$D^+_{(s)}$ decays and their CPV

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Role of Charm Physics

- Threefold impact of contemporary charm physics
  1. Decay Rates
     ↪ Hadronic decays ⇒ test of $SU(3)$ symmetry and better understanding of decay dynamics
     check talk of Jonas Rademaker given Y-day
     ↪ (Semi-)Leptonic decays ⇒ test LQCD calculations (used in interpretations of results from B sector)
     check talks of Sheldon Stone and Karl Ecklund given Y-day
  2. Spectroscopy
     ↪ D_{sJ}, $c\overline{c}$, ... *see talks in Quarkonia and Beyond session Tomorrow*
  3. **Self-standing field of SM measurements and New Physics searches**
     ↪ $D^0 - \overline{D}^0$ mixing *talk of Nicola Neri in this session*
     ↪ rare decays, e.g. $D^0 \to \ell^- \ell^+$
     ↪ **Search for CP Violation** *talk of M. Martinelli in this session*

This talk is focused on direct CPV in $D^+_{(s)} \to PP$ decays

CPV in charm decays

Baryon number asymmetry in the Universe requires CPV

- observed levels of CPV in B decays not enough $\Rightarrow$ New Physics

Direct CP violation

- two amplitudes needed with different weak (ϕ) and strong phases (δ)
- final state interactions large $\Rightarrow$ $sin\Delta\delta \neq 0$

$$\mathbf{A_{CP}} = \frac{\Gamma(D\to f)-\Gamma(\overline{D}\to \bar{f})}{\Gamma(D\to f)+\Gamma(\overline{D}\to \bar{f})} \propto \mathbf{\sin\Delta\delta\sin\Delta\phi}$$

CPV in charm decays within the SM

- only one (tree) amplitude in CF or DCS decays **(no CPV)**
- **very small weak phase** in SCS decays

$$\hookrightarrow V_{cs} = 1... + \lambda^4 \quad \Rightarrow \quad \mathbf{A_{CP}^{SM}} \sim \mathcal{O}(0.1)\%$$

If $A_{CP} \sim \mathcal{O}(1)\%$ is observed $\Rightarrow$ processes beyond SM.

CPV in $D^+_{(s)} \to PP$ decays

What is so special about $D^+_{(s)} \to K_S h^+$ decays?

- $D^+ \to K_S\pi^+$ appears to be a CF mode, however the same final state can be reached through a DCS amplitude

  $\hookrightarrow D^+ \to \overline{K}^0\pi^+ / K^0\pi^+ \to K_S\pi^+$

  $\star$ two interfering amplitudes generate asymmetry $\sim \mathcal{O}(10^{-4})$

- The CP impurity in the K_S wave function induces larger asymmetry

  $\star$ $A_{CP}(D^+ \to K_S\pi^+) \simeq \frac{|q_K|^2-|p_K|^2}{|q_K|^2+|p_K|^2} \simeq -(0.332 \pm 0.006)\%$

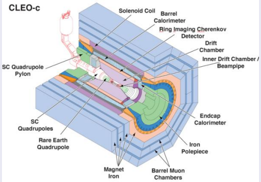
Experimental challenges in A_{CP} measurements

- one has to aim for 10^{-3} sensitivity levels
- *CPV* can be faked by detector biases, production asymmetries, etc.

Large samples and good control over systematics are needed!

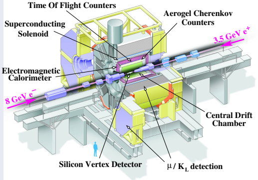
Data samples used in presented measurements

Cleo-c

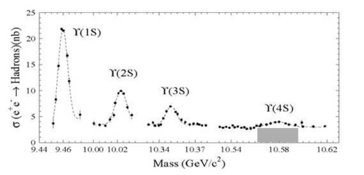


- 0.818/fb at $\psi(3770)$
  - $\star$ 2.4×10^6 D^+D^- pairs
- 0.586/fb at $\psi(4170)$
  - $\star$ 0.54×10^6 $D_s^{*\pm}D_s^{\mp}$ pairs

