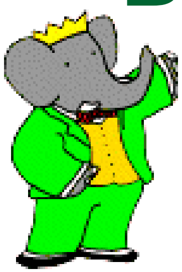
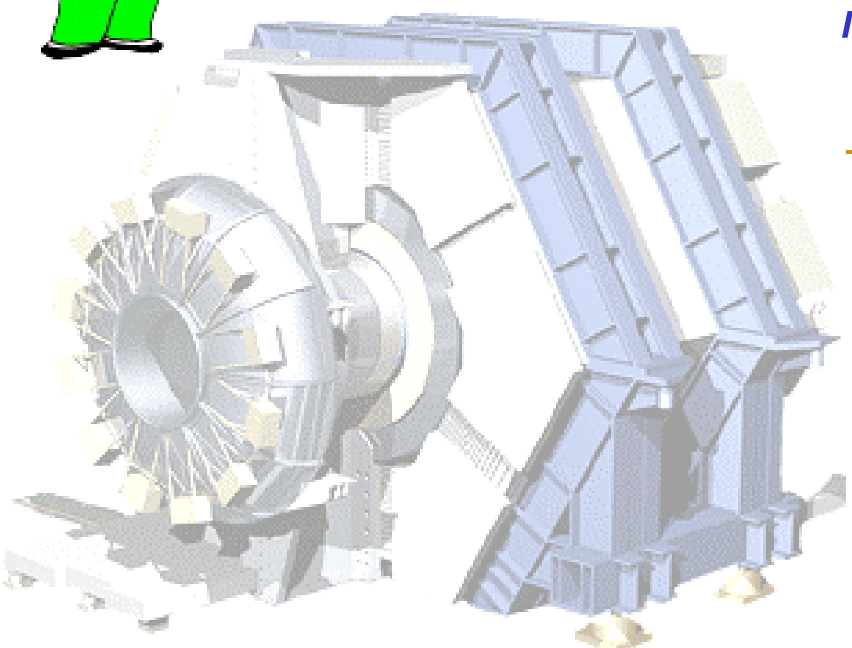
CP-Violating Asymmetries in Charmless B Decays: Towards a measurement of α



On behalf of the BaBar Collaboration



International Conference on High Energy Physics
Amsterdam, July 24-31, 2002

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CP asymmetries in $\pi^+\pi^-$ and $K^+\pi^-$
Submitted to Phys Rev (hep-ex/0207055)

Decay rates for $\pi^+\pi^0$ and $\pi^0\pi^0$
hep-ex/0207065 and hep-ex/0207063

CP asymmetries in $\rho^+\pi^-$ and ρ^+K^-
hep-ex/0207068

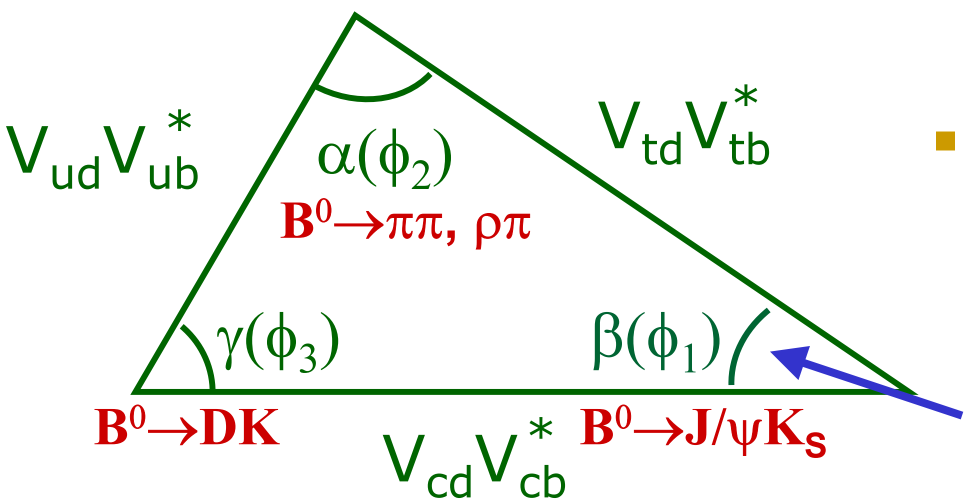
CP Violation in the Standard Model

- CP symmetry can be violated in any field theory with at least one irremovable complex phase in the Lagrangian
- This condition is satisfied in the Standard Model through the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix

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

Unitarity Triangle

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



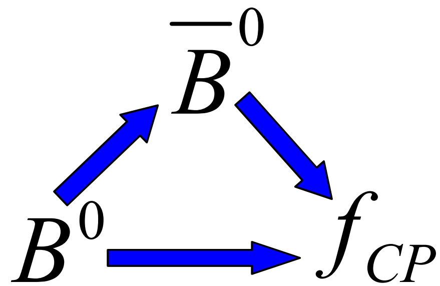
- The angles (α,β,γ) are related to CP-violating asymmetries in specific B decays
  - One down, two to go…

$$\sin 2\beta_{\rm BaBar} = 0.741 \pm 0.067 \pm 0.033$$

ICHEP 2002

Observing CP violation at the $\Upsilon(4S)$

- At the $\Upsilon(4S)$, $B\bar{B}$ pairs are produced in a coherent P-wave
- Three observable interference effects:
  - CP violation in mixing ($|q/p| \neq 1$)
  - (direct) CP violation in decay ($|\bar{A}/A| \neq 1$)
  - (indirect) CP violation in mixing and decay ($\mathrm{Im}\lambda \neq 0$)



$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

Observable in time evolution of $B^0\bar{B}^0$ system (assume $\Delta\Gamma=0$)

$$f(\overline{B}^0_{phys} \to f_{CP}, \Delta t) = \tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 + S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)\right]$$

$$f(B^0_{phys} \to f_{CP}, \Delta t) = \tfrac{\Gamma}{4} e^{-\Gamma|\Delta t|}\left[1 - S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)\right]$$

direct CP violation $\rightarrow$ C ≠ 0

indirect CP violation $\rightarrow$ S ≠ 0

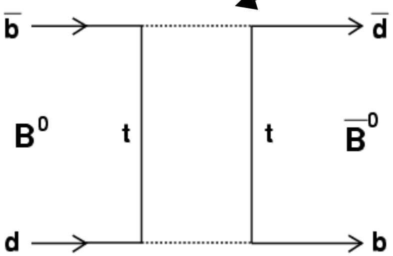
$$S_f = \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2} \qquad C_f = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$

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

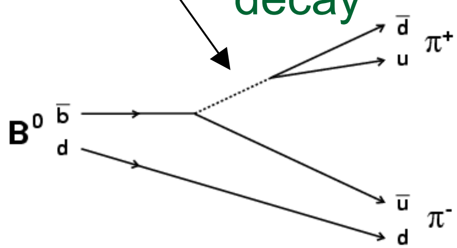
Tree (T) Level:

$$\lambda_{\pi\pi} = \underbrace{\frac{V_{tb}^{*}V_{td}}{V_{tb}V_{td}^{*}}}_{\text{mixing}}\;\underbrace{\frac{V_{ud}^{*}V_{ub}}{V_{ud}V_{ub}^{*}}}_{\text{decay}}$$

mixing



decay

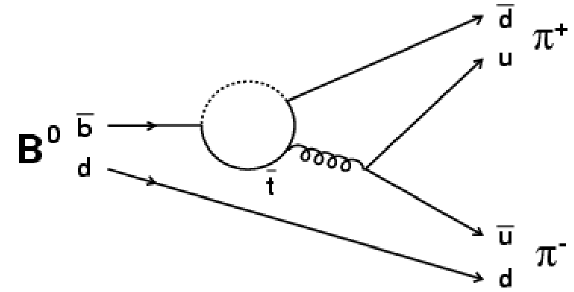


$$\lambda_{\pi\pi} = e^{2i\alpha}$$

$$C_{\pi\pi} = 0$$

$$S_{\pi\pi} = \sin(2\alpha)$$

With Penguins (P):



