Time-dependent CP Violation Measurements from Belle

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representing the

Belle Collaboration

Les Rencontres de Physique de la Vallée d'Aoste

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Introduction

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

where A, λ, ρ, η are Wolfenstein parameters

From unitarity ($V_{CKM}^* V_{CKM} = 1$):

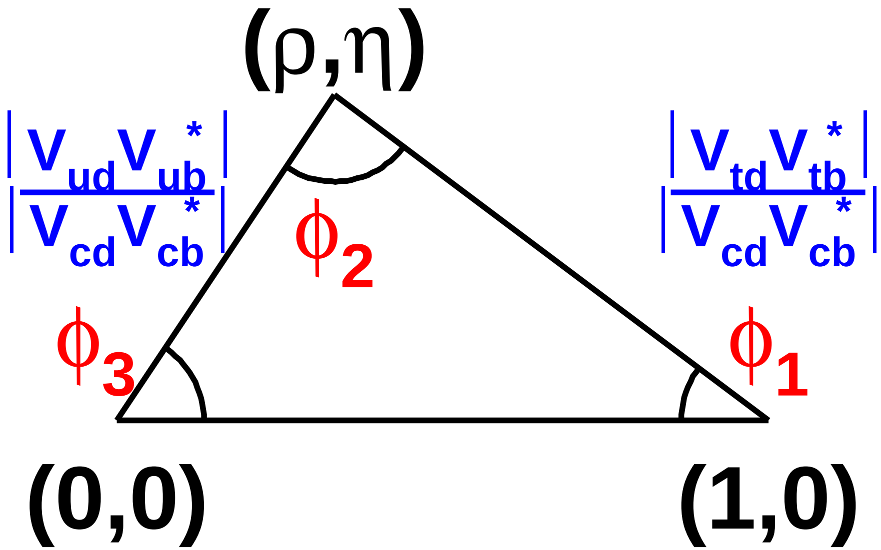
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The Unitarity Triangle

$\phi_1 \leftrightarrow \beta$

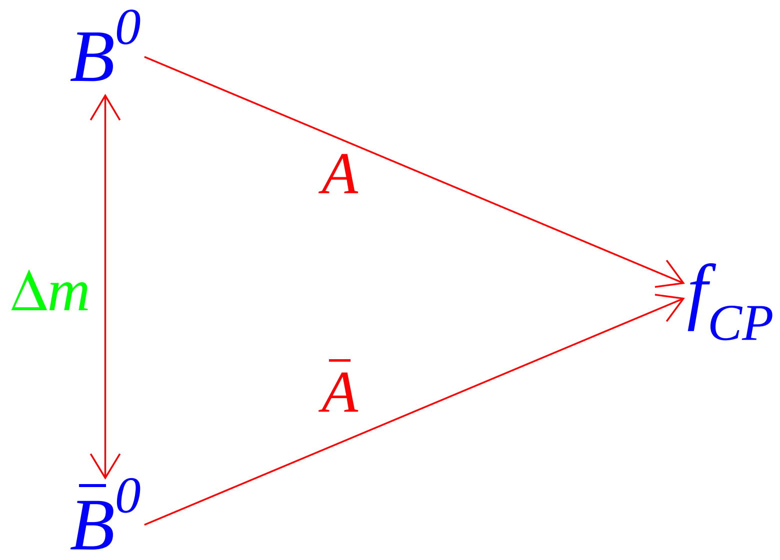
$\phi_2 \leftrightarrow \alpha$

$\phi_3 \leftrightarrow \gamma$



Time-Dependent CP Violation Phenomenology

- Interference between different paths to a final state $\Rightarrow$ time-dependent CP violation
- Consider $B^0/\bar{B}^0$ decaying to a CP eigenstate
- Define $\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$
  - p, q from $B^0 - \bar{B}^0$ mixing
  - Standard Model : $\frac{q}{p} \sim e^{-2\phi_1}$
- Simplest scenario:
  - $\left|\frac{q}{p}\right| = 1$, $\left|\frac{\bar{A}}{A}\right| = 1 \Rightarrow S_{CP} = \mathrm{Im}(\lambda_{CP})$



- At B factories, measure Δt from decay time of other B (tagged as B^0 $(q = +1)$ or $\bar{B}^0$ $(q = -1)$)

$$P^q_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left\{S_{CP}\sin(\Delta m \Delta t)\right\}\right]$$

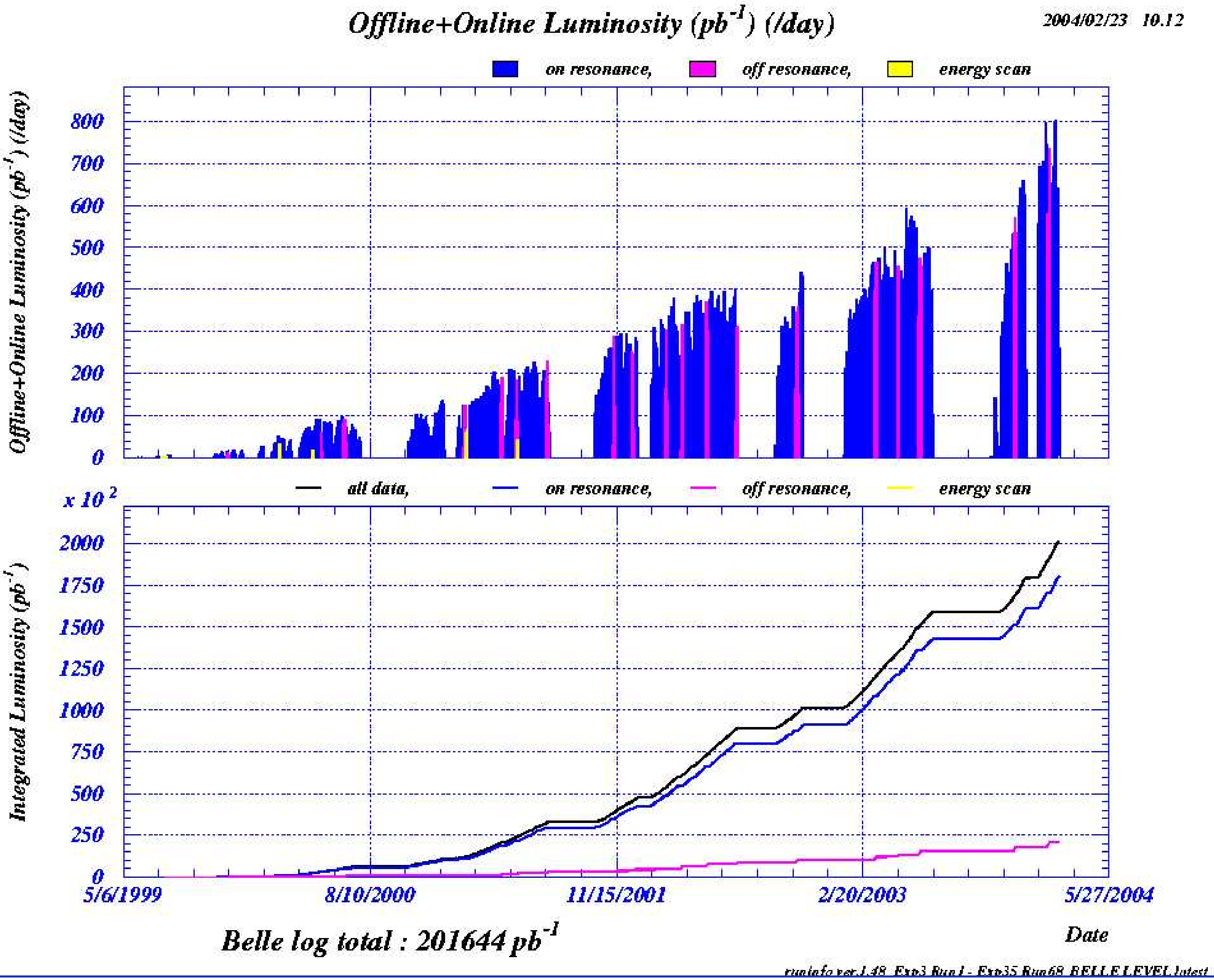
How To Measure Time-Dependent CP Violation

(at an asymmetric energy B factory)

1. Collect a large sample of $B - \bar{B}$ decays
2. Identify and select events containing relevant final state
3. Tag the flavour of the other B
4. Measure Δt from $\Delta z = z_{CP} - z_{\mathrm{tag}} \approx (\beta\gamma)_{\Upsilon} c \Delta t$
5. Fit the sample

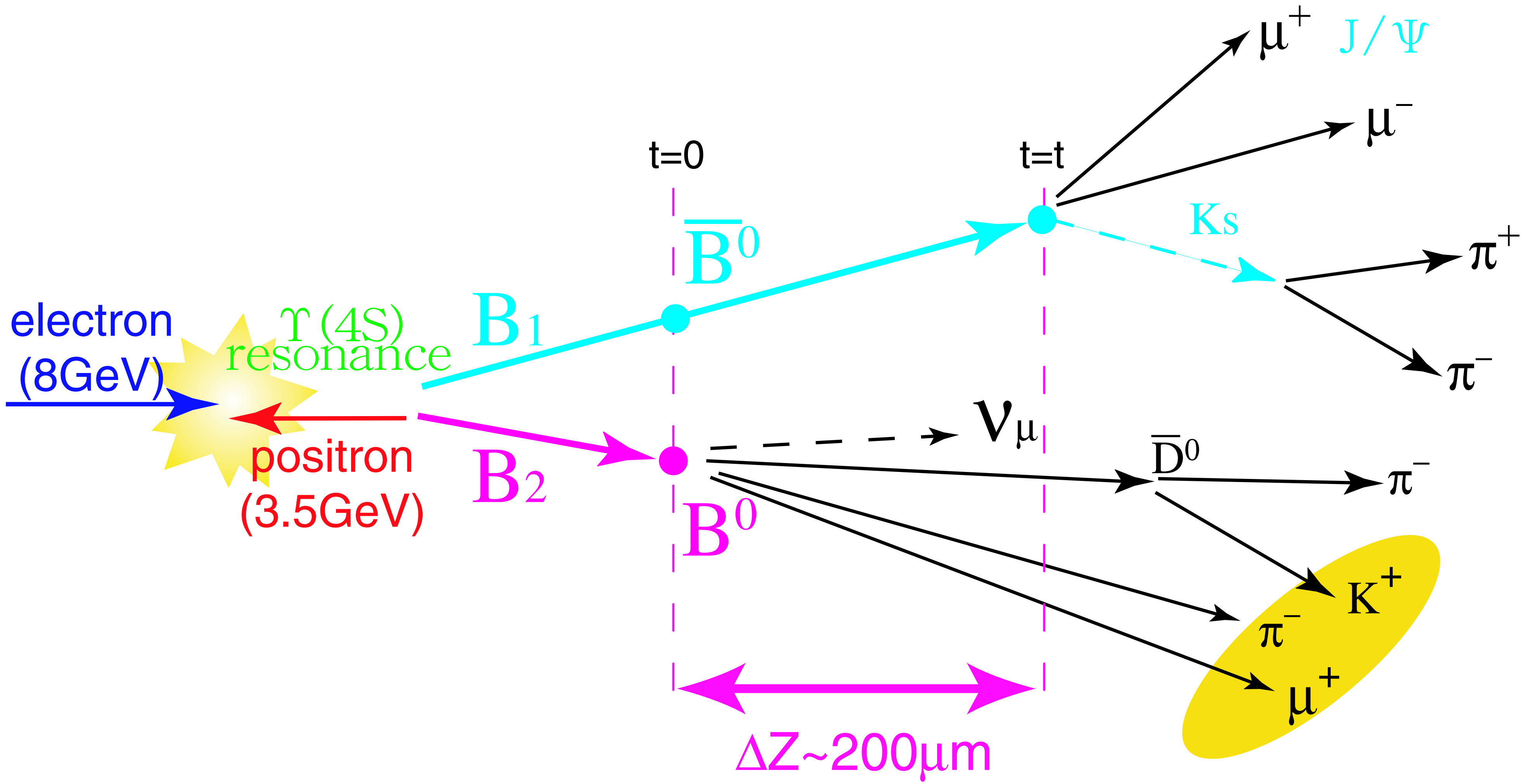
Lots of Bs!

