DHEP Annual Meeting
Search for CP violation in the radiative mode $D^0 \to \phi\gamma$

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Motivation

- CP violation in the charm sector had been investigated for a number of modes in the Belle Experiment. A few recent results are

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$
$$A_{CP}(D^0 \to K_s^0\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$$

(N.K.Nisar et al. arXiv:1404.1266[hep-ex] 2014)

$$A_{CP}(D^+ \to K_s^0 K^+) = (-0.25 \pm 0.28 \pm 0.14)\%$$

(B.R.Ko et al. arXiv:1212.6112 [hep-ex] 2013)

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

(B.R.Ko et al. arXiv:1001.3202[hep-ex] 2012)

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

(M.Staric et al. arXiv:1110.0694 [hep-ex] 2011)

- The paper by Gino Isidori and Jernej F. Kamenik (2012)(PhysRevLett.109.171801) using models beyond SM, predicts sizeable CP Asymmetry in modes of the kind $D^0 \to V\gamma$ where V is a vector particle, upto several percent.
- Thus this can be an important search for physics beyond the standard model. We intend to search for CP violation in the mode $D^0 \to \phi\gamma$

Why study $D^0 \to \phi\pi^0$?

- The modes $D^0 \to \phi\pi^0$ and $D^0 \to \phi\eta$ are important backgrounds for our signal mode $D^0 \to \phi\gamma$ as both the π^0 and η decay into two photons and if one of the photons is not reconstructed, it would resemble our signal.
- The branching fractions of the modes are (PDG, PR D86, 010001 (2012))

$$\mathcal{B}(D^0 \to \phi\pi^0,\, \phi \to K^+K^-) = (6.4 \pm 0.4) \times 10^{-4}$$
$$\mathcal{B}(D^0 \to \phi\eta) = (1.4 \pm 0.5) \times 10^{-4}$$
$$\mathcal{B}(D^0 \to \phi\gamma) = (2.7 \pm 0.35) \times 10^{-5}$$

- We study the mode $D^0 \to \phi\pi^0$ because of its relatively higher branching fraction (more than 20 times the signal $D^0 \to \phi\gamma$) and because it will familiarize us with the fitting and extraction procedure for A_{CP}

Cuts Applied ($D \to \phi\pi^0$)

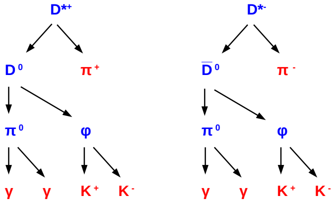


Figure : Signal Process Diagrams for $D^0 \to \phi\pi^0$ and $\overline{D^0} \to \phi\pi^0$

- $|dr|_{K^\pm,\pi_s} < 1.0$ cm
- $|dz|_{K^\pm,\pi_s} < 3.0$ cm
- $\mathcal{R}_{K^\pm}$ (Kaon Likelyhood) > 0.1
- $\mathcal{R}_{\pi_s}$ (Kaon Likelyhood) < 0.9
- 1.01 GeV $< M_\phi <$ 1.03 GeV
- $E_\gamma > 50 MeV$ (Barrel)
- $E_\gamma > 100 MeV$ (Endcap)
- 119 MeV $< M_{\pi^0} <$ 151 MeV
- $P^*_{D^*} > 2.5 GeV$ (optimized)
- $P_{\pi^0} > 380 MeV$ (optimized)
- 1.83 GeV $< M_{D^0} <$ 1.89 GeV (optimized)
- 140 MeV $< \Delta M <$ 160 MeV

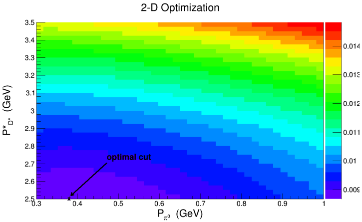


Figure : 2-D cut optimization

- Since the $P^*_{D^*} - P_{\pi^0}$ variables are correlated, a 2-D optimization , varying each cut independently, is performed.
- The optimizations are performed by minimizing the figure of merit,

$$\epsilon = \frac{\sqrt{N_{sig} + N_{bkg}}}{N_{sig}}$$

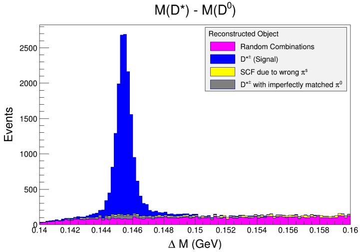


Figure : ΔM distribution.

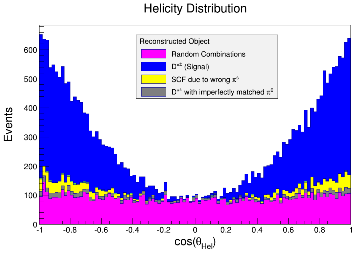


Figure : $\cos\theta_{\text{hel}}$ distribution.

