Status and plan of $B^0 \to K^0 \pi^0$ Time-dependent study

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Thanks to M. Sevior for initial help

$^1$Tata Institute of Fundamental Research

October 21, 2021 @B2GM
Outline

- Motivation & Status at Belle II
- Goal and current development
- $4D (\Delta E, M_{bc}, \Delta t, C'_{out})$ PDFs modeling
- $A_{CP} & S_{CP}$ measurement
- $B^{0} \rightarrow J/\psi K_{S}^{0}$ control sample study
- B Lifetime, $A_{CP} & S_{CP}$ measurement
- Summary and Plans
Motivation

- In the SM, the decay $B^0 \to K^0 \pi^0$ proceeds via $b \to s$ loop diagrams.
- Such FCNC transitions are highly suppressed in the SM and sensitive to non-SM particles appearing in the loops.

**Sum rule relation for $B \to K \pi$ decays**

\[
l_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_B^0}{\tau_{B^+}} - 2A_{K^+\pi^0} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \tau_{B^+} - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} = 0
\]

Predicting $A_{K^0\pi^0} = -0.17 \pm 0.06$ (Phys.Lett. B627 (2005) 82-8)
Status at Belle II

- Measurement of $B$ and $A_{CP}$ shown on Moriond using 62.8 $fb^{-1}$

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Validation study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>62.8 $fb^{-1}$ MC cocktail</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.F. ($\times 10^{-6}$)</td>
<td>$9.08^{+1.57}_{-1.50}$</td>
</tr>
<tr>
<td>$N_{qq}$</td>
<td>$262.1^{+17.2}_{-16.9}$ (exp.=254)</td>
</tr>
<tr>
<td>$N_{bb}$</td>
<td>$12.7^{+1.0}_{-1.0}$ (exp.=13)</td>
</tr>
<tr>
<td>$q\bar{q}\Delta E$ slope</td>
<td>$-1.5442^{+0.3271}_{-0.3182}$</td>
</tr>
</tbody>
</table>

Belle II simulation

$\int L dt = 62.8 fb^{-1}$

Parameter

| $B^{0} \rightarrow K^{0}\pi^{0}$ | October 21, 2021 @B2GM | 4 / 27 |
Current development

- Aim is to do time-dependent analysis
- Adding the $\Delta t$ in the fitter
- To improve the precision on $A_{CP}$ & $S_{CP}$ measurement, include the log transform continuum suppression ($C'_{out}$) variable
- $4D \ (\Delta E, M_{bc}, \Delta t, C'_{out})$
- Targeting LEPTON-PHOTON to use 200 $fb^{-1}$
Selection criteria

\( B^0 \to K_S^0 \pi^0 \) selection

- \( 120 < m_{\pi^0} < 145 \text{ MeV} \) and \( |\cos \theta_H| < 0.98 \)
- Barrel \( E_\gamma > 30 \), Backward \( E_\gamma > 60 \) and Forward \( E_\gamma > 80 \) MeV
- \( 482 < m_{K_S^0} < 513 \) MeV
- \( 5.24 < M_{bc} < 5.3 \) GeV and \( -0.3 < \Delta E < 0.3 \) GeV

\( B^0 \to J/\psi K_S^0 \) selection

- Criteria are taken from BELLE2-NOTE-PH-202.
- \( dr < 0.5 \) cm, \( |dz| < 3 \) cm, for muon tracks.
- \( \text{muonID}(\mu^+) \) or \( \text{muonID}(\mu^+) > 0.2 \)
- \( 2.80 < M_{J/\psi} < 3.40 \) GeV and \( 482 < M_{K_S^0} < 513 \) MeV
- \( 5.2 < M_{bc} < 5.3 \) GeV and \( |\Delta E| < 0.05 \) GeV

- For CP-side: IP constraint and only \( K_S^0 \) vertexing
- For tag-side: IP constraint
- \( \sigma_{\Delta t} < 2.5 \) ps
4D \left( \Delta E, M_{bc}, \Delta t, \dot{C}_{\text{out}} \right)
**Signal Modeling**

