UNIVERSIDAD TECNICA
FEDERICO SANTA MARIA

BABAR

Search for CP Violation in Charm at the B-Factories

Ryan Mackenzie White
U. of South Carolina / U. Técnica Federico Santa María

FPCP, Rio de Janeiro, 19 - 24 May 2013

USC HEP
University of South Carolina
High Energy Physics Group

BELLE

Outline

Introduction to CP Violation (CPV) in Mesons

Experimental observation of CPV in Charm meson decays

Measurements of CPV in Charm decays

- Indirect CPV and mixing in two-body decays
- Direct CPV in two-body decays
  - Interference between tree-level and penguin-level amplitudes in singly Cabibbo-suppressed decays.
  - Interference between Cabibbo-favored and doubly Cabibbo-suppressed amplitudes.
- Direct CPV in three-body singly Cabibbo-suppressed decays

Conclusions

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

USC HEP University of South Carolina High Energy Physics Group

CP Violation in Decays of Mesons

BABAR BELLE

- **CP Violation in decay to final states *f* and $\bar{f}$** $|A_f| \neq |\bar{A}_{\bar{f}}|$

Two amplitudes with different weak and strong phases

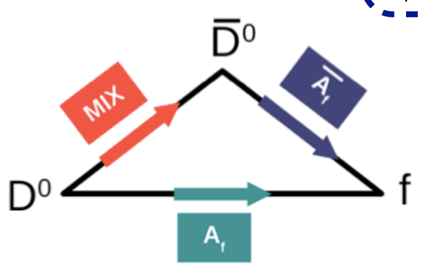
$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

- **CP violation in mixing if** $r_m = |q/p| \neq 1$

Probability of $D^0 \rightarrow \bar{D}^0$ is different than CP conjugate $\bar{D}^0 \rightarrow D^0$

$$|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \qquad \left(\frac{q}{p}\right)^2 = \frac{M^*_{12} - \frac{1}{2}\Gamma^*_{12}}{M_{12} - \frac{1}{2}\Gamma_{12}}$$

- **CP violation in the *interference* between the decay with and without mixing if** $\phi_f \neq 0$



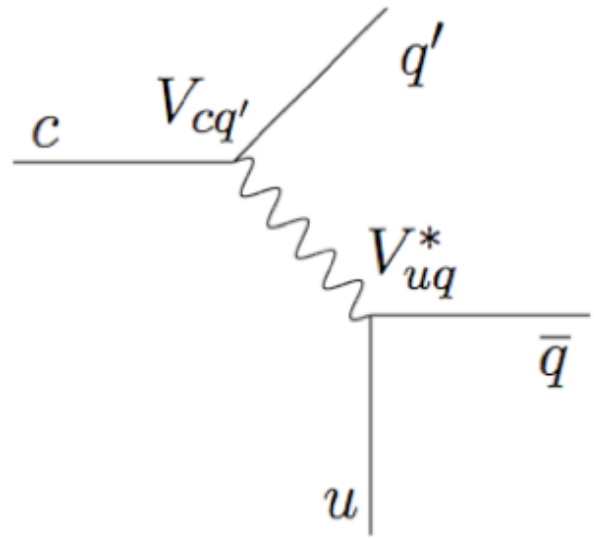
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = |\frac{q}{p}\frac{\bar{A}_f}{A_f}|exp[i(\delta_f + \phi_f)]$$

strong + *weak* phase

D meson Decays

Three types of D meson decays

- **Cabibbo-favored**
  - examples: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$
  - $A_T \sim |V_{cs}V_{ud}|$
- **singly Cabibbo-suppressed (SCS)**
  - examples: $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, $D^+ \to K^+K^-\pi^+$
  - $A_T \sim |V_{cd}V_{ud}|$, $|V_{cs}V_{us}|$
- **doubly Cabibbo-suppressed (DCS)**
  - $D^0 \to K^+\pi^-$
  - $A_T \sim |V_{cd}V_{us}|$



$$q, q' = s, d$$

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA
USC HEP University of South Carolina High Energy Physics Group

Why search for CP Violation in Charm Decays?

BABAR
BELLE

- CP-violating asymmetries in charm decays provide a unique probe for physics beyond the Standard Model (SM)
- Standard Model charm physics is CP conserving to first order approximation.
- CP-violating asymmetries in charm are small.
- New Physics can enhance CP violating observables.

Wolfenstein parameterization of the CKM matrix

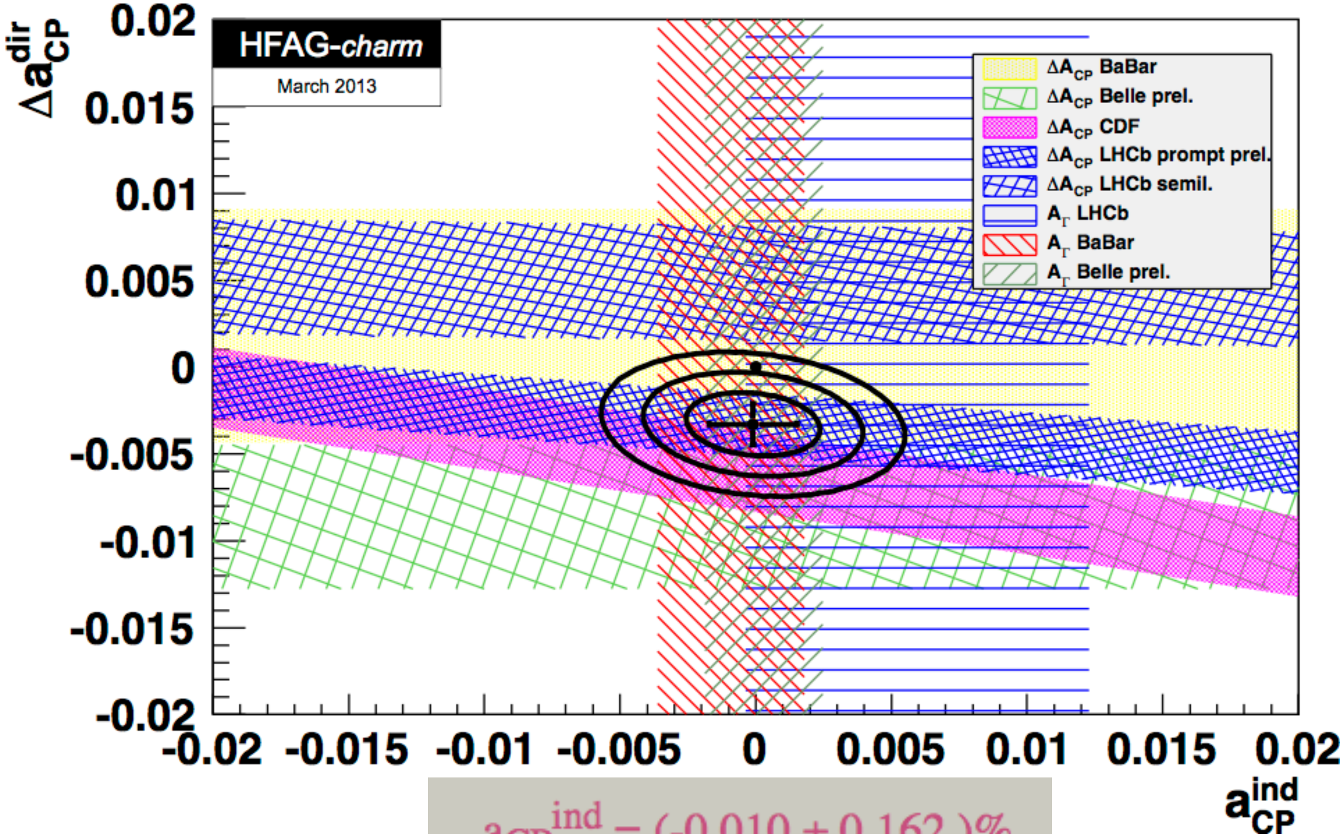
Standard Model: *CP* Violation arises from KM phase in CKM quark mixing matrix

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

Charm Mesons:
- *CP* Violation is CKM suppressed at 10^{-3} or less.

$\lambda = 0.22$

Experimental Situation



$a_{CP}^{ind} = (-0.010 \pm 0.162\ )\%$

$\Delta a_{CP}^{dir} = (-0.329 \pm 0.121\ )\%$

Current data consistent with no CPV at 2.1% CL

Is this an observation of new physics? No straightforward answer, could be SM or NP.
More measurements with greater precision required!

Measurements in Charm Decays

- Precision measurements of the lifetimes of neutral D^0 meson two-body decays -- indirect CPV and mixing.

Mixing

$$y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$$

CP Violation

$$\Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$$

- Direct CPV measurements in two-body SCS decays probe the interference between tree-level and penguin-level amplitudes.
  - Separate direct CPV contribution from D^0 two-body decays to CP-even eigenstates.
  - SCS decays with K_S^0 in final state - direct CPV compared with contribution from indirect CPV in K^0 mixing.

- Direct CPV probing the interference between DCS and CF charged $D_{(s)}$ decays with K_s in the final state. Compare to expected SM CP violation from neutral Kaons.

Direct CPV can only arise due to an additional phase from New Physics

- Direct CPV exploiting final state interactions in 3-body decays. Measure asymmetries as a function of position on the Dalitz plot (3-body).

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

USC HEP
University of South Carolina High Energy Physics Group

BABAR

BELLE

D^0 Mixing and CP Violation Observables

Mixing and CP violation observables are obtained from the partial widths of the decays:

$$D^0(\bar{D}^0) \to h^+h^-, h^\pm = K^\pm, \pi^\pm$$

Mixing

$$y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$$

CP Violation

$$\Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$$

$$\Delta Y = (1 + y_{CP})A_\Gamma \qquad A_\Gamma = \frac{\Gamma^+ - \bar{\Gamma}^+}{\Gamma^+ + \bar{\Gamma}^+}$$

CP Eigenstates

Γ^+ is the width of the decay to $D^0 \to \mathrm{CP}^+$

$\bar{\Gamma}^+$ is the width of the decay to $\bar{D}^0 \to \mathrm{CP}^+$

- Mixing appears when the width of CP eigenstates differs from the flavor (CP-mixed) eigenstates, CF and DCS decays $D^0 \to K^\mp\pi^\pm$.
- CP is violated if the width for D^0 and $\bar{D}^0$ differs when decaying to the same CP eigenstate.
- The flavor (CP-mixed) eigenstates $D^0 \to K^\mp\pi^\pm$ are assumed to be described by the average lifetime Γ.