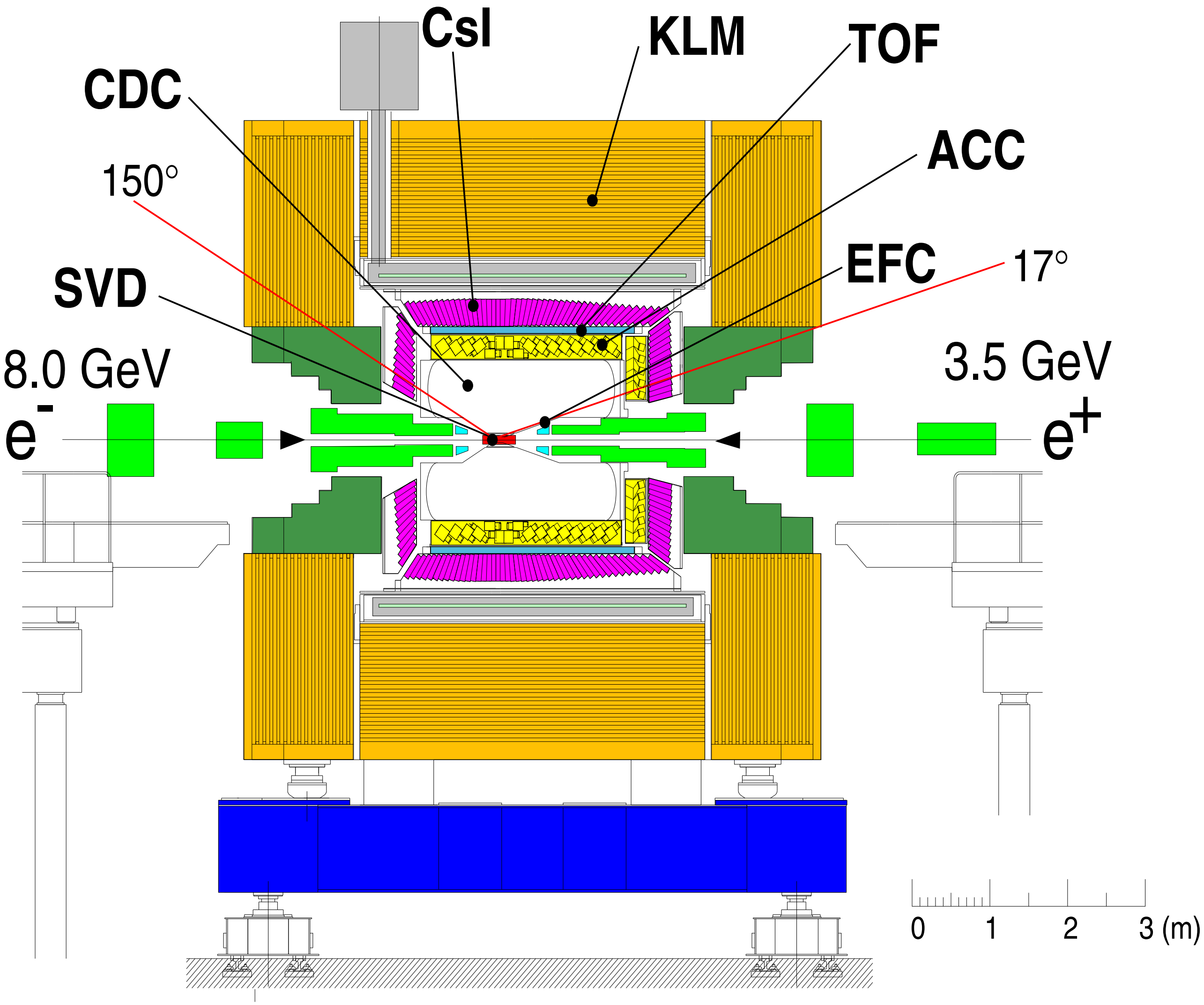
Results presented today use 140 fb^{-1} on $\Upsilon(4S) \stackrel{\sim}{\equiv} 150 \times 10^6$ $B\bar{B}$ pairs



How To Measure Time-Dependent CP Violation

Illustrated using $\bar{B}^0 \to J/\psi K_S$, $B^0 \to D^{*-}\mu^+\nu_\mu$



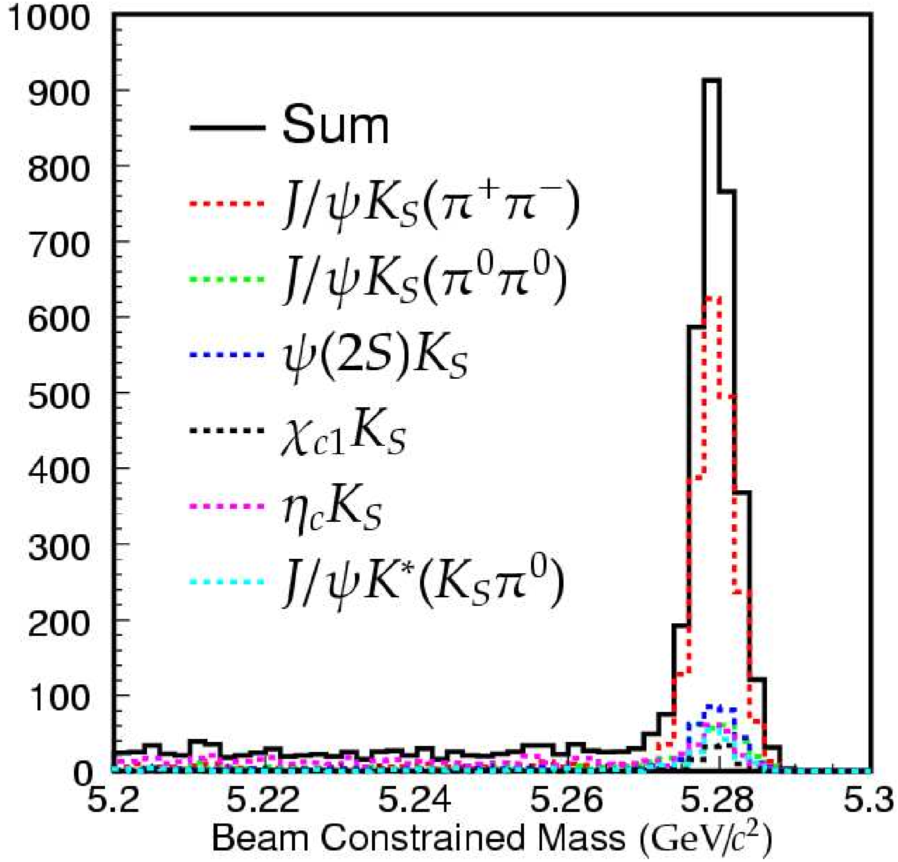


- SVD 3 DSSD layers
  $\sigma \sim 55\ \mu$m for 1 GeV/c @ 90°
- CDC 50 layers
  $\sigma_p/p \sim 0.35\%$ @ 1 GeV/c
  $\sigma_\pi(dE/dx) \sim 7\%$
- TOF $\sigma_t \sim 95$ ps
- ACC ($n = 1.01 \rightarrow 1.03$)
  K/π separation up to 3.5 GeV/c
- CsI $\sigma_E/E_\gamma \sim 1.8\%$ @ 1 GeV
- KLM 14 RPC layers
- 1.5 T magnetic field

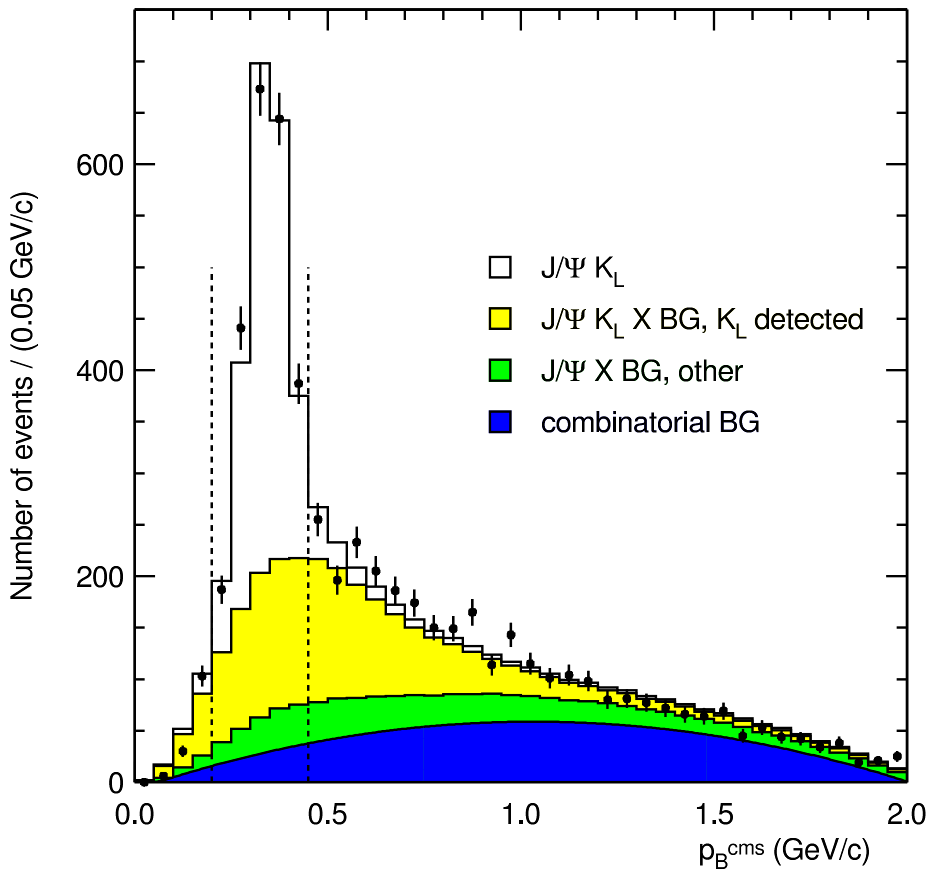
$b \to c\bar{c}s$ transitions are dominated by a single weak phase

measure sin $(2\phi_1)$

$J/\psi K_S$, *etc.*
3085 candidates



$J/\psi K_L$
2332 candidates



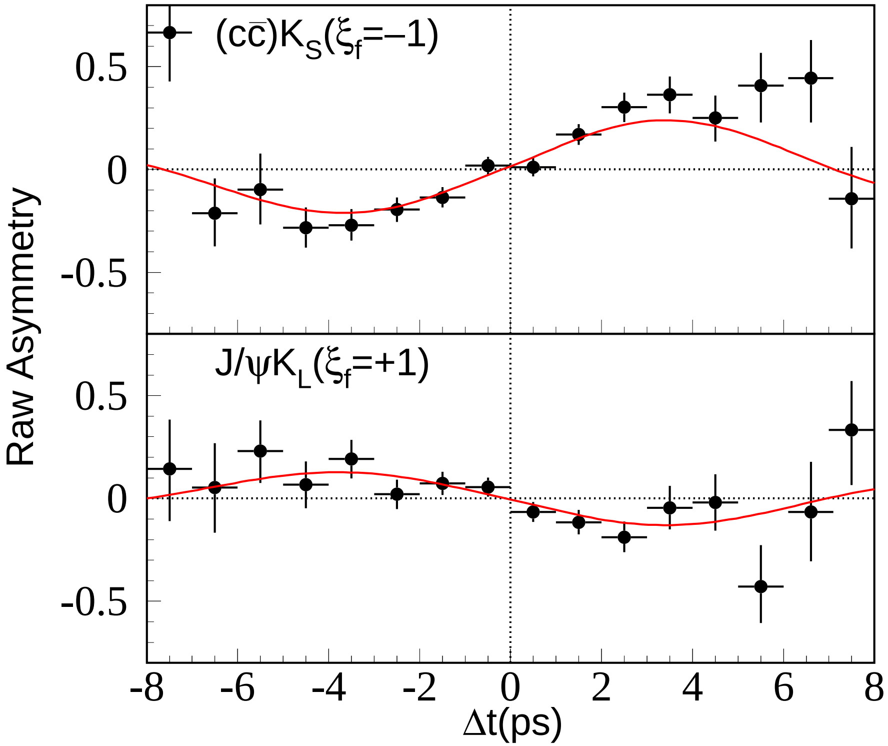
Analysis Procedure

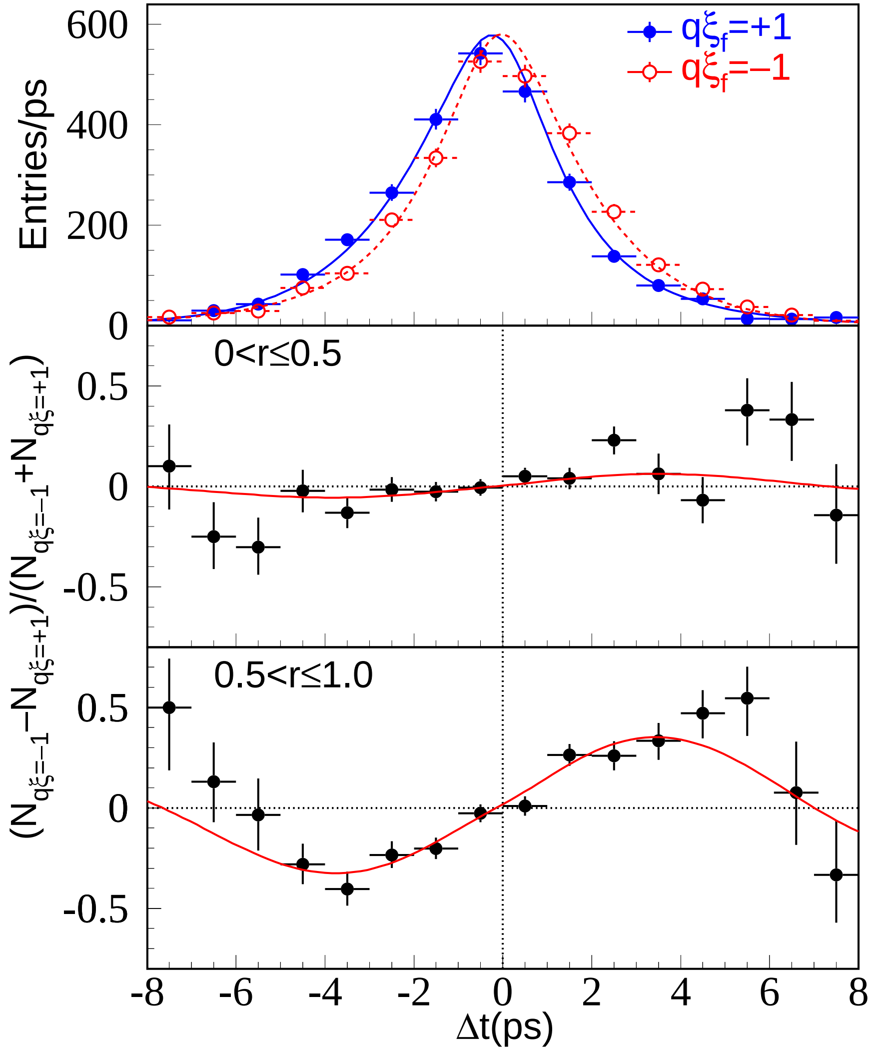
- Flavour tagging
  - Use flavour specific, inclusive properties of decay products
  - Include correlations in a multi-dimensional likelihood
  - Assign $q = \pm 1$ & $r \in 0, 1$
  - Divide data in categories: 6 of $r \times$ 2 of q
- Vertexing
  - Require SVD hits to obtain precise vertex
  - Use run-dependent interaction point profile
- Fitting
  - Use unbinned maximum likelihood fits
  - Wrong tag fraction for each q,r bin
  - Event-by-event signal probability based on ΔE, $M_{\rm bc}$
  - Event-by-event resolution function based on vertex errors

