$\sin(2\phi_1 + \phi_3)$ from $B \to D^*\pi$ using Partial Reconstructio

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SuperKEKB ϕ_3 Meeting

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Recap

Measure $\sin(2\phi_1 + \phi_3)$ in $D^*\pi$ system through small sin-like time-dependence

$$
\begin{aligned}
\Gamma_{B^0 \to D^{*-}\pi^+} &= Ce^{-\gamma\Delta t}\left[(1+R^2_{D^*\pi}) + (1-R^2_{D^*\pi})\cos(\Delta m\Delta t) - 2R_{D^*\pi}\sin(\phi_w - \delta_{D^*\pi})\sin(\Delta m\Delta t)\right] \\
\Gamma_{\bar{B}^0 \to D^{*+}\pi^-} &= Ce^{-\gamma\Delta t}\left[(1+R^2_{D^*\pi}) + (1-R^2_{D^*\pi})\cos(\Delta m\Delta t) + 2R_{D^*\pi}\sin(\phi_w + \delta_{D^*\pi})\sin(\Delta m\Delta t)\right] \\
\Gamma_{B^0 \to D^{*+}\pi^-} &= Ce^{-\gamma\Delta t}\left[(1+R^2_{D^*\pi}) - (1-R^2_{D^*\pi})\cos(\Delta m\Delta t) - 2R_{D^*\pi}\sin(\phi_w + \delta_{D^*\pi})\sin(\Delta m\Delta t)\right] \\
\Gamma_{\bar{B}^0 \to D^{*-}\pi^+} &= Ce^{-\gamma\Delta t}\left[(1+R^2_{D^*\pi}) - (1-R^2_{D^*\pi})\cos(\Delta m\Delta t) + 2R_{D^*\pi}\sin(\phi_w - \delta_{D^*\pi})\sin(\Delta m\Delta t)\right]
\end{aligned}
$$

Parameters :	C	normalization	
	γ	width = $1/\tau_B$	from PDG 2002
	$R_{D^*\pi}$	decay ratio	from $D_s\pi/D^*\pi^0$/theory $\sim$ 0.02
	Δm	mixing	from PDG 2002 (or measure)
	ϕ_w	CP violation	$2\phi_1 + \phi_3$
	$\delta_{D^*\pi}$	strong phase	$\to$ ambiguity

Use partial reconstruction $\to$ large event sample

- Identify signal using fast pion (π_f) and slow (from D^*) pion only
- Tag using high momentum lepton (l) $\Leftrightarrow$ reduce continuum background
- Measure Δz as $z_{\pi_f} - z_l$ ($\Delta z = (\beta\gamma)_\Upsilon c\Delta t$)

$R_{D^*\pi}$ - ratio of decay amplitudes

$$R_{D^*\pi} = \frac{\text{SUPPRESSED}}{\text{FAVOURED}} = \left| \frac{V_{cd}^* V_{ub}}{V_{cb}^* V_{ud}} \right| r_{D^*\pi} \approx 0.02\, r_{D^*\pi}$$

- Can measure it from $D_s^+ \pi^-$:

$$\mathcal{B}(B^0 \to D_s^+ \pi^-) \approx \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)}{\tan^2\theta_C} \left(\frac{f_{D_s}^2}{f_{D^*}^2} \right) R_{D^*\pi}^2$$

- Assuming: $f_{D_s}^2 / f_{D^*}^2 = 1$, $\tan\theta_C = 0.22$,
  $\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-) = (2.76 \pm 0.21) \times 10^{-3}$ (PDG 2002),

- Use BaBar & Belle $\mathcal{B}(B^0 \to D_s^+\pi^-) \times \mathcal{B}(D_s^+ \to \phi\pi^+)$ numbers,
  with NEW Belle & CLEO $\mathcal{B}(D_s^+ \to \phi\pi^+)$ numbers

$$\frac{\mathcal{B}(B^0 \to D_s^+\pi^-)}{10^{-5}} = \frac{\langle (11.3 \pm 3.3 \pm 2.1) + (8.6^{+3.7}_{-3.0} \pm 1.1) \rangle}{\langle (3.72 \pm 0.39^{+0.47}_{-0.39}) + (3.59 \pm 0.77 \pm 0.48) \rangle} = 2.72 \pm 0.84$$

$$\rightsquigarrow R_{D^*\pi} \approx 0.022 \pm 0.007$$

$R_{D^*\pi}$ - ratio of decay amplitudes

- Looks like just need to keep improving measurements of $\mathcal{B}(B^0 \to D_s^+ \pi^-)$ & $\mathcal{B}(D_s^+ \to \phi \pi^+)$
- BUT what about
  - possible contributions from W-exchange & annihilation diagrams
  - the $SU(3)$ approximation $f_{D_s}^2 / f_{D^*}^2 = 1$ (?)
- BaBar people assume 30% theoretical error on $R_{D^*\pi}$ from this method $\rightsquigarrow$ as big as the experimental error now!
- With more statistics can measure $\mathcal{B}(B^- \to D^{*-}\pi^0)$

$$\frac{\mathcal{B}\left(B^- \to D^{*-}\pi^0\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{*+}\pi^-\right)} = \frac{1}{2} R_{D^*\pi}^2$$