How we measure CP asymmetry, A_{CP}

- A_{rec} is defined in terms of signal yield (N_{rec})

$$A_{rec} = \frac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to \overline{D^0}\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to \overline{D^0}\pi_s^-}}$$

A_{rec} is the sum of three terms. $A_{rec} = A_{cp} + A_{FB} + A_{\epsilon}^{\pi_s}$

- It has been demonstrated from previous CP asymmetry studies that the pion detection efficiency asymmetry $A_{\epsilon}^{\pi_s} = +0.11\%$
- Since A_{FB} is an odd function of $\cos(\theta^*_{D*})$,we divide the data in bins of $\cos(\theta^*_{D*})$ and extract A_{cp} and A_{FB} from it by adding and subtracting bins at $\pm cos(\theta^*_{D*})$

$$A_{CP} = \frac{A_{rec}^{cor}(cos(\theta^*_{D*}) + A_{rec}^{cor}(-cos(\theta^*_{D*})}{2} \text{ and}$$

$$A_{FB} = \frac{A_{rec}^{cor}(cos(\theta^*_{D*}) - A_{rec}^{cor}(-cos(\theta^*_{D*})}{2}$$

Full $\Upsilon(4S)$ MC ΔM Fit: Shift in $\cos\theta_{\mathrm{hel}}$ distribution

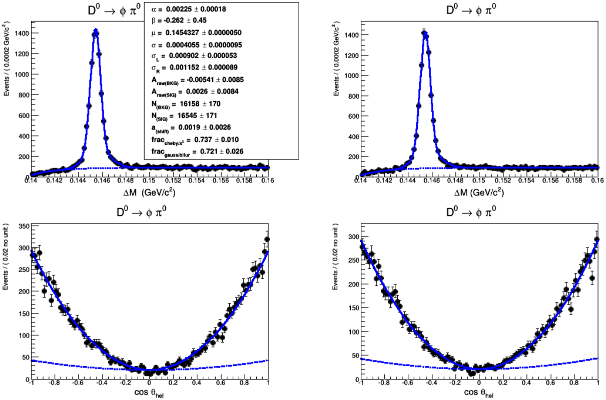


Figure : Simultaneous fit of the Full Υ(4S) generic MC (711 fb^{-1})

For the Helicity component, the signal shape is modeled by an $(x-a)^2$ function. The fitted value obtained for the helicity shift parameter is $a_{\mathrm{shift}} = 0.0019 \pm 0.0026$

Full $\Upsilon(4S)$ Data 2D Fit: Shift in $\cos\theta_{\rm hel}$ distribution

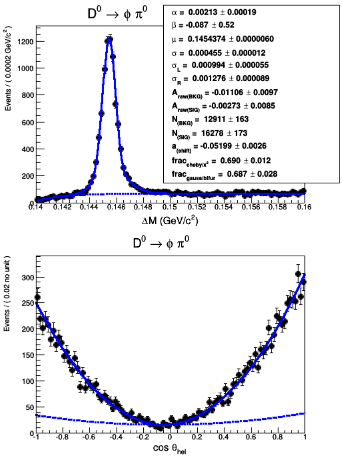


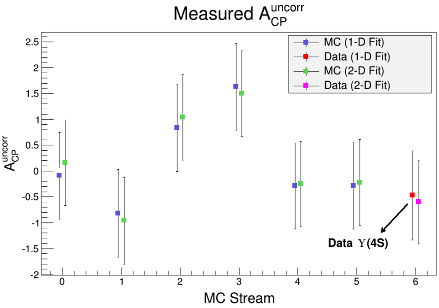
Figure : Simultaneous 2-D fit of the Full $\Upsilon(4S)$ Data (711 fb^{-1})

The fitted value obtained for the helicity shift parameter is $a_{\rm shift} = -0.05199 \pm 0.0026$ ($\sim 20\sigma$ *effect*)

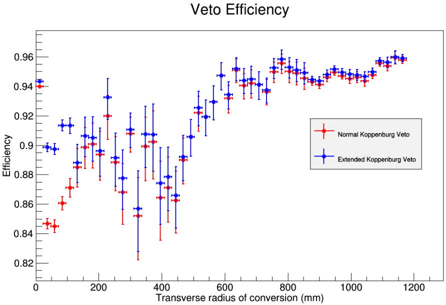
Results : $A_{CP}^{uncorrected}$ at the $\Upsilon(4S)$ resonance ($711\ fb^{-1}$)

