Singly Cabibbo Suppressed Charm Decays:
CP Violation, Branching Ratio Measurement, and Amplitude Analysis

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Outline

CP Violation

The weak force, unlike the strong and electromagnetic forces, does not obey the C or P symmetries.

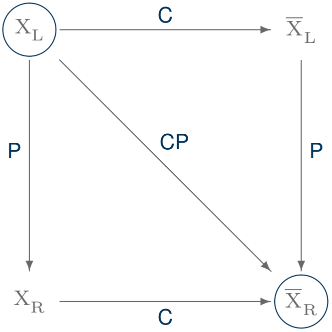
In fact, it maximally breaks them:

$$\mathcal{A}_{\mathrm{C}}^{\mathrm{W}} \equiv \frac{\Gamma_{\mathrm{W}}(\mathrm{X_L}) - \Gamma_{\mathrm{W}}(\overline{\mathrm{X}}_{\mathrm{L}})}{\Gamma_{\mathrm{W}}(\mathrm{X_L}) + \Gamma_{\mathrm{W}}(\overline{\mathrm{X}}_{\mathrm{L}})} = 1,$$

$$\mathcal{A}_{\mathrm{P}}^{\mathrm{W}} \equiv \frac{\Gamma_{\mathrm{W}}(\mathrm{X_L}) - \Gamma_{\mathrm{W}}(\mathrm{X_R})}{\Gamma_{\mathrm{W}}(\mathrm{X_L}) + \Gamma_{\mathrm{W}}(\mathrm{X_R})} = 1.$$

But the same does not hold necessarily for CP:

$$\mathcal{A}_{\mathrm{CP}} \equiv \frac{\Gamma_{\mathrm{W}}(\mathrm{X_L}) - \Gamma_{\mathrm{W}}(\overline{\mathrm{X}}_{\mathrm{R}})}{\Gamma_{\mathrm{W}}(\mathrm{X_L}) + \Gamma_{\mathrm{W}}(\overline{\mathrm{X}}_{\mathrm{R}})} \in (-1, 1).$$



How do we as *Particle Physicists* study it?

We look for CP Violation in the quark sector by looking for asymmetries in the decays of heavy quarks into light quarks:

$$\mathrm{b} \rightarrow \mathrm{c},\ \mathrm{s},\ \mathrm{d},\ \mathrm{u}$$

$$\mathrm{c} \rightarrow \mathrm{s},\ \mathrm{d},\ \mathrm{u}.$$

We measure decay rate asymmetries:

$$\mathcal{A}_{\mathsf{CP}} = \frac{\Gamma_{\mathrm{c}} - \Gamma_{\overline{\mathrm{c}}}}{\Gamma_{\mathrm{c}} + \Gamma_{\overline{\mathrm{c}}}}.$$

Singly-Cabibbo-Suppressed Decays ...

A Singly Cabibbo Suppressed (SCS) decay involves a vertex connecting c with d, *or* u with s.

This leads to amplitudes involving the CKM parameter V_{cd} *or* V_{us}, both of which have magnitude $\cos\theta_{\mathrm{c}} \simeq 22\%$.

These are suppressed relative to the decays involving only the diagonal elements of the CKM matrix. But are not as suppressed as decays involving V_{cd} *and* V_{us} ($\cos^2\theta_{\mathrm{c}} = 5\%$), which are called Doubly Cabibbo Suppressed (DCS).

... As a Probe for New Physics

The Standard Model predicts CPV smaller than $\mathcal{O}(10^{-3})$ for SCS D decays. A signal at the present level of experimental sensitivity, $\mathcal{O}(10^{-2})$, would clearly signal NP (arXiv:hep-ph/0609178).

The neutral D system probes (supersymmetric) NP models in which the up sector plays a special role.

SCS decays are sensitive to NP contributions to penguin and dipole operators.

