Belle achievements and Belle II prospects for CP violation

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The Unitarity Triangle

- All flavor variables constrained in the SM CKM fit are in good agreement with experimental observations.
- Some variables still to be measured precisely, therefore a lot of room for surprises!

\[
V \approx \begin{pmatrix}
1 & \lambda & \lambda^3 \\
-\lambda & 1 & \lambda^2 \\
-\lambda^3 & -\lambda^2 & 1
\end{pmatrix}
\]

\[\lambda \approx 0.22: \text{Cabibbo angle}\]
Time dependent measurements

- Y(4S) is the first resonance just above the B\overline{B} production threshold
- Only B\overline{B} pairs are produced, and are at rest in the Y(4S) frame

Resolution on \( \Delta t \) will be dominated by the resolution of the tagging side vertex.

\[ \Delta t = \frac{\Delta z}{\beta \gamma c} \]

Quantum entangled neutral B meson pair production

\[ \mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[ 1 + q \left( A_{CP} \cos \Delta m_d \Delta t + S_{CP} \sin \Delta m_d \Delta t \right) \right] \]
\[ \sin(2\beta) : b \rightarrow c\bar{c}s \]

**Irreducible systematic errors:**
- Vertexing (without detector upgrade)
- Tag-side interference
  - More sophisticated treatment will be considered

**TABLE II.** \( CP \) violation parameters for each \( B^0 \rightarrow f_{CP} \) mode and from the simultaneous fit for all modes together. The first and second errors are statistical and systematic uncertainties, respectively.

| Decay mode | \( \sin 2\phi_1 = -\xi f S_f \) | \( A_f \) |
|------------|---------------------------------|--------|
| \( J/\psi K_S^0 \)          | +0.670 ± 0.029 ± 0.013          | -0.015 ± 0.021 ± 0.045 |
| \( \psi(2S)K_S^0 \)       | +0.738 ± 0.079 ± 0.036          | +0.104 ± 0.055 ± 0.047 |
| \( \chi_c K_S^0 \)        | +0.640 ± 0.117 ± 0.040          | -0.017 ± 0.083 ± 0.046 |
| \( J/\psi K_L^0 \)        | +0.642 ± 0.047 ± 0.021          | +0.019 ± 0.026 ± 0.041 |
| All modes                | +0.667 ± 0.023 ± 0.012          | +0.006 ± 0.016 ± 0.012 |

**Source** | **Irreducible Error on** \( S \) | **Error on** \( A \) |
|------------|-------------------------------|-------------------|
| Vertexing  | X                             | ±0.007 ±0.007     |
| \( \Delta t \) resolution |                  | ±0.007 ±0.001   |
| Tag-side interference | X               | ±0.001 ±0.008 |
| Flavor tagging                        | ±0.004 ±0.003     |
| Possible fit bias                      | ±0.004 ±0.005     |
| Signal fraction                        | ±0.004 ±0.002     |
| Background \( \Delta t \) PDFs       | ±0.001 <0.001     |
| Physics parameters                     | ±0.001 <0.001     |
| Total                                   | ±0.012 ±0.012     |

**FIG. 2** (color online). The background-subtracted \( \Delta t \) distribution (top) for \( q = +1 \) (red) and \( q = -1 \) (blue) events and asymmetry (bottom) for good tag quality \( (r > 0.5) \) events for all \( CP \)-odd modes combined (left) and the \( CP \)-even mode (right).
SuperKEKB

Peak luminosity
- KEKB = $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- SuperKEKB = $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

e$^+$e$^-$ beams energy
- KEKB = 8 GeV / 3.5 GeV
- SuperKEKB = 7 GeV / 4 GeV

SuperKEKB Nanobeam
Belle II

Time of Propagation counter
with 20 mm quartz bars
MCP-PMT readout

$K_S^0/\mu$ Detector (outside)
RPC Plates and plastic
scintillators with SiPM readout

