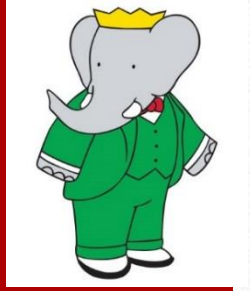
Recent results on violation of discrete symmetries in charm decays at BaBar and Belle



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on behalf of the BaBar Collaboration

CHARM 2015
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Outline

- CPV in charm decays
- Recent BaBar results
  - CPV in $D^+ \to K^+K^-\pi^+$

    PRD 87, 052010 (2013)
    $L = 476\ \text{fb}^{-1}$
  - CPV in $D^+ \to K^0_S K^+$, $D^+_s \to K^0_S K^+$, $D^+_s \to K^0_S \pi^+$

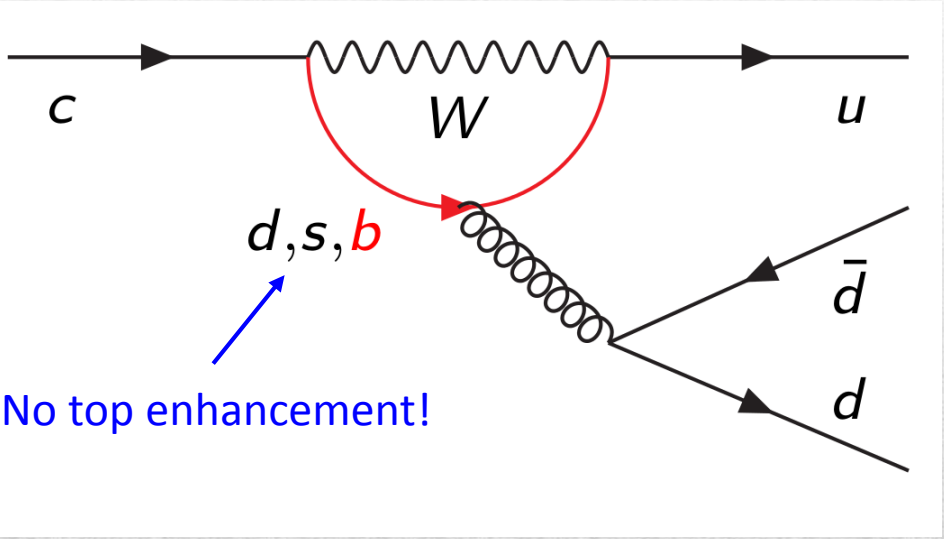
    PRD 87, 052012 (2013)
    $L = 469\ \text{fb}^{-1}$
- Recent Belle results
  - Time-dependent analysis of $D^0 \to K^0_S \pi^+\pi^-$

    PRD 89, 091103 (2014)
    $L = 921\ \text{fb}^{-1}$
- Conclusions

(the use of charge conjugate reactions is implied thourough)

CPV in charm sector

In the SM, CPV in processes involving charm hadrons
is expected to be small, at the level of 10^{-3} or less

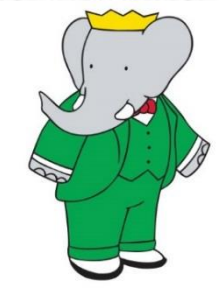


GIM and CKM suppression

$$A_{CP} \propto \log\frac{m_b}{m_c} \times \lambda^5 = O(10^{-3})$$

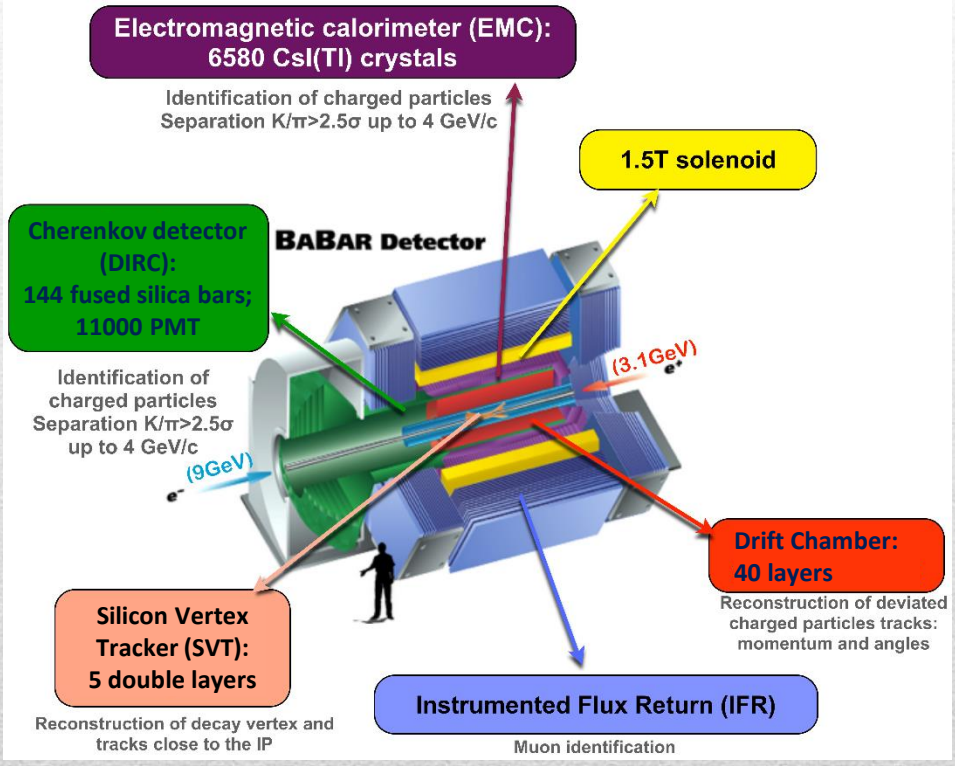
Any CPV signal is likely due to New Physics,
although sizeable long-distance effects might affect some SM predictions

