$D^0 - \bar{D}^0$ mixing and CP violation results from Belle

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3 Mixing in $D^0 \rightarrow K_S^0\pi^+\pi^-$

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Neutral D meson system

- The time evolution is given by

\[ i \frac{d}{dt} \left( \left| D_0^0(t) \right\rangle \right) = \underbrace{\left( M - \frac{i}{2} \Gamma \right)}_{\mathcal{H}} \left( \left| D_0^0(t) \right\rangle \right) \]

- Mass eigenstates are different from the flavor eigenstates

\[ |D_{H,L}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle \quad \text{(eigenstates of } \mathcal{H}) \]

\[ |D_{H,L}\rangle \text{ are mass eigenstates with masses } m_H, m_L \text{ and widths } \Gamma_H, \Gamma_L \]

Solution:

\[ |D^0(t)\rangle = e^{-(\Gamma/2+i m)t} [\cosh \left( \frac{y+ix}{2} \Gamma t \right) |D^0\rangle + \frac{q}{p} \sinh \left( \frac{y+ix}{2} \Gamma t \right) |\bar{D}^0\rangle] \]

\[ |\bar{D}^0(t)\rangle = e^{-(\Gamma/2+i m)t} [\frac{p}{q} \sinh \left( \frac{y+ix}{2} \Gamma t \right) |D^0\rangle + \cosh \left( \frac{y+ix}{2} \Gamma t \right) |\bar{D}^0\rangle] \]

- Mixing parameters

\[ x = \frac{m_H-m_L}{\Gamma}, \quad y = \frac{\Gamma_H-\Gamma_L}{2\Gamma} \]

\[ \Gamma = \frac{\Gamma_H+\Gamma_L}{2}, \quad m = \frac{m_H+m_L}{2} \]
$D^0 - \bar{D}^0$ mixing

Since the mixing is very small in $D^0$ system, $|x|, |y| \ll 1$

$$|D^0(t)\rangle = e^{-(\Gamma/2+im)t}[|D^0\rangle + \frac{q}{p} (\frac{y+ix}{2}\Gamma t) |\bar{D}^0\rangle]$$

Time dependent decay rate for $D^0 \rightarrow f$:

$$\frac{d}{dt} (N_{D^0 \rightarrow f}) \propto |\langle f | \mathcal{H} | D^0(t) \rangle|^2 = e^{-\Gamma t} |\langle f | \mathcal{H} | D^0 \rangle + \frac{q}{p} (\frac{y+ix}{2}\Gamma t) \langle f | \mathcal{H} | \bar{D}^0 \rangle|^2$$

$\Rightarrow$ exponential in lifetime, $\tau = 1/\Gamma$, modulated by $x$ and $y$

Present mixing results on:

1. Wrong sign hadronic decays ($D^0 \rightarrow K^+\pi^-$)
   
   $x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$
   
   $y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$

2. Decays to a self-conjugate state ($D^0 \rightarrow K^0_S\pi^+\pi^-$)

   $x$, $y$, $|p/q|$ and $\text{arg}(p/q)$
\[
\frac{p}{q} = \left| \frac{p}{q} \right| e^{i\phi}
\]

1. \( \left| \frac{p}{q} \right| \neq 1 \Rightarrow \text{CP violation in mixing} \\
2. \( \phi \neq 0, \pi \Rightarrow \text{CP violation due to interference of decays with and without mixing} \\
3. |A(D^0 \to f)| \neq |A(\bar{D}^0 \to \bar{f})| \Rightarrow \text{Direct CP violation} \\

Present CPV results:

1. \( D^0 \to \pi^0\pi^0 \)
2. \( D^0 \to K_S^0\pi^+\pi^- \)

Indirect CPV
\[ \frac{p}{q} = \left| \frac{p}{q} \right| e^{i\phi} \]

1. \[ \left| \frac{p}{q} \right| \neq 1 \Rightarrow \text{CP violation in mixing} \]

