Study of $\sin(2\phi_1+\phi_3)$

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Outline

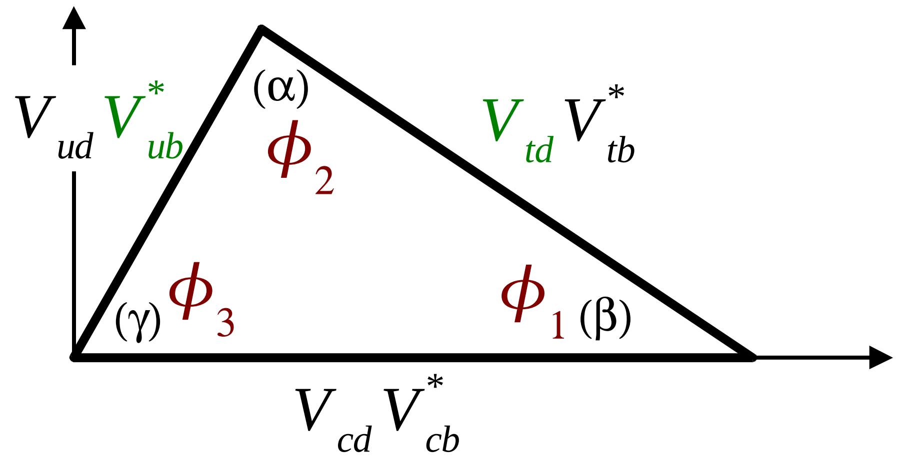
1. Theoretical Background
2. Measurement of Δm_d as First Step
3. Future Prospects

Introduction

From CKM matrix and unitarity:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

CP Violation is proportional to the area of the triangle.



sin $2\phi_1$ measured by *Belle* and *BaBar*...

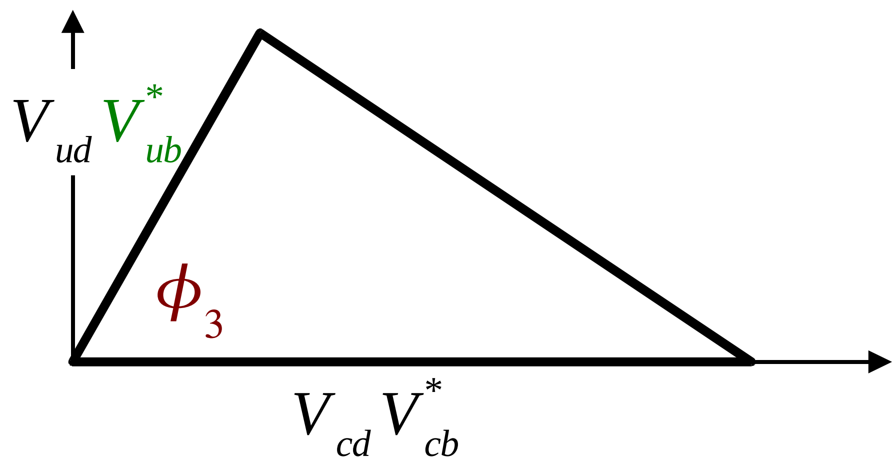
Belle	$0.82 \pm 0.12 \pm 0.05$
BaBar	$0.75 \pm 0.09 \pm 0.04$
World Average	0.78 ± 0.08

Now go after other angles....

Strategy

- Consult favorite theorist...
- Search for:

$$\Gamma(B_d(t)\to f)\neq\Gamma(\bar{B}_d(t)\to\bar{f})$$
$$\Gamma(B_d(t)\to\bar{f})\neq\Gamma(\bar{B}_d(t)\to f)$$



- Requires interference between two amplitudes with different CKM matrix elements.

$$\phi_3 \equiv arg\left(-\frac{V^*_{ub}V_{ud}}{V_{cd}V^*_{cb}}\right)$$

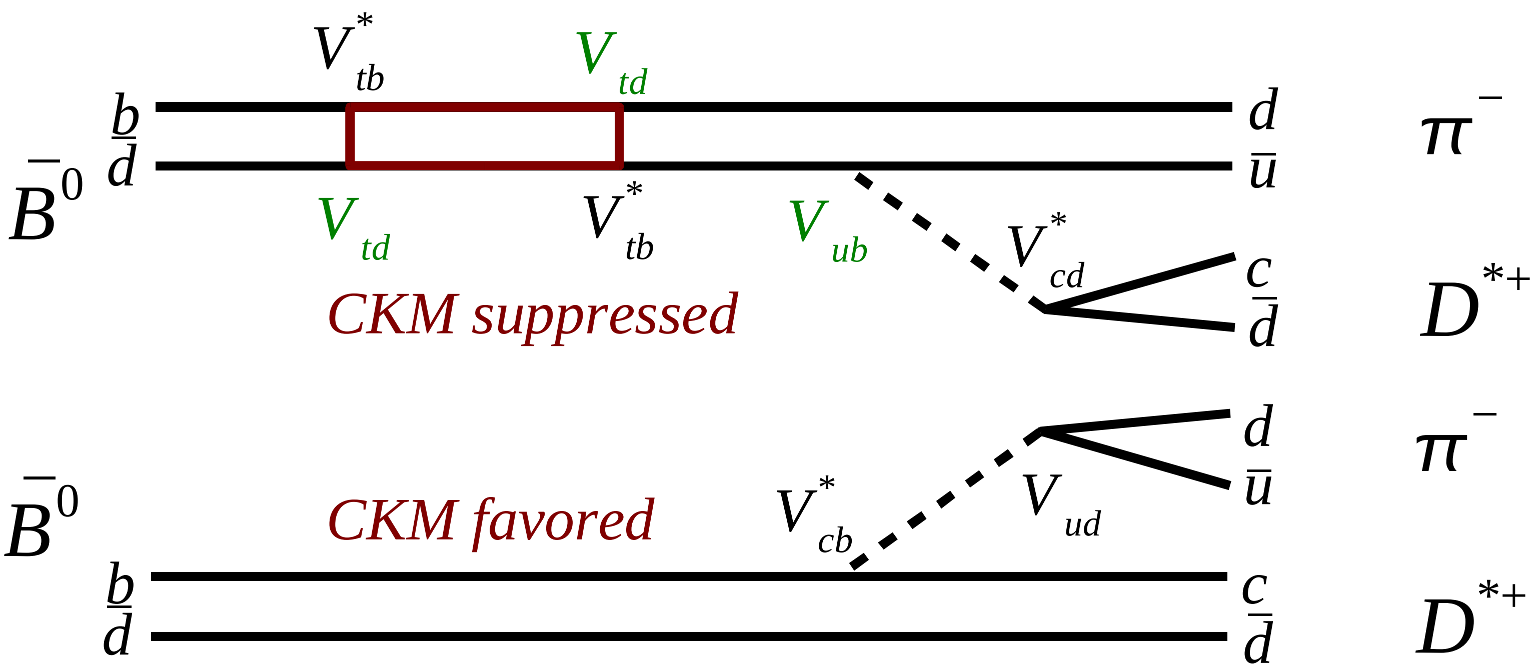
- For ϕ_3, theorists suggest:

$$B_d \to D^{(*)\mp}\pi^{\pm}$$

e.g. Dunietz 1997

Decay Diagrams

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



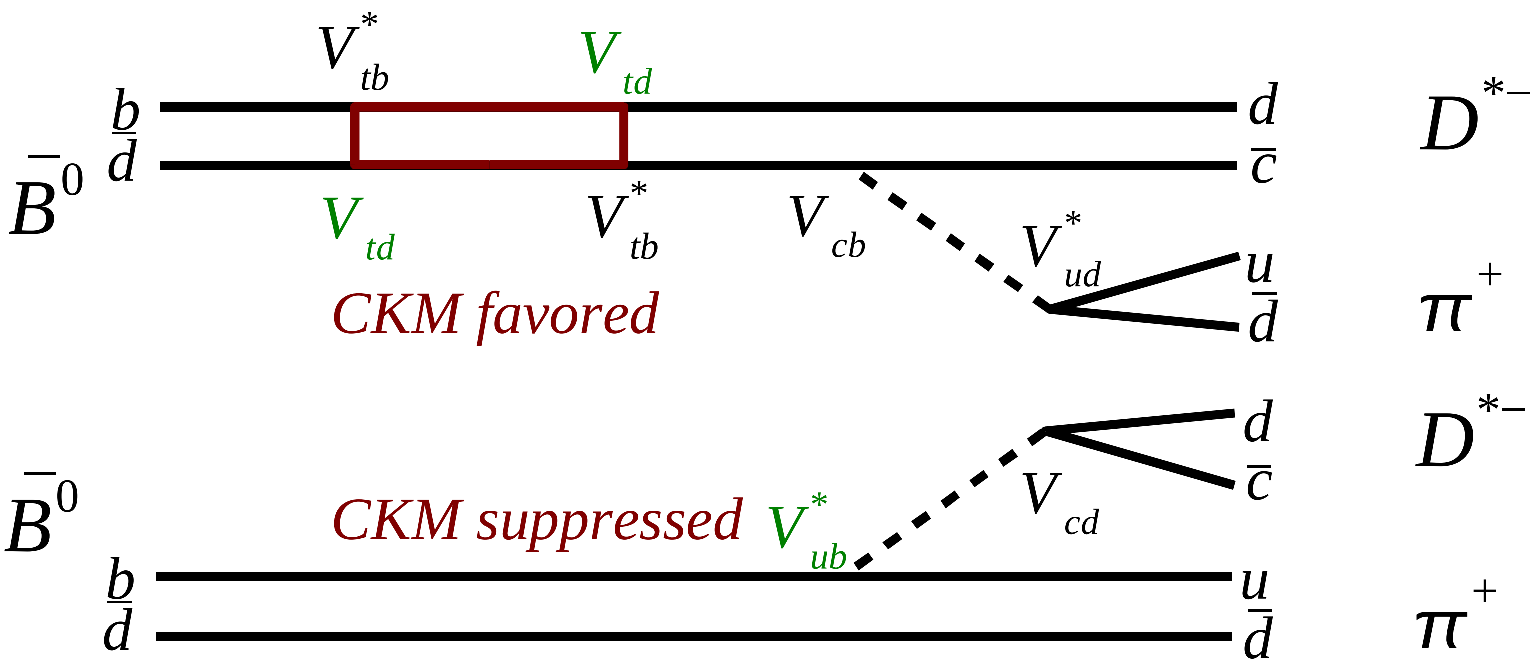
- Weak phase difference:

$$arg\left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}} \cdot \frac{V^*_{ud}V_{cb}}{V_{cd}V^*_{ub}}\right)$$

And...

Decay Diagrams

- Two more diagrams:



- Weak phase difference:

$$arg\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \cdot \frac{V_{ud}^* V_{cb}}{V_{cd} V_{ub}^*}\right)$$

Same!

Phases

$$\arg\left(\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}\cdot\frac{V_{ud}^{*}V_{cb}}{V_{cd}V_{ub}^{*}}\right) = \arg\left(\frac{V_{tb}^{*}V_{td}}{V_{cd}V_{cb}^{*}}\cdot\frac{V_{tb}^{*}V_{td}}{V_{cd}V_{cb}^{*}}\cdot\frac{V_{cb}^{*}V_{cd}}{V_{ud}V_{ub}^{*}}\right)$$

$$= \pi - 2\phi_1 - \phi_3$$

$$\phi_1 \equiv \arg\left(-\frac{V_{cb}^{*}V_{cd}}{V_{td}V_{tb}^{*}}\right) \qquad \phi_3 \equiv \arg\left(-\frac{V_{ub}^{*}V_{ud}}{V_{cd}V_{cb}^{*}}\right)$$

Notation

$$|B_L\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}\left(p|B^0\rangle + q|\bar{B}^0\rangle\right)$$

$$\Gamma = \frac{\Gamma_H + \Gamma_L}{2}$$

$$|B_H\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}\left(p|B^0\rangle - q|\bar{B}^0\rangle\right)$$

$$\Delta m \equiv m_H - m_L$$

$$\xi \equiv \sin(2\phi_1 + \phi_3 + \delta)$$

$$\bar{\xi} \equiv \sin(2\phi_1 + \phi_3 - \delta)$$

$\delta \equiv$ Strong phase difference between Cabibbo supressed and favored decays.

$$|\rho| \equiv \left|\frac{\langle D^{*+}\pi^-|B^0\rangle}{\langle D^{*-}\pi^+|B^0\rangle}\right| = \left|\frac{V_{ub}^* V_{cd}}{V_{cb} V_{ud}^*}\right| \approx 0.4\,\lambda^2 \approx 0.022$$

