CPV at $e^+/e^-$ colliders

FPCP2024, Chulalongkorn University,
Bangkok Thailand
30/05/2024

Stefano Lacaprara
for the Belle II collaboration
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CPV in Standard Model: CKM matrix

- CPV: a key for matter-antimatter asymmetry in the universe
  - In SM, only source is complex phase in CKM matrix
  - (and possible similar phase in PMNS matrix)

$$ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} $$

- From CKM unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
  - Triangle in complex plane
  - Three angles
  - Other triangles exist

Dirac Medal 2010
Nobel Prize 2008
- Precise test of SM by over constraining Unitarity Triangle
- Search for New Physics effects, especially in loop mediated diagrams
- At $e^+/e^-$ collider:
  - clean environment, full reconstruction, access to modes with neutrals in the final states
SuperKEKB and Belle II

- $e^+/e^-$ (4/7 GeV) at KEK
  - Around $\Upsilon(4S)$ resonance
- Run 1 operation 2019-2022
  - 424 fb$^{-1}$ collected - 362 fb$^{-1}$ at $\Upsilon(4S)$
- Long Shutdown 1 (LS1) until end of 2023
  - For accelerator and detector upgrades
- Run 2 operation from Jan 2024

Luminosity record $4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$
- 2x KEKB
- Goal to collect multi ab$^{-1}$ of data
B-Factory variables

- Two key variables to discriminate fully reconstructed (hadronic) signal from background
  - Background from continuum (qq-bar) and from BB
- Discrimination against continuum (qq-bar) background using event-shape variables via a multivariate classifier

\[ \Delta E = E_B^* - \frac{\sqrt{s}}{2} \]

\[ M_{bc} = \sqrt{\frac{s}{4} - P_B^*^2} \]
Time-Dependent (TD) CPV analysis

- $B_{CP}$: fully reconstructed CP eigenstate
- $B_{tag}$: vertex and flavour information
- Complex analysis, many key elements:
  - high signal efficiency
  - excellent vertex resolution $\sigma_z \sim 26/50\mu m$ (signal/tag side)
  - high flavour-tagging efficiency $\varepsilon = 37\%$

Flagship measurement at B factories
Still very important at Belle II

$$A_{CP}(\Delta t) = \frac{\Gamma(B_{tag}=B^0(\Delta t) \rightarrow f_{CP}) - \Gamma(B_{tag}=\bar{B}^0(\Delta t) \rightarrow f_{CP})}{\Gamma(B_{tag}=B^0(\Delta t) \rightarrow f_{CP}) + \Gamma(B_{tag}=\bar{B}^0(\Delta t) \rightarrow f_{CP})} =$$

$$= S \cdot \sin(\Delta m_d \Delta t) - C \cdot \cos(\Delta m_d \Delta t)$$

$S_{CP} = \sin(2\phi_i^{eff})$
Mixing induced CPV

$A_{CP} = -C_{CP}$
Direct CPV

$|B\rangle \not\rightarrow |f\rangle$

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B flavour tagging: GFlaT

- CPV analysis in Belle II used a category-based (CB) algorithm [Eur. Phys. J. 82, 283 (2022)]
- A more advanced algorithm GFlaT, based on graph convolutional neural network (GNN), was developed
  - Using 25 variables for each track from the $B_{tag}$ decay
- Performance evaluated on data using self-tagging $B^0 \rightarrow D^{(*)-}\pi^+$ decays
- Significant improvement in performance
  - $+18\%$ (relative)

$$\varepsilon_{tag}(CB) = (31.7 \pm 0.5 \pm 0.4)\%$$
$$\varepsilon_{tag}(GFlaT) = (37.4 \pm 0.4 \pm 0.3)\%$$
\[\sin(2\phi_1/\beta) \text{ from } B \rightarrow J/\psi K_S\]

- Golden channel, almost background free
- Updated results using improved GFLaT flavour tagger
- Fit \(\Delta E\) distribution to subtract background
- Fit background-subtracted \(\Delta t\) distribution to extract CPV parameters

\[
\begin{align*}
S &= 0.724 \pm 0.035 \pm 0.014 \\
C &= -0.035 \pm 0.026 \pm 0.013
\end{align*}
\]

- Statistical uncertainties 8% smaller than with category-based Flavour Tagger

\[\text{arXiv:2402.17260} \quad \text{Accepted by PRD}\]
TDPCPV in Charmless B decay

- $B \rightarrow \eta' K_S$
  - $\eta' \rightarrow \eta(\rightarrow \gamma \gamma) \pi^+ \pi^-$
  - $\eta' \rightarrow \rho \gamma$
- High $B$, theoretically clean
  - $\sim 800$ signal events
- $\sim 800$ signal events

