Measurements of CP asymmetries and branching fractions in

$B^0 \rightarrow \pi^+\pi^-, K^+\pi^-, K^+K^-$

Paul Dauncey
Imperial College, University of London
For the BaBar Collaboration

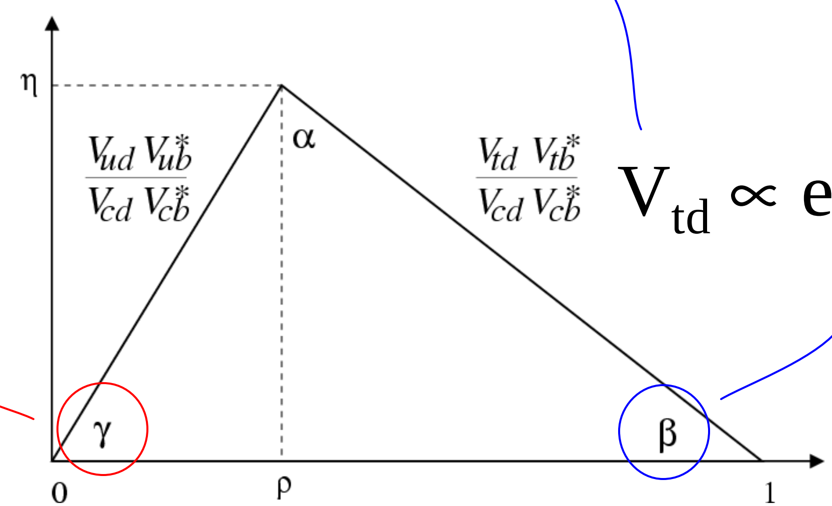
CP violation in the Standard Model

CP violation arises due to complex CKM matrix; e.g. Wolfenstein parametrisation:

$$\mathbf{V} = \begin{pmatrix} \mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\ \mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\ \mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \end{pmatrix} = \begin{pmatrix} \mathbf{1} - \frac{\mathbf{1}}{\mathbf{2}}\lambda^2 & \lambda & \mathbf{A}\lambda^3(\rho - \mathbf{i}\eta) \\ -\lambda & \mathbf{1} - \frac{\mathbf{1}}{\mathbf{2}}\lambda^2 & \mathbf{A}\lambda^2 \\ \mathbf{A}\lambda^3(\mathbf{1} - \rho - \mathbf{i}\eta) & -\mathbf{A}\lambda^2 & \mathbf{1} \end{pmatrix} + \mathbf{O}(\lambda^4)$$

CKM unitarity; represent as triangle in ρ,η plane

$V_{ub} \propto e^{-i\gamma}$

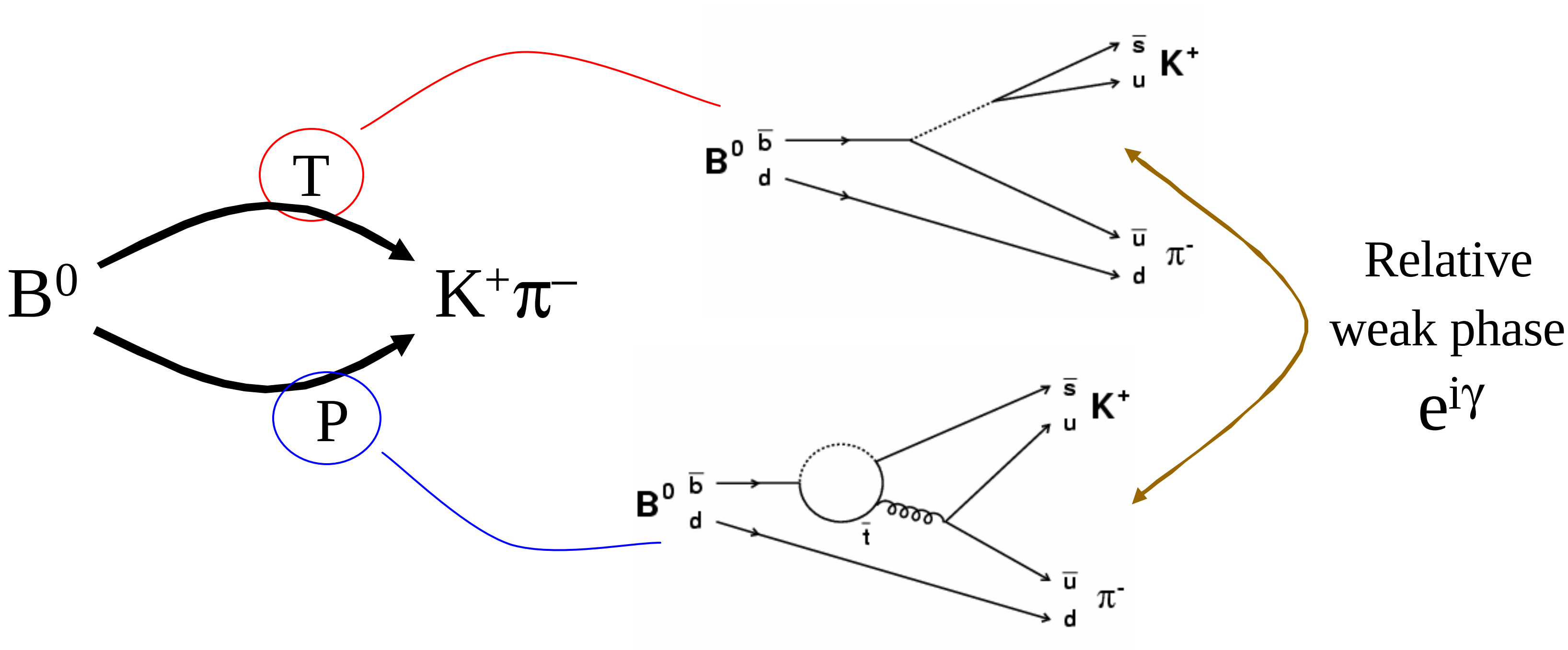


$V_{td} \propto e^{-i\beta}$

α is third internal angle

Direct CP violation

CP violation requires interference between at least two amplitudes with different phases, e.g. $B^0 \to K^+\pi^-$



