Charm *CP*, *T* Violation Studies with BaBar

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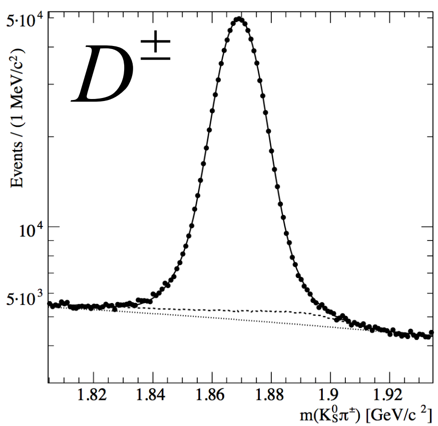
On Behalf of the BaBar Collaboration

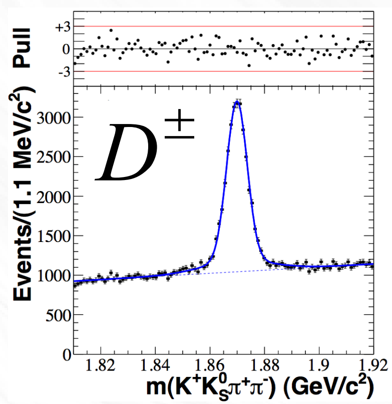
DPF Conference Brown U., August 9-13, 2011

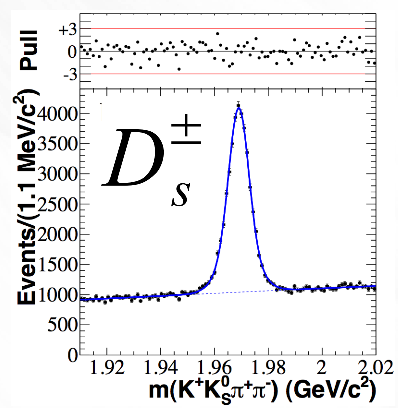
CP, *T* Violation Studies

- The BaBar Experiment and Dataset
- Search for *CP* Violation in $D^{\pm} \rightarrow K_S^0 \pi^{\pm}$
- Search for *T* Violation in

$$D^0(\bar{D}^0) \rightarrow K^+ K^- \pi^+ \pi^+,\ D^{\pm}_{(s)} \rightarrow K^{\pm} K_S^0 \pi^+ \pi^-$$