For $B \rightarrow J/\psi K_s$

$$|\rho| = 1$$

$$\delta = 0$$

Decay Probabilities

$$P_{B^0\rightarrow D^{*-}\pi^+}(\Delta t)=\frac{1}{4\tau_{B^0}}e^{-\frac{|\Delta t|}{\tau_{B^0}}}\left[(1+|\rho|^2)+(1-|\rho|^2)\cos\Delta m\Delta t-2|\rho|\xi\sin\Delta m\Delta t\right]$$

$$P_{\bar{B}^0\rightarrow D^{*+}\pi^-}(\Delta t)=\frac{1}{4\tau_{B^0}}e^{-\frac{|\Delta t|}{\tau_{B^0}}}\left[(1+|\rho|^2)+(1-|\rho|^2)\cos\Delta m\Delta t+2|\rho|\bar{\xi}\sin\Delta m\Delta t\right]$$

$$P_{B^0\rightarrow D^{*+}\pi^-}(\Delta t)=\frac{1}{4\tau_{B^0}}e^{-\frac{|\Delta t|}{\tau_{B^0}}}\left[(1+|\rho|^2)-(1-|\rho|^2)\cos\Delta m\Delta t-2|\rho|\bar{\xi}\sin\Delta m\Delta t\right]$$

$$P_{\bar{B}^0\rightarrow D^{*-}\pi^+}(\Delta t)=\frac{1}{4\tau_{B^0}}e^{-\frac{|\Delta t|}{\tau_{B^0}}}\left[(1+|\rho|^2)-(1-|\rho|^2)\cos\Delta m\Delta t+2|\rho|\xi\sin\Delta m\Delta t\right]$$