Superconducting Magnet
homogeneous field of 1.5 T

Electromagnetic Calorimeter
8000 CsI Crystals, 16 $X_0$
PMT/APD readout

Pixel Vertex Detector
2 layer pixel detector (8MP)
DEPFET technology

Silicon Vertex Detector
4 layer double sided strips
20 – 50 ns shaping time

Central Drift Chamber
proportional wire drift chamber
15000 sense wires in 58 layers

Aerogel RICH
Proximity focusing RICH with silica aerogel
Belle II Pixel Vertex Detector

- 40 times increase of luminosity → higher background
- Lower boost → smaller separation between the B mesons

Pixel detector needed

Most suited technology : DEPFET

- Innermost detector system as close as possible to IP
- Highly granular pixel sensors provide most accurate 2D position information

- Reconstruction of primary and secondary vertices of short-lived particles
- Decay of particles is typical in the order of 100μm from the IP
The impact parameter

The impact parameters: $d_0$ and $z_0$

- defined as the projections of distance from the point of closest approach to the origin
- good measure of the overall performance of the tracking system
- used to find the optimal tracker configuration

Almost a factor 2 improvement respect to BaBar
Vertex fit

Tag side vertex fit: Using RAVE Adaptive Vertex Fit (AVF) algorithm:

Down-weights outliers dynamically, instead of using hard cutoffs (important for 3+ track vertices). CMS NOTE 2008/033.

Kinematic fit: J/ψ → μ μ

Tag side vertex fit

Belle II
Bias = 2.0 μm
Resolution = 25.6 μm

Belle converted MC
Bias = 0.2 μm
Resolution = 43 μm

All tracks apart from the ones from Ks

Δt resolution

Belle II
Bias = -0.003 ps
Resolution = 0.77 ps

Belle
Bias = 0.20 ps
Resolution = 0.92 ps

Tag side vertex fit

Belle II
Bias = 5.9 μm
Resolution = 53 μm

Belle
Bias = 29 μm
Resolution = 89 μm

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Flavor tagging

**Categories**

| Categories                  | Targets                  |
|-----------------------------|--------------------------|
| Electron                    | $e^-$, $e^+$             |
| Intermediate Electron       | $\mu^-$, $\mu^+$         |
| Muon                        | $\ell^-$, $\ell^+$       |
| Intermediate Muon           | $K^-$, $\pi^+$           |
| KinLepton                   | $K^-$, $\pi^+$           |
| Intermediate KinLepton      | $\ell^-$, $\pi^+$        |
| Kaon                        | $\ell^-$, $\pi^+$        |
| KaonPion                    | $\ell^-$, $\pi^+$        |
| SlowPion                    | $\ell^-$, $\pi^+$        |
| FastPion                    | $\ell^-$, $\pi^+$        |
| MaximumP                    | $\ell^-$, $\pi^+$        |
| FSC                         | $\ell^-$, $\pi^+$        |
| Lambda                      | $\Lambda$                |
| Total                       | 13                       |

**Figure:**

- **Top left diagram:**
  - Tracks 
  - ECL+KLM Clusters 
  - Not used for $B_{CP}$
  - Tagging variables 
  - TMVA track level 
  - $p_{\text{track}}$ 
  - Select track with highest $p_{\text{track}}$ 
  - Tagging variables 
  - $q_{\text{track}} \cdot p_{\text{cat}}$ 
  - $p_{\text{cat}}$ 
  - TMVA event level 
  - $q_{\text{combined}} \cdot r_{\text{combined}}$

- **Top right graph:**
  - $\ell^-$
  - $B^0$
  - $B^0$
  - Number of Events/0.02

- **Bottom left diagram:**
  - $B^0$
  - $D^0$
  - $\bar{B}^0$
  - $D^{*+}$
  - $K^-$
  - $\pi^+$
  - $\bar{\nu}_\ell$
  - $\ell^-$

- **Bottom right graph:**
  - $K^-$
  - $B^0$
  - $B^0$
  - Number of Events/0.02

