$\sin(2\phi_1 + \phi_3)$ measurements at Belle

386×10^6 $B\bar{B}$, *PRD 73, 092003 (2006)*

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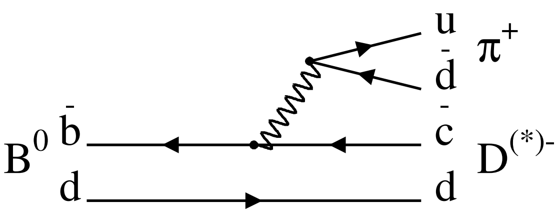
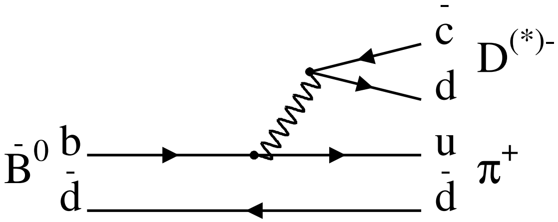
Time Dependent $B^0 \to D^{(*)-}\pi^+$ Decays



Cabibbo-favored



Doubly-Cabibbo-suppressed

$$R^{(*)} \equiv \left| \frac{A_{\mathrm{DCSD}}}{A_{\mathrm{CFD}}} \right| \simeq 0.02$$

$$\delta^{(*)} = \phi_s^{\mathrm{DCSD}} - \phi_s^{\mathrm{CFD}}$$

Interference of $A(\mathrm{CFD})$ and $A(B^0 \to \overline{B}^0 \to \mathrm{DCSD})$ leads to time-dependent asymmetry

$$\frac{\Gamma(\bar{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\bar{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)$$

Final State	S	C
$D^+\pi^-$	$+2R\sin(2\phi_1 + \phi_3 + \delta) \equiv S^+$	$+1$
$D^-\pi^+$	$+2R\sin(2\phi_1 + \phi_3 - \delta) \equiv S^-$	-1
$D^{*+}\pi^-$	$-2R^*\sin(2\phi_1 + \phi_3 + \delta^*) \equiv -S^{+(*)}$	$+1$
$D^{*-}\pi^+$	$-2R^*\sin(2\phi_1 + \phi_3 - \delta^*) \equiv -S^{-(*)}$	-1

$$|C| = \frac{1 - R^2}{(1 + R^2)} \simeq 1$$

Provide theoretically clean extraction of $\sin(2\phi_1 + \phi_3)$, but observable effect is only a few %

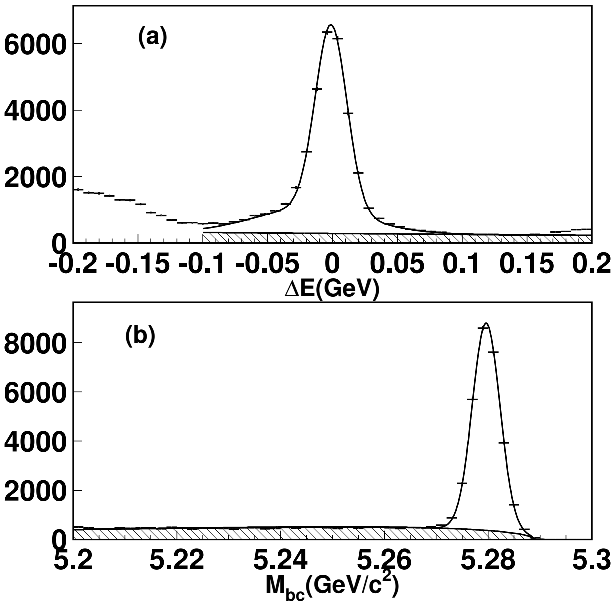
$R^{(*)} \simeq \underbrace{\left| \frac{V_{cd}^* V_{ub}}{V_{cb}^* V_{ud}} \right|}_{\sim 0.02} \cdot \underbrace{\frac{f_{D^{(*)}} F^{B\pi}}{f_\pi F^{BD^{(*)}}}}_{(0.81\sim 1.33)}$ must come from theory or other measurements

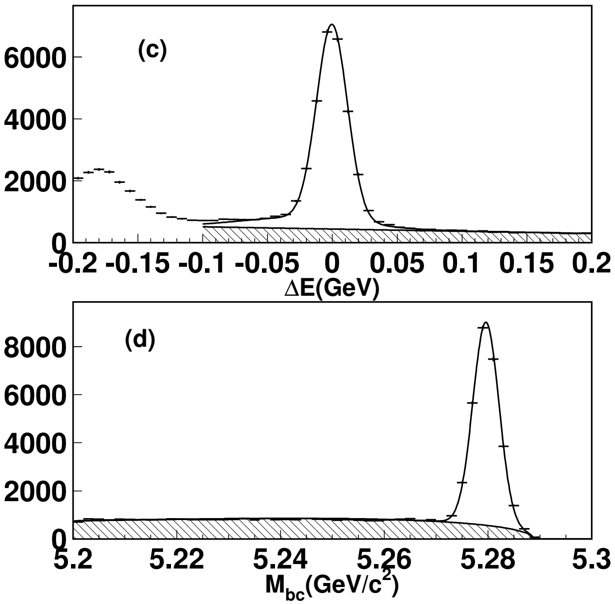
$D^{(*)-}\pi^+$ Full Rreconstruction

$B^0 \to D^{*-}\pi^+$
$\hookrightarrow \overline{D}^0\pi_s^-$
$\hookrightarrow D^-\pi_s^0$

