Search for CP Violation in charm decays

$$D^{\pm} \to K^0_S K^{\pm}$$
$$D_s^{\pm} \to K^0_S K^{\pm}$$
$$D_s^{\pm} \to K^0_S \pi^{\pm}$$

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CP violation in the SM

- CP violation in the SM results from KM complex phases in the CKM quark mixing matrix:

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}$$

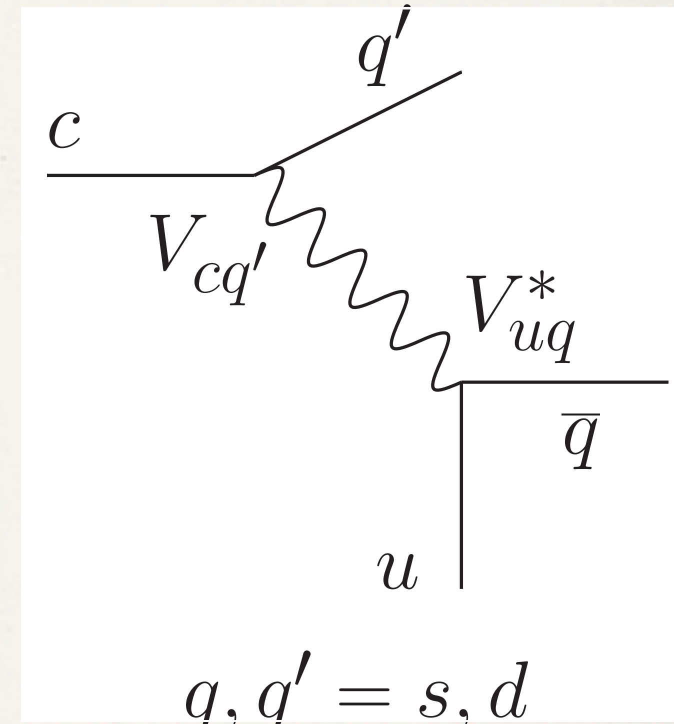
- Using the Wolfenstein parametrization:

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

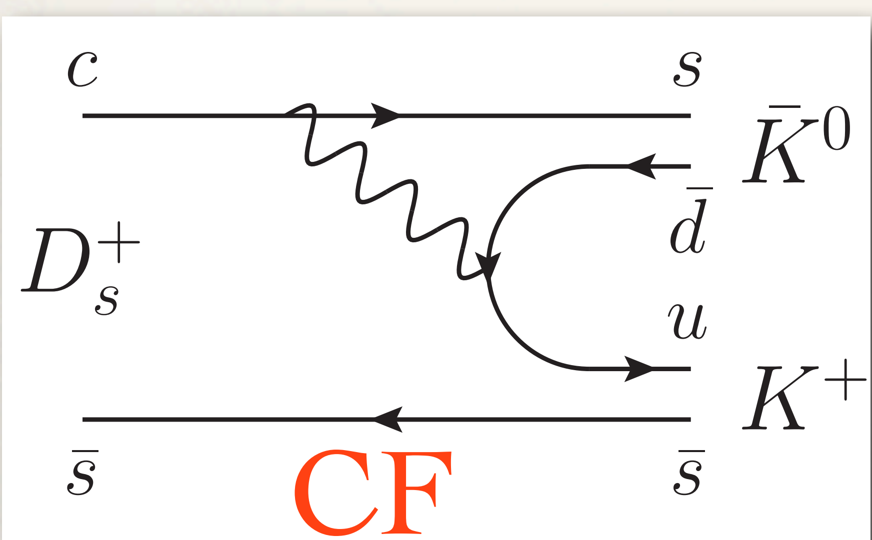
- Charmed mesons: CP violation is CKM suppressed $\mathcal{O}(10^{-3})$
- Observing deviations from these small effects would be a sign of New Physics

Cabibbo-allowed decay modes

- Type of transitions:
  - Cabibbo Favored (CF) $c \to s\bar{d}u$
  - Singly-Cabibbo-Suppressed (SCS) $c \to s\bar{s}u, c \to d\bar{d}u$
  - Doubly-Cabibbo-Suppressed (DCS) $c \to d\bar{s}u$
  - $D_s^\pm \to K_S^0 K^\pm$ decay can proceed through CF and DCS transitions, but CF dominates: one phase and CPV from SM is negligible



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



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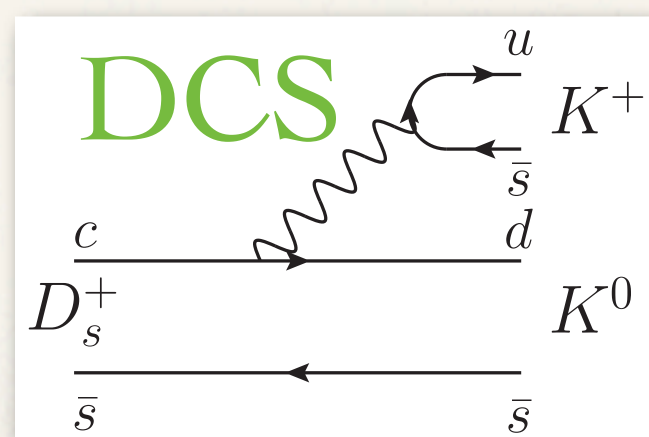
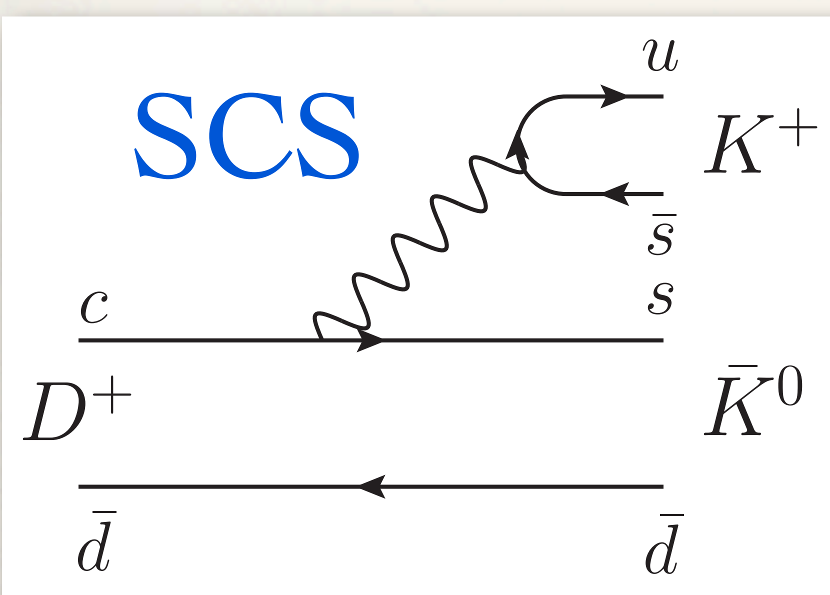


$$CPV \simeq 0$$

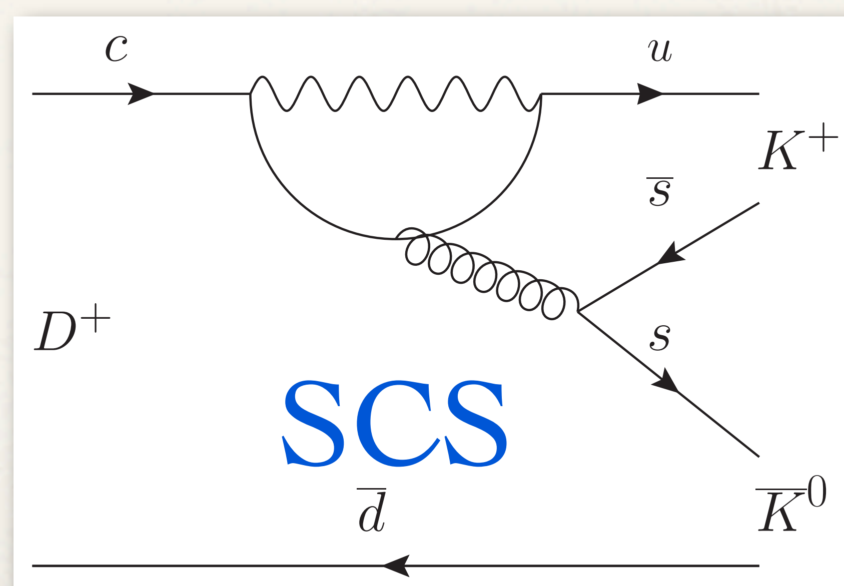
Cabibbo-suppressed decay modes

- No CF transition for some decays, so amplitude for tree and penguin diagrams are comparable (penguins can proceed only through SCS transitions)
- Penguins carry a weak phase relative to the tree amplitude, so there is a relevant tree-penguin interference

