BELLE Time Dependent CP Asymmetries

1. Indirect CP violation in B decay
2. KEKB performance and the Belle detector
3. sin($2\phi_1$) from $b \to c\bar{c}s$
   - Measuring the time dependence of decays
   - Flavour tagging CP eigenstates
   - CP event selection
4. Asymmetry in $B \to \pi^+\pi^-$ decays
5. Other emerging CP asymmetries
   - $B \to \eta' K_S^0$
   - $B \to K^+K^-K_S^0$
6. Summary

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The CKM Triangle

Unitary CKM matrix governs weak decay of quarks

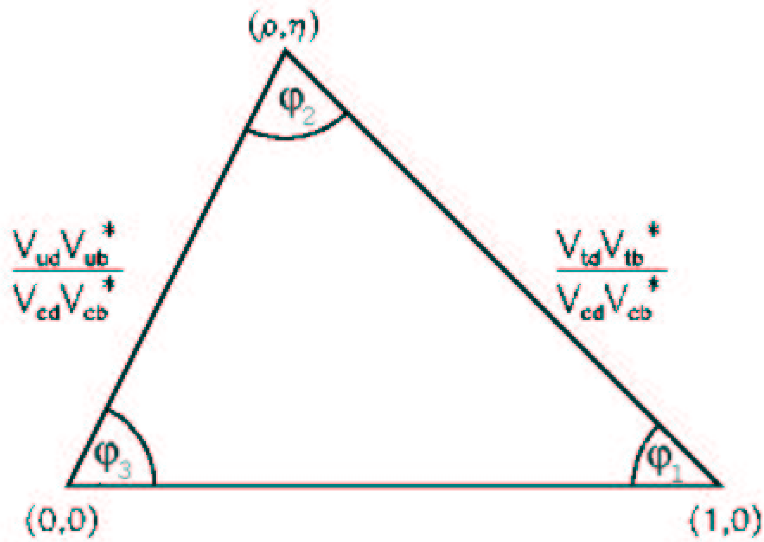
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parametrisation:

$$V_{\text{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

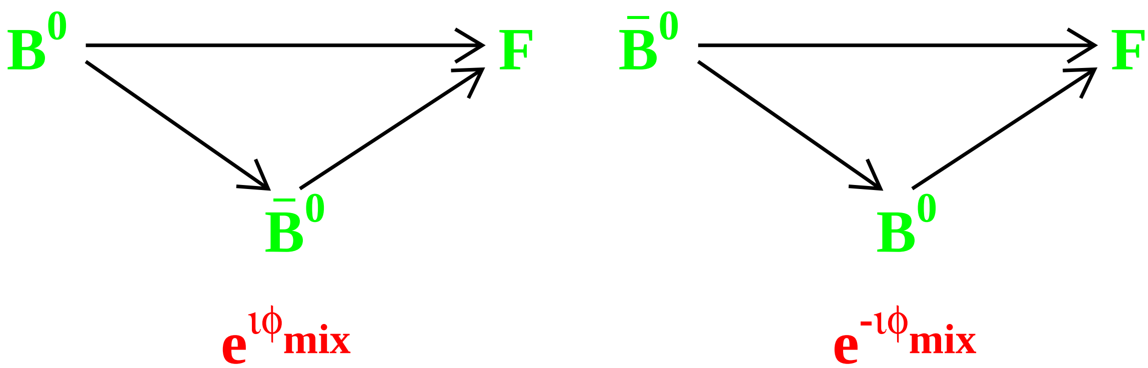
Unitarity $\rightarrow V^\dagger V = 1$ gives:

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



$$\phi_2 = \arg\left(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \phi_1 = \arg\left(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \phi_3 = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Indirect CP Asymmetry

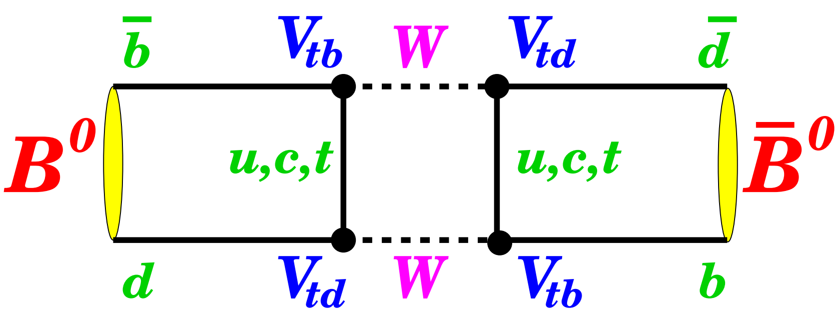


- If no direct CP violation then:

$$\frac{dN}{dt}(B^0 \to J/\psi K_\xi) \sim 1 + \xi_K \sin\ 2\phi_1\ \sin\ \Delta m \Delta t$$

$$\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_\xi) \sim 1 - \xi_K \sin\ 2\phi_1\ \sin\ \Delta m \Delta t$$

- CP phase easily seen in CKM matrix element V_{td}



- B^0 and $\bar{B}^0$ produced at equal rates develop an asymmetry:

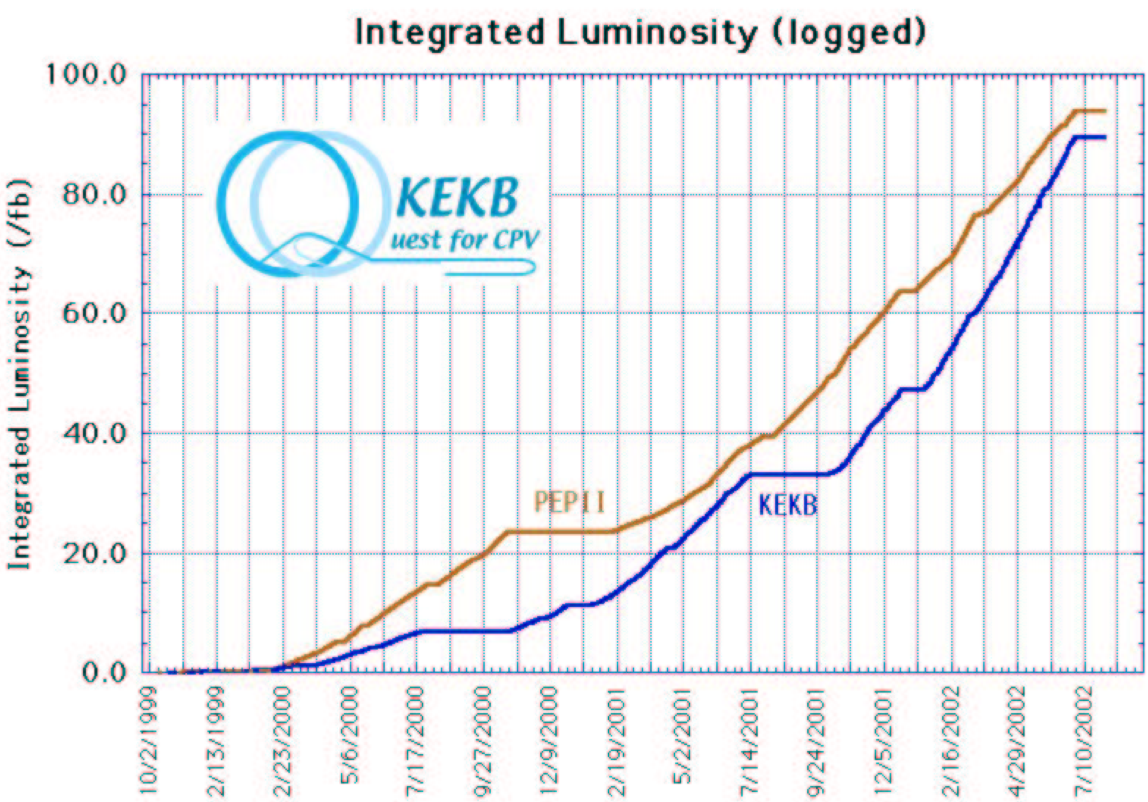
$$A_{CP}(\Delta t) = \frac{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_\xi) - \frac{dN}{dt}(B^0 \to J/\psi K_\xi)}{\frac{dN}{dt}(\bar{B}^0 \to J/\psi K_\xi) + \frac{dN}{dt}(B^0 \to J/\psi K_\xi}$$

$$= -\ \xi_K \sin\ 2\phi_1\ \sin\ \Delta m \Delta t$$

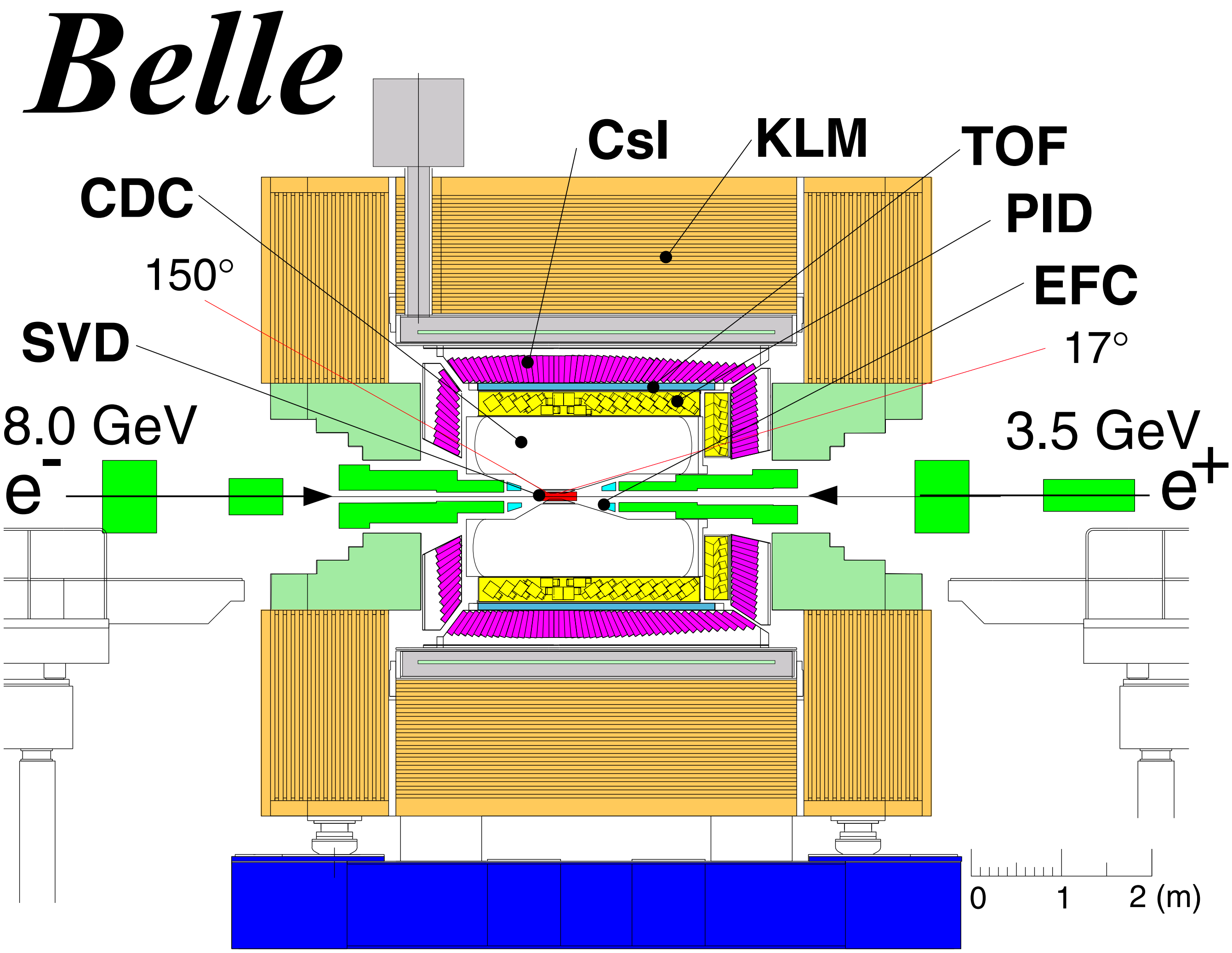
The KEK-B Collider

- 8.0 GeV electrons and 3.5 GeV positrons
  - $\sqrt{s} = 10.6$ GeV and $\beta\gamma = 0.425$
- 11 mrad crossing angle → reduces backgrounds

