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

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Belle collaboration


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Outline

- Search for CPV in $D^+_{(s)} \to \phi\pi^+$
- Search for CPV in $D^0 \to K^0_S\pi^0, K^0_S\eta, K^0_S\eta'$
- Search for CPV in $D^+ \to \pi^+\eta, \pi^+\eta'$
- Observation of DCS decays $D^+ \to K^+\eta, K^+\eta'$

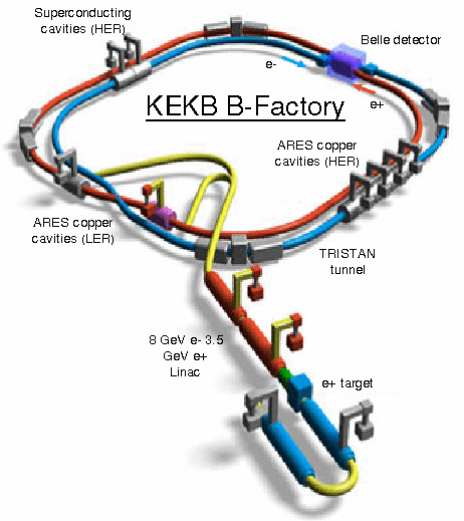
CP violation in charm

- Provides a unique possibility to search for new physics (NP)
- Very small effect in SM:
  - time integrated decay rate asymmetry $A_{CP} \lesssim \mathcal{O}(0.1\%)$
  - NP can enhance A_{CP} to $\mathcal{O}(1\%)$
- Two kinds of CPV:
  - CPV in decays (direct CPV) $\rightarrow$ decay mode dependent
  - mixing induced CPV (indirect) $\rightarrow$ common to all D^0 decays
- Charged D mesons $\rightarrow$ only direct CPV
- Direct CPV in NP models:
  - SCS decays (loop & tree) likely to be affected
  - CF or DCS (tree) very unlikely

Charm production at Belle

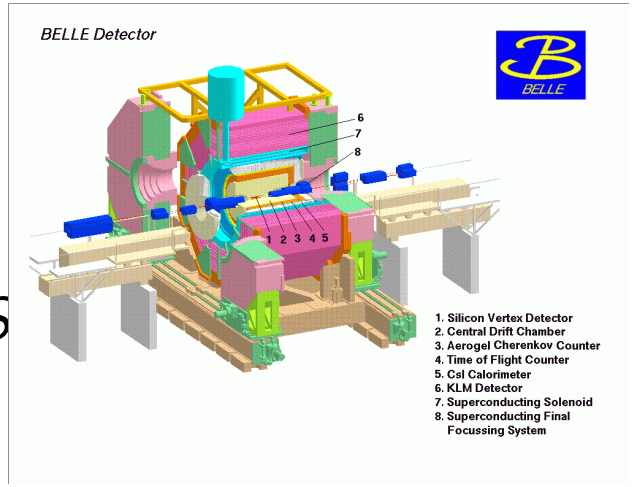
B-factories are also charm-factories: $\sigma_{c\bar{c}} \approx \sigma_{b\bar{b}}$

KEKB B-factory



- Asymmetric e^+e^- collider
- primarily at $\Upsilon(4S)$
- also $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(5S$
- $\int \mathcal{L} dt = 1\ \mathrm{ab}^{-1}$

Belle detector



- Charm production $\sigma_{c\bar{c}} \sim 1\ \mathrm{nb} \longrightarrow \sim 10^9$ charm events at Belle
- Easy to reject D mesons from B decays using simple kinematic cuts:
  - $p^*_D > 2.5\ \mathrm{GeV/c}$ at $\Upsilon(4S)$
  - $p^*_D > 3.1\ \mathrm{GeV/c}$ at $\Upsilon(5S)$

Belle II will collect 50 times more

Search for CPV in $D^+_{(s)} \to \phi\pi^+$ 955 fb^{-1}

- By measuring A_{CP} difference btw. $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$
  - $D^+ \to \phi\pi^+$ is SCS decay
  - $D_s^+ \to \phi\pi^+$ is CF decay (CPV very unlikely)
- ϕ reconstructed in $\phi \to K^+K^-$
- Measured decay rate asymmetry:

$$A_{\rm rec} = A_{CP} + A_{FB}(\cos\theta^*) + A_\epsilon^{KK} + A_\epsilon^\pi(p_\pi, \cos\theta_\pi)$$