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Combiner output

**TMVA FastBDT**
- $B^0$ tag
- $B^0$ tag
- $\varepsilon_{\text{Eff}} = 35.84\%$
- $\Delta \varepsilon_{\text{Eff}} = -0.69\%$

**FANN MLP**
- $B^0$ tag
- $B^0$ tag
- $\varepsilon_{\text{Eff}} = 35.89\%$
- $\Delta \varepsilon_{\text{Eff}} = -0.76\%$
Belle Data – MC comparison

Efficiency
- Belle Converted MC = 32 %
- Belle = 29 %

Belle MC and data
Belle II flavor tagging algorithm

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\[
\sigma_{\text{total}} = \sqrt{\left(\sigma_{\text{stat}}^{2}\right)_{\text{Belle}} + \left(\sigma_{\text{syst Red}}^{2}\right)_{\text{Belle}}} \times \frac{L_{\text{Belle}}}{L} \ + \sigma_{\text{syst Non Red}}^{2}_{\text{Belle}}
\]

- **Sin(2\(\beta\))**: will remain the most precise measurement on the Unitarity Triangle parameters
- In Belle II the measurement will be dominated by systematics
  - Effort concentrated in understand and reducing them

  - **Belle measurement statistical error**
  - **Belle measurement reducible systematic error**
  - **Belle measurement non reducible systematic error**
  - **Integrated luminosity used in Belle measurement**
  - **Belle II expected integrated luminosity**

**Three hypotheses:**
- **Belle**: same Belle non reducible systematics
- **Belle II**: vertex systematic \(\ast \frac{1}{2}\)
- **Leptonic category**: only leptonic categories for the flavor tagging
$\sin(2\beta): b \rightarrow \bar{q}q\bar{s}$

In principle measures $\sin^2\beta$, but sensitive to new physics

B2TIP report: to be published

| Mode | QCDF [33] | QCDF (scan) [33] | $SU(3)$ | Data |
|------|-----------|-----------------|---------|------|
| $\pi^0 K_S$ | $0.07^{+0.05}_{-0.04}$ | $[0.02, 0.15]$ | $[-0.11, 0.12]$ [47] | $-0.11^{+0.17}_{-0.17}$ |
| $\rho^0 K_S$ | $-0.08^{+0.08}_{-0.12}$ | $[-0.29, 0.02]$ | | $-0.14^{+0.18}_{-0.21}$ |
| $\eta' K_S$ | $0.01^{+0.01}_{-0.01}$ | $[0.00, 0.03]$ | $(0 \pm 0.36) \times 2 \cos(\phi_d) \sin\gamma$ [48] | $-0.05 \pm 0.06$ |
| $\eta K_S$ | $0.10^{+0.11}_{-0.07}$ | $[-1.67, 0.27]$ | | |
| $\phi K_S$ | $0.02^{+0.01}_{-0.01}$ | $[0.01, 0.05]$ | $(0 \pm 0.25) \times 2 \cos(\phi_d) \sin\gamma$ [48] | $0.06^{+0.11}_{-0.13}$ |
| $\omega K_S$ | $0.13^{+0.08}_{-0.08}$ | $[0.01, 0.21]$ | | $0.03^{+0.21}_{-0.21}$ |

Table 1.4: $\Delta S_f$ predictions for charmless two-body final states, compared to experimental values calculated from the HFAG (Summer 2016) averages [2].
$$B^0 \to \phi \ K_s$$

1) $\phi \ K_s^0 \rightarrow \pi^+ \pi^-$
   Cleanest mode, all charged particles in final state
   $\text{BF}(\phi \rightarrow K^+K^-) \sim 50\%$
   $\text{BF}(\phi \rightarrow \pi^+\pi^-\pi^0) \sim 15\%$
   $\text{BF}(K_s \rightarrow \pi^+\pi^-) \sim 69\%$
   $\text{BF}(K_s \rightarrow \pi^0\pi^0) \sim 31\%$

