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

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

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

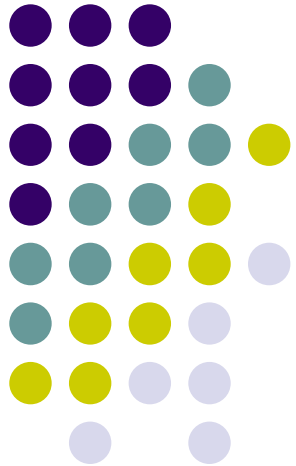
$B^0 \to \pi^0\pi^0$

Measurement of the time-dependent CP asymmetry for $B^0 \to \pi^+\pi^-$ and related modes at the BaBar detector

Division of Particles and Fields

Riverside, California

August 30, 2004



Nick Danielson

The BaBar Collaboration

Princeton University

CP violation

- CKM matrix describes mixing between flavor and weak eigenstates in the Standard Model.
  - 3×3 unitary matrix
  - One irreducible complex phase → CP violation

CKM Matrix

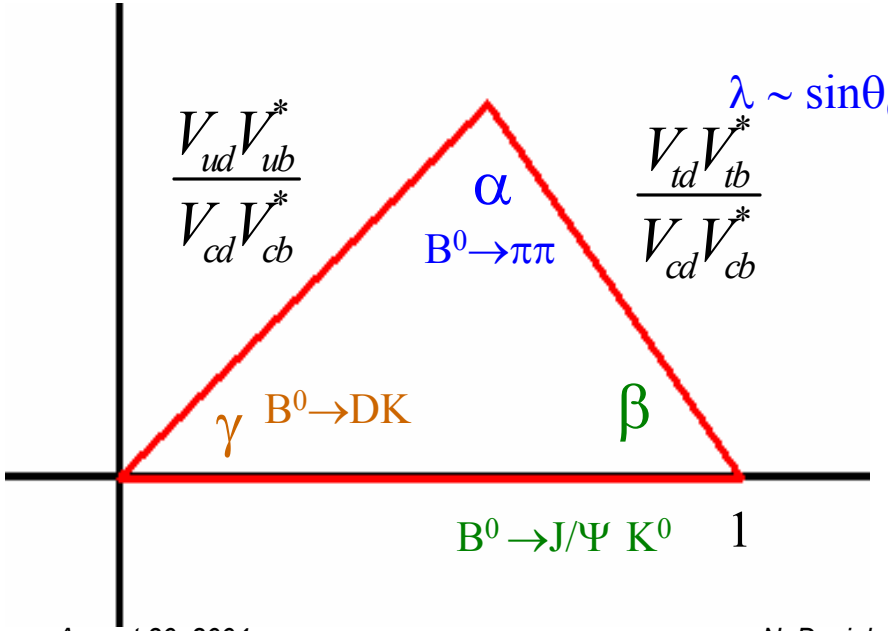
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein Parameterization

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

$\lambda \sim \sin\theta_C$

CP-violating phase



- The unitarity implies:

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

- area of triangle reflects amount of CP violation in the model.

CP Violation

$$a(t) = \frac{\Gamma_{\bar{B}^0 \to \pi^+\pi^-} - \Gamma_{B^0 \to \pi^+\pi^-}}{\Gamma_{\bar{B}^0 \to \pi^+\pi^-} + \Gamma_{B^0 \to \pi^+\pi^-}} = S_{\pi\pi} \sin(\Delta m \Delta t) - C_{\pi\pi} \cos(\Delta m \Delta t)$$

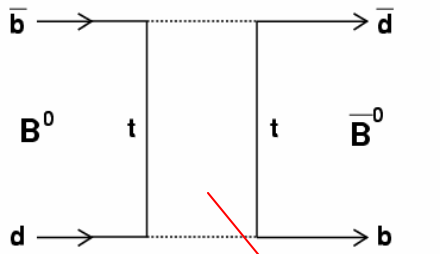
$$|B_{L/H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

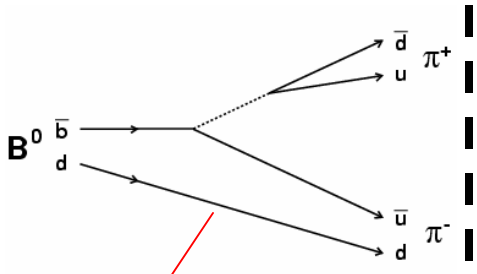
$$\lambda_{\pi\pi} = \frac{q}{p}\frac{\bar{A}_{\pi\pi}}{A_{\pi\pi}} \qquad S_{\pi\pi} = \frac{2\,\mathrm{Im}\lambda_{\pi\pi}}{1+|\lambda_{\pi\pi}|^2} \qquad C_{\pi\pi} = \frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2}$$

- 3 classes of CP violation
  - q≠p. CP violation in mixing
  - $|\bar{A}_{\pi\pi}/A_{\pi\pi}| \neq 1 \rightarrow C \neq 0$. Direct CP violation in decay
  - $\mathrm{Im}\lambda \neq 0 \rightarrow S \neq 0$. Indirect CP violation in mixing and decay

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

Tree level





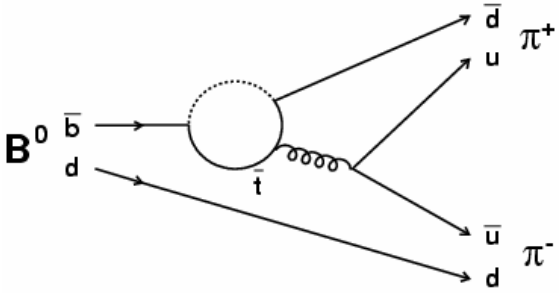
$$\lambda = \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right)$$

