Time-dependent analysis of $b \rightarrow s\gamma$ transitions

S. Bilokin
IPHCP Strasbourg, France

France-Ukraine Workshop, LAL
Scientific motivation

- Belle II @ SuperKEKB is the new $e^+e^-$ facility at intensity frontier, which studies properties of rare B meson decays – **b-factory**
  - Successor of **Belle @ KEKB** and **BaBar @ PEP II**
  - Rich physics program
    - Direct searches of BSM
      - Dark matter, axions, exotics ...
    - Indirect searches
      - B physics (CKM, EW penguins, radiative decays)
      - Charm physics
      - Tau physics
    - Quarkonium and QCD studies
- No New Physics (NP) particles have been discovered at the LHC yet
  - Importance of the indirect searches is rising
  - Belle II can reach beyond the energy frontier sensitivity
- **Constructive complementarity & competition with LHC**
Belle II at SuperKEKB

- Most of the data will be taken at the Y(4S) resonance
  \[ E(e^-) = 7 \text{ GeV}, \quad E(e^+) = 4 \text{ GeV} \]
- Nano-beam scheme and doubling the beam current
  - Vertical beam size is 50nm
  - Higher beam background
- \[ \mathcal{L} = 8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1} (\text{KEKB x 40}) \]
- Improved vertex resolution, PID, tracking, etc...
- High detection efficiency $\gamma, \pi^0, K_{S,L}^0$
- Detector commissioning has started and full Belle II will be next year

Plan to collect 50 ab$^{-1}$ by 2025
Introduction

- We are interested in time-dependent CP analysis of $b \to s\gamma$ transitions

  - In Standard Model no time-dependent CP violation (TDCPV) is expected due to its V-A structure and photon polarization
  - Sensitive to New Physics effects

- We are studying two channels:
  - $B^0 \to K^0_S\pi^0\gamma$
  - $B^0 \to K^0_S\pi^+\pi^-\gamma$
  - BR: $9.5 \times 10^{-6}$
  - $7 \times 10^{-6}$ (with $K^0_S \to \pi^+\pi^-$)

- These processes go through several resonances $K^{*0}$ and higher $K_{10}^0$, $K_{20}^0$, ... etc, often called $X_{sd}$

  - $B^0 \to K^0_S\pi^0\gamma$ goes through $K^{*0}$ and $X_{sd}$
  - $B^0 \to K^0_S\pi^+\pi^-\gamma$ only through higher resonances $X_{sd}$
Results by the previous experiments

\[ B^0 \rightarrow K^0_S \pi^0 \gamma \quad \sim 0.42 \text{ ab}^{-1} \]

\[
\begin{align*}
S_{K^*0\gamma} & = -0.32^{+0.36}_{-0.33} \text{(stat)} \pm 0.05 \\
A_{K^*0\gamma} & = -0.20 \pm 0.24 \text{(stat)} \pm 0.05 \\
S_{K^0_S\pi^0\gamma} & = -0.10 \pm 0.31 \text{(stat)} \pm 0.07 \\
A_{K^0_S\pi^0\gamma} & = -0.20 \pm 0.20 \text{(stat)} \pm 0.06
\end{align*}
\]

\[ B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma \quad \sim 0.6 \text{ ab}^{-1} \]

\[
\begin{align*}
S_{K^0_S\pi^+\pi^-\gamma} & = 0.09 \pm 0.27^{+0.04}_{-0.07} \\
A_{K^0_S\pi^+\pi^-\gamma} & = 0.05 \pm 0.18 \pm 0.06
\end{align*}
\]

\[ B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma \quad \sim 0.43 \text{ ab}^{-1} \]

\[
\begin{align*}
S_{K^0_S\pi^+\pi^-\gamma} & = 0.14 \pm 0.25 \pm 0.03, \\
C_{K^0_S\pi^+\pi^-\gamma} & = -0.39 \pm 0.20^{+0.03}_{-0.02}.
\end{align*}
\]