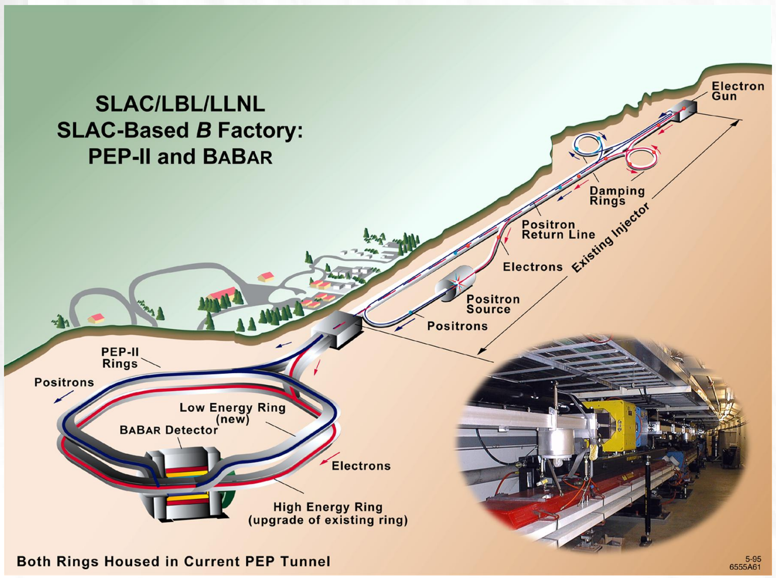




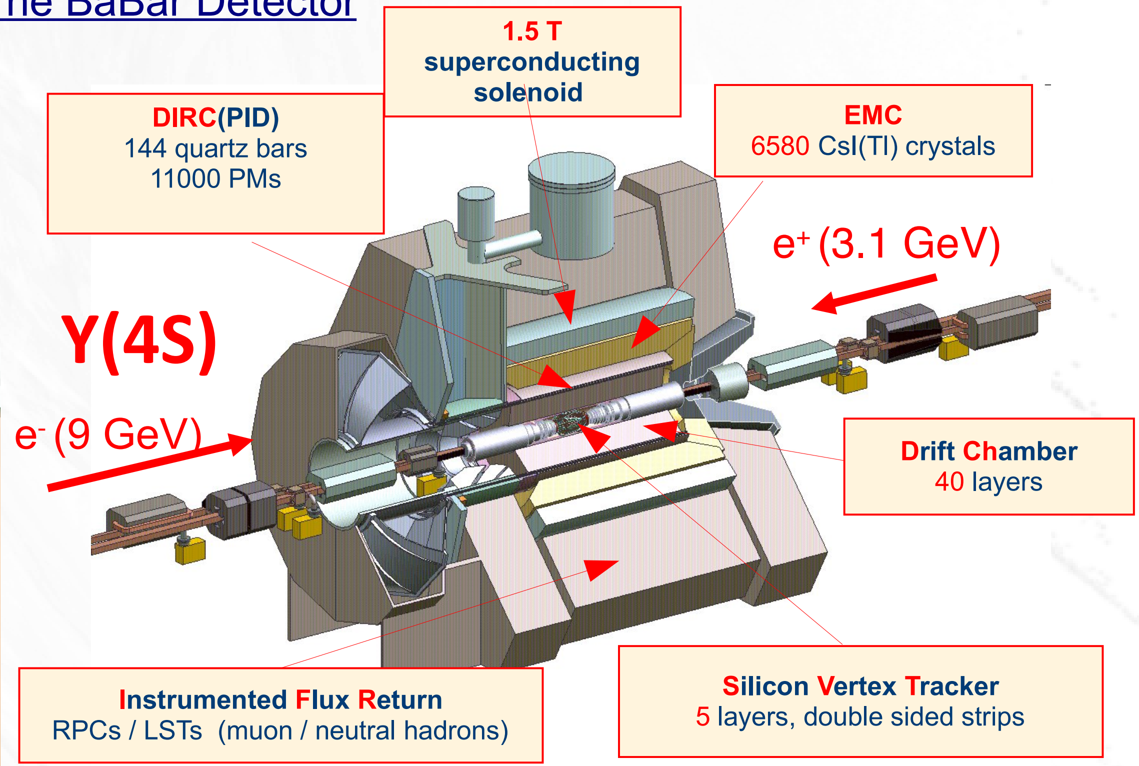


The BaBar Experiment

PEP-II asymmetric-energy B factory at SLAC running primarily at the Υ(4S) (10.58 GeV) with a center-of-mass boost βγ = 0.55



The BaBar Detector



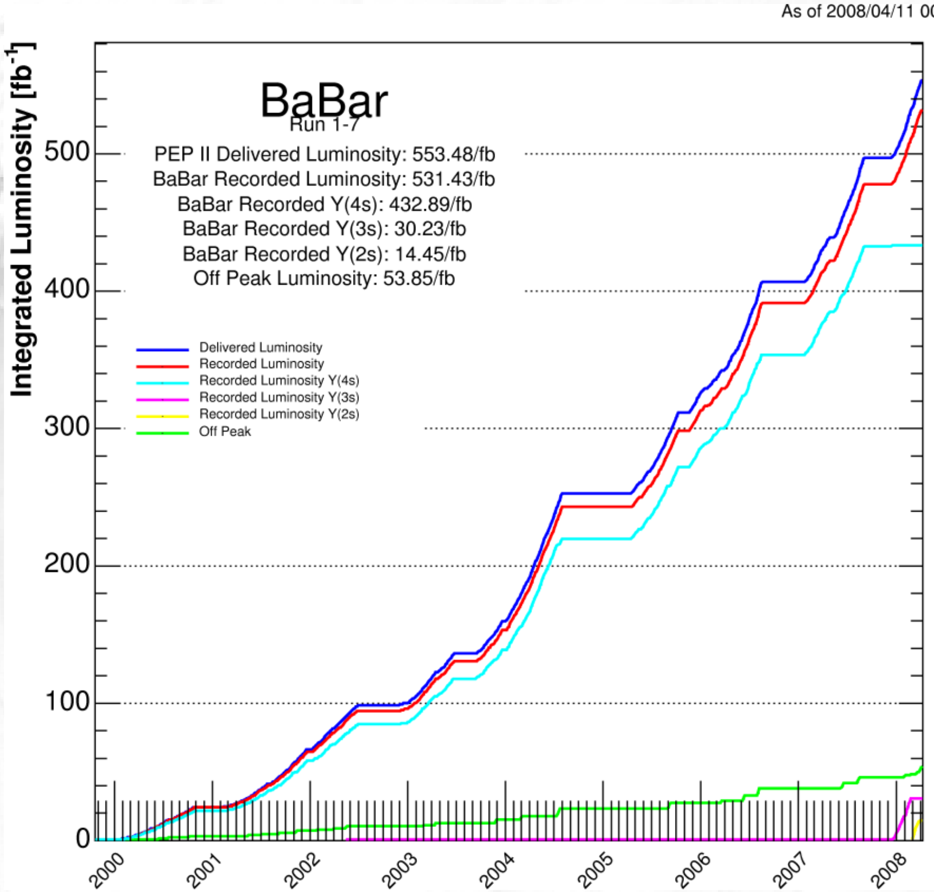
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