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

USC HEP University of South Carolina High Energy Physics Group

BABAR BELLE

D^0 decays to CP-even Eigenstates K^+K^-, $\pi^+\pi^-$

Experimentally we measure the lifetimes of CP-even and CP-mixed eigenstates.

Experimental assumptions:

(i) small mixing ($|x|, |y| << 1$) proper time distributions are exponential with corresponding effective lifetimes to very good approximation.

(ii) not sensitive to direct CPV and weak phase does not depend on final state → KK and ππ share the same common effective lifetime. [PRD 80, 076008 (2009)]

Effective lifetimes - measured quantities

$$\tau^+ = \tau(D^0 \to h^+h^-)$$
$$\bar{\tau}^+ = \tau(\bar{D}^0 \to h^+h^-)$$
$$\tau_D = \tau(D^0 \to K^\mp\pi^\pm)$$
$$h^\pm = K^\pm, \pi^\pm$$

Mixing: $$y_{CP} = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} + \frac{1}{\bar{\tau}^+}\right) - 1$$

CP Violation: $$\Delta Y = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} - \frac{1}{\bar{\tau}^+}\right)$$

If CP is conserved $y_{CP} \equiv y$ and $\Delta Y = A_\Gamma = 0$

Reconstruction Techniques

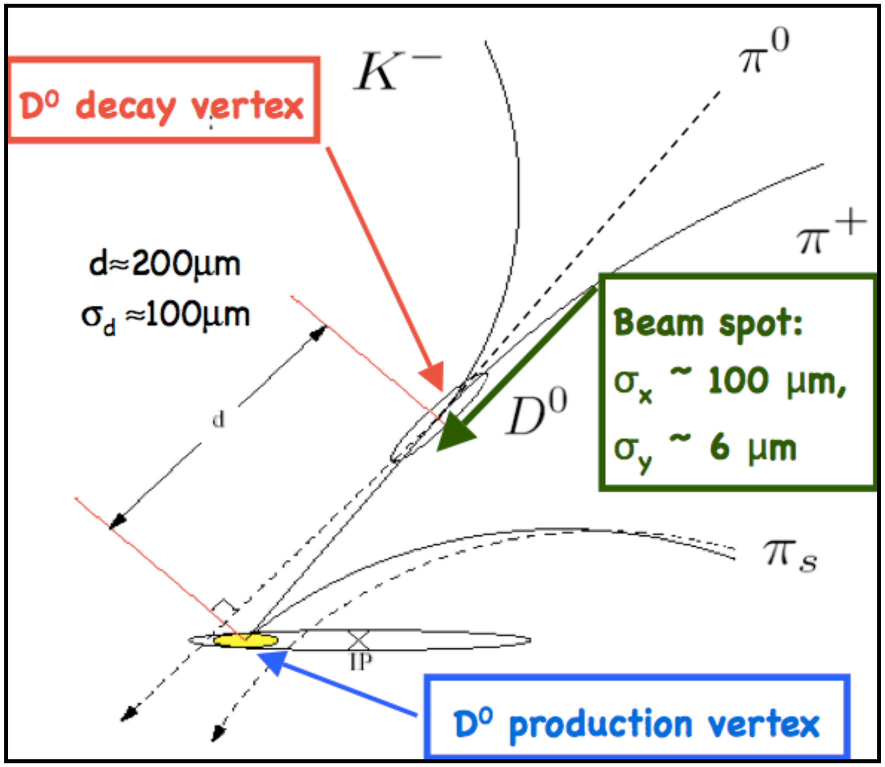
Tagged Candidates $D^* \to D^0 \pi_s$, sample purities > 98%

- Slow pion reconstructed and D^0 decays selected with two dimensional cut [m(D^0), q]

$$q = (M_D^* - M(h^+h^-) - m_\pi)c^2$$

Untagged $D^0 \to K^+K^-$, $K^\mp\pi^\pm$ candidates with sample purities ~ 75%.

- Statistically independent samples used in BaBar analysis to improve sensitivity of y_{CP} and Δy.



Resolution on proper time adequate for mixing measurements.

Decay time uncertainty evaluated event-by-event from error matrices from production and decay vertices

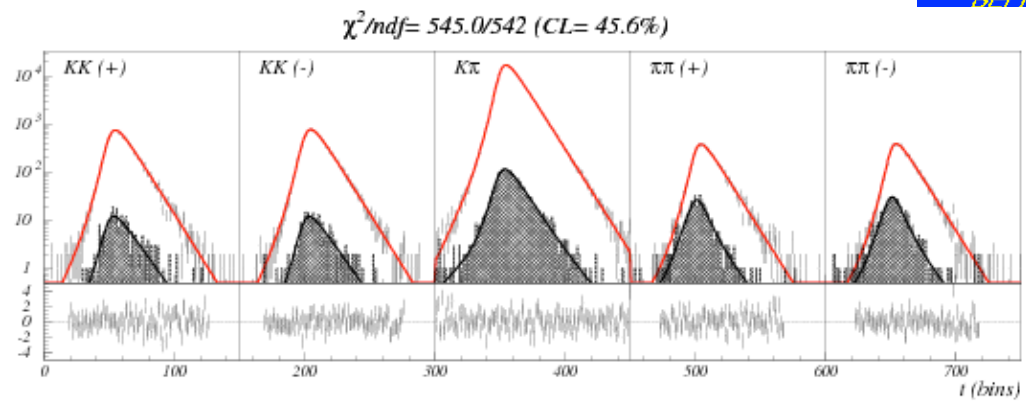
Selection of signal events

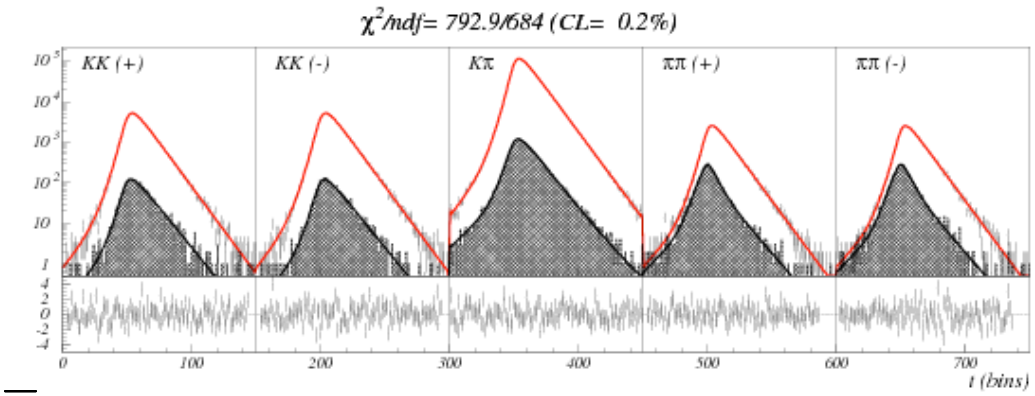
- remove D from B decays, $p_{CM}(D^0) > 2.5$ GeV/c
- Belle measures D^0 lifetime in intervals of p_{CM} due to resolution function offset. Increase $p_{CM}(D^0) > 3.1$ GeV/c for Y(5S) dataset
- Vertex fit requirements, Particle ID using Cherenkov detectors.

Belle Lifetime Ratio Analysis

arXiv: 1212.3478

- Belle uses tagged decays
- Full dataset 976 fb^{-1}
- Many systematics cancel in the relative lifetime measurements.
- Measured in intervals of the D^0 center-of-mass polar angle due to resolution function offset dependence.





$$D^{*+} \to D^0 \pi_s^+; D^0 \to K^+K^-$$
$$D^{*+} \to D^0 \pi_s^+; D^0 \to \pi^+\pi^-$$
$$D^{*+} \to D^0 \pi_s^+; D^0 \to K^-\pi^+, K^+\pi^-$$

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%,$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%,$$

Evidence for mixing at 4.5σ

BaBar Lifetime Ratio Analysis

BaBar uses independent datasets of tagged and untagged decays with full dataset 468 fb^{-1}.

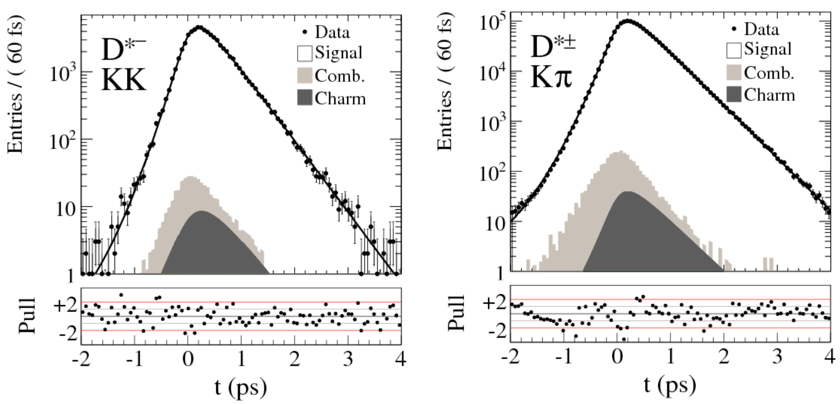
Simultaneous fit to all decays both tagged and untagged to measure the lifetime.