$$\Delta t\equiv t-t_0$$

$t_0\equiv$ time of pure B^0 or $\bar{B}^0$ state

Three observables: $|\rho|,\xi,\bar{\xi}$

Decay Probabilities

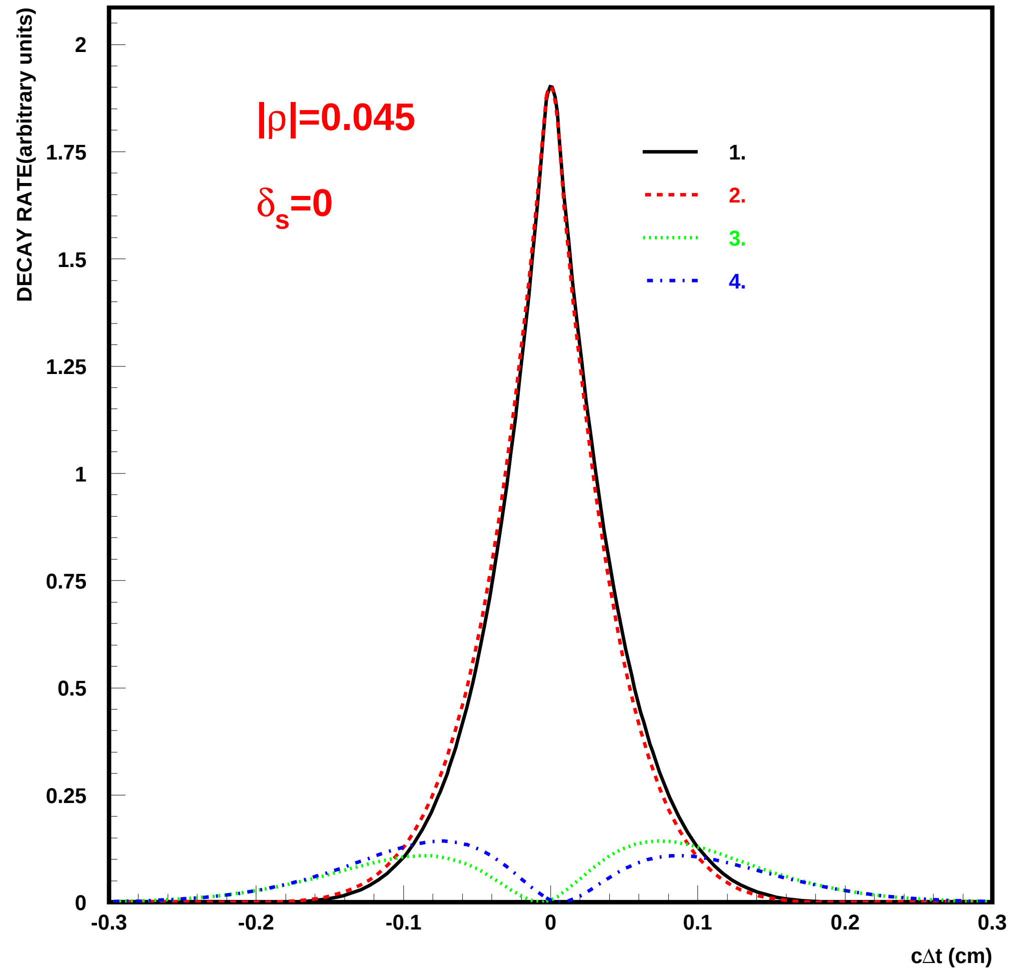
$1.\ B^0 \rightarrow D^{*-}\pi^+$

$2.\ \bar{B}^0 \rightarrow D^{*+}\pi^-$

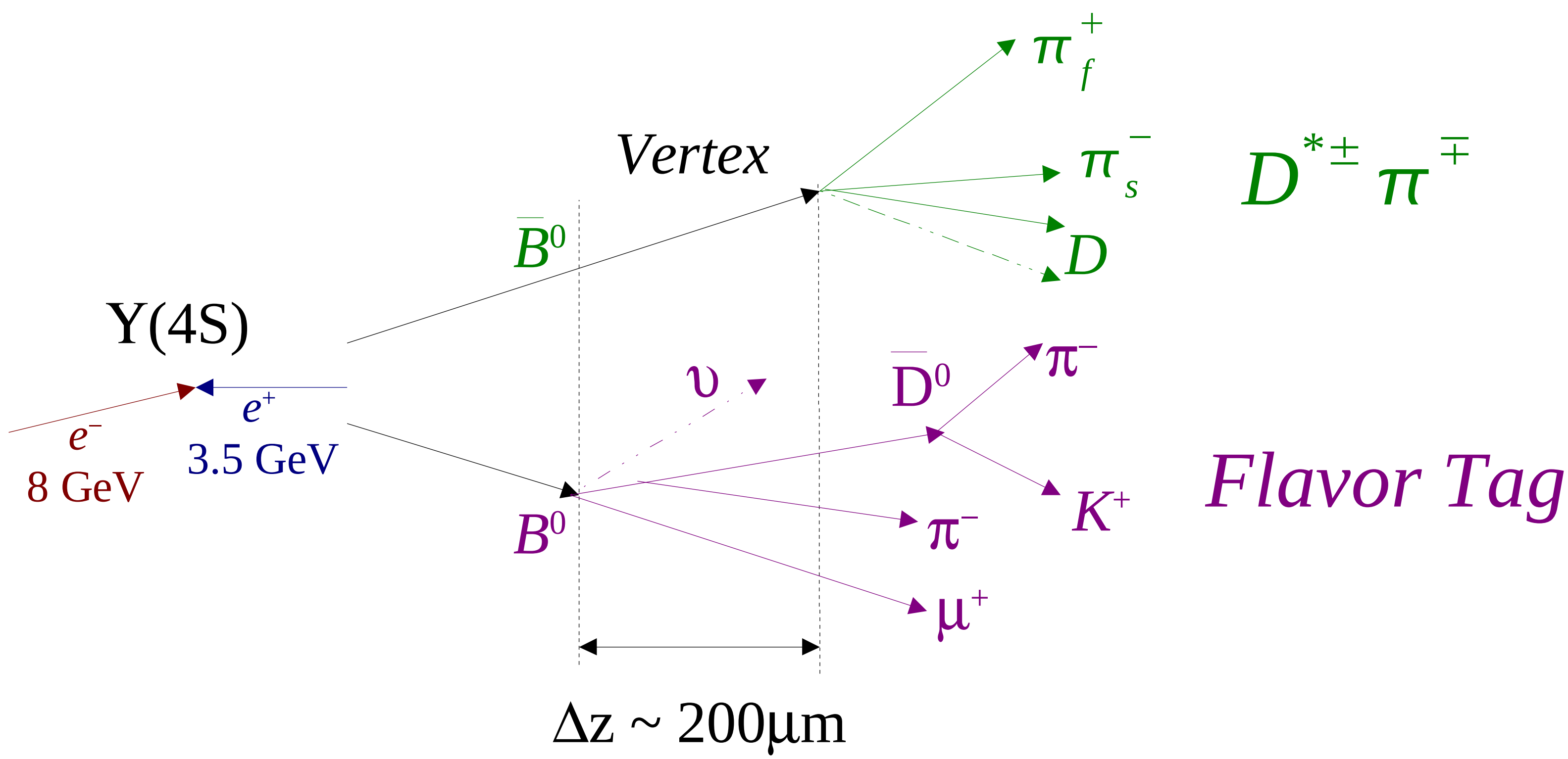
$3.\ B^0 \rightarrow D^{*+}\pi^-$

$4.\ \bar{B}^0 \rightarrow D^{*-}\pi^+$

|ρ| twice expected value to make difference visible



Measurement Strategy



Steps: *Reconstruct, tag, vertex, fit.*

B_d Mixing: A first step

- Large event sample needed to measure $\sin(2\phi_1+\phi_3)$.
- Mixing measurement uses same techniques:
  - Event Signals, Backgrounds, Vertexing, Tagging, Fitting
- Fit to:

$$P^{OF}(\Delta t)=\frac{1}{4\tau_B}e^{-\frac{|\Delta t|}{\tau_{B_d}}}[1+\cos(\Delta m_d \Delta t)]$$ *Opposite flavor, unmixed.*

$$P^{SF}(\Delta t)=\frac{1}{4\tau_B}e^{-\frac{|\Delta t|}{\tau_{B_d}}}[1-\cos(\Delta m_d \Delta t)]$$ *Same flavor, mixed.*

Assume ρ small (<1% error in Δm_d).

Event Selection

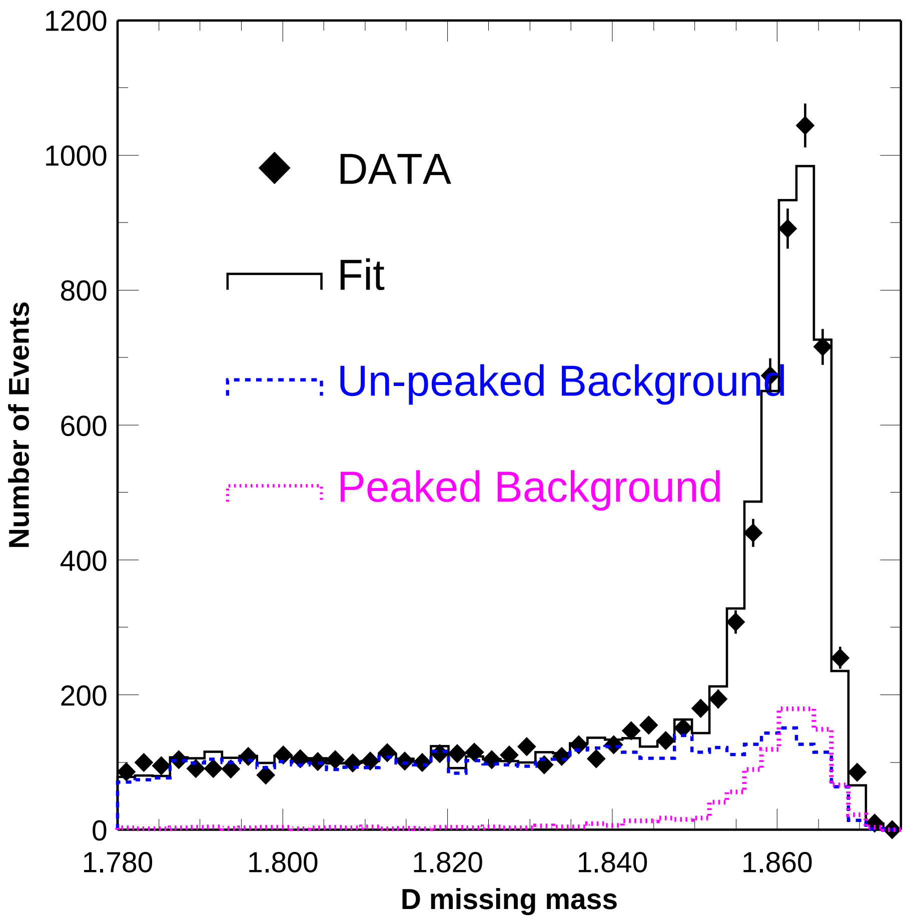
- Partial Reconstruction of $B \to D^* \pi_f$:
  - Fast, prompt π_f from B.
  - Slow π_s from $D^* \to D\pi_s$ reflects D^* momentum.
  - D not reconstructed.
  - 5 Particles: $B,\ D^*,\ \pi_f,\ D,\ \pi_s$
  - 5*4 = 20 degrees of freedom, 20 constraints.
  - Two kinematic variables used:

$$M^2_{D\,miss} = m_B^2 + m_{\pi_f}^2 + m_{\pi_s}^2 - 2E_B E_{\pi_f} - 2E_B E_{\pi_s} + 2E_{\pi_f} E_{\pi_s}$$
$$+2|\vec{p}_B||\vec{p}_{\pi_f}|\cos\vartheta_{B\pi_f} + 2|\vec{p}_B||\vec{p}_{\pi_s}|\cos\vartheta_{B\pi_s} - 2|\vec{p}_{\pi_f}||\vec{p}_{\pi_f}|\cos\vartheta_{\pi_f\pi_s}$$