$$\lambda_{\pi\pi} = e^{2i\alpha}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$

$$C_{\pi\pi} \propto \sin(\delta)$$

$$S_{\pi\pi} = \sqrt{1-C_{\pi\pi}^2}\,\sin(2\alpha_{\text{eff}})$$

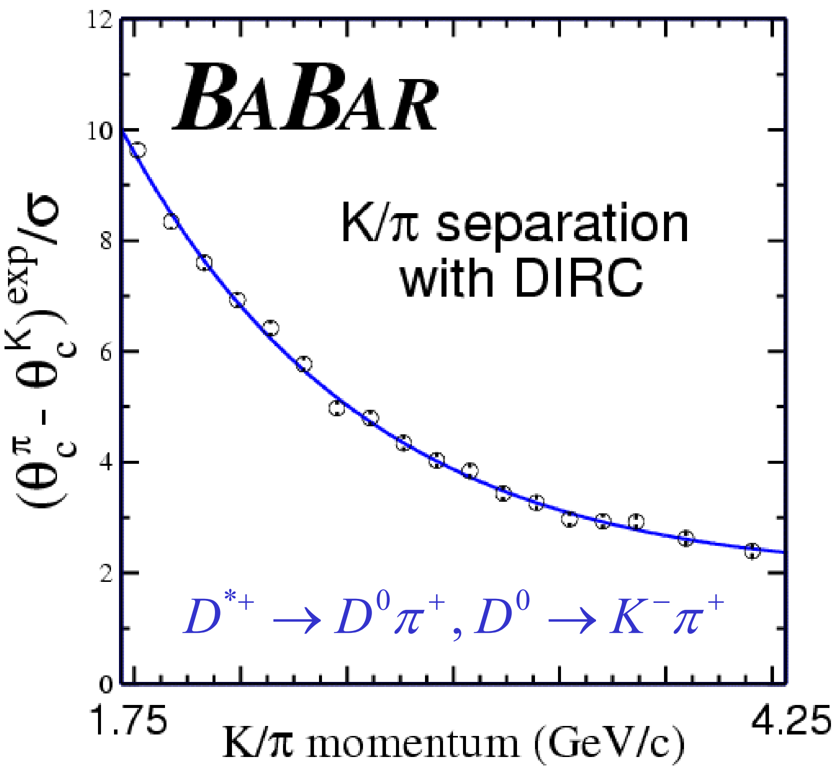
Need branching fractions for $\pi^+\pi^-$, $\pi^\pm\pi^0$, and $\pi^0\pi^0$ to get α from $\alpha_{\text{eff}} \rightarrow$ isospin analysis

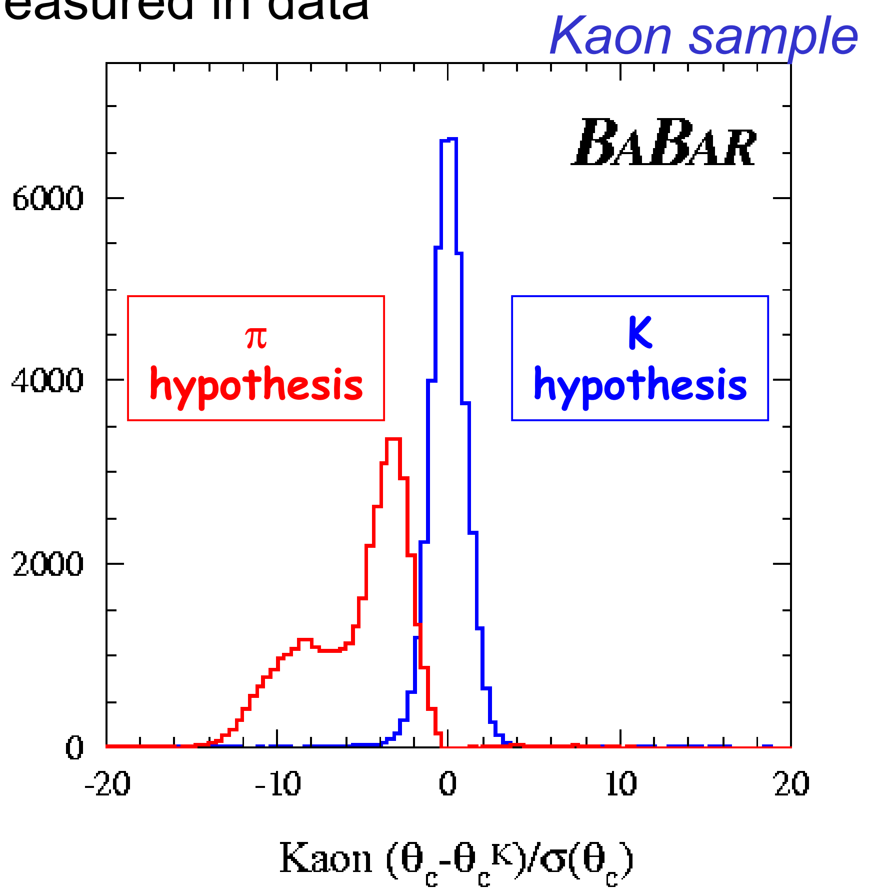
Overview of Analyses

- Analysis issues: charmless B decays
  - Rare decays! BR ~ 10^{-5}-10^{-6} → need lots of data (PEP-II)
  - Backgrounds:
    - Large background from $e^+e^- \to q\bar{q}$ → need background suppression
    - Modes with π^0 suffer backgrounds from other B decays
  - Ambiguity between π and K → need excellent particle ID (DIRC)
- Time-dependent CP analysis issues:
  - Need to determine vertex position of both B mesons → silicon
  - Need to know the flavor of "other" B → particle ID
- We use maximum likelihood (ML) fits to extract signal yields and CP-violating asymmetries
  - Kinematic and topological information to separate signal from light-quark background
  - Particle ID to separate pions and kaons
- The data sample corresponds to 87.9 million $B\bar{B}$ pairs

K/π Separation with the DIRC

- Cherenkov angle θ_c used in the maximum likelihood fit to distinguish pions and kaons
- Resolution and K-π separation measured in data





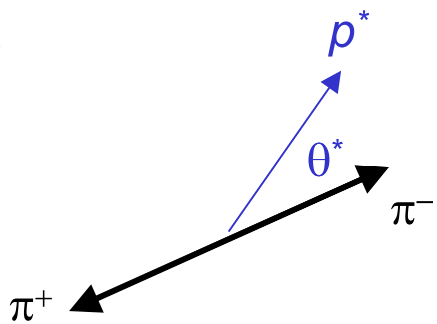
Analysis of $B \to \pi\pi$, $K\pi$, KK

- Analysis proceeds in two steps:
  - Time-independent fit for yields and $K\pi$ charge asymmetry
  - Time-dependent fit for $S_{\pi\pi}$, and $C_{\pi\pi}$
- Kinematically select B candidates with m_{ES}, ΔE

$$m_{\mathrm{ES}} = \sqrt{E_{\mathrm{beam}}^{*2} - p_B^{*2}} \qquad \Delta E = E_B^* - E_{\mathrm{beam}}^*$$

- Suppress $q\bar{q}$ background with Fisher discriminant

$$F = 0.53 - 0.60 \times \sum_i p_i^* + 1.27 \times \sum_i p_i^* \left|\cos(\theta_i^*)\right|^2$$



- Fit yields and charge asymmetry

$$A_{CP}^{K\pi} \equiv \frac{N(K^-\pi^+) - N(K^+\pi^-)}{N(K^-\pi^+) + N(K^+\pi^-)}$$