Reasoning on SU(3) flavor symmetry, order-of-magnitude estimates and sum rules for the SCS D decays were calculated by
Grossman, Kagan, Zupan; arXiv:1204.3557
Atwood, Soni; arXiv:1211.1026

A Sign of New Physics?

The $\Delta\mathcal{A}_{\mathrm{CP}}$ surprise

The diagrams of $\mathrm{D}^0 \to \pi^+\pi^-$ and $\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-$ are the same but for down quarks swapped for strange quarks. SU(3)$_{\mathrm{I}}$ of $\{\mathrm{u}, \mathrm{d}, \mathrm{s}\}$ leads to

$$\mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-) \simeq -\mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^+\pi^-) \simeq \frac{1}{2}\Delta\mathcal{A}_{\mathrm{CP}},$$

$$\begin{aligned}
\Delta\mathcal{A}_{\mathrm{CP}} &\equiv \mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-) - \mathcal{A}_{\mathrm{CP}}(\mathrm{D}^0 \to \pi^+\pi^-) \\
&= (-0.82 \pm 0.21 \pm 0.11)\ \% \qquad [\text{LHCb, arXiv:1112.0938}] \\
&= (-0.62 \pm 0.21 \pm 0.10)\ \% \qquad [\text{CDF, arXiv:1207.2158}] \\
&= (-0.43 \pm 0.30 \pm 0.11)_{\mathrm{K}^+\mathrm{K}^-}\ \% \\
&- (+0.43 \pm 0.52 \pm 0.12)_{\pi^+\pi^-}\ \% \qquad [\text{Belle, arXiv:0807.0148}]
\end{aligned}$$

Though current LHCb results shift smaller:

$$\begin{aligned}
(0.49 \pm 0.30 \pm 0.14)\ \% &\qquad [\text{from } \mathrm{B}\text{, arXiv:1303.2614}] \\
(-0.34 \pm 0.15 \pm 0.10)\ \% &\qquad [\text{from } \mathrm{D}^*\text{, LHCb-CONF-2013-003}]
\end{aligned}$$

OK, But Belle is a B Factory

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Yes, Belle is a B Factory. But it produces just as much $\mathrm{c\bar{c}}$ as $\mathrm{b\bar{b}}$.

How do we find our decays?

We don't have the benefit of $\mathrm{e^-e^+} \to \mathrm{B\overline{B}}$ for nice event variables like M_{beam} and ΔE.

But if we look at the decay chain $\mathrm{D^*} \to \pi_{\mathrm{s}}\mathrm{D} \to \mathrm{X}$, we can use the variables: M_{D} and

$$q \equiv M_{\mathrm{D^*}} - M_{\mathrm{D}} - m_{\pi_{\mathrm{s}}},$$

which is the energy released in the $\mathrm{D^*}$ decay. The charge of the π_{s} is used to determine the flavour of the D (i.e. if it is a D or a $\overline{\mathrm{D}}$).

In practice, it's often best to use $(M_{\mathrm{D}})^2$ and $\sqrt{q}$, since the first is a kinematic invariant and the second corresponds to phase space volume more closely.