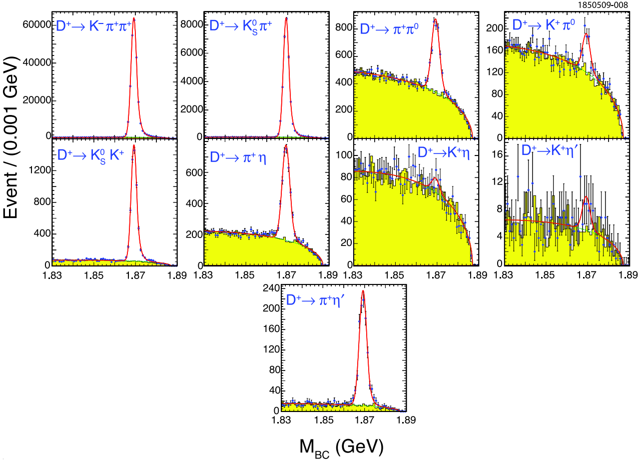
Belle



- 673/fb at or near $\Upsilon(4S)$
  - $\star > 800 \times 10^6$ $e^+e^- \to D\overline{D}X$



$D^+ \to PP$, $P = K^\pm, \pi^\pm, \eta, \eta', \pi^0$ or K^0



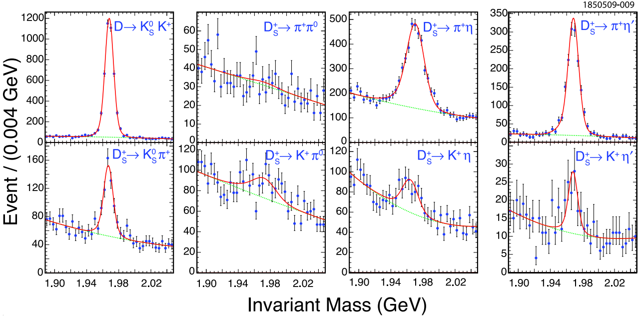
$$M_{BC} = \sqrt{E^2_{\text{beam}} - |\vec{p}_D|^2}$$

Yields

$D^+ \to$	Yield
$K^-\pi^+\pi^+$	231058 ± 515
$K^0_S K^+$	5161 ± 86
$\pi^+\pi^0$	2649 ± 76
$K^0_S\pi^+$	30095 ± 191
$K^+\pi^0$	343 ± 37
$K^+\eta$	60 ± 24
$\pi^+\eta$	2940 ± 68
$K^+\eta'$	23 ± 18
$\pi^+\eta'$	1037 ± 35

CPV in $D^+_{(s)} \to PP$ from CLEO [PRD81,052013]

$D_s^+ \to PP$, $P =\ K^{\pm},\ \pi^{\pm},\ \eta,\ \eta',\ \pi^0$ or K^0



Yields

$D_s^+ \to$	Yield
$K_S^0 K^+$	4076 ± 71
$\pi^+\pi^0$	19 ± 28
$K_S^0\pi^+$	393 ± 33
$K^+\pi^0$	202 ± 70
$K^+\eta$	222 ± 41
$\pi^+\eta$	2587 ± 89
$K^+\eta'$	56 ± 17
$\pi^+\eta'$	1436 ± 47

CPV in $D^+_{(s)} \to PP$ from CLEO [PRD81,052013]

D^+

$D^+ \to$	$\mathcal{A}_{CP}$ (%)	First m.
$K^-\pi^+\pi^+$	-0.1 ± 0.4 ± 0.9	
$K^0_S K^+$	-0.2 ± 1.5 ± 0.9	
$\pi^+\pi^0$	2.9 ± 2.9 ± 0.3	⋆
$K^0_S\pi^+$	-1.3 ± 0.7 ± 0.3	
$K^+\pi^0$	-3.5 ± 10.7 ± 0.9	⋆
$\pi^+\eta$	-2.0 ± 2.3 ± 0.3	⋆
$\pi^+\eta'$	-4.0 ± 3.4 ± 0.3	⋆