Branching Fraction Results

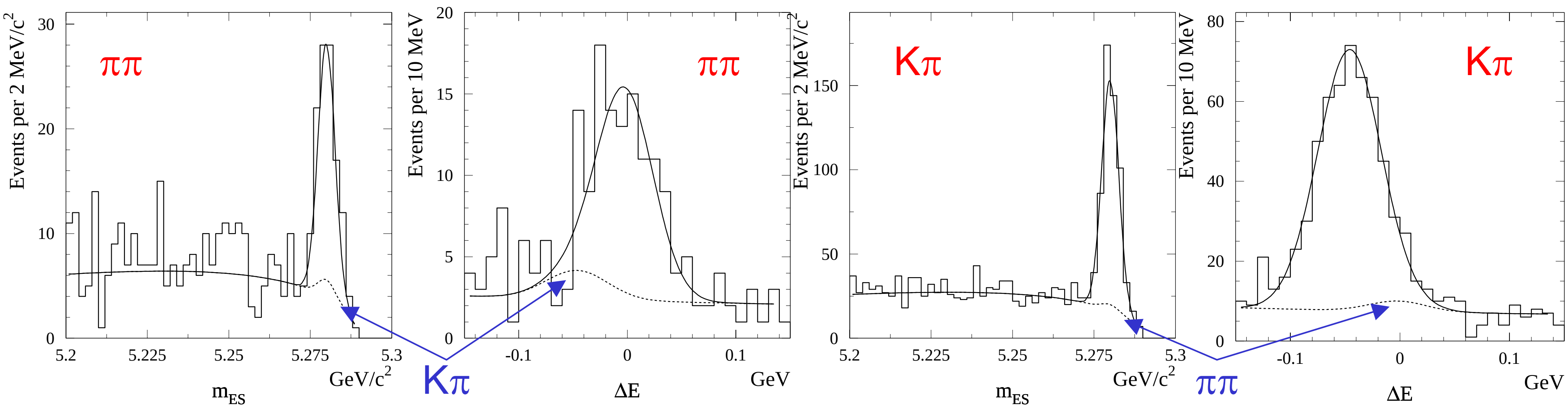
Submitted to Phys Rev (hep-ex/0207055)

87.9±1.1 million $B\bar{B}$

Mode	Yield	BR (10^{-6})	$A_{CP}(K\pi)$
$B^0 \rightarrow \pi^+\pi^-$	157 ± 19	$4.7 \pm 0.6 \pm 0.2$	
	589 ± 30	$17.9 \pm 0.9 \pm 0.7$	$-0.102 \pm 0.050 \pm 0.016$
$B^0 \rightarrow K^+K^-$	1 ± 8	< 0.6 (90% CL)	

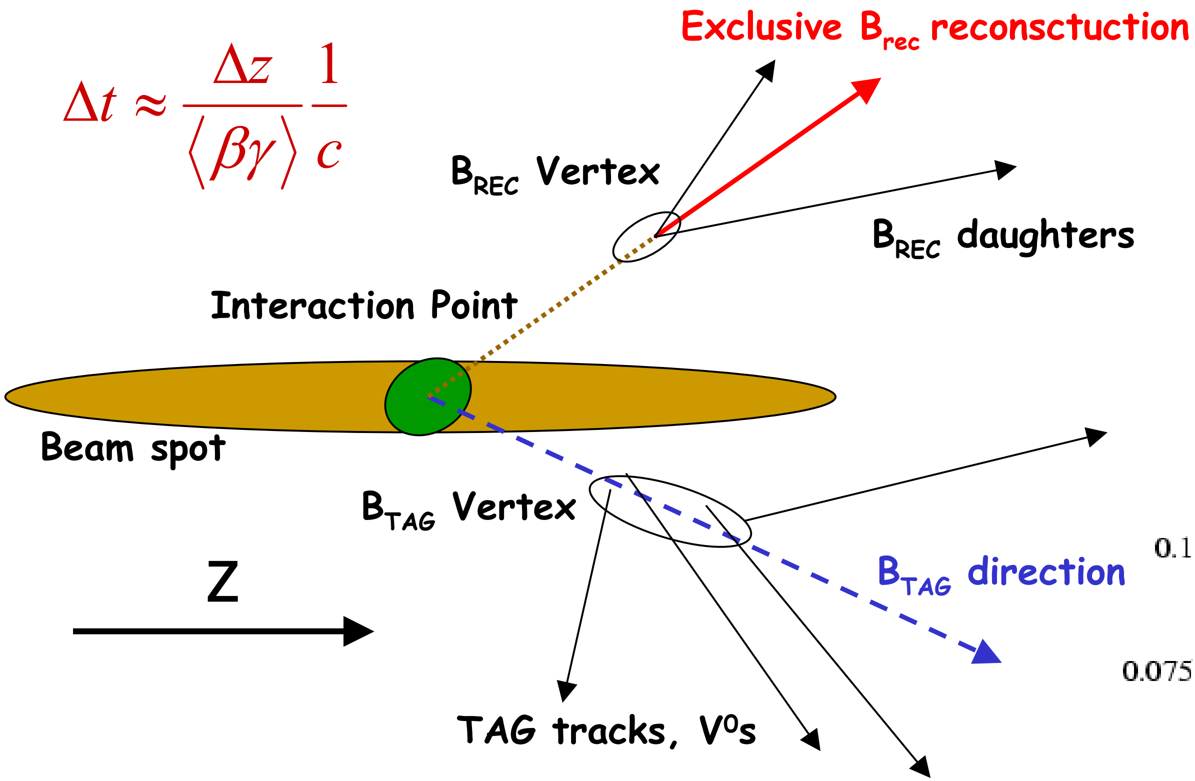
Preliminary

Projections in m_{ES} and ΔE



Vertex Reconstruction

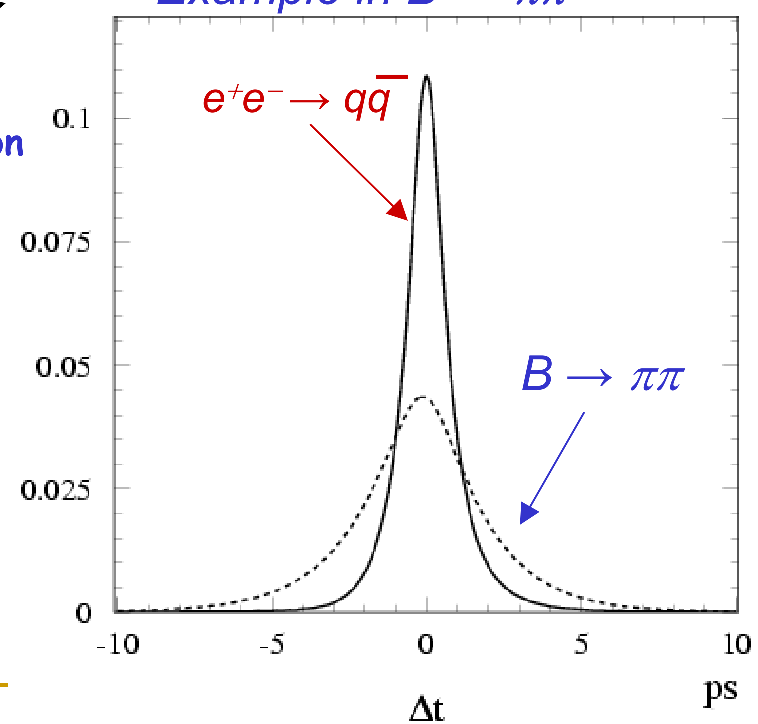
$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle} \frac{1}{c}$$



Δz resolution dominated by tag side → same resolution function as charmonium ($\sin 2\beta$) sample