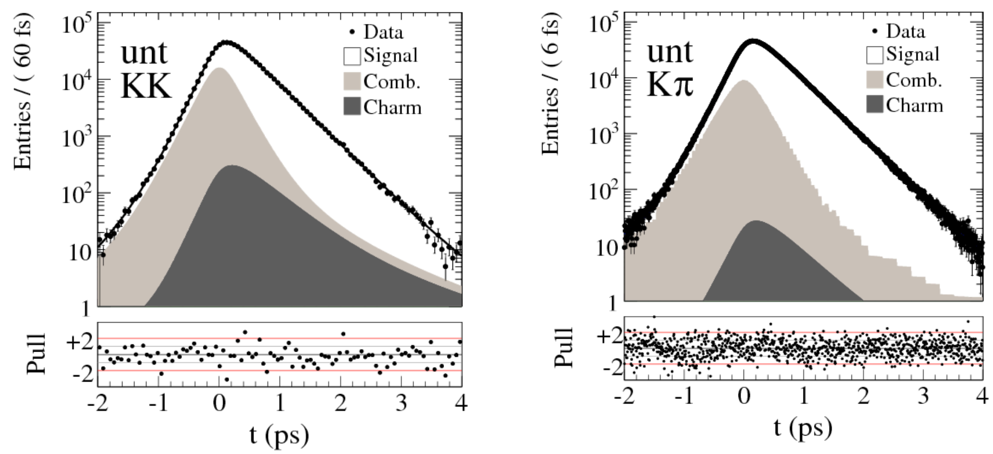
Flavor tagged

$D^{*+} \to D^0\pi_s^+; D^0 \to K^+K^-$
$D^{*+} \to D^0\pi_s^+; D^0 \to \pi^+\pi^-$
$D^{*+} \to D^0\pi_s^+; D^0 \to K^-\pi^+, K^+\pi^-$

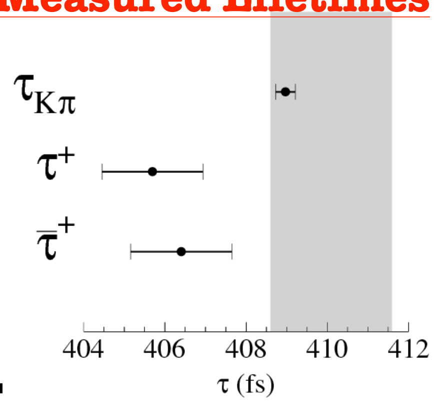
Flavor untagged

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





Measured Lifetimes

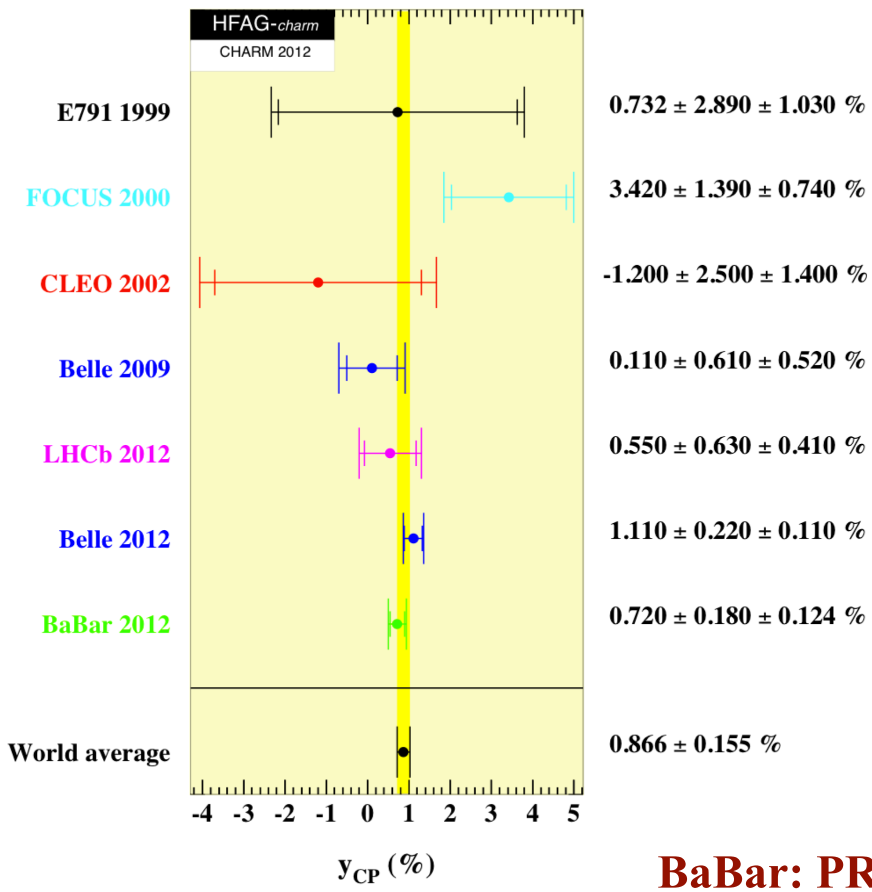


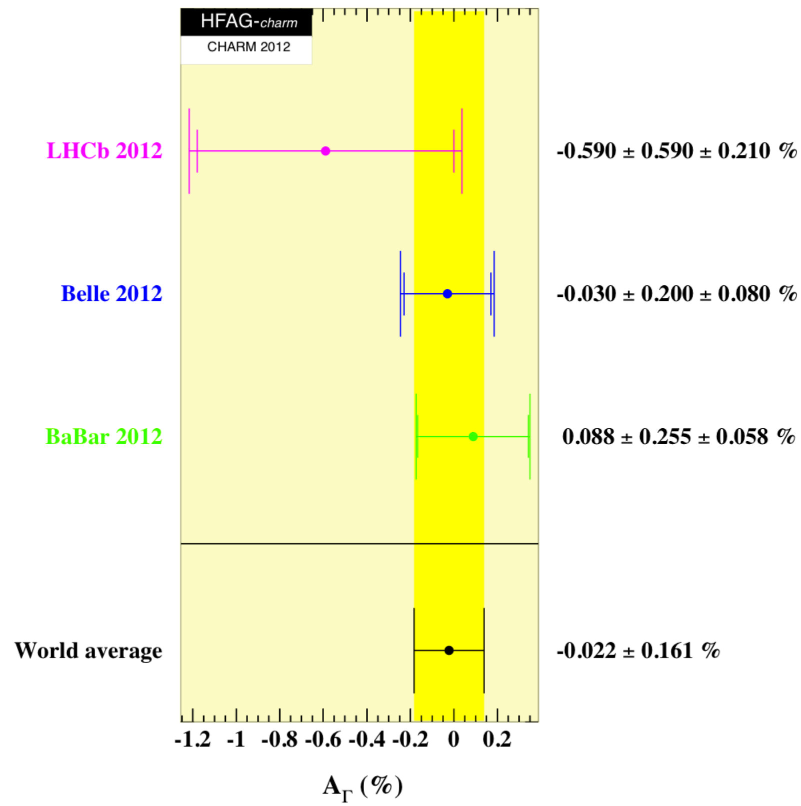
Evidence for mixing at 3.3σ

$$y_{CP} = [0.72 \pm 0.18(\text{stat}) \pm 0.12(\text{syst})]\%,$$
$$\Delta Y = [0.09 \pm 0.26(\text{stat}) \pm 0.06(\text{syst})]\%.$$

PRD 87, 012004 (2013)

D^0-$\bar{D}^0$ Mixing and CP Violation





BaBar: PRD 87, 012004 (2013)

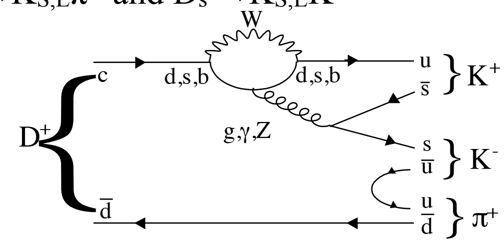
Belle: arXiv: 1212.3478

BaBar has most precise measurement for mixing parameter y_{CP}.
BaBar central value is closer to zero.

Direct CP Violation

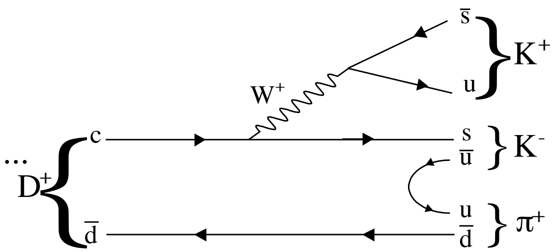
Direct CPV due to interference of CF and DCS decays

- Direct CPV is evidence of NP in interference between CF and DCS amplitudes in $D^{\pm}\rightarrow K_{S,L}\pi^{\pm}$ and $D_s \rightarrow K_{S,L}K^{\pm}$
- Single weak phase in SM, therefore expect NO CPV
- SM contribution due to K^0 mixing $A_{SM} \sim 3.3\times10^{-3}$
- Experimental uncertainties at sub percent level



Direct CPV in SCS decays

- $D^{\pm}\rightarrow K^+K^-\pi^{\pm}$, $D^0\rightarrow h^+h^-\pi^0$, $D^{\pm}\rightarrow K_SK^{\pm}$, $D_s\rightarrow K_S\pi^{\pm}$, $D^0\rightarrow K^+K^-$, $D^0\rightarrow\pi^+\pi^-$, decays with η ...
- SCS decays are unique - probe gluonic penguin operators.
- CP asymmetry generated from interference of tree-level and penguin-level amplitudes.
- In SM effects up 10^{-3} may be observable with NP models generating ~ 10^{-2}.



Grossman, Kagan, Nir PRD 75, 036008 (2007)

- Source of new physics most likely contributes to decay via loop-diagrams.

$$A(D\rightarrow f)\equiv A_f = |A_1|e^{i\delta_1}e^{i\phi_1} + |A_2|e^{i\delta_2}e^{i\phi_2}, \quad \Delta\delta\neq 0, \Delta\phi\neq 0$$

$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = \frac{2|A_1A_2|\sin(\delta_2-\delta_1)\sin(\phi_2-\phi_1)}{|A_1|^2+|A_2|^2+2A_1A_2\cos(\delta_2-\delta_1)}$$

D^0 decays to CP-even Eigenstates K^+K^-, $\pi^+\pi^-$

For final CP eigenstates, indirect CPV is universal. Difference in time-integrated CP asymmetry separates non-universal direct CPV contribution.