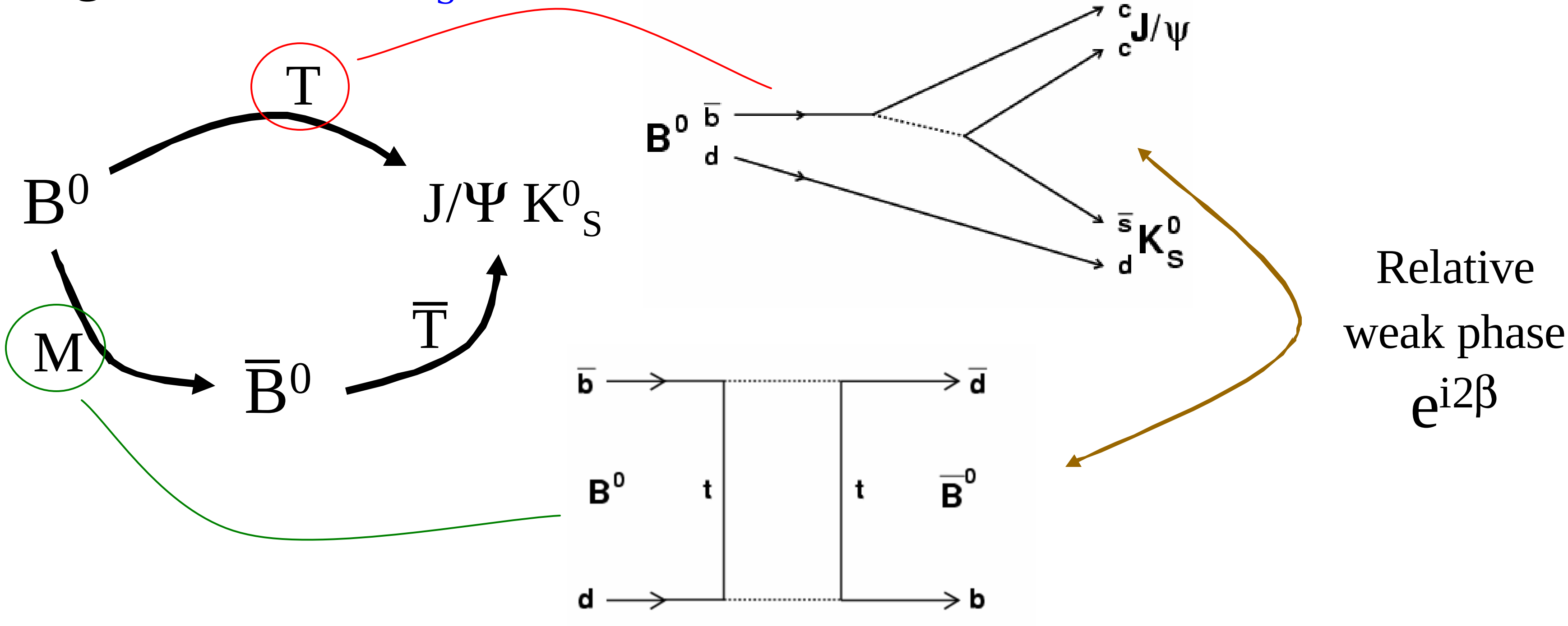
CP violation gives a non-zero asymmetry:

$A_{K\pi} = \Gamma(\bar{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) / \Gamma(\bar{B}^0 \to K^-\pi^+) + \Gamma(B^0 \to K^+\pi^-)$

In principle leads to γ measurement

Indirect CP violation

Mixing gives two paths if final state accessible from B^0 and $\bar{B}^0$,
e.g. $B^0 \to J/\Psi\ K^0_S$



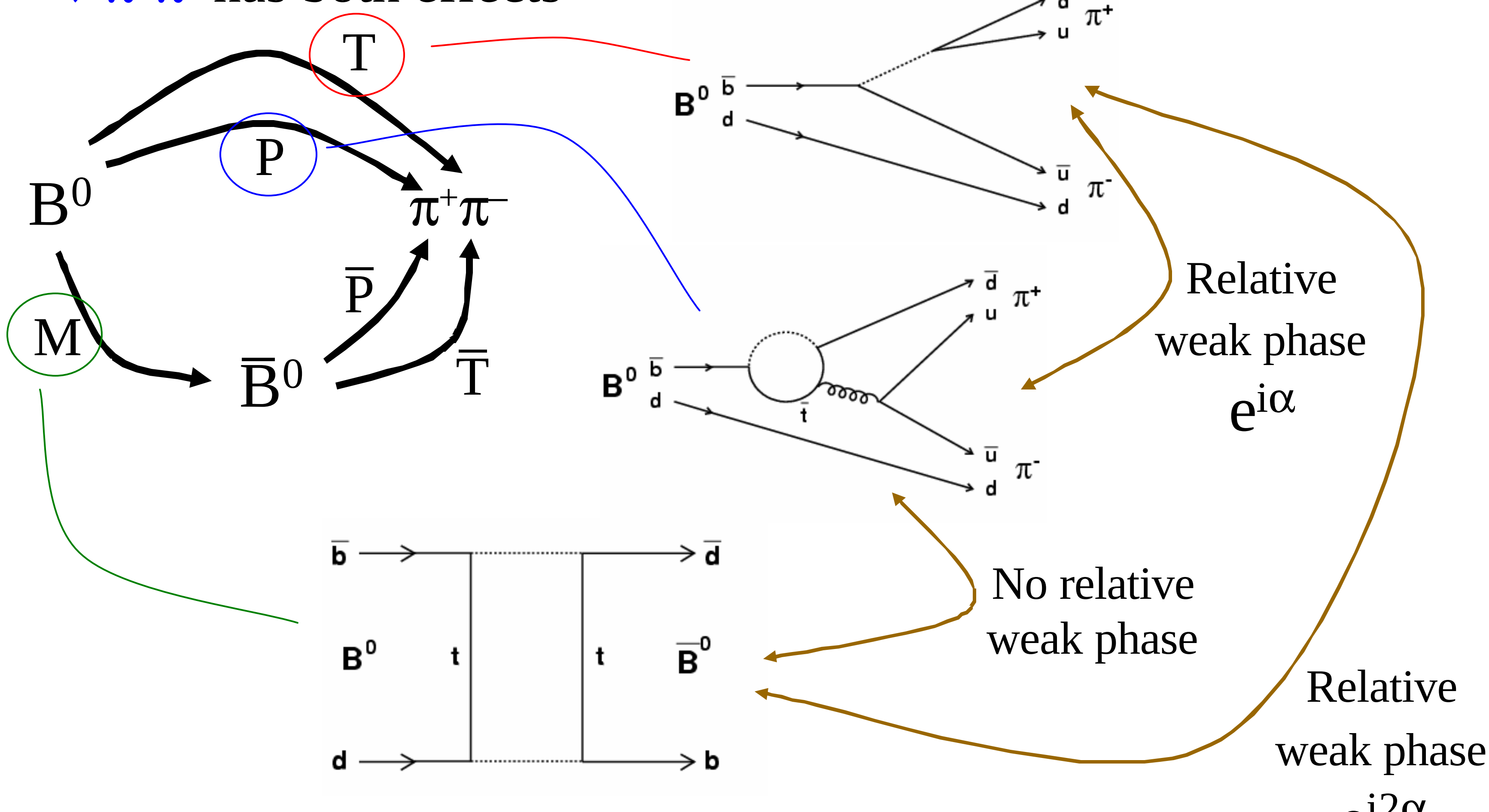
CP violation gives a time-dependent asymmetry:

$$\text{Amplitude} = \text{Im}(e^{i2\beta}) = \sin 2\beta$$

Leads to β measurement: see talk by S. Rahatlou

CP violation in $B^0 \to \pi^+\pi^-$

$B^0 \to \pi^+\pi^-$ has both effects



If both tree and penguin significant: parametrise as $\sin 2\alpha_{eff}$

Interpretation also depends on strong amplitudes

Experimental reality

Analysis is different from $B^0 \to J/\Psi\, K^0_S$…

- No clean $\pi\pi$ or $K\pi$ sample; need to determine particle type
  - Particle identification needed
  - Analyse both modes simultaneously; also include KK
- No clean signal sample; high backgrounds from udsc
  - Branching fractions are ~ $10^{-6} – 10^{-5}$
  - Need to use kinematics and event shapes to distinguish modes
  - Use unbinned maximum likelihood fit to extract signals