- $B \rightarrow \phi K_S$
- Challenge: non resonant background with opposite-CP
  - $\sim 160$ signal events

- $B \rightarrow K_S K_S K_S$
- Challenge: no prompt tracks from $B$ vertex
  - Use $K_S \rightarrow \pi^+ \pi^-$ extrapolated to IP
  - $\sim 160$ signal events

- See also S.Raiz talk on Tue

\[ S = 0.67 \pm 0.10 \pm 0.04 \]
\[ C = -0.19 \pm 0.08 \pm 0.03 \]

\[ S = 0.54 \pm 0.26 \pm 0.06 \]
\[ C = -0.31 \pm 0.20 \pm 0.05 \]

\[ S = -1.37 \pm 0.35 \pm 0.03 \]
\[ C = -0.07 \pm 0.20 \pm 0.05 \]
B → K_S \pi^0 \gamma

- B^0 \to K_S \pi^0 \gamma is expected to have small/none mixing induced CPV in SM
  - b\to s\gamma_R is helicity suppressed (m_s/m_b) wrt b\to s\gamma_L
  - B^0\to s\gamma_L vs B^0\to \bar{B}^0\to s\gamma_R
- Vertex from K_S \to \pi^+\pi^- and IP constraint
- Measured separately for resonant K^*(0) \to K_S \pi^0 \gamma

\begin{align*}
S &= 0.00 \pm 0.27 \pm 0.03 \\
C &= 0.10 \pm 0.13 \pm 0.03
\end{align*}

- and inclusive (non resonant) decay K_S \pi^0 \gamma

\begin{align*}
S &= 0.04 \pm 0.45 \pm 0.10 \\
C &= -0.06 \pm 0.25 \pm 0.07
\end{align*}

Most precise result so far
**CPV in $B^0 \to K^0_S \pi^0$**

- First Belle II measurement of TDPCPV in $B^0 \to K^0_S \pi^0$
  - Signal yield: $415^{+26}_{-25}$ events
- Key ingredient in Isospin Sum Rule

\[
I_{K\pi} = \mathcal{A}_{K\pi}^{CP} + \mathcal{A}_{K\pi}^{0,0,0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K\pi}^{0,0,0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{0,0,0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \approx 0 \quad \text{(within -1%)}
\]

- $B^0 \to K^+ \pi^-$
  - $\mathcal{B}(K^+\pi^-) = (20.67 \pm 0.37 \pm 0.62) \times 10^{-6}$
  - $\mathcal{A}_{CP}(K^+\pi^-) = -0.072 \pm 0.019 \pm 0.007$

- $B^+ \to K^0_S \pi^+$
  - $\mathcal{B}(K^0_S\pi^+) = (24.40 \pm 0.71 \pm 0.86) \times 10^{-6}$
  - $\mathcal{A}_{CP}(K^0_S\pi^+) = +0.046 \pm 0.029 \pm 0.007$

- $B^0 \to K^0_S \pi^0$
  - $\mathcal{B} = (10.50 \pm 0.62 \pm 0.67) \times 10^{-6}$
  - $\mathcal{A}_{CP} = -0.01 \pm 0.12 \pm 0.05$

- $I_{K\pi} = -0.03 \pm 0.13 \pm 0.05$ (world average $0.13 \pm 0.11$)

- Precision on par with W/A! $\to$ 5% uncertainty achievable @ 10 ab$^{-1}$

**Belle II**

- $\int L dt = 362$ fb$^{-1}$
- Signal yield: 415$^{+26}_{-25}$ events
- $S = 0.75^{+0.20}_{-0.23} \pm 0.04$
- $C = -0.04^{+0.14}_{-0.15} \pm 0.05$

**References**

- PRL 131, 111803 (2023)
- PRD 109, 012001 (2024)
Toward $\phi_2/\alpha$: $B^0 \rightarrow \pi^0\pi^0$

- Update on $B$ and $A_{CP}$ using full Run1 statistics:
- Improved selections, new flavour tagger (GFlaT), reduction of systematics
  - Background dominated by continuum, then $B\bar{B}$ ($B^+\rightarrow\rho^+ (\rightarrow \pi^+\pi^0)\pi^0$, $B^0\rightarrow K^0_S (\rightarrow \pi^0\pi^0)\pi^0$)
  - Photons selected with BDT, continuum suppression trained on off-resonance data
  - 4D fit including $M_{BC}$, $\Delta E$, cont.suppression, $w$ (wrong tag probability - unbinned)
  - Validated on $B^+\rightarrow K^+\pi^0$ / $B^0\rightarrow \bar{D}^0(K^+\pi^-\pi^0)\pi^0$

$$B = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$A_{CP} = 0.06 \pm 0.30 \pm 0.06$$