$B^0 \to D^-\pi^+$

B Decay	D Decay Mode	ϵ	$\mathcal{B} \times \epsilon$
$B^0 \to D^{*-}\pi^+$	$\overline{D}^0 \to K^+\pi^-$	0.300	0.0077
	$\overline{D}^0 \to K^+\pi^-\pi^0$	0.120	0.0114
	$\overline{D}^0 \to K^+\pi^-\pi^-\pi^+$	0.144	0.0075
	$\overline{D}^0 \to K_s\pi^+\pi^-$	0.051	0.0100
	$D^- \to K^+\pi^-\pi^-$	0.112	0.0033
$B^0 \to D^-\pi^+$	$D^- \to K^+\pi^-\pi^-$	0.320	0.0304


$B \to D^*\pi$


$B \to D\pi$

Flavor Tagging (Full Reconstruction)

Belle standard method

- Construct two variables using remaining charged tracks
  - $q = +1$ for B^0, -1 for $\overline{B}^0$
  - Categorize events into 6 r bins. $r = 1$ for perfect tag , 0 for no information
- Wrong tag fractions are determined from τ_B and Δm

Tag side can have CPV when going through hadronic decays, $B^0 \to \overline{D}\ \overline{X}$ and $\overline{B}^0 \to D\ X$

Parameterize the effects by $S^{\pm}_{\mathrm{tag}}$

$$B^0 \to D^{(*)+}\pi^-: S^+ \to (S^+ - S^+_{\mathrm{tag}})$$
$$B^0 \to D^{(*)-}\pi^+: S^- \to (S^- + S^+_{\mathrm{tag}})$$
$$\overline{B}^0 \to D^{(*)+}\pi^-: S^+ \to (S^+ + S^-_{\mathrm{tag}})$$
$$\overline{B}^0 \to D^{(*)-}\pi^+: S^- \to (S^- - S^-_{\mathrm{tag}})$$

Determine using $B \to D^*\ell\nu$ $(S^{\pm} = 0)$

r	S^+_{tag}	S^-_{tag}
0.000 – 0.250	-0.058 ± 0.130	$+0.060 \pm 0.130$
0.250 – 0.500	$+0.001 \pm 0.040$	$+0.018 \pm 0.040$
0.500 – 0.625	$+0.027 \pm 0.032$	-0.030 ± 0.032
0.625 – 0.750	$+0.026 \pm 0.025$	$+0.022 \pm 0.025$
0.750 – 0.875	-0.011 ± 0.025	$+0.027 \pm 0.025$
0.875 – 1.000	-0.005 ± 0.014	$+0.024 \pm 0.014$

Δt Fits (Full Reconstruction)

$386 \times 10^6 \; B\bar{B}$

	Signal Yield	Purity
$D^*\pi$	31,491	0.89
$D\pi$	31,725	0.83

Unbinned Maximum Likelihood Fit

$$\mathcal{L}_i = (1 - f_{\rm ol}) \left[f_{\rm sig} P_{\rm sig} \otimes R_{\rm sig} + (1 - f_{\rm sig}) P_{\rm bkg} \otimes R_{\rm bkg} \right] + f_{\rm ol} P_{\rm ol}$$

Outlier ($f_{\rm ol}$, $P_{\rm ol}$) determined from τ_B fit ($\sim 1\%$)

Signal PDF

$$P(q = -1, D^{(*)\pm}\pi^{\mp}) = (1 - w_-)\Gamma(B^0 \to D^{(*)\pm}\pi^{\mp}) + w_+\Gamma(\overline{B}^0 \to D^{(*)\pm}\pi^{\mp})$$