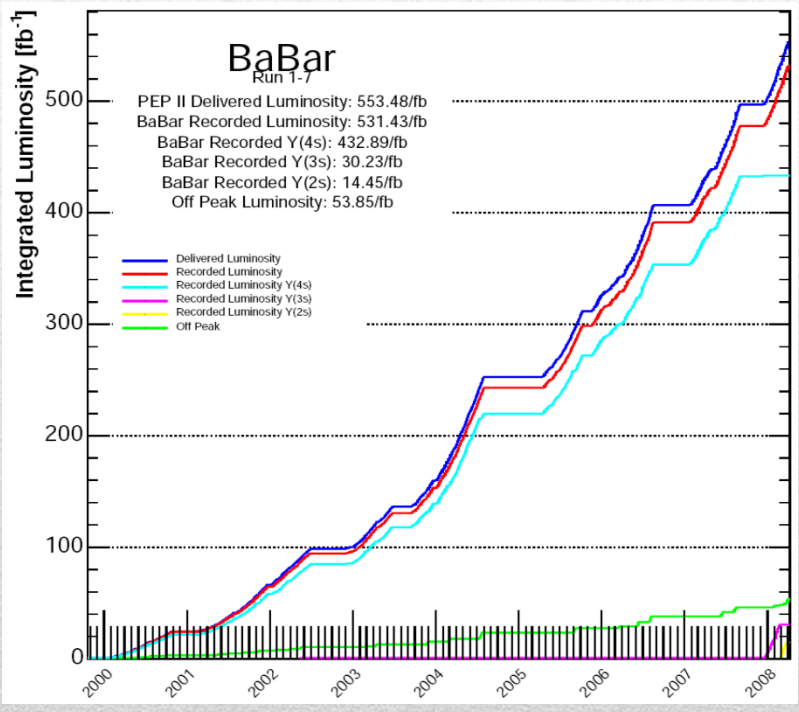
The BaBar experiment



The Babar detector was located at the interaction point of PEP II at SLAC

Asymmetric e^+e^- collider, mostly at $\sqrt{s} \sim 10.58$ GeV



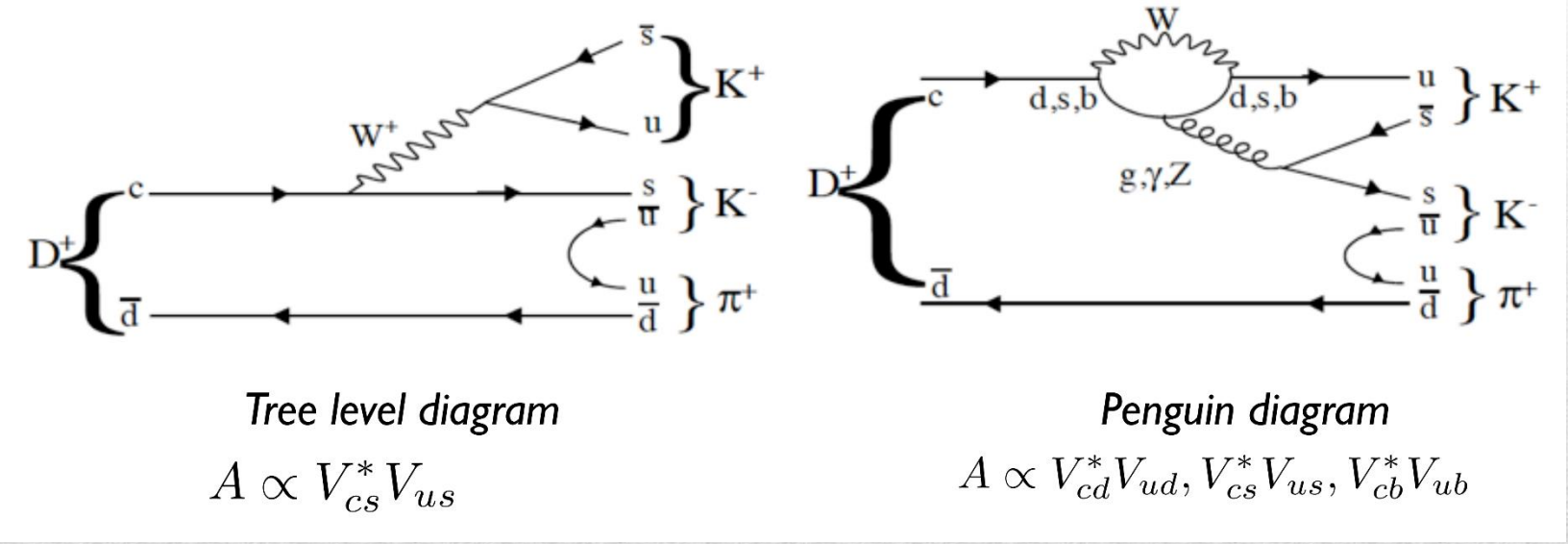


$\int L\,dt \sim 517\ \text{fb}^{-1}$ close to the $\Upsilon(4S), \Upsilon(2S), \Upsilon(3S)$ peaks, $670 \times 10^6\ c\bar{c}$ pairs

Dalitz plot analysis of $D^+ \to K^+K^-\pi^+$

Singly Cabibbo-suppressed decays, uniquely sensitive to new physics

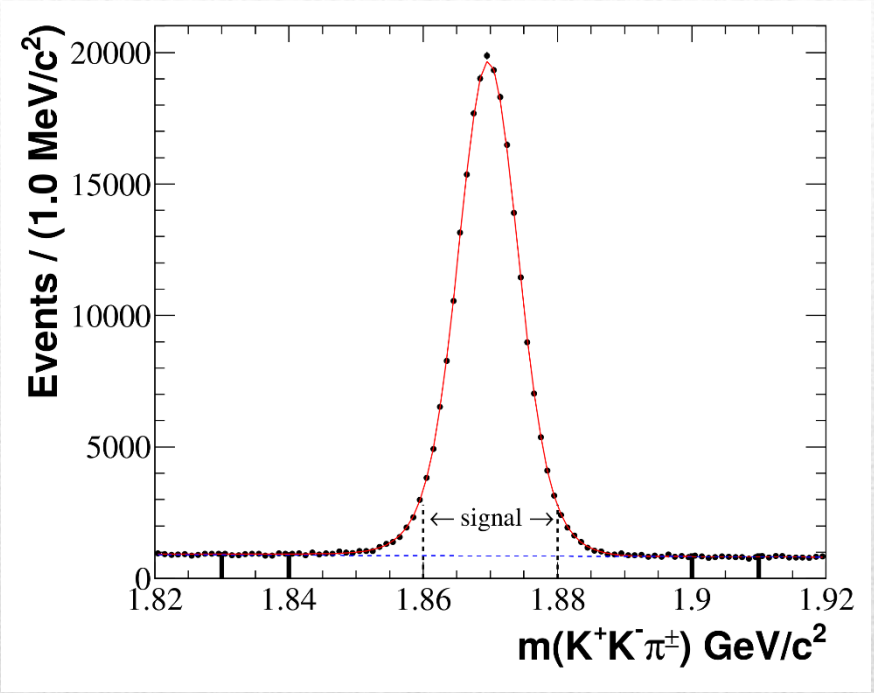
Probe gluonic penguin and chromomagnetic dipole operators



3-body decay allows the search for CP asymmetries in the Dalitz plot

Event selection and signal reconstruction

- Two tracks consistent with K hypothesis
- $p_T(\pi) > 300$ MeV/c, good track quality
- $p_D \in [2.4, 5.0]$ GeV/c, reject B background
- Background from misidentified $D^{*+} \to D^0\pi^+$ removed
- Joint PDF for flight distance and p_D^{CM} help in discriminating signal from background

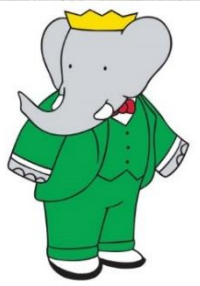


228k D^+ signal yield, 92% purity

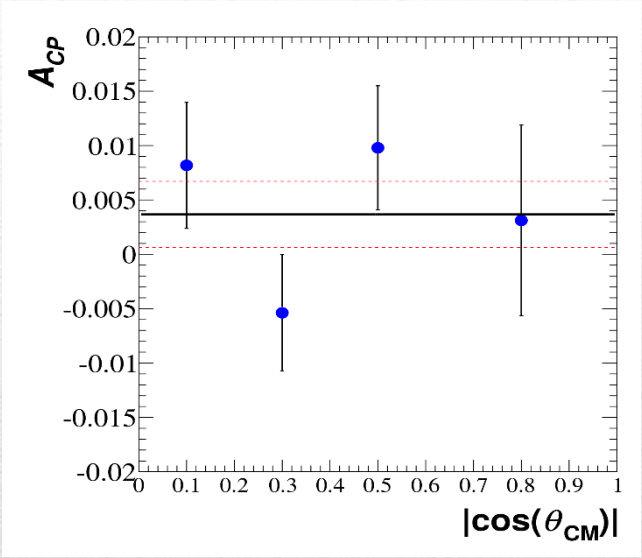
Search for CPV with:

1. A_{CP} integrated over the Dalitz plot
2. A_{CP} in 4 Dalitz plot regions
3. Comparison of binned $D^{\pm}$ Dalitz plot
4. Comparison of Legendre polynomial moment distributions for K^+K^- and $K^-\pi^+$ systems
5. Comparison of parametrized fits to Dalitz plot (model-dependent)