$D^{\pm} \to \pi^{\pm}\pi^{0}$

$D^{\pm} \to \pi^{\pm}\pi^{0}$

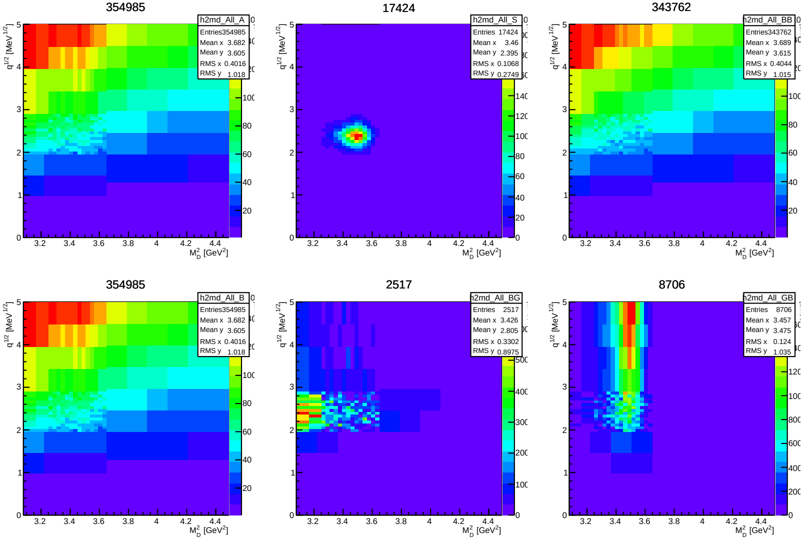
Currently the only measurement of $\mathcal{A}_{\mathrm{CP}}(\pi^{\pm}\,\pi^{0})$ comes from CLEO-c:

$$\mathcal{A}_{\mathrm{CP}}(D^{\pm} \to \pi^{\pm}\pi^{0}) = (2.9 \pm 2.9 \pm 0.3)\ \%$$

from arXiv:0906.3198, measured at the $\psi(3770)$ resonance with an integrated luminosity of $586\,\mathrm{pb}^{-1}$.
2649 ± 76 decays with an efficiency of $(48.69 \pm 0.15)\%$.

$D^\pm \to \pi^\pm \pi^0$

Signal and Background Distributions



$D^0 \to \pi^+\pi^-\pi^+\pi^-$

Measurements of Branching Ratios, Amplitude Analysis

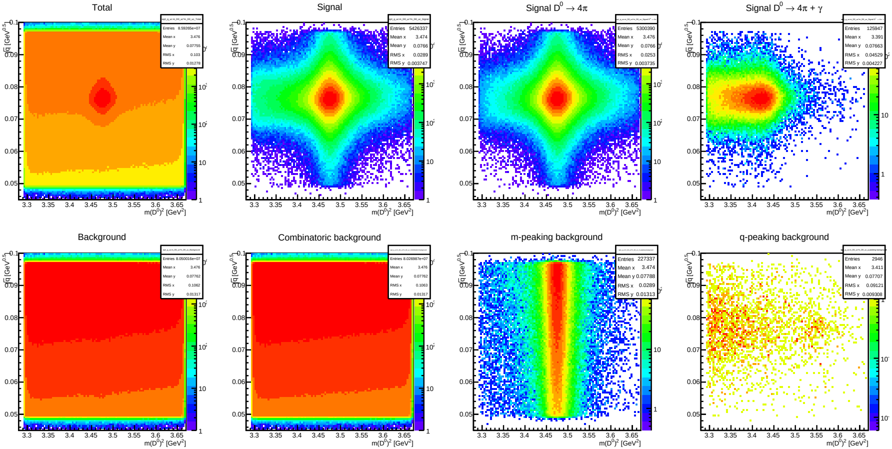
The channel $D^0 \to \pi^+\pi^-\pi^+\pi^-$ is interesting for its rich $\mathcal{A}_{CP}$ studies (for each resonance, and polarization) but also for its rich resonance structure, containing $a_1\pi$, $\rho\rho$, $\sigma\pi\pi$, $f_0\pi\pi$, $f_2\pi\pi$.

Previous measurements of branching rations and CPV:

Experiment	Number of events	Comments and link
BESII	$(274.4 \pm 31.8) - (112.5 \pm 19.0)$	arXiv:hep-ex/0502045
WA82	64 ± 12	http://dx.doi.org/10.1016/0370-2693(92)90791-2
CLEO	345 ± 50	http://dx.doi.org/10.1103/PhysRevD.44.3383
CLEO-c	7331 ± 130	arXiv:hep-ex/0512063
E691	66 ± 12	
E687	79 ± 17	http://dx.doi.org/10.1016/0370-2693(95)00693-F
E687	814 ± 52	http://dx.doi.org/10.1016/0370-2693(92)90292-C
FOCUS (E831)	6360 ± 115	Amplitude analysis. arXiv:hep-ex/0701001
LHCb	3.3×10^5	Model-independent search for CPV, consistent with no CPV. No amplitude analysis.
BaBar		–
Belle	4×10^5	Expected signal events for this analysis.

