Searches for CP violation in D^0 decays from BaBar and Belle

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CP violation in D^0 decays

- Standard Model: CP violation from KM phase in CKM quark mixing matrix:

$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{\lambda^2}{2} - \boxed{i\eta A^2\lambda^4} & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

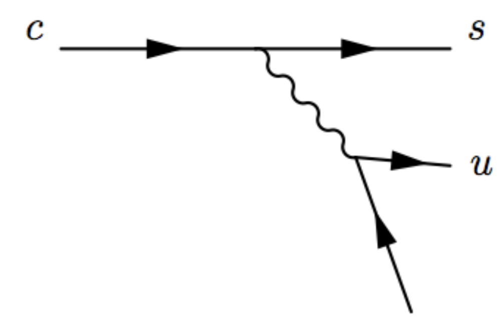
- Charmed Mesons:
  - CP violation is CKM suppressed $\mathcal{O}(10^{-3})$
  - Experimental Sensitivity $\mathcal{O}(10^{-2})$

1% Signal = New Physics

New Physics Scenario

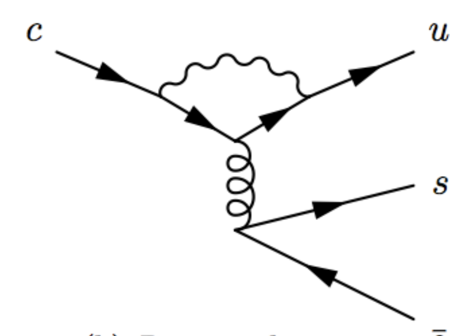
CPV ~ 1% Strong Evidence for non-SM processes

- Direct CP violation at tree level («1%)
  - extra quarks in SM vector-like representations
  - supersymmetry without R-parity models
  - two Higgs doublet models



(a) *Tree diagram.*

- Direct CP violation at one-loop (1%)
  - QCD penguin and dipole operators
  - FCNCs in supersymmetric flavor models.



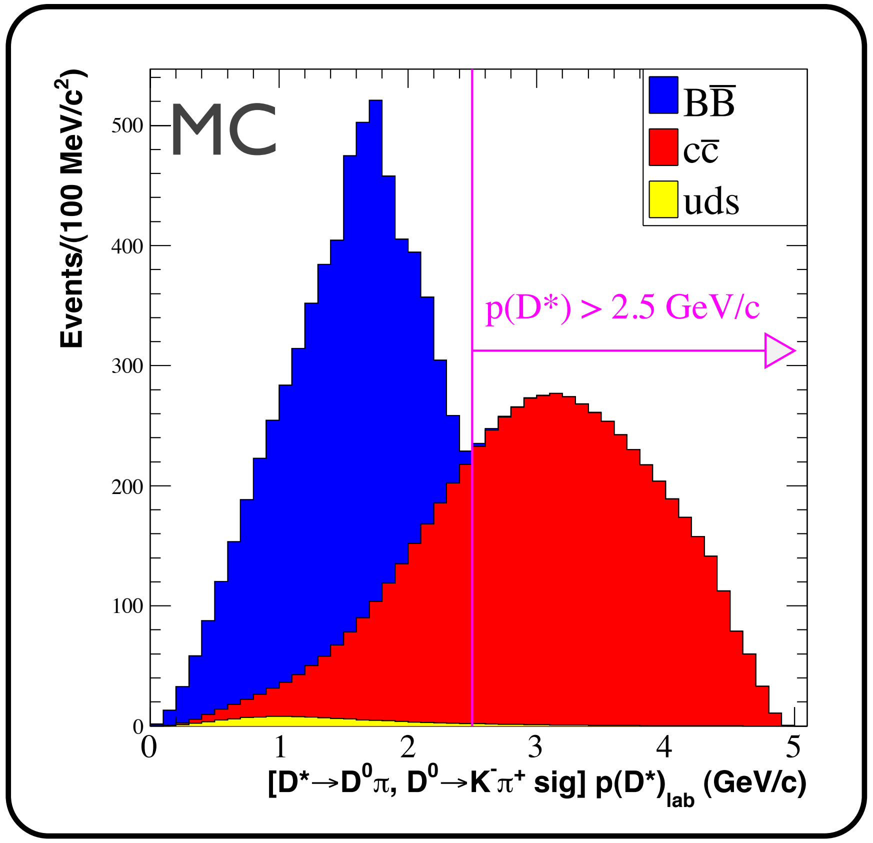
(b) *Penguin diagram.*

Singly Cabibbo Suppressed (CS) decays are uniquely sensitive to $c \to uq\bar{q}$
Cabibbo Favoured and Double CS are not

Details:
Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D75, 036008 (2007)
I. I. Bigi, hep-ph/0104008 (2001)

Charm & B-factories

- Why search for CP violation at B-factories:
  - $\Upsilon(4S)$: ccbar cross section = 1/4 total
  - require $p^{*}(D) > 2.5$ GeV/c to reduce background
  - $D^{*+} \rightarrow D^0\pi^+$ provides D^0 flavor



- Drawback: Electroweak Forward-Backward asymmetry

Experimental Searches

- Direct CP violation
- Dalitz Plot analysis
- Time dependent
- T odd correlations

Direct CP violation

$$A_{CP} = \frac{\Gamma_{D^0} - \Gamma_{\overline{D}^0}}{\Gamma_{D^0} + \Gamma_{\overline{D}^0}}$$

Γ = yields

- In asymmetric detectors like BABAR and Belle, forward-backward asymmetry could bias these measurements
- FB asymmetry = EW+EM currents interference

$$N_c / N_{\bar{c}} = f(\cos\theta^*)$$

- Two solutions:
  - estimate FB asymmetry contribution
  - normalize CP asymmetry to CF channels

$$A_{CP} = \frac{R_{D^0} - R_{\overline{D}^0}}{R_{D^0} + R_{\overline{D}^0}}, \quad \text{with } R = \frac{\Gamma_{CS}}{\Gamma_{CF}}$$

Doubly Cabibbo Suppressed $D^0 \to K^+\pi^-(n\pi)$

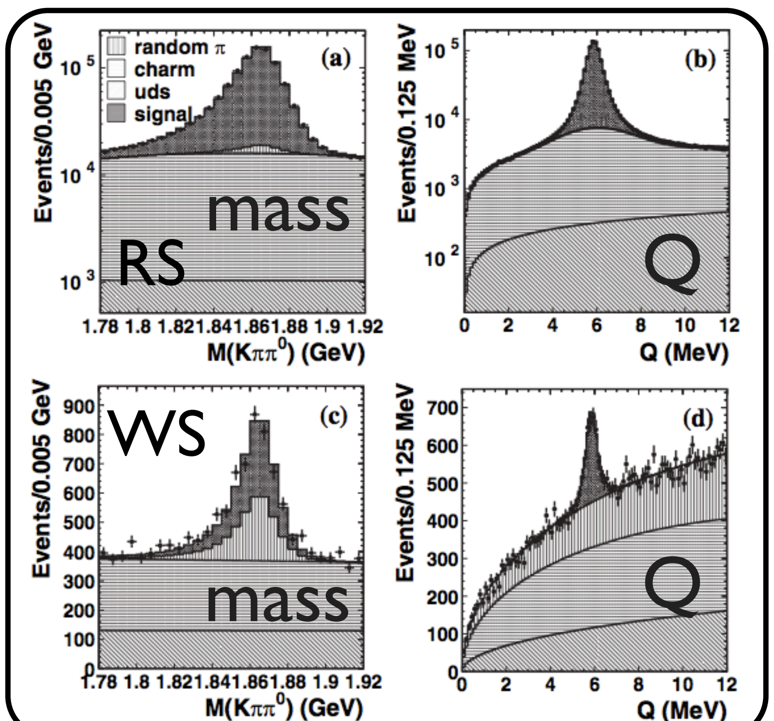
Phys. Rev. Lett. 95, 231801 (2005)