BaBar coll.
PRD 87, 052010 (2013)
$L = 476\ \text{fb}^{-1}$

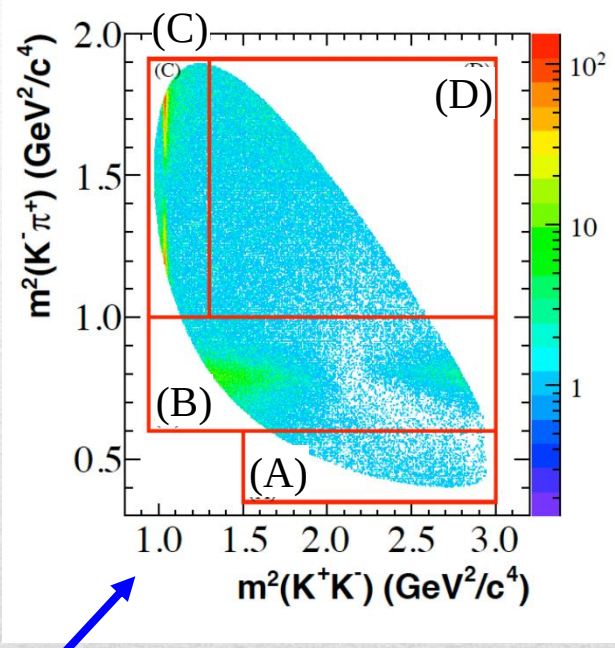


A_{CP} in the Dalitz plot regions



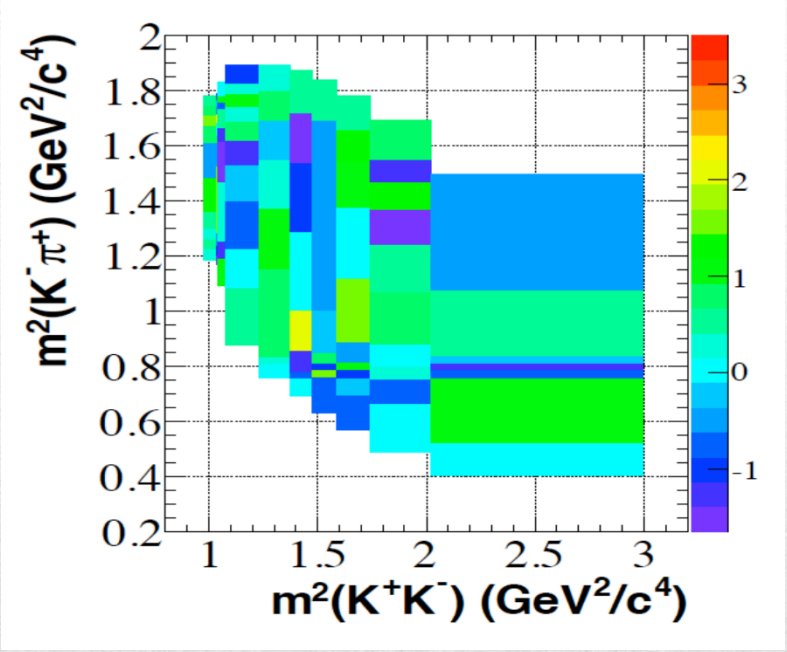
Asymmetry integrated over the Dalitz plot

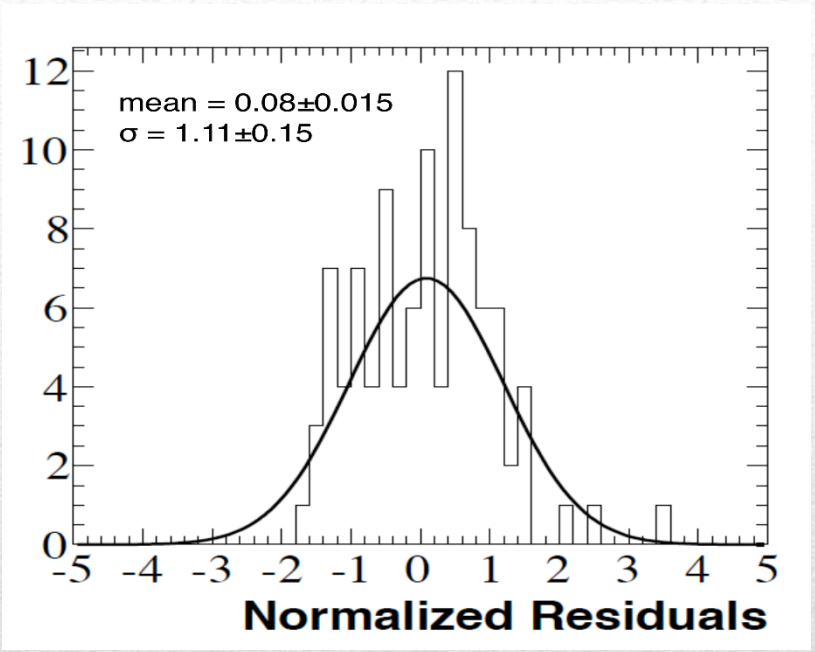
$$A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$$



Dalitz plot region	$N(D^+)$	$\epsilon(D^+)[\%]$	$N(D^-)$	$\epsilon(D^-)[\%]$	$A_{CP}[\%]$
(A) Below $\bar{K}^*(892)^0$	1882 ± 70	7.00	1859 ± 90	6.97	$-0.7 \pm 1.6 \pm 1.7$
(B) $\bar{K}^*(892)^0$	36770 ± 251	7.53	36262 ± 257	7.53	$-0.3 \pm 0.4 \pm 0.2$
(C) $\phi(1020)$	48856 ± 289	8.57	48009 ± 289	8.54	$-0.3 \pm 0.3 \pm 0.5$
(D) Above $\bar{K}^*(892)^0$ and $\phi(1020)$	25616 ± 244	8.01	24560 ± 242	8.00	$1.1 \pm 0.5 \pm 0.3$

Model-independent searches for CPV



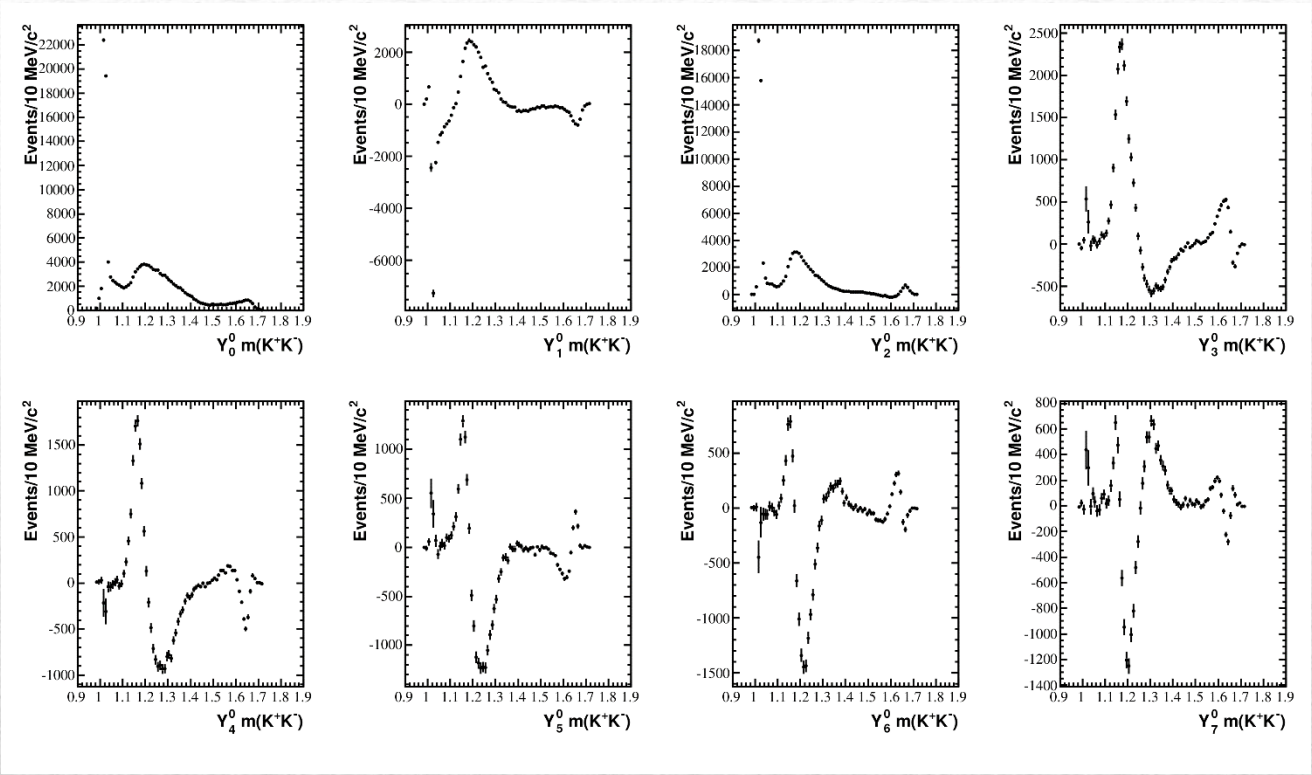


Normalized residual analysis $\Delta = \frac{n(D^+) - Rn(D^-)}{\sqrt{\sigma^2(D^+) + R^2\sigma^2(D^-)}}$,

