Charm Mixing and CP Violation at Belle

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on behalf of the Belle Collaboration

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Introduction

- Neutral D mesons mix via weak interaction
- Time evolution of flavor eigenstates:

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

- CP eigenstates D_1 and D_2:

$$|D_{1,2}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$$

$$|D_{1,2}(t)\rangle = e^{-i(M_{1,2}-i\Gamma_{1,2}/2)t}|D_{1,2}(t=0)\rangle$$

$$x = \frac{\Delta M}{\Gamma} = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

CP Violation in Charm

- Suppressed in the Standard Model: O(10^{-3})
- O(1%) CPV: New Physics (NP)

$$A_{CP}^{f} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

$$\approx a_f^d(\text{decay}) + a_f^m(\text{mixing}) + a_f^i(\text{interference})$$

$$A_f \neq \bar{A}_f \qquad |\frac{q}{p}| \neq 1 \qquad \phi \neq 0/\pi$$

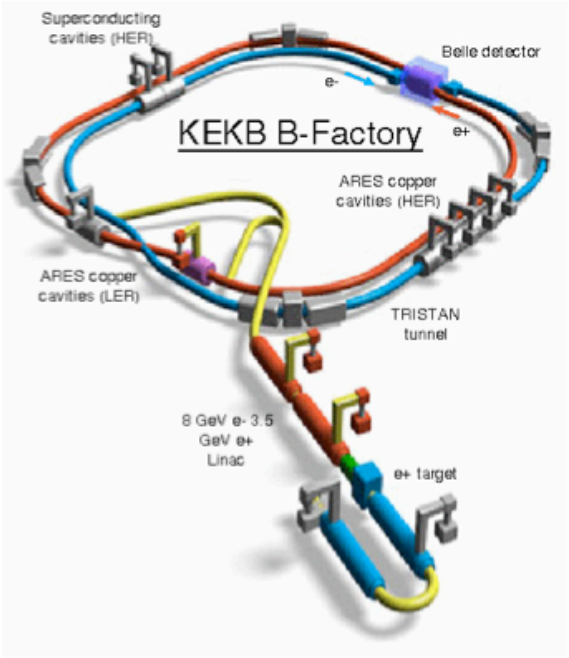
$$\phi = arg(q\bar{A}_f/pA_f)$$

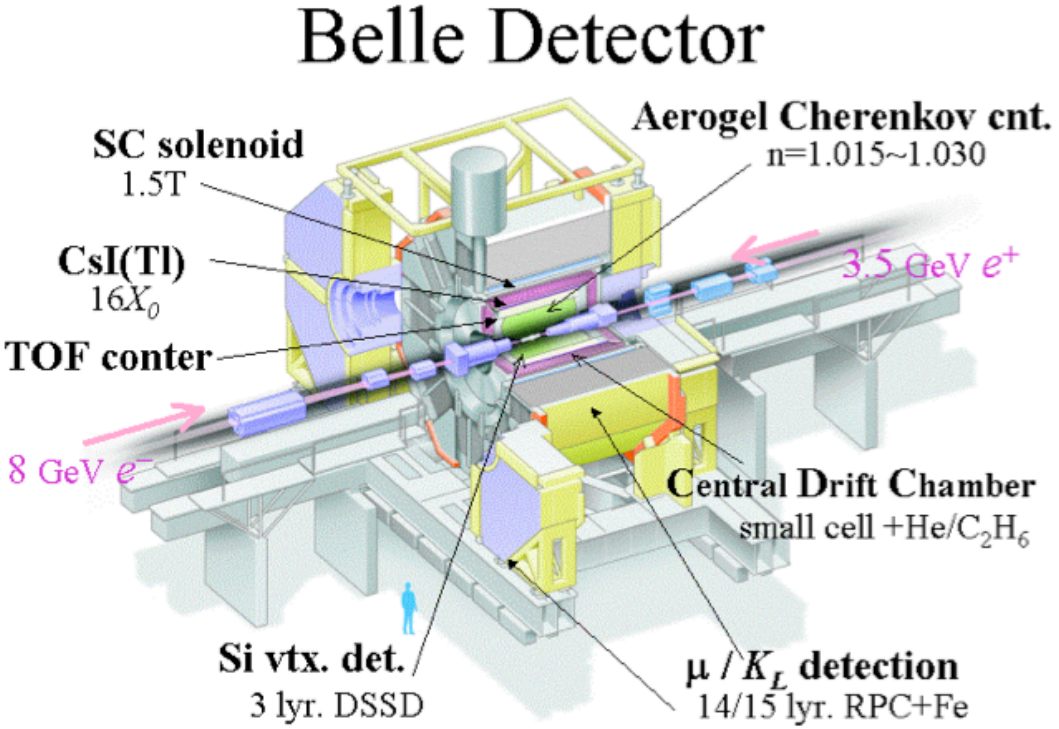
Recent results from Belle

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

- Updated charm mixing results will be available soon.

