Search for CP Violation in Charm at the B-Factories

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Outline

Introduction to CP Violation (CPV) in Mesons

Experimental observation of CPV in Charm meson decays

Measurements of CPV in Charm decays

- Indirect CPV and mixing in two-body decays
- Direct CPV in two-body decays
  - Interference between tree-level and penguin-level amplitudes in singly Cabibbo-suppressed decays.
  - Interference between Cabibbo-favored and doubly Cabibbo-suppressed amplitudes.
- Direct CPV in three-body singly Cabibbo-suppressed decays

Conclusions
CP Violation in Decays of Mesons

CP Violation in decay to final states $f$ and $\bar{f}$

Two amplitudes with different weak and strong phases

$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

CP violation in mixing if

$$r_m = \frac{|q/p|}{1}$$

Probability of $D^0 \rightarrow \bar{D}^0$ is different than CP conjugate $\bar{D}^0 \rightarrow D^0$

$$|D_{1,2}^0\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle \left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{1}{2} \Gamma_{12}^*}{M_{12} - \frac{1}{2} \Gamma_{12}}$$

CP violation in the interference between the decay with and without mixing if

$$\phi_f \neq 0$$

$$\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} = \left|\frac{q}{p} \frac{\bar{A}_f}{A_f}\right| exp[i(\delta_f + \phi_f)]$$
Three types of D meson decays

- **Cabibbo-favored**
  - examples: $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+\pi^+$
  - $A_T \sim |V_{cs}V_{ud}|$

- **singly Cabibbo-suppressed (SCS)**
  - examples: $D^0 \rightarrow K^+K^-$, $D^0 \rightarrow \pi^+\pi^-$, $D^+ \rightarrow K^+K^-\pi^+$
  - $A_T \sim |V_{cd}V_{ud}|, |V_{cs}V_{us}|$

- **doubly Cabibbo-suppressed (DCS)**
  - $D^0 \rightarrow K^+\pi^-$
  - $A_T \sim |V_{cd}V_{us}|$
• CP-violating asymmetries in charm decays provide a unique probe for physics beyond the Standard Model (SM)

• Standard Model charm physics is CP conserving to first order approximation.

• CP-violating asymmetries in charm are small.

• New Physics can enhance CP violating observables.

**Wolfenstein parameterization of the CKM matrix**

**Standard Model: CP Violation arises from KM phase in CKM quark mixing matrix**

\[
V = \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta + \frac{1}{2}\eta\lambda^2\right) \\
-\lambda & 1 - \frac{1}{2} \lambda^2 - i\eta A^2\lambda^4 & A\lambda^2(1 + i\eta\lambda^2) \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

**Charm Mesons:**
• CP Violation is CKM suppressed at $10^{-3}$ or less.

\[
\lambda = 0.22
\]
Current data consistent with no CPV at 2.1% CL

Is this an observation of new physics? No straightforward answer, could be SM or NP. More measurements with greater precision required!
Measurements in Charm Decays

✴ Precision measurements of the lifetimes of neutral D⁰ meson two-body decays -- indirect CPV and mixing.

\[
y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1
\]

✴ Direct CPV measurements in two-body SCS decays probe the interference between tree-level and penguin-level amplitudes.

› Separate direct CPV contribution from D⁰ two-body decays to CP-even eigenstates.

› SCS decays with K_s⁰ in final state - direct CPV compared with contribution from indirect CPV in K⁰ mixing.

✴ Direct CPV probing the interference between DCS and CF charged D_s⁰ decays with K_s in the final state. Compare to expected SM CP violation from neutral Kaons.

\textit{Direct CPV can only arise due to an additional phase from New Physics}

✴ Direct CPV exploiting final state interactions in 3-body decays. Measure asymmetries as a function of position on the Dalitz plot (3-body).
Mixing and CP violation observables are obtained from the partial widths of the decays:

\[ D^0(\bar{D}^0) \rightarrow h^+ h^-, \quad h^\pm = K^\pm, \pi^\pm \]

- **Mixing**
  \[ y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1 \]

- **CP Violation**
  \[ \Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma} \]

\[ \Delta Y = (1 + y_{CP}) A_\Gamma \]

\[ A_\Gamma = \frac{\Gamma^+ - \bar{\Gamma}^+}{\Gamma^+ + \bar{\Gamma}^+} \]