Belle ($281 fb^{-1}$)

- D* tagged
- Identification of Right Sign and Wrong Sign decay using K charge
- Both are DCS, using ratio DCS/CF yields
- 2D binned maximum likelihood fit to ($m(D^0)$, Δm)

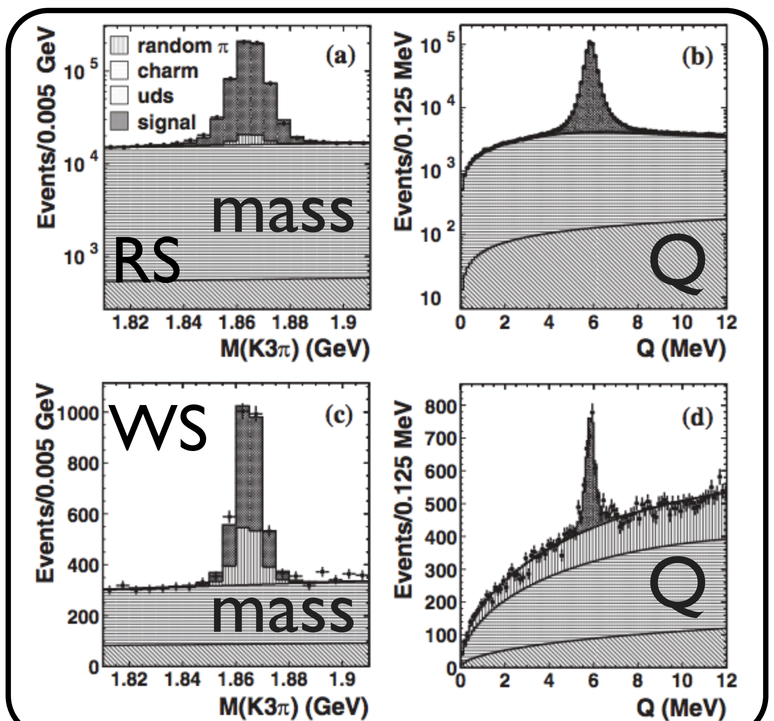
$$A_{CP} = \frac{R_{WS}^{D^0 \to K^+\pi^-(n\pi)} - R_{WS}^{\overline{D}^0 \to K^+\pi^-(n\pi)}}{R_{WS}^{D^0 \to K^+\pi^-(n\pi)} + R_{WS}^{D^0 \to K^+\pi^-(n\pi)}}, \quad \text{with } R_{WS} = \frac{\Gamma(K^+\pi^-(n\pi))}{\Gamma(K^-\pi^+(n\pi))}$$

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



$N_D^{tot}=1978\pm104$

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



$N_D^{tot}=1721\pm75$

syst. < 0.01

$A_{CP}^{K\pi\pi} = -0.018\pm0.044$

$A_{CP}^{K\pi\pi\pi} = -0.006\pm0.053$

Cabibbo Suppressed Decays: $D^0 \rightarrow h^+h^-$

$$A_{CP} = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)} = \boxed{A^{hh}_{CP,dir}} + \boxed{A^{hh}_{CP,ind}}$$

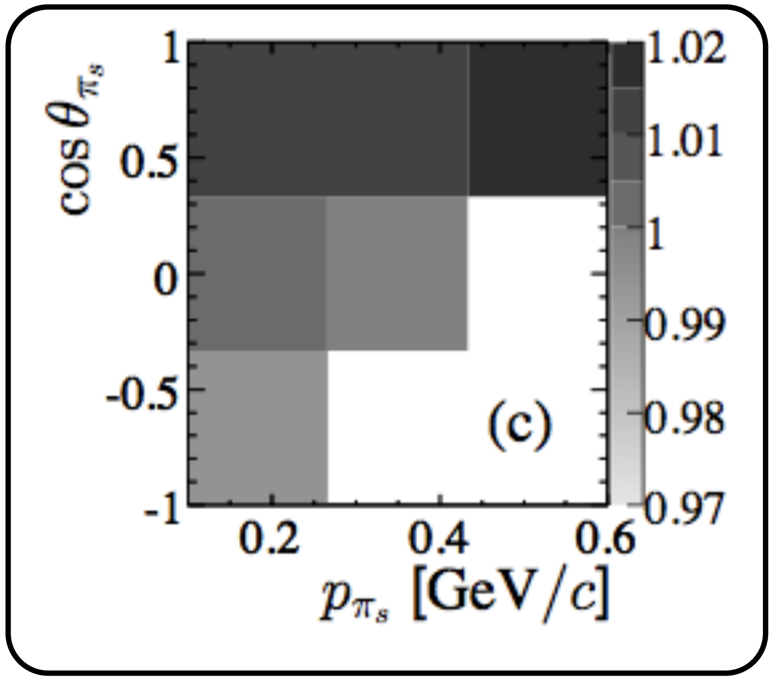
from mixing analysis

- Major issue: asymmetry in D^0 tagging
  - FB asymmetry
  - soft pion(π_s) reconstruction asymmetry

Need to separate contributions to A_{CP}

$$A^{hh}_{CP,dir} = A^{hh}_{CP} + A_{FB} + A_{\pi_s}$$

Cabibbo Suppressed Decays: $D^0 \to h^+h^-$



- map the π_s asymmetry using $D^0 \to K^-\pi^+$ tagged and untagged data to retrieve the weighting factors to correct D^0 yield

$$a^{\pm}(\cos\theta^*) = \frac{n_{D^0}(\pm|\cos\theta^*|) - n_{\overline{D}^0}(\pm|\cos\theta^*|)}{n_{D^0}(\pm|\cos\theta^*|) + n_{\overline{D}^0}(\pm|\cos\theta^*|)}$$

$$A_{CP} \simeq [a^+(\cos\theta^*) + a^-(\cos\theta^*)]/2$$

$$A_{FB} \simeq [a^+(\cos\theta^*) - a^-(\cos\theta^*)]/2$$

even: A_{CP} uniform over cosθ

odd: A_{FB} asymmetric over cosθ

- measure A_{CP} in cosθ bins in order to isolate production asymmetry

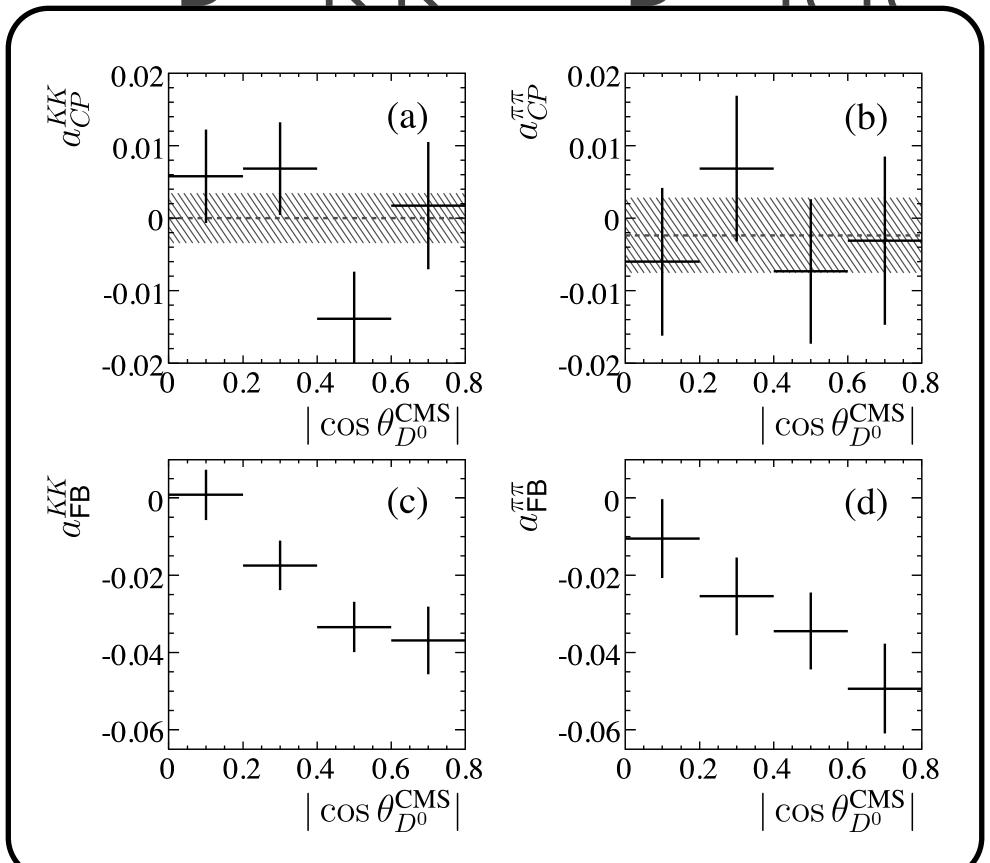
- measure A_{CP} from χ^2 fit over cosθ bins