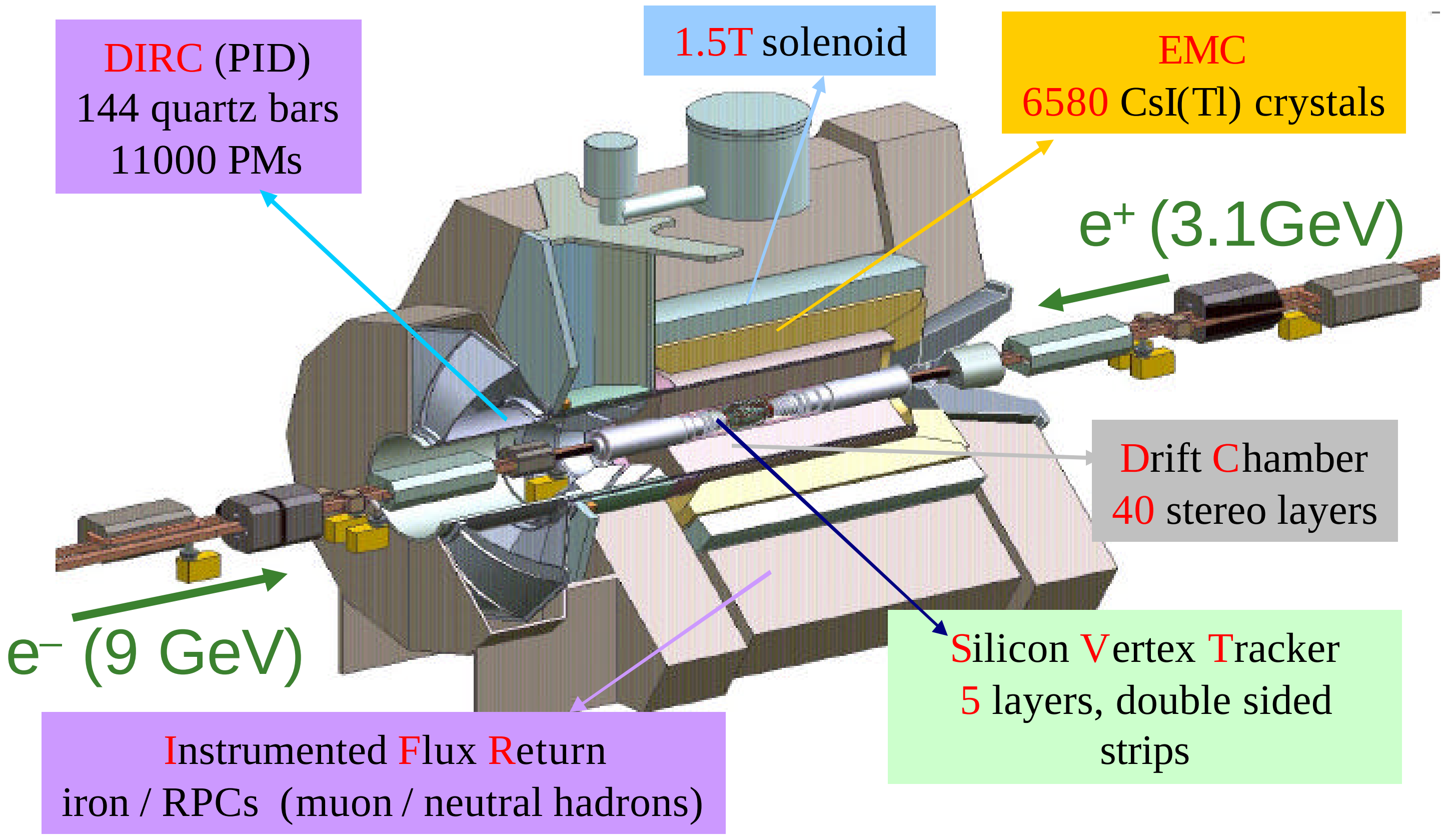
…but some elements are identical:

- Need to “tag” the other B to find if B^0 or $\overline{B}^0$
  - Use lepton charge, K charge or neural networks
  - Inefficiency and impurity (“dilution”)
- Cannot measure time directly
  - Time difference Δt between two B decays

The BaBar detector

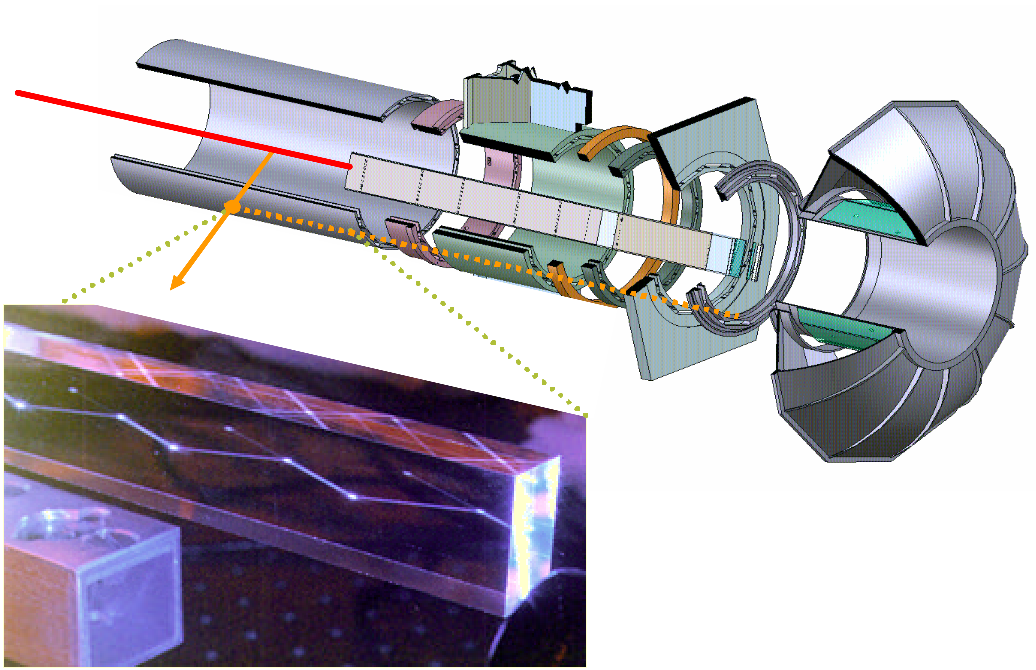
Pep-II delivers boosted $e^+e^- \to \Upsilon(4s) \to B\bar{B}$, on and off the $\Upsilon(4s)$

Integrated luminosity: 55.6 fb^{-1} on peak, 60.2 ± 0.7 million $B\bar{B}$ events