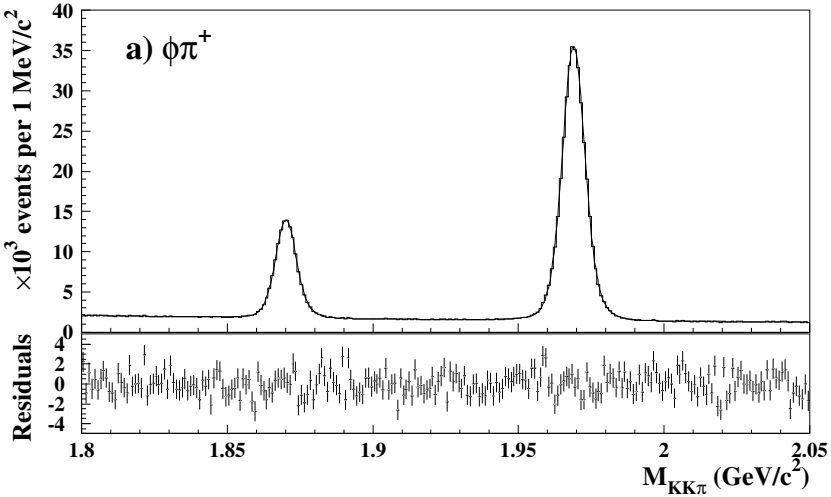
  - $A_{FB}(\cos\theta^*)$ is an odd function of $\cos\theta^*$
  - $A_\epsilon^{KK} = 0$ for $\phi \to K^+K^-$, however due to interference of ϕ with other intermediate states it's slightly different from zero (backup slide)
- Taking the difference btw. D^+ and D_s^+ in bins of $(\cos\theta^*, p_\pi, \cos\theta_\pi)$:

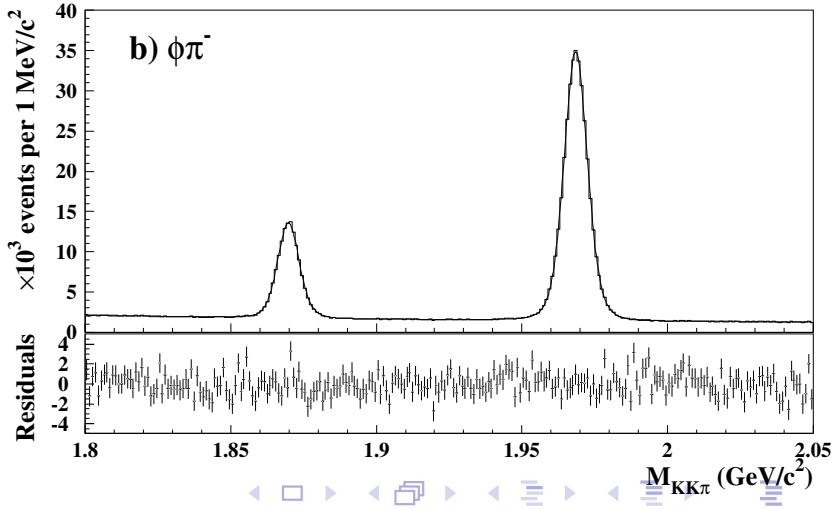
$$\Delta A_{rec}(\cos\theta^*, p_\pi, \cos\theta_\pi) = \Delta A_{CP} + \Delta A_{FB}(\cos\theta^*)$$

- To obtain ΔA_{CP}:
  - calculate weighted average of ΔA_{rec} in bins of $\cos\theta^*$
  - extract ΔA_{CP} and ΔA_{FB} by adding/subtracting bins at $\pm\cos\theta^*$