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



$\simeq$



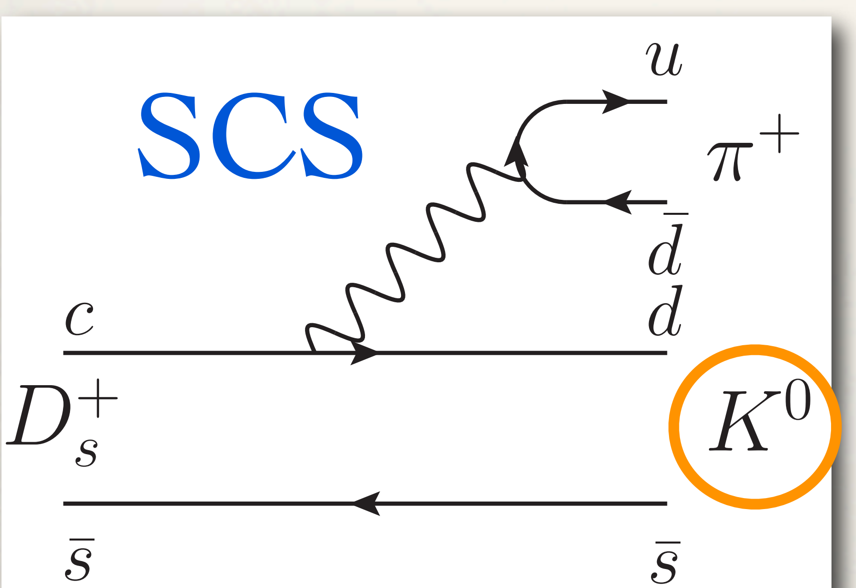
$CPV \sim 0.1\%$

Cabibbo-suppressed decay modes

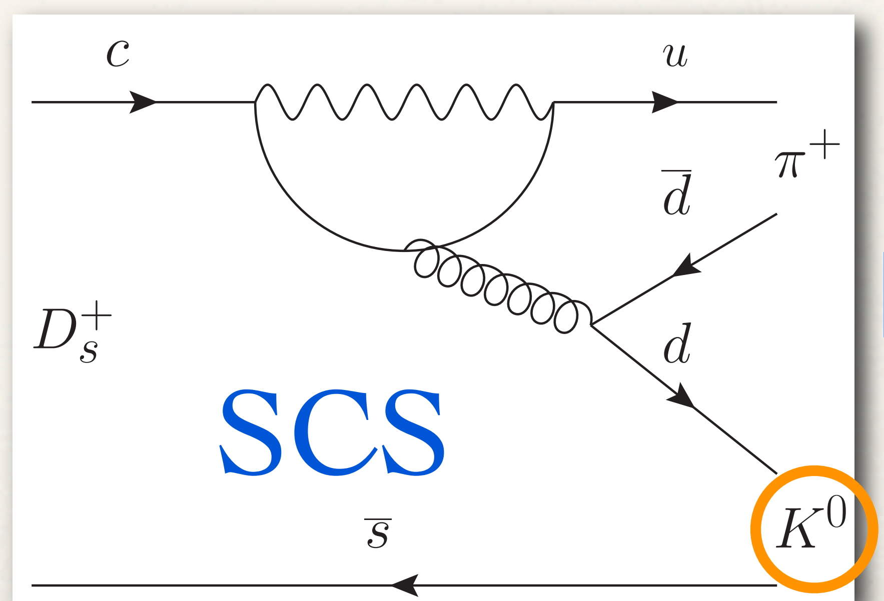
- No CF transition for some decays, so amplitude for tree and penguin diagrams are comparable (penguins can proceed only through SCS transitions)
- Penguins carry a weak phase relative to the tree amplitude, so there is a relevant tree-penguin interference

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

K^0 **instead of** $\overline{K}^0$



$\simeq$



$CPV \sim 0.1\%$

CP asymmetry measurement

- Time integrated CP asymmetry

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

- Many systematics cancel out, sensitivity down to **~0.2%**
- Charged mesons, only direct CPV
- Contribution from $K^0 - \overline{K}^0$ mixing [PDG 2010]: **+(-)0.332±0.006%** when a K^0 ($\overline{K}^0$) is in the final state
- Any deviation would be evidence of CP violation in the charm system
- Already published by BaBar: $D^\pm \to K^0_S \pi^\pm$ [Phys. Rev. D 83, 071103(R) (2011)]
  A$_{CP}$=(-0.11±0.13(stat)±0.10(syst))% (after removing $K^0 - \overline{K}^0$ mixing contrib.)

Reconstructed asymmetry

- Measured asymmetry is the sum of three contributions:

$$A_{\mathrm{rec}}^{D_{(s)}} = A_{CP}^{D_{(s)}} + A_{FB}^{D_{(s)}}(\cos\theta^*_{D_{(s)}}) + A_{\varepsilon}^{(\pi,K)}(p^{\mathrm{lab}}_{(\pi,K)}, \cos\theta^{\mathrm{lab}}_{(\pi,K)})$$

  - **CP asymmetry, A_{CP}**
  - **Fwd/Bwd asymmetry in $c\bar{c}$ production, A_{FB}**
    - virtual photon interference with virtual Z^0
  - **Detector-induced charge reconstruction asymmetry, A_{ε}**
    - reconstruction asymmetries and material interactions
    - affecting only the track not coming from the K_S
- Corrections will be applied to remove A_{ε} , while A_{CP} and A_{FB} are measured

Charge asymmetry in reconstruction

- Data-driven method to remove detector-induced asymmetry A_ε
- **100M generic tracks with no asymmetry from physics:** Υ(4S) events, after continuum subtraction

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

- **Step 1**: criteria to strongly reduce the asymmetry:
  - veto on tracks identified as **proton** and **electron**
  - **Pion**: veto on tracks identified as **kaon**
  - **Kaon**: tracks should be identified as **kaon** but not as **pion**
  - $p_T > 0.4$ GeV/c
- Residual asymmetry: pions -0.25±0.03%, kaons 0.23±0.05% (compatible with Υ(4S) MC)
- **Step 2:** corrections to remove the residual asymmetry

