Charm Mixing and CP Violation at BaBar

Giulia Casarosa
SLAC National Accelerator Laboratory
INFN & Università di Pisa

on behalf of the BaBar Collaboration

ICHEP2012 Melbourne

36th International Conference on High Energy Physics

4 – 11 July 2012
Melbourne Convention and Exhibition Centre

outline

- Mixing and *CP* Violation (CPV) in the Charm Sector
- Search for *direct* CP Violation:
  - $D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis
  - $D^+ \to K^+ K^- \pi^+$ analysis
- $D^0 - \overline{D}^0$ Mixing and search for *indirect* CP Violation:
  - $D^0 \to K^+K^-, \pi^+\pi^- \,/\, D^0 \to K^\pm \pi^\mp$ lifetime ratio analysis
- Conclusions

`NOTE: charge conjugation is implied from now on`

Flavour Mixing and CPV in the Charm Sector

Mixing

mass eigenstates ≠ flavour eigenstates

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

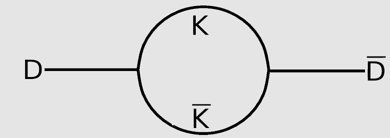
$m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $|D_{1,2}\rangle$ and $\Gamma_D = (\Gamma_1 + \Gamma_2)/2$

Mixing Parameters

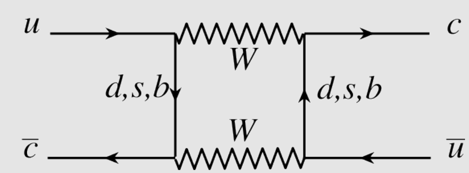
$$x = \frac{m_1 - m_2}{\Gamma_D} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

NOTE: $|p|^2 + |q|^2 = 1$ (CPT conserved), CP $|D^0\rangle = +\,|\bar{D}^0\rangle$

- *long-distance* contributions: dominant but affected by large theory uncertainties



- *short-distance* contributions: GIM and CKM suppressed in SM



CP Violation

direct CPV, $A_D^f \neq 0$

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

$$A_f = \langle D^0 | \mathcal{H} | f \rangle$$
$$A_{\bar{f}} = \langle D^0 | \mathcal{H} | \bar{f} \rangle$$
$$\bar{A}_f = \langle \bar{D}^0 | \mathcal{H} | f \rangle$$
$$\bar{A}_{\bar{f}} = \langle \bar{D}^0 | \mathcal{H} | \bar{f} \rangle$$

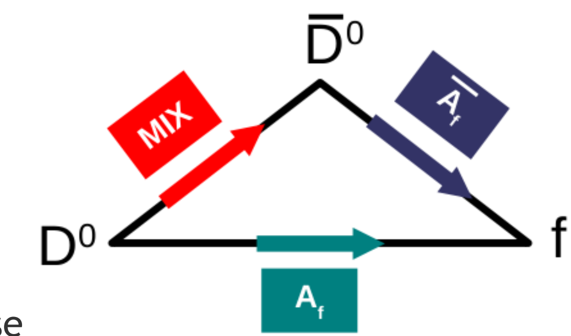
CPV in mixing, $A_M \neq 0$

$$A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}, \qquad R_M = \left|\frac{q}{p}\right|$$

CPV in the interference, $\phi_f \neq 0$

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

strong + weak phase

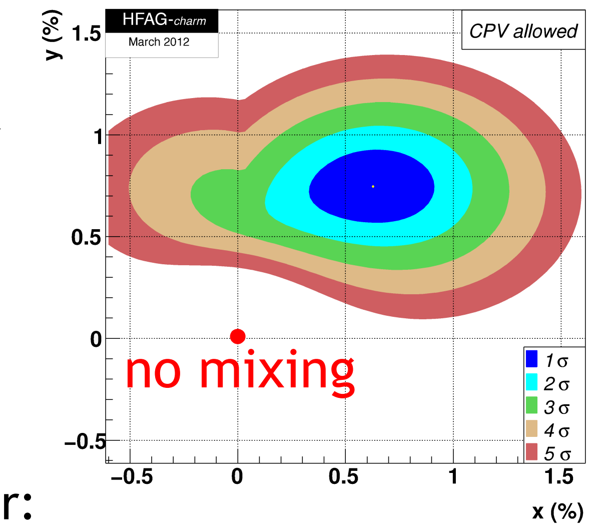


Experimental Status

[http://www.slac.stanford.edu/xorg/hfag/charm/index.html]

Mixing

- mixing in the D^0 system is well established, significance ~10σ
- Standard Model (SM) predictions affected by large uncertainties: $x^{theo}, y^{theo} \sim o(10^{-2} - 10^{-7})$ [IJMP A21, 5686 (2006)]



- measurements of x and y are at the upper limit of SM, New Physics (NP) may contribute in short-distance diagrams;

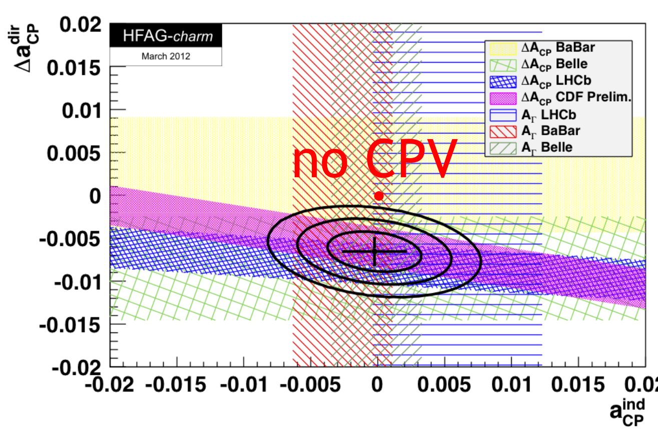
CPV

- the **first evidence** of **CPV** in the charm sector:

LHCb: $A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi) = (-0.82 \pm 0.21^{stat} \pm 0.11^{syst})$ [PRL108, 111602 (2012)]

CDF: $A_{CP}(D^0 \to KK) - A_{CP}(D^0 \to \pi\pi) = (-0.62 \pm 0.21^{stat} \pm 0.10^{syst})$ [CDF note 10784 (2012)]

- these CP asymmetries are *marginally compatible* with the SM, but uncertainties on the predictions prevent establishing whether this is or not a sign of NP
- CPV in *mixing* would be a clear sign of NP
- what to do now?
  - improve precision (also for the single asymmetries)
  - measure single asymmetries in more decay channels



no CPV excluded with CL of 0.006%

outline

- Mixing and *CP* Violation (CPV) in the Charm Sector
- Search for *direct* CP Violation:
  - $D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis
  - $D^+ \to K^+ K^- \pi^+$ analysis
- $D^0 - \overline{D}^0$ Mixing and search for *indirect* CP Violation:
  - $D^0 \to K^+K^-, \pi^+\pi^- \,/\, D^0 \to K^\pm\pi^\mp$ lifetime ratio analysis
- Conclusions

