Quantum correlated measurements at CLEO-c and its CP violation sensitivity in Belle

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Outline

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- Calculation of CP content F_+
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Introduction

CKM angles - current status

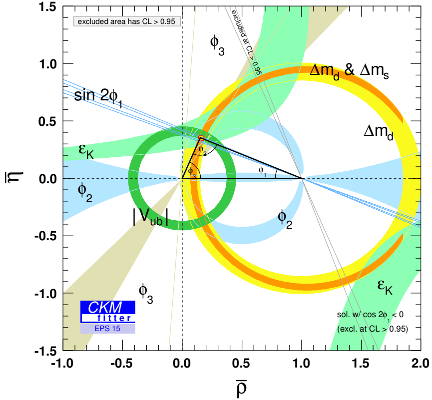


Figure : Constraints on CKM parameters as of 2015 [1].

Current best results for CKM angles

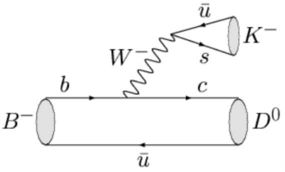
- $\phi_1 = 21.5^{+0.8}_{-0.7}$ deg.
- $\phi_2 = 85.4^{+4.0}_{-3.8}$ deg.
- $\phi_3 = 73.2^{+6.3}_{-7.0}$ deg.

Recent results from LHCb

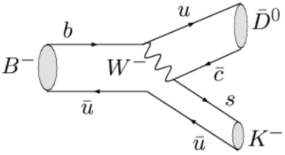
- $\phi_3 = 72.2^{+6.8}_{-7.3}$ deg. [2]

[1] http://ckmfitter.in2p3.fr
[2] arXiv:1611.03076v1 [hep-ex]

- Determine ϕ_3 via interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$



colour allowed
$B^- \to D^0 K^- \approx V_{cb} V_{us}^*$



colour suppressed
$B^- \to \bar{D}^0 K^- \approx V_{ub} V_{cs}^*$

- The above two amplitudes are related by

$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

- $r_B = \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|, \delta_B = \delta(B^- \to \bar{D}^0 K^-) - \delta(B^- \to D^0 K^-)$.
- No loop contribution $\Rightarrow$ **clean way** to measure ϕ_3.

ϕ_3 measurements - different methods

- Gronau - London - Wyler (GLW) method [3]
  - Modes with known CP content (F_+) [4] can be used along with CP eigenstates.
- Giri - Grossman - Soffer - Zupan (GGSZ) method [5]
  - Binned Dalitz plot analysis of multibody D final states like $K_S^0\pi^+\pi^-$, $K_S^0K^+K^-$, $K_S^0\pi^+\pi^-\pi^0$.

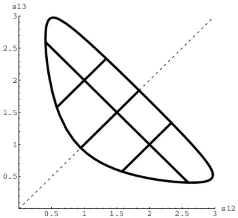


Figure : A typical Dalitz plot binning for a three body D decay.

- For the decay $B^- \to D(K_S^0h^+h^-)K^-$

$$\Gamma_i^- = K_i + r_B^2\bar{K}_i + 2\sqrt{K_i\bar{K}_i}(c_ix_- + s_iy_-),$$

  and for $B^+ \to D(K_S^0h^+h^-)K^+$,

$$\Gamma_i^+ = \bar{K}_i + r_B^2K_i + 2\sqrt{K_i\bar{K}_i}(c_ix_+ - s_iy_+).$$

- $x_\pm = r_B\cos(\delta_B \pm \phi_3)$; $y_\pm = r_B\sin(\delta_B \pm \phi_3)$.
- c_i, s_i - cos and sin of the strong phase difference between D^0 and $\bar{D}^0$ averaged over the region of phase space.

[3] M. Gronau and D. London, Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).

[4] M. Nayak *et al.* (CLEO collaboration), Phys. Lett. B **740**, 1 (2015).