KEKB and Belle

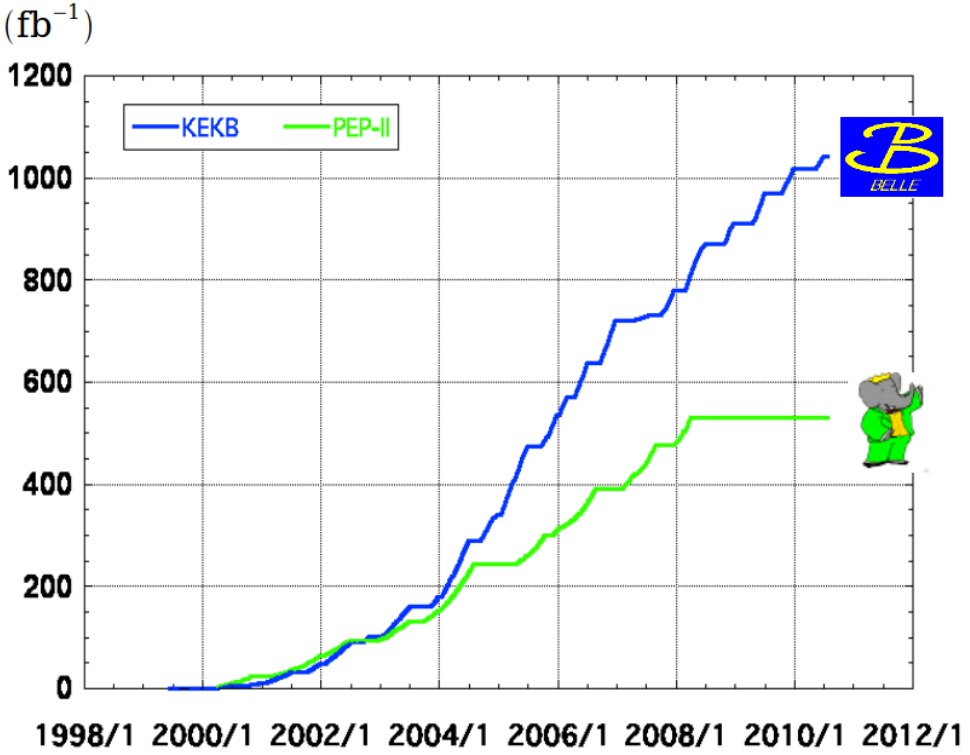




- B factories serve as Charm factories as charm is produced as the continuum under Y (4S)

Charm production at Belle

Integrated luminosity of B factories



> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

$$e^+e^- \to \Upsilon \to c\bar{c}(1.3\text{nb}) \ (\sim 1.3 \times 10^9 c\bar{c}\,\text{events})$$

D mesons from $b \to c$ are eliminated with $p^*_D > 2.5\,GeV/c^2$

Charm Mixing Results

Final state	Belle	BaBar	CDF	Cleo	E791	Focus
$K^+\pi^-$	√	★	★	√	√	√
KK, $\pi\pi$	★	★		√	√	√
$K^0_S\pi\pi$	√	√		√		
$K^0_S KK$	√	√				
$K^+\pi^-\pi^0$		★				
$K^+\pi^-\pi^-\pi^+$		√				
$K^+\ell^-\nu_\ell$	√	√		√	√	
quantum corr. in $\psi(3770) \to D^0\overline{D}^0$				√		