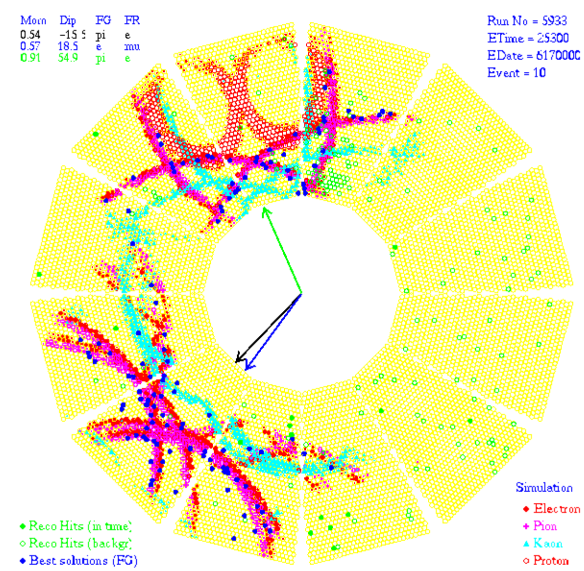
Particle identification with the DIRC

Detector of Internally Reflected Cherenkov light (DIRC): essential for this analysis to distinguish K from π



Cherenkov light transmitted down quartz bars by internal reflection

Reconstruct Cherenkov angle $\cos\theta_C = 1/n\beta$ from rings seen in PMTs



Analysis overview

Analysis is done in two stages:

- Direct CP; extract branching fractions for $\pi\pi$, $K\pi$ and KK and also the $K\pi$ decay CP asymmetry $A_{K\pi}$
  - Maximum likelihood fit to kinematic/event shape quantities
  - Requires no tag or vertex measurement
  - Separate fit reduces systematic error
- Indirect CP; extract $\pi\pi$ CP asymmetry $\sin 2\alpha_{eff}$
  - Fix branching fractions and $A_{K\pi}$ to above results
  - Requires tag to determine if B^0 or $\overline{B}^0$
  - Requires vertex information to find time dependence

All results are preliminary

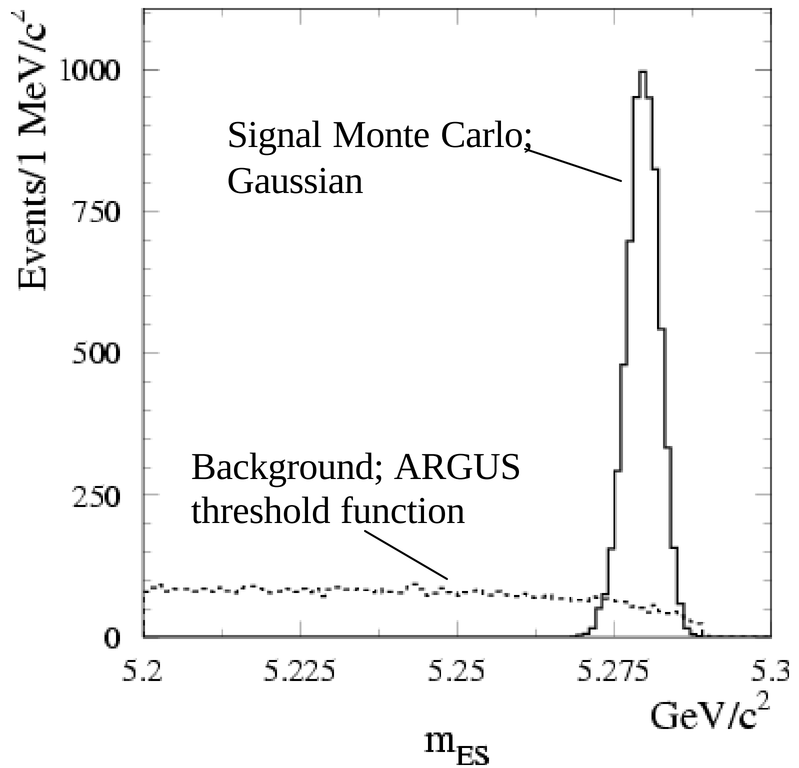
Kinematic variables - m_{ES}

B candidate mass using beam "energy substitution"

$$m_{ES} = \sqrt{(E_{beam}^2 - p_B^2)} \quad \text{in CM}$$

Select $5.2 < m_{ES} < 5.3$ GeV/c^2

- Depends on reconstructed momentum of B candidate, $p_B \sim 325$ MeV
- Same for all signal modes
- Resolution dominated by beam energy uncertainty
- $\sigma(m_{ES}) \sim 2.6$ MeV/c^2
- Signal shape from MC, background from fit