**CP Eigenstates**
- \( \Gamma^+ \) is the width of the decay to \( D^0 \rightarrow CP^+ \)
- \( \bar{\Gamma}^+ \) is the width of the decay to \( \bar{D}^0 \rightarrow CP^+ \)

- **Mixing appears** when the width of CP eigenstates differs from the flavor (CP-mixed) eigenstates, CF and DCS decays \( D^0 \rightarrow K^\mp \pi^\pm \).
- **CP is violated** if the width for \( D^0 \) and \( \bar{D}^0 \) differs when decaying to the same CP eigenstate.
- **The flavor (CP-mixed) eigenstates** \( D^0 \rightarrow K^\mp \pi^\pm \) are assumed to be described by the average lifetime \( \Gamma \).
D⁰ decays to CP-even Eigenstates K⁺K⁻, π⁺π⁻

**Experimentally we measure the lifetimes of CP-even and CP-mixed eigenstates.**

**Experimental assumptions:**

(i) small mixing (|x|, |y| << 1) proper time distributions are exponential with corresponding effective lifetimes to very good approximation.

(ii) not sensitive to direct CPV and weak phase does not depend on final state → KK and ππ share the same common effective lifetime. [PRD 80, 076008 (2009)]

**Effective lifetimes - measured quantities**

\[
\tau^+ = \tau(D^0 \rightarrow h^+ h^-) \\
\bar{\tau}^+ = \tau(\bar{D}^0 \rightarrow h^+ h^-) \\
\tau_D = \tau(D^0 \rightarrow K^{\mp}\pi^{\pm}) \\
h^{\pm} = K^{\pm}, \pi^{\pm}
\]

Mixing: \( y_{CP} = \frac{\tau_D}{2} \left( \frac{1}{\tau^+} + \frac{1}{\bar{\tau}^+} \right) - 1 \)

CP Violation: \( \Delta Y = \frac{\tau_D}{2} \left( \frac{1}{\tau^+} - \frac{1}{\bar{\tau}^+} \right) \)

**If CP is conserved** \( y_{CP} \equiv y \) **and** \( \Delta Y = A_\Gamma = 0 \)
Reconstruction Techniques

Tagged Candidates $D^* \to D^0 \pi_s$, sample purities > 98%

- Slow pion reconstructed and $D^0$ decays selected with two dimensional cut $[m(D^0), q]$

\[ q = (M^*_D - M(h^+ h^-) - m_\pi) c^2 \]

Untagged $D^0 \to K^+ K^-, K^\mp \pi^\pm$ candidates with sample purities ~ 75%.

- Statistically independent samples used in BaBar analysis to improve sensitivity of $\gamma_{CP}$ and $\Delta y$.

Selection of signal events

- remove $D$ from $B$ decays, $p_{CM}(D^0) > 2.5$ GeV/c

- Belle measures $D^0$ lifetime in intervals of $p_{CM}$ due to resolution function offset. Increase $p_{CM}(D^0) > 3.1$ GeV/c for $\Upsilon(5S)$ dataset

- Vertex fit requirements, Particle ID using Cherenkov detectors.
Belle Lifetime Ratio Analysis

**arXiv: 1212.3478**

- Belle uses tagged decays
- Full dataset 976 fb⁻¹
- Many systematics cancel in the relative lifetime measurements.
- Measured in intervals of the D⁰ center-of-mass polar angle due to resolution function offset dependence.

\[
\begin{align*}
D^{*+} & \to D^{0}\pi^{+}; D^{0} \to K^{+}K^{-} \\
D^{*+} & \to D^{0}\pi^{+}; D^{0} \to \pi^{+}\pi^{-} \\
D^{*+} & \to D^{0}\pi^{+}; D^{0} \to K^{-}\pi^{+}, K^{+}\pi^{-}
\end{align*}
\]

\[
\begin{align*}
\chi^2/ndf & = 545.0/542 \ (CL = 45.6\%) \\
\chi^2/ndf & = 792.9/584 \ (CL = 0.2\%)
\end{align*}
\]

\[
y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%, \\
A_{\Gamma} = (-0.03 \pm 0.20 \pm 0.08)\%.
\]

**Evidence for mixing at 4.5σ**
BaBar uses independent datasets of tagged and untagged decays with full dataset 468 fb$^{-1}$.