Searches for Direct CPV

- need at least 2 amplitudes with different weak and strong phases:
  - Singly Cabibbo Suppressed: tree + penguin
  - Cabibbo Favoured + Doubly Cabibbo Suppressed

$D^+ \to K^+K^-\pi^+$	SCS	tree+penguin
$D_s^+ \to K_S K^+$	CF + DCS	
$D^+ \to K_S K^+$	SCS	tree+penguin
$D_s^+ \to K_S \pi^+$	SCS	tree+penguin

- time-integrated CP asymmetries:

$$A_{CP} = \frac{\mathcal{B}(D \to f) - \mathcal{B}(\overline{D} \to \bar{f})}{\mathcal{B}(D \to f) + \mathcal{B}(\overline{D} \to \bar{f})}$$

- if a K_S is present in the final state there is a contribution from CPV in K^0 mixing:

$A_{CP} = A_{CP}^{\Delta C} + A_{CP}^{K^0}$ where $A_{CP}^{K^0} = (\pm 0.332 \pm 0.006)\%$ (+ if K^0 and – if $\overline{K}^0$)

- experimentally: $A_{reco} = A_{CP} + A_{FB}(\cos\theta^*) + A_\epsilon^h(p, \cos\theta_h)$

Forward-Backward asym. from $\gamma - Z^0$ interf. coupled to detector asym.
- odd in $\cos\theta^*$ → decouple from A_{CP} (independent of $\cos\theta^*$)

$$A_{CP} = \frac{A(+|\cos\theta^*|) + A(-|\cos\theta^*|)}{2}$$

(both analysis)
- use data-corrected MC ($D^+ \to K^+K^-\pi^+$)

detector-induced charge-reconstructed asymmetry;
to evaluate it and correct for it:
- data-driven method ($D^+_{(s)} \to K_S h^+$)
- $e^+e^- \to \tau^+\tau^-$ data sample ($D^+ \to K^+K^-\pi^+$)

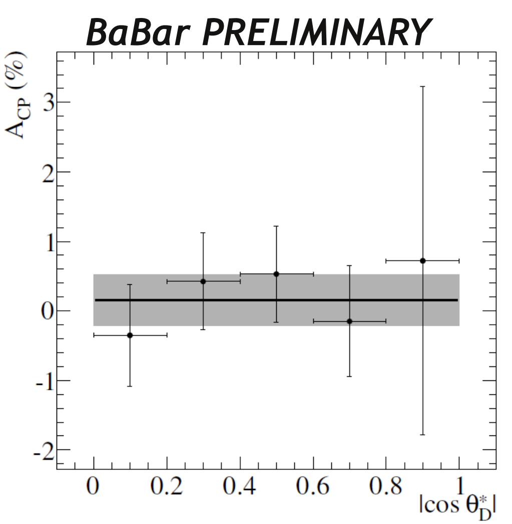
- In three-body decays CPV effects can be enhanced in certain Dalitz Plot (DP) regions
  - DP model-dependent and model-independent searches

$D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis

L = 469 fb^{-1}

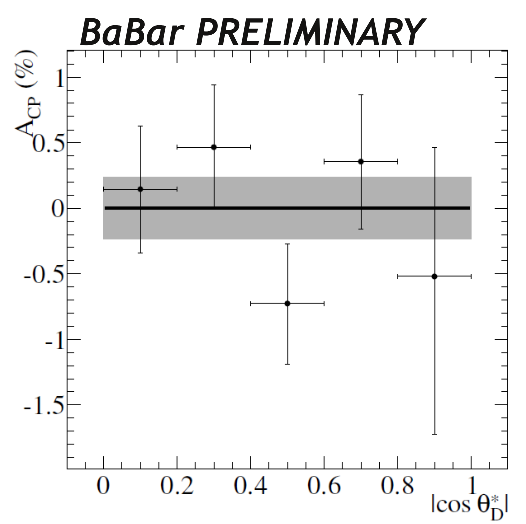
- Precision goal is $o(10^{-3})$, need to keep systematic errors at that level
  - correct for the detector-induced charge-reconstruction asymmetry using a *data driven* method that makes use of physical-asymmetries-free charged track sample from B decays [PRD 83, 071103 (2011)]
- Perform simultaneous mass fit and extract the number of $D_{(s)}^+$ and $D_{(s)}^-$ in 10 bins of cosθ*
  - decouple CP from FB asymmetry and perform a χ^2 fit to a constant value, A_{CP}:

$D^+ \to K_S K^+$
159k evts



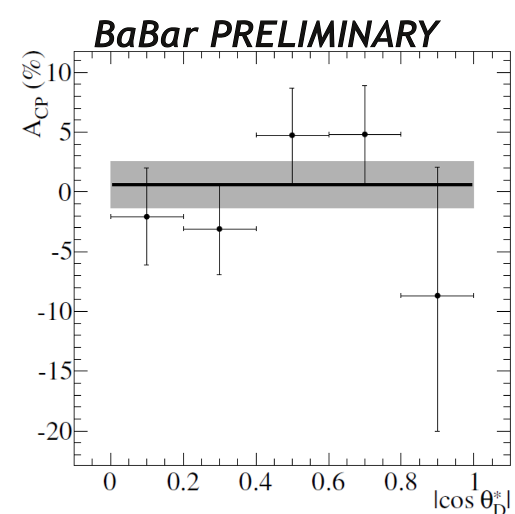
$$A_{CP} = (0.16 \pm 0.36)\%$$

$D_s^+ \to K_S K^+$
288k evts



$$A_{CP} = (0.00 \pm 0.23)\%$$

$D_s^+ \to K_S \pi^+$
14k evts



$$A_{CP} = (0.6 \pm 2.0)\%$$

$D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ results

- Dominant systematic uncertainties:
  - statistics of the control sample used to correct for the charge asymmetry ($D^+_{(S)} \to K_S K^+$)
  - binning in cosθ* to decouple CP from FB asymmetry ($D^+_S \to K_S \pi^+$)

- Apply corrections and evaluate the contribution of CPV from charm:

	$D^\pm \to K^0_S K^\pm$	$D^\pm_s \to K^0_S K^\pm$	$D^\pm_s \to K^0_S \pi^\pm$
A_{CP} value from the fit	$(+0.16 \pm 0.36)\%$	$(0.00 \pm 0.23)\%$	$(+0.6 \pm 2.0)\%$
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 $K^0 - \overline{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(+0.332 \pm 0.006)\%$
A_{CP} final value (charm only)	$(+0.46 \pm 0.36 \pm 0.25)\%$	$(+0.28 \pm 0.23 \pm 0.24)\%$	$(+0.3 \pm 2.0 \pm 0.3)\%$

no CP Violation observed in charm

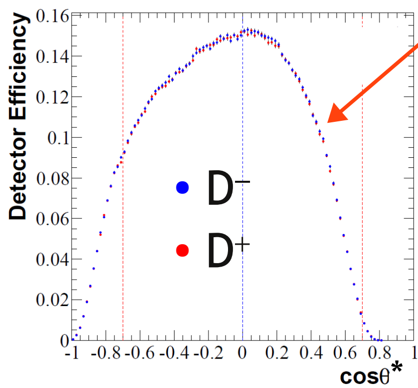
$D^+ \rightarrow K^+K^-\pi^+$, integrated asymmetry

