . At one-loop level these transitions are dominated by a virtual intermediate top quark coupling to a W boson (Figure 1).

Radiative decays of the  $B^0$  meson were first observed by the CLEO collaboration in 1993 in the decay mode  $B^0 \rightarrow K^* \gamma$  [2]. The latest theoretical predictions from NNLO calculations using soft-collinear effective

theory give us the values of branching fraction for decays  $B^0 \rightarrow K^* \gamma$  and  $B_s^0 \rightarrow \phi \gamma$  [3]:

$$B(B^0 \rightarrow K^* \gamma) = (4.3 \pm 1.4) \times 10^{-5}$$

$$B(B_s^0 \rightarrow \phi \gamma) = (4.3 \pm 1.4) \times 10^{-5},$$

which suffer from large uncertainties from hadronic form factors. A better-predicted quantity is the ratio of branching fractions, as it benefits from partial cancellations of theoretical uncertainties.

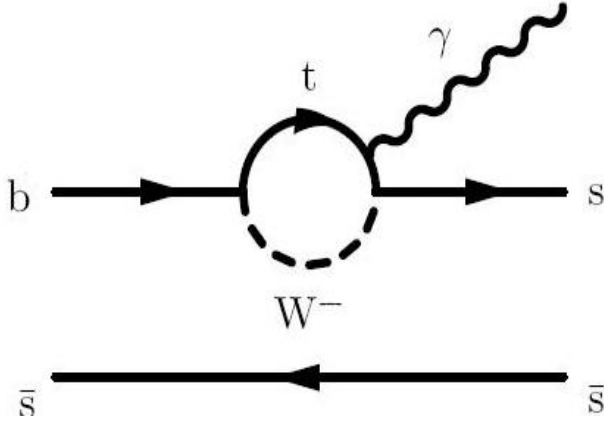


Figure 1. Feynman diagram describing the dominant process for the radiative penguin decay  $B_s^0 \rightarrow \phi \gamma$ .

The data used to measure the ratio of  $B(B^0 \rightarrow K^* \gamma)/B(B_s^0 \rightarrow \phi \gamma)$  corresponds to  $1.0 \text{ fb}^{-1}$  of  $pp$  collisions collected in 2011 at the LHCb with a center-of-mass energy of  $\sqrt{s} = 7 \text{ TeV}$ . The invariant mass distribution of the  $K\pi\gamma$  candidates and the  $K^+K^-$  candidates are shown on Figure 2.

The ratio of branching fractions is measured as:

$$\frac{B(B^0 \rightarrow K^* \gamma)}{B(B_s^0 \rightarrow \phi \gamma)} = \frac{y_{B^0 \rightarrow K^* \gamma}}{y_{B_s^0 \rightarrow \phi \gamma}} \frac{B(\phi \rightarrow K^+ K^-)}{B(K^{*0} \rightarrow K^+ \pi^-)} \frac{f_s}{f_d} \frac{\varepsilon_{B_s^0 \rightarrow \phi \gamma}}{\varepsilon_{B^0 \rightarrow K^* \gamma}},$$

where  $y_{B^0 \rightarrow K^* \gamma}$  and  $y_{B_s^0 \rightarrow \phi \gamma}$  are the observed yields of signal candidates on Figure 2,  $B(\phi \rightarrow K^+ K^-)/B(K^{*0} \rightarrow K^+ \pi^-) = 0.735 \pm 0.008$  [5] is the ratio of branching fractions of the vector mesons,  $f_s/f_d = 0.267^{+0.021}_{-0.020}$  is the ratio of the  $B^0$  and  $B_s^0$  hadronization fractions in  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$ , and  $\varepsilon_{B_s^0 \rightarrow \phi \gamma}/\varepsilon_{B^0 \rightarrow K^* \gamma}$  is the ratio of total reconstruction and selection efficiencies of the two decays.