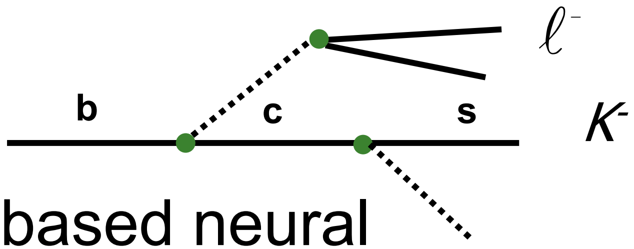
Average Δz resolution ~ 180μm

Example in $B \to \pi\pi$



- Resolution function parameters obtained from data for both signal and background
  - Signal from sample of fully reconstructed B decays to flavor eigenstates: $D^*(\pi, \rho, a_1)$
  - Background from data sidebands

B Flavor Tagging



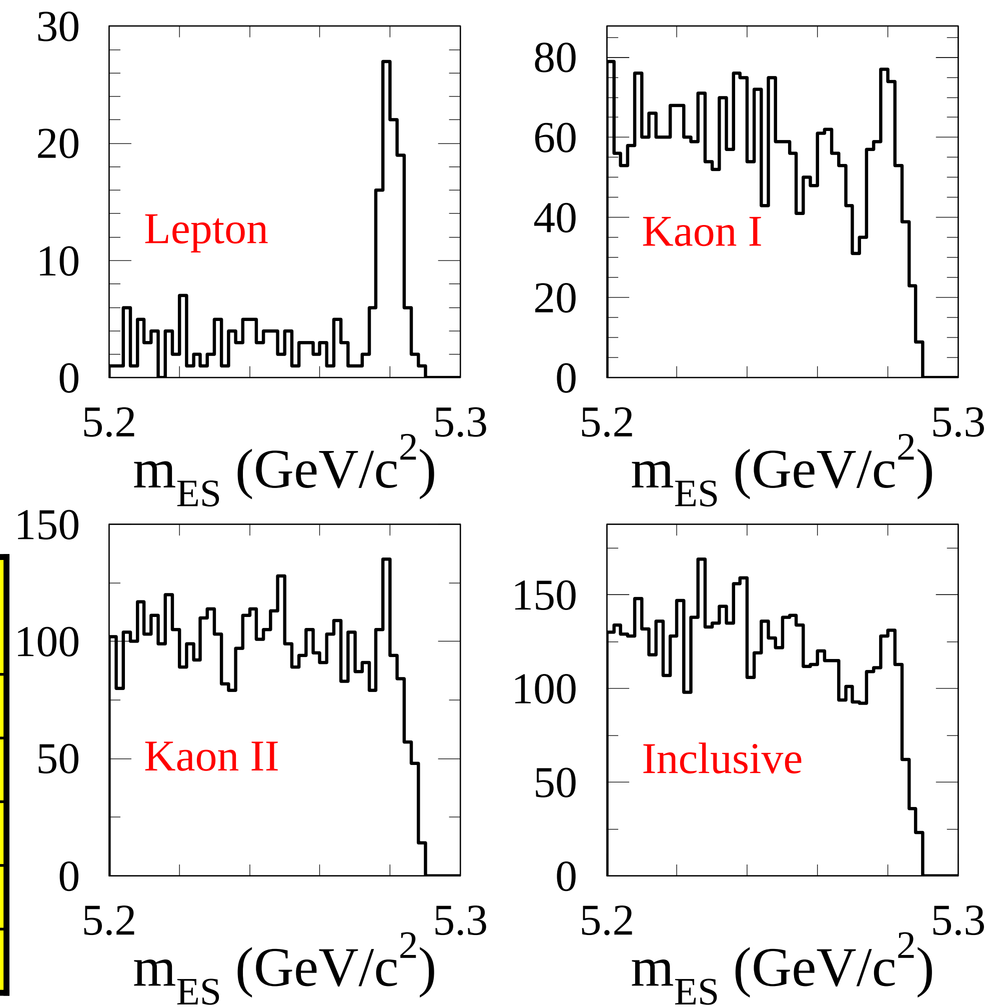
- New tagging algorithm with physics-based neural networks
  - Inputs include leptons, kaons, slow-π (from D*), and high-momentum tracks
  - Outputs combined and categorized by mistag prob (w)
- 5 mutually exclusive categories:
  - Lepton – isolated high-momentum leptons
  - Kaon I – high quality kaons or correlated K^- and slow-π^+
  - Kaon II – lower quality kaons, or slow-π
  - Inclusive – unidentified leptons, poor-quality kaons, high-momentum tracks
  - Untagged – no flavor information is used

~7% improvement in $Q = \varepsilon(1-2w)^2$

Tagging in Charmless B Decays

- Tagging efficiency is very different for signal and bkg
  - Strong bkg suppression in categories with the lowest mistag prob (Lepton/Kaon)
  - Different bkg tagging efficiencies for ππ, Kπ, KK

81/fb B→ h^+h^- sample split by tagging category



Tagging Efficiencies (%)

Category	Signal	Background ππ	Background Kπ	Background KK
Lepton	9.1	0.5	0.4	0.6
Kaon I	16.6	8.9	12.7	7.8
Kaon II	19.8	15.5	19.4	14.4
Inclusive	20.1	21.5	19.2	21.7
Untagged	34.4	53.6	48.3	55.6

Validation of Tagging, Vertexing, and ML Fit

- $K\pi$ decays are self-tagging
  - T = tag charge
  - Q = kaon charge

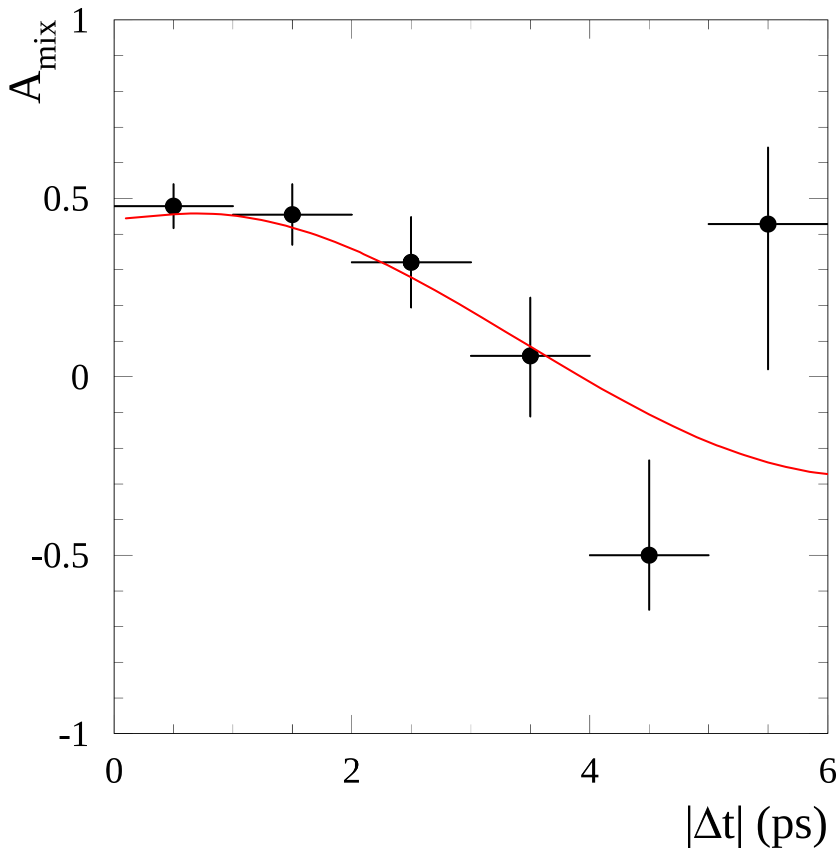
$$f_{T,Q}^{K\pi}(\Delta t) \approx \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 - TQ(1-2w)\cos(\Delta m_d \Delta t)\right]$$