  BUT again might worry about W-exchange/annihilation
- Another suggestion to measure $R_{D^*\pi}$ from $R_{D^*\rho}$ (longitudinal component) BUT kinematics may be different
- Will need to worry about this for $< 10\%$ measurement of $\sin(2\phi_1 + \phi_3)$

Principle of partial reconstruction well-established:

$$B \to D^{*-}\pi_f^+$$
$$\hookrightarrow \bar{D}^0\pi_s^-$$
$$\hookrightarrow X\,Y\,Z$$

Degrees of freedom:

— 4 momentum of

- B, D^*, π_f, D^0, $\pi_s \Rightarrow$ 20

Constraints from

- 4 momentum conservation (8)
- Assumed particle masses (5)
- Measured 3 momentum (π_f, π_s) (6)
- Beam energy (1)

Can solve the system!

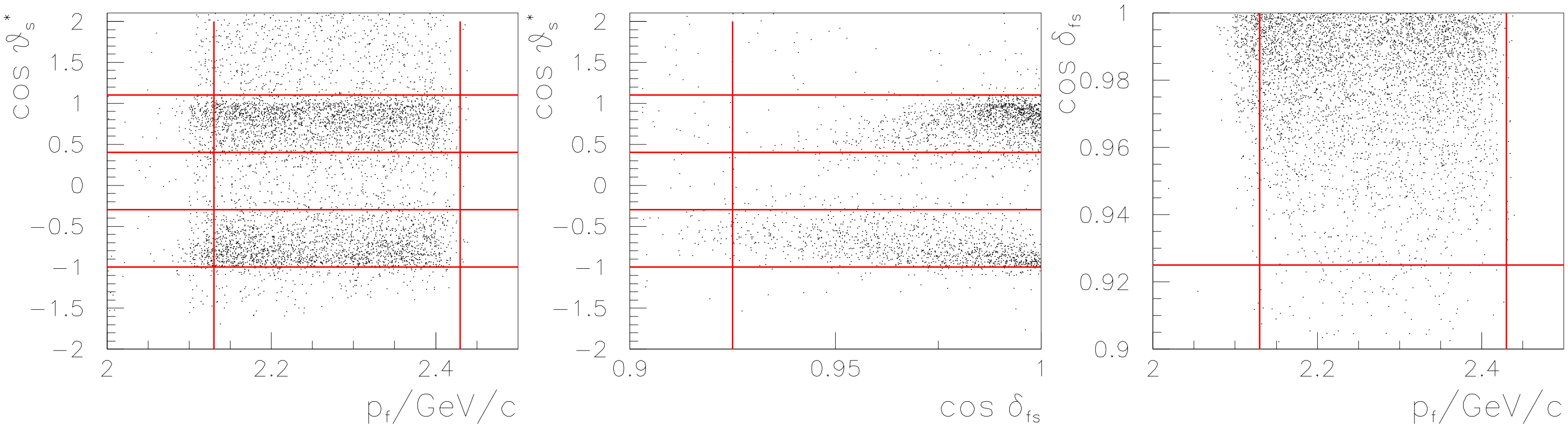
Have 6 pieces of information $(\mathbf{p}_{\pi_f}, \mathbf{p}_{\pi_s})$,

BUT π_f isotropic in detector & π_s has no preferred direction around π_f

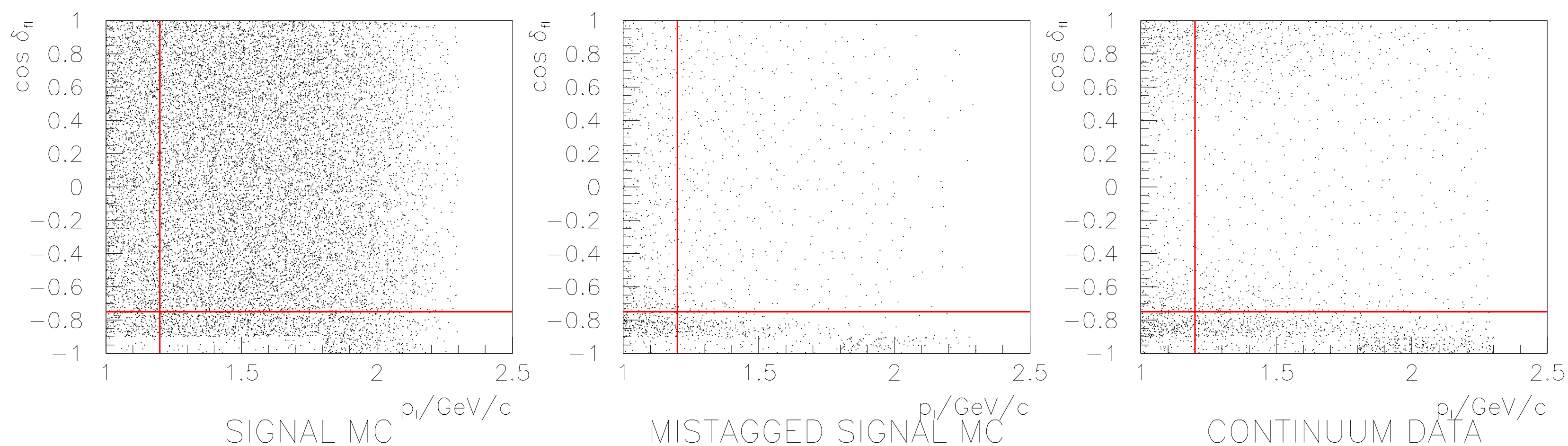
$\rightarrow$ can use (up to) 3 kinematic variables to separate signal from background