Cabibbo Suppressed Decays: $D^0 \to h^+h^-$

Phys. Rev. Lett. 100, 061803 (2008)

BABAR ($385 fb^{-1}$)

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



Systematic errors

Category	ΔA_{CP}^{KK}	$\Delta A_{CP}^{\pi\pi}$
2-dim PDF shapes	±0.04%	±0.05%
π_s corrections	±0.08%	±0.08%
A_{CP} corrections	±0.09%	±0.20%
Quadrature sum	±0.13%	±0.22%

two-dimensional fit to D^0 and Δm

Sample	Size
$K^-\pi^+$ untag	6.6×10^6
$K^-\pi^+$ tag	1.5×10^6
K^+K^-	130×10^3
$\pi^+\pi^-$	64×10^3

Results

$$A_{CP}^{KK} = (0.00 \pm 0.34_{stat} \pm 0.13_{syst})\%$$

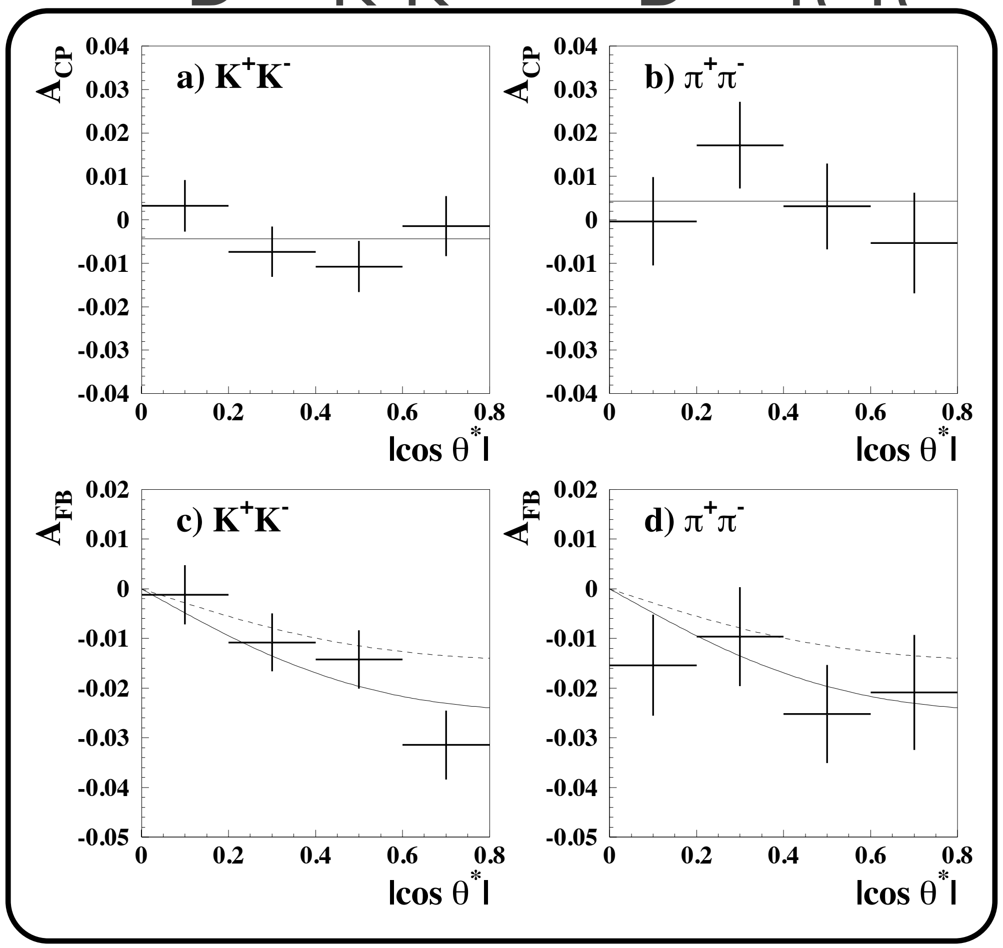
$$A_{CP}^{\pi\pi} = (-0.24 \pm 0.52_{stat} \pm 0.22_{syst})\%$$

Cabibbo Suppressed Decays: $D^0 \to h^+h^-$

Phys. Lett. B670.190 (2008)

Belle ($540 fb^{-1}$)

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



Sample	Size	Purity
$K^-\pi^+$ untag	6.3×10^6	80%
$K^-\pi^+$ tag	1.3×10^6	99%
K^+K^-	120×10^3	97%
$\pi^+\pi^-$	51×10^3	91%

Systematic errors

Category	ΔA_{CP}^{KK}	$\Delta A_{CP}^{\pi\pi}$
Signal Counting	±0.04%	±0.06%
π_s corrections	±0.10%	±0.10%
A_{CP} extraction	±0.03%	±0.04%
Quadrature sum	±0.11%	±0.12%