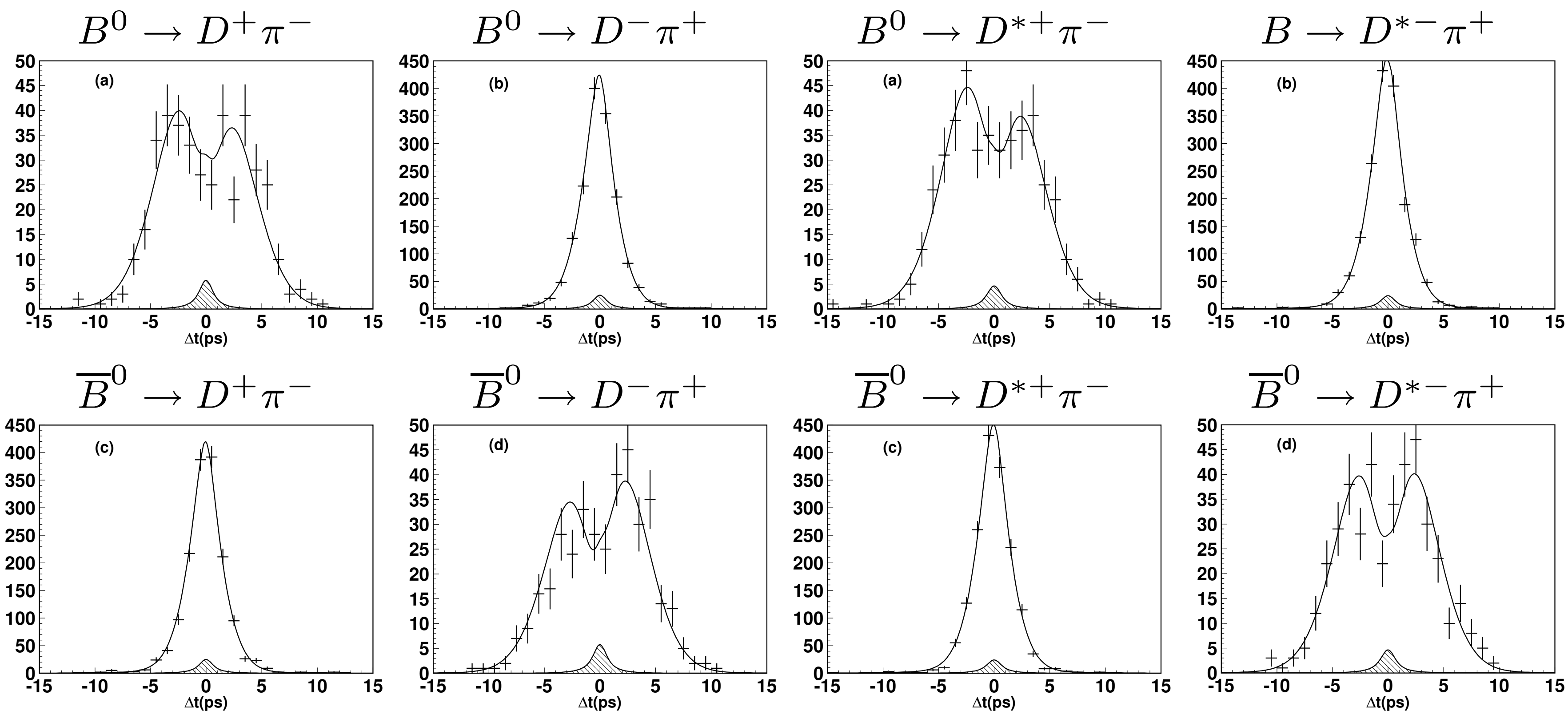
$$P_{(}q = +1, D^{(*)\pm}\pi^{\mp}) = (1 - w_+)\Gamma(\overline{B}^0 \to D^{(*)\pm}\pi^{\mp}) + w_-\Gamma(B^0 \to D^{(*)\pm}\pi^{\mp})$$

$$\Gamma(B^0 \to D^{(*)\pm}\pi^{\mp}) \propto 1 \mp \cos(\Delta m \Delta t) - S^{\pm} \sin(\Delta m \Delta t)$$
$$\Gamma(\overline{B}^0 \to D^{(*)\pm}\pi^{\mp}) \propto 1 \pm \cos(\Delta m \Delta t) + S^{\pm} \sin(\Delta m \Delta t)$$

Background PDF determined from ΔE-$M_{\rm bc}$ sideband

Δt resolution determined from τ_B, Δm fit

Δt for Fully Reconstructed $B^0 \to D^{(*)\mp}\pi^{\pm}$



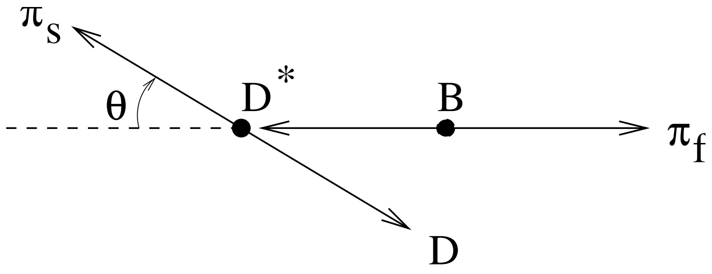
Data points: subsample (about 14%) of good flavor tag ($0.875 < r < 1.0$)