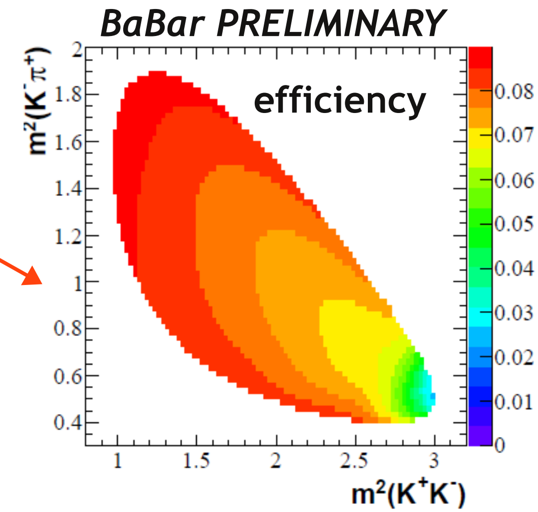
L = 476 fb^{-1}

228k evts
purity 92%

➔ The *reconstruction efficiency* is determined from MC (phase-space DP)

- the MC has been corrected for:
  - FB asymmetry using a PDF in (p*, cosθ*)
  - detector-induced charge-reconstruction asymmetry
- $\epsilon_i^{\pm} = \frac{N^{\pm}_{\text{i,reco}}}{N^{\pm}_{\text{i,gen}}}$ evaluated in bins of cosθ* and in DP bins



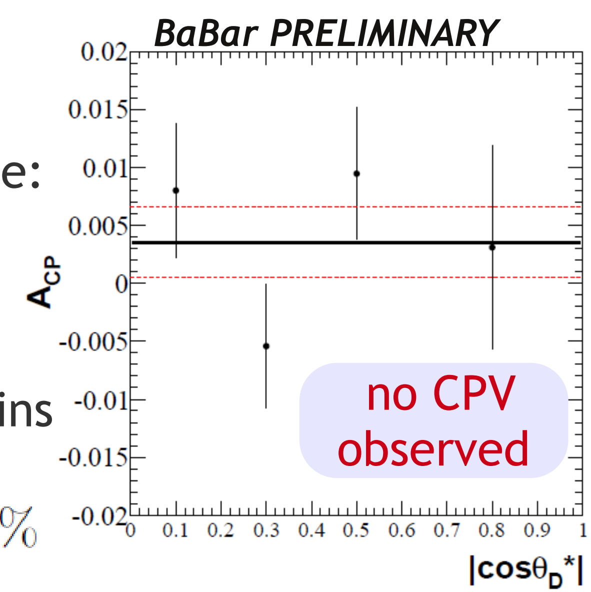


➔ Dalitz Plot integrated measurement:

- evaluate N(D$^{\pm}$) fitting the mass distributions in 8 bins of cosθ*
- in each bin, correct N(D$^{\pm}$) by the corresponding ϵ(D$^{\pm}$) and compute:

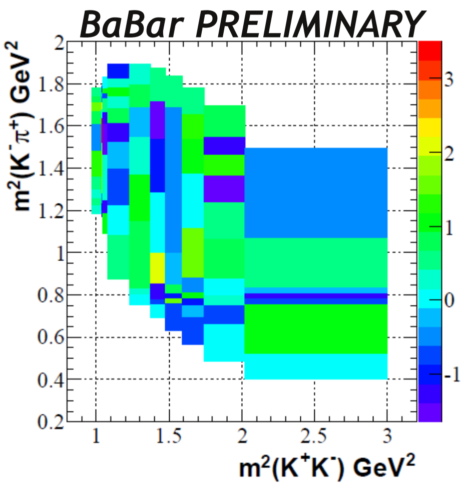
$$A_i = \frac{N_i(D^+)/\epsilon_i(D^+) - N_i(D^-)/\epsilon_i(D^-)}{N_i(D^+)/\epsilon_i(D^+) + N_i(D^-)/\epsilon_i(D^-)}$$

- decouple CP from residual FB asymmetry combining symmetric bins in cosθ*
- perform a χ^2 fit to a constant value: $A_{CP} = (0.35 \pm 0.30 \pm 0.15)\%$



$D^+ \to K^+K^-\pi^+$, model independent analysis

➔ Normalized residuals of efficiency-corrected and background-subtracted DP for D^+ and D^-:

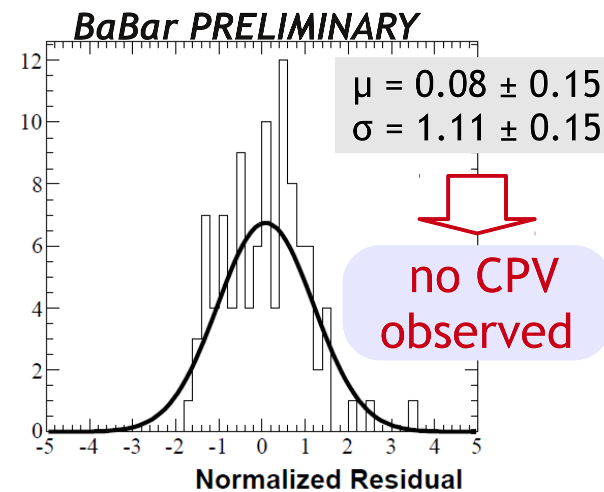


- in each DP adaptive bin:

$$\Delta_i = \frac{n_i^2(D^+) - R n_i^2(D^-)}{\sqrt{\sigma_i^2(D^+) + R^2\sigma_i^2(D^-)}},\ n_i = N_i/\epsilon_i$$

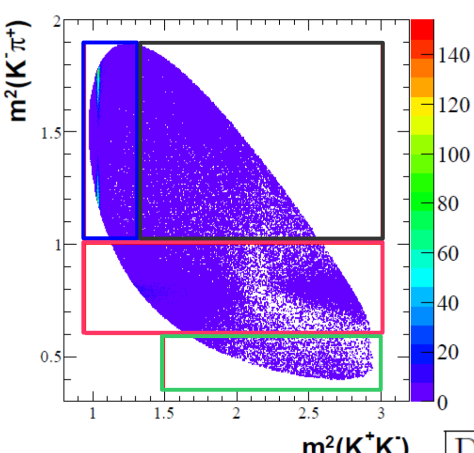
where R corrects for residual A_{FB}:

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



no CPV observed

➔ Measurement of CP Violation in 4 regions of the DP:



- divide the DP into 4 regions
- evaluate $N(D^\pm)$ in each region by fitting the mass distribution
- correct $N(D^\pm)$ by the corresponding $\epsilon(D^\pm)$, and $N(D^-)$ by R (A_{FB}):

$$A_{CP} \equiv \frac{N(D^+)/\epsilon(D^+) - R\,N(D^-)/\epsilon(D^-)}{N(D^+)/\epsilon(D^+) + R\,N(D^-)/\epsilon(D^-)}$$

no CPV observed

BaBar PRELIMINARY

Dalitz plot region	$N(D^+)$	$\epsilon(D^+)[\%]$	$N(D^-)$	$\epsilon(D^-)[\%]$	$A_{CP}[\%]$
Below $\bar{K}^*(892)^0$	1882 ± 70	7.00	1859 ± 90	6.97	-0.65 ± 1.64 ± 1.73
$\bar{K}^*(892)^0$	36770 ± 251	7.53	36262 ± 257	7.53	-0.28± 0.37 ± 0.21
$\phi(1020)$	48856 ± 289	8.57	48009 ± 289	8.54	-0.26 ± 0.32 ± 0.45
Above $\bar{K}^*(892)^0$ and $\phi(1020)$	25616 ± 244	8.01	24560 ± 242	8.00	1.05 ± 0.45 ± 0.31

$D^+ \rightarrow K^+K^-\pi^+$, model dependent analysis

➔ Legendre polynomial moments analysis [PRD 78 051102] (model-independent method) shows no evidence of CPV.

