Recent Charm Results from BaBar

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Outline

- Introduction:
  - Charm Physics
    - probe for Physics beyond the Standard Model
    - experimental reference point for lattice QCD calculations
- Recent results from BaBar:
    - Search for CP violation in $D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$
    - Mixing and CP violation with a lifetime ratio analysis of $D^0 \to K^+K^-, \pi^+\pi^-$ to $D^0 \to K^-\pi^+$
    - Precision measurement of the $D^*(2010)^+$ total width and the $D^*(2010)^+$-D^0 mass difference
  - recent charm results not covered in this talk
    - Search for CP violation in $D^+ \to K^+K^-\pi^+$ (See Purohit talk at Charm 2012)
    - Search for $D^0 \to l^+l^-$ $(l = \mu, e)$ (See Ferrarotto talk at this conference)
    - Search for $D^0 \to \gamma\gamma$ arXiv:1110.6480 accepted for publication in PRD(RC)
- Summary

Introduction

Charm Physics topics at BaBar

- Recent evidence of CP violation (CPV) in D^0 decays from LHCb has renewed the interest for searching new physics in the charm sector:
  - observed asymmetries are marginally compatible with the Standard Model (SM) but not conclusive for establishing new Physics. See for example: arXiv:1111.5000, arXiv:1203.3131, arXiv:1111.4987
- Some hot topics in Charm Physics:
  - Search for CP violation in singly-Cabibbo-suppressed (SCS) decays, uniquely sensitive to new physics through tree-penguin interference:
    - measure CP asymmetries in individual decay modes and keep improving precision;
    - measure additional decay modes with similar quark transitions: $c \to u\, d\, \bar{d}$, $c \to u\, s\, \bar{s}$.
  - Search for indirect CP violation in D^0-$\overline{D}^0$ mixing: it would be a clear sign of new physics
  - Measurements of charm meson properties for lattice QCD validation:
    - D_s^+ decay constant (not covered in this talk)
    - D^{*+} total width
- Other topics not covered in this talk:
  - rare and forbidden decays, spectroscopy of charm mesons and baryons, Dalitz plot analyses, etc.

Understanding origin of CPV in SCS decays

- Many theory papers. Some examples:
  - Enrico Franco, Satoshi Mishima and Luca Silvestrini arXiv:1203.3131

    "... the observed asymmetries are marginally compatible with the Standard Model. Improving the experimental accuracy could lead to an indirect signal of new physics."

  - Gino Isidori, Jernej F. Kamenik, Zoltan Ligeti and Gilad Perez arXiv:1111.4987

    . Another important experimental handle to decide whether the observed signal can or cannot be accommodated in the SM would be observing or constraining CP violation in other decay modes, corresponding to the same quark-level transitions.

Decays that are accessible at the B factories, not a complete list!

- $D^0 \to \pi^+\pi^-, \pi^+\pi^-\pi^0, 2\pi^+2\pi^-, 2\pi^0$
- $D^+ \to \pi^+\pi^0, \pi^+\eta, \pi^+\eta', 2\pi^+\pi^-, 2\pi^+\pi^-\pi^0$
- $D_s^+ \to K_s\pi^+, K^+\pi^+\pi^-, K_s\pi^+\pi^0, K^+\pi^0, K^+\eta, K^+\eta'$
- $\Lambda_c^+ \to p\pi^+\pi^-, p2\pi^+2\pi^-$
- $D^0 \to K^+K^-, K^+K^-\pi^0, K_sK^-\pi^+, K_sK^+\pi^-$
- $D^+ \to K_sK^+, \pi^+\Phi, K^+K^-\pi^+\pi^0, K_sK^+\pi^+\pi^-$
- $D_s^+ \to 2K^+K^-$
- $\Lambda_c^+ \to pK^+K^-$

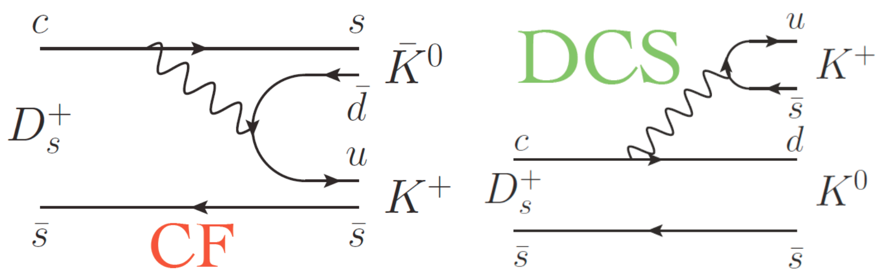
CP violation in D decays with a K_S in the final state

- CP asymmetry in charm decays with a K_S in the final state is expected to be (±0.332±0.006)% whether a K^0 or a $\overline{K}^0$ is produced, due to CPV in K^0-$\overline{K}^0$ mixing.
- Sizable difference from this value would indicate CP violation in the ΔC=1 transition (very small in the SM) indicating possible new physics effects.

$$A_{CP} = \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)} = A^{\Delta C}_{CP} + A^{\bar{K}^0}_{CP} \qquad h = (\pi, K)$$

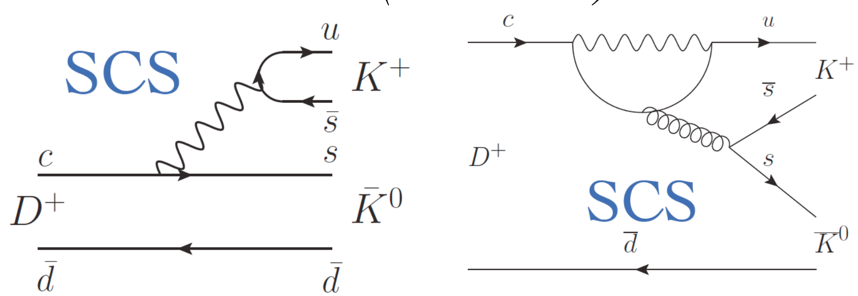
$A^{\bar{K}^0}_{CP}$ → (-0.332±0.006)%

$D_s^{\pm}\to K_S K^{\pm}$ ($D^{\pm}\to K_S\pi^{\pm}$)



CF = Cabibbo favored DCS = doubly-Cabibbo suppressed

$D^{\pm}\to K_S K^{\pm}$ ($D_s^{\pm}\to K_S\pi^{\pm}$)



SCS = singly-Cabibbo suppressed

Recent results

Search for CP violation in $D_{(s)}^{\pm} \to K_S\pi^{\pm}, K_SK^{\pm}$

- Time-integrated *CP* asymmetry:

$$A_{CP} = \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)}$$

- Reconstructed asymmetry:

$$A_{rec} = A_{CP} + A_{FB}\left(\cos\theta^*_D\right) + A^h_\epsilon\left(p, \cos\theta_h\right)$$

  - A_{FB} originates from the forward-backward (FB) asymmetry in $e^+e^- \to c\bar{c}$ production, coupled with the asymmetric acceptance of the detector. It is measured on data.
  - A^h_ϵ is the detector-induced charge reconstruction asymmetry. It is estimated directly from data using control samples and then applied corrections to A_{rec}.

Charge asymmetry in reconstruction

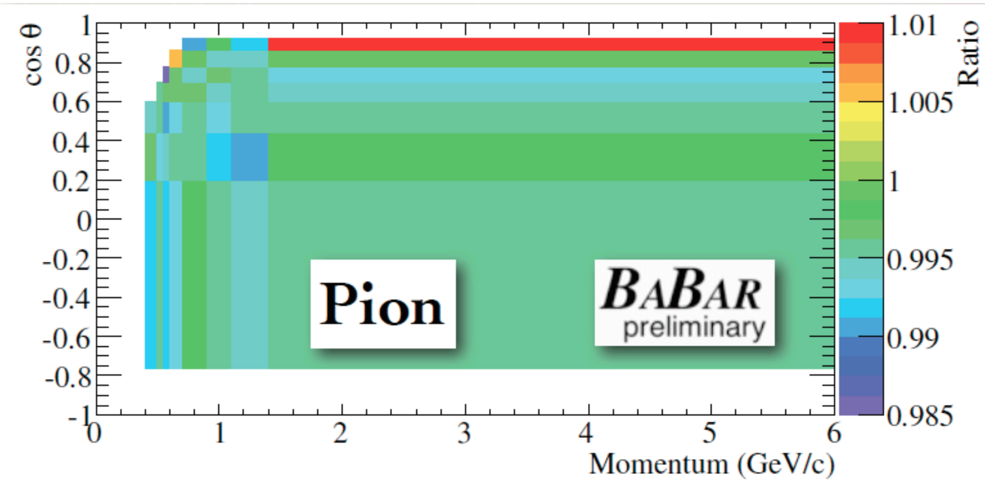
- Use a new data-driven method to determine charge asymmetry in track reconstruction. Use tracks from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ free from any physics induced asymmetry.
- Use track quality cuts, reject tracks identified as protons or electrons, require p_t>0.4 GeV/c.

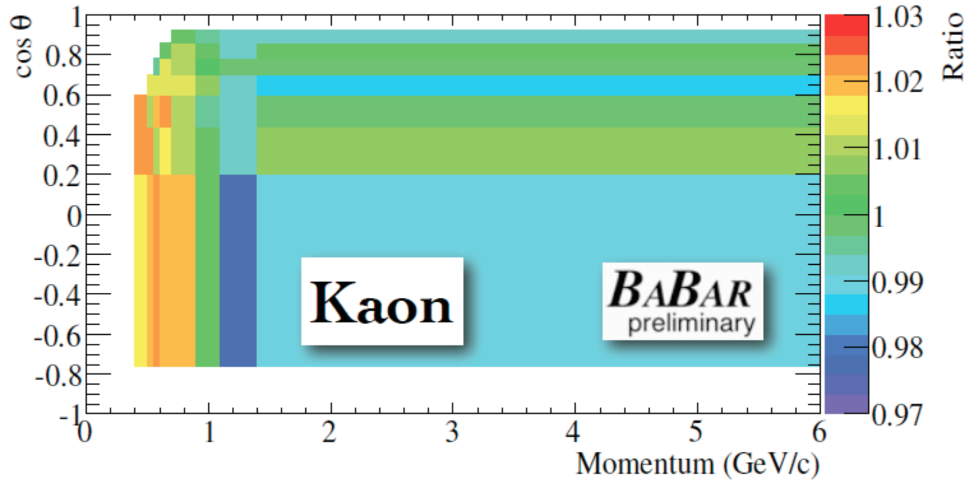
100M generic tracks with no asymmetry from physics:
Υ(4S) events, after continuum subtraction

$$N_{rec}(\vec{p}) = N_{recOnPeak}(\vec{p}) - N_{recOffPeak}(\vec{p}) \cdot \frac{\mathcal{L}_{OnPeak}}{\mathcal{L}_{OffPeak}}$$

$$R = \frac{\epsilon^+(\vec{p})}{\epsilon^-(\vec{p})} = \frac{N^+_{rec}(\vec{p})}{N^-_{rec}(\vec{p})}$$

$N^{\pm}_{rec}$ = positive/negative tracks





Method for A_{FB} and A_{CP} extraction

- After correcting for the charge asymmetry in reconstruction:

$$A = \frac{N(D^+_{(s)}) - N(D^-_{(s)})}{N(D^+_{(s)}) + N(D^-_{(s)})} = \frac{A_{CP} + A_{FB}}{1 + A_{CP}A_{FB}} \simeq A_{CP} + A_{FB}$$

- A_{FB} (A_{CP}) is an odd (even) function of cosθ^*, hence

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

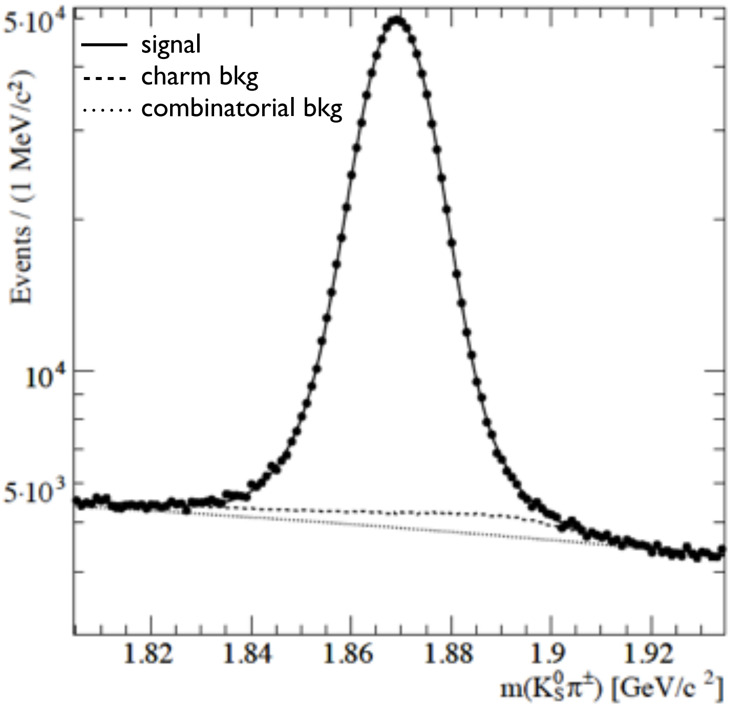
$$A_{CP}(\cos\theta^*_D) = \frac{A(+|\cos\theta^*_D|) + A(-|\cos\theta^*_D|)}{2}$$

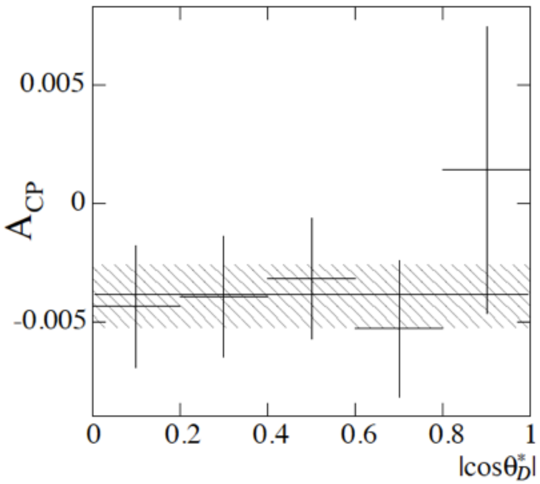
- The measurement is performed using pairs of symmetric bins of cos(θ^*). Values are combined using a χ^2 minimization.