one-dimensional fit to D^0 mass spectrum

Results

$$A_{CP}^{KK} = (-0.43 \pm 0.30_{stat} \pm 0.11_{syst})\%$$

$$A_{CP}^{\pi\pi} = (+0.43 \pm 0.52_{stat} \pm 0.12_{syst})\%$$

Dalitz Plot Analysis

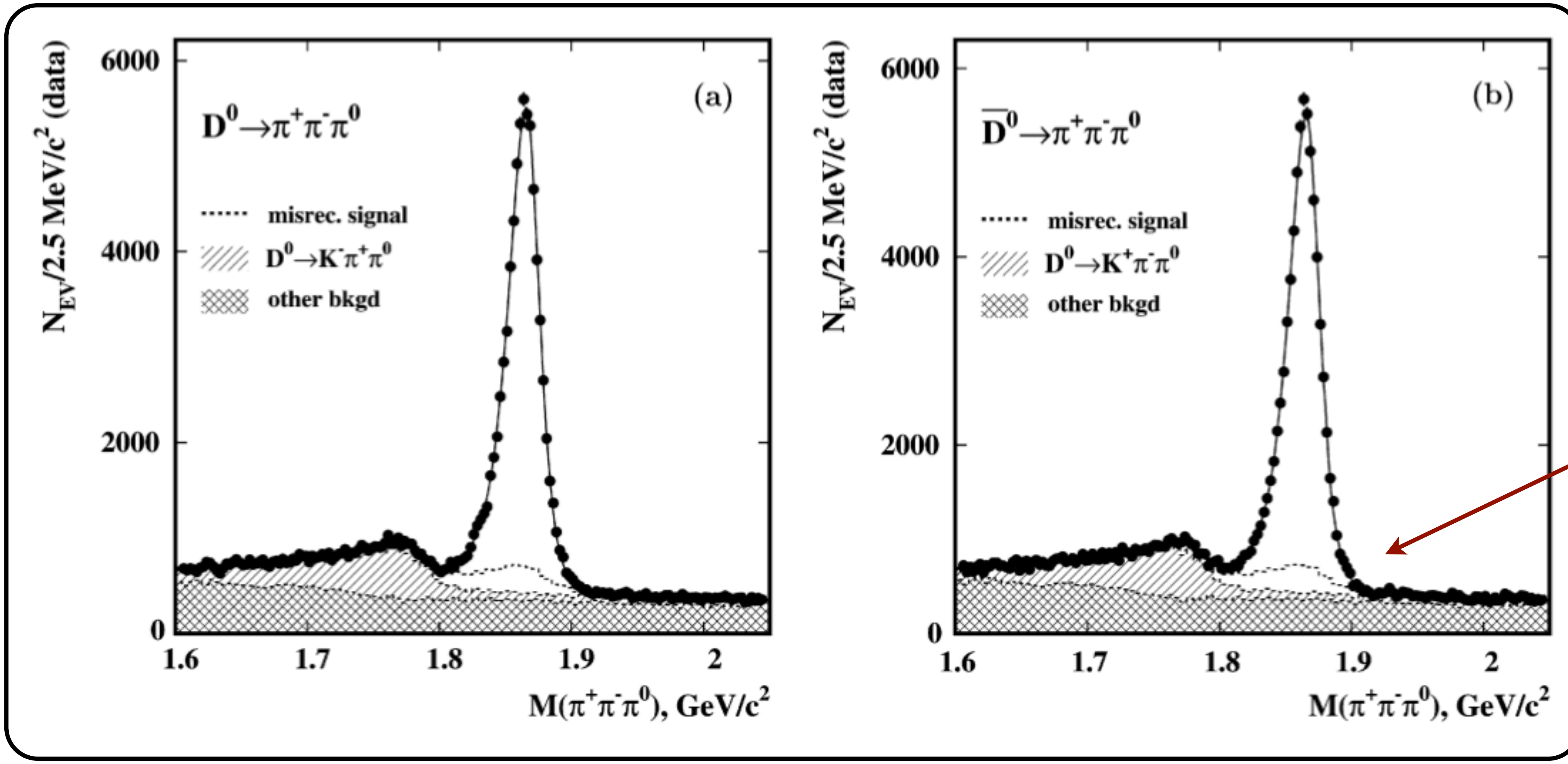
- Quantities that can be measured:
  - Asymmetry on the Dalitz Plot
  - Asymmetry in the angular moments
  - Asymmetry in the amplitudes (model dependent)
  - Phase Space integrated asymmetry

Cabibbo Suppressed Decay $D^0 \to \pi^+\pi^-\pi^0$

Phys. Lett. B662.102 (2008)

Belle ($532 fb^{-1}$)

Phase Space integrated asymmetry measurement



Sample	Yields
$\pi^+\pi^-\pi^0$	2.4×10^6

peaking background from D^0+random π_s

fit PDF from MC

Systematics

Source	MC stat.	Tracking	Fit	K_S veto	PID	Binning	A_{FB}	Total
σ (%)	0.24	1.01	0.58	0.23	0.15	0.05	0.15	1.23

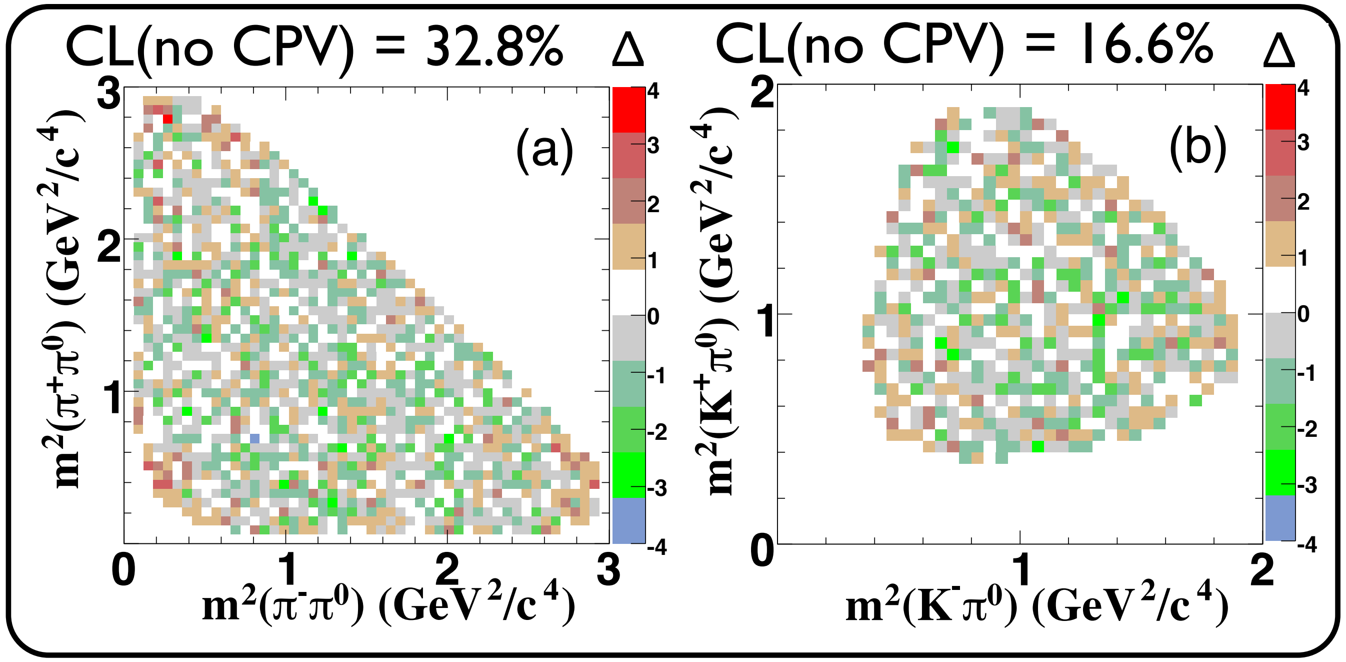
$$A_{CP} = (0.43 \pm 0.41_{stat} \pm 1.30_{syst})\%$$

Cabibbo Suppressed Decay $D^0 \to h^+h^-\pi^0$

Phys. Rev. D78, 051102(R) (2008)

BABAR ($385 fb^{-1}$)

Search for asymmetries in the Dalitz plot



(a)$D^0 \to \pi^+\pi^-\pi^0$ (b)$D^0 \to K^+K^-\pi^0$

Normalized Residuals

$$\Delta = \frac{(n_{\bar{D}^0} - R \cdot n_{D^0})}{\sqrt{\sigma^2_{n_{\bar{D}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}}$$