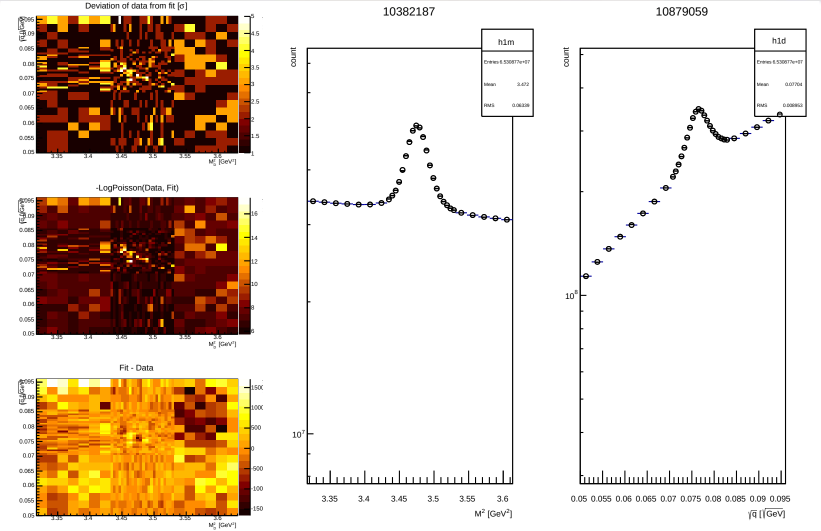
$D^0 \to \pi^+\pi^-\pi^+\pi^-$

MC Signal and Background Distributions



MC Signal and background distributions, $\sqrt{q}$ vs. $m^2_{D^0}$

Fits of Signal and Background Shapes



All

Fits of Signal and Background Shapes

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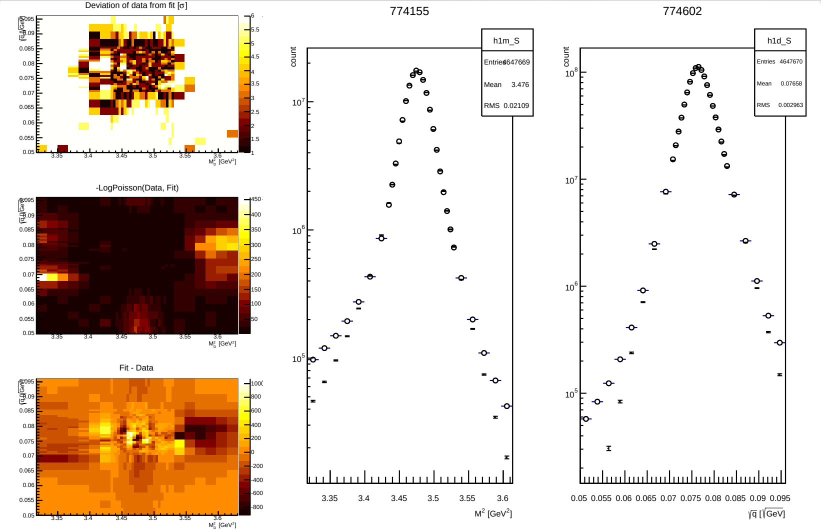
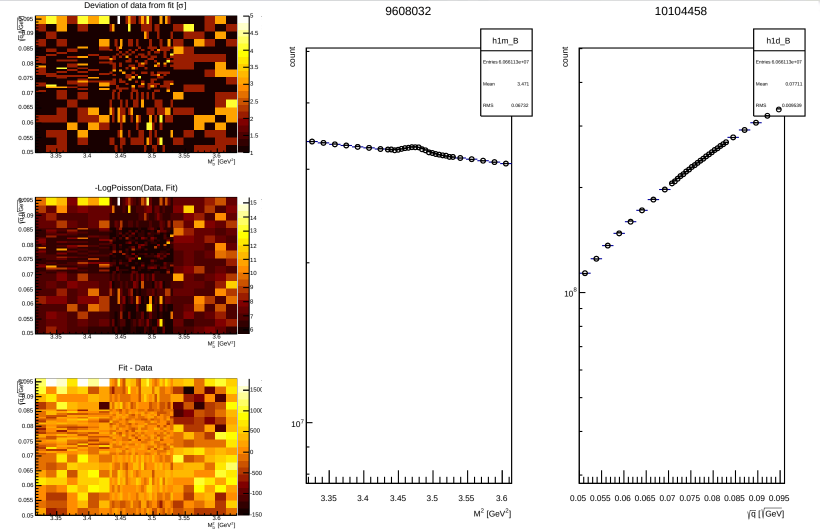