2. \( \phi \neq 0, \pi \Rightarrow \text{CP violation due to interference of decays with and without mixing} \)

3. \[ |A(D^0 \to f)| \neq |A(\bar{D}^0 \to \bar{f})| \Rightarrow \text{Direct CP violation} \]

- Present CPV results:
  1. \( D^0 \to \pi^0 \pi^0 \)
  2. \( D^0 \to K_S^0 \pi^+ \pi^- \)

Direct CPV
Experimental methods

1. **Flavor tagging**
   \[ D^{*+} \rightarrow D^0 \pi^+ \]
   → Charge conjugation is applied throughout
   → Definition: \( \Delta M = m_{D^{*+}} - m_{D^0} \)

2. **Requirement on \( p^*(D^*) \)**
   - Suppresses \( D^* \) from \( B \) decays
   - Reduces combinatorial background significantly

3. **Measure the \( D^0 \) proper decay time**
   \[ t = m_{D^0} \frac{l_{dec} \cdot \vec{p}_{D^0}}{|\vec{p}_{D^0}|^2} \]
$D^0 - \bar{D}^0$ mixing in $D^0 \rightarrow K^+\pi^-$ (976 fb$^{-1}$)


- Mixing

$D^0 \rightarrow \bar{D}^0$

$K^-\pi^+$

Right Sign (RS)

$D^0 \rightarrow \bar{D}^0$

CF

$K^+\pi^-$

Wrong Sign (WS)

DCS

- Time-dependent ratio of the WS to RS decay (no CPV, $|x|, |y| \ll 1$)

$$R(\tilde{t}/\tau) = \frac{\Gamma_{WS}(\tilde{t}/\tau)}{\Gamma_{WS}(\tilde{t}/\tau)} \approx \frac{\text{DCS}/\text{CF}}{R_D} + \sqrt{R_D} y' \left( \frac{\tilde{t}}{\tau} \right) + \frac{x'^2 + y'^2}{4} \left( \frac{\tilde{t}}{\tau} \right)^2$$

- We measure

$$R(t/\tau) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS}(\tilde{t}/\tau) \mathcal{R}(t/\tau - \tilde{t}/\tau) d(\tilde{t}/\tau)}{\int_{-\infty}^{+\infty} \Gamma_{RS}(\tilde{t}/\tau) \mathcal{R}(t/\tau - \tilde{t}/\tau) d(\tilde{t}/\tau)}$$

where, $\mathcal{R}(t/\tau - \tilde{t}/\tau)$, resolution function

- Proper decay time → convolution of an exponential with the resolution function

Events/(0.1 t/\tau)

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$D^0-\bar{D}^0$ mixing in $D^0 \rightarrow K^+\pi^-$ ($976$ fb$^{-1}$)

Stringent criteria on particle identification likelihood to reduce $K^-\pi^+$ misidentification

To estimate $R(t/\tau)$, we divide the sample into 10 bins of proper decay time and fit with

1. Mixing hypothesis ($x', y'$ are free)
2. No mixing hypothesis ($x' = y' = 0$)

<table>
<thead>
<tr>
<th>Test hypothesis</th>
<th>Parameters</th>
<th>Fit results ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing (4.2/7)</td>
<td>$R_D$</td>
<td>3.53±0.13</td>
</tr>
<tr>
<td></td>
<td>$y'$</td>
<td>4.6±3.4</td>
</tr>
<tr>
<td></td>
<td>$x'^2$</td>
<td>0.09±0.22</td>
</tr>
<tr>
<td>No mixing (33.5/9)</td>
<td>$R_D$</td>
<td>3.864±0.059</td>
</tr>
</tbody>
</table>

Observation of mixing with $>5\sigma$ significance
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$ time-dependent Dalitz Analysis (921 fb$^{-1}$)


- Allows a direct measurement of $x$, $y$ with a simultaneous search for CPV
- Study the distribution of events across the Dalitz plot (DP) as a function of the proper decay time
  $\rightarrow$ DP variables $(m_+^2, m_-^2) = (m_{K_S^0 \pi^+}^2, m_{K_S^0 \pi^-}^2)$