$\sin(2\phi_1)$ Fit Result

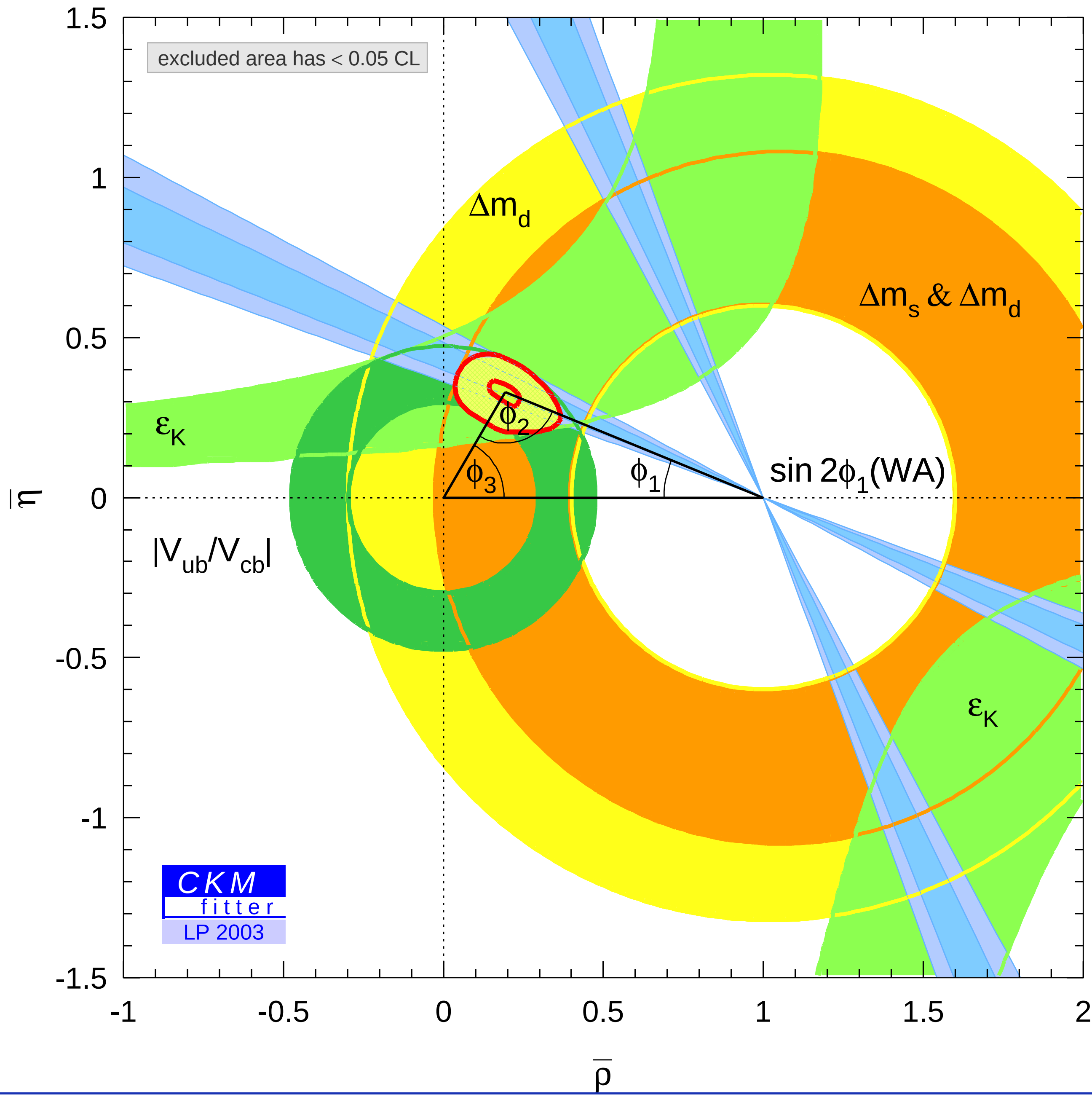
PRELIMINARY

$$\sin(2\phi_1) = 0.733 \pm 0.057 \pm 0.028$$

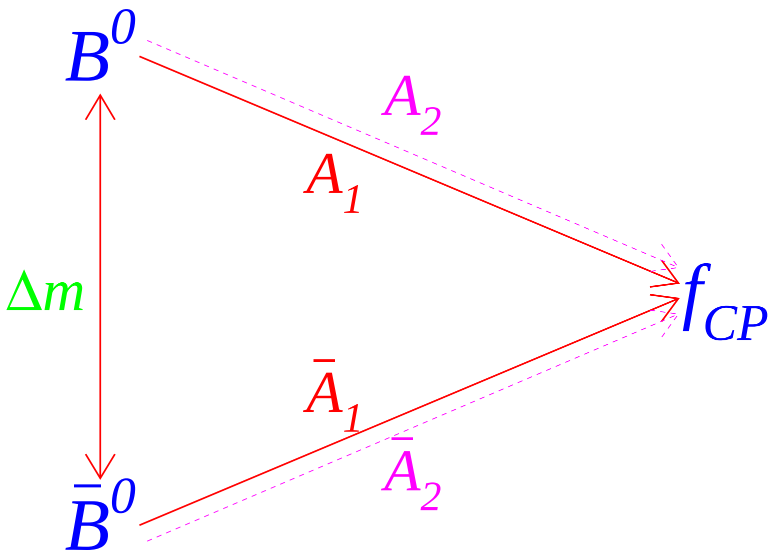




$\rho - \eta$ Constraint



- If more than weak phase contributes, $A = A_1 + A_2$, $\bar{A} = \bar{A}_1 + \bar{A}_2 \Rightarrow \left|\frac{\bar{A}}{A}\right| \neq 1$



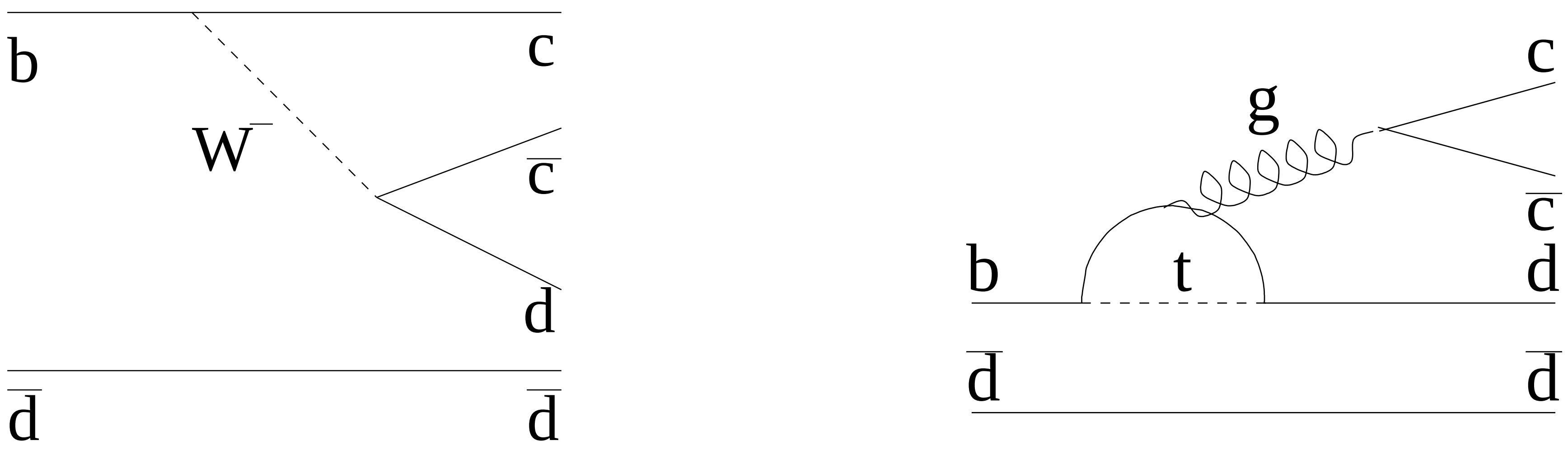
- Remember $\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$

- $S_{CP} = \frac{2\,\mathrm{Im}(\lambda_{CP})}{|\lambda_{CP}|^2+1}, \quad A_{CP} = \frac{|\lambda_{CP}|^2-1}{|\lambda_{CP}|^2+1}$

- If $\left|\frac{q}{p}\right| = 1$, $A_{CP} = \frac{\Gamma_{\bar{B}^0\to f_{CP}} - \Gamma_{B^0\to f_{CP}}}{\Gamma_{\bar{B}^0\to f_{CP}} + \Gamma_{B^0\to f_{CP}}} \equiv$ time-integrated (direct) CP asymmetry

$$P^q_{CP}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left\{S_{CP}\sin(\Delta m \Delta t) + A_{CP}\cos(\Delta m \Delta t)\right\}\right]$$

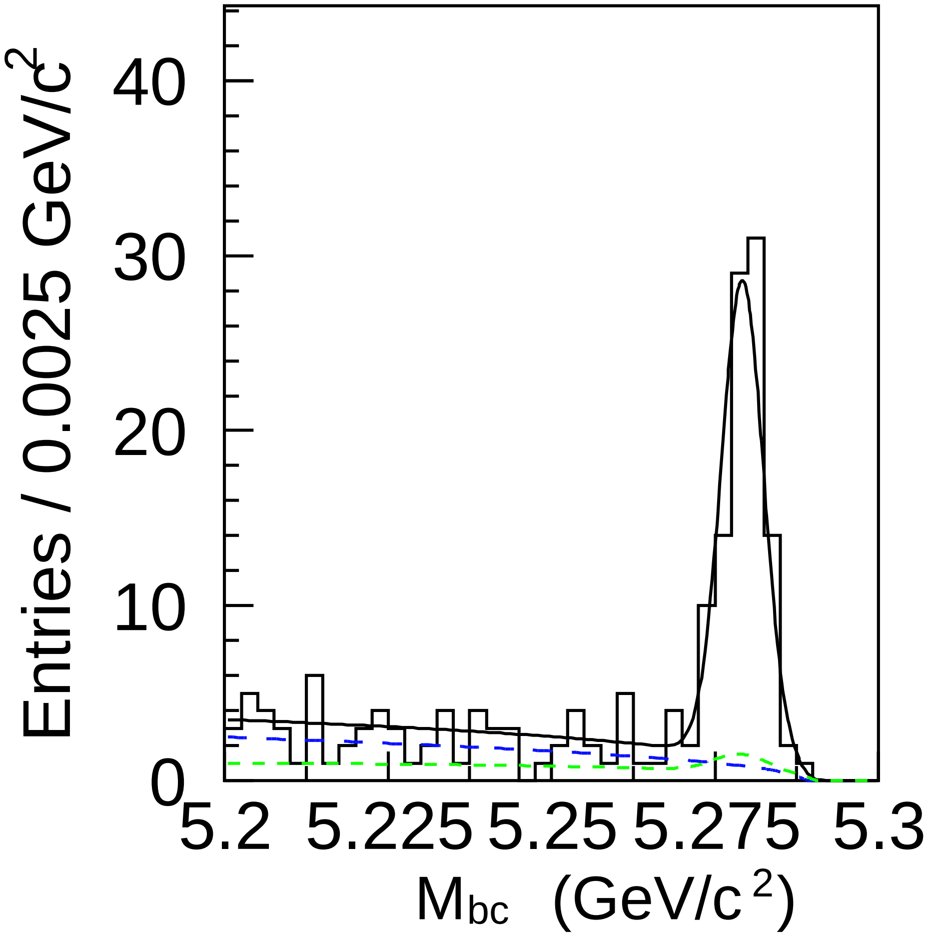
Contributions from tree and penguin amplitudes