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

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

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

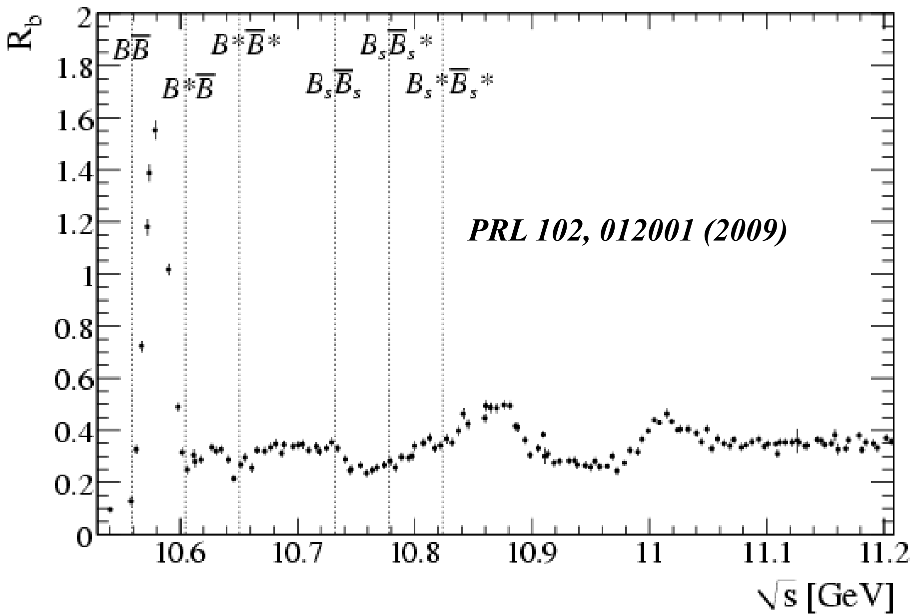
The BaBar Dataset



	Υ(2S)	Υ(3S)	Υ(4S)
BaBar	14 fb^{-1}	33 fb^{-1}	433 fb^{-1}

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

Recorded Luminosity ~530 fb^{-1}
Peak Luminosity ~ 12×10^{33} $cm^{-2}s^{-1}$
Design Luminosity ~ 3×10^{33} $cm^{-2}s^{-1}$



CP Violation in D Decays with K_S in Final State

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.
- Presence of K_s^0 in final state introduces time-integrated *CPV* (-0.332 +/- 0.006)% due to neutral kaon mixing.
- Experimental sensitivity at the level of SM prediction (10^{-3}).

1% Asymmetry indicates presence of New Physics

Search for *CP* Violation in $D^{\pm} \to K_S^0 \pi^{\pm}$

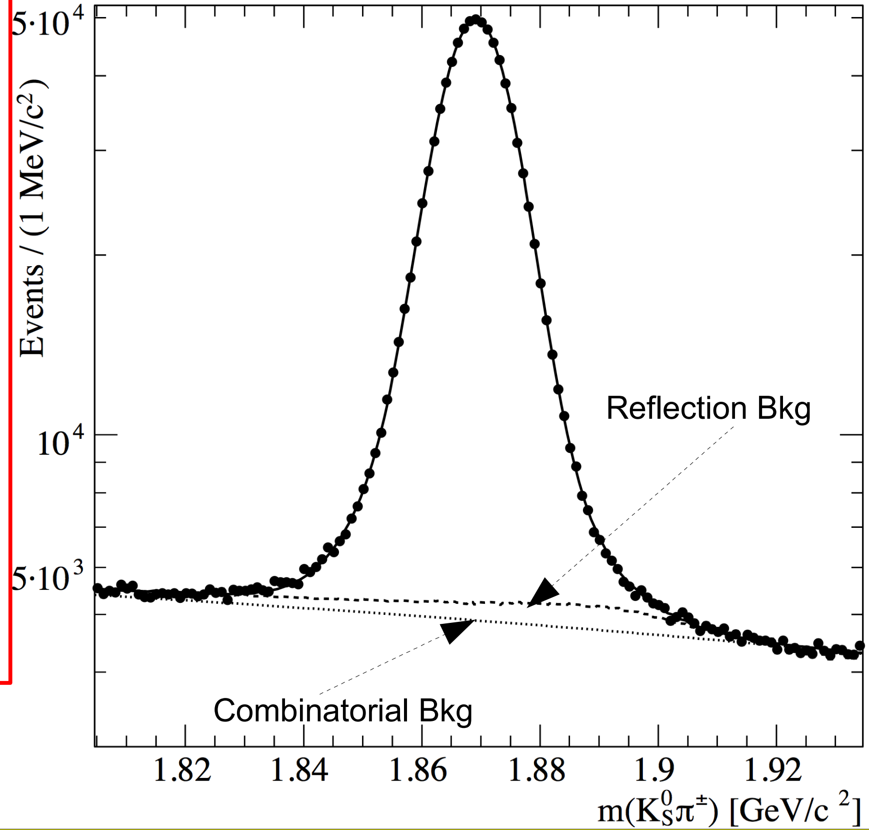
PRD 83, 071103 (2011)

Direct CP Asymmetry from K_S mixing : (-0.332 +- 0.006)%

$$A_{CP} = \frac{\Gamma(D^+ \to K_S^0 \pi^+) - \Gamma(D^- \to K_S^0 \pi^-)}{\Gamma(D^+ \to K_S^0 \pi^+) + \Gamma(D^- \to K_S^0 \pi^-)}$$

$(807.4 \pm 0.1) \times 10^3$ *signal events* $[469\ fb^{-1}]$

- **Candidate Selection**:
  - D^+ and K_S kinematic fits
  - $2 < p^*(D^+) < 5$ (GeV/c)
  - Lifetime $-12.5 < \tau(D^+) < 31.3$ ps
  - Impact parameter $|d_0(D^+)| < 0.3$cm
  - K_S decay flight significance > 3
  - Pion track $p_T > 0.1$ GeV/c
  - **Boosted Decision Tree: $\tau(D)$, $L_{xy}(D)$, $p^*(D)$, K_S and π momentum and p_T**



