Measurement of Branching Fractions of B→ Xs?+?- Decays at the Belle II experiment

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論 文 内 容 要 旨

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学位論文の 題　　　目	Measurement of Branching Fractions of $B \rightarrow X_s \ell^+ \ell^-$ Decays at the Belle II experiment (Belle II 実験における $B \rightarrow X_s \ell^+ \ell^-$過程の崩壊分岐比の測定)		

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A. MC Calibration

B. Lepton ID efficiency Correction and Uncertainty with Two-photon Events

The Standard Model (SM) of elementary particle physics is an outstanding theory to match various experiment results. Despite great successes, the SM is thought to be not perfect theory. There remain some open questions, for example, absence of the dark matter candidates, and a description of gravity is not included in the SM. Therefore, the effort to search for physics beyond the SM from both experimental and theoretical aspects is highly motivated.

The electroweak penguin $b \rightarrow s \ell^+ \ell^-$ decays are a good probe to search physics beyond the SM. This process is proceeded via 1-loop diagram and thus suppressed in the SM. New heavy particles may enter the loop or even proceed via tree diagrams, which induce a deviation on observables with the SM prediction. Furthermore, in recent years, some tensions with the SM in the analysis of $B \rightarrow K^{(*)} \ell^+ \ell^-$ decays, which is proceeded by $b \rightarrow s \ell^+ \ell^-$ at the quark level, have been reported by LHCb,

Belle, and ATLAS.
Inclusive $B \to X_s \ell^+\ell^-$ decays, where X_s is an inclusive hadronic state including a s-quark, provide information to $b \to s\ell^+\ell^-$ with good theoretical predictions. Compared with exclusive $B \to K^{(*)}\ell^+\ell^-$ decays, the hadronic uncertainty is under better control. Complementary information to the exclusive decays can be provided to shed light on the anomalies. The B-factory experiment at an electron-positron collider is suitable for the analysis on $B \to X_s \ell^+\ell^-$ thanks to the low background environment. Belle II is a unique experiment to achieve the measurements on $B \to X_s \ell^+\ell^-$ with large statistics.
The goal of the thesis is to perform the measurement of the branching fraction of $B \to X_s \ell^+\ell^-$ decays. This analysis is based on data accumulated on the $Y(4S)$ resonance. The amount of data corresponds to an integrated luminosity of 34.6 fb^{-1} which contains 37.7×10^6 BB pairs. This is the first measurement on $B \to X_s \ell^+\ell^-$ decays at Belle II.
This study is performed as a blind analysis: the analysis procedure is optimized using Monte-Carlo (MC) simulation samples. A difference between data and MC is corrected with data-driven study and taken into account as systematic uncertainty.
In this analysis, the inclusive $B \to X_s \ell^+\ell^-$ decays are reconstructed with the sum-of-exclusive approach. The hadronic system X_s is reconstructed from $Kn\pi$ $(0 \leq n \leq 4)$ and $3K$ final states allowing at most one π^0 and one K_S.
Signal MC sample of $B \to X_s \ell^+\ell^-$ is produced separately from three components, $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$, non-resonant $B \to X_s \ell^+\ell^-$. These three components are mixed according to the SM predictions of branching fractions. According to the MC samples, the fraction of the X_s covered by this study is 63.0%. If the fraction of states containing K_L is taken to be equal to that containing K_S, the missing fraction is 16.9%.
Charged particles are selected from tracks originating from the interaction point. Type of the charged particles is identified using the particle identification information obtained by the sub detector systems. The K_S candidates are reconstructed from two oppositely charged tracks and the π^0 candidates are formed by combining two photons which are reconstructed at ECL. The hadronic system X_s is reconstructed with sum-of-exclusive approach. The B-meson candidate is selected by applying a cut on $M_{bc} \equiv [(E_{beam}^*)^2 - |p_{B^*}|^2]^{1/2}$ where E_{beam}^* is the beam energy in the centre-of-mass (CM) system of e^+e^- and p_{B^*} is the reconstructed momentum of B-meson in the CM system; $5.2 < M_{bc} < 5.3$ GeV/c^2. The M_{bc} is used to extract signal yields by fitting.
One of the dominant background sources is $B \to X_s J/\psi$ with $J/\psi \to \ell^+\ell^-$. This process has the same final state with signal events. They are eliminated by imposing vetoes on the invariant mass of the lepton pair.
Other dominant backgrounds are BB events and cc continuum event in which B-meson and charm quark decays semi-leptonically. These backgrounds are suppressed by combining many variables with FastBDT, which is a machine learning technique, to distinguish signal from backgrounds.
The BB backgrounds due to mis-identification of particles may peak at M_{bc} distribution. The amount of the peaking backgrounds is estimated from data to extract signal yields correctly.