Curves: fit results using entire sample

$B^0 \to D^*\pi$ Partial Reconstruction

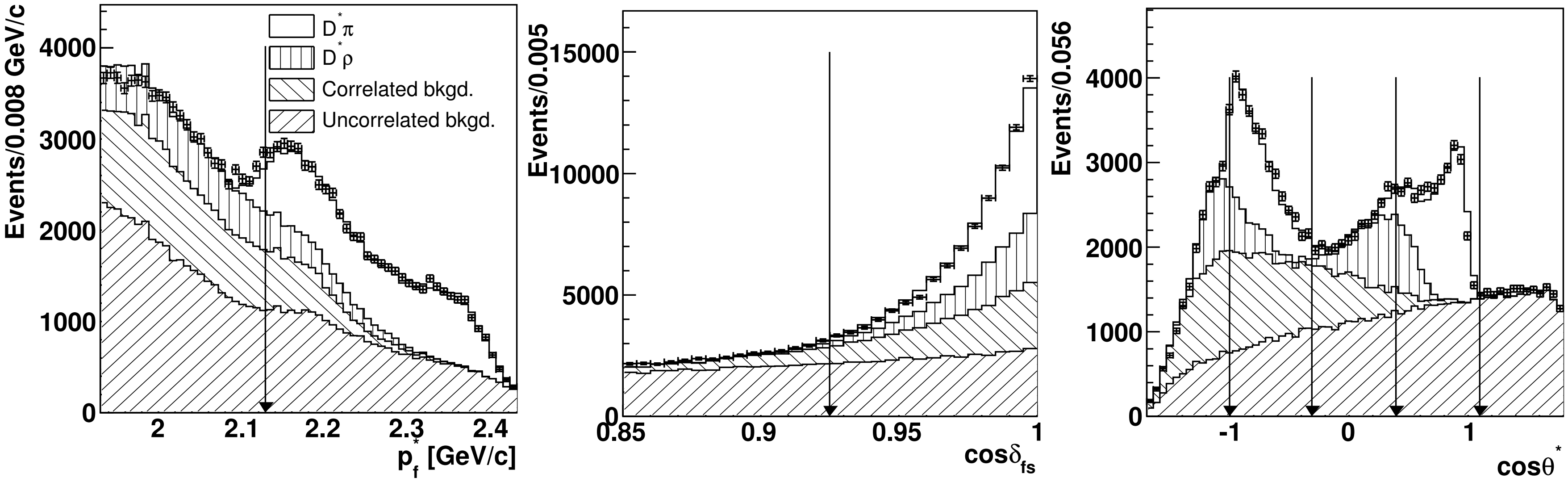
Try to gain statistics by avoiding full reconstruction of D decays.

$$\begin{aligned} B^0 &\to D^{*-}\pi_f^+ \\ &\qquad \hookrightarrow \bar{D}^0\pi_s^- \end{aligned}$$



Signal shows distinct pattern

- Fast π^+ and slow π^- come out nearly back to back
- π_s^- distributes as $\cos^2\theta$ in D^* rest frame
- Direction of flavor-tagging lepton is not correlated to π_f^+



Δt Fit (Partial Reconstruction)

$386 \times 10^6 \ B\bar{B}$

	Candidates	Fraction
Data	32844 ± 181	–
$D^*\pi$	21741 ± 217	0.662 ± 0.007
$D^*\rho$	2091 ± 45	0.064 ± 0.001
Correlated background	2703 ± 42	0.082 ± 0.001
Uncorrelated background	6287 ± 40	0.191 ± 0.001

Fully reconstructed $D^*\pi$: 31491 with purity 0.89

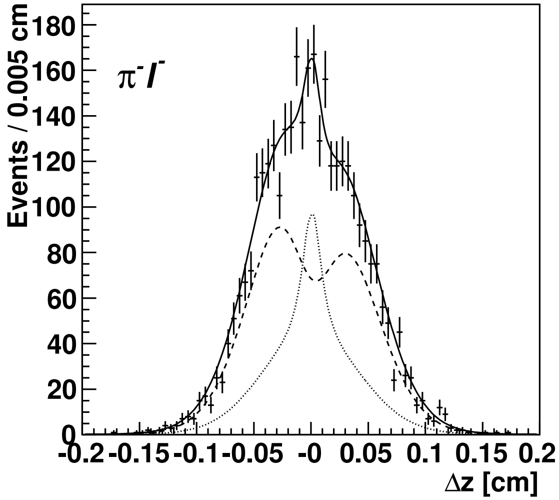
- Flavor tagging using leptons only with $1.2 \ \mathrm{GeV}/c < p_{l_{\mathrm{tag}}} < 2.3 \ \mathrm{GeV}/c$
- Δt determination using only π_f and l_{tag} (Δt resolution from $J/\psi \to \mu^+\mu^-$)
- Unbinned maximum likelihood fit

$$\mathcal{L}_i = f_{D^*\pi} P_{D^*\pi} + f_{D^*\rho} P_{D^*\rho} + f_{\mathrm{unco}} P_{\mathrm{unco}} + f_{\mathrm{corr}} P_{\mathrm{corr}}$$

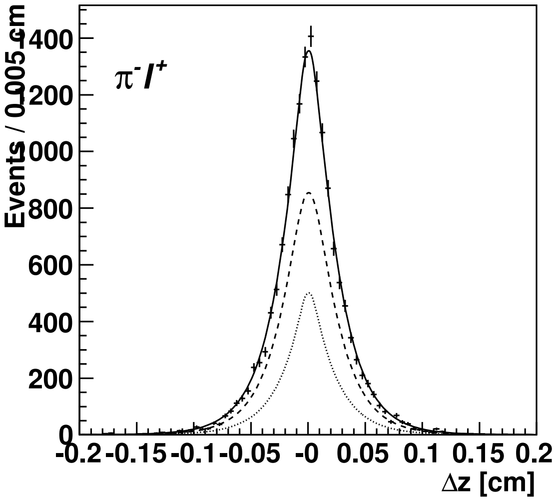
- Signal PDFs are same as full reconstruction
- Three background types
  Correlated background: π_f^+ and π_s^- are correlated