- Dalitz model:
  $\pi^+ \pi^-$ S-wave: K-matrix model
  $K\pi$ S-wave: LASS model

- Decay time integrated fit to DP; keeping amplitudes and phases for intermediate states free, separately for $D^0$ and $\bar{D^0} \Rightarrow \bar{A}_f = A_{\bar{f}}$
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$ time-dependent Dalitz Analysis (921 fb$^{-1}$)

- Time-dependent decay rates for $D^0$ and $\bar{D}^0$ decays to final state $f$ as

\[
|\mathcal{M}(f, t)|^2 = \frac{e^{-\Gamma t}}{2} \left( |A_f|^2 + \left|\frac{q}{p}\right|^2 |A_{\bar{f}}|^2 \right) \cosh(\Gamma yt) \\
+ \left( |A_f| - \left|\frac{q}{p}\right| |A_{\bar{f}}| \right) \cos(\Gamma xt) \\
+ 2\Re \left( \frac{q}{p} A_f A_{\bar{f}}^* \right) \sinh(\Gamma yt) \\
- 2\Im \left( \frac{p}{q} A_f A_{\bar{f}}^* \right) \sin(\Gamma xt)
\]

\[
|\tilde{\mathcal{M}}(f, t)|^2 = \frac{e^{-\Gamma t}}{2} \left( |A_{\bar{f}}|^2 + \left|\frac{q}{p}\right|^2 |A_f|^2 \right) \cosh(\Gamma yt) \\
+ \left( |A_{\bar{f}}| - \left|\frac{q}{p}\right| |A_f| \right) \cos(\Gamma xt) \\
+ 2\Re \left( \frac{q}{p} A_{\bar{f}} A_f^* \right) \sinh(\Gamma yt) \\
- 2\Im \left( \frac{p}{q} A_{\bar{f}} A_f^* \right) \sin(\Gamma xt)
\]

- Signal yield $1231731 \pm 1633$ (purity 95.5\%) from a 2D fit to the $M - Q$ distribution

\[
M = M_{K_S^0 \pi^+ \pi^-} \\
Q = (M_{K_S^0 \pi^+ \pi^-} - m_{\pi_s}) c^2
\]

Signal region

| $M - m_{D^0}$ | < 15 MeV  \\| 5.75 < Q < 5.95 MeV
Extraction of mixing parameters assuming CP is conserved:

- Keep following parameters free: $x$, $y$, $\tau_{D^0}$, proper decay time resolution parameters and Dalitz model parameters.

\[
x = (0.56 \pm 0.19)^{+0.03+0.06}_{-0.09-0.09} \%
\]
\[
y = (0.30 \pm 0.15)^{+0.04+0.03}_{-0.05-0.06} \%
\]
\[
\tau_{D} = (410.3 \pm 0.6) \text{ fs}
\]

Extraction of CPV parameters:

- CPV parameters $|q/p|$ and $\text{arg}(q/p)$ are included in PDF.
- Values obtained for mixing parameters are identical to those from the CP-conserved fit.

\[
|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}
\]
\[
\text{arg}(q/p) = (-6\pm11 \pm 3^{+3}_{-4})^\circ
\]
LHCb and CDF measured a large CP asymmetry difference between $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ decay, $\Delta A_{CP}$

Isospin consideration relates $\Delta A_{CP}$ with the CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$


The only existing measurement is from CLEO, $A_{CP} = (+0.1 \pm 4.8)\%$

PRD 63, 071101 (2001)
Time-integrated CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$ (966 fb$^{-1}$)


- **CP asymmetry**
  \[
  A_{CP} = \frac{\Gamma(D^0 \rightarrow \pi^0\pi^0) - \Gamma(\bar{D}^0 \rightarrow \pi^0\pi^0)}{\Gamma(D^0 \rightarrow \pi^0\pi^0) + \Gamma(\bar{D}^0 \rightarrow \pi^0\pi^0)}
  = A_{CP}^d + A_{CP}^m + A_{CP}^i
  \]