[5] A. Giri, Yu. Grossman, A. Soffer and J. Zupan, Phys. Rev. D **68**, 054018 (2003).

Motivation

- Information on the D decay is required to determine x,y.
- Quantum correlated $D\bar{D}$ mesons produced in e^+e^- collisions at an energy corresponding to $\Psi(3770)$ at CLEO-c can be used.
- A D decay mode not yet used is $K_S^0\pi^+\pi^-\pi^0$.
- The decay $D^0 \to K_S^0\pi^+\pi^-\pi^0$ has a relatively large branching fraction of 5.2% which is almost twice that of $K_S^0\pi^+\pi^-$ [6].
- Interesting resonance substructure.
  - $K_S^0\omega$ - CP eigenstate - GLW like.
  - $K^-\pi^+\pi^0$ - Cabibbo-favored state (CF) - ADS like.
- As powerful as $K_S^0\pi^+\pi^-$ in the determination of ϕ_3?

[6] C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C **40**, 100001 (2016).

CLEO-c and quantum correlation

Quantum correlated D mesons at CLEO-c

- $\Psi \to D\bar{D}$ are produced coherently in the $C = -1$ state.

$$\frac{\left(|D\rangle\,|\bar{D}\rangle - |\bar{D}\rangle\,|D\rangle\right)}{\sqrt{2}}$$

- If $\Psi(3770)$ decays into two states F and G, then decay rate (Γ) depends on their CP eigenvalue.

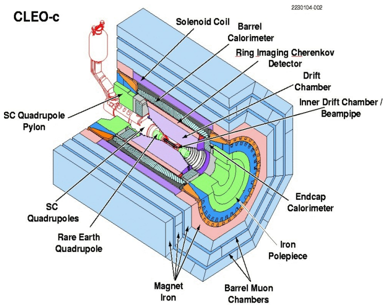


Figure : CLEO-c detector.

- $F = \mathrm{CP\ even\ (odd)}$, $G = \mathrm{CP\ odd\ (even)} \Rightarrow$ two-fold enhancement.
- $F = \mathrm{CP\ even\ (odd)}$, $G = \mathrm{CP\ even\ (odd)} \Rightarrow$ zero.
- Γ changes with F or G being quasi CP states $(\pi^+\pi^-\pi^0)$ or self conjugate states $(K_S^0\pi^+\pi^-)$.

CLEO-c data sample and signal selection

- A total of 818 pb^{-1} data collected at the CLEO-c - $D\bar{D}$ pairs from the $\Psi(3770)$.
- One of the D mesons reconstructed to $K_S^0\pi^+\pi^-\pi^0$ (signal) and the other one to any other channel (tag).

- Fully reconstructed modes - M_{bc} and ΔE.
- Partially reconstructed modes - missing mass technique.

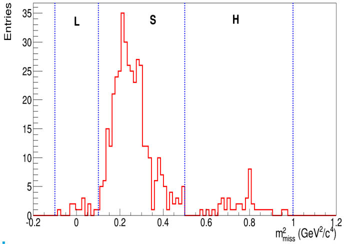


Figure : M^2_{miss} plot for $K_L^0\pi^0$ tag for the data sample.

Type	mode	yield
CP even tags	K^+K^-	200.7 ± 14.2
	$\pi^+\pi^-$	91.45 ± 9.59
	$K_S^0\pi^0\pi^0$	106.3 ± 10.9
	$K_L^0\pi^0$	357.3 ± 20.2
	$K_L^0\omega$	162.1 ± 13.7
CP odd tags	$K_S^0\pi^0$	93.97 ± 9.84
	$K_S^0\eta$	11.64 ± 3.68
	$K_S^0\eta'$	7 ± 3
Quasi CP tags	$\pi^+\pi^-\pi^0$	428.8 ± 21.7
Self conjugate tags	$K_S^0\pi^+\pi^-$	504.8 ± 23.3
	$K_L^0\pi^+\pi^-$	864.1 ± 46.1
	$K_s^0\pi^+\pi^-\pi^0$	176.4 ± 14.8
Flavour tag	$K^\pm e^\mp\nu$	1010 ± 32