- Float τ and Δm_d in same sample used to extract CP asymmetries:

$$\tau = (1.56 \pm 0.07)\text{ps}$$

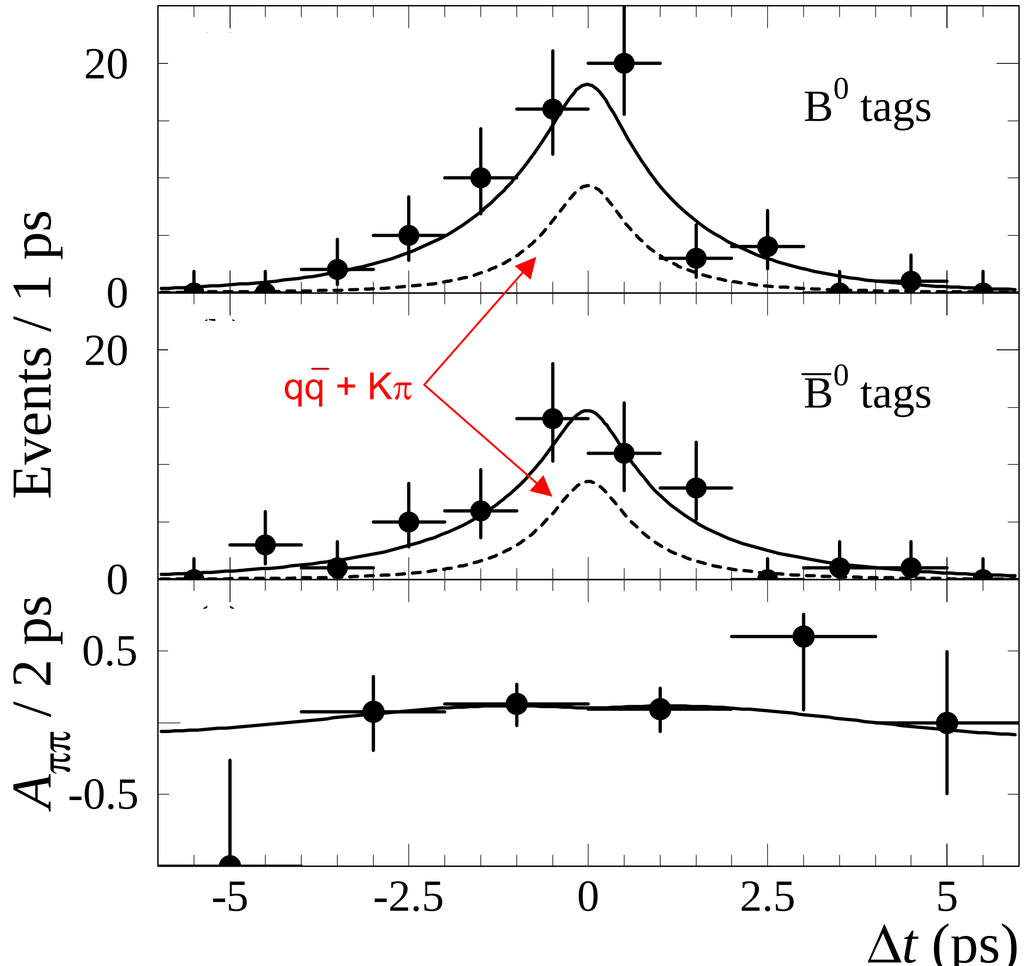
$$\Delta m_d = (0.52 \pm 0.05)\text{ps}^{-1}$$

Fit projection in sample of $K\pi$-selected events



CP Asymmetry Results

Fit projection in sample of $\pi\pi$-selected events



Preliminary

$$S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05$$

$$C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04$$

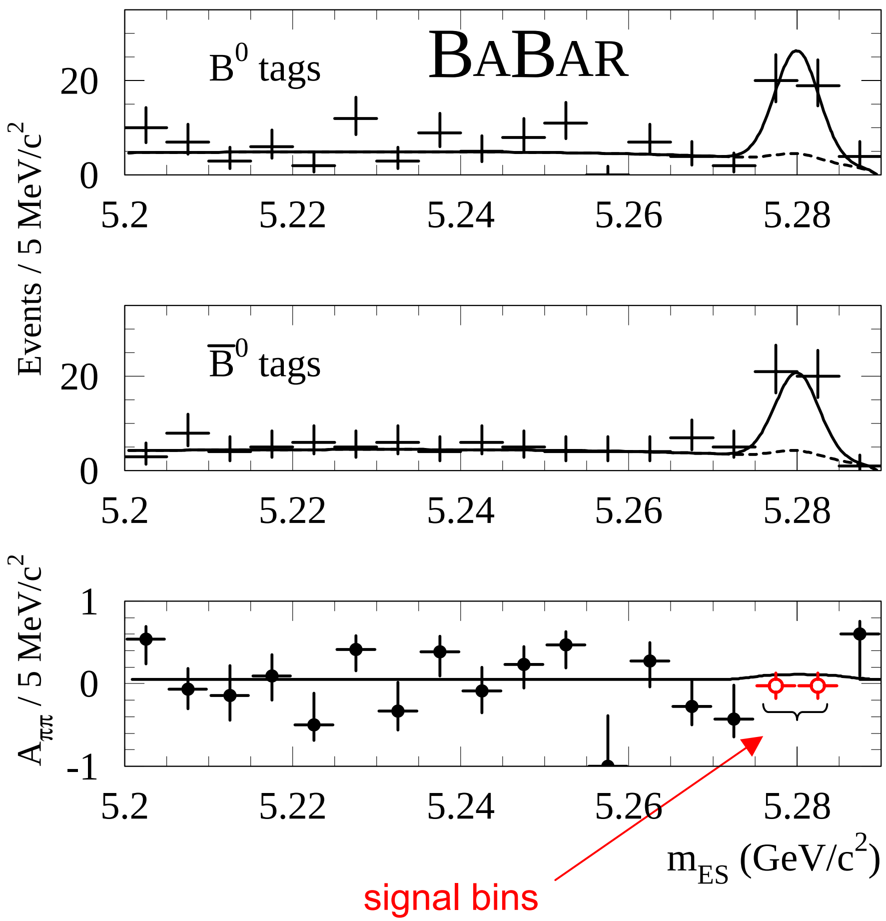
Submitted to Phys Rev (hep-ex/0207055)

$$A_{\pi\pi}(\Delta t) \equiv \frac{N\left(B^0_{tag}\right) - N\left(\overline{B}^0_{tag}\right)}{N\left(B^0_{tag}\right) + N\left(\overline{B}^0_{tag}\right)} = S_{\pi\pi}\sin(\Delta m_d \Delta t) - C_{\pi\pi}\cos(\Delta m_d \Delta t)$$

Cross-checks

- Inspect $\pi\pi$-selected sample
  - 2-param fit consistent with full fit
  - asymmetry vs. m_{ES}
    - Asymmetry in yields consistent with measured value of $C_{\pi\pi}$, but does not suggest large direct CP violation
- Toy MC generated over all allowed values of $S_{\pi\pi}$ and $C_{\pi\pi}$
  - Expected errors consistent with data
  - No significant bias observed
- Validated in large samples of signal and background MC events
- Systematic errors dominated by uncertainty in PDF shapes