➔ use a model to describe the DP distribution and allow each resonance to have a different amplitude and phase for D^+ and D^- .

- each resonance is parameterized with 4 parameters:

$\mathcal{M}_r,\ \phi_r$ → amplitude and phase of the D^+

CPV parameters

$$r = \frac{|\mathcal{M}_r|^2 - |\overline{\mathcal{M}}_r|^2}{|\mathcal{M}_r|^2 + |\overline{\mathcal{M}}_r|^2}$$

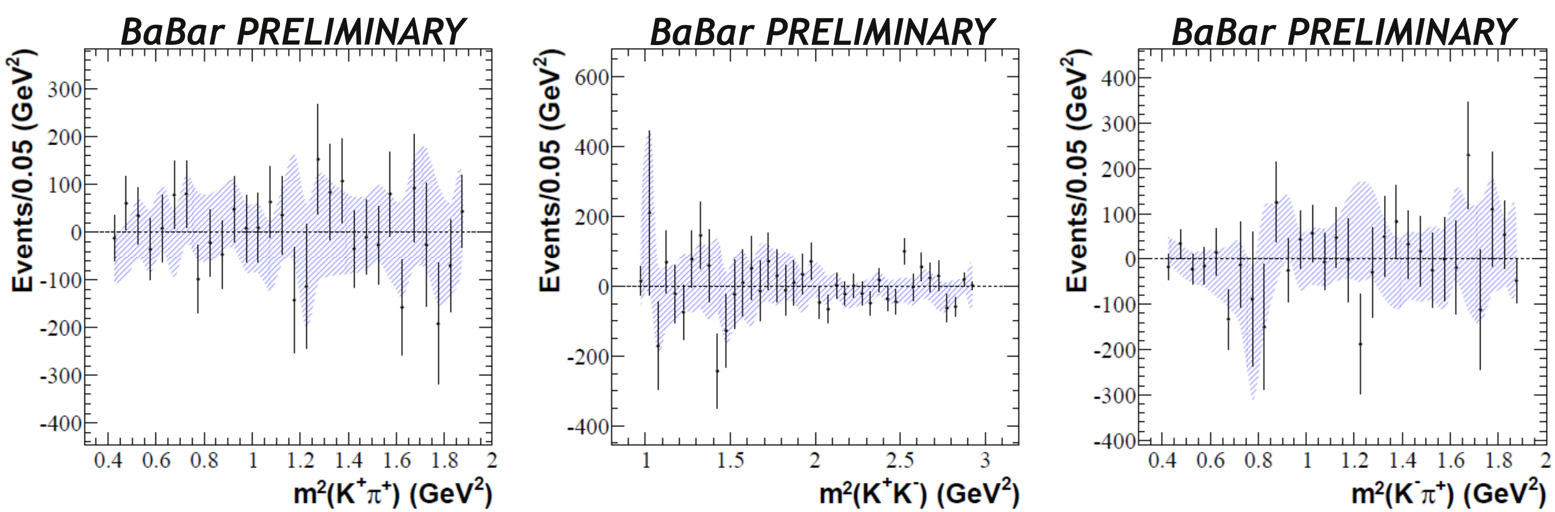
$$\Delta\phi = \phi_r - \overline{\phi}_r$$

- a simultaneous fit to the D^+ and D^- DPs is performed

BaBar PRELIMINARY

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	$-14.30^{+11.67}_{-12.57} \pm 5.98$	$-2.56^{+7.01}_{-6.17} \pm 8.91$
$\kappa(800)$	$2.00^{+5.09}_{-4.96} \pm 1.85$	$2.10^{+2.42}_{-2.45} \pm 1.01$
$a_0(1450)^0$	$5.07^{+6.86}_{-6.54} \pm 9.39$	$4.00^{+4.04}_{-3.96} \pm 3.83$
	Δx	Δy
$f_0(980)$	$-0.199^{+0.106}_{-0.110} \pm 0.084$	$-0.231^{+0.100}_{-0.105} \pm 0.079$
$f_0(1370)$	$0.019^{+0.049}_{-0.048} \pm 0.022$	$-0.0045^{+0.037}_{-0.039} \pm 0.016$

difference of the DP proj. of data (points) and fit (blue curve) ± 1σ:



no CPV observed

outline

- Mixing and *CP* Violation (CPV) in the Charm Sector
- Search for *direct* CP Violation:
  - $D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis
  - $D^+ \to K^+ K^- \pi^+$ analysis
- $D^0 - \overline{D}^0$ Mixing and search for *indirect* CP Violation:
  - $D^0 \to K^+K^-, \pi^+\pi^- / D^0 \to K^\pm \pi^\mp$ lifetime ratio analysis
- Conclusions

Mixing and CPV with Lifetime Ratio Analysis

➔ Perform a simultaneous fit to 5 signal channels and extract:

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

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

- Mixing:

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

- Indirect CPV:

$$\Delta Y = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} - \frac{1}{\overline{\tau}^+}\right)$$

- in general y_{CP} and ΔY depend on the final state
- in case of no *CP* violation: $y_{CP} = y$ and $\Delta Y = 0$

- τ_D = D^0 lifetime ($K^\pm\pi^\mp$)
- τ^+ ($\overline{\tau}^+$) = D^0 ($\overline{D}^0$) effective lifetime for decays to CP+ eigenstates (K^+K^- , $\pi^+\pi^-$)

➔ Experimental assumptions:

- small mixing ($|x|$, $|y|$ << 1) → proper time distributions are exponential with corresponding effective lifetimes to a very good approximation;
- not sensitive to direct CPV + weak phase φ does not depend on final state → KK and ππ modes share common effective lifetimes,

[PRD 80. 076008 (2009)]