$\mathcal{L}$	KEK-B	PEP-II
Peak ($\times 10^{33}$)	7.4	4.6
Record Day (pb^{-1})	399	303
Record Month (fb^{-1})	8.8	6.7
Total (fb^{-1})	90	94



The BELLE Detector



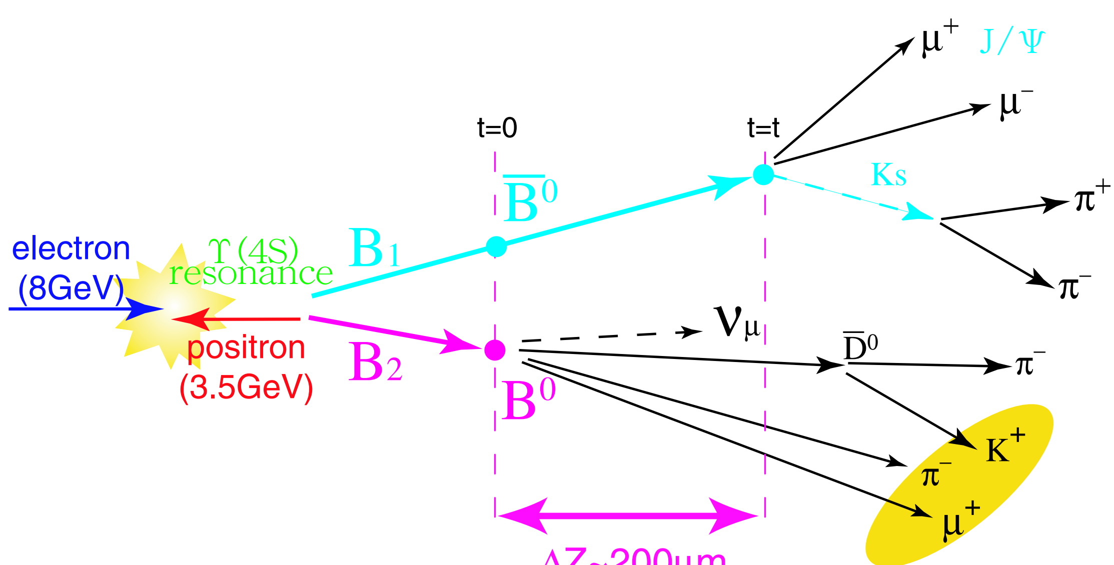
CP Violation Analysis Roadmap

1. Select $B^0 \to$ CP-eigenstate candidates ($J/\psi K_\xi$)

2. Find decay vertex and measure decay separation (Δt)

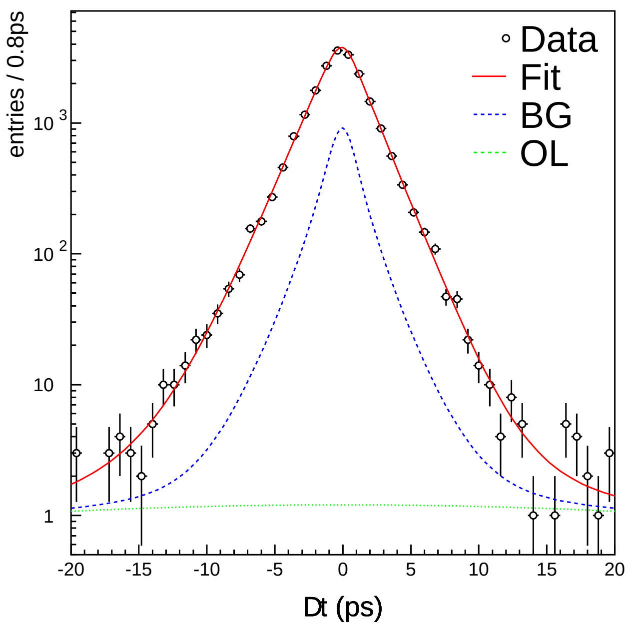
3. Tag flavour of "other B"

4. Fit time dependent flavour asymmetry

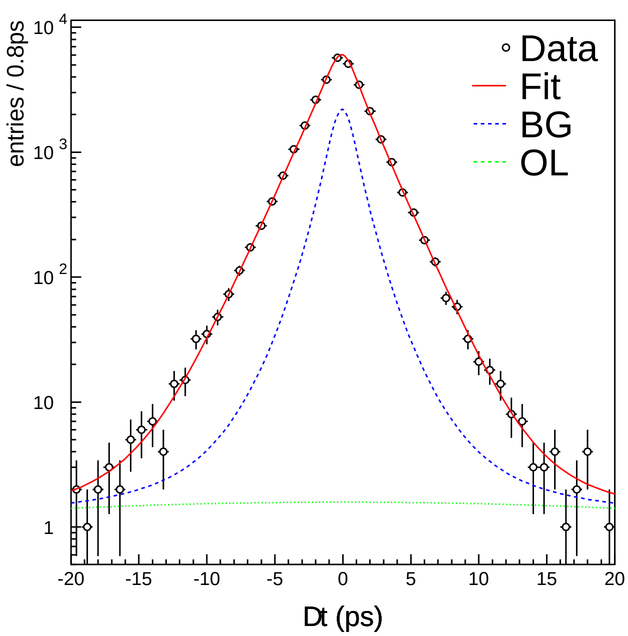


Measuring the Decay Vertices

- Measure the separation in decay vertex
  - Subtle since detector resolution $\approx B$ flight distance
- Parametrise resolution function carefully
  - CP side has 75μm rms resolution
  - Tagging side has 140μm rms resolution
- Resolutions well understood beyond 10 B lifetimes



$\tau_{\bar{B}0}$=$1.554 \pm 0.030 \pm 0.019$ ps



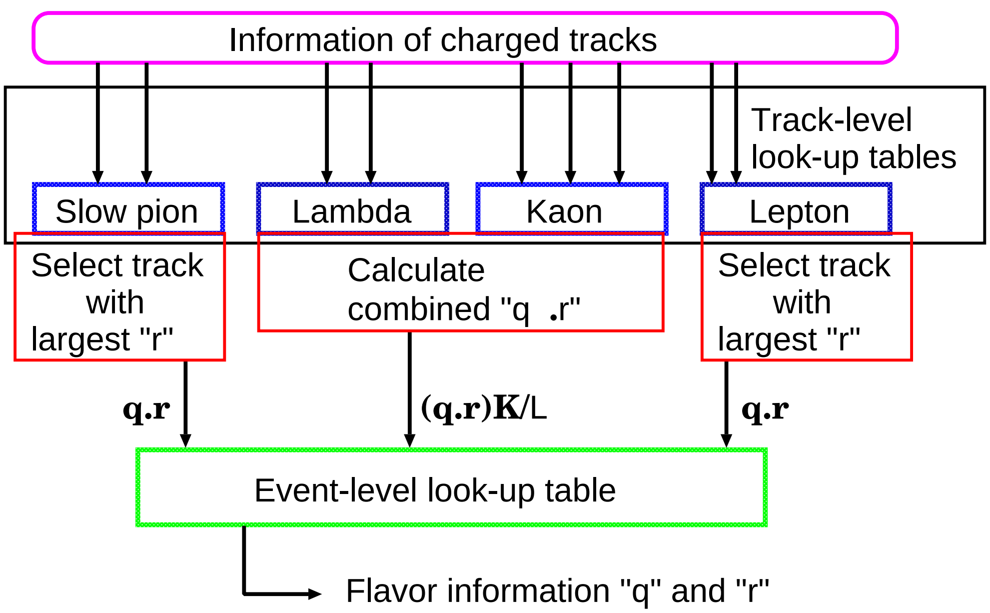
τ_{B^-}=$1.695 \pm 0.026 \pm 0.015$ ps

$$\frac{\tau_{B^-}}{\tau_{\bar{B}0}} = 1.09 \pm 0.03$$

(PRL 88, 171801 (2002))

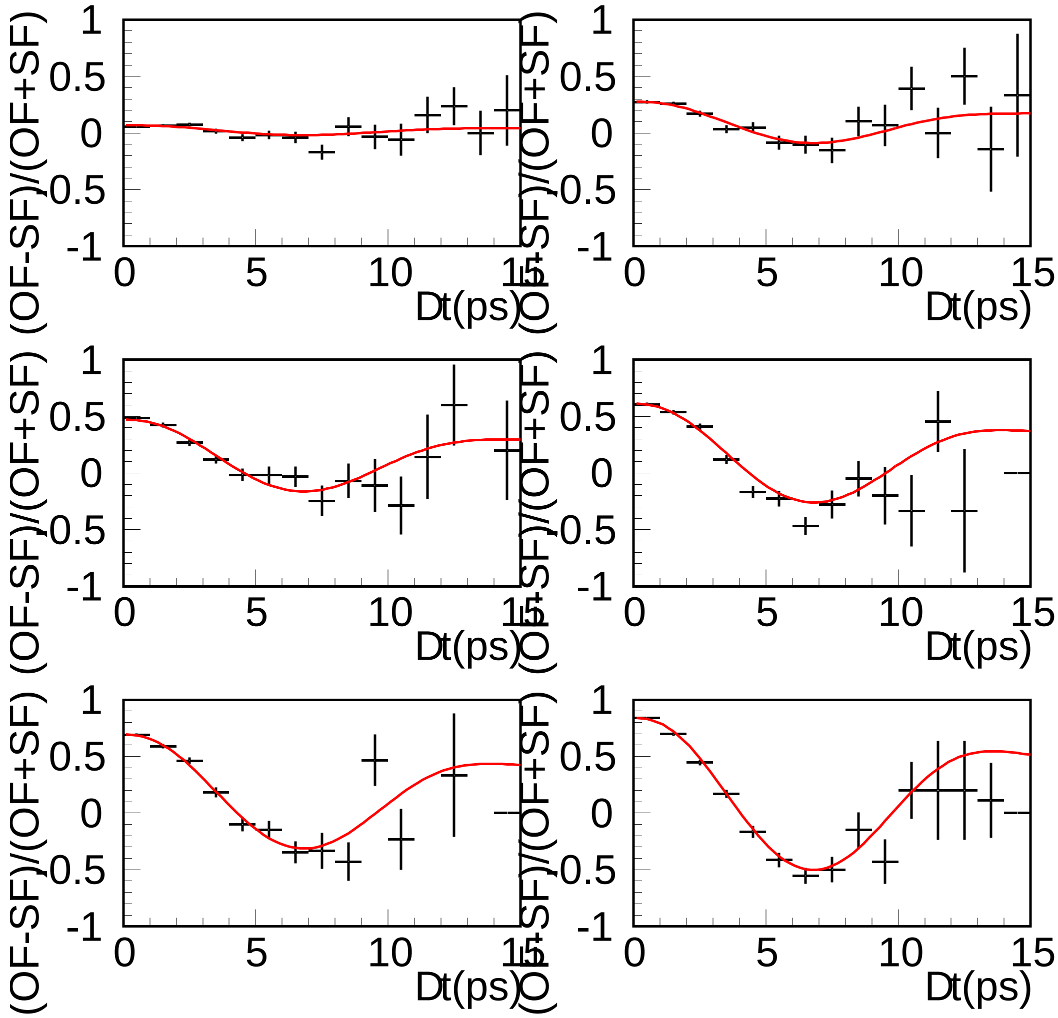
Flavour Tagging Method

- We look for time dependent asymmetry in CP eigenstate
- Must tag "other" B using a combination of:
  - high p_t leptons ($b \to cl\nu$: l^-)
  - lower p_t leptons ($b \to c \to sl\nu$:l^+)
  - Kaons ($b \to c \to sX$: K^-)
  - low momentum pions ($B \to D^* \to D\pi$:π^-)
  - and other information
- Apply tagging criteria to B^0 control samples