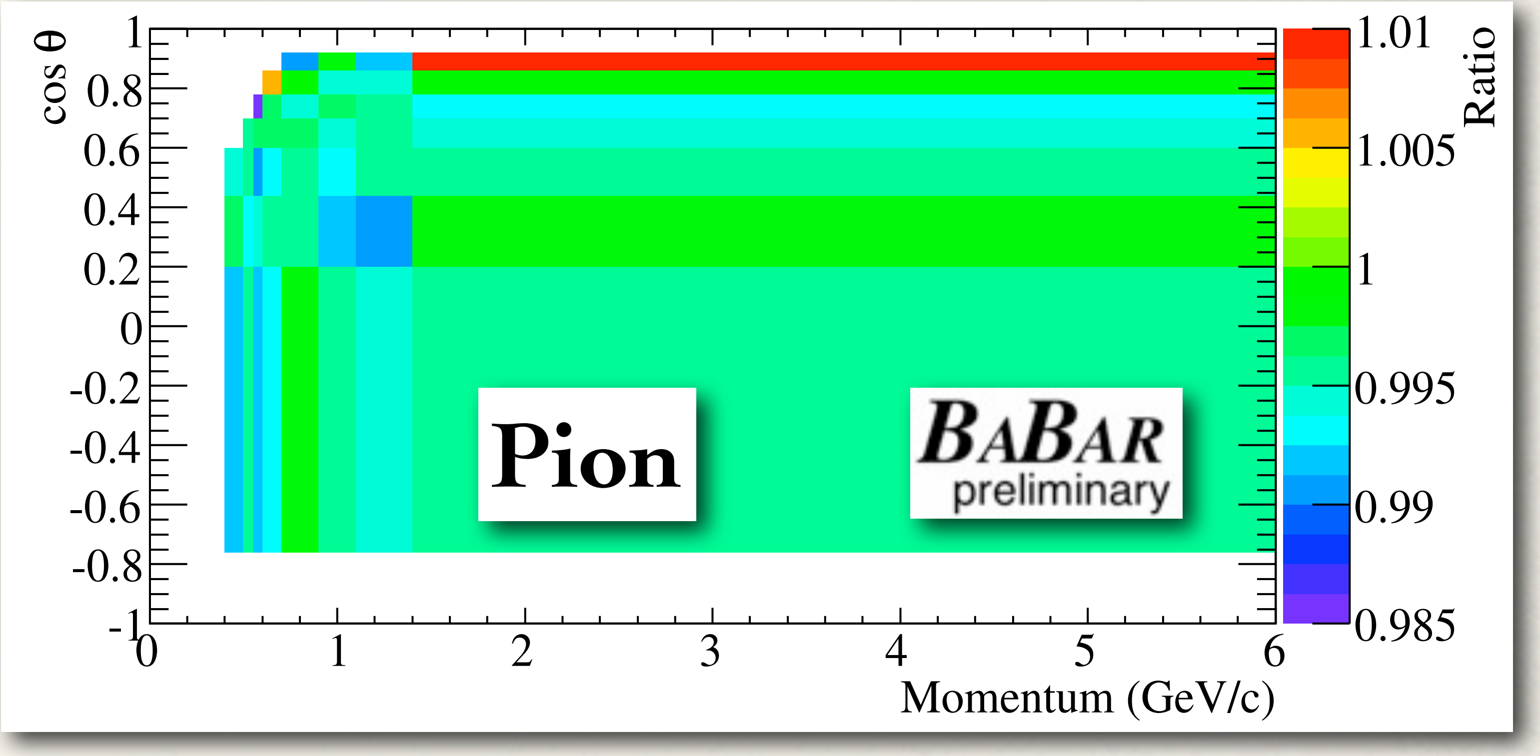
Charge asymmetry correction

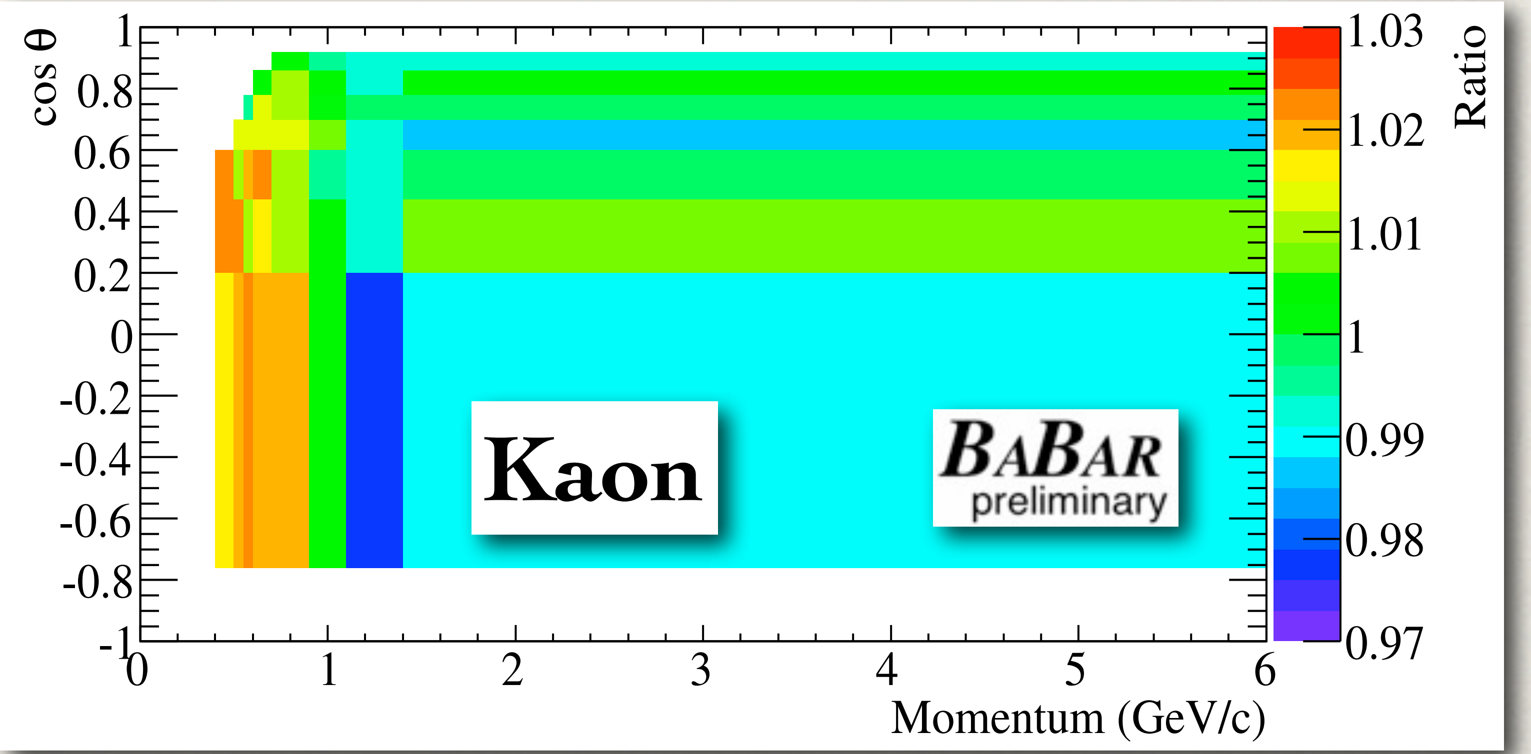
$$R = \frac{\epsilon^+(\vec{p})}{\epsilon^-(\vec{p})} = \frac{N^+_{\rm rec}(\vec{p})}{N^-_{\rm rec}(\vec{p})}$$

- Equally populated bins of momentum magnitude and cosine of polar angle

- Small correction (~1-2%) applied to negative $D_{(s)}$ candidates

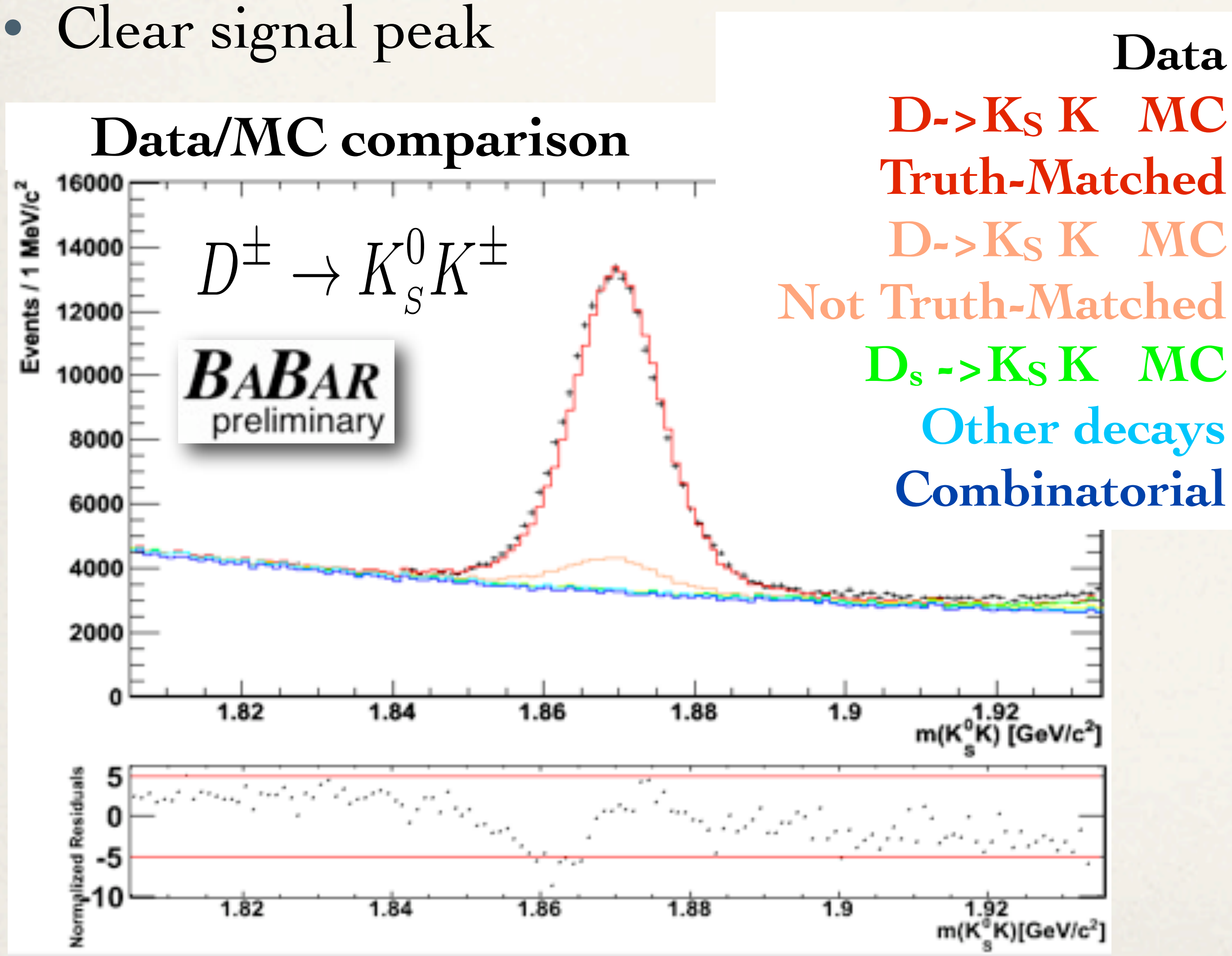
- Systematic contribution will be included later