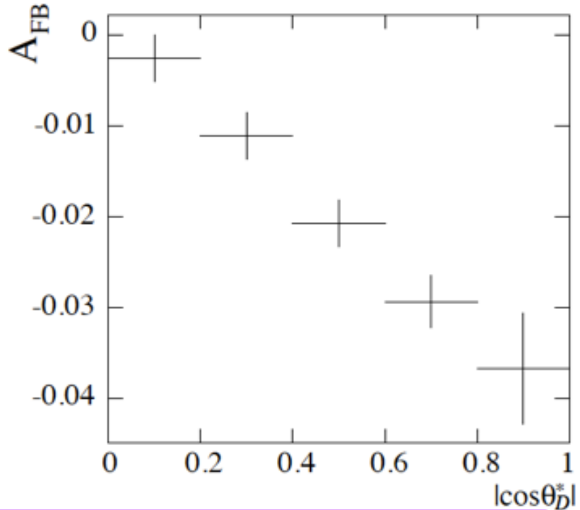
Search for CP violation in $D^+ \to K_S \pi^+$

CF decay

$(807.4 \pm 0.1) \times 10^3$ signal events







Phys.Rev.D 83:071103,2011 BaBar 469 fb^{-1}

$$A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\,\%$$

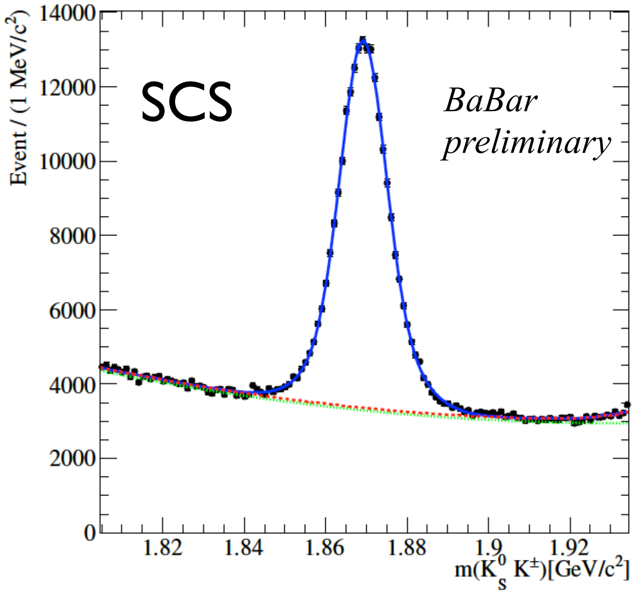
arXiv:1203.6409v1 Belle 977 fb^{-1}

A_{CP} = (-0.36 +- 0.09 +- 0.07)%

NEW

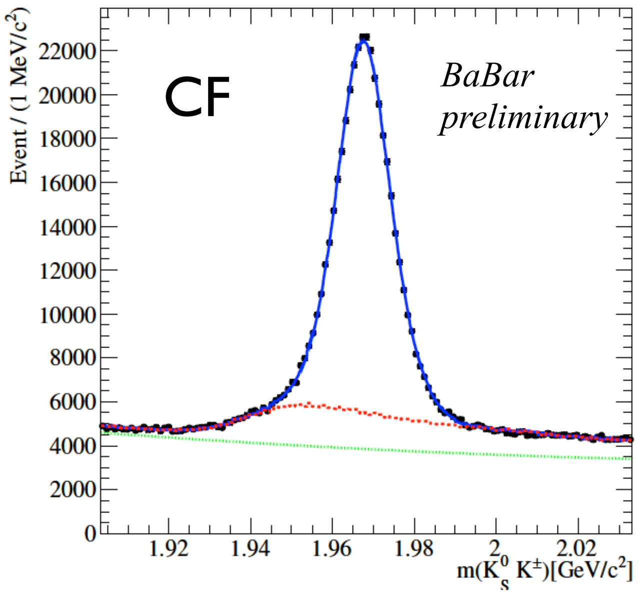
Search for CP violation in $D_{(s)}^+ \to K_S K^+$ and $D_s^+ \to K_S \pi^+$

$D^{\pm} \to K_S^0 K^{\pm}$



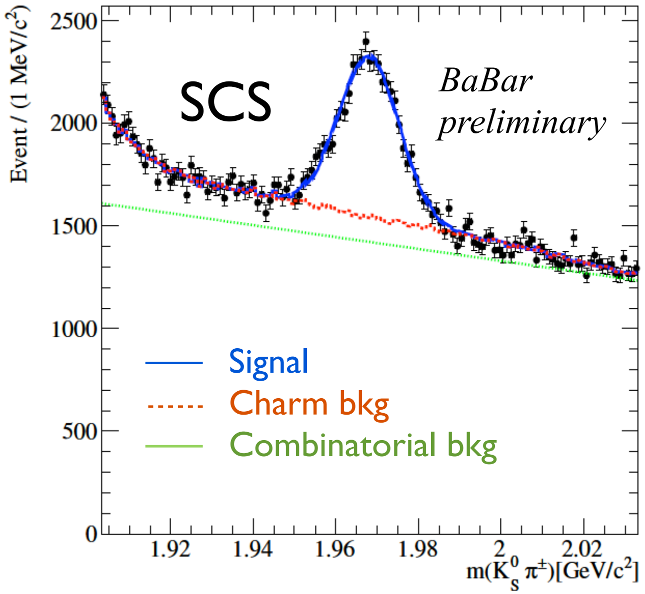
Signal events 159400±800

$D_s^{\pm} \to K_S^0 K^{\pm}$



Signal events 288200±1100

$D_s^{\pm} \to K_S^0 \pi^{\pm}$



Signal events 14330±310

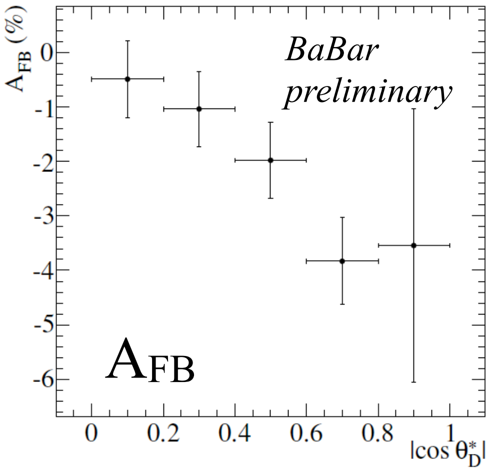
Fit to invariant mass distributions:

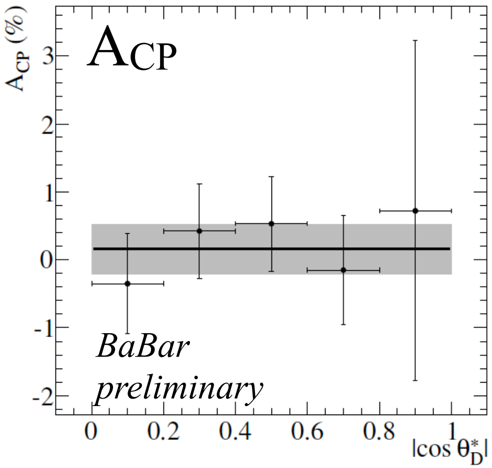
- Signal = 2 or 1 Gaussian functions
- Charm background = 1D non-parametric PDF from Monte Carlo
- Combinatorial background = 2nd or 1st order polynomial function

A_{CP} and A_{FB} measurements (fit values)

NEW

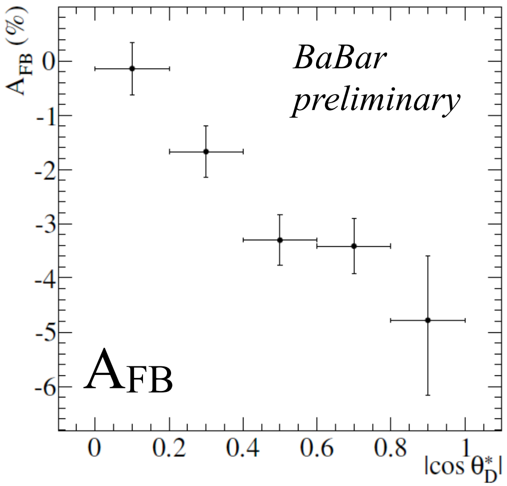
$D^{\pm} \to K_S^0 K^{\pm}$

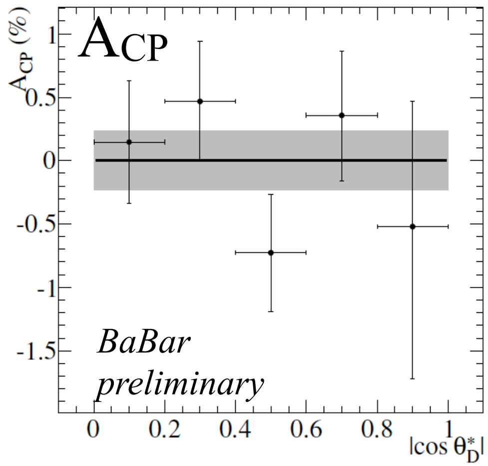




A_{CP} 0.155±0.36%

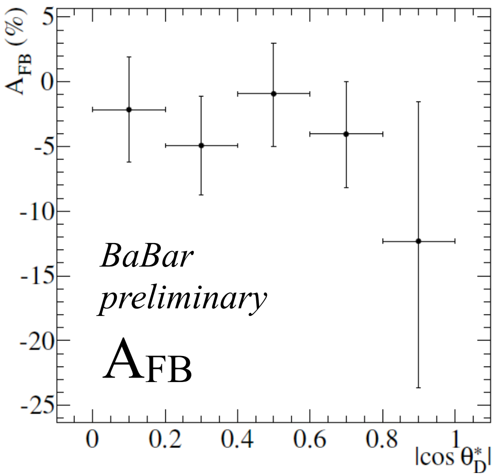
$D_s^{\pm} \to K_S^0 K^{\pm}$

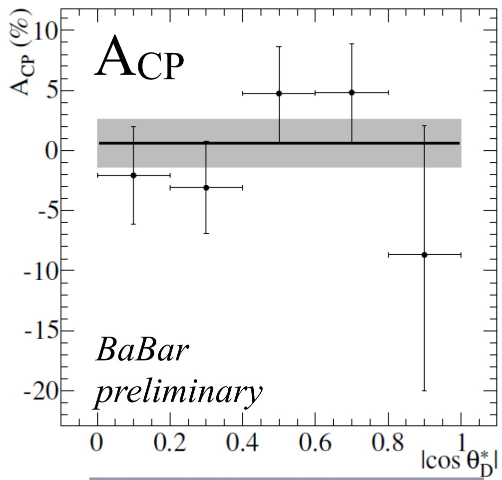




A_{CP} 0.00±0.23%

$D_s^{\pm} \to K_S^0 \pi^{\pm}$





A_{CP} 0.6±2.0%

Systematic uncertainties

- Dominant contributions:
  - correction of charge asymmetry in track reconstruction;
  - choice of binning in cosθ^* for $D_s^\pm \to K_S\pi^\pm$

Systematic uncertainty [%]	$D^\pm \to K_S^0 K^\pm$	$D_s^\pm \to K_S^0 K^\pm$	$D_s^\pm \to K_S^0 \pi^\pm$
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 $\cos\Theta$	0.04%	0.02%	0.27%
$K^0 - \overline{K}^0$ regeneration [1]	0.05%	0.05%	0.06%
$K_S^0 - K_L^0$ interference [2]	0.015%	0.014%	0.008%
Total	0.25%	0.24%	0.29%

[1] B. R. Ko *et al.*, arXiv:1006.1938 [hep-ex] (2010).
[2] Y. Grossman and Y. Nir, JHEP **1204**, 002 (2012).

Final A_{CP} results

- CP asymmetries corrected for possible biases and interference effects:

BaBar 469 fb^{-1}

	$D^{\pm} \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S \pi^{\pm}$
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)	$(+0.46 \pm 0.36 \pm 0.25)\%$	$(+0.28 \pm 0.23 \pm 0.24)\%$	$(+0.3 \pm 2.0 \pm 0.3)\%$

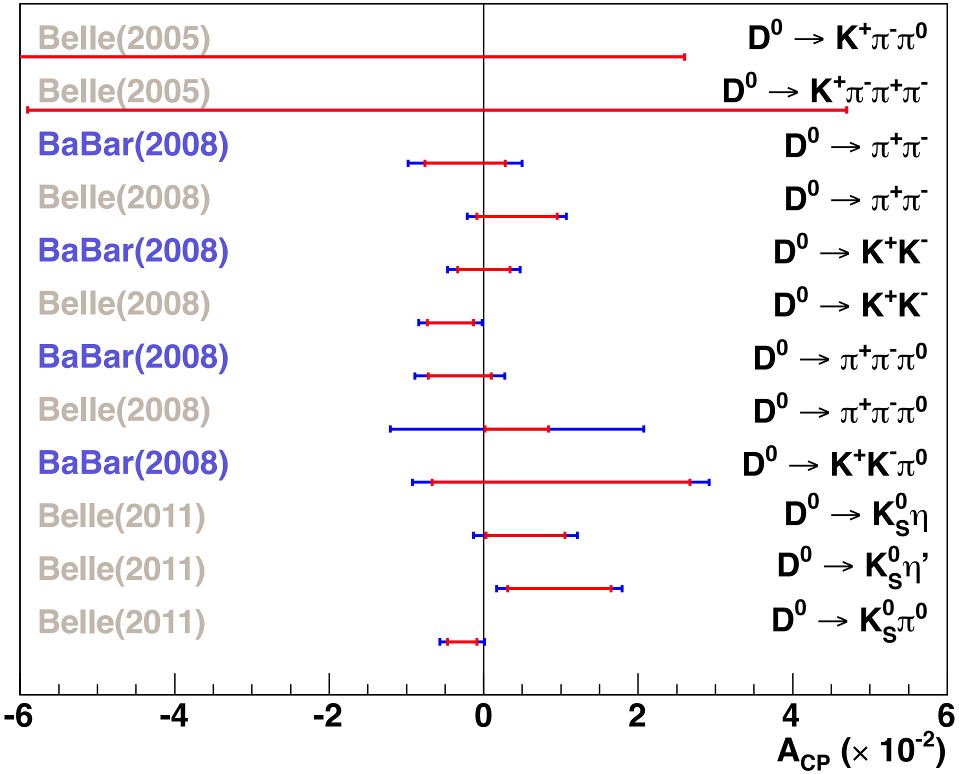
- sign since $\overline{K}^0$ is produced

+ sign since K^0 is produced

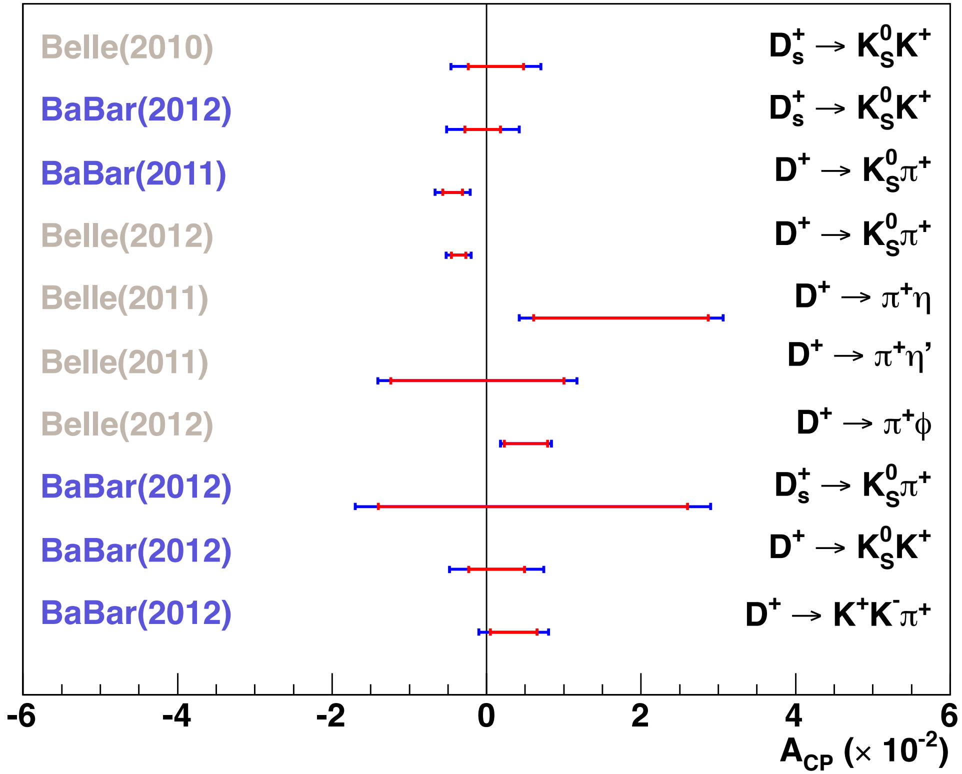
- Results are compatible with SM expectations
- No evidence of CP violation in the ΔC transition

Time-integrated CPV measurements at the B factories

D^0 modes: direct + indirect CPV



$D_{(s)}^+$ modes: direct CPV



At the B factories was found evidence of CP violation in $D^+ \to K_S^0\pi^+$ decays as expected in the SM. Systematic errors kept under control below the 10^{-3} level.