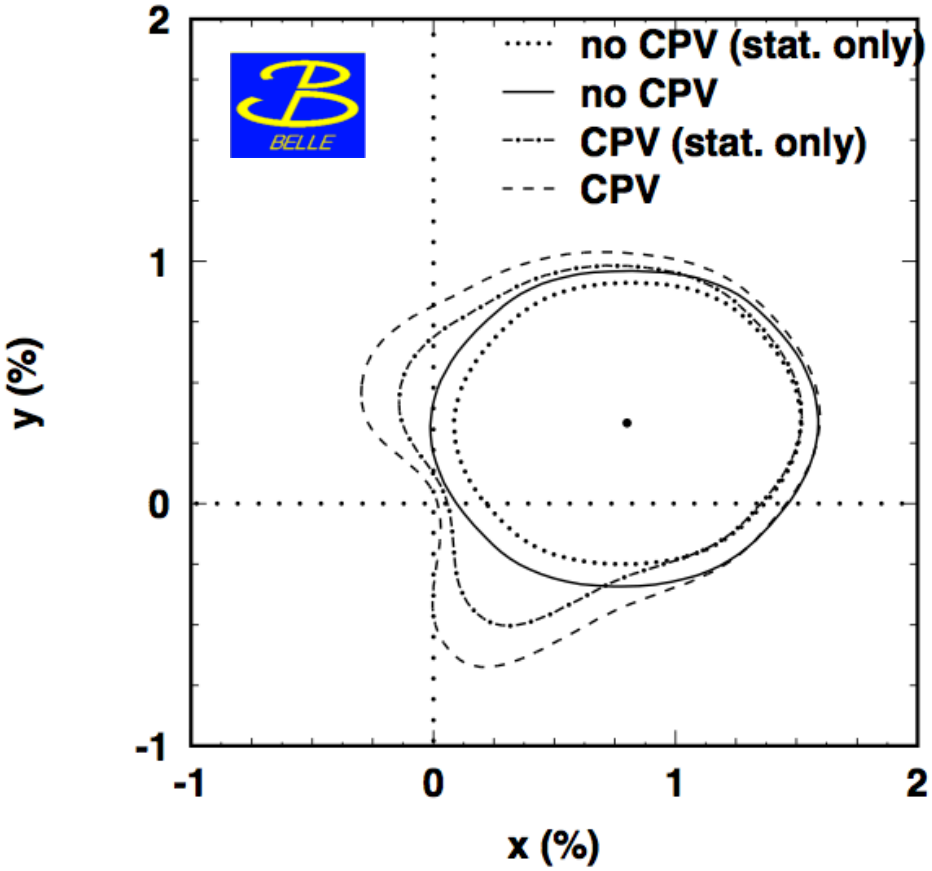
will be updated soon

√ – measurement performed; ★ – evidence for mixing

Full list of all $D^0 - \overline{D}^0$ mixing measurements is available at:
http://www.slac.stanford.edu/xorg/hfag/charm/index.html

Previous results for $D^0 \to K^0_s\pi^+\pi^-$

95% confidence level contours



Belle@540 fb^{-1} [PRL99,131803]

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

Conserved CP symmetry ($|q/p| = 1$ & $\phi = 0$)

$$x = (0.80 \pm 0.29^{+0.13}_{-0.16})\%$$
$$y = (0.33 \pm 0.24^{+0.10}_{-0.14})\%$$

CPV allowed ($|q/p|$ & ϕ free parameters of the fit)

$$|q/p| = 0.86 \pm 0.30 \pm 0.09$$
$$\phi = -0.24 \pm 0.30 \pm 0.09$$

Consistent with no CPV!

BaBar@469 fb^{-1} [PRL105,081803]

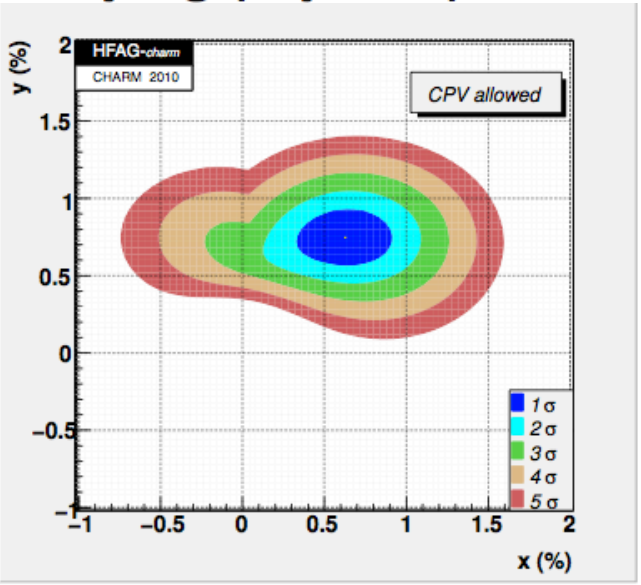
$D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$

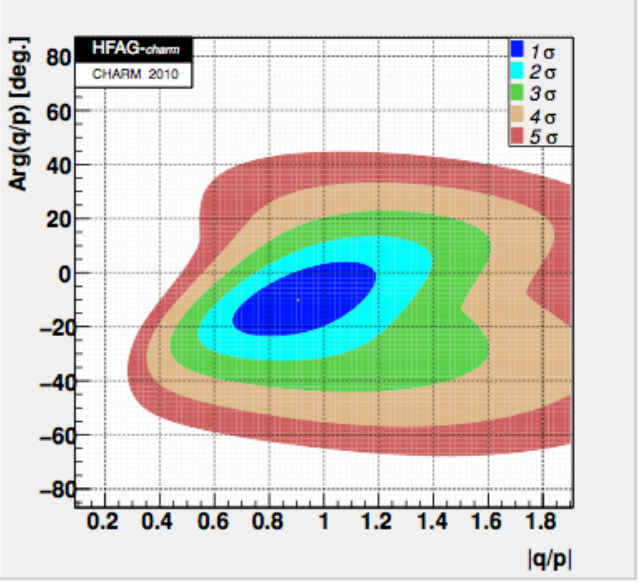
$$x = (0.16 \pm 0.23 \pm 0.14)\%$$
$$y = (0.57 \pm 0.20 \pm 0.15)\%$$

Updated Belle results with a dataset twice as big is being prepared

HFAG World Average

- Heavy Flavor Averaging Group (HFAG) performs an average of 8 underlying physics parameters from 30 observables.





$$x = (0.63 \pm 0.20)\%$$
$$y = (0.80 \pm 0.13)\%$$

$$|q/p| = 0.91^{+0.18}_{-0.16}$$
$$\phi(^\circ) = -10.0^{+9.4}_{-8.9}$$

- No-mixing point $(x, y) = (0, 0)$ is excluded at 10.2σ, while no-CPV point $(|q/p|, \phi) = (1, 0)$ is consistent within 1σ.