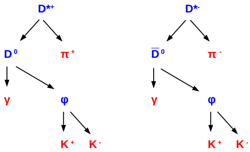
Sample	A_{CP}^{uncorr} (1-D Fit) %	A_{CP}^{uncorr} (2-D Fit) %
MC 0	-0.09 ± 0.84	$+0.16 \pm 0.83$
MC 1	-0.82 ± 0.85	-0.96 ± 0.84
MC 2	$+0.83 \pm 0.84$	$+1.04 \pm 0.83$
MC 3	$+1.63 \pm 0.84$	$+1.50 \pm 0.83$
MC 4	-0.29 ± 0.83	-0.25 ± 0.82
MC 5	-0.28 ± 0.84	-0.22 ± 0.83
Data	-0.047 ± 0.86	-0.60 ± 0.81

Since we do not correct for the slow Pion detection efficiency asymmetry, we measure $A_{CP}^{uncorrected} = A_{CP} + A_{\epsilon}^{\pi_s}$



$D^0 \to \phi\gamma$ Study : Efficiency of the Extended π^0 Veto



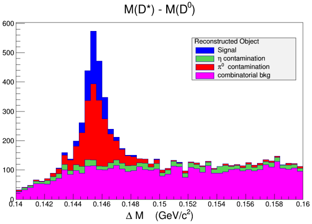


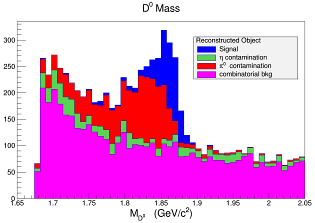
- The candidate photon in in our main channel $D \to \phi\gamma$ is clubbed up with all other photons in the event and a probability is assigned for each combination on whether they come from a decayed π^0.
- We have tried to improve the Vetoing efficiency by including in our list of photons in the given event, photons that have converted into an e^+e^- pair.

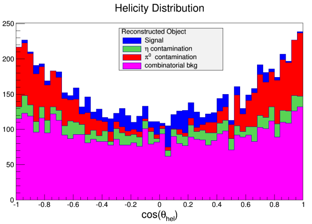
Summary of cuts

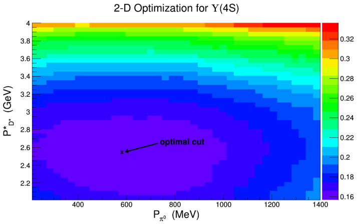
Variable	Cut-$\Upsilon(4S)$	Eff. (%) Loss	Cut-$\Upsilon(5S)$	Eff.(%) Loss
$\lvert dr\rvert_{K^+,K^-,\pi_s}$	$<$ 1.0 cm		$<$ 1.0 cm	
$\lvert dz\rvert_{K^+,K^-,\pi_s}$	$<$ 3.0 cm		$<$ 3.0 cm	
$\mathcal{R}_{K^+,K^-}$	$>$ 0.1	0.91	$>$ 0.1	0.83
$\mathcal{R}_{\pi_s}$	$<$ 0.9	0.14	$<$ 0.9	0.08
M_ϕ	1.01 - 1.03 (GeV)	10.71	1.01 - 1.03 (GeV)	11.01
	($\sim \pm 2.9\sigma$)		($\sim \pm 2.9\sigma$)	
M_{D^0}	1.68 - 2.05 (GeV)	0.52	1.68 - 2.05 (GeV)	0.53
ΔM	140 - 160 (MeV)	0.18	140 - 160 (MeV)	0.19
π^0 probability	$<$ 0.049	54.29	$<$ 0.055	53.90
η probability	$<$ 0.359	7.01	$<$ 0.390	5.69
E9/E25	$>$ 0.938	7.72	$>$ 0.941	7.96
E_γ	$>$ 580 MeV		$>$ 610 MeV	
		33.56 (2-D)		53.90 (2-D)
$P^*_{D^*}$	$>$ 2.55 GeV		$>$ 3.10 GeV	

$D^0 \to \phi\gamma$: Backgrounds, 2-D optimization









Comparison of different fitting schemes

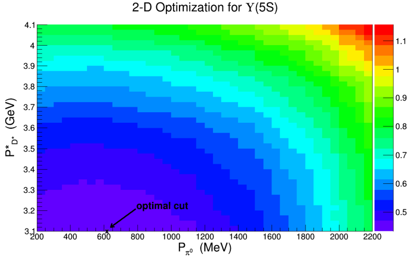
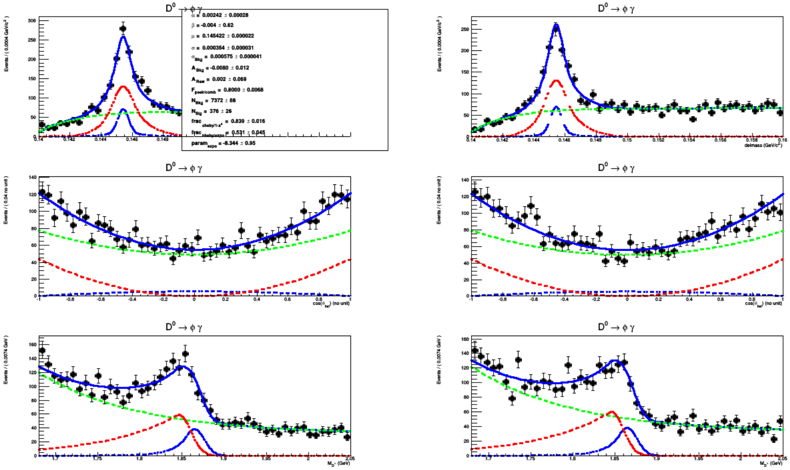