Mixing in lifetime ratio of the CP-even eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$ vs $K^-\pi^+$

- Mixing and CPV will alter the decay time distributions of CP eigenstates to exponentials with effective lifetimes τ^+_{hh} $\overline{\tau}^+_{hh}$ *(h=K,π)*

Assuming $(|x| \ll 1, |y| \ll 1)$ we have:

$$r(t) \propto \exp(-t/\tau^+_{hh})$$
$$\overline{r}(t) \propto \exp(-t/\overline{\tau}^+_{hh})$$

$$\tau^+_{hh} = \tau(D^0 \to h^+h^-) = \frac{1}{\Gamma^+}$$
$$\overline{\tau}^+_{hh} = \tau(\overline{D}^0 \to h^+h^-) = \frac{1}{\Gamma^-}$$
$$\tau_{K\pi} = \tau(D^0 \to K^-\pi^+) = \frac{1}{\Gamma_D}$$

measured quantities

We then extract the mixing parameter:

$$y_{CP} = \frac{\tau_{K\pi}}{2}\left(\frac{1}{\tau^+_{hh}} + \frac{1}{\overline{\tau}^+_{hh}}\right) - 1$$
$$y_{CP} = \frac{\Gamma^+ + \Gamma^-}{2\Gamma_D} - 1$$

$y_{CP} \neq 0 \Rightarrow$ Mixing

if CP conserved $\Rightarrow y_{CP} \equiv y$

Search for CPV in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

- Differences in D^0-$\overline{D}^0$ lifetimes are sensitive to contributions from CPV in mixing and in the interference between mixing and decay:

$$\Delta Y \overset{def.}{=} \frac{\Gamma^+ + \Gamma^-}{2\Gamma_D}\frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

$$A_\Gamma = \frac{\overline{\tau}^+_{hh} - \tau^+_{hh}}{\overline{\tau}^+_{hh} + \tau^+_{hh}}$$

$$\Delta Y = \frac{\tau_{K\pi}}{2}\left(\frac{1}{\tau^+_{hh}} - \frac{1}{\overline{\tau}^+_{hh}}\right) \neq 0 \Rightarrow CPV$$

$$\Delta Y = (1 + y_{CP})A_\Gamma$$

Assume CP conservation in the decay (i.e. $A_D^K=0$; $A_D^\pi=0$) in this analysis. Neglected terms of $O(10^{-4})$ that are beyond the experimental sensitivity. A_M is sensitive to CPV in mixing.

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

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

$$y_{CP}^{hh} = y\cos\phi_{hh} + \frac{1}{2}\left[A_M + A_D^{hh}\right] x\sin\phi_{hh} - \frac{1}{4}A_M A_D^{hh}\, y\cos\phi_{hh}$$

$$\Delta Y^{hh} = -x\sin\phi_{hh} + \frac{1}{2}\left[A_M + A_D^{hh}\right] y\cos\phi_{hh} + \frac{1}{4}A_M A_D^{hh}\, x\sin\phi_{hh}.$$

Assuming CP conservation in the decay and no weak phase in the decay amplitude ⇒

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

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

* Note that this definition for ΔY has different sign convention with respect to our previous published result.

Reconstruction and selection criteria

NEW

- Extract the final value of y_{CP} and ΔY using 468 fb^{-1} of data.
- Perform a simultaneous fit of 5 different D^0 decay modes from:
  - "flavor tagged" at production according to the pion charge $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+, K^+K^-$ and $\pi^+\pi^-$
  - "flavor untagged" $D^0 \to K^-\pi^+, K^+K^-$ only for y_{CP} measurement. Four times statistics wrt "flavor tagged" sample. Lower purity.

- Selection criteria are similar for tagged and untagged. Chosen to maximize signal significance. Most relevant criteria:
  - Identify Kaon and pion tracks applying relatively loose criteria;
  - $p^*(D^0)$>2.5GeV/c rejecting D^0 from B decays and improving signal significance;
  - tagged and untagged datasets are independent by construction.

p^* *implies* e^+e^- *center-of-mass frame*

Proper time reconstruction

Measure D^0 proper time, *t*, and its error σ_t, by reconstructing D^0 momentum and 3D flight length $\vec{L}$:

Requires a precision vertex detector (SVT) and a significant flight path ($\vec{L}$)

$$t = \frac{L}{\beta\gamma c} = \vec{L} \cdot \frac{\vec{p}}{p} \frac{m_{D^0}}{p}$$

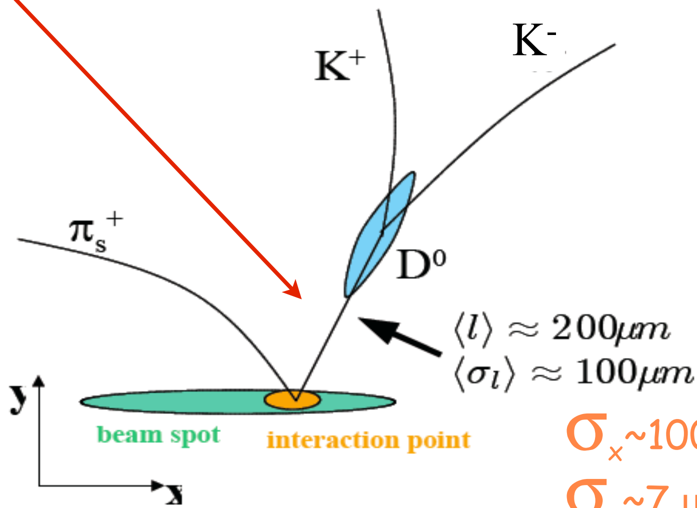
Typical time-dependent analysis criteria

Vertexing:

- D^0 and π_s constrained to luminous region
- Fit probability > 0.1%
- Reconstructed decay time, t: $-2<t<4$ ps
- Estimated decay time error, $\sigma_t<0.5$ps

Resolution on proper-time: $\sigma_t \lesssim \frac{\tau}{2}$

$$\sigma_\tau \simeq \sqrt{\frac{\tau^2+\sigma_t^2}{N}} = 1.12\frac{\tau}{\sqrt{N}}$$

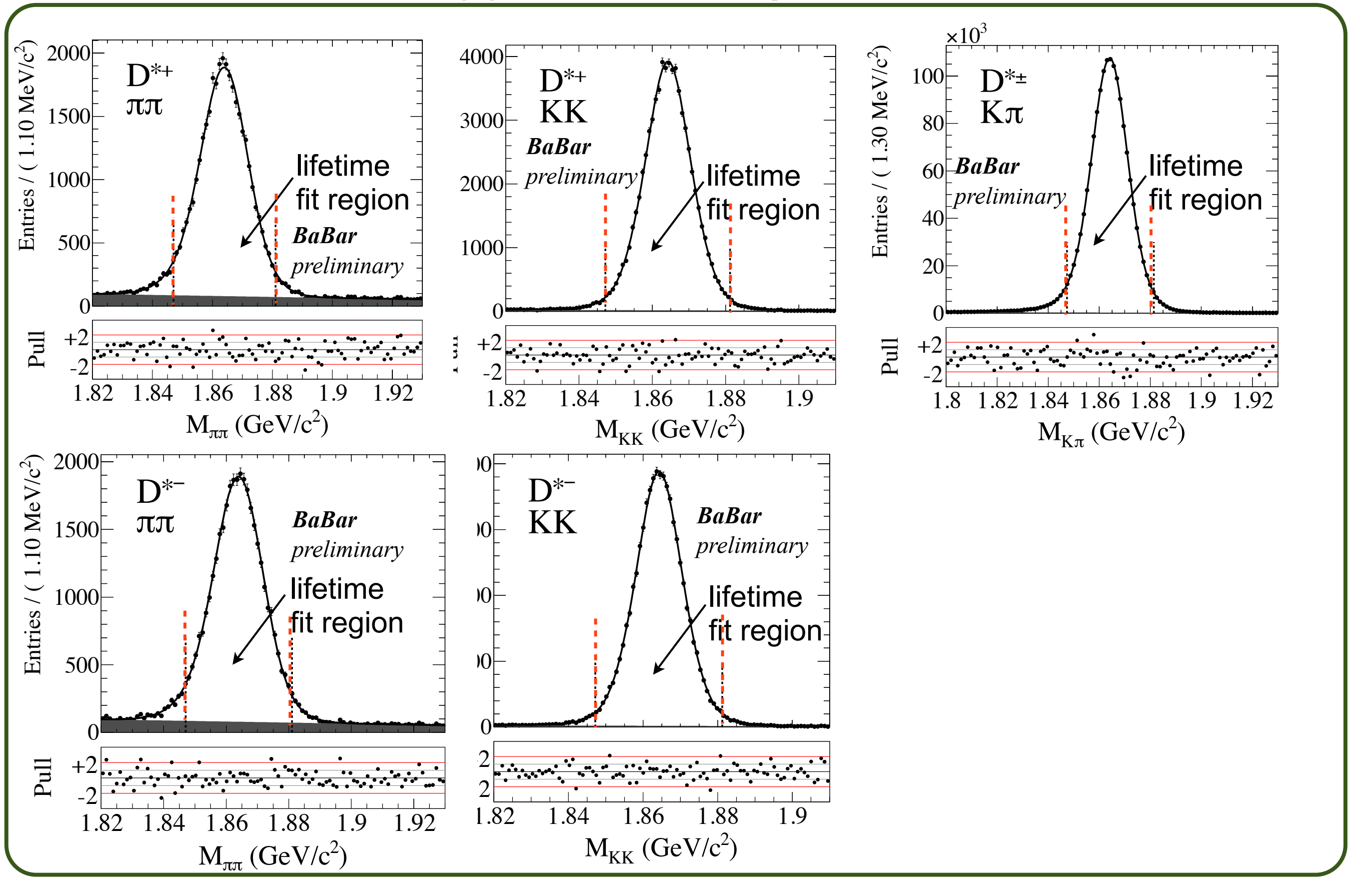


3D flight path reconstruction

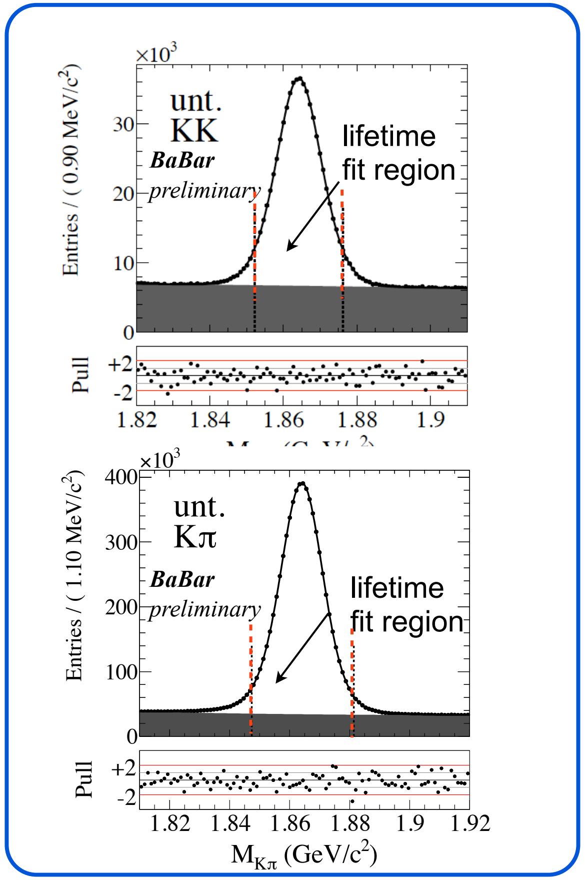
σ_x~100 μm
σ_y~7 μm
σ_z~8 mm

Signal yields for Tagged and Untagged samples

Tagged D^0 samples

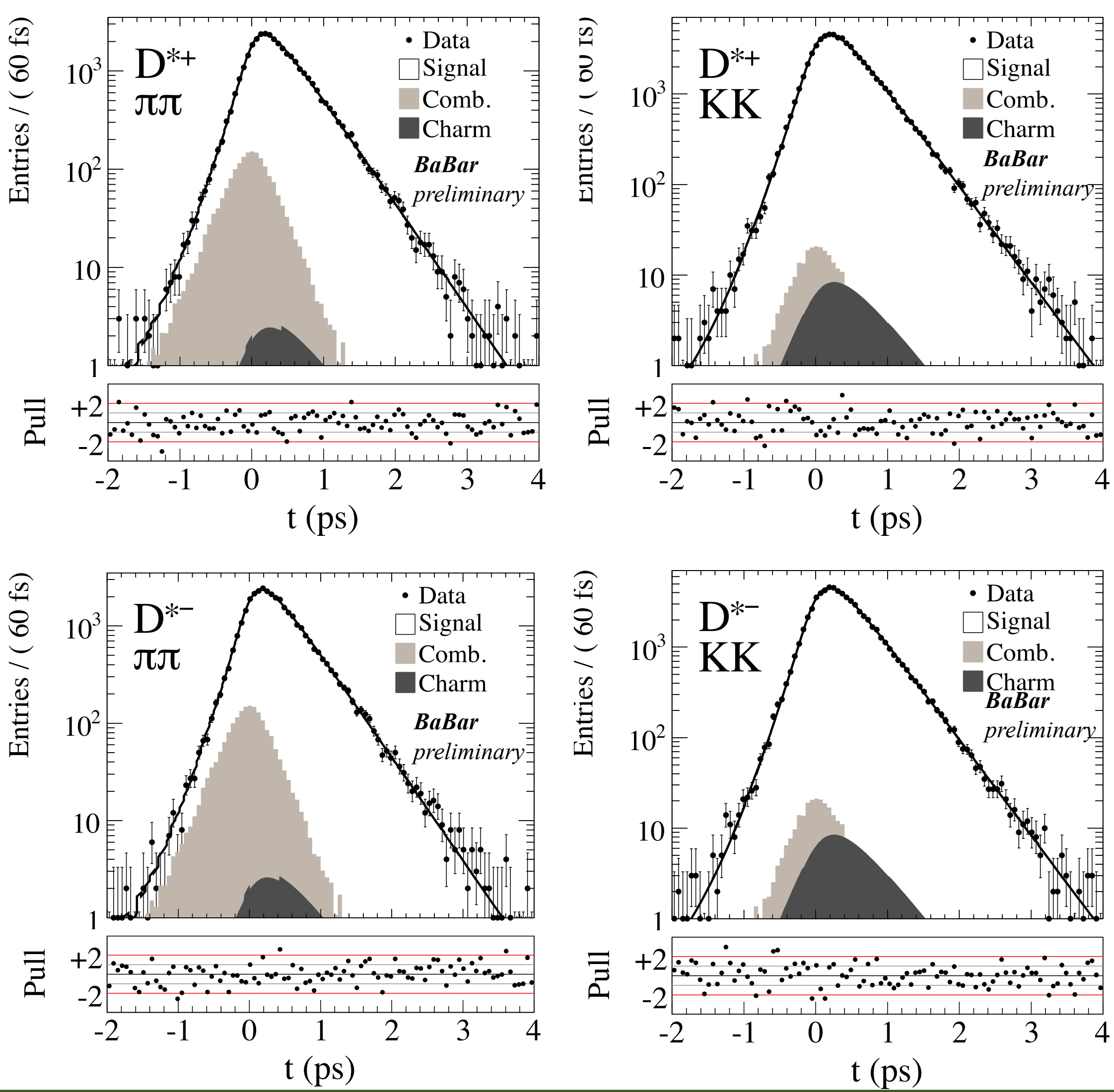


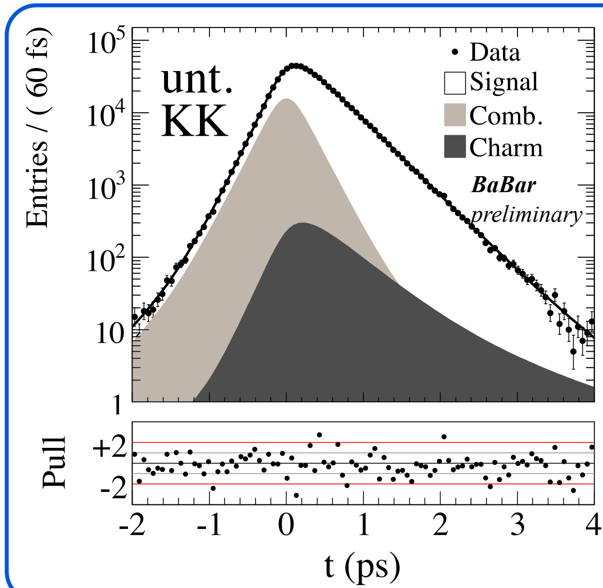
Untagged D^0 samples



- Flavor tagged sample: $\pi^+\pi^-$ (65K events, purity 94.4%), K^+K^- (137K events, purity 99.3%), $K^-\pi^+$ (1.487M events, purity 99.8%)
- Flavor untagged sample: K^+K^- (496K events, purity 74.4%), $K^-\pi^+$ (5.825M events, purity 84.7%)