Calculation of F_+

CP content (F_+)

- The double tagged yield for the signal and tag

$$M(S|T) = 2N_{D\bar{D}} \times BF(S) \times BF(T) \times \epsilon(S|T) \times [1 - \lambda_{CP}(2F_+ - 1)] \,.$$

- The single tag yield

$$S(T) = 2N_{D\bar{D}} \times BF(T) \times \epsilon(T).$$

- If we assume $\epsilon(S|T) = \epsilon(S)\epsilon(T)$, then we get N^+ for CP odd tag and N^- for CP even tag as follows:

$$N^{\pm} = \frac{M(S|T)}{S(T)} = BF(S) \times \epsilon(S) \times [1 - \lambda_{CP}(2F_+ - 1)] \,.$$

- From these, we can calculate F_+ as

$$F_+ = \frac{N^+}{N^+ + N^-}; \qquad F_+ = 1 \Rightarrow \text{CP even}, F_+ = 0 \Rightarrow \text{CP odd}.$$

Calculation of F_+ - CP tags

- The CP odd and CP even tags are used to evaluate N^+ and N^- respectively.

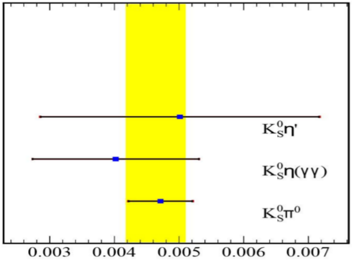


Figure : N^+ values for the CP odd tags. The yellow region shows the average value

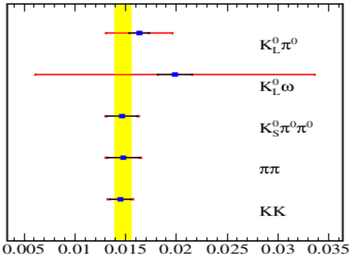


Figure : N^- values for the CP even tags. The yellow region shows the average value

Note: The x-axis scale for N^+ is much smaller than that of N^-.

- The value of F_+ is obtained to be **0.240±0.021**, *i.e* $K^0_S\pi^+\pi^-\pi^0$ is significantly **CP odd**.

Calculation of F_+ - $\pi^+\pi^-\pi^0$ tag

- F_+ for $\pi^+\pi^-\pi^0 = 0.973 \pm 0.017$ [7].
- Define $N^{\pi^+\pi^-\pi^0}$ as the ratio of double tagged events and $\pi^+\pi^-\pi^0$ single tag events

$$N^{\pi^+\pi^-\pi^0} = \frac{M(K_S^0\pi^+\pi^-\pi^0|\pi^+\pi^-\pi^0)}{S(\pi^+\pi^-\pi^0)}.$$

- Then with N^+ from CP tags, we can get

$$F_+^{K_S^0\pi^+\pi^-\pi^0} = \frac{N^+ F_+^{\pi^+\pi^-\pi^0}}{N^{\pi^+\pi^-\pi^0} - N^+ + 2N^+ F_+^{\pi^+\pi^-\pi^0}}.$$

- With CP and $\pi^+\pi^-\pi^0$ tags, F_+ is **0.244**$\pm$**0.021**.

[7] S. Malde *et.al*, Phys. Lett. B **747**, 9 (2015).

Calculation of F_+ - $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags

- The $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ Dalitz plots are binned according to Equal δ_D BABAR 2008 scheme [8].