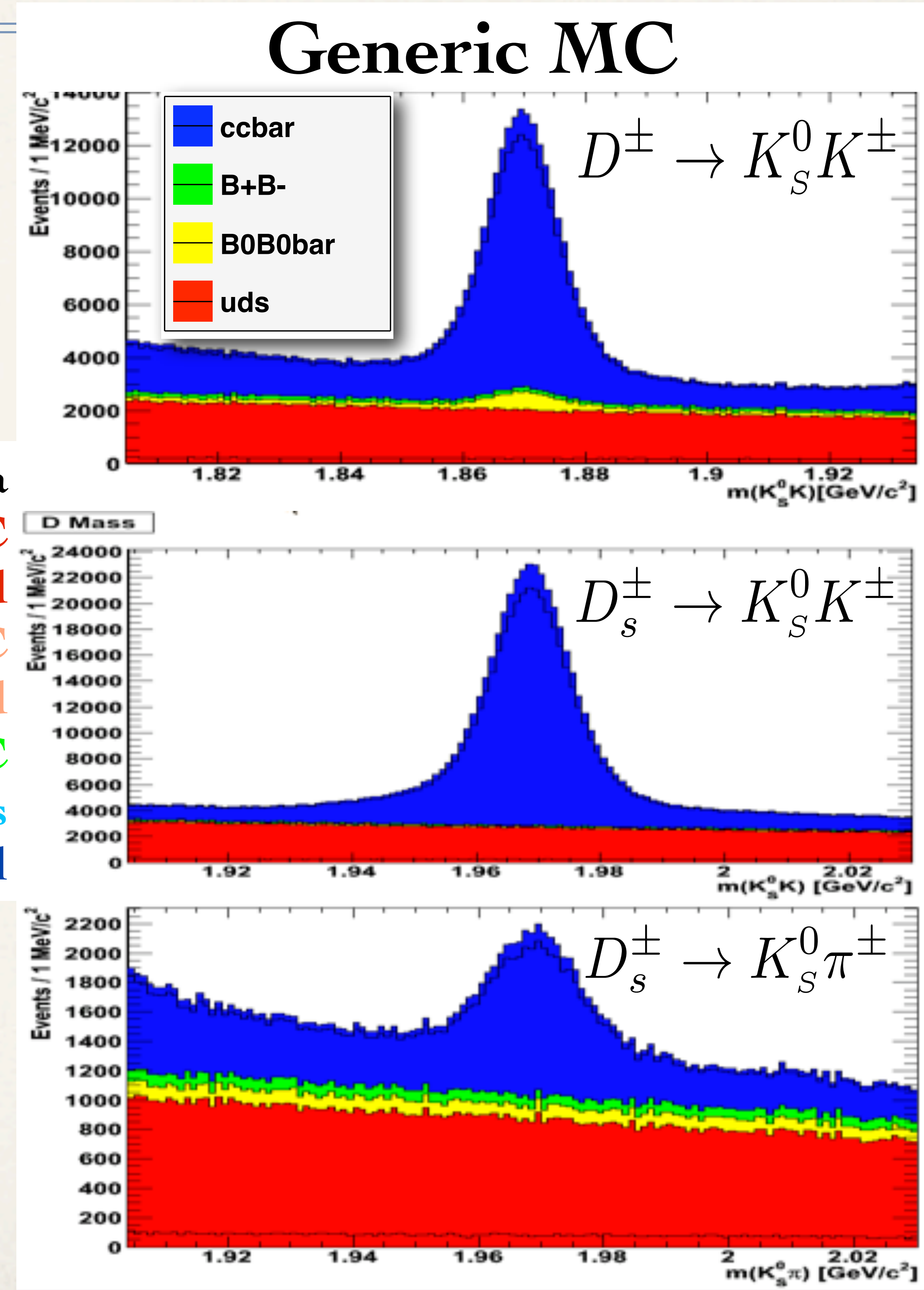




Invariant Mass Distributions

- D(s) candidates fully reconstructed plus standard selection
- Relevant cut, CMS momentum:
  - p* > 2.0 GeV/c for D mode
  - p* > 2.6 GeV/c for D_s modes
- Clear signal peak

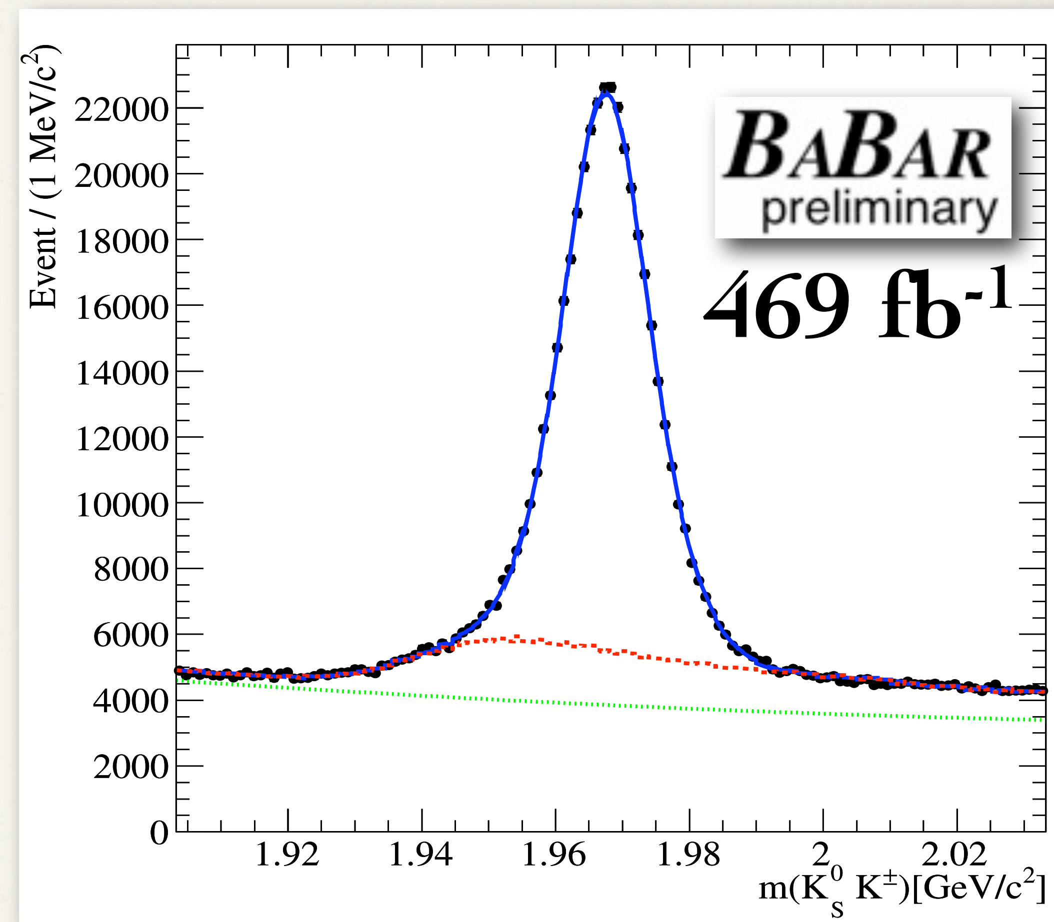




PDF components

- Fit to invariant mass distributions using three components:
  - **Signal**: 2 or 1 Gaussian functions
  - **Charm background** from other charm modes (see table) with similar invariant mass or mis-id pion/kaon: 1D not parametric PDF from MC
  - **Combinatorial background**: 2nd or 1st order polynomial

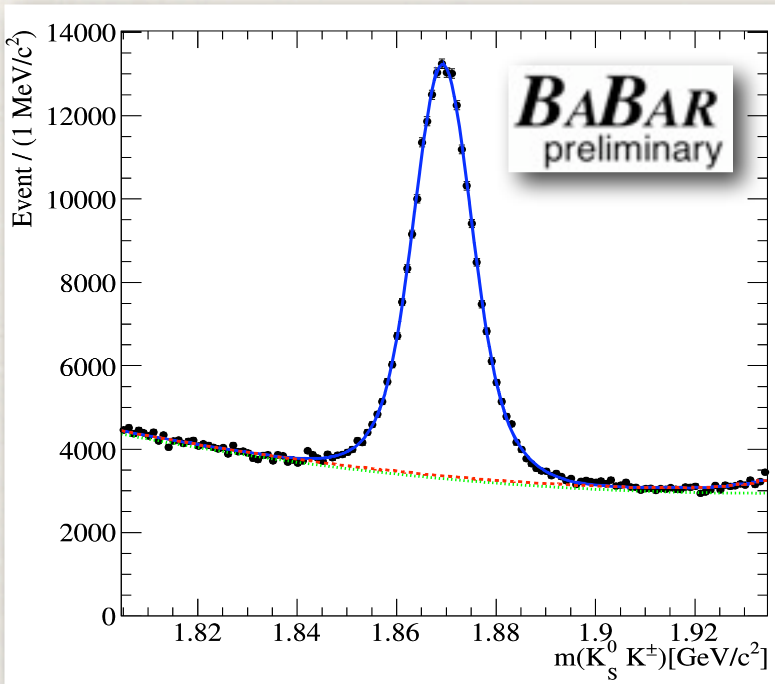
$D_s^{\pm} \to K_S^0 K^{\pm}$



	$D^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 \pi^{\pm}$
Signal PDF	2 Gauss	2 Gauss	1 Gauss
Charm Bkg PDF	$D_s^{\pm} \to K_S^0 K^{\pm}$	$D^{\pm} \to K_S^0 \pi^{\pm}$	$D^{\pm} \to K_S^0 \pi^{\pm}$
Combinatorial PDF	$2^{\rm nd}$ order poly	$2^{\rm nd}$ order poly	$1^{\rm st}$ order poly