Decay time distributions for CP modes





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

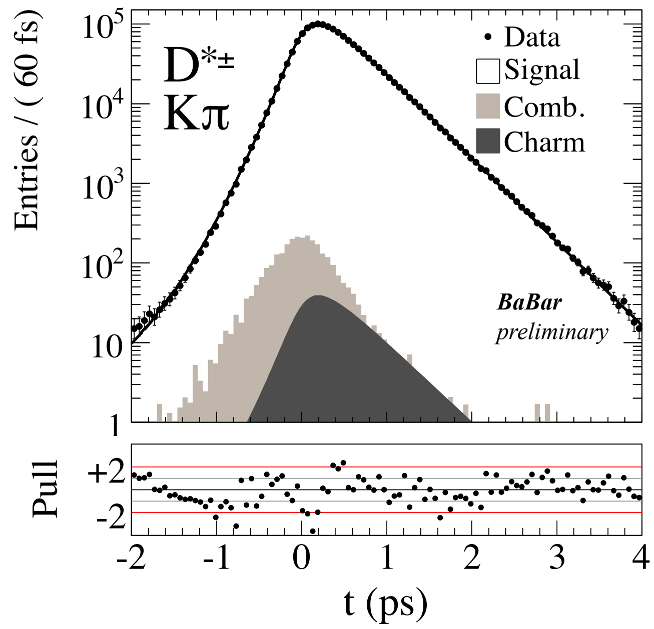
statistical error only

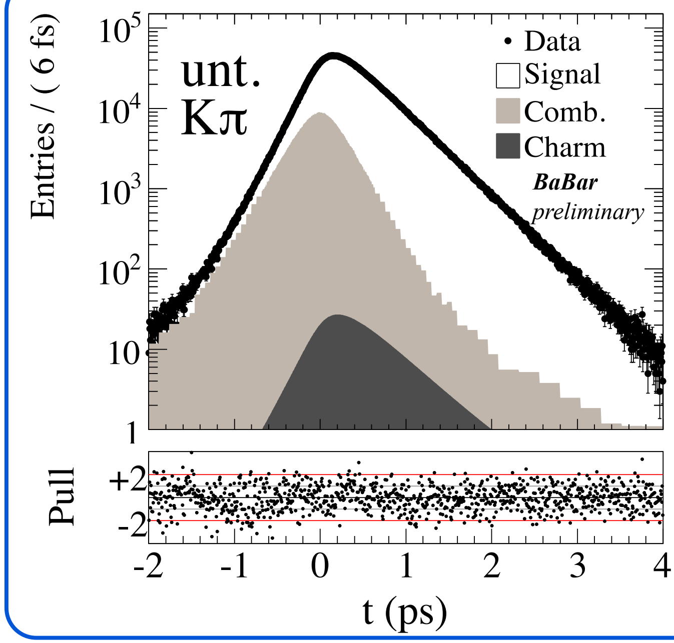
$$\overline{\tau}^{+}_{hh} = (406.40 \pm 1.25)\ \text{fs}$$

statistical error only

Decay time distributions for CP mixed modes

NEW





- $\tau_{K\pi} = (408.97 \pm 0.24)\ \text{fs}$ ***statistical error only.***
- Compatible with PDG average (410.1 ± 1.5) fs.

Best measurement from FOCUS
409.6±1.9 fs

Systematic uncertainties

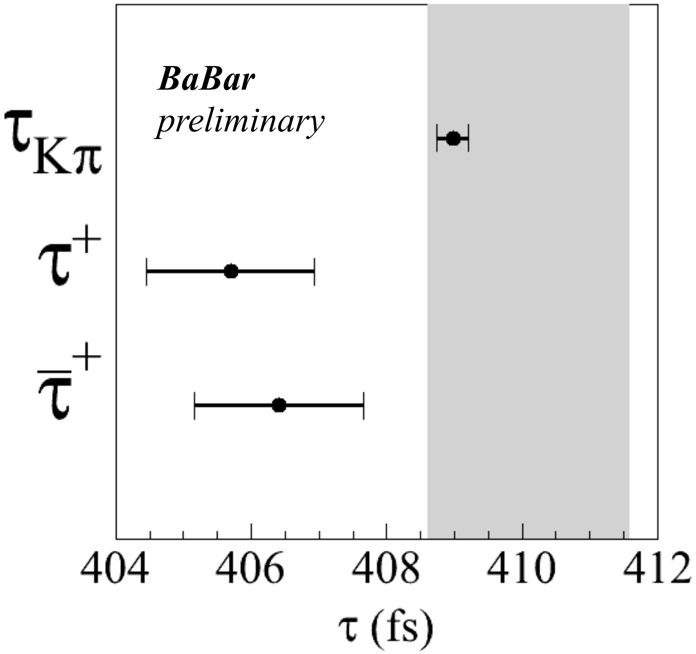
NEW

Category	Fit Variation	$\|\Delta[y_{CP}]\|$ (%)	$\|\Delta[\Delta Y]\|$ (%)
Fit Region	width of `sigBox`	0.057	0.022
	position of `sigBox`	0.005	0.001
Signal	`KKUnt` σ_t signal PDF	0.022	0.0
	Mistag Fraction	0.0	0.0
	D^0 Fraction in `KKUnt`	0.001	0.0
Charm Bkg	lifetimes	0.042	0.001
	yields	0.016	0.0
Combinatorial Bkg	yields	0.043	0.002
	weighting parameter	0.004	0.001
	PDF from sidebands	0.066	0.0
Selection	σ_t cut	0.052	0.053
	adjudication	0.028	0.011
	Total Systematic Error	0.124	0.058

Measurement of y_{CP} and ΔY at BaBar

NEW

τ_D PDG ($\pm 1\sigma$ region)



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

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

- no mixing hypothesis excluded at 3.3 σ level
- no CPV observed

→ *Previous* BaBar results on y_{CP} and ΔY (L_{data}= 384 fb^{-1})

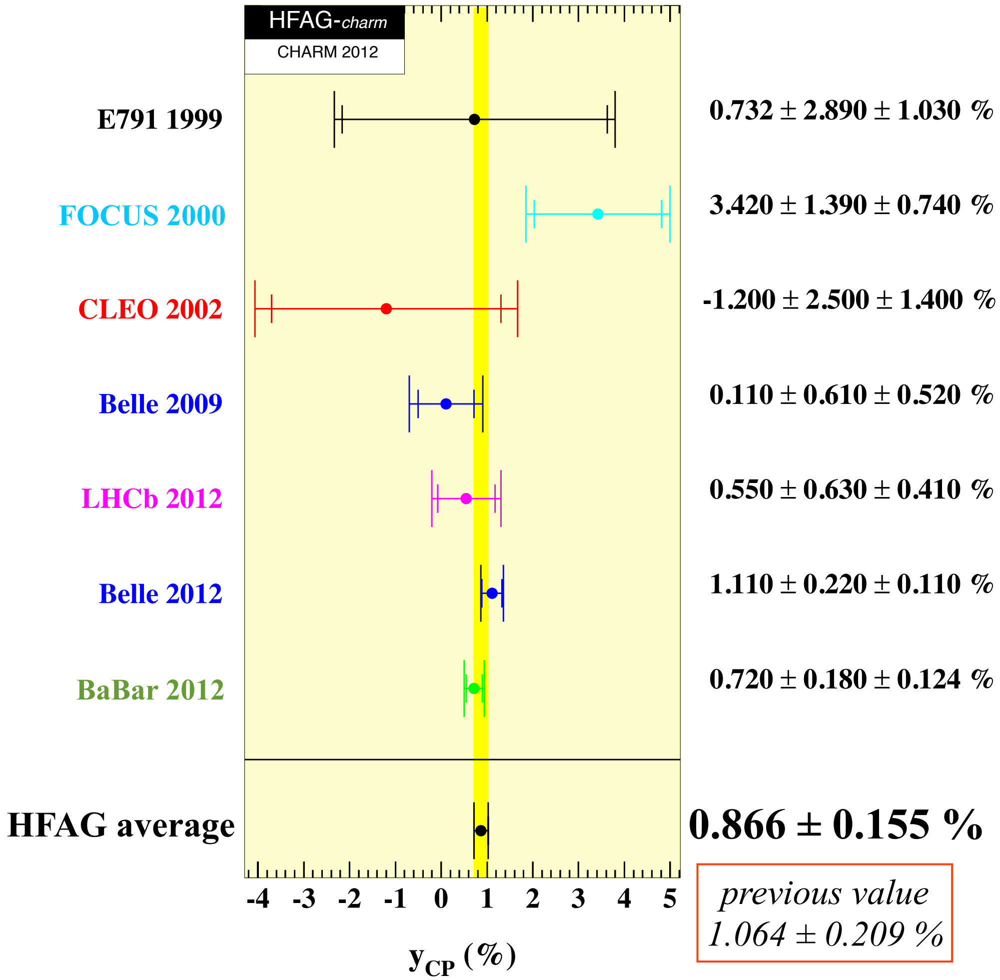
$y_{CP} = (1.16 \pm 0.22 \pm 0.18)\%$; $\Delta Y = (-0.26 \pm 0.36 \pm 0.08)\%$

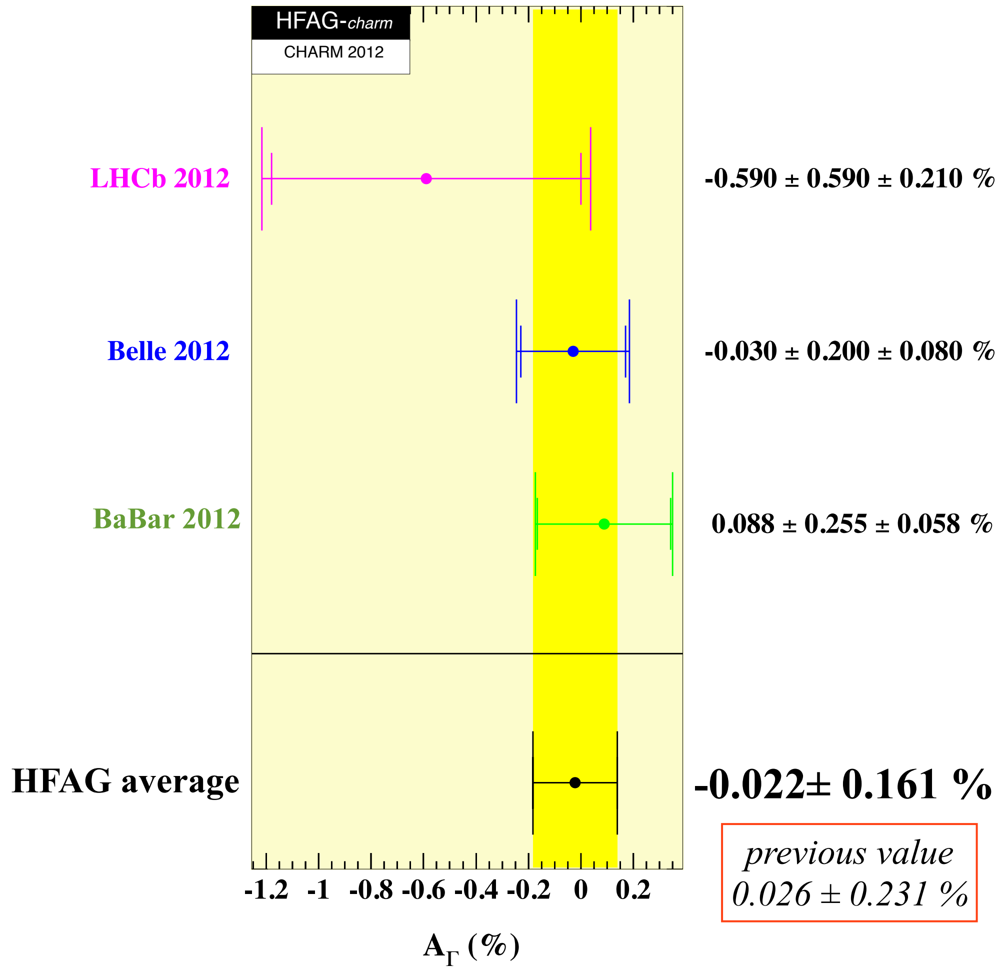
[PRD 78, 011105 (2008)]
[PRD 80(7), 071103 (2009)]

- Significant improvement for the statistical and the systematic errors. These results supersede the previous ones.
- New y_{CP} value is consistent with the direct measurement of $y=(0.456\pm0.186)\%$ (HFAG average)

New HFAG averages for y_{CP} and A_Γ

NEW





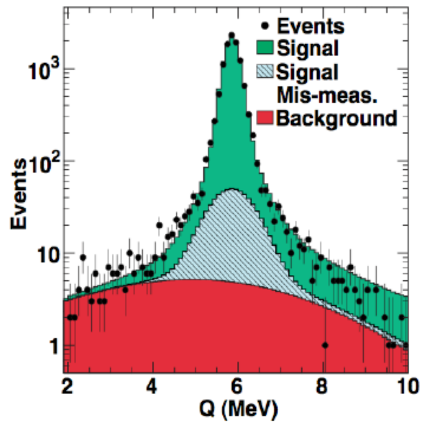
Including new BaBar and Belle results: significant improvement in the uncertainty and lower value for y_{CP}.

$D^*(2010)^+$ total width and $D^*(2010)^+$-D^0 mass difference

- Precision measurement of $\Gamma(D^{*+})$ provides useful information for the understanding of nonperturbative strong physics involving systems composed by heavy-light quarks:
  - test of chiral quark model framework for for the calculation of pseudoscalar meson hadronic transitions among heavy-light excited and ground states. **Phys. Rev. D 64, 114004 (2001)**
  - strong coupling (g) between heavy-light-vector and heavy-light-pseudoscalar mesons and a low-momentum pion in a heavy-meson chiral Lagrangian **Phys. Rev. C 83, 025205 (2011)**
  - reference experimental point for lattice QCD calculations **Eur. Phys. J. C 71:1734 (2011)**

- Experimental result from CLEO :
  - $\Gamma(D^{*+}) = (96\pm4\pm22)$ keV **Phys. Rev. D 65, 032003 (2002)**
  - 11,000 signal events in $D^{*+}\to D^0\pi^+$, $D^0\to K^-\pi^+$
  - Dominant systematic error (16 keV): variation of the fit results as a function of the kinematic parameters of D^{*+} decay

CLEO data sample 9 fb^{-1}



Experimental method

- Reconstruct $\Delta m = m(D^{*+}) - m(D^0)$ in $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+, K^-\pi^+\pi^-\pi^+$:
  - good experimental resolution on Δm (FWHM~300 keV)
  - since $\Gamma(D^0) \ll \Gamma(D^{*+})$ the width of Δm is the convolution of the shape given by $\Gamma(D^{*+})$ with the experimental resolution function;

Relativistic Breit-Wigner (RBW) for D^{*+} width lineshape:

Γ_0 parameter to measure

$$\frac{dN}{dm} = \left(\frac{p}{p_0}\right)^3 \left(\frac{1+r^2p_0^2}{1+r^2p^2}\right) \frac{(m_0\Gamma_0)^2}{(m_0^2 - m^2)^2 + (m_0\Gamma_{\text{Total}}(m))^2}$$

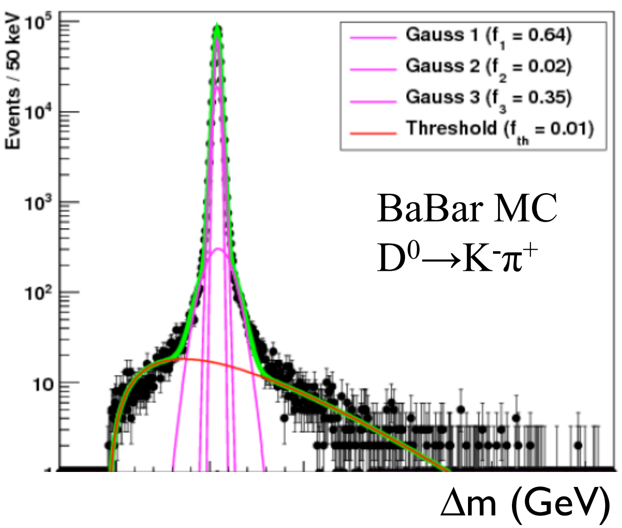
Partial width: $\Gamma_{D^*D\pi}(m) = \Gamma_0 \left(\frac{1+r^2p_0^2}{1+r^2p^2}\right)\left(\frac{p}{p_0}\right)^3\left(\frac{m_0}{m}\right)$ $\quad \Gamma_{\text{Total}}(m) = \Gamma_{D^*D\pi}(m) + \Gamma_{D^*D\gamma}(m) \approx \Gamma_{D^*D\pi}(m)$