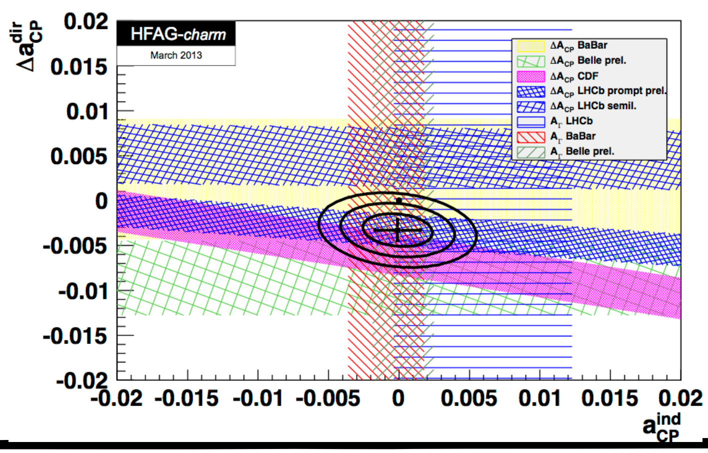
$$\Delta A_{CP}^{direct} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

HFAG world average: $\Delta A_{CP} = (-0.329 \pm 0.121)\%$

LHCb D^0 production modes : (1) inclusive semileptonic b-hadron decays (2) direct production of charm $D^{*+} \to D^0\pi_s$

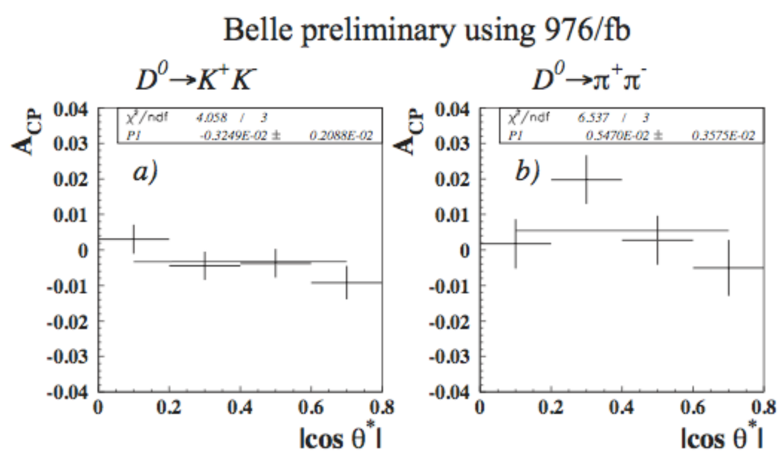
Measurement (1): $\Delta A_{CP} = (0.49 \pm 0.30 \pm 0.14)\%$ [arXiv 1303.2614]

Measurement (2): $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$ [LHCb-CONF-2013-003]



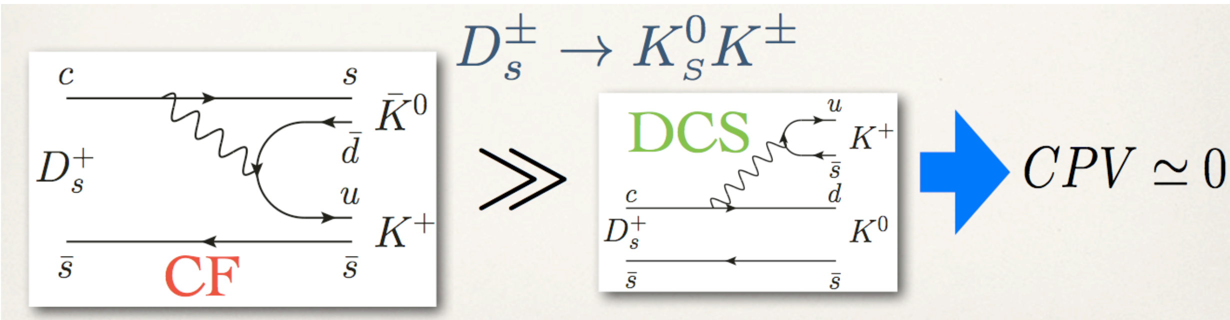
Belle (ICHEP 2012 976 fb^{-1}) [arXiv: 1212.5320]

$\Delta A_{CP} = -0.87 \pm 0.41 \pm 0.06$



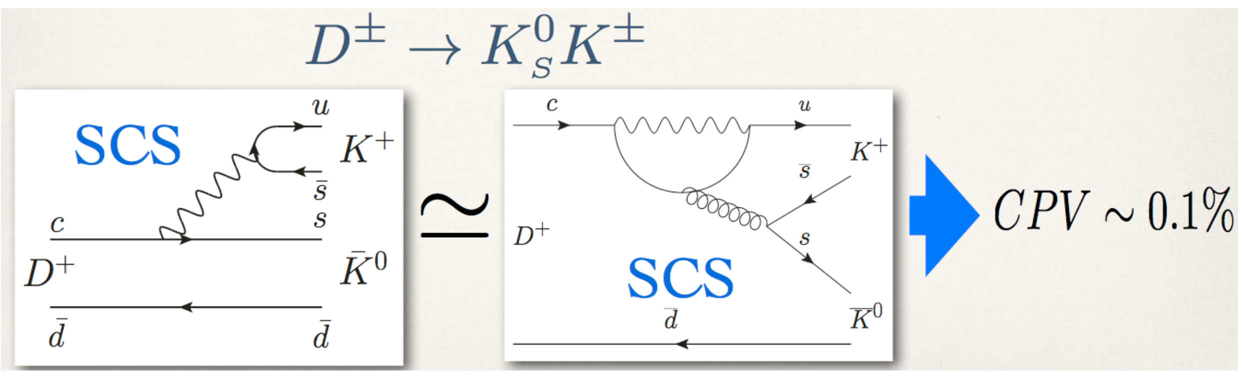
Search for CPV in presence of indirect CPV from K^0 mixing

$$A_{CP} = \frac{\mathcal{B}\left(D^+_{(s)} \to K^0_S(\pi^+, K^+)\right) - \mathcal{B}\left(D^-_{(s)} \to K^0_S(\pi^-, K^-)\right)}{\mathcal{B}\left(D^+_{(s)} \to K^0_S(\pi^+, K^+)\right) + \mathcal{B}\left(D^-_{(s)} \to K^0_S(\pi^-, K^-)\right)}$$



$D_s^\pm \to K_S^0 K^\pm$
$D^\pm \to K_S^0 \pi^\pm$

Proceeds through CF and DCS transitions. CF dominates - single phase and no SM CPV.



$D_s^\pm \to K_S^0 \pi^\pm$
$D^\pm \to K_S^0 K^\pm$

No CF transition - amplitude for tree-level and penguin level are comparable.
Penguin amplitude has relative weak phase to tree-amplitude - relevant interference.

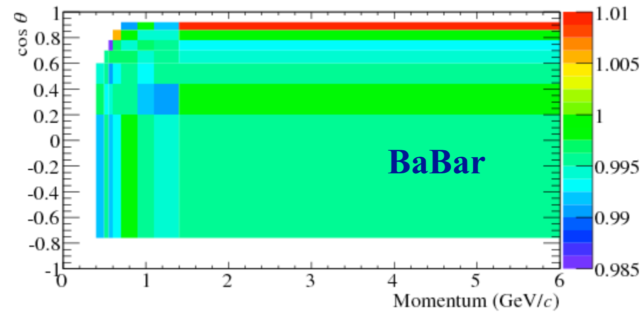
CPV contribution from K^0 mixing [PDG 2012]: + (-) 0.332 ± 0.006 % when K^0 ($\overline{K}^0$) in final state.

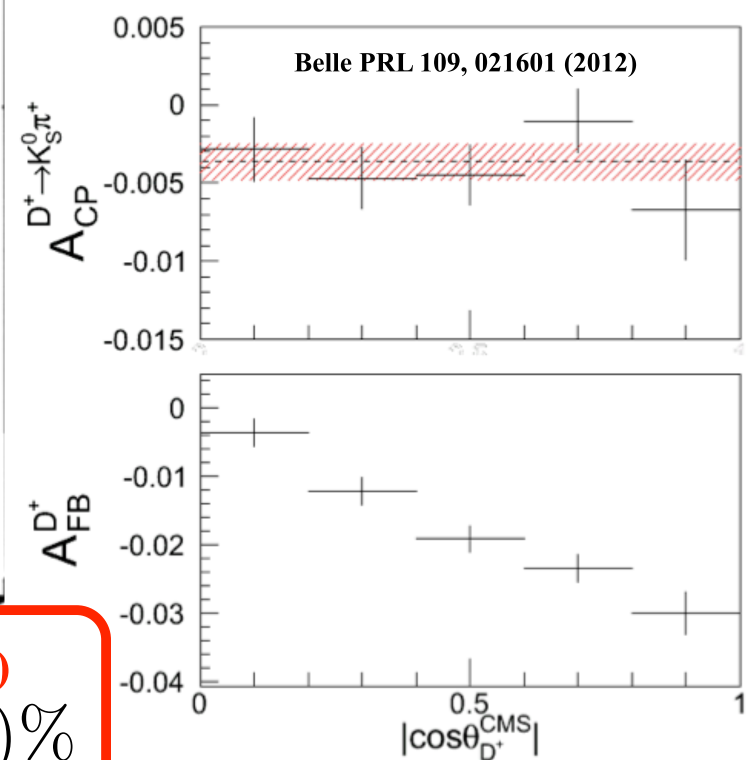
$A_{CP}^{D^+ \to K_S^0 \pi^+}$ Belle has most precise measurement for direct CPV in charm. All channels analyzed by BaBar and Belle. Results consistent with CPV from K^0 mixing.

Search for CPV in presence of indirect CPV from K^0 mixing

$$A_{rec}^{D_{(s)}^{\pm} \to K_S^0 h^{\pm}} = \frac{N_{rec}^{+} - N_{rec}^{-}}{N_{rec}^{+} + N_{rec}^{-}}$$

Map of charged particle reconstruction correction





Reconstructed asymmetry A_{rec} contributions:

(1)CPV from the decay of the charm meson - what we want to measure

(2)CPV in the K^0 system, depends on the K_S^0 lifetime [Grossman and Nir, JHEP 4 (2012), 2]

(3)Production asymmetry of the D meson, odd as a function of the D meson polar angle in the center-of-mass. Extract directly by measuring reconstructed asymmetry in intervals of the polar angle.