- $\Delta t$: RooBCPGenDecay PDF PDF convolved with double Gaussian:
  \[
  P_{\text{sig}}(\Delta t, q) = \frac{\exp^{-|\Delta t|/\tau_{B^0}^2}}{4\tau_{B^0}^4} ([1 - q\Delta w + q\mu_i(1 - 2w)] + [q(1 - 2w) + \mu_i(1 - q\Delta w)](A_{CP} \cos(\Delta m \Delta t) - S_{CP} \cos(\Delta m \Delta t)))
  \]
  Core and tail Gaussian, $\tau_{B^0} = 1.520$ ps and $\Delta m = 0.507$/ps

- $\Delta E$: Crystal Ball + double Gaussian with common mean

- $M_{bc}$: Crystal Ball + Gaussian, $C_{\text{out}}$: Bifurcated + Gaussian

Example plot of integrated $q \cdot r$ bin

- In same way performed 7 $q \cdot r$ bin fit to extract the PDFs parameters

(S.Hazra)
Continuum bkg modeling

- \( \Delta t \): RooDecay PDF convolved with double Gaussian: \( e^{-|t|/\tau} \)
  - Core and tail Gaussian
- \( \Delta E \): Linear function
- \( M_{bc} \): ARGUS function, \( C_{\text{out}}' \): Bifurcated + Gaussian

\[
\begin{align*}
\Delta t & : \text{RooDecay PDF convolved with double Gaussian: } e^{-|t|/\tau} \\
\Delta E & : \text{Linear function} \\
M_{bc} & : \text{ARGUS function, } C_{\text{out}}' \text{: Bifurcated + Gaussian}
\end{align*}
\]
\( B \bar{B} \) bkg Modeling

- \( \Delta t \): RooDecay PDF convolved with double Gaussian: \( e^{-|t|/\tau} \)

- Core and tail Gaussian

- 2D Kernel estimation PDF used for \( \Delta E - M_{bc} \) modeling

- \( C'_{out} \): Bifurcated + Gaussian

(S.Hazra)
TDCPV binned model

- Divide the signal, continuum and $B\bar{B}$ bkg dataset in $7 \, q \cdot r$ bins
- Use the same PDFs (signal, continuum and $B\bar{B}$) for all the bin
- Signal PDFs shape parameters are taken from each bin fit
- Continuum and $B\bar{B}$ BKG PDFs shape parameters are same for all the bin and taken from integrated $q \cdot r$ bin fit
- All the PDFs shape parameters are fixed except $A_{CP}$, $S_{CP}$ and Yield for simultaneous fit
- $500 \, fb^{-1}$ cocktail of signal, continuum and $B\bar{B}$ used
7-bin fit projection

Example plot of single bin

- Rest of the bin fit projection shown in backup slide
Pure toy test

- To validate the fitter, 1000 toy experiments performed
- Signal, continuum and $B\bar{B}$ dataset are generated
- Expected $A_{CP}$: 0.0 and $S_{CP}$: 0.0

There is no significant bias!

(S.Hazra)
GSIM Toy test

- Signal dataset are used from the corresponding MC sample
- Continuum and $B\bar{B}$ dataset are generated using the PDF shape
- $\sin(2\beta) = \sin(2\phi_1) = S_{CP} = 0.7032$, where $\beta = 0.39 \text{ rad}$
- Expected $A_{CP}: 0.0$ and $S_{CP}: 0.7032$

There is no significant bias!

(S. Hazra)
Toy results

- Signal efficiency $= 0.140$ (all selection + loose cont. supp. cut + $\sigma_{\Delta t}$)

```
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fitted value</th>
<th>Expected value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Yield</td>
<td>$364 \pm 24$</td>
<td>$353$</td>
</tr>
<tr>
<td>Continuum Yield</td>
<td>$7654 \pm 92$</td>
<td>$7683$</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>$-0.011 \pm 0.157$</td>
<td>$0.0$</td>
</tr>
<tr>
<td>$S_{CP}$</td>
<td>$0.004 \pm 0.247$</td>
<td>$0.0$</td>
</tr>
</tbody>
</table>
```