Simultaneous fit to all decays both tagged and untagged to measure the lifetime.

**Flavor tagged**

\[ D^*+ \rightarrow D^0 \pi^+; \ D^0 \rightarrow K^+ K^- \]
\[ D^+ \rightarrow D^0 \pi^+; \ D^0 \rightarrow \pi^+ \pi^- \]
\[ D^*+ \rightarrow D^0 \pi^+_s; \ D^0 \rightarrow K^- \pi^+, K^+ \pi^- \]

**Flavor untagged**

\[ D^0 \rightarrow K^+ K^- \]
\[ D^0 \rightarrow K^- \pi^+, K^+ \pi^- \]

**Measured Lifetimes**

<table>
<thead>
<tr>
<th>( \tau ) (fs)</th>
<th>( \tau_{K\pi} )</th>
<th>( \tau^+ )</th>
<th>( \tau^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>404</td>
<td>408</td>
<td>410</td>
<td>412</td>
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</table>

**Evidence for mixing at 3.3\( \sigma \)**

\[ y_{CP} = [0.72 \pm 0.18 \text{(stat)} \pm 0.12 \text{(syst)}] \% , \]
\[ \Delta Y = [0.09 \pm 0.26 \text{(stat)} \pm 0.06 \text{(syst)}] \% . \]

**PRD 87, 012004 (2013)**
BaBar has most precise measurement for mixing parameter $y_{CP}$. BaBar central value is closer to zero.
Direct CP Violation

Direct CPV due to interference of CF and DCS decays

- Direct CPV is evidence of NP in interference between CF and DCS amplitudes in $D^\pm \to K_{S,L} \pi^\pm$ and $D_s \to K_{S,L} K^\pm$
- Single weak phase in SM, therefore expect NO CPV
- SM contribution due to $K^0$ mixing $A_{SM} \sim 3.3 \times 10^{-3}$
- Experimental uncertainties at sub percent level

Direct CPV in SCS decays

- $D^\pm \to K^+ K^- \pi^\pm$, $D^0 \to h^+ h^0$, $D_s \to K_s K^\pm$, $D_s \to K_s \pi^\pm$, $D^0 \to K^+ K^-$, $D^0 \to \pi^+ \pi^-$, decays with $\eta$ ...
- SCS decays are unique - probe gluonic penguin operators.
- CP asymmetry generated from interference of tree-level and penguin-level amplitudes.
- In SM effects up $10^{-3}$ may be observable with NP models generating $\sim 10^{-2}$. [Grossman, Kagan, Nir PRD 75, 036008 (2007)]
- Source of new physics most likely contributes to decay via loop-diagrams.

$$A(D \to f) \equiv A_f = |A_1|e^{i\delta_1}e^{i\phi_1} + |A_2|e^{i\delta_2}e^{i\phi_2}, \quad \Delta \delta \neq 0, \Delta \phi \neq 0$$

$$A_{CP} = \frac{2|A_1 A_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|A_1|^2 + |A_2|^2 + 2A_1 A_2 \cos(\delta_2 - \delta_1)}$$
D⁰ decays to CP-even Eigenstates K⁺K⁻, π⁺π⁻

For final CP eigenstates, indirect CPV is universal. Difference in time-integrated CP asymmetry separates non-universal direct CPV contribution.

\[ \Delta A_{CP}^{direct} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \]

HFAF world average: \( \Delta A_{CP} = (-0.329 \pm 0.121)\% \)

LHCb D⁰ production modes: (1) inclusive semileptonic b-hadron decays (2) direct production of charm \( D^{*+} \rightarrow D^0\pi_s \)

Measurement (1): \( \Delta A_{CP} = (0.49 \pm 0.30 \pm 0.14)\% \) [arXiv 1303.2614]

Measurement (2): \( \Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\% \) [LHCb-CONF-2013-003]

Belle (ICHEP 2012 976 fb⁻¹)
[arXiv: 1212.5320]

\( \Delta A_{CP} = -0.87 \pm 0.41 \pm 0.06 \)