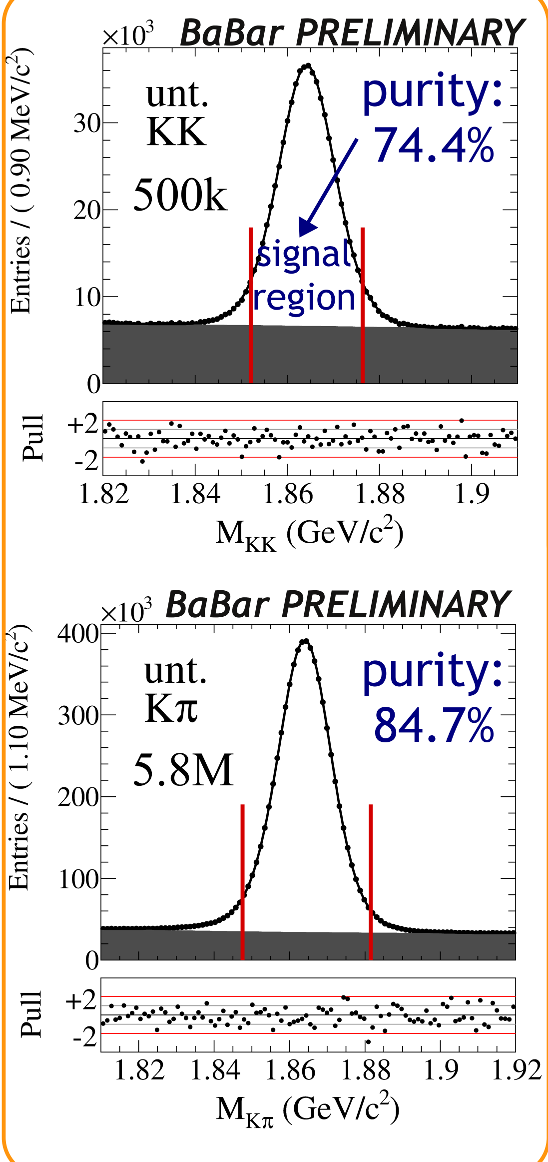
$$y_{CP} = y\cos\phi - \frac{A_M}{2} x\sin\phi$$

$$\Delta Y = -x\sin\phi + \frac{A_M}{2} y\cos\phi$$

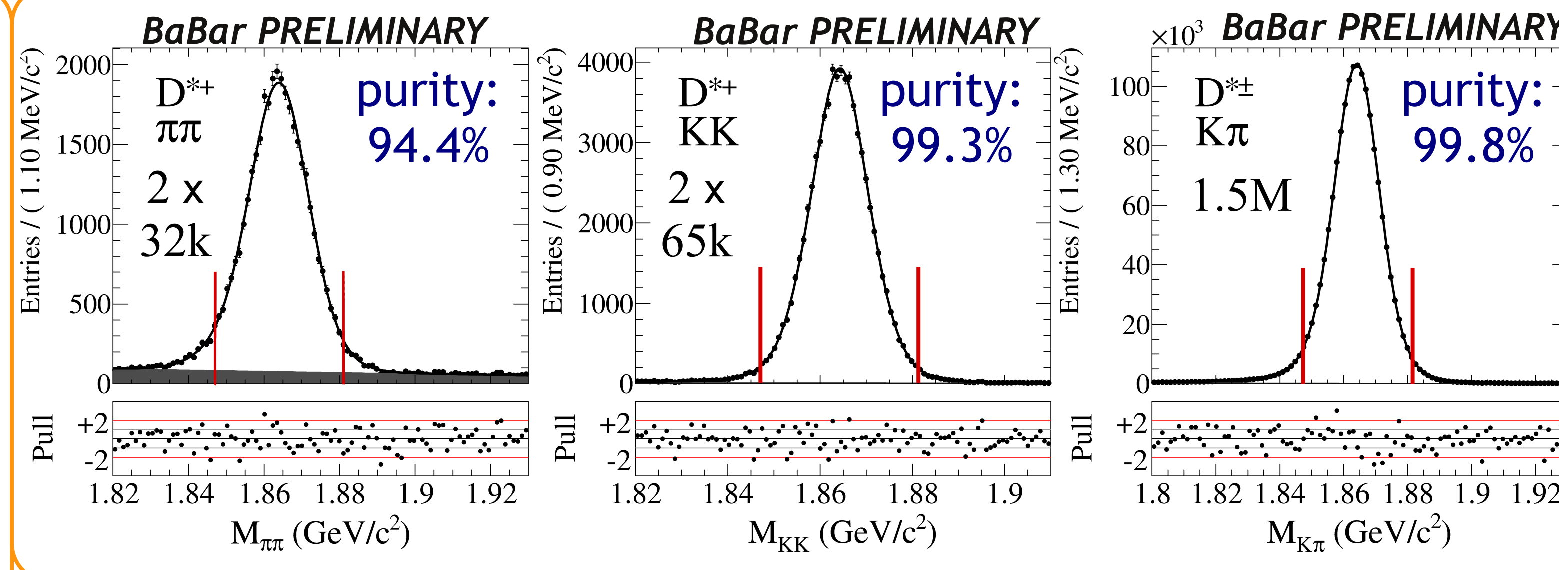
✔ crosscheck fit on data.

Backgrounds and Data Mass Fits

flavour untagged:



flavour tagged:



combinatorial background:

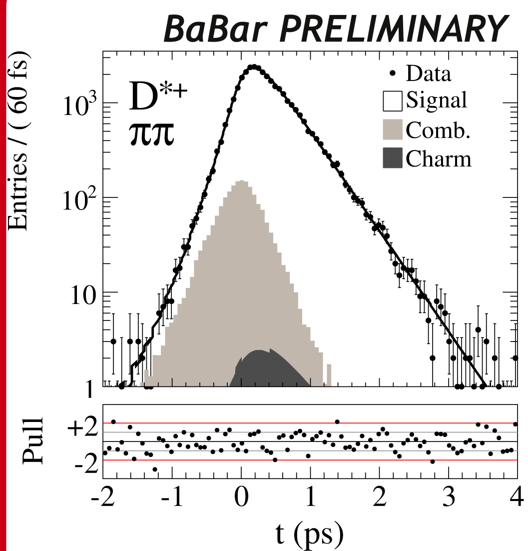
- ➔ random tracks → ~ zero-lifetime component
- ➔ main background
- ➔ lifetime PDF is extracted from data sidebands

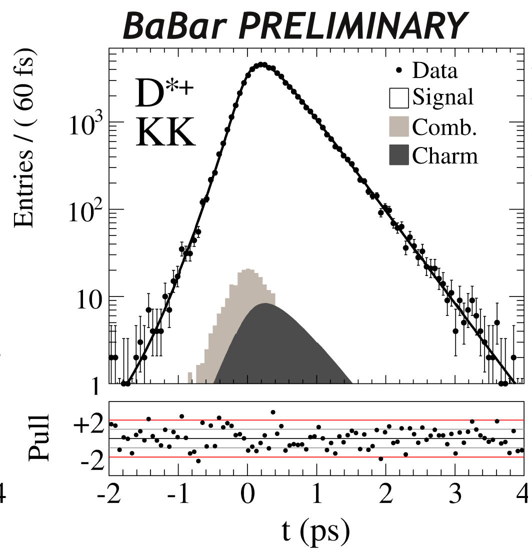
charm background:

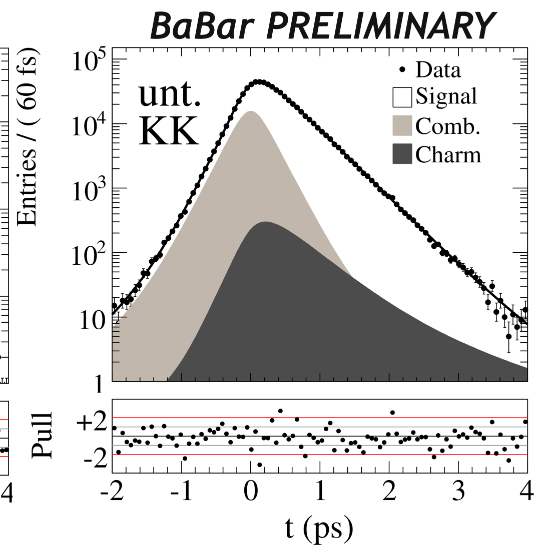
- ➔ common ancestor of the D^0 products is a long-living charm meson → signal-like long lifetime
- ➔ very small component in the signal region (<0.7%)
- ➔ lifetime PDF is extracted from MC

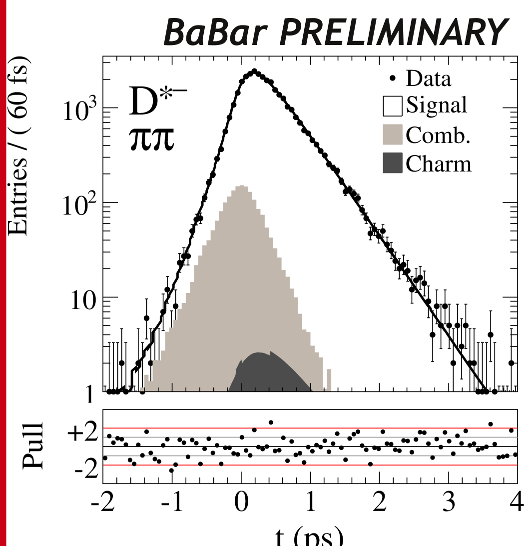
Proper Time Fit Projections

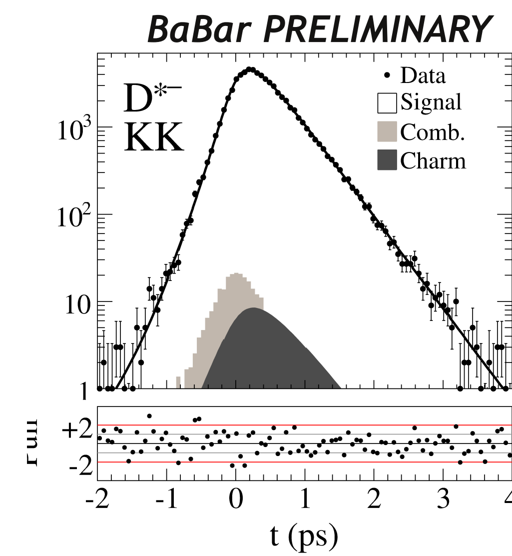
CP+ eigenstates



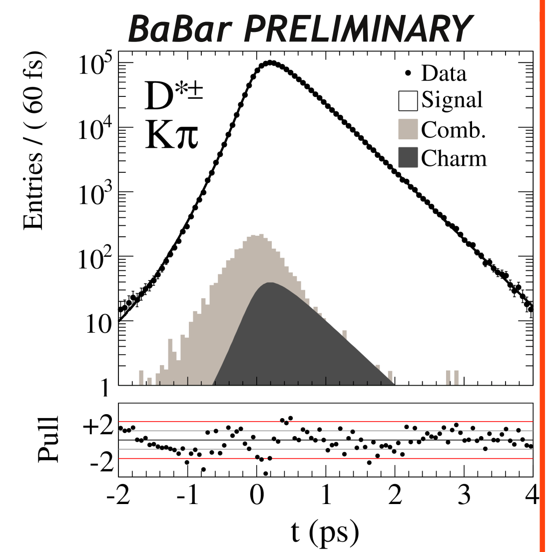


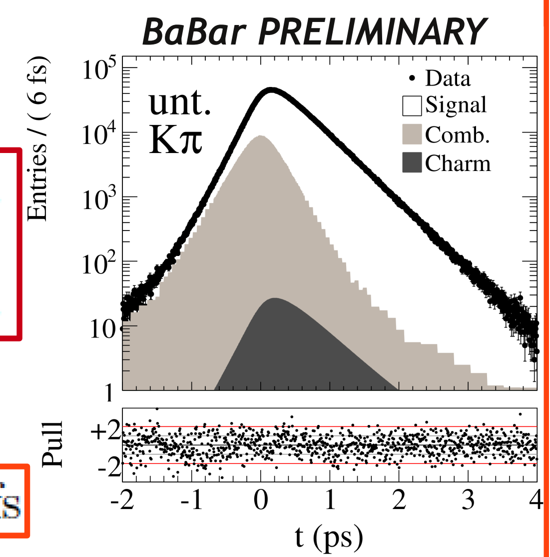






CP mixed states





CP+ lifetimes

$$\tau^+ = (405.69 \pm 1.25)\ \text{fs}$$

$$\bar{\tau}^+ = (406.40 \pm 1.25)\ \text{fs}$$

[stat error only]

D^0 lifetime

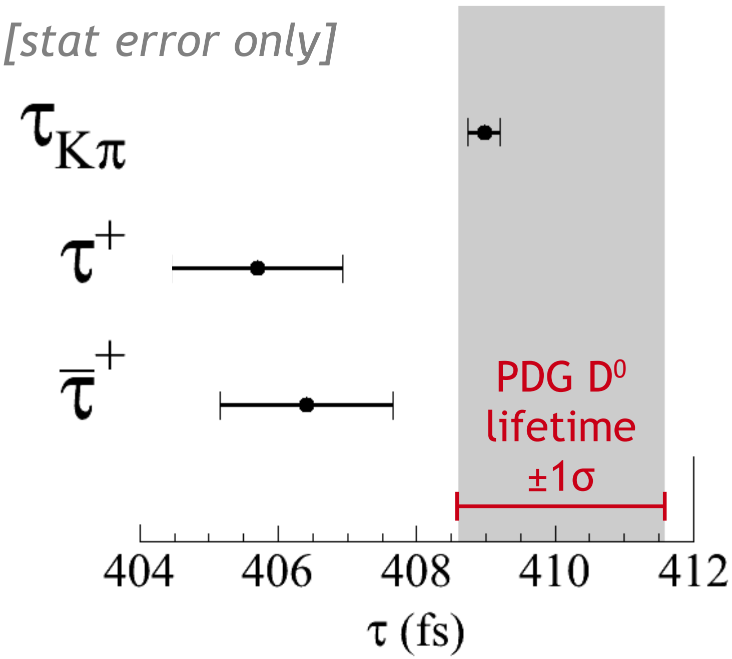
$$\tau_{K\pi} = (408.97 \pm 0.24)\ \text{fs}$$