D_s^+

$D_s^+ \to$	$\mathcal{A}_{CP}$ (%)	First m.
$K^0_S K^+$	4.7 ± 1.8 ± 0.9	⋆
$K^0_S\pi^+$	16.3 ± 7.3 ± 0.3	⋆
$K^+\pi^0$	-26.6 ± 23.8 ± 0.9	⋆
$K^+\eta$	9.3 ± 15.2 ± 0.9	⋆
$\pi^+\eta$	-4.6 ± 2.9 ± 0.3	⋆
$K^+\eta'$	6.0 ± 18.9 ± 0.9	⋆
$\pi^+\eta'$	-6.1 ± 3.0 ± 0.3	⋆

[⋆] first measurement of A_{CP} for given decay

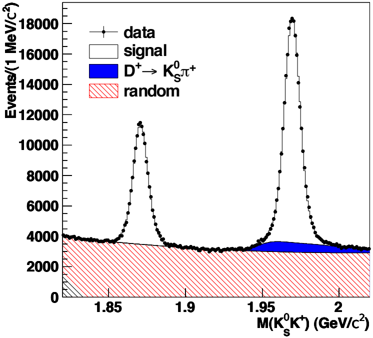
- Cleo-c's data allowed for the first time a test of direct *CPV* in the $D_{(s)^+} \to PP$ decays

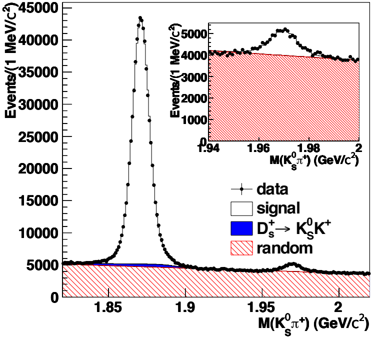
  ↪ with sensitivity reaching % level

- One source of systematic uncertainty

  ↪ charged pion/kaon tracking identification efficiencies estimated using data and MC simulations

Study of $D^+_{(s)} \to K_S h^+$ at Belle [PRD80,111101]





Decay modes	Yields
$D^+ \to K^0_s K^+$	100855 ± 561
$D^+_s \to K^0_s K^+$	204093 ± 768
$D^+ \to K^0_s \pi^+$	566285 ± 1162
$D^+_s \to K^0_s \pi^+$	17583 ± 481

20$\times$ (50$\times$) higher D (D_s) signal yields compared to Cleo.

Most precise measurement of SCS/CF ratio:

$R(D^+) = 0.1899 \pm 0.0011 \pm 0.0022$

$R(D^+_s) = 0.0803 \pm 0.0024 \pm 0.0019$

PDG2008 WA:

$R(D^+) = 0.206 \pm 0.014$

$R(D^+_s) = 0.084 \pm 0.009$

CPV in $D^+_{(s)} \rightarrow K_S h^+$ from Belle [PRL104,181602]

Key is to distinguish possible *CPV* asymmetry from detector effects and production asymmetry in reconstructed asymmetry

$$A^{\rm reco} = \frac{N^{\rm reco}_{D^+} - N^{\rm reco}_{D^-}}{N^{\rm reco}_{D^+} + N^{\rm reco}_{D^-}}$$

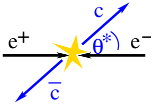
$$N^{\rm reco}_D = N^{\rm prod}_D \cdot \mathcal{B}(D \rightarrow f) \cdot \varepsilon_f \Longrightarrow \text{if } A_i \ll 1 \Longrightarrow \boxed{\mathbf{A^{reco} = A^D_{FB} + A^f_{CP} + A^f_\epsilon}}$$

$\mathbf{A_{CP}}$
CP asymmetry

independent of any kinematic variable

$\mathbf{A_{FB}}$
Production asymmetry

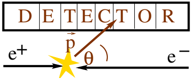
due to γ/Z interference in $e^+e^- \rightarrow c\overline{c}$



(anti-symmetric in $cos\theta^*_D$)

$\mathbf{A^f_\epsilon}$
Reconstruction asymmetry

$h^\pm$ reconstruction efficiency asymmetry



$(p^{\rm lab}_h,\ cos\theta^{\rm lab}_h)$

In order to control systematics $\mathbf{A_i}$'s are estimated on real data sample!