Penguin contains $V_{td} \rightsquigarrow$ different phase

$J/\psi\pi^0$ Results

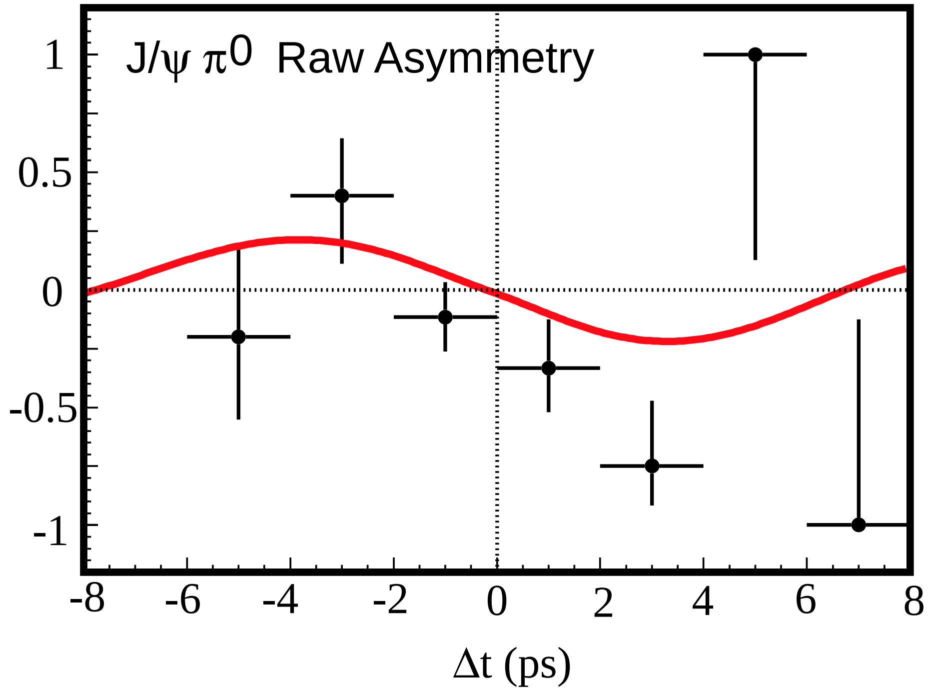
103 candidate events



PRELIMINARY

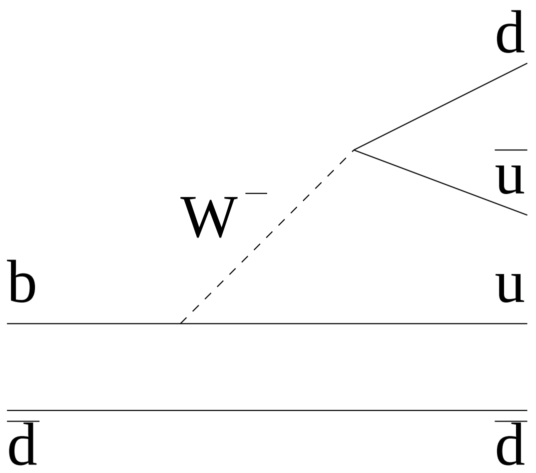
$$S_{J/\psi\pi^0} = -0.72 \pm 0.42 \pm 0.08$$

$$A_{J/\psi\pi^0} = -0.01 \pm 0.29 \pm 0.07$$

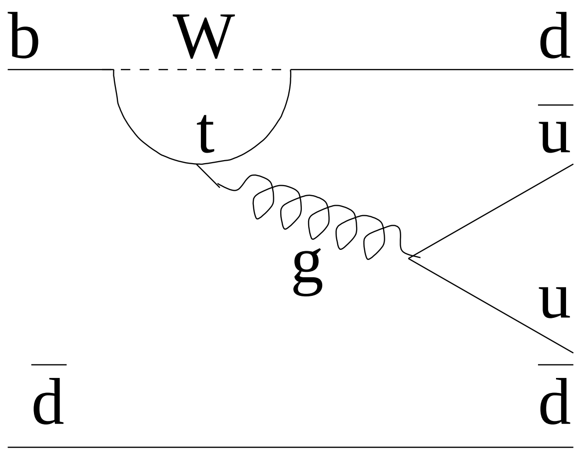


Contributions from tree and penguin amplitudes

tree contains V_{ub}



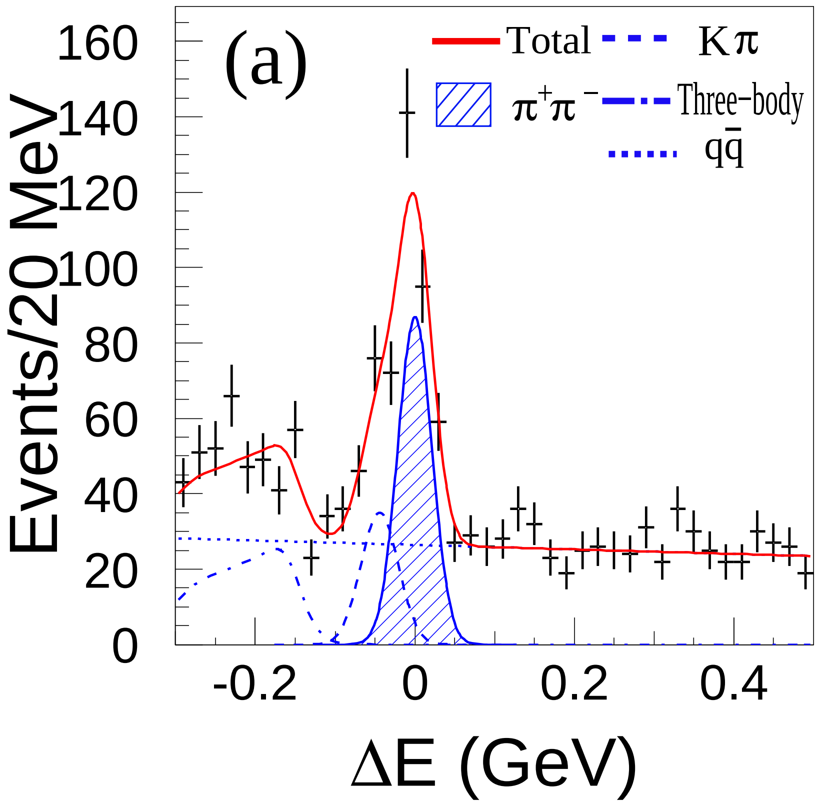
penguin contains V_{td}



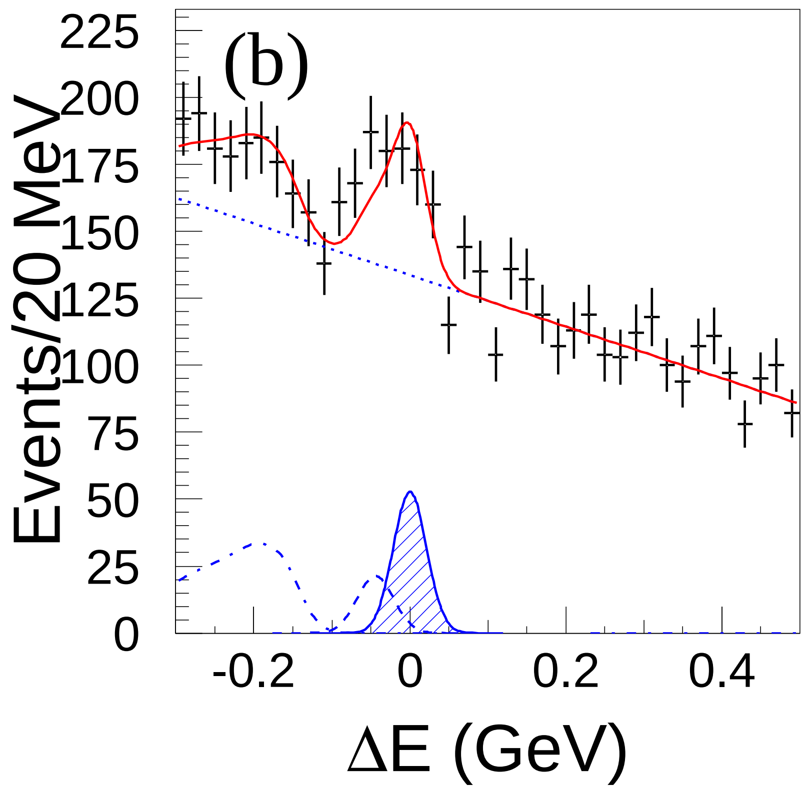
- Small branching fraction ($\sim 4 \times 10^{-6}$)
- Large background from $e^+e^- \to q\bar{q} \quad (q = u, d, s, c)$
- Background from $B \to K^+\pi^-$

Categorize candidates based on level of $q\bar{q}$ background

High quality



Low quality



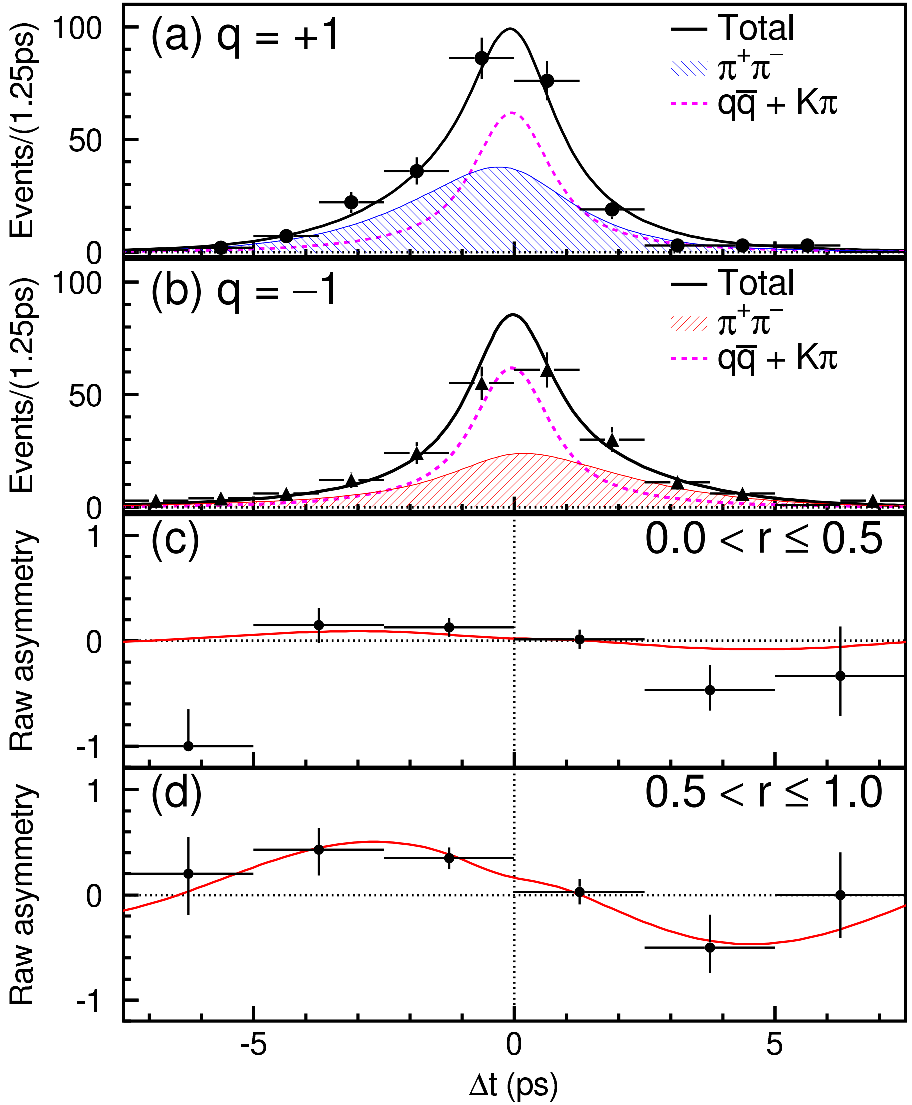
$B \to \pi^+\pi^-$ Fit Result

- 1529 candidates
- 372 ± 32 $\pi^+\pi^-$ signal events

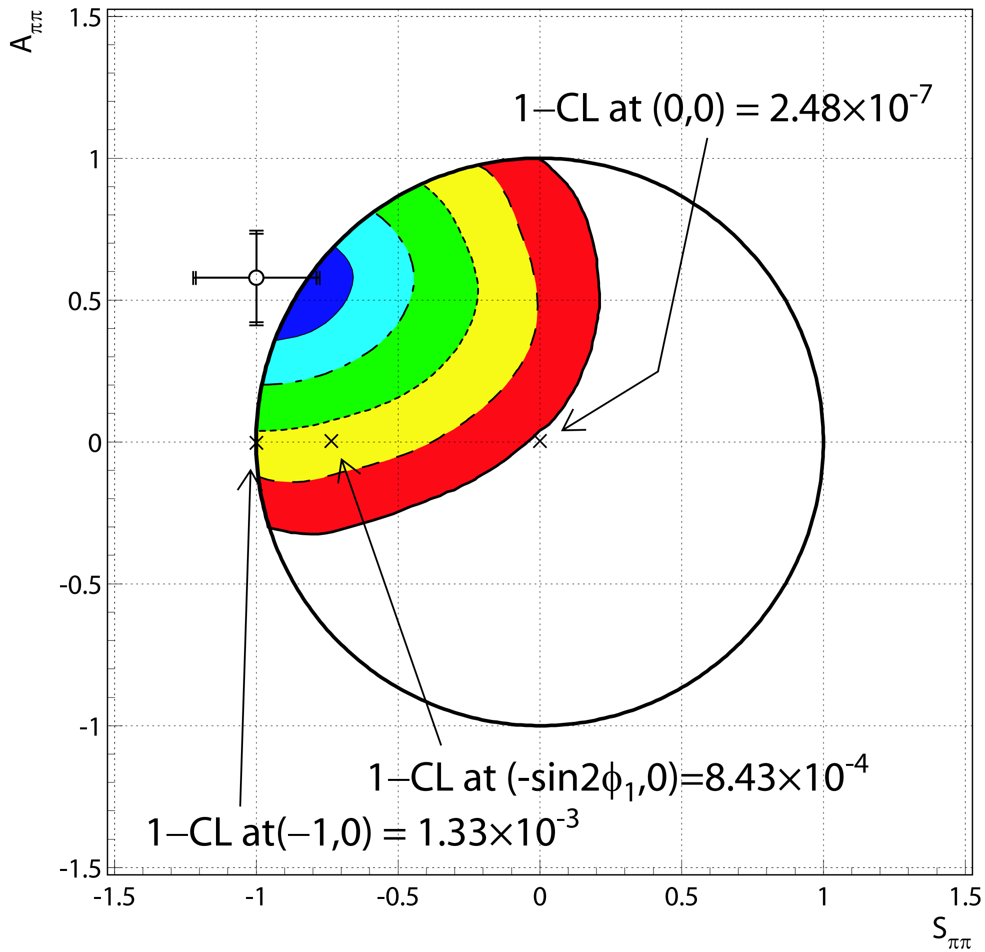
$$\boxed{S_{\pi^+\pi^-} = -1.00 \pm 0.21 \pm 0.07}$$

$$\boxed{A_{\pi^+\pi^-} = +0.58 \pm 0.15 \pm 0.07}$$

- Many cross-checks performed
  - $K\pi$ control sample
  - $q\bar{q}$ control sample
  - Various subsamples
  - Toy Monte Carlo studies
  - Binned fit