Δz for Partial Reconstruction Sample

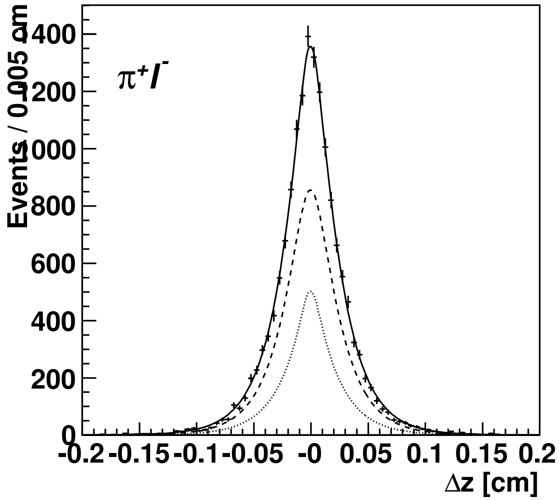
$B^0 \to D^{*+}\pi^-$



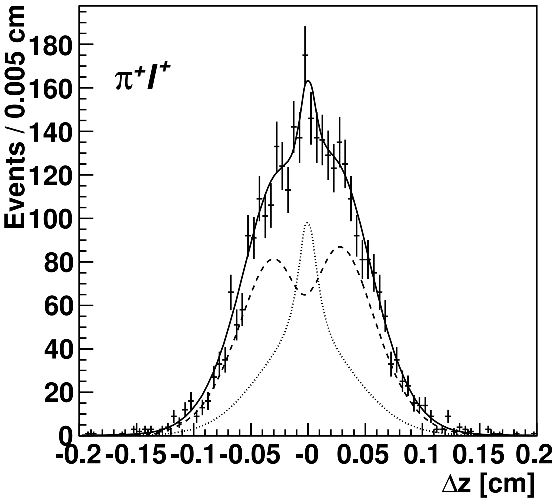
$\overline{B}^0 \to D^{*+}\pi^-$



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



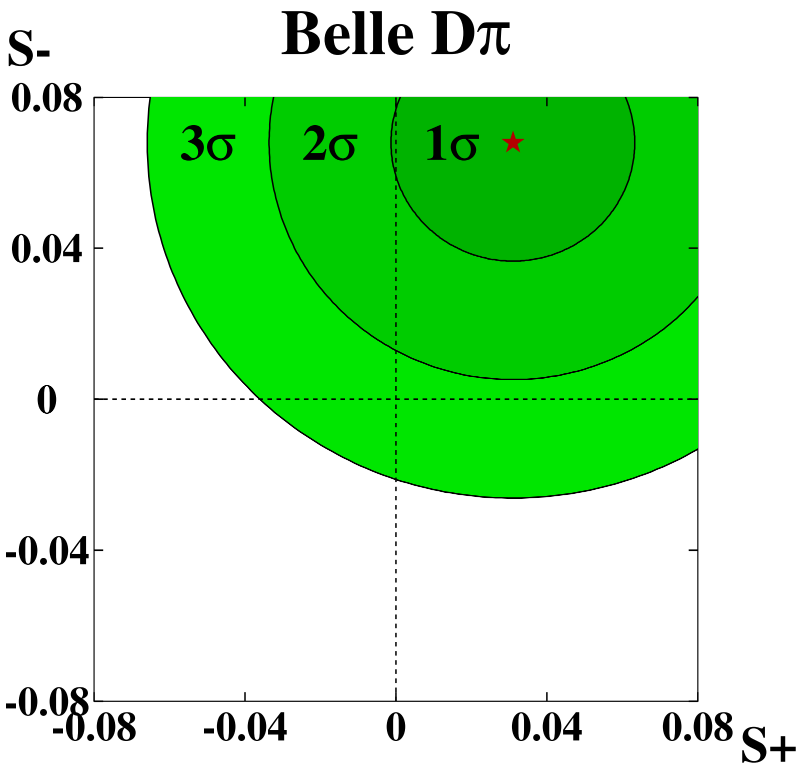
$\overline{B}^0 \to D^{*-}\pi^+$



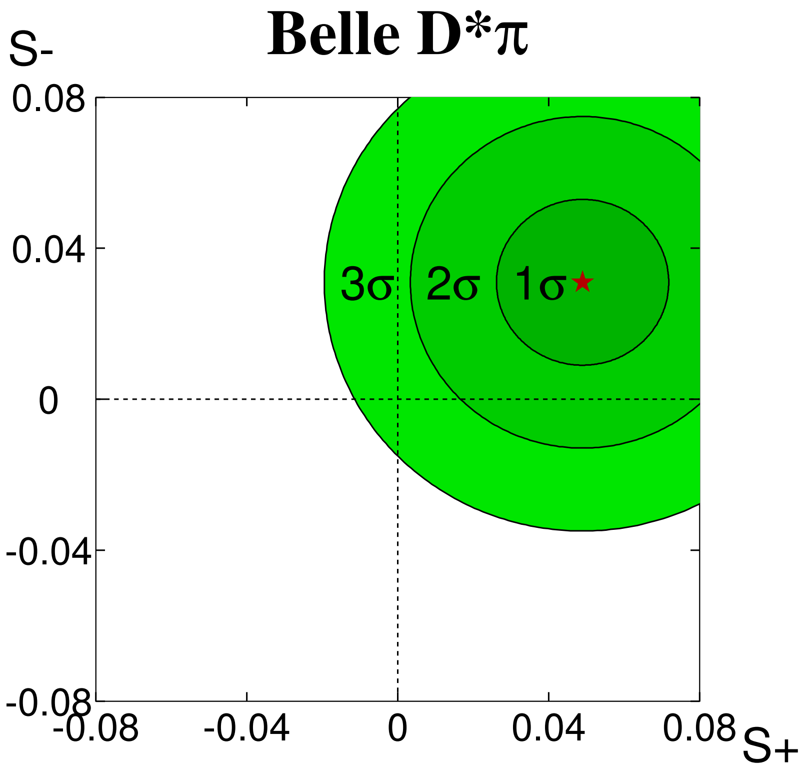
Fit Results: S^- vs S^+

	Full recon.	Partial recon.	Combined
$S^+(D\pi)$	$0.031 \pm 0.030 \pm 0.012$		
$S^-(D\pi)$	$0.068 \pm 0.029 \pm 0.012$		
$S^+(D^*\pi)$	$0.050 \pm 0.029 \pm 0.013$	$0.048 \pm 0.028 \pm 0.017$	$0.049 \pm 0.020 \pm 0.011$