$D^+_{(s)} \to K_S\pi^+$ channels

Use $D^+_s \to \phi\pi^+$ decays to correct for:

- production asymmetry A_{FB}
- reconstruction asymmetry $A^{\pi^+}_\epsilon$
- no asymmetry due to $\phi \to K^+K^-$ reconstruction

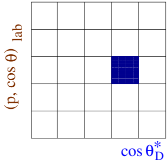
Method

In each $(p^{\text{lab}}_\pi,\ cos\theta^{\text{lab}}_\pi, cos\theta^*_D)$ bin

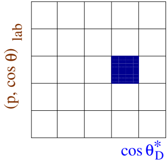
1. Measure $A^{D^+_{(s)}\to K_S\pi^+}_{rec} = A^{D_{(s)}}_{FB} + A^{\pi^+}_\epsilon + A^{D_{(s)}\to K^0_s\pi^+}_{CP}$
2. Measure $A^{D^+_s\to\phi\pi^+}_{rec} = A^{D_s}_{FB} + A^{\pi^+}_\epsilon$
3. Subtract measured asymmetries

$$A^{D^+\to K_S\pi^+}_{CP} = A^{D^+\to K_S\pi^+}_{rec} - A^{D^+_s\to\phi\pi^+}_{rec}$$

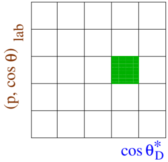
1. A_{rec} in $D^+ \to K_S\pi^+$



2. A_{rec} in $D^+_s \to \phi\pi^+$

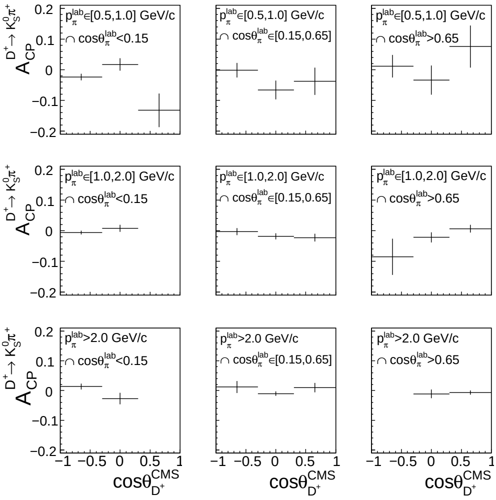


3. Subtraction gives A_{CP}



$D^+_{(s)} \to K_S\pi^+$ channels

Measured $A_{CP}^{D^+\to K_S\pi^+}$ in bins of $(p_\pi^{\mathrm{lab}},\ cos\theta_\pi^{\mathrm{lab}},\ cos\theta_{D^+_{(s)}}^{\mathrm{CMS}})$



$$A_{CP}^{D^+\to K_S\pi^+} = -(0.71 \pm 0.26)\%$$
$$A_{CP}^{D_s^+\to K_S\pi^+} = (5.45 \pm 2.50)\%$$

$D^+_{(s)} \to K_S K^+$ channels

Use $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ decays to correct for:

- reconstruction asymmetry $A_\epsilon^{K^+}$

Method

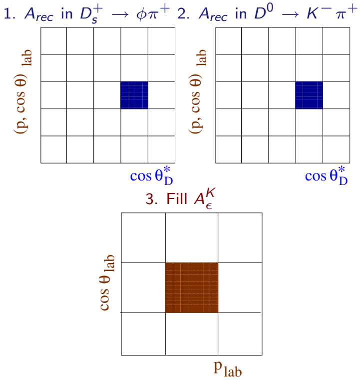
In each $(p_\pi^{\mathrm{lab}},\ cos\theta_\pi^{\mathrm{lab}}, cos\theta_D^*)$ bin

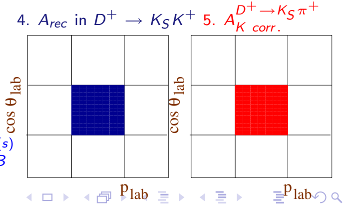
1. Measure $A_{rec}^{D_s^+\to\phi\pi^+} = A_{FB}^{D_s} + A_\epsilon^\pi$
2. Measure $A_{rec}^{D^0\to K^-\pi^+} = A_{FB}^{D^0} + A_\epsilon^\pi + A_\epsilon^K$