CPV in $D^+_{(s)} \to \phi\pi^+$

- A_{CP} difference
  - SCS decay $D^+ \to \phi\pi^+$
  - CF decay $D_s^+ \to \phi\pi^+$
- Decay rate asymmetry:

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

  - $A_{FB}(cos\theta^*)$ is an odd function of $cos\theta^*$
  - $A_\epsilon^{KK} = 0$ for $\phi \to K^+K^-$ (next slide)
- Difference of D^+ and D_s^+ in bins of $(cos\theta^*, p_\pi, cos\theta_\pi)$:

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

CPV in $D^+_{(s)} \to \phi\pi^+$

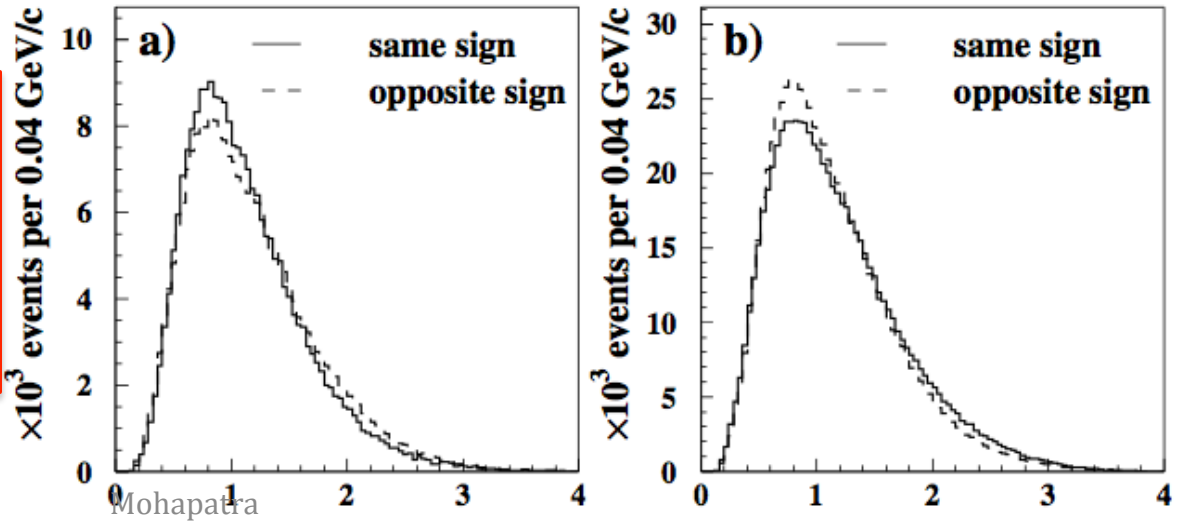
$A^{KK}_\epsilon \neq 0$ (but small)

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

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

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

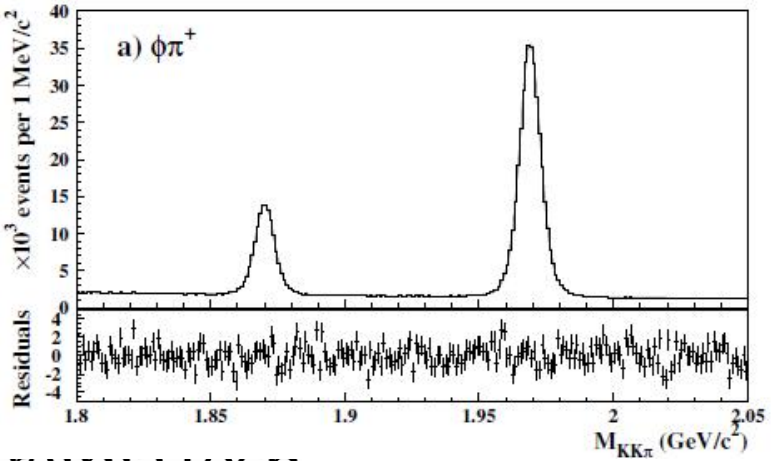
	A^{KK}_ϵ (%)
D^+	$+0.060 \pm 0.013$
D^+_s	-0.051 ± 0.012
ΔA^{KK}_ϵ	$+0.111 \pm 0.025$