- Compatible with known values
- World-best $B$ determination.
- $A_{CP}$ on par with world best

$$B = (1.59 \pm 0.26) \times 10^{-6}$$
$$A_{CP} = 0.30 \pm 0.20$$

Previous results
[PRD107 (2023) 112009]

See also S.Raiz talk on Tue
Toward $\phi_2/\alpha$: $B \to \pi\pi$

$\text{B} (B^0 \to \pi^+\pi^-) = (5.83 \pm 0.22 \pm 0.17) \times 10^{-6}$

$\text{B} (\pi^+\pi^0) = (5.10 \pm 0.29 \pm 0.32) \times 10^{-6}$

$A_{CP} (\pi^+\pi^0) = -0.081 \pm 0.054 \pm 0.008$

- Compatible and competitive with WA
- Modes with $\pi^0$ limited by $\pi^0$ systematics: will be reduced with more data
Results on $\gamma/\phi_3$

- $\gamma/\phi_3$ from interference of tree level amplitudes:
  - Fundamental input of CKM UT fit
- $\phi_3$ can be measured using interference $B \to D K$ and $B \to \bar{D} K$ (or $D^* K^*$, $D \pi$)

- Amplitude ratio $r_B$ and strong phase $\delta_B$ are mode-dependent

$$B^- \to D^0 K^- \approx V_{cb} V_{us}^*$$
$$A_1 \approx V_{ub} V_{cs}^*$$
$$A_1 r_B e^{i(\delta_B - \phi_3)}$$
Belle/BelleII combined results on $\gamma/\phi_3$

- Several methods used
  - GLW $B^\pm \rightarrow D^0_{CP} K^\pm$ arXiv:2308.05048 [hep-ex]
    - Use CP eigenstate of D meson
  - ADS PRL 78 (1997) 3257
    - Enhancement of CP violation by using doubly Cabibbo suppressed decays.
  - BPGGSZ $D^0 \rightarrow K_S h^+ h^-$ JHEP 2022(2022), 63
    - Different amplitude and strong phase in different region of Dalitz plot.
  - GLS $D^0 \rightarrow K_S K\pi$ JHEP 09(2023)146

- D-decay strong phase from CLEO-c & BESIII
  - Need improvement by BESIII

LHCb: $\phi_3 = (63.8 \pm 3.6)^\circ$ LHCb-CONF-2022-003
Few ab$^{-1}$ needed for a meaningful comparison

- Likelihood with 60 input observables
  - including 15 auxiliary inputs (D-decay)
  - 16 free parameters

- $r_B(\delta_B)$ with little high-fluctuation
  - Worse precision with WA values
Belle + Belle II Combined $\gamma/\phi_3$

- Example:
  - $B^\pm \rightarrow D_{CP}K^\pm$ (GLW)
  - CP-odd $D_{CP} \rightarrow K_S \pi^0$: only in Belle(II)
  - Combined Belle and BelleII analysis

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Data set ($B$ + Belle II) [fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow K^0\pi^0, K^-K^+$</td>
<td>GLW</td>
<td>711 + 189</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow K^+\pi^-, K^+\pi^-\pi^0$</td>
<td>ADS</td>
<td>711 + 0</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow K^0K^-\pi^+$</td>
<td>GLS</td>
<td>711 + 362</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow K^0h^-h^+$</td>
<td>BPGGSZ (m.i.)</td>
<td>711 + 128</td>
</tr>
<tr>
<td>$B^+ \rightarrow Dh^+$</td>
<td>$D \rightarrow K^0\pi^-\pi^0$</td>
<td>BPGGSZ (m.i.)</td>
<td>711 + 0</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$D^* \rightarrow D\pi^0, D \rightarrow K^0\pi^0, K^0\phi, K^0\omega$</td>
<td>GLW</td>
<td>210 + 0</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$K^-K^+, \pi^-\pi^0$</td>
<td>GLW</td>
<td>210 + 0</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$D^* \rightarrow D\pi^0, D\gamma, D \rightarrow K^0\pi^-\pi^+$</td>
<td>BPGGSZ (m.d.)</td>
<td>605 + 0</td>
</tr>
</tbody>
</table>
BESIII @ Beijing Electron-Positron Collider (BEPC-II)