Feldman-Cousins Analysis



<u>OBSERVATION OF CP VIOLATION</u>

5.2σ

EVIDENCE FOR DIRECT CP VIOLATION

3.2σ

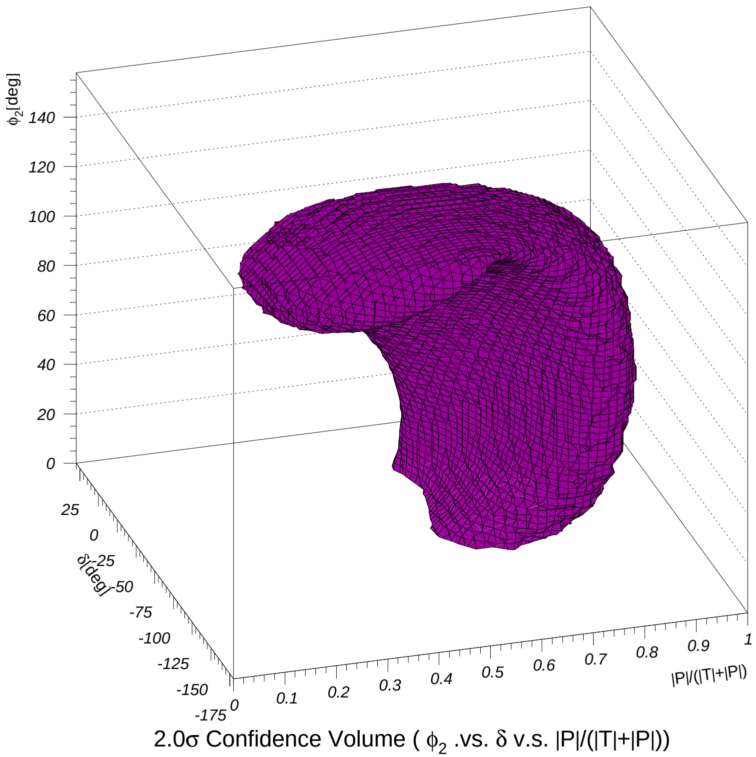
Constraint on ϕ_2

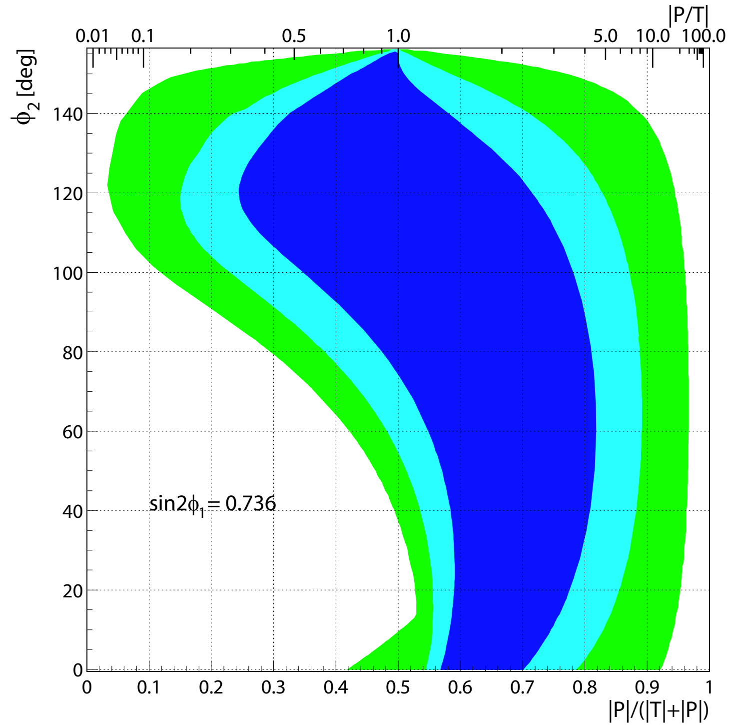
- $S_{\pi^+\pi^-}$ & $A_{\pi^+\pi^-}$ can be written as functions of ϕ_1, ϕ_2, P/T & δ

  M. Gronau & J.L. Rosner, PRD **65**, 093012 (2002)

- Using measured ϕ_1, translate contraint on $S_{\pi^+\pi^-}$ & $A_{\pi^+\pi^-}$

  $\rightarrow$ *confidence volume* in $(\phi_2, P/T, \delta)$ space





95.5% confidence level limits:

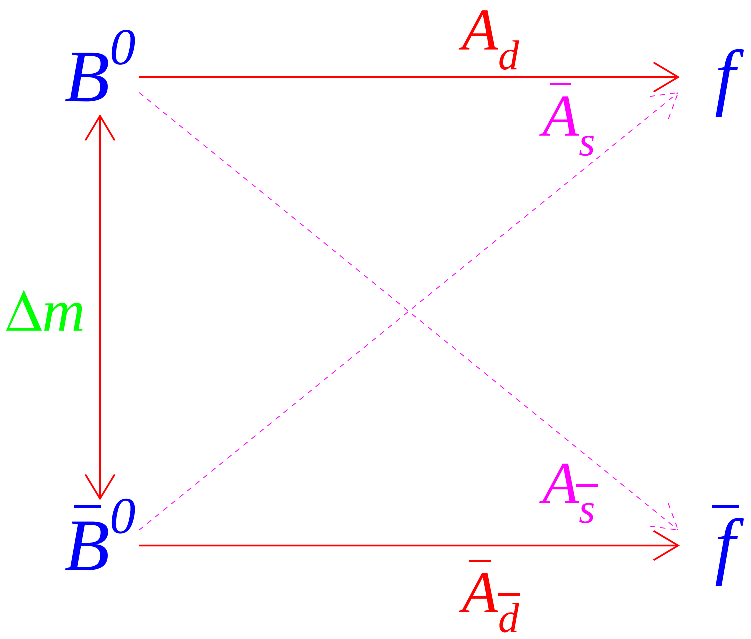
- $\star$ $P/T > 0.17$ (any ϕ_2, δ)
- $\star$ $90^\circ \leq \phi_2 \leq 146^\circ$ ($P/T \leq 0.45$, any δ)

- Consider now $B^0/\bar{B}^0$ decaying to a non-CP eigenstate

- dominant and suppressed contributions

- Define $\rho = \frac{q}{p}\frac{\bar{A}_s}{A_d}, \quad \bar{\rho} = \frac{p}{q}\frac{A_{\bar{s}}}{\bar{A}_{\bar{d}}}$

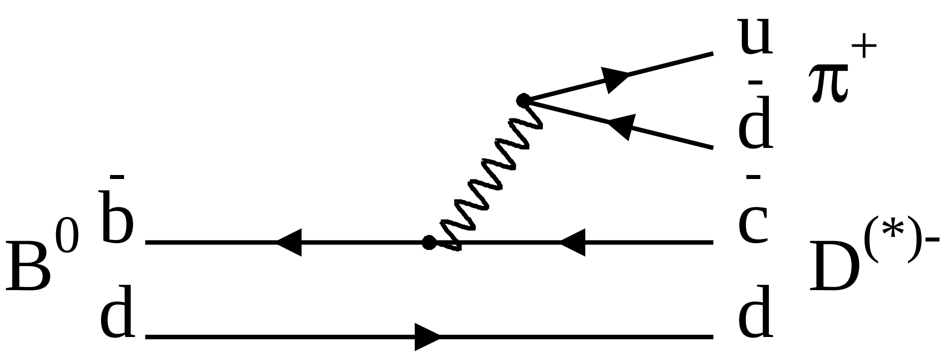
- Simple scenario:
  - $\left|\frac{q}{p}\right| = 1, \left|\frac{\bar{\rho}}{\rho}\right| = 1, |\rho| \ll 1$



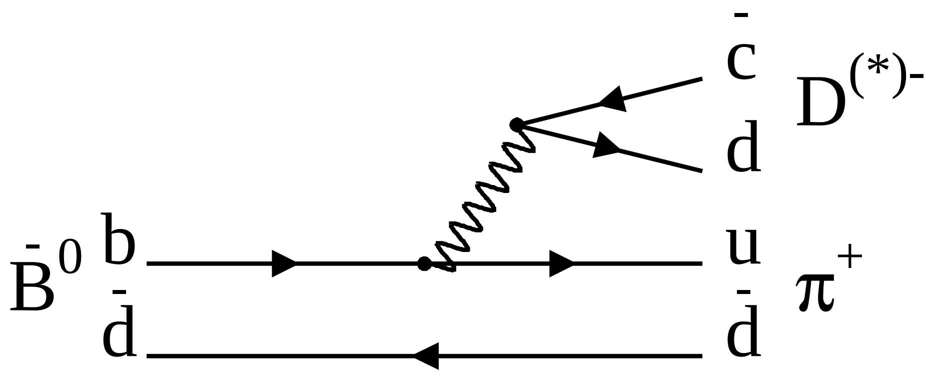
$$P^q_f(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 - q\left(\cos(\Delta m \Delta t) + 2\,\Im(\rho)\sin(\Delta m \Delta t)\right)\right]$$

$$P^q_{\bar{f}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\cos(\Delta m \Delta t) + 2\,\Im(\bar{\rho})\sin(\Delta m \Delta t)\right)\right]$$

dominant $\sim V_{cb}V_{ud}$



suppressed $\sim V_{ub}V_{cd}$



Can naively predict $\left|\frac{A_s}{A_d}\right| \sim 0.02$

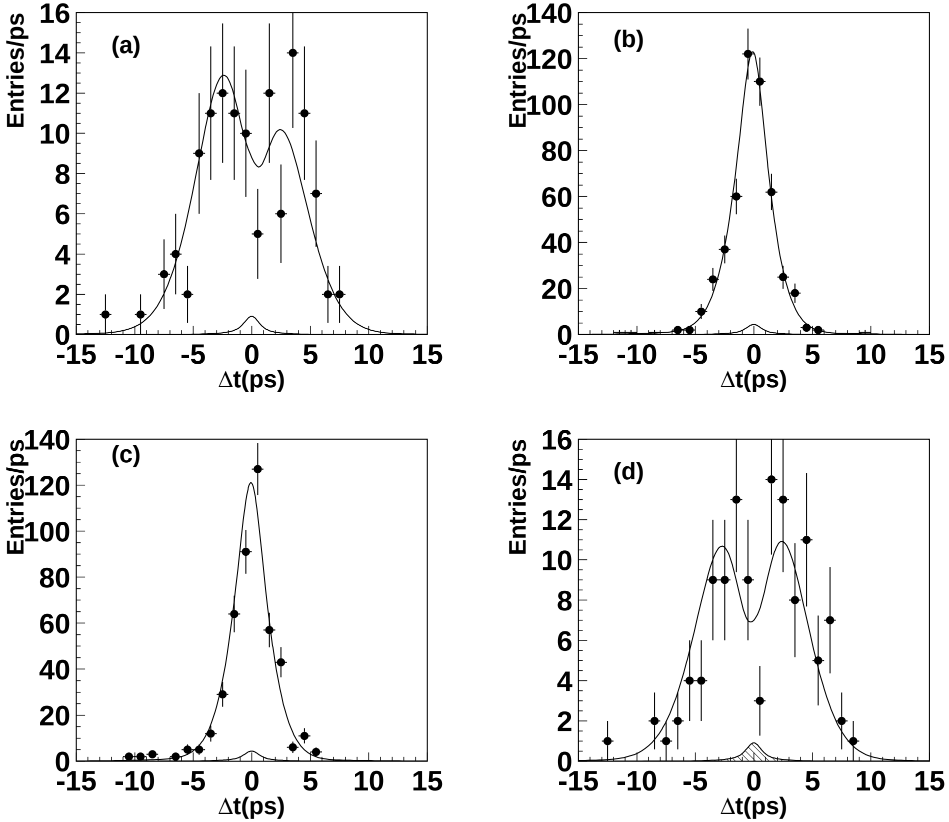
Weak phase difference is $2\phi_1 + \phi_3$