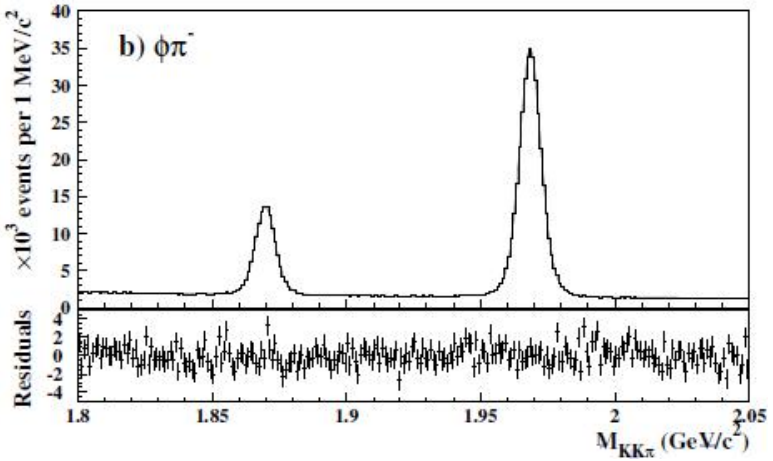


CPV in $D^+_{(s)} \to \phi\pi^+$

$955\,\mathrm{fb}^{-1}$

- Event selection
  - standard track and particle selections
  - decay and production vertex fits
  - $p^*_D > 2.5\ (3.1)\ \mathrm{GeV/c}$ to reject D 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 $(\cos\theta^*, p_\pi, \cos\theta_\pi)$





CPV in $D^+_{(s)} \to \phi\pi^+$

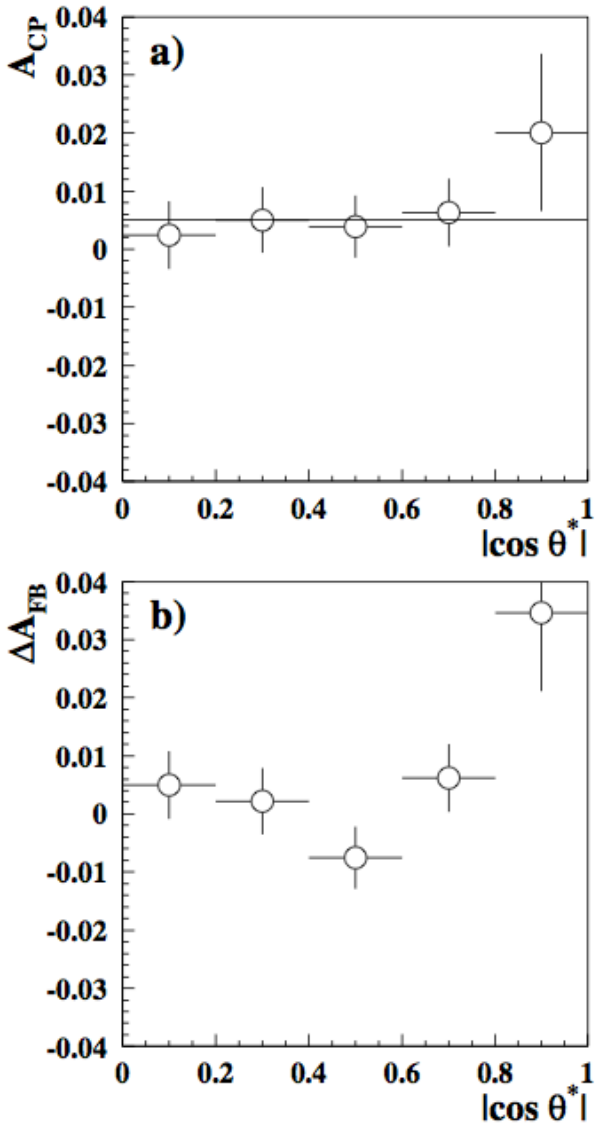
$955\,\mathrm{fb}^{-1}$

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 $\to$ agrees with SM
- Precision improved by 5$\times$ against previous measurements (Cleo, BaBar)
- No significant difference in A_{FB} btw. D^+ and D_s^+



CPV in $D^0 \to K_s\pi^0, K_s\eta^{(\prime)}$

PRL **106**, 211801 (2011)

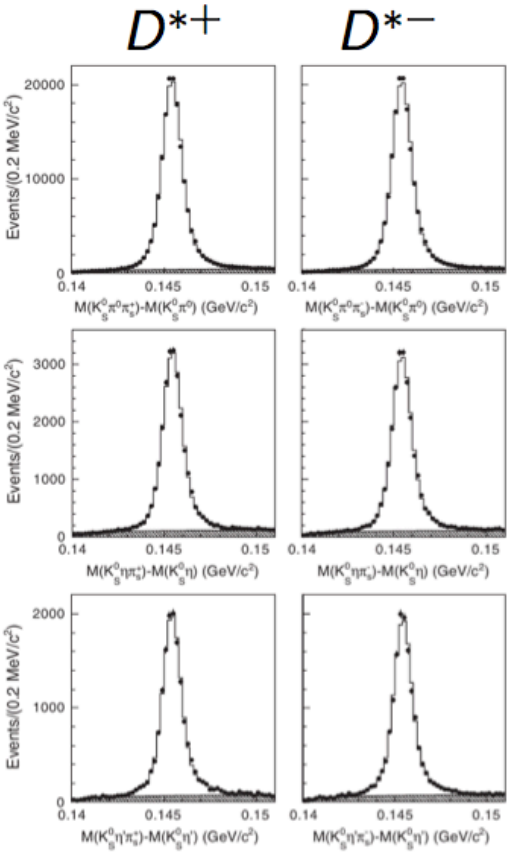
- These decays are mixtures of CF and DCS
- Decay $D^{*+} \to D^0\pi^+$ used to tag flavor of D^0
- Measured decay rate asymmetry:

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

- A_ϵ^π measured using tagged and untagged $D^0 \to K^-\pi^+$
- correct measured asymmetry

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

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



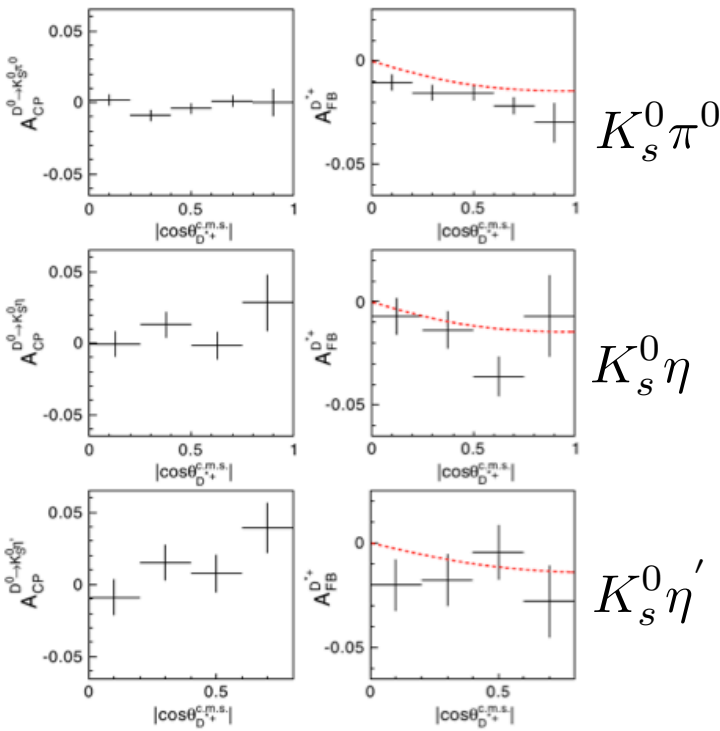
mass difference

CPV in $D^0 \to K_s\pi^0, K_s\eta^{(\prime)}$

Results

$791\,\mathrm{fb}^{-1}$

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



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

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

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

$$a^{\mathrm{ind}} = A_{CP} - A_{CP}^{K^0} = (+0.05 \pm 0.19 \pm 0.10)\%$$

CPV in $D^+ \to \pi^+\eta^{(\prime)}$

arXiv:1107.0553 (submitted to PRL)

$791\,\mathrm{fb}^{-1}$

- 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:
  - standard pion selection
  - reconstruction of π^0, η and η'
  - 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

CPV in $D^+ \to \pi^+ \eta^{(\prime)}$

- 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 $D_s^+ \to \phi\pi^+$ (asuming 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