$$\lambda = e^{2i\alpha}$$

$$S = \sin 2\alpha$$

$$C = 0$$

Penguin



- Shifts α to α_{eff}
- C can be nonzero

Extraction of α in the presence of penguins

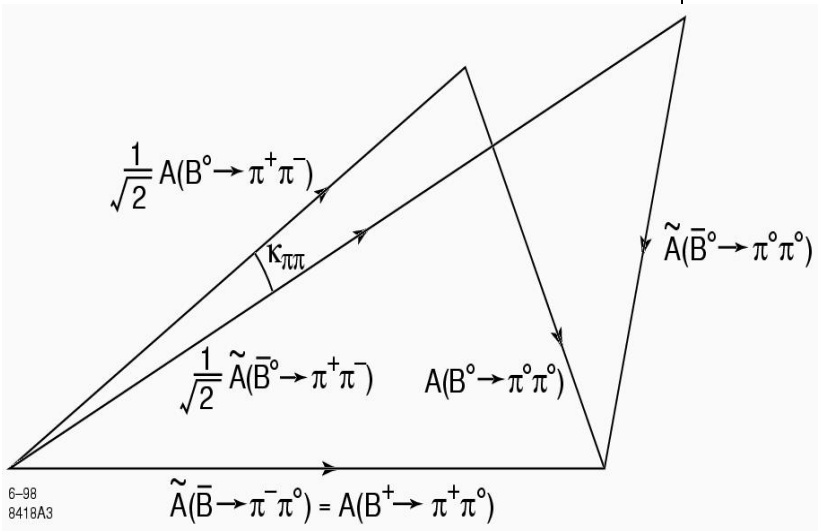
- Tree level diagram yields alpha, but penguins aren't negligible
  - Penguin carries phase of $-\beta$
  - Measure α_{eff}
- Isospin analysis relates amplitudes for