- CM Energies: [2-4.95] GeV: $\tau$-charm region
  - Luminosity: $\sim 10^{33}$ cm$^{-2}$s$^{-1}$
- Collected 10 billion $J/\psi$ and 3 billion $\psi(2S)$
  - Possible to study CPV on **hyperons**
  - $\sim 10^7$ entangled hyperon pairs

<table>
<thead>
<tr>
<th>Decay</th>
<th>$B \times 10^{-5}$</th>
<th>Events at BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \rightarrow \Lambda \bar{\Lambda}$</td>
<td>$189 \pm 9$</td>
<td>$18.9 \times 10^6$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \Sigma^+ \Sigma^-$</td>
<td>$150 \pm 24$</td>
<td>$15.0 \times 10^6$</td>
</tr>
<tr>
<td>$J/\psi \rightarrow \Xi \bar{\Xi}$</td>
<td>$97 \pm 8$</td>
<td>$9.7 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \Sigma \bar{\Sigma}$</td>
<td>$23.2 \pm 1.2$</td>
<td>$116 \times 10^3$</td>
</tr>
<tr>
<td>$\psi(2S) \rightarrow \Omega \bar{\Omega}$</td>
<td>$5.66 \pm 0.30$</td>
<td>$28 \times 10^3$</td>
</tr>
</tbody>
</table>

*Front. Phys. 12(5), 121301 (2017)*

More on BESIII and BEBC-II on Luyan Tao talk on Monday
CPV in Hyperon decay

- Polarized and entangled pair of hyperons from $J/\psi$ decays
- Decay asymmetry parameters $\alpha$ from S-wave (parity conserving) and P-wave (parity violating) amplitudes. $\bar{\alpha}$ for anti-hyperons
  - $\alpha$ is CP-odd
  - Non zero $\Rightarrow$ CP violation
- Events: $J/\psi \rightarrow \Sigma^+ \text{ anti-}\Sigma^-$, $\Sigma^+ \rightarrow n\pi^+$, anti-$\Sigma^-$ $\rightarrow \bar{p}\pi^0$ or c.c.
  - 10 billion $J/\psi \rightarrow \Sigma^+ \text{ anti-}\Sigma^-$
  - Complex angular analysis: 5 observables
  - First CPV result with neutron in the final state

\[
\frac{dN}{d\Omega} = \frac{1}{4\pi} \left( 1 + \alpha \mathbf{P}_\Sigma \cdot \hat{n} \right)
\]

Moment of polarization

Non flat $\Rightarrow$ polarization observed

$A_{CP} = 0.080 \pm 0.052 \pm 0.028$
$e^+e^- \rightarrow J/\psi \rightarrow \Xi^0\text{anti-}\Xi^0$, $\Xi^0 \rightarrow \Lambda (\rightarrow p\pi^-)\pi^0 + \text{cc}$

- Even more complex angular analysis (9 helicity angles)
- 8 free parameters (plus other in daughter’s decay)
  - 10 billion $J/\psi$ events:
  - 320k signal events with little background
- Results:
  - $\Xi^-$ polarization observed (first time)
  - Independent measurement of $\Lambda$ decay parameters
  - First measurement of weak phase difference in $\Xi$ decay
  - Three independent CP test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This work</th>
<th>Previous result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{CP}^\Xi$</td>
<td>$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$</td>
<td>$(-0.7 \pm 8.5) \times 10^{-2}$ [49]</td>
</tr>
<tr>
<td>$\Delta\phi_{CP}(\text{rad})$</td>
<td>$(-0.1 \pm 6.9 \pm 0.9) \times 10^{-3}$</td>
<td>$(-7.9 \pm 8.3) \times 10^{-2}$ [49]</td>
</tr>
<tr>
<td>$A_{CP}^\pi$</td>
<td>$(6.9 \pm 5.8 \pm 1.8) \times 10^{-3}$</td>
<td>$(-2.5 \pm 4.8) \times 10^{-3}$ [20]</td>
</tr>
</tbody>
</table>

Similar results for $e^+e^- \rightarrow J/\psi \rightarrow \Xi^+\Xi^- \rightarrow \Lambda (\rightarrow p\pi^-)\pi^- \Lambda (\rightarrow \bar{n}\pi^0)\pi^+$

[PhysRevD.108.L031106 (2023)]

Stefano Lacaprara, INFN Padova, FPCP2024, Bangkok 30/5/2024
Perspective

- Belle II goal: $L = 6 \times 10^{35} \text{cm}^2\text{s}^{-1}$; $L_{\text{int}} \sim 50 \text{ab}^{-1}$

- BESIII and Super Tau-Charm Facility
  - today $10^{10} J/\psi$
  - At super $J/\psi$ factory $10^{12} J/\psi$ per year
    - $L \sim 10^{35} \text{cm}^2\text{s}^{-1}$
    - polarized beam (phase II)

- CPV sensitivity in hyperon’s decay
  - $10^{-4} - 10^{-5}$
  - challenging SM predictions

- Together with LHCb will further constrain UT
- Unique measurements in many modes
- UT consistent with SM or not?