$S^-(D^*\pi)$	$0.028 \pm 0.028 \pm 0.013$	$0.034 \pm 0.027 \pm 0.017$	$0.031 \pm 0.019 \pm 0.011$

$D^*\pi$ candidates from the two methods are mostly independent (only 0.2% overlap)



Belle Dπ



Belle D*π

Systematic Uncertainties

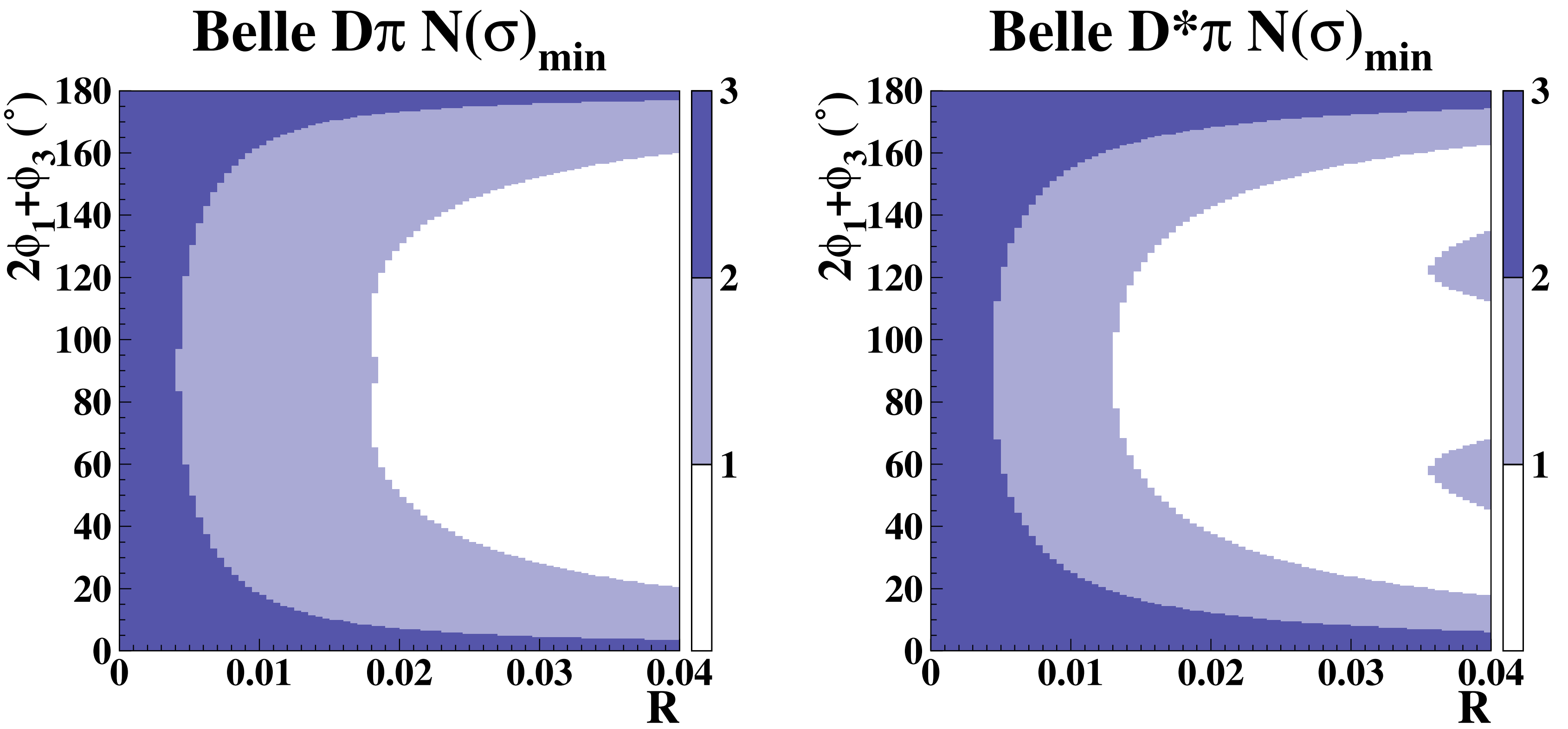
Full Reconstruction

Sources	$D^*\pi$	$D\pi$
Signal Δt resol.	0.005	0.004
Bkg Δt shape	~ 0	~ 0
Bkg fraction	0.002	0.001
Wrong tag frac.	0.002	0.002
Vertexing	0.004	0.002
$\Delta m, \tau_{B^0}$	0.001	0.001
Tag side asym.	0.005	0.005
Fit bias	0.010	0.010
Total	0.013	0.012