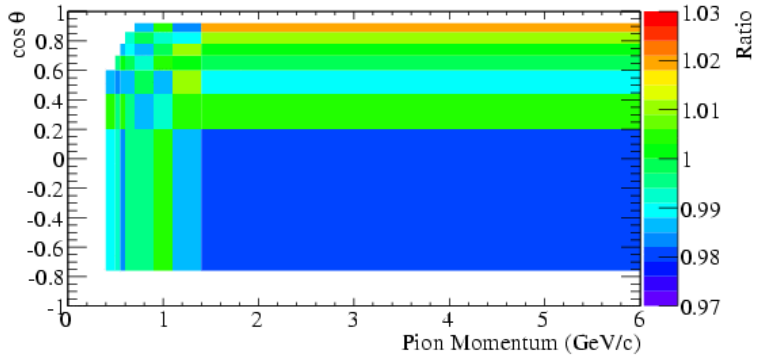
New physics affecting doubly Cabibbo-suppressed amplitude could enhance it to the 1% level

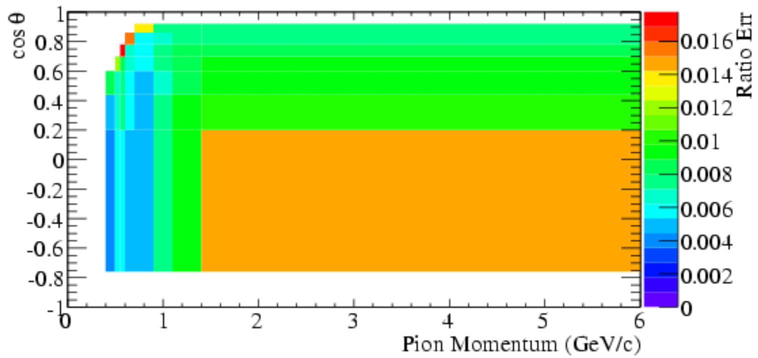
Search for *CP* Violation in $D^{\pm} \rightarrow K_S^0 \pi^{\pm}$

Phys. Rev. D 83, 071103 (2011)

Tracking

- **Dominant systematic uncertainty due to charge asymmetry correction 0.08%**
- **Data-driven technique to determine charge asymmetry in track reconstruction.**
- **Use tracks from:** $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- **Physics process nearly free of any physics-induced asymmetry.**





$K^0 - \bar{K}^0$ *Regeneration*

- Asymmetry dilution due to neutral kaon regeneration in detector material 0.05%.
- Similar approach as Belle **[arxiv:1006.1938].**
- Integrated probability of neutral kaons to interact inside tracking system.

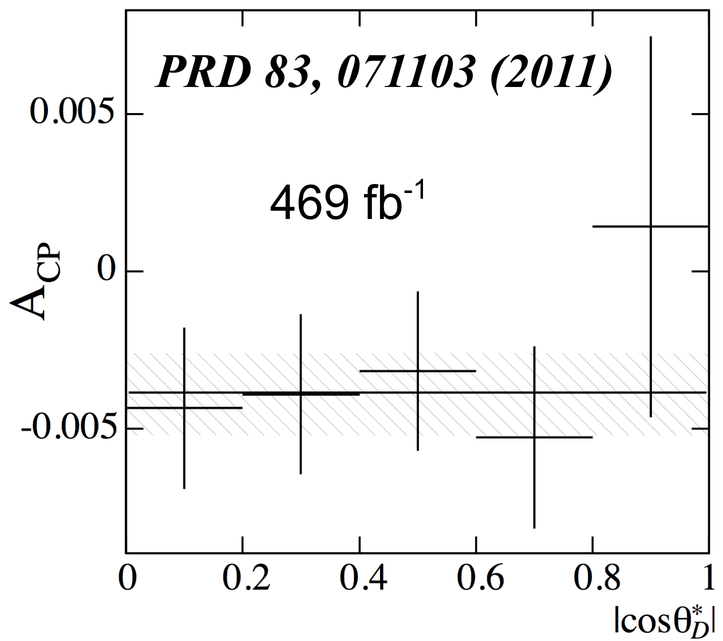
- Charge Asymmetry Correction 0.08%.
- Neutral Kaon regeneration 0.05%.
- Additional Systematics 0.011%:
  - MC Statistics
  - Mass fit PDFs
  - Binning on cosθ*

Search for CP Violation in $D^{\pm} \to K^0_S \pi^{\pm}$

PRD 83, 071103 (2011)