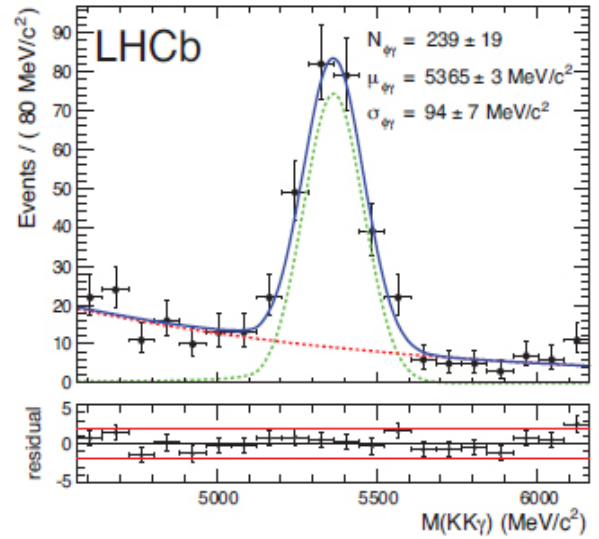
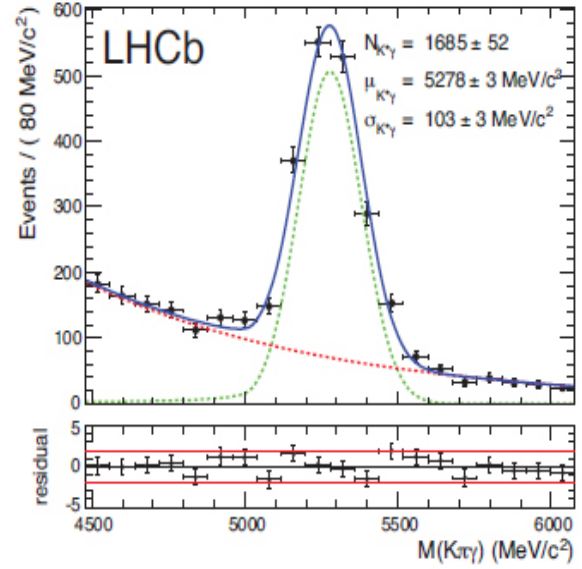


Figure 2. The invariant mass distribution of selected (top)  $B^0 \rightarrow K^* \gamma$  and (bottom)  $B_s^0 \rightarrow \phi \gamma$  candidates selected from  $1.0 \text{ fb}^{-1}$  of data collected at  $\sqrt{s} = 7 \text{ TeV}$  during 2011 [4].

The value of the ratio of branching fractions is measured and the value of  $B(B_s^0 \rightarrow \phi \gamma)$  is calculated using the world average for  $B(B^0 \rightarrow K^* \gamma)$  [5]:

$$\frac{B(B^0 \rightarrow K^* \gamma)}{B(B_s^0 \rightarrow \phi \gamma)} = 1.12^{+0.23}_{-0.20}$$

$$B(B_s^0 \rightarrow \phi \gamma) = (3.3 \pm 0.3) \times 10^{-5},$$

where the quoted error is a combination of the statistical and systematic uncertainties. The measurement of the ratio of branching fractions ensures the cancellation of most of the systematic errors. This is the most precise measurement of  $B(B_s^0 \rightarrow \phi \gamma)$  to date.

### Radiation Monitoring System for LHCb Inner Tracker

To perform successfully the scientific program of LHCb experiment one of the crucial tasks is to provide nominal conditions of the experiment for sufficient functioning of sub-detector systems. In experiments with high luminosity the radiation is the biggest problem. The radiation loads during 10 LHC-years of normal operation will reach 50 MRad at closest to Interaction Point regions [6]. Especially, high radiation loads are dangerous for Si-detectors and their readout electronics, which switches on only in case of stable beam. One of the systems to control radiation doses and beam condition is the Radiation Monitoring System (RMS) developed at Kiev Institute for Nuclear Research.

The RMS is based on the Metal Foil Detector (MFD) technology [7, 8]. The principle of the MFD operation is Secondary Electron Emission (SEE) from the metal foil surface (emission layer ~ 10–50 nm) caused by impinging charge particles. SEE causes positive charge on a foil which is readout by sensitive Charge Integrator (ChI).