Flavour Tagging Calibration

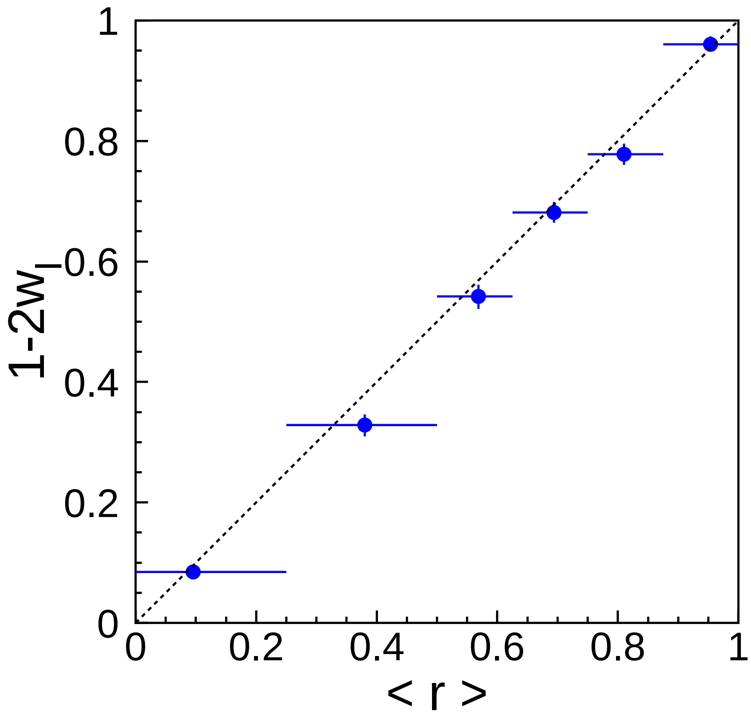
- Calibrate effectiveness on control data samples
- Measure $B^0\bar{B}^0$ (using $D^*l\nu$ sample) mixing in 6 intervals of r



- Amplitude measures wrong tag fractions (w_r)

Flavour Tagging Quality

- $1-2w_r$ gives the correct tag probability

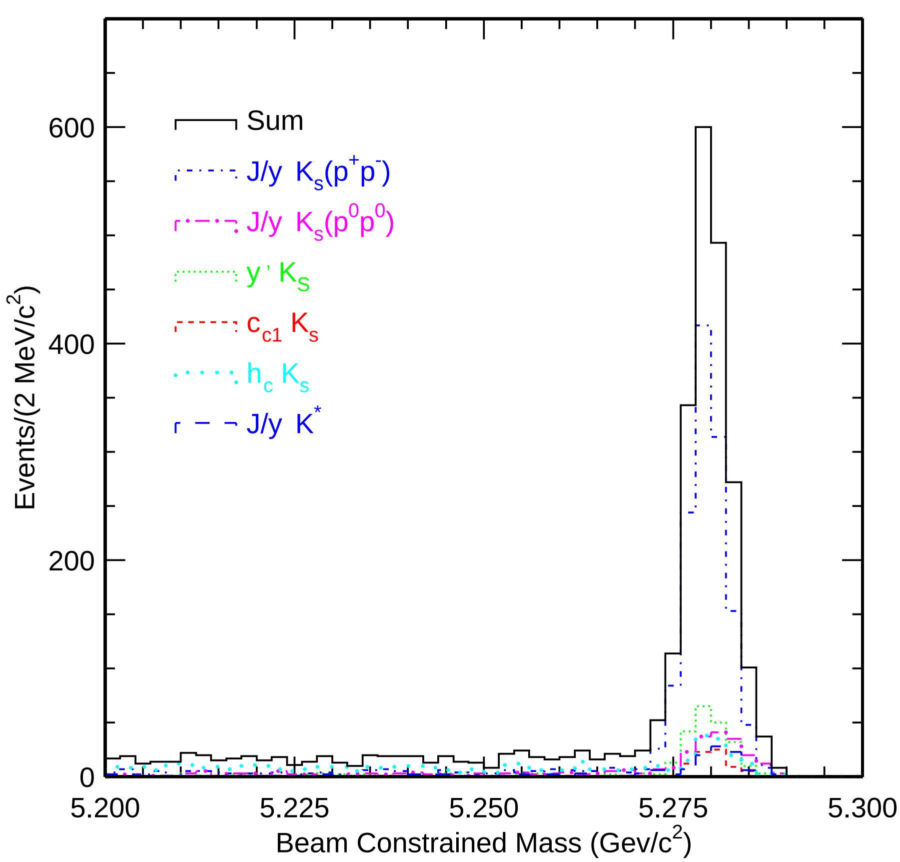


- These are measured from data control samples
- Extract flavour information from 99.5% of candidates
- No tagging bias observed
- Effectively tag 28.8 ± 0.6 % of B^0 decays
  - Improved from 27.0 ± 1.2% in prior analyses
  - This comes from
    - improved low momentum tracking
    - improved silicon alignment

Belle's $c\bar{c}s$ Event Sample

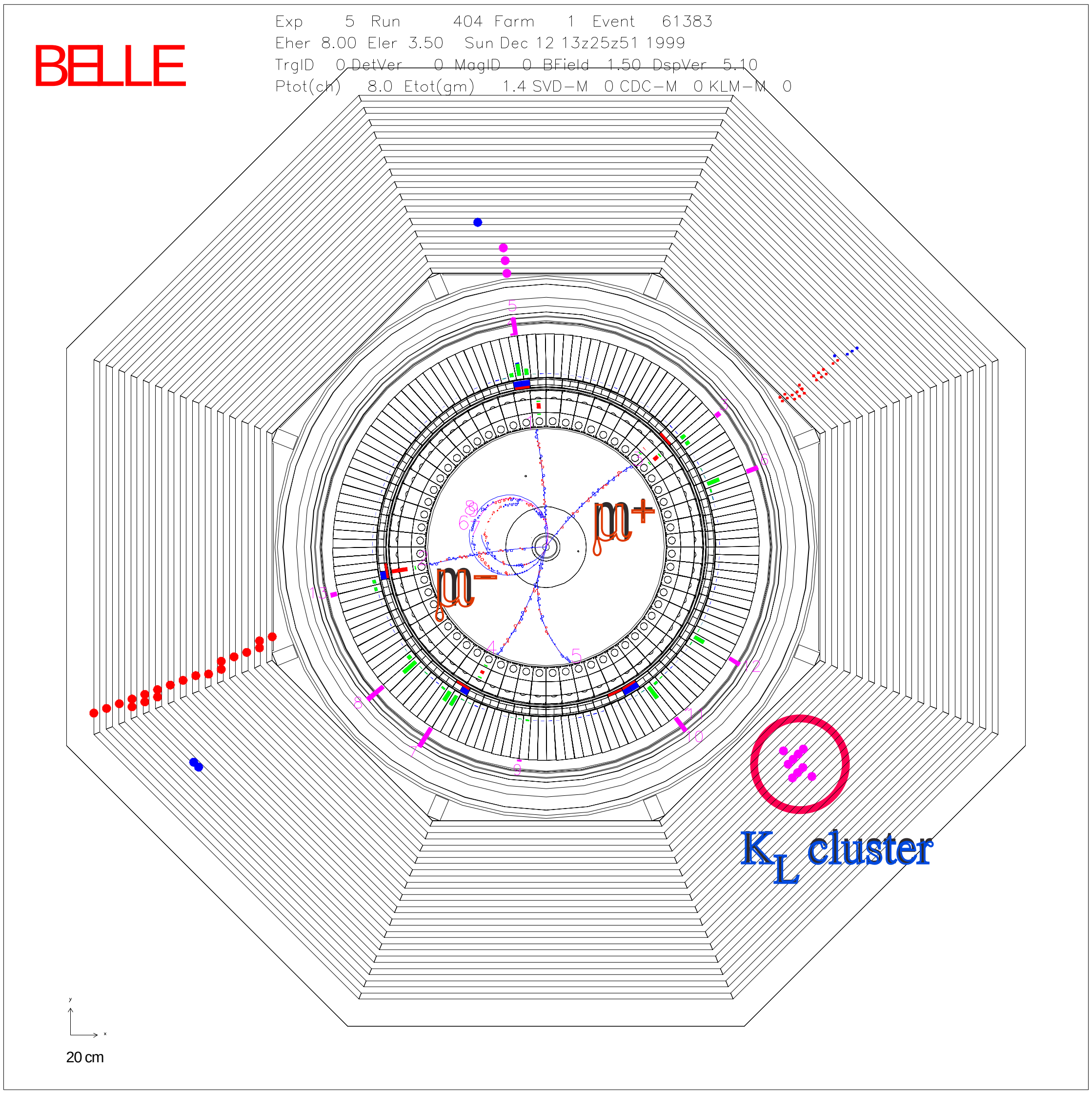
- Sample from $78 fb^{-1}$ of $\Upsilon(4S)$ resonance data

Mode	CP (ξ_K)	Candidates	Purity (%)
$J/\psi K^0_S(\pi^+\pi^-)$	-1	1116	98
$J/\psi K^0_S(\pi^0\pi^0)$	-1	162	82
$\psi(2S)K^0_S$	-1	172	93
$\chi_{c1}K^0_S$	-1	67	96
$\eta_c K^0_S$	-1	122	68
$J/\psi K^{*0}(K^0_S\pi^0)$	1(81%)	89	92
$J/\psi K^0_L$	1	1230	63
Total		2958	



Using $J/\psi K_L^0$ Candidates

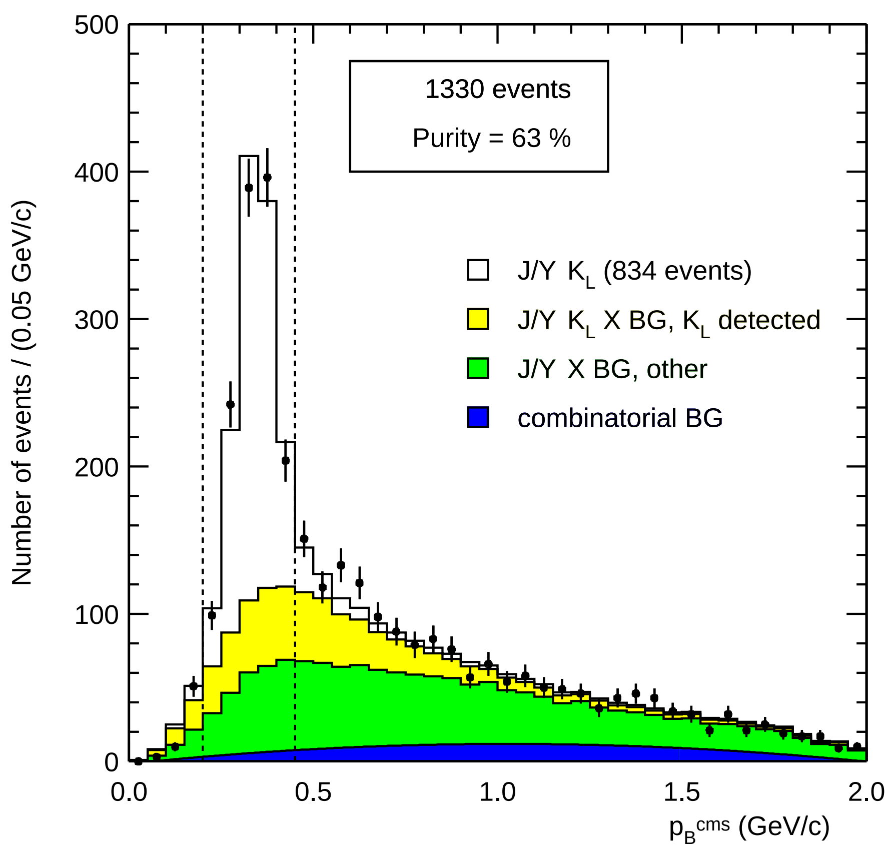
- Less information from detector to reconstruct K_L^0 candidates