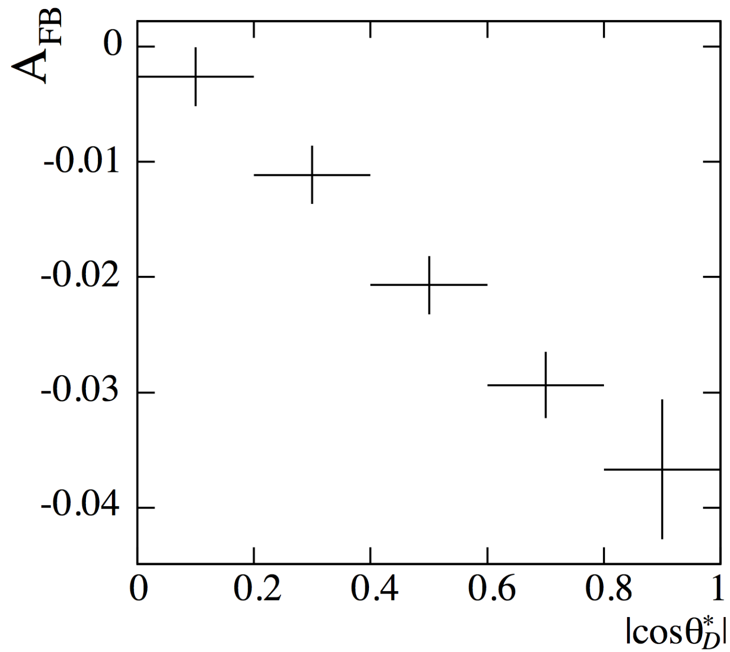
CP violating asymmetry – even as a function of $\cos\theta^*_D$

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



Forward-Backward asymmetry due to γ-Z^0 interference and to detector efficiency asymmetry – odd as function of $\cos\theta^*_D$

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



A_{CP} = (-0.44 +/- 0.13 +/- 0.10)% [469 fb^{-1}]

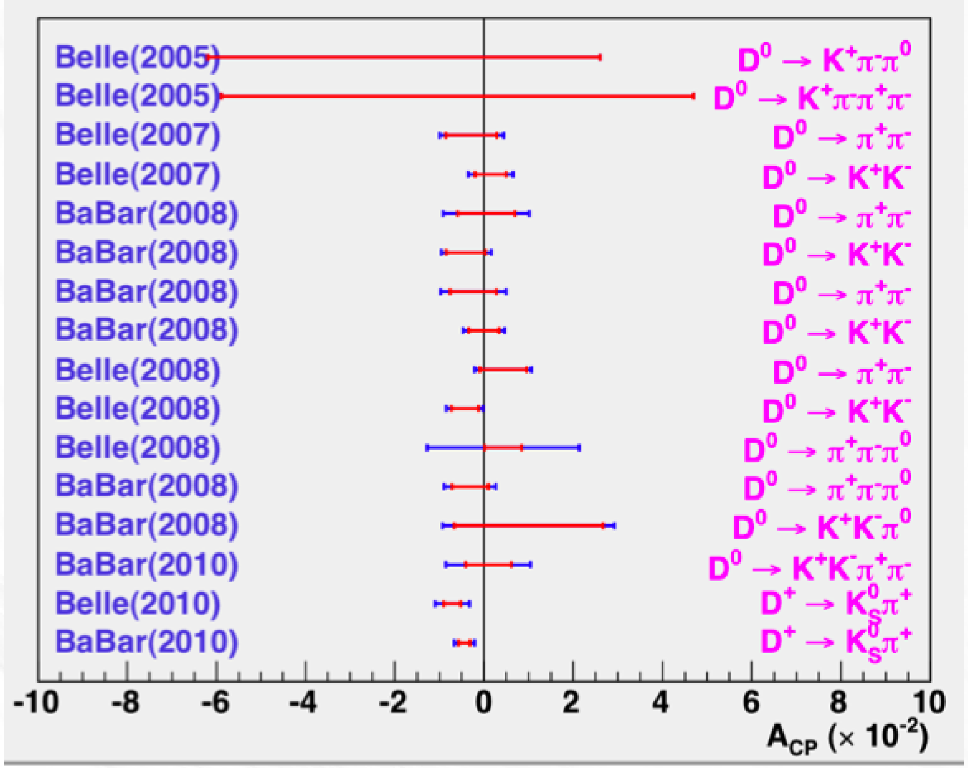
[SM prediction] (-0.332 +/- 0.006)%

Summary of time-integrated *CP*V measurements

$D^{\pm} \rightarrow K_S^0 \pi^{\pm}$

A_{CP} = (-0.44 +/- 0.13 +/- 0.10)% (BaBar 469 fb^{-1})

A_{CP} = (-0.71 +/- 0.19 +/- 0.20)% (Belle – 673 fb^{-1})



Recent CDF Measurement in $D^0 \to \pi^+\pi^-, K^+K^-$ (5.94 fb^{-1})

$$A_{CP}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24\ (stat.) \pm 0.11\ (syst.)]\%$$

$$A_{CP}(D^0 \to K^+K^-) = [-0.24 \pm 0.22\ (stat.) \pm 0.10\ (syst.)]\%$$

arXiv:1105.2979v1[hep-ex]

PoS BEAUTY2011:014,2011

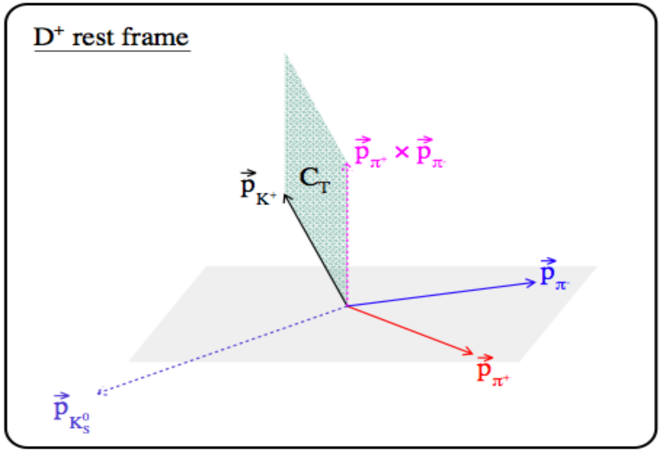
Search for *CP* Violation using T-Odd Correlations in 4-body Charm Decays