$B^0 \to \pi^+\pi^-$, $\quad \overline{B}^0 \to \pi^+\pi^-$,

$B^0 \to \pi^0\pi^0$, and $\quad \overline{B}^0 \to \pi^0\pi^0$, and

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

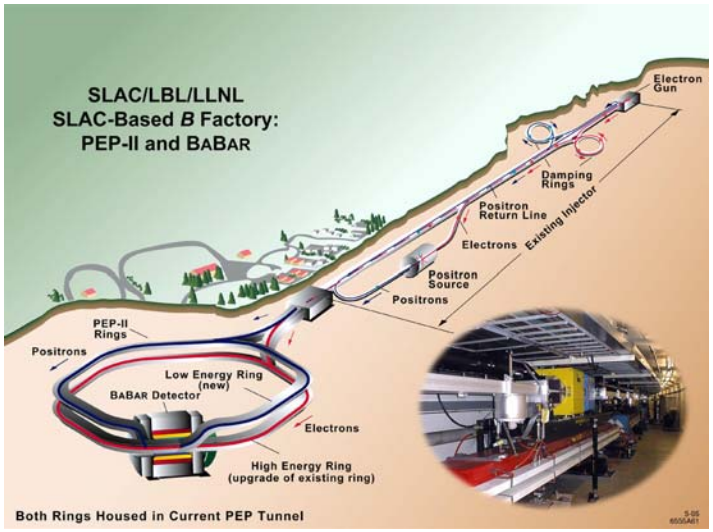
to α

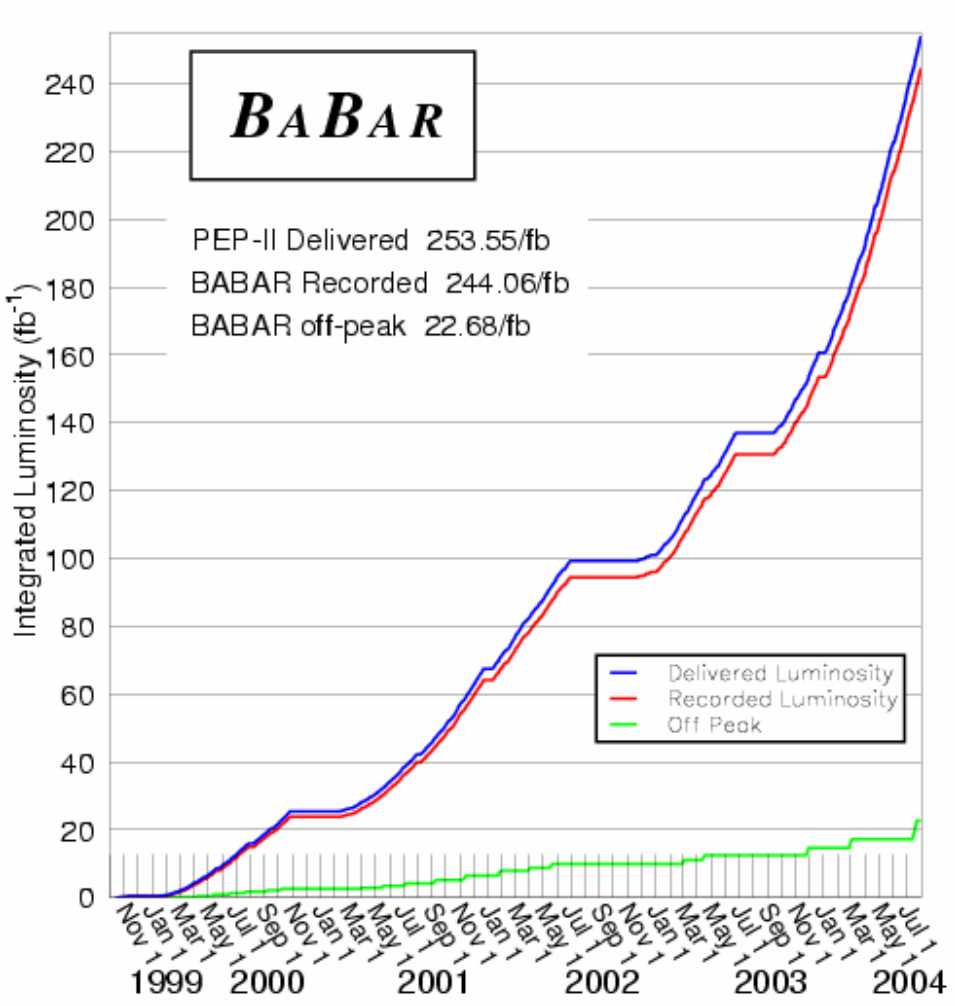


Isospin analysis

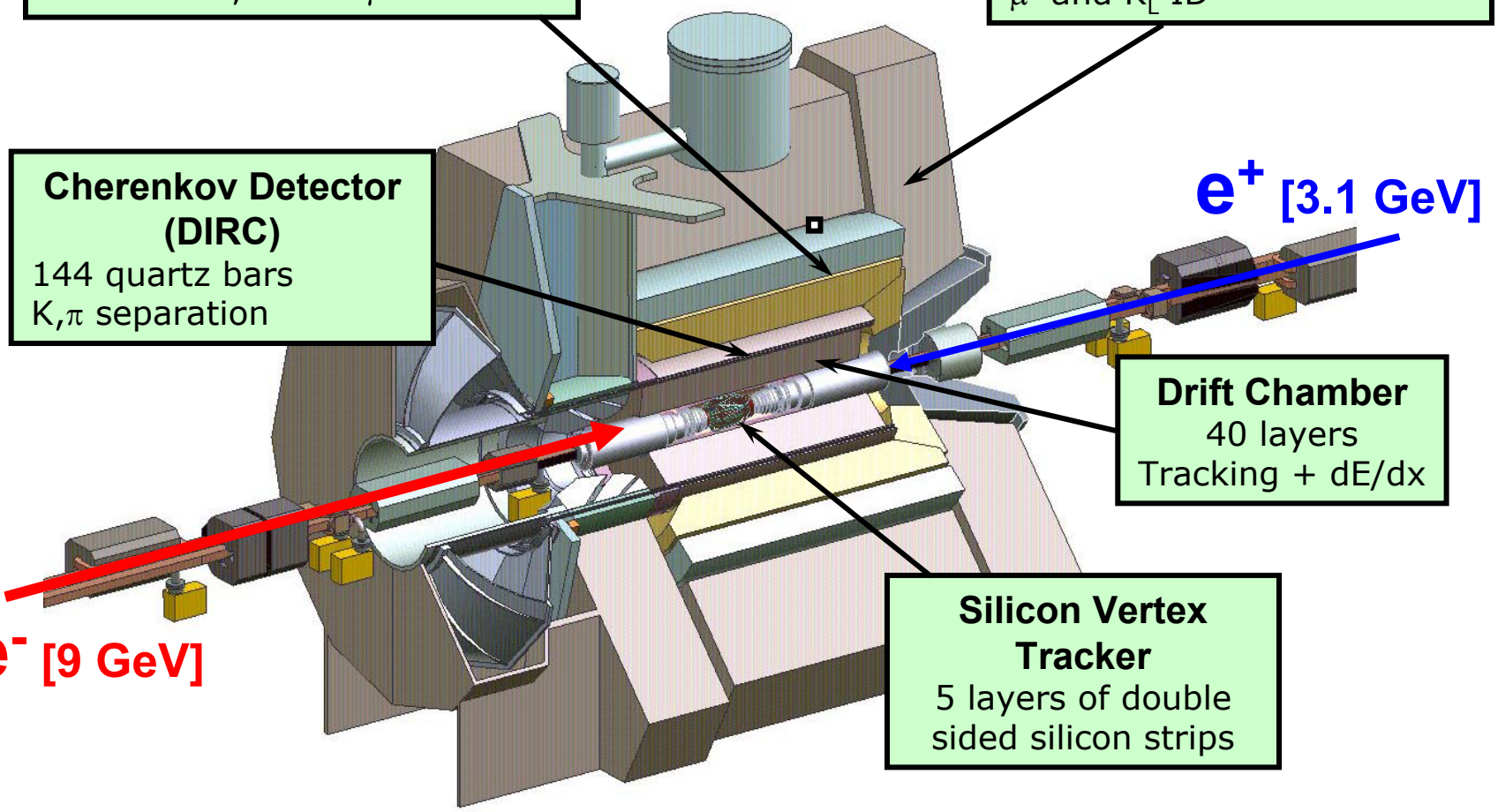
BaBar

- PEP-II top luminosity: $9.2 \times 10^{33} cm^{-2} s^{-1}$
- In this analysis: Run 1-4 data
- On peak
  - 205 fb-1
  - 227M *BB* pairs