(4)Detection asymmetry of the $\pi^{\pm}$ or the $K^{\pm}$. Corrected from the detection efficiency measured from high-statistics control samples.

(5)Dilution asymmetry from different nuclear cross-sections.

Belle 977 fb^{-1} PRL 109, 021601 (2012)

$$A_{CP}^{D^+ \to K_S^0 \pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$

Direct CPV Searches in Dalitz plot decays

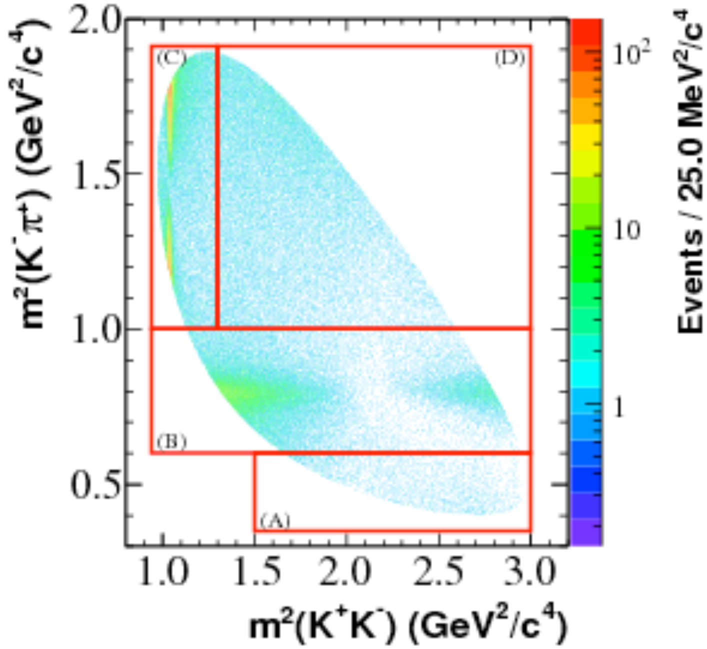
Decouple localized and DP-integrated A_{CP}

CP asymmetry can be:

- Localized in a specific part of the Dalitz plot.
- Integrated over the entire phase space.

The two must be decoupled:

- Obtain phase-space integrated asymmetry.
- Model independent techniques require normalizing D^+ and D^- events to have same integrated yield. Measure the ratio of efficiency corrected yields *R*.
- Model dependent - measure asymmetry in a particular resonance. Magnitudes / phases w.r.t. to one resonance, e.g. K*0(892)



Probing for direct CPV with SCS Dalitz plot decays take advantage of final state interactions.

Final state interactions can affect / produce amplitudes of resonances and strong phases.

Important for CP violation studies since small NP CP phases can be enhanced in localized regions of Dalitz plot and differential observables can shed light on the mechanisms at play.

Direct CPV in $D^{\pm}\to K^{+}K^{-}\pi^{\pm}$

As with two-body measurements, phase-space integrated direct CPV measured as function of the production angle.

- A_{rec} has several contributions: A_{FB}, $A_{K,\pi}$, ... additional asymmetries must be accounted for.

Analysis techniques of BaBar and Belle - complementary but different

- Belle uses larger dataset of SCS and CF decays to search for CPV in $D^{\pm}\to\varphi\pi^{\pm}$.
- Belle measures asymmetry difference between the SCS decay $D^{\pm}\to\varphi\pi^{\pm}$ and the CF decay $D_s^{\pm}\to\varphi\pi^{\pm}$.

$$\Delta A_{rec} = \frac{N(D^+)-N(D^-)}{N(D^+)+N(D^-)} - \frac{N(D_s^+)-N(D_s^-)}{N(D_s^+)+N(D_s^-)}$$

- BaBar measures phase-space integrated A_{CP} and searches for CPV in localized regions of the Dalitz plot and the resonances.
- BaBar measures asymmetry from efficiency-corrected yields and relies on the reconstruction efficiency determined from phase-space generated Monte Carlo (MC) events, correcting for additional asymmetries not accurately modeled in the MC from the data.
  - Advantage that the systematic uncertainties can be evaluated equally for model-independent, phase-space integrated, and Dalitz plot amplitude analysis and the efficiency is a function of the Dalitz plot.

$$A(\cos(\theta_{CM})) \equiv \frac{N_{D^+}/\epsilon_{D^+} - N_{D^-}/\epsilon_{D^-}}{N_{D^+}/\epsilon_{D^+} + N_{D^-}/\epsilon_{D^-}}$$

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

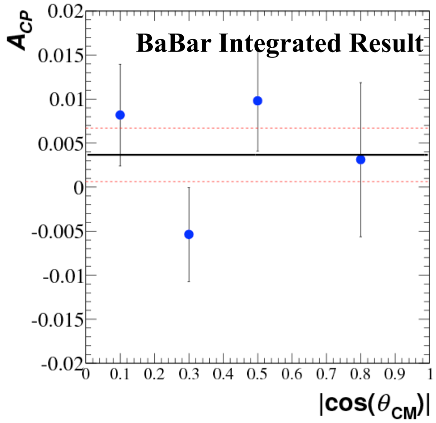
USC HEP
University of South Carolina High Energy Physics Group

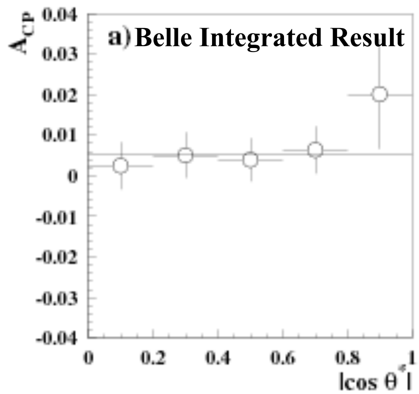
BABAR

BELLE

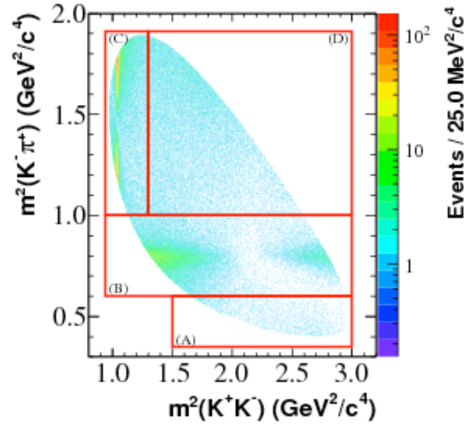
Overview of Methods

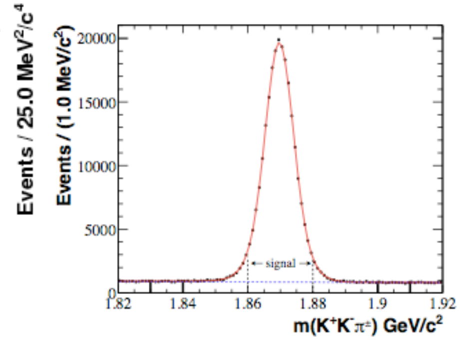
Asymmetry in bins of production angle.





Localized CP Asymmetry [BaBar/Belle]



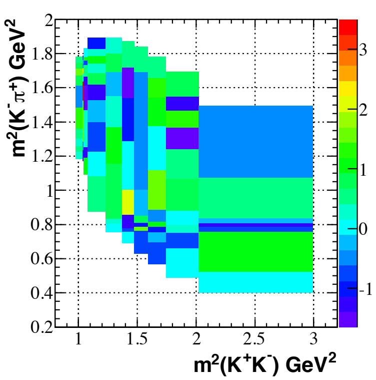


$$A_{CP} = \frac{N(D^+) - RN(D^-)}{N(D^+) + RN(D^-)}$$

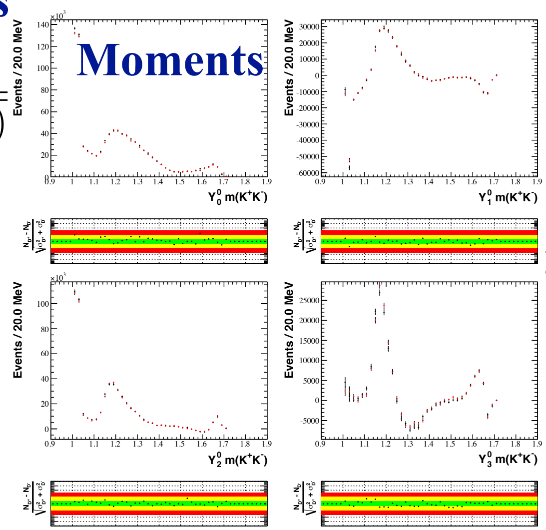
Model Independent Techniques [BaBar]

Normalized Residuals

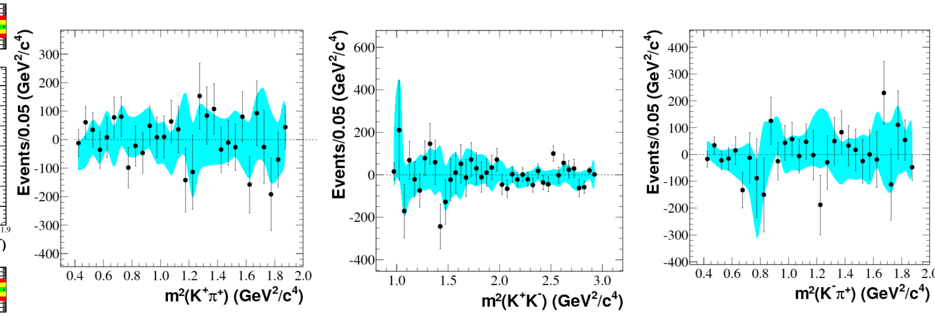
$$\Delta \equiv \frac{n(D^+) - Rn(D^-)}{\sqrt{\sigma^2(D^+) + R^2\sigma^2(D^-)}}$$



Moments



Dalitz Plot Analysis [BaBar]