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

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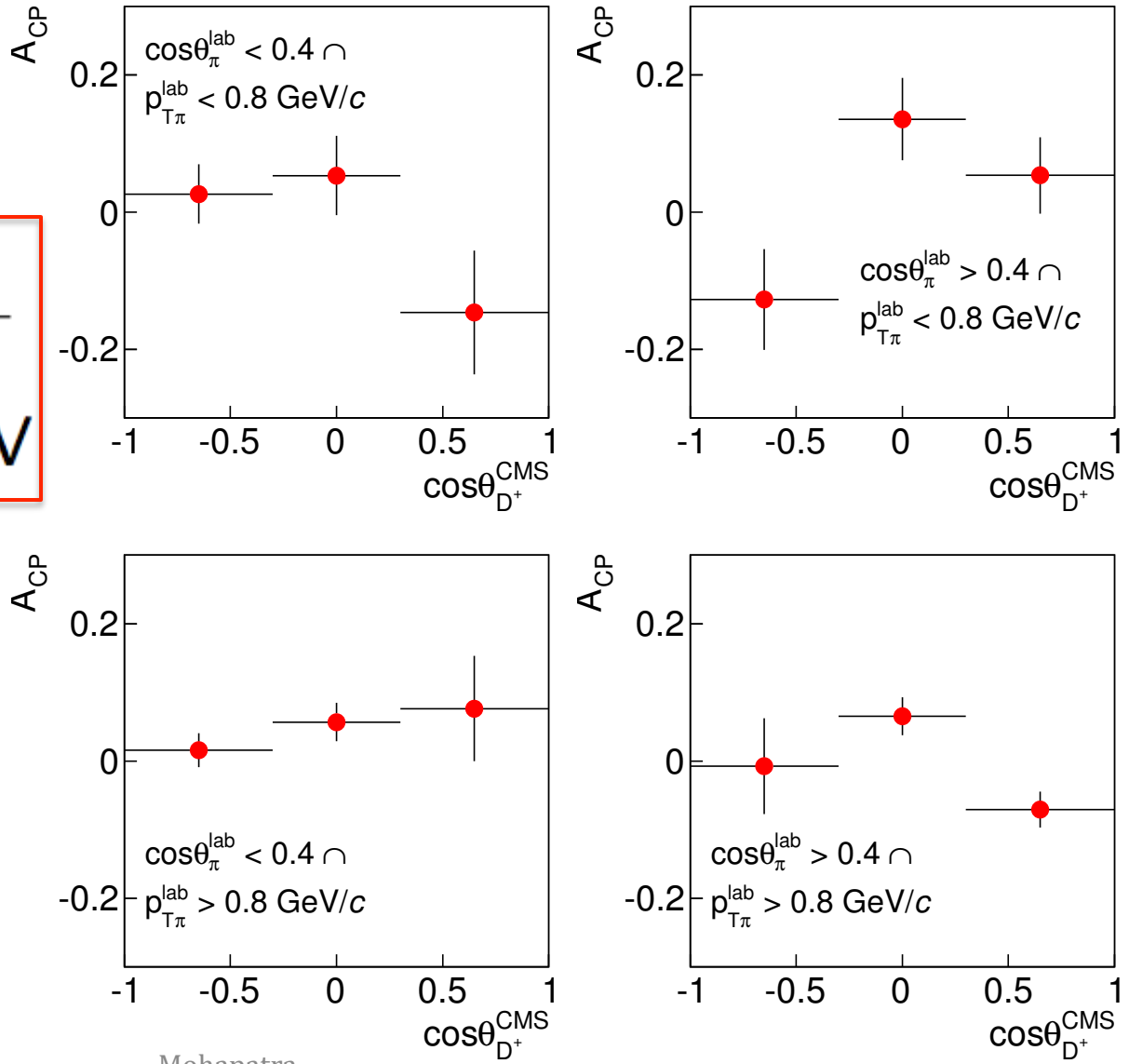
A_{CP} (%)
$+1.74 \pm 1.13 \pm 0.20$
No evidence for CPV