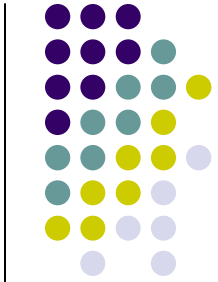




The BaBar detector



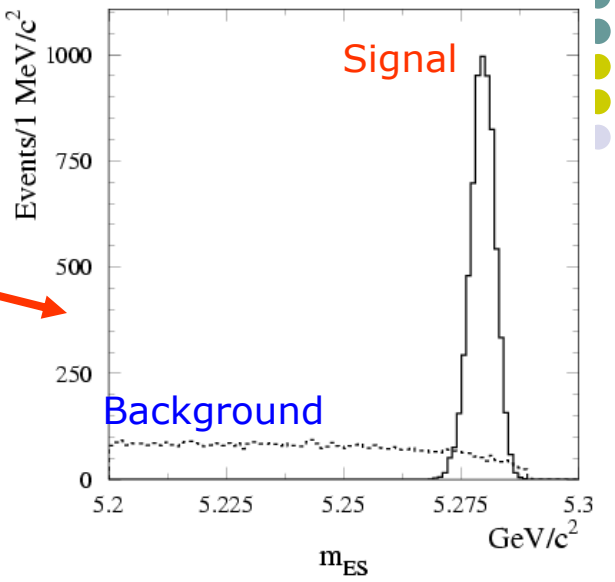
Charmless B decays

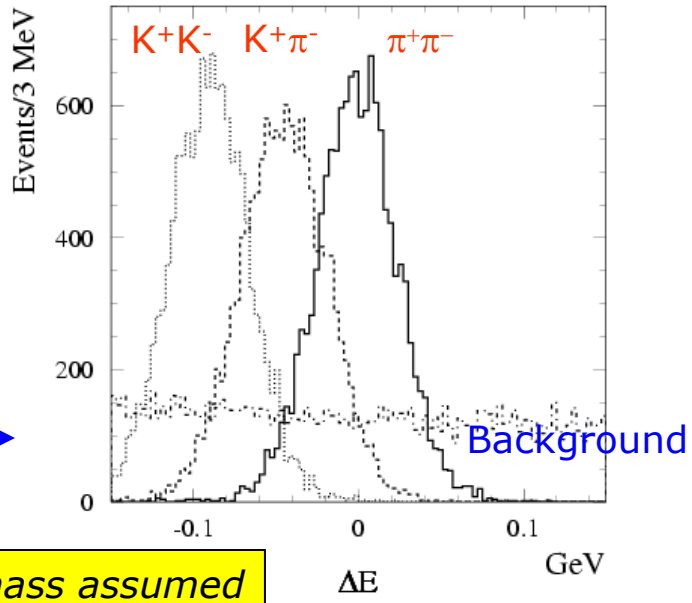


- Analysis issues
  - BR ~ 10^{-5}-10^{-6}
  - Backgrounds:
    - Large background from $e^+e^- \rightarrow q\bar{q} \rightarrow$ need background suppression
    - Backgrounds from other B decays in π^0 modes
  - Need ability to separate K-π: DIRC
- Time-dependent CP analysis issues:
  - Need to determine vertex position of both B's
  - Need to know the flavor of "other" B $\rightarrow$ B-tagging
- We use maximum likelihood (ML) fits to extract signal yields and CP-violating asymmetries
  - Kinematic and topological information to separate signal from $q\bar{q}$ background

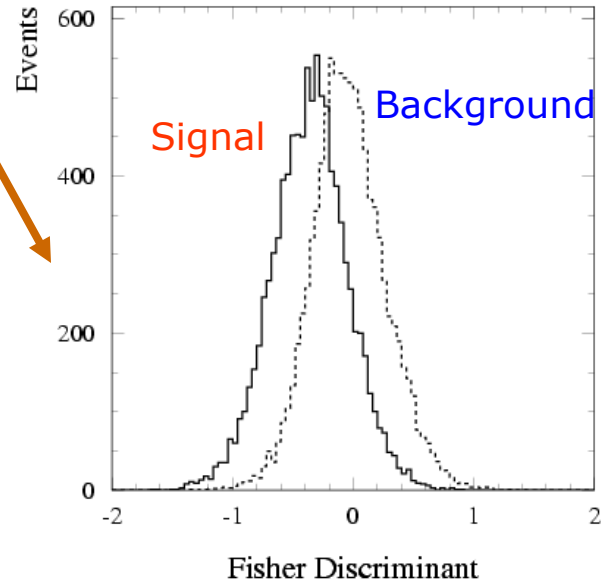
Common analysis issues: Background suppression

- The B candidate's mass
- The B candidate's energy
- A multivariate parameter that distinguishes between signal and background by event shape ("Fisher discriminant")
  - Signal isotropic, background jet-like



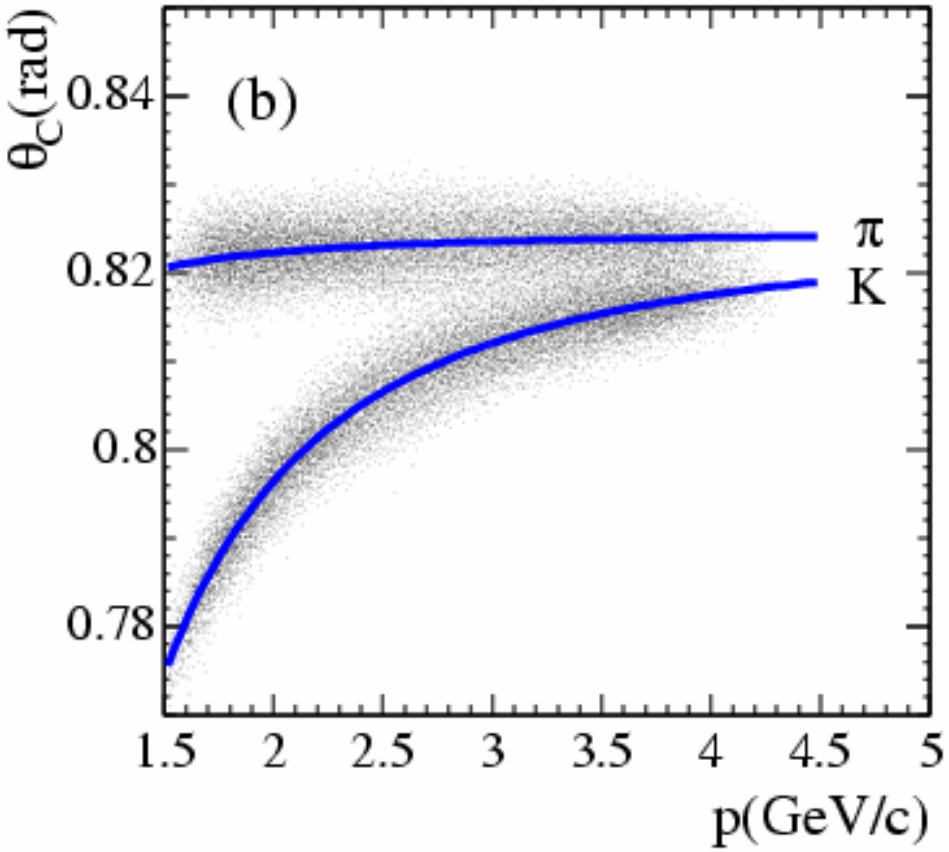


Pion mass assumed

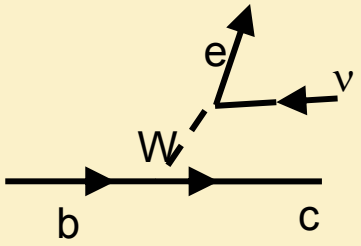


Pion/kaon discrimination

- BaBar's Detector of Internally Reflected Cerenkov light (DIRC) provides the excellent pion/kaon separation which is crucial for this analysis.