- **Measure the reconstruction asymmetry in**
  $D^{*+} \rightarrow D^0(\pi^0\pi^0)\pi^+_s$
  \[
  A_{rec} = \frac{N_{rec}^{D^{*+}} - N_{rec}^{D^{*-}}}{N_{rec}^{D^{*+}} + N_{rec}^{D^{*-}}}
  = A_{CP} + A_{FB}(\cos \theta^*) + A_{\pi^s}
  \]

- **Detection efficiency asymmetry**: use self tagged decay mode, $D^0 \rightarrow K^-\pi^+$
  \[
  A_{rec}^{tag}(K\pi) = A_{CP} + A_{FB} + A_{\epsilon}^{K\pi} + A_{\pi^s}
  \]
  \[
  A_{rec}^{untag}(K\pi) = A_{CP} + A_{FB} + A_{\epsilon}^{K\pi}
  \]
  - done in 2d bins of $(p_T, \cos \theta)$
  - apply $A_{\pi^s}$ correction in 2D bins for $A_{rec}^{cor}$

\[\text{N}(D^0/\bar{D}^0) = 34460 \pm 273\]
Time-integrated CP asymmetry in $D^0 \to \pi^0 \pi^0$ (966 fb$^{-1}$)

- Extraction of $A_{CP}$ and $A_{FB}$
  - $A_{FB}$ (asymmetry in the production of $D^*$) is an odd function of $\cos \theta^*$
  - $A_{rec}^{cor}$ is divided into 10 bins of $\cos \theta^*$ while addition and subtraction of $A_{rec}^{cor}$'s with the same value of $|\cos \theta^*|$ give
    \[
    A_{CP} = \frac{[A_{rec}^{cor}(\cos \theta^*) + A_{rec}^{cor}(-\cos \theta^*)]}{2} \\
    A_{FB} = \frac{[A_{rec}^{cor}(\cos \theta^*) - A_{rec}^{cor}(-\cos \theta^*)]}{2}
    \]
  - $A_{CP}(\pi^0 \pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$
  - Also updated $A_{CP}(K_S^0 \pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$
First observation of $D^0$-$\bar{D}^0$ mixing in $e^+e^-$ collision in the measurement of time-dependent ratio of WS to RS decay rates

\[ x''^2 = (0.09 \pm 0.22) \times 10^{-3} \quad y' = (4.6 \pm 3.4) \times 10^{-3} \]
\[ \Rightarrow \text{no mixing hypothesis is excluded at } 5.1\sigma \text{ level} \]

Updated measurement of $D^0$-$\bar{D}^0$ mixing in $D^0 \rightarrow K_S^0\pi^+\pi^-$

\[ x = (0.56 \pm 0.19)\% \quad y = (0.30 \pm 0.15)\% \]
\[ \Rightarrow \text{significance of mixing is estimated to be } 2.5\sigma \]
\[ \Rightarrow \text{No evidence for CP violation in the decay} \]

Significantly improved measurement of time-integrated CP violating asymmetry $A_{CP}$ in $D^0 \rightarrow \pi^0\pi^0$ and the result is consistent with no CPV

\[ A_{CP}(\pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\% \]
\[ \Rightarrow \text{updated the existing measurement of CP asymmetry in } D^0 \rightarrow K_S^0\pi^0 \]
Backup
HFAG average for mixing

![Graph showing HFAG-charm results for mixing and CP violation from Belle]