Partial Reconstruction

Source	Error
Resolution fit	0.002
Resolution models	0.008
Kinematic smearing	0.002
Non-primary tracks	0.004
Background shapes	~ 0
Kinematic fit	0.007
τ_{B^0}, Δm	0.001
CPV in $D^*\rho$ and corr. bkgd.	0.004
Vertexing	0.011
Total	0.017

Allowed Regions of $(2\phi_1 + \phi_3)$ vs R

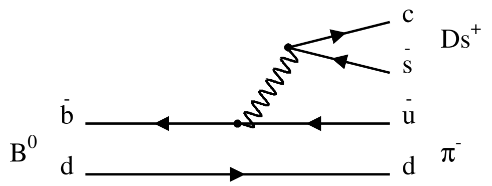


Estimation of $R^{(*)}$

Use available branching fractions and lattice calculation of decay constants

Assume SU(3) symmetry and ignore W-exchange contributions (about 30% error on R)

$$\underbrace{\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)}_{\text{pure } b\to u} = \underbrace{\mathcal{B}(B^0 \to D^{(*)-}\pi^+)\cdot R^{(*)2}}_{\text{DCSD}} \cdot \frac{1}{\lambda^2}\cdot\left(\frac{f_{D_s^{(*)}}}{f_{D^{(*)}}}\right)^2$$

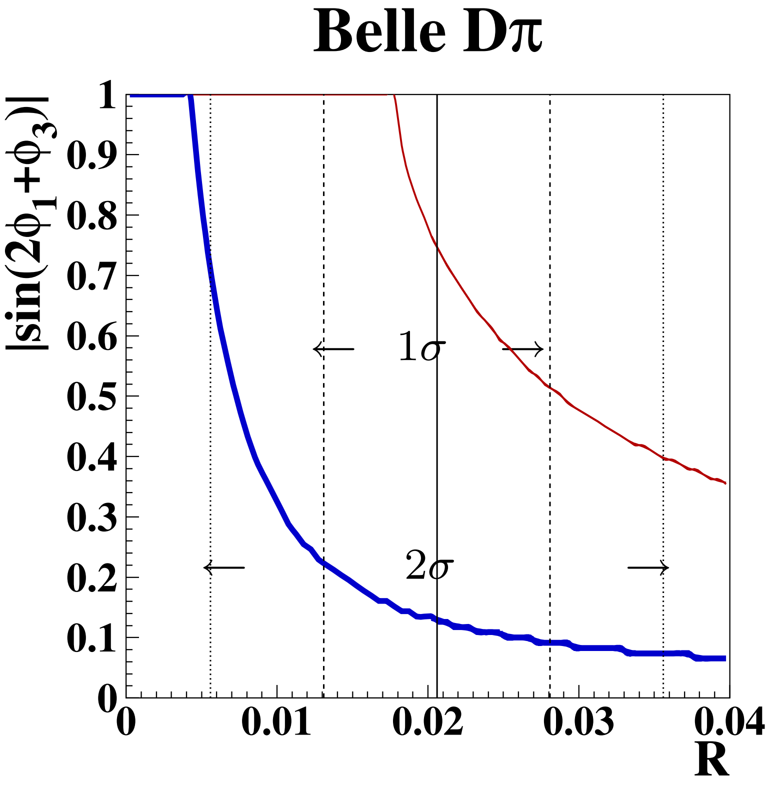


$\mathcal{B}(B^0 \to D^-\pi^+)$	$(2.76 \pm 0.25)\times 10^{-3}$	PDG 2004
$\mathcal{B}(B^0 \to D^{*-}\pi^+)$	$(2.76 \pm 0.21)\times 10^{-3}$	PDG 2004
$\mathcal{B}(B^0 \to D_s^+\pi^-)$	$(2.7 \pm 1.0)\times 10^{-5}$ $(1.3 \pm 0.3 \pm 0.2)\times 10^{-5}$	PDG 2004 BaBar (230 million $B\bar{B}$)new
$\mathcal{B}(B^0 \to D_s^{*+}\pi^-)$	$(1.9^{+1.2}_{-1.3} \pm 0.5)\times 10^{-5}$ $(2.8 \pm 0.6 \pm 0.5)\times 10^{-5}$	BaBar 84 million $B\bar{B}$ BaBar (230 million $B\bar{B}$) new
f_D/f_{D_s} $f_{D^*}/f_{D_s^*}$	$0.90 \pm 0.01 \pm 0.01$ $1.04 \pm 0.01 \pm 0.02$	UKQCD collaboration Nucl. Phys. 619 (2001) 507