2) $\phi \ K_s^0 \rightarrow \pi^0\pi^0$
   Lower statistics and harder (because of $\pi^0$'s)

3) $\phi \ K_s^0 \rightarrow \pi^+\pi^-$
   Never tried before at BaBar and Belle
   $\text{BF}(K_s \rightarrow \pi^+\pi^-) \sim 69\%$
   $\text{BF}(K_s \rightarrow \pi^0\pi^0) \sim 31\%$

4) $\phi \ K_L^0$
   Not yet started looking at $K_L^0$'s
Vertex resolution

Using “iptube” + $K_S^0$ flight direction constraints

$\phi \rightarrow K^+K^-$

resolution: 0.752 ps

$\phi \rightarrow \pi^+\pi^0\pi^0$

resolution: 0.777 ps
## Expected sensitivity

**B2TIP report: to be published**

| Channel | $\varepsilon_{\text{reco}}$ | Yield | $\sigma(S)$ |
|---------|-----------------|-------|-------------|
| 1 ab$^{-1}$ scenario: | | | |
| $\phi(K^+K^-)K_S(\pi^+\pi^-)$ | 35% | 456 | 0.174 |
| $\phi(K^+K^-)K_S(\pi^0\pi^0)$ | 25% | 153 | 0.295 |
| $\phi(\pi^+\pi^-\pi^0)K_S(\pi^+\pi^-)$ | 28% | 109 | 0.338 |
| $K_S$ modes combination | | | 0.135 |
| $K_S + K_L$ modes combination | | | 0.108 |
| 5 ab$^{-1}$ scenario: | | | |
| $\phi(K^+K^-)K_S(\pi^+\pi^-)$ | 35% | 2280 | 0.078 |
| $\phi(K^+K^-)K_S(\pi^0\pi^0)$ | 25% | 765 | 0.132 |
| $\phi(\pi^+\pi^-\pi^0)K_S(\pi^+\pi^-)$ | 28% | 545 | 0.151 |
| $K_S$ modes combination | | | 0.060 |
| $K_S + K_L$ modes combination | | | 0.048 |

We estimate the expected yield of $\phi K^0_L$ based on previous BaBar and Belle analyses (but use the same $\Delta t$ resolution we estimate in $\phi \rightarrow K^+K^-$ for Belle II).
$B^0 \rightarrow \eta' K_S$: expected sensitivity

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Table 1.12: $\Delta t$ resolution for true, SxF and all selected candidates, for $\eta(2\gamma)K^0_S(\pi^\pm)$ and $\eta(3\pi)K^0_S(\pi^\pm)$ channels.

| Channel               | True  | SxF   | All   |
|-----------------------|-------|-------|-------|
| $\eta(2\gamma)K^0_S(\pi^\pm)$ | 1.22 ps | 2.87 ps | 1.45 ps |
| $\eta(3\pi)K^0_S(\pi^\pm)$     | 1.17 ps | 2.36 ps | 1.50 ps |

Similar Belle sensitivity given the same integrated luminosity

Table 1.13: Estimated rms from Toy MC studies for CP-violation parameters $S$ and $C$ for an integrated luminosity of 1 and 5 $ab^{-1}$ for the different channels.

| Channel               | Strategy | 1 $ab^{-1}$ | 5 $ab^{-1}$ |
|-----------------------|----------|-------------|-------------|
|                       |          | $S$ | rms $S$ | $C$ | rms $C$ | $S$ | rms $S$ | $C$ | rms $C$ |
| $\eta(2\gamma)K^0_S(\pi^\pm)$ | C        | 0.71 | 0.07 | -0.11 | 0.06 | 0.71 | 0.04 | -0.11 | 0.03 |
| $\eta(3\pi)K^0_S(\pi^\pm)$     | B        | 0.74 | 0.17 | -0.131 | 0.10 | 0.73 | 0.07 | -0.13 | 0.04 |
BaBar + Belle $B^0 \rightarrow D_{CP} h^0$