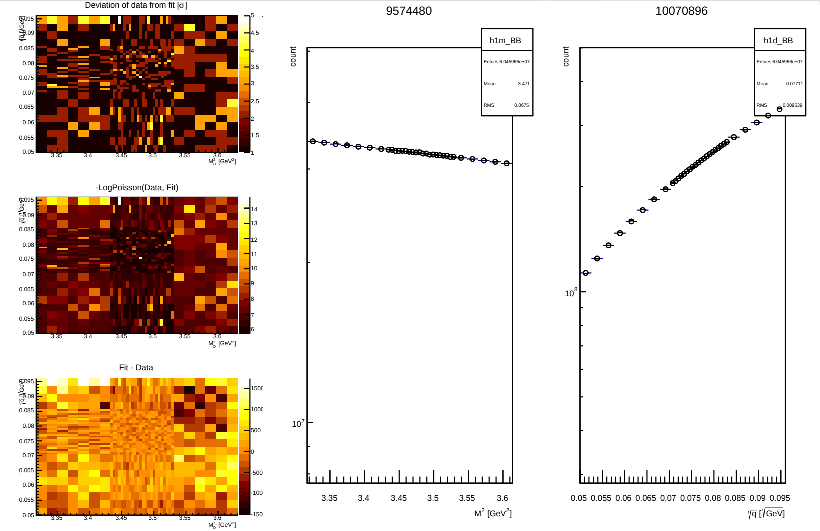
Signal. Double crystal ball (DCB) ($m^2_{D^0}$), DCB ($\sqrt{q}$), bivariate Gaussian ($m^2_{D^0}$, $\sqrt{q}$).

Fits of Signal and Background Shapes



Total Background.

Fits of Signal and Background Shapes



Combinatoric background. Linear ($m^2_{D^0}$), quadratic ($\sqrt{q}$).

Fits of Signal and Background Shapes

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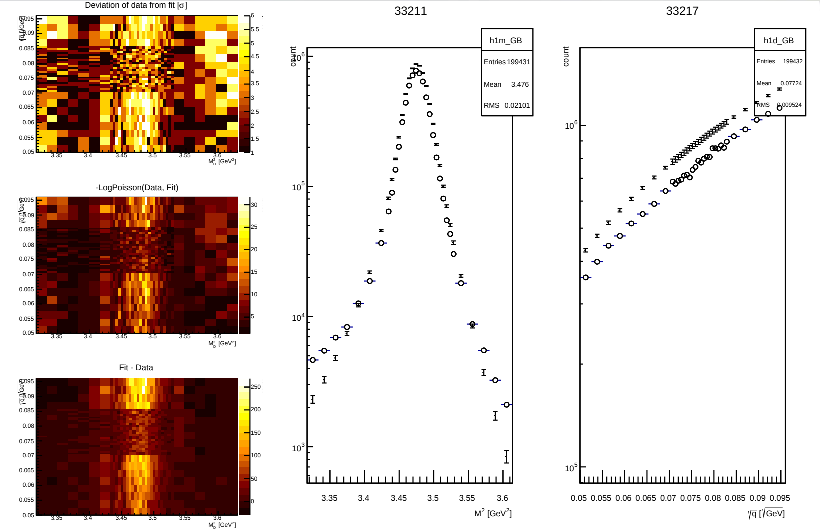

Mass-peaking background. Signal shape ($m^2_{D^0}$), combinatoric background shape ($\sqrt{q}$).