$A_{\pi\pi}$ vs. m_{ES} in sample of $\pi\pi$-selected events



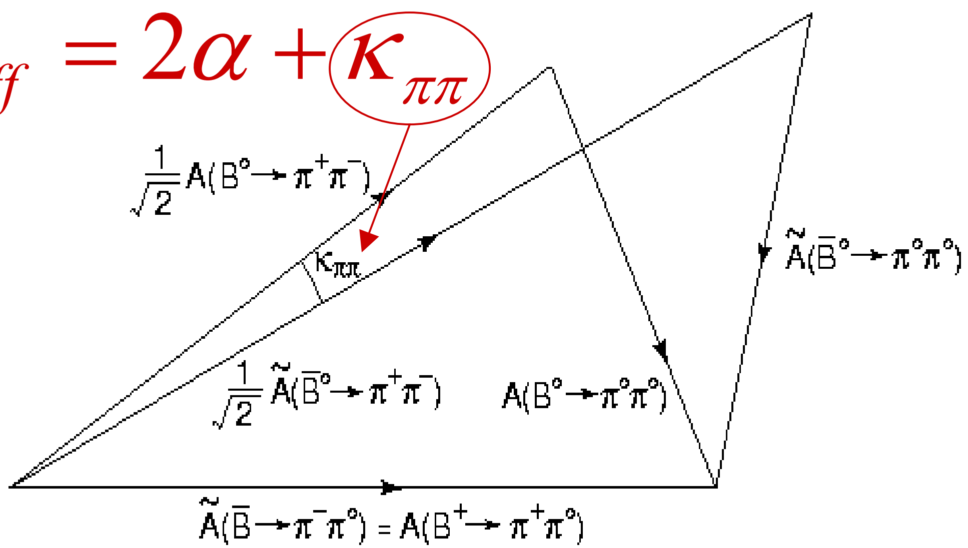
Taming the Penguins: Isospin Analysis

Gronau and London, Phys. Rev. Lett. 65, 3381 (1991)

- The decays $B\to \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ are related by isospin
- Central observation is that $\pi\pi$ states can have I = 2 or 0
  - (gluonic) penguins only contribute to I = 0 (ΔI = 1/2)
  - $\pi^+\pi^0$ is pure I = 2 (ΔI = 1/2) so has only tree amplitude

  $\to$ ($|A^{+0}| = |A^{-0}|$)
- Triangle relations allow determination of penguin-induced shift in α

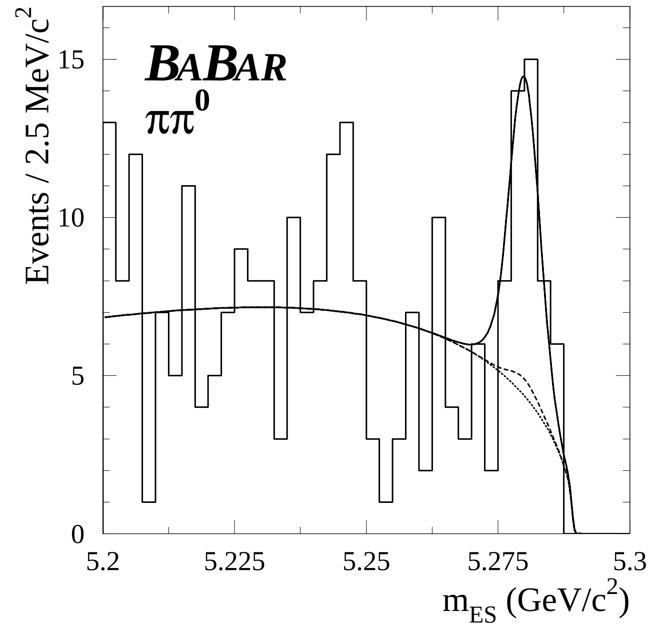
$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$

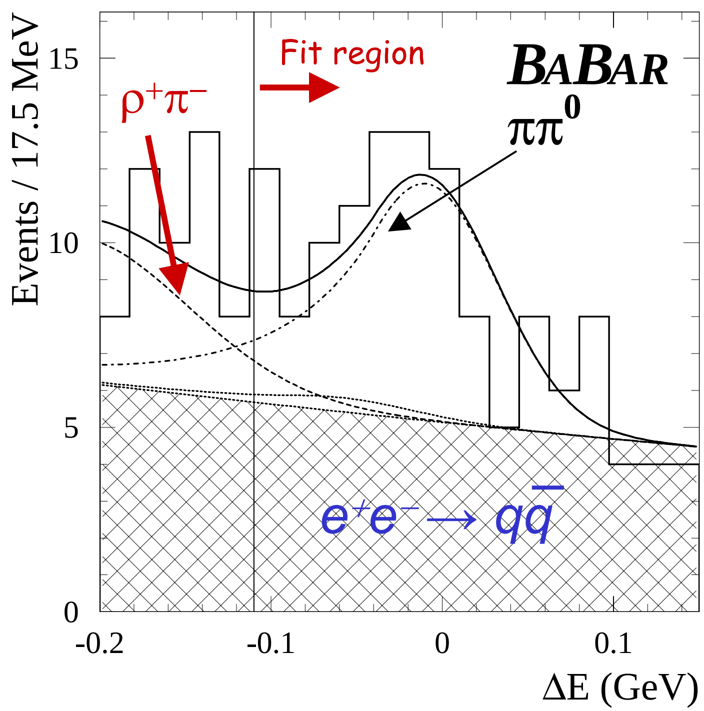


But, need branching fractions for all three decay modes, and for B^0 and $\overline{B^0}$ separately

The Base of the Isospin Triangle: $B^+ \to \pi^+\pi^0$

- Analysis issues:
  - Usual charmless two-body; large $q\bar{q}$ background, π/K separation
  - Potential feeddown from $\rho^+\pi^-$
    - Minimize with tight cut on ΔE





Simultaneous fit to ππ⁰/Kπ⁰

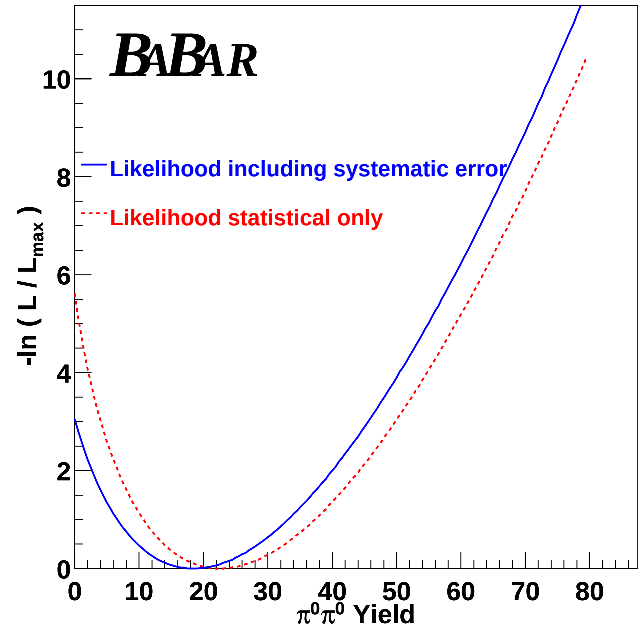
Mode	Yield	BR (10^{-6})	A_{CP}
$B^+ \to \pi^+\pi^0$	125^{+23}_{-21}	$5.5^{+1.0}_{-0.9} \pm 0.6$	$-0.03^{+0.18}_{-0.17} \pm 0.02$
$B^+ \to K^+\pi^0$	239^{+21}_{-22}	$12.8^{+1.2}_{-1.1} \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$

Preliminary

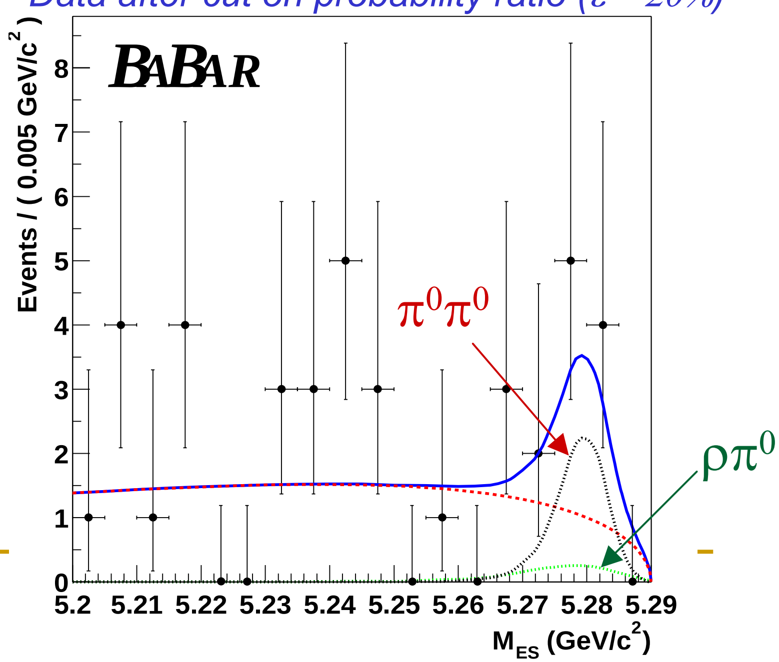
hep-ex/0207065

Next Side Please: $B^0 \rightarrow \pi^0\pi^0$

- Analysis issues:
  - Small signal!
  - $\rho\pi^0$ feeddown
- Background suppression:
  - Event shape and flavor tagging to reduce $q\bar{q}$
  - Cut on $M(\pi^+\pi^0)$ and ΔE to reduce $\rho\pi^0$ background, then fix in the fit