More on STCF on Qipeng Hu talk later today
Summary

- CPV studies are a key ingredient of $e^+/e^-$ colliders
- Large CPV program in B physics at Belle II
  - Precise measurement of Unitary Triangles
  - Search for new physics
  - Results on Run1 show significantly better performance compared to Belle
- Hyperon polarization in $J/\psi$, $\psi(2S)$ decays at BESIII
  - new way to study CPV
Backup

AS REQUESTED, I FIT MY PRESENTATION ON ONE POWERPOINT SLIDE.

I HAD TO USE ALL OF THE WHITE SPACE, BUT I THINK IT WAS WORTH IT TO FIT EVERYTHING ON ONE PAGE.

IT'S ACTUALLY ONLY ONE BULLET POINT, BUT IT'S A LONG ONE.
Belle and Belle II

- Asymmetric $e^+e^-$ colliders - B factories, also charm and $\tau$ factories
- Belle Belle II: $e^+(3.5 \text{ GeV}) e^-(8 \text{ GeV})$  $e^+(4 \text{ GeV}) e^-(7 \text{ GeV})$
- Improved vertex resolution allows lower boost
- 424 fb$^{-1}$ (362 fb$^{-1}$ at $\Upsilon(4S)$) collected at Belle II so far; Goal: 50 ab$^{-1}$
sin(2\phi_1/\beta) future

- Expected to be dominated by systematics with 50/ab
- Mostly from alignment of vertex detector and tag-side interference
- Penguin pollution will need to be constrained from B → J/ψπ^0

![Belle II Physics Book](https:// doi.org/10.1093/ptep/ptz106)
Flavour Tagger

- Used to determine the quark-flavour of $B_{tag}$
- Many different final states considered, combined with two layers of MVA discriminators.
  - Developed also a Deep Neural Network with similar performance.

Performance measured on data using $B^0\to D^{(*)}h^+$ decays

- Effective efficiency:

$$\varepsilon_{eff} = \sum_i \varepsilon_i (1 - 2w_i)^2$$

$$= (30.0 \pm 1.2 \pm 0.4)\%$$
**Time dependent $B \rightarrow \eta'K_S$**

- Mediated by loop diagram, CPV expected to be the same as in $B^0 \rightarrow J/\psi K_S$ (tree)
- Deviation would be indication of new physics in the loop
- Reconstruct in 2 sub-channels:
  - $\eta' \rightarrow \eta(\rightarrow \gamma \gamma)\pi^+\pi^-$, $\eta' \rightarrow \rho\gamma$ (and $\eta' \rightarrow \eta(\rightarrow \pi^+\pi^-\pi^0)\pi^+\pi^-$)
- Found ~800 signal in total, performed time dependent fit in $\Delta E$, $M_{BC}$, ContSupp and $\Delta T$ variables

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal yield</th>
<th>$C_{\eta'K_S}$</th>
<th>$S_{\eta'K_S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow \eta(\gamma\gamma)\pi^+\pi^-$</td>
<td>358 ± 20</td>
<td>-0.10 ± 0.13</td>
<td>0.69 ± 0.14</td>
</tr>
<tr>
<td>$\eta' \rightarrow \rho\gamma$</td>
<td>471 ± 29</td>
<td>-0.24 ± 0.10</td>
<td>0.65 ± 0.13</td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta(\pi^+\pi^-\pi^0)\pi^+\pi^-$</td>
<td>55 ± 8</td>
<td>0.11 ± 0.32</td>
<td>0.25 ± 0.50</td>
</tr>
<tr>
<td>Sim. fit</td>
<td>829 ± 35</td>
<td>-0.19 ± 0.08</td>
<td>0.67 ± 0.10</td>
</tr>
</tbody>
</table>

- In agreement with WA and $B^0 \rightarrow J/\psi K_S$ result
Time dependent $B \rightarrow \eta' K_S$ 

arXiv:2402.03713
Time dependent $B \rightarrow \phi'K_S$

- Two tracks from $\phi$, clean signature
- Major challenge: non resonant background with opposite-CP
- Helicity for longitudinal polarization
- Found $\sim 160$ signal in total, performed time dependent fit in $\Delta E$, $M_{BC}$, ContSupp and $\Delta T$ variables

\[ S = 0.54 \pm 0.26 \pm 0.06 \]
\[ C = -0.31 \pm 0.20 \pm 0.05 \]