- consistent with no CPV at 72% level

$$R = \frac{N(D^+)/\epsilon^+}{N(D^-)/\epsilon^-} = 1.020 \pm 0.006$$

Model-independent searches for CPV



Method introduced by Babar coll.
PRD 76, 011102 (2007)

Legendre polynomial moment analysis:

Two body mass distributions $m(K^+K^-)$ and $m(K^-\pi^+)$ weighted by $\sqrt{(2l+1)/4\pi}\, P_l(\cos\theta_H)$

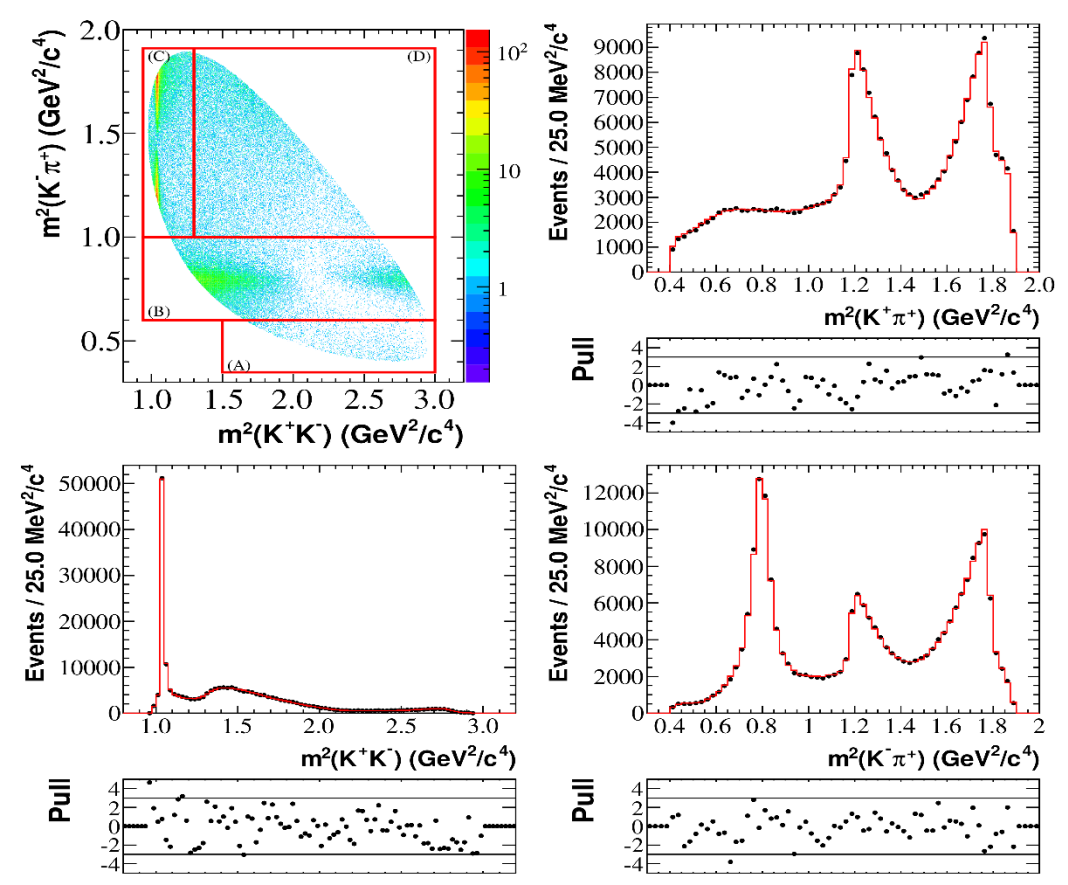
$X_i^l = \frac{W_i^l(D^+) - R W_i^l(D^-)}{\sqrt{\sigma_i^{(l)2}(D^+) + R^2 \sigma_i^{(l)2}(D^-)}}$, with W_i^l the weighted i^{th} mass bin, and $0 \le l \le 7$

consistent with no CPV at 11% and 13% level

Model-dependent search for CPV

Fit to Dalitz plot using isobar model

Firstly to combined $D^{\pm}$ datasets (no CPV)



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
$\kappa(800)$	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
$\bar{K}^*(1680)$	0.05 ± 0.16
$f_0(1710)$	0.04 ± 0.03
$f_2'(1525)$	0.02 ± 0.01
Sum	97.92 ± 3.09

Resonances modeled with RBW

$f_0(980)$ with an effective BW

Model-dependent search for CPV

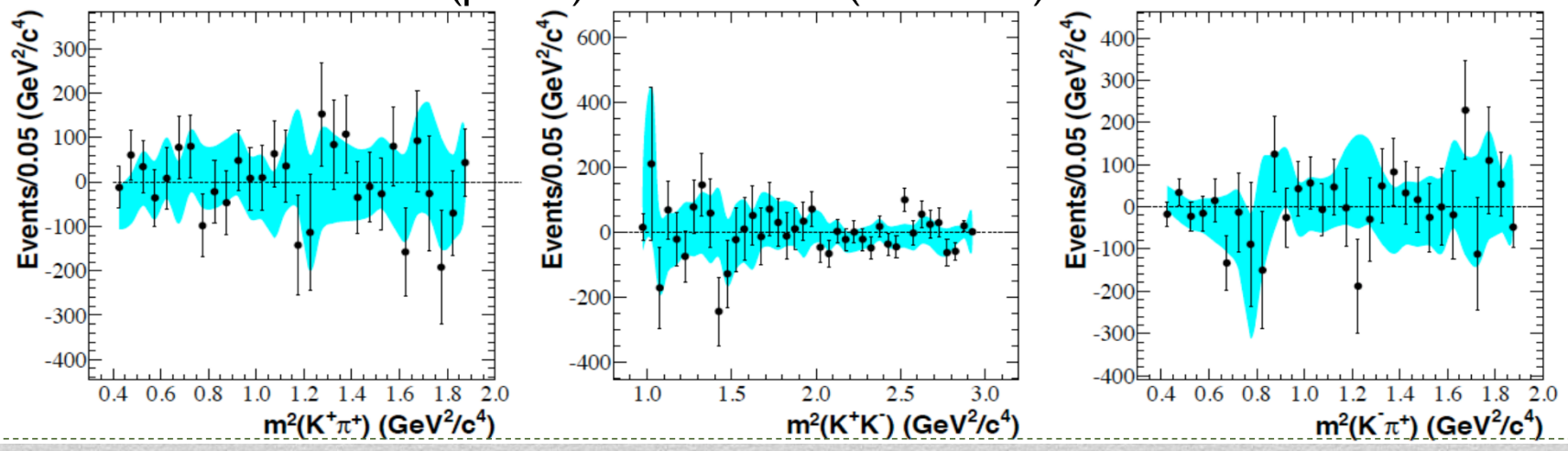
Allow CPV in resonances with at least 1% fit fraction

$$r_{CP} = \frac{|M_r|^2 - |\overline{M_r}|^2}{|M_r|^2 + |\overline{M_r}|^2}, \Delta\phi_{CP} = \phi_r - \overline{\phi_r}$$

$$x_r = M_r \cos\phi_r, y_r = M_r \sin\phi_r$$

Resonance	r_{CP} (%)	$\Delta\phi$ (°)
$\bar{K}^*(892)^0$	0. (FIXED)	0. (FIXED)
$\phi(1020)$	$0.35^{+0.82}_{-0.82} \pm 0.60$	$7.43^{+3.55}_{-3.50} \pm 2.35$
$\bar{K}_0^*(1430)^0$	$-9.40^{+5.65}_{-5.36} \pm 4.42$	$-6.11^{+3.29}_{-3.24} \pm 1.39$
NR	$-14.30^{+11.67}_{-12.57} \pm 5.98$	$-2.56^{+7.01}_{-6.17} \pm 8.91$
$\kappa(800)$	$2.00^{+5.09}_{-4.96} \pm 1.85$	$2.10^{+2.42}_{-2.45} \pm 1.01$
$a_0(1450)^0$	$5.07^{+6.86}_{-6.54} \pm 9.39$	$4.00^{+4.04}_{-3.96} \pm 3.83$
	Δx	Δy
$f_0(980)$	$-0.199^{+0.106}_{-0.110} \pm 0.084$	$-0.231^{+0.100}_{-0.105} \pm 0.079$
$f_0(1370)$	$0.019^{+0.049}_{-0.048} \pm 0.022$	$-0.0045^{+0.037}_{-0.039} \pm 0.016$