Search for CPV in $D^+_{(s)} \to \phi\pi^+$ 955 fb^{-1}

- Event selection
  - decay and production vertex fits
  - $p^*_D > 2.5\ (3.1)\ \mathrm{GeV/c}$ to reject D's from B decays
  - $|M_{KK} - m_\phi| < 16\ \mathrm{MeV/c^2}$
  - $p_\pi > 0.38\ \mathrm{GeV/c}$
  - $|\cos\theta_{\mathrm{hel}}| > 0.28$
- $D^\pm_{(s)}$ yields obtained by fitting inv. mass distributions in 10×10×10 bins of $(\cos\theta^*, p_\pi, \cos\theta_\pi)$
  - found 238×10^3 D^+ and 723×10^3 D^+_s





Search for CPV in $D^+_{(s)} \to \phi\pi^+$ 955 fb^{-1}

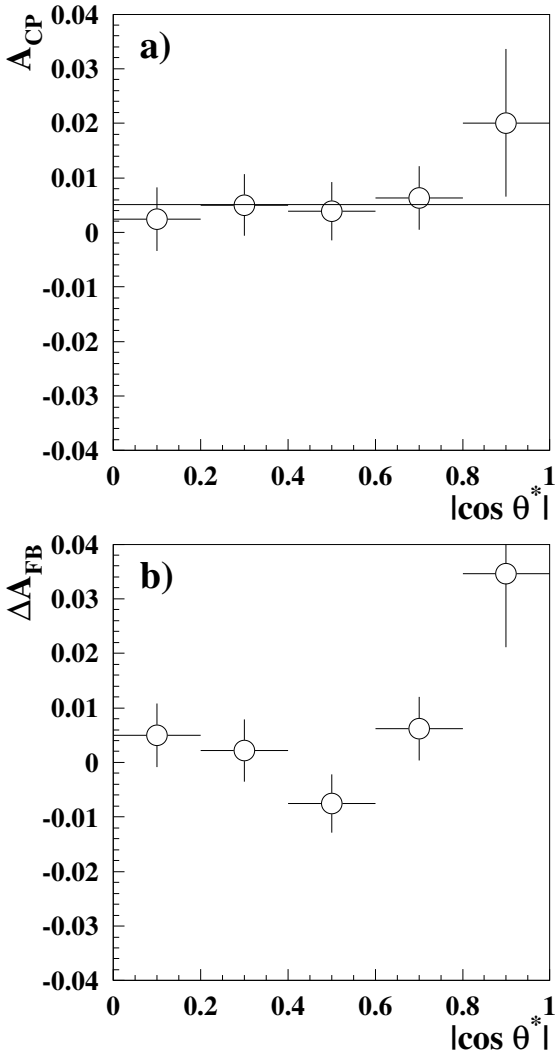
Results

- Assuming negligible CPV in $D^+_s \to \phi\pi^+$

$$A_{CP}^{D^+\to\phi\pi^+} = (+0.51 \pm 0.28 \pm 0.05)\%.$$

- No evidence for CPV in agreement with SM expectations
- Precision improved by 5$\times$ compared to previous results (CLEO, BaBar)
- No significant difference in A_{FB} btw. D^+ and D^+_s

to be submitted to PRL



Search for CPV in $D^0 \to K^0_s\pi^0, K^0_s\eta, K^0_s\eta'$ 791 fb^{-1}

PRL **106**, 211801 (2011)

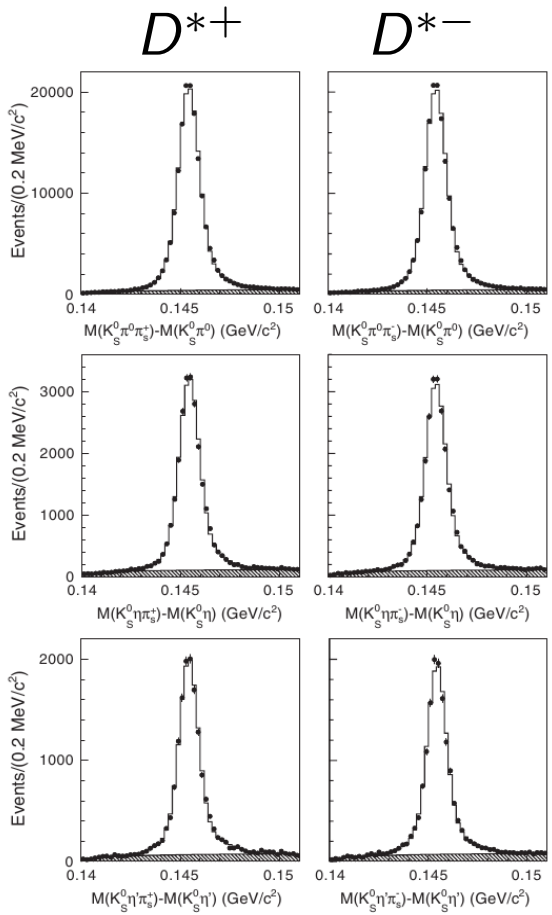
- These decays are mixtures of CF and DCS
- Decay $D^{*+} \to D^0\pi^+$ used to tag flavor of D^0
- Measured decay rate asymmetry:

$$A_{\rm rec} = A_{CP} + A_{FB}(\cos\theta^*) + A^{\pi}_{\epsilon}(p_{\pi}, \cos\theta_{\pi})$$

- A^{π}_{ϵ} measured using tagged and untagged $D^0 \to K^-\pi^+$
- correct measured asymmetry

$$A^{\rm cor}_{\rm rec} = A_{\rm rec} - A^{\pi}_{\epsilon}$$

- extract A_{CP} and A_{FB} by adding/subtracting bins at $\pm\cos\theta^*$

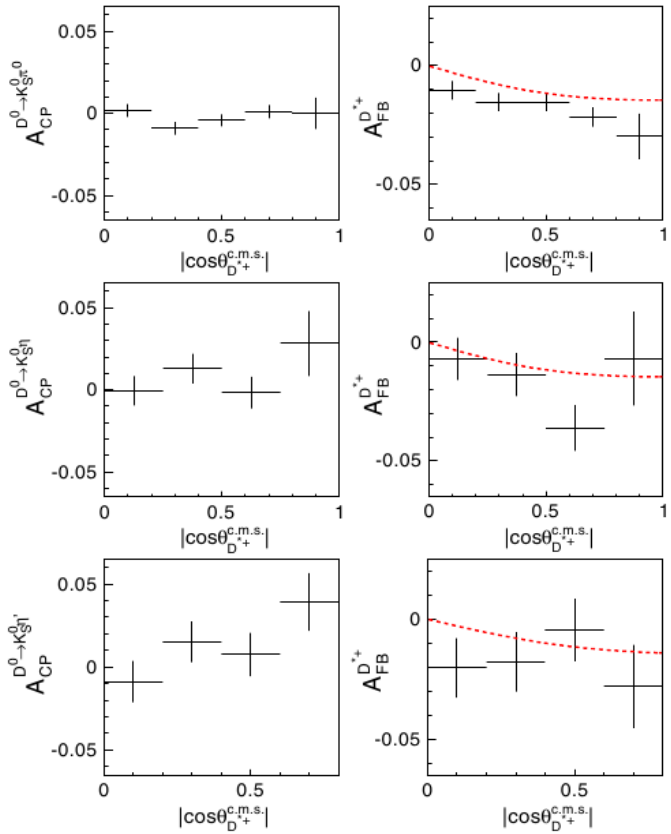


mode	yield
$K^0_s\pi^0$	326×10^3
$K^0_s\eta$	46×10^3
$K^0_s\eta'$	27×10^3

Search for CPV in $D^0 \to K^0_s\pi^0, K^0_s\eta, K^0_s\eta'$ 791 fb^{-1}

Results

decay	A_{CP} (%)	
$D^0 \to K^0_s\pi^0$	$-0.28 \pm 0.19 \pm 0.10$	most precise A_{CP}
$D^0 \to K^0_s\eta$	$+0.54 \pm 0.51 \pm 0.16$	first measurement
$D^0 \to K^0_s\eta'$	$+0.98 \pm 0.67 \pm 0.14$	first measurement