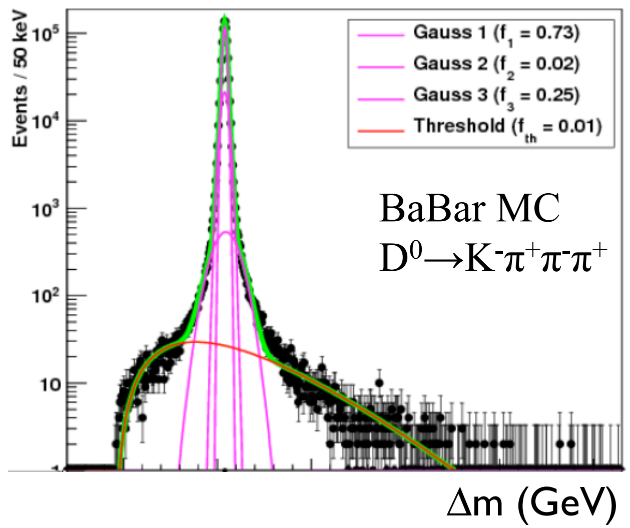
m, p = running $D\pi$ mass, momentum
m_0, p_0 = m, p at pole position

r= Blatt-Weisskopf radius = 1.6 GeV^{-1} (0.3 fm)
Phys. Lett. B 308, 435 (1993)

Modeling experimental resolution

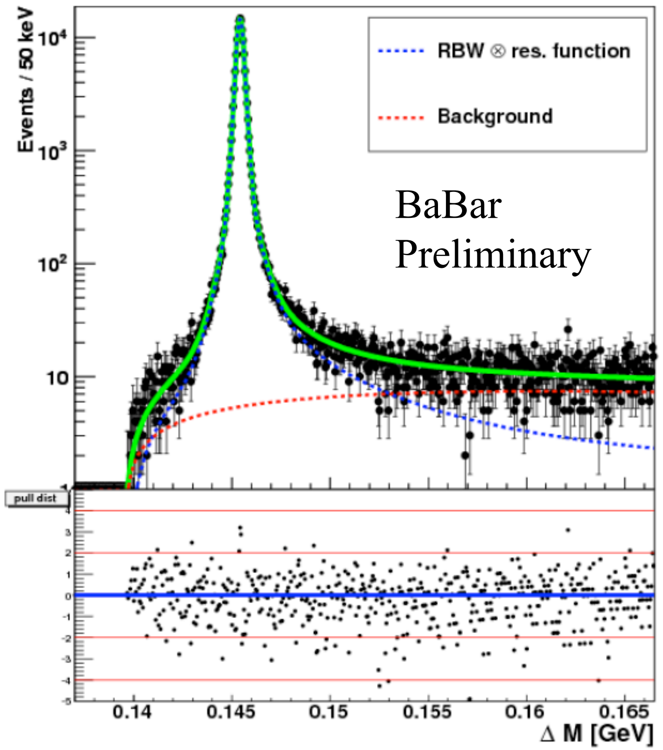
- Use Monte Carlo events to simulate experimental resolution:
  - observed shape is due to resolution effects with $\Gamma(D^{*+})\sim 0$ in MC
  - use 3 Gaussian model + additional contribution for slow pion decaying in flight for modeling experimental resolution
- Allow for data/MC differences in the fit to data: scale factor for sigma $(1+\epsilon)$ and offset for mean (δ) of the 3 Gaussian model.





Fit results

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

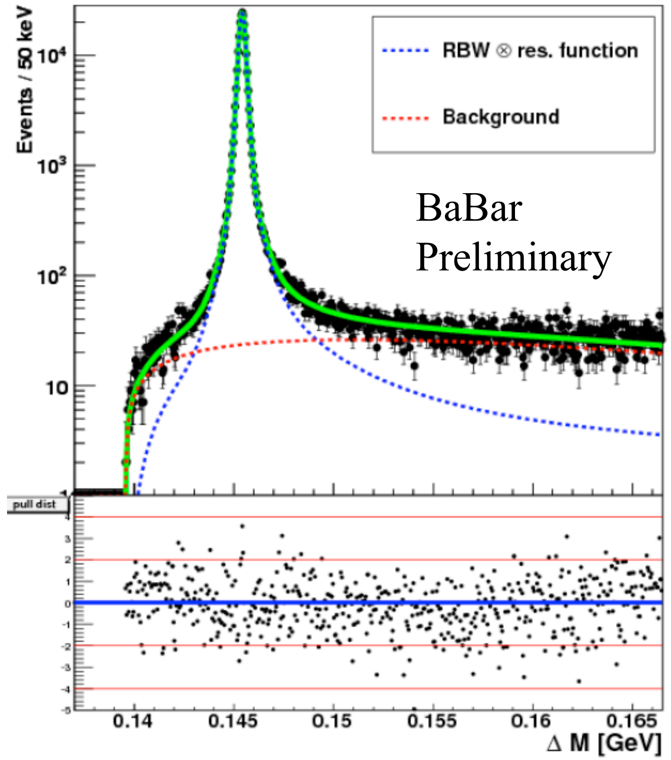


Signal events 142000

$\Gamma(K^-\pi^+) = 83.5\pm1.7\pm1.2$ keV

Δm pole $(K^-\pi^+) = 145425.5\pm0.6\pm2.6$ keV

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



Signal events 231000

$\Gamma(K^-\pi^+\pi^-\pi^+)$ = under study, available soon.

Δm pole $(K^-\pi^+\pi^-\pi^+) = 145426.4\pm0.4\pm2.6$ keV

Measurement of chiral coupling, g

- Using isospin symmetry, extract the value of the strong coupling g between heavy vector and pseudoscalar mesons to pions, in a chiral quark model approach:

$$\Gamma\left(D^{*+}\right) = \frac{2g^2}{12\pi f_\pi^2} p_{\pi^+}^3 + \frac{g^2}{12\pi f_\pi^2} p_{\pi^0}^3 + \frac{\alpha g_{D^*\to D\gamma}^2}{3} p_\gamma^3$$

- $g^8{}_A$ strong coupling, defined in **Phys. Rev. D 64, 114004 (2001)**, should be universal but BaBar results show a disagreement.

Mode	Width	$g^8{}_A$
CLEO $D^*(2010)^+$	92 ± 22 keV	0.82 ± 0.09
Lattice (from D&E)		0.53±0.11
$D_1(2420)^0$	31.4 ± 1.4 MeV	1.40 ± 0.04
$D_2{}^*(2460)^0$	50.5 ± 0.9 MeV	1.15 ± 0.01
$D^*(2010)^+$ (This analysis)	83.5 ± 2.1 keV (preliminary)	0.76±0.01

From BaBar paper Phys. Rev. D 82, 111101(R) (2010)

Conclusions

- Recent evidence of CPV in Charm decays has renewed the interest for searching for new physics in the Charm sector.
- BaBar is still very active and contributing in the understanding and possibly constraining the SM effects by measuring CPV observables and studying also decay modes that are not easily accessible at the LHC.
- An overview of the recent BaBar results has been presented covering CP violation searches in Charm decays, measurement of D^0 mixing parameters and precision measurement of the D^{*+} total width:
  - CPV asymmetries in $D^+ \to K_S\pi^+$, $D_{(s)}^+ \to K_SK^+$ and $D_s^+ \to K_S\pi^+$ are compatible with SM expectations. Experimental precision has reached the level of few per mil.
  - Most precise measurement of the D^0 mixing parameters y_{CP} and search for CPV in mixing:

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

  - Most precise measurement of D^{*+} total width, more than a factor 10 improvement with respect to the previous measurement: $\Gamma(D^{*+}) = 83.5 \pm 1.7 \pm 1.2$ keV

Backup slides

Search for CPV using T-odd correlations in $D_{(s)}^+ \to K^+ K_S \pi^+ \pi^-$ decays

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

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)

- It is a measurement of T violation and of CP violation assuming CPT is conserved.
- T-odd observable: $C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$

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

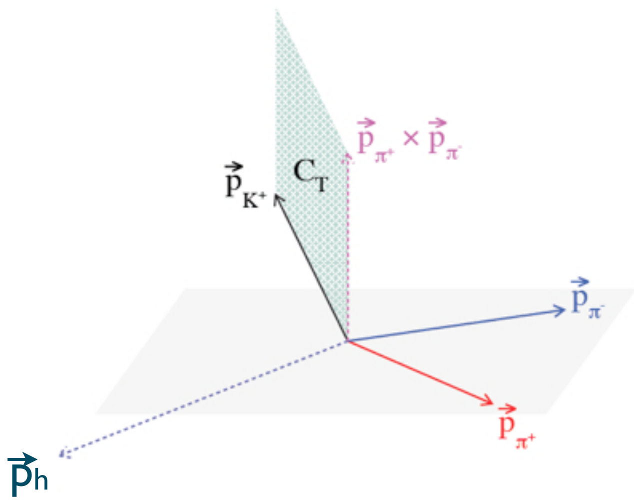
measured on D^+

$D_{(s)}^+$ rest frame

- Final state interaction (FSI) could introduce fake T-odd asymmetries $A_T \neq 0$.
- T-violating observable, removes FSI effects:

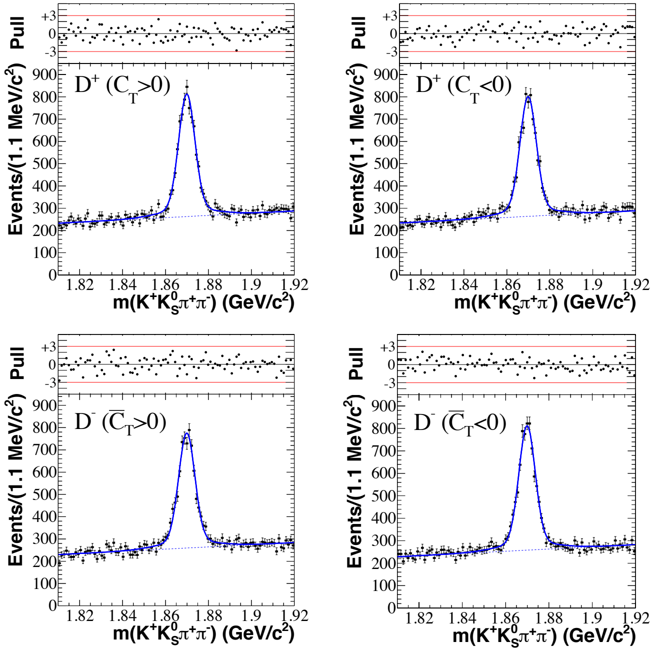
$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T)$$

measured on D^-

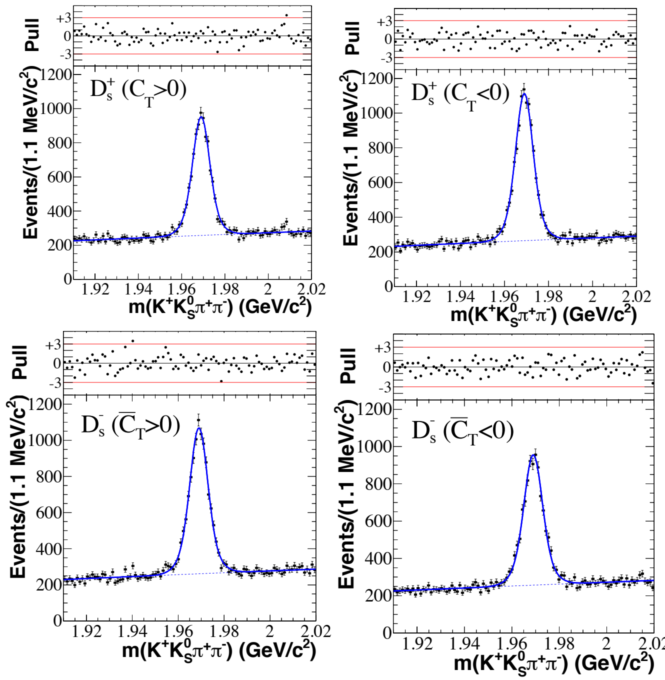


$D^+ \to K^+K_S\pi^+\pi^-$ and $D_s^+ \to K^+K_S\pi^+\pi^-$ events

D^+ Fit projections in signal region



D_s^+



520 fb^{-1}

Phys. Rev. D 84, 031103 (RC) (2011)

- Inclusive $D_{(s)}^+$ reconstruction;
- $p^*(D) > 2.5$ GeV/c;
- use data sidebands for bkg parameterization;
- 20,000 D^+ Cabibbo suppressed and 30,000 D_s^+ Cabibbo favored decays;

Systematic errors

x 10^{-3}

	$\mathcal{A}_T(D^+)$	$A_T(D^+)$	$\bar{A}_T(D^-)$	$\mathcal{A}_T(D_s^+)$	$A_T(D_s^+)$	$\bar{A}_T(D_s^-)$
1) Reconstruction	2.05	2.84	1.26	1.00	1.00	1.27
2) Likelihood Ratio	1.08	3.41	5.58	2.46	7.77	8.16
3) Fit Model	1.30	1.14	1.46	0.10	0.78	0.70
4) Particle Identification	3.70	3.33	4.08	2.22	2.47	6.73
Total	4.56	5.66	7.18	3.43	8.25	10.67

Final results

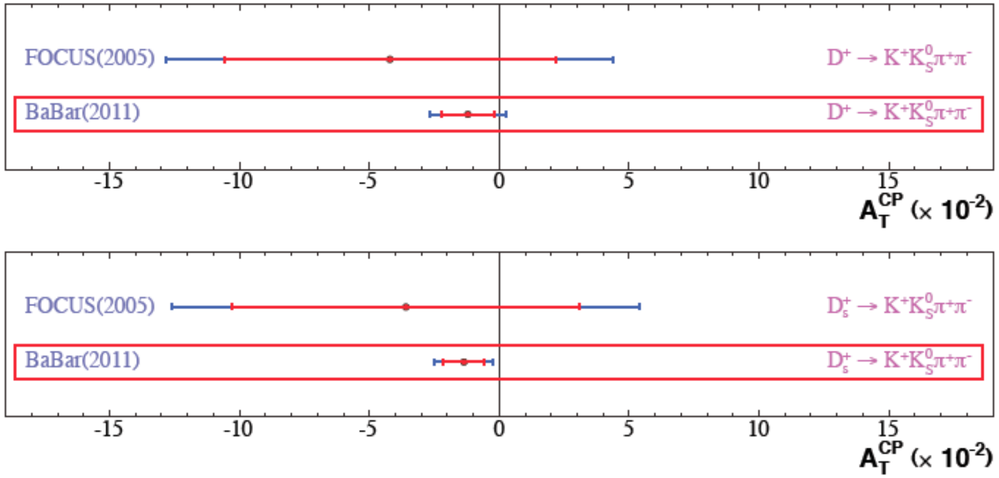
Phys. Rev. D 84, 031103 (RC) (2011) 520 fb^{-1}

$$\mathcal{A}_T(D^+) = (+11.2 \pm 14.1_{\text{stat}} \pm 5.7_{\text{syst}}) \times 10^{-3}$$
$$\bar{\mathcal{A}}_T(D^-) = (+35.1 \pm 14.3_{\text{stat}} \pm 7.2_{\text{syst}}) \times 10^{-3}$$
$$\mathcal{A}_T(D_s^+) = (-99.2 \pm 10.7_{\text{stat}} \pm 8.3_{\text{syst}}) \times 10^{-3}$$
$$\bar{\mathcal{A}}_T(D_s^-) = (-72.1 \pm 10.9_{\text{stat}} \pm 10.7_{\text{syst}}) \times 10^{-3}$$

Final state interaction effects seem to be larger in D_s^+ than D^+ decays

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

T violation parameter consistent to 0.
Factor 10 better than previous result.