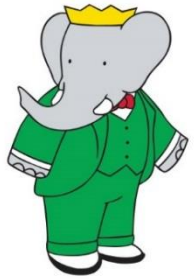
D^+/D^- difference in data (points) and fit model (blue band): no evidence for CP violation



Search for CPV in $D^+_{(s)} \to K^0_S K^+, D^+_S \to K^0_S \pi^+$

In the SM A_{CP} expected to be dominated by CPV in $K^0 - \overline{K^0}$ mixing

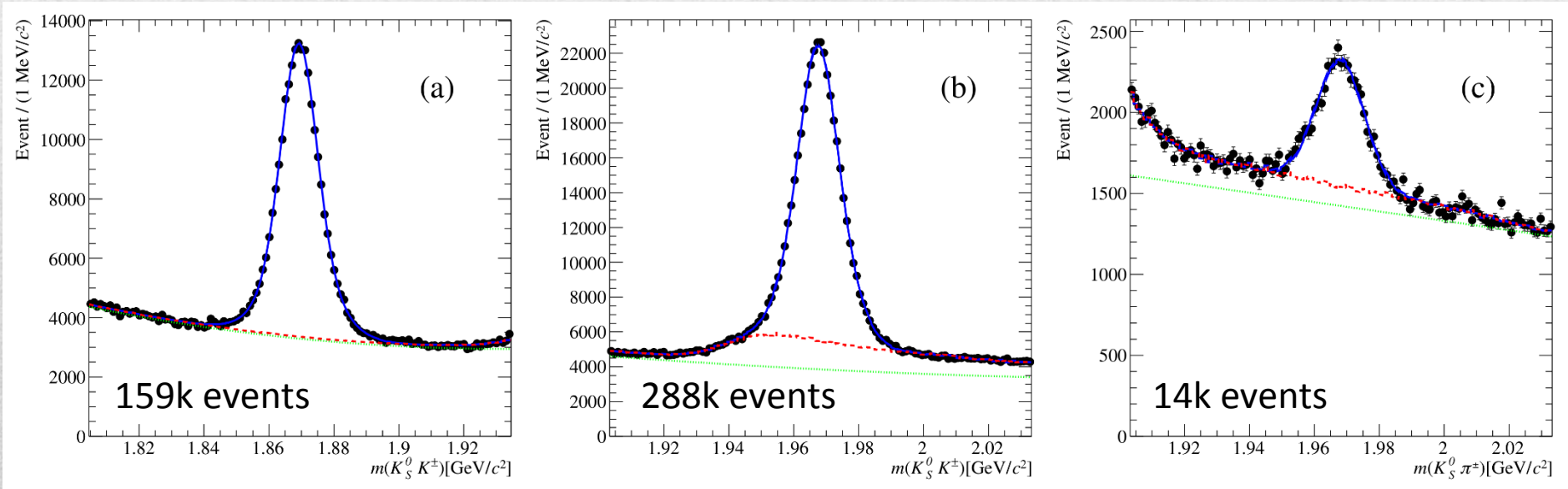
BaBar coll. PRD 87, 052012
$L = 469\ \text{fb}^{-1}$



- K^+ and π^+ PID, $p_T > 400$ MeV/c
- $p_D \in [2.6, 5.0]$ GeV/c, $p_{D_s} \in [2.0, 5.0]$ GeV/c
- K^0_S flight length $> 3 \times$ significance

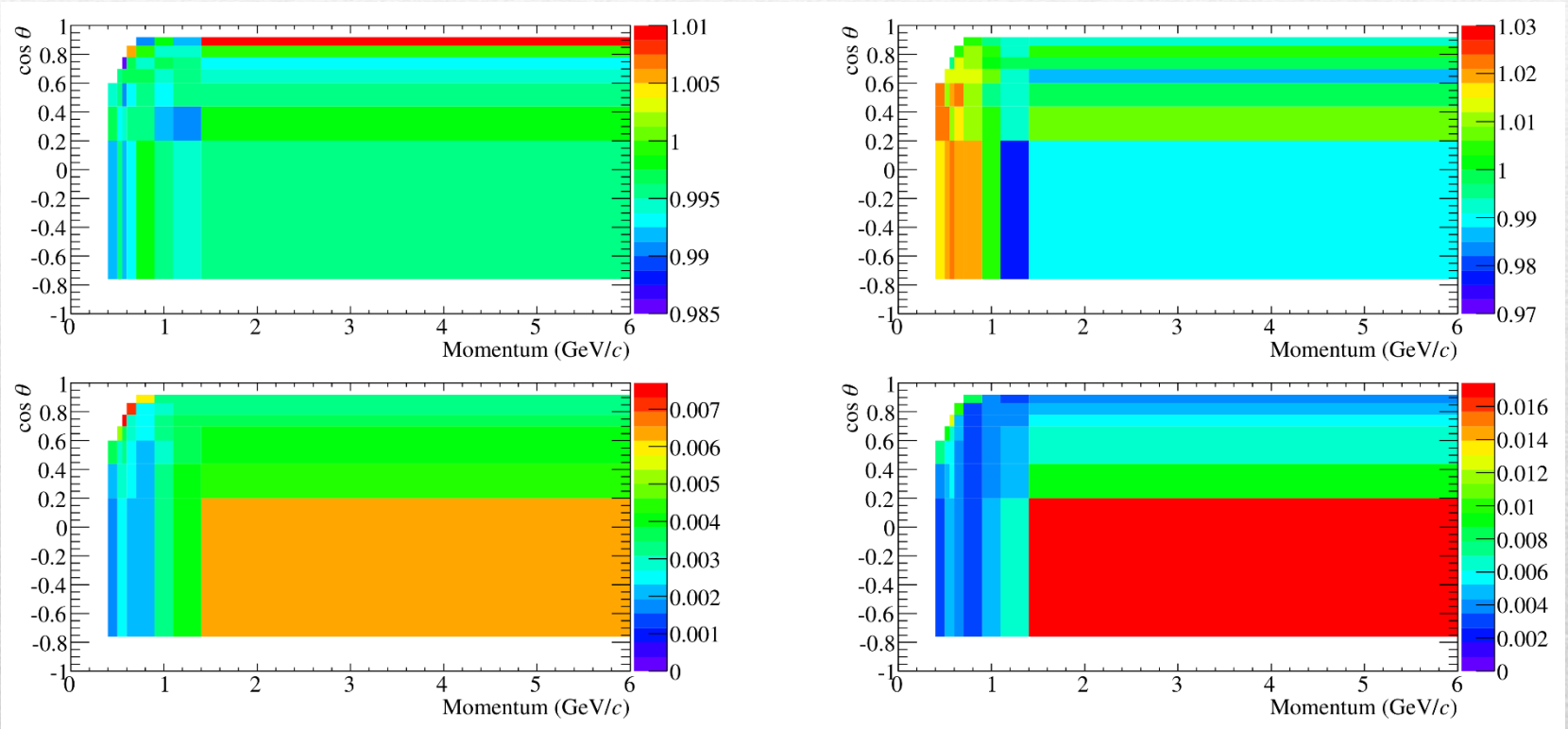
Multivariate analysis to further improve S/B

$D^+ \to K^0_S K^+$ $\quad$ $D^+_s \to K^0_S K^+$ $\quad$ $D^+_S \to K^0_S \pi^+$