$B \to D^{(*)}\pi$ Candidates

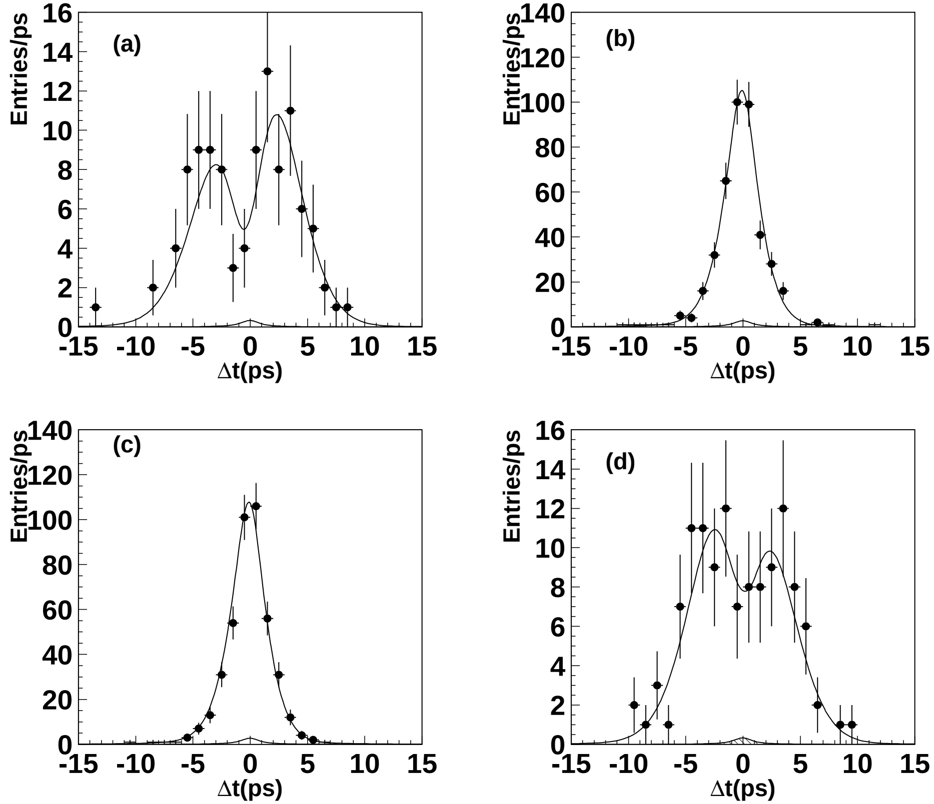
For $B \to D^{(*)}\pi$

$$\Im(\rho) = (-1)^{L+1} R_{D^{(*)}\pi} \sin(2\phi_1 + \phi_3 - \delta_{D^{(*)}\pi}) \qquad \Im(\bar{\rho}) = (-1)^{L} R_{D^{(*)}\pi} \sin(2\phi_1 + \phi_3 + \delta_{D^{(*)}\pi})$$

$D\pi$ - 12,027 candidates



$D^{*}\pi$ - 10,622 candidates



Data: best quality flavour tagging; Curves: Fit result for entire data

$B \to D^{(*)}\pi$ Fit Result

$$2\,R_{D^*\pi}\sin(2\phi_1+\phi_3+\delta_{D^*\pi}) = 0.109 \pm 0.057 \pm 0.019$$
$$2\,R_{D^*\pi}\sin(2\phi_1+\phi_3-\delta_{D^*\pi}) = 0.011 \pm 0.057 \pm 0.019$$
$$2\,R_{D\pi}\sin(2\phi_1+\phi_3+\delta_{D\pi}) = 0.087 \pm 0.054 \pm 0.018$$
$$2\,R_{D\pi}\sin(2\phi_1+\phi_3-\delta_{D\pi}) = 0.037 \pm 0.052 \pm 0.018$$

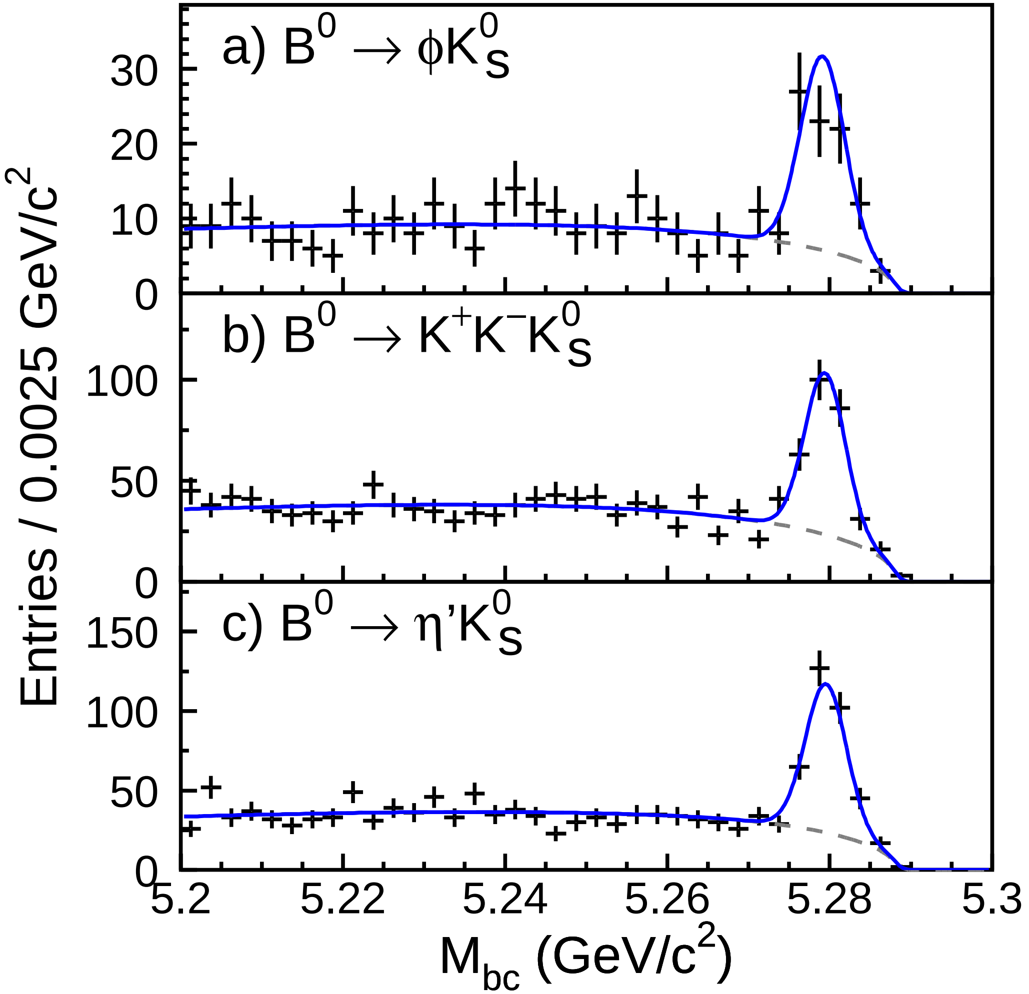
Assume that $\delta_{D^{(*)}\pi} = 0$ or π:

$$|2\,R_{D^*\pi}\sin(2\phi_1+\phi_3)| = 0.060 \pm 0.040 \pm 0.019$$
$$|2\,R_{D\pi}\sin(2\phi_1+\phi_3)| = 0.061 \pm 0.037 \pm 0.018$$

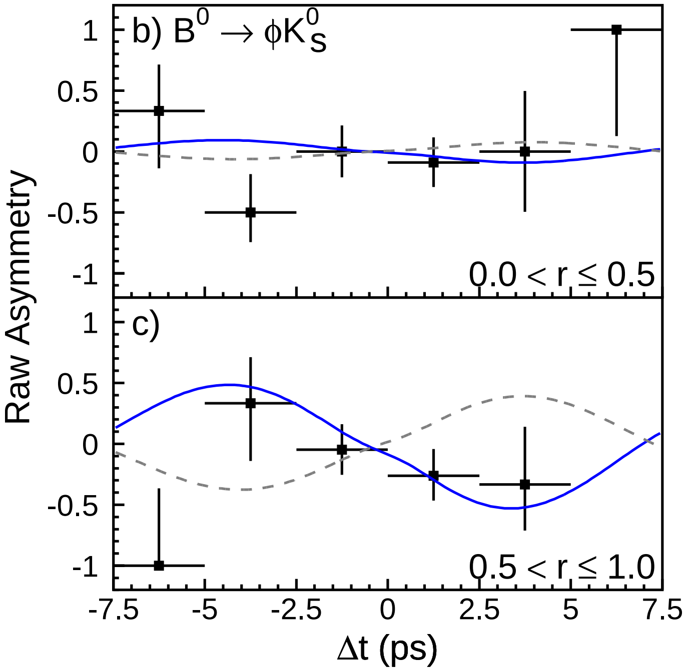
Much more data required to constrain $\sin(2\phi_1+\phi_3)$

- $b \longrightarrow sq\bar{q}$ contains same weak phase as $b \longrightarrow c\bar{c}s$
  $\hookrightarrow -\xi_{sq\bar{q}} S_{sq\bar{q}}$ should also measure $\sin(2\phi_1)$
- $S_{sq\bar{q}} \neq S_{c\bar{c}s}$ can be caused by new physics in $b \longrightarrow s$ penguin

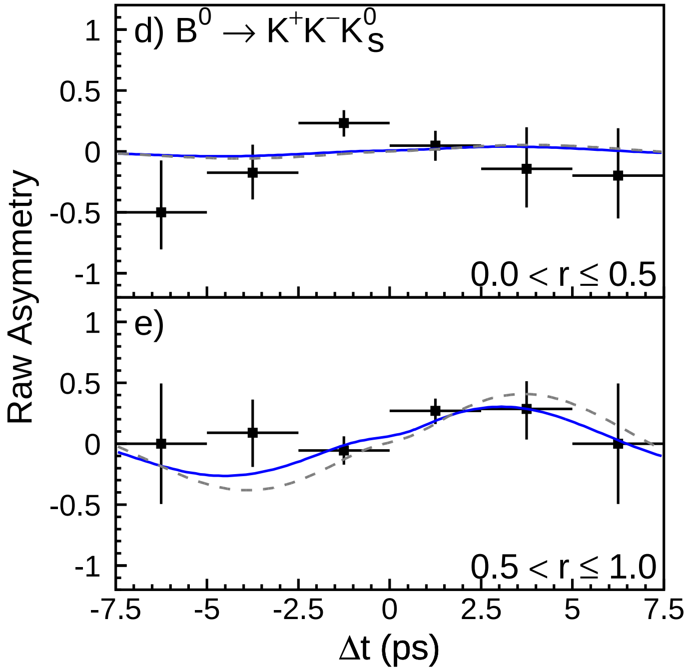
  - $B \longrightarrow \phi K_S$: CP odd
    106 candidates
  - $B \longrightarrow K^+K^-K_S$: CP even
    361 candidates
    (ϕ contribution is vetoed)
  - $B \longrightarrow \eta' K_S$: CP odd
    421 candidates