R = efficiency corrected N_{D0bar}/N_{D0}

$$\chi^2/\nu = \left(\sum_{i=1}^{\nu} \Delta_i^2\right)/\nu$$

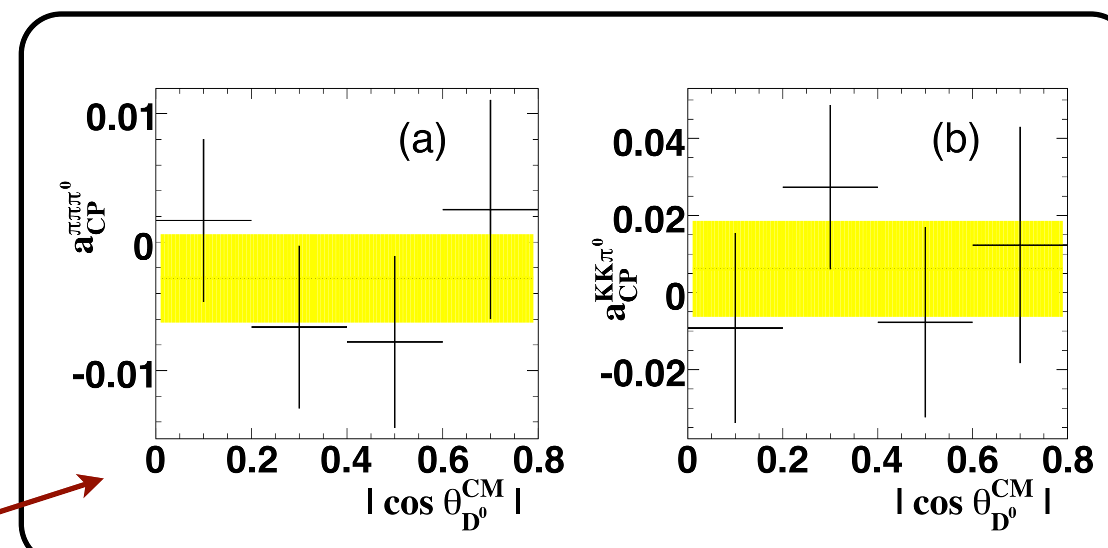
CL = one sided gaussian Confidence Level for consistency with no CPV hypothesis

Sample	Size	Purity
$K^+K^-\pi^0$	11×10^3	98%
$\pi^+\pi^-\pi^0$	82×10^3	98%

$A_{CP}^{KK\pi}=(1.00\pm1.67_{stat}\pm0.25_{syst})\%$

$A_{CP}^{\pi\pi\pi}=(-0.31\pm0.41_{stat}\pm0.17_{syst})\%$

average on cosθ to cancel FB asymmetry



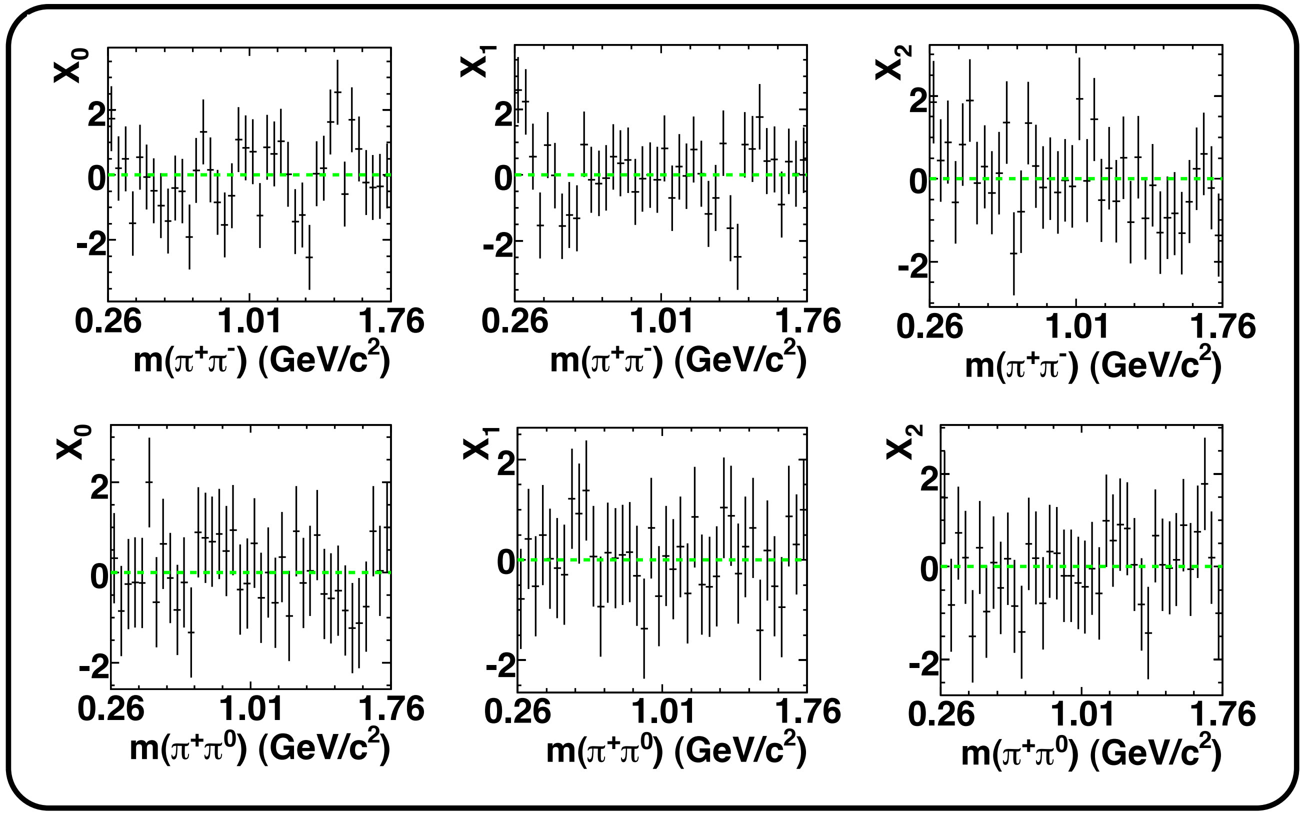
continued

Cabibbo Suppressed Decay $D^0 \to h^+h^-\pi^0$

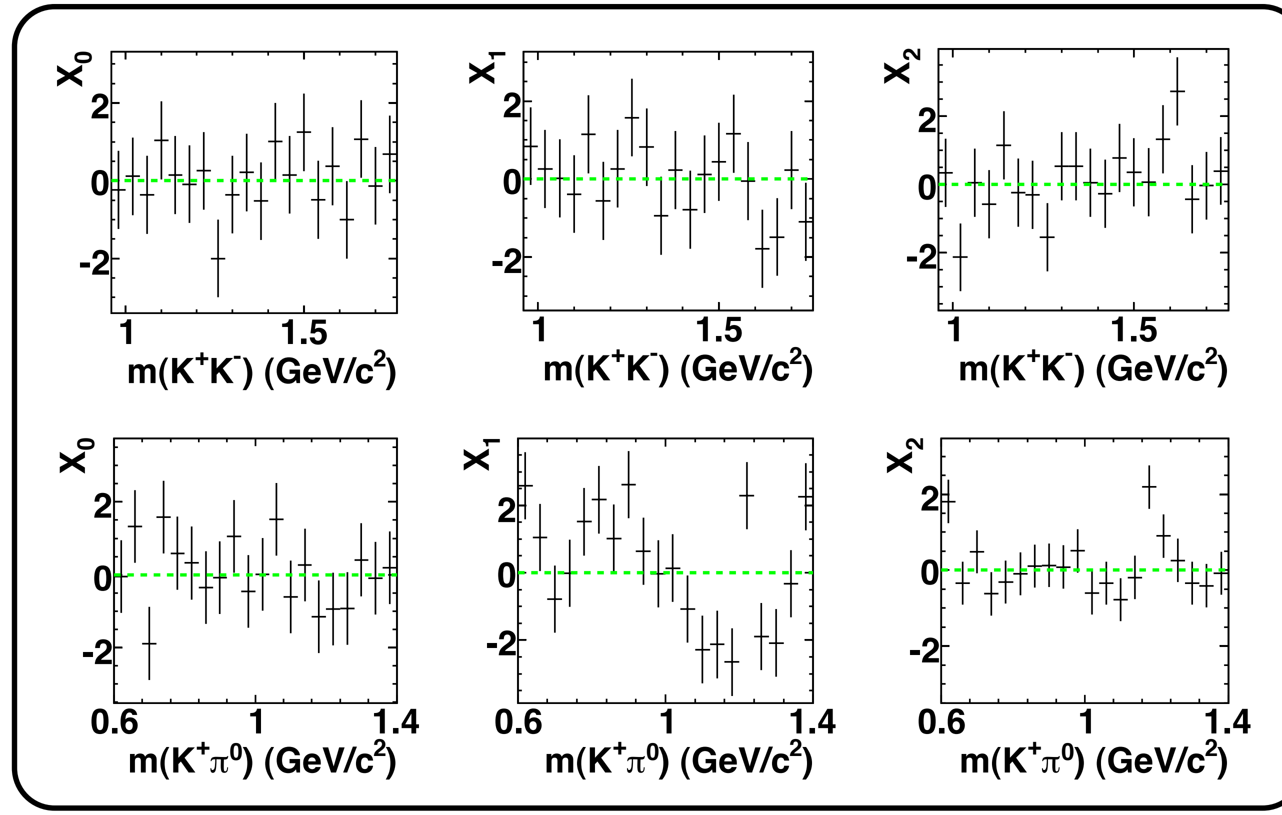
Phys. Rev. D78, 051102(R) (2008)