- Leading order: tree
- Sub-leading order: tree, phase within the SM
- Independent form NP in loops
- Suitable to measure $\beta$
- Branching fraction is the limiting factor

\[ B_0 \rightarrow D^0 h^0, h^0 = \pi^0, \eta, \omega \]
\[ D^0 \rightarrow K^+K^-, K_s \pi^0 \text{ and } K_s \omega \]

Yields =
- 508±31 events (BaBar)
- 757±44 events (Belle)

\[ -\eta_f S = +0.66 \pm 0.10 \text{ (stat.)} \pm 0.06 \text{ (syst.)}, \]
\[ C = -0.02 \pm 0.07 \text{ (stat.)} \pm 0.03 \text{ (syst.)}. \]

- First observation of CPV(5.4σ)
- Belle II: $\delta(\beta) \sim 0.015$
- Important test for $b \rightarrow c \bar{c} s$

Phys. Rev. Lett. 115, 121604
\[ \cos 2\beta \text{ with } B^0 \rightarrow D_{CP} h^0 \]

**D^0 multi-body decay: D^0 \rightarrow Ks \pi \pi** model independent

\[ \cos 2\beta \text{ and } \sin 2\beta \text{ can be extracted independently } \text{PLB 6241 (2005)} \]

**Equation:**

\[ P_i (\Delta t, \varphi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \left[ 1 + q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos (\Delta m_B \Delta t) + 2q_B \xi h^0 (-1)^L \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin (\Delta m_B \Delta t) (S_i \cos 2\varphi_1 + C_i \sin 2\varphi_1) \right] \]

\[ \sin 2\varphi_1 = 0.43 \pm 0.27 \text{(stat) } \pm 0.08 \text{(syst)}, \]

\[ \cos 2\varphi_1 = 1.06 \pm 0.33 \text{(stat) } ^{+0.21}_{-0.15} \text{(syst)}, \]

\[ \varphi_1 = 11.7^\circ \pm 7.8^\circ \text{(stat) } \pm 2.1^\circ \text{(syst)}. \]
Measurement of $\alpha$

M. Gronau and D. London, PRL 65 3381 (1990)

Proceeds mainly through $b \to u \bar{u}d$ tree diagram, but penguin contributions introduce additional phases

\[ \sin(2\alpha) \to \sin(2\alpha_{\text{eff}}) \quad \alpha_{\text{eff}} = \alpha + \Delta \alpha \]

To relate $\alpha$ to $\alpha_{\text{eff}}$:

\[ \frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0} \]
\[ \frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{-0} \]
\[ A^{+0} = \bar{A}^{-0} \text{ (pure tree)} \]

Isospin analysis

Used decay modes:
- $B \to \pi\pi$
- $B \to \rho\rho$
- $B \to \rho\pi$

Extra weak and strong phases $+ |P/T|$ modify $\alpha$ by $\Delta \alpha$:
$B \to \pi \pi$

extrapolated to $50ab^{-1}$ (wo/ $S_{C,P}^{\pi^0\pi^0}$)

$\phi_2 = \alpha = 90.6^{+3.9/-1.1}\degree$

- stat error $\times 0.15$ ($\sim 50ab^{-1}$)
- syst error $\times 0.7$ (conservative guess)

8 fold ambiguity!
\[ \mathbf{B}^0 \rightarrow \pi^0 \pi^0 : \text{converted photons} \]

P. Vanhoefer @ 3rd B2TIP

with \( S_{CP}^{\pi^0 \pi^0} = 0.92 \pm 0.26 \)

(arXiv:hep-ex/0703039)

\[ 1 - \text{CL} \]

\( \phi_2 (\degree) \)

- \( S_{CP}^{\pi^0 \pi^0} \rightarrow 2 \text{ fold ambiguity (sin}(2\phi_2)) \)
- \( \delta \phi_2 \sim 3\degree \)

mean values important, too!