B Tagging/Vertexing



- For time-dependent analyses we must know the flavor of B_{CP} when B_{tag} decays (t=0).
- This is done by looking at the decay products of B_{tag}. For instance, leptons and kaons.
- The "mistag" rate, dilutes the measured asymmetry.

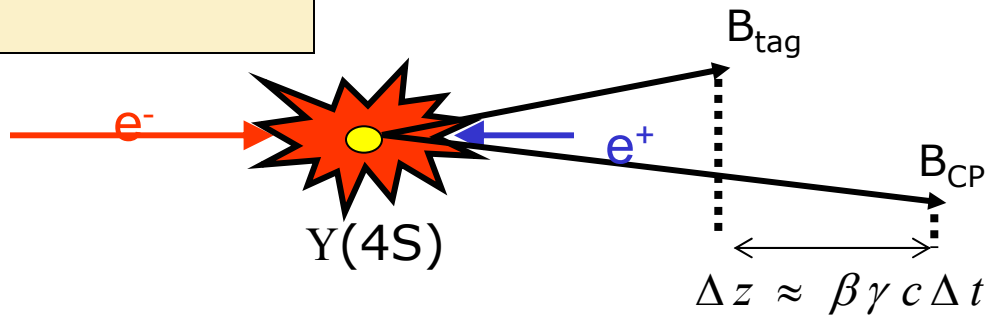
$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm \frac{\Delta D}{2} \pm \langle D \rangle S \sin(\Delta m \Delta t) \mp \langle D \rangle C \cos(\Delta m \Delta t)\right]$$

$$D \equiv 1 - 2w$$

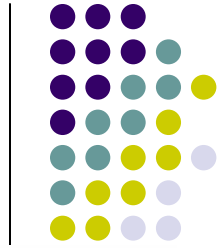
$$\Delta D \equiv D - \overline{D}$$

- Measurement of Δt requires measurement of the decay vertices.
- Resolution in Δt is dominated by the tagging side.

Determine resolution parameters and mistag rates from a large sample of fully reconstructed B events.



$B^0 \to \pi^+\pi^-$: CP Asymmetry, and first leg of the isospin triangle

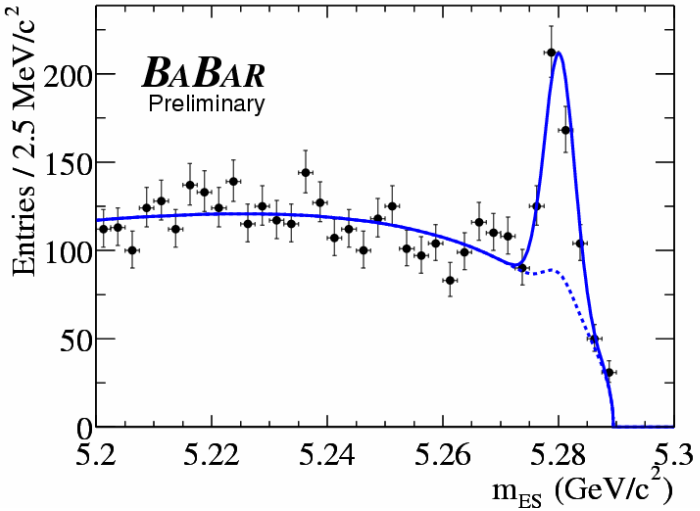


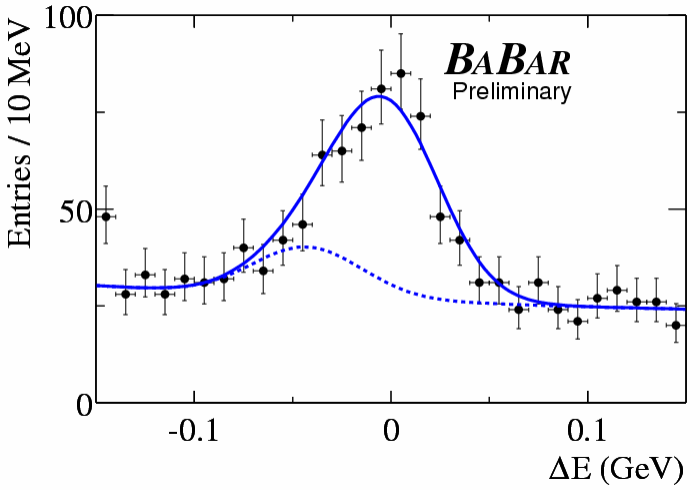
- ML fit includes
  - M_{ES}, ΔE, Fisher, θ_C, Δt, tagging
- Two sequential fits
  - Fit for yields: $\pi^+\pi^-$, $K^+\pi^-$, K^+K^-, and the asymmetry

$$A_{K\pi} \equiv \frac{N_{K^-\pi^+} - N_{K^+\pi^-}}{N_{K^-\pi^+} + N_{K^+\pi^-}}$$

  - Fit for $S_{\pi\pi}$, $C_{\pi\pi}$

$$N_{\pi\pi} = 467 \pm 33$$
$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$