BABAR ($385 fb^{-1}$)

Study of the Angular Moments to search for asymmetries



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



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

particle combination	$\pi^+\pi^-$	$\pi^+\pi^0$	K^+K^-	$K^+\pi^0$
CL (No CPV)	28.2%	28.4%	63.1%	23.8%

No CPV found in Dalitz amplitudes comparing amplitudes, phases and fractions

Time Dependent (TD)

for a definition of x, y, r_m and φ_f see Nicola's talk on D^0 mixing

- D^0 mixing affects D^0 decay times (h=K,π)

$$\tau_{hh}^{+} = \tau_{K\pi}\left[1 + r_m\left(y\cos\varphi_f - x\sin\varphi_f\right)\right]^{-1}$$

$$\tau_{hh}^{-} = \tau_{K\pi}\left[1 + r_m^{-1}\left(y\cos\varphi_f - x\sin\varphi_f\right)\right]^{-1}$$

- defining

$$\tau_{hh} = \frac{\tau_{hh}^{+} + \tau_{hh}^{-}}{2} \qquad A_\tau = \frac{\tau_{hh}^{+} - \tau_{hh}^{-}}{\tau_{hh}^{+} + \tau_{hh}^{-}}$$

- ΔY is a probe for CP violation in decay times

(r_m=1, φ_f =0)

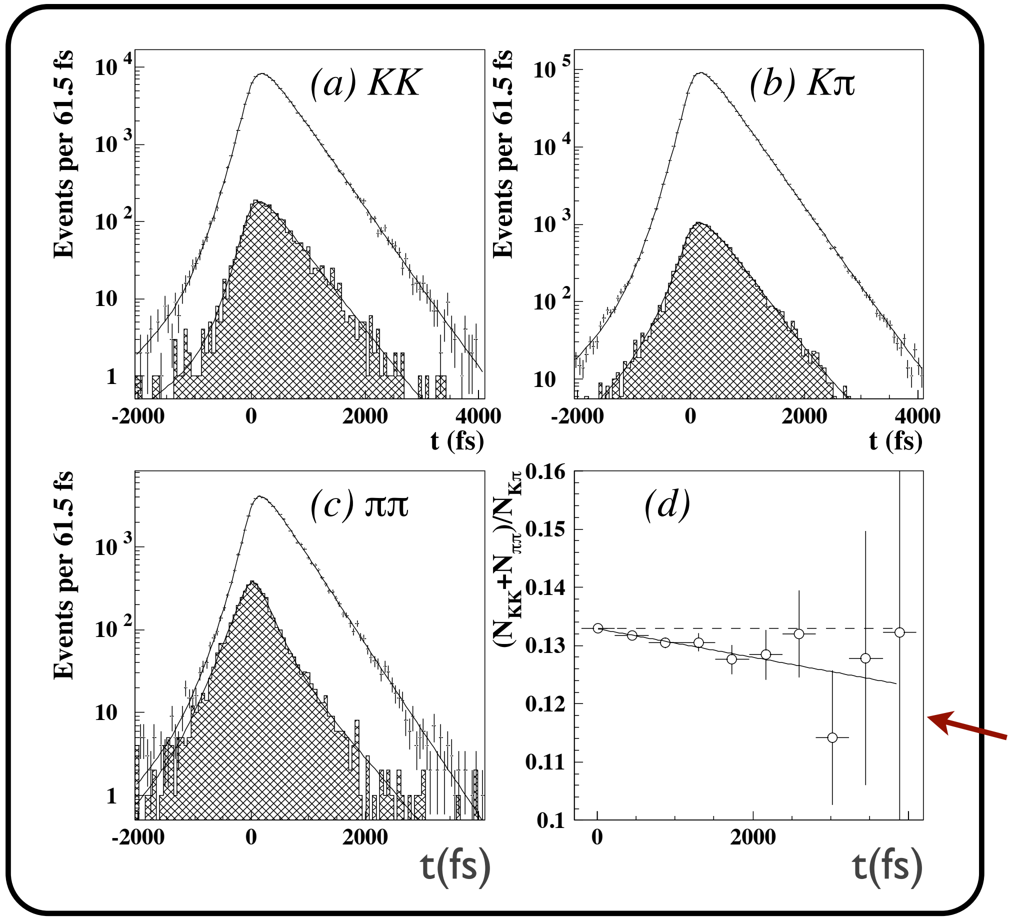
$$\Delta Y = \frac{\tau_{K\pi}}{\tau_{hh}} A_\tau$$

(SM: ΔY=0)

Cabibbo Suppressed Decay $D^0 \to h^+h^-$ (TD)

Phys. Rev. Lett. 98.211803 (2007)

Belle ($540 fb^{-1}$)



$$t = m_{D^0}\vec{L}\cdot\vec{p}/p^2$$

- D* tagged events
- many systematics cancel in lifetime ratio

Sample	Size	Purity
$K^-\pi^+$	111×10^3	98%
K^+K^-	1220×10^3	99%
$\pi^+\pi^-$	49×10^3	92%

$y_{CP} \neq 0$

($A_\Gamma = -A_\tau$)

