The re-discovery of the decays for the CP violation measurements

Chiara La Licata (Kavli IMPU WPI) for the Belle II Collaboration
PHENO 2021, University of Pittsburgh, 24 May 2021
Legacy from B Factories

B factories lead to significant understanding of the flavor dynamics in the Standard Model [arxiv1406.6311]

• Discovery of CP violation in B meson transitions and confirmation of the CKM description of flavor physics
• Precision measurement of the CKM matrix elements and the angles of the unitarity triangle

What we know today about CKM triangle:

Precision measurements of the CKM triangle sides and angles will provide test of the Standard Model. The existing constraints do not exclude the possibility of contributions from NP

• World average: $\sin 2\phi_1 = 0.699 \pm 0.017$
• Our aim: perform a measurement of $\sin 2\phi_1$ using decay modes that are more sensitive to NP effects

$\phi_1 = \beta, \phi_2 = \alpha, \phi_3 = \gamma$
SuperKEKB - high luminosity

Our target:

\[ L_{\text{peak}} = 6.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1} \]
\[ L_{\text{Int}} = 50 \text{ ab}^{-1} \ (50 \times \text{KEKB}) \]

How to increase luminosity:

- Increase current: x1.5
- Reduced beam spot size (nano beam scheme): x20

Consequences:

- Deal with more severe background conditions
- Boost factor is reduced (\( \beta\gamma = 0.43 \rightarrow 0.28 \) )

=> Many upgrades for Belle II detector to increase the performance and cope with much more severe background conditions
**sin2φ₁ - measurement strategy**

CPV in the interference between $B \rightarrow J/ΨK_s$ and $B \rightarrow \bar{B}^0 \rightarrow J/ΨK_s$ can be measured through the raw asymmetry:

$$A_{CP}^{raw} = \frac{\Gamma(\bar{B}^0_{t=0} \rightarrow J/ΨK_s) - \Gamma(B^0_{t=0} \rightarrow J/ΨK_s)}{\Gamma(\bar{B}^0_{t=0} \rightarrow J/ΨK_s) + \Gamma(B^0_{t=0} \rightarrow J/ΨK_s)} = \sin(\Delta m_d \Delta t) \sin(2φ₁).$$

**Key aspects:**
- measurement of $Δt$
- flavor of $B_{tag}$
Key aspect - $\Delta t$ measurement

- $\Delta t$ measured from the distance $\Delta z$ between $B_{CP}$ and $B_{tag}$ \( \Rightarrow \Delta t \sim \Delta z / \beta \gamma \c c \)
- $Y(4s)$ is boosted along the beam axis with a smaller $\beta \gamma$ wrt Belle:
  - $\beta \gamma = 0.43 \rightarrow \beta \gamma = 0.28 \Rightarrow \Delta z = 200 \mu m \rightarrow \Delta z = 130 \mu m$
  - $\Rightarrow$ two new layers of pixel detectors have been added to improve precision in $\Delta t$

- We need to consider also the effect of $\Delta t$ resolution function

$$A_{CP} = A_{CP}^{raw} \otimes R(\Delta t) = \sin(\Delta m d \Delta t) \sin(2\phi_1) \otimes R(\Delta t)$$

- $A_{CP}^{raw}$ defined in slide 4

- simple 1D model assumed for $R(\Delta t)$ so far
- more refined model needed for precision measurement of $\sin 2\phi_1$
Key aspect - flavor tagger

- We need to determine the quark-flavor content of $B_{\text{tag}}$

- Many $B$ decay channels provide unambiguous flavor signatures through a flavor-specific final state but it is unfeasible to fully reconstruct a large number of flavor-specific $B_{\text{tag}}$ decays

- Instead of a full reconstruction, the flavor tagger applies a complex multivariate algorithm

Performance of flavor tagger is evaluated looking at:
- wrong tag fraction $w$
- efficiency $\varepsilon = N_{\text{tag}}/N$ => dilution effect of $w$ => effective efficiency $\varepsilon_{\text{eff}} = \varepsilon (1-2w)^2$