- No evidence for CPV
- Contribution from CPV in K^0:

$$A^{K^0}_{CP} = (-0.332 \pm 0.006)\%$$

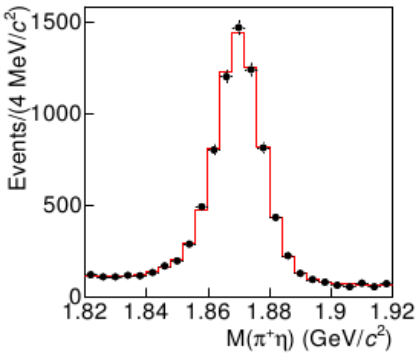
- Subtract $A^{K^0}_{CP}$ to get intrinsic charm CPV
- Assuming no direct CPV in $D^0 \to K^0_s\pi^0$

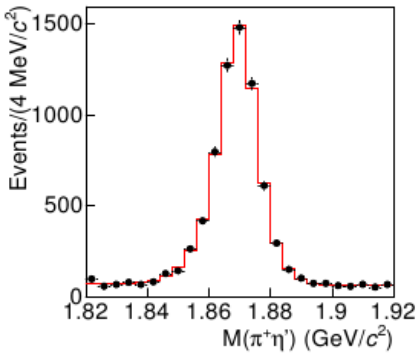
$$a^{\rm ind} = A^{K^0_s\pi^0}_{CP} - A^{K^0}_{CP} = (+0.05 \pm 0.19 \pm 0.10)\%$$

Search for CPV in $D^+ \to \pi^+\eta, \pi^+\eta'$ 791 fb^{-1}

arXiv:1107.0553 (submitted to PRL)

- These are SCS decays; we search for direct CPV.
- $D^+ \to \pi^+\eta$ reconstructed in $\eta \to \pi^+\pi^-\pi^0$ (to fit decay vertex)
- $D^+ \to \pi^+\eta'$ reconstructed in $\eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma$
- Event selection:
  - decay vertex fit
  - decay vertex required to be detached from e^+e^- IP
  - cut on $\eta(\eta')$ momentum
  - cut on D^+ CMS momentum
  - last three criteria optimized by maximizing N_s/σ_s using MC





decay	yield
$D^+ \to \pi^+\eta$	6476 ± 110
$D^+ \to \pi^+\eta'$	6023 ± 93

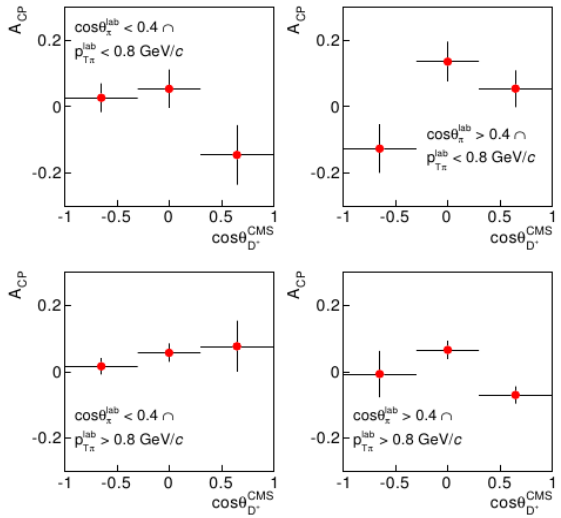
Search for CPV in $D^+ \to \pi^+\eta, \pi^+\eta'$ 791 fb^{-1}

- Measured decay rate asymmetry:

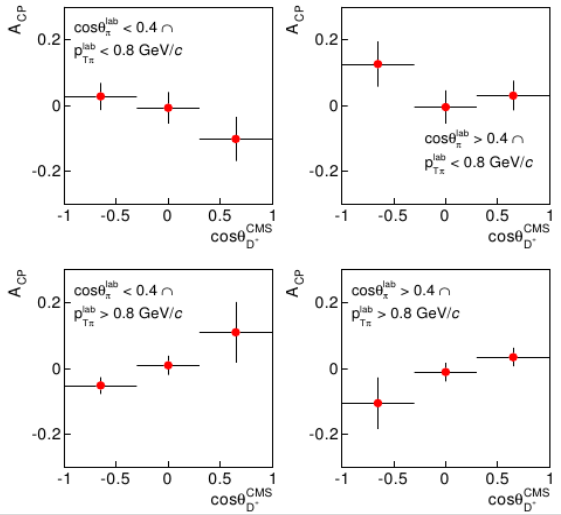
$$A_{\rm rec} = A_{CP} + A_{FB}(\cos\theta^*) + A_\epsilon^\pi(p_T^\pi, \cos\theta_\pi)$$