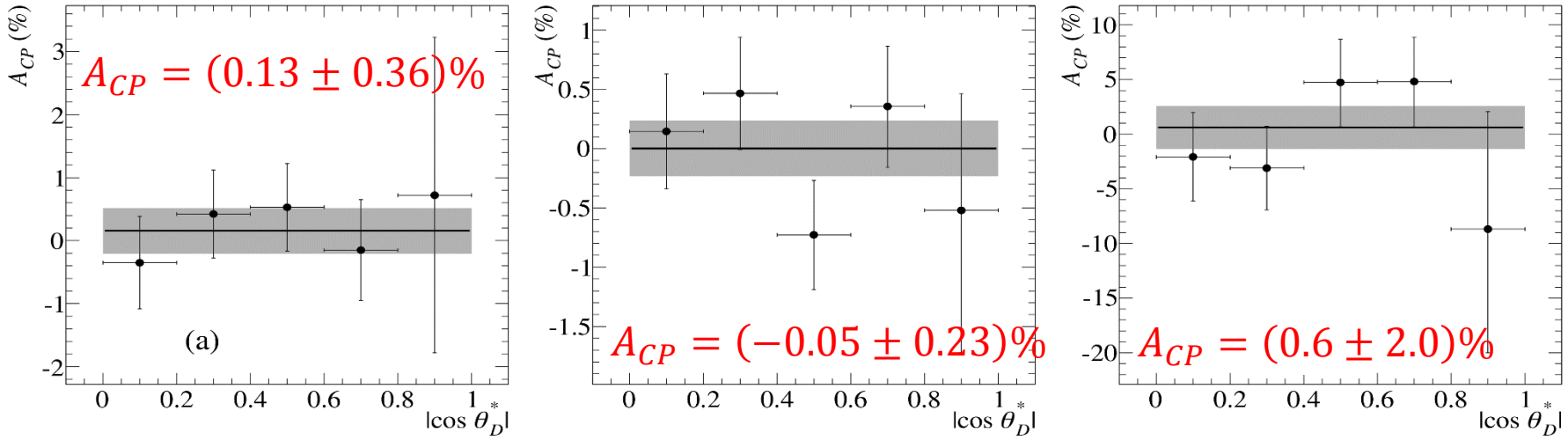
Analysis of detector-induced asymmetries

A large sample of π and K tracks from $B\bar{B}$ events to estimate detector-induced asymmetries
Correction factors have been measured and applied to the signal



A_{CP} results and systematic errors

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



Systematic uncertainty	$D^\pm \to K^0_S K^\pm$	$D^\pm_s \to K^0_S K^\pm$	$D^\pm_s \to K^0_S \pi^\pm$
Efficiency of PID selectors	0.05%	0.05%	0.05%
Statistics of the control sample	0.23%	0.23%	0.06%
Misidentified tracks in the control sample	0.01%	0.01%	0.01%
$\cos\theta^*_D$ interval size	0.04%	0.02%	0.27%
$K^0 - \overline{K}^0$ regeneration	0.05%	0.05%	0.06%
$K^0_S - K^0_L$ interference	0.015%	0.014%	0.008%
Total	0.25%	0.24%	0.29%

Final A_{CP} results

	$D^{\pm} \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S \pi^{\pm}$
A_{CP} value from the fit	$(+0.155 \pm 0.360)\%$	$(0.00 \pm 0.23)\%$	$(+0.6 \pm 2.0)\%$
Correction for the bias from toy MC experiments	$+0.013\%$	-0.01%	–
Correction for the bias in the PID selectors	-0.05%	-0.05%	-0.05%
Correction for the $K^0_S - K^0_L$ interference (ΔA_{CP})	$+0.015\%$	$+0.014\%$	-0.008%
A_{CP} final value	$(+0.13 \pm 0.36 \pm 0.25)\%$	$(-0.05 \pm 0.23 \pm 0.24)\%$	$(+0.6 \pm 2.0 \pm 0.3)\%$
A_{CP} contribution from $K^0 - \bar{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(+0.332 \pm 0.006)\%$
A_{CP} final value (charm only)	$(+0.46 \pm 0.36 \pm 0.25)\%$	$(+0.28 \pm 0.23 \pm 0.24)\%$	$(+0.3 \pm 2.0 \pm 0.3)\%$

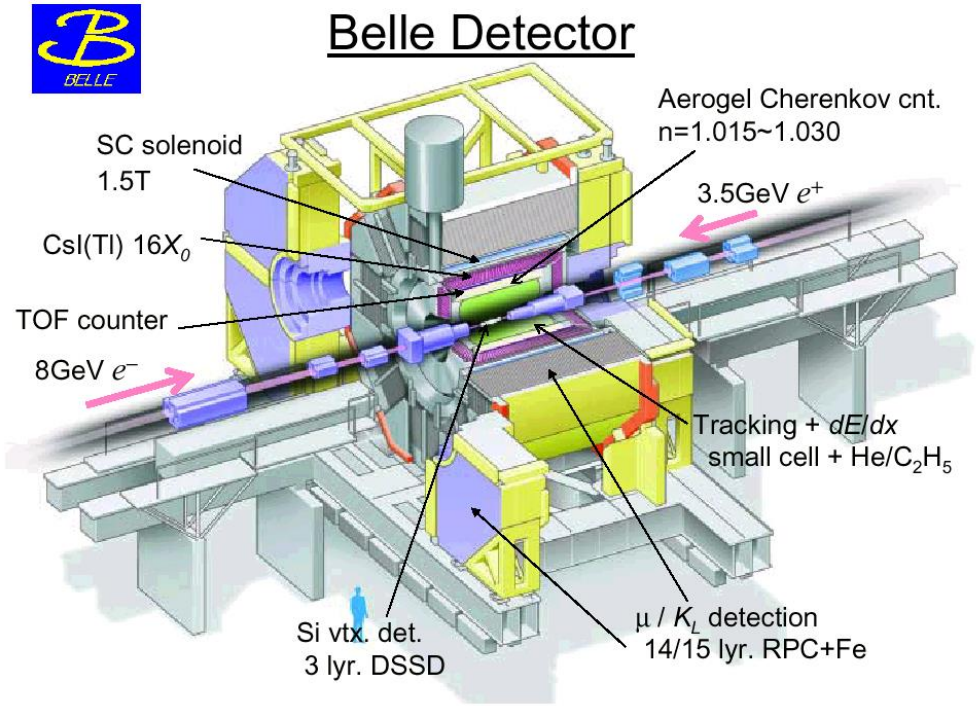
$\overline{K^0}$ produced, $-$ sign

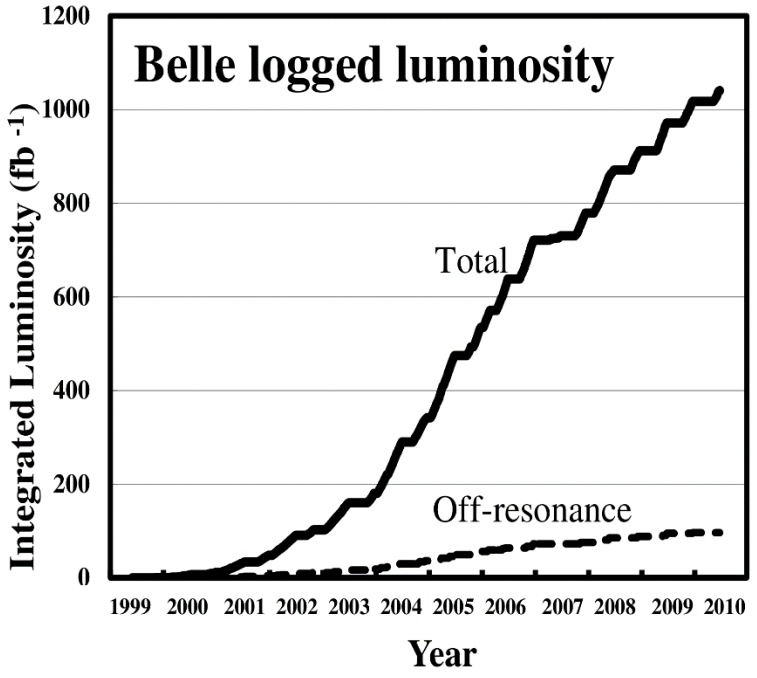
K^0 produced, $+$ sign

- Results are compatible with SM expectations
- CPV dominated by Kaon mixing
- No evidence of CPV in the ΔC transitions