$D^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$ Dalitz plot Analysis

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

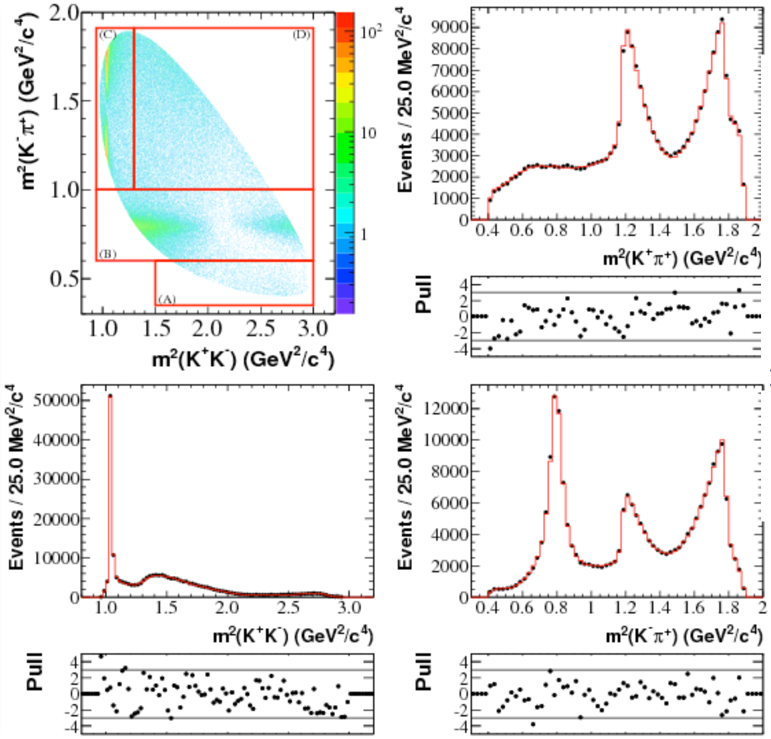
USC HEP — University of South Carolina High Energy Physics Group

BABAR

BELLE

Unbinned Maximum likelihood fit to determine best model to test for CPV in the resonant and non-resonant structure of the Dalitz plot.

Resonance	Fraction (%)
$\bar{K}^*(892)^0$	21.15 ± 0.20
$\phi(1020)$	28.42 ± 0.13
$\bar{K}_0^*(1430)^0$	25.32 ± 2.24
NR	6.38 ± 1.82
κ	7.08 ± 0.63
$a_0(1450)^0$	3.84 ± 0.69
$f_0(980)$	2.47 ± 0.30
$f_0(1370)$	1.17 ± 0.21
$\phi(1680)$	0.82 ± 0.12
$\bar{K}_1^*(1410)$	0.47 ± 0.37
$f_0(1500)$	0.36 ± 0.08
$a_2(1320)$	0.16 ± 0.03
$f_2(1270)$	0.13 ± 0.03
$\bar{K}_2^*(1430)$	0.06 ± 0.02
$\bar{K}_1^*(1680)$	0.05 ± 0.16
$f_0(1710)$	0.04 ± 0.03
$f_2'(1525)$	0.02 ± 0.008
Sum	97.92 ± 3.09



Likelihood function

$$-2\ln\mathcal{L} = -2\sum_{i=1}^{N}\ln\left[p(m_i)\frac{\epsilon_{MC}(x_1,x_2)S(x_1,x_2)}{\iint \epsilon_{MC}(x_1,x_2)S(x_1,x_2)\mathrm{d}x_1\mathrm{d}x_2} + (1-p(m_i))\frac{B(x_1,x_2)}{\iint B(x_1,x_2)\mathrm{d}x_1\mathrm{d}x_2}\right],$$

Mass-dependent signal probability

$$p(m_i) = \frac{S(m_i)}{S(m_i)+B(m_i)}$$

MC efficiency as a function of DP position corrected for differences in production and tracking efficiency asymmetry

$$\epsilon_{MC} \rightarrow \epsilon'_{MC} = P_R(p_{CM}, \cos(\theta)_{CM}) R_{Track}\, \epsilon_{MC}$$

$S(x_1,x_2)$ = **Isobar model for the decay of the D meson**

$B(x_1,x_2)$ = **Background modeled from data sidebands**

χ^2/ndof = 1.2

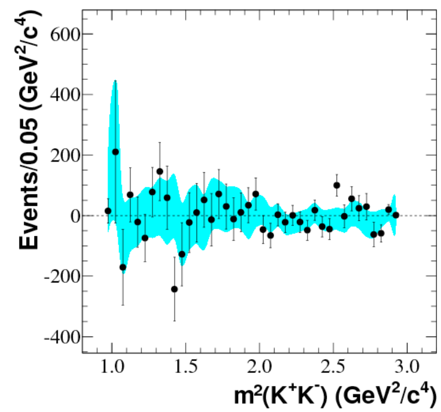
Resonance	Mass (MeV)	Width (MeV)
$\bar{K}^*(892)^0$	895.53 ± 0.17	44.90 ± 0.30
$\phi(1020)$	1019.48 ± 0.01	4.37 ± 0.02
$a_0(1450)$	1441.59 ± 3.77	268.58 ± 5.28
$\bar{K}_0^*(1430)^0$	1431.88 ± 5.89	293.62 ± 3.83
$\bar{K}^*(1680)^0$	1716.88 ± 21.03	319.28 ± 109.07
$f_0(1370)$	1221.59 ± 2.46	281.48 ± 6.6
κ	798.35 ± 1.79	405.25 ± 5.05

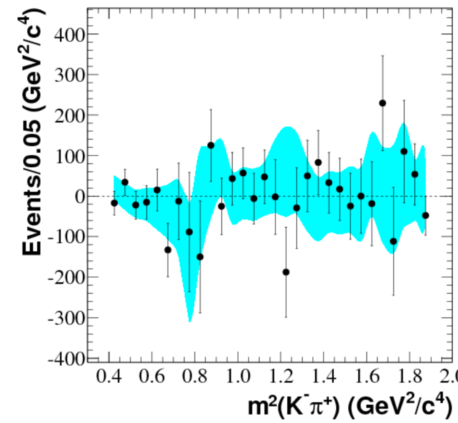
Fit masses & widths of several resonances.
$f_0(980)$ effective parameterization from $D_s \rightarrow K K \pi$
Several $K\pi$ s-wave parameterizations tested:
best fit obtained from $K^*(1430)^0 + \kappa$ + non-resonant.

$D^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$ Dalitz plot CP Asymmetry

D^+/D^- difference in data and **model**. Correct for integrated difference ($R = 1.02 \pm 0.006$).

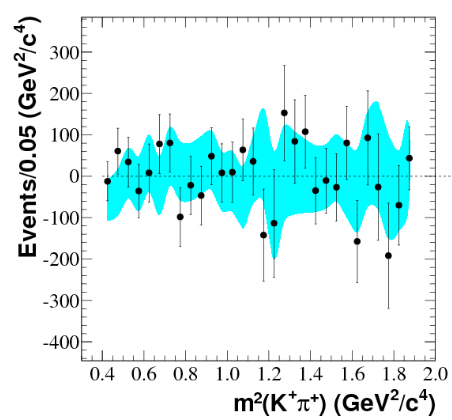
Resonance	r (%)	$\Delta\phi$ (°)
$\bar{K}^*(892)^0$	0. (FIXED)	0. (FIXED)
$\bar{K}_0^*(1430)^0$	$-9.40^{+5.65}_{-5.36} \pm 4.42$	$-6.11^{+3.29}_{-3.24} \pm 1.39$
$\phi(1020)$	$0.35^{+0.82}_{-0.82} \pm 0.60$	$7.43^{+3.55}_{-3.50} \pm 2.35$
NR	$-14.30^{+11.67}_{-12.57} \pm 5.98$	$-2.56^{+7.01}_{-6.17} \pm 8.91$
κ	$2.00^{+5.09}_{-4.96} \pm 1.85$	$2.10^{+2.42}_{-2.45} \pm 1.01$
$a_0(1450)^0$	$5.07^{+6.86}_{-6.54} \pm 9.39$	$4.00^{+4.04}_{-3.96} \pm 3.83$
	Δx	Δy
$f_0(980)$	$-0.199^{+0.106}_{-0.110} \pm 0.084$	$-0.231^{+0.100}_{-0.105} \pm 0.079$
$f_0(1370)$	$0.019^{+0.049}_{-0.048} \pm 0.022$	$-0.0045^{+0.037}_{-0.039} \pm 0.016$





Allow different amplitude for D^+/D^- events

$$\mathcal{A} = \sum_i \mathcal{M}_i e^{i\phi_i} F_i \qquad \bar{\mathcal{A}} = \sum_i \bar{\mathcal{M}}_i e^{i\bar{\phi}_i} F_i$$



- Dominant systematics are model-dependent.
- Good fit of Dalitz plot χ^2/ndof = 1.2.
- Requires additional resonances to describe signal events.
- These resonances contribute to ~ 1% of fit fraction. Assume no CP violation in these resonances.

CP Violating Parameters

$$r_i = \frac{|\mathcal{M}_i|^2 - |\bar{\mathcal{M}}_i|^2}{|\mathcal{M}_i|^2 + |\bar{\mathcal{M}}_i|^2} \qquad \Delta\phi_i = \phi_i - \bar{\phi}_i.$$

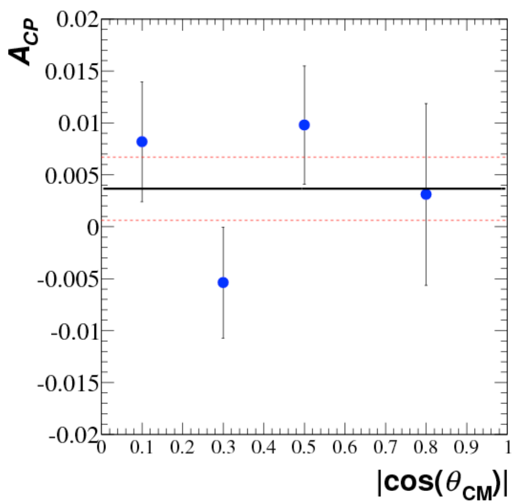
$$x(D^{\pm}) = x \pm \Delta x/2$$

$$y(D^{\pm}) = y \pm \Delta y/2$$

Direct CPV in $D^{\pm} \to K^{+}K^{-}\pi^{\pm}$

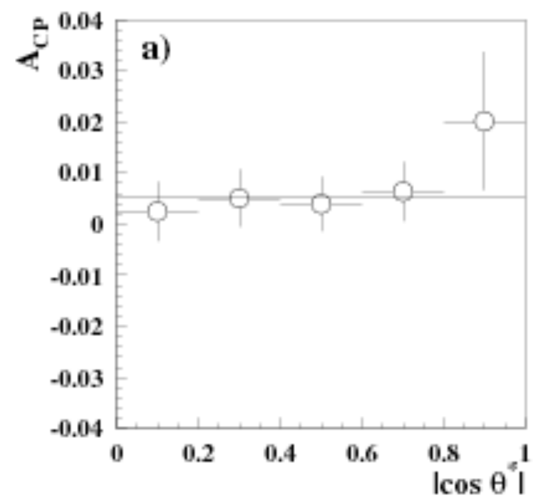
BaBar [PRD 87, 052010 (2013)]
A_{CP} = (0.37 ± 0.30 ± 0.15)%

PRD 83, 052010 (2013)



Belle [PRL 108, 071801 (2012)]
$A_{CP}(D^{\pm} \to \varphi \pi^{\pm})$ = (0.51 ± 0.28 ± 0.05)%

PRL 108, 071801 (2012)



No evidence of CP violation measured as a function of the center-of-mass polar angle of D^{+} meson.