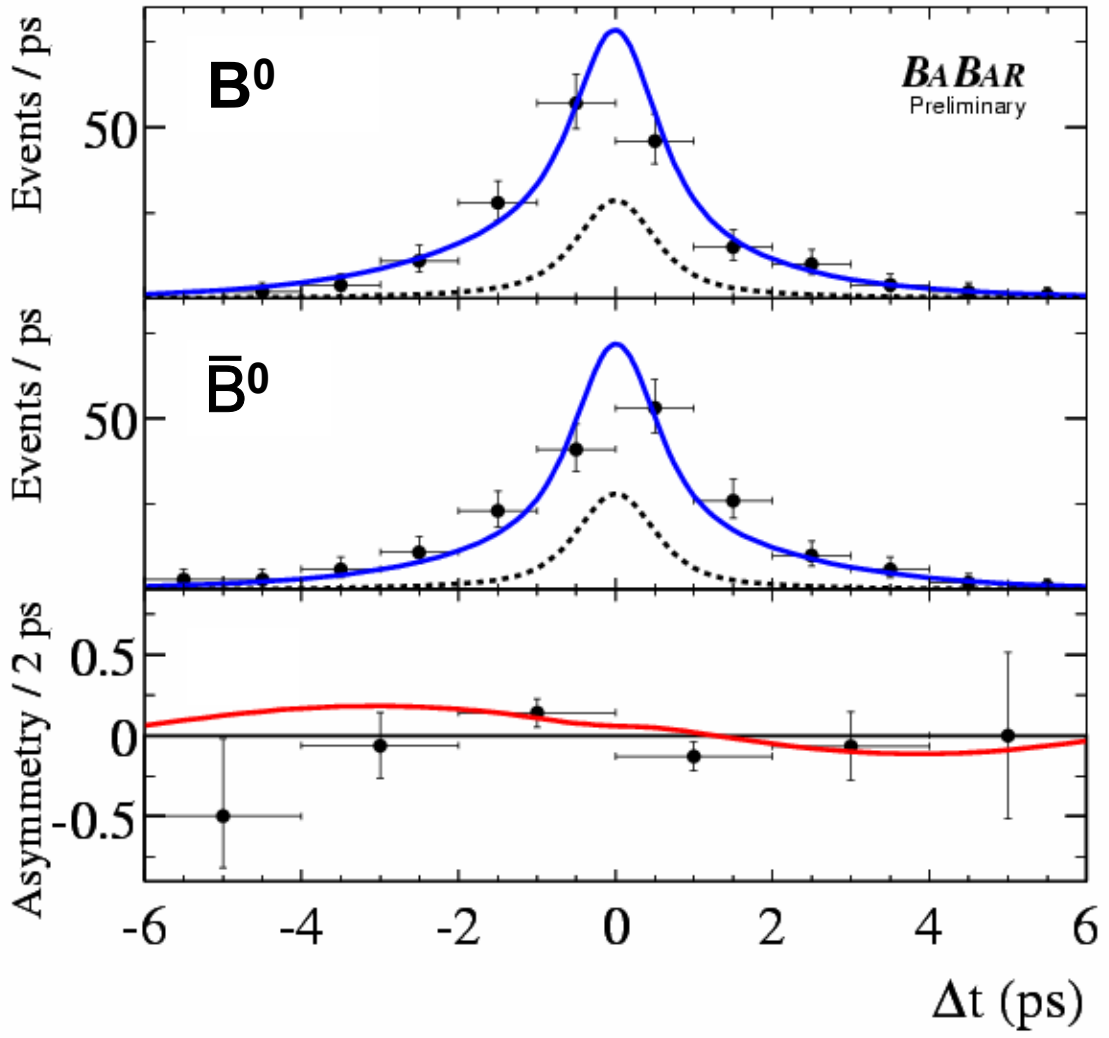
$B^0 \to \pi^+\pi^-$: CP asymmetry

$$N_{\pi\pi} = 467 \pm 33$$
$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$

Float τ and Δm_d in same sample:

$$\Delta m_d = 0.509 \pm 0.029 \text{ps}^{-1}$$
$$\tau_{B^0} = 1.62 \pm 0.05 \text{ps}$$

Consistent with PDG



$A_{K\pi}$

hep-ex/0407057

- First step of $\pi^+\pi^-$ fit involves measuring the asymmetry $A_{K\pi}$

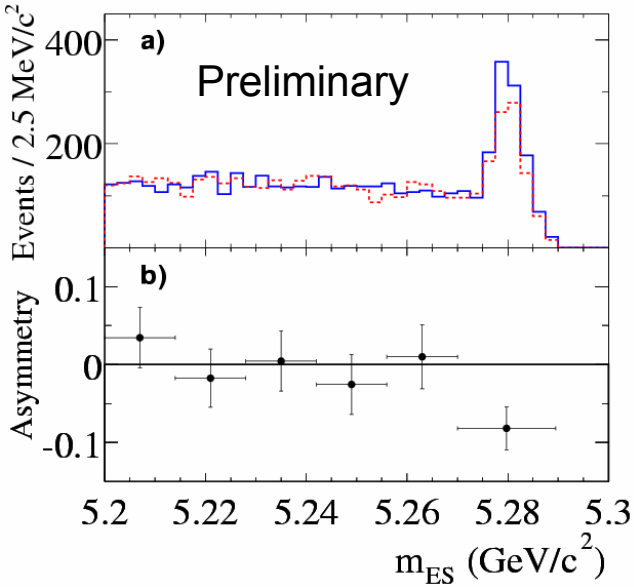
$$A_{K\pi} \equiv \frac{N_{K^-\pi^+} - N_{K^+\pi^-}}{N_{K^-\pi^+} + N_{K^+\pi^-}}$$

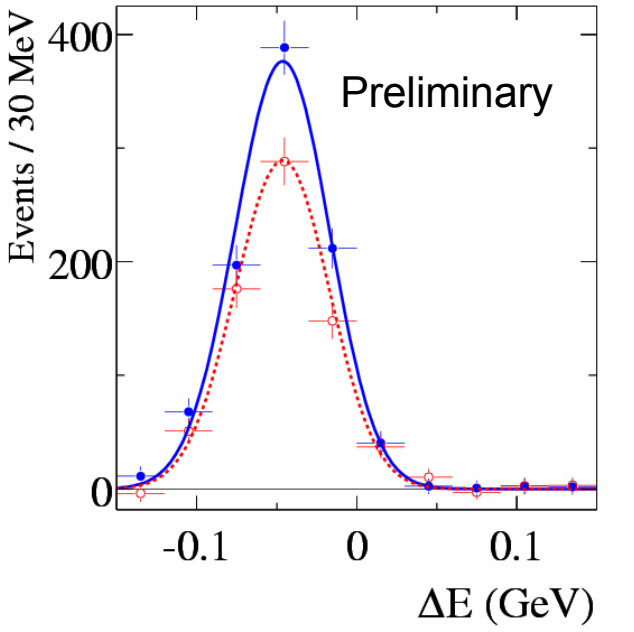
- $A_{K\pi} \neq 0 \rightarrow$ Direct CP violation

$$N_{K\pi} = 1606 \pm 51$$
$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$
$$4.2\sigma \text{ direct CP violation}$$