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<td>$356 \pm 24$</td>
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</tr>
<tr>
<td>Continuum Yield</td>
<td>$7639 \pm 88$</td>
<td>$7683$</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>$-0.0152 \pm 0.152$</td>
<td>$0.0$</td>
</tr>
<tr>
<td>$S_{CP}$</td>
<td>$0.677 \pm 0.236$</td>
<td>$0.703$</td>
</tr>
</tbody>
</table>
```

(S.Hazra)
Control Sample study $B^0 \rightarrow J/\psi K^0_S$

B Lifetime

$A_{CP} \& S_{CP}$
Signal Modeling

- \( \Delta t \): RooBCPGenDecay PDF convolved with double Gaussian:
  \[
P_{\text{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} \exp\left(\frac{-|\Delta t|}{\tau_{B^0}}\right) \left([1 - q\Delta w + q\mu_i(1 - 2w)] + [q(1 - 2w) + \mu_i(1 - q\Delta w)](A_{CP} \cos(\Delta m_d \Delta t) - S_{CP} \cos(\Delta m_d \Delta t))\right)
  \]

  Core and tail Gaussian

- \( M_{bc} \): Crystal Ball function

\[\begin{array}{c}
\text{Signal } \Delta T \\
\begin{array}{c}
\text{Signal Mbc}
\end{array}
\end{array}\]
$B\bar{B}$ modeling

- Peaking compoment peaking at the true $B$ mass ($2 - 3\%$ of signal events)
- $\Delta t$: RooDecay PDF convolved with double Gaussian: $e^{-|t|/\tau}$
  Core and tail Gaussian
- $M_{bc}$: ARGUS + Gaussian function
$q\bar{q}$ modeling

- $\Delta t$: RooDecay PDF convolved with double Gaussian: $e^{-|t|/\tau}$
  Core and tail Gaussian
- $M_{bc}$: ARGUS function
**$B$ Lifetime fit**

- **200 $fb^{-1}$** cocktail of signal, background are generated from PDFs.
- All shape parameters are fixed

![Graphs showing $\Delta T$ and $M_{BC}$ projections with signal yields and lifetimes.]

**Signal $\Delta T$**

- **Lifetime** = 1.528 ± 0.141
- **Continued Yield** = 272 ± 19
- **Signal Yield** = 1047 ± 33
### GSIM toy

**Parameter** | **Fitted value** | **Expected value**
--- | --- | ---
Signal Yield | $1045 \pm 33$ | 1044
Background Yield | $275 \pm 18$ | 275
Lifetime (ps) | $1.523 \pm 0.136$ | 1.52
Validation of TDCPV fitter
7-bin fit projection

Example plot of few bin

![Graphs showing ΔT (Projection) for bin 4, M_{BC} (Projection) for bin 4, ΔT (Projection) for bin 5, M_{BC} (Projection) for bin 5.]

- Rest of the bin fit projection shown in backup slide
Pure toy test

- To validate the fitter, 1000 toy experiments performed
- Signal, continuum and $B\bar{B}$ dataset are generated using the shape
- Expected $A_{CP}$: 0.0 and $S_{CP}$: 0.0

There is no significant bias!

(S.Hazra)
GSIM Toy test

- Signal dataset are used from the corresponding MC sample
- Continuum and $B\bar{B}$ dataset are generated using the PDF shape
- Expected $A_{CP}$: 0.0 and $S_{CP}$: 0.74

There is no significant bias!

(S.Hazra)
Toy results

- Expected signal yield = 1044 (200 $fb^{-1}$)

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**Pure toy**

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<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Signal Yield</td>
<td>1043 ± 33</td>
<td>1044</td>
</tr>
<tr>
<td>Continuum Yield</td>
<td>275 ± 18</td>
<td>275</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>$-0.007 \pm 0.093$</td>
<td>0.0</td>
</tr>
<tr>
<td>$S_{CP}$</td>
<td>$0.010 \pm 0.151$</td>
<td>0.0</td>
</tr>
</tbody>
</table>

---

**GSIM toy**

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<td>Continuum Yield</td>
<td>274 ± 18</td>
<td>275</td>
</tr>