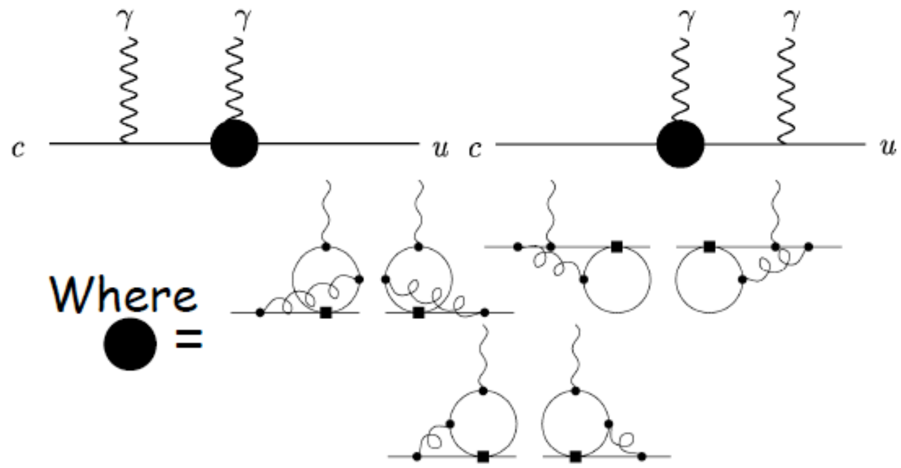
Physics motivations for studying $D^0 \to \gamma\gamma$ decay

- FCNC Decay
  - Forbidden at the tree-level
  - 1-loop GIM suppressed

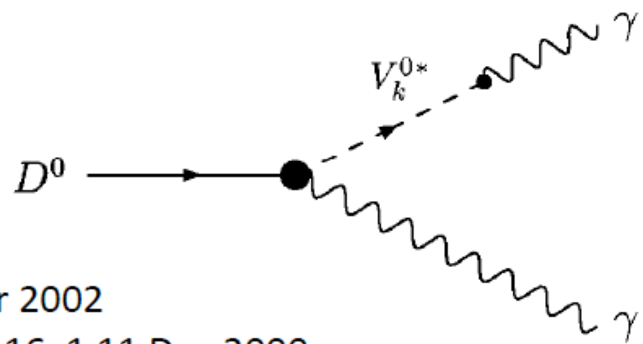
- Dominated by long distance effects [1]
  - Short-range (2-loop dominate): $B(D^0 \to \gamma\gamma) \approx 3 \times 10^{-11}$
  - Long-range (VMD contribution dominates): $B(D^0 \to \gamma\gamma) \approx 3.5 \times 10^{-8}$

- However, possible 10^2 enhancement from new physics (gluino-exchange of MSSM) [2]
- Within the range of BaBar sensitivity.
- Excellent (but difficult) mode to search for new physics

Short Distance



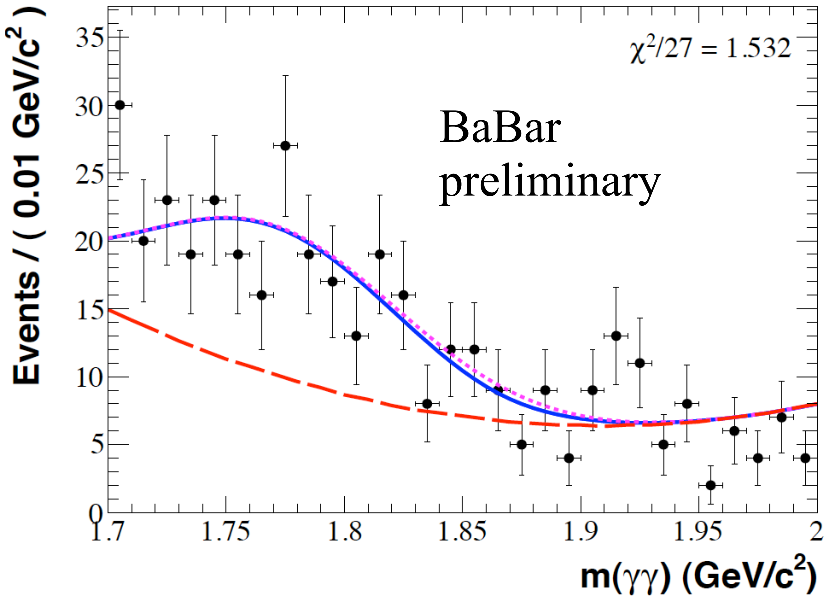
Long Distance

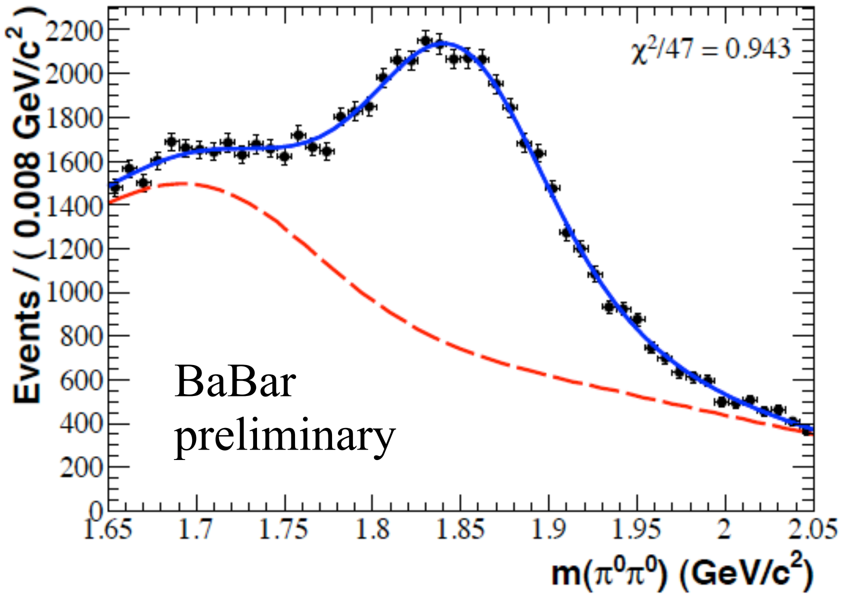


[1] Burdman et al. hep-ph/0112235v2 1 Mar 2002
[2] S. Prelovsek and D. Wyler, hep-ph/0012116v1 11 Dec 2000

Search for $D^0 \to \gamma\gamma$ and BR measurement of the $D^0 \to \pi^0\pi^0$ decay

arXiv:1110.6480v1 470.5 fb^{-1}





Use $D^0 \to K^0_S\pi^0$ as BR normalizing mode

Systematic	$\sigma(D^0 \to \gamma\gamma)$ (%)	$\sigma(D^0 \to \pi^0\pi^0)$ (%)
Tracking (K^0_S) and Vertexing	0.96	0.96
Photon Reconstruction	0.60	3.00
π^0 Veto	1.80	-
D^{*+} Fragmentation	0.02	0.03
Signal Shape	*	0.20
Background Shape	*	0.80
Cut selection	*	2.50
$D^0 \to K^0_s\pi^0$ Signal Shape	0.53	0.17
$D^0 \to K^0_s\pi^0$ Background Shape	0.01	0.63
$D^0 \to K^0_s\pi^0$ Cut selection	0.76	0.76
Total Systematic Uncertainty	*	4.23

$$B(D^0 \to \pi^0\pi^0) = (8.4 \pm 0.1 \pm 0.4 \pm 0.3) \times 10^{-4}$$

comparable precision with CLEO measurement

$$B(D^0 \to \gamma\gamma) < 2.4 \times 10^{-6}$$

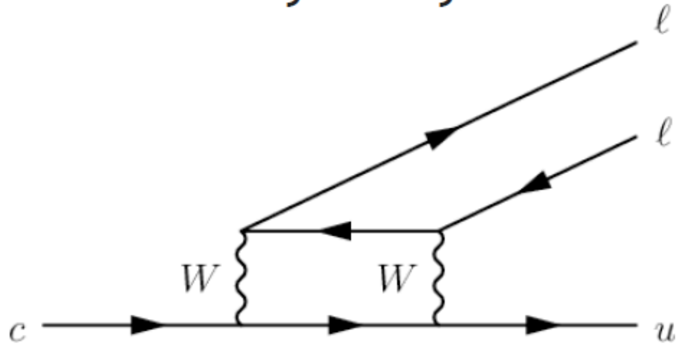
at the 90% confidence level.

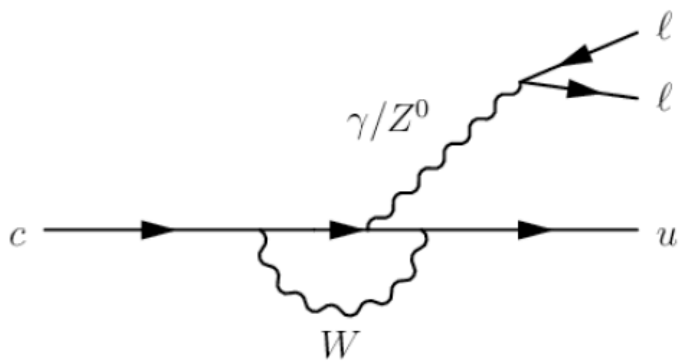
- About factor of 10 improvement on previous CLEO measurement

Physics interest in searching for FCNC decays

Search for Flavor-Changing Neutral-Current (FCNC) decays

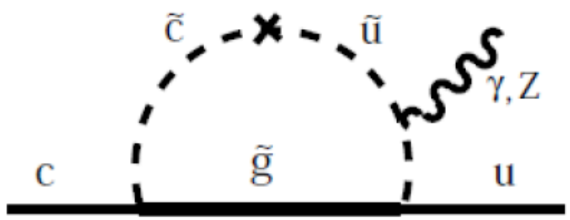
FCNC decays only occur in loop diagrams in SM:





Charm decays heavily GIM suppressed in SM: BF($c \rightarrow ull$)~10^{-8}

New physics can introduce new particles into loop



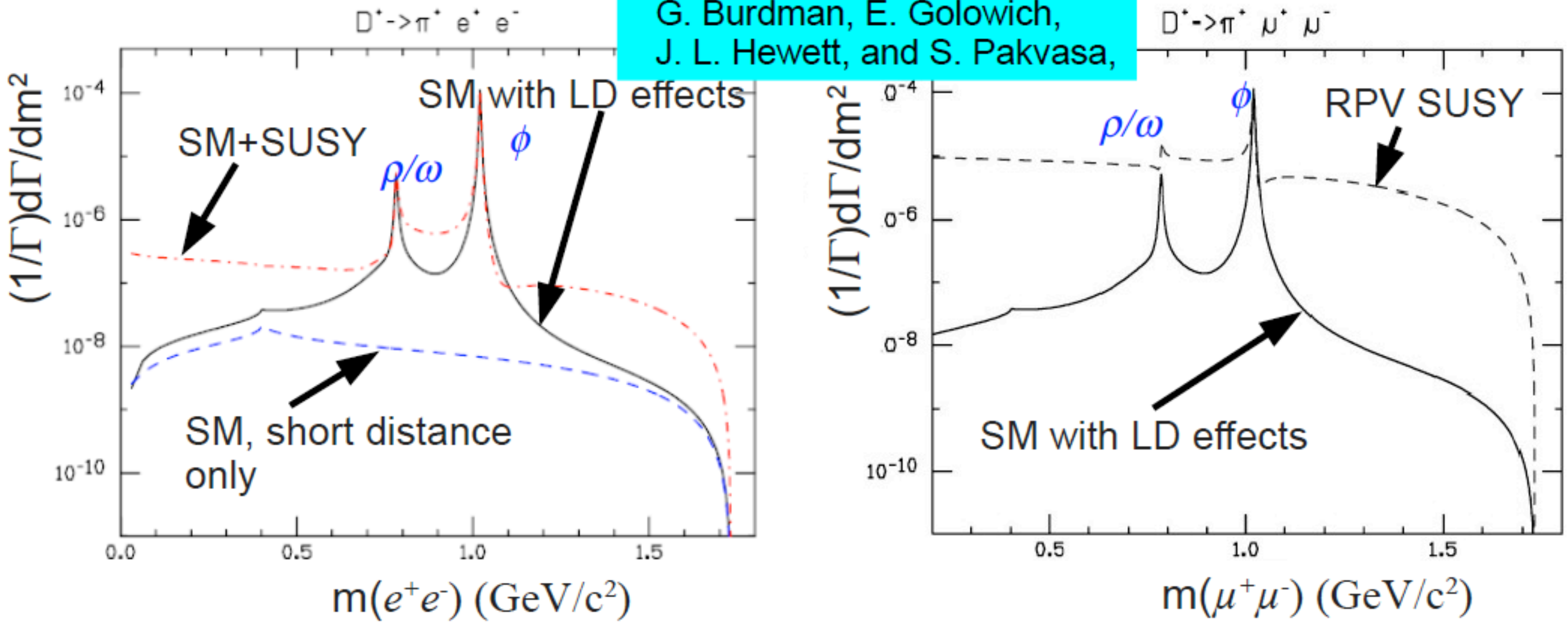
Some models increase BF($c \rightarrow ull$) to 10^{-6}—10^{-5}

Also look for exotic decays violating lepton flavor and/or lepton number

Standard Model predictions for signal and bkg

- While FCNC predicted to be low in SM, do have contribution from leptonic decays of intermediate resonances in $D_{(s)}^{+} \to h^{+}V,\ V \to l^{+}l^{-}$

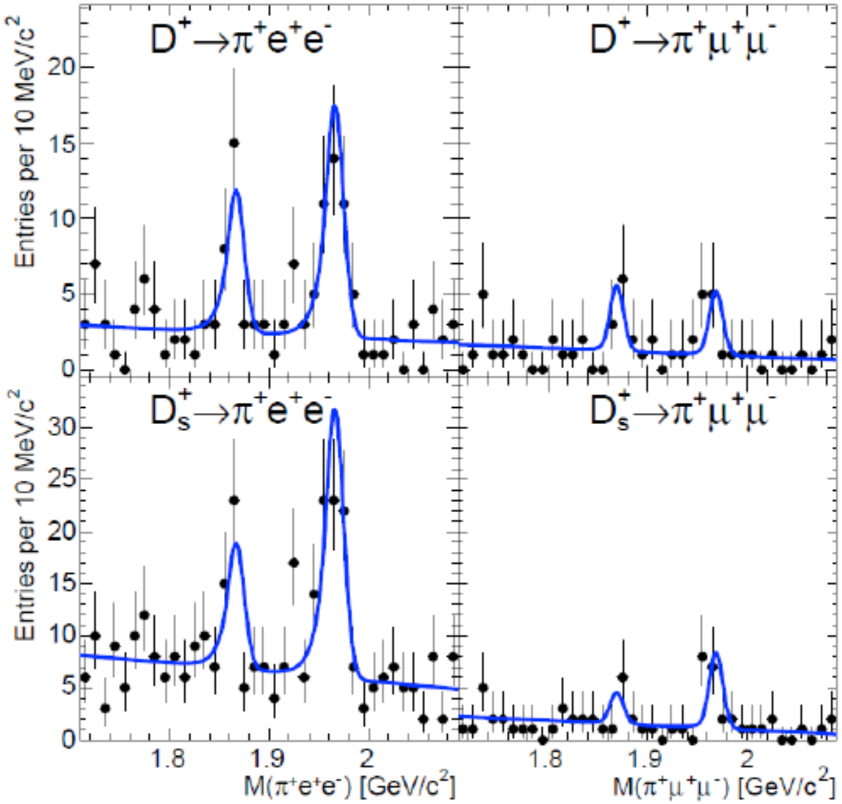
PRD 66, 014009 (2002)
G. Burdman, E. Golowich,
J. L. Hewett, and S. Pakvasa,



At current sensitivity, only ϕ resonance contributes
Can be removed by cut on $l^{+}l^{-}$ invariant mass

Validating the analysis using control modes

- Before unblinding, checked procedure using ϕ resonance
  - Reverse l^+l^- mass cut:
    $0.995<m(e^+e^-)<1.030$ GeV/c^2
    $1.005<m(\mu^+\mu^-)<1.030$ GeV/c^2
- Significant signal seen in 3 of 4 modes
- Yield is about as expected
  - 1.5σ low in $D_s^+\to\pi\phi$, $\phi\to e^+e^-$