Belle preliminary using 976/fb
Search for CPV in presence of indirect CPV from K⁰ mixing

\[ A_{CP} = \frac{\mathcal{B}(D^+_s \rightarrow K^0_S(\pi^+,K^+)) - \mathcal{B}(D^-_s \rightarrow K^0_S(\pi^-,K^-))}{\mathcal{B}(D^+_s \rightarrow K^0_S(\pi^+,K^+)) + \mathcal{B}(D^-_s \rightarrow K^0_S(\pi^-,K^-))} \]

- \[ D^\pm_s \rightarrow K^0_S K^\pm \] Proceeds through CF and DCS transitions. CF dominates - single phase and no SM CPV.
- \[ D^\pm \rightarrow K^0_S \pi^\pm \]

No CF transition - amplitude for tree-level and penguin level are comparable. Penguin amplitude has relative weak phase to tree-amplitude - relevant interference.

CPV contribution from K⁰ mixing [PDG 2012]: \(+ (-) 0.332 \pm 0.006 \) % when K⁰ (\overline{K}⁰) in final state.

\[ A_{D^+ \rightarrow K^0_S \pi^+} \]

Belle has most precise measurement for direct CPV in charm. All channels analyzed by BaBar and Belle. Results consistent with CPV from K⁰ mixing.
Search for CPV in presence of indirect CPV from $K^0$ mixing

\[ D^\pm_{(s)} \rightarrow K^0_S h^\pm \quad \Rightarrow \quad A_{rec}^{D^+} = \frac{N^+_{rec} - N^-_{rec}}{N^+_{rec} + N^-_{rec}} \]

Reconstructed asymmetry $A_{rec}$ contributions:

1. CPV from the decay of the charm meson - what we want to measure
2. CPV in the $K^0$ system, depends on the $K_S^0$ lifetime [Grossman and Nir, JHEP 4 (2012), 2]
3. Production asymmetry of the D meson, odd as a function of the D meson polar angle in the center-of-mass. Extract directly by measuring reconstructed asymmetry in intervals of the polar angle.
4. Detection asymmetry of the $\pi^\pm$ or the $K^\pm$. Corrected from the detection efficiency measured from high-statistics control samples.
5. Dilution asymmetry from different nuclear cross-sections.

Belle 977 fb^{-1} PRL 109, 021601 (2012)
Direct CPV Searches in Dalitz plot decays

Decouple localized and DP-integrated $A_{CP}$

**CP asymmetry can be:**

- Localized in a specific part of the Dalitz plot.
- Integrated over the entire phase space.

**The two must be decoupled:**

- Obtain phase-space integrated asymmetry.
- Model independent techniques require normalizing $D^+$ and $D^-$ events to have same integrated yield. Measure the ratio of efficiency corrected yields $R$.
- Model dependent - measure asymmetry in a particular resonance. Magnitudes / phases w.r.t. to one resonance, e.g. $K^*0(892)$

Probing for direct CPV with SCS Dalitz plot decays take advantage of final state interactions.

Final state interactions can affect / produce amplitudes of resonances and strong phases.

Important for CP violation studies since small NP CP phases can be enhanced in localized regions of Dalitz plot and differential observables can shed light on the mechanisms at play.
As with two-body measurements, phase-space integrated direct CPV measured as function of the production angle.

- $A_{\text{rec}}$ has several contributions: $A_{FB}$, $A_{K,\pi}$, ... additional asymmetries must be accounted for.

**Analysis techniques of BaBar and Belle - complementary but different**

- Belle uses larger dataset of SCS and CF decays to search for CPV in $D^{\pm} \rightarrow \phi \pi^\pm$.

- Belle measures asymmetry difference between the SCS decay $D^{\pm} \rightarrow \phi \pi^\pm$ and the CF decay $D_s^{\pm} \rightarrow \phi \pi^\pm$.

\[
\Delta A_{\text{rec}} = \frac{N(D^+) - N(D^-)}{N(D^+) + N(D^-)} - \frac{N(D_s^+) - N(D_s^-)}{N(D_s^+) + N(D_s^-)}
\]

- BaBar measures phase-space integrated $A_{CP}$ and searches for CPV in localized regions of the Dalitz plot and the resonances.

- BaBar measures asymmetry from efficiency-corrected yields and relies on the reconstruction efficiency determined from phase-space generated Monte Carlo (MC) events, correcting for additional asymmetries not accurately modeled in the MC from the data.