[stat error only]

Lifetime Fit Results

BaBar PRELIMINARY

[stat error only]

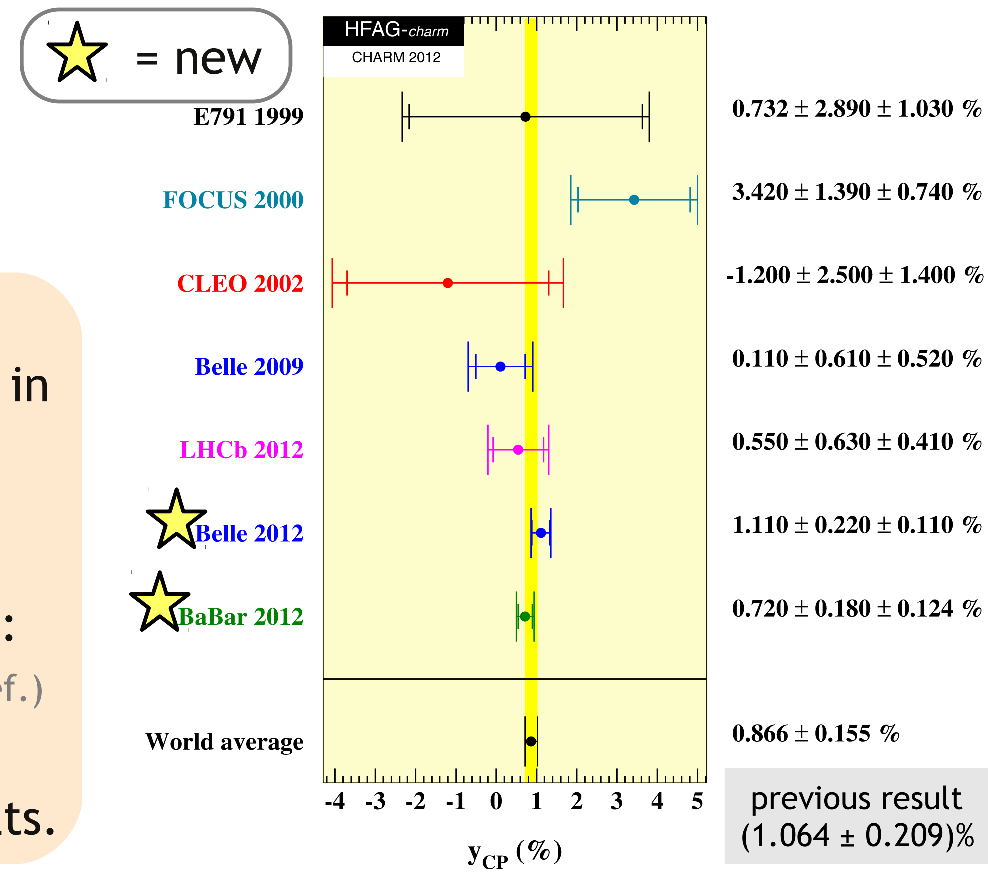


BaBar PRELIMINARY

$$y_{CP} = [0.720 \pm 0.180(\text{stat}) \pm 0.124(\text{syst})]\%$$

$$\Delta Y = [0.088 \pm 0.255(\text{stat}) \pm 0.058(\text{syst})]\%$$

- ➔ exclude no-mixing hypothesis @ 3.3σ
- ➔ no CP Violation observed



- ➔ most precise single measurement of y_{CP};
- ➔ this measurement favors a lower value for y_{CP}, in closer agreement with HFAG value for y;
  - HFAG y =(0.456 ± 0.186) % from direct meas.
- ➔ this result is compatible with previous BaBar results [PRD 80, 071103 (2009)], [PRD 78, 011105 (2008)] :
  - ΔY = (-0.26±0.36±0.08) % (sign difference in the def.)
  - y_{CP} = (1.16±0.22±0.18) %
- ➔ this result supersedes the previous BaBar results.

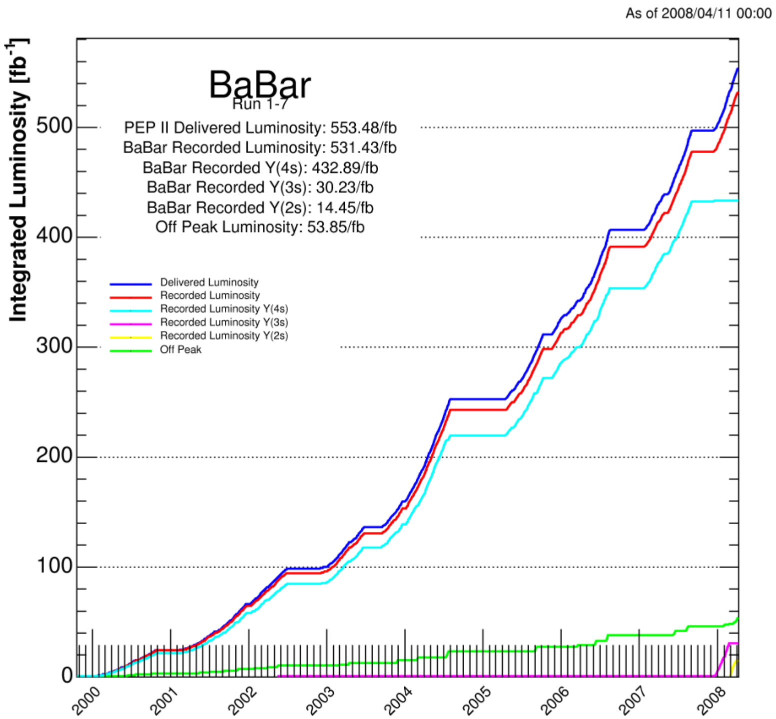
Conclusions

- Increase in precision and inclusion of more channels are needed to understand the origin of the CP Violation reported by LHCb and CDF
- We have searched for CP Violating effects with the full BaBar data sample reaching a precision down to $o(10^{-3})$
- We have found no evidence of direct or indirect CP Violation in the following channels:
  - $D^+ \rightarrow K^+K^-\pi^+$ (direct CPV)
  - $D^+ \rightarrow K_S K^+$, $D_s^+ \rightarrow K_S K^+$, $D_s^+ \rightarrow K_S \pi^+$ (direct CPV)
  - $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ (indirect CPV)
- We have measured y_{CP} with the highest precision to date, and excluded the no-mixing hypothesis at 3.3σ significance.

thank you!