BaBar studied the asymmetry as a function of the Dalitz plot. No evidence for CP violation found in the Dalitz plot amplitude analysis or with model-independent techniques.

Conclusions

- The current data samples from the B-factories are being used effectively to complete many analyses of mixing and CP violation in Charm decays.
- Hints of CP violation in charm sector -- cannot rule out SM or NP.
- Evidence for mixing approaching 5σ for individual B-factory results. All consistent with no CP violation.
- Direct CP Violation in Charm decays not observed at the e^+e^- collider experiments.

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

USC HEP University of South Carolina High Energy Physics Group

Flavor Mixing and CP Violation

BABAR BELLE

- Flavor mixing occurs when flavor eigenstates differ from the mass eigenstates: experimentally observed in neutral K, B_d, B_s, and in the D system at the B factories.

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

$$\left(\frac{q}{p}\right)^2 = \frac{M^*_{12} - \frac{1}{2}\Gamma^*_{12}}{M_{12} - \frac{1}{2}\Gamma_{12}}$$

$$|p|^2 + |q|^2 = 1$$

$$|A_f/\bar{A}_f| \neq 1$$

$$\phi_f = arg\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$$

$$r_m = |q/p| \neq 1$$

Two-body $D_{(s)}$ decays with K_S^0 in final state

BaBar results

PRD 83, 071103(R) (2011)

PRD 87, 052012 (2013)

BaBar results completed with the full data set

Belle results

PRL 104, 181602(2010)

PRL 109, 021601 (2012)

JHEP 02 098 (2013)

Belle has most precise measurement for direct CPV in charm using full data set in $D^{\pm} \to K_S^0 \pi^{\pm}$

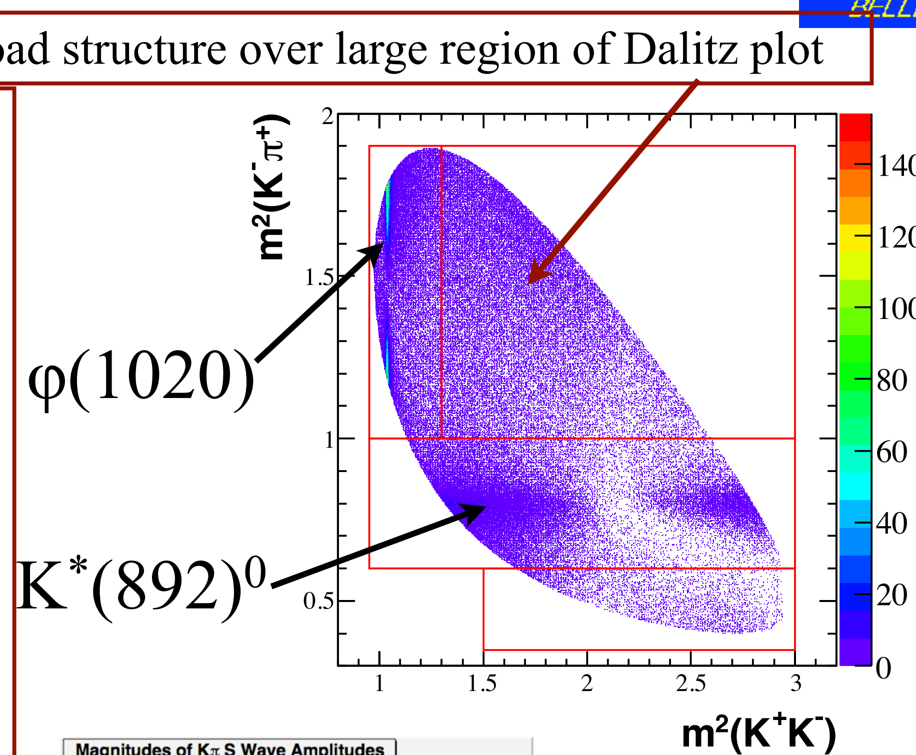
	BaBar	Belle
$D^{\pm} \to K_S^0 \pi^{\pm}$	(-0.44 ± 0.13 ± 0.10)%	(-0.363 ± 0.094 ± 0.067)%
$D_s^{\pm} \to K_S^0 K^{\pm}$	(-0.05±0.23±0.25)%	(0.12±0.36±0.22)%
$D^{\pm} \to K_S^0 K^{\pm}$	(0.13±0.36±0.25)%	(-0.16 ± 0.58 ± 0.25)%
$D_s^{\pm} \to K_S^0 \pi^{\pm}$	(0.6±2.0±0.3)%	(5.45±2.50±0.33)%

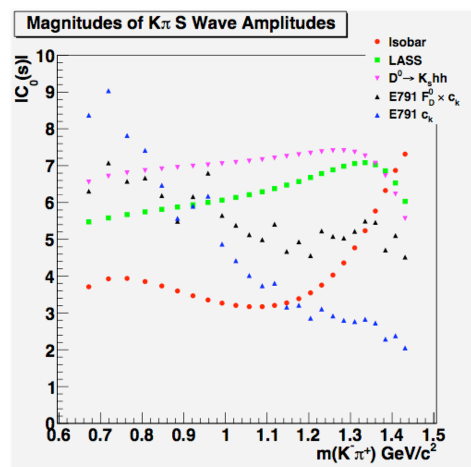
Full dataset

Results include SM contribution of indirect CPV from K^0 mixing

$D^{\pm} \to K^+K^-\pi^{\pm}$ Dalitz plot Analysis

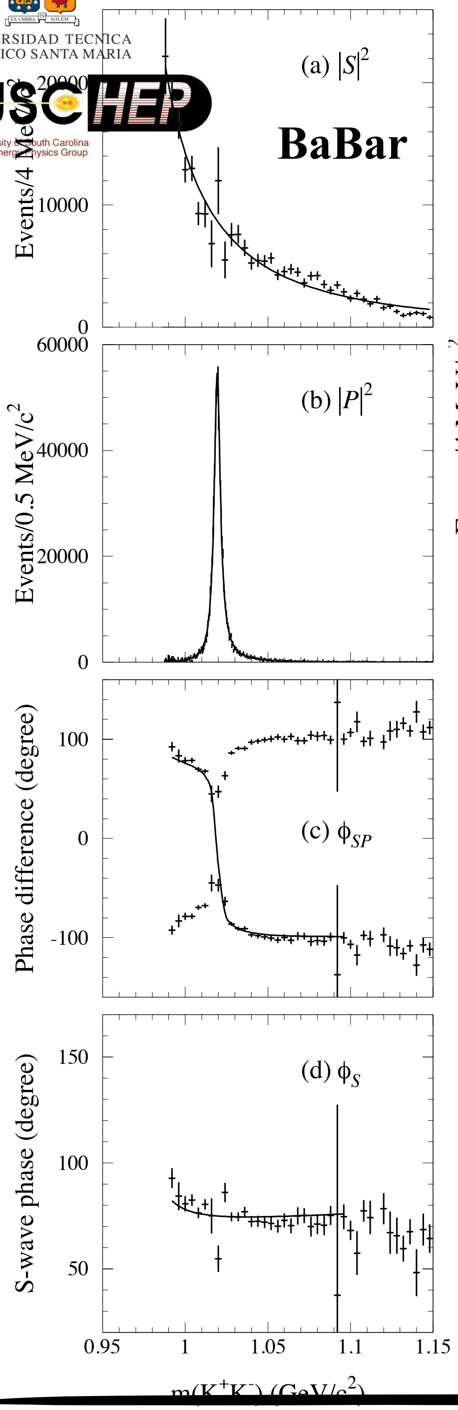
- Neural network describes the Dalitz plot efficiency.
- Combined parametric and non-parametric model to describe the background (using the sidebands)
- S-wave dependence near the φ(1020) resonance taken from $D_s \to KK\pi$ analysis [PRD 83, 052001 (2011)]
- Several models tested for Kπ S-wave.
- Two step unbinned maximum likelihood fit:
  - Assume no CP asymmetry and find the Dalitz plot model which best describes the data (determined from the goodness-of-fit).
  - Allow for CP asymmetry in the dominant resonances.