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$x'^{2}, \ y'$ measurement

Belle LHCb CDF BABAR

![Graph showing $x'^{2}$ on the x-axis and $y'$ on the y-axis with data points from Belle, LHCb, CDF, and BABAR.](image-url)
### Resonances in $D^0 \rightarrow K^0_S \pi^+ \pi^-$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^-$</td>
<td>$1.590 \pm 0.003$</td>
<td>$131.8 \pm 0.2$</td>
<td>$0.6045$</td>
</tr>
<tr>
<td>$K_0^*(1430)^-$</td>
<td>$2.059 \pm 0.010$</td>
<td>$-194.6 \pm 1.7$</td>
<td>$0.0702$</td>
</tr>
<tr>
<td>$K_2^*(1430)^-$</td>
<td>$1.150 \pm 0.009$</td>
<td>$-41.5 \pm 0.4$</td>
<td>$0.0221$</td>
</tr>
<tr>
<td>$K^*(1410)^-$</td>
<td>$0.496 \pm 0.011$</td>
<td>$83.4 \pm 0.9$</td>
<td>$0.0026$</td>
</tr>
<tr>
<td>$K^*(1680)^-$</td>
<td>$1.556 \pm 0.097$</td>
<td>$-83.2 \pm 1.2$</td>
<td>$0.0016$</td>
</tr>
<tr>
<td>$K^*(892)^+$</td>
<td>$0.139 \pm 0.002$</td>
<td>$-42.1 \pm 0.7$</td>
<td>$0.0046$</td>
</tr>
<tr>
<td>$K_0^*(1430)^+$</td>
<td>$0.176 \pm 0.007$</td>
<td>$-102.3 \pm 2.1$</td>
<td>$0.0005$</td>
</tr>
<tr>
<td>$K_2^*(1430)^+$</td>
<td>$0.077 \pm 0.007$</td>
<td>$-32.2 \pm 4.7$</td>
<td>$0.0001$</td>
</tr>
<tr>
<td>$K^*(1410)^+$</td>
<td>$0.248 \pm 0.010$</td>
<td>$-145.7 \pm 2.9$</td>
<td>$0.0007$</td>
</tr>
<tr>
<td>$K^*(1680)^+$</td>
<td>$1.407 \pm 0.053$</td>
<td>$86.1 \pm 2.7$</td>
<td>$0.0013$</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td>$0.2000$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.0370 \pm 0.0004$</td>
<td>$114.9 \pm 0.6$</td>
<td>$0.0057$</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$1.300 \pm 0.013$</td>
<td>$-31.6 \pm 0.5$</td>
<td>$0.0141$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>$0.532 \pm 0.027$</td>
<td>$80.8 \pm 2.1$</td>
<td>$0.0012$</td>
</tr>
</tbody>
</table>

#### $\pi\pi$ S wave
- $\beta_1$: $4.23 \pm 0.02$ | $164.0 \pm 0.2$
- $\beta_2$: $10.90 \pm 0.02$ | $15.6 \pm 0.2$
- $\beta_3$: $37.4 \pm 0.3$ | $3.3 \pm 0.4$
- $\beta_4$: $14.7 \pm 0.1$ | $-8.9 \pm 0.3$
- $f_{11}^{\text{psd}}$: $12.76 \pm 0.05$ | $-161.1 \pm 0.3$
- $f_{12}^{\text{psd}}$: $14.2 \pm 0.2$ | $-176.2 \pm 0.6$
- $f_{13}^{\text{psd}}$: $10.0 \pm 0.5$ | $-124.7 \pm 2.1$

#### $K\pi$ S wave
- Parameters
- $M$ (MeV/c$^2$): $1461.7 \pm 0.8$
- $\Gamma$ (MeV/c$^2$): $268.3 \pm 1.1$
- $F$: $0.4524 \pm 0.005$
- $\phi_F$ (rad): $0.248 \pm 0.003$
- $R$: 1 (fixed)
- $\phi_R$ (rad): $2.495 \pm 0.009$
- $a$ (GeV/c$^{-1}$): $0.172 \pm 0.006$
- $r$ (GeV/c$^{-1}$): $-20.6 \pm 0.3$