384 fb^{-1} **Phys. Rev. D 84, 07200 (2011)**

Decay mode	Yield (events)	Efficiency (%)	Expected yield (events)
$D^+\to\pi^+\phi_{e^+e^-}$	$21.8\pm5.8\pm1.5$	5.65	22.2 ± 1.1
$D^+\to\pi^+\phi_{\mu^+\mu^-}$	$7.5\pm3.4\pm1.4$	1.11	4.5 ± 0.4
$D_s^+\to\pi^+\phi_{e^+e^-}$	$62.8\pm9.9\pm3.0$	6.46	79 ± 3
$D_s^+\to\pi^+\phi_{\mu^+\mu^-}$	$12.7\pm4.3\pm2.6$	1.07	13.1 ± 1.2

Fit results and comparison with previous limits

- Most channels improve upon previous limits
  - Many modes by more than order of magnitude
  - Dimuon modes have the worst limits (lowest efficiency)

Decay mode	BF UL (10^{-6}) 90% CL	Previous	Experiment
$D^+ \to \pi^+ e^+ e^-$	1.1	5.9	CLEO-c
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5	3.9	D0
$D^+ \to \pi^+ e^+ \mu^-$	2.9	34	E791
$D^+ \to \pi^+ \mu^+ e^-$	3.6	34	E791
$D_s^+ \to \pi^+ e^+ e^-$	13	22	CLEO-c
$D_s^+ \to \pi^+ \mu^+ \mu^-$	43	26	FOCUS
$D_s^+ \to \pi^+ e^+ \mu^-$	12	610	E791
$D_s^+ \to \pi^+ \mu^+ e^-$	20	610	E791
$D^+ \to K^+ e^+ e^-$	1.0	3.0	CLEO-c
$D^+ \to K^+ \mu^+ \mu^-$	4.3	9.2	FOCUS
$D^+ \to K^+ e^+ \mu^-$	1.2	68	E791
$D^+ \to K^+ \mu^+ e^-$	2.8	68	E791
$D_s^+ \to K^+ e^+ e^-$	3.7	52	CLEO-c
$D_s^+ \to K^+ \mu^+ \mu^-$	21	36	FOCUS
$D_s^+ \to K^+ e^+ \mu^-$	14	630	E791
$D_s^+ \to K^+ \mu^+ e^-$	9.7	630	E791
$\Lambda_c^+ \to p e^+ e^-$	5.5	340	E653
$\Lambda_c^+ \to p \mu^+ \mu^-$	44	New results	
$\Lambda_c^+ \to p e^+ \mu^-$	9.9		
$\Lambda_c^+ \to p \mu^+ e^-$	19		

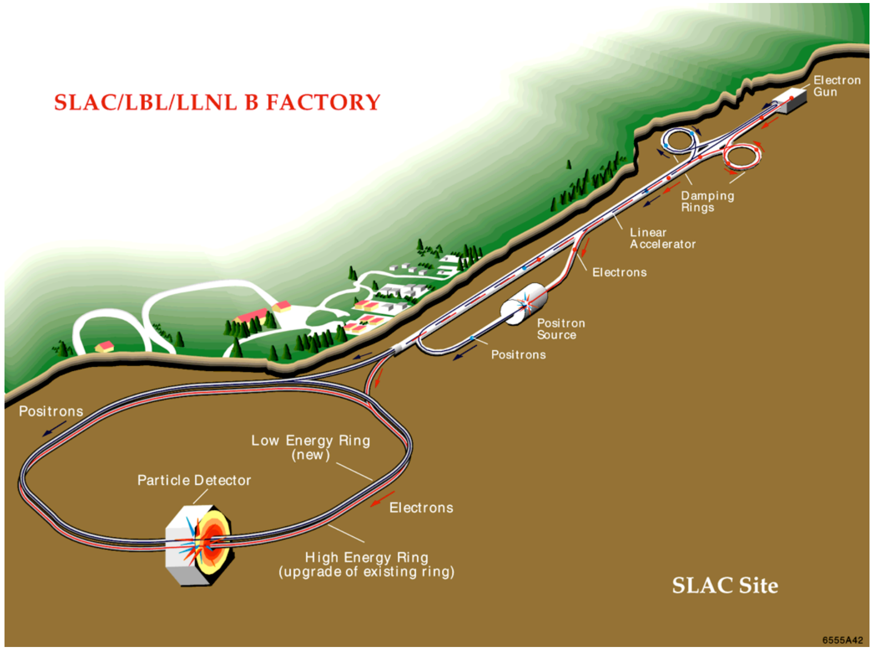
Decay mode	BF UL (10^{-6}) 90% CL	Previous	Experiment
$D^+ \to \pi^- e^+ e^+$	1.9	1.1	CLEO-c
$D^+ \to \pi^- \mu^+ \mu^+$	2.0	4.8	FOCUS
$D^+ \to \pi^- \mu^+ e^+$	2.0	50	E791
$D_s^+ \to \pi^- e^+ e^+$	4.1	18	CLEO-c
$D_s^+ \to \pi^- \mu^+ \mu^+$	14	29	FOCUS
$D_s^+ \to \pi^- \mu^+ e^+$	8.4	730	E791
$D^+ \to K^- e^+ e^+$	0.9	3.5	CLEO-c
$D^+ \to K^- \mu^+ \mu^+$	10	13	FOCUS
$D^+ \to K^- \mu^+ e^+$	1.9	130	E687
$D_s^+ \to K^- e^+ e^+$	5.2	17	CLEO-c
$D_s^+ \to K^- \mu^+ \mu^+$	13	13	FOCUS
$D_s^+ \to K^- \mu^+ e^+$	6.1	680	E791
$\Lambda_c^+ \to \overline{p} e^+ e^+$	2.7	New results	
$\Lambda_c^+ \to \overline{p} \mu^+ \mu^+$	9.4		
$\Lambda_c^+ \to \overline{p} \mu^+ e^+$	16		

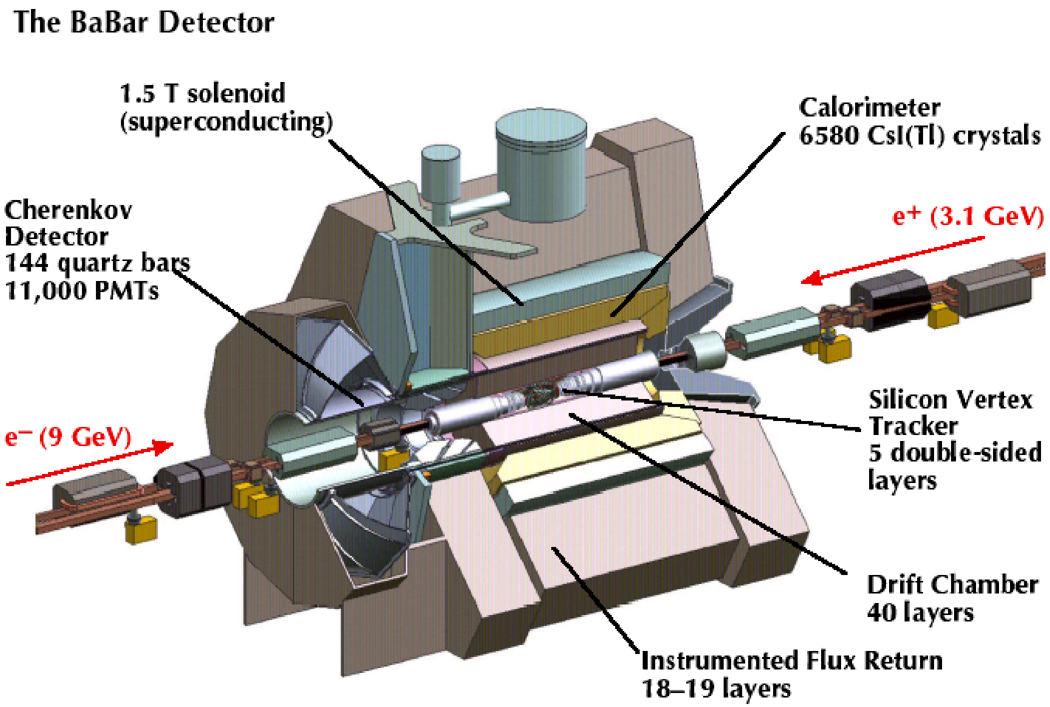
Phys. Rev. D 84, 07200 (2011) 384 fb^{-1}

New Limits approach theoretically interesting region

The BaBar experiment

PEP-II is an asymmetric-energy B factory at SLAC running mostly at the Υ(4S) (10.58 GeV) with a center-of-mass boost with $\beta\gamma=0.55$





SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

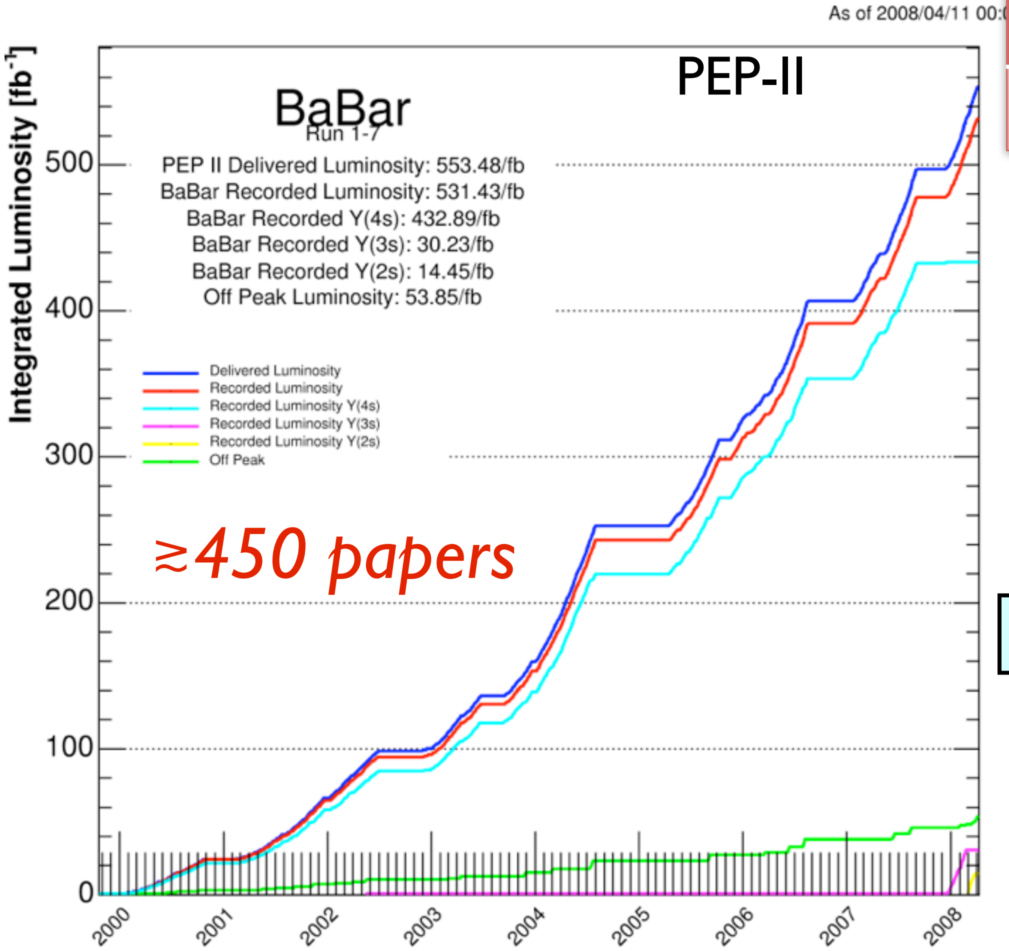
SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T + 0.45\ \%$, $\sigma(z_0)=65\ \mu m$ @ 1GeV/c

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

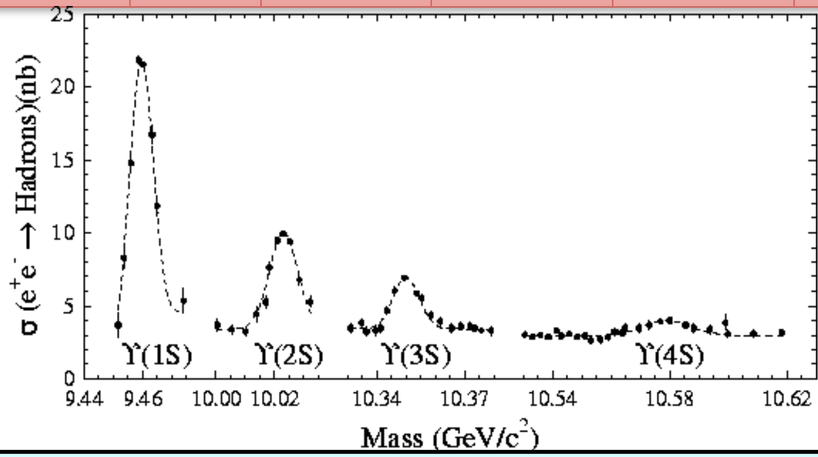
The BaBar dataset

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(4S)$	$\Upsilon(5S)$
BaBar	-	14 fb^{-1}	30 fb^{-1}	433 fb^{-1}	-

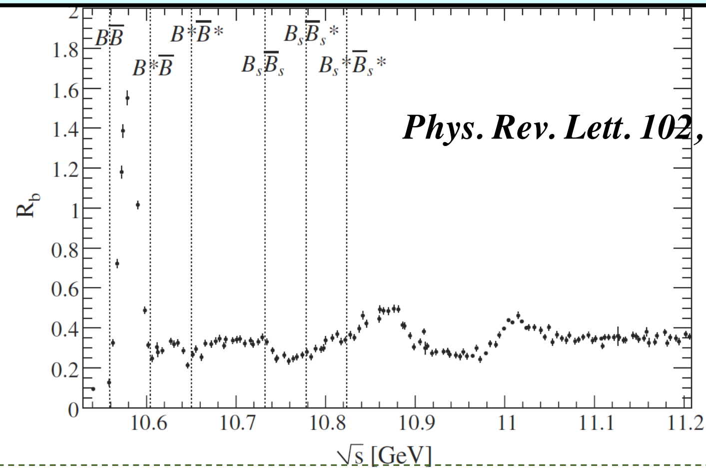


≳450 papers

Recorded luminosity ~530 fb^{-1}
Peak luminosity ~12×10^{33} $cm^{-2}s^{-1}$



Offpeak (10.54GeV) + Scan above Y(4S): 53.9 fb^{-1}



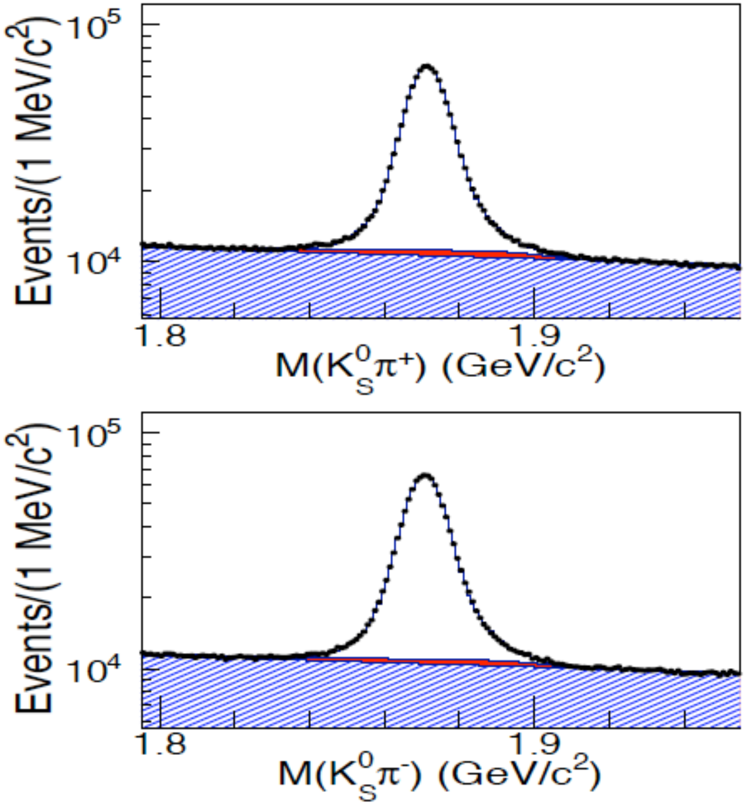
Phys. Rev. Lett. 102, 012001 (2009)