- To correct for A_{FB} and A_ϵ^π we use CF decays $D_s^+ \to \phi\pi^+$ (assuming no CPV and equal A_{FB})
- Subtraction done in bins of $(p_T^\pi, \cos\theta_\pi, \cos\theta^*)$
- binning optimized to avoid large statistical fluctuations in bins

$D^+ \to \pi^+\eta$



$D^+ \to \pi^+\eta'$



Results:

decay	A_{CP} (%)
$D^+ \to \pi^+\eta$	$+1.74 \pm 1.13 \pm 0.20$
$D^+ \to \pi^+\eta'$	$-0.12 \pm 1.12 \pm 0.20$

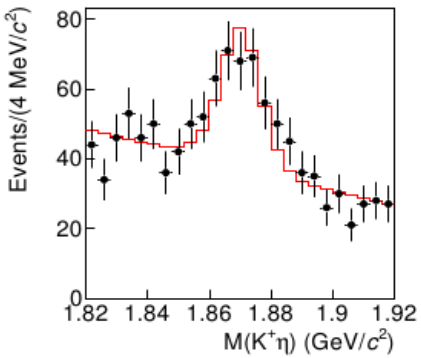
No evidence for CPV, improved sensitivity (2-3×)

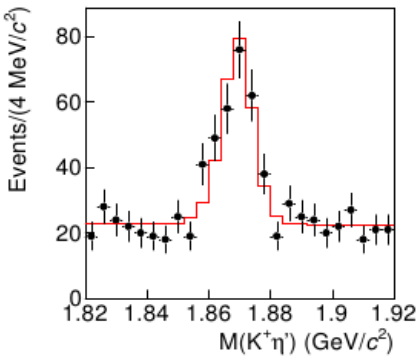
Observation of DCS decays $D^+ \to K^+\eta(\eta')$ 791 fb^{-1}

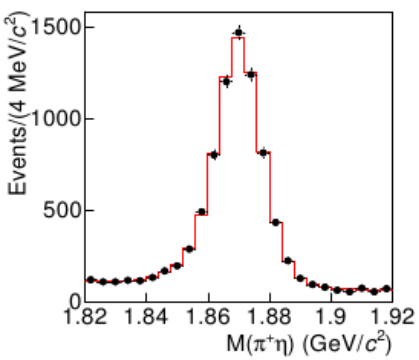
- Within the same analysis we searched for DCS decays $D^+ \to K^+\eta(\eta')$
- Last three selection criteria re-optimized: maximizing $\epsilon_{\rm sig}/\sqrt{N_B}$
- First observation of DCS decays:

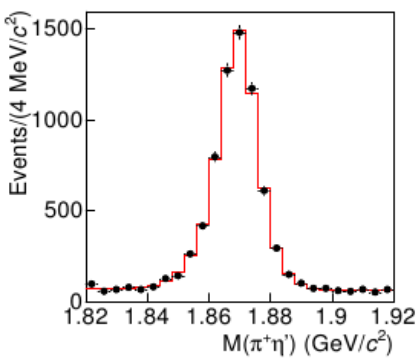
decay	yield	significance
$D^+ \to K^+\eta$	166 ± 23	9σ
$D^+ \to K^+\eta'$	180 ± 19	$> 10\sigma$

$D^+ \to K^+\eta$ $D^+ \to K^+\eta'$ $D^+ \to \pi^+\eta$ $D^+ \to \pi^+\eta'$









Observation of DCS decays $D^+ \to K^+\eta(\eta')$ 791 fb^{-1}

- Branching fraction ratio DCS/SCS:

$$\mathcal{B}(D^+ \to K^+\eta)/\mathcal{B}(D^+ \to \pi^+\eta) = (3.06 \pm 0.43 \pm 0.14)\%$$

$$\mathcal{B}(D^+ \to K^+\eta')/\mathcal{B}(D^+ \to \pi^+\eta') = (3.77 \pm 0.39 \pm 0.10)\%$$