### Parameters
- $K^*(892)$
- $M_{K^*(892)}$ (MeV/c$^2$): $893.68 \pm 0.04$
- $\Gamma_{K^*(892)}$ (MeV/c$^2$): $47.49 \pm 0.06$
Systematics for $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Major source of systematic uncertainties
  1. fitting the $\Delta M$ distributions
  2. Resolution function
  3. Binning of proper decay time
  4. Reconstruction efficiencies of WS and RS decays
Systematics for $D^0 \rightarrow K^0_S \pi^+ \pi^-$

| Source                              | No CPV | | CPV |
|-------------------------------------|--------|--------|
|                                     | Δx/10^{-4} | Δy/10^{-4} | Δx/10^{-4} | Δy/10^{-4} | |q/p|/10^{-2} | arg(q/p)/° |
| Best candidate selection            | +1.0   | +1.9   | +1.3   | +2.0   | -2.3  | +2.2 |
| Signal and background yields        | ±0.3   | ±0.3   | ±0.4   | ±0.4   | ±1.2  | ±0.8 |
| Fraction of wrong-tagged events     | -0.7   | -0.4   | -0.5   | +0.4   | +1.1  | +0.8 |
| Time resolution of signal           | -1.4   | -0.9   | -1.2   | -0.8   | +0.8  | -1.2 |
| Efficiency                          | -1.1   | -2.1   | -1.4   | -2.2   | +3.1  | +1.3 |
| Combinatorial PDF                   | +1.9   | +2.3   | +2.4   | +2.9   | +1.2  | +2.8 |
| $K^*(892)$ DCS/CF reduced by 5%     | -7.3   | +2.3   | -6.9   | +3.1   | +3.3  | -1.4 |
| $K_2^*(1430)$ DCS/CF reduced by 5%  | +1.7   | -0.7   | +2.2   | -0.2   | +1.1  | +0.4 |
| Total                               | +2.8   | +3.7   | +3.6   | +4.3   | +5.0  | +3.3 |

| Source                              | No CPV | | CPV |
|-------------------------------------|--------|--------|
|                                     | Δx/10^{-4} | Δy/10^{-4} | Δx/10^{-4} | Δy/10^{-4} | |q/p|/10^{-2} | arg(q/p)/° |
| Resonance M & Π                     | ±1.4   | ±1.2   | ±1.2   | ±1.3   | ±2.1  | ±1.0 |
| $K^*(1680)^+$ removal               | -1.8   | -3.0   | -2.2   | -2.8   | +2.1  | -1.2 |
| $K^*(1410)^-$ removal               | -1.2   | -3.6   | -1.7   | -3.9   | -1.3  | +1.4 |
| $\rho(1450)$ removal                | +2.1   | +0.3   | +2.1   | +0.5   | -1.9  | +0.9 |
| Form factors                        | +4.0   | +2.4   | +4.3   | +2.0   | -2.4  | -1.0 |
| $\Gamma(q^2) = constant$            | +3.3   | -1.6   | +4.1   | -2.3   | -1.6  | +1.3 |
| Angular dependence                  | -8.5   | -3.9   | -7.4   | -3.6   | +5.6  | -3.2 |
| $K$-matrix formalism                | -2.2   | +1.8   | -3.5   | +2.4   | -3.6  | +1.1 |
| Total                               | ±5.8   | ±3.2   | ±6.4   | ±3.4   | ±6.4  | ±2.5 |
Systematics for $D^0 \rightarrow \pi^0 \pi^0$

<table>
<thead>
<tr>
<th>Source</th>
<th>$\pi^0 \pi^0$</th>
<th>$K_S^0 d^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal shape</td>
<td>±0.03</td>
<td>±0.01</td>
</tr>
<tr>
<td>Slow pion correction</td>
<td>±0.07</td>
<td>±0.07</td>
</tr>
<tr>
<td>$A_{CP}$ extraction method</td>
<td>±0.07</td>
<td>±0.02</td>
</tr>
<tr>
<td>$K^0 / \bar{K}^0$-material effects</td>
<td>⋮</td>
<td>±0.01</td>
</tr>
<tr>
<td>Total</td>
<td>±0.10</td>
<td>±0.07</td>
</tr>
</tbody>
</table>