Partial Reconstruction - Event Selection

- Identify signal using 3 ≈ independent variables: p_{π_f}, $\cos\delta_{fs}$, $\cos\theta^*_s$



- Tag using high momentum lepton



Backgrounds

Identify four categories of background:

- ⋆ $D^*\rho$ ⇝ same quark level process as $D^*\pi$
- ⋆ Correlated background ⇝ *egs.* $D^{**}\pi$, $D^* l\nu$
- ⋆ Uncorrelated background ⇝ *egs.* $D\pi$, $D\rho$
- ⋆ Continuum background ⇝ $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$

Different background categories have different p_{π_f}, $\cos\delta_{fs}$, $\cos\theta^*_s$ distributions

Extract signal yield and event-by-event signal/background probabilities from a 3 dimensional binned fit $(p_{\pi_f}, \cos\delta_{fs}, \cos\theta^*_s)$

Use 78 fb^{-1} of Belle data (collected up to summer 2002)

Measure $D^*\pi$, $D^*\rho$ & correlated background shapes from Monte Carlo

Combine uncorrelated, continuum backgrounds & get shape from "wrong sign" data

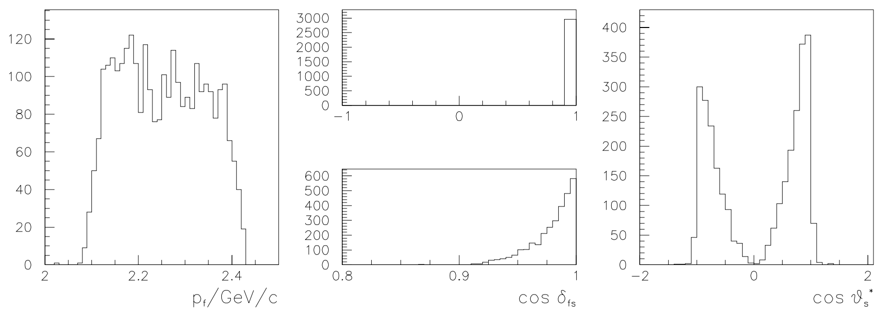
"wrong sign" = fast and slow pions have same charge

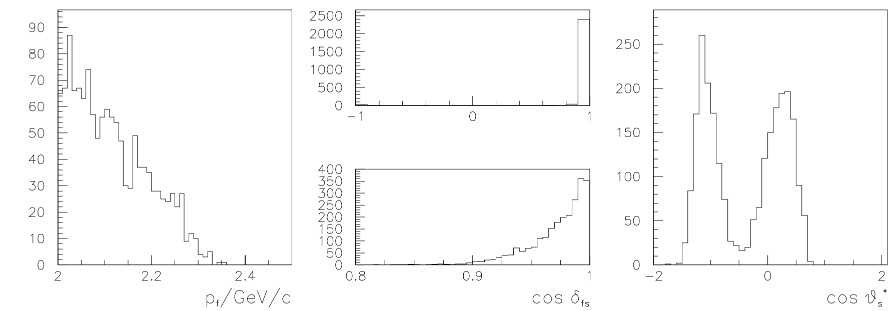
Fit independently for: "same flavour" $\pi_f^- l^-$, $\pi_f^+ l^+$