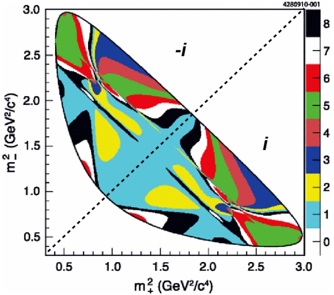


Figure : $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot.

$$Y_i^{K_S^0\pi^+\pi^-} = h_{K_S^0\pi^+\pi^-}\left(K_i^{K_S^0\pi^+\pi^-} + K_{-i}^{K_S^0\pi^+\pi^-} - 2c_i\sqrt{K_i^{K_S^0\pi^+\pi^-} K_{-i}^{K_S^0\pi^+\pi^-}}(2F_+^{K_S^0\pi^+\pi^-\pi^0} - 1)\right).$$

$$Y_i^{K_L^0\pi^+\pi^-} = h_{K_L^0\pi^+\pi^-}\left(K_i^{K_L^0\pi^+\pi^-} + K_{-i}^{K_L^0\pi^+\pi^-} + 2c_i\sqrt{K_i^{K_L^0\pi^+\pi^-} K_{-i}^{K_L^0\pi^+\pi^-}}(2F_+^{K_S^0\pi^+\pi^-\pi^0} - 1)\right).$$

[8] B. Aubert *et al.* (BaBar collaboration), Phys. Rev. D **78**, 034023 (2008).

Calculation of F_+ - $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags

- Fit with 64 observables; $\frac{\chi^2}{\mathrm{DoF}} = 1.3$.

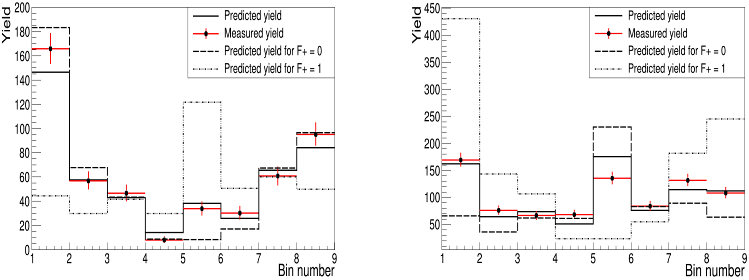


Figure : The predicted and measured yields for $K_S^0\pi^+\pi^-$ (left) and $K_L^0\pi^+\pi^-$ (right).

- F_+ is found to be **0.265±0.029**.
- With all the three methods, the average F_+ is **0.246±0.018**.

Extraction of c_i and s_i

Binning $K_S^0\pi^+\pi^-\pi^0$ phase space

- $N_{\rm bins} > 4 \Rightarrow \phi_3$ extraction in $B^\pm \to DK^\pm$ data in GGSZ framework - requires c_i, s_i, K_i and $\bar{K}_i$.
- Dividing the 5-D phase space of $K_S^0\pi^+\pi^-\pi^0$ - not as trivial as the 2-D phase space of $K_S^0\pi^+\pi^-$ $\Rightarrow$ i and $-i$ symmetry non-trivial.
- Amplitude model not available $\Rightarrow$ a proper optimisation difficult.
- Split the phase-space into a series of bins around the resonances and work out partial rates in each.
- Exclusive binning.

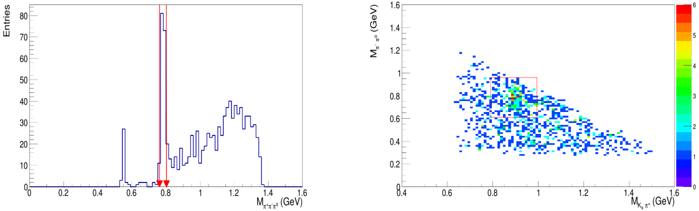


Figure : Invariant mass distribution for $\pi^+\pi^-\pi^0$ (left) and 2-D distribution between the invariant masses of $K_S^0\pi^-$ and $\pi^+\pi^0$ (right).

Extraction of c_i and s_i

- For a CP tag, the double tagged yield is given by

$$M_i^{\pm} = h_{CP}\left[K_i + \bar{K}_i \pm 2\sqrt{K_i\bar{K}_i}c_i\right].$$

For $\pi^+\pi^-\pi^0$ tag, the c_i sensitive term is scaled by $(2F_+ - 1)$ rather than 1.