- Results competitive with best measurements
  - HFLAV $C_{CP} = 0.01 \pm 0.14$, $S_{CP} = 0.74^{+0.11}_{-0.13}$

\[ \text{arXiv:2307.02802} \]
Time dependent $\mathbf{B} \rightarrow \mathbf{K}_S \mathbf{K}_S \mathbf{K}_S$

- $b\rightarrow s$ decay mediated by penguin loop, potentially sensitive to new physics
  - Very reliable theoretically
- B vertex challenging: no prompt tracks from B, but only reconstructed $\mathbf{K}_S \rightarrow \pi^+ \pi^-$ extrapolated back;
  - For TD analysis ($S_{\text{CP}}$), using only candidates with enough hits on inner silicon vertex detector;
- Signal from 3-dimensional fit: $M_{\mathbf{BC}}$, $M_{\mathbf{KsKsKs}}$, BDT $\text{Cont.Supp.}$
- Signal yield = 158 ± 14 events

$S = -1.37^{+0.35}_{-0.45} \pm 0.03$
$C = -0.07 \pm 0.20 \pm 0.05$
Measurement of $\phi_2/\alpha$

- The measurement of $\phi_2$ from $B \rightarrow \pi\pi$ (or $B \rightarrow \rho\rho$) final states comes from an isospin analysis:

  The following equalities hold:

  \[ \frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0} \]
  \[ \frac{1}{\sqrt{2}} \tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0} \]
  \[ A^{+0} = \tilde{A}^{+0} \]

- Observables (for e.g. $B \rightarrow \pi\pi$):
  - branching fractions of: $B^0 \rightarrow \pi^+\pi^0, \pi^+\pi^-, \pi^0\pi^0$;
  - direct (time-independent) CP asymmetries: $C^{+}$, $C^{00}$;
  - time-dependent CP asymmetries: $S^{+}$, $S^{00}$.

- Belle II will be able to measure all these observables;
- We expect to push the sensitivity to $\alpha$ to $\sim 1^\circ$.

M. Gronau and D. London, PRL 65 (1990), 3381
Measurement of $\phi_2/\alpha$

Two amplitudes of comparable size with different weak phase:

\[
\phi_2 = (\bar{A}^+, A^0), \quad \phi^\text{eff}_2 = (\bar{A}^{+-}, A^{++})
\]

Isospin analysis [Gronau-London PRL, 64 3381 (1990)].

Constraints:

- $B^0$ and $B^\pm$ amplitudes:
  \[
  A^{+0} = A^{+-}/\sqrt{2} + A^{00}
  \]
  \[
  \bar{A}^{+0} = \bar{A}^{+-}/\sqrt{2} + \bar{A}^{00}
  \]
  \[
  |A^{+0}| = |\bar{A}^{+0}|
  \]

Similar for $B \rightarrow \rho\rho$

- Need all branching fractions;
- Direct CP asymmetries: $C^{+-}$, $C^{00}$;
- TD CP asymmetries: $S^{+-}$, $S^{00}$;
  - $S^{00}$ reduces folding ambiguities
- Belle II will be able to measure all these observables
  - Final sensitivity $\sim 1^\circ$
Toward $\phi_2/\alpha$: $B^0 \rightarrow \pi^0 \pi^0$

New for FCPC 2024

Previous results
[PRD107 (2023) 112009]
Toward $\phi_2/\alpha$: $B^0 \rightarrow \pi^0\pi^0$

**Table I.** Fractional systematic uncertainties on the branching fraction and absolute systematic uncertainties on the $CP$ asymmetry. Total systematic uncertainties, resulting from their sums in quadrature, are also given, and compared with statistical uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\mathcal{B}$</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$ efficiency</td>
<td>8.6 %</td>
<td>n/a</td>
</tr>
<tr>
<td>$\Upsilon(4S)$ branching fractions (1 + f^+/f^0)</td>
<td>2.5 %</td>
<td>n/a</td>
</tr>
<tr>
<td>Continuum-suppression efficiency</td>
<td>1.9 %</td>
<td>n/a</td>
</tr>
<tr>
<td>$B\bar{B}$-background model</td>
<td>1.7 %</td>
<td>0.034</td>
</tr>
<tr>
<td>Sample size $N_{BB}$</td>
<td>1.5 %</td>
<td>n/a</td>
</tr>
<tr>
<td>Signal model</td>
<td>1.2 %</td>
<td>0.021</td>
</tr>
<tr>
<td>Continuum-background model</td>
<td>0.9 %</td>
<td>0.025</td>
</tr>
<tr>
<td>Wrong-tag probability calibration</td>
<td>n/a</td>
<td>0.008</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>9.6 %</td>
<td>0.048</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>15.9 %</td>
<td>0.303</td>
</tr>
</tbody>
</table>