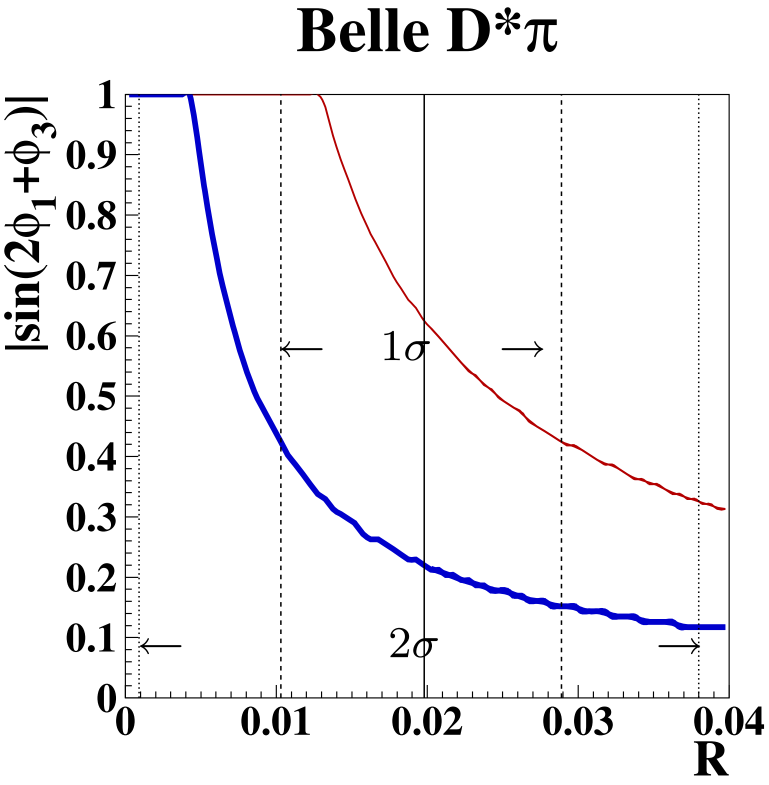
PRD 73, 092003 (2006)   New BaBar results not used

$R = 0.021 \pm 0.004 \pm 0.006\ (\text{theory})$ $R^* = 0.020 \pm 0.007 \pm 0.006\ (\text{theory})$

Constraints on $|\sin(2\phi_1 + \phi_3)|$


Belle Dπ

$|\sin(2\phi_1 + \phi_3)| > 0.52(0.07)$
at 68% (95%)CL


Belle D*π

$|\sin(2\phi_1 + \phi_3)| > 0.44(0.13)$
at 68% (95%)CL

Future Prospect

Can this method ever compete with $B \to DK$ Dalitz analysis? Difficult

- $(S^+ + S^-)/2 = 2R\sin(2\phi_1 + \phi_3)\cos\delta$ 2.5σ away from zero
  $\phi_3 = (53^{+15}_{-18} \pm 3 \pm 9)^\circ$ (DK Dalitz analysis)
- Still, important to confirm that we reach the same ϕ_3

Increasing statistics ? Limitted room for improving analysis. More luminosity

- Include kaon-tag to partial reconstruction sample (BaBar has done)
- Statistical errors still twice larger than systematic errors

Knowing R values ? Experimentally very challenging. How about 30% theory error?

- $B^+ \to D^{(*)+}\pi^0$ provides “direct” measurement
  (assumig isospin symmetry and ignoring W-exchange contributions)

$$R^2 = \frac{\mathcal{B}(B^0 \to D^{(*)+}\pi^-)}{\mathcal{B}(B^0 \to D^{(*)-}\pi^+)} = \frac{2\mathcal{B}(B^+ \to D^{(*)+}\pi^0)}{\mathcal{B}(B^0 \to D^{(*)-}\pi^+)}$$

- Time-dependent angular analysis of $B^0 \to D^{*-}\rho^+$ in principle provides R as well as $\sin(2\phi_1 + \phi_3)$ and δ

Backup: Estimations of R

Suprun, Chiang, Rosner, PRD 65, 054025 (2002)

$$R(D^*\pi) = \frac{f_{D^*} F_1^{B\pi}(m_{D^*}^2)}{f_\pi A_0^{BD^*}(m_\pi^2)}$$

$$R(D\pi) = \frac{f_D(m_B^2 - m_\pi^2) F_0^{B\pi}(m_D^2)}{f_\pi(m_B^2 - m_D^2) F_0^{BD}(m_\pi^2)}$$

	$r(D^*\pi)$	$r(D\pi)$
Light Front Model	0.81	0.72
BSW II Model	1.33	1.11
NS Model	0.88	0.72
LCSR Model	1.01	0.87
MS Model	0.92	0.82

Lattice Calculation of Decay Constants

Bowler *et al.*,UKQCD Nucl. Phys. **B619**, 507 (2001)

$$f_{D_s}/f_D = 1.11(1) \pm 1$$

$$f_{D^*}/f_{D_s^*} = 1.04(1) \pm 2$$

Becirevic, Nucl. Phys. **B94**, 337 (2001)

$$f_{D_s^*}/f_{D^*} = 1.10 \pm 0.02$$

(note the ratio is reversed)

Becirevic *et al.*, hep-ex/9811003

$$f_{D_s}/f_D = 1.13(3) \pm 1$$