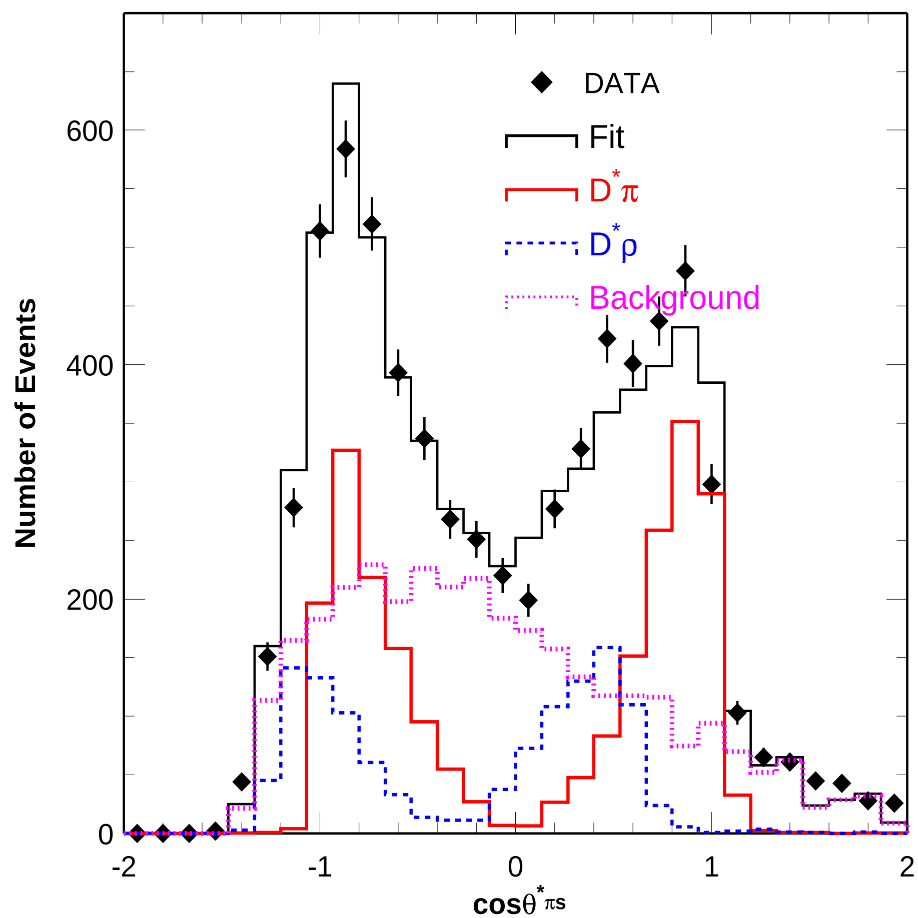
$$\cos\vartheta^*_{\pi_s} = \frac{\beta_{D^*}(E^*_D - D^*_{\pi_s})}{2|\vec{p}^{\,*}_{\pi_s}|} - \frac{|\vec{p}_D|^2 - |\vec{p}_{\pi_s}|^2}{2\gamma^2_{D^*}\beta_{D^*} m_{D^*}|\vec{p}^{\,*}_{\pi_s}|}$$

Helicity angle of soft pion in D^* restframe.

Signal Events



D missing mass



Helicity angle of soft pion

Tagging and Vertexing

- Tagging:
  - Signal *B* determined by charge of fast pion.
  - Accompanying *B* tagged by charge of high momentum lepton.
    - Important also for background rejection. $p_{com} > 1.1\,GeV/c$
    - Incorrect tags:
      - J/ψ dileptons, rejected by J/ψ mass cut.
      - Secondary leptons from charm, rejected by momentum and angle cuts.
      - Misidentified hadrons.
- Vertexing:
  - z−vertices: intersection of π_f and lepton track with profile of interaction point convoluted with average *B* flight length (~20μm).

$$\sigma_x^{IP} \simeq 110\,\mu m \qquad \sigma_y^{IP} \simeq 5\,\mu m \qquad \sigma_z^{IP} \simeq 2500\,\mu m$$

$$\Delta z \;\equiv\; z_{\pi_f} - z_l \;\simeq\; c\beta\tau\Delta t$$

Fitting

- PDF's: $$F_{sig}(\Delta t)=\int_{-\infty}^{\infty} P(\Delta t')R_{sig}(\Delta t-\Delta t')\,d\Delta t'$$

- Resolution function:
  - Sum of three Gaussians from J/ψ dilepton events.

$$R_{sig}(\Delta t) \;=\; f_1 G(\Delta t;\mu_{1,}\sigma_1) \;+\; f_2 G(\Delta t;\mu_{2,}\sigma_2) \;+\; (1-f_1-f_2)G(\Delta t;\mu_{3,}\sigma_3)$$

- Likelihood: $$L=\prod_i \left((1-f_{bkg}^{OF})F_{sig}^{OF}(\Delta t_i) \;+\; f_{bkg}^{OF}F_{bkg}^{OF}(\Delta t_i)\right) \;\times$$ $$\prod_j \left((1-f_{bkg}^{SF})F_{sig}^{SF}(\Delta t_j) \;+\; f_{bkg}^{SF}F_{bkg}^{SF}(\Delta t_i)\right)$$

- Background PDF includes terms for:
  - with, without lifetime
  - peaked, non−peaked
  - mixed, unmixed

Result

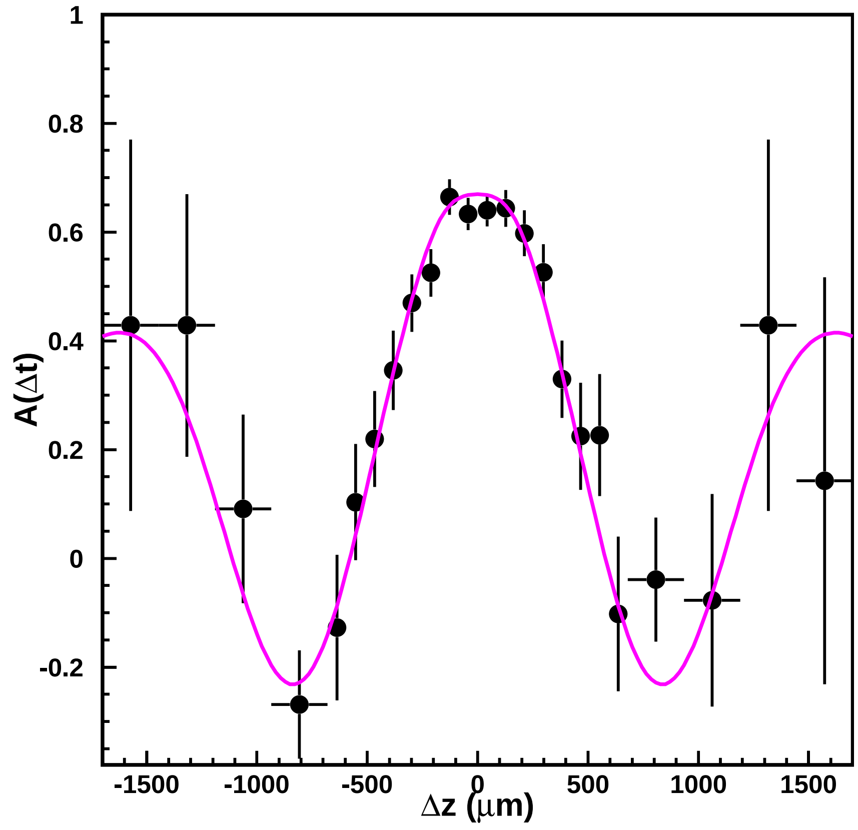
- Fit to:

$$A(\Delta t) \equiv \frac{P^{OF}(\Delta t) - P^{SF}(\Delta t)}{P^{OF}(\Delta t) + P^{SF}(\Delta t)} = \cos(\Delta m_d \Delta t)$$

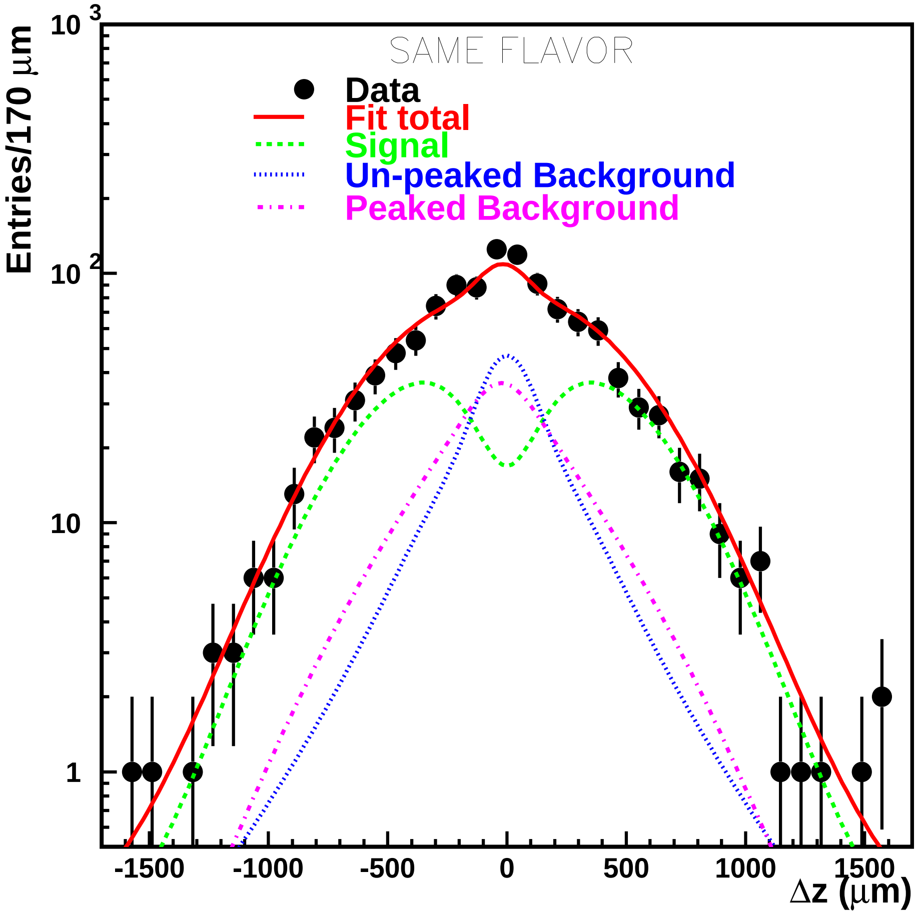
$$\Delta m = 0.505 \pm 0.017 \pm 0.020\ ps^{-1}$$

$$29.1\ fb^{-1}$$

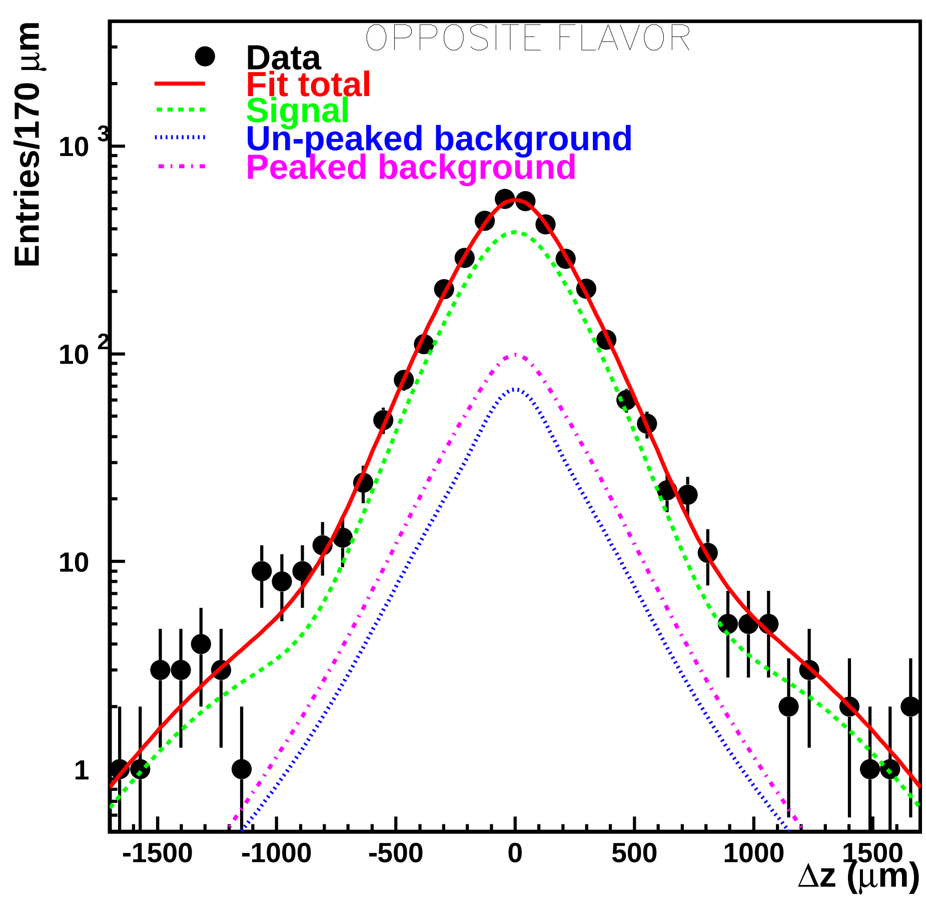
PDG: $0.479 \pm 0.012\ ps^{-1}$



Fit



$$\Delta m_d = 0.511 \pm 0.035\, ps^{-1}$$



$$\Delta m_d = 0.504 \pm 0.019\, ps^{-1}$$

Monte Carlo Study of $\sin(2\phi_1+\phi_3)$

- Same technique as for mixing.
- Signal events generated with:

$$\sin(2\phi_1+\phi_3)=0.985$$

$$|\rho|=0.045 \qquad \delta=0$$

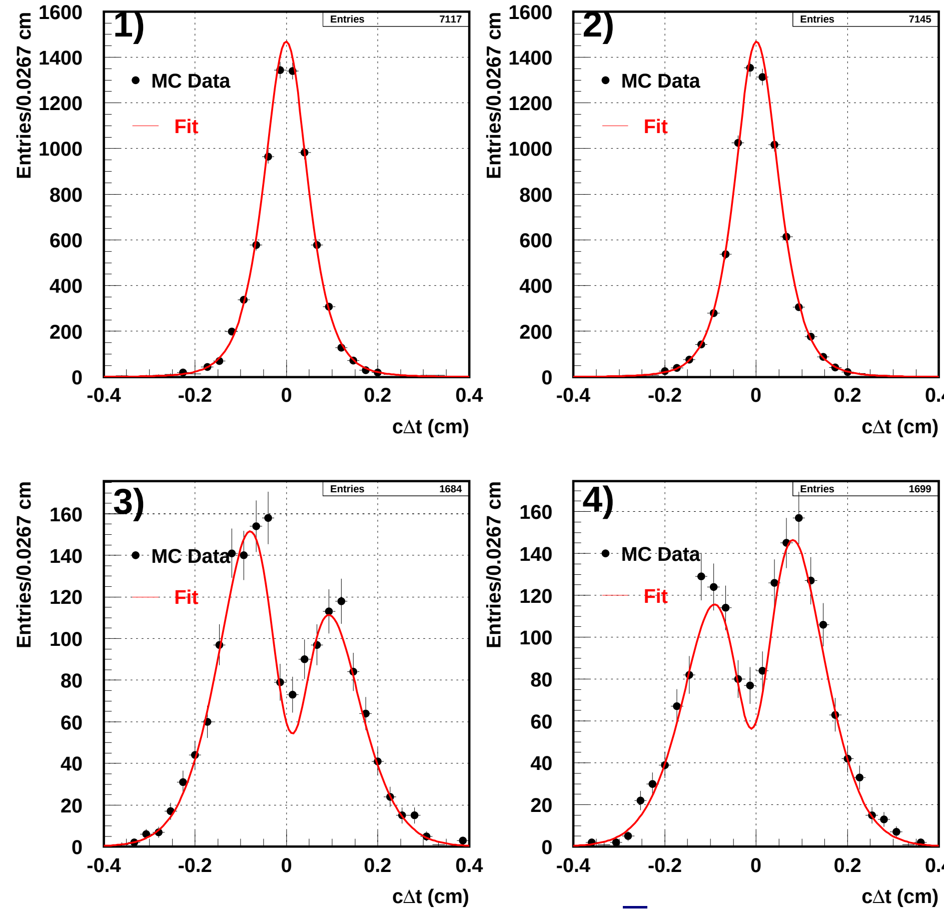
- Fit results:

$$\sin(2\phi_1+\phi_3+\delta)=1.15\pm0.17$$

$$\sin(2\phi_1+\phi_3-\delta)=0.88\pm0.17$$

No Background

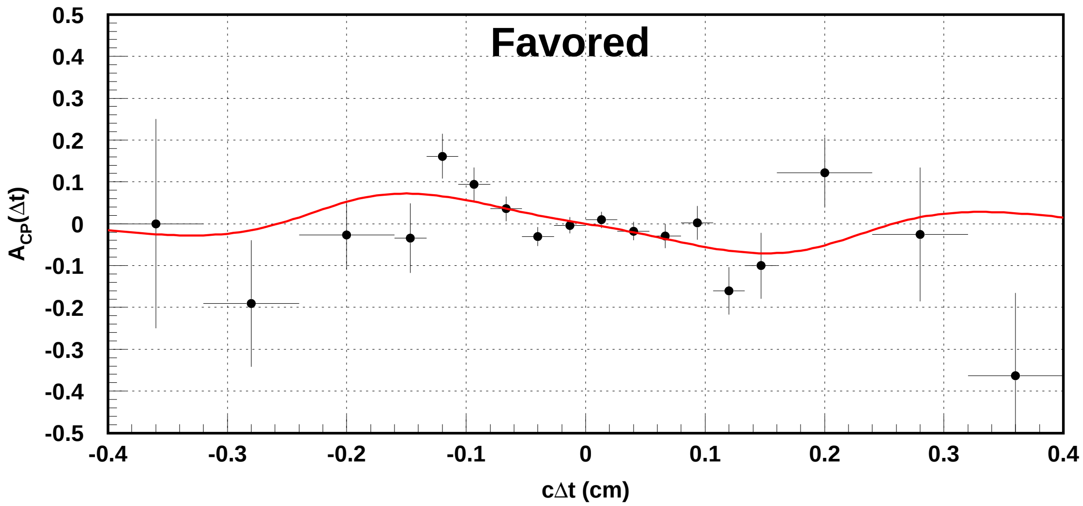
$B^0 \to D^{*-}\pi^+$ $\qquad$ $\bar{B}^0 \to D^{*+}\pi^-$



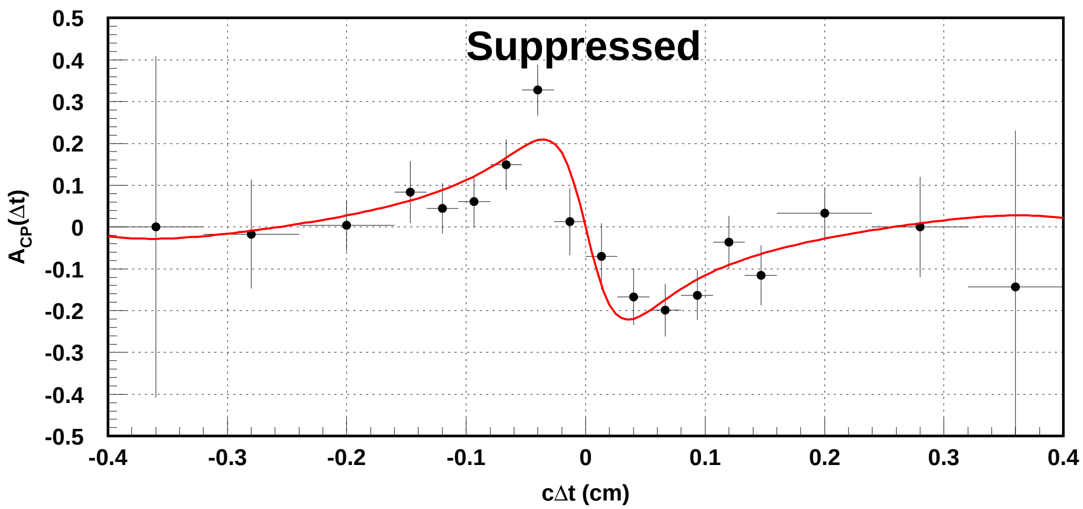
$B^0 \to D^{*+}\pi^-$ $\qquad$ $\bar{B}^0 \to D^{*-}\pi^+$