- Muons leave continuous tracks in KL/muon detector
- K_L^0 leave a hadronic shower (cluster of hits)
- Only measure K_L^0 direction, not its energy/momentum

Identifying K_L^0 Candidates

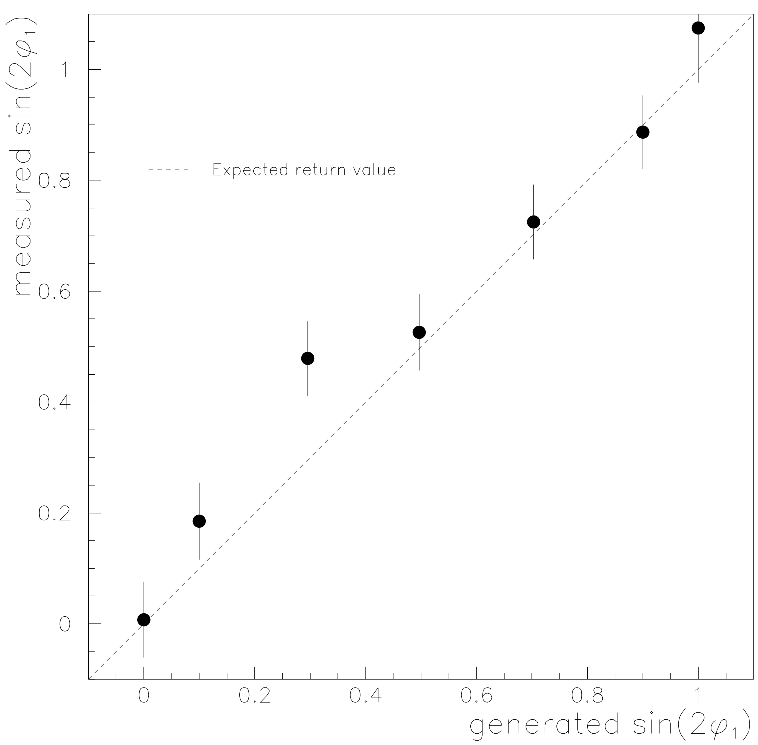
- Constrain K_L^0 momentum to give B mass. Know:
  - $\vec{p}^{\,*}_B = \vec{p}^{\,*}_{J/\psi} + \vec{p}^{\,*}_{K_L^0}$
  - $E^*_{J/\psi} + E^*_{K_L^0} = \frac{1}{2} m_\Upsilon$
  - Given $\hat{p}_{K_L^0}$ this gives a unique $|\vec{p}^{\,*}_{K_L^0}|$
- Look for signal (peak near 330 MeV/c^2) in p^*_B distribution



- Veto all other $J/\psi X$ candidates found
- B decay backgrounds (K_L^0 detected, No K_L^0 detected)
- Select 1330 events ($0.2 \leq p^*_B \leq 0.45$ GeV/c) with 63% purity

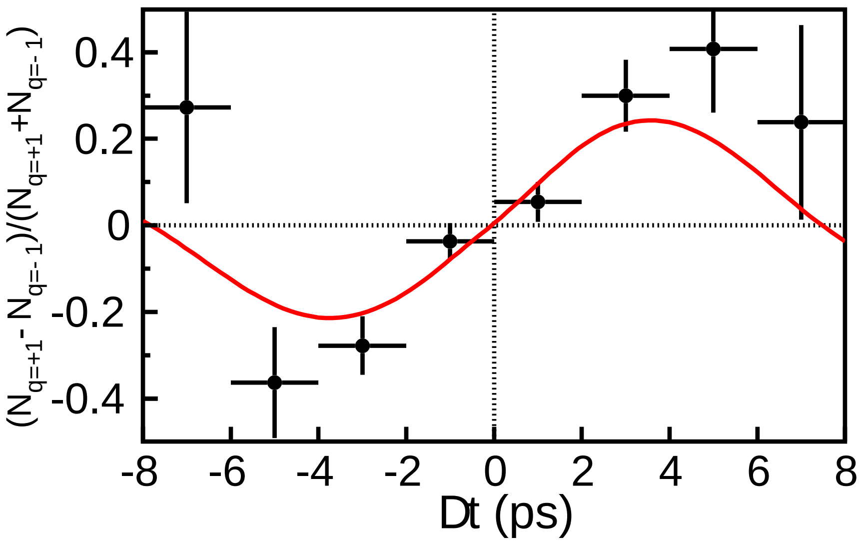
Cross-check $J/\psi K_L^0$ Background Treatment

- Eight charmonium background classes according to CP
- Predict CP asymmetry from *EVTGEN* simulation
- Fit includes these asymmetries
- Test validity of these corrections

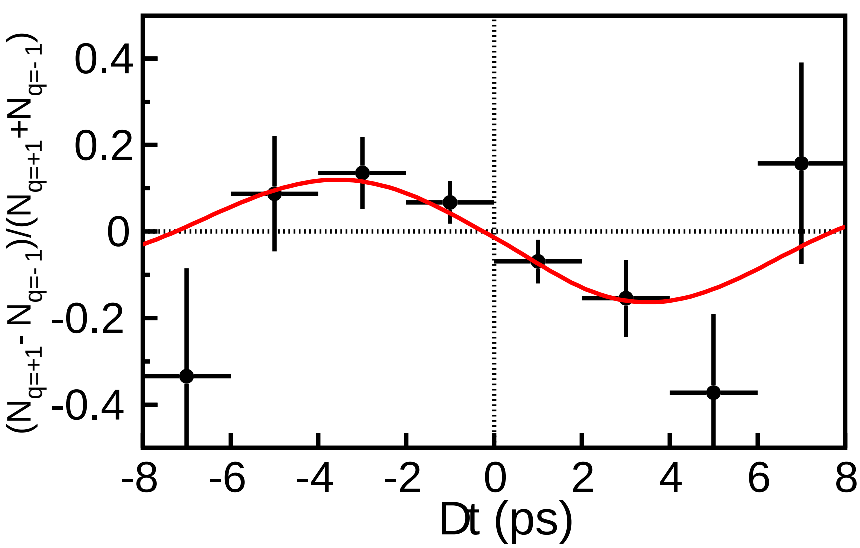


- Variations included in background systematic

CP fit Comparison ($c\bar{c}K_S^0$ vs. $J/\psi K_L^0$)



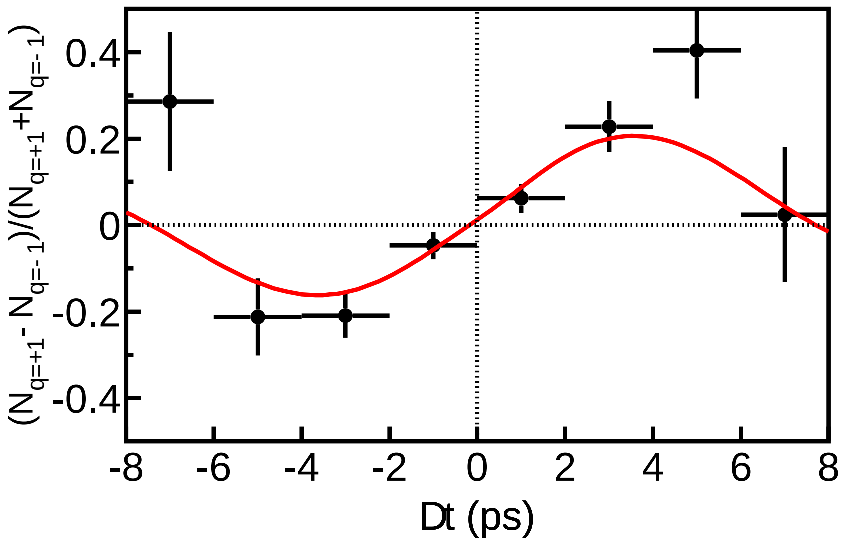
$\sin 2\phi_1 = 0.716 \pm 0.083(\mathrm{stat})$



$\sin 2\phi_1 = 0.781 \pm 0.167(\mathrm{stat})$

Combined Fit for $\sin 2\phi_1$

Preliminary result from $78 fb^{-1}$



$\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{sys})$

Uncertainty Source	Value
Vertexing Reconstruction	0.022
Flavour Tagging	0.015
Vertex Resolution	0.014
Fit parametrisation	0.011
$J/\psi K_L^0$ Background	0.010
Δm_d, τ_B	≤ 0.010
Total	0.035

Cross checks for $c\bar{c}s$ Asymmetry

- We test for direct CP-violation by generalising:

$$A_{CP}(\Delta t) = \frac{-\xi_K 2\mathcal{I}m\lambda}{|\lambda|^2+1} \sin(\Delta m \Delta t) + \frac{|\lambda|^2-1}{|\lambda|^2+1} \cos(\Delta m \Delta t)$$

- we find:

$$|\lambda| = 0.950 \pm 0.049(\text{stat}) \pm 0.025(\text{sys})$$

$$-2\,\xi_K \mathcal{I}m\lambda/|\lambda| \equiv \sin(2\phi_1) = 0.720 \pm 0.074(\text{stat})$$

- We see no evidence for direct CP violation in these decays

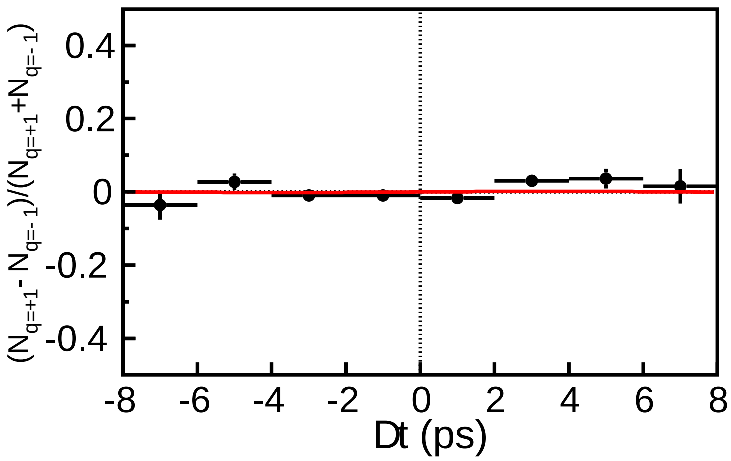
- Other cross-checks

Subsample (stat error only)	
$J/\psi K_S^0(\pi^+\pi^-)$	0.73 ± 0.10
$(c\bar{c})K_S^0$ (except $J/\psi K_S^0(\pi^+\pi^-)$)	0.67 ± 0.17
$J/\psi K_L^0$	0.78 ± 0.17
$f_{tag} = B^0$	0.65 ± 0.12
$f_{tag} = \bar{B}^0$	0.77 ± 0.09
$r \leq 0.5$	1.26 ± 0.36
$0.5 \leq r \leq 0.75$	0.62 ± 0.15
$0.75 \leq r$	0.72 ± 0.09
All	0.72 ± 0.07