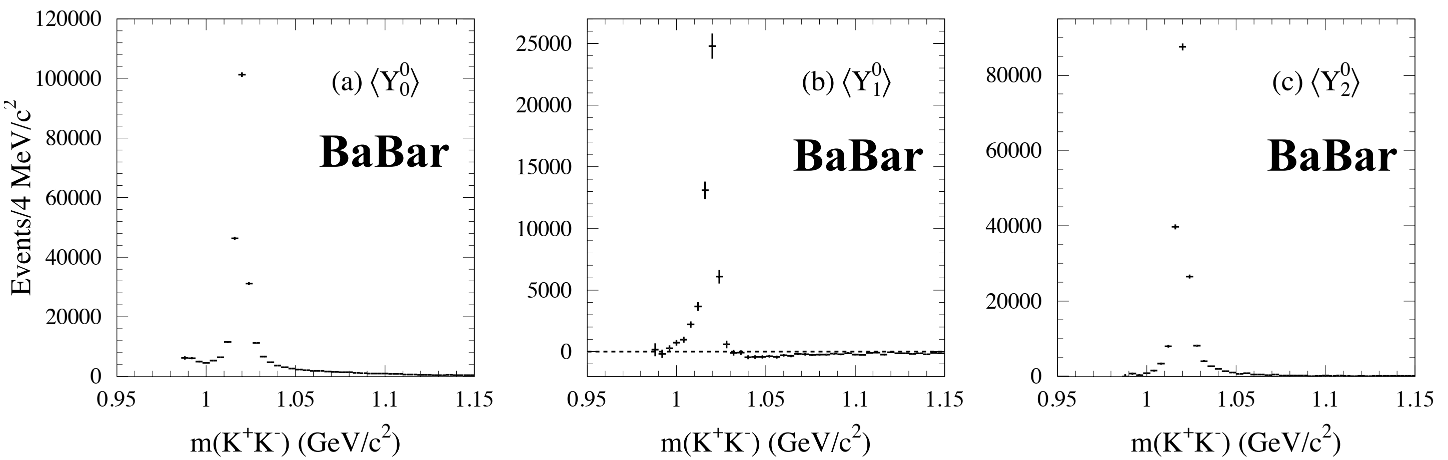




$D_s^+ \to K^+K^-\pi^+$ PWA

Effective S-wave parameterization





$$\sqrt{4\pi}\,\langle Y_0^0 \rangle = |S|^2 + |P|^2$$
$$\sqrt{4\pi}\,\langle Y_1^0 \rangle = 2|S||P|\cos\phi_{SP}$$
$$\sqrt{4\pi}\,\langle Y_2^0 \rangle = \frac{2}{\sqrt{5}}|P|^2$$

PRD 83, 052001 (2011)

Simultaneous Binned Fit:

- $S \equiv C_{f_0(980)} A_{f_0(980)}$
- $P \equiv C_\phi A_\phi$
- $S + P \equiv C_\phi A_\phi + C_{f_0(980)} e^{i\delta} A_{f_0(980)}$

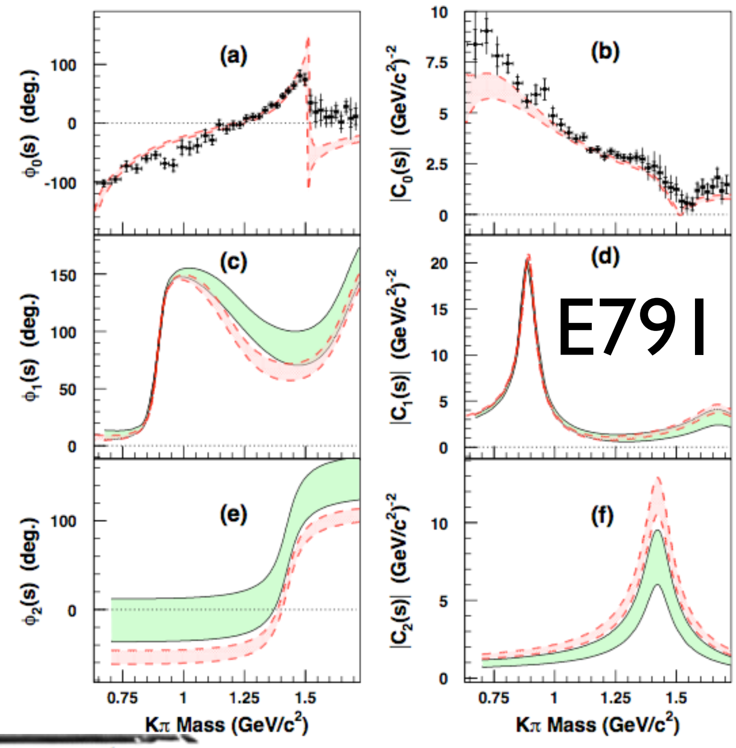
Fitting Model

$A_\phi = \frac{F_R F_D}{m_0^2 - m^2 - i m_0 \Gamma} \times (-4pq)$ **Relativistic Breit-Wigner**

$$A_{f_0(980)} = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0 \rho_{K\bar{K}}}$$ **Formula**

Kπ S-wave Model

- Isobar Model -- Kappa + $K^*(1430)^0$ + Non-resonant amplitude.
- Model-Independent partial wave MIPWA (E791). [PRD 73, 032004 (2006)]
- K-matrix approach, reduces to Kπ scattering amplitude from LASS. Parameterization from $D^0 \to K_S\pi^+\pi^-$ mixing analysis. [PRL 105, 081803 (2010)]



$$T_R = Be^{i\phi_B}\frac{(\cos\phi_B + \cot\delta_B \sin\phi_B)\sqrt{s}}{q(s)\cot\delta_B - iq(s)} + Re^{i\phi_R}e^{i2(\delta_B+\phi_B)}\frac{m_R\Gamma_R m_R/q_0}{m_R^2 - s - im_R\Gamma(s)}$$

with

$$q(s)\cot\delta_B = \frac{1}{a} + \frac{rq(s)^2}{2}$$

and

$$e^{i2\delta_B} = \frac{q(s)\cot\delta_B + iq(s)}{q(s)\cot\delta_B - iq(s)}$$

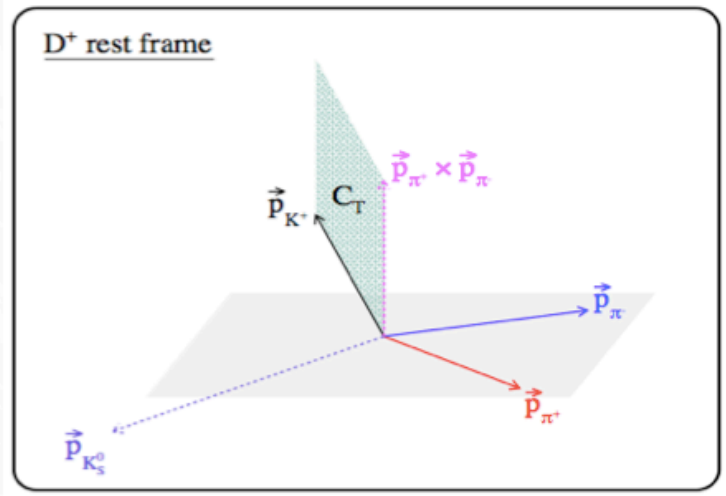
T-odd Observables

I.I. Bigi hep-ph/0107102

- Assuming CPT invariance, T-violation implies CP violation.
- C_T observable is odd under T-reversal $\quad C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$

$$A_T \equiv \frac{\Gamma(C_T>0) - \Gamma(C_T<0)}{\Gamma(C_T>0) + \Gamma(C_T<0)}$$

Measured on D^+



- Final-state interactions (FSI) may introduce T-odd asymmetries $A_T \neq 0$.
- Measuring the T-violating observable removes FSI effects:

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

Measured on D^-

BaBar Results
T-odd Observables

UNIVERSIDAD TECNICA FEDERICO SANTA MARIA

USC HEP — University of South Carolina High Energy Physics Group

BaBar

Belle

$$A_T(D^+) = (+11.2 \pm 14.1_{stat} \pm 5.7_{syst}) \times 10^{-3}$$
$$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{stat} \pm 7.2_{syst}) \times 10^{-3}$$

PRD 84, 031103 (R) (2011)
PRD 81, 111103 (R) (2010)

520 fb^{-1}

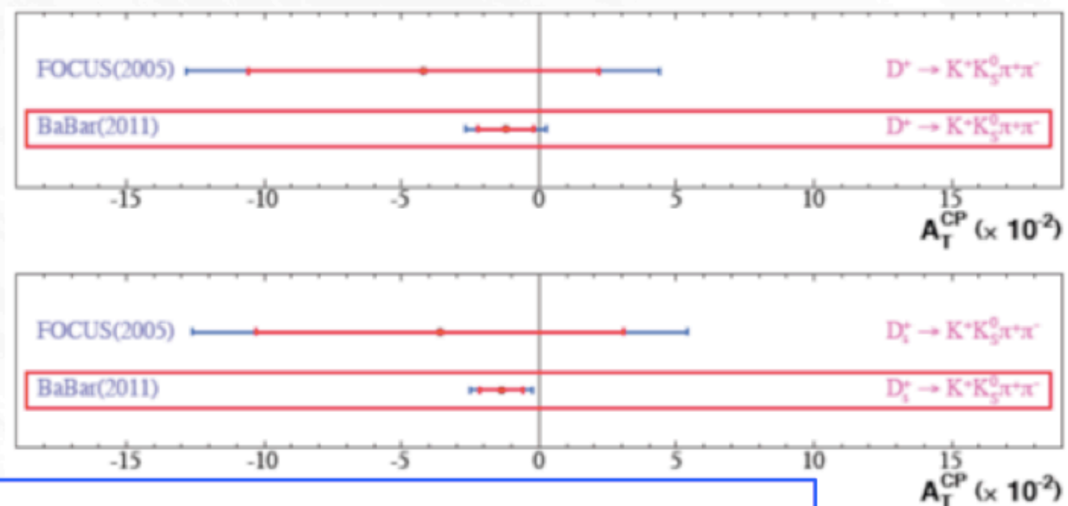
$$A_T(D_s^+) = (-99.2 \pm 10.7_{stat} \pm 8.3_{syst}) \times 10^{-3}$$
$$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{stat} \pm 10.7_{syst}) \times 10^{-3}$$

→ FSI effects appear larger in D_s

T-violating observable consistent with 0.

$$\mathcal{A}_T(D^+) = (-12.0 \pm 10.0_{\rm stat} \pm 4.6_{\rm syst}) \times 10^{-3}$$
$$\mathcal{A}_T(D_s^+) = (-13.6 \pm 7.7_{\rm stat} \pm 3.4_{\rm syst}) \times 10^{-3}$$

X10 improvement over previous result.



$\mathcal{A}_T(D^0) = (+1.0 \pm 5.1_{\rm stat} \pm 4.4_{\rm syst}) \times 10^{-3}$ ***PRD 81, 111103 (R) (2010)***