$\varepsilon_{\text{eff}}(\text{Belle II}) = (33.8 \pm 3.6)\%$
$\varepsilon_{\text{eff}}(\text{Belle}) = (30.1 \pm 0.4)\%$

$$A_{CP} = A_{CP}^{\text{raw}} \cdot (1 - 2w) \otimes R(\Delta t) =$$
$$= \sin(\Delta m_d \Delta t) \sin(2\phi_1) \cdot (1 - 2w) \otimes R(\Delta t)$$
**\( \Delta m_d \) measurement**

\( \Delta m_d \) can be determined from the asymmetry:

\[
A(\Delta t) = \frac{N_{OF} - N_{SF}}{N_{OF} + N_{SF}} = \cos(\Delta m_d \Delta t)(1 - 2w) \otimes R(\Delta t)
\]

We performed a time-dependent measurement of \( \Delta m_d \) using the \( B^0 \to D^- (K^+ \pi^- \pi^-) \pi^+ \) mode.

\[ \Delta m_d = (0.531 \pm 0.046 \text{ (stat)} \pm 0.013 \text{ (syst)}) \text{ ps}^{-1} \]

PDG: \( \Delta m_d = (0.5065 \pm 0.0019) \text{ ps}^{-1} \)
Decays for $\sin2\phi_1$ measurement

- The angle $\phi_1$ can be measured in processes with a tree dominant interaction ($B \to J/\psi K^0$) or with penguin quark transitions ($B \to \eta' K^0_s$).
- Penguin-dominated modes are potentially very sensitive to NP effects.
- We performed the first measurement at Belle II of $\text{Br}$ for $B \to \eta' K^0_s$ decay but we are still limited by statistics for now.
- Meantime we are developing all the tools and performed the first CPV measurement using $B^0 \to J/\psi K^0_s$.

Based on simulation (50$\text{ab}^{-1}$)

$B^0 \to J/\psi K^0_s$
- clean signature
- contribution from penguin diagram less than 1%
B → \eta' Ks decay mode

- B → \eta'K is a charmless decay dominated by penguin transition so measurement of CP violation sensitive to new physics in the penguin loop.
- no competition with LHCb expected in this mode due to neutrals in the final state
- Only rediscovery and BR measurement (CP measurement not done yet)
  \[ B^\pm \rightarrow \eta'K^\pm \text{ with } \eta' \rightarrow \eta\pi^+\pi^- \text{ or } \eta' \rightarrow \rho\gamma \]
  \[ B^0 \rightarrow \eta'K_s \text{ with } \eta' \rightarrow \eta\pi^+\pi^- \text{ or } \eta' \rightarrow \rho\gamma \]

AVERAGE values from BaBar (467M BB) and Belle(386M BB):

<table>
<thead>
<tr>
<th></th>
<th>B^\pm → \eta'K^\pm</th>
<th>B^0 → \eta'K_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(10^{-6})</td>
<td>70.4 ± 2.5</td>
<td>66 ± 4</td>
</tr>
</tbody>
</table>

Considering the available luminosity (62.8 fb^{-1}) this measurement is not competitive yet.
First measurement of $B \rightarrow \eta' K_\pm$ at Belle II

$B^\pm \rightarrow \eta' K^\pm$ with $\eta' \rightarrow \eta \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B(10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \rightarrow \eta' (\rightarrow \eta (\rightarrow \gamma \gamma) \pi^+ \pi^-) K^\pm$</td>
<td>$63.9^{+4.6}_{-4.4} \pm 4.0$</td>
</tr>
<tr>
<td>$B^\pm \rightarrow \eta' (\rightarrow \eta (\rightarrow \pi^+ \pi^-) \gamma) K^\pm$</td>
<td>$62.9^{+4.8}_{-4.8} \pm 5.5$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta' (\rightarrow \eta (\rightarrow \gamma \gamma) \pi^+ \pi^-) K^0$</td>
<td>$61.6^{+8.6}_{-8.0} \pm 3.9$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \eta' (\rightarrow \eta (\rightarrow \gamma \gamma) \pi^+ \pi^-) K^0_S$</td>
<td>$58.5^{+7.9}_{-7.4} \pm 4.4$</td>
</tr>
</tbody>
</table>