Photon conversion inside the Belle II detector (Beam pipe + PXD)

- 3% of \( \mathbf{B}^0 \rightarrow \pi^0 \pi^0 \) events
- \( \sim 5\% \) including \( \pi^0 \) Dalitz decay
- Reconstruction efficiency will be crucial
$B^0_{sc} \rightarrow \pi^0_{ss} \pi^0_{sc}$

$\rightarrow \gamma_s \gamma_c$

$\rightarrow e^+ e^-$

$B^0_{dal} \rightarrow \pi^0_{ss} \pi^0_{dal}$

$\rightarrow e^+ e^- \gamma$

At least one track ($e^+$ or $e^-$) has one PXD Hit

At least one track ($e^+$ or $e^-$) has one PXD Hit
\[ B^{0} \rightarrow \rho^{+} \rho^{-} \]

Flavor integrated

Four pion final state

\[ B(B^{0} \rightarrow \rho^{+} \rho^{-}) = (28.3 \pm 1.5 \text{ (stat)} \pm 1.5 \text{ (syst)}) \times 10^{-6}, \]

\[ f_{L} = 0.988 \pm 0.012 \text{ (stat)} \pm 0.023 \text{ (syst)}, \]

\[ A_{CP} = 0.00 \pm 0.10 \text{ (stat)} \pm 0.06 \text{ (syst)}, \]

\[ S_{CP} = -0.13 \pm 0.15 \text{ (stat)} \pm 0.05 \text{ (syst)}. \]

- Precision improvement with respect to the previously published result is factor 2.
- Increase of data, simultaneous extraction of observables and analysis optimization for high signal yield.
$B \rightarrow \rho \rho$

extrapolated to $50ab^{-1}$ (wo/$S_{CP}^{0\rho^0\rho^0}$)

Belle2:

$S_{CP}^{0\rho^0\rho^0}$ will provide an additional constraint

$\delta \phi_2 \sim 3^\circ$

error depends also on mean values, isospin triangles do not close!
Photon polarization

Radiative B decays, with $b \to s \gamma$ transitions, dominated by loop (penguin) diagrams
New physics could enter at same order (1-loop) as Standard Model

Standard Model makes definite prediction of photon helicity
(D. Atwood et al., Phys. Rev. Lett. 79, 185 (1997)):
- $B^0 \to X_s \gamma_R$
- $\bar{B}^0 \to X_s \gamma_L$

If a helicity flip occurs, the photon will also flip its helicity, producing $B^0 \to X_s \gamma_L$
- Rate $\sim m_s/m_b$ at the leading contribution (P. Ball and R. Zwicky, Phys. Lett. B 642, 478 (2006))
- Corrections can increase this value

No common final state for $B^0$ and $\bar{B}^0$
- Suppression of asymmetry $S$ due to interference between $B^0$ mixing and decay diagrams (TD CP asymmetry)

$$S_{SM}^{SM} = - \sin 2\phi_1 \frac{m_s}{m_b} [2 + O(\alpha_s)] + S_{SM, s\gamma g}$$

$C < 0.01$ (direct CP violation) (Greub et al., Nucl. Phys B 434, 39 (1995))

- TD CP asymmetry measurements give an indirect measurement of photon polarization
B^0 \rightarrow Ks \pi^0 \gamma : TD analysis

\[ S_{K_S^0 \pi^0 \gamma} = -0.10 \pm 0.31 \text{(stat)} \pm 0.07 \text{(syst)} , \]
\[ A_{K_S^0 \pi^0 \gamma} = -0.20 \pm 0.20 \text{(stat)} \pm 0.06 \text{(syst)} , \]

No significant CP asymmetry

\[ S_{K^{*0} \gamma} = -0.32^{+0.36}_{-0.33} \pm 0.05 \]
\[ A_{K^{*0} \gamma} = -0.20 \pm 0.24 \pm 0.05 \]
Very important decay mode for Belle II
Outlook

Before the B-factories

After the B-factories

CKM mechanism will be tested at 1% level

After Belle II?

Lucky scenario