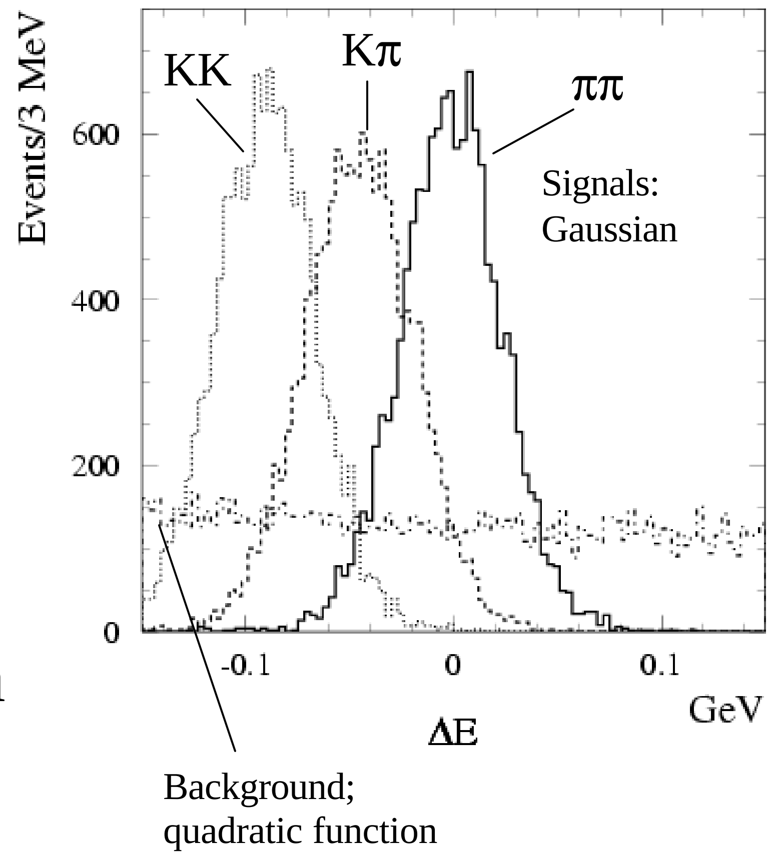
Kinematic variables - ΔE

B candidate energy difference from beam energy

$\Delta E = E_B - E_{beam}$ in CM

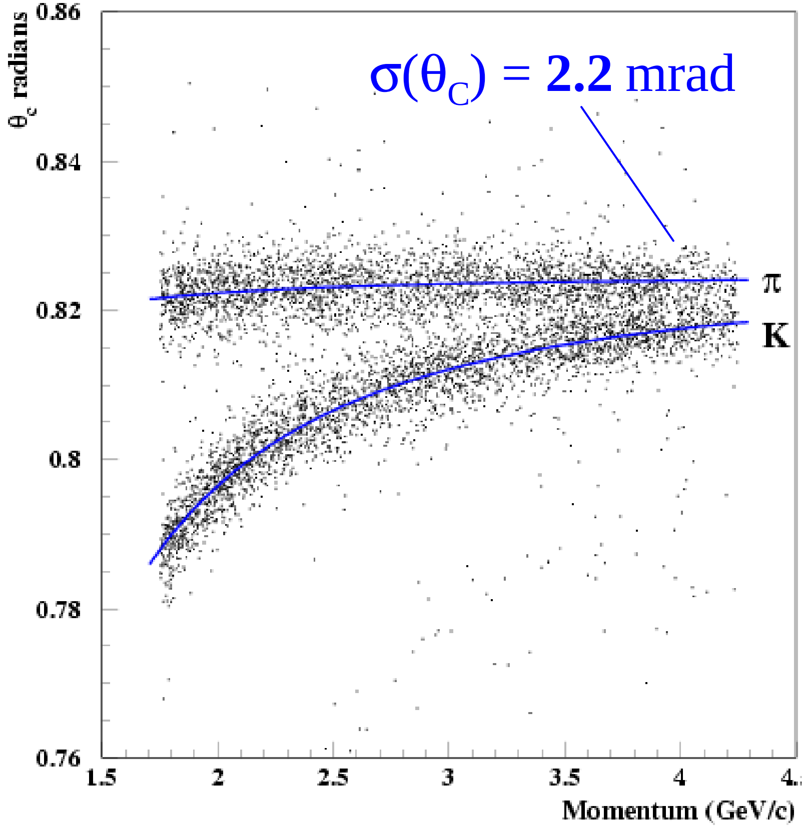
Select | ΔE | < 0.15 GeV

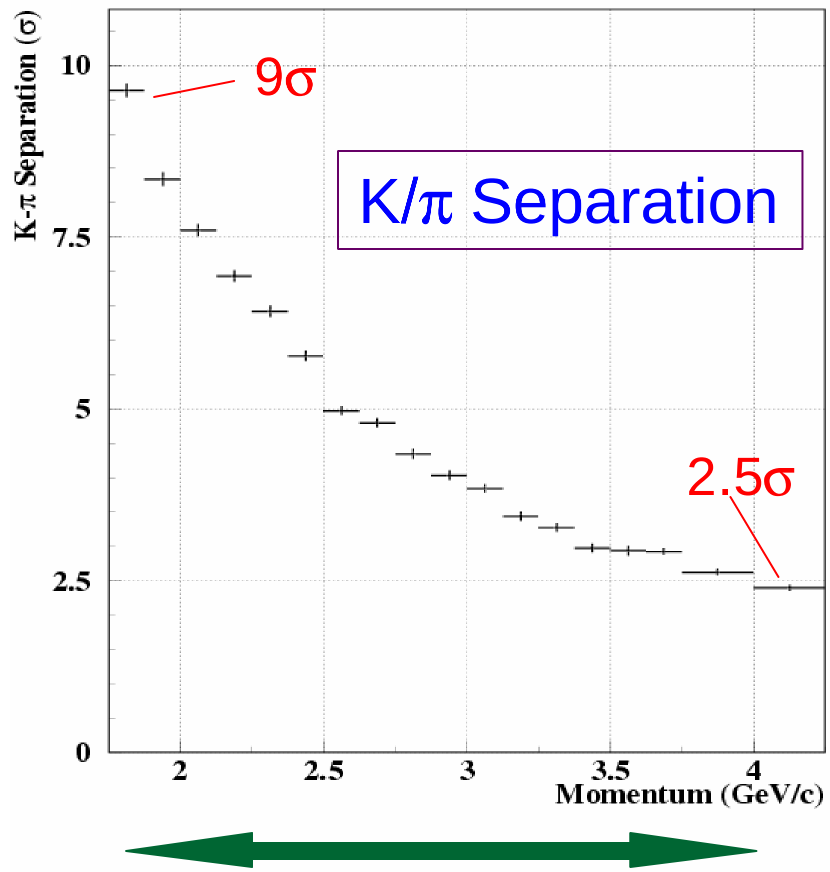
- Depends on masses of B decay products; π mass assumed
- Kπ and KK shifted to non-zero average; ~ 45 MeV per K
- Resolution dominated by tracking
- σ(ΔE) ~ 26 MeV
- Signal shape parametrised from MC; background from fit



Particle identification - θ_c

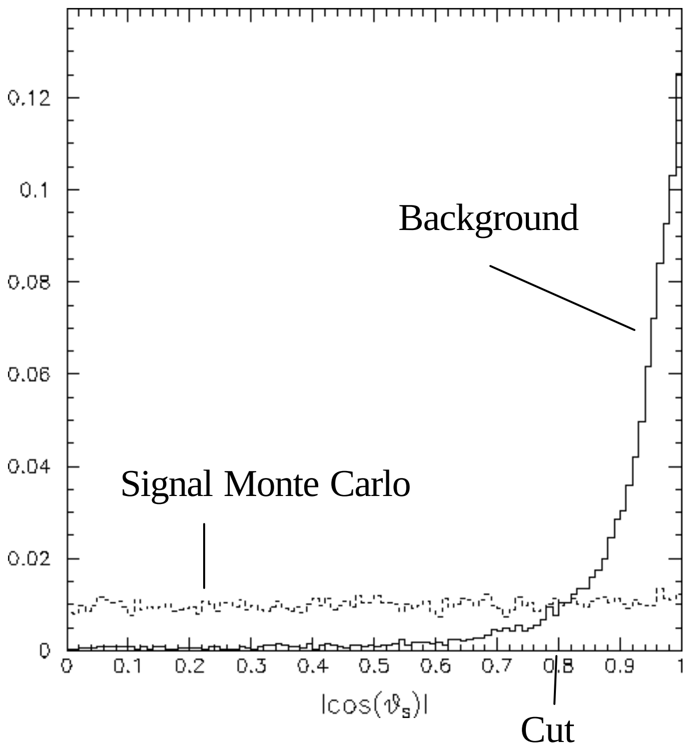
DIRC θ_c mean and resolution parametrised from data using $D^{*+} \rightarrow D^0\pi^+ \rightarrow (K^-\pi^+)\pi^+$ decays