- The results of the previous b-factories, Belle and BaBar are statistically limited → increase sensitivity \( \sim \times 10 \) with Belle II
TDCPV measurement

- Reconstruct the signal B candidate
- Tag B meson flavour and measure $\Delta t$ using tag side and signal side B candidate vertices
  - Effective flavour tagging efficiency is 33.6%
    - Detector improvement: +3%
    - Algorithm improvement: +3%
- Compute discriminating observables
- Build signal and background probability density functions (PDFs) models and extract S and A TDCPV parameters

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[ 1 + q(S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)) \right]$$
Reconstruction quality

- Using full Belle II simulation sample 1 ab$^{-1}$:

$$B^0 \rightarrow K^0_S \pi^0 \gamma \text{ (all mass spectrum)}$$

\begin{align*}
B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma
\end{align*}

\begin{align*}
\Delta E &= E_{B}^{c.m.s.} - E_{beam}^{c.m.s.} \\
m_{bc} &= \sqrt{(E_{beam}^{c.m.s.})^2 - (p_{B}^{c.m.s.})^2}
\end{align*}

\begin{align*}
\text{TM Signal} & \quad \text{Continuum} \quad \text{BB bkg} \\
\text{TM Signal} & \quad \text{Continuum} \quad \text{BB bkg}
\end{align*}

\begin{align*}
\text{~3.7\% MC efficiency} & \\
\text{~4.2\% MC efficiency}
\end{align*}
Reconstruction quality

- Using full Belle II simulation signal samples:

\[ B^0 \rightarrow K_S^0 \pi^0 \gamma \]

\[ B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma \]

\(~1.8 \text{ ps RMS}\)

\(~1.25 \text{ ps RMS}\)
Fit of $B^0 \rightarrow K_S^0 \pi^0 \gamma$

- Using MC sample of $L = 1 \text{ ab}^{-1}$, $K^*$ mass region:

4D unbinned likelihood fit gives the precision on TDCPV parameters $A$ & $S$

- 2 background models and 1 signal model

- Continuum bkg shape, signal fraction, $A$ and $S$ are determined from the fit

MC numbers:

- $N(\text{total}) = 1029$
- $N(\text{signal}) = 203$

Fit results:

- $N(\text{signal}) = 220 \pm 18$
- $A = +0.03 \pm 0.19$
- $S = +0.02 \pm 0.30$
Fit of $B^0 \rightarrow K_S^0 \pi^+ \pi^- \gamma$

- Using MC sample of $L = 1$ ab$^{-1}$:

- 4D unbinned likelihood fit gives the precision on TDCPV parameters $A$ & $S$
- 2 background models and 1 signal model
- Continuum bkg shape, signal fraction, $A$ and $S$ are determined from the fit

MC numbers:
- $N(\text{total}) = 6002$
- $N(\text{signal}) = 436$

Fit results:
- $N(\text{signal}) = 428 \pm 29$
- $A = -0.21 \pm 0.17$
- $S = -0.09 \pm 0.20$
Preliminary prospects for $B^0 \to K_S^0 \pi^0 \gamma$

- 200 Toy MC experiments, K*0 mass region:

- The statistical error of full Belle II dataset is on the level of systematics

*Belle and BaBar errors are for S parameter
Preliminary prospects for $B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma$

- 200 Toy MC experiments:

- Non CP eigenstates can dilute the precision on S by $\sim 20\%$
Summary

- Radiative processes, like $b \rightarrow s\gamma$, are sensitive probes for New Physics
  - The $e^+e^-$ collisions at Belle II is an excellent environment to study radiative processes
- For $B^0 \rightarrow K_S^0\pi^+\pi^-\gamma$ statistical uncertainty on $\delta S \sim 0.043$ is reachable
- Another channel $B^0 \rightarrow K_S^0\pi^0\gamma$ gives $\delta S \sim 0.045$, it is easier to interpret