- Advantage that the systematic uncertainties can be evaluated equally for model-independent, phase-space integrated, and Dalitz plot amplitude analysis and the efficiency is a function of the Dalitz plot.

\[
A(\cos(\theta_{\text{CM}})) = \frac{N_D^+/\epsilon_D^+ - N_D^-/\epsilon_D^-}{N_D^+/\epsilon_D^+ + N_D^-/\epsilon_D^-}
\]
Overview of Methods

Asymmetry in bins of production angle.

Model Independent Techniques [BaBar]

Normalized Residuals

\[ \Delta \equiv \frac{n(D^+) - Rn(D^-)}{\sqrt{\sigma^2(D^+) + R^2\sigma^2(D^-)}} \]

Localized CP Asymmetry [BaBar/Belle]

\[ A_{CP} = \frac{N(D^+) - RN(D^-)}{N(D^+) + RN(D^-)} \]

Dalitz Plot Analysis [BaBar]
**D^± → K^+K^-π^± Dalitz plot Analysis**

Unbinned Maximum likelihood fit to determine best model to test for CPV in the resonant and non-resonant structure of the Dalitz plot.

**Likelihood function**

$$-2 \ln \mathcal{L} = -2 \sum_{i=1}^{N} \ln \left[ p(m_i) \epsilon_{MC}(x_1, x_2) S(x_1, x_2) \int \epsilon_{MC}(x_1, x_2) S(x_1, x_2) dx_1 dx_2 \right] + \left(1 - p(m_i)\right) \frac{B(x_1, x_2)}{\int B(x_1, x_2) dx_1 dx_2}$$

**Mass-dependent signal probability**

$$p(m_i) = \frac{S(m_i)}{S(m_i) + B(m_i)}$$

**MC efficiency as a function of DP position corrected for differences in production and tracking efficiency asymmetry**

$$\epsilon_{MC} \rightarrow \epsilon'_{MC} = P_R (P_{CM} \cdot \cos(\theta)_{CM}) R_{Track} \epsilon_{MC}$$

$$S(x_1, x_2) = \text{Isobar model for the decay of the D meson}$$

$$B(x_1, x_2) = \text{Background modeled from data sidebands}$$

**χ²/ndof = 1.2**

Fit masses & widths of several resonances. 

**f₀(980) effective parameterization from D_s → KKπ**

Several Kπ s-wave parameterizations tested:

best fit obtained from K*(1430)⁰ + κ + non-resonant.
\[ D^{\pm} \rightarrow K^{\pm}K^{-}\pi^{\pm} \] Dalitz plot CP Asymmetry

\[ \text{D}^+/\text{D}^- \text{ difference in data and model. Correct for integrated difference (R = 1.02 \pm 0.006).} \]

<table>
<thead>
<tr>
<th>Resonance</th>
<th>( r ) (%)</th>
<th>( \Delta \phi ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^*(892)^0 )</td>
<td>0. (FIXED)</td>
<td>0. (FIXED)</td>
</tr>
<tr>
<td>( K^*_0(1430)^0 )</td>
<td>-9.40(^{+5.65}_{-5.36}) (\pm 4.42)</td>
<td>-6.11(^{+3.29}_{-3.24}) (\pm 1.39)</td>
</tr>
<tr>
<td>( \phi(1020) )</td>
<td>0.35(^{+0.82}_{-0.82}) (\pm 0.60)</td>
<td>7.43(^{+3.55}_{-3.50}) (\pm 2.35)</td>
</tr>
<tr>
<td>NR</td>
<td>-14.30(^{+11.67}_{-12.57}) (\pm 5.98)</td>
<td>-2.56(^{+7.01}_{-6.17}) (\pm 8.91)</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>2.00(^{+5.09}_{-4.96}) (\pm 1.85)</td>
<td>2.10(^{+2.42}_{-2.45}) (\pm 1.01)</td>
</tr>
<tr>
<td>( a_0(1450)^0 )</td>
<td>5.07(^{+6.86}_{-6.54}) (\pm 9.39)</td>
<td>4.00(^{+4.04}_{-3.96}) (\pm 3.83)</td>
</tr>
</tbody>
</table>

\[ f_0(980) \quad \Delta x = -0.199^{+0.106}_{-0.110} \pm 0.084 \]
\[ f_0(1370) \quad \Delta y = -0.231^{+0.100}_{-0.105} \pm 0.079 \]