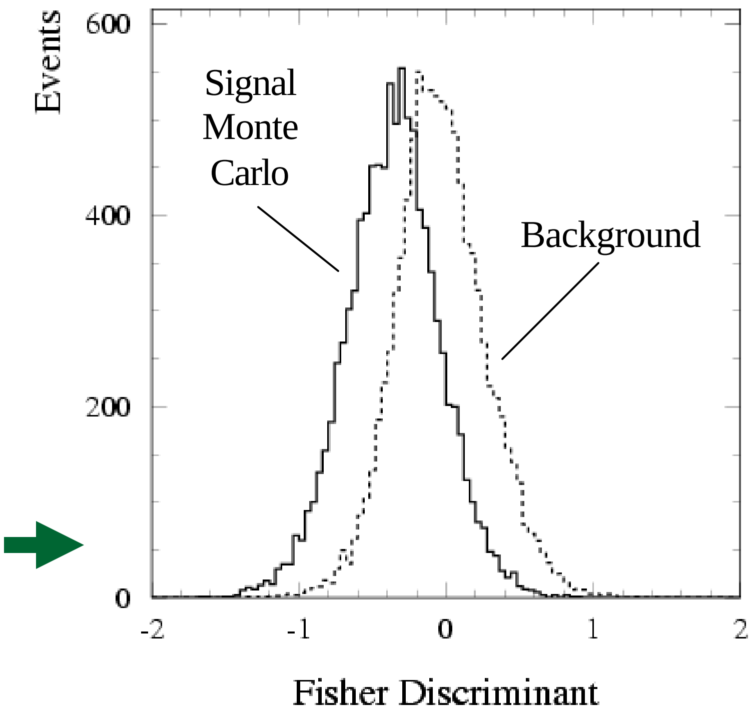
Momentum range of decays

Background suppression - Fisher



Cut on angle between B candidate and sphericity of the other tracks in the event: $|\cos \theta_s| < 0.8$

F - optimized linear combination of energy flow into nine cones around candidate (CLEO Fisher discriminant). Signal shape from MC, background from fit



Branching fraction maximum likelihood fit

Five input variables per event; assume independent (uncorrelated) PDFs for each:

- m_{ES}
- F
- ΔE
- θ_C^+
- θ_C^-

m_{ES}, F, ΔE: Discriminate signal from background

ΔE, θ_C^+, θ_C^-: Discriminate different signal modes

Eight fit parameters: four for signal, four for background

- $N(\pi^+\pi^-)$
- $N(K^+\pi^-)$
- $N(\pi^+K^-)$
- $N(K^+K^-)$

$N(K^+\pi^-)$, $N(\pi^+K^-)$: Fit directly for $N(K\pi)$ and $A_{K\pi}$:

$$N(K^+\pi^-) = N(K\pi)\,(1-A_{K\pi})/2$$

$$N(\pi^+K^-) = N(K\pi)\,(1+A_{K\pi})/2$$

Branching fraction results

Fit results are:

Mode	Yield (events)	Branching Fraction (10^{-6})	Kπ Asymmetry, $A_{K\pi}$
$B^0 \rightarrow p^+ p^-$	124^{+16+7}_{-15-9}	$5.4 \pm 0.7 \pm 0.4$	
$B^0 \rightarrow K^+ p^-$	$403 \pm 24 \pm 15$	$17.8 \pm 1.1 \pm 0.8$	$-0.05 \pm 0.06 \pm 0.01$
$B^0 \rightarrow K^+ K^-$	< 15.6 (90% C.L.)	< 1.1 (90% C.L.)	

No significant direct CP violation seen in $B^0 \rightarrow K^+\pi^-$

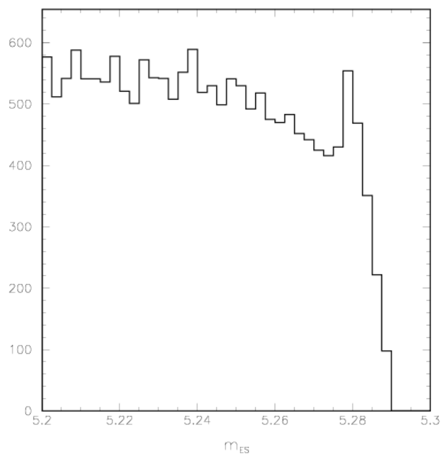
- 90% C.L. $-0.14 < A_{K\pi} < 0.05$

Main systematics:

- Branching fractions – uncertainty in shape of θ_C PDF
- Asymmetry - possible charge bias in track and θ_C reconstruction

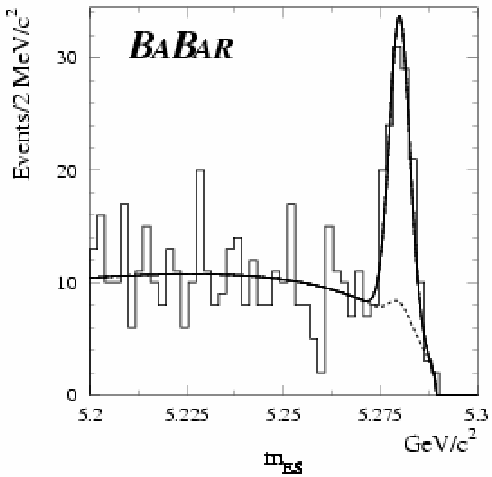
Branching fraction projections

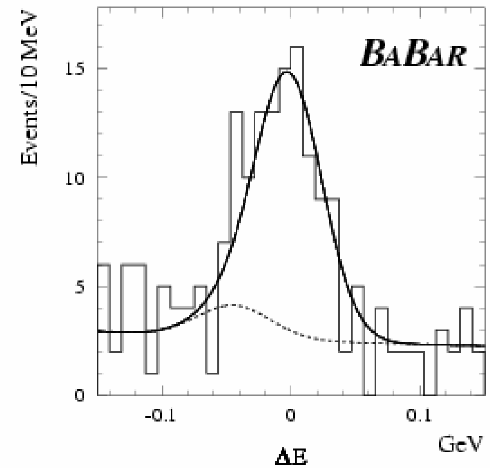
Likelihood projections: remove one variable from fit and cut on fit probabilities to give enhanced signal samples:



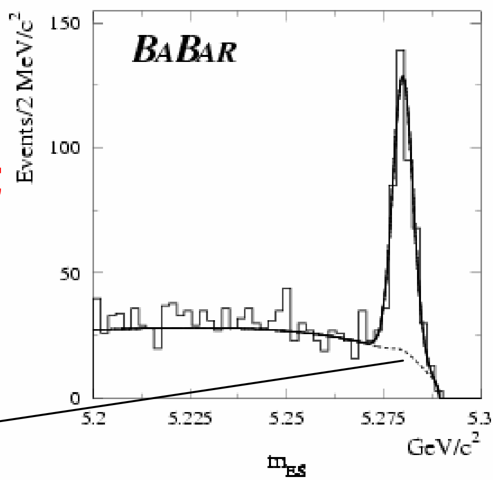
Fit sample: 17585 candidates, ε ~ 38%

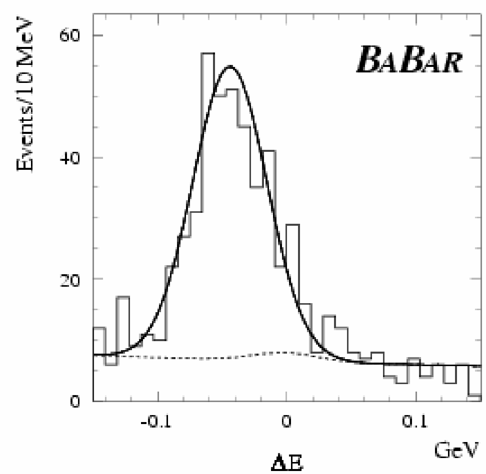
$B^0 \rightarrow \pi\pi$





$B^0 \rightarrow K\pi$





Background and crossfeed

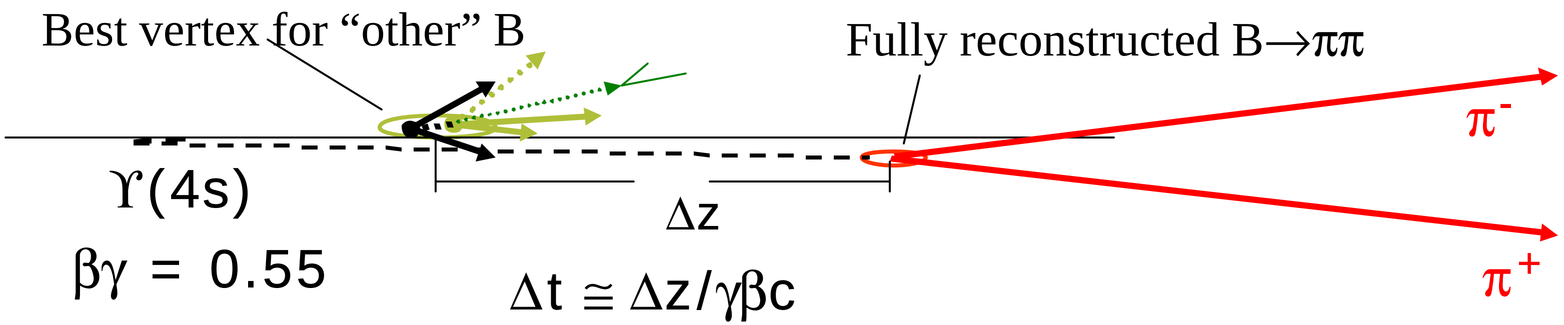
Measuring indirect CP violation

Extend the branching fraction analysis to extract indirect CP information:

- Needs extra information on:
  - Time of decay (vertexing); reconstruct “other” B decay point and find time difference of B decays
  - Flavour of the decaying B^0 (tagging); use tracks whose charge carries flavour information
  - Use identical techniques to sin2β analysis
- Fit for CP violation asymmetries while holding branching fractions and Kπ asymmetry to previously determined values
  - Vary these parameters within determined errors for systematics; small effect for asymmetries

Vertexing and Δt

Asymmetric beam energies mean Y(4s) is boosted:



Δt is time difference between the two decays:

- Resolution is dominated by the “other” B, $\sigma(\Delta t) \sim 0.8$ ps
- Independent of signal type
- Can use same resolution model as $\sin 2\beta$ analysis
- Exploit mixing to measure signal performance (dilutions) and efficiencies
- Signal resolution determined from large sample of fully reconstructed B’s, background shape determined from fit

Signal yield time dependences

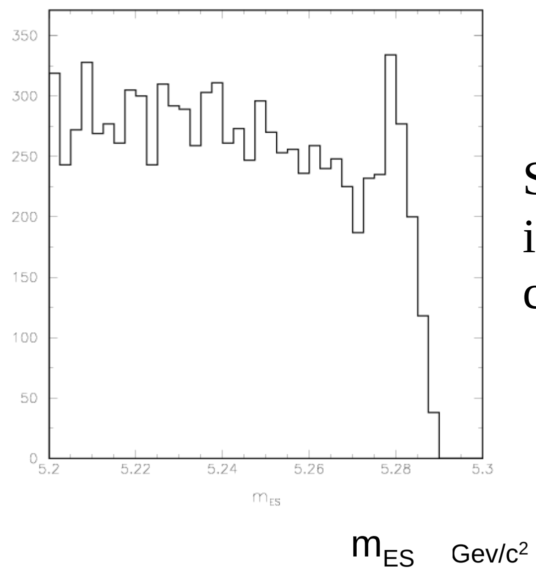
The signal modes depend differently on Δt:

- $\pi\pi$ general form allows for both tree and penguin: rates
  - $f(\Delta t) \sim 1 \pm S_{\pi\pi} \sin(\Delta m_d \Delta t) \mp C_{\pi\pi} \cos(\Delta m_d \Delta t)$ for $B^0(\bar{B}^0)$ tag
  - $S_{\pi\pi} = 2\mathrm{Im}(\lambda)/(1+|\lambda|^2)$ and $C_{\pi\pi} = (1-|\lambda|^2)/(1+|\lambda|^2)$
  - For pure tree, $\lambda = e^{i2\alpha}$ so $S_{\pi\pi} = \sin 2\alpha$ and $C_{\pi\pi} = 0$
  - With some penguin contribution, $C_{\pi\pi} \neq 0$ and $S_{\pi\pi} = \sqrt{(1-C_{\pi\pi}^2)} \sin 2\alpha_{eff}$
- $K\pi$ time dependence due to B^0 mixing: rates
  - $f(\Delta t) \sim 1 \pm \cos(\Delta m_d \Delta t)$ for unmixed (mixed) B^0
- KK general form similar to $\pi\pi$ in principle
  - Model with simple exponential
- Actual PDFs used in fit:
  - Diluted due to mistags
  - Convolved with Δt resolution functions