Belle II will provide enough data to have statistical uncertainties comparable to the systematic ones for the radiative TDCPV studies
Thank you!
Delta T

- Change of S and A parameters and influence of experimental resolution
Initial SuperKEKB planning

Goal of Belle II / SuperKEKB

Phase 3 - Physics run

9 months/year
20 days/month
# Belle II parameters

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Configuration</th>
<th>Readout</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>Beryllium double-wall</td>
<td>Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PXD</td>
<td>Silicon pixel (DEPFET)</td>
<td>Sensor size: 15×100 (120) mm² pixel size: 50×50 (75) μm² 2 layers: 8 (12) sensors</td>
<td>10 M</td>
<td>impact parameter resolution ( \sigma_{z_0} \sim 20 \mu m ) (PXD and SVD)</td>
</tr>
<tr>
<td>SVD</td>
<td>Double sided Silicon strip</td>
<td>Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors</td>
<td>245 k</td>
<td></td>
</tr>
<tr>
<td>CDC</td>
<td>Small cell drift chamber</td>
<td>56 layers, 32 axial, 24 stereo  ( r = 16 - 112 \text{ cm} )  (-83 \leq z \leq 159 \text{ cm} )</td>
<td>14 k</td>
<td>( \sigma_{r\phi} = 100 \mu m, \sigma_z = 2 \text{ mm} ) ( \sigma_{p_t}/p_t = \sqrt{(0.2%p_t)^2 + (0.3%/\beta)^2} ) ( \sigma_{p_t}/p_t = \sqrt{(0.1%p_t)^2 + (0.3%/\beta)^2} ) (with SVD) ( \sigma_{dE/dx} = 5% )</td>
</tr>
<tr>
<td>TOP</td>
<td>RICH with quartz radiator</td>
<td>16 segments in ( \phi ) at ( r \sim 120 \text{ cm} ) 275 cm long, 2 cm thick quartz bars with 4x4 channel MCP PMTs</td>
<td>8 k</td>
<td>( N_{p.e.} \sim 20, \sigma_t = 40 \text{ ps} ) ( K/\pi ) separation : efficiency &gt; 99% at &lt; 0.5% pion fake prob. for ( B \rightarrow \rho \gamma ) decays</td>
</tr>
<tr>
<td>ARICH</td>
<td>RICH with aerogel radiator</td>
<td>4 cm thick focusing radiator and HAPD photodetectors for the forward end-cap</td>
<td>78 k</td>
<td>( N_{p.e.} \sim 13 ) ( K/\pi ) separation at 4 GeV/c; efficiency 96% at 1% pion fake prob.</td>
</tr>
<tr>
<td>ECL</td>
<td>CsI(Tl) (Towered structure)</td>
<td>Barrel: ( r = 125 - 162 \text{ cm} )  End-cap: ( z = -102 \text{ cm} ) and +196 cm</td>
<td>6624 ( \sigma_E/E = 0.2% \oplus 1.2% ) ( \sigma_{pos} = 0.5 \text{ cm}/\sqrt{E} ) (E in GeV)</td>
<td></td>
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<tr>
<td>KLM</td>
<td>barrel: RPCs</td>
<td>14 layers (5 cm Fe + 4 cm gap) 2 RPCs in each gap</td>
<td>( \theta: 16 \text{ k}, \phi: 16 \text{ k} )</td>
<td>( \Delta \phi = \Delta \theta = 20 ) mradian for ( K_L ) ( \sim 1% ) hadron fake for muons</td>
</tr>
<tr>
<td></td>
<td>end-caps:</td>
<td>14 layers of ((7 - 10) \times 40 \text{ mm}^2) strips</td>
<td>17 k</td>
<td>( \Delta \phi = \Delta \theta = 10 ) mradian for ( K_L ) ( \sigma_{p}/p = 18% ) for 1 GeV/c ( K_L )</td>
</tr>
</tbody>
</table>