I.I. Bigi hep-ph/0107102

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

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

Measured on D^+



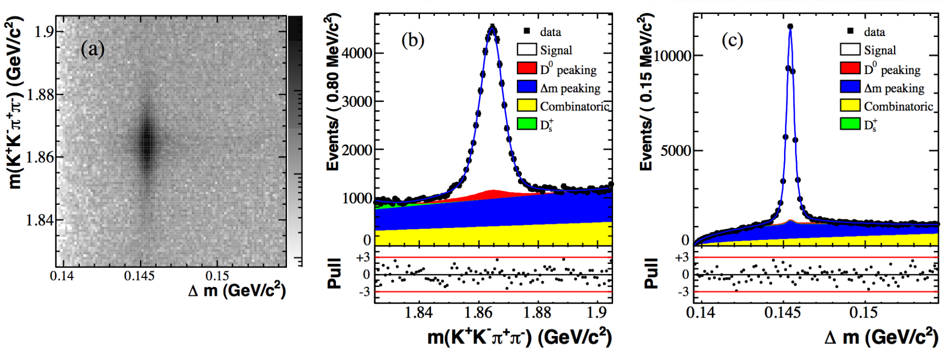
- Final-state interactions (FSI) may introduce T-odd asymmetries $A_T \neq 0$.
- Measuring the T-violating observable removes FSI effects:

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

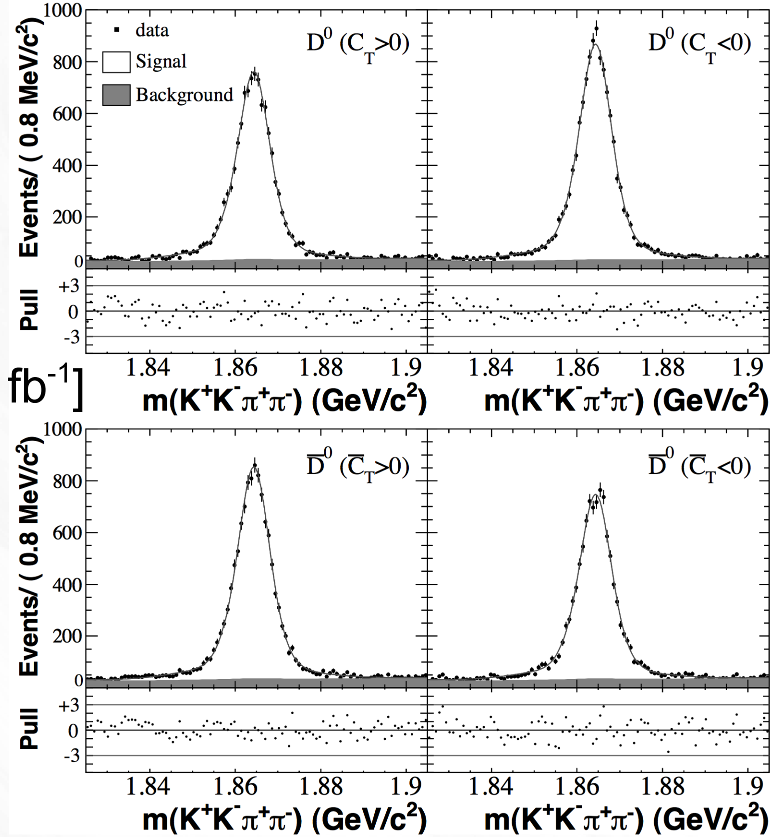
Measured on D^-

Search for *CP* Violation using T-Odd Correlations in 4-body Charm Decays

$$e^+e^- \to XD^{*\pm};\ D^{*\pm} \to D^0(\bar{D}^0)\pi^\pm;\ D^0(\bar{D}^0) \to K^+K^-\pi^+\pi^-$$



Phys. Rev. D 81, 111103 (R) (2010)



Subsample	Events
(a) D^0, $C_T > 0$	10974 ± 117
(b) D^0, $C_T < 0$	12587 ± 125
(c) $\overline{D}^0$, $\overline{C}_T > 0$	10749 ± 116
(d) $\overline{D}^0$, $\overline{C}_T < 0$	12380 ± 124