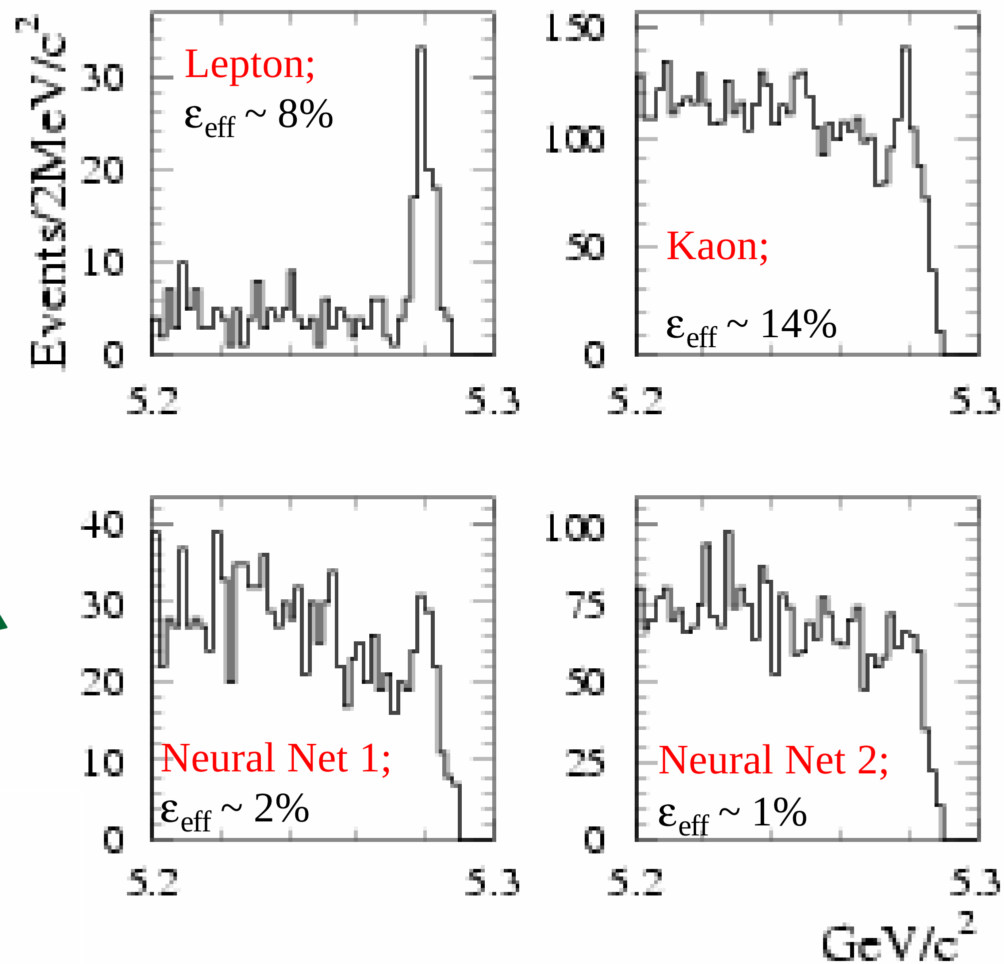
Flavour tagging

Use same flavour tagging as sin2β measurement:

Fit sample: 9220 tagged candidates



Separate into tag categories



Untagged events (~ 33%) retained in the fit to determine background shapes

Time-dependent fit results

Fit results in:

$$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$$

$$C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$$

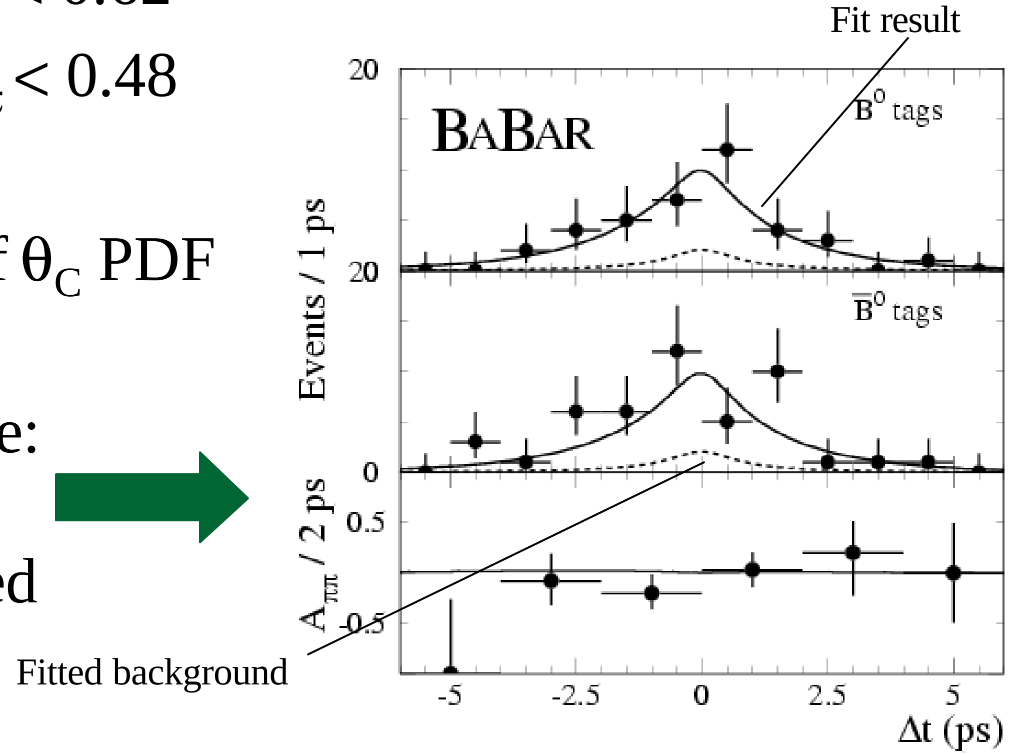
No significant indirect CP violation seen in $B^0 \rightarrow \pi^+\pi^-$

- 90% C.L. $-0.66 < S_{\pi\pi} < 0.62$
- 90% C.L. $-0.54 < C_{\pi\pi} < 0.48$

Main systematic:

- Uncertainty in shape of θ_C PDF

Enhanced $B \rightarrow \pi\pi$ sample: Δt distributions and asymmetry between mixed and unmixed events.



Time-dependent fit cross checks

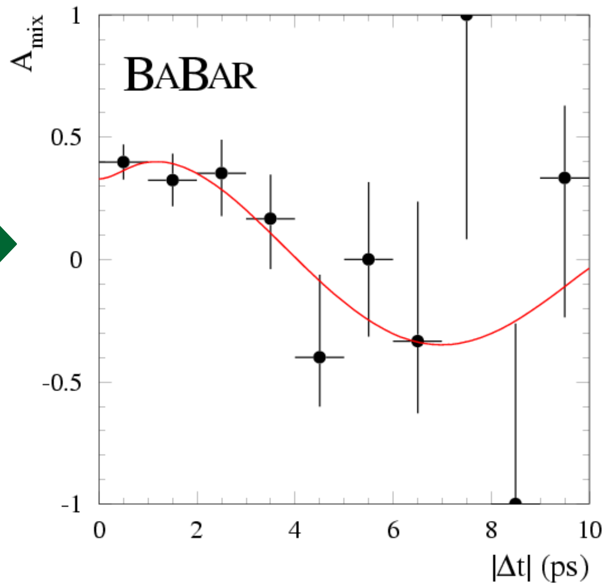
Fit checked using "toy" studies of simulated experiments

- All parameters unbiased
- All errors consistent with expectations
- Likelihood value (goodness of fit) consistent with expectations

Fit holds B lifetime and mixing constant: cross check by fitting

- $\tau_B = 1.66 \pm 0.09$ ps (c.f. PDG value 1.54 ± 0.02 ps)
- $\Delta m_d = 0.517 \pm 0.062\ \mathrm{ps}^{-1}$ (c.f. PDG value $0.479 \pm 0.012\ \mathrm{ps}^{-1}$)

Enhanced $B \to K\pi$ sample: asymmetry between unmixed and mixed events.



Summary of BaBar preliminary results

Branching fractions:

$$\mathcal{B}(B^0 \rightarrow \pi^+\pi^-) = (5.4 \pm 0.7 \pm 0.4) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^+\pi^-) = (17.8 \pm 1.1 \pm 0.8) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^+K^-) = < 1.1 \times 10^{-6} \text{ (90\% C.L.)}$$

CP asymmetries; no evidence for CP violation:

$S_{\pi\pi} = -0.01 \pm 0.37 \pm 0.07$ or 90% C.L. $-0.66 < S_{\pi\pi} < 0.62$

$C_{\pi\pi} = -0.02 \pm 0.29 \pm 0.07$ or 90% C.L. $-0.54 < C_{\pi\pi} < 0.48$

$A_{K\pi} = -0.05 \pm 0.06 \pm 0.01$ or 90% C.L. $-0.14 < A_{K\pi} < 0.05$