$A_\Gamma^{KK} = (0.15 \pm 0.35_{stat})\%$

$A_\Gamma^{\pi\pi} = (-0.28 \pm 0.57_{stat})\%$

Systematics

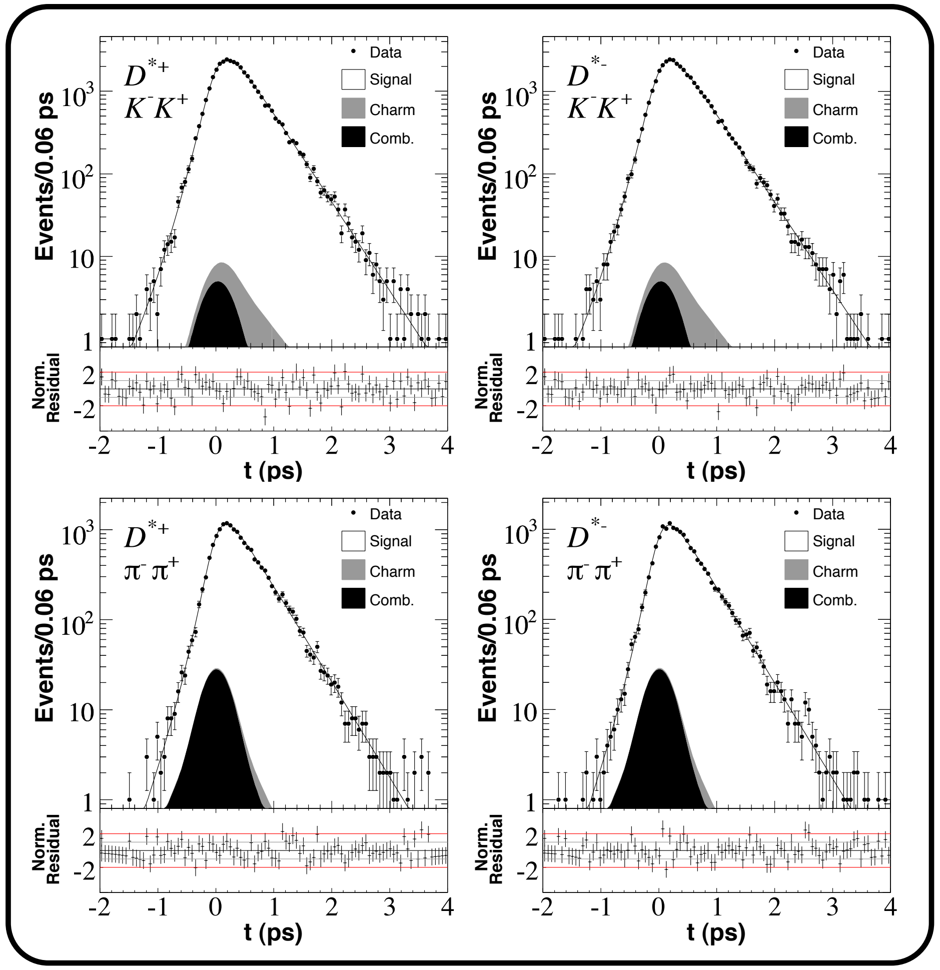
Source	Acceptance	Equal t_0	M window	Sig/SB bkg	Bkg B(t)	Res Func	Selection	Binning	Total
σ (%)	0.07	0.08	<0.01	0.06	0.07	0.01	0.05	0.01	0.15

$$A_\Gamma = (0.01 \pm 0.30_{stat} \pm 0.15_{syst})\%$$

Cabibbo Suppressed Decay $D^0 \to h^+h^-$ (TD)

Phys. Rev. D78.011105 (2008)

BABAR ($385 fb^{-1}$)



- D* tagged events
- many systematics cancel in lifetime ratio

Sample	Size	Purity
$K^-\pi^+$	731×10^3	99.9%
K^+K^-	67×10^3	99.6%
$\pi^+\pi^-$	31×10^3	98.0%

$$\Delta Y^{KK} = (-0.40 \pm 0.44_{stat} \pm 0.12_{syst})\%$$

$$\Delta Y^{\pi\pi} = (0.05 \pm 0.64_{stat} \pm 0.32_{syst})\%$$

Systematics

Source	Sig Model	Charm Bkg	Comb Bkg	Selection	Detector Model	Total
σ (%) KK	0.072	0.001	0.001	0.083	0.054	0.122
σ (%) π π	0.265	0.002	0.005	0.172	0.040	0.318
σ (%) average	0.062	0.001	0.002	0.011	0.054	0.083

$$\Delta Y = (-0.26 \pm 0.36_{stat} \pm 0.08_{syst})\%$$

T odd correlations

W. Bensalem, A. Datta and D. London, Phys. Rev. D66, 094004 (2002)
W. Bensalem and D. London, Phys. Rev. D64, 116003 (2001)
W. Bensalem, A. Datta and D. London, Phys. Lett. B538, 309 (2002)

- Asymmetry in T-odd observable → T violation → CPV (assuming CPT invariance)

- T-odd observable (v = spin or momentum)

measured on D^0

$$A_T = \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}$$

- Final State Interactions could fake the measure producing $A_T \neq 0$

- Remove FSI effects

measured on $\overline{D}^0$

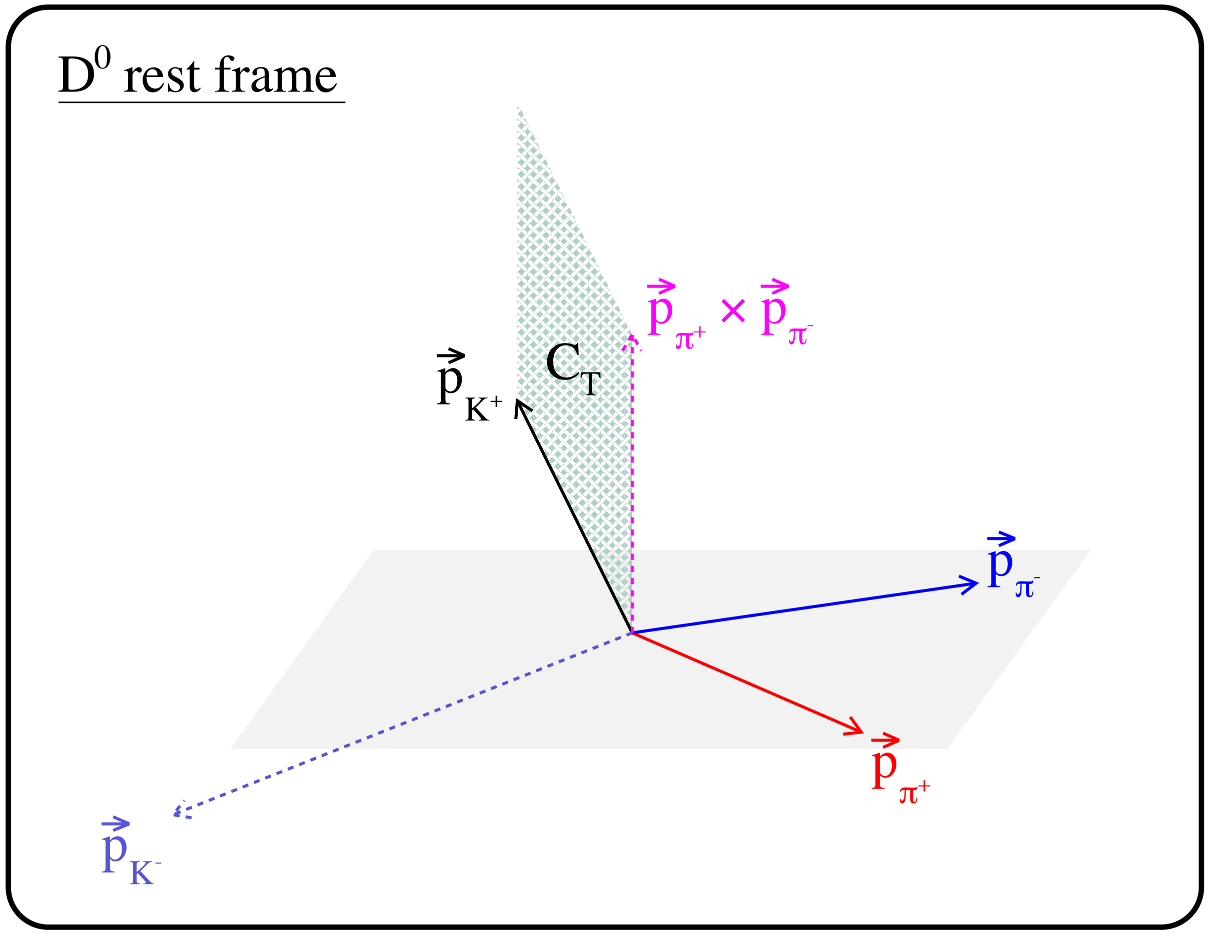
$$\mathcal{A}_T = \frac{1}{2}\left(A_T - \bar{A}_T\right)$$

T violating observable

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

I. I. Bigi, hep-ph/0107102 (2001)

- T-odd correlation observable (C_T) can be built using final state particle momenta:



$$C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

$$A_T = \frac{\Gamma(D^0, C_T > 0) - \Gamma(D^0, C_T < 0)}{\Gamma(D^0, C_T > 0) + \Gamma(D^0, C_T < 0)}$$

$$\bar{A}_T = \frac{\Gamma(\overline{D}^0, -\bar{C}_T > 0) - \Gamma(\overline{D}^0, -\bar{C}_T < 0)}{\Gamma(\overline{D}^0, -\bar{C}_T > 0) + \Gamma(\overline{D}^0, -\bar{C}_T < 0)}$$