"opposite flavour" $\pi_f^- l^+$, $\pi_f^+ l^-$

Background Shapes

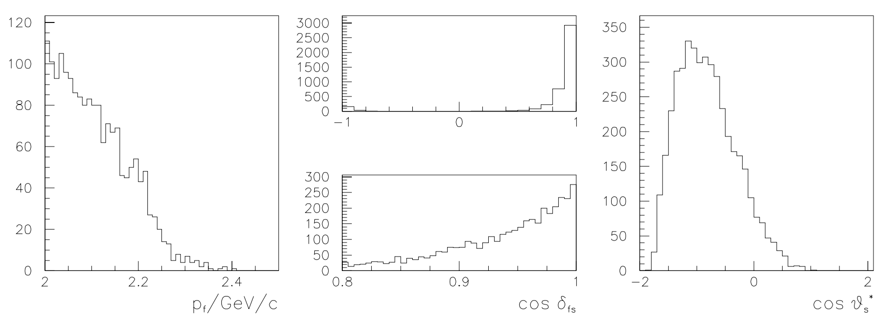
$D^*\pi$ $D^*\rho$

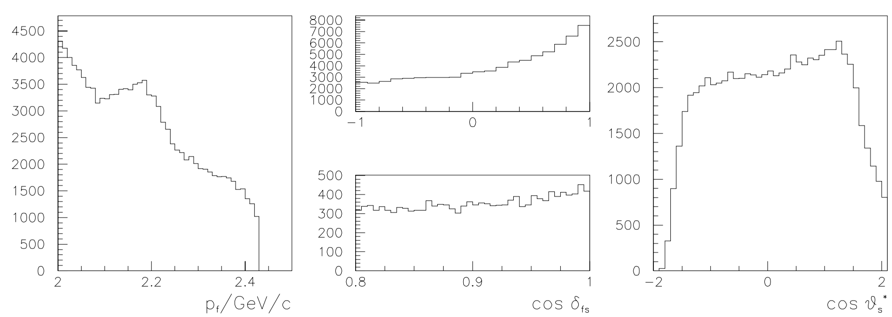




Correlated background

Uncorrelated background





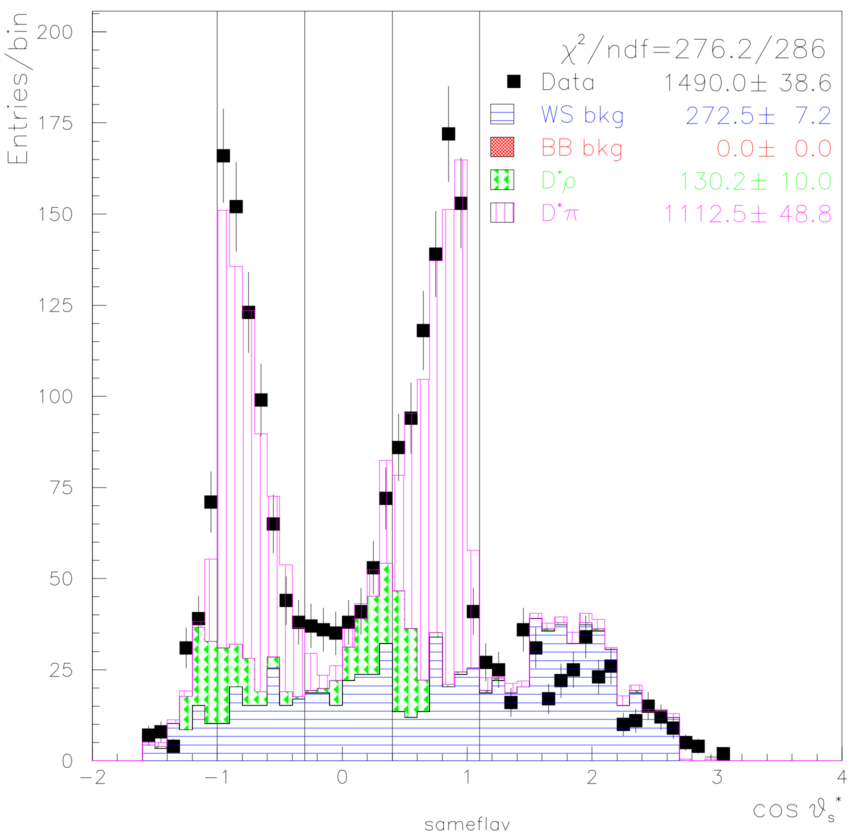
If background systematics get too high just select bins with the best S/B
(lazy trade between statistical/systematic error)