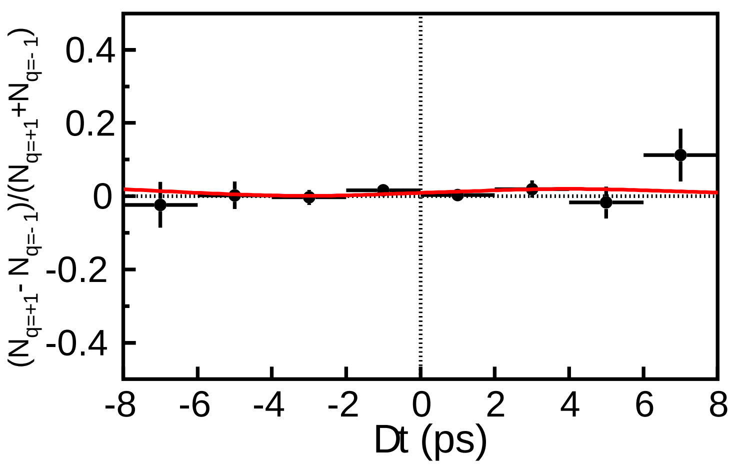
Fits to Control Samples

- Non-CP eigenstates should not exhibit asymmetry

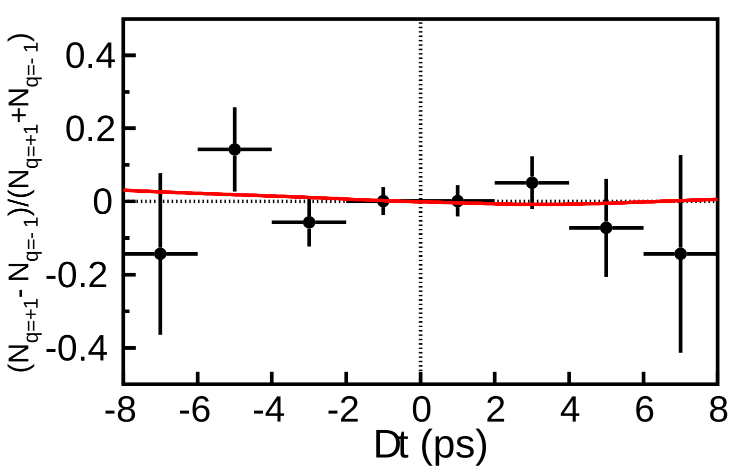
"sin $2\phi_1$"



$D^* l\nu$:
-0.004 ± 0.017

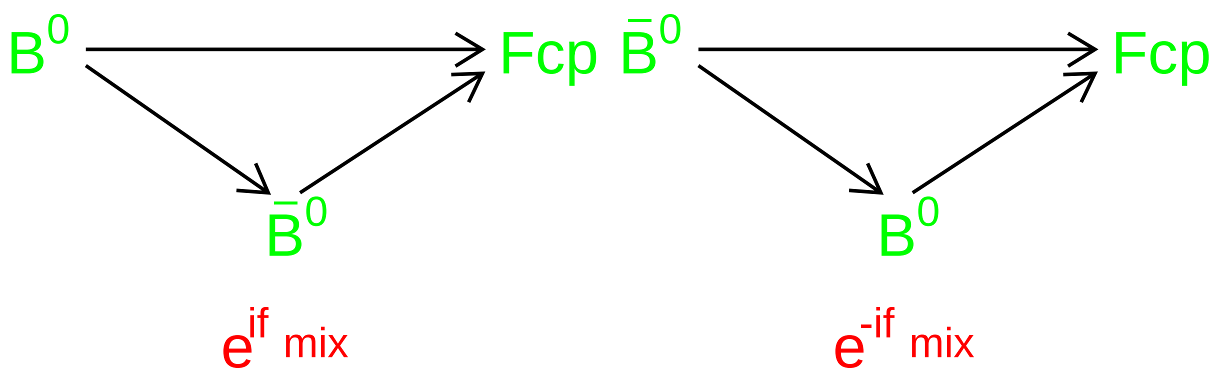


$D^{(*)}(\pi, \rho)$:
0.035 ± 0.032



$J/\psi K^*(K^+\pi^-)$:
-0.021 ± 0.093

Direct and Indirect CP Asymmetry



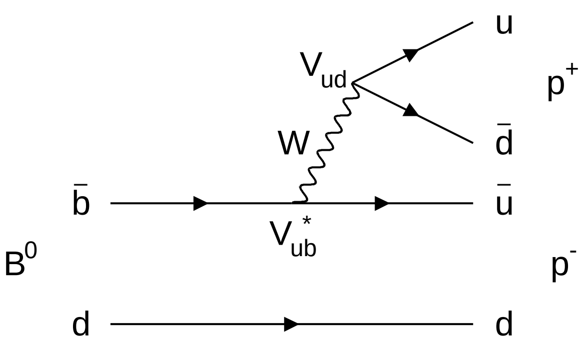
- More than one path for $B^0 \to F_{\rm CP}$ direct CP violation possible:

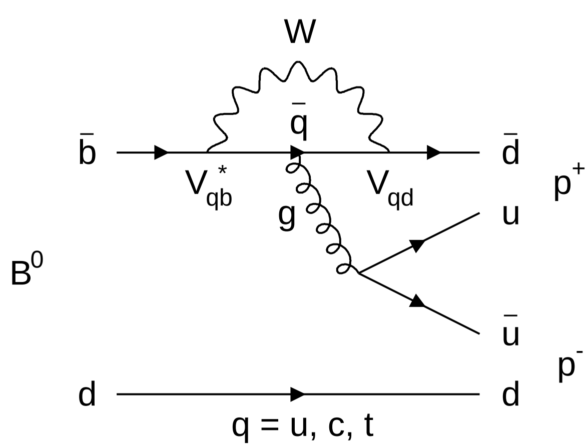
$$A_{CP}(\Delta t) = \frac{\frac{dN}{dt}(\bar{B}^0 \to F_{\rm CP}) - \frac{dN}{dt}(B^0 \to F_{\rm CP})}{\frac{dN}{dt}(\bar{B}^0 \to F_{\rm CP}) + \frac{dN}{dt}(B^0 \to F_{\rm CP})}$$

$$= S_F \sin\ \Delta m \Delta t + A_F \cos\ \Delta m \Delta t$$

- $B^0 \to \pi^+\pi^-$ final states have contributions from:

Tree and Penguin

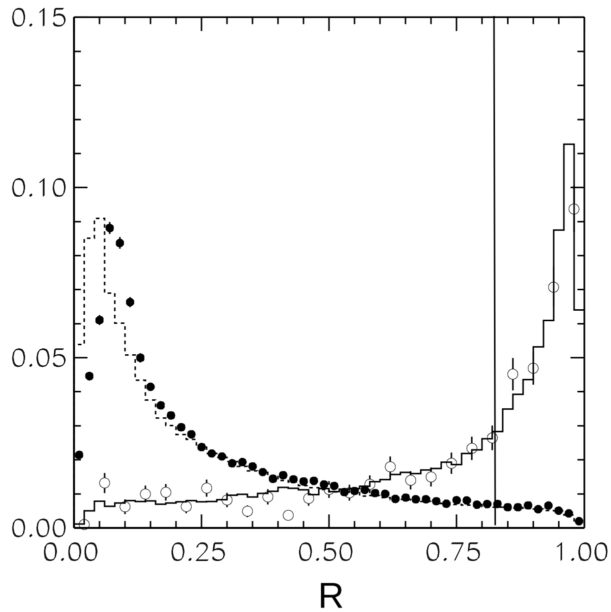




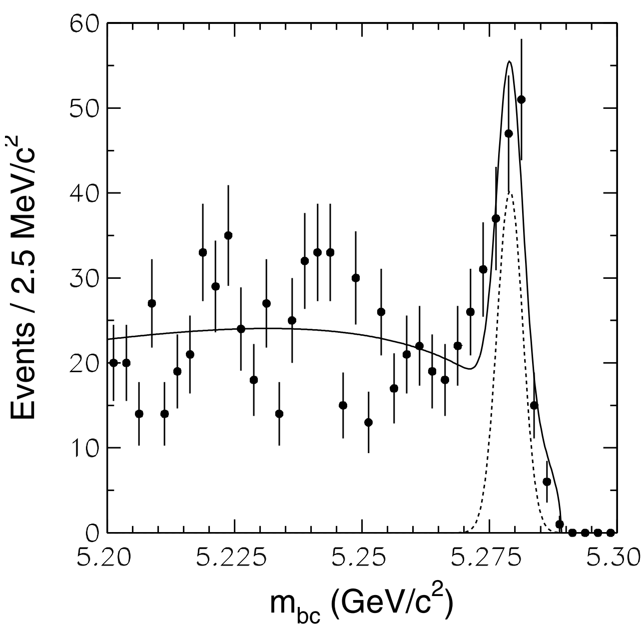
- In general this leads to
  - $S_{\pi\pi} = \sin(2\phi_2 + \theta) \neq \sin(2\phi_2)$
  - Direct CP violation: $A_{\pi\pi}$ different from 0

Selection of $B^0 \to h^+h^-$

- Select pairs of oppositely charged high momentum tracks
- Reject leptons, select π with particle ID
- Suppress continuum background with
  - Fox-Wolfram moments, "B^0" direction



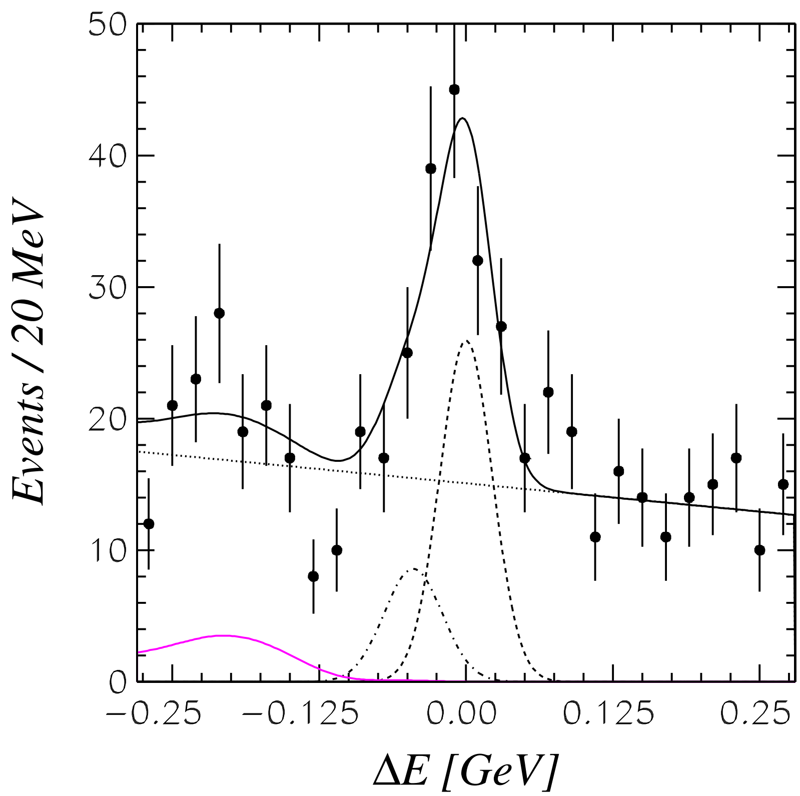
- Require $M_{bc} = \sqrt{(E_{\text{cm}}/2)^2 - (\vec{p}_{h^+} + \vec{p}_{h^-})^2}$ above 5.2 GeV/c^2



- $\pi^+\pi^-$ not distinguished from $K^+\pi^-$ in M_{bc}

Final Selection of $B^0 \to \pi^+\pi^-$

- $K^+\pi^-$ can be distinguished by
  - $\Delta E = E_{h^+} + E_{h^-} - E_{\rm cm}/2$
  - Assume pion mass for both tracks $\Rightarrow$
    - $K^+\pi^-$ shifted (down) by 45 MeV in ΔE