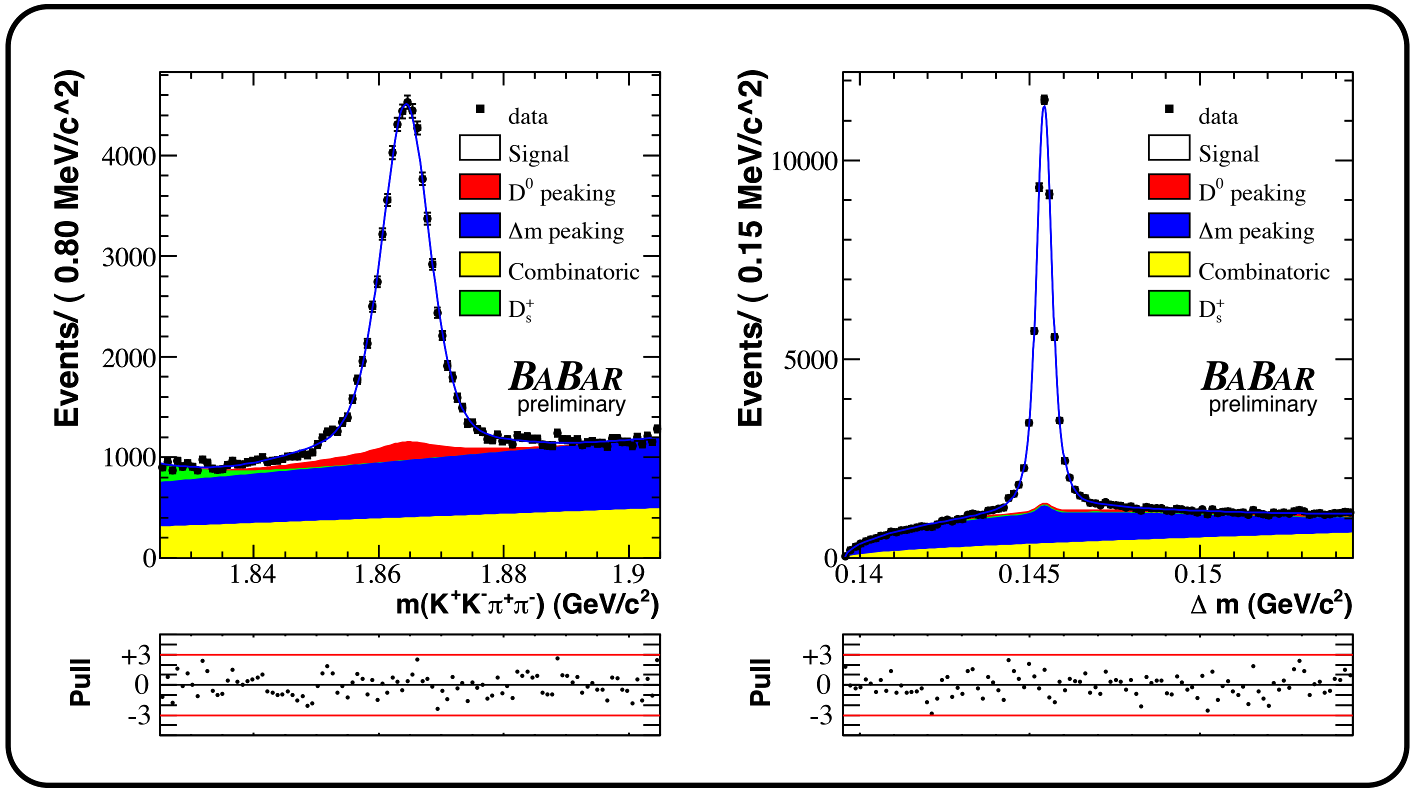
Cabibbo Suppressed Decay $D^0 \to K^+K^-\pi^+\pi^-$

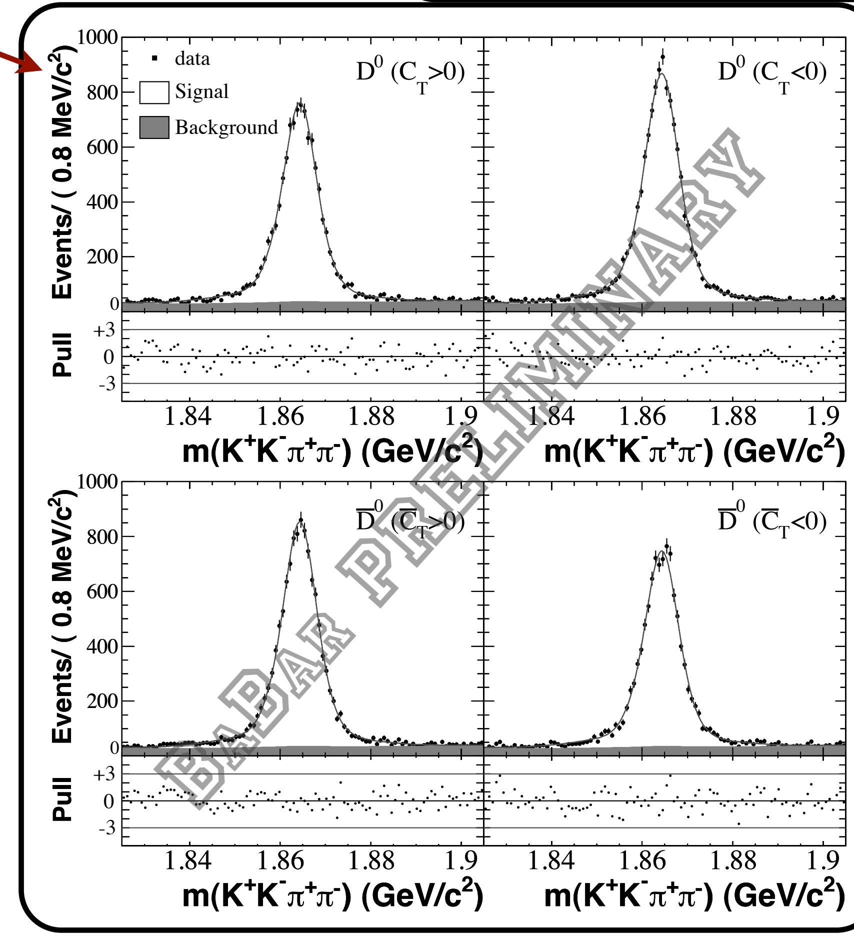
hep-ex/1003.3397 (accepted by PRD)

BABAR ($470 fb^{-1}$)

fit projections signal region

- D^* tagged events
- 2D fit to ($m(D^0)$, Δm)
- 47000 signal events





$$A_T = (-68.5 \pm 7.3_{\rm stat} \pm 5.8_{\rm syst}) \times 10^{-3}$$

$$\bar{A}_T = (-70.5 \pm 7.3_{\rm stat} \pm 3.9_{\rm syst}) \times 10^{-3}$$

Systematics:

Effect	signal PDF	Δm peak PDF	bin size	PID	$p^*(D^0)$	$\cos\theta^*$	fit bias	mistag	det asym	Total
$\sigma(\times 10^{-3})$	0.2	0.5	0.2	3.5	1.7	0.9	1.4	0.0	1.1	4.4

$$\mathcal{A}_T = (1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$$

Conclusions

- D^0 and charm decays provide a powerful probe for non SM processes involving CPV
- Experimental sensitivity comparable to higher SM predictions
- Many experimental techniques developed by BABAR and BELLE
- No evidence of CPV found yet
- Is the best yet to come?