- Suppressed compared to naive expectation of $\tan^2\theta_C = 5.35 \times 10^{-2}$
- Branching fractions:

decay	Belle	CLEO	SU(3)
$D^+ \to K^+\eta$	$(1.08 \pm 0.17) \times 10^{-4}$	$< 1.3 \times 10^{-4}$	1.06×10^{-4}
$D^+ \to K^+\eta'$	$(1.76 \pm 0.22) \times 10^{-4}$	$< 1.9 \times 10^{-4}$	1.16×10^{-4}

- $K^+\eta$ in agreement with SU(3) based expectation, $K^+\eta'$ is larger (almost 3σ)

Conclusions

- We searched for CPV in decays $D^+_{(s)} \to \phi\pi^+$, $D^0 \to K^0_S\pi^0, K^0_S\eta, K^0_S\eta'$ and $D^+ \to \pi^+\eta, \pi^+\eta'$ with sensitivities of 0.2% - 1% in A_{CP}.
- We found no evidence for either direct or indirect CPV in these decays
- We observed for the first time the DCS decays $D^+ \to K^+\eta$ and $D^+ \to K^+\eta'$
- Both are found to be suppressed compared to the naive expectation of $\tan^2\theta_C$.
- While $D^+ \to K^+\eta$ is in agreement with the SU(3) based expectation, the $D^+ \to K^+\eta'$ is measured to be larger.

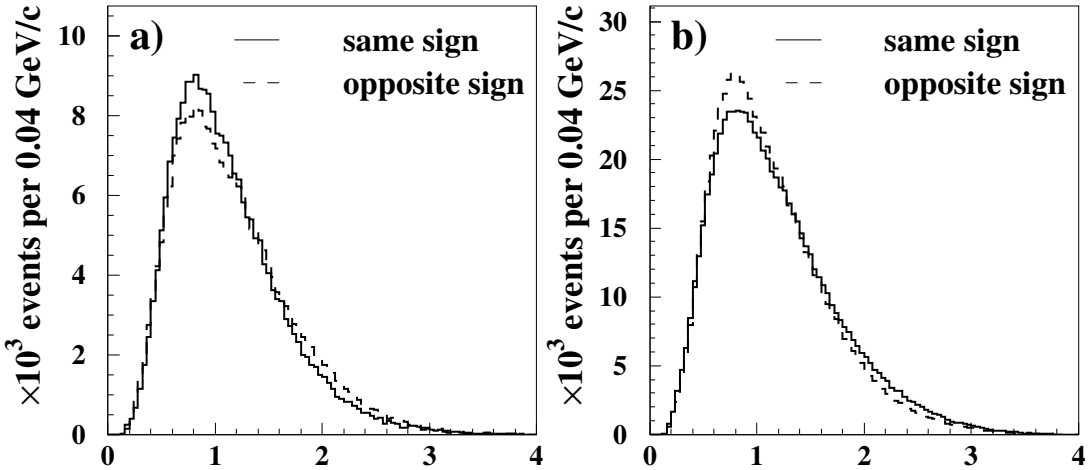
Backup slide

$A_\epsilon^{KK} \neq 0$ (but small)

- same-sign and opposite-sign kaon momentum distributions differ due to interference of ϕ with other intermediate states
- Easy to show:

$$A_\epsilon^{KK} = \int (P_1(x) - P_2(x)) A_\epsilon^K(x) dx, \quad x \equiv (p_K, \cos\theta_K)$$

  - $P_1(x)$, $P_2(x)$ normalized distributions of same- and opposite-sign K
  - A_ϵ^K kaon detection asymmetry, measured with $D^0 \to K^-\pi^+$ and $D_s^+ \to \phi\pi^+$



	A_ϵ^{KK} (%)
D^+	$+0.060 \pm 0.013$
D_s^+	-0.051 ± 0.012
ΔA_ϵ^{KK}	$+0.111 \pm 0.025$