The Belle experiment

The Belle detector was located at the interaction point at KEKB in Japan





$\int L\,dt \sim 977\ \text{fb}^{-1}$ close to the $\Upsilon(1S-5S)$ peaks, $1.3\times10^9\ c\bar{c}$ pairs

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

Mass eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$

$$\frac{d\Gamma_{D^0}}{e^{-\Gamma t}\,dt} \propto \left(|A_f|^2 + \left|\frac{q}{p}\right|^2 |\overline{A_f}|^2\right)\cosh \Gamma y t + \left(|A_f|^2 - \left|\frac{q}{p}\right|^2 |\overline{A_f}|^2\right)\cos \Gamma x t$$
$$+2Re\left(\frac{q}{p}\overline{A_f}A_f^*\right)\sinh \Gamma y t - 2Im\left(\frac{q}{p}\overline{A_f}A_f^*\right)\sin \Gamma x t$$

$$\frac{d\Gamma_{\overline{D^0}}}{e^{-\Gamma t}\,dt} \propto \left(|\overline{A_f}|^2 + \left|\frac{p}{q}\right|^2 |A_f|^2\right)\cosh \Gamma y t + \left(|\overline{A_f}|^2 - \left|\frac{p}{q}\right|^2 |A_f|^2\right)\cos \Gamma x t$$
$$+2Re\left(\frac{p}{q}A_f\overline{A_f^*}\right)\sinh \Gamma y t - 2Im\left(\frac{p}{q}A_f\overline{A_f^*}\right)\sin \Gamma x t$$

Mixing parameters $x = \frac{\Delta m}{\Gamma}, y = \frac{\Delta \Gamma}{2\Gamma}$

Mixing CPV $\left|\frac{q}{p}\right| \neq 1$

Interference CPV $\arg\frac{q}{p} \neq 0$

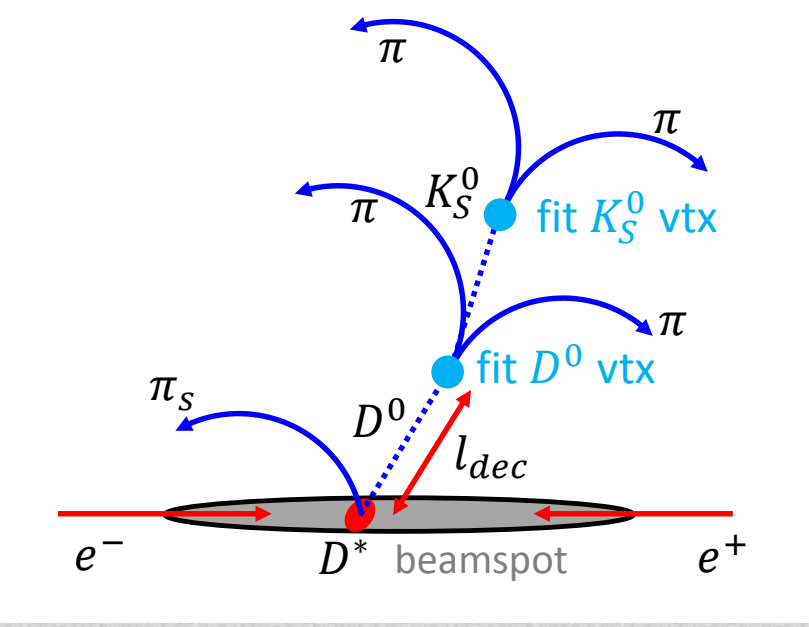
Mixing and CPV in $D^0 \to K^0_S \pi^+ \pi^-$

Total amplitude parametrized as a sum of
quasi two-body resonant amplitudes (isobar model)

$$A_f = \sum_r a_r\, e^{i\phi_r} A_r(m^2_-, m^2_+)\,, \qquad \overline{A_f} = \sum_r \overline{a_r}\, e^{i\overline{\phi_r}} A_r(m^2_-, m^2_+)\,, \qquad m^2_\pm = m^2(K^0_S \pi^\pm)$$

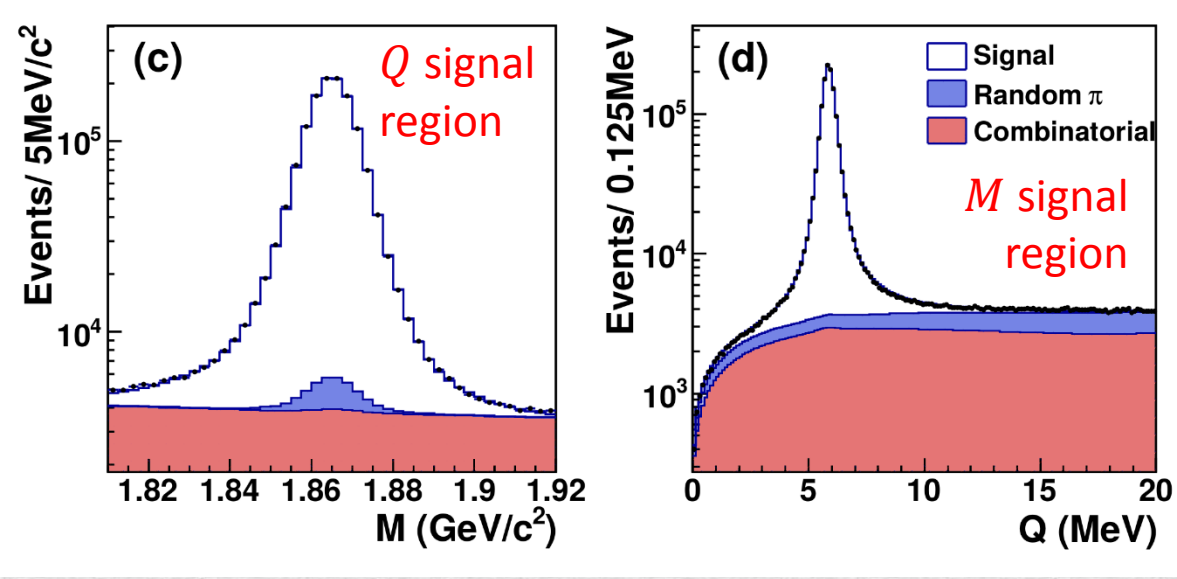
A time-dependent Dalitz plot analysis is needed to extract mixing and CPV parameters

- Reconstruct $D^{*+} \to D^0 \pi^+_s$
  - Flavor tagging by π_s charge
  - Background suppression
- D^0 proper decay time measurement
  - $t = \dfrac{\overrightarrow{l_{dec}}}{c\,\beta\gamma} \cdot \dfrac{\overrightarrow{p_{D^0}}}{p_{D^0}}, \;\; \beta\gamma = \dfrac{p_{D^0}}{m_{D^0}}$



Event selection

- $p_D > 2.5$ GeV @$\Upsilon(4S)$,
  $p_D > 3.1$ GeV @$\Upsilon(5S)$,
- Removed events with poorly determined t
- Cuts on M_D and $Q = M_{D^*} - M_D - M_\pi$