<tr>
<td>$A_{CP}$</td>
<td>0.0 ± 0.09</td>
<td>0.0</td>
</tr>
<tr>
<td>$S_{CP}$</td>
<td>0.744 ± 0.140</td>
<td>0.74</td>
</tr>
</tbody>
</table>

- $S_{CP} = 0.749 \pm 0.055$ (500$fb^{-1}$) BELLE2-NOTE-PH-202.
Summary and plans

- $A_{CP}$ & $S_{CP}$ measurement
- $B$ lifetime, $A_{CP}$ & $S_{CP}$ measurement measurement in control sample
- Validate with toy study

- $B$ Lifetime, $A_{CP}$ & $S_{CP}$ measurement in data
- Full phase analysis report will be ready by Oct. end

- Two groups are working on $B^0 \rightarrow K^0_s \pi^0$ time-dependent analysis
- Expect to have preliminary result in next winter conference.

Thank You

(S.Hazra)
Continuum suppression validation

- FatBDT as the multivariate classifier.
- Same number of signal and background events.
- $800 \text{ fb}^{-1}$ for training and $400 \text{ fb}^{-1}$ for testing.
- Use only continuum $(u, d, s, c)$ background instead of generic $(u, d, s, c, B\bar{B})$ background.
- Same classifier input used (BELLE2-NOTE-PH-2020-046).

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**Classifier Output**

Our study: BELLE2-NOTE-PH-2020-046

![Graphs showing BDT output and CSMVA distribution for different categories.](graph.png)

(S.Hazra)
# Background rejection comparison

## Using our CS weight file

1) generic BKG to train CS

<table>
<thead>
<tr>
<th>Cut</th>
<th>BKG rej.</th>
<th>#u̅u</th>
<th>#d̅d</th>
<th>#s̅s</th>
<th>#c̅c</th>
<th>#B^0 B^0</th>
<th>#B^+ B^-</th>
<th># signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td></td>
<td>5434</td>
<td>2287</td>
<td>4180</td>
<td>4280</td>
<td>109</td>
<td>22</td>
<td>98</td>
</tr>
<tr>
<td>0.9</td>
<td>98.33 %</td>
<td>80</td>
<td>46</td>
<td>52</td>
<td>90</td>
<td>58</td>
<td>11</td>
<td>53</td>
</tr>
</tbody>
</table>

2) Continuum BKG to train CS

<table>
<thead>
<tr>
<th>Cut</th>
<th>BKG rej.</th>
<th>#u̅u</th>
<th>#d̅d</th>
<th>#s̅s</th>
<th>#c̅c</th>
<th>#B^0 B^0</th>
<th>#B^+ B^-</th>
<th># signal</th>
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<tr>
<td>0.9</td>
<td>98.25 %</td>
<td>90</td>
<td>49</td>
<td>58</td>
<td>84</td>
<td>54</td>
<td>9</td>
<td>48</td>
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</tbody>
</table>

## Using BELLE2-NOTE-PH-2020-046 CS weight file


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<td>22</td>
<td>98</td>
</tr>
<tr>
<td>0.9</td>
<td>98.39 %</td>
<td>74</td>
<td>45</td>
<td>52</td>
<td>88</td>
<td>54</td>
<td>11</td>
<td>48</td>
</tr>
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</table>

- Now we use the common BToCharmless weight file for CS

(S.Hazra)
only $K^0_S$ vertexing

- After including only $K^0_S$ in the vertexing we get double peak in both cases.
We observe the second peak due to fewer hits in VXD.
Effect of IP constraint

- After applying IP constraint in tag side $\Delta t$ resolution improves.
- Similar trend is seen in the control channel.
We plots number of hits in VXD and CDC to find out the double peak structure in the Δₜₑᵣᵣ distribution.
\( \Delta t_{err} \) vs. Hits

- We plots number of hits in VXD and CDC to find out the double peak structure in the \( \Delta t_{err} \) distribution.
DeltaTErr and Ks Vertex Position

- Location of Ks vertex on x-y plane
- Cut of 2.5 on DeltaTErr corresponds to the 5th layer of the SVD
- This means the cut requires two hits in the SVD