Previous results
[PRD107 (2023) 112009]
$B^+ \rightarrow K^+\pi^0 / \pi^+\pi^0$

- $B^+\rightarrow K^+\pi^0$ enters in “Kπ” puzzle
- Using common selection for both channels
  - Enhance pion and kaon final state
  - Background from continuum $qq\bar{q}$ reduced with MVA
- $BR$ and $A^{CP}$ from 3D fit on $M_{bc}$, $\Delta E$, BDT
  - Simultaneous fit to both samples
  - $D^+\rightarrow K_s\pi^+$ and $D^0\rightarrow K^-\pi^+$ for detector asymmetries
- Results:

$$B(\pi^+\pi^0) = (6.1 \pm 0.5 \pm 0.5) \times 10^{-6}$$
$$B(K^+\pi^0) = (14.3 \pm 0.7 \pm 0.8) \times 10^{-6}$$
$$A^{CP}(\pi^+\pi^0) = -0.09 \pm 0.09 \pm 0.02$$
$$A^{CP}(K^+\pi^0) = 0.01 \pm 0.05 \pm 0.01$$

WA: $A^{CP}_{K^+\pi^0} = 0.030 \pm 0.013$, $A^{CP}_{\pi^+\pi^0} = 0.03 \pm 0.04$
Toward $\phi_2/\alpha$: $B \to \rho \rho$

- Broad resonances of vector mesons, $\pi^0$ in final state
  - multiple non-negligible peaking background contributions
- CP analysis requires measurement of longitudinal polarization:
  - angular analysis using helicity angles of $\rho$’s

$$B^0 \to \rho^+ \rho^-$$

$$B^+ \to \rho^+ \rho^0$$

$B(B^0 \to \rho^+ \rho^-) = [2.67 \pm 0.28\,\text{(stat)} \pm 0.28\,\text{(syst)}] \times 10^{-5}$,

$f_L = 0.956 \pm 0.035\,\text{(stat)} \pm 0.033\,\text{(syst)}$,
Toward $\phi_2/\alpha$: $B^+ \rightarrow \rho^+\rho^0$

- Similar to $B^0 \rightarrow \rho^+\rho^-$
- 6D fit: $\Delta E$, BDT, $2*M(\pi\pi)$, 2*helicity angles
  - Template fit w/ correlation
- Results:
  - $N(sig) = 345 \pm 31$

\[
\mathcal{A}^{CP} = -0.069 \pm 0.068 \text{ (stat)} \pm 0.060 \text{ (syst)}
\]
\[
B = (23.2^{+2.2}_{-2.1}) \text{ (stat)} \pm 2.7 \text{ (syst))} \cdot 10^{-6}
\]
\[
f_L = 0.943^{+0.035}_{-0.033} \text{ (stat)} \pm 0.027 \text{ (syst)}
\]

WA: $\mathcal{A}^{CP} = -0.05 \pm 0.05, B = (24.0 \pm 1.9) \cdot 10^{-6}$

arXiv:2206.12362
Toward $\phi_2/\alpha$: $B^0 \to \pi^0\pi^0$

- $\phi_2/\alpha$ from isospin analysis of $B \to \pi\pi/\rho\rho$ modes
  - Belle II will measure all modes
- $B^0 \to \pi^0\pi^0$ most challenging mode, very hard for LHCb
- Fake photons background reduced with multivariate algorithm for $\pi^0 \to \gamma\gamma$ purity
  - Control channel: $B^0 \to D^0(K^+\pi^0)\pi^0$
- Using Flavour Tagger to get direct CP asymmetry
- Results:
  - N Yield: $93 \pm 18$
  - $B = (1.38 \pm 0.27 \pm 0.22) \times 10^{-6}$
  - $A_{\text{CP}} = 0.14 \pm 0.46 \pm 0.07$
- Competitive with Belle with $1/3$ of dataset
Belle/Belle II combined results on $\gamma/\phi_3$

- Best sensitivity from the BPGGSZ method, exploiting the interference in the $D^0 \to K_S \pi^+ \pi^-$ Dalitz plot:


$$A_{CP\pm} \equiv \frac{B(B^- \to D_{CP\pm} K^-) - B(B^+ \to D_{CP\pm} K^+)}{B(B^- \to D_{CP\pm} K^-) + B(B^+ \to D_{CP\pm} K^+)}$$

$$R_{CP\pm} \equiv \frac{B(B^- \to D_{CP\pm} K^-) + B(B^+ \to D_{CP\pm} K^+)}{B(B^- \to D_{flav} K^-) + B(B^+ \to D_{flav} K^+)}$$

which are related to $\phi_3$:

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos \delta_B \cos \phi_3$$

$$A_{CP\pm} = \pm 2r_B \sin \delta_B \sin \phi_3 / R_{CP\pm}$$
Belle/Belle II combined results on $\gamma/\phi_3$

- Considering $D^0 \to K^+K^-$ as CP+, $D^0 \to K_S\pi^0$ as CP-, and $D^0 \to K^-\pi^+$ as flavor specific final state, we measure (on the Belle + Belle II data set):

$$R_{CP^+} = 1.164 \pm 0.081 \pm 0.036,$$
$$R_{CP^-} = 1.151 \pm 0.074 \pm 0.019,$$
$$A_{CP^+} = (+12.5 \pm 5.8 \pm 1.4)\%,$$
$$A_{CP^-} = (-16.7 \pm 5.7 \pm 0.6)\%.$$  

- The $A_{CP}$’s differ from each other at $\sim 3.5\sigma$;
- This translates into constraints on $\phi_3$:

<table>
<thead>
<tr>
<th>$\phi_3$ (°)</th>
<th>68.3% CL</th>
<th>95.4% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[8.7, 20.5]$</td>
<td>$[83.8, 96.1]$</td>
<td></td>
</tr>
<tr>
<td>$[163.4, 173.1]$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $\tau_B$ | 0.282, 0.489 | 0.069, 0.560 |

Stefano Lacaprara, INFN Padova, FPCP2024, Bangkok 30/5/2024

arXiv:2308.05048 [hep-ex]
Polarized hyperon pairs in $e^+e^-$ collisions

- Angular distribution of $\frac{d^2\sigma}{d\Omega} \propto 1 + \alpha_\psi \cos^2 \theta$, $\alpha_\psi \in [-1.0, 1.0]$
- Unpolarized $e^+e^-$ beams $\Rightarrow$ transverse polarized hyperon (if $\Delta \Phi \neq 0$):
\[ e^+ e^- \rightarrow J/\psi \rightarrow \Xi^+ \Xi^- \rightarrow \Lambda (\rightarrow p \pi^- \pi^-) \Lambda (\rightarrow \bar{n} \pi^0) \pi^+ + cc \]

- CPV in hyperons might arise from interference of S and P-wave
  - 10 billion \( J/\psi \) events: \((144+123)k\) signal events (91% purity)
  - 9 helicity angles, 8 global parameters
- Several decay properties of \( \Xi^- \) and \( \Lambda \) are determined:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>This work</th>
<th>Previous result</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_J/J )</td>
<td>0.611 ± 0.007( ^{+0.013}_{-0.007} )</td>
<td>0.586 ± 0.012 ± 0.010 [18]</td>
</tr>
<tr>
<td>( \Delta \Phi_{J/J} ) (rad)</td>
<td>1.30 ± 0.03( ^{+0.02}_{-0.03} )</td>
<td>1.213 ± 0.046 ± 0.016 [18]</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>-0.867 ± 0.015( ^{+0.014}_{-0.010} )</td>
<td>1.01 ± 0.07 [29]</td>
</tr>
<tr>
<td>( \sigma_3 )</td>
<td>0.863 ± 0.014( ^{+0.012}_{-0.008} )</td>
<td>0.913 ± 0.028 ± 0.012 [17]</td>
</tr>
<tr>
<td>( \alpha_A/J )</td>
<td>0.877 ± 0.015( ^{+0.014}_{-0.010} )</td>
<td>1.01 ± 0.07 [29]</td>
</tr>
<tr>
<td>( \alpha_B/J )</td>
<td>0.863 ± 0.014( ^{+0.012}_{-0.008} )</td>
<td>0.913 ± 0.028 ± 0.012 [17]</td>
</tr>
</tbody>
</table>

No CPV at \(<10^{-2}\) precision level
- SM predictions \(~10^{-4}-10^{-5}\)
- \( \Delta I = \frac{3}{2} \) transition in \( \Lambda \) decay
Hyperon at Super Tau-Charm Facility (STCF)

- Many (null) results so far
  - BESIII and Belle
- BESIII: today
  - 10 billion $J/\psi$
- At super $J/\psi$ factory
  - $10^{12} J/\psi$ per year
- CPV sensitivity in hyperon’s decay
  - $10^{-4} - 10^{-5}$
  - challenging SM predictions