2D fit to M_D and Q,
Yield 1.2M, purity 96%

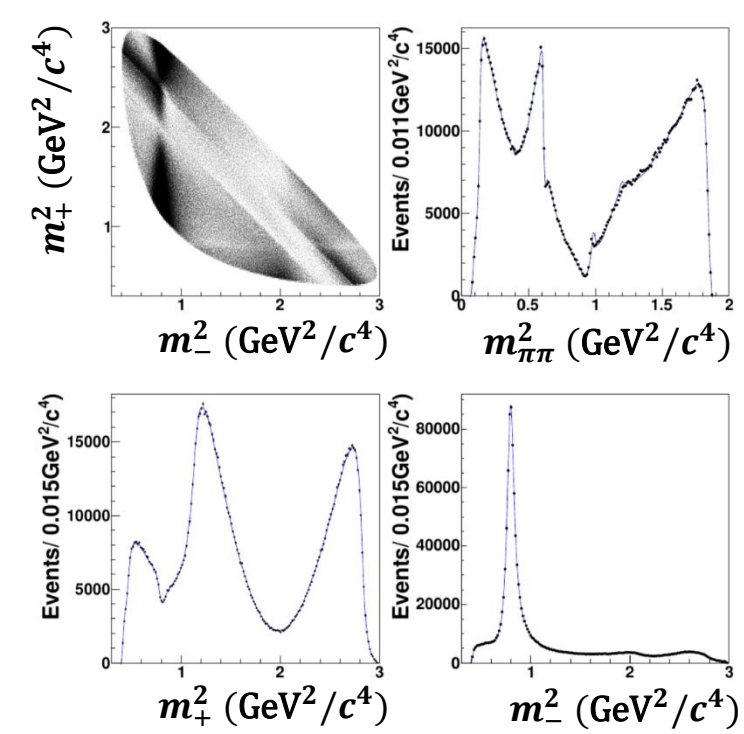
Signal region in $\left|M_D - M_D^{PDG}\right| < 15$ MeV
and $Q \in [5.75, 5.95]$ MeV

$L = 977\ \text{fb}^{-1}$

Belle coll. PRD 89, 091103(R) (2014)

3D analysis of $D^0 \to K^0_S \pi^+ \pi^-$

- Unbinned ML fit in (m_+, m_-, t)
- Fit model with 16 resonances
- Background estimated from sidebands:
  - Combinatorial: M sideband
  - Random π_S: Q sideband
- Resolution function: 3 Gaussians



RBW / K matrix / LASS

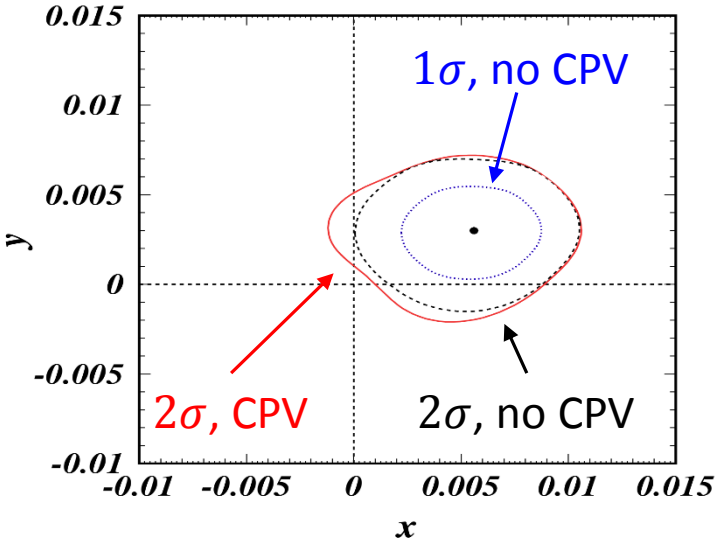
Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K^*_0(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K^*_2(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K^*_0(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K^*_2(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012
$\pi\pi$ S-wave			0.1288
β_1	4.23 ± 0.02	164.0 ± 0.2	
β_2	10.90 ± 0.02	15.6 ± 0.2	
β_3	37.4 ± 0.3	3.3 ± 0.4	
β_4	14.7 ± 0.1	-8.9 ± 0.3	
f^{prod}_{11}	12.76 ± 0.05	-161.1 ± 0.3	
f^{prod}_{12}	14.2 ± 0.2	-176.2 ± 0.6	
f^{prod}_{13}	10.0 ± 0.5	-124.7 ± 2.1	
$K\pi$ S-wave	Parameters		
M(MeV/c^2)	1461.7 ± 0.8		
Γ(MeV/c^2)	268.3 ± 1.1		
F	0.4524 ± 0.005		
$\phi_F(rad)$	0.248 ± 0.003		
R	1(fixed)		
$\phi_R(rad)$	2.495 ± 0.009		
a(GeV/c^{-1})	0.172 ± 0.006		
r(GeV/c^{-1})	-20.6 ± 0.3		
$K^*(892)$	Parameters		
$M_{K^*(892)}$(MeV/c^2)	893.68 ± 0.04		
$\Gamma_{K^*(892)}$(MeV/c^2)	47.49 ± 0.06		

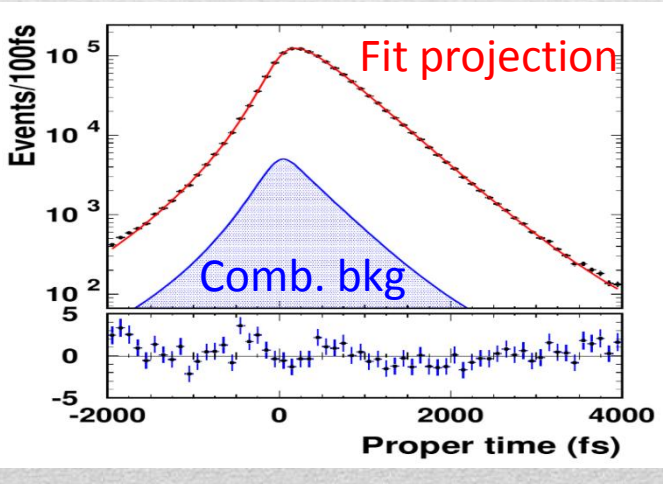
$D^0 \to K^0_S \pi^+ \pi^-$: results

(a_r, ϕ_r) consistent with $(\overline{a_{\bar{r}}}, \overline{\phi_{\bar{r}}})$: no CPV in decay, set $A_{\bar{f}} = \overline{A_f}$ in the fit

Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03\,+0.06}_{-0.09\,-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04\,+0.03}_{-0.05\,-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04\,+0.06}_{-0.08\,-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04\,+0.03}_{-0.05\,-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16\,+0.05\,+0.06}_{-0.15\,-0.04\,-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

Third error on DP model





Mixing significance at 2.5σ

No evidence for CPV

$\tau = (410.3 \pm 0.6)$ fs, to compare with

$\tau = (410.1 \pm 1.5)$ fs (PDG 2014)

Conclusions

Charm CPV is a powerful tool to search BSM physics!

An overview of recent BaBar and Belle results has been presented:

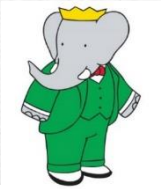
- CP asymmetries in SCS $D^+ \to K^+K^-\pi^+$ decays at BaBar using different approaches
- CP asymmetries in $D^+_{(s)} \to K^0_S K^+$ and $D^+_s \to K^0_S \pi^+$ decays at BaBar
- Mixing and CPV parameters in $D^0 \to K^0_S \pi^+\pi^-$ at Belle
- (for CPV search in $D^0 \to \pi^0\pi^0$ at Belle, see T. Nanut's talk)

No evidence of CPV found so far

Thank you!

BACKUP

Direct CPV at Belle/BaBar



PRD 87, 052010 (2013)

JHEP 1302, 098 (2013)

Channel	Luminosity (fb^{-1})	A_{CP} (%)	Luminosity (fb^{-1})	A_{CP} (%)
$D^+ \to K^+K^-\pi^+$	476	$0.37 \pm 0.30 \pm 0.15$	–	–
$D^+ \to K^0_S K^+$	469	$0.46 \pm 0.36 \pm 0.25$	977	$0.08 \pm 0.28 \pm 0.14$
$D^+_s \to K^0_S K^+$	469	$0.28 \pm 0.23 \pm 0.24$	673	$0.45 \pm 0.36 \pm 0.22$
$D^+_s \to K^0_S \pi^+$	469	$0.3 \pm 2.0 \pm 0.3$	673	$5.12 \pm 2.50 \pm 0.33$

PRD 87, 052012 (2013)

PRL 104, 181602 (2010)

(contribution of CP asymmetry of K^0_S subtracted)

HFAG averages on mixing/CPV