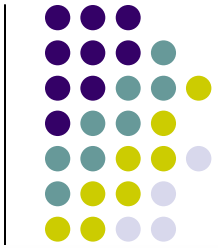
Dominant systematic comes from fitting for the asymmetry in the background. It is zero within errors

$$A^b_{K\pi} = 0.001 \pm 0.008$$

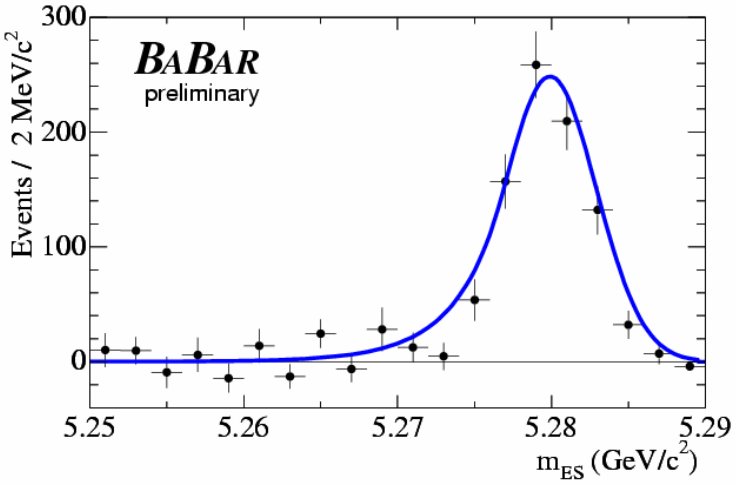




$B^+ \to \pi^+\pi^0$: Base of the isospin triangle

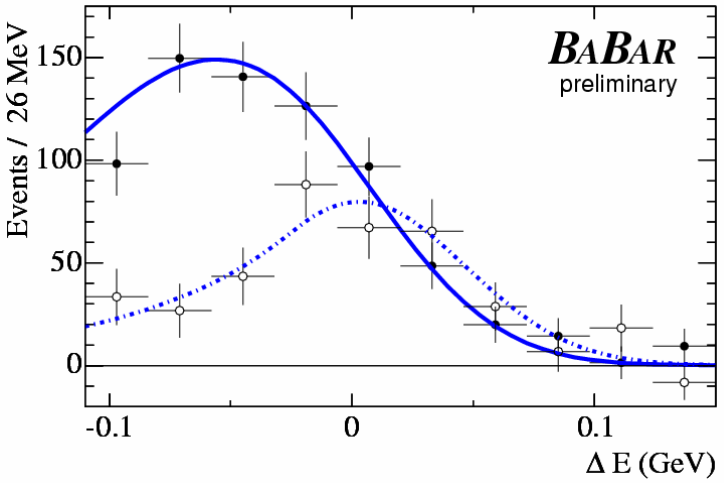


- ML fit includes
  - M_{ES}, ΔE, Fisher, θ_C
- Fit for $K^+\pi^0$ and $\pi^+\pi^0$ simultaneously
- Bkg from light $q\bar{q}$ and $\rho^+\pi^-$
- Cut on ΔE to remove $\rho\pi$

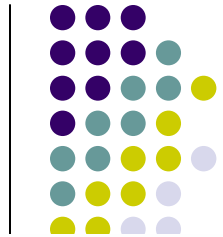


$$N_{\pi\pi^0} = 379 \pm 41$$

$$BF(B \to \pi^{\pm}\pi^0) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$$



$B^0 \to \pi^0\pi^0$: Last leg of the isospin triangle



- ML fit includes
  - M_{ES}, ΔE, Fisher, tagging
- Small signal!
- Bkg from light $q\bar{q}$ and $\rho^+\pi^0$
- Also measure time-integrated CP asymmetry

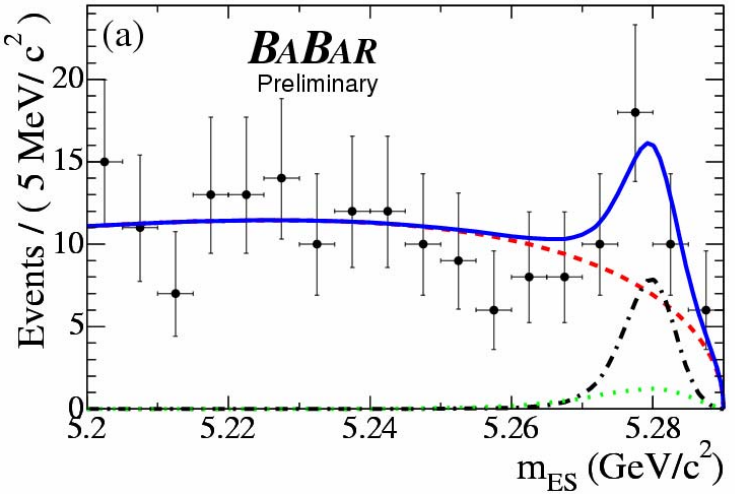
$$C_{\pi^0\pi^0} = \frac{N(B^0 \to \pi^0\pi^0) - N(\overline{B}^0 \to \pi^0\pi^0)}{N(B^0 \to \pi^0\pi^0) + N(\overline{B}^0 \to \pi^0\pi^0)}$$