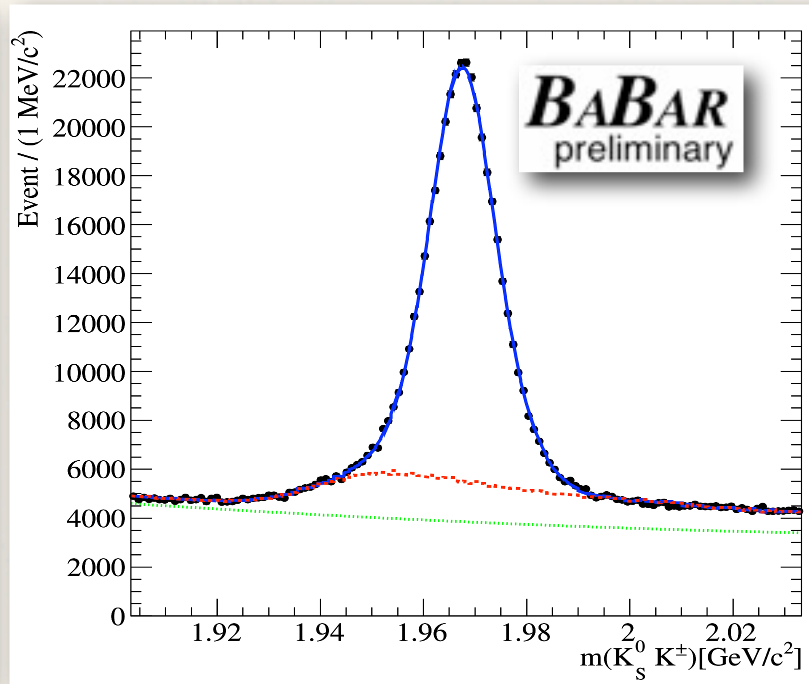
Simultaneous fit

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



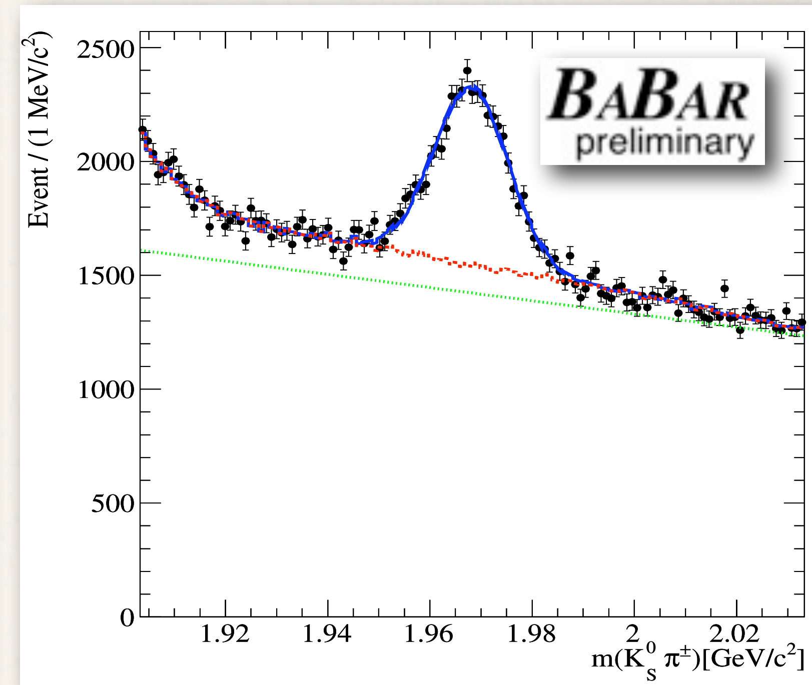
Signal Yield 159400±800

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



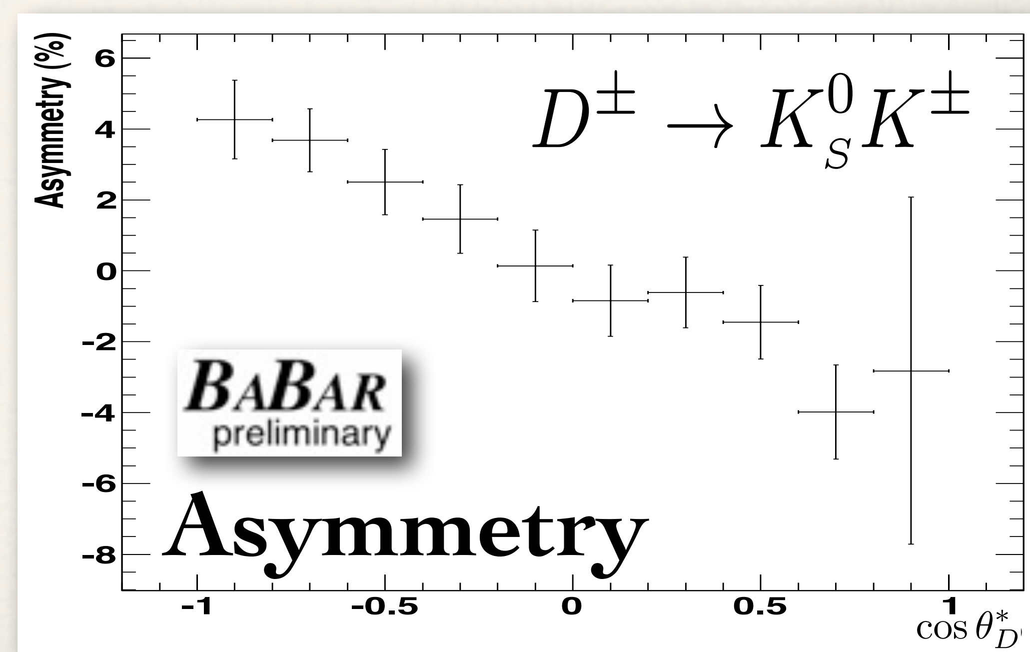
Signal Yield 288200±1100

$D_s^{\pm} \to K^0_S \pi^{\pm}$



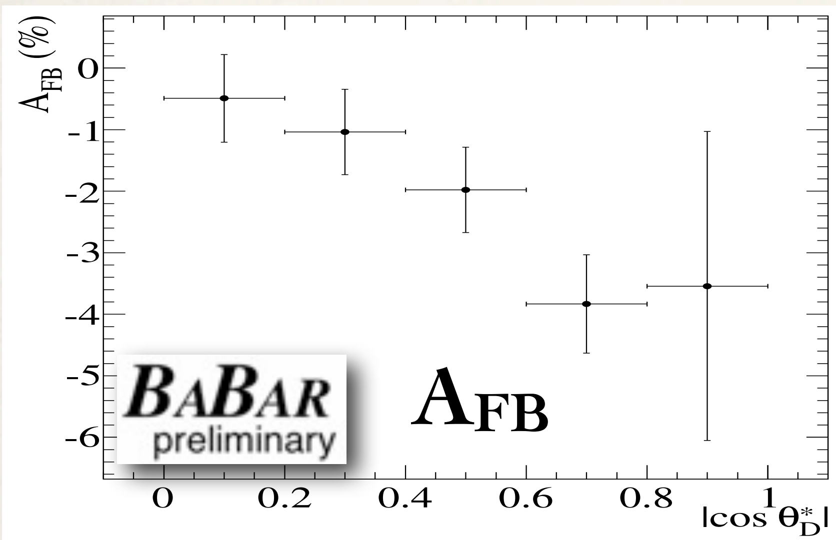
Signal Yield 14330±310

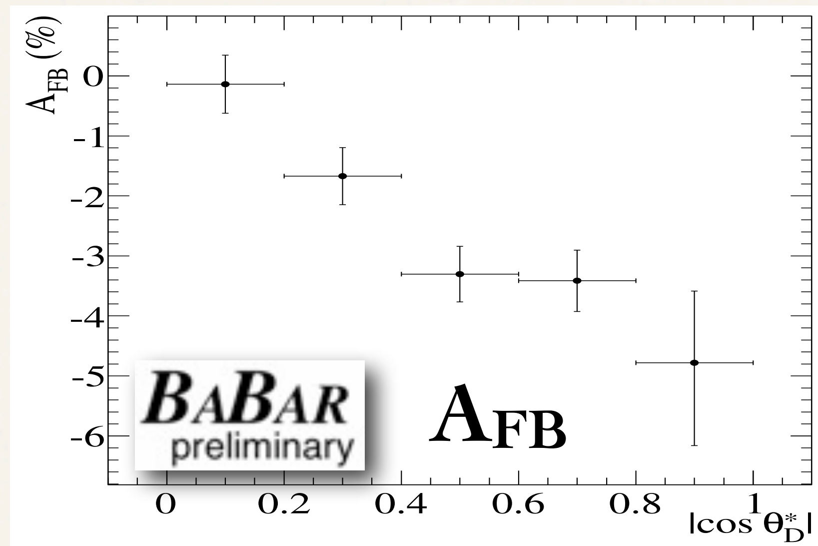
- **Simultaneous binned extended maximum likelihood fit** to 20 sub-samples: positive and negative candidates, 10 bins of $\cos\theta^*_{D_{(s)}}$
- 70, 80, and 64 free parameters for $D^{\pm} \to K^0_S K^{\pm}$, $D_s^{\pm} \to K^0_S K^{\pm}$, and $D_s^{\pm} \to K^0_S \pi^{\pm}$, respectively
- 10 asymmetry values are extracted for each mode