Fit in different $\eta'$ decays are independent good agreement between $Br$
First time-dependent CP violation measurement at Belle II
- Performed with 34.6 fb\(^{-1}\)
- Decay mode: \(B^0 \rightarrow J/\psi K_s\) with \(J/\psi \rightarrow \mu\mu\) or \(J/\psi \rightarrow ee\)

\[
\sin^2\phi_1 = (0.55 \pm 0.21 \text{ (stat)} \pm 0.04 \text{ (syst)}) \text{ ps}^{-1}
\]

significance \(\sim 2.7\sigma\)
First measurement of $B^0 \rightarrow J/\psi K_L$ at Belle II

Rediscovery of $J/\psi K_L$ with 62.8 fb$^{-1}$

- $B^0 \rightarrow J/\psi K^0$ provides the most precise determination of $\sin(2\phi_1)$
- $B^0 \rightarrow J/\psi K^0_L$ provides a measurement of $\sin(2\phi_1)$ independent from $J/\psi K^0_S$ with $\eta_{KL} = -\eta_{KS}$

- The event yield of $(7.3\pm0.4)$/fb$^{-1}$, consistent with Belle
- Next: time-dependent analysis for CPV measurement
Summary

• The existing constraints of CKM triangle angles and sides do not exclude the possibility of contributions from NP
• $\sin^2\phi_1$ measured in loop-dominated modes can provide a powerful way to find evidence of NP
• No competition with LHCb expected in $B \rightarrow \eta'K$ mode (first measurement at Belle II)
• First measurement of $\sin^2\phi_1$ from the early Belle II data done using $J/\psi K^0_S \Rightarrow 2.7 \sigma$ hint for time-dependent CPV
• Towards precision measurements using tree-dominated modes:
  • collect more statistics
  • add more decay modes: first measurement of $B^0 \rightarrow J/\psi K^0_L$ at Belle II
  • improved model for the resolution function

So far Belle II has demonstrated good vertex reconstruction capabilities and flavor tagging performance. This is a good starting point towards the measurement of $\sin^2\phi_1$ with penguin-dominated modes
Backup
Continuum suppression in $B \rightarrow \eta' K_s$ measurement

- Dominant background from random combination of particles in continuum events
- A set of variables which are sensitive to the event shape is used in a multivariate approach
  - Kakuno-Super-Fox- Wolfram momenta, Cleo cones, angles of the thrust axis of signal B with respect to the rest of event and the beam axis
- All variables which exhibit a correlation greater than 10% with $M_{bc}$ and $\Delta E$ are excluded
- The classifier used is based on FastBDT algorithm
- FastBDT Validated on off-resonance data:
Background components in $B^0 \rightarrow J/\psi K_L$

- Background is essentially due to $B^0\overline{B}^0$ and $B^+B^-\overline{B}^+\overline{B}^-$ decays (in same amount)
- Due to strong $J/\psi$ signature, no events from the qq continuum survive the selection cuts
- Background classification:
  - events with a wrong combination of a real $J/\psi$ and a real $K^0_L$
  - events with a fake $J/\psi$
  - events with a true $J/\psi$ and a fake $K^0_L$ (dominant background)

- The fraction of peaking background is determined from fits to the $\Delta E$ distributions of generic Montecarlo events
  - $f_{\text{peak}} = (0.4 \pm 3.1)\%$ in $\mu\mu$ final state
  - $f_{\text{peak}} = (0.0 \pm 3.1)\%$ in $ee$ final state