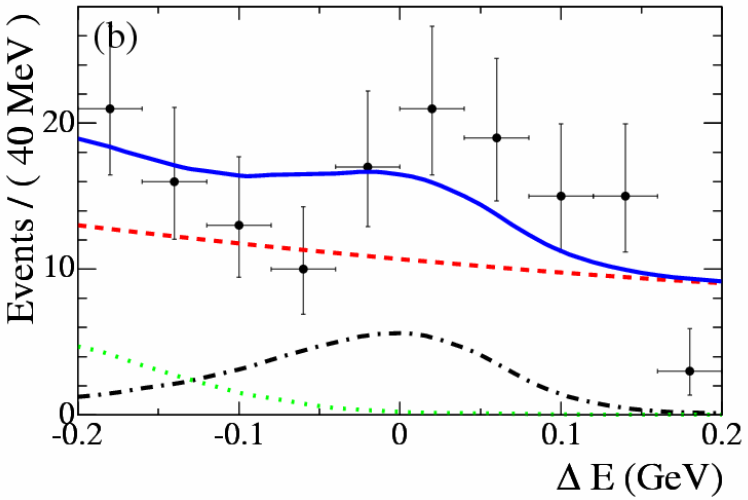
$$N_{\pi^0\pi^0} = 61 \pm 17 \pm 5$$

4.9σ significance

$$BF(B \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$

$$C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$$

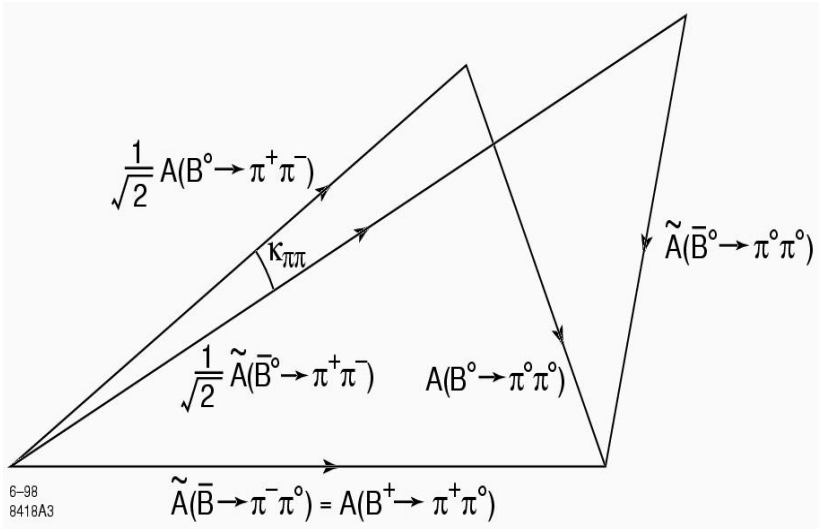


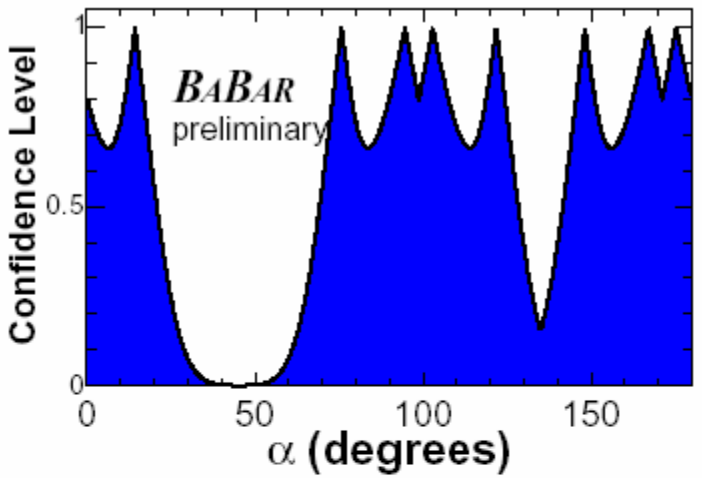


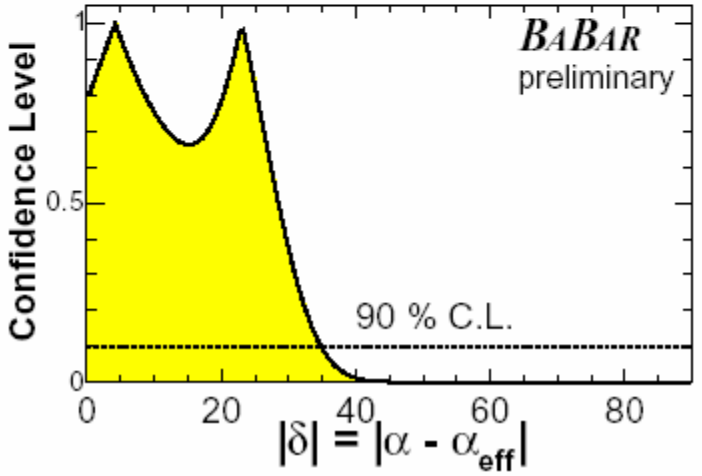
Putting it all together

- Use the recipe of Gronau and London, *Phys. Rev. Lett.* 65, 3381 (1990)
- Use BF for $B \to \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$
- Use CP asymmetries $C_{\pi\pi}$ and $C_{\pi^0\pi^0}$

$$|\alpha - \alpha_{eff}| < 35^\circ \ (90\%\ \text{C.L.})$$







Summary

- 205 fb^{-1} of data
- Improved measurements of $S_{\pi\pi}$ and $C_{\pi\pi}$
- Observation of direct CP violation in $B^0 \to K^+\pi^-$ decays
- BF measurements for $B \to \pi^0\pi^0$, $\pi^+\pi^0$
- Constraint on the shift on α due to the presence of penguins

$$N_{\pi\pi} = 467 \pm 33$$
$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$C_{\pi\pi} = -0.09 \pm 0.15 \pm 0.04$$

$$N_{K\pi} = 1606 \pm 51$$
$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$
$$4.2\sigma \text{ direct CP violation}$$

$$N_{\pi^\pm\pi^0} = 379 \pm 41$$
$$BF(B \to \pi^\pm\pi^0) = (5.8 \pm 0.6 \pm 0.4) \times 10^{-6}$$

$$N_{\pi^0\pi^0} = 61 \pm 17 \pm 5$$
$$4.9\sigma \text{ significance}$$
$$BF(B \to \pi^0\pi^0) = (1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$$
$$C_{\pi^0\pi^0} = -0.12 \pm 0.56 \pm 0.06$$

$$|\alpha - \alpha_{eff}| < 35^\circ \text{ (90\% C.L.)}$$