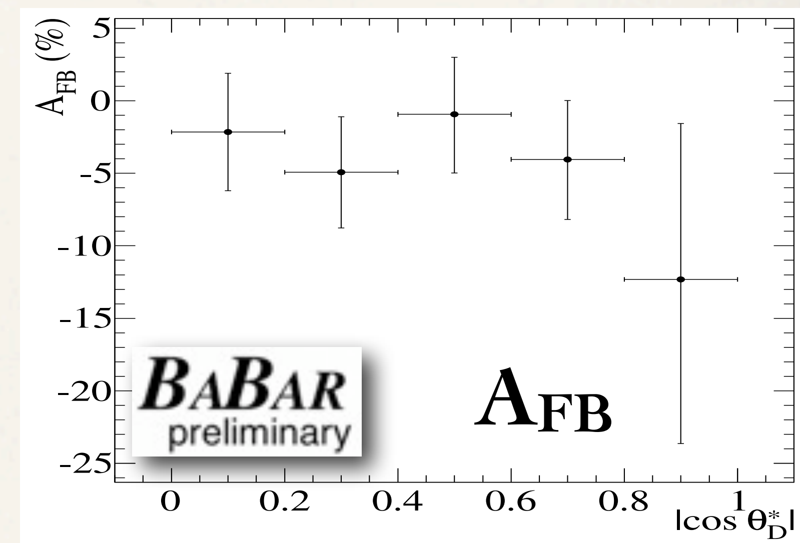


A_{CP}, A_{FB} extraction

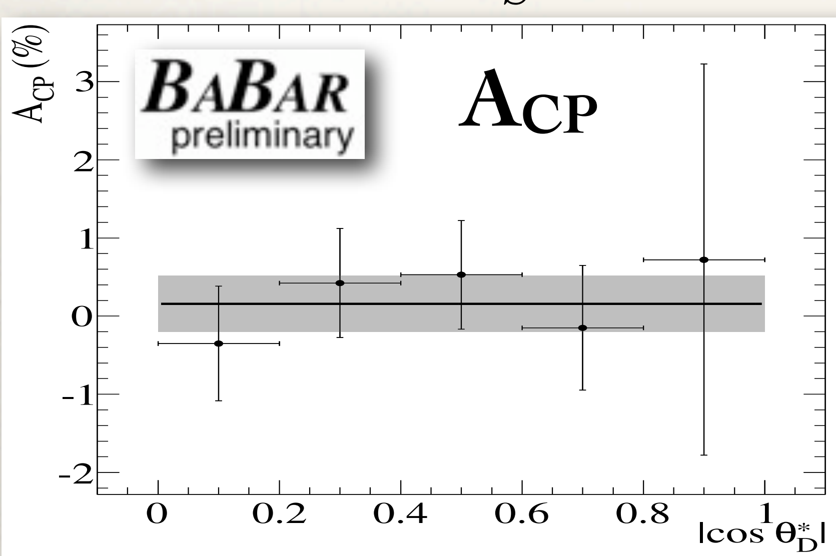
$$A_{FB}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) - A(-|\cos\theta_D^*|)}{2} \qquad A_{CP}(|\cos\theta_D^*|) = \frac{A(+|\cos\theta_D^*|) + A(-|\cos\theta_D^*|)}{2}$$

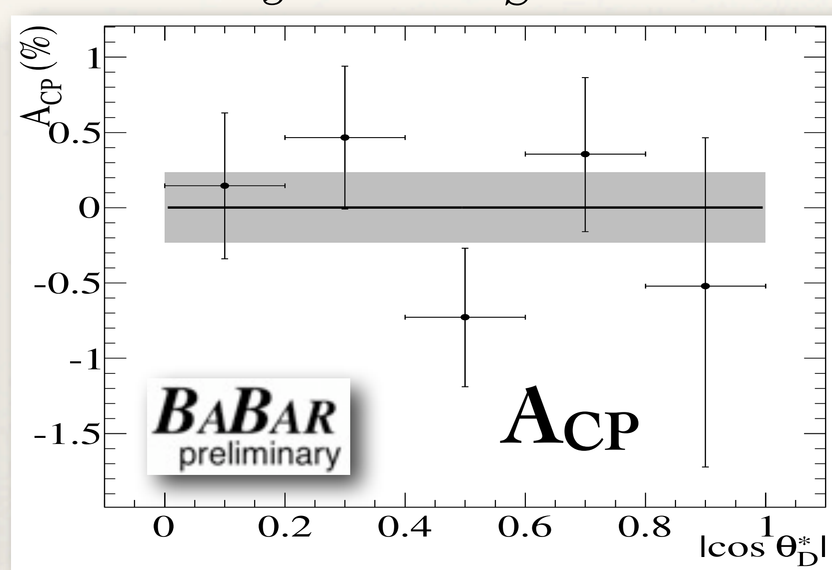


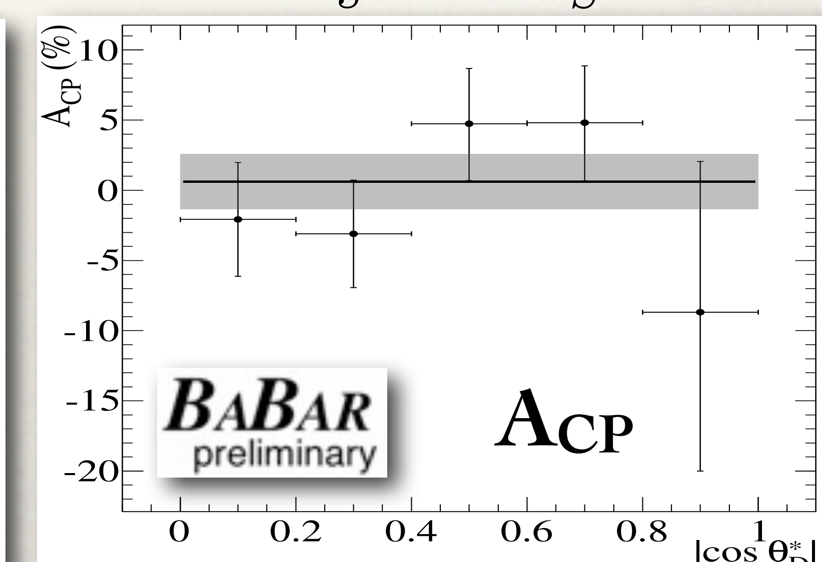




$D^{\pm} \to K_S^0 K^{\pm}$ $\qquad D_s^{\pm} \to K_S^0 K^{\pm}$ $\qquad D_s^{\pm} \to K_S^0 \pi^{\pm}$







A_{CP} 0.155±0.36% **A_{CP} 0.00±0.23%** **A_{CP} 0.6±2.0%**

Systematics

- Dominant contributions:
  - correction of detector-induced asymmetry
  - choice of binning (only for $D_s^{\pm} \to K_S^0 \pi^{\pm}$)

Syst. uncertainty (absolute)	$D^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 K^{\pm}$	$D_s^{\pm} \to K_S^0 \pi^{\pm}$
Efficiency of PID selectors	0.05%		0.05%
Statistics of control sample	0.23%		0.06%
Selection of control sample	0.01%		0.01%
$\cos\Theta^*$ binning	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] arxiv:1006.1938
[2] arXiv:1110.3790v1

Final values

- Corrections to the final values for biases and interference effect

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

469 fb^{-1}

(value)±(stat)±(syst)

- No sign of physics beyond the SM

Conclusions

- We measure the time-integrated CP asymmetry in the following modes:

$$D^{\pm} \to K^0_S K^{\pm} \qquad D^{\pm}_s \to K^0_S K^{\pm} \qquad D^{\pm}_s \to K^0_S \pi^{\pm}$$

- Systematic error down to 0.2% by using a data-driven method to remove asymmetry induced by detector effects

- Final values are compatible with SM predictions within one standard deviation

	BABAR(469 fb^{-1})	Belle(673 fb^{-1}) [1]
$D^+ \to K^0_S K^+$	$(+0.13 \pm 0.36 \pm 0.25)\%$	$(-0.16 \pm 0.58 \pm 0.25)\%$
$D^+_s \to K^0_S K^+$	$(-0.05 \pm 0.23 \pm 0.25)\%$	$(+0.12 \pm 0.36 \pm 0.22)\%$
$D^+_s \to K^0_S \pi^+$	$(+0.6 \pm 2.0 \pm 0.3)\%$	$(5.45 \pm 2.50 \pm 0.33)\%$

[1] Phys. Rev. Lett. 104, 181602 (2010)

CP asymmetry extraction

- After removing the charge asymmetry induced by detector effect, the measured asymmetry can be written as:

$$A = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}} = \frac{A_{FB} + A_{CP}}{1 + A_{FB}A_{CP}} \approx A_{FB} + A_{CP}$$

- A_{FB} asymmetry is an odd function of the D polar angle Θ in CMS (only first order term below):

$$A_{FB}(\cos\Theta) = \frac{8}{3} a_{FB} \frac{\cos\Theta}{1 + \cos^2\Theta}$$

$$A_{FB} = \frac{A^{\cos\Theta>0} + A^{\cos\Theta<0}}{2}$$

$$A_{CP} = \frac{A^{\cos\Theta>0} - A^{\cos\Theta<0}}{2}$$

- Each pairs of symmetric $\cos\Theta$ bins produces one asymmetry value
- Values are combined using a χ^2 minimization