Table : Comparison of fitting results

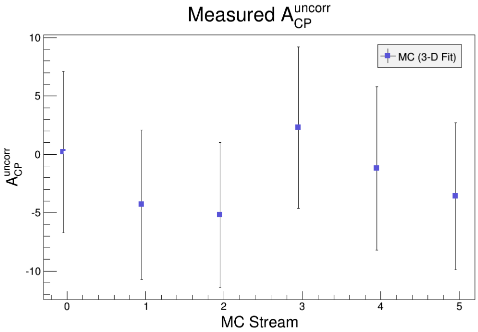
Fit type	A_{raw} measured %
ΔM-$\cos\theta_{hel}$ 2-D Fit	-4.5 $\pm$ 8.5
M_D-$\cos\theta_{hel}$ 2-D Fit	-2.7 $\pm$ 7.5
3-D Fit	0.2 $\pm$ 6.9

- For the ΔM-$\cos\theta_{hel}$ fit, we use an optimized M_D signal window (1.84 - 1.89 GeV), and for the M_D-$\cos\theta_{hel}$ fit, we use an optimized ΔM signal window (142 - 148 MeV)
- The 3-D fit has the smallest uncertainty in A_{CP}

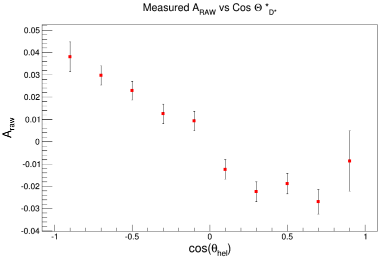
Projections of the 3-D fit to the variables ΔM, M_D and $\cos\theta_{hel}$

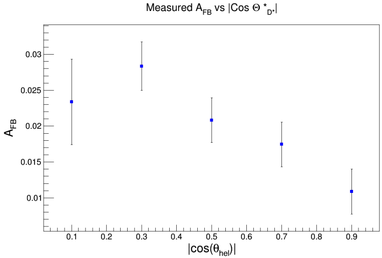


MC Stream	A_{CP}^{uncorr} (3-D Fit)(%)
0	$+0.2 \pm 6.9$
1	-4.3 ± 6.4
2	-5.2 ± 6.2
3	$+2.3 \pm 6.9$
4	-1.2 ± 7.0
5	-3.6 ± 6.3



The method of reweighting: A_{Raw} for $D \to K_S \pi^0$





- Since we do not expect large statistics for the main mode $D \to \phi\gamma$, the method of binning in the D^* production direction to correct for A_{FB} is not viable.
- Instead, we use a high statistics mode like $D \to K_S \pi^0$ to estimate A_{FB} bin by bin, and we use these values to appropriately assign weights to our signal mode, during the simultaneous fitting, in order to correct for A_{FB}.

The method of reweighting

Table : Comparison of total A_{CP} measurements for the mode $D \to K_S\pi^0$

Number of bins	Total A_{CP} (%) by the binning method	Total A_{CP} (%) by the reweighting method
2	0.07 ± 0.15	0.07 ± 0.15
4	0.00 ± 0.15	0.00 ± 0.15
10	0.01 ± 0.15	0.02 ± 0.15
20	0.01 ± 0.15	0.01 ± 0.15
30	0.00 ± 0.15	0.00 ± 0.15

Table : Comparison of total A_{CP} measurements for the mode $D \to \phi\pi^0$

Fit method	Total A_{CP}^{uncorr} (%) by the binning method	Total A_{CP}^{uncorr} (%) by the reweighting method
1-D Fit	-0.47 ± 0.86	-0.56 ± 0.85
2-D Fit	-0.60 ± 0.81	-0.66 ± 0.84

Current status

- Extensive Monte Carlo studies have been performed on the sources of backgrounds and the A_{CP} estimation procedure. We have also estimated the sensitivity of our final A_{CP} measurement using various streams of generic MC.
- The studies performed are under collaboration wide review, and once the scrutiny is completed, we expect to look at A_{CP} in real data.

THANK YOU!