Yield Fit Results

Shown here the results of the fit projected onto the $\cos\theta^*_s$ axis

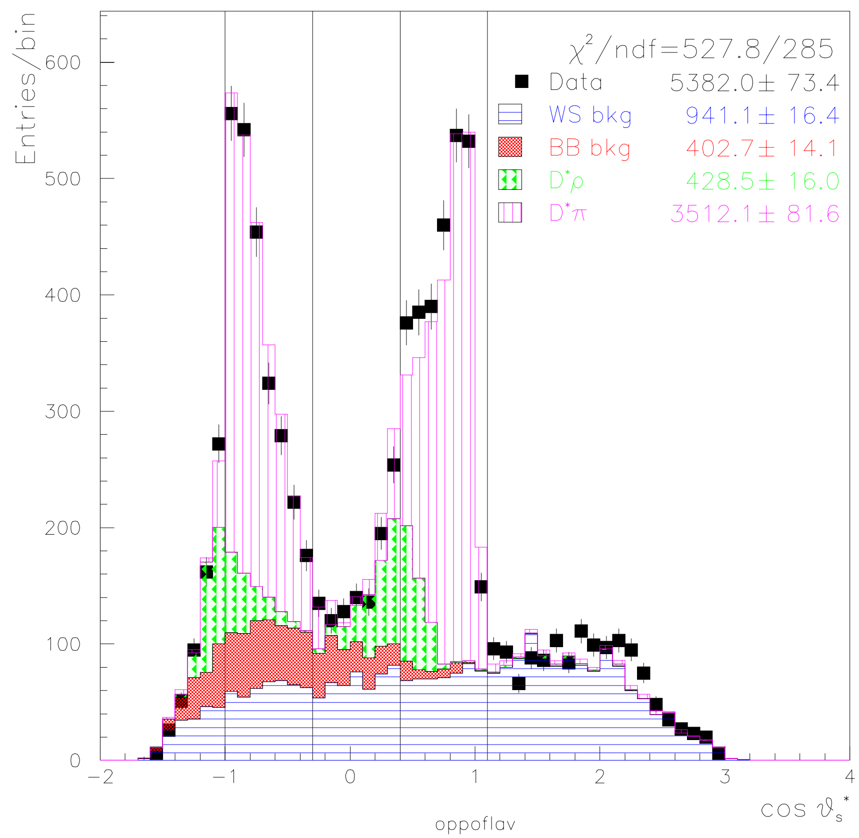
SAME FLAVOUR EVENTS

1490 candidates / 1110 $\pm$ 50 signal



OPPOSITE FLAVOUR EVENTS

5382 candidates / 3510 $\pm$ 80 signal



Yield Fit Results

Mode	χ^2/ndf	Data	$D^*\pi$	$D^*\rho$	Corr. bkg.	WS bkg.	"S/B"	$\frac{D^*\pi}{D^*\rho}$
SF	276.2/286	1490.0±38.6	1112.5±48.8	130.2±10.0	0.0±0.0	272.5±7.2	4.6±0.2	8.5±0
OF	527.8/285	5382.0±73.4	3512.1±81.6	428.5±16.0	402.7±14.1	941.1±16.4	2.9±0.1	8.2±0

From MC expect

	$D^*\pi$	:	$D^*\rho$	:	CBG
SF	2079	:	204	:	128
OF	10359	:	934	:	966

$$L = \Pi_i \left(f_{\mathrm{SIG}} P_{\mathrm{SIG}} \otimes R_{\mathrm{SIG}} + \Sigma_j f_{\mathrm{BKG}} P_{\mathrm{BKG}} \otimes R_{\mathrm{BKG}} \right)$$

i runs over events and j runs over background sources

- Terms of order $R^2_{D^*\pi}$ are neglected in P_{SIG}
- cos and sin terms in P_{SIG} diluted by $(1 - 2w)$
- f_{SIG} $(f_{D^*\pi}, f_{D^*\rho})$ and f_{BKG} (f_{WS}, f_{CB}) obtained from kinematic variables
- f_{BKG} corrected for SF/OF events to retain proper normalization
- $R_{\mathrm{SIG}} = R_{\mathrm{det}} \otimes R_k$
  - R_{det} parameters obtained from J/ψ decays
  - default R_k parameters used
- P_{BKG} parametrized and parameters measured from relevant sidebands
- $R_{\mathrm{BKG}} = R_{\mathrm{det}} \otimes R_k$ for parts from B decay
  $R_{\mathrm{BKG}} = R_{\mathrm{det}}$ for δ function parts
- Wrong tag fraction w measured from mixing amplitude

What is the Background?

Numbers of events in signal region from $B\bar{B}$ MC after reweighting

CORRELATED BACKGROUND			
MIXED		CHARGED	
$D^*\pi\pi^0$	176	$D^{**0}\pi$	346
$D^{**}\pi$	190	$D^*\pi\pi$	72
D^*K	164		
$D^*\mu\nu_\mu$	126		
$D^*e\nu_e$	82		

UNCORRELATED BACKGROUND			
MIXED		CHARGED	
$D\pi$	524	$D^{*0}\pi$	826
$D\rho$	235	$D^0\pi$	816
$D^{**}\pi$	132	$D^0\rho$	280
		$D^{*0}\rho$	266
		$D^{**0}\pi$	77

$$P_{\mathrm{BKG}} = \left(f_\delta \delta(\Delta z) + (1 - f_\delta) \frac{1}{2\tau_{\mathrm{BKG}}} \left\{ (1 - f_{\mathrm{MIX}}) + k_{\mathrm{MIX}} f_{\mathrm{MIX}} (1 \pm \cos(\Delta m \Delta t)) \right\} e^{-|\Delta t|/\tau_{\mathrm{BKG}}} \right) \otimes F$$

$$\Delta t = \frac{\Delta z}{\beta\gamma c} \qquad k_{\mathrm{MIX}} = \left(1 \pm \frac{1}{1 + \Delta m^2 \tau_{B^0}^2} \right)^{-1}$$