Data after cut on probability ratio ($\varepsilon \sim 20\%$)



hep-ex/0207063

$$N_{\pi^0\pi^0} = 23^{+10}_{-9}$$

Preliminary

$$B(B^0 \rightarrow \pi^0\pi^0) < 3.6\times10^{-6} \text{ @ } 90\% \text{ C.L.}$$

Significance including systematic errors = 2.5σ

Setting a Bound on Penguin Pollution

- Can still get information on α with only an upper bound on $\pi^0\pi^0$:
  - For example: Grossman-Quinn bound (assume only isospin)

$$\sin^2(\alpha_{\text{eff}} - \alpha) < \frac{\frac{1}{2}\left[BR(B^0 \to \pi^0\pi^0) + BR(\overline{B}^0 \to \pi^0\pi^0)\right]}{BR(B^\pm \to \pi^\pm\pi^0)}$$

$$< 0.61 @ 90\% \text{ C.L.}$$

Correlations and systematic errors included

$$|\alpha_{\text{eff}} - \alpha| < 51^\circ @ 90\% \text{ C.L.}$$

- Many other bounds on the market
  - Charles, Gronau/London/Sinha/Sinha, etc…

CP-Violating Asymmetries in $B^0 \rightarrow \rho^+\pi^-, \rho^+K^-$

R. Aleksan et al., Nucl. Phys. B361, 141 (1991)

- Opportunity and challenges
  - In principle, can measure α directly, even with penguins
  - Much more difficult than $\pi^+\pi^-$
    - Three-body topology with neutral pion (combinatorics, lower efficiency)
    - Significant fraction of misreconstructed signal events and backgrounds from other B decays
    - Need much larger sample than currently available to extract α cleanly
- We perform a "quasi-two-body" analysis:
  - Select the ρ-dominated region of the $\pi^+\pi^-\pi^0$/$K^+\pi^-\pi^0$ Dalitz plane
  - Use multivariate techniques to suppress $q\bar{q}$ backgrounds
  - Simultaneous fit for $\rho^+\pi^-$ and ρ^+K^-

Not a CP eigenstate, (at least) four amplitudes contribute:

Time-integrated asymmetry:

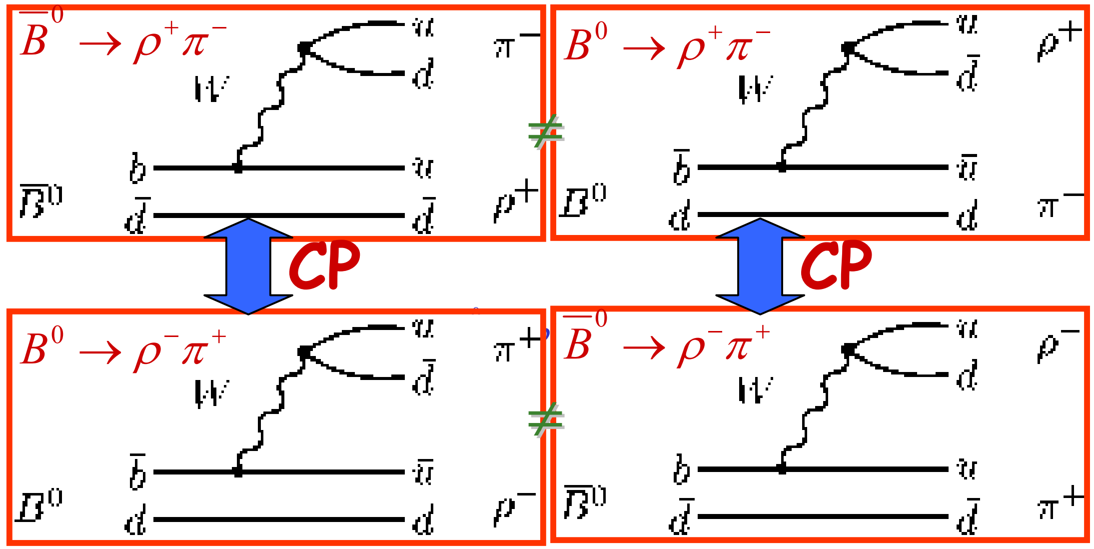
$$A_{CP}^{\rho h} = \frac{N(\rho^+ h^-) - N(\rho^- h^+)}{N(\rho^+ h^-) + N(\rho^- h^+)}$$

Time evolution includes:

$$(S_{\rho h} + Q\Delta S_{\rho h})\sin(\Delta m_d \Delta t)$$

$$(C_{\rho h} + Q\Delta C_{\rho h})\cos(\Delta m_d \Delta t)$$

Q is the ρ charge



direct CP violation → A_{CP} and C ≠ 0

indirect CP violation → S ≠ 0

ΔC and ΔS are insensitive to CP violation

ρK is self-tagging:

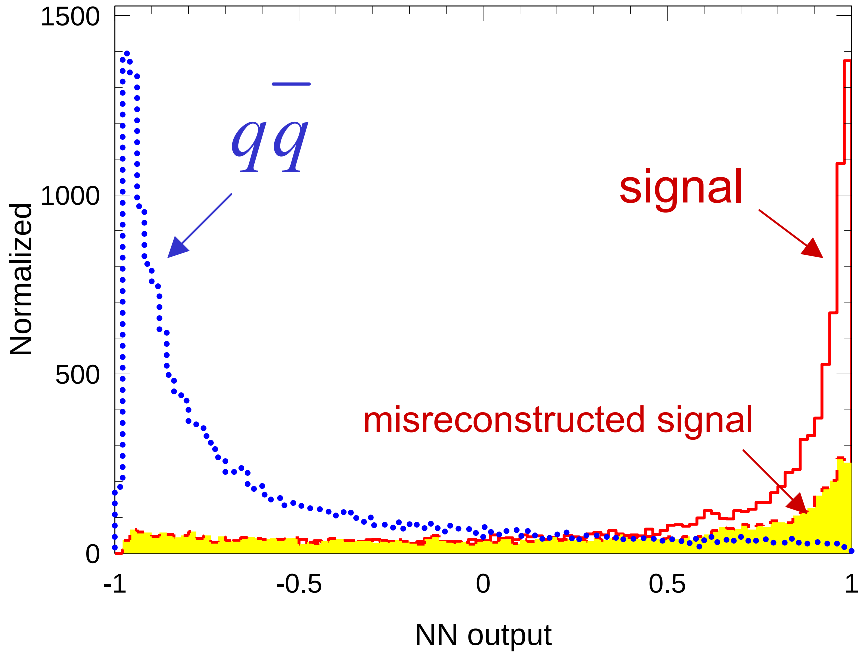
$$C_{\rho K} = 0, \Delta C_{\rho K} = -1, S_{\rho K} = 0, \Delta S_{\rho K} = 0$$

Fit for:

$$A_{CP}^{\rho\pi}, A_{CP}^{\rho K}, C_{\rho\pi}, \Delta C_{\rho\pi}, S_{\rho\pi}, \Delta S_{\rho\pi}$$