In each $(p_K^{\mathrm{lab}},\ cos\theta_K^{\mathrm{lab}})$ bin

1. Obtain $A_\epsilon^K = A_{rec}^{D^0\to K^-\pi^+} - A_{rec}^{D_s\to\phi\pi^+}$
2. Measure $A_{rec}^{D_{(s)}^+\to K_S K^+} = A_{FB}^{D_{(s)}} + A_\epsilon^{K^+} + A_{CP}^{D_{(s)}\to K_s^0 K^+}$
3. Obtain

$$A_{K\ corr.}^{D^+\to K_S\pi^+} = A_{rec}^{D^+\to K_S\pi^+} - A_{\pi\ corr.}^{D^0\to K^-\pi^+} = A_{CP}^{D^+\to K_S\pi^+} + A_{FB}^{D_{(s)}}$$



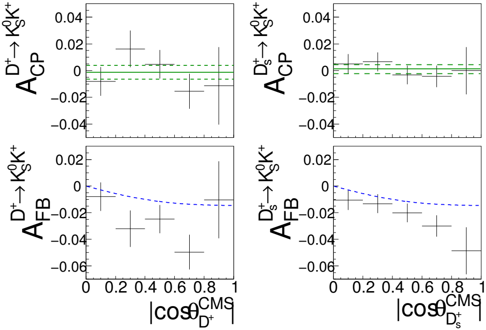


$D^+_{(s)} \to K_S K^+$ channels

Using (anti-)symmetric properties of A_{CP} (A_{FB}) in $cos\theta_D^{\rm CMS}$

$$A_{CP}^D = \frac{1}{2}\left[A_{K\ corr}^D(cos\theta_D^{\rm CMS}) + A_{K\ corr}^D(-cos\theta_D^{\rm CMS})\right]$$

$$A_{FB}^D = \frac{1}{2}\left[A_{\pi\ corr}^D(cos\theta_D^{\rm CMS}) - A_{\pi\ corr}^D(-cos\theta_D^{\rm CMS})\right]$$



$$A_{CP}^{D^+\to K_S K^+} = -(0.16 \pm 0.58)\%$$
$$A_{CP}^{D_s^+\to K_S K^+} = (0.12 \pm 0.36)\%$$

Dashed line in A_{FB} plots: leading order prediction for $A_{FB}^{c\bar{c}}$

CPV in $D^+_{(s)} \to K_S h^+$ decays: Results

A_{CP} in	Belle (%)	Cleo (%)	HFAG WA (%)	A_{CP}^{SM} (%)
$D^+ \to K_S\pi^+$	$-0.71\pm0.19\pm0.20$	$-1.3\pm0.7\pm0.3$	-0.72 ± 0.26	$-0.332^{\dagger}$
$D_s^+ \to K_S\pi^+$	$+5.45\pm2.50\pm0.33$	$+16.3\pm7.3\pm0.3$	$+6.5 \pm 2.5$	$+0.332$
$D^+ \to K_S K^+$	$-0.16\pm0.58\pm0.25$	$-0.2\pm1.5\pm0.9$	-0.09 ± 0.63	-0.332
$D_s^+ \to K_S K^+$	$+0.12\pm0.36\pm0.22$	$+4.7\pm1.8\pm0.9$	$+0.28 \pm 0.41$	$-0.332^{\dagger}$

† Interference of CF and DCS amplitudes is neglected.

- Major source of systematics is due to $h^{\pm}$ reconstruction asymmetry correction (limited sample sizes of $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$)
  - Scales with luminosity!

Conclusions

- Measurement of CPV in $D^+_{(s)} \to PP$ presented
  - No evidence for direct CPV found
- Starting to approach interesting levels of sensitivity
  - Methods established and can be used also in precision measurements of CPV in B decays
- Next round of experiments (Super-B factories, LHCb) should be able to go below 0.1% sensitivity level
  - Data from Tevatron experiments and BaBar not used so far
  - results in other decay modes can soon be expected