Mode	WS params F(DELTA)	WS params TAU(BKG)	WS params F(MIX)	CB params F(DELTA)	CB params TAU(BKG)	CB params F(MIX)
SF	$0.407^{+0.066}_{-0.071}$	$2.249^{+0.273}_{-0.237}$	$0.000^{+0.000}_{-0.000}$	N/A	N/A	N/A
OF	$0.293^{+0.033}_{-0.034}$	$1.703^{+0.082}_{-0.078}$	$0.000^{+0.000}_{-0.000}$	$0.000^{+0.009}_{-0.000}$	$1.317^{+0.046}_{-0.045}$	$0.000^{+0.000}_{-0.000}$

Effect of CP Violation

$$
\begin{aligned}
\Gamma_{B^0\to D^{*-}\pi^+} &= Ce^{-\gamma|\Delta t|}\,[1 + (1-2w)\cos(\Delta m\Delta t) - (1-2w)2R_{D^*\pi}\sin(\phi_w - \delta_{D^*\pi})\sin(\Delta m\Delta t)]\\
\Gamma_{\bar{B}^0\to D^{*+}\pi^-} &= Ce^{-\gamma|\Delta t|}\,[1 + (1-2w)\cos(\Delta m\Delta t) + (1-2w)2R_{D^*\pi}\sin(\phi_w + \delta_{D^*\pi})\sin(\Delta m\Delta t)]\\
\Gamma_{B^0\to D^{*+}\pi^-} &= Ce^{-\gamma|\Delta t|}\,[1 - (1-2w)\cos(\Delta m\Delta t) - (1-2w)2R_{D^*\pi}\sin(\phi_w + \delta_{D^*\pi})\sin(\Delta m\Delta t)]\\
\Gamma_{\bar{B}^0\to D^{*-}\pi^+} &= Ce^{-\gamma|\Delta t|}\,[1 - (1-2w)\cos(\Delta m\Delta t) + (1-2w)2R_{D^*\pi}\sin(\phi_w - \delta_{D^*\pi})\sin(\Delta m\Delta t)]
\end{aligned}
$$

Effect of non-zero $\sin(\phi_w)$ shows up as:

- Asymmetric peaks in SF distributions
- OF asymmetry : $\Gamma_{B^0\to D^{*-}\pi^+} \neq \Gamma_{\bar{B}^0\to D^{*+}\pi^-}$
- SF asymmetry : $\Gamma_{B^0\to D^{*+}\pi^-} \neq \Gamma_{\bar{B}^0\to D^{*-}\pi^+}$
- Shifted mixing distributions:

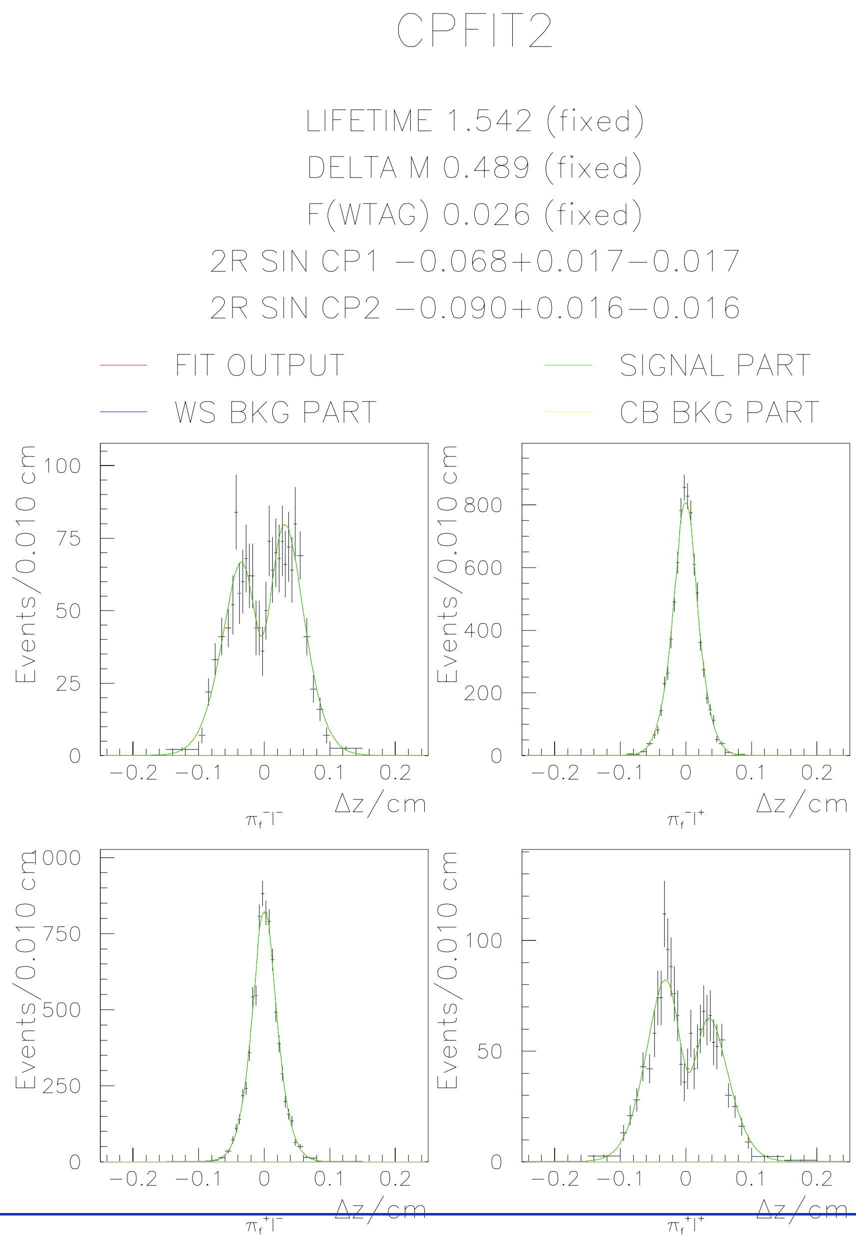
$$
\frac{\Gamma_{B^0\to D^{*-}\pi^+} - \Gamma_{\bar{B}^0\to D^{*-}\pi^+}}{\Gamma_{B^0\to D^{*-}\pi^+} + \Gamma_{\bar{B}^0\to D^{*-}\pi^+}} \approx (1-2w)\cos\left(\Delta m\Delta t + \epsilon_-\right)
$$