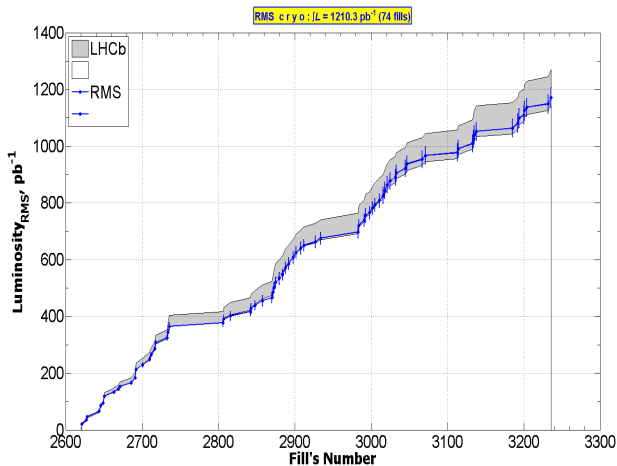


Figure 3. Delivered luminosity in 2012 (75 fills with highest delivered luminosity per fill) measured by LHCb (grey area) and RMS sensors (blue line). The data is shown only for one of four system modules ‘CRYO’ (mean value of 7 sensors).

Several MFD advantages have determined our choice for the IT RMS: the possibility to provide extremely low mass of the detecting material (from practical point of view – few tens  $\mu\text{m}$ ); simple readout

electronics (charge integrators and scalers); low operating voltage (24 V); high radiation tolerance; long term performance with minimal maintenance and low cost. More detailed description of RMS could be found in [9].

It was shown in 2010 that RMS response is correlated with luminosity measured by LHCb [10]. Figure 3 illustrates comparison of the delivered luminosity measured by RMS-module and LHCb in 2012.

In 2012 a simulation for proton-proton collisions at  $\sqrt{s} = 7$  TeV was made by exploring code FLUKA [11] to estimate radiation load at LHCb. The highest fluence of charged hadrons at Inner Tracker region was evaluated  $\sim 10^{12} \text{ cm}^{-2}$  for  $2.2 \text{ fb}^{-1}$ .

MIP fluxes and absorbed dose distribution measured by the RMS is in agreement with the Monte-Carlo simulations. The distribution of the charged particles fluence for  $2.2 \text{ fb}^{-1}$  of luminosity over the Inner Tracker Si-sensors measured by RMS is shown on Figure 4. Up to  $4 \cdot 10^{12} \text{ MIP/cm}^2$  have passed through silicon sensors. These fluence corresponds to a dose of (0.15 – 1) kGy absorbed by different sensors. Correspondingly calculated leakage currents increase in Si-sensors constitutes (50 – 100)  $\mu\text{A}$ . This is in agreement with the selected leakage current measurements.

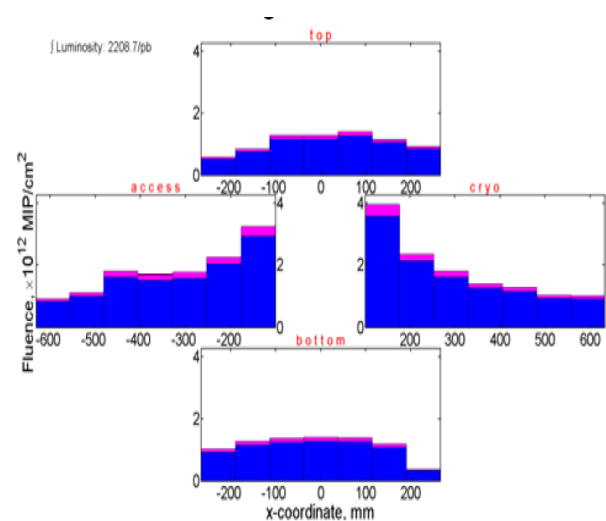


Figure 4. Charged particles fluence distribution at Inner Tracker region measured by the RMS in 2012 for  $2.2 \text{ fb}^{-1}$ .