Analysis

- Multi-dimensional ML fit
  - m_{ES}, ΔE, Neural Net (NN), θ_c, Δt
- Components
  - Signal $\rho\pi$ and ρK
  - Misreconstructed signal events
    - Mostly due to wrong photon(s)
  - B backgrounds
    - from $b \to c$ and charmless B decays
    - Same lifetime as signal
  - $e^+e^- \to q\bar{q}$
- Fix B background yields, fit for signal yields and CP asymmetries



Validation:

$$\tau = (1.59 \pm 0.12)\text{ps}$$

$$\Delta m_d = (0.51 \pm 0.09)\text{ps}^{-1}$$

Yields and Charge Asymmetries

$$N_{\rho\pi} = 413^{+34}_{-33}$$

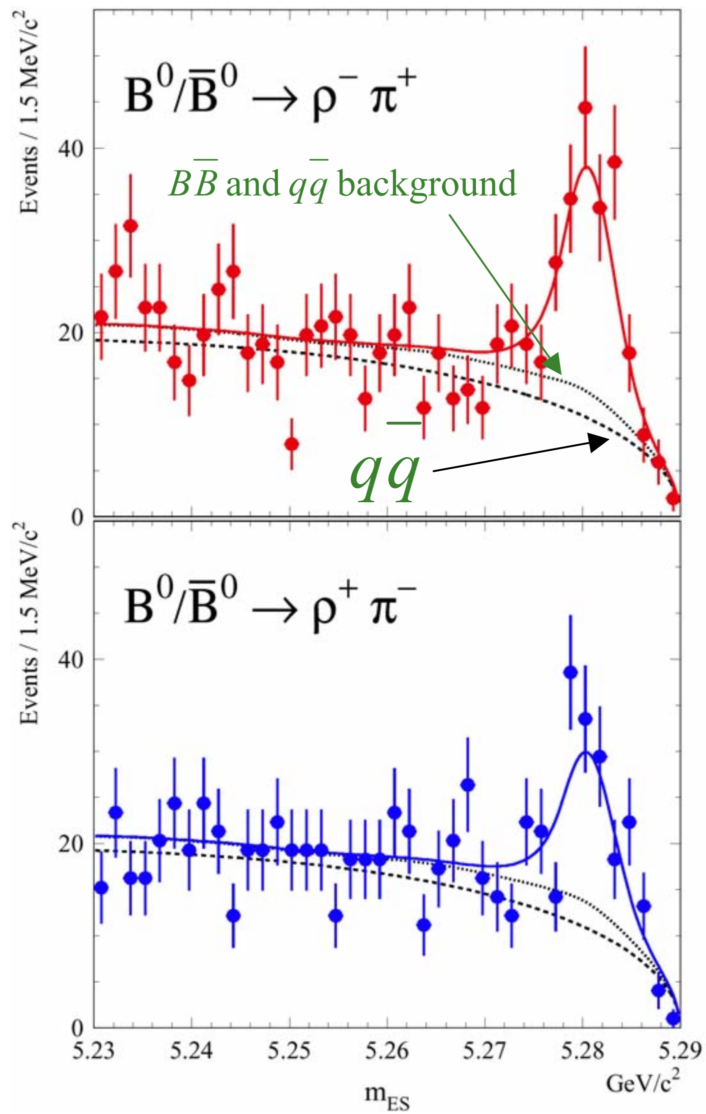
$$N_{\rho K} = 147^{+22}_{-21}$$

hep-ex/0207068

$$A_{CP}^{\rho\pi} = -0.22^{+0.08}_{-0.08}(stat) \pm 0.07(syst)$$

$$A_{CP}^{\rho K} = 0.19^{+0.14}_{-0.14}(stat) \pm 0.11(syst)$$

Preliminary



$B^0 \rightarrow \rho\pi$ time-dependent asymmetry

hep-ex/0207068

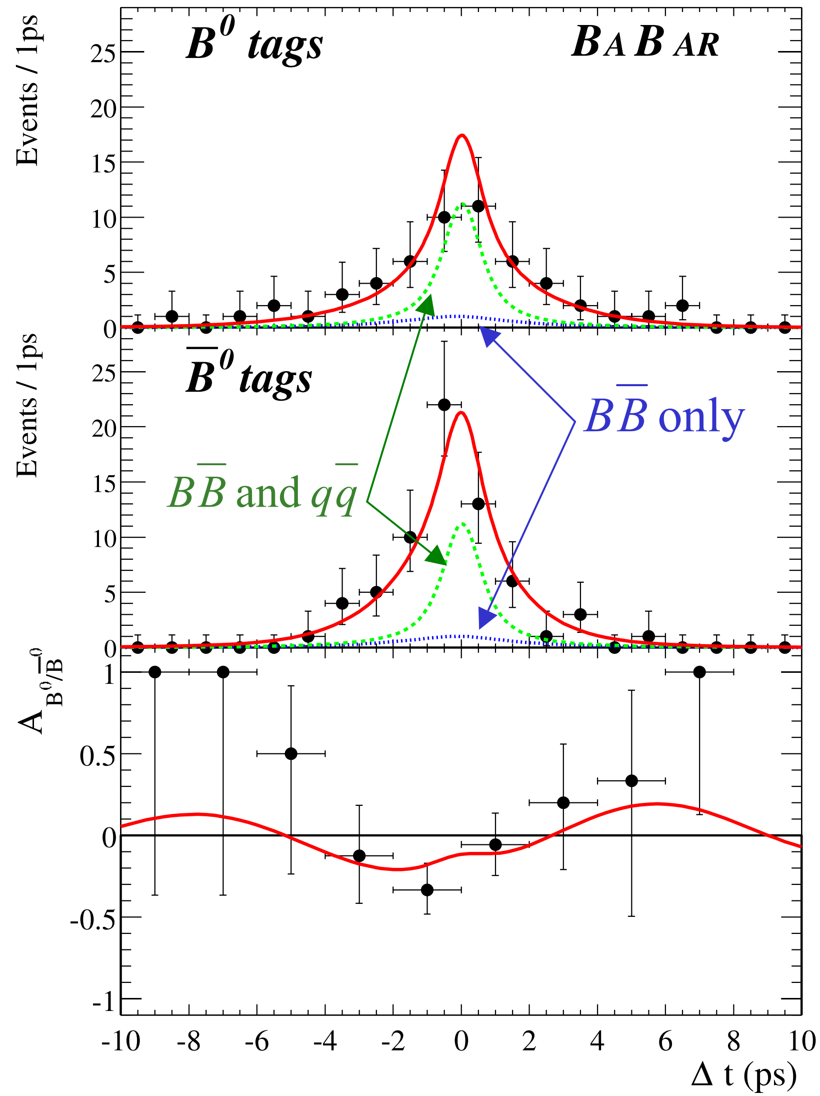
$$C_{\rho\pi} = 0.45^{+0.18}_{-0.19}(stat) \pm 0.09(syst)$$

$$S_{\rho\pi} = 0.16^{+0.25}_{-0.25}(stat) \pm 0.07(syst)$$

Preliminary

$$\Delta C_{\rho\pi} = 0.38^{+0.19}_{-0.20}(stat) \pm 0.11(syst)$$

$$\Delta S_{\rho\pi} = 0.15^{+0.25}_{-0.25}(stat) \pm 0.05(syst)$$



Systematic error dominated by uncertainty on B backgrounds

Summary

- Hyperactive effort within BaBar to constrain, measure, and otherwise determine α
- Charmless two-body decays:
  - No evidence for large direct or indirect CP violation in $\pi\pi$
  - Beginning to piece together the necessary inputs to the isospin analysis
    - Measurements of decay rates for $\pi\pi^0$ and $\pi^0\pi^0$ (upper limit)
    - Too early for a significant constraint
- Charmless three-body decays
  - First measurement of CP asymmetries in $\rho\pi$ and ρK

The next few years will be interesting indeed!