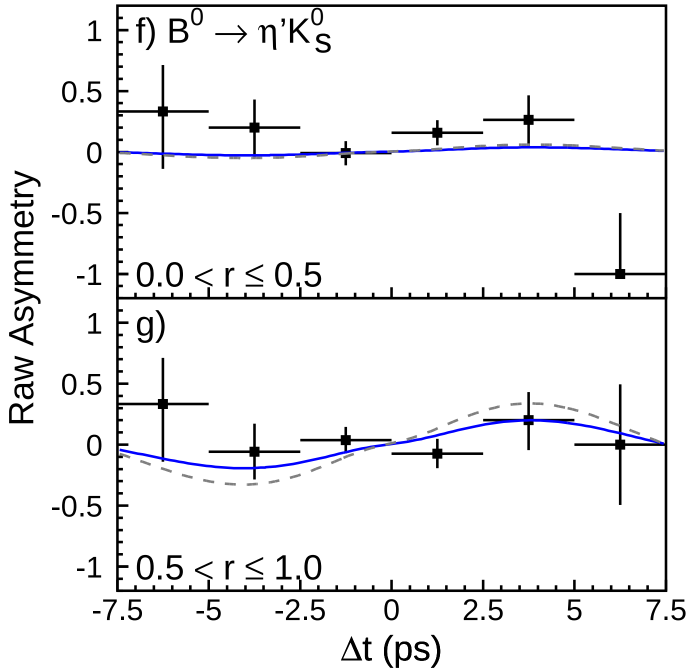
$B \rightarrow \phi K_S$



$B \rightarrow K^+K^-K_S$



$B \rightarrow \eta' K_S$



$$S_{\phi K_s} = -0.96 \pm 0.50^{+0.09}_{-0.11}$$

$$A_{\phi K_s} = -0.15 \pm 0.29 \pm 0.07$$

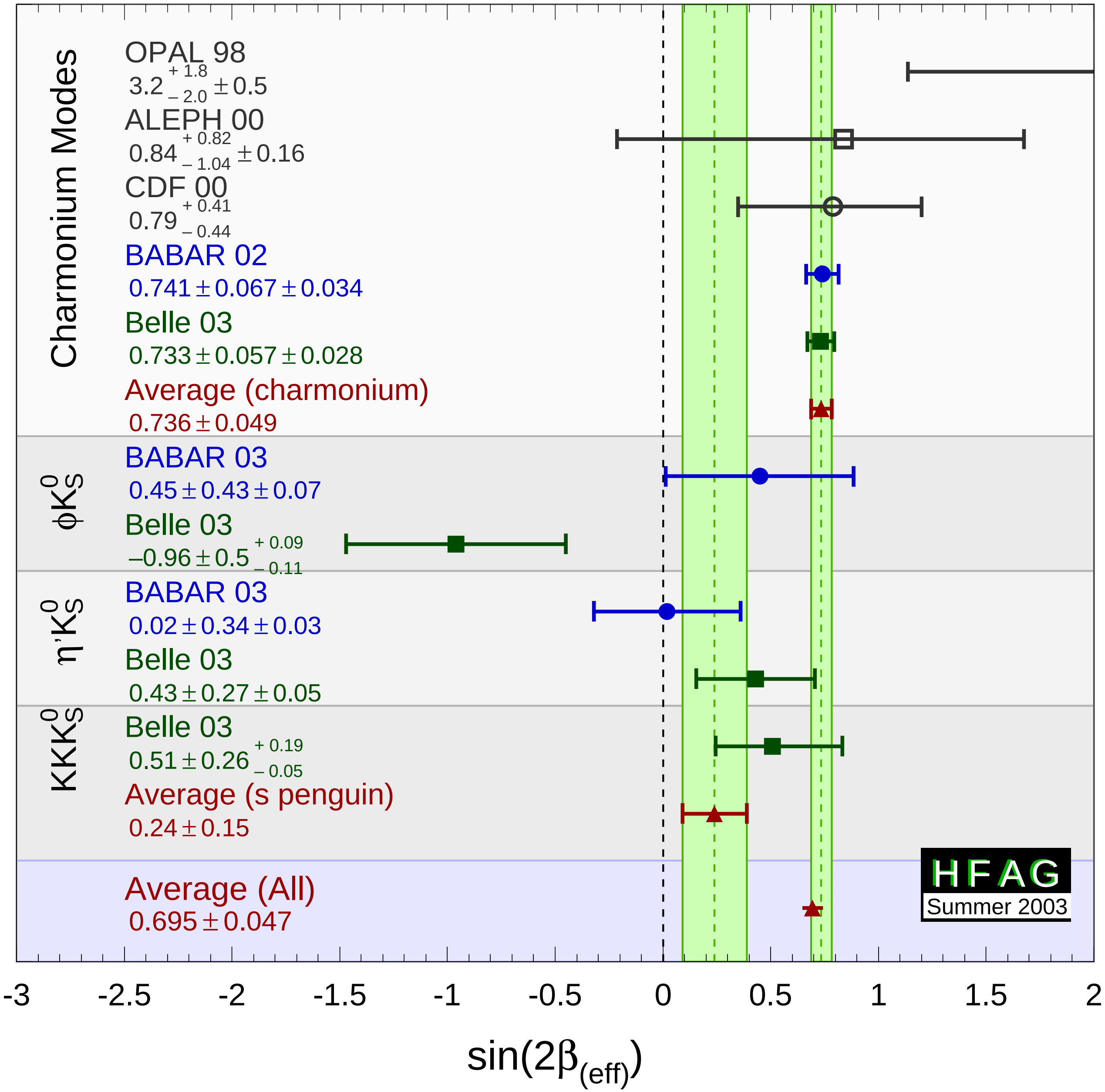
$$S_{\eta' K_s} = +0.43 \pm 0.27 \pm 0.05$$

$$A_{\eta' K_s} = -0.01 \pm 0.16 \pm 0.04$$

$$-S_{K^+K^-K_s} = +0.51 \pm 0.26 \pm 0.05^{+0.18}_{-0.00}$$

$$A_{K^+K^-K_s} = -0.17 \pm 0.16 \pm 0.04$$

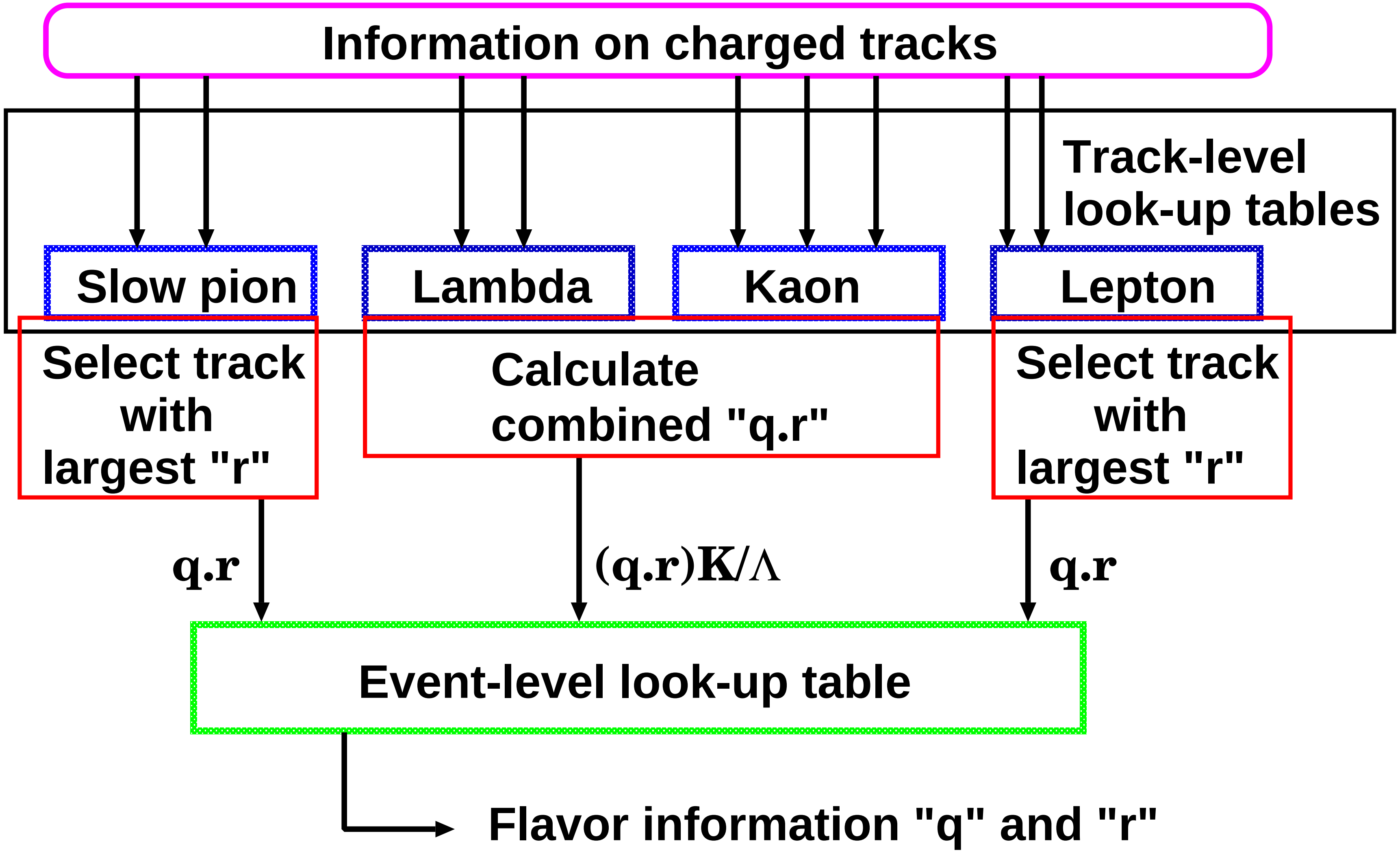
$b \longrightarrow sq\bar{q}$ World Average



Summary

- $\sin(2\phi_1)$ is the most constraining CP violation measurement
- CP violation in $B \to \pi^+\pi^-$ has been observed
- Evidence for direct CP violation in B decays
- Evidence for new physics in $B \to \phi K_S$
- Much more luminosity has been, is being, and will be accumulated
  $\Rightarrow$ new and improved measurements are coming soon

BACKUP SLIDES



Information on charged tracks
Track-level look-up tables
Slow pion
Lambda
Kaon
Lepton
Select track with largest "r"
Calculate combined "q.r"
Select track with largest "r"
q.r
(q.r)K/Λ
q.r
Event-level look-up table
Flavor information "q" and "r"

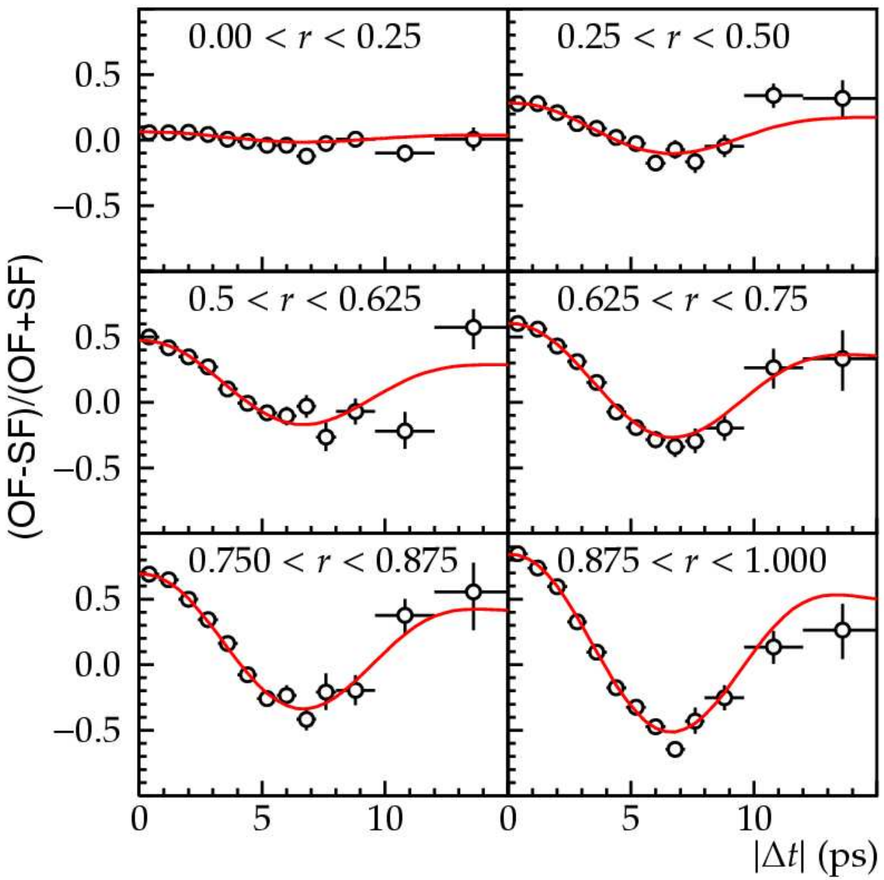
Flavour Tagging Performance

Mixing asymmetry:

$$\frac{OF - SF}{OF + SF} \propto (1 - 2w)\cos(\Delta m \Delta t)$$

TABLE I: The event fractions ϵ_l, wrong-tag fractions w_l, wrong-tag fraction differences Δw_l, and average effective tagging efficiencies $\epsilon^l_{\rm eff} = \epsilon_l(1-2w_l)^2$ for each r interval. The errors include both statistical and systematic uncertainties. The event fractions are obtained from the $J/\psi K^0_S$ simulation.

l	r interval	ϵ_l	w_l	Δw_l	$\epsilon^l_{\rm eff}$
1	0.000 – 0.250	0.398	0.464 ± 0.006	-0.011 ± 0.006	0.002 ± 0.001
2	0.250 – 0.500	0.146	0.331 ± 0.008	$+0.004 \pm 0.010$	0.017 ± 0.002
3	0.500 – 0.625	0.104	0.231 ± 0.009	-0.011 ± 0.010	0.030 ± 0.002
4	0.625 – 0.750	0.122	0.163 ± 0.008	-0.007 ± 0.009	0.055 ± 0.003
5	0.750 – 0.875	0.094	0.109 ± 0.007	$+0.016 \pm 0.009$	0.057 ± 0.002
6	0.875 – 1.000	0.136	0.020 ± 0.005	$+0.003 \pm 0.006$	0.126 ± 0.003



Effective tagging efficiency $\approx$ 28.7%

$\sin(2\phi_1)$ Selection

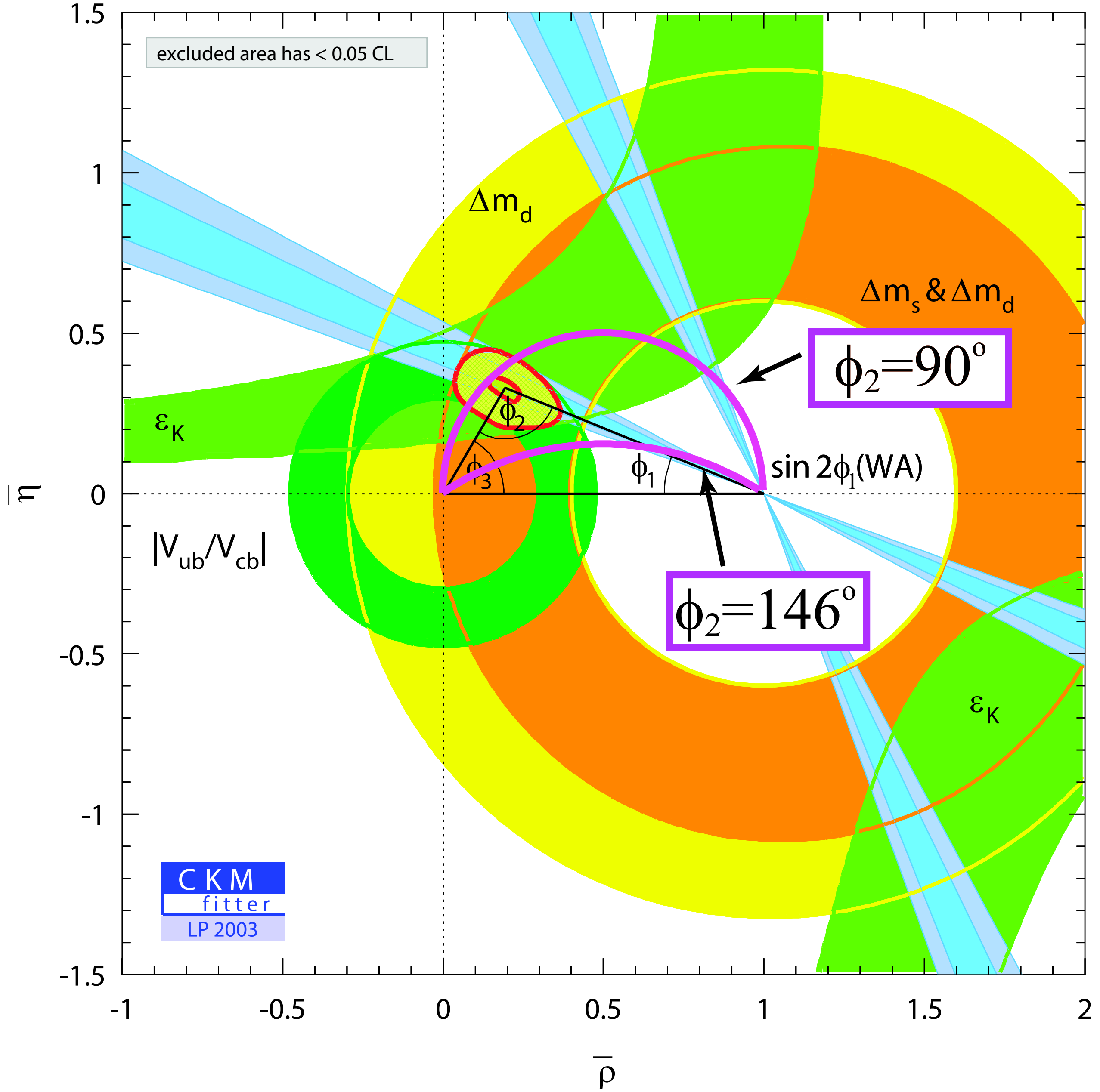
TABLE II: The numbers of reconstructed $B \to f_{CP}$ candidates after flavor tagging and vertex reconstruction, $N_{\rm ev}$, and the estimated signal purity, p, in the signal region for each f_{CP} mode. J/ψ mesons are reconstructed in $J/\psi \to \mu^+\mu^-$ or e^+e^- decays. Candidate K_S^0 mesons are reconstructed in $K_S^0 \to \pi^+\pi^-$ decays unless otherwise written explicitly.