Assuming 3 years (2010-2012) of LHC operation, about  $3.3 \text{ fb}^{-1}$  of integrated

luminosity was delivered at LHCb. In total, this corresponds to charged particles fluence of  $(1 - 6) \cdot 10^{12}$  MIP/cm<sup>2</sup>, absorbed dose – (0.3 - 1.5) kGy, increase of leakage current to (50 - 500) μA. This requires Si-sensor cooling down till (0 - 5) °C and bias voltage tuning to keep reliable operational of Inner Tracker.

Data from RMS is included in Beam and Background monitoring tools and is displayed online in LHCb Control Room for preventing the damages of silicon detectors from unexpected radiation incidents during LHC operation, especially during the beam injection.

### Conclusion

In summary, the LHCb experiment has entered the precision physics studies. By the end of February 2013, with about  $3.3 \text{ fb}^{-1}$  of integrated luminosity in total, a large amount of signal events is available for many

channels. The results of the measurements are the most precise measurement to date and have provided a powerful selective tool between various theoretical models. However, all measurements are in agreement with SM, which motivates further research.

In 2012 RMS has shown a reliable performance. The fluence of charged particles in the Inner Tracker region was estimated. Measured integrated luminosity is in agreement with other LHCb monitoring systems. To provide nominal conditions for LHCb detector, RMS was integrated into online Beam and Background monitoring tools.

*We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at CERN and at the LHCb institutes.*

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## РАДІАЦІЙНІ РОЗПАДИ $B^0 \rightarrow K^* \gamma$ ТА $B_s^0 \rightarrow \phi \gamma$ В ЕКСПЕРИМЕНТІ ЛНСЬ

Експеримент ЛНСь на Великому адронному колайдері, присвячений вивченню рідкісних явищ у розпадах за участю  $b$  та  $c$  кварків. Ці дослідження забезпечують можливість точної перевірки Стандартної Моделі та відкриття проявів Нової Фізики. Представлено нещодавні результати вимірювань радіаційних пінгвінних рідкісних розпадів  $B^0 \rightarrow K^* \gamma$  та  $B_s^0 \rightarrow \phi \gamma$ , використовуючи експериментальні дані накопичені в детекторі ЛНСь при енергії  $\sqrt{s} = 7$  ТеВ. Обговорюється також вимірювання радіаційних навантажень на внутрішній кремнієвій трековій системі та вимірювання інтегральної світимості експерименту ЛНСь Системою Радіаційного Моніторингу, яка розроблена в Київському Інституті Ядерних Досліджень.

**Ключові слова:** ЛНС, експеримент ЛНСь, порушення CP парності,  $B_s^0$  мезон, радіаційний розпад, система радіаційного моніторингу.

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## РАДИАЦИОННЫЕ РАСПАДЫ $B^0 \rightarrow K^* \gamma$ И $B_s^0 \rightarrow \phi \gamma$ В ЭКСПЕРИМЕНТЕ ЛНСЬ

Эксперимент ЛНСь на Большом адронном коллайдере посвящен изучению редких явлений в распадах с участием  $b$  и  $c$  кварков. Эти исследования обеспечивают возможность точной проверки Стандартной Модели и открытия проявлений Новой Физики. Представлены недавние результаты измерений радиационных пингвинных редких распадов  $B^0 \rightarrow K^* \gamma$  и  $B_s^0 \rightarrow \phi \gamma$ , используя экспериментальные данные, накопленные в детекторе ЛНСь при энергии  $\sqrt{s} = 7$  ТэВ. Обсуждаются также измерения радиационных нагрузок на внутренний кремниевый трекер и измерения интегральной светимости эксперимента ЛНСь Системой Радиационного Мониторинга, которая разработана в Киевском Институте ядерных исследований.

**Ключевые слова:** ЛНС, эксперимент ЛНСь, нарушение CP четности,  $B_s^0$  мезон, радиационный распад, система радиационного мониторинга.