Number of signal events is extracted by fitting of the M_{bc} distribution. Then, the branching fraction if calculated with the following function,

$Br(B\to X_s \ell^+\ell^-) = N_{signal} / (2N_{BB} \times \varepsilon)$.

where N_{BB} is the number of B-meson pairs and ε is the reconstruction efficiency. The probability density functions (PDF) are prepared for following categories, Signal, Self cross-feed, Non-peaking backgrounds, and three Peaking backgrounds.

The branching fractions of $B\to X_s e^+e^-$ and $B\to X_s \mu^+\mu^-$ are calculated by fitting each M_{bc} distribution. That of $B\to X_s \ell^+\ell^-$ is obtained by simultaneous fitting of both M_{bc} distributions of electron and muon modes.

The systematic uncertainty of the branching fraction is estimated from the following sources:

- Uncertainty of the number of B-meson pairs
- Efficiency correction uncertainty
- Fitter bias
- PDF uncertainty
- Signal modeling of non-resonant X_s

The central values of the branching fractions are measured as followings:

$Br(B\to X_s e^+e^-) = [4.86^{+2.75}_{-2.42}(\mathrm{stat})^{+1.02}_{-0.92}(\mathrm{syst})] \times 10^{-6}$

$Br(B\to X_s \mu^+\mu^-) = [0.78^{+2.21}_{-1.85}(\mathrm{stat})^{+0.43}_{-0.38}(\mathrm{syst})] \times 10^{-6}$

$Br(B\to X_s \ell^+\ell^-) = [2.78^{+1.85}_{-1.65}(\mathrm{stat})^{+0.66}_{-0.61}(\mathrm{syst})] \times 10^{-6}$

The statistical significance of the observation of the signal events is calculated as followings, 2.0σ, 0.40σ, and 0.17σ for the $B\to X_s e^+e^-$, $B\to X_s \mu^+\mu^-$, and $B\to X_s \ell^+\ell^-$, respectively. Since the significance of the signals are below 2σ for $B\to X_s \mu^+\mu^-$ and $B\to X_s \ell^+\ell^-$, upper limits at 90% and 95% confidence levels (CL) are determined for the branching fraction.

The results on the branching fractions are

$Br(B\to X_s e^+e^-) = [4.86^{+2.75}_{-2.42}(\mathrm{stat})^{+1.02}_{-0.92}(\mathrm{syst})] \times 10^{-6}$

$Br(B\to X_s \mu^+\mu^-) < 4.67\ (5.61) \times 10^{-6}$ at 90% (95%) CL

$Br(B\to X_s \ell^+\ell^-) < 5.54\ (6.30) \times 10^{-6}$ at 90% (95%) CL

The obtained results are compared with other measurements and SM predictions. The branching fraction of $B\to X_s e^+e^-$ and $B\to X_s \mu^+\mu^-$ is consistent with previous measurements and the SM prediction. Result of $B\to X_s \ell^+\ell^-$ is consistent with the world average, Belle measurement and the SM prediction, while the difference from BaBar is at 1.4σ level.

The analysis procedure of $B\to X_s \ell^+\ell^-$ decays at Belle II experiment well established and we have got ready to lead to decisive conclusions regarding the anomalies which are observed in the exclusive $B\to K^{(*)}\ell^+\ell^-$ decays with upcoming Belle II data.

別　紙

論文審査の結果の要旨

本博士研究では，B 中間子の電弱ペンギン崩壊 B -> Xs l+ l- の崩壊分岐比の測定を行った。2018 年より本格的にデータ取得を開始した Belle II 実験のデータを使った解析としては，初めての結果である。

この崩壊過程は，クォークレベルでは b -> s l+l-の遷移であり，標準模型では高次のループが関与する過程である。素粒子の標準模型にはない未知の粒子がループの中に出現した場合，崩壊分岐比の標準模型からのずれとして観測される可能性がある。本博士研究では，s-quark を含む全てのハドロン状態である Xs を多くの排他的な終状態を足し合わせることで観測した。このような観測手法により得られる結果は，精度の高い理論的予測値との比較が可能であるという点で重要である。本博士研究で得られた測定結果は標準模型と無矛盾であり，先行研究の結果とも一致するものであった。

この解析モードは Belle II 実験における最重要課題の一つである。佐藤瑶氏は，運用開始直後である Belle II での測定を実現するために，解析手法を独力で完成させた。解析手法には，機械学習（FastBDT）を用いた背景事象の除去手法を導入し，非常に稀な崩壊過程である信号事象を正確に抽出し，測定することに成功した。加えて，測定器性能に由来する系統誤差の評価や，Belle II 実験グループが共通で使用する解析ソフトウェアの開発も行った。これらの成果は，Belle II グループへ大きな貢献である。

Belle II 実験はデータ取得を継続しており，今後 1 年間で先行研究に匹敵する統計量を取得する計画である。2022 年 3 月には，世界最高精度での測定結果を論文として出版することを予定している。

博士論文は，自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって，佐藤瑶氏提出の博士論文は，博士（理学）の学位論文として合格と認める。