- For $K_S^0\pi^+\pi^-\pi^0$ double tagged events, the yield is given by

$$M_{ij} = h_{corr}\left[K_i\bar{K}_j + \bar{K}_iK_j - 2\sqrt{K_i\bar{K}_j\bar{K}_iK_j}(c_ic_j + s_is_j)\right].$$

- For $K_S^0\pi^+\pi^-$ tag

$$M_{i\pm j}^{K_S\pi\pi} = h_{K_S\pi\pi}\left[K_iK_{\mp j}^{K_S\pi\pi} + \bar{K}_iK_{\pm j}^{K_S\pi\pi} - 2\sqrt{K_iK_{\pm j}^{K_S\pi\pi}\bar{K}_iK_{\mp j}^{K_S\pi\pi}}(c_ic_j^{K_S\pi\pi} \pm s_is_j^{K_S\pi\pi})\right].$$

- Similarly for $K_L^0\pi^+\pi^-$ tag,

$$M_{i\pm j}^{K_L\pi\pi} = h_{K_L\pi\pi}\left[K_iK_{\mp j}^{K_L\pi\pi} + \bar{K}_iK_{\pm j}^{K_L\pi\pi} + 2\sqrt{K_iK_{\pm j}^{K_L\pi\pi}\bar{K}_iK_{\mp j}^{K_L\pi\pi}}(c_ic_j^{K_L\pi\pi} \pm s_is_j^{K_L\pi\pi})\right].$$

Extraction of c_i and s_i

Bin number	Specification	K_i	$\bar{K}_i$
1	$m(\pi^+\pi^-\pi^0) \approx m(\omega)$	0.222 ± 0.019	0.176 ± 0.017
2	$m(K_S^0\pi^-) \approx m(K^{*-})$ & $m(\pi^+\pi^0) \approx m(\rho^+)$	0.394 ± 0.022	0.190 ± 0.017
3	$m(K_S^0\pi^+) \approx m(K^{*+})$ & $m(\pi^-\pi^0) \approx m(\rho^-)$	0.087 ± 0.013	0.316 ± 0.021
4	$m(K_S^0\pi^-) \approx m(K^{*-})$	0.076 ± 0.012	0.046 ± 0.009
5	$m(K_S^0\pi^+) \approx m(K^{*+})$	0.057 ± 0.010	0.065 ± 0.011
6	$m(K_S^0\pi^0) \approx m(K^{*0})$	0.059 ± 0.011	0.092 ± 0.013
7	$m(\pi^+\pi^0) \approx m(\rho^+)$	0.045 ± 0.009	0.045 ± 0.009
8	Remainder	0.061 ± 0.011	0.070 ± 0.011

- The semileptonic tag $K^{\pm}e^{\mp}\nu$ is used to calculate K_i and $\bar{K}_i$, the fraction of decays in each bin.
- The double tagged yields are given to the fitter along with the c_i, s_i, K_i and $\bar{K}_i$ values for $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ [9] as input.
- Corrected for bin-to-bin migration.

[9] J. Libby *et al.* (CLEO collaboration), Phys. Rev. D **82**, 112006 (2010).

c_i and s_i results - preliminary

- The combined fit: 472 observables including different tag yields in each bin; $\frac{\chi^2}{\mathrm{DoF}} = 1.04$.

Bin	c_i	s_i
1	-1.12 ± 0.12	0.12 ± 0.17
2	-0.29 ± 0.07	0.11 ± 0.13
3	-0.41 ± 0.09	-0.08 ± 0.18
4	-0.84 ± 0.12	-0.73 ± 0.34
5	-0.54 ± 0.13	0.65 ± 0.13
6	-0.22 ± 0.12	1.37 ± 0.22
7	-0.90 ± 0.16	-0.12 ± 0.40
8	-0.70 ± 0.14	-0.03 ± 0.44

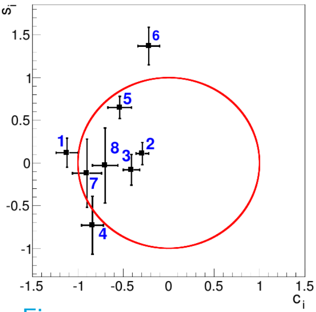


Figure : c_i and s_i values in each bin.