~46K Signal Events [470 fb^{-1}]

$$A_T = (-68.5 \pm 7.3_{\rm stat} \pm 4.5_{\rm syst}) \times 10^{-3}$$

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

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

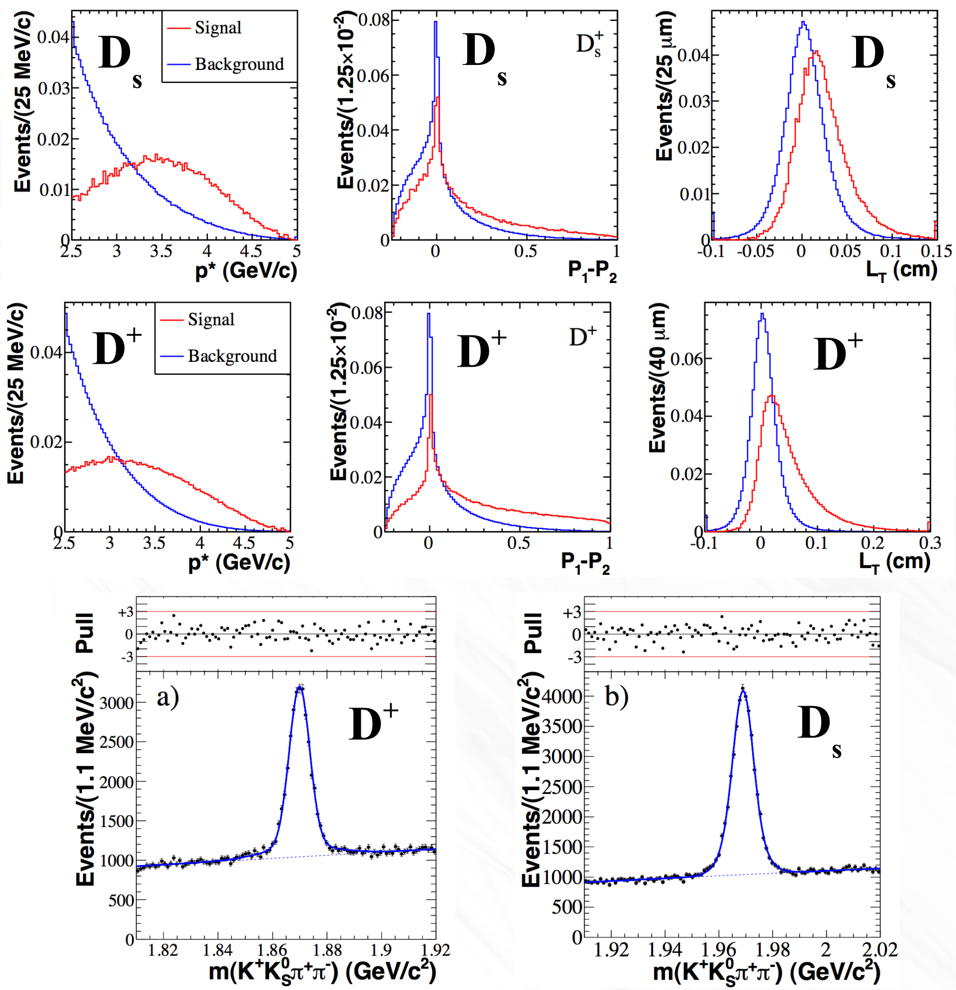
Systematic uncertainties at level of statistical error!

Search for *CP* Violation using T-Odd Correlations in 4-body Charm Decays

$$e^+e^- \to X D^{\pm}_{(s)} ;\ D^{\pm}_{(s)} \to K^{\pm} K^0_S \pi^+ \pi^- ;\ K^0_S \to \pi^+ \pi^-$$