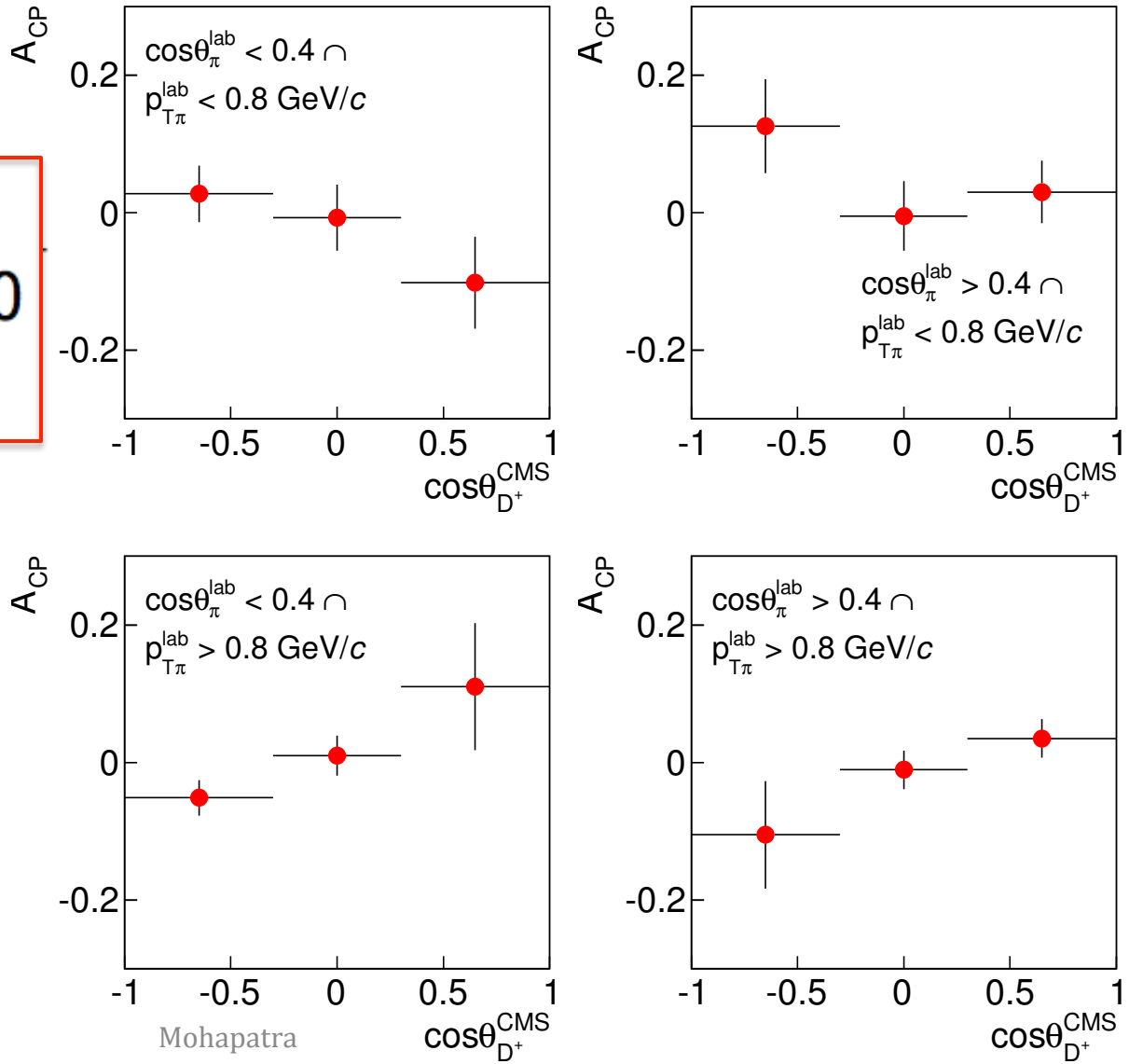
CPV in $D^+ \to \pi^+ \eta'$

$791\ \text{fb}^{-1}$

A_{CP} (%)

$-0.12 \pm 1.12 \pm 0.20$

No evidence for CPV



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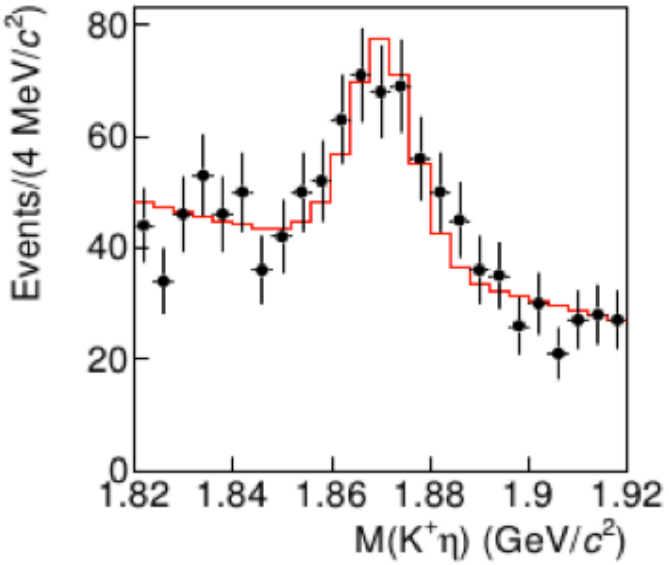
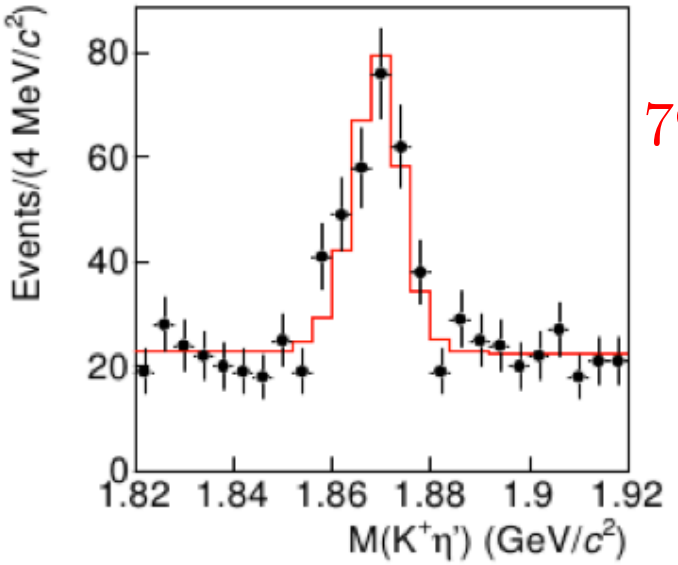
DCS decays $D^+ \to K^+\eta^{(\prime)}$

- First observation of DCS decays:

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





$791\,\mathrm{fb}^{-1}$

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

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DCS decays $D^+ \to K^+\eta^{(\prime)}$

$791\,\mathrm{fb}^{-1}$

- 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 (at around 3σ)

Summary

- We searched for CPV in the following Charm modes
  - $D^+_{(s)} \to \phi\pi^+$
  - $D^0 \to K_s\pi^0, K_s\eta^{(\prime)}$
  - $D^+ \to \pi^+\eta^{(\prime)}$
- We reported first observation of DCS decays $D^+ \to K^+\eta^{(\prime)}$
- Updated charm mixing results will be available soon.

Thank you all

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