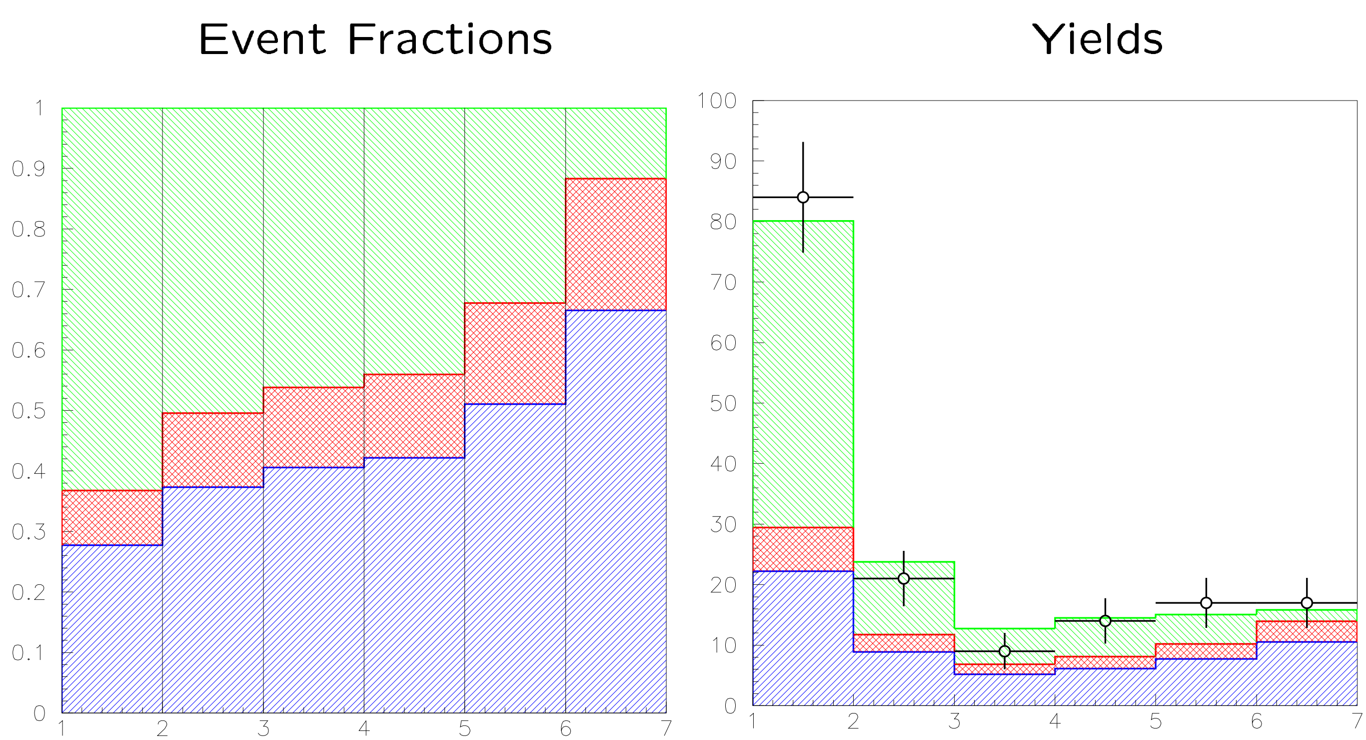


- Signal region: $5.271 \leq M_{\rm bc} \leq 5.287$ GeV/c^2

- In $|\Delta E| \leq 0.067$ GeV
  - $N_{\pi^+\pi^-} = 74 \pm 14$ signal
  - $N_{K^+\pi^-} = 28 \pm 12$ feed-across background
  - $N_{q\bar{q}} = 99$ continuum background (total constrained)

Asymmetry Fit for $B^0 \to \pi^+\pi^-$

- Flavour-tag B^0 and measure Δt as for $J/\psi K^0_S$
- Events weighted in fit depending on
  - Continuum rejection likelihood
  - tag reliability, r
  - decay time difference, Δt
  - ΔE

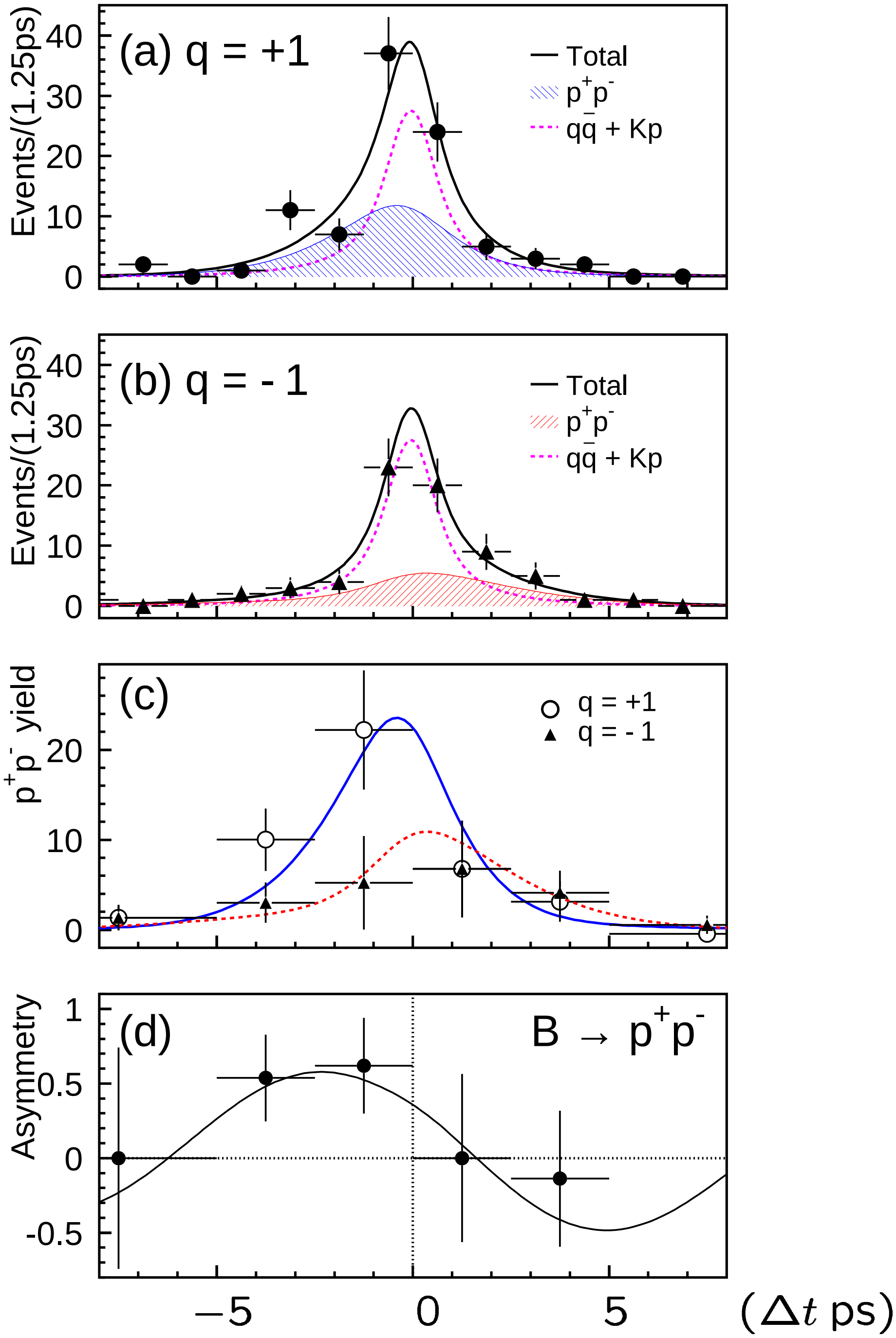


$\bullet \pi^+\pi^-$ signal, $\bullet K^+\pi^-$ background, $\bullet q\bar{q}$ background

- Consciously select a clean $\pi^+\pi^-$ sample

CP Asymmetry in $\pi^+\pi^-$

PRL 89, 071801 (2002).



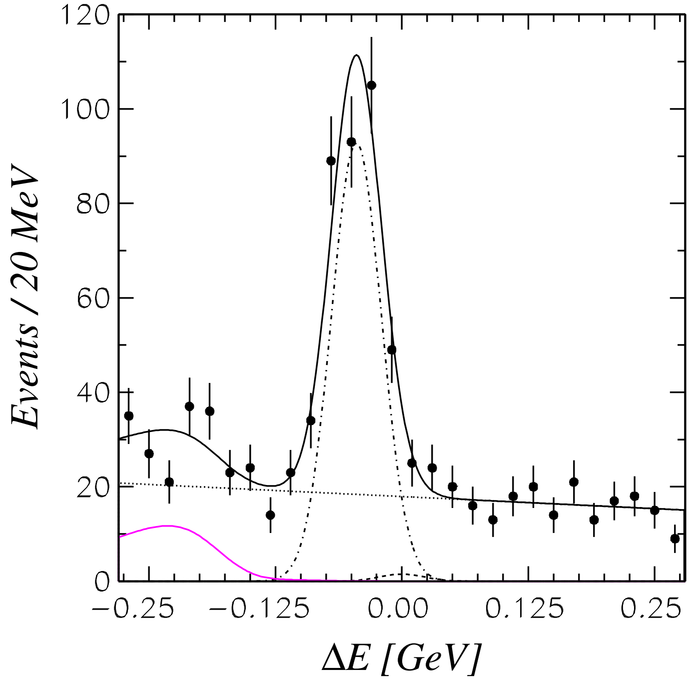
- Event-by-event likelihood fit gives

$$S_{\pi\pi} = -1.21^{+0.38}_{-0.27}(\text{stat})\,^{+0.16}_{-0.13}(\text{sys})$$
$$A_{\pi\pi} = \quad 0.94^{+0.25}_{-0.31}(\text{stat}) \pm 0.09(\text{sys})$$

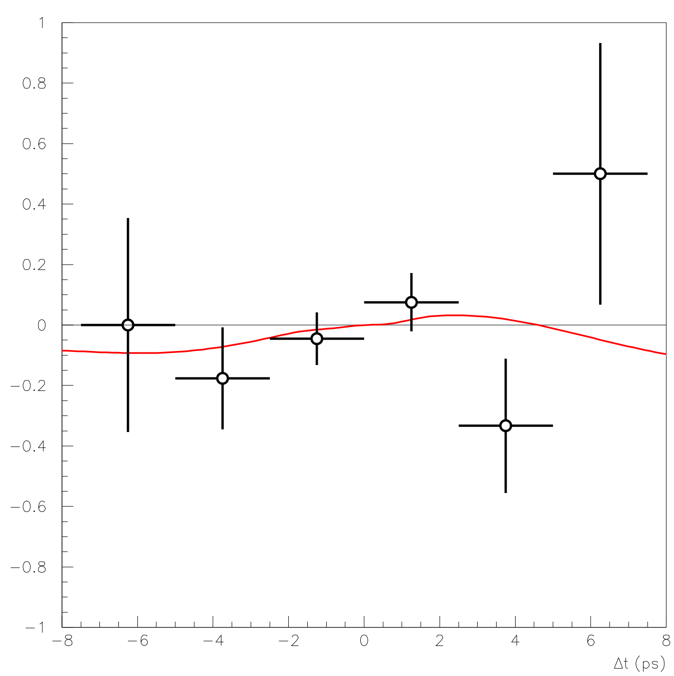
- Evidence for direct CP and large $\sin(2\phi_2)$

Cross-checks with $K^+\pi^-$ Sample

- Invert particle ID to enhance $K\pi$ fraction (290 ± 22 candidates)



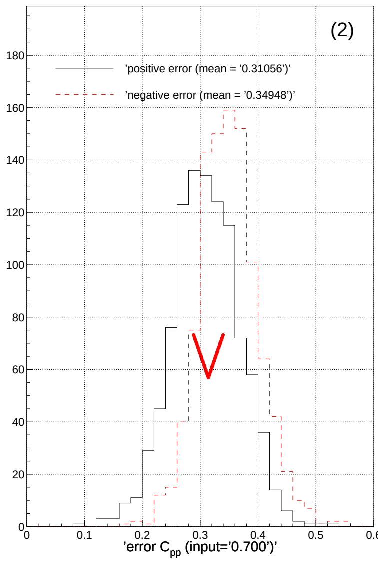
- Extract asymmetries from this sample



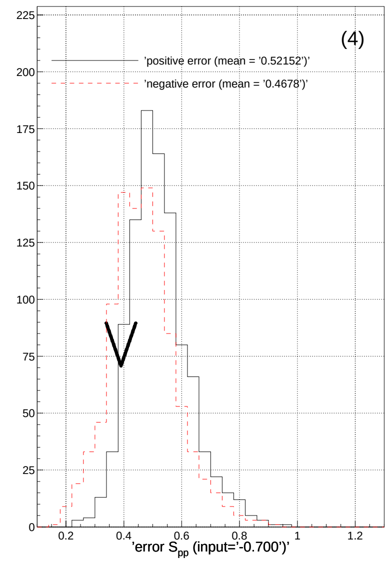
- Fit yields:
  - $"S_{K\pi}" = 0.15 \pm 0.24$ $"A_{K\pi}" = 0.07 \pm 0.17$