Fits of Signal and Background Shapes

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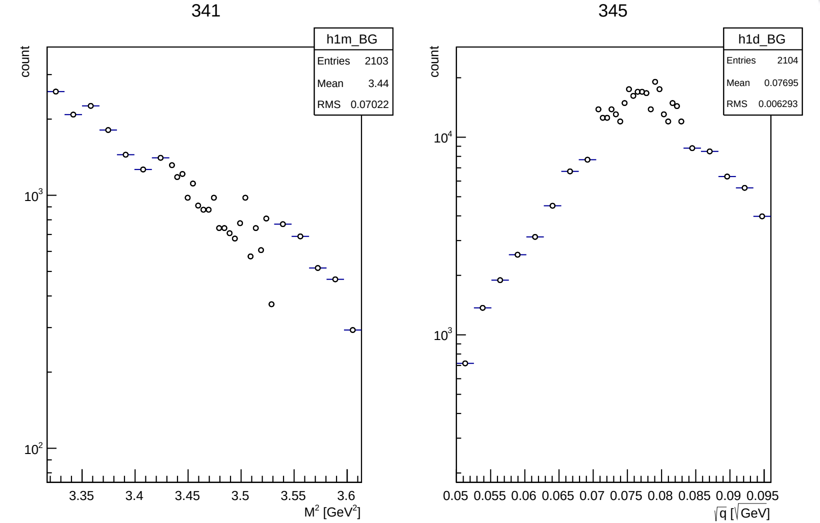

Q-peaking background (not fitted).

$D^{\pm} \rightarrow \pi^{\pm}\pi^{0}$, $D^{0} \rightarrow \pi^{+}\pi^{-}\pi^{+}\pi^{-}$

Current Status of the Analyses

Current status:

- Developed event selection and analysis modules based on MC.
- Developed fitting routine for signal- and background-shapes and yields. The fits are done with the Bayesian Analysis Toolkit (BAT) with Markov Chains.

Next steps:

- amplitude analysis on real data.
- CPV analysis with amplitudes from amplitude analysis.

$D^+ \to \pi^+\pi^+\pi^-\pi^0, D^+ \to K^+K^-\pi^+$

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$D^+ \to \pi^+\pi^+\pi^-\pi^0$ [+CP]

A previous analysis in Belle only looked into this channel with $\pi^+ \pi^- \pi^0$ confined to the η mass region.
$D^\pm \to \pi^+\pi^-\pi^\pm\pi^0$ as listed in the PDG contains $\pi^\pm\eta$ and $\pi^\pm\omega$ as intermediate states.

$D^+ \to K^+K^-\pi^+$ [+CP]
$D_s^+ \to K^+K^-\pi^+$ [+CP] (can be used as a CP normalizing channel, i.e. for calibrating $\pi^- \pi^+$ detection asymmetries)

A previous analysis in Belle only looked into this channel with $K^+ K^-$ confined to the ϕ mass region.

We are currently working event selection and cut optimization. We are planning to do amplitude analyses on these channels, which would be the first amplitude analysis of such decays at Belle.

Summary and Outlook

SCS D decays provide a good probe for NP. The Standard Model predicts CPV smaller than $\mathcal{O}(10^{-3})$. A signal at the present level of experimental sensitivity, $\mathcal{O}(10^{-2})$, would clearly signal NP.

We are analyzing several channels and want to search for CPV.

We also want to do amplitude analyses of our channels, which have either not been done before, or with much smaller data sets.

Thank you for your attention!