- The uncertainties shown are statistical only.
- $c_i < 0 \Rightarrow$ **CP oddness** of $K_S^0\pi^+\pi^-\pi^0$.

CPV sensitivity in Belle

Estimates of ϕ_3 sensitivity with $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$

- Assumed increase in BF compensated by loss of efficiency due to π^0 in final state.
- With 1200 events (Belle sample of $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$) $\sigma_{\phi_3} = 25^\circ$ - 1000 pseudo experiments using c_i, s_i, K_i and $\bar{K}_i$ measurements reported.
- Project to a 50 ab^{-1} sample $\sigma_{\phi_3} = 3.5^\circ$.
- Compare to $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$ $\sigma_{\phi_3} \sim 2^\circ$.

- Improvements:
  - Optimized binning once a $D^0 \to K_S^0\pi^+\pi^-\pi^0$ amplitude model developed.
  - Finer binning possible with 10 fb^{-1} of BESIII data.
- Caveat: background to be studied.

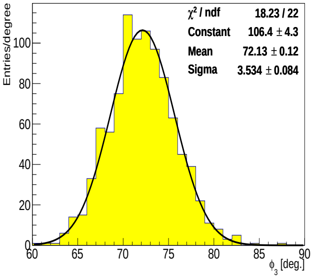


Figure : ϕ_3 sensitivity with 50 ab^{-1} Belle II sample.

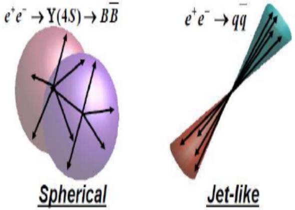
$B^{\pm} \to D(K_S^0\pi^+\pi^-\pi^0)K^{\pm}$ at Belle

- The currently dominant measurement sensitive to ϕ_3 uses $B \to DK^{\pm}$ where D goes to a three-body final state of $K_s^0\pi^+\pi^-$ [10].
- $B^{\pm} \to D(K_s^0\pi^+\pi^-\pi^0)K^{\pm}$ - similar sensitivity.
- GGSZ framework - input from CLEO-c results.
- We propose to use a data sample corresponding to an integrated luminosity of 711 fb^{-1} (772 million $B\bar{B}$ pairs) collected at Belle.
- Variables CM-energy difference $\Delta E = \Sigma E_i - E_{beam}$ and the beam constrained B meson mass $M_{bc} = \sqrt{E_{beam}^2 - (\Sigma\vec{p_i})^2}$.
- The invariant mass of D meson would be constrained to the invariant mass of its decay products.

[10] H. Aihara *et al.* (Belle collaboration), Phys. Rev. D **85**, 112014 (2012).

$B^{\pm} \to D(K_S^0\pi^+\pi^-\pi^0)K^{\pm}$ at Belle

- The background due to $e^+e^- \to q\bar{q}$ with $q = u, d, s, c$ needs to be eliminated from the signal.



- Signal yield to be extracted from an extended maximum likelihood fit in each bin and proceed to study ϕ_3 sensitivity.

Summary

- Calculated the CP content F_+ for the decay $D^0 \to K_S^0\pi^+\pi^-\pi^0$ from CLEO-c data to be $\mathbf{0.246 \pm 0.018}$.
- Addition of this mode to quasi-GLW methods to determine ϕ_3.
- Extracted the strong phase differences by introducing an eight bin scheme for the $K_S^0\pi^+\pi^-\pi^0$ phase space.
- Addition to GGSZ formalism to determine ϕ_3.
- Sensitivity to ϕ_3 from a 50 ab^{-1} sample, $\sigma_{\phi_3} = 3.5^\circ$.