backup slides

The BaBar Detector

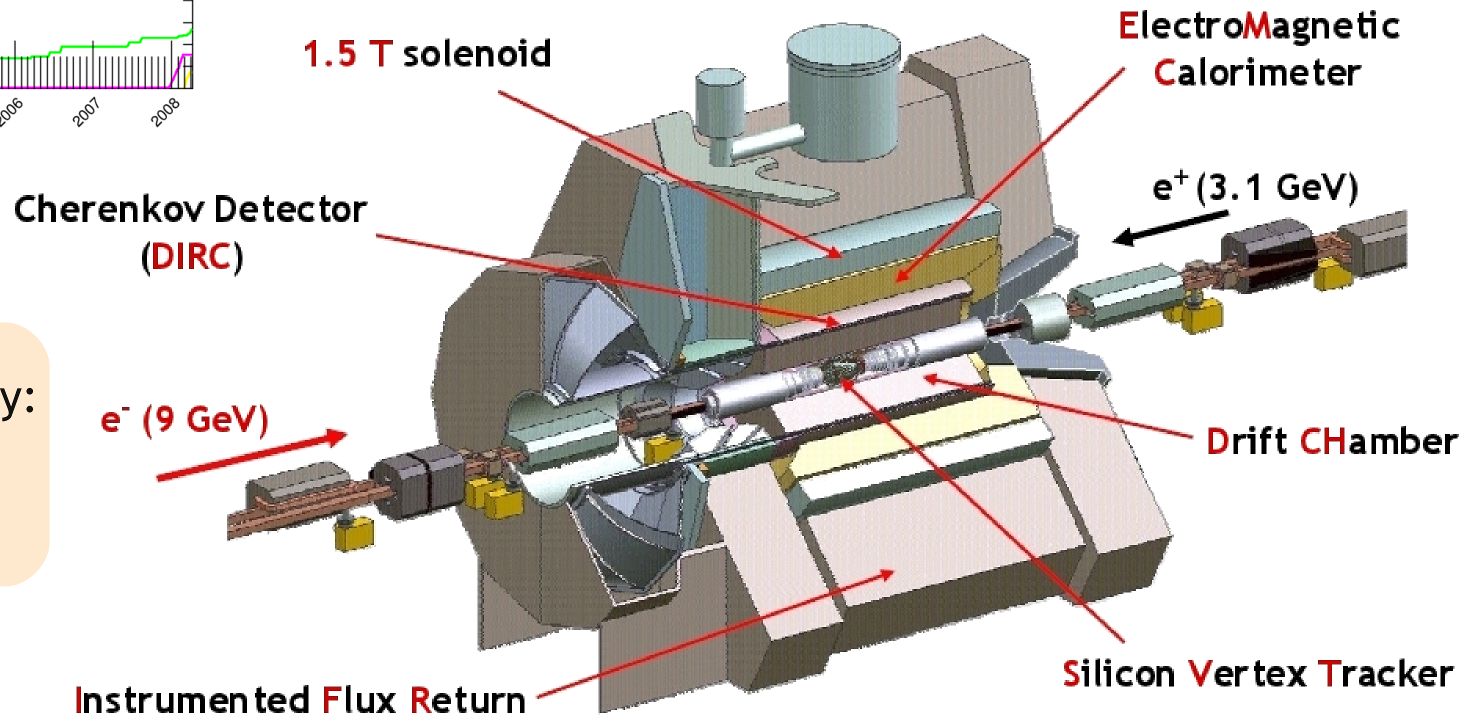


$e^+e^- \rightarrow Y(4S)$

Run1 to Run6: L(on + off peak) = 474 fb^{-1}

$e^+e^- \rightarrow Y(3S), Y(2S)$

Run7: L(on + off peak) = 47 fb^{-1}



PEPII is also a charm-Factory: it produced around 690M of $e^+e^- \rightarrow c\bar{c}$ events

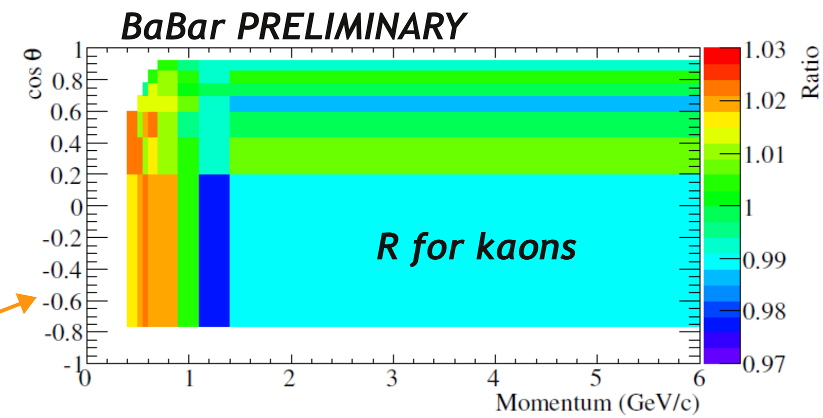
$D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis

➔ Correction for the detector-induced charge-reconstruction asymmetry:

data driven method makes use of 100M $\Upsilon(4S) \to B\bar{B}$ decays:

sample free of any physical asymmetries:

- quality cuts to remove *p* and *e*, $p_T > 0.4$ GeV/c
- continuum (Off) is subtracted: $N^{\pm}_{\rm rec}(\vec{p}) = N^{\pm}_{\rm recOn}(\vec{p}) - N^{\pm}_{\rm recOff}(\vec{p})\frac{\mathcal{L}_{\rm On}}{\mathcal{L}_{\rm Off}}$
- evaluate the efficiency correction as a function of track momentum $R(\vec{p}) = \frac{\epsilon^+(\vec{p})}{\epsilon^-(\vec{p})} = \frac{N^+(\vec{p})}{N^-(\vec{p})}$



➔ Systematic uncertainties:

correction of charge asymmetry ← Statistics of the control sample

decoupling CP from FB asymmetry ← Binning in cos Θ

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%
Mis-identified tracks in the control sample	0.01%	0.01%	0.01%
Binning in cos Θ	0.04%	0.02%	0.27%
$K^0 - \overline{K}^0$ regeneration[1]	0.05%	0.05%	0.06%
$K^0_S - K^0_L$ interference[2]	0.015%	0.014%	0.008%
Total	0.25%	0.24%	0.29%

[1] arXiv:1006.1938 [hep/ex] (2010)

[2] JHEP 1204, 002 (2012)

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

➔ Sources of systematic uncertainties:

- event selection
- corrections applied to MC
- tracking asymmetry correction
- binning in cosθ*
- Dalitz Plot model

➔ Breakdown of the systematic uncertainties for the Integrated Measurement:

Average $\cos\theta$ asymmetry	ΔA_{CP}[%]
Event selection	0.07
Single forward and backward bin	0.01
$\cos\theta_{CM}$ binning	0.04
Track asymmetry correction	0.12

Lifetime Ratio analysis

➔ Systematic uncertainties:

BaBar PRELIMINARY

Systematic	$\lvert\Delta[y_{CP}]\rvert$ (%)	$\lvert\Delta[\Delta Y]\rvert$ (%)
Fit Region	0.057	0.022
Selection	0.059	0.054
Signal PDF	0.022	0.0
Charm PDF and yields	0.045	0.001
Comb. PDF and yields	0.079	0.002
Total	0.124	0.058

total systematics reduced w.r.t. previous BaBar analyses

- tagged-only analysis [PRD 78, 011105 (2008)]
- untagged-only analysis [PRD 80, 071103 (2009)]