arXiv:1105.4410 [hep-ex]
Submitted to PRD-RC

520 fb^{-1}

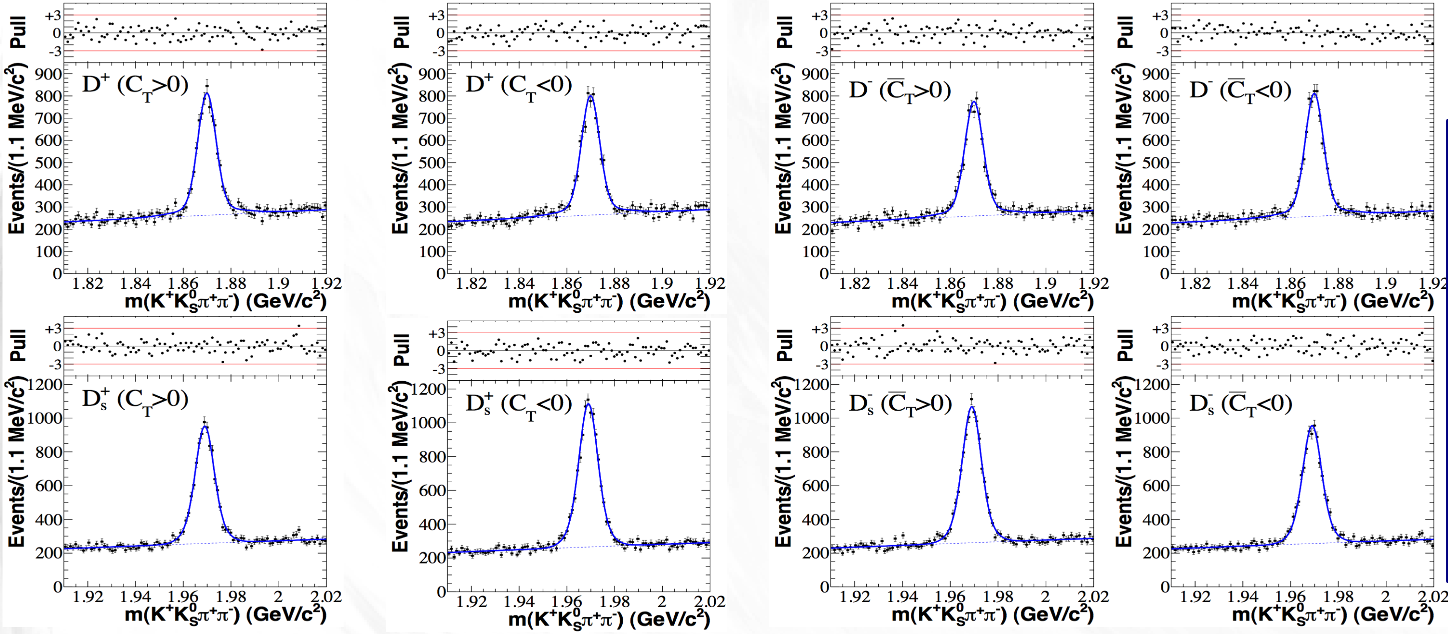


- Inclusive $D_{(s)}^+$ reconstruction
- $p^*(D_{(s)}) > 2.5$ GeV/c
- 20,000 D^+ Cabibbo-suppressed
- 30,000 D_s^+ Cabibbo-favored
- Likelihood ratio:
  - Decay distance in transverse plane L_{xy}, p*, vertex probability difference $P_1 - P_2$
    P_1: 4 particle vertex
    P_2: primary vertex

Search for *CP* Violation using T-Odd Correlations in 4-body Charm Decays

$$e^+ e^- \rightarrow X D^\pm_{(s)}\,;\, D^\pm_{(s)} \rightarrow K^\pm K^0_S \pi^+ \pi^-\,;\, K^0_S \rightarrow \pi^+ \pi^-$$

arXiv:1105.4410 [hep-ex]



520 fb^{-1}

- Inclusive $D^+_{(s)}$ reconstruction
- $p^*(D_{(s)}) > 2.5$ GeV/c
- 20,000 D^+ Cabibbo-suppressed
- 30,000 D_s^+ Cabibbo-favored

Systematic Uncertainties

Effect	$\mathcal{A}_T\ (D^+)$	$\mathcal{A}_T\ (D^+)$	$\bar{\mathcal{A}}_T\ (D^-)$	$\mathcal{A}_T\ (D_s^+)$	$\mathcal{A}_T\ (D_s^+)$	$\bar{\mathcal{A}}_T\ (D_s^-)$
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

Search for *CP* Violation using T-Odd Correlations in 4-body Charm Decays

$A_T(D^+) = (+11.2 \pm 14.1_{stat} \pm 5.7_{syst}) \times 10^{-3}$

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

Submitted to PRD (RC)
arXiv:1105.4410 [hep-ex]

520 fb^{-1}

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

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

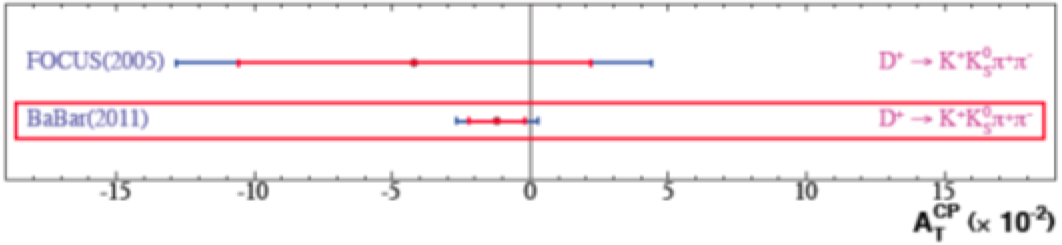
► FSI effects appear larger in D_s

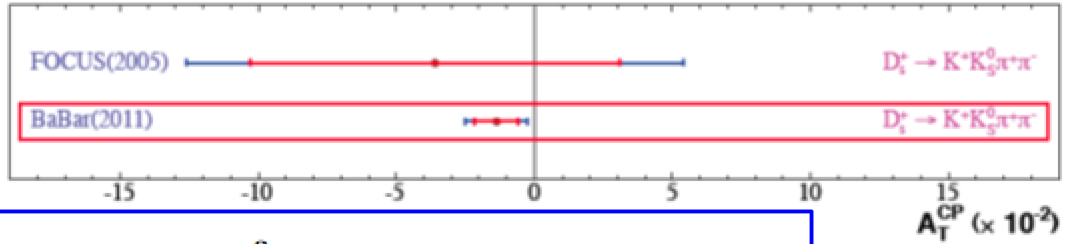
T-violating observable consistent with 0.

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

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

X10 improvement over previous result.





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

Conclusion

- Present BaBar searches for *CP* or *T* violation in Charm decays in agreement with Standard Model predictions within uncertainties.
- Systematic uncertainties at the level of statistical error!
- Larger data sample, compared to BaBar, is needed to obtain precision below Standard Model predictions and probe for New Physics.
- Flavor physics provides an alternate and complementary path for searches for New Physics with respect to LHC direct searches.
- Future experiments SuperB and Belle-II will provide such a probe.