Allow different amplitude for \(\text{D}^+/\text{D}^-\) events

\[ \mathcal{A} = \sum_i \mathcal{M}_i e^{i\phi_i} F_i \quad \bar{\mathcal{A}} = \sum_i \mathcal{M}_i e^{i\bar{\phi}_i} F_i \]

**CP Violating Parameters**

\[ r_i = \frac{|\mathcal{M}_i|^2 - |\bar{\mathcal{M}}_i|^2}{|\mathcal{M}_i|^2 + |\bar{\mathcal{M}}_i|^2} \]
\[ \Delta \phi_i = \phi_i - \bar{\phi}_i \]

\[ x(D^\pm) = x \pm \Delta x/2 \]
\[ y(D^\pm) = y \pm \Delta y/2 \]

Dominant systematics are model-dependent.
Good fit of Dalitz plot \(\chi^2/\text{ndof} = 1.2\).
Requires additional resonances to describe signal events.
These resonances contribute to \(~1\%\) of fit fraction. Assume no CP violation in these resonances.
Direct CPV in $D^\pm \rightarrow K^+K^-\pi^\pm$

BaBar [PRD 87, 052010 (2013)]
$A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$

Belle [PRL 108, 071801 (2012)]
$A_{CP} (D^\pm \rightarrow \phi \pi^\pm) = (0.51 \pm 0.28 \pm 0.05)\%$

No evidence of CP violation measured as a function of the center-of-mass polar angle of $D^+$ meson.

BaBar studied the asymmetry as a function of the Dalitz plot. No evidence for CP violation found in the Dalitz plot amplitude analysis or with model-independent techniques.
Conclusions

- The current data samples from the B-factories are being used effectively to complete many analyses of mixing and CP violation in Charm decays.

- Hints of CP violation in charm sector -- cannot rule out SM or NP.

- Evidence for mixing approaching $5\sigma$ for individual B-factory results. All consistent with no CP violation.

- Direct CP Violation in Charm decays not observed at the $e^+e^-$ collider experiments.
Flavor Mixing and CP Violation

- Flavor mixing occurs when flavor eigenstates differ from the mass eigenstates: experimentally observed in neutral K, B_d, B_s, and in the D system at the B factories.

\[ |D_{1,2}^0\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \]

\[ |p|^2 + |q|^2 = 1 \]

\[ |A_f/\bar{A}_f| \neq 1 \]

\[ r_m = |q/p| \neq 1 \]

\[ \left( \frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{1}{2} \Gamma_{12}^*}{M_{12} - \frac{1}{2} \Gamma_{12}} \]

\[ \phi_f = \text{arg} \left( \frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 0 \]
**Two-body $D_{(s)}$ decays with $K_S^0$ in final state**

**BaBar results**

- PRD 83, 071103(R) (2011)
- PRD 87, 052012 (2013)

**Belle results**

- PRL 104, 181602(2010)
- PRL 109, 021601 (2012)
- JHEP 02 098 (2013)

**BaBar results completed with the full data set**

<table>
<thead>
<tr>
<th>Decay</th>
<th>BaBar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^\pm \to K_S^0 \pi^\pm$</td>
<td>$(-0.44 \pm 0.13 \pm 0.10)%$</td>
<td>$(-0.363 \pm 0.094 \pm 0.067)%$</td>
</tr>
<tr>
<td>$D_s^\pm \to K_S^0 K^\pm$</td>
<td>$(-0.05\pm0.23\pm0.25)%$</td>
<td>$(0.12\pm0.36\pm0.22)%$</td>
</tr>
<tr>
<td>$D^\pm \to K_S^0 K^\pm$</td>
<td>$(0.13\pm0.36\pm0.25)%$</td>
<td>$(-0.16 \pm 0.58 \pm 0.25)%$</td>
</tr>
<tr>
<td>$D_s^\pm \to K_S^0 \pi^\pm$</td>
<td>$(0.6\pm2.0\pm0.3)%$</td>
<td>$(5.45\pm2.50\pm0.33)%$</td>
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**Full dataset**

Results include SM contribution of indirect CPV from $K^0$ mixing.
D^± → K^+K^-\pi^± Dalitz plot Analysis

- Neural network describes the Dalitz plot efficiency.
- Combined parametric and non-parametric model to describe the background (using the sidebands)
- S-wave dependence near the φ(1020) resonance taken from D_s→KKπ analysis [PRD 83, 052001 (2011)]
- Several models tested for Kπ S-wave.
- Two step unbinned maximum likelihood fit:
  - Assume no CP asymmetry and find the Dalitz plot model which best describes the data (determined from the goodness-of-fit).
  - Allow for CP asymmetry in the dominant resonances.