$$
\frac{\Gamma_{\bar{B}^0\to D^{*+}\pi^-} - \Gamma_{B^0\to D^{*+}\pi^-}}{\Gamma_{\bar{B}^0\to D^{*+}\pi^-} + \Gamma_{B^0\to D^{*+}\pi^-}} \approx (1-2w)\cos\left(\Delta m\Delta t - \epsilon_+\right)
$$

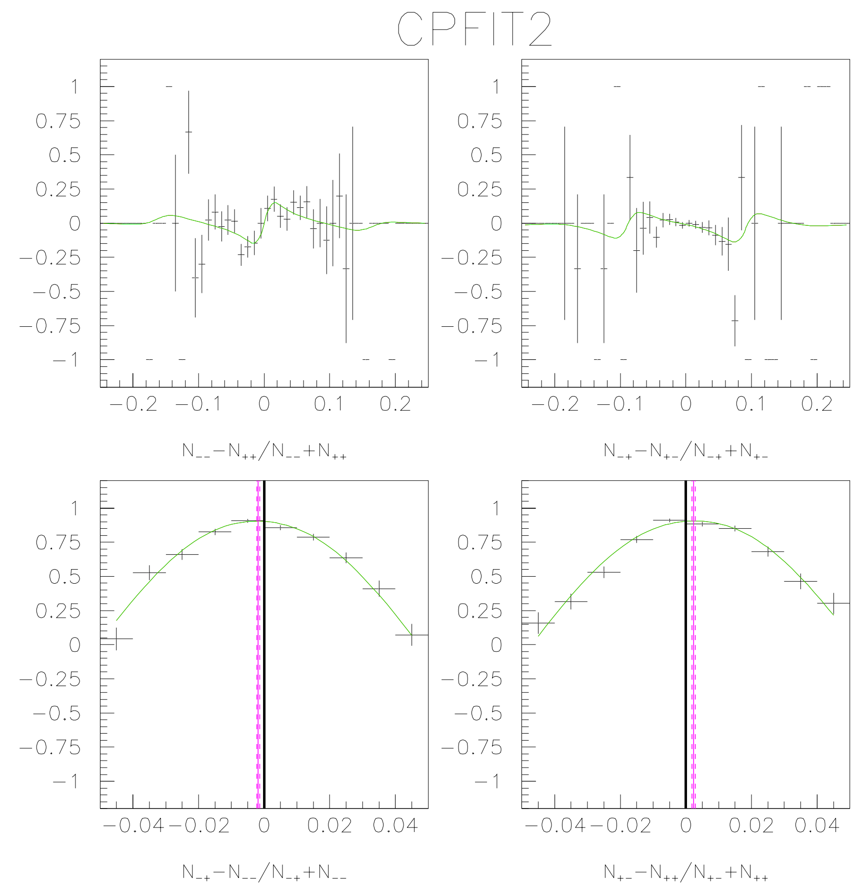
where $\epsilon_\pm = 2R_{D^*\pi}\sin(\phi_w \pm \delta_{D^*\pi})$

$\rightsquigarrow$ very sensitive to μm level vertexing biases

Check with EvtGen Signal Monte Carlo



	INPUT	MEASURED
$2R_{D^*\pi}\sin(2\phi_1+\phi_3+\delta_{D^*\pi})$	-0.068	-0.068 ± 0.017
$2R_{D^*\pi}\sin(2\phi_1+\phi_3-\delta_{D^*\pi})$	-0.085	-0.090 ± 0.016



Vertexing Systematics

- Expect vertex biases at μm level in general
- Need to find a good method to control and correct them
- Ideally, design procedure so that resulting systematics depend on statistical error of some control sample
- Optimistic scenario:
  vertexing systematics scale with statistical error
  $\rightsquigarrow$ this systematic is never a problem
- Pessimistic scenario:
  we cannot control the vertexing systematics
  $\rightsquigarrow$ we never get a result from this method
- Note vertexing systematics different for full reconstruction
  also for partial reconstruction technique used by BaBar.