Search for CP violation in $D^+ \to K^0_S \pi^+$

$$A_{\rm rec}^{D^+\to K^0_S\pi^+} = \frac{N_{\rm rec}^{D^+\to K^0_S\pi^+} - N_{\rm rec}^{D^-\to K^0_S\pi^-}}{N_{\rm rec}^{D^+\to K^0_S\pi^+} + N_{\rm rec}^{D^-\to K^0_S\pi^-}}$$

$$A_{\rm rec}^{D^+\to K^0_S\pi^+} = A_{CP}^{D^+\to K^0_S\pi^+} + A_{FB}^{D^+}(\cos\theta_{D^+}^{\rm CMS}) + A_\epsilon^{\pi^+}(p_{T\pi^+}^{\rm lab}, \cos\theta_{\pi^+}^{\rm lab})$$

arXiv:1203.6409v1 977 fb^{-1} 1738 K



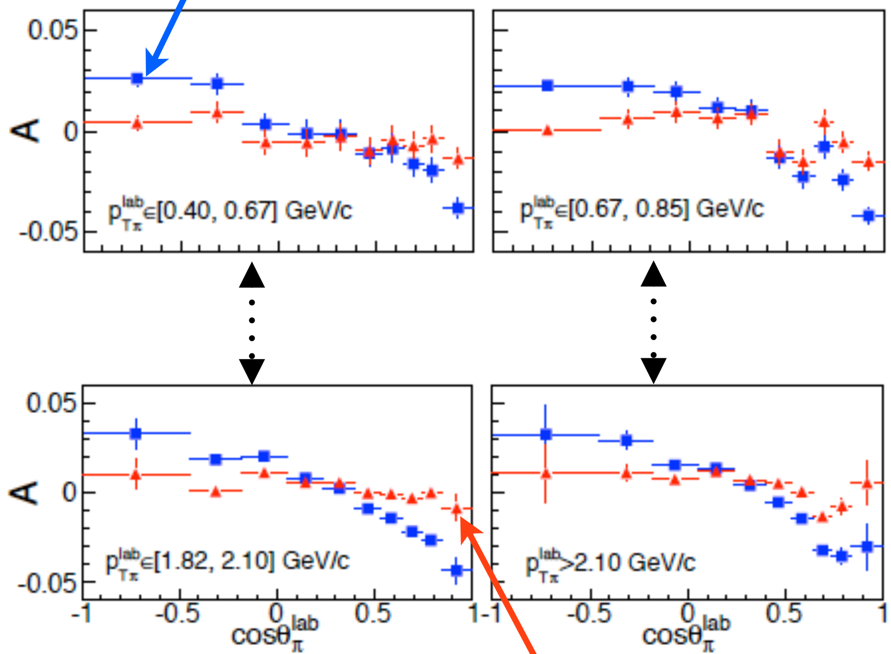
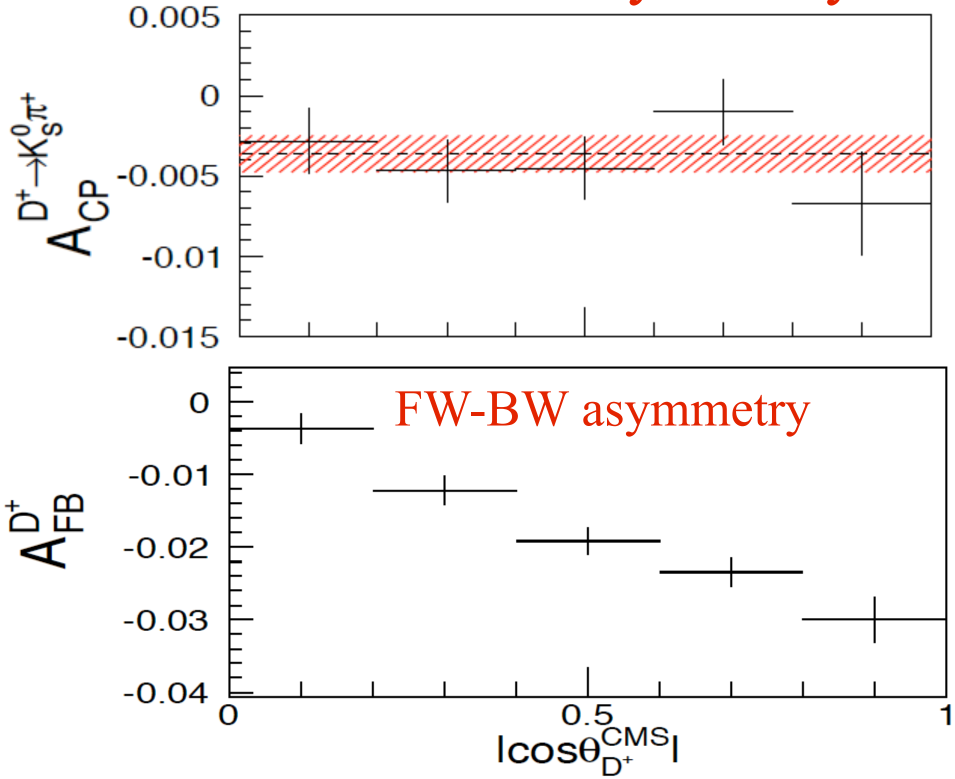


FIG. 2: $A_\epsilon^{\pi^+}$ map in bins of $p_T^{\rm lab}$ and $\cos\theta^{\rm lab}$ of the π^+ obtained with the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ samples (triangles). The $A_{\rm rec}^{D^+\to K^-\pi^+\pi^+}$ map is also shown (rectangles)for comparison, include A_{FB}, $A_\epsilon^{K^-}$, and $A_\epsilon^{\pi^+}$

Search for CP violation in $D^+ \to K^0_S \pi^+$



Systematic errors

Source	$\sigma_{A_{CP}}$ (%)
$A_\epsilon^{\pi^+}$ determination	0.064
Fitting	0.003
$\cos\theta_{D^+}^{CMS}$ binning	0.008
$A_\mathcal{D}$ correction	0.016
Total	0.067

- *A_D is due to different K^0-$\overline{K^0}$ interaction with material*
- *Asymmetry due to neutral kaons to be corrected with acceptance effects as a function of K_S decay time by (1.040±0.005)* Y. Grossman and Y. Nir, arXiv:1110.3790

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

3.2 standard deviations away from zero

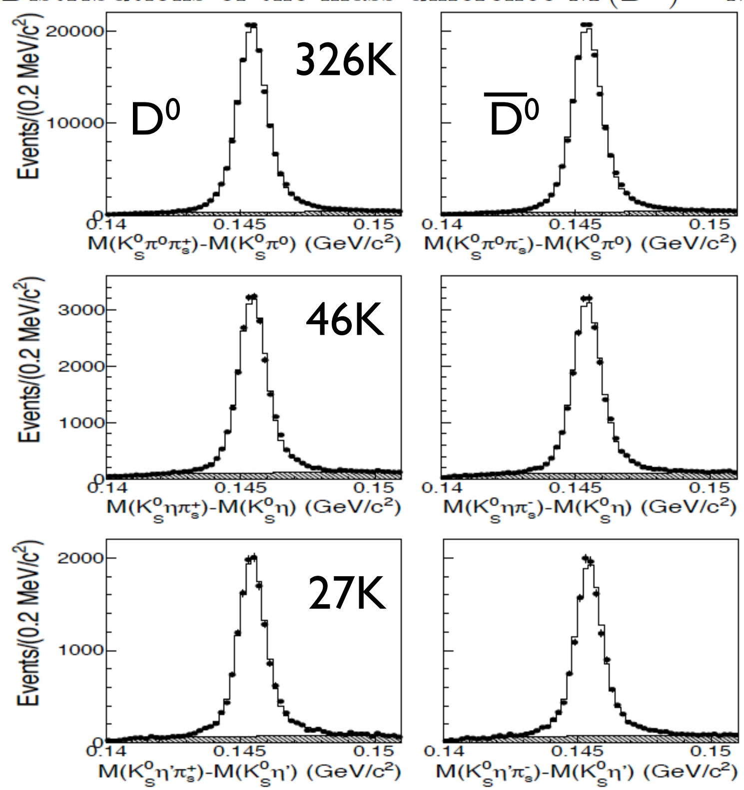
977 fb^{-1}

arXiv:1203.6409v1

Phys. Rev. Lett. 106, 211801 (2011) 791 fb^{-1}

Search for CPV in $D^0 \to K^0_S P^0$ decays

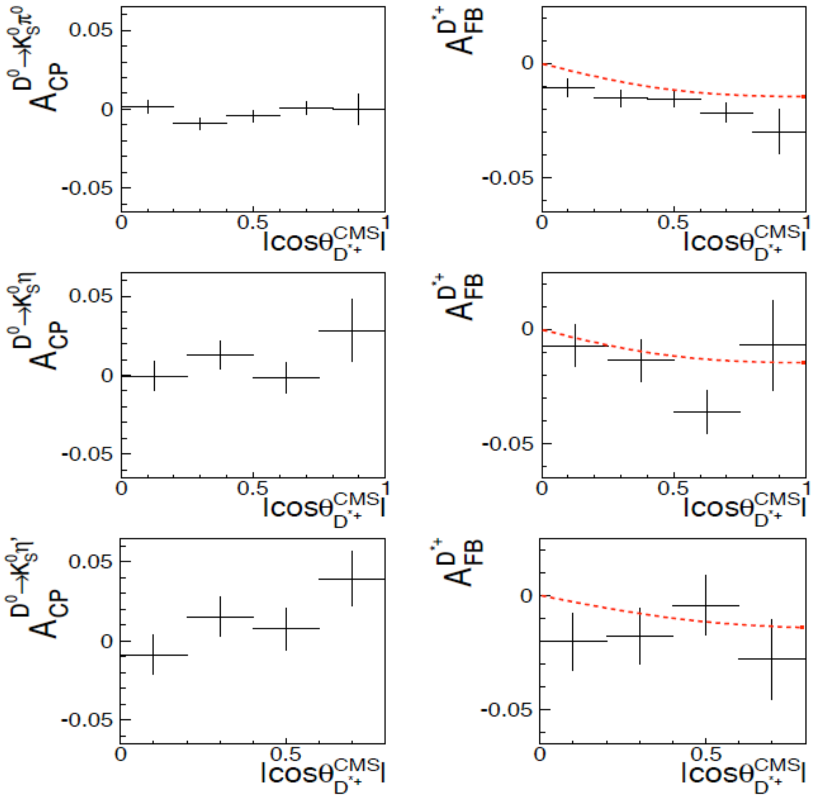
Distributions of the mass difference $M(D^*) - M(D)$



$K_S\pi^0$

$K_S\eta$

$K_S\eta'$

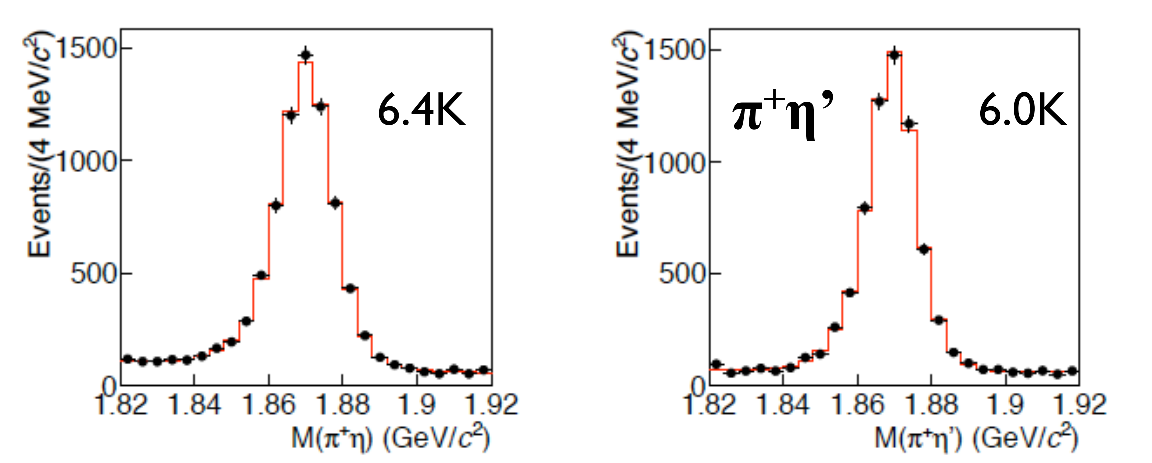


	Belle (%)
$A_{CP}^{D^0\to K^0_S\pi^0}$	$-0.28\pm0.19\pm0.10$
$A_{CP}^{D^0\to K^0_S\eta}$	$+0.54\pm0.51\pm0.16$
$A_{CP}^{D^0\to K^0_S\eta'}$	$+0.98\pm0.67\pm0.14$

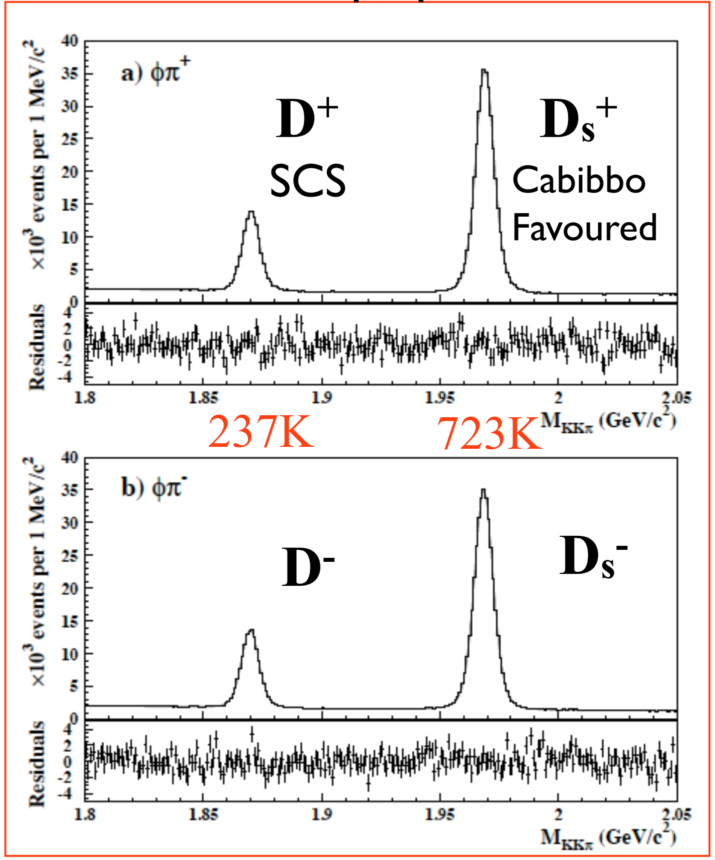
Source	$K^0_S\pi^0$ (%)	$K^0_S\eta$ (%)	$K^0_S\eta'$ (%)
$A_\epsilon^{\pi_s^+}$ determination	0.08	0.08	0.08
Fitting	0.02	0.12	0.10
$\cos\theta^{CMS}_{D^{*+}}$ binning	<0.01	0.01	0.03
$K^0/\bar{K}^0$-material effects	0.06	0.06	0.06
Total	0.10	0.16	0.14

Search for CP violation in SCS $D^+ \to \pi^+\eta^{(\prime)}$ and $D^+ \to \pi^+\phi$ decays

$D^+ \to \pi^+\eta,\ \eta \to \pi^+\pi^-\pi^0$ **$D^+ \to \pi^+\eta',\ \eta' \to \pi^+\pi^-\eta_{\gamma\gamma}$**



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



791 fb^{-1} **Phys. Rev. Lett. 107, 221801 (2011)**

$$A_{CP}^{D^+\to\pi^+\eta} = (+1.74 \pm 1.13 \pm 0.19)\%$$
$$A_{CP}^{D^+\to\pi^+\eta'} = (-0.12 \pm 1.12 \pm 0.17)\%.$$

955 fb^{-1} arXiv:1110.0694v2

$$A_{CP}^{D^+\to\phi\pi^+} = (+0.51 \pm 0.28 \pm 0.05)\%$$

assuming no CPV in CF $D_s^+ \to \pi^+\phi$