Statistical Cross-checks

- It has been noticed:
  - Has "smallish" uncertainties given our statistics

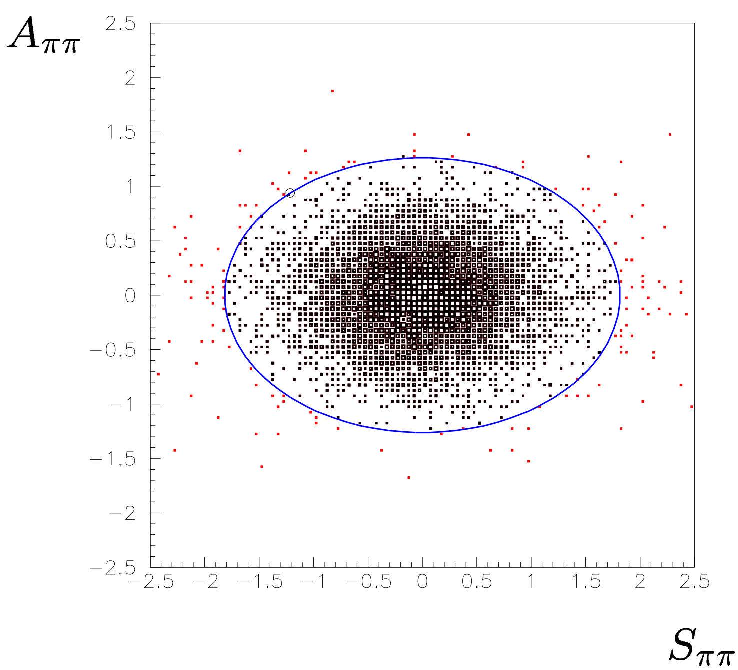


$\delta A_{\pi\pi}$



$\delta S_{\pi\pi}$

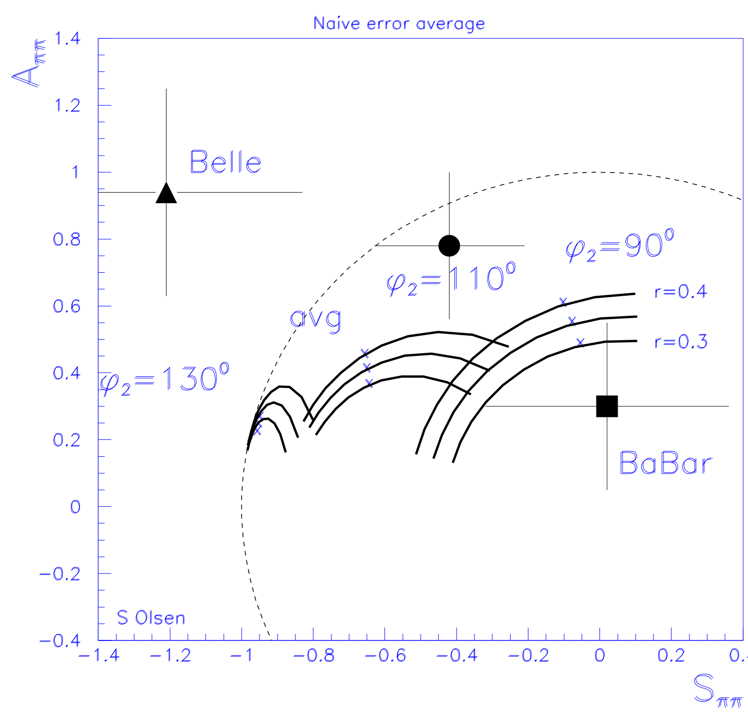
    - 5% chance to get $\delta S_{\pi\pi}$ smaller than our fit
  - $S_{\pi\pi}$ and $A_{\pi\pi}$ are 2.9 standard deviations from 0
    - An ensemble test shows



  - 1.6% lie further away from (0,0) than our result

What might this be telling us?

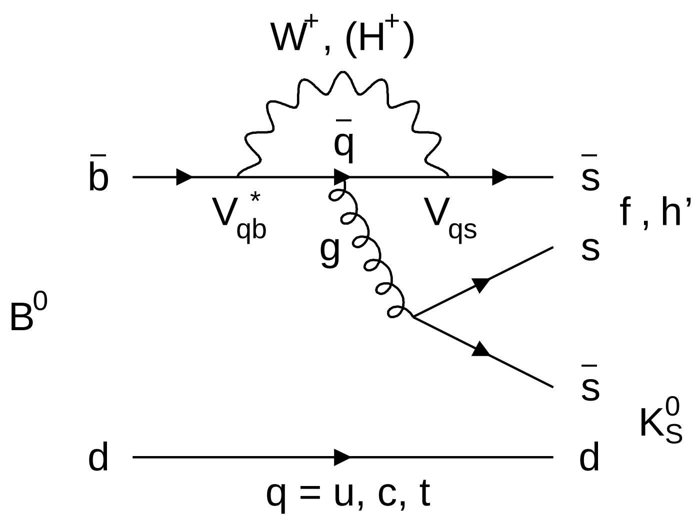
- We have found no problems with our analysis
- BaBar's result is inconsistent with ours by 2 σ
- At face value it hints at two large asymmetries
- Gronau and Rosner (hep-ph/0202170) relate:
  - $S_{\pi\pi} \propto \sin(2\phi_2) + 2r\sin(\phi_1 - \phi_2)\cos\delta - r^2\sin(2\phi_1)$
  - $A_{\pi\pi} \propto 2r\sin(\phi_1 + \phi_2)\sin\delta$
  - r is ratio of penguin to tree amplitudes (0.3 preferred?),
  - δ is the difference of strong phases



- Extraction of ϕ_2 simplified if asymmetry large

CP Asymmetries in Other Modes

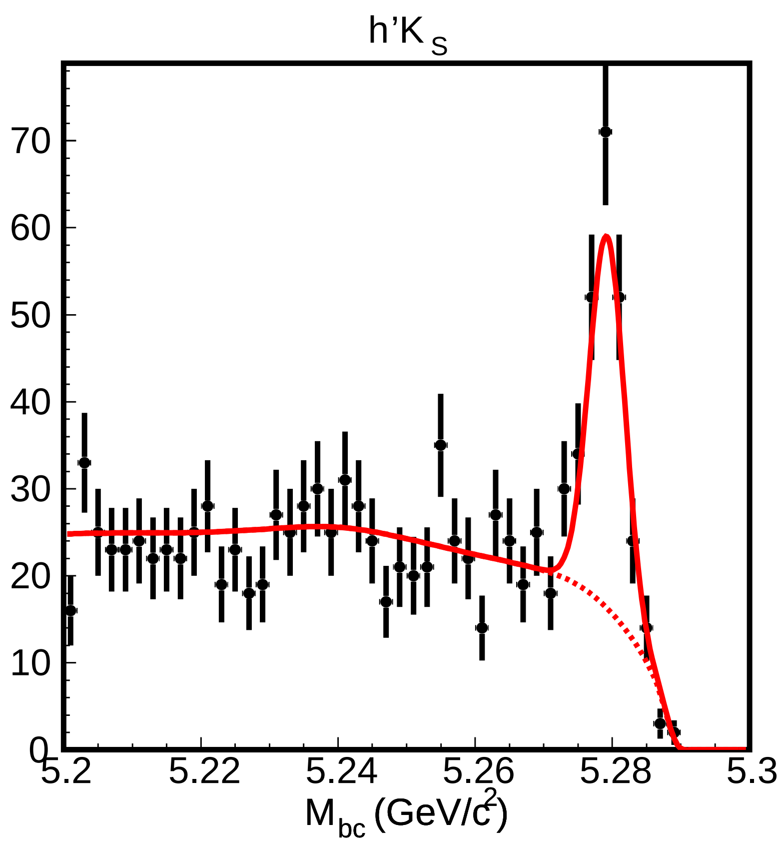
- In the Standard Model $B^0 \to \phi K_S^0$ very similar to $J/\psi K_S^0$



- However $\mathcal{B}(B^0 \to \eta' K_S^0)$ at 5×10^{-5} is
  - bigger than the un-seen ηK mode
  - not easy to explain theoretically
  - may hint at new physics in penguin loop
- New physics $\Rightarrow$ possible new phases
  - $S_{sss} = \sin(2\phi_1 + \Theta_{\text{New Physics}})$?

Selection of $B^0 \to \eta' K_S^0$

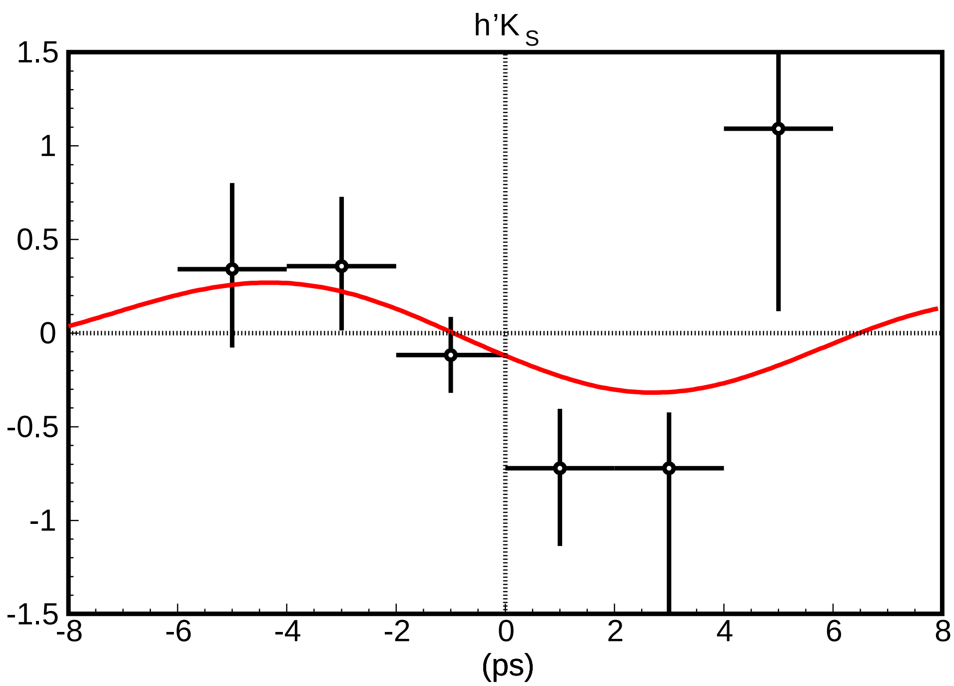
- Result from 42 fb^{-1} accepted by PLB (hep-ex 0207033)
- Select η' in two modes:
    - $\eta' \to \eta\pi^+\pi^-$ ($\eta \to \gamma\gamma$)
    - $\eta' \to \rho^0\gamma$
- Add a K_S^0 and look for signal in $M_{\rm bc}$ and ΔE