Situation With 78 fb^{-1}

- Statistical error measured from 78 fb^{-1} of Belle data

$$\boxed{\Delta 2R_{D^*\pi}\sin(2\phi_1+\phi_3\pm\delta_{D^*\pi})\approx 0.029}$$

... assume $R_{D^*\pi}=0.02$, $\delta_{D^*\pi}=0 \rightsquigarrow \Delta\sin(2\phi_1+\phi_3)\approx 0.5$

- BUT cannot safely assume $\delta_{D^*\pi}=0$!

- Dominant systematics currently from:

CP component in background	$\to$	improve background parametrization
Vertexing systematics	$\to$	ongoing studies
Kinematic part of resolution function	$\to$	measure more accurately using MC

- Other improvements in analysis technique (separate w bins, lower p_l cut)

$\to$ may reduce statistical error by 10% – 20% (guess)

- Optimistic statistical error with 3 ab^{-1}:

$$\boxed{\Delta 2R_{D^*\pi}\sin(2\phi_1+\phi_3\pm\delta_{D^*\pi})\approx 0.004}$$

We have measured the amplitudes of the sin-like terms to be

$$2R_{D^*\pi}\,\mathsf{sin}(2\phi_1+\phi_3+\delta_{D^*\pi}) = AAAAA \pm 0.004(\mathsf{stat}) \pm 0.003(\mathsf{syst}),$$

$$2R_{D^*\pi}\,\mathsf{sin}(2\phi_1+\phi_3-\delta_{D^*\pi}) = BBBBB \pm 0.004(\mathsf{stat}) \pm 0.003(\mathsf{syst}).$$

Since these results are compatible with the convincing argument of CCCCC that $\delta_{D^*\pi} \equiv 0$, we combine them to obtain

$$2R_{D^*\pi}\,\mathsf{sin}(2\phi_1+\phi_3) = DDDDD \pm 0.003(\mathsf{stat}) \pm 0.002(\mathsf{syst}).$$

We have also measured the ratio of amplitudes $R_{D^*\pi}$ to be

$$R_{D^*\pi} = EEEEE \pm 0.002(\mathsf{stat}) \pm 0.002(\mathsf{syst}) \pm 0.002(\mathsf{theo}),$$

where the theoretical error is taken from the paper of FFFFF.

Combining these values we find

$$\mathsf{sin}(2\phi_1+\phi_3) = GGGGG \times (1.0 \pm 0.1)$$

Methods to Measure ϕ_3 from $B \to DX$

Please see `http://belle.kek.jp/~gershon/talks/ckm_ws_proc.pdf`

What	Who	
$D_{CP}^{(*)} K^{(*)-}$	Sugi, Swain	No rush to update again
$D_{ADS}^{(*)} K^{(*)-}$	Saigo, Swain	Search for signal & DCPV with 150 fb^{-1}
$D_{K^*K}^{(*)} K^{(*)-}$	Kent	Few events with 150 fb^{-1}
$DK\pi$	No-one	BaBar are studying
$D^{(*)0} K^{(*)0}$	Krokovny	$\bar{B}^0 \to \bar{D}^0 \bar{K}^{*0}$ with 150 fb^{-1}
$D_{K_S\pi\pi}^{(*)} K^{(*)-}$	Poluektov	Measure ϕ_3 with 150 fb^{-1}
$D_{\rm other}^{(*)} K^{(*)-}$	Nobody	Other final states available ($K_S\pi\pi\pi^0$)
$D^*\pi$ partial	Gershon, Zheng	First measurements with 150 fb^{-1}?
$D^*\pi$, $D\pi$, $D\rho$ full	Handa, Sarangi	First measurements with 150 fb^{-1}?
$D^*\rho$ angular	Itoh, Trabelsi	Polarization result by this summer, CP later?
Da_1, D^*a_1 full	No-one	BaBar are studying?
$D^*\rho$, D^*a_1 partial	No-one	BaBar are studying?
$D_{(CP)}^{(*)0}\pi^0$ time-dep	No-one (Blyth)	Interesting study for Super-KEKB
$D_{(CP)}^{(*)0} K^{(*)0}$ time-dep	No-one (Krokovny)	Interesting study for Super-KEKB