Backup

Selection

- Charged Tracks: $|dr| < 2cm$, $|dz| < 4cm$, 2 SVD hits in $r\phi$- and z-plane
- π/K ID: $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi) > 0.6$ for K and <0.6 for π
  - ⋆ 86% recon. efficiency and 10% misidentification probability
- K_S reconstruction/selection: two oppositely charged tracks (± 9 MeV wide window)
  - ⋆ displaced vertex
- $D^\pm_{(s)}$: vertex fit ($K_S + h^\pm$) with probability $> 0.1\%$
  - ⋆ to remove peaking bkg. from $D^\pm_{(s)} \to \pi^+\pi^-h^\pm$ require $\chi^2/ndf > 10$ for vertex fit $(\pi^+ + \pi^- + h^\pm)$
  - ⋆ Asymmetry $\mathcal{A} \equiv \frac{|p_{K_S} - p_{h^+}|}{|p_{K_S} + p_{h^+}|} < 0.6$
  - ⋆ $p^*_{D^+_{(s)}} > 2.6$ GeV

$D_{(s)}^+ \to K_S\pi^+$ channels

Reconstructed asymmetry:

$$A_{rec}^{D_{(s)}^+ \to K_S\pi^+} = A_{FB}^{D_{(s)}} + A_{\epsilon}^{\pi^+} + A_{CP}^{D_{(s)} \to K_s^0\pi^+}$$

Asymmetry in $D_s^+ \to \phi\pi^+$ used to correct for $A_{FB}^{D_{(s)}}$ and $A_{\epsilon}^{\pi^+}$:

$$A_{rec}^{D_s^+ \to \phi\pi^+} = A_{FB}^{D_s} + A_{\epsilon}^{\pi^+}$$

- assume no CPV in $D_s^+ \to \phi\pi^+$ decays (CF) and $A_{FB}^{D_s} = A_{FB}^{D}$

Performed in 3D space of p_{π}^{lab}, $cos\theta_{\pi}^{\mathrm{lab}}$ and $cos\theta_{D_{(s)}^+}^{\mathrm{CMS}}$ for $D^+ \to K_S\pi^+$

$$A_{CP}^{D^+ \to K_S\pi^+} = A_{rec}^{D^+ \to K_S\pi^+} - A_{rec}^{D_s^+ \to \phi\pi^+}$$

- sensitivity of $D_s^+ \to K_S\pi^+$ too low to perform 3D correction
  - correct with an inclusive correction

$$A_{CP}^{D^+ \to K_S\pi^+} - A_{rec}^{D^+ \to K_S\pi^+} = -(A_{FB}^{D} + A_{\epsilon}^{\pi^+}) = -(0.34 \pm 0.18)\%$$

Systematics

Source		$D^+ \to K_S\pi^+$	$D_s^+ \to K_S\pi^+$	$D^+ \to K_S K^+$	$D_s^+ \to K_S K^+$
$A_{\rm rec}^{D_s^+\to\phi\pi^+}$	$D_s^+ \to \phi\pi^+$ statistics	0.18	0.18	-	-
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	0.03	0.03	-	-
	$M(K^+K^-)$ window	0.03	0.03	-	-
$A_\epsilon^{K^-}$	$D_s^+ \to \phi\pi^+$ statistics	-	-	0.18	0.18
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	-	-	0.03	0.03
	$M(K^+K^-)$ window	-	-	0.03	0.03
	$D^0 \to K^-\pi^+$ statistics	-	-	0.06	0.06
	$A_\epsilon^{K^-}$ binning	-	-	0.04	0.04
	Possible $A_{CP}^{D^0\to K^-\pi^+}$	-	-	0.01	0.01
$\cos\theta_{D_{(s)}^+}^{\rm CMS}$ binning		-	-	0.06	0.06
Fitting		0.04	0.27	0.12	0.05
$K^0/\bar{K}^0$-material effects		0.06	0.06	0.06	0.06
Total		0.20	0.33	0.25	0.22

Table of systematic uncertainty in A_{CP} (%).

$D^+_{(s)} \to K_s h^+$ - $K^0\overline{K}^0$ systematics

- differences in interactions of K^0 and $\overline{K}^0$ mesons material
- mesons interact with material near IP
- produces a asymmetry originating from different strong interactions of mesons
- differences between K^0 and $\overline{K}^0$ interactions $\approx$ difference K^+ and K^-
- calculate the probability of K^0 and $\bar{K}^0$-nucleons interactions using the known K^+ and K^- cross sections
- take into account the time evolution of neutral kaons.
- uncertainty in CP asymmetry due to $K^0/\overline{K}^0$-material effects $\approx 0.06\%$