Broad structure over large region of Dalitz plot

φ(1020)
\[ D_s^+ \rightarrow K^+K^-\pi^+ \text{ PWA} \]

Effective S-wave parameterization

\[ \sqrt{4\pi} \langle Y_0^0 \rangle = |S|^2 + |P|^2 \]

\[ \sqrt{4\pi} \langle Y_1^1 \rangle = 2|S||P| \cos \phi_{SP} \]

\[ \sqrt{4\pi} \langle Y_2^2 \rangle = \frac{2}{\sqrt{5}} |P|^2 \]

Simultaneous Binned Fit:
- \( S \equiv C_{f_0(980)} A_{f_0(980)} \)
- \( P \equiv C_{\phi} A_{\phi} \)
- \( S + P \equiv C_{\phi} A_{\phi} + C_{f_0(980)} e^{i\delta} A_{f_0(980)} \)

Fitting Model

\[ A_{\phi} = \frac{F_{\pi} F_D}{m_0^2 - m^2 - im_0 \Gamma} \times (-4pq) \text{ Relativistic Breit-Wigner} \]

\[ A_{f_0(980)} = \frac{1}{m_0^2 - m^2 - im_0 \Gamma_0 \rho_{KK}} \]
Kπ S-wave Model

- Isobar Model -- Kappa + K*(1430)0 + Non-resonant amplitude.

- Model-Independent partial wave MIPWA (E791). [PRD 73, 032004 (2006)]

- K-matrix approach, reduces to Kπ scattering amplitude from LASS. Parameterization from D0→K_Sπ⁺π⁻ mixing analysis. [PRL 105, 081803 (2010)]

\[ T_R = B e^{i \phi_B} \left( \frac{\cos \phi_B + \cot \delta_B \sin \phi_B}{q(s) \cot \delta_B - i q(s)} \right) + R e^{i \phi_R} e^{i 2(\delta_B + \phi_B)} \frac{m_R \Gamma_R m_R^2}{m_R^2 - s - i m_R \Gamma(s)} \]

with

\[ q(s) \cot \delta_B = \frac{1}{a} + \frac{r q(s)^2}{2} \]

and

\[ e^{i 2 \delta_B} = \frac{q(s) \cot \delta_B + i q(s)}{q(s) \cot \delta_B - i q(s)} \]
T-odd Observables

I.I. Bigi hep-ph/0107102

- Assuming CPT invariance, T-violation implies CP violation.
- $C_T$ observable is odd under T-reversal

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

- Final-state interactions (FSI) may introduce T-odd asymmetries $A_T \neq 0$.
- Measuring the T-violating observable removes FSI effects:

$$A_T \equiv \frac{1}{2} (A_T - \bar{A}_T)$$
BaBar Results

T-odd Observables

\[ A_T(D^+) = (+11.2 \pm 14.1_{\text{stat}} \pm 5.7_{\text{syst}}) \times 10^{-3} \]
\[ \bar{A}_T(D^-) = (+35.1 \pm 14.3_{\text{stat}} \pm 7.2_{\text{syst}}) \times 10^{-3} \]
\[ A_T(D_s^+) = (-99.2 \pm 10.7_{\text{stat}} \pm 8.3_{\text{syst}}) \times 10^{-3} \]
\[ \bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\text{stat}} \pm 10.7_{\text{syst}}) \times 10^{-3} \]

520 fb\(^{-1}\)
FSI effects appear larger in \(D_s\)

T-violating observable consistent with 0.

X10 improvement over previous result.

\[ A_T(D^0) = (+1.0 \pm 5.1_{\text{stat}} \pm 4.4_{\text{syst}}) \times 10^{-3} \]

PRD 84, 031103 (R) (2011)
PRD 81, 111103 (R) (2010)