- 128 ± 14 candidates (background of 105) for CP fit

CP Asymmetry in $B^0 \to \eta' K^0_S$

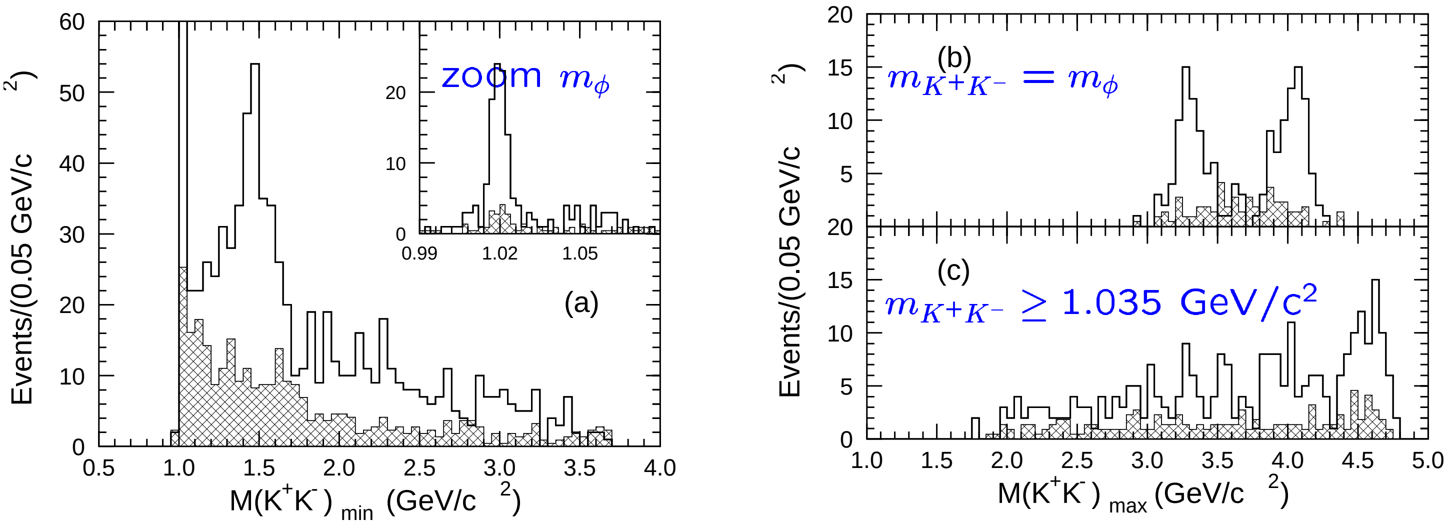
- Flavour tag and measure Δt as for other modes



- Fit gives
  - $S_{\eta' K^0_S} = 0.76 \pm 0.36(\text{stat}) \pm 0.06(\text{sys})$
  - $A_{\eta' K^0_S} = 0.26 \pm 0.22(\text{stat}) \pm 0.03(\text{sys})$
- Check $\eta' K^+$ asymmetries – find none.
- Errors about as expected for a sample this size
- Will soon reach interesting precision

Selection of $B^0 \to K^+K^-K^0_S$

- Belle systematically studying three body final states
- In particular $B^+ \to K^+K^-K^+$ very interesting



- Suppose $K^+K^-K^0_S$ is a mixture of CP-even and CP-odd
- $B \to KK\pi$ shows $b \to u\bar{u}s$ isospin violating trees small ($\lesssim 3\%$)
- $b \to q\bar{q}s$ penguin transitions conserve isospin

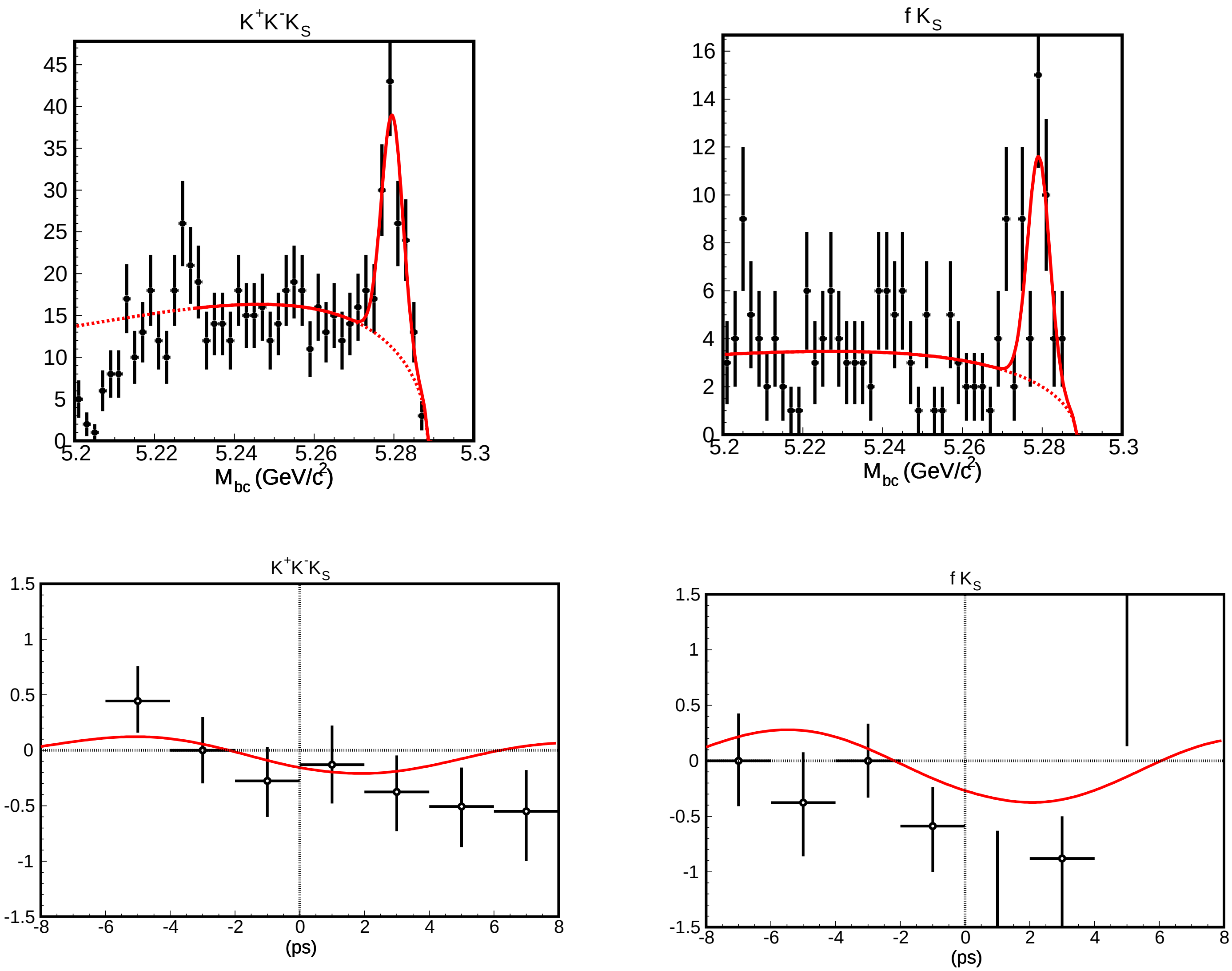
$$|K^+K^-K^0_S> \;=\; \alpha\,|>_{\text{CP}=+1} \;+\; \beta\,|>_{\text{CP}=-1}$$

$$|K^0\bar{K}^0K^+> \;=\; \alpha\,\frac{(|K^+K^0_SK^0_S>+|K^+K^0_LK^0_L>)}{\sqrt{2}} \;+\; \beta\,|K^+K^0_SK^0_L>$$

- From $\mathcal{B}(B^+ \to K^+K^0_SK^0_S)$ and $\mathcal{B}(B^0 \to K^+K^-K^0)$ conclude
  - $|K^+K^-K^0_S>_{\text{non}-\phi}$ is $97^{+3}_{-16}\%$ even
- While $B^0 \to \phi K^0_S$ is CP-odd

CP Asymmetry in $B^0 \to K^+K^-K^0_S$

- CP-signal consists of
  - 95 ± 7 $K^+K^-K^0_S$ candidates with $m_{K^+K^-} \neq m_\phi$
  - 35 ± 3 ϕK^0_S candidates



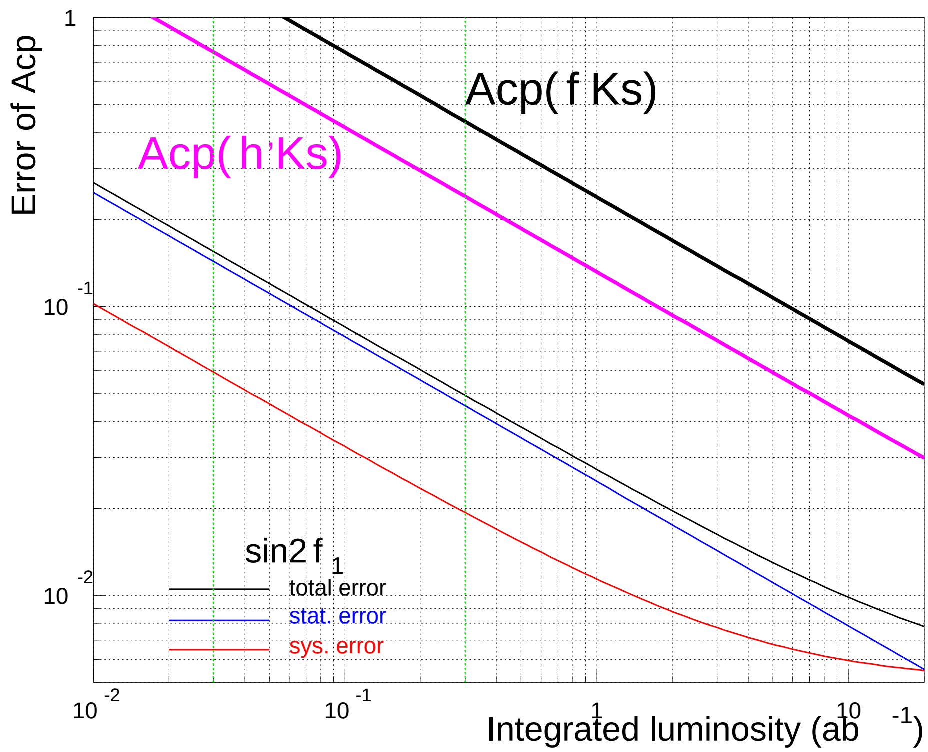
- Fit gives

$$-\xi_{CP}\, S_{K^+K^-K^0_S} = 0.52 \pm 0.46(\text{stat}) \pm 0.11\ (\text{sys})\ {}^{+0.27}_{-0.03}\ (\text{CP})$$
$$-\xi_{CP}\, S_{\phi K^0_S} = -0.73 \pm 0.64(\text{stat}) \pm 0.18\ (\text{sys})$$

- Higher mass K^+K^- modes make channel accessible sooner

Outlook for $\sin(2\phi_1)$

- Projections based on $\sqrt{N}$ scaling
  - Most systematics still limited by size of control samples



- Precision of 0.2 on $S_{\eta' K_S^0}$ potentially interesting

- ϕK_S^0 asymmetry precision better with non-ϕ K^+K^-

Summary

- $\sin 2\phi_1 = 0.719 \pm 0.074(\text{stat}) \pm 0.035(\text{sys})$
- Indications of a non-zero asymmetry in $\pi^+\pi^-$

$$S_{\pi\pi} = -1.21^{+0.38}_{-0.27}(\text{stat})^{+0.16}_{-0.13}(\text{sys})$$
$$A_{\pi\pi} = 0.94^{+0.25}_{-0.31}(\text{stat}) \pm 0.09(\text{sys})$$

- New modes starting to have finite uncertainties

$$-\xi_{CP}\, S_{\eta' K^0_s} = 0.76 \pm 0.36(\text{stat}) \pm 0.06(\text{sys})$$
$$-\xi_{CP}\, S_{\phi K^0_s} = -0.73 \pm 0.64(\text{stat}) \pm 0.18(\text{sys})$$
$$-\xi_{CP}\, S_{K^+K^-K^0_s} = 0.52 \pm 0.46(\text{stat}) \pm 0.11(\text{sys})^{+0.27}_{-0.03}(\text{CP})$$

- Looking forward to 0.25 ab^{-1} sample
  - Should further clarify matters