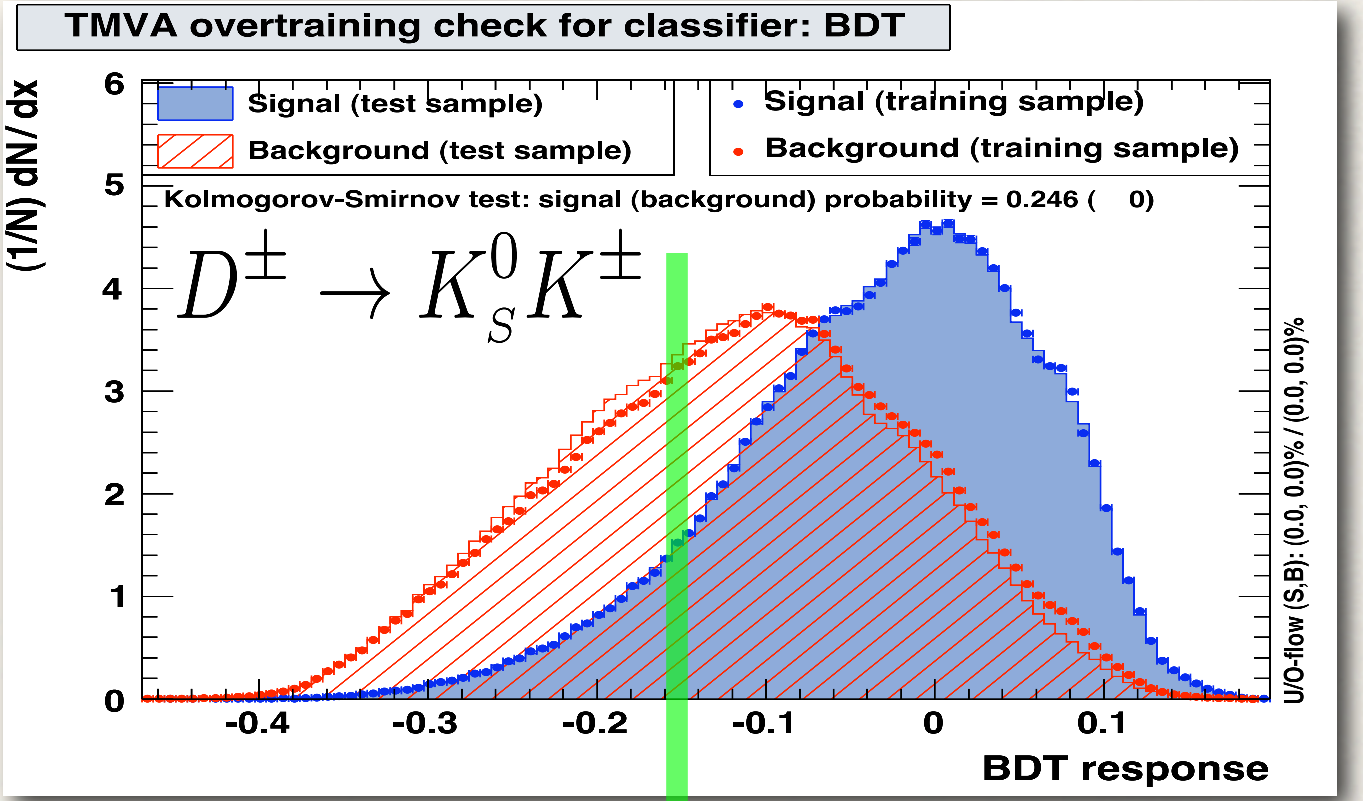
Cut-based analysis selection

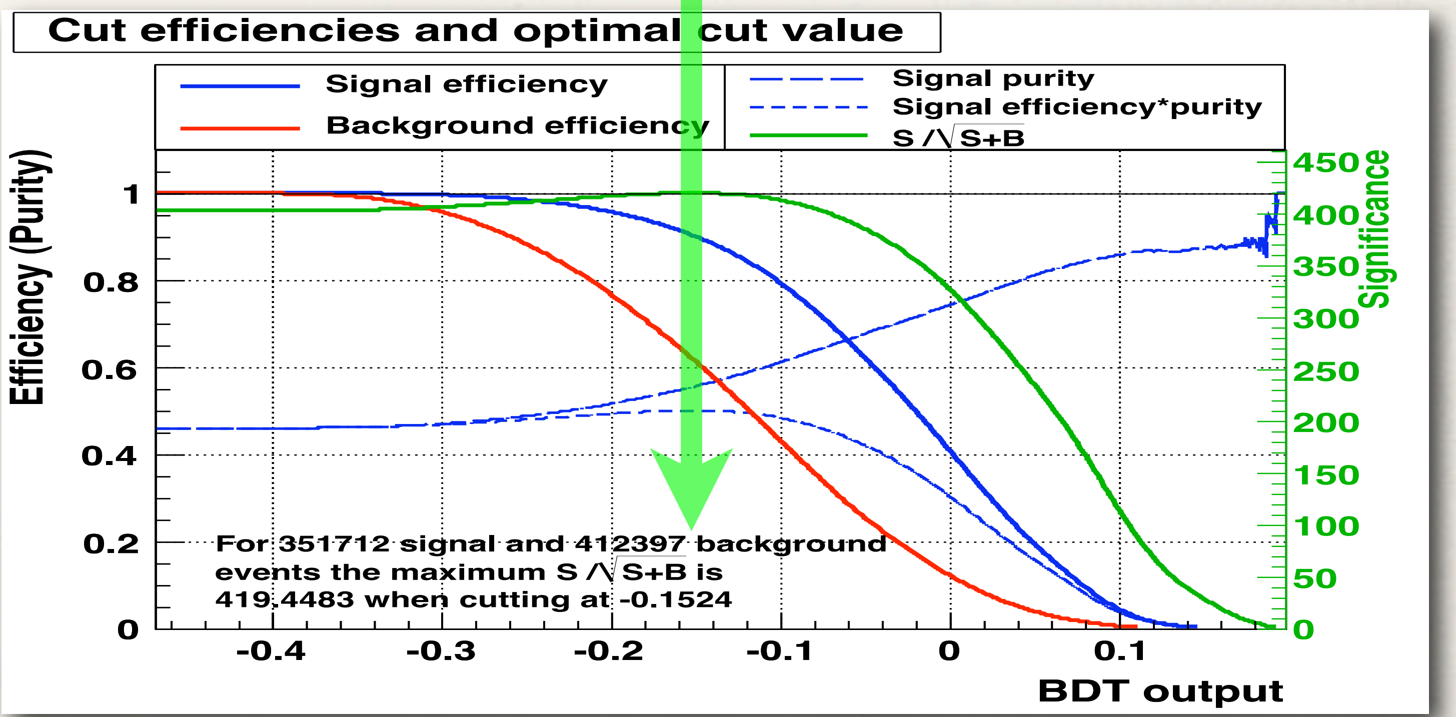
- D(s) candidates fully reconstructed
- Selection during processing
  - D(s) candidate
    - Chi^2 probabilities for the kinematic fit more than 0.1%
  - Ks candidate
    - Decay length significance, greater than 3
    - Chi^2 probabilities for the kinematic fit more than 0.1%
- Selection cuts:
  - $D_{(s)}$ candidate
    - Invariant mass, within 65 MeV/c^2 from nominal mass
    - CMS momentum, $p^* > 2$ for D mode, $p^* > 2.6$ for D_s, for both $p^* < 5$ GeV/c,
    - Transverse distance, $|d_0| < 0.3$ cm
    - Lifetime using decay distance in the transverse plane, $-15 < \tau < 35$ ps
  - K_S candidate
    - Invariant mass, within 10 MeV/c^2 from nominal mass

- For data/MC agreement, truth matched charm decays are rescaled to account for not exact branching fractions in the simulation

Multivariate Selection

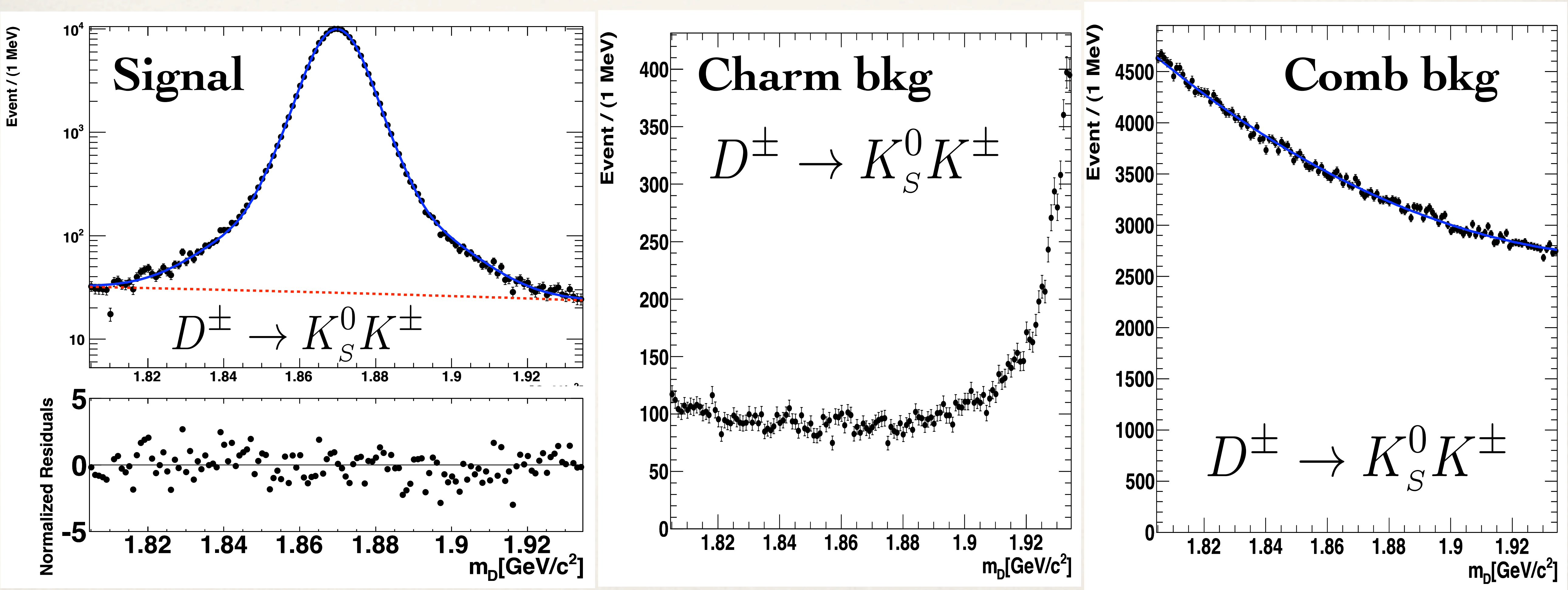
- Multivariate analysis using a Boosted Decision Tree (BDT)/ Likelihood method trained on MC events
- 7 kinematic variables:
  - $D_{(s)}$: lifetime, CMS mom and decay distance in transverse plane
  - K_S and pion: momentum and transverse momentum
- Criterion optimized using significance: $S/\sqrt{(S+B)}$