Mode	ξ_f	$N_{\rm ev}$	p
$J/\psi K_S^0$	-1	1997	0.976 ± 0.001
$J/\psi K_S^0(\pi^0\pi^0)$	-1	288	0.82 ± 0.02
$\psi(2S)(\ell^+\ell^-)K_S^0$	-1	145	0.93 ± 0.01
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	-1	163	0.88 ± 0.01
$\chi_{c1}(J/\psi\gamma)K_S^0$	-1	101	0.92 ± 0.01
$\eta_c(K_S^0K^-\pi^+)K_S^0$	-1	123	0.72 ± 0.03
$\eta_c(K^+K^-\pi^0)K_S^0$	-1	74	0.70 ± 0.04
$\eta_c(p\overline{p})K_S^0$	-1	20	0.91 ± 0.02
All with $\xi_f = -1$	-1	2911	0.933 ± 0.002
$J/\psi K^{*0}(K_S^0\pi^0)$	$+1(81\%)$	174	0.93 ± 0.01
$J/\psi K_L^0$	$+1$	2332	0.60 ± 0.03

TABLE III: The numbers of candidate events, N_{ev}, and values of $\sin 2\phi_1$ for various subsamples (statistical errors only).

Sample	N_{ev}	$\sin 2\phi_1$
$J/\psi K^0_S(\pi^+\pi^-)$	1997	0.67 ± 0.08
$J/\psi K^0_S(\pi^0\pi^0)$	288	0.72 ± 0.20
$\psi(2S)K^0_S$	308	0.89 ± 0.20
$\chi_{c1}K^0_S$	101	1.54 ± 0.49
$\eta_c K^0_S$	217	1.32 ± 0.29
All with $\xi_f = -1$	2911	0.73 ± 0.06
$J/\psi K^0_L$	2332	0.80 ± 0.13
$J/\psi K^{*0}(K^0_S\pi^0)$	174	0.10 ± 0.45
$f_{tag} = B^0$ $(q = +1)$	2717	0.72 ± 0.09
$f_{tag} = \overline{B}^0$ $(q = -1)$	2700	0.74 ± 0.08
$0 < r \leq 0.5$	2985	0.95 ± 0.26
$0.5 < r \leq 0.75$	1224	0.68 ± 0.11
$0.75 < r \leq 1$	1208	0.74 ± 0.07
data set I (78 fb^{-1})	3013	0.73 ± 0.07
data set II (62 fb^{-1})	2404	0.74 ± 0.09
All	5417	0.733 ± 0.057

$\rho - \eta$ Constraint With $\pi^+\pi^-$ Result



$\pi^+\pi^-$ Systematics

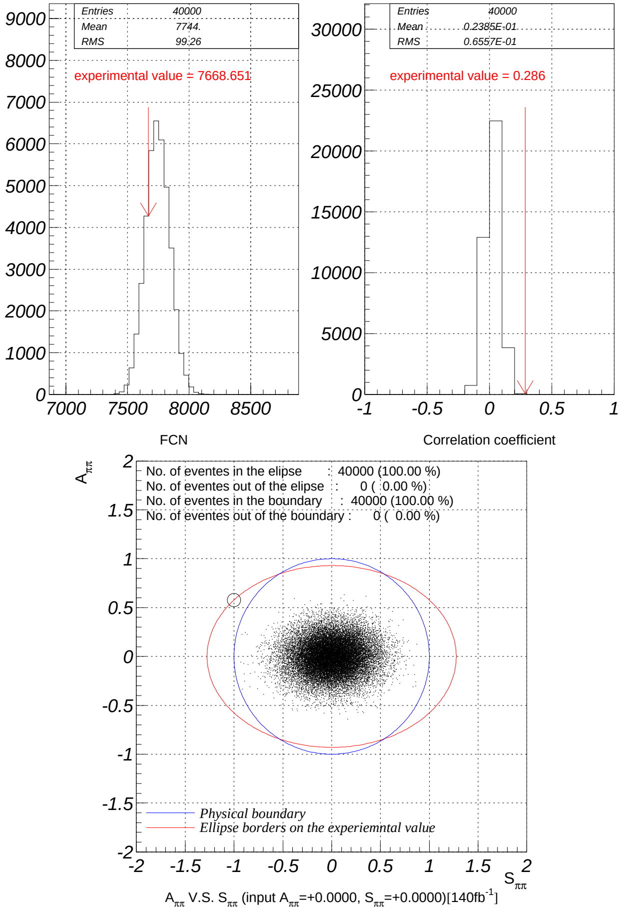
Systematic Uncertainties	*A*	*S*
Wrong tag fraction	0.009	0.009
Physics ($_B$, m$_d$, A_k)	0.024	0.007
Resolution function	0.010	0.020
Background shape	0.014	0.021
Background fractions	0.028	0.025
Fit bias	0.018	0.023
Vertexing	0.039	0.045
Tag side interference	0.027	0.011
Total	**0.066**	**0.066**

Systematic error < Statistical error

$\pi^+\pi^-$ Monte Carlo Pseudo-Experiments

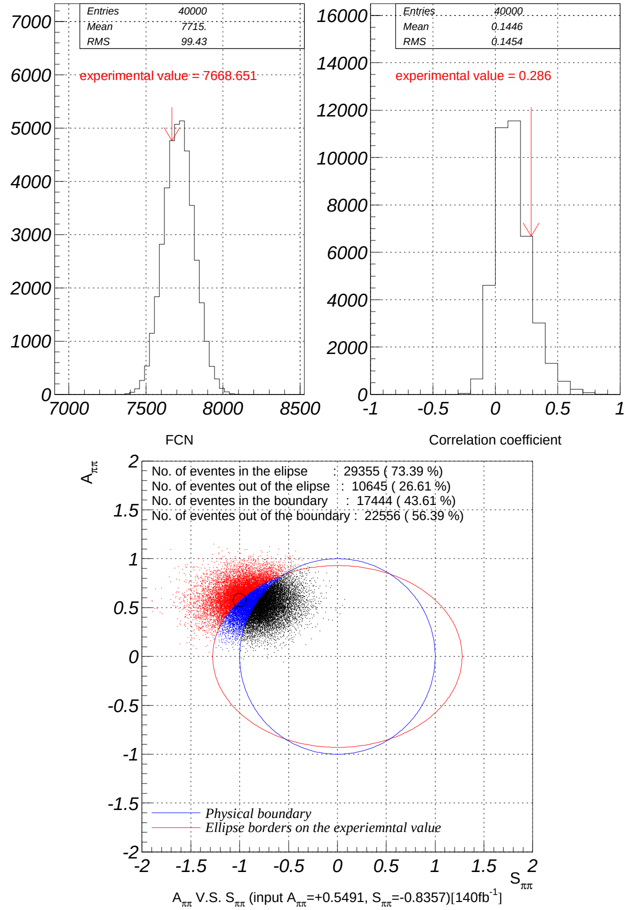
10^7 pseudo-experiments generated with:

$$\left(S_{\pi^+\pi^-}, A_{\pi^+\pi^-}\right)_{\text{true}} = (0, 0)$$



$$P\,(\text{Belle result}) < 10^{-7}$$

$$\left(S_{\pi^+\pi^-}, A_{\pi^+\pi^-}\right)_{\text{true}} = (+0.55, -0.83)$$



$$P\,(\text{Belle result}) \sim 27\%$$

$K^+K^-K_S$ CP composition

- CP of $K^+K^-K_S$ depends on angular momentum of K^+K^-
  - spin-0 $\Rightarrow CP = +1$ *eg.* $f_0 K_S$
  - spin-1 $\Rightarrow CP = -1$ *eg.* ϕK_S
- Determine $CP = +1$ fraction (α^2) using isospin relation between three kaon final states

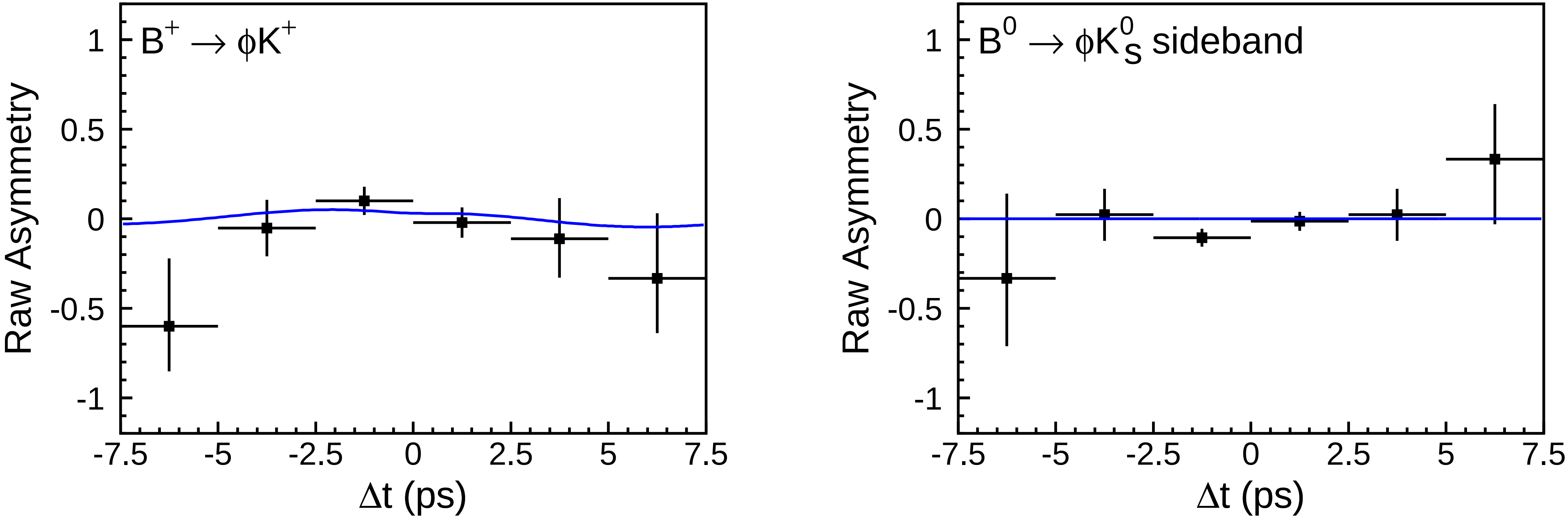
$$\frac{1}{\tau_{B^0}}\mathcal{B}\left(B^0 \to K^+K^-K^0\right) = \frac{1}{\tau_{B^+}}\mathcal{B}\left(B^+ \to K^0\bar{K}^0K^+\right)$$

$$K^0\bar{K}^0K^+ = \alpha\left(K_SK_SK^+ + K_LK_LK^+\right) + \beta K_SK_LK^+$$

$$\mathcal{B}\left(B^+ \to K_SK_SK^+\right) = \mathcal{B}\left(B^+ \to K_LK_LK^+\right)$$

$$\alpha^2 = 2 \times \frac{\mathcal{B}\left(B^+ \to K_SK_SK^+\right)}{\mathcal{B}\left(B^0 \to K^+K^-K^0\right)} \times \frac{\tau_{B^0}}{\tau_{B^+}}$$

- Measure $\alpha^2 = 1.03 \pm 0.15 \pm 0.05$



$B^+ \rightarrow \phi K^+$
Raw Asymmetry
1
0.5
0
-0.5
-1
-7.5
-5
-2.5
0
2.5
5
7.5
Δt (ps)
$B^0 \rightarrow \phi K^0_S$ sideband
Raw Asymmetry
1
0.5
0
-0.5
-1
-7.5
-5
-2.5
0
2.5
5
7.5
Δt (ps)