DeltaTErr and Ks Vertex Position

$0 < \text{DeltaTErr} < 2.5$

$0 < \text{DeltaTErr} < 0.7$
(First peak)

Tim Green, University of Melbourne

$B^0 \rightarrow K^0 \pi^0$
Signal mode
The expected signal yield is calculated as

\[ N_{\text{sig}}^{\text{expected}} = \mathcal{B} \cdot \epsilon \cdot \mathcal{B}_s \cdot 2 \cdot N_{B^0\bar{B}^0} \]  

(1)

- \( N_{B^0\bar{B}^0} = \int \mathcal{L} \cdot \sigma \cdot f^{00} \), where \( \sigma = 1.110 \) and \( f^{00} = 0.487 \)
- \( \mathcal{B}_s = 0.5 \), probability of \( K^0 \rightarrow K_S^0/K_L^0 \)
- \( \mathcal{B}(B^0 \rightarrow K^0\pi^0) = 9.93 \times 10^{-6} \) (PDG value 2020)
- Signal efficiency = 0.140 (all selection + loose cont. supp. cut + \( \sigma_{\Delta t} \))
- \( N_{\text{sig}}^{\text{exp}} = 353 \) (500 fb\(^{-1}\))
Modified $M_{bc}$

- $M_{bc} = \sqrt{E_{\text{beam}}^* - \mathbf{p}_B^*}$
- $\mathbf{p}_B^* = \mathbf{p}_{K_S^0}^* + \mathbf{p}_{\pi^0}^*$
- $\mathbf{p}_B^* = \mathbf{p}_{K_S^0}^* + \frac{\mathbf{p}_{\pi^0}^*}{|\mathbf{p}_{\pi^0}^*|} \left( \sqrt{(E_{\text{beam}}^* - E_{K_S^0}^*)^2 - m_{\pi^0}^2} \right)$

**cor=0.143**(signal)  
**cor=-0.03**(signal)
Adding extra dimension to the fitter

- We transform the BDT classifier output ($C_{out}$) to ($C'_{out}$) in order to parametrize using a simple PDF.
- Transform continuum suppression variable is defined as

$$C'_{out} = \log\left(\frac{C_{out} - C_{out_{\text{min}}}}{C_{out_{\text{max}}} - C_{out}}\right)$$

(2)

where $C_{out_{\text{max}}}=0.999339$ and $C_{out_{\text{min}}}=0.6$
7-bin fit projection

Δ T (Projection) for bin 0

M_{BC} (Projection) for bin 0

Δ E (Projection) for bin 0

CS (Projection) for bin 0

(S.Hazra)
7-bin fit projection

$\Delta T$ (Projection) for bin 1

$M_{BC}$ (Projection) for bin 1

$\Delta E$ (Projection) for bin 1

CS (Projection) for bin 1

(S.Hazra)
7-bin fit projection

\[ \Delta T (\text{Projection}) \text{ for bin 2} \]

\[ M_{BC} (\text{Projection}) \text{ for bin 2} \]

\[ \Delta E (\text{Projection}) \text{ for bin 2} \]

\[ \text{CS (Projection)} \text{ for bin 2} \]
7-bin fit projection

$\Delta T$ (Projection) for bin 3

$M_{BC}$ (Projection) for bin 3

$\Delta E$ (Projection) for bin 3

CS (Projection) for bin 3
7-bin fit projection

\[ \Delta T \text{ (Projection) for bin 4} \]

\[ M_{BC} \text{ (Projection) for bin 4} \]

\[ \Delta E \text{ (Projection) for bin 4} \]

\[ \text{CS (Projection) for bin 4} \]
Control mode
7-bin fit projection

\(\Delta T\) (Projection) for bin 0

\(M_{bc}\) (Projection) for bin 0

\(\Delta T\) (Projection) for bin 1

\(M_{bc}\) (Projection) for bin 1
7-bin fit projection

\( \Delta T \) (Projection) for bin 2

\( M_{BC} \) (Projection) for bin 2

\( \Delta T \) (Projection) for bin 3

\( M_{BC} \) (Projection) for bin 3
7-bin fit projection

\( \Delta T \) (Projection) for bin 5

\( M_{BC} \) (Projection) for bin 5

\( \Delta T \) (Projection) for bin 6

\( M_{BC} \) (Projection) for bin 6
Lifetime fit on Signal MC

- $\Delta t$: RooBCPGenDecay PDF convolved with double Gaussian:

$$P_{\text{sig}}(\Delta t, q) = \exp\left(-\frac{\Delta t}{\tau_{B^0}}\right) \left([1 - q \Delta w + q \mu_i (1 - 2w)] + [q(1 - 2w) + \mu_i (1 - q \Delta w)](A_{CP} \cos(\Delta m_d \Delta t) - S_{CP} \cos(\Delta m_d \Delta t))\right)$$

Core and tail Gaussian

$B^0 \rightarrow J/\psi K^0_S$