Fit to PDF components on MC

- Fit to MC distributions for different components:
  - **Signal**: Sum of 3 Gaussian functions, two with the same mean, plus a 1st order polynomial
  - **Charm background** from other charm modes with similar invariant mass or mis-id pion/kaon, 1D not parametric pdf from MC
  - Almost-flat **combinatorial background** (2nd order polynomial)



Simultaneous fit, parameters splitting

- **Simultaneous binned extended maximum likelihood fit** to 20 separated sub-samples: positive and negative candidates, 10 bins of $\cos\theta^*_{D_{(s)}}$(bin b0 [-1.0,-0.8], ..., bin b9 [+0.8,+1.0])
- Complicate splitting, not for all the parameters or for all the bins. Some parameters are set to a constant value

Name	Description	$D^\pm \to K^0_s K^\pm$	$D^\pm_s \to K^0_s K^\pm$	$D^\pm_s \to K^0_s \pi^\pm$
$N_{\rm sig}$	Signal yield	10	10	10
$A_{\rm sig}$	Signal asymmetry	10	10	10
$A_{\rm charm}$	Charm bkg asymmetry	-	-	1
$N_{\rm charm}$	Charm bkg yield	10	10	10
$N_{\rm comb}$	Combin. bkg yield	7 (b0-2: $N_{\rm comb} = 0$)	10	10
$A_{\rm comb}$	Combin. bkg asymm	10	10	10
m_1	Mean of 1st Gaussian	1	1	1
σ_1	Width of 1st Gaussian	10	10	b0-3,b4,b5, b6,b7,b8,b9
m_2	Mean of 2nd Gaussian	1	1	-
σ_2	Width of 2nd Gaussian	1	1	-
f_1	Fraction of 1st Gaussian	b0,b1,b2-8 (b9: $f_1 = 1$)	9 (b9: $f_1 = 1$)	-
a	1st coef. of combin. bkg	b0,b1,b2, b3-7,b8,b9	b0,b1,b2,b3, b4-7,b8,b9	b0,b1-6,b7, b8,b9
b	2nd coef. of combin. bkg	1	1	-
Total # of floating parameters		70	80	64

Systematics

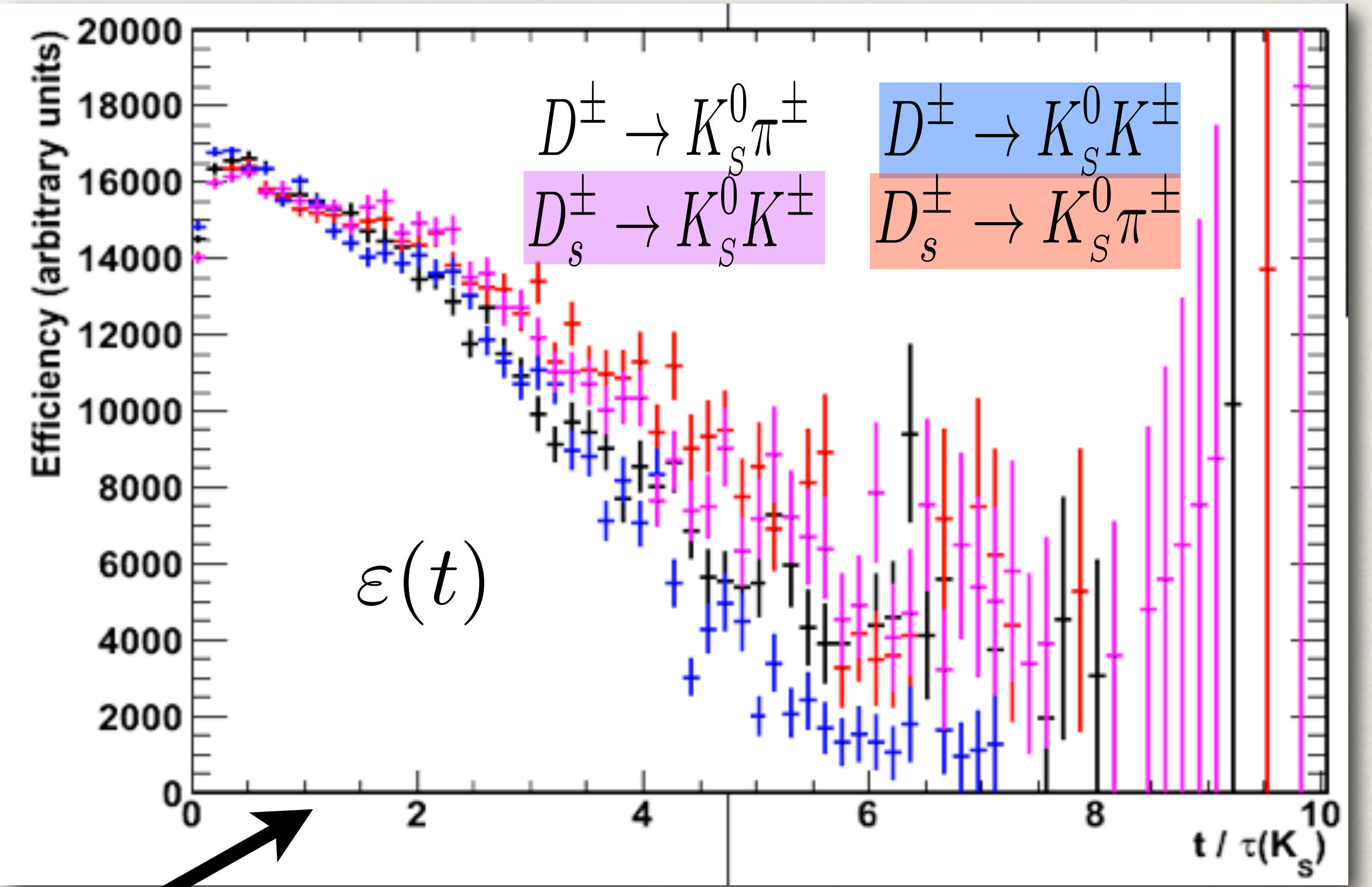
- Similar to those for the $D^{\pm} \to K_S^0 \pi^{\pm}$ mode:
  - Contamination of control sample due to charge asymmetry in PID selector efficiency, estimated using the A_{CP} deviation in the fit to the MC sample with and w/o corrections (a correction to the final value is also applied for this effect)
  - Uncertainty for correction factors of detector induced asymmetry, estimated using A_{CP} standard deviation for 500 fits to the data sample where correction factors are smeared by their errors
  - Basic selection for generic tracks sample, estimated using the asymmetry in the MC for truth matched tracks
  - Choice of binning $\cos\theta^*_{D_{(s)}}$, estimated using the largest A_{CP} deviation in the fit with 8 and 12 bins
  - Deviation due to $K^0 - \overline{K}^0$ regeneration([arxiv:1006.1938]), estimated integrating the nuclear cross-section for K^+/K^- (isospin symmetry), the material in the BaBar tracking system, and our K_S reconstruction efficiency (from MC)
  - Deviation due to K_S-K_L interference (see next slide)

K_S-K_L interference

- Reconstructed state is ππ, not pure K_S, but overlap of K_S and K_L
- Effective A_{CP} asymmetry calculation using correct BF's K^0-> ππ plus K^0 reconstruction efficiency vs time [arXiv:1110.3790v1]

$$A_{\text{effective}} = \frac{\int_0^\infty \varepsilon(t)\left(\Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)\right)dt}{\int_0^\infty \varepsilon(t)\left(\Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)\right)dt}$$

- Reconstruction efficiency from MC
- Small deviations, few percent or less



	Deviation
$D^\pm \to K^0_S\pi^\pm$	-0.003%
$D^\pm \to K^0_S K^\pm$	-0.015%
$D_s^\pm \to K^0_S K^\pm$	-0.014%
$D_s^\pm \to K^0_S\pi^\pm$	+0.008%