Asymmetry Fit results

$$A_{favored} \equiv \frac{B^0 \to D^{*-}\pi^+ - \bar{B}^0 \to D^{*+}\pi^-}{B^0 \to D^{*-}\pi^+ + \bar{B}^0 \to D^{*+}\pi^-}$$



$$A_{supressed} \equiv \frac{B^0 \to D^{*+}\pi^- - \bar{B}^0 \to D^{*-}\pi^+}{B^0 \to D^{*+}\pi^- + \bar{B}^0 \to D^{*-}\pi^+}$$



Sensitivity

- Estimated sensitivity with 200 fb^{-1}:

For $|\rho|=0.045$:

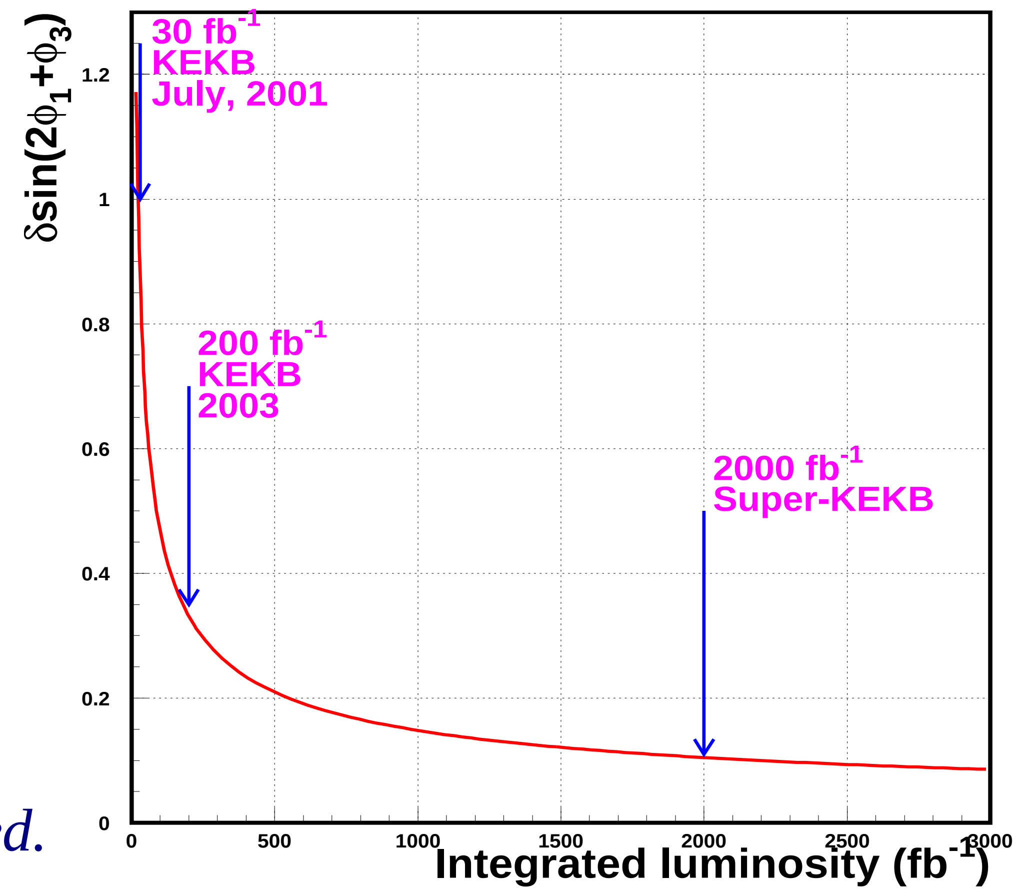
$$\delta(\sin(2\phi_1+\phi_3))=\pm 0.17$$

For $|\rho|=0.022$:

$$\delta(\sin(2\phi_1+\phi_3))=\pm 0.34$$

Caveat:

Backgrounds (e.g. $B\rightarrow D^{*}\rho$) and mistagging not included.



Conclusion

$$Using \quad B \rightarrow D^{*\pm} \pi^{\mp}:$$

$$\Delta m_d = 0.505 \ \pm \ 0.017 \ \pm \ 0.020 \, ps^{-1}$$

$$29.1 \, fb^{-1}$$

$$For \quad |\rho| = 0.022:$$

$$\delta(\sin(2\phi_1 + \phi_3)) = \pm 0.34$$

$$200 \, fb^{-1}$$

$$Summer\ 2002: \ 90 \, fb^{-1}$$

$$Summer\ 2003: 200 \, fb^{-1}$$

Systematic Errors

Source	Errors (ps^{-1})
Signal Resolution Function	0.012
Background Fraction	0.014
Background Shape	0.004
B^0_d Background	0.005
Detector Resolution	0.002
Total	0.020

Asymmetries

$$A_{favored} \equiv \frac{B^0 \to D^{*-}\pi^+ - \bar{B}^0 \to D^{*+}\pi^-}{B^0 \to D^{*-}\pi^+ + \bar{B}^0 \to D^{*+}\pi^-}$$

$$= \frac{-|\rho|(\xi+\bar{\xi})\sin\Delta m\Delta t}{(1+|\rho|^2)+(1-|\rho|^2)\cos\Delta m\Delta t+|\rho|(\xi-\bar{\xi})\sin\Delta m\Delta t}$$

$$A_{supressed} \equiv \frac{B^0 \to D^{*+}\pi^- - \bar{B}^0 \to D^{*-}\pi^+}{B^0 \to D^{*+}\pi^- + \bar{B}^0 \to D^{*-}\pi^+}$$

$$= \frac{-|\rho|(\xi+\bar{\xi})\sin\Delta m\Delta t}{(1+|\rho|^2)-(1-|\rho|^2)\cos\Delta m\Delta t+|\rho|